John Adams Institute for Accelerator Science

Imperial College London

Royal Holloway University of London

University of Oxford

Evolution of scientific instruments

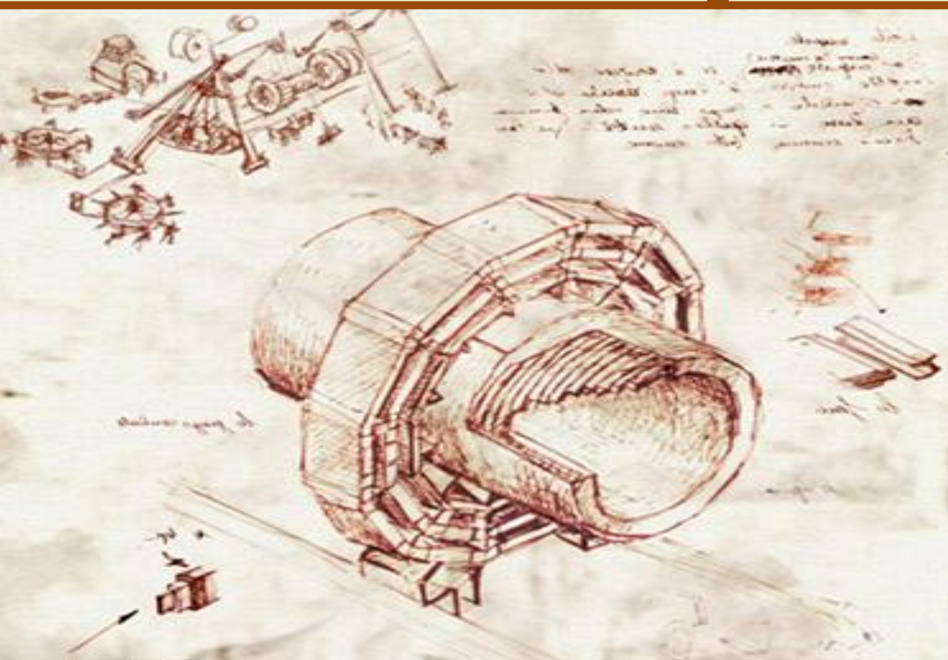
(From methodology of inventiveness to applications of plasma acceleration)

Prof. Andrei A. Seryi

John Adams Institute

JUAS seminar

6 March 2017



LHC sketches by Sergio Cittolin (CERN) – used with permission

Scientific revolutions – what drives them?

Two points of view:

Philosopher Thomas Kuhn:

scientific revolutions are concept-driven

"paradigm shifts"

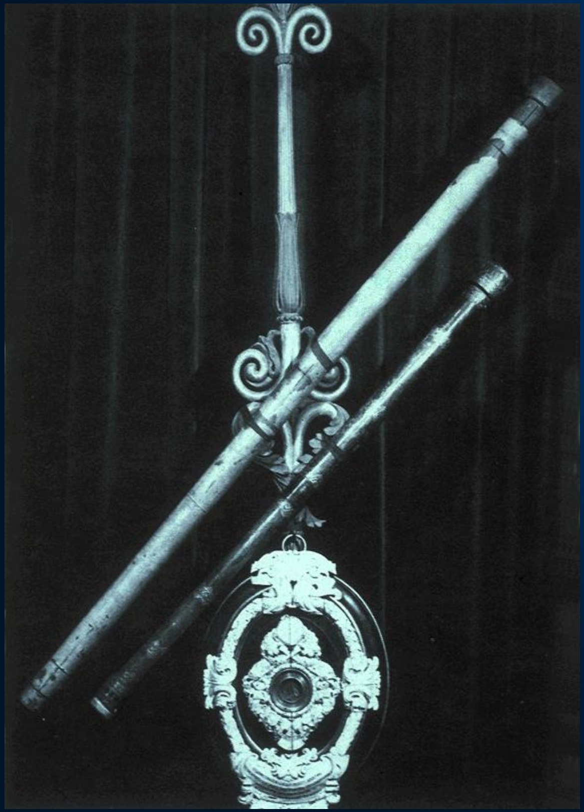
Physicist Freeman Dyson:

scientific revolutions are tool-driven

"The human heritage that gave us toolmaking hands and inquisitive brains did not die. In every human culture, the hand and the brain work together to create the style that makes a civilization….

Science will continue to generate unpredictable new ideas and opportunities. And human beings will continue to respond to new ideas and opportunities with new skills and inventions. We remain toolmaking animals, and science will continue to exercise the creativity programmed into our genes."

"Measure what is measurable,
and make measurable what is not so"



Galileo Galilei
1564-1642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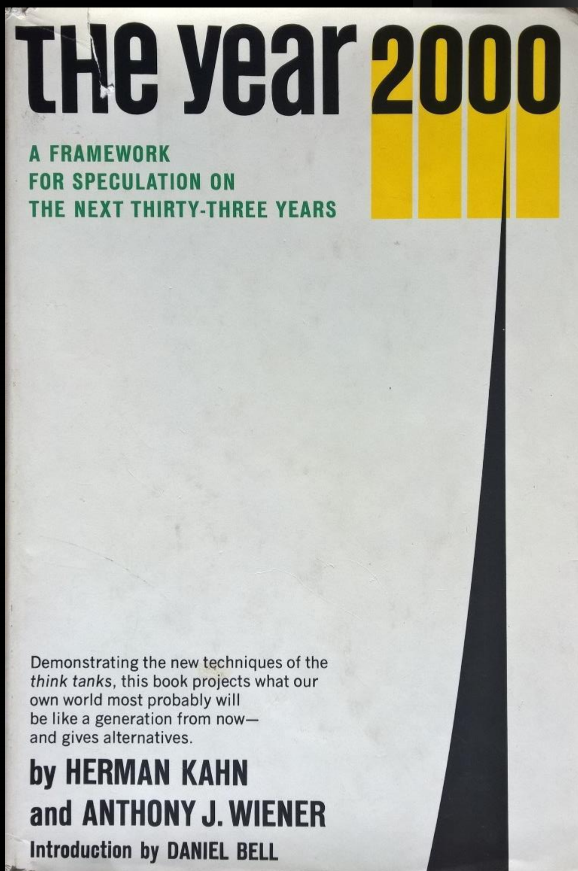
We would like to predict how our field will look like in the second half of 21 century

What scientific instruments will be developed and built?

Predictions made in 1968 for the year 2000



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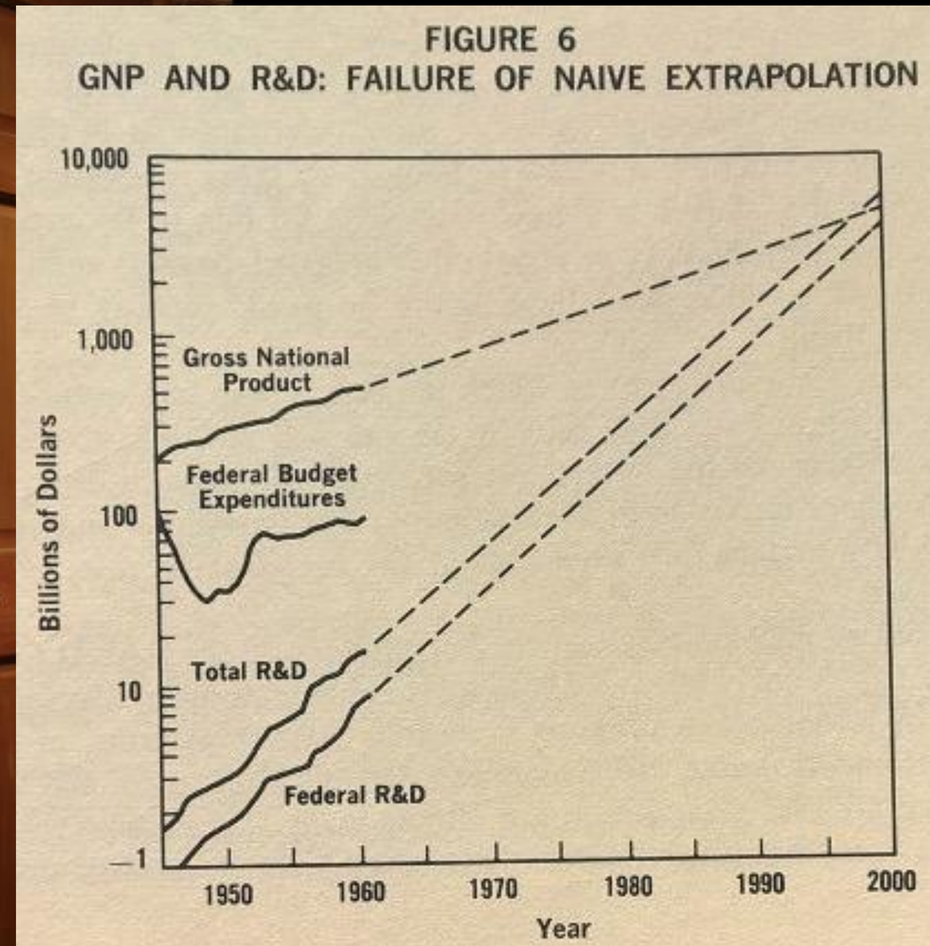


"The Year 2000", 1968
K. Herman, A. Wiener
ISBN 978-0025604407

Importance of rigorous methodology

Predictions made in 1968 for the year 2000, examples:

1- Multiple applications of lasers for sensing, communication, cutting, welding… ✓

31- Some control of weather and/or climate

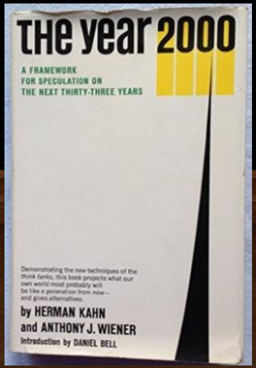
35 – human hibernation for extensive periods (months to years)

58- Chemical methods for improving memory and learning

67- Commercial extraction of oil from shale ✓

81- Personal "pagers" and perhaps even two-way pocket phones ✓

99- Artificial moon for lighting large areas at night



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Some predictions were accurate, some not

To make viable predictions:

Understand the general laws of evolution of science & technical systems

…look across different disciplines

…and explore where other areas of science and technology are dreaming to be in the second half of 21 century

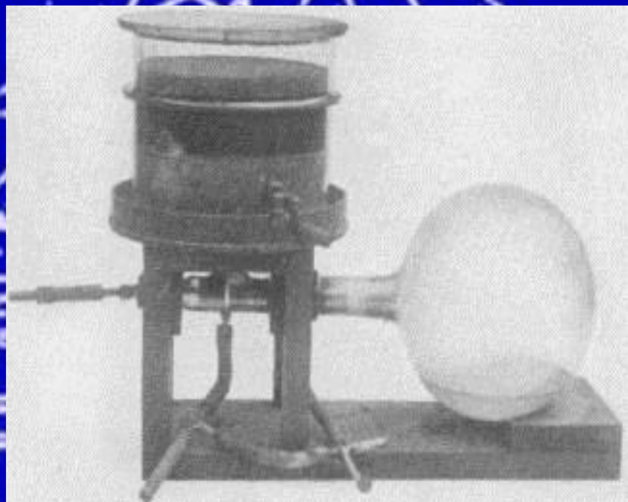
Evolution laws and principles

Are there some patterns in evolution of scientific instruments?

Are there some principles that connect inventions of different instruments?

Let's look at some familiar examples from a different angle

Cloud and bubble chambers

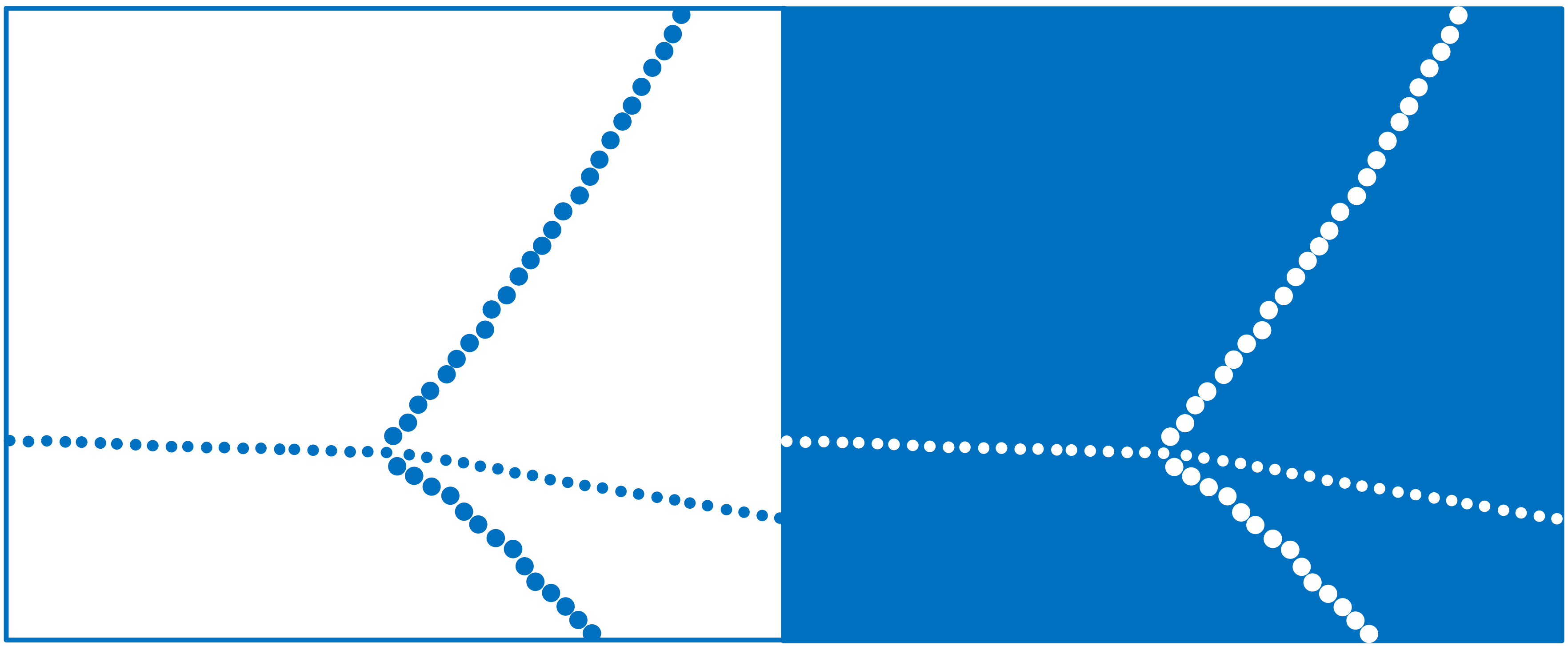


Wilson's Cloud chamber invented in 1911

Bubble Chamber (invented in 1952 by D. Glaser – Nobel prize 1960)

On the photo Bubble chamber being installed near Fermilab

Cloud and bubble chambers

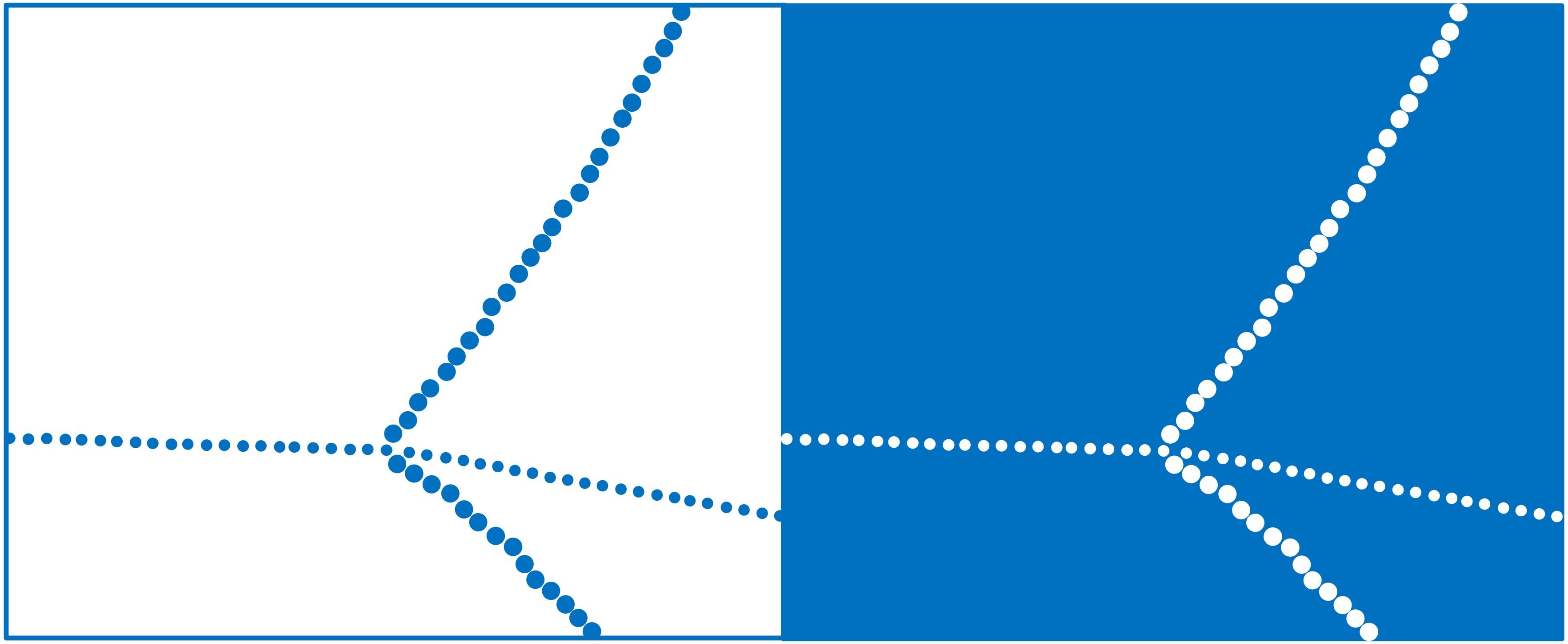


Wilson's Cloud chamber invented in 1911

Glaser's Bubble chamber, invented in 1952

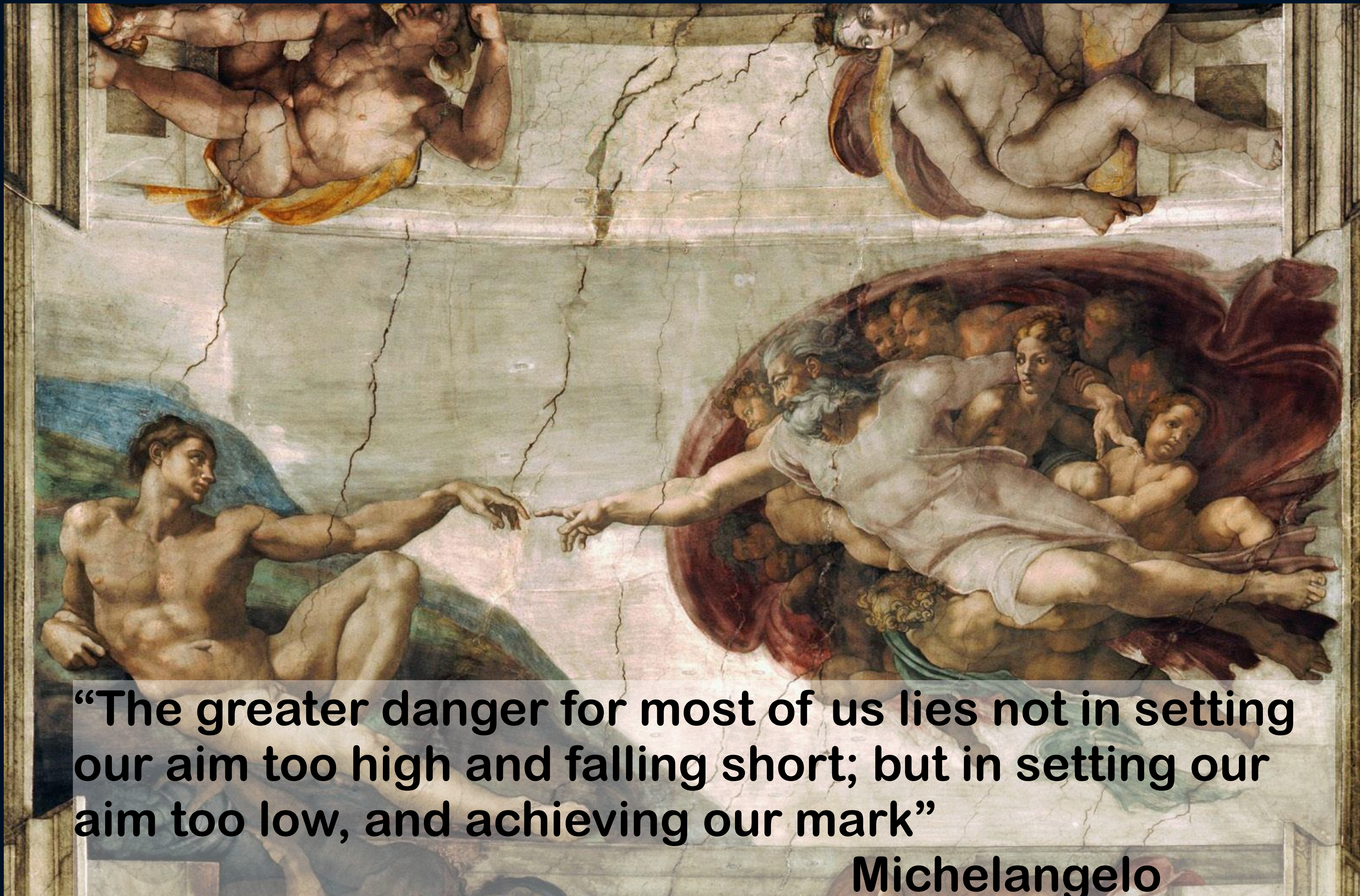
It seems these two instruments are connected via some general principle… Let's call it principle of "the other way around" or "system and anti-system"

Cloud and bubble chambers



Wilson's Cloud chamber invented in 1911 | **Glaser's Bubble chamber, invented in 1952**

Bubble chamber could have been invented immediately, and not 40 years later after the cloud chamber, if we would have applied the principle of "system and anti-system"



"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark"

Michelangelo

Two scientific instruments

What are these two instruments?

What is in common?

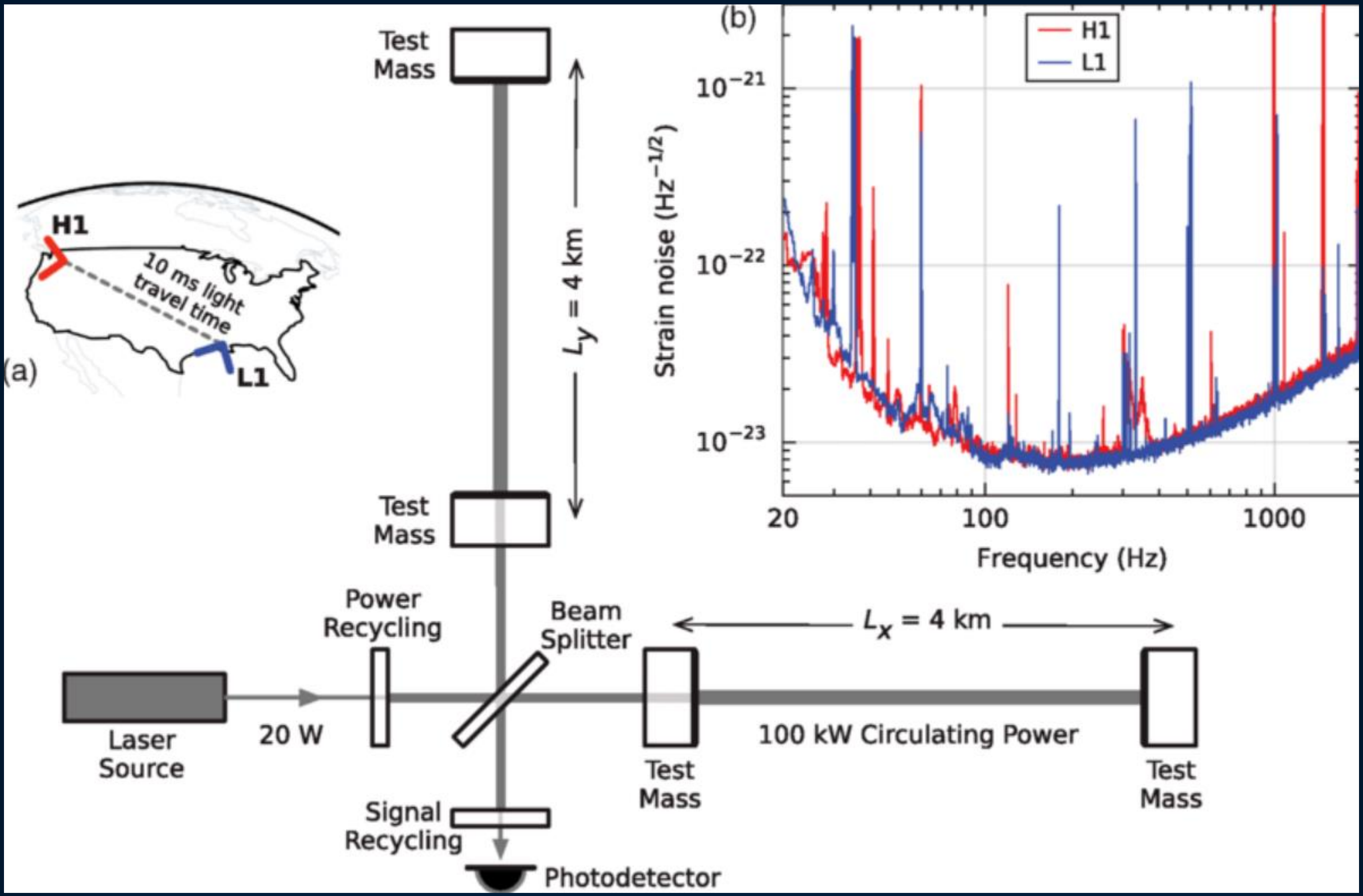
Two scientific instruments

LIGO, Hanford

SLC, Stanford

A lot. And also sensitivity to seismic noises.

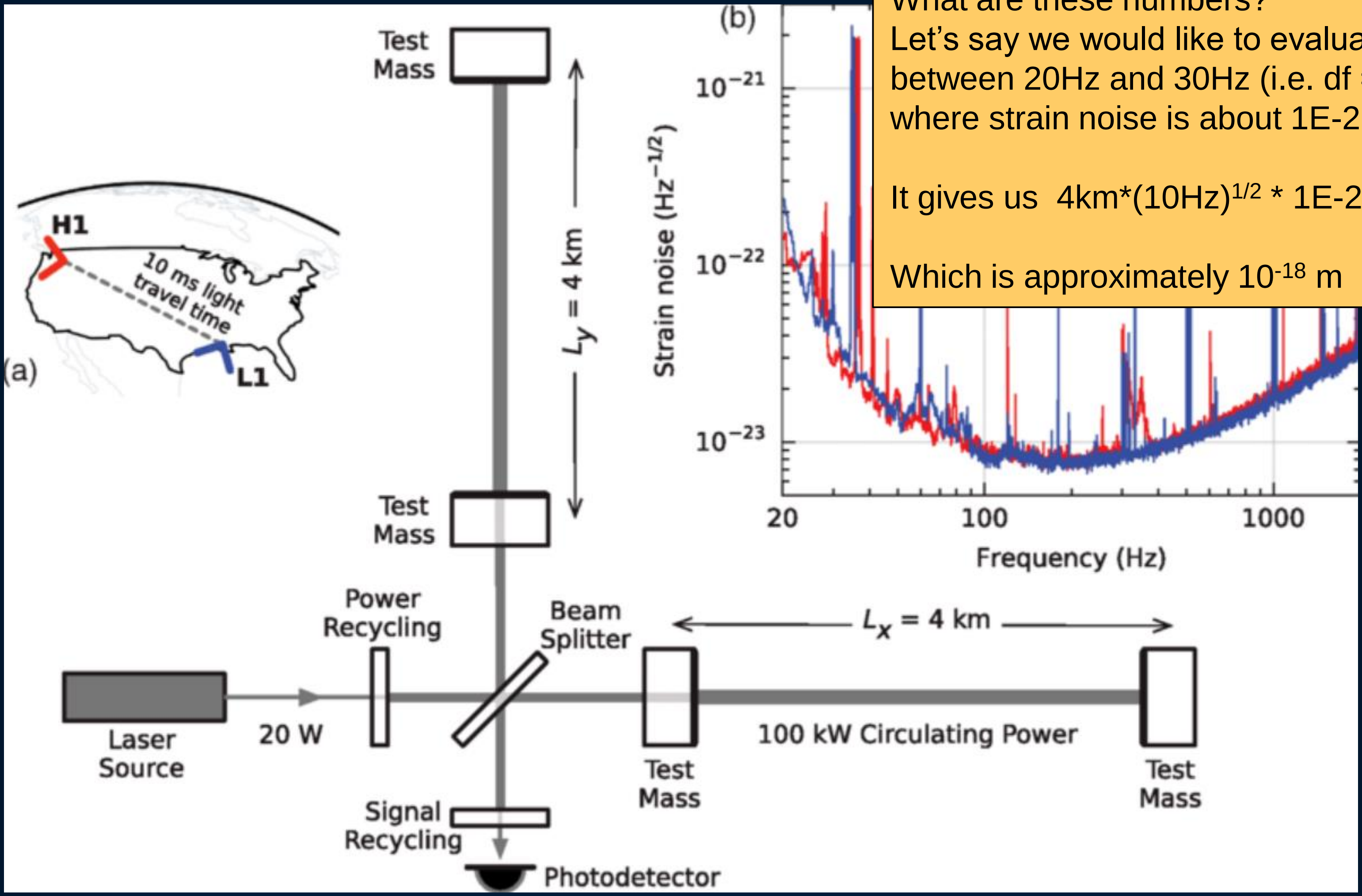
LIGO



LIGO layout and sensitivity curve

Source: PRL 116, 061102 (2016)

LIGO



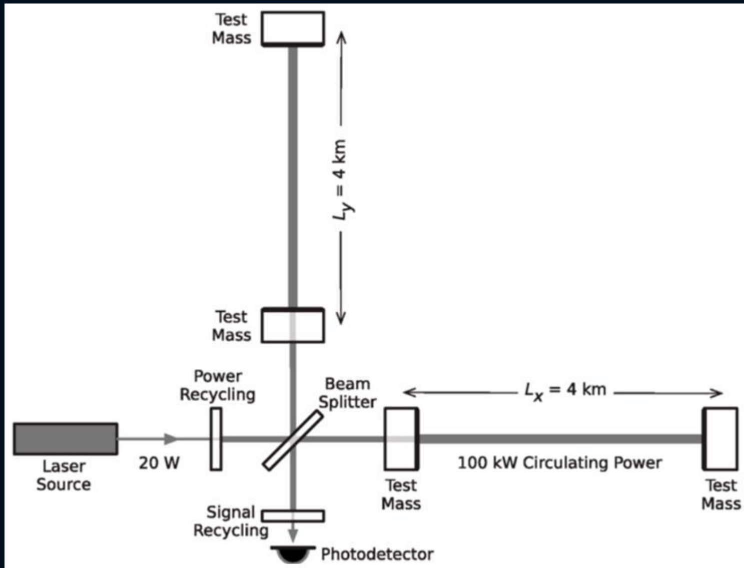
What are these numbers?
Let's say we would like to evaluate noise between 20Hz and 30Hz (i.e. df = 10Hz), where strain noise is about 1E-22 Hz$^{-1/2}$

It gives us 4km*(10Hz)$^{1/2}$ * 1E-22 Hz$^{-1/2}$

Which is approximately 10^{-18} m

LIGO layout and sensitivity curve

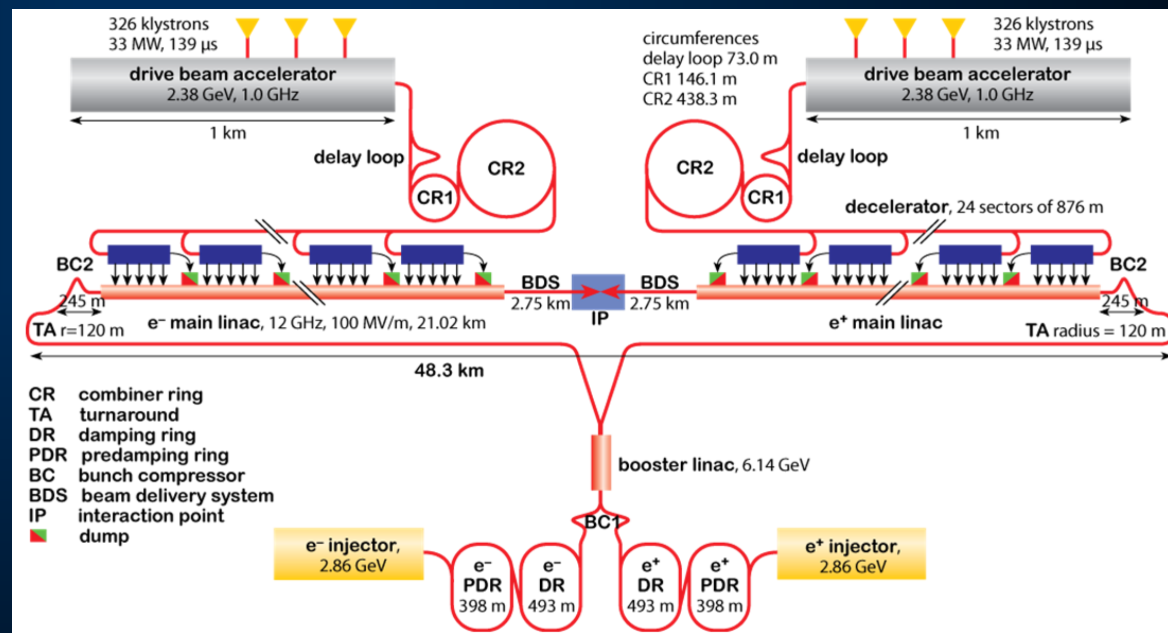
Source: PRL 116, 061102 (2016)



These two instruments

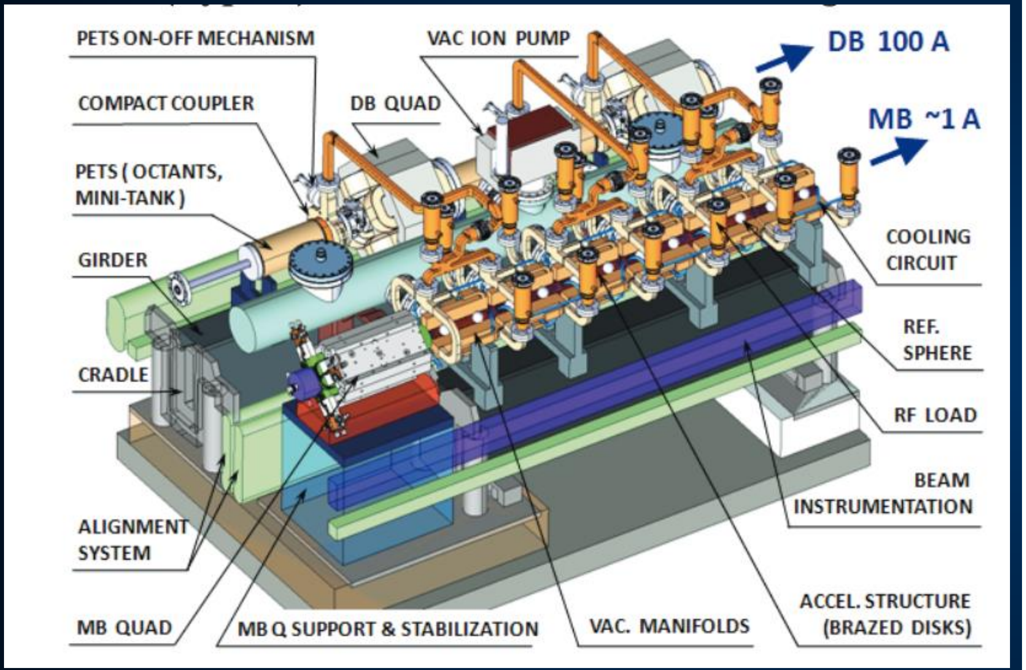
LIGO: keep two objects placed 4km apart stable* to about 1e-9 nm

CLIC – Compact Linear Collider: keep 100,000 objects distributed over 50km stable* to about 10 nm

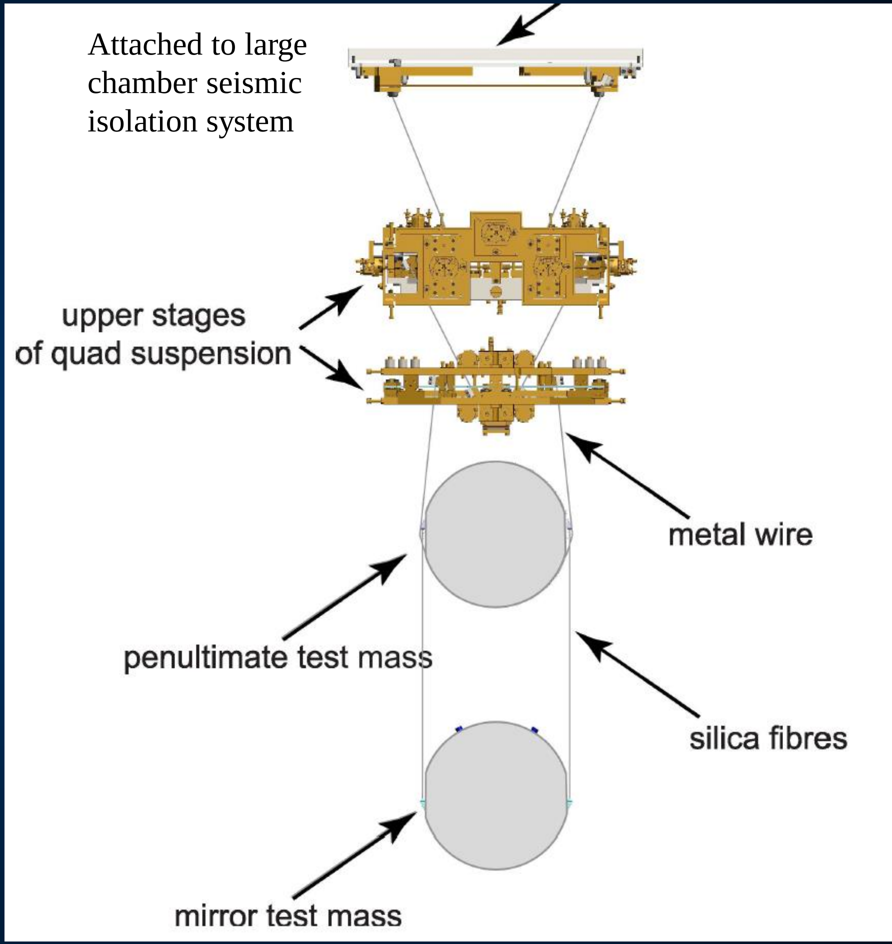


*) approximately, and in certain frequency range

CLIC stability & LIGO test mass isolation



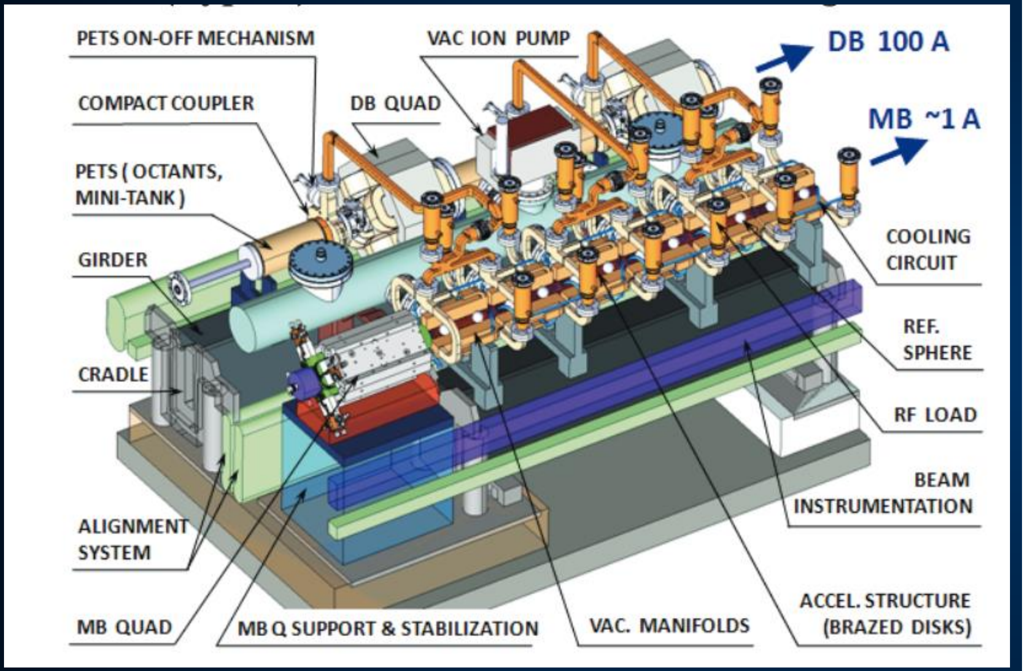
Nested stabilization/alignment systems of CLIC two-beam module

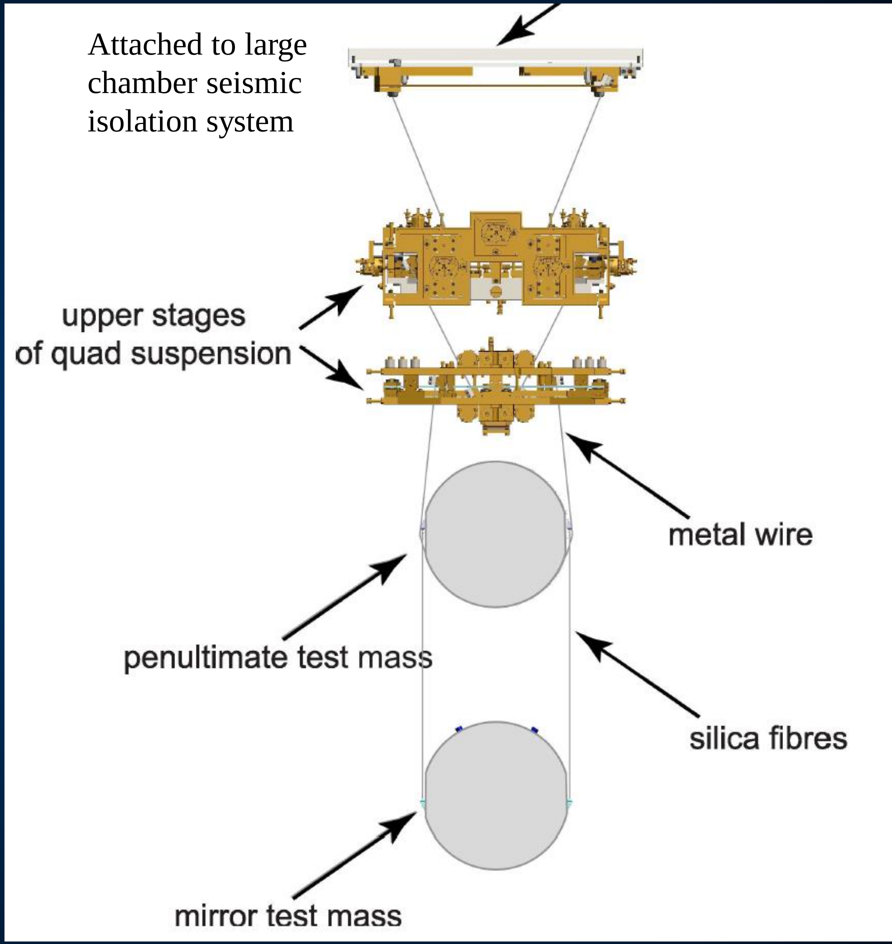


Nested pendulums of LIGO

Source: arXiv:1102.3355

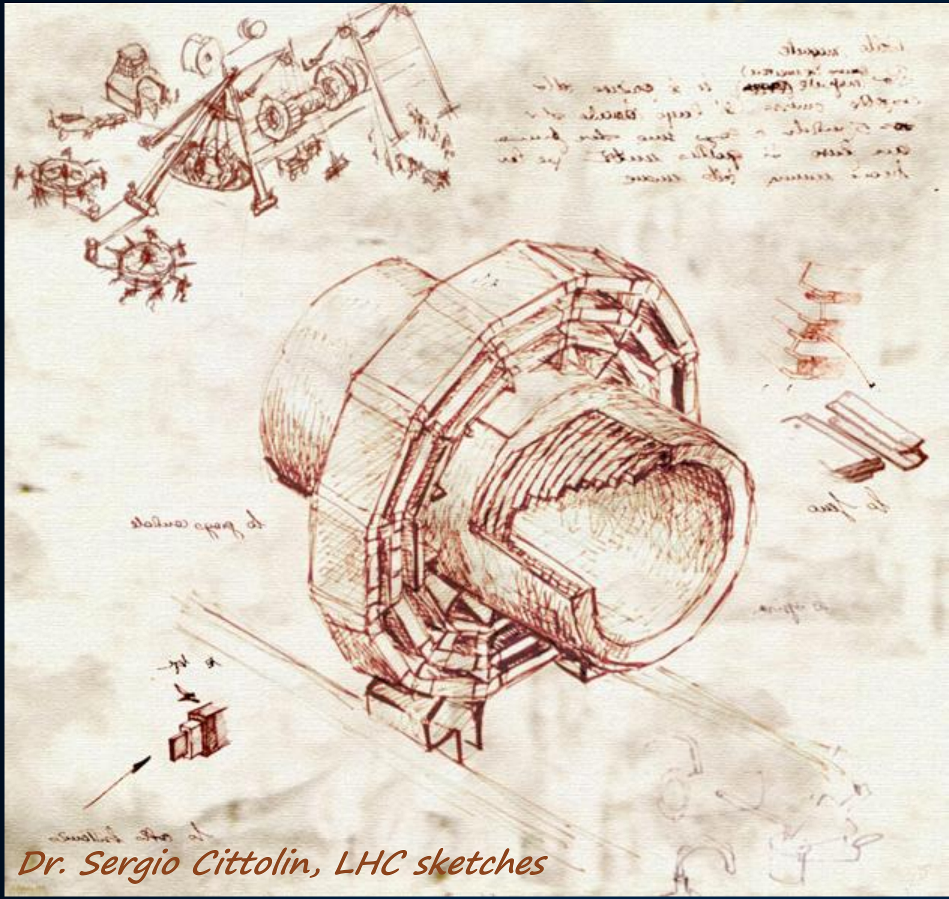
CLIC stability & LIGO test mass isolation

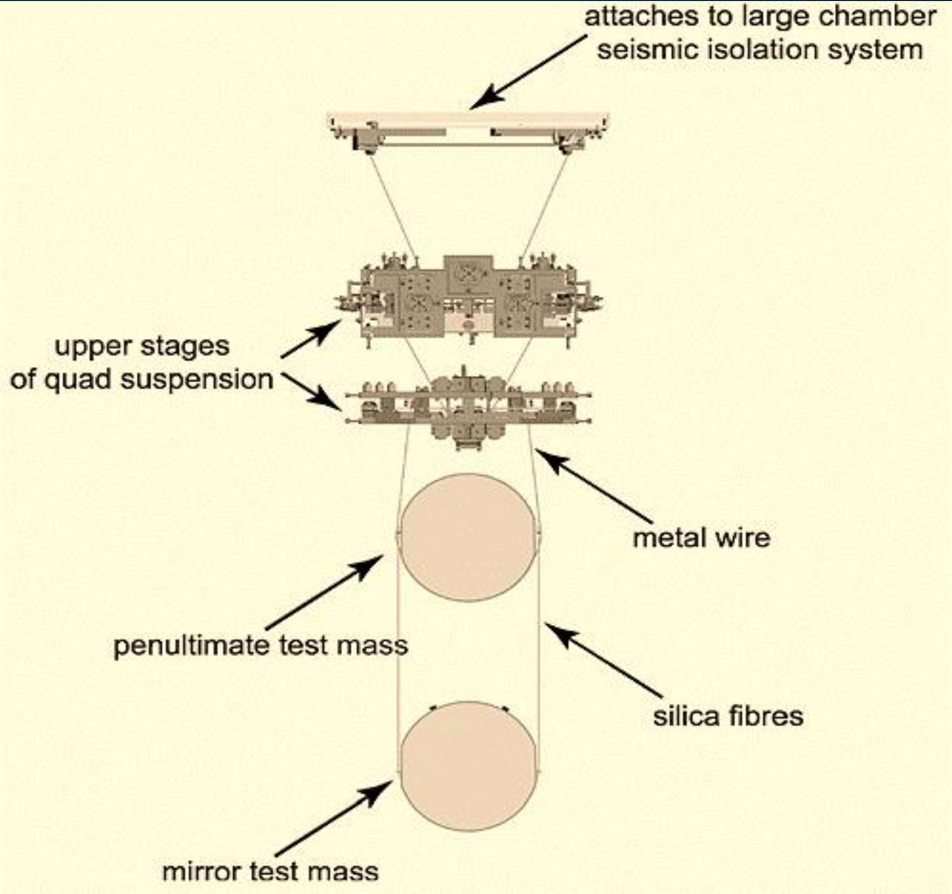




… it seems that this is again some general principle! Let's call it the principle of "nested dolls"

Particle or gravitational waves detectors are arranged just as nested dolls…





Examples of “nested dolls” *inventive principle* can be found in various areas

The principle of “nested dolls” in poetry

“This is the house that Jack built”

This is the house that Jack built.

This is the malt
That lay in the house that Jack built.

This is the rat,
That ate the malt
That lay in the house that Jack built.

This is the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

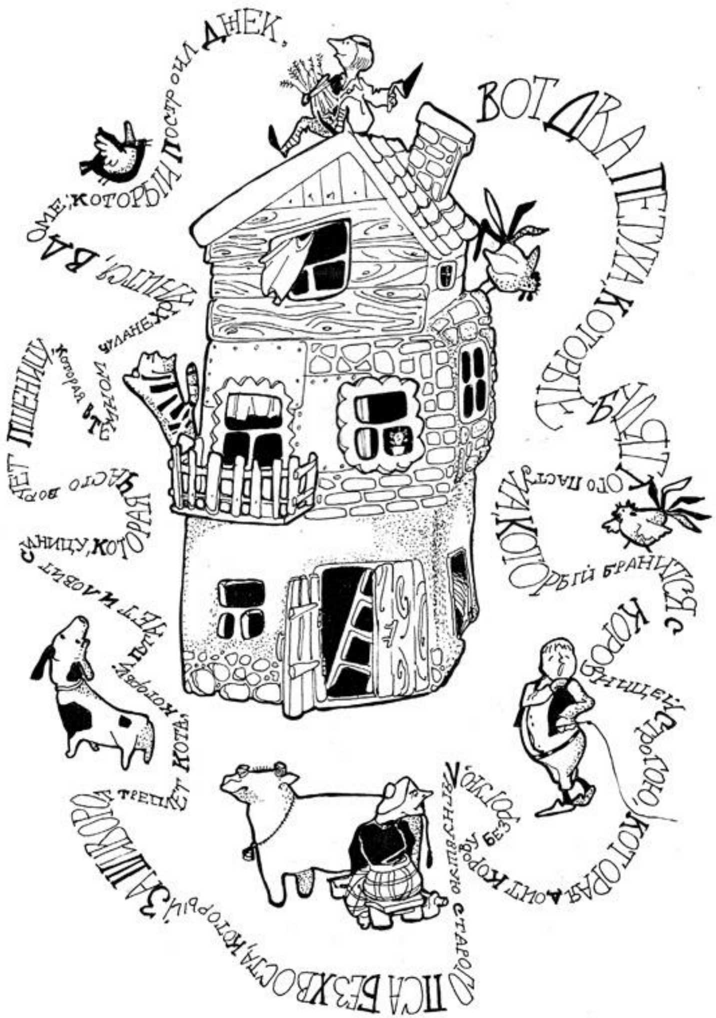


Illustration by Olga Rubtsova (Atroshenko)

This is the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the farmer sowing his corn,
That kept the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

Mother Goose Rhymes

The principle of “nested dolls” in poetry

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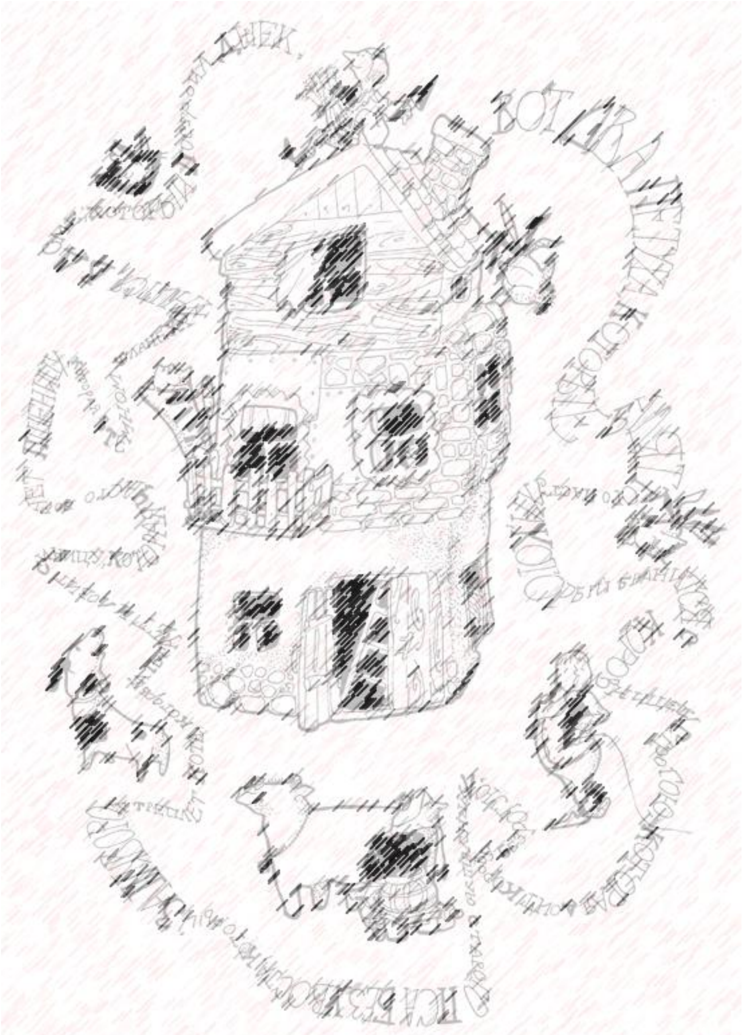

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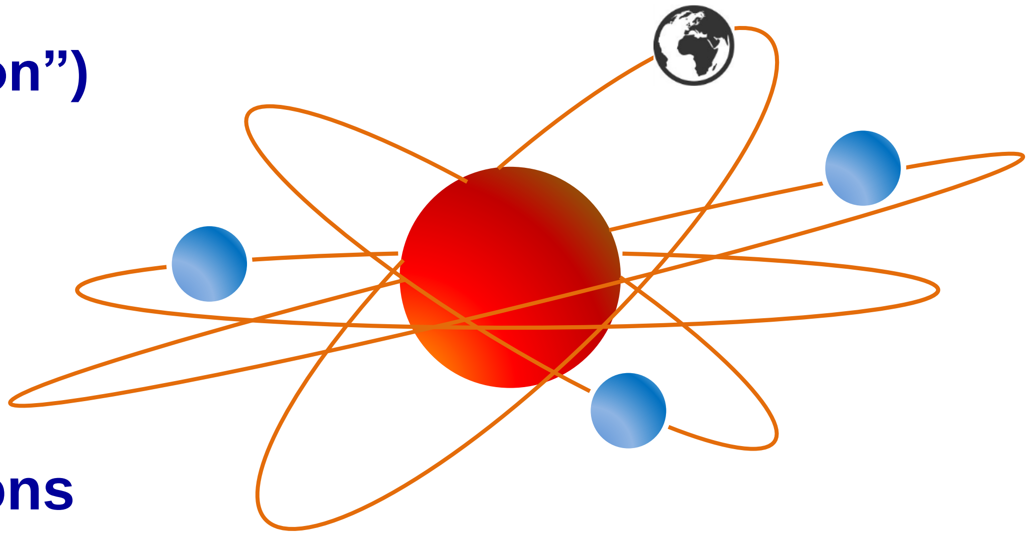
That lay in the house that Jack built.

Mother Goose Rhymes

Is there any example of this principle in science fiction?

The principle of “nested dolls” in sci-fi poetry

Valery Bryusov – 1920 poem
“Atom” (“The World of Electron”)



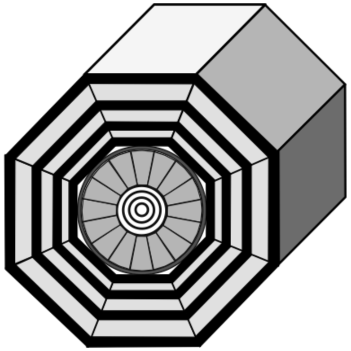
Can you imagine that electrons
Are planets circling their Suns?
Space exploration, wars, elections
And hundreds of computer tongues
…

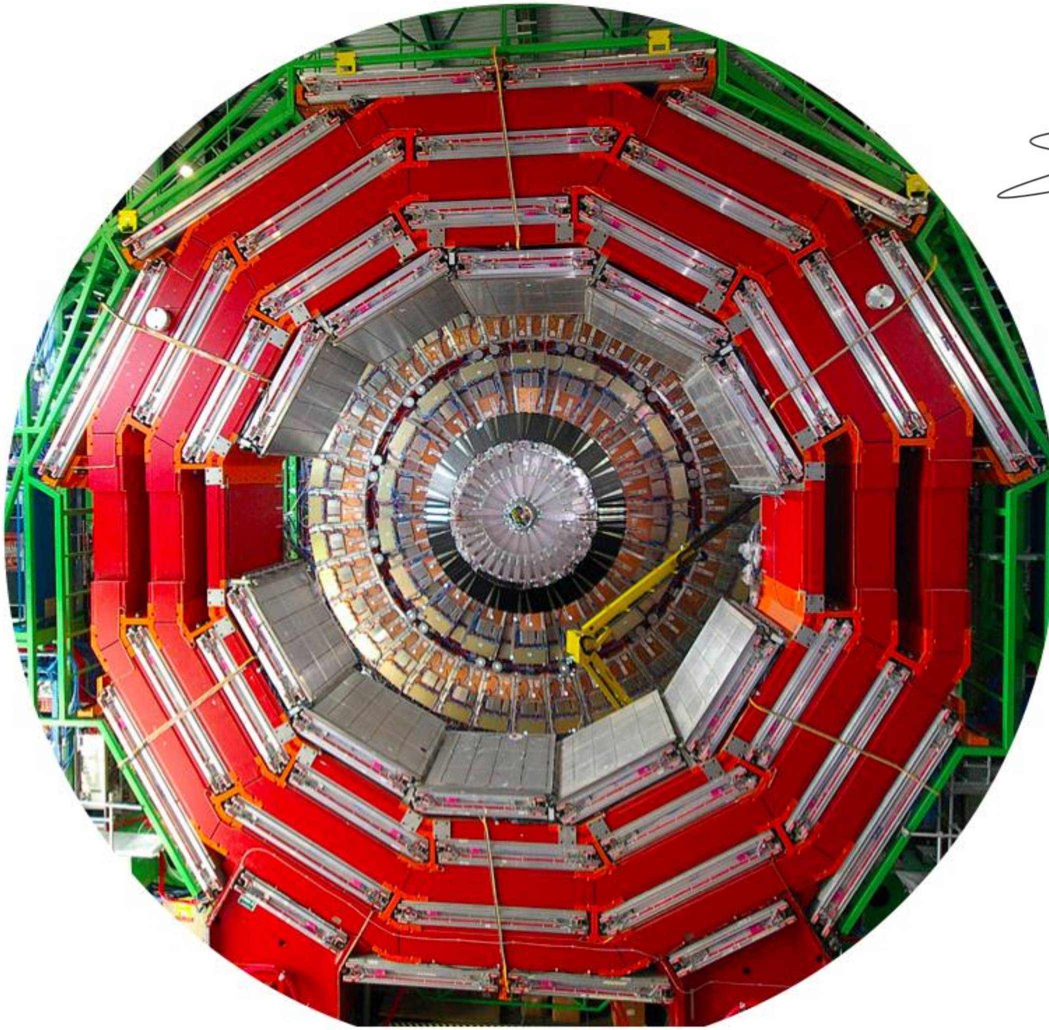
Remake-translation by A.Seryi

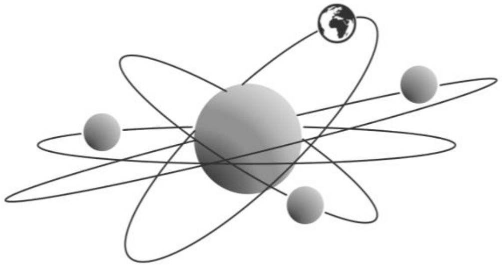
Быть может, эти электроны
Миры, где пять материков,
Искусства, знанья, войны, троны
И память сорока веков!

Ещё, быть может, каждый атом —
Вселенная, где сто планет;
Там — всё, что здесь, в объёме сжатом,
Но также то, чего здесь нет.
…

Is there world inside of an electron?

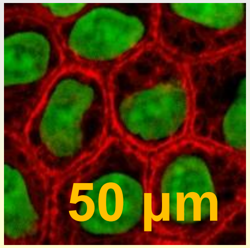






Accelerators and detectors can help to understand whether there is a world inside of an electron

Chemistry Nobel 2014 & inventive principles?



Extra magnification?

CELLS
Twenty per mm

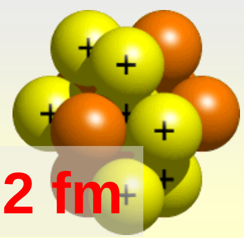
Microscope

x 25 thousand

DNA
Five hundred thousand per mm

Electron microscope

x 1 million



Nucleus
Five hundred billion per mm

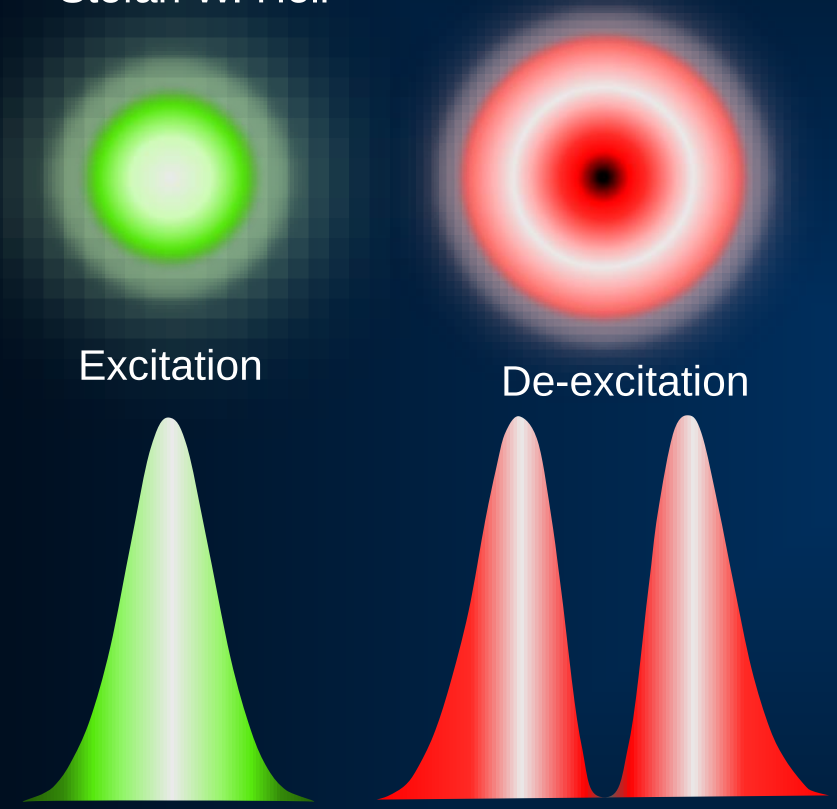
Particle Accelerators

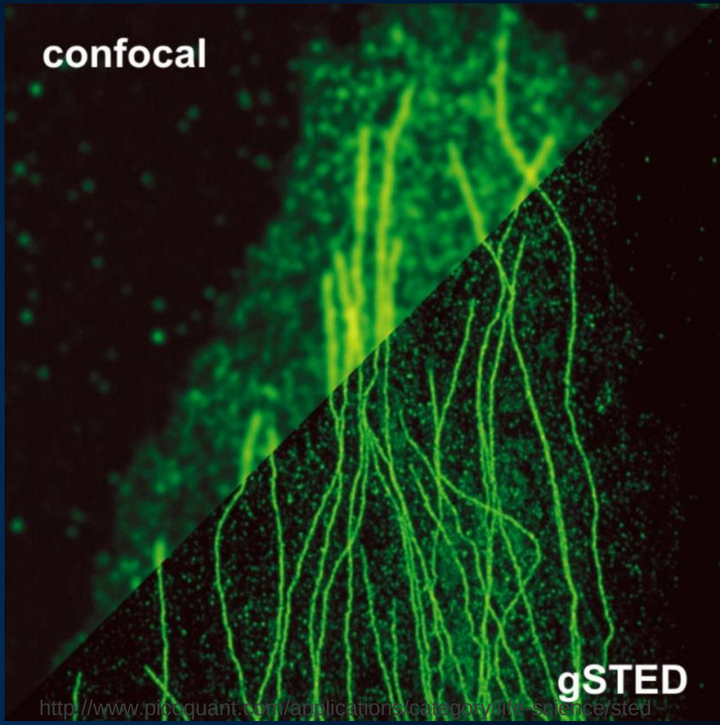
x 2 thousand

Quarks
More than one million billion per mm

Chemistry Nobel 2014 …

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell



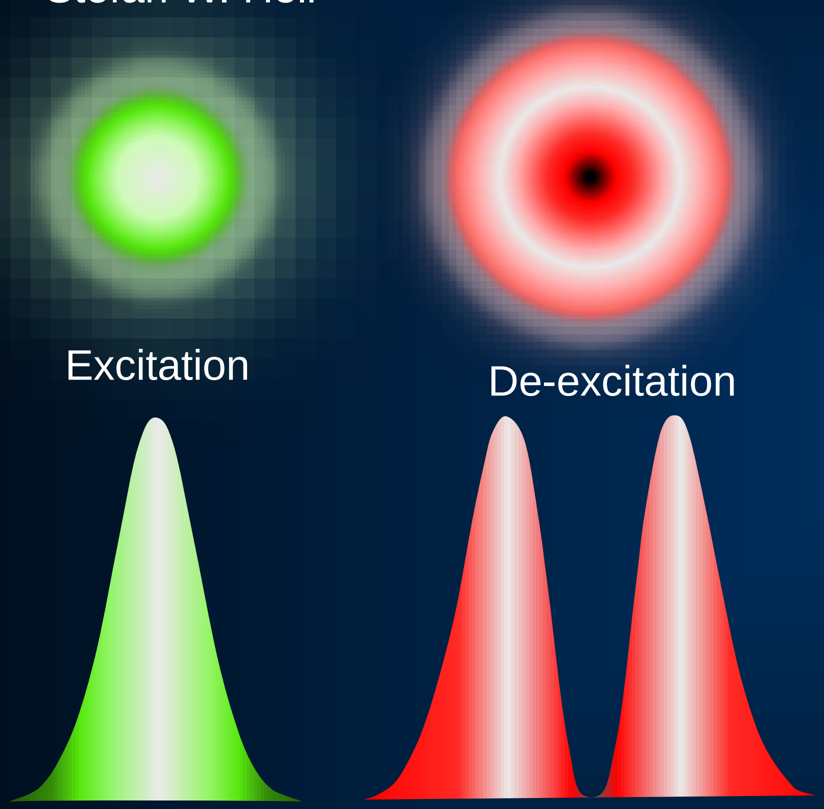


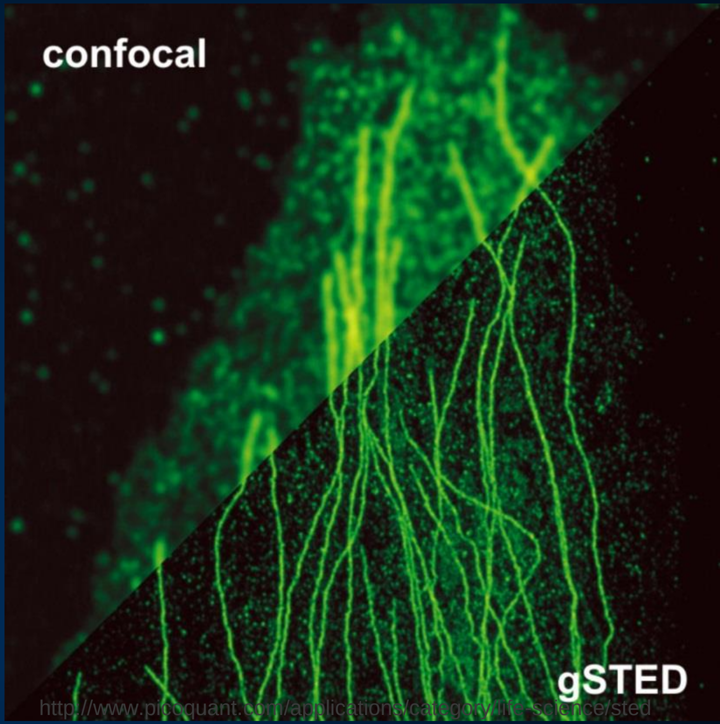
(gated) STED image of Tubulin vs standard confocal image

This can improve the resolution to be a factor of several below the wavelength of light

Chemistry Nobel 2014 & inventive principles

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell





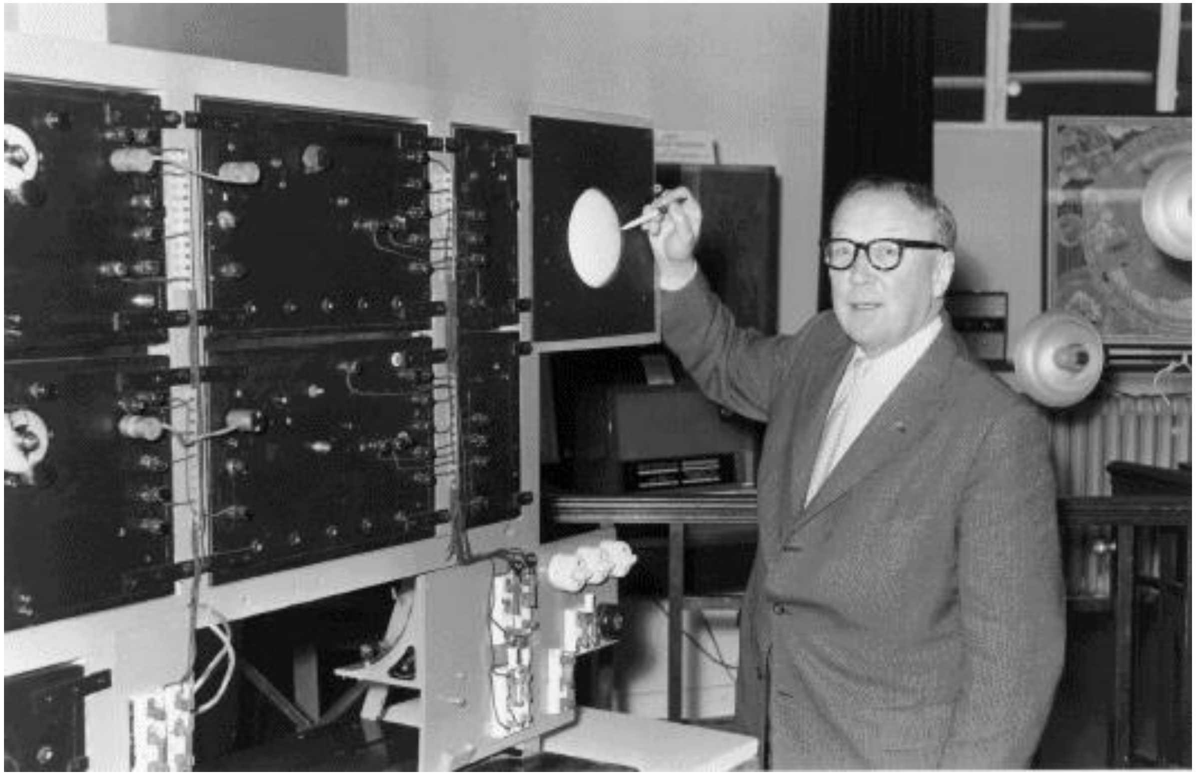
(gated) STED image of Tubulin vs standard confocal image

And this can be viewed as a combination of the inventive principles “system and anti-system” and “nested dolls”

Development of Radar

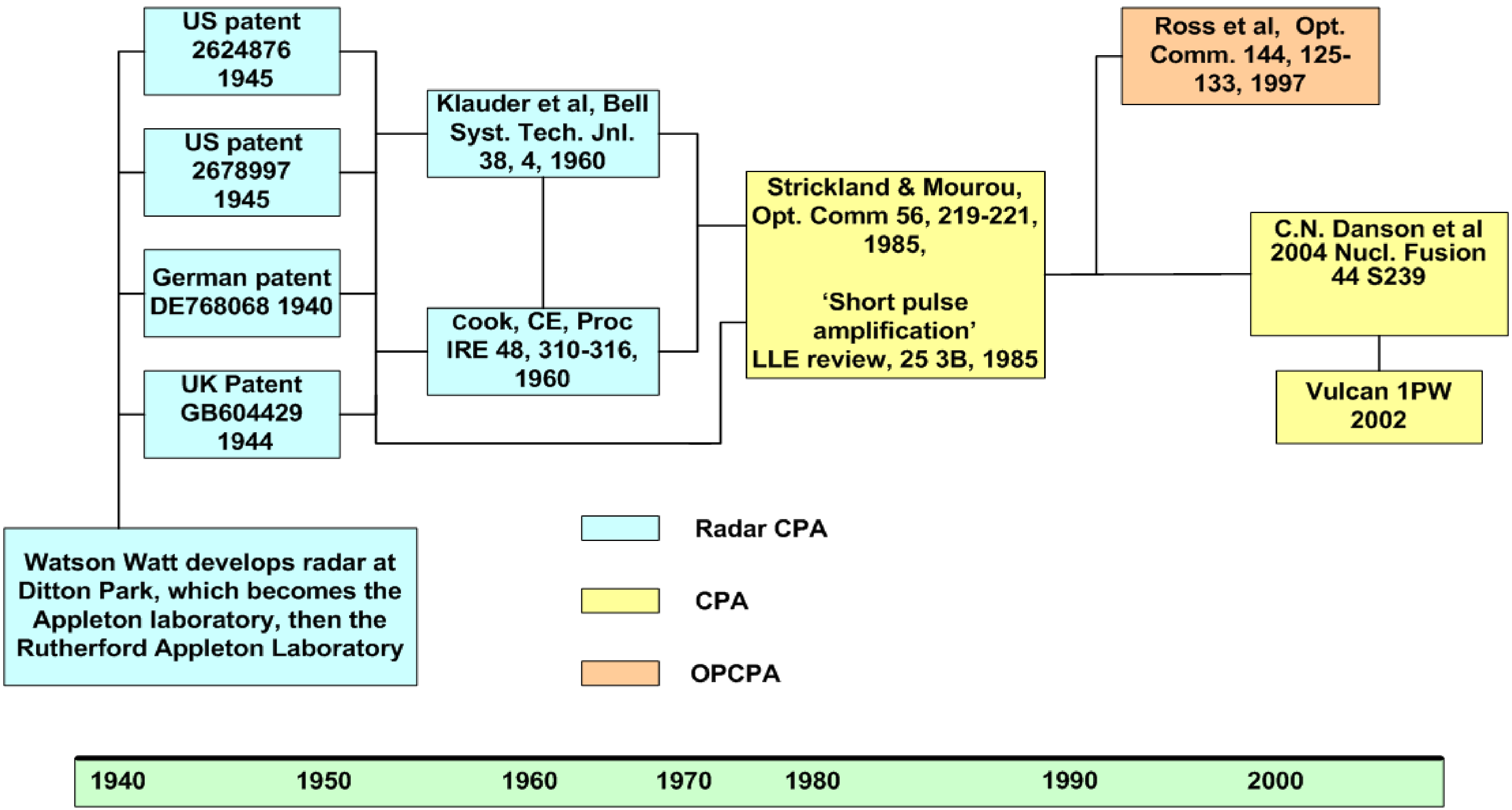
Sir Robert Watson-Watt with the original British Radar Apparatus made at Ditton Park in 1935 this became the Appleton Laboratory Merged with the Rutherford Laboratory to become Rutherford Appleton Laboratory.

This apparatus is now in the London Science Museum.



Slide from Bob Bingham, CLF, STFC

Radar and Laser Amplification

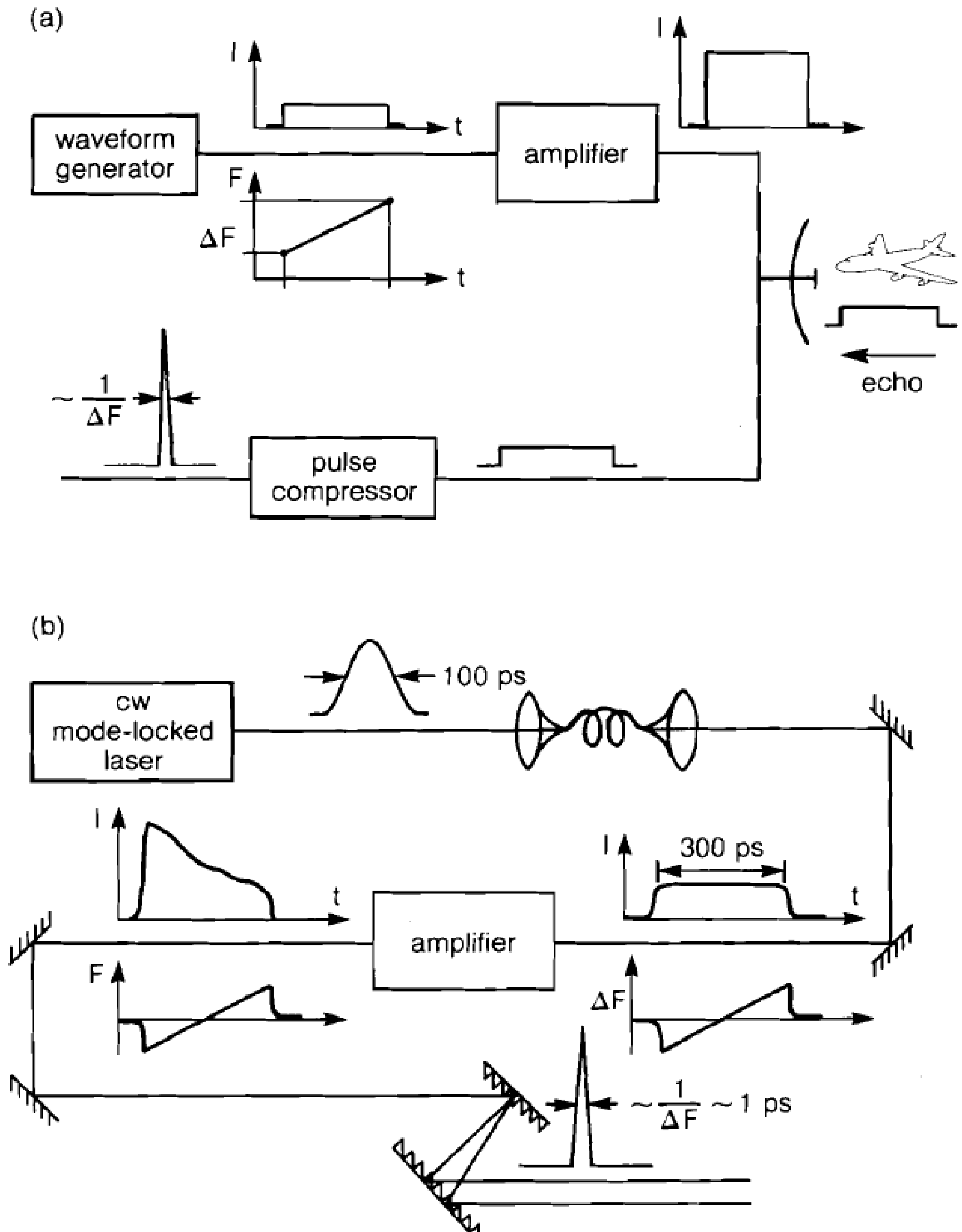


Slide from Bob Bingham, CLF, STFC

Chirped pulse amplification from Radar to Lasers (CPA)

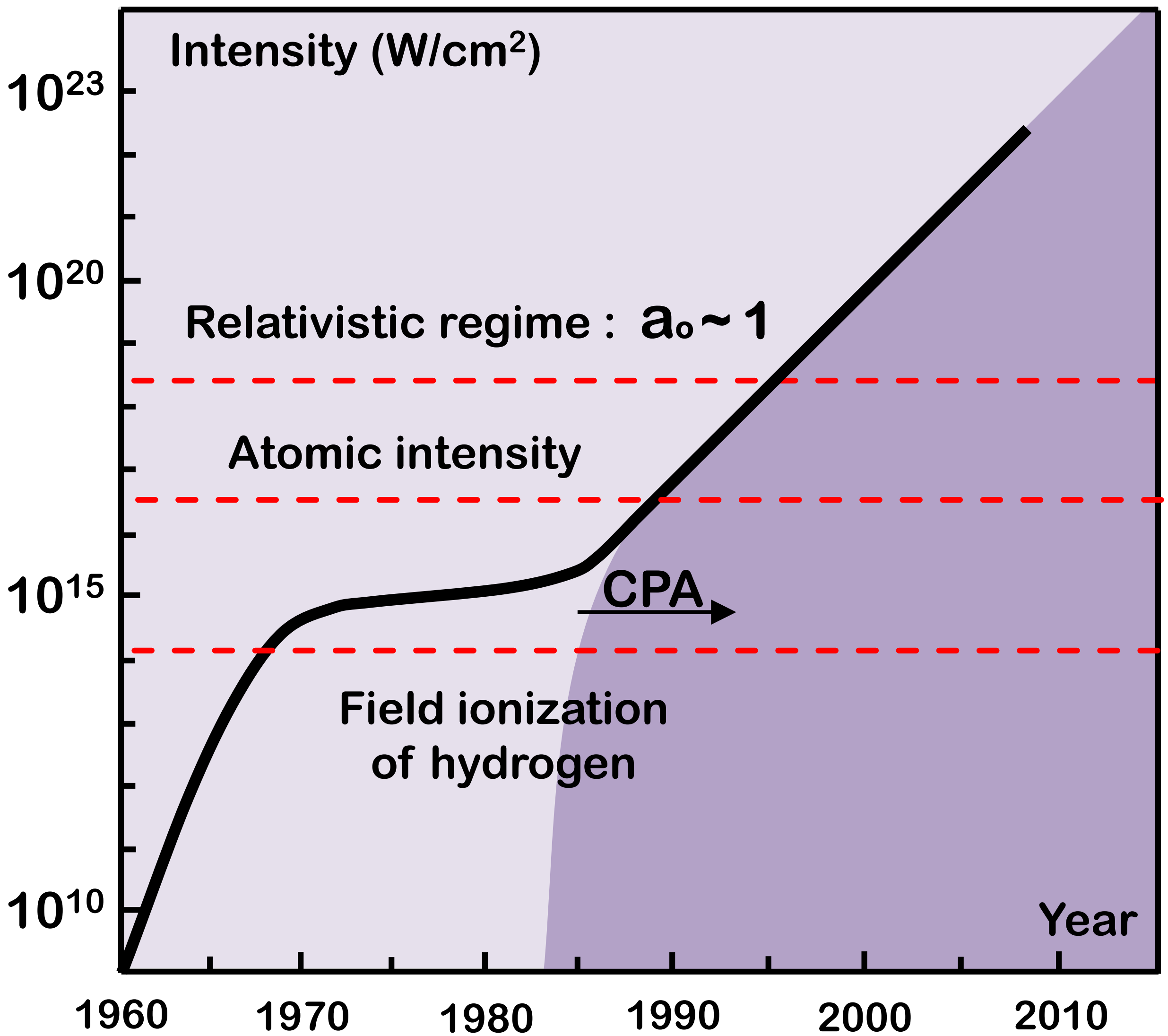
Diagrams taken from early LLE review On the comparison between RADAR chirped pulse amplification from the 1940 onwards upper diagram and laser chirped pulse amplification bottom diagram carried out at the LLE Rochester.

LLE Review 25 3B 1985.



Slide from Bob Bingham, CLF, STFC

CPA invention: exponential growth of laser power



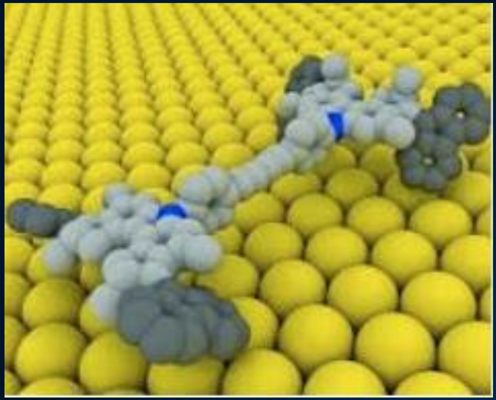
Progress in peak intensity since laser invention in 1960

Radar and CPA

Evolution from chirped pulse amplification in radars to lasers seem to demonstrate one of the general trends in science and technology:

From mechanical oscillations to EM, and within EM from microwave to optical frequencies

Nobel prize 2016 – molecular machines



Pierre Sauvage, J. Fraser Stoddart, and Ben L. Feringa, Chemistry Nobel Prize 2016

This is a machine…

Are there some laws, developed in conventional machinery, that allow to predict what parts of molecular machine would be invented next?

We will come back to this later in the talk…

Let's now talk about inventiveness

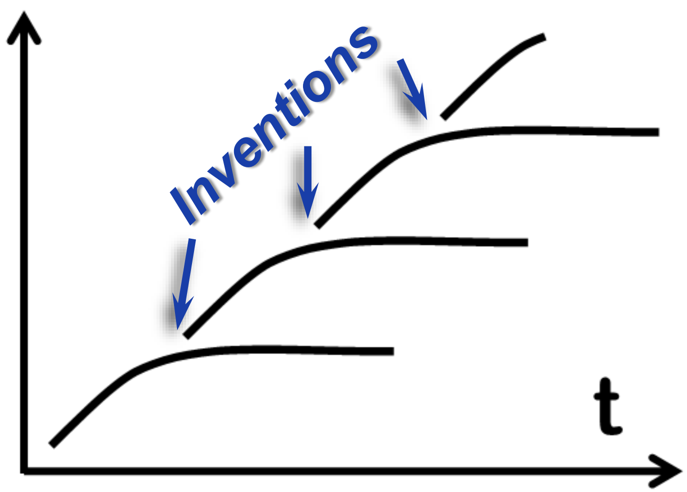
We have seen several examples of what seem to be some general inventive principles and evolution laws

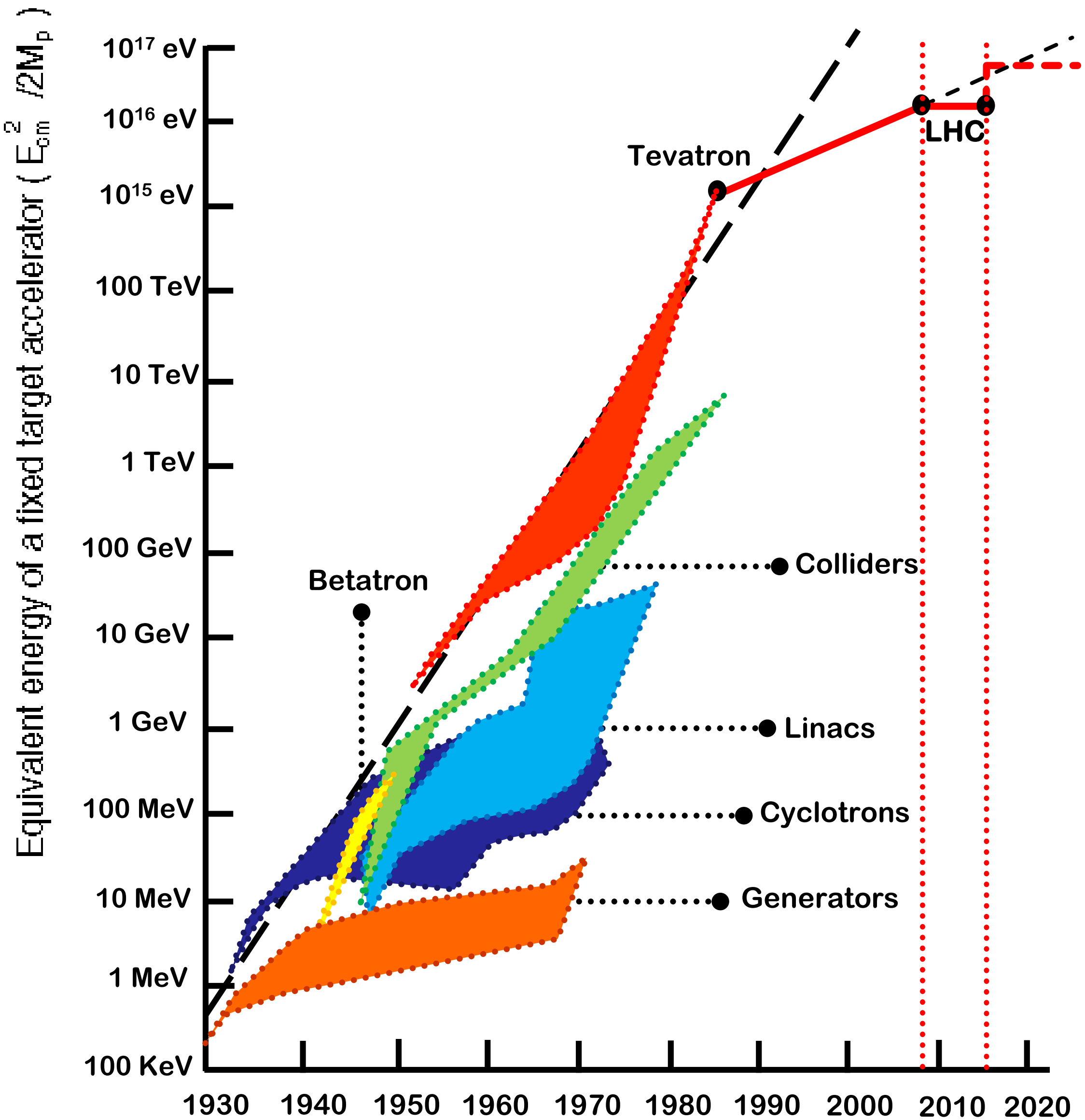
It happens that many of such inventive principles and evolution laws are known for half a century and widely used…
…but so far not in science

Let's discuss this in more detail, but before we start let's look at couple of inventions in accelerator areas…

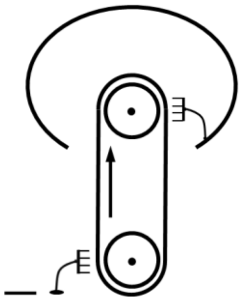
"Livingston plot"

- History of accelerators…
- …and evolution *(and saturation)* of particular technologies of acceleration, and birth of the new technologies *via inventions*

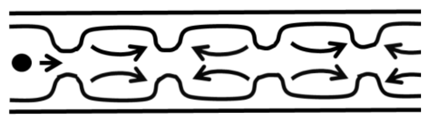




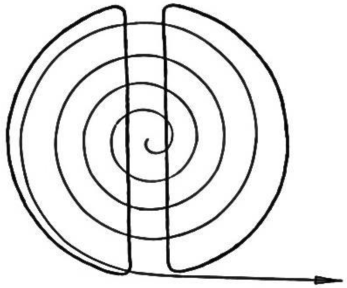
Accelerators – selected inventions



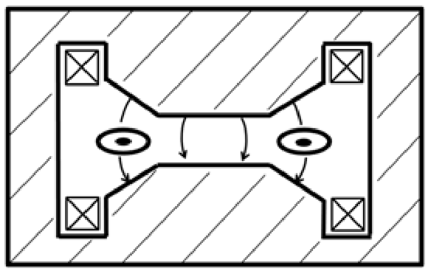
Electrostatic Acc.



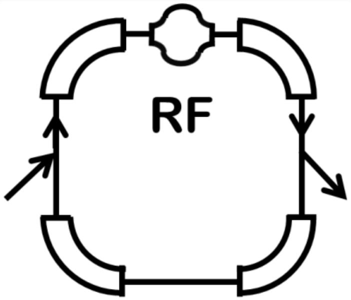
Resonant Linear Acc.



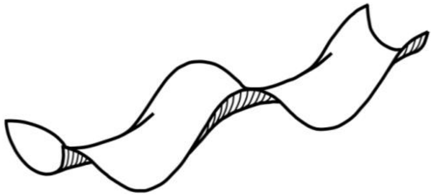
Cyclotron



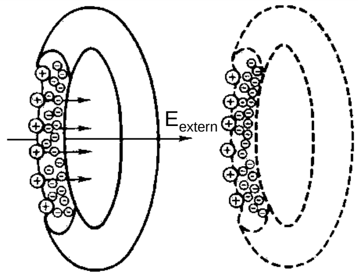
Betatron



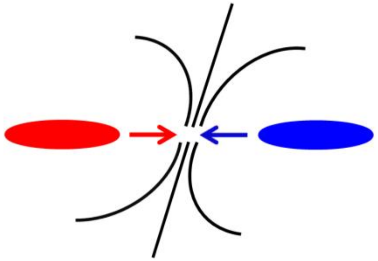
Synchrotron



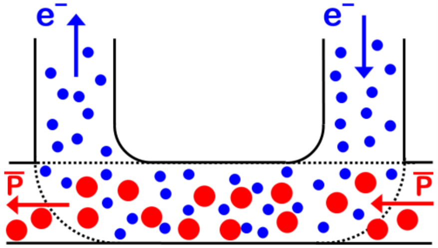
Strong focusing



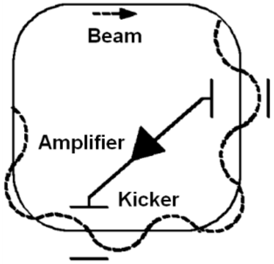
Collective acceleration



Colliders

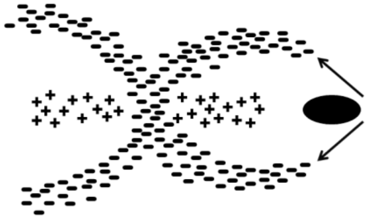


Electron cooling



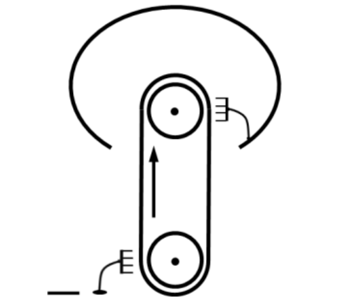
Stochastic cooling

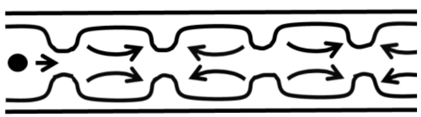
SC magnets and RF

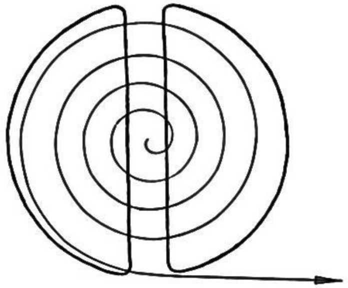


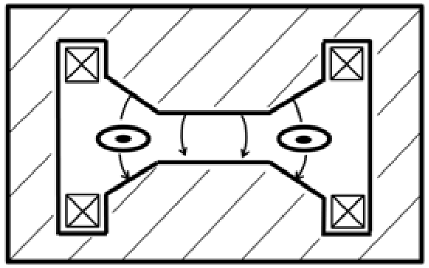
Plasma acceleration

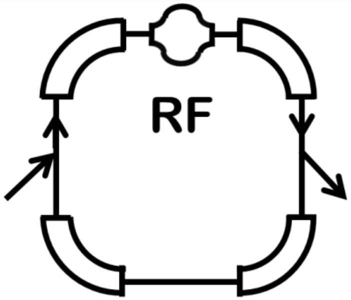
Accelerators – selected inventions


Electrostatic Acc.

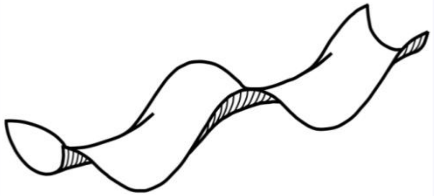

Resonant Linear Acc.

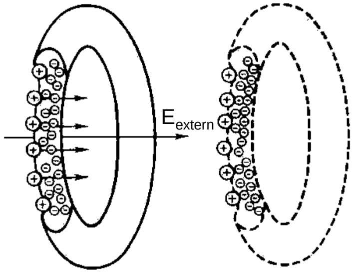

Cyclotron


Betatron

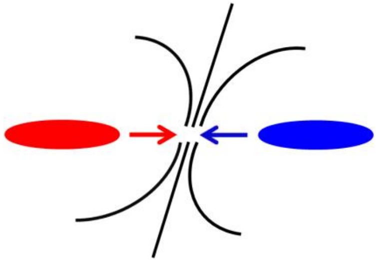


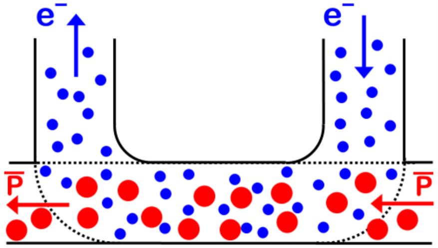
Synchrotron


Strong focusing

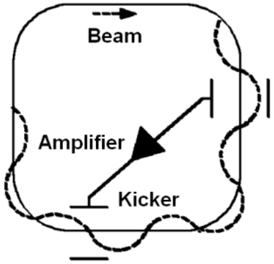


Collective acceleration


Colliders

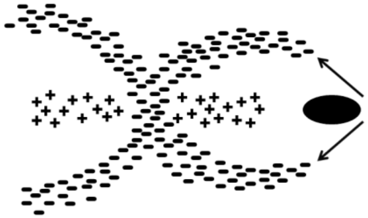


Electron cooling



Stochastic cooling

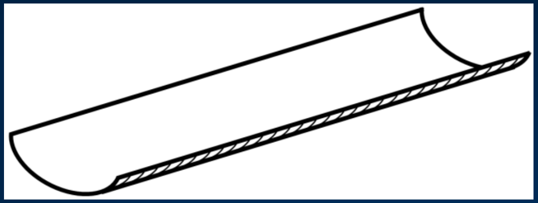

SC magnets and RF

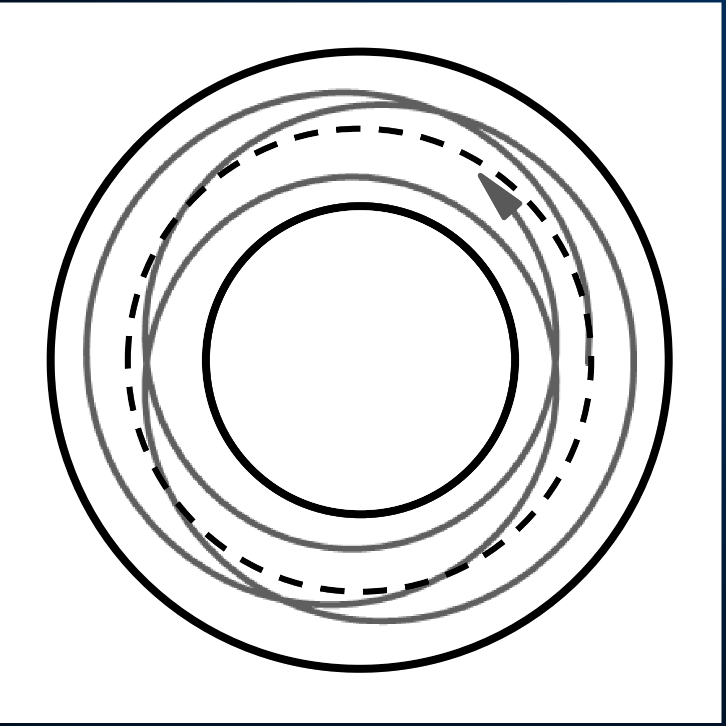

Plasma acceleration

Focusing

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter

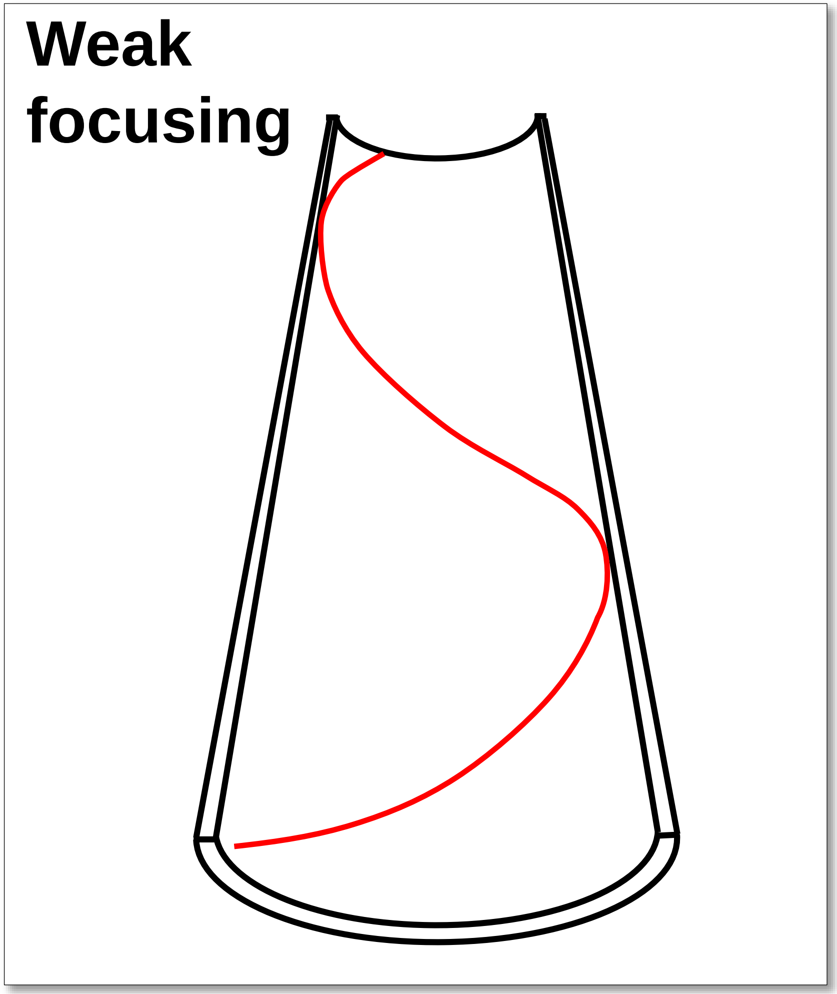


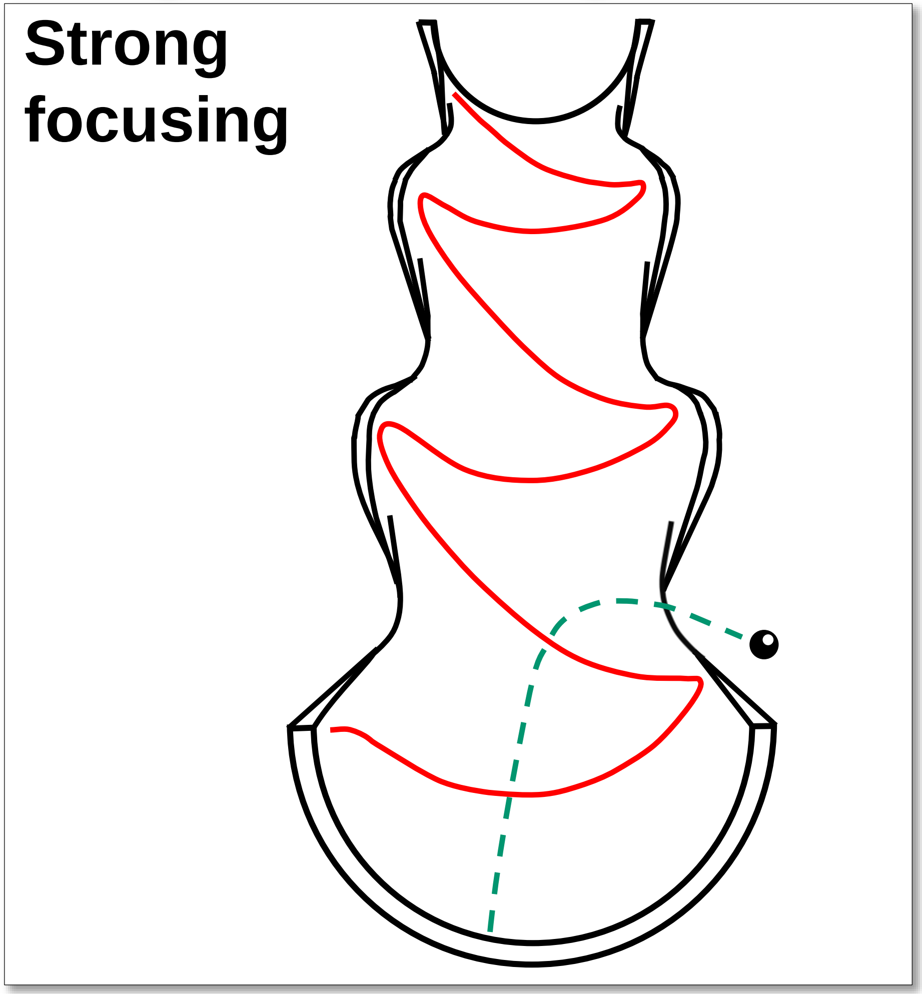


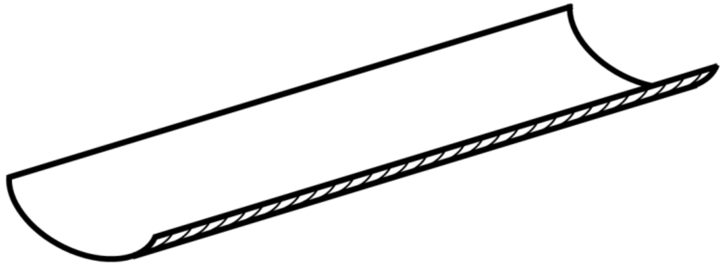
The first accelerators had weak focusing with spatial period greater than the perimeter of the accelerator

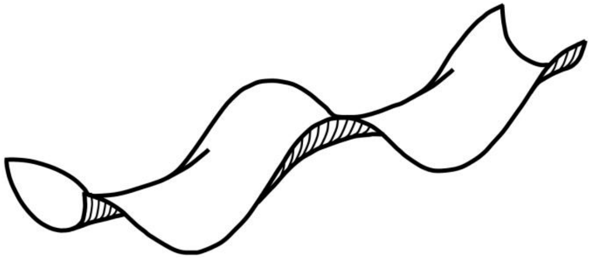
The trajectories of particles in an accelerator with weak focusing

Weak and strong focusing

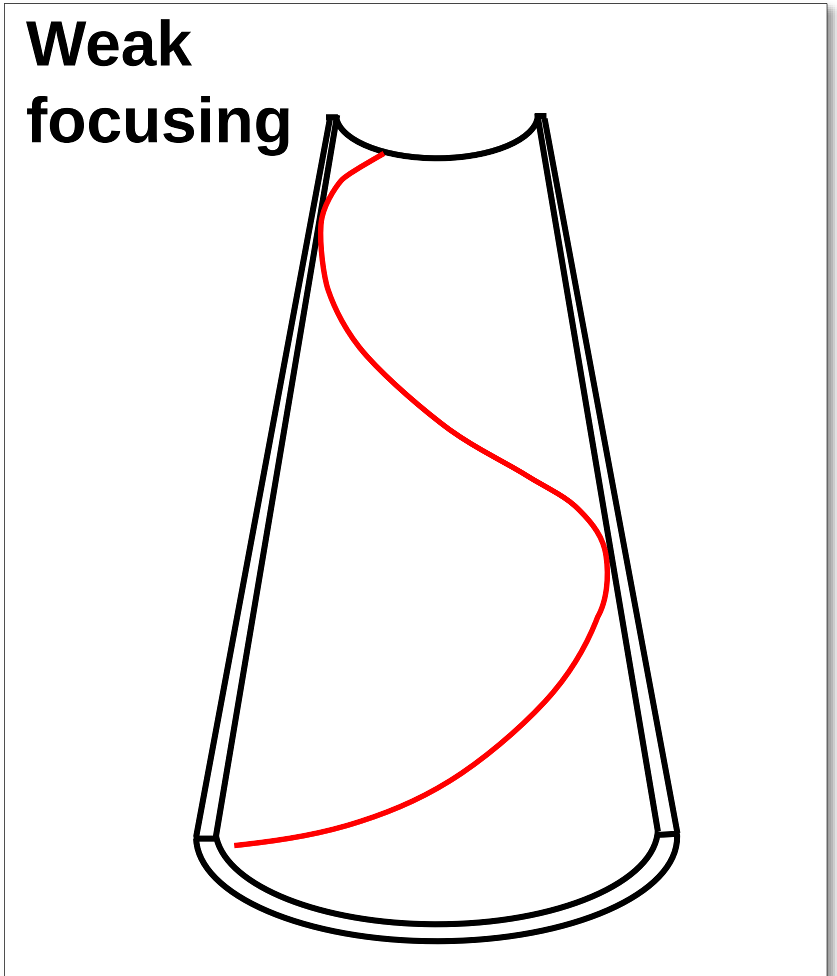


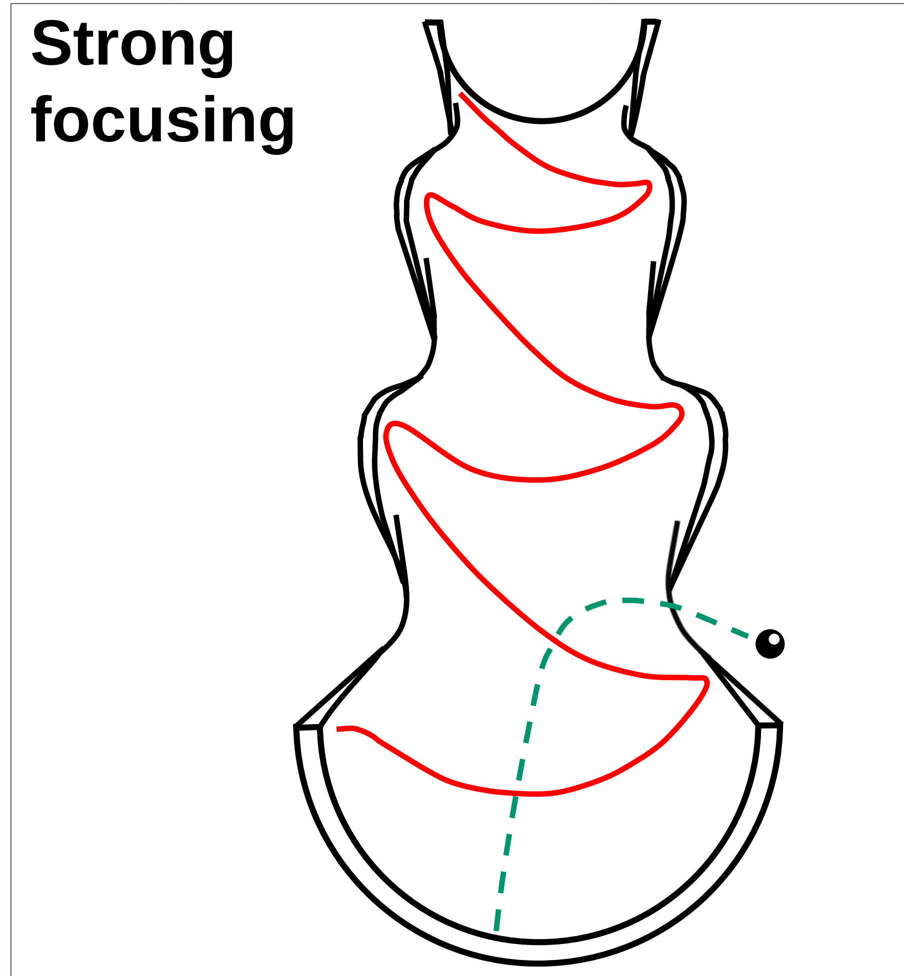


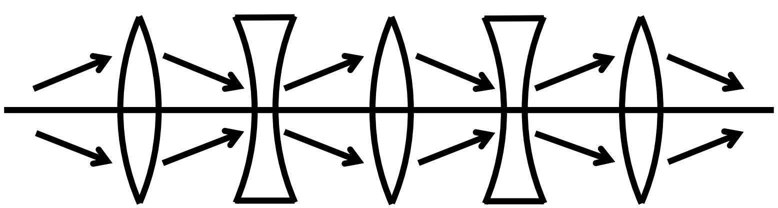




Weak and strong focusing



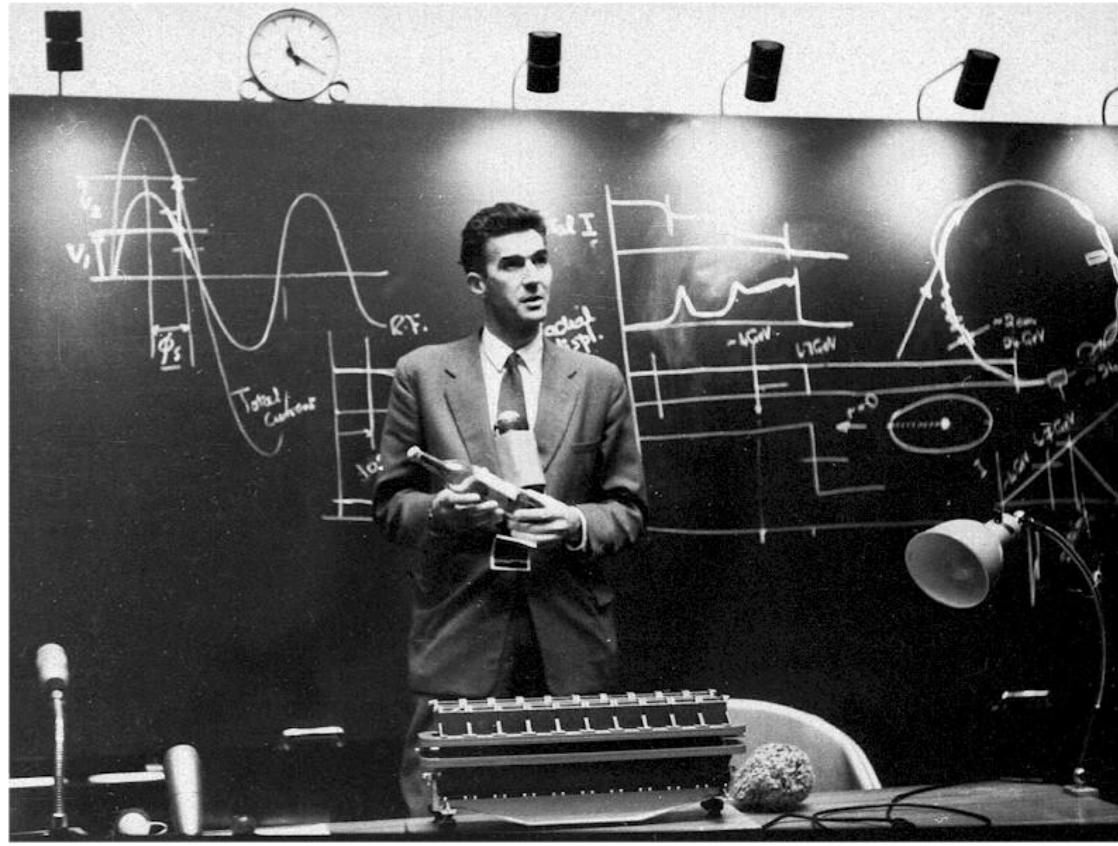




Strong focusing and JA history

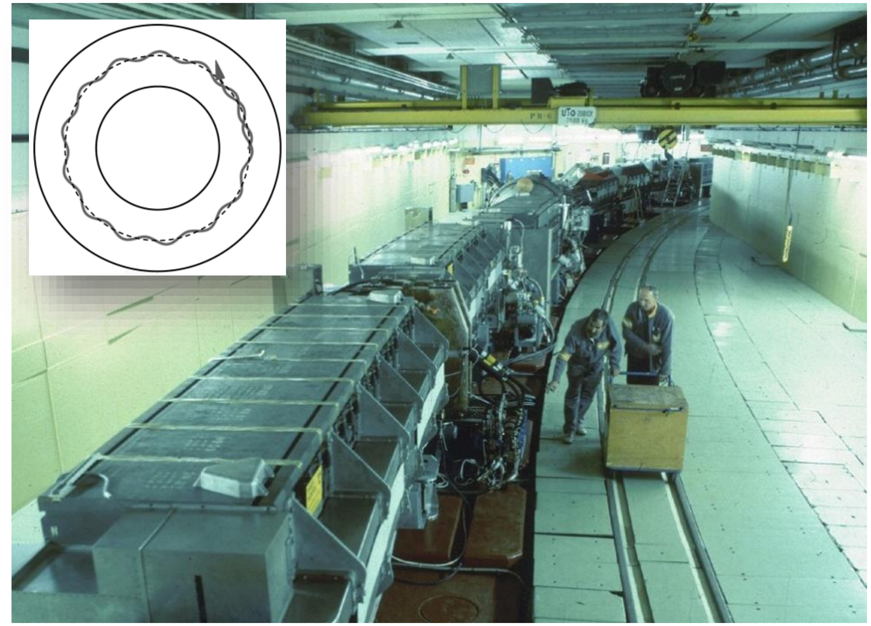
John Bertram Adams led the realization of the first strong-focusing proton accelerator.

This was the courageous decision – to cancel (in Oct 1952) the already approved 10 GeV weak focusing accelerator for a totally innovative 25 GeV Proton Synchrotron.



On the photo above Sir John Adams is announcing (on 25 Nov 1959) that CERN's PS just reached 24GeV and passed the Dubna's Synchrophasotron world record of 10GeV. This image shows Adams addressing the audience with a token of the victory – a bottled polaroid photograph showing the 24 GeV pulse in the machine ready to be sent back to the Joint Institute for Nuclear Research at Dubna as a sign that CERN had broken Dubna's record of 10 GeV.

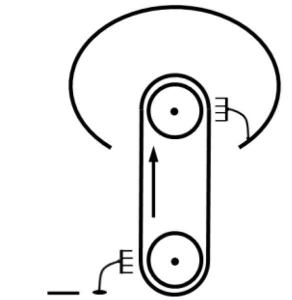
Weak and strong



10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for his time. It is ~60m diameter ring, and its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

CERN's Proton Synchrotron, the first operating strong-focusing accelerator, reached 24 GeV in 1959. It is a ~200-m diameter ring, weight of magnets 3,800 tons.

Accelerators – selected inventions



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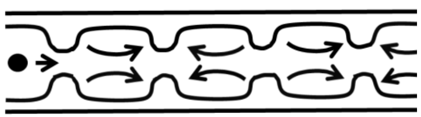

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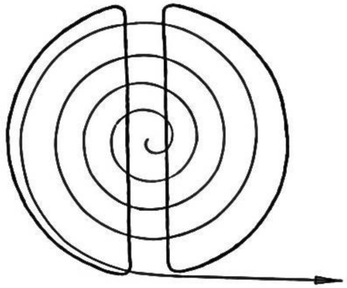
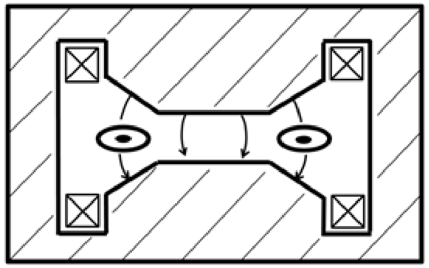
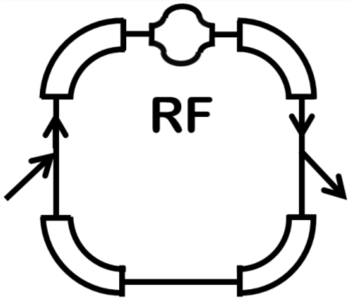


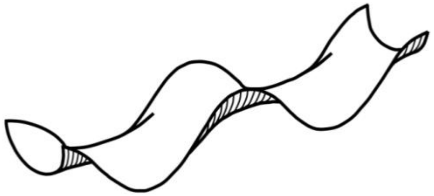
Cyclotron



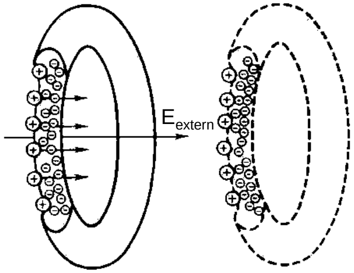
Betatron



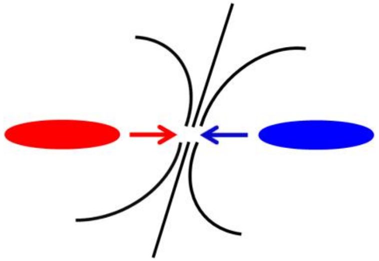
Synchrotron



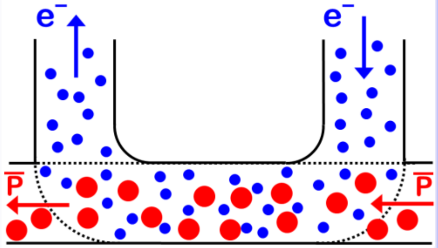
Strong focusing



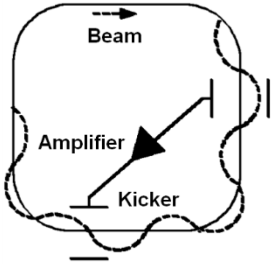
Collective acceleration



Colliders

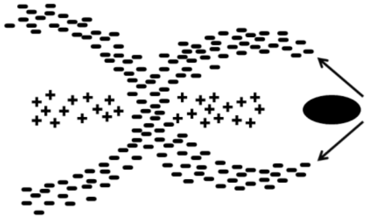


Electron cooling



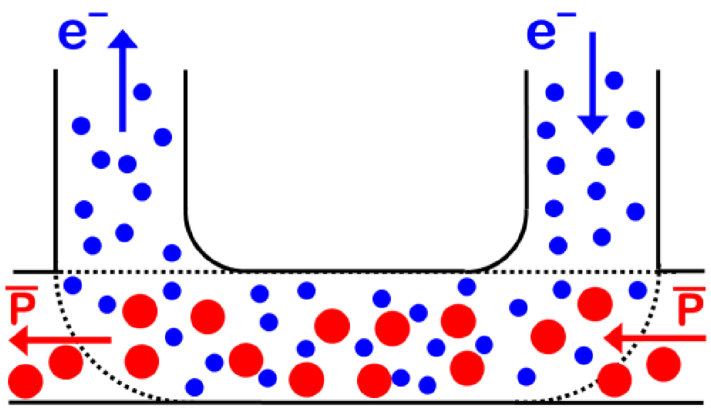
Stochastic cooling

SC magnets and RF



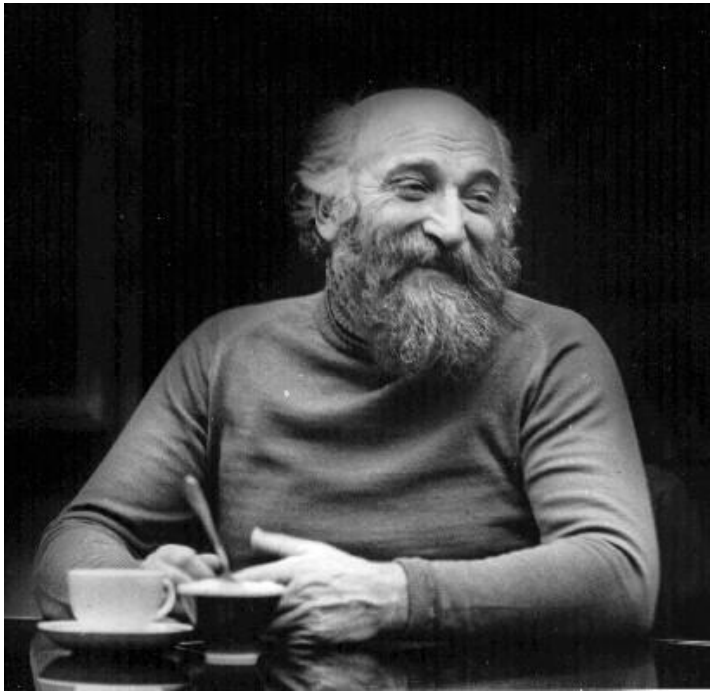
Plasma acceleration

Beam cooling



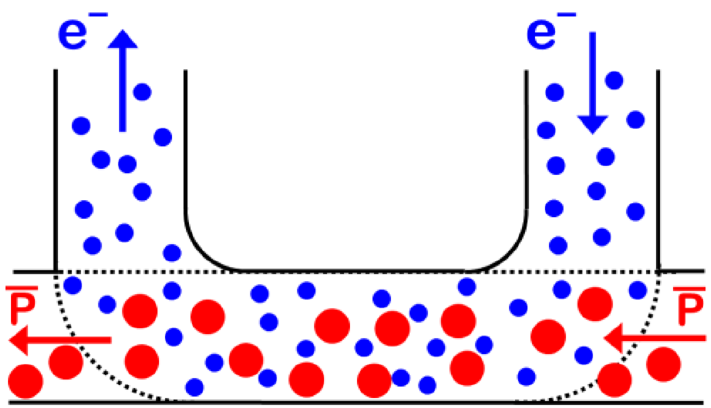
Electron cooling

Cooling is necessary especially for antiparticles such as antiprotons



A.M. Budker - founder and first director of the Institute of Nuclear Physics, Novosibirsk. Author of many inventions in the field of physics, including the idea of electron cooling.

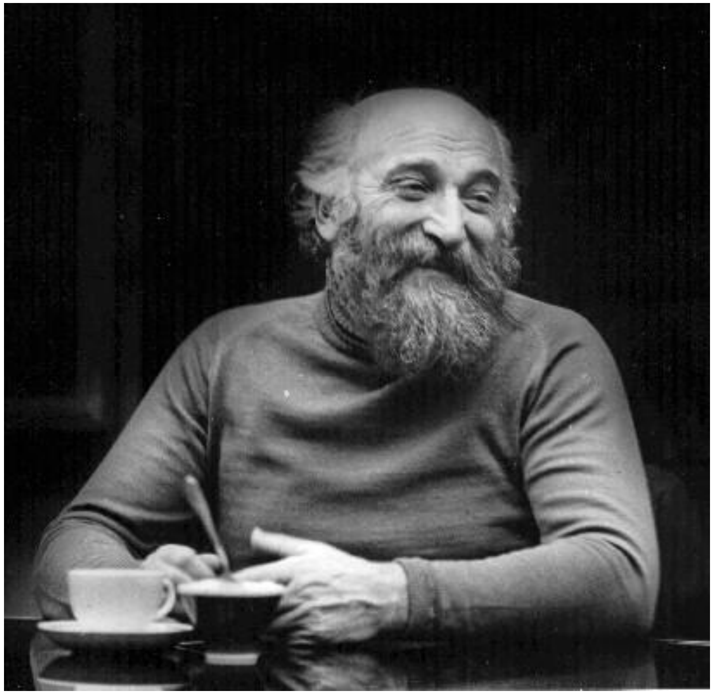
Beam cooling



Electron cooling

When electron cooling was first proposed, the common opinion was "brilliant idea, but unfortunately non-realistic"

Cooling is necessary especially for antiparticles such as antiprotons



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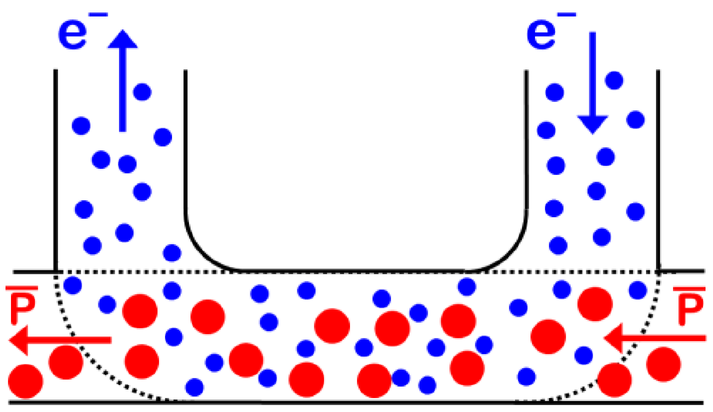
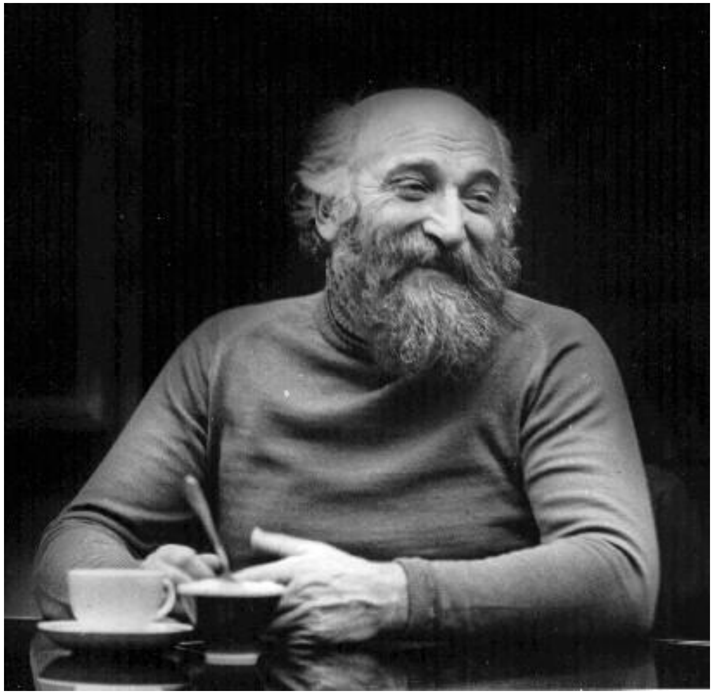
Beam cooling



Electron cooling

First e-cooler at BINP

Cooling is necessary especially for antiparticles such as antiprotons



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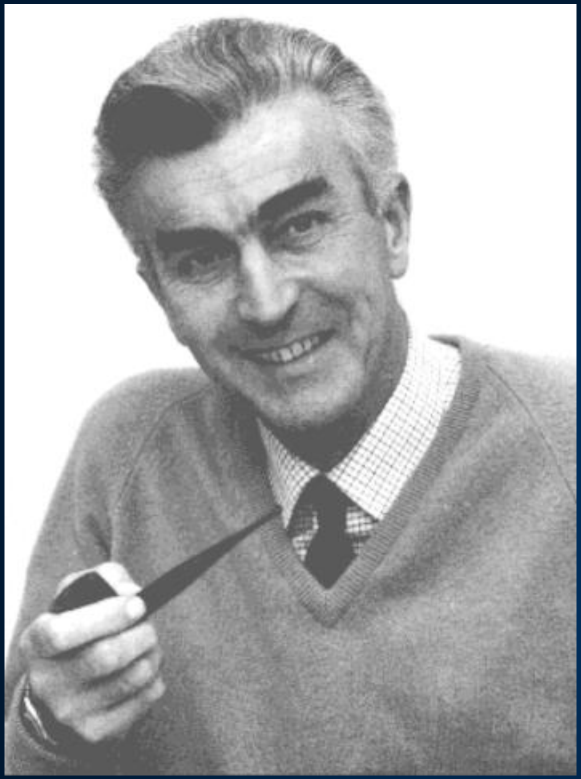
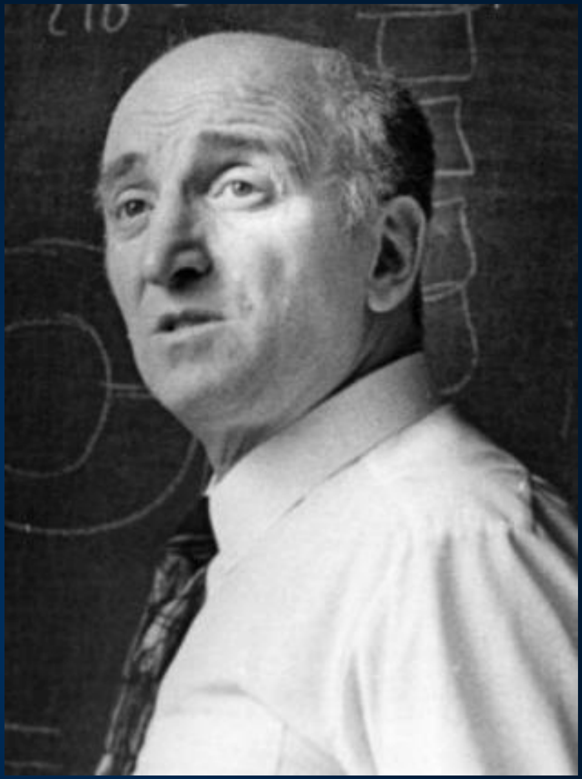
One more connection

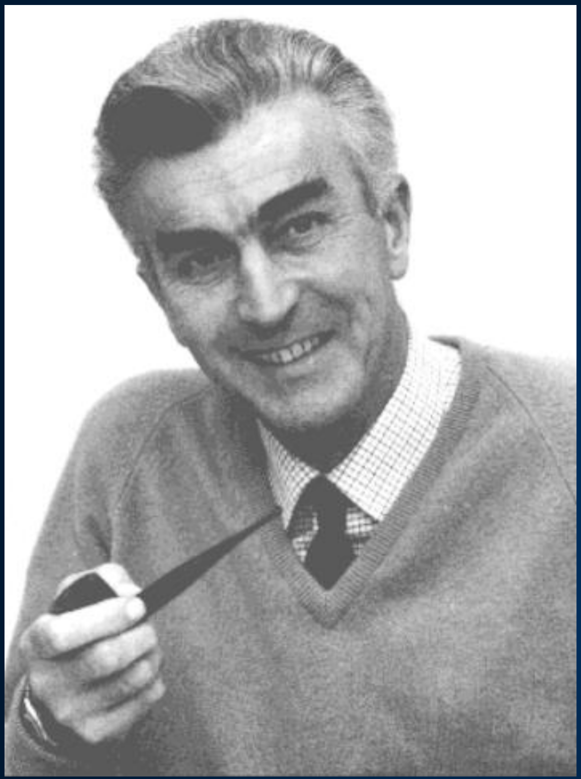


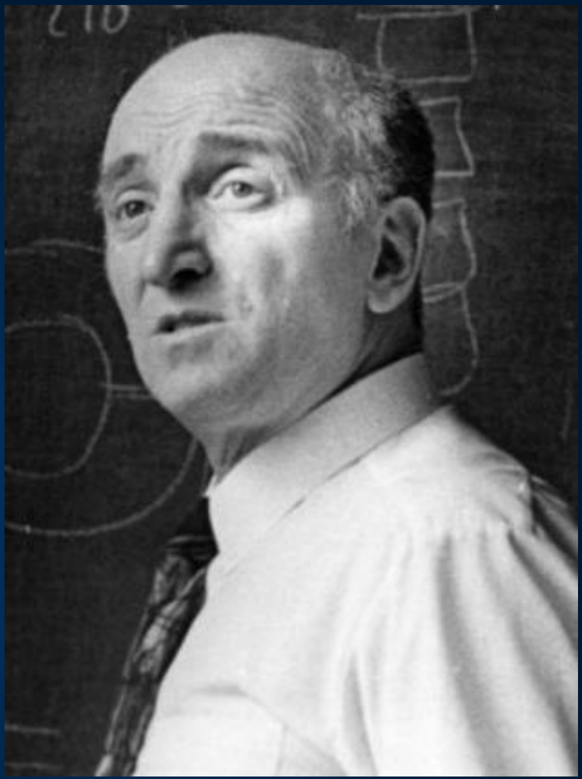


Sir John Adams – unique combination of scientific and engineering abilities

A.M. Budker – was once called by Lev Landau a "relativistic engineer"

One more connection





Sir John Adams – unique combination of scientific and engineering abilities

A.M. Budker – was once called by Lev Landau a "relativistic engineer"

…and the art of inventiveness that we are about to discuss came from engineering

How to invent more efficiently?

Forbes

Haydn Shaughnessy, Contributor
I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

What Makes Samsung Such An Innovative Company?

What was that magic bullet?
…wait a few slides…

But it was [redacted] that became the bedrock of innovation at Samsung. And it was introduced at Samsung by [redacted] whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 [redacted] led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over $100 million. [redacted] is now an obligatory skill set if you want to advance within Samsung.

How to invent – evolution of the methods

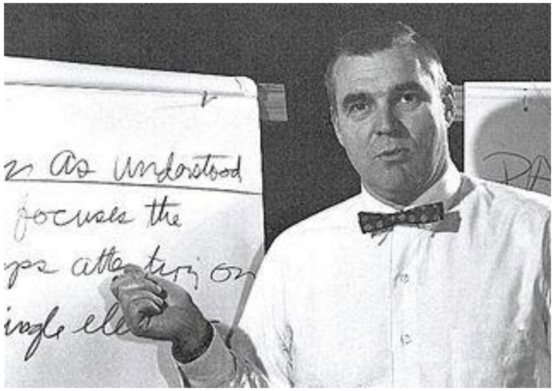
- **Brute-force or exhaustive search**
  - consider any possible ideas
- **Brainstorming**
  - psychological method which helps to solve problems and to invent
  - The main feature of brainstorming – separate the process of idea generation from the process of their critical analysis
  - The method of brainstorming did not meet expectations
    - the absence of feedback, which is the power of the method, is simultaneously its handicap, as feedback is needed for development and adjusting of an idea

Alex Osborn (1888 – 1966)

The author of brainstorming Alex Osborn introduced the method around 1950s

How to invent – evolution of the methods

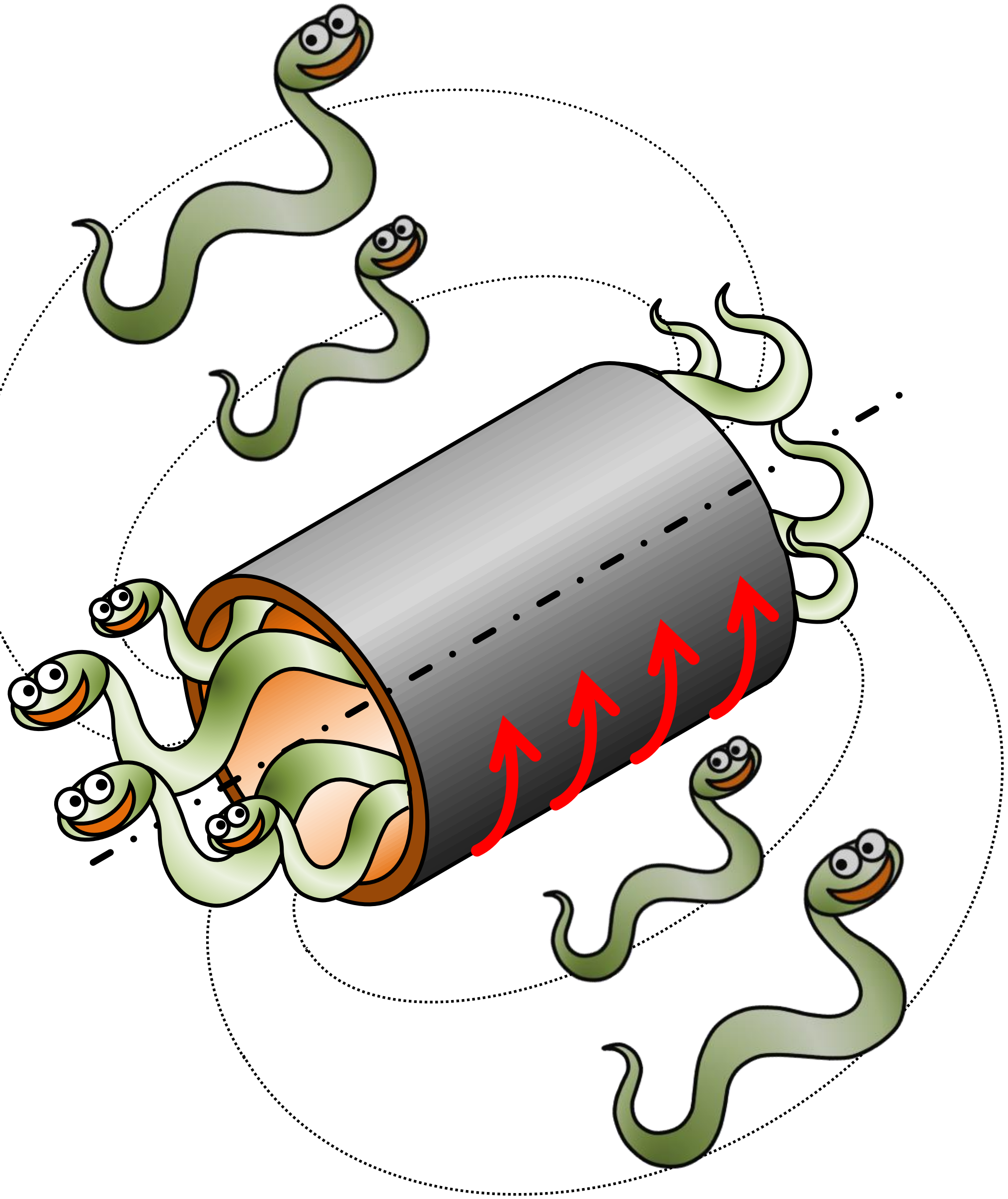
- **Synectics – improved Brainstorming**
- **Features of Synectics:**
  - **Permanent groups for problem solving**
    - **whose members with time become less sensitive to critics and more efficient in problem solving**
  - **Emphasis on the importance to see familiar behind unknown and vice versa**
    - **which should help to solve a new and unfamiliar problem with known methods**
  - **Importance of a fresh view at a problem**
  - **Use of analogies to generate fresh view**
    - **direct (any analogy, e.g. from nature);**
    - **empathic (attempting to look at the problem identifying yourself with the object);**
    - **symbolic (finding a short symbolic description of the problem and the object);**
    - **metaphorical (describing the problem in terms of fairy-tales and legends);**



Attempting to improve brainstorming, George Prince (on the photo) and William Gordon introduced the method of Synectics

Synectics : use of analogies

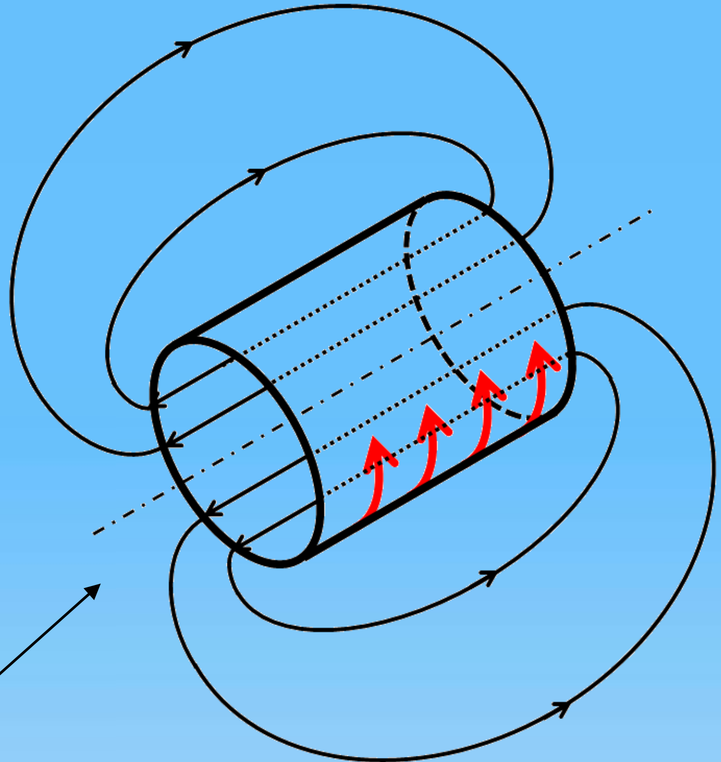
- Use of analogies to generate fresh view
    - …
    - empathic (attempting to look at the problem identifying yourself with the object);
    - …
    - metaphorical (describing the problem in terms of fairy-tales and legends);

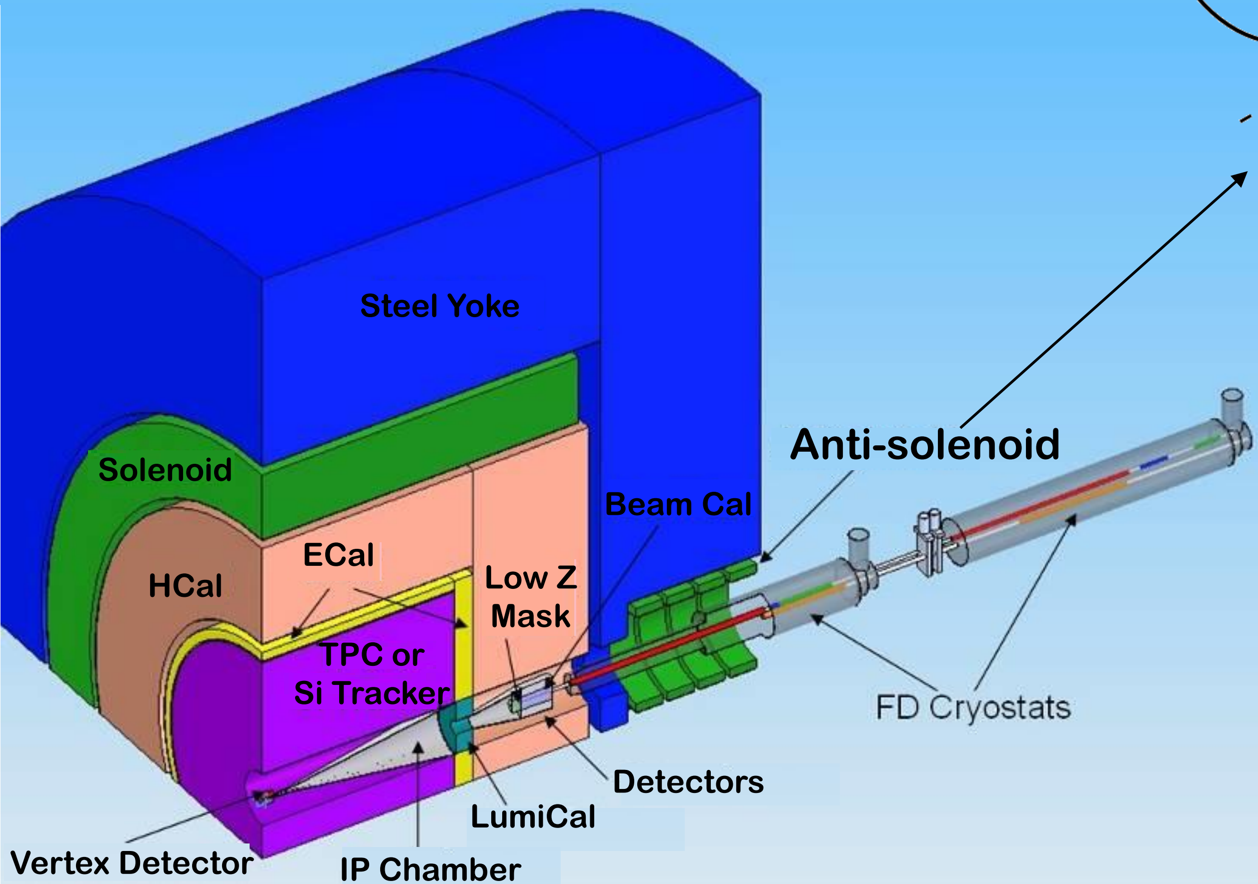


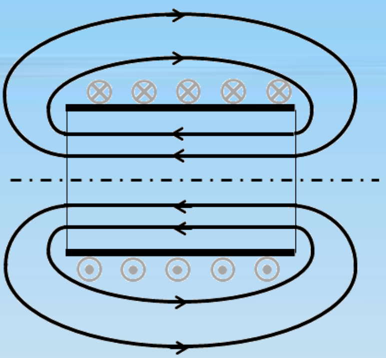
How to contain the magnetic flux?

ILC Interaction Region…

Anti-solenoid is needed, but it would be pulled into the main solenoid with humongous force

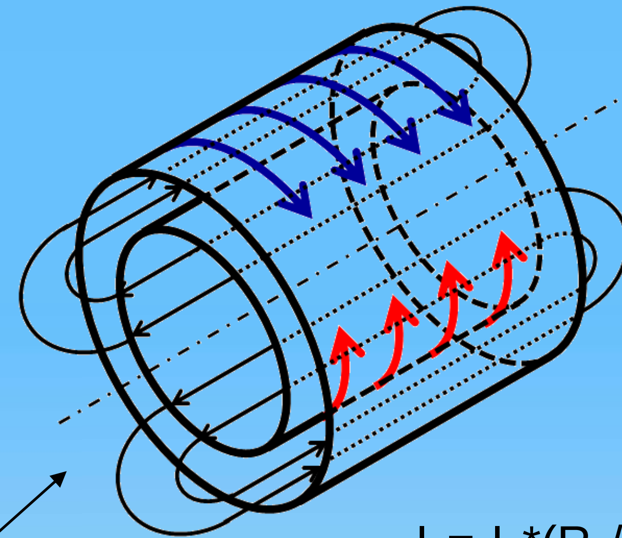




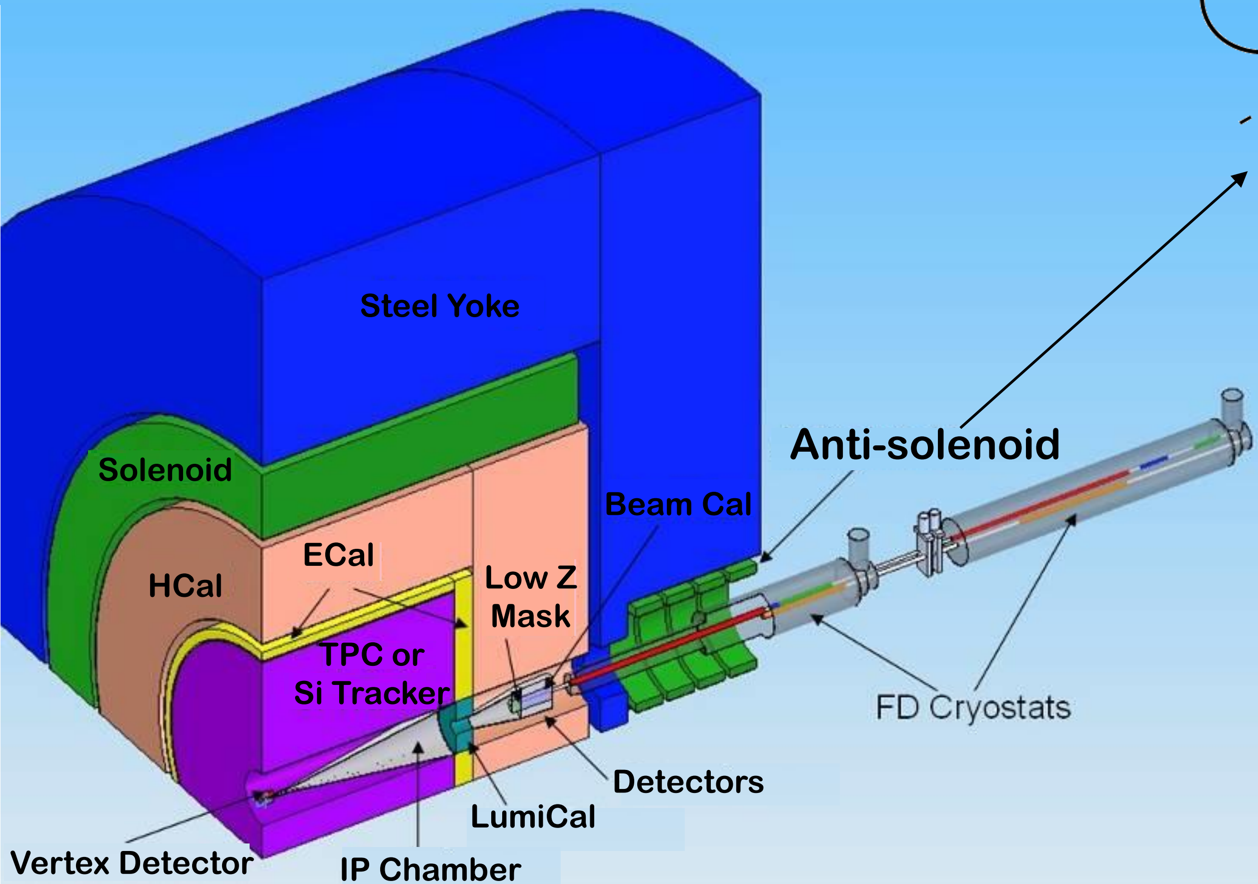


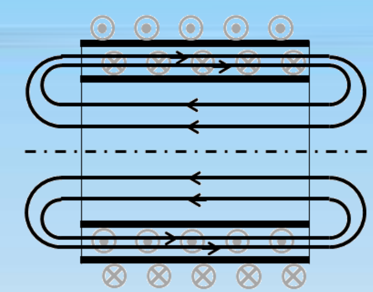
ILC Interaction Region…

Dual anti-solenoid is used, to cancel its external field – this makes it force-neutral



$I_2 = -I_1 * (R_1/R_2)^2$

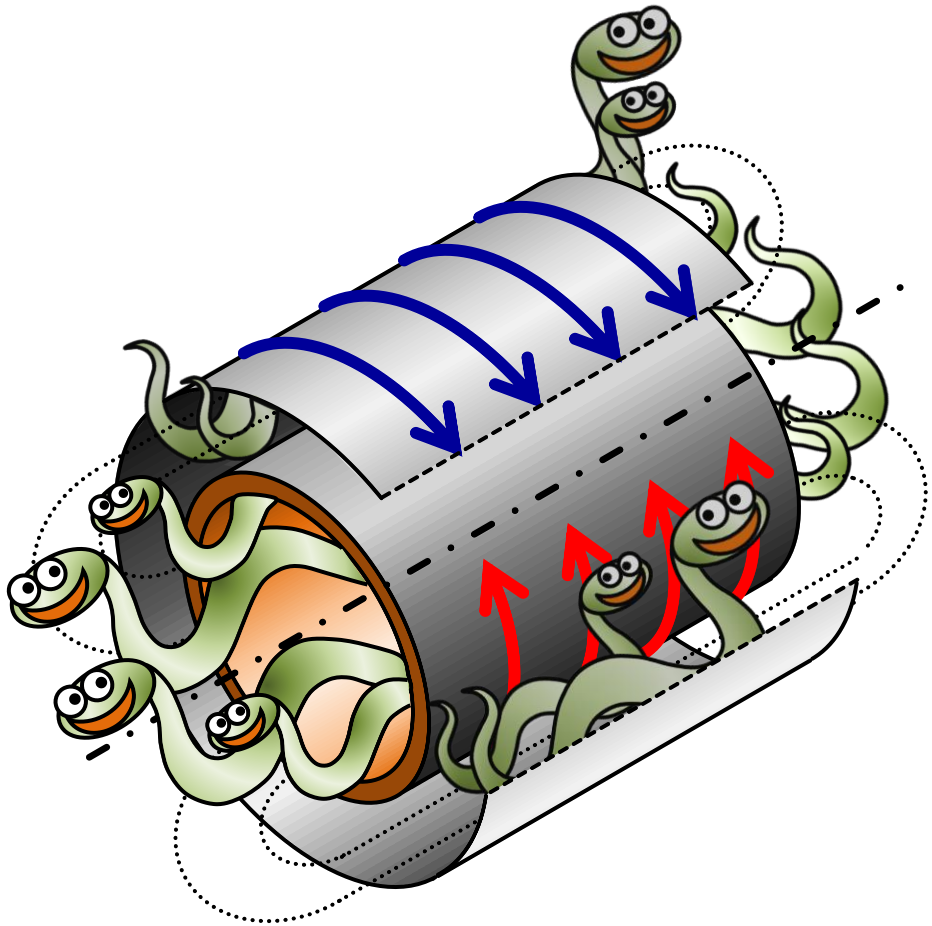




This is nested doll & system – anti-system!

Synectics and use of analogies

- Use of analogies to generate fresh view
  - …
  - empathic (attempting to look at the problem identifying yourself with the object);
  - …
  - metaphorical (describing the problem in terms of fairy-tales and legends);



Synectics does not help

How to invent – evolution of the methods

- **Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search**
  - **Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a natural and universal formula "the action has to happen itself"**

How to invent – evolution of the methods

- Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search
  - Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a **natural and universal formula "the action has to happen itself"**
  - **One should aim at such formula in any invention, armed with precise identification of physical contradiction – essence of TRIZ**

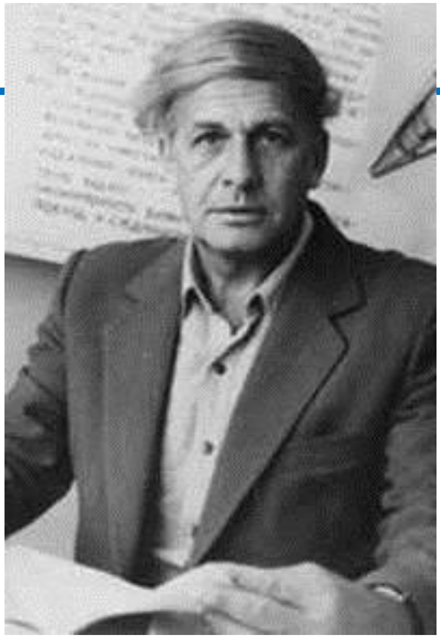
Illustration by Sasha Seraia

How to invent – TRIZ

- **TRIZ –** ***T****eoria* ***R****eshenia* ***I****zobretatelskikh* ***Z****adach*

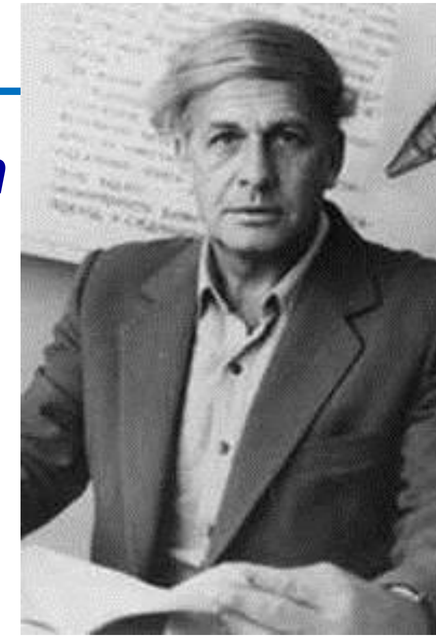
= Theory of Inventive Problem Solving

- **Developed by Genrikh Altshuller in SU**
  - **Work in patent office in 1946**
  - **Analysed 40000 patents, discovered patterns and identified what makes a patent successful**
  - **Formulated TRIZ in 1956-1985**



Genrikh Altshuller
(aka Altov)1926-1998

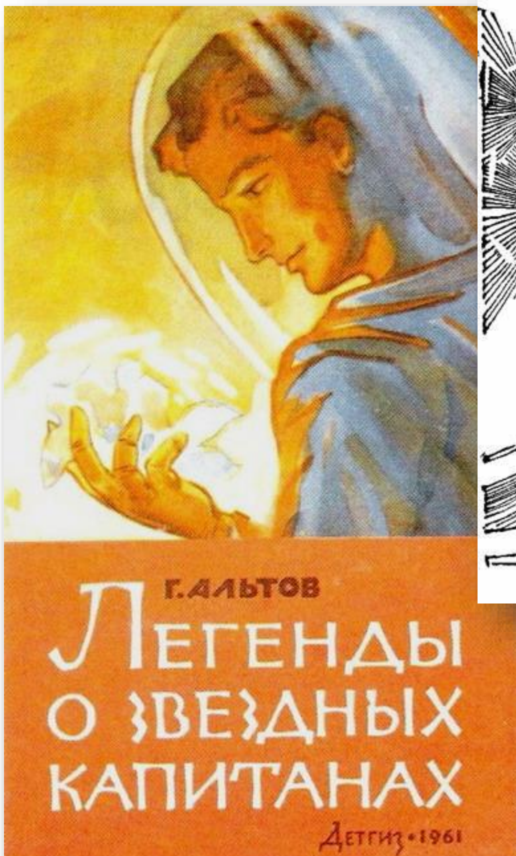
How to invent – TRIZ



- **TRIZ –** ***T**eoria **R**eshenia **I**zobretatelskikh **Z**adach*

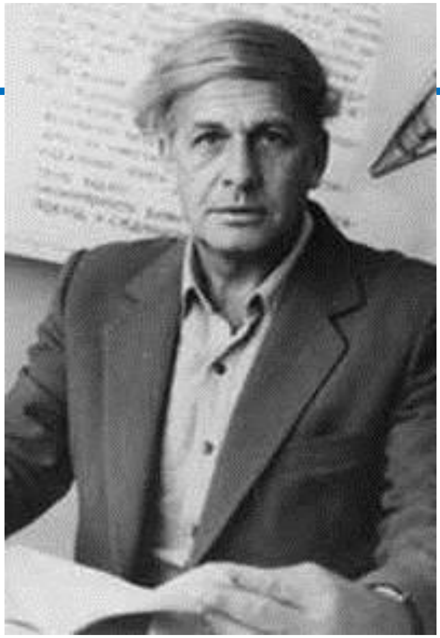
= Theory of Inventive Problem Solving

- **Developed by Genrikh Altshuller in SU**



Genrikh Altshuller
(aka Altov)1926-1998

How to invent – TRIZ



Genrikh Altshuller (aka Altov)1926-1998

- **TRIZ – *Teoria Reshenia Izobretatelskikh Zadach***

= Theory of Inventive Problem Solving

- **Developed by Genrikh Altshuller in SU**
  - **Work in patent office in 1946**
  - **Analysed 40000 patents, discovered patterns and identified what makes a patent successful**
  - **Formulated TRIZ in 1956-1985**
- **Four key discoveries of TRIZ:**
  - **The same Problems and Solutions appear again and again but in different industries**
  - **There is a recognisable Technological Evolution path for all industries**
  - **Innovative patents (23% of total) used science/engineering theories outside their own area/industry**
  - **An Innovative Patent uncovers and solves contradictions**

How to invent more efficiently?

Forbes

Haydn Shaughnessy, Contributor
I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

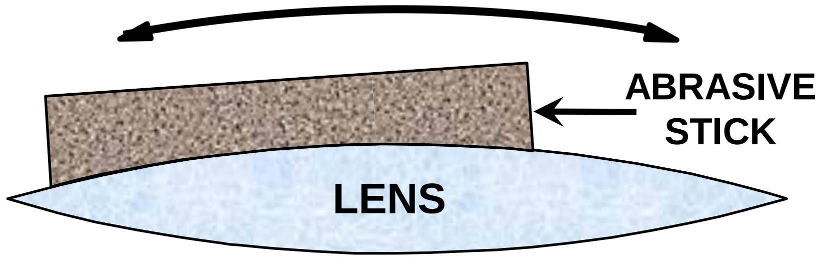
What Makes Samsung Such An Innovative Company?

Why are we interested in this in relation to science?
…wait a few more slides…

But it was TRIZ that became the bedrock of innovation at Samsung. And it was introduced at Samsung by Russian engineers whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 TRIZ led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over $100 million. TRIZ is now an obligatory skill set if you want to advance within Samsung.

TRIZ in action - example



Problem: Lens polished – heat generated. Heat degrades optical properties. Existing cooling methods ineffective, as cannot achieve uniform cooling at each abrasive particle

To be improved: SPEED, What gets worse: TEMPERATURE

Has anyone else solved such contradiction?

1) Define the problem in terms of generic Contradiction parameters

TRIZ Generic Problem

TRIZ Generic Solution

3) Translate generic Inventive Principles into specific solution

Specific Problem

2) Use Contradiction Matrix to obtain relevant Inventive Principles

Specific Solution

Example: following J.Scanlan, School of Engineering Sciences, Univ. of Southampton

Elements of TRIZ contradiction matrix

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force (Intensity)
11. Stress or pressure
12. Shape
13. Stability of the object
14. Strength
15. Durability of moving object
16. Durability of non moving object
17. Temperature
18. Illumination intensity
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Loss of Energy
23. Loss of substance
24. Loss of Information
25. Loss of Time
26. Quantity of substance/the
27. Reliability
28. Measurement accuracy
29. Manufacturing precision
30. Object-affected harmful
31. Object-generated harmful
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatility
36. Device complexity
37. Difficulty of detecting
38. Extent of automation
39. Productivity

Only 39 Matrix parameters!!!

TRIZ Inventive Principles

1. Segmentation
2. Taking out
3. Local quality
4. Asymmetry
5. Merging
6. Universality
7. Russian dolls
8. Anti-weight
9. Preliminary anti-action
10. Preliminary action
11. Beforehand cushioning
12. Equipotentiality
13. "The other way round"
14. Spheroidality - Curvature
15. Dynamics
16. Partial or excessive actions
17. Another dimension
18. Mechanical vibration
19. Periodic action
20. Continuity of useful action
21. Skipping
22. Blessing in disguise
23. Feedback
24. Intermediary
25. Self-service
26. Copying
27. Cheap short-lived objects
28. Mechanics substitution
29. Pneumatics and hydraulics
30. Flexible shells and thin films
31. Porous materials
32. Colour changes
33. Homogeneity
34. Discarding and recovering
35. Parameter changes
36. Phase transitions
37. Thermal expansion
38. Strong oxidants
39. Inert atmosphere
40. Composite materials

Only 40 Principles !!!

TRIZ Principles and Contradiction matrix

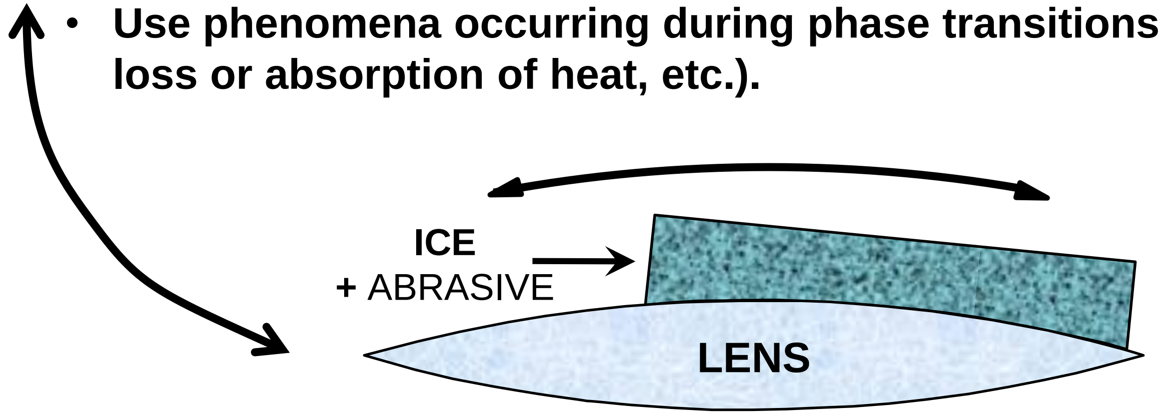
For our example with the lens:

	Parameter that deteriorates				
Improving Parameter	**…**	**9. Speed**	**…**	**17. Temperature**	**…**
…					
9. Speed				2, 28, 30, 36	
…					
17. Temperature					
…					

Suggested Principles that have solved similar Contradictions before

TRIZ in action - example

- **Perform lookup* of TRIZ Matrix for this contradiction:**
  - **Improving 9: SPEED without damaging 17: TEMPERATURE**
- **Find Principles to solve this contradiction:**
  - **2. Taking out**
  - **28. Mechanics substitution**
  - **30. Flexible shells and thin films**
  - **36. Phase transitions**
    - **Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).**



Abrasive + Ice - Inventive Principle ‘Phase Transition’

*) E.g. at http://www.triz40.com/

Can TRIZ be used in science?

First of all – your rightful critics:

In science we cannot rely on or use such prescriptive step-by-step methods with pre-defined tables of contradictions

And we cannot teach TRIZ to scientists the same way it is taught in engineering schools and companies

The only way to introduce TRIZ to science is via the process of pro-active re-creation of TRIZ for science

TRIZ for science

is very useful

Pro-active re-creation of TRIZ for science is used in this book:
- helps to connect different areas
- helps to learn inventiveness methods

The re-interpreted and extended TRIZ is called in this book Accelerating Science TRIZ (AS-TRIZ)
-it means that any area of science can be accelerated

Creating TRIZ for science through the process of analysing and re-building TRIZ will also help us to study it proactively

Major components of TRIZ that should be kept for AS-TRIZ (in extended & re-defined shape) are, to start with:

- **-inventive principles**
- **-laws of evolution of systems**

TRIZ for Science

Looking at the world "through the prism of TRIZ"

Illustration by Sasha Seraia

40 inventive principles in illustrations

- **You can find many illustrations of inventive principles based on engineering examples**
- **On the next pages you will find illustrations based on accelerator science and some other areas of science**
  - You will notice that some of the standard definitions of TRIZ principles are re-defined

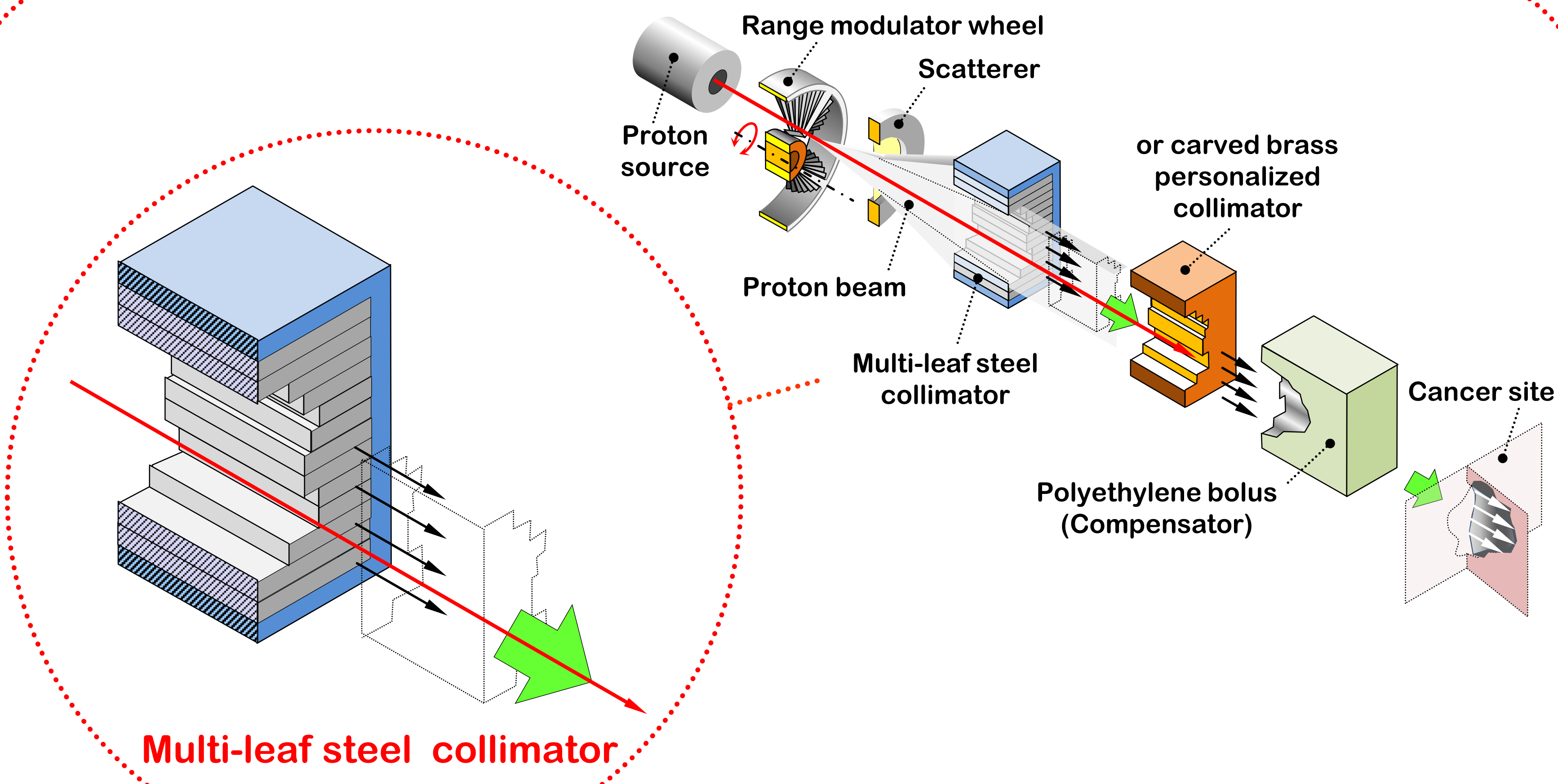
See more details in:

Accelerating Science TRIZ inventive methodology in illustrations
Elena Seraia, Andrei Seryi

arXiv:1608.00536 [physics.ed-ph]
https://arxiv.org/abs/1608.00536

1. Segmentation

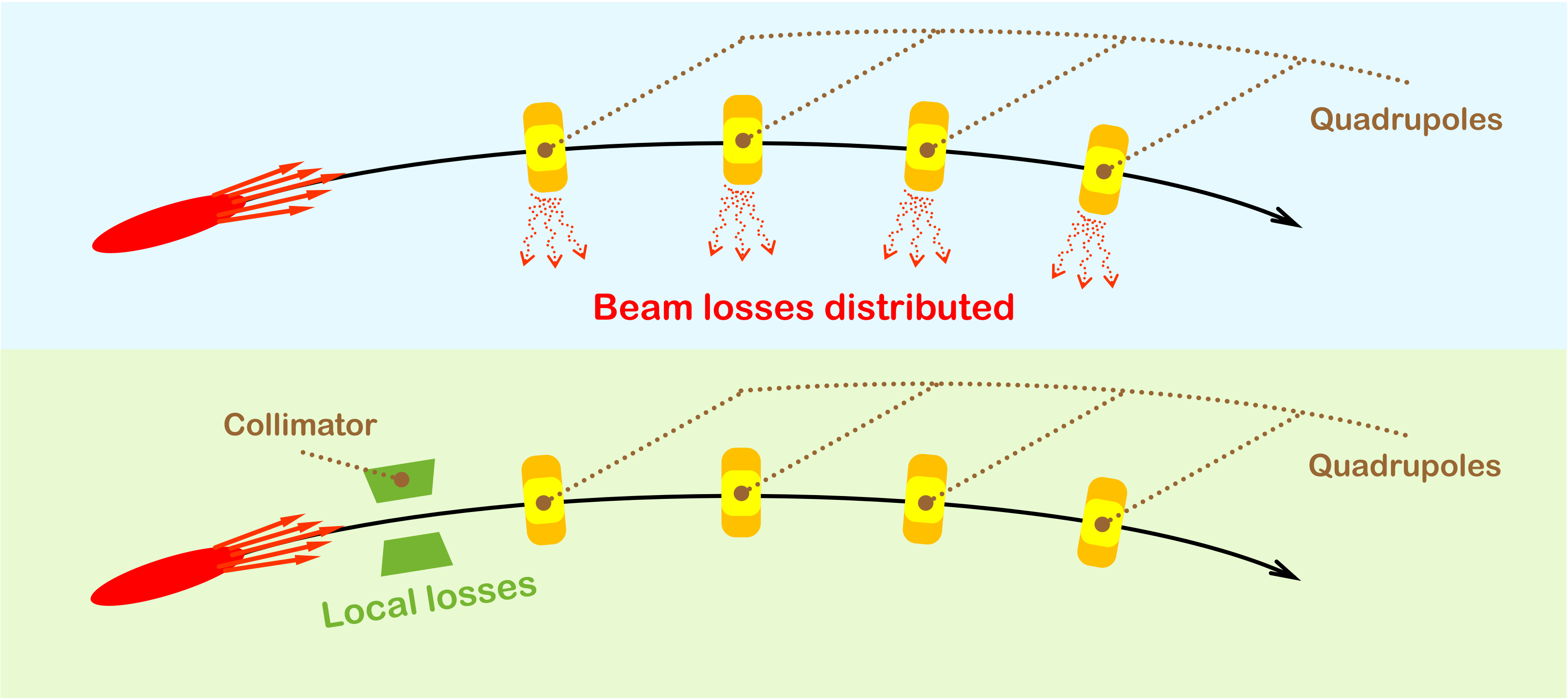
- Divide an object into independent parts.
- Make an object easy to disassemble.
- Increase the degree of fragmentation or segmentation.



Proton therapy

2.Taking out

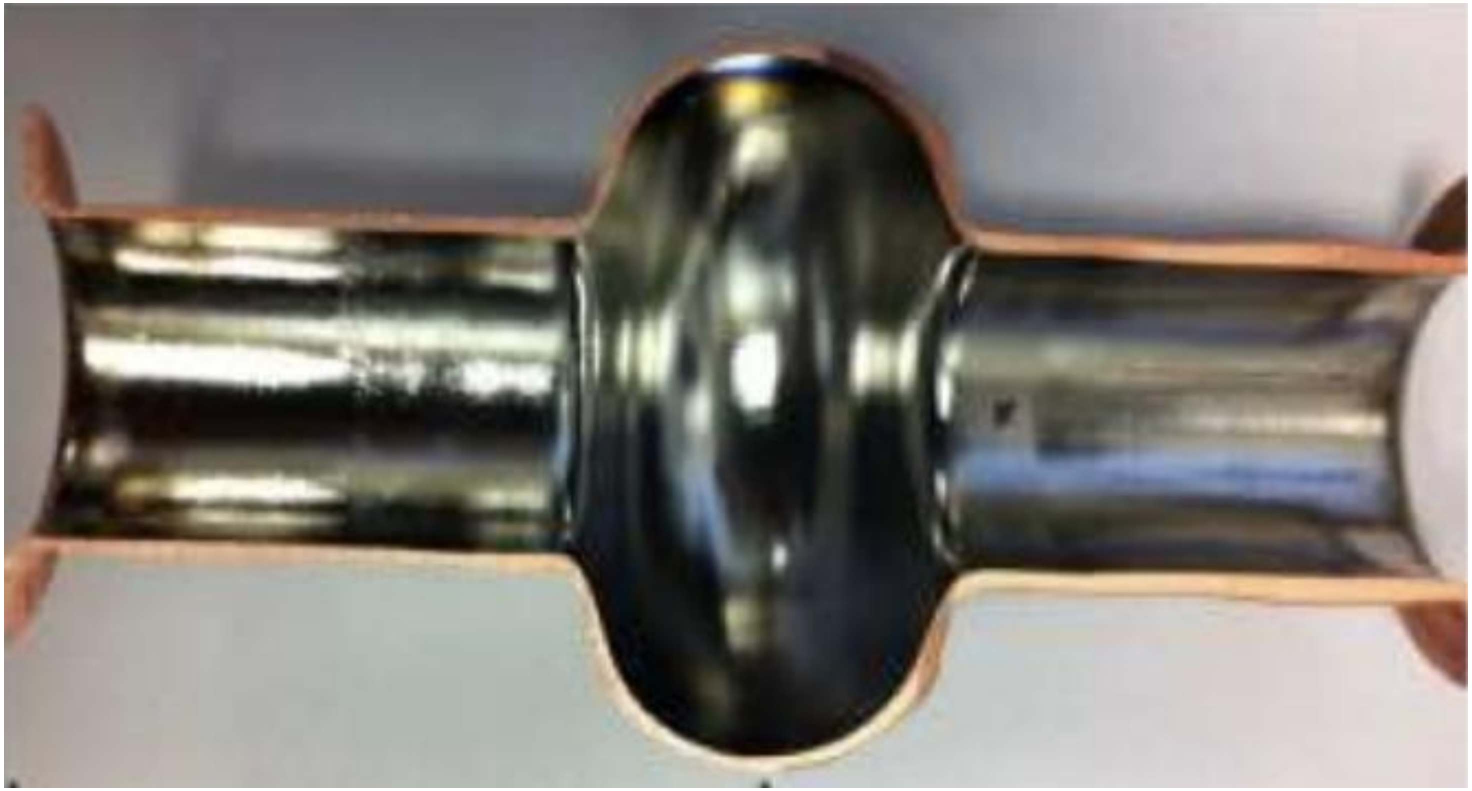
- Separate an interfering part or property from an object;
- Single out the only necessary part (or property) of an object.



Collimation of the beam to localize beam losses

3. Local quality

- **Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.**
- **Make each part of an object function in conditions most suitable for its operation.**
- **Make each part of an object fulfill a different and useful function.**

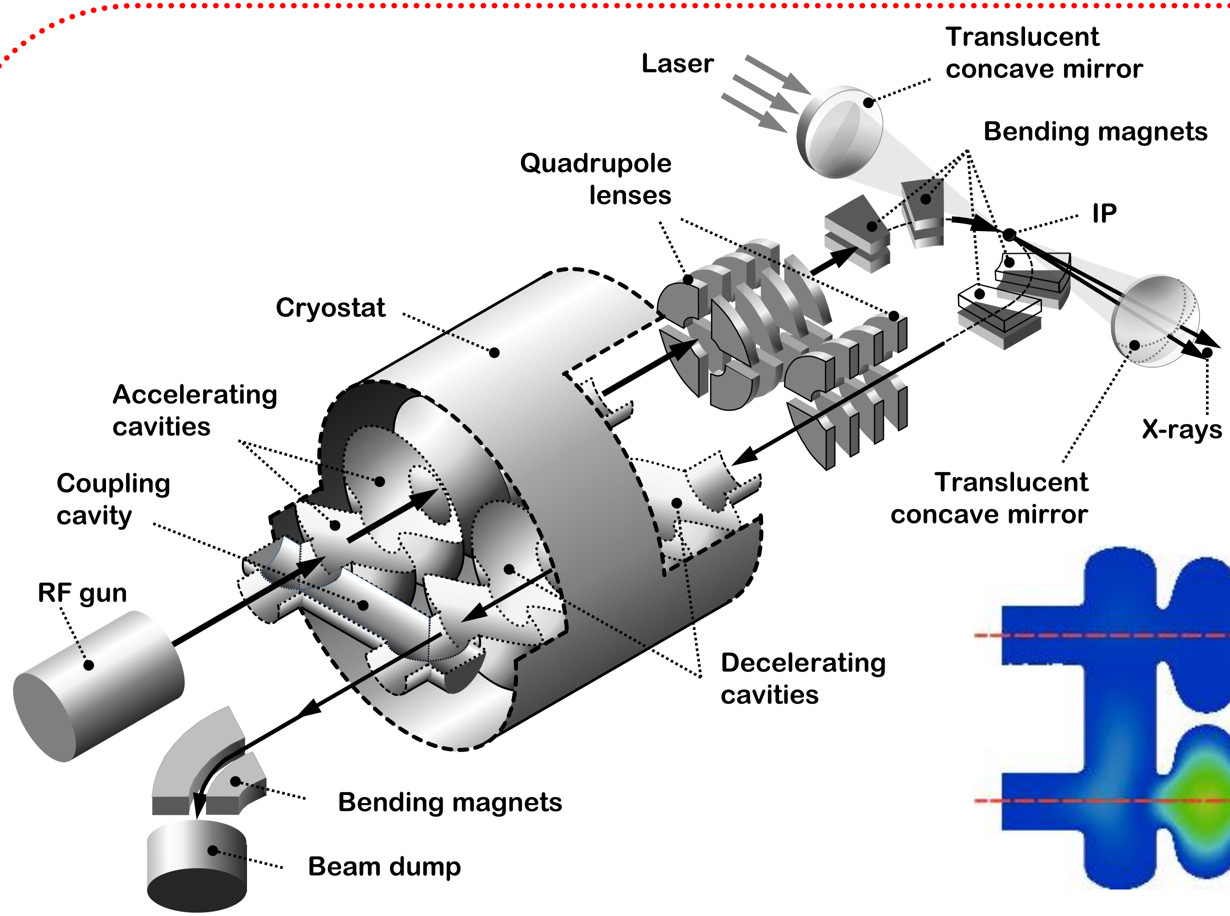


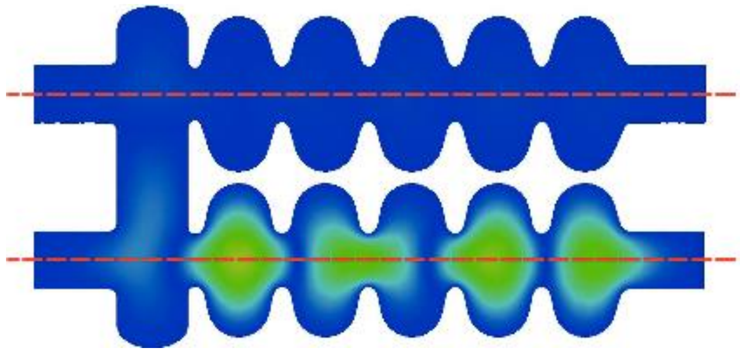
Nb coated copper cavity

Enzo Palmieri, A.A.Rossi, R. Vaglio, “Experimental Results on Thermal Boundary Resistance for Nb and Nb/Cu”, Science, Oct 2014

4. Asymmetry

- Change the shape of an object from symmetrical to asymmetrical.
  - If an object is asymmetrical, increase its degree of asymmetry.





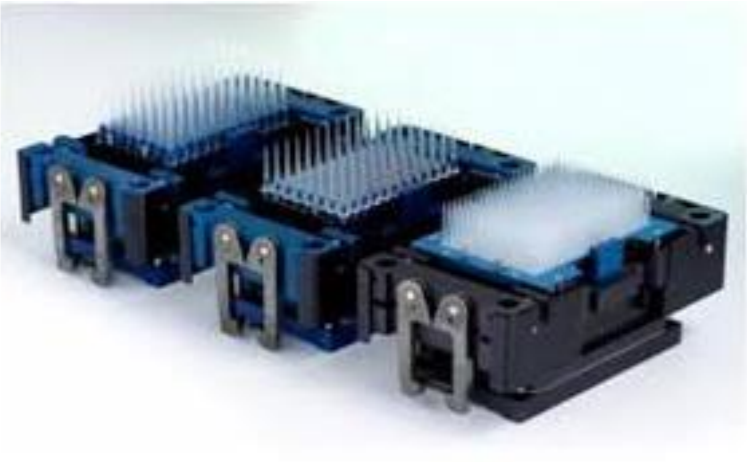
Cavities are slightly different to resonate on the main mode but be decoupled for all higher order modes

R. Ainsworth, G. Burt, I. V. Konoplev, A. Seryi, arXiv:1509.03675, 2015

5. Merging

- Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.
- Make operations contiguous or parallel; bring them together in time.

Single-channel and Multi-channel (8- and 12-) pipettes

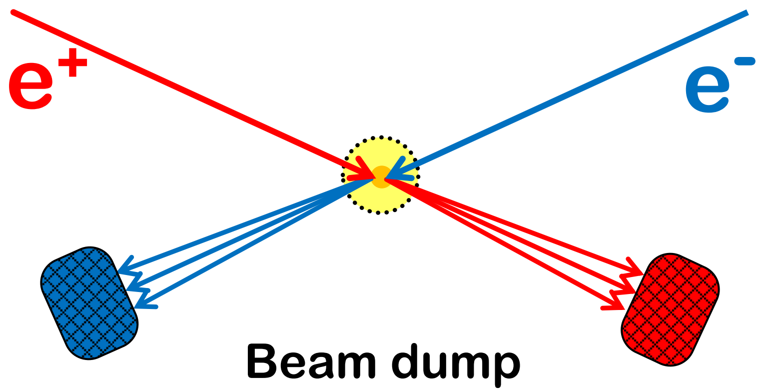


96- or 384-channel Modular Dispense Technology™ (MDT) dispense heads. PerkinElmer Janus.

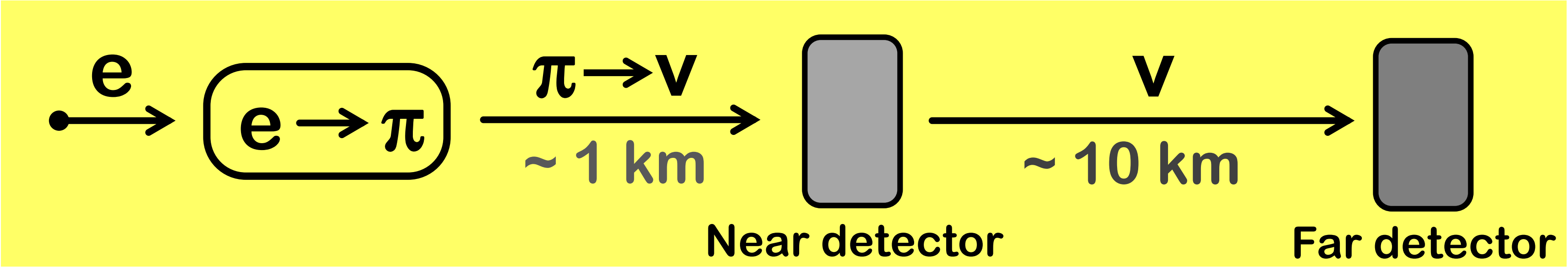
Illustration: PerkinElmer

6. Universality

- **Make a part or object perform multiple functions; eliminate the need for other parts.**



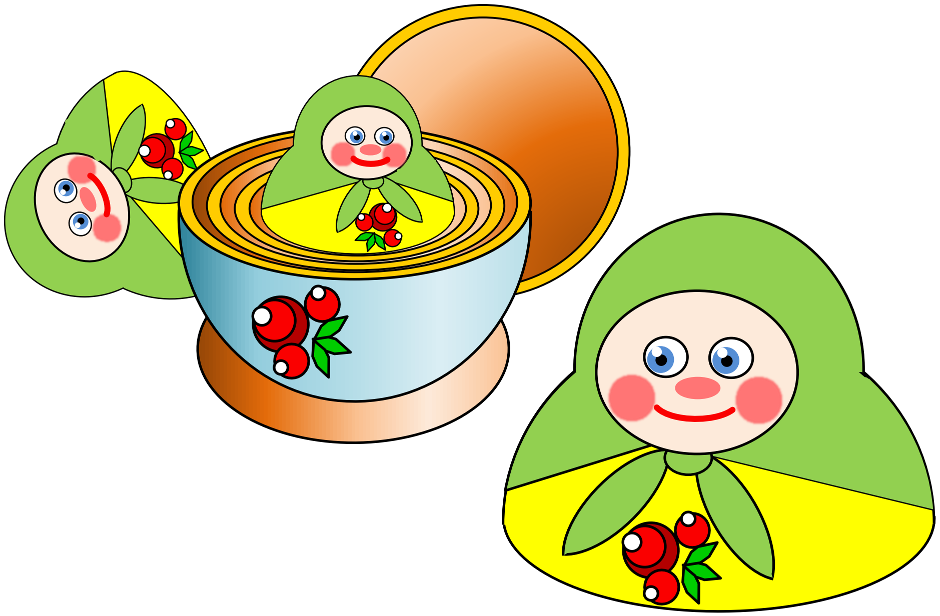
Make beam dump of linear collider to be sub-critical reactor to generate power or make neutrino factory out of it

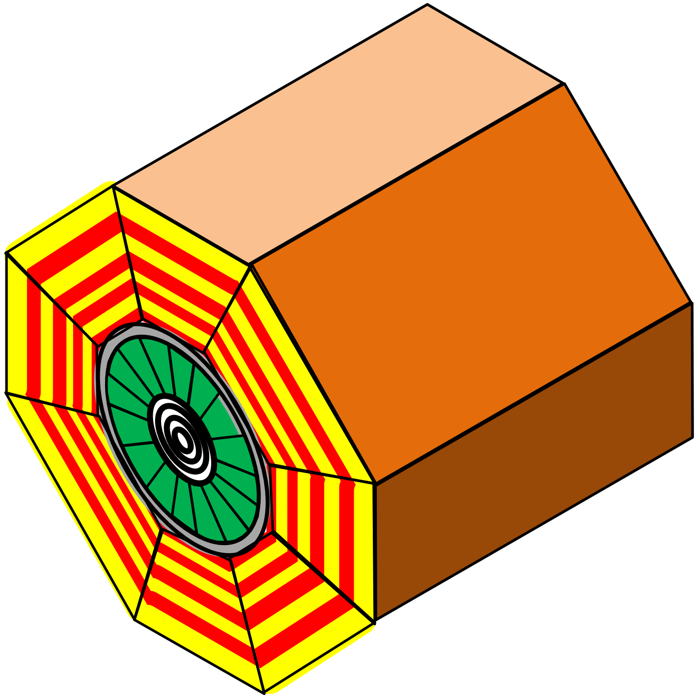


I.F. Ginzburg, arXiv:1411.3295, 2014

7. Nested doll

- Place one object inside another; place each object, in turn, inside the other.
- Make one part pass through a cavity in the other.

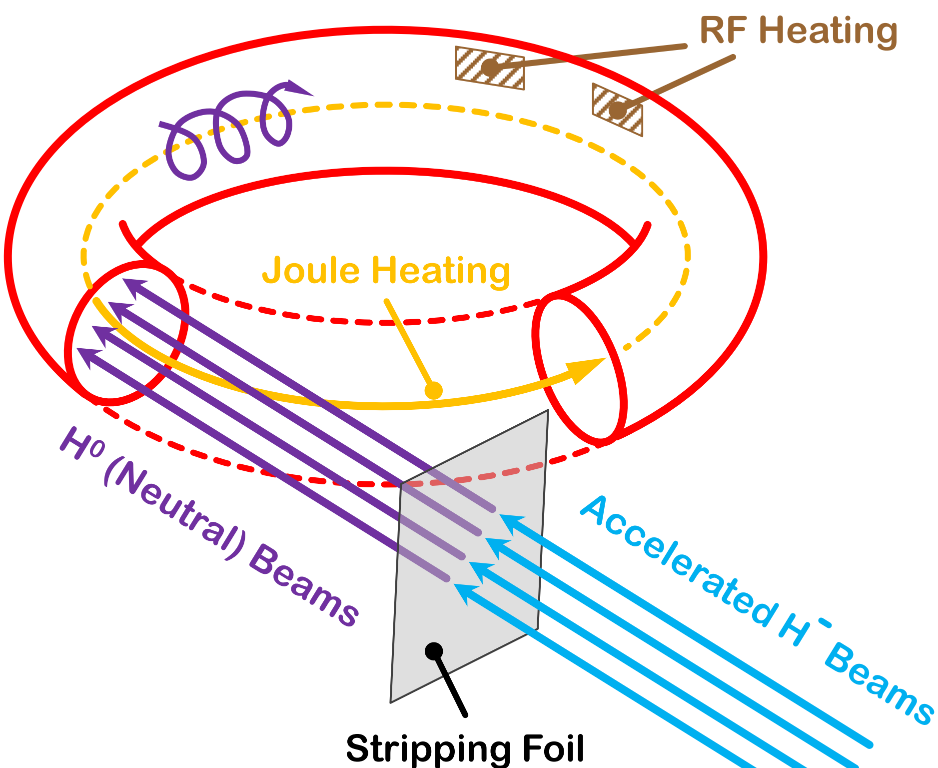




High energy physics detectors

8. Anti-~~weight~~ force

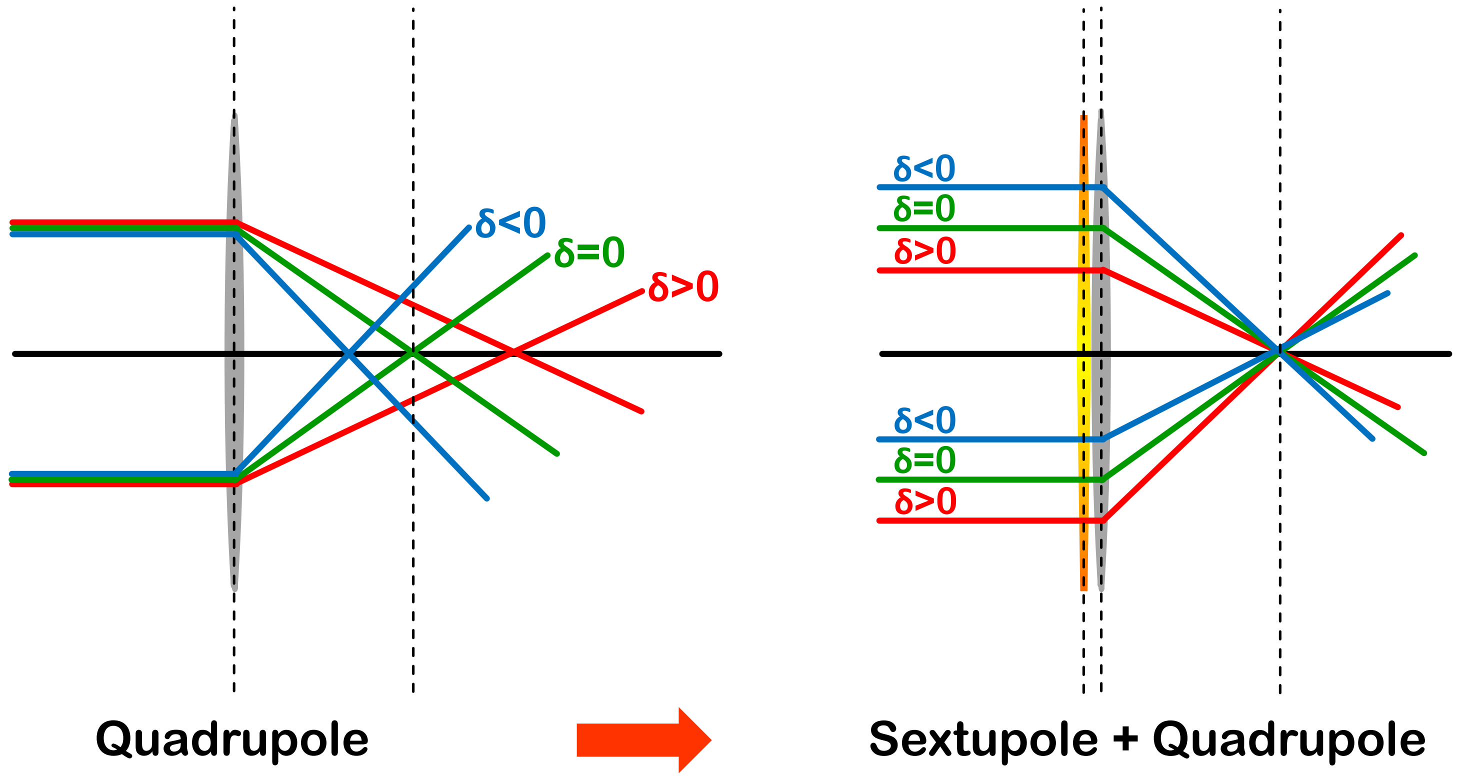
- To compensate for the ~~weight of~~ force on an object, merge it with other objects that provide compensating force.
- To compensate for the ~~weight of~~ force on an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).



Heating of plasma with neutral beams

9. Preliminary anti-action

- If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.
- Create beforehand stresses in an object that will oppose known undesirable working stresses later on.

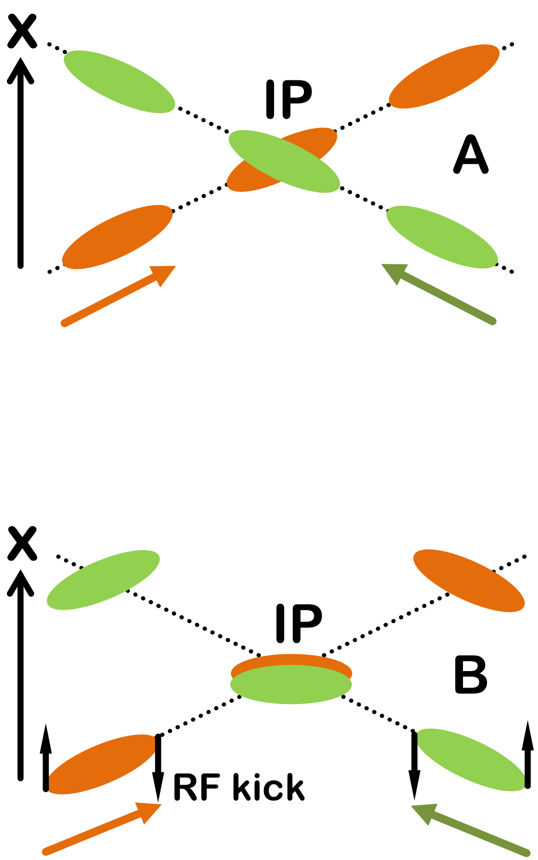


Local chromatic correction

P. Raimondi, A. Seryi, PRL, 86, 3779 (2001)

10. Preliminary action

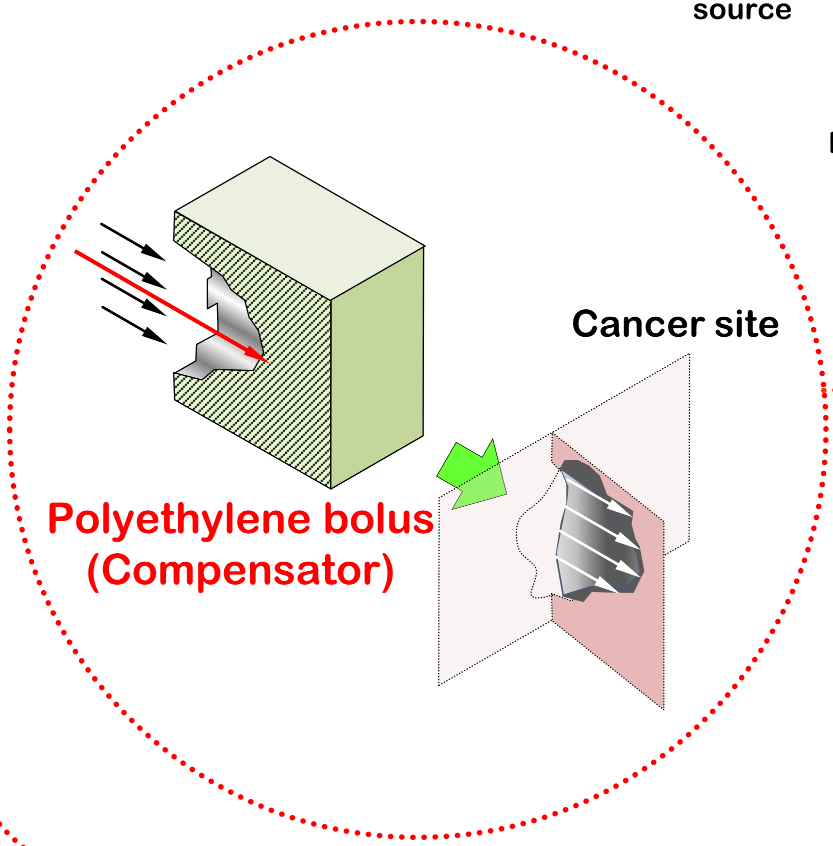
- **Perform, before it is needed, the required change of an object (either fully or partially).**
- **Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.**

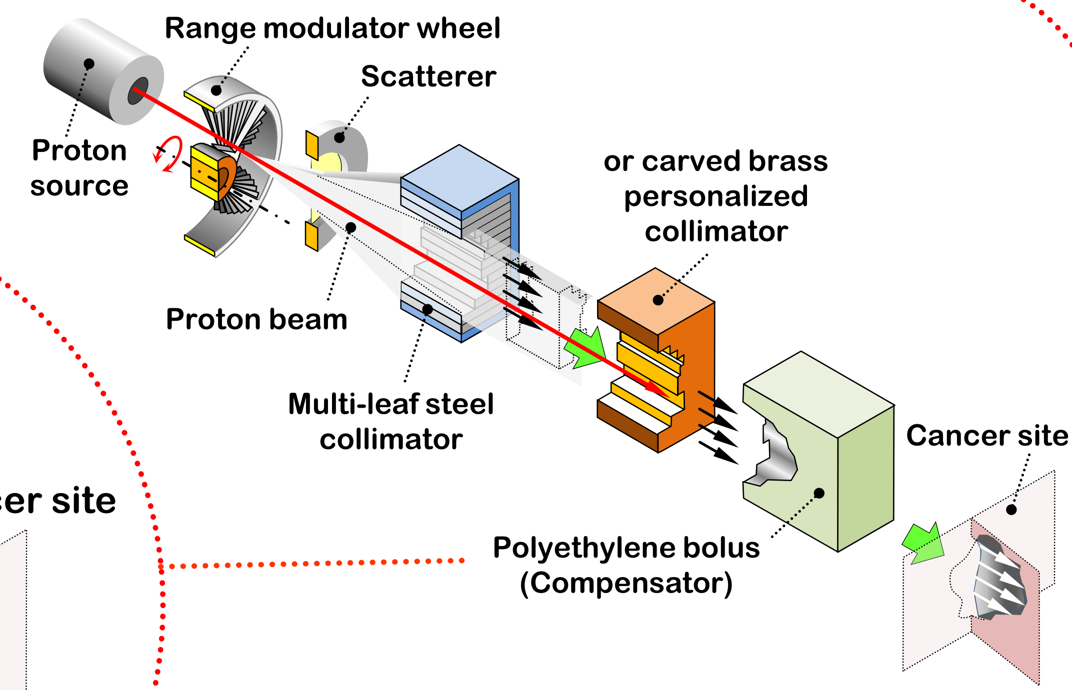


Crabbed collisions

11. Beforehand cushioning

- Prepare emergency means beforehand to compensate for the relatively low reliability of an object.

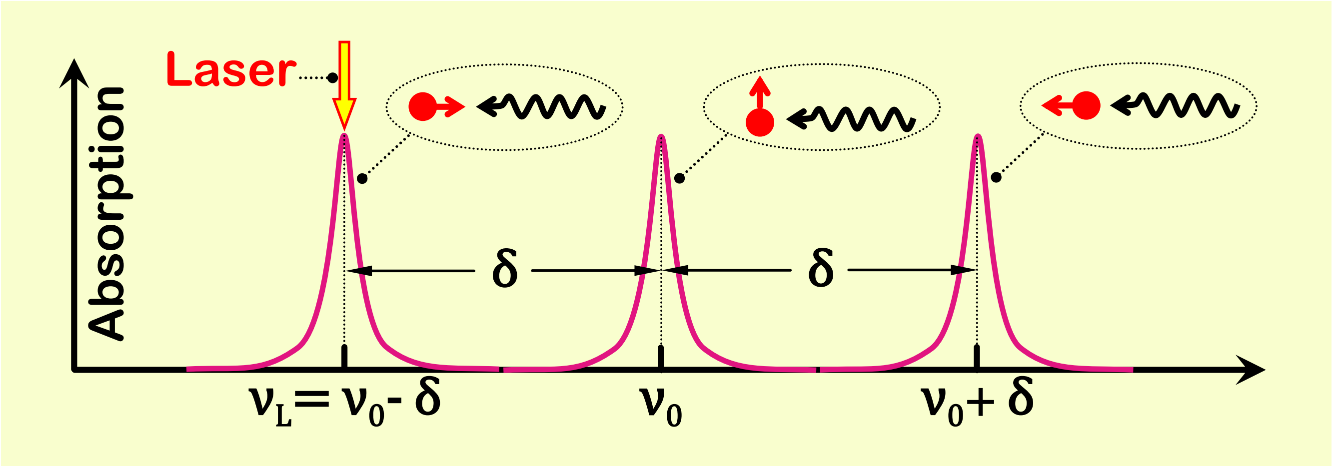




Proton therapy

12. Equipotentiality

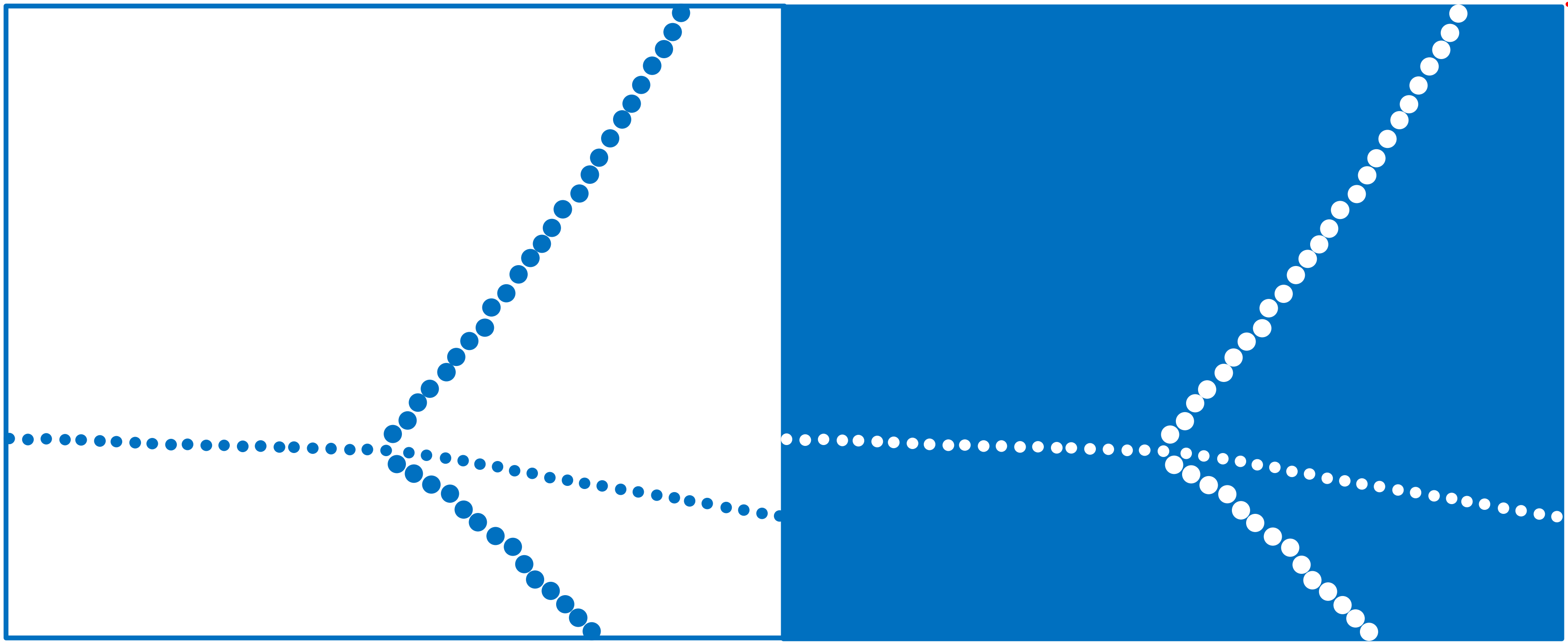
- In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).



Laser cooling

13. The other way round

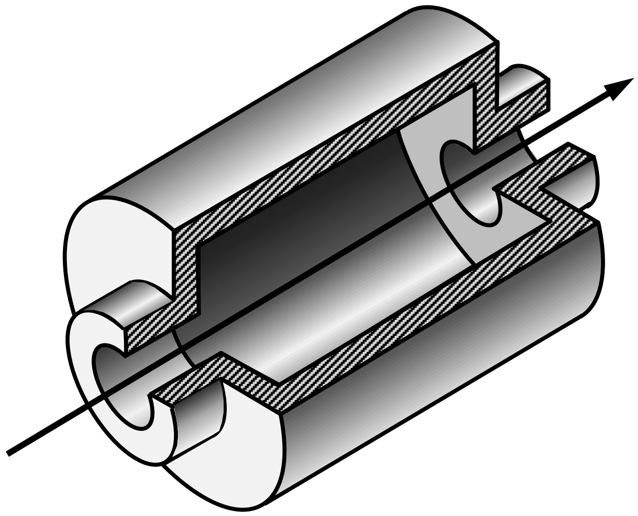
- Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).
- Make movable parts (or the external environment) fixed, and fixed parts movable.
- Turn the object (or process) “upside down”.

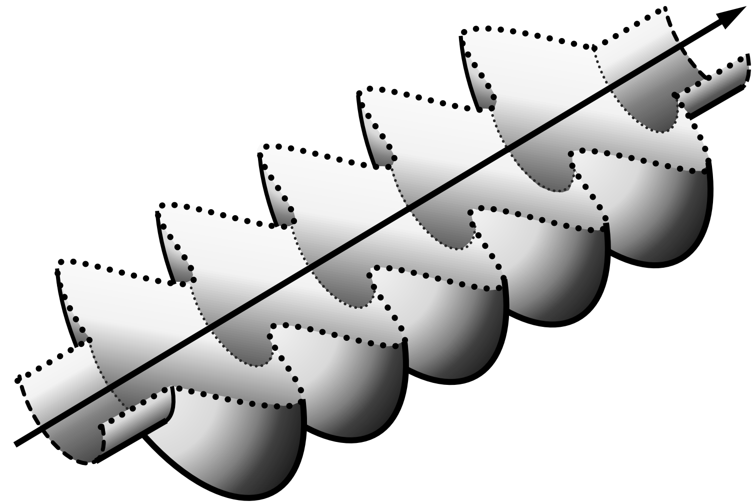


Cloud and bubble chambers

14. Spheroidality – Curvature

- Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.
- Use rollers, balls, spirals, domes.
- Go from linear to rotary motion, use centrifugal forces.

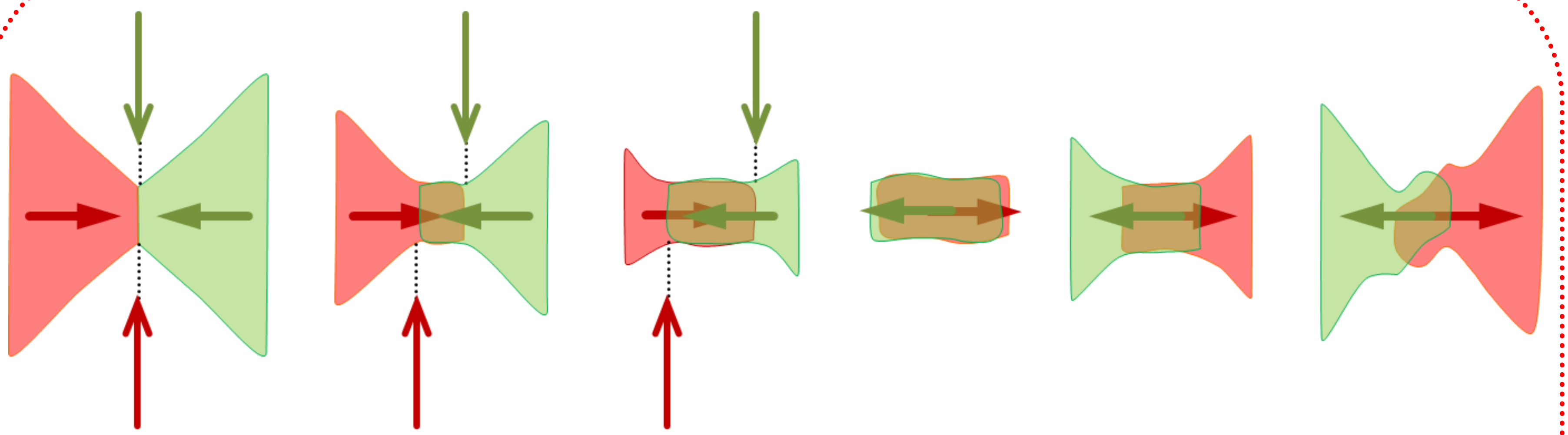




Pill-box and crab-cavity

15. Dynamics

- Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.
- Divide an object into parts capable of movement relative to each other.
- If an object (or process) is rigid or inflexible, make it movable or adaptive.

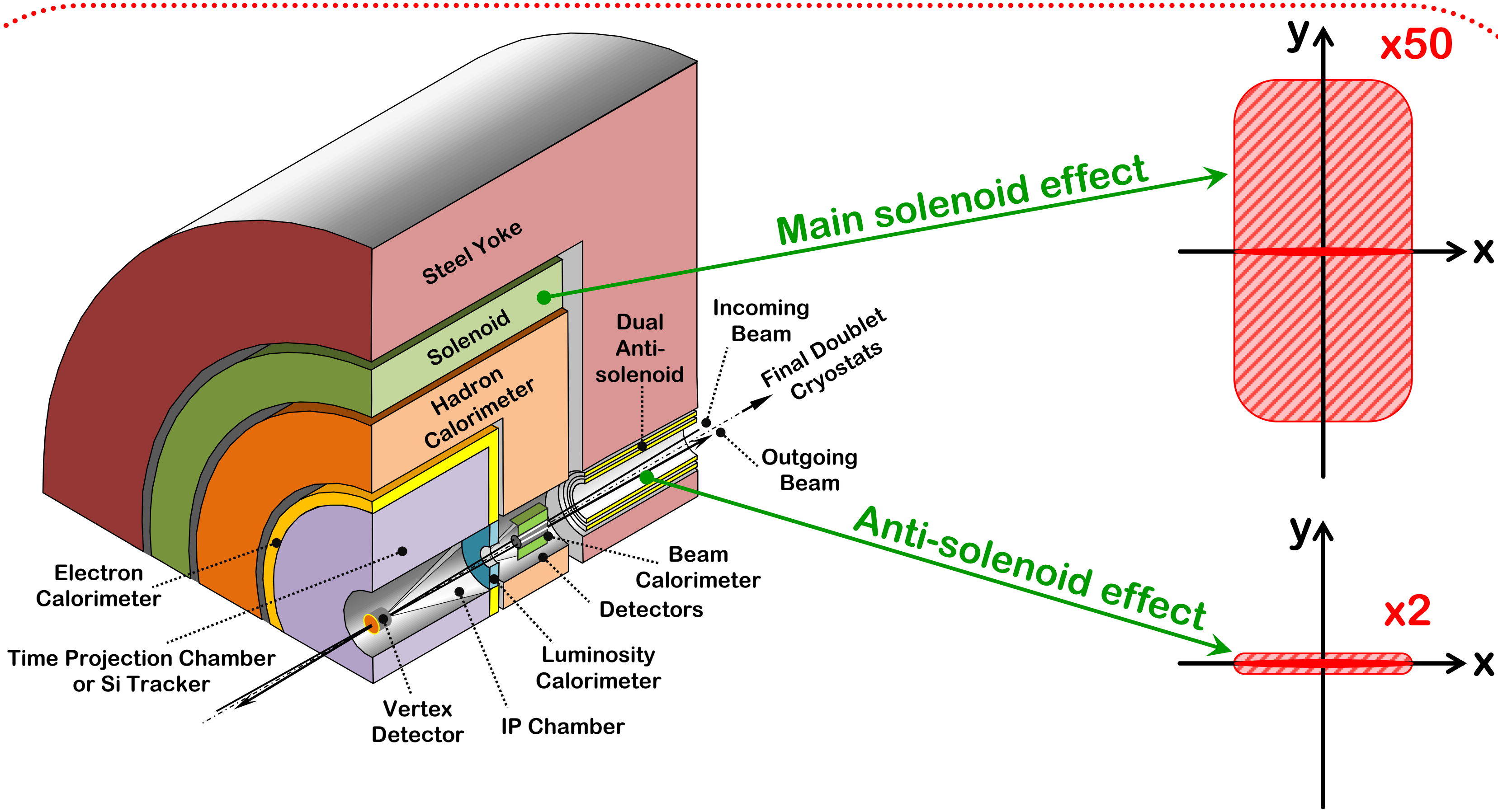


Travelling focus

V. Balakin, 1991

16. Partial or excessive actions

- If 100 percent of an object is hard to achieve using a given solution method then, by using "slightly less" or "slightly more" of the same method, the problem may be considerably easier to solve.

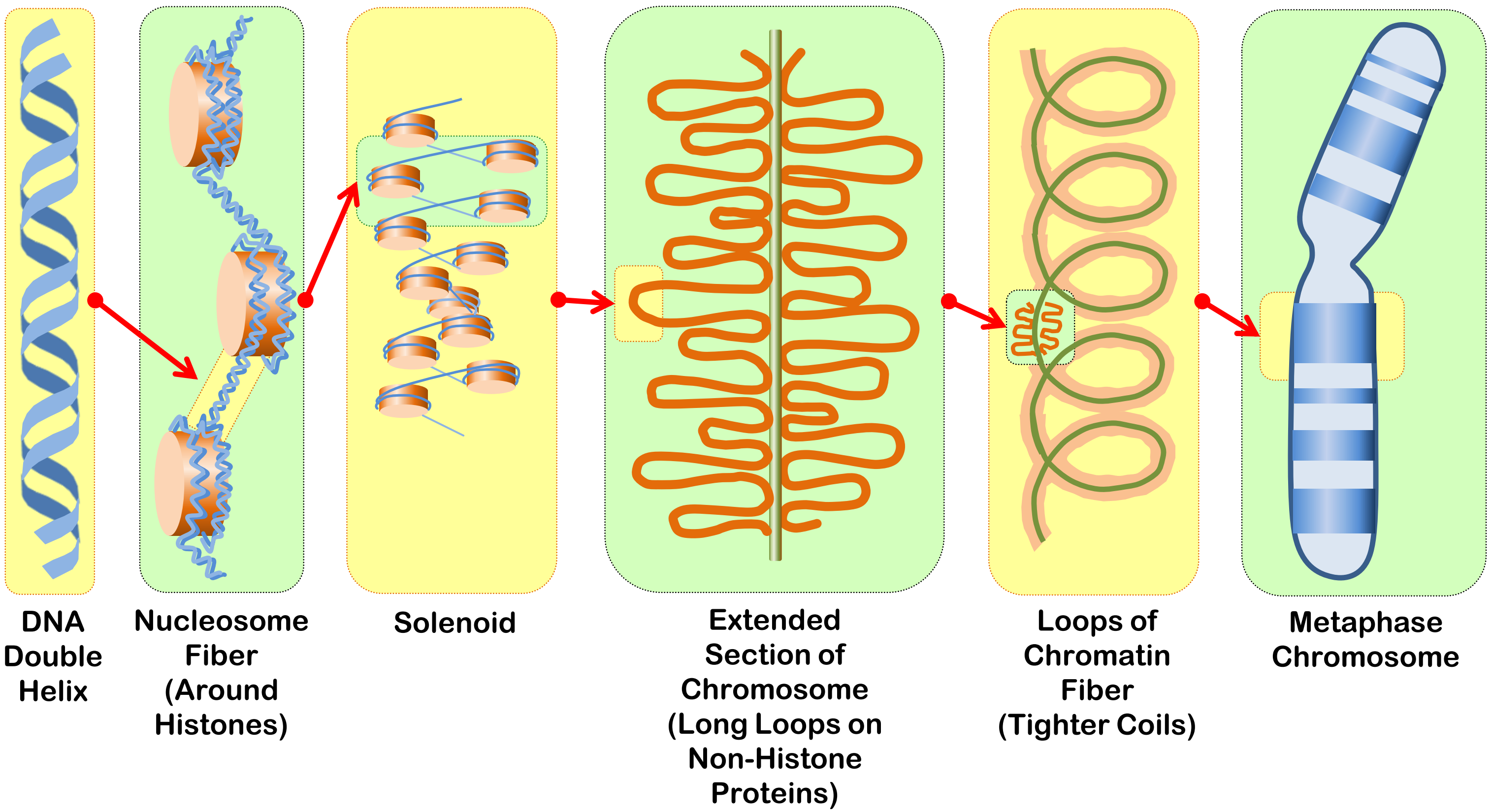


Huge coupling due to overlap of solenoid with Final Doublet quads => partial compensation by weak anti-solenoid

Y. Nosochkov, A. Seryi, PRSTAB, 8, 021001 (2005)

17. Another dimension

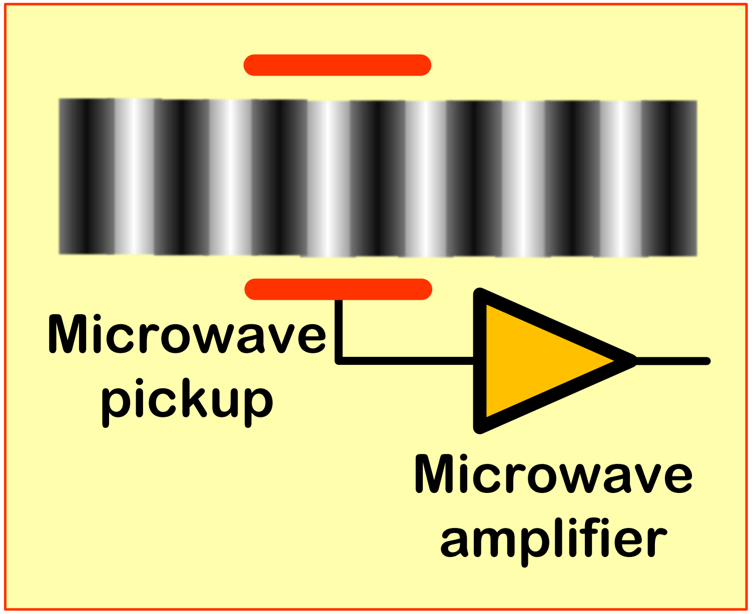
- To move into an additional dimension.
- Use a multi-story arrangement of objects instead of a single-story arrangement.
- Tilt or re-orient the object, lay it on its side.
- Use “another side” of a given area.

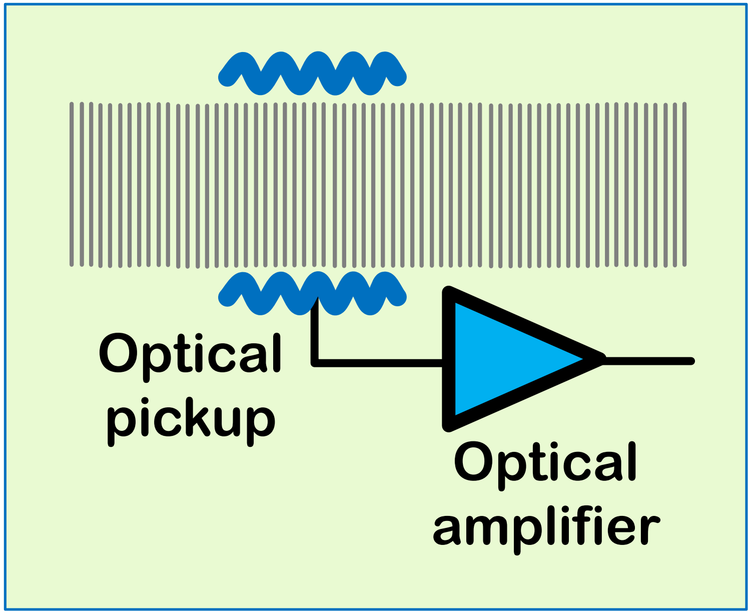


DNA packaging levels

18. ~~Mechanical vibration~~ Oscillations and resonances

- Cause an object to oscillate or vibrate.
- Increase its frequency (~~even up to the ultrasonic~~ from microwave to optical).
- Use an object's resonant frequency.
- Use piezoelectric vibrators instead of mechanical ones.
- Use combined ultrasonic and electromagnetic field oscillations.

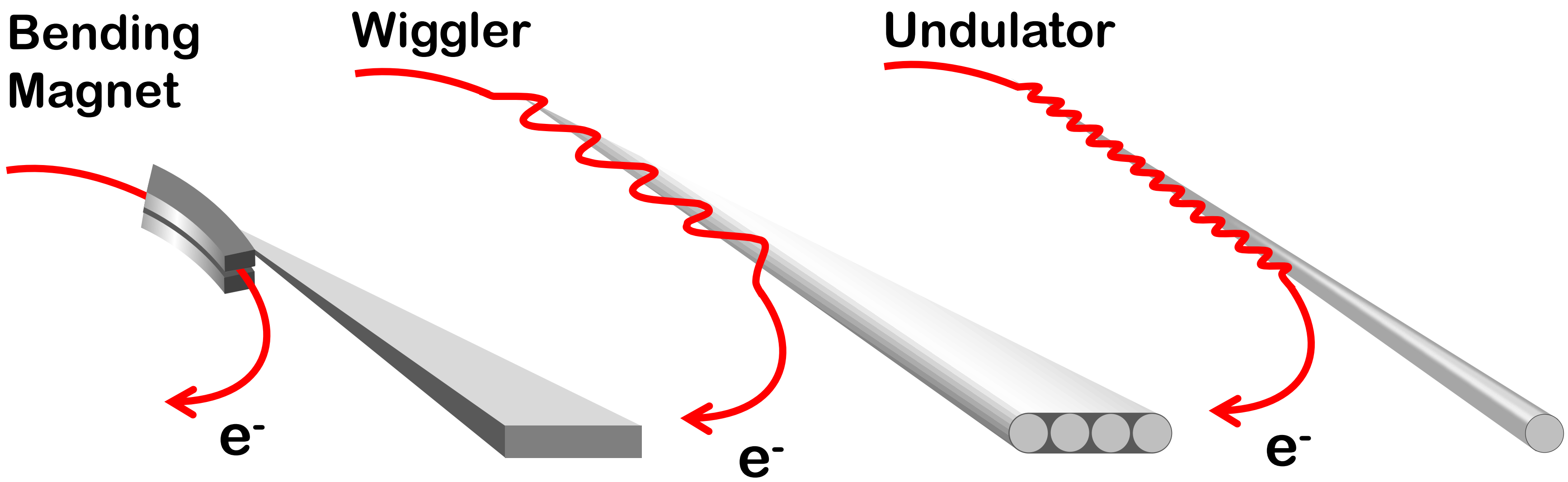




Stochastic cooling => optical stochastic cooling

19. Periodic action

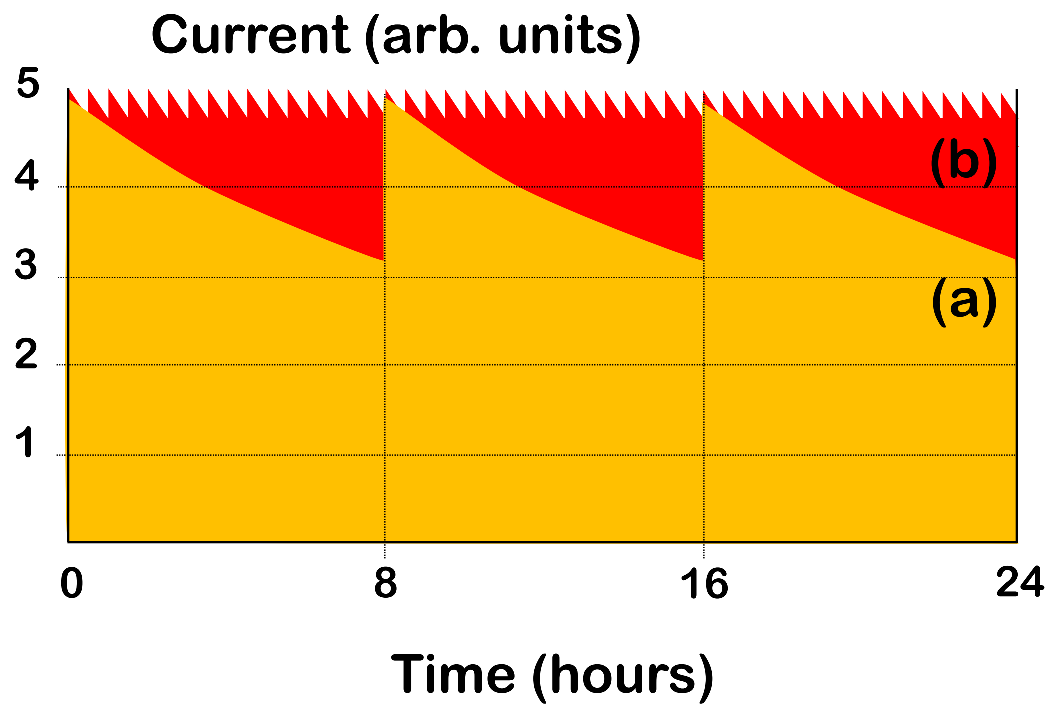
- Instead of continuous action, use periodic or pulsating actions.
- If an action is already periodic, change the periodic magnitude or frequency.
- Use pauses between impulses to perform a different action.



Devices for generation of synchrotron radiation

20. Continuity of useful action

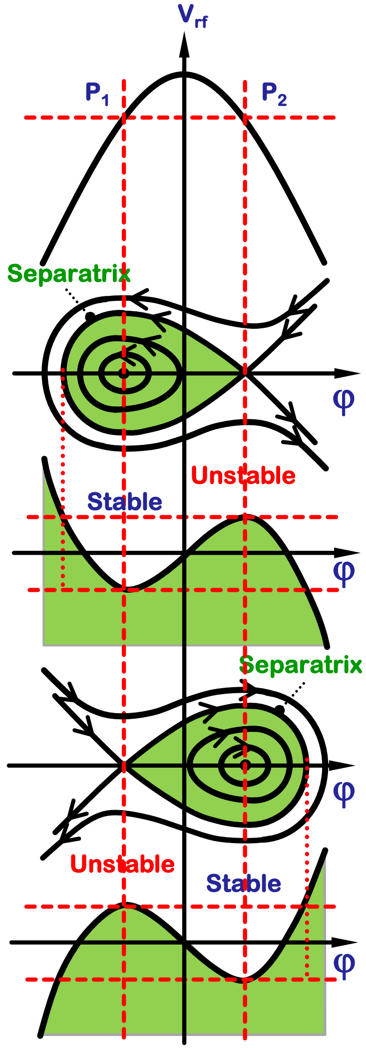
- Carry on work continuously; make all parts of an object work at full load, all the time.
- Eliminate all idle or intermittent actions or work.

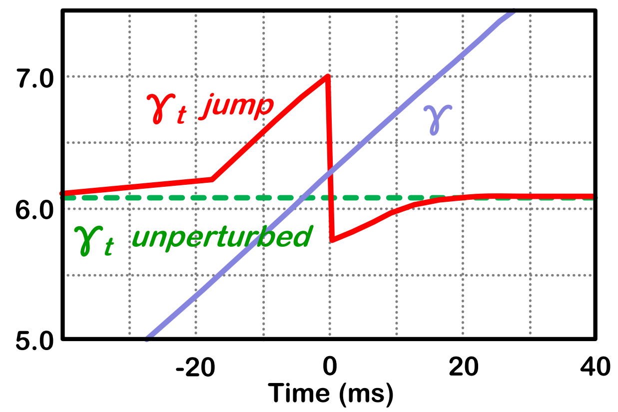


Top off injection

21. Skipping

- Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

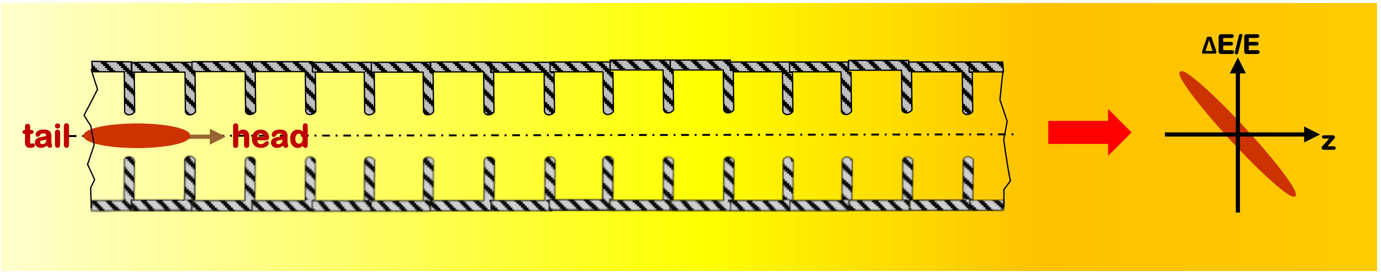




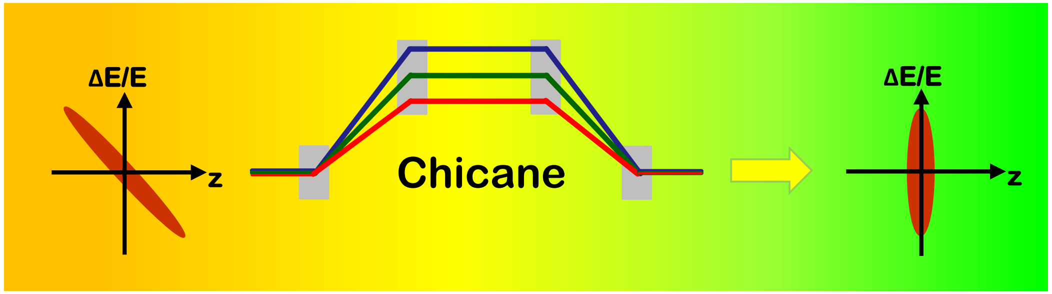
Crossing transition energy with γ_t jump technique

22. "Blessing in disguise" or "Turn Lemons into Lemonade"

- Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
- Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.
- Amplify a harmful factor to such a degree that it is no longer harmful.



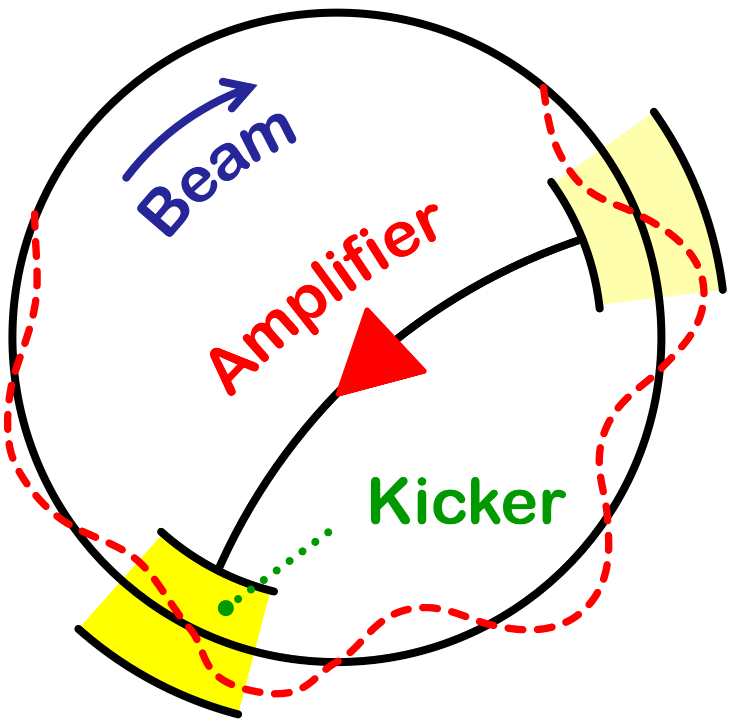
Wakefields in long Linac are harmful.
They can be made useful by compressing bunch for use in FEL.



Linac wake for FEL use

23. Feedback

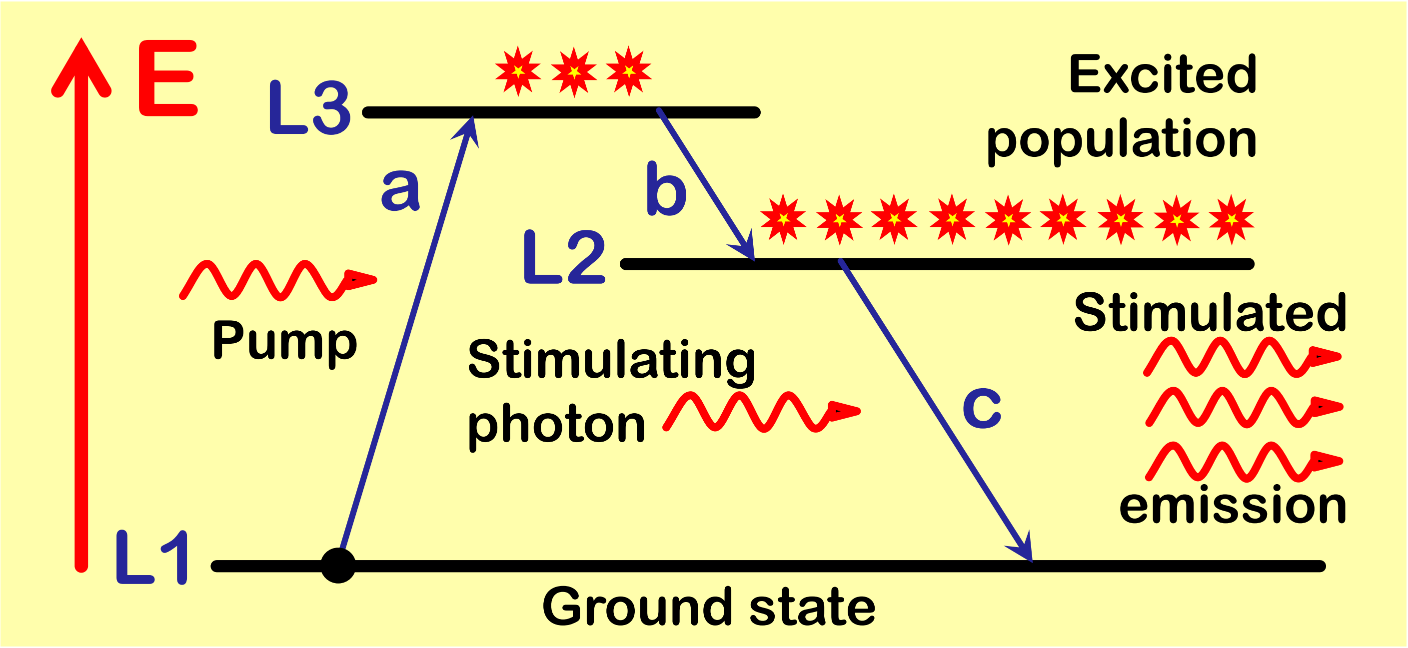
- Introduce feedback (referring back, cross-checking) to improve a process or action.
- If feedback is already used, change its magnitude or influence.



Stochastic cooling

24. Intermediary

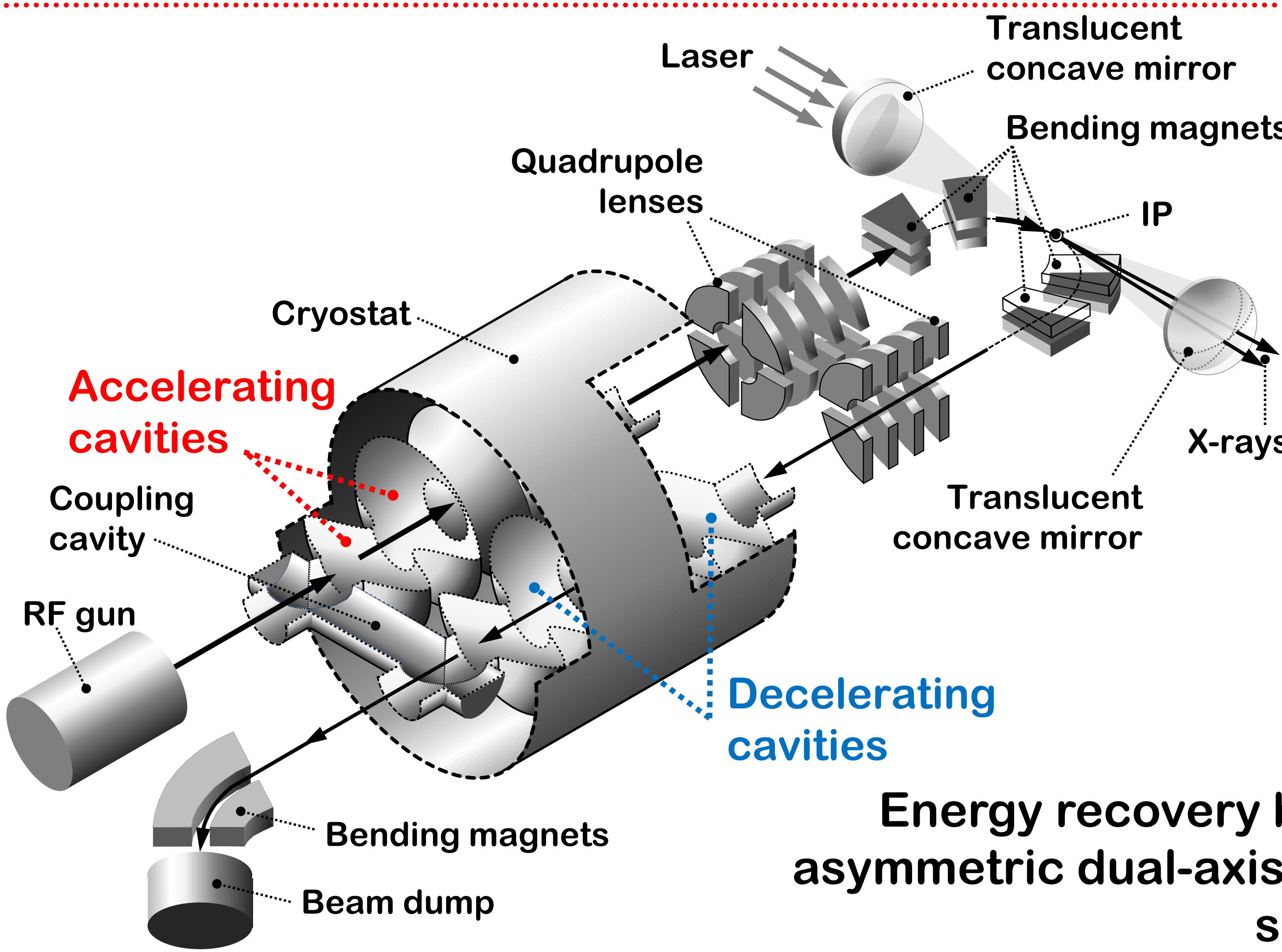
- Use an intermediary carrier object or intermediary process.
- Merge one object temporarily with another (which can be easily removed).



Three-level laser

25. Self service

- Make an object serve itself by performing auxiliary helpful functions
- Use waste resources, energy, or substances.

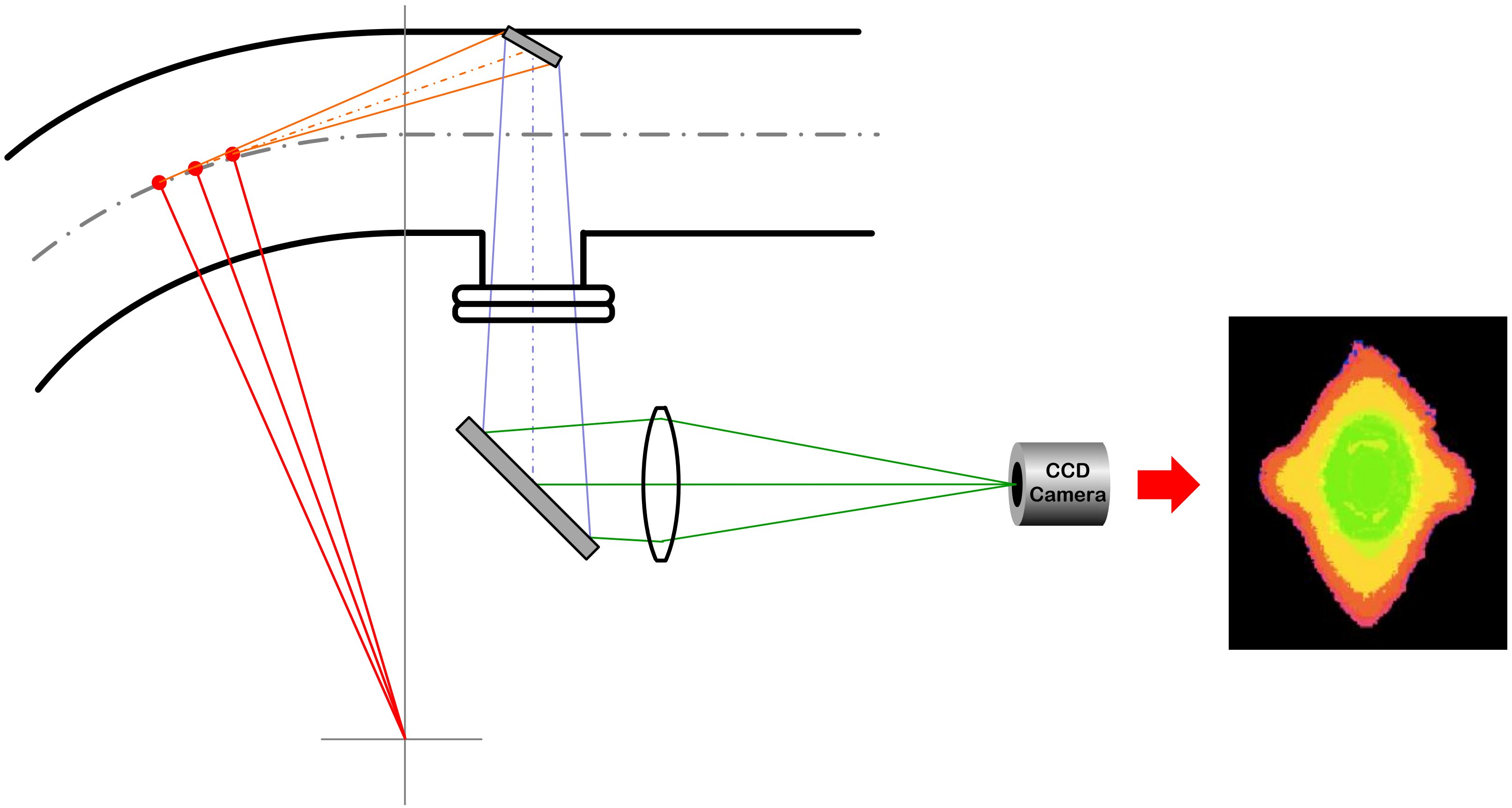


Energy recovery based asymmetric dual-axis X-ray source

R. Ainsworth, G. Burt, I. V. Konoplev, A. Seryi, arXiv:1509.03675, 2015

26. Copying

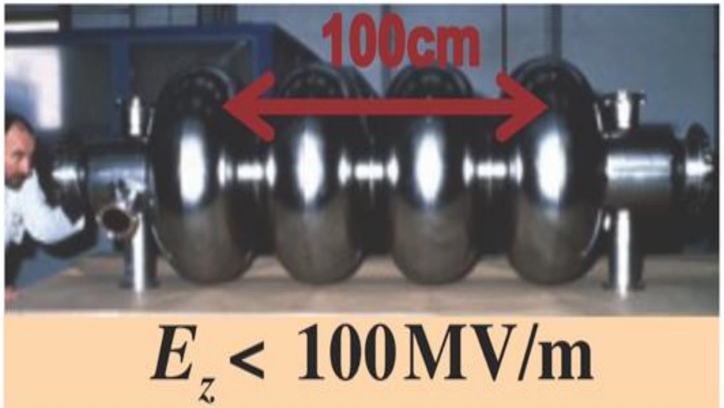
- Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.
- Replace an object, or process with optical copies.
- If visible optical copies are already used, move to infrared or ultraviolet copies.



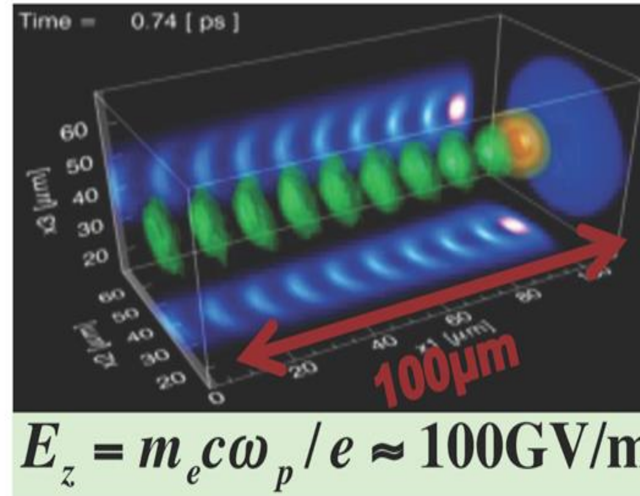
Synchrotron radiation profile monitor

27. Cheap short-living objects

- Replace an expensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).



Accelerating structure, metal (normal conductive or super-conductive)

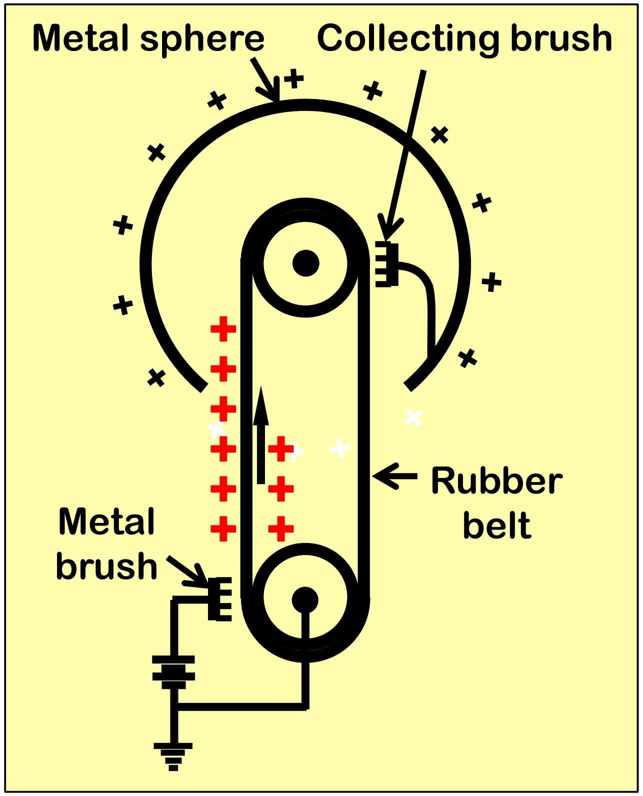


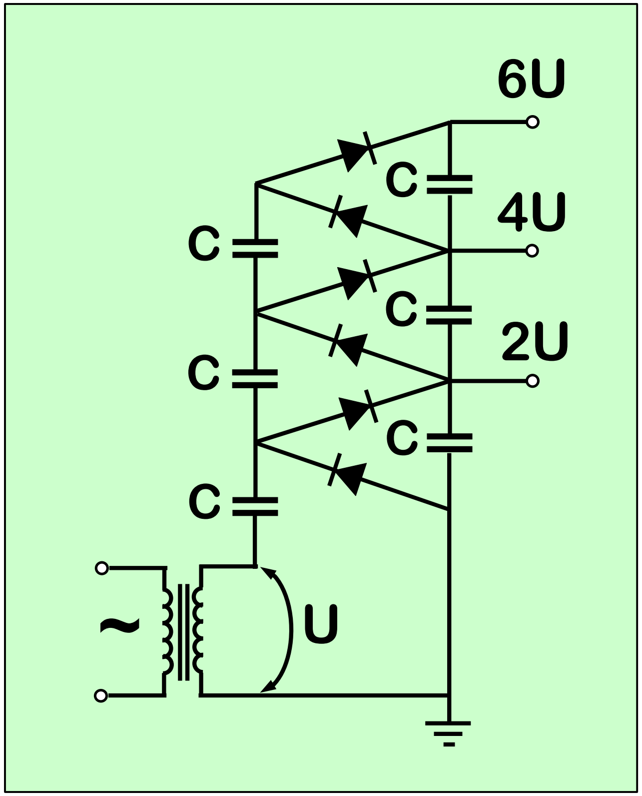
"Accelerating structure" produced on-the-fly in plasma by laser pulse

Plasma acceleration

28. Mechanics substitution

- Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
- Use electric, magnetic and electromagnetic fields to interact with the object.
- Change from static to movable fields, from unstructured fields to those having structure.
- Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.

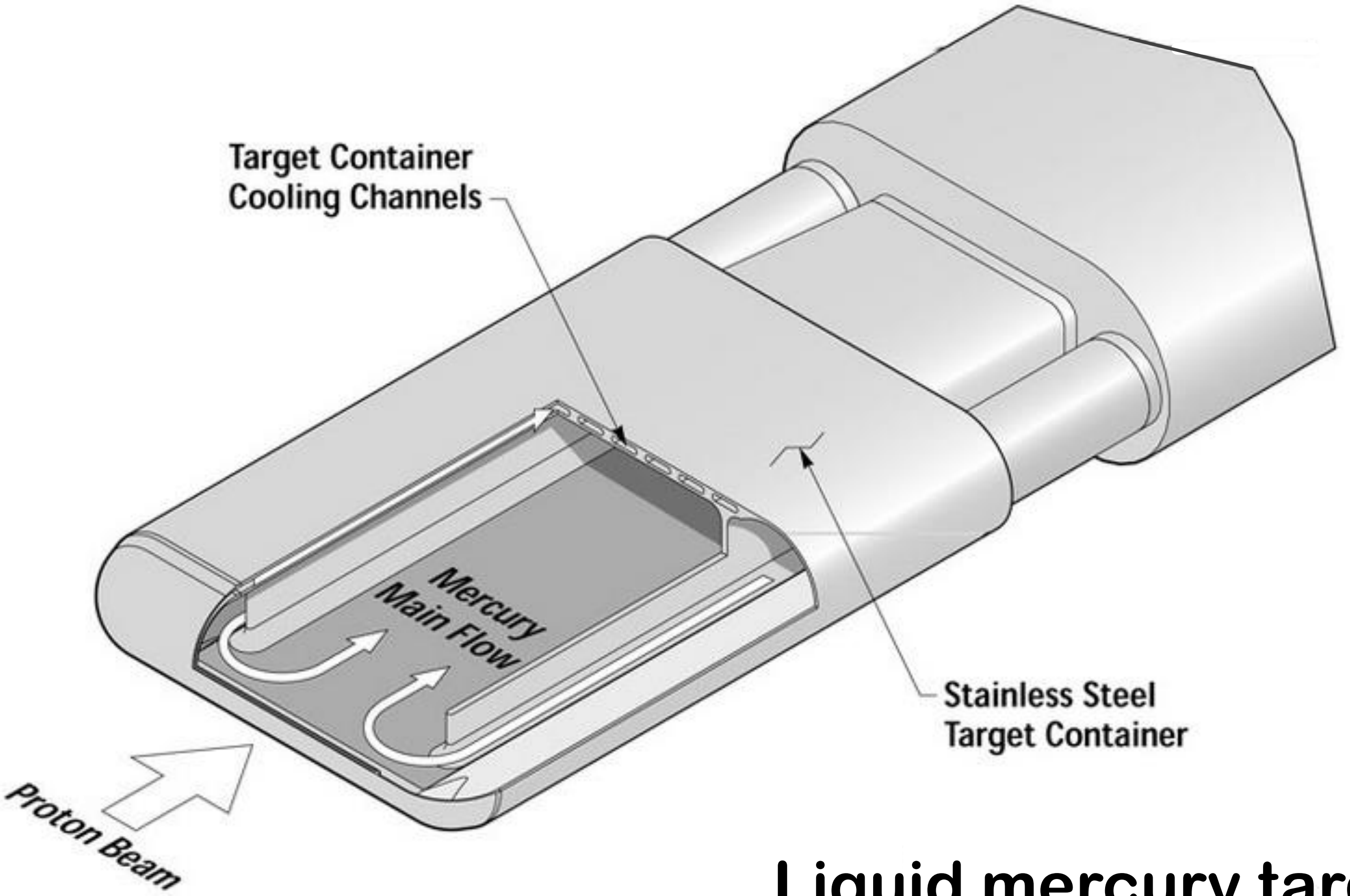




Van der Graaf to Cockroft-Walton generator

29.Pneumatics and hydraulics

- **Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).**

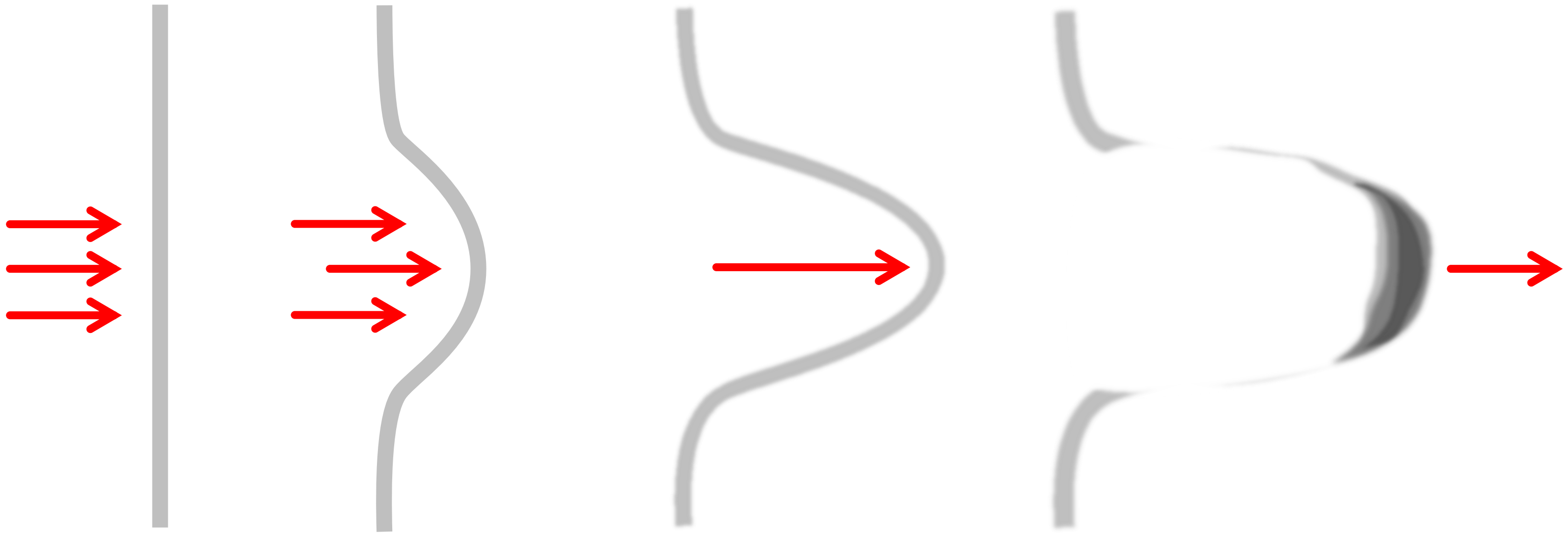


Liquid mercury target

Illustration: ORNL

30. Flexible shells and thin films

- Use flexible shells and thin films instead of three dimensional structures
- Isolate the object from the external environment using flexible shells and thin films.



Light sail laser-plasma ion acceleration

31. Porous materials

Make an object porous or add porous elements (inserts, coatings, etc.). If an object is already porous, use the pores to introduce a useful substance or function.

Membranes made with ion beams

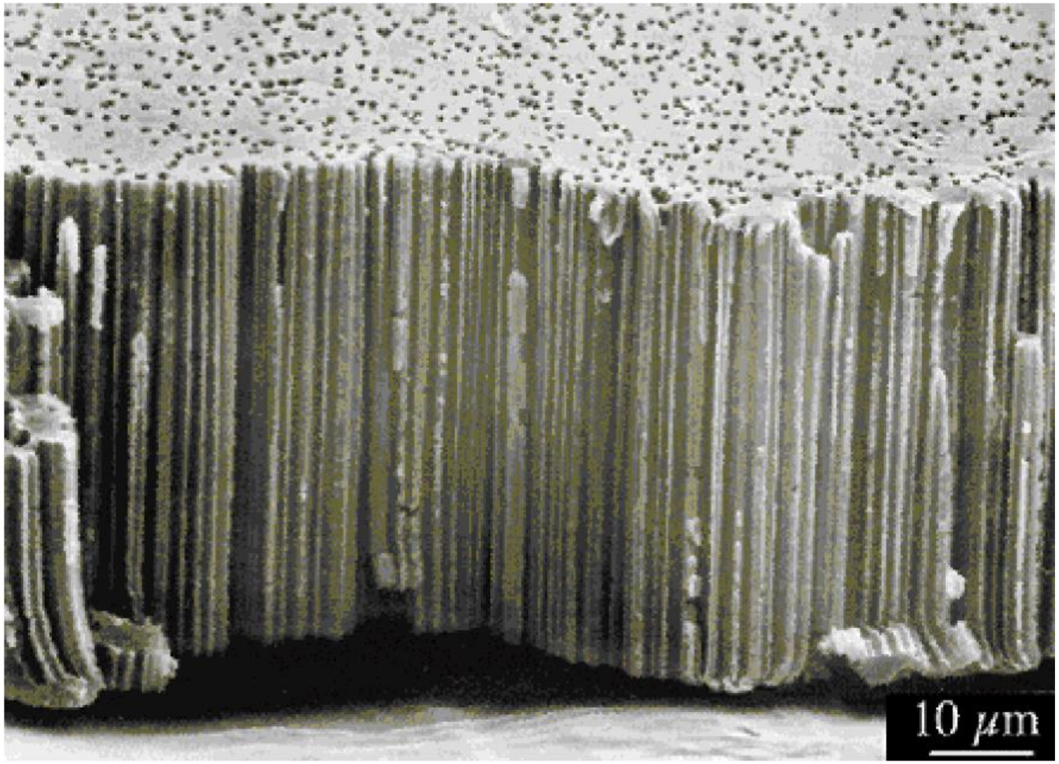
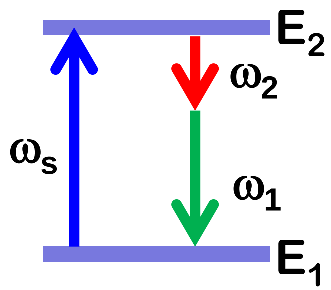


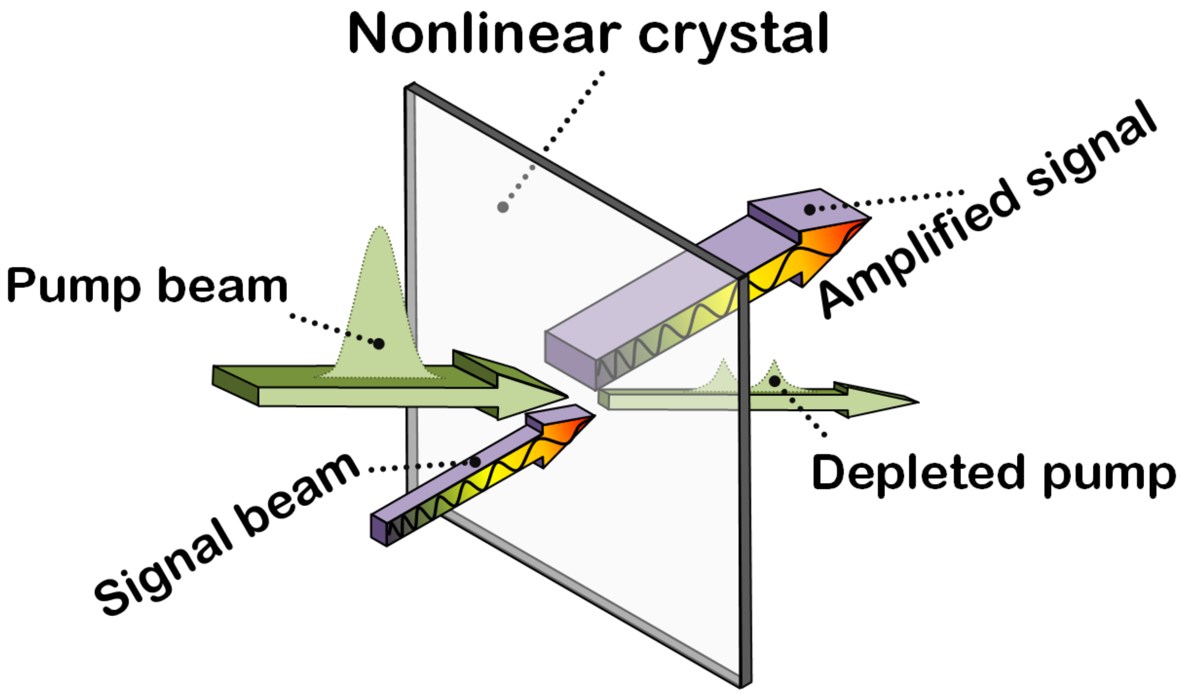
Illustration from "Engines of Discovery: A Century of Particle Accelerators", A. Sessler and T. Wilson, 2007

32. Color changes

- Change the color of an object or its external environment.
- Change the transparency of an object or its external environment.
- To improve observability of things that are difficult to see, use colored additives or luminescent elements.
- Change the emissivity properties of an object subject to radiant heating.



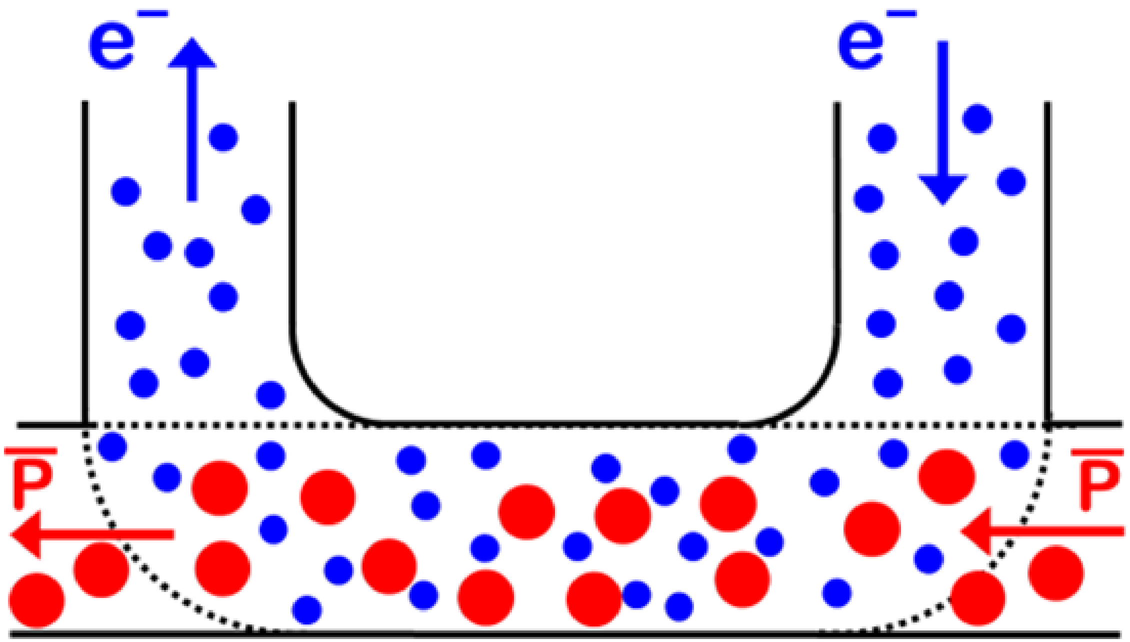
Optical Parametric process



Optical Parametric Chirped Pulse Amplification - OPCPA

33. Homogeneity *(Similia similibus curantur)*

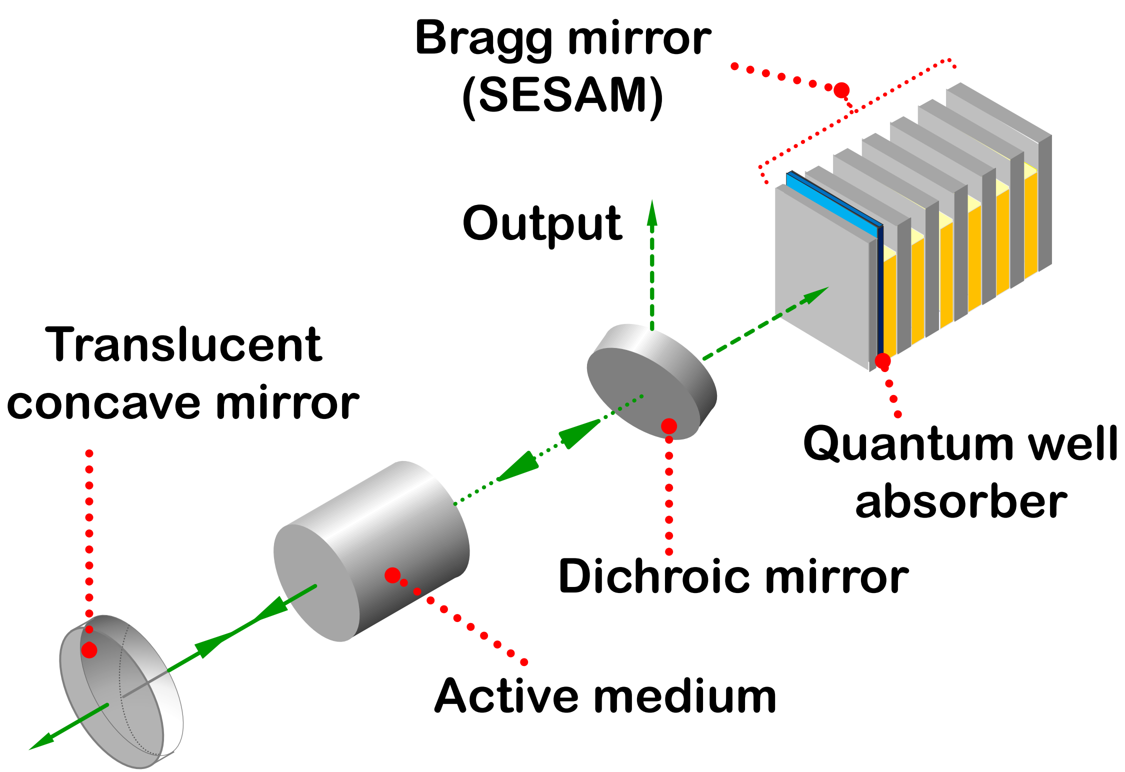
- **Make objects interacting with a given object of the same material (or material with identical properties).**



Electron cooling

34.Discarding and recovering

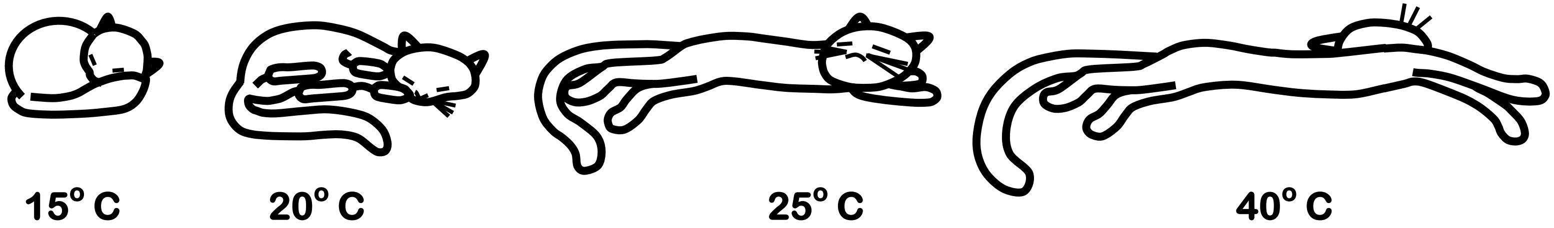
- Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
- Conversely, restore consumable parts of an object directly in operation.

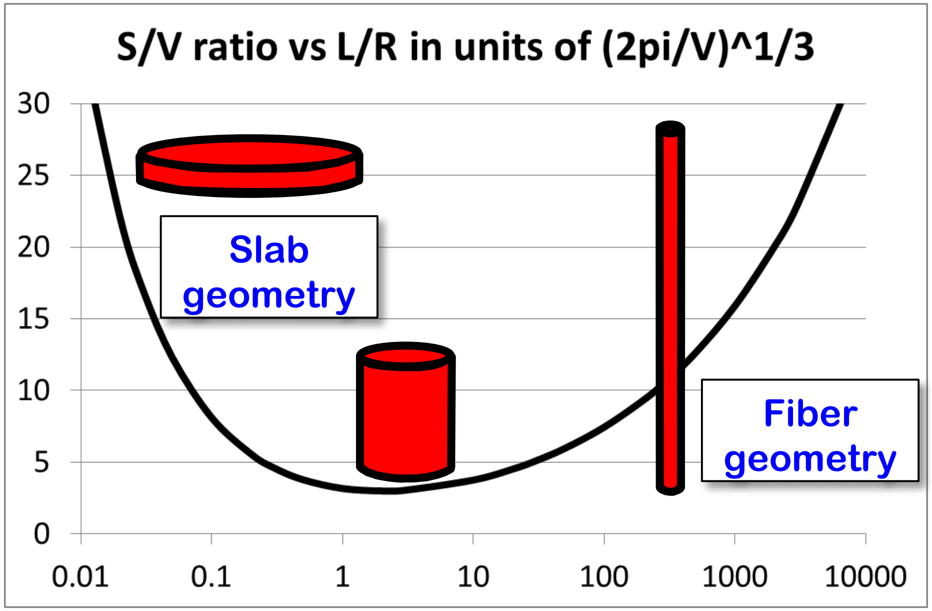


Semiconductor Saturable Absorber Mirror - SESAM

35. Parameter changes

- Change an object's physical state (e.g. to a gas, liquid, or solid.)
- Change the concentration or consistency.
- Change the degree of flexibility.
- Change the temperature.

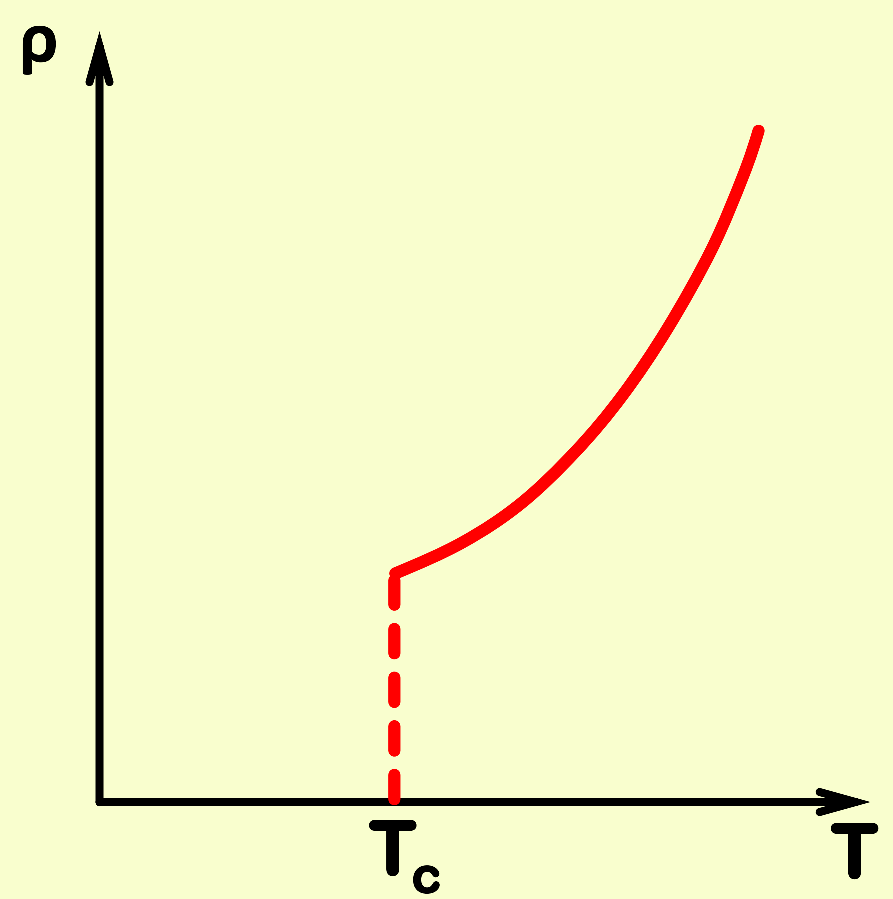




Fiber lasers

36. Phase transitions

- Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

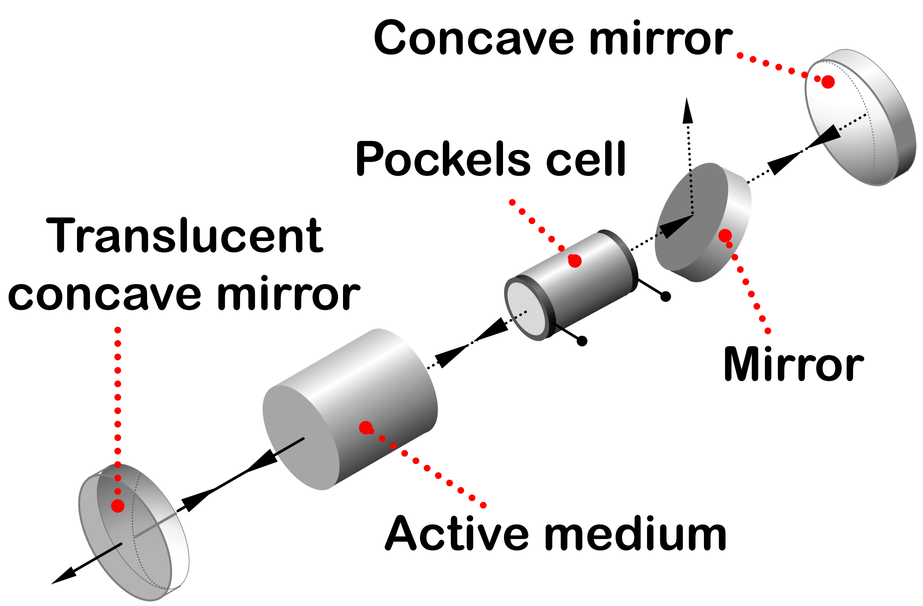


Phase transition

Superconductivity

37. Thermal or electrical expansion or property change

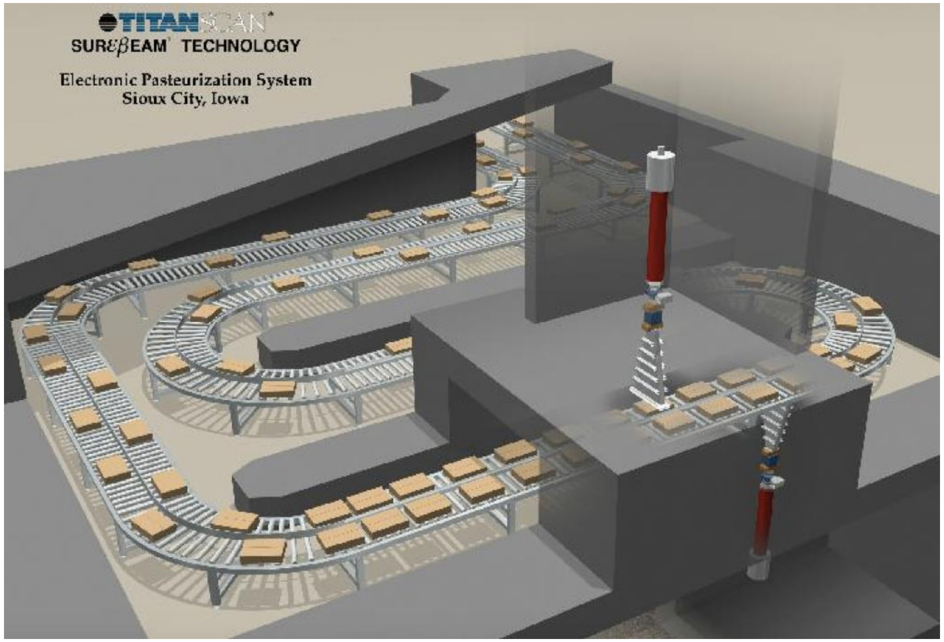
- Use thermal or electrical expansion (or contraction) or other property change of materials.
- If thermal or electrical expansion (property change) is being used, use multiple materials with different coefficients of thermal expansion (property change).



Electro-optic effect — dependence of optical properties of objects such as absorption or refraction (Pockels effect) on the applied electric field

38. Strong oxidants

- Replace common air with oxygen-enriched air.
- Replace enriched air with pure oxygen.
- Expose air or oxygen to ionizing radiation.
- Use ionized oxygen.
- Replace ozonized (or ionized) oxygen with ozone.



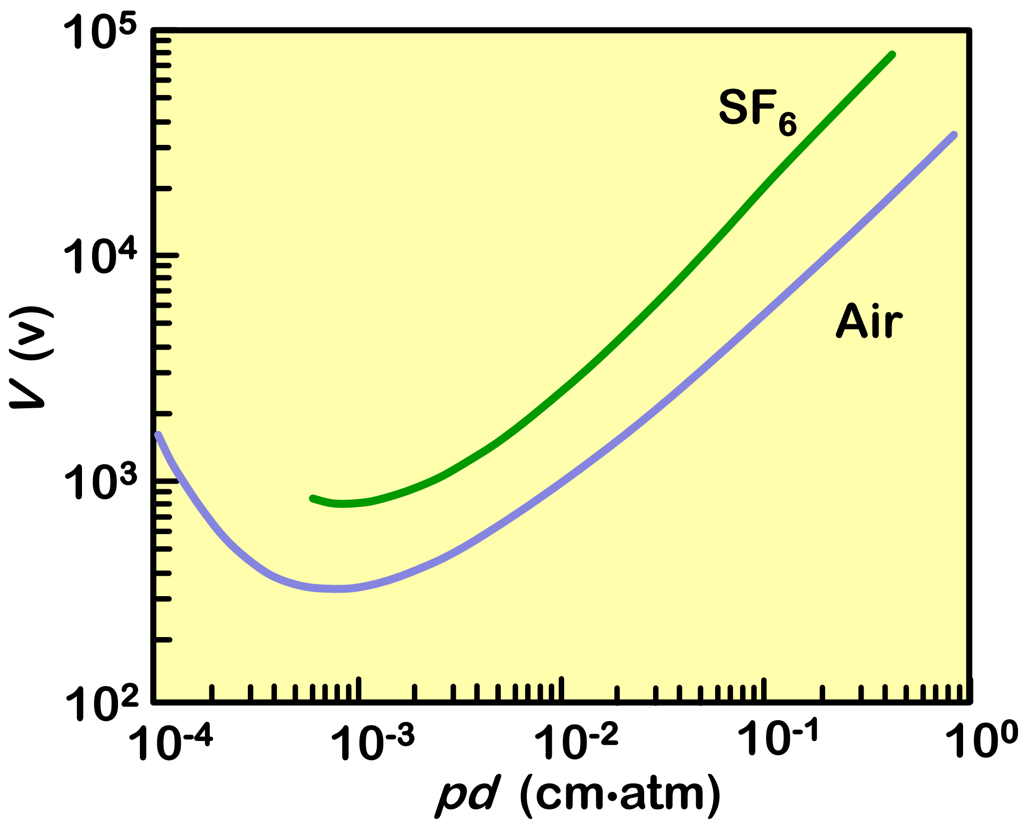
TITANSCAN*
SUR$\varepsilon\beta$EAM TECHNOLOGY
Electronic Pasteurization System
Sioux City, Iowa

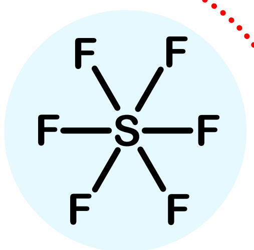
Irradiation of food for sterilisation

Illustration: TITANSCAN

39. Inert atmosphere

- Replace a normal environment with an inert one.
- Add neutral parts, or inert additives to an object.





Sulfur hexafluoride (SF6 or Elegas) is a colorless non-flammable gas with excellent electric insulating and arc-quenching capacity. It is widely used in the fields of electric, laser, medical, meteorological, freezing, fire-fighting, chemical, military, space aviation, nonferrous metallurgy and physical research areas.

40. Composite materials

- Change from uniform to composite (multiple) materials.

Ion beam surface treatment
Hardening an artificial knee joint using ion implantation

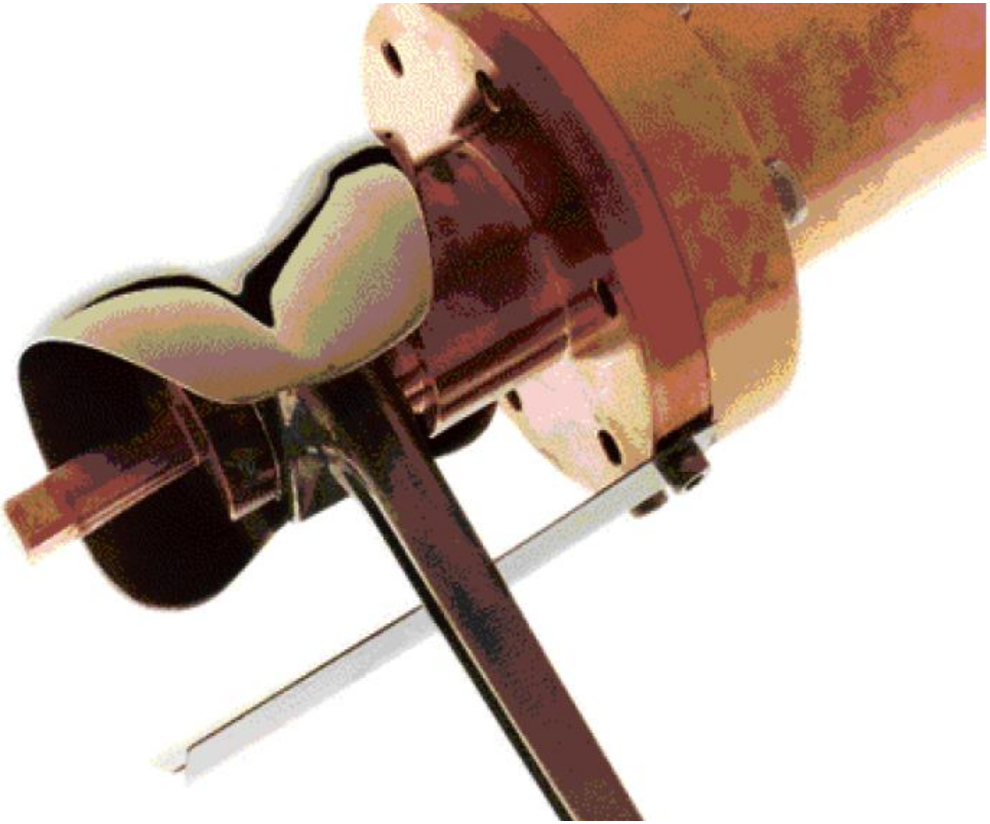


Illustration from "Engines of Discovery: A Century of Particle Accelerators"
A. Sessler and T. Wilson, 2007


Physical Review Letters
Physical Review Letters
Patent
Niels Bohr
Louis Pasteur
Accelerator Science & Technology
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
Patent
Protons/Ions
Fundamental knowledge
Consideration of use


PHYSICAL REVIEW LETTERS
PHYSICAL REVIEW LETTERS
Patent
Preferred direction – light sources
Niels Bohr
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PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
Patent
Protons/Ions
Fundamental knowledge
Consideration of use

Light sources & Pasteur quadrants

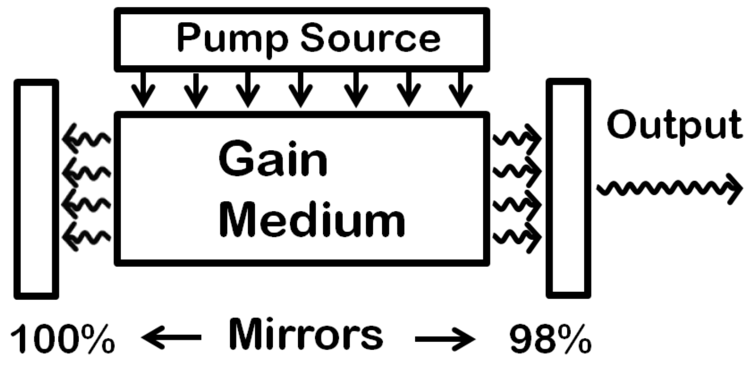
Light sources is preferred direction in the Pasteur quadrant

So, let's now talk about light sources

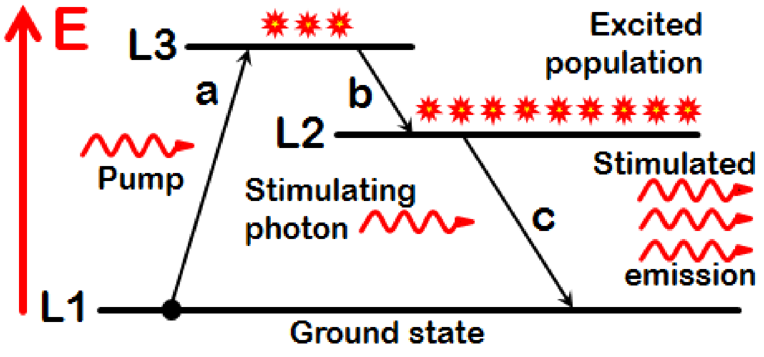
…and in particular those based on plasma acceleration

…but let's first recall lasers

Lasers – scheme & transitions in 3 level laser



Laser scheme



Three level laser

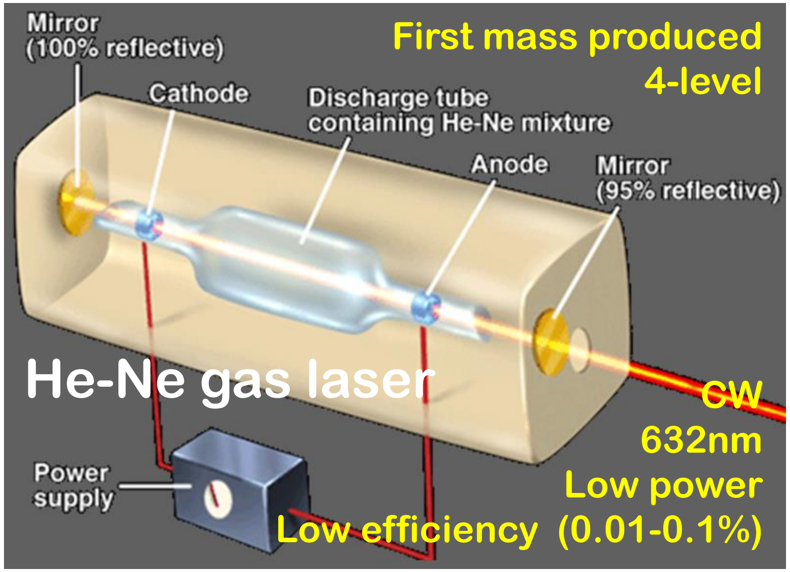
- **Laser components**
  - **Gain Medium (amplifies the light)**
  - **Resonator (gives optical feedback)**
  - **Pump Source (makes population inversion)**

a. **The pump gets population from ground state L1 to the higher energy level L3**

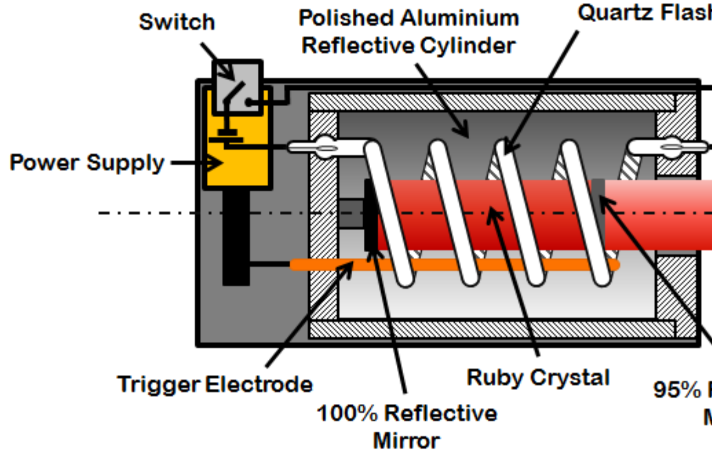
b. **The excited population gets from L3 to L2 through non radiative decay**
   - **The lifetime of L3 is very short and all the population in state L3 decays to state L2**

c. **Stimulated emission from L2 to state L1**
   - **Lifetime of energy state L2 is long => population inversion occurs with respect to state L1**
   - **Once the population inversion is obtained, stimulated emission will give optical gain**

Examples of laser types

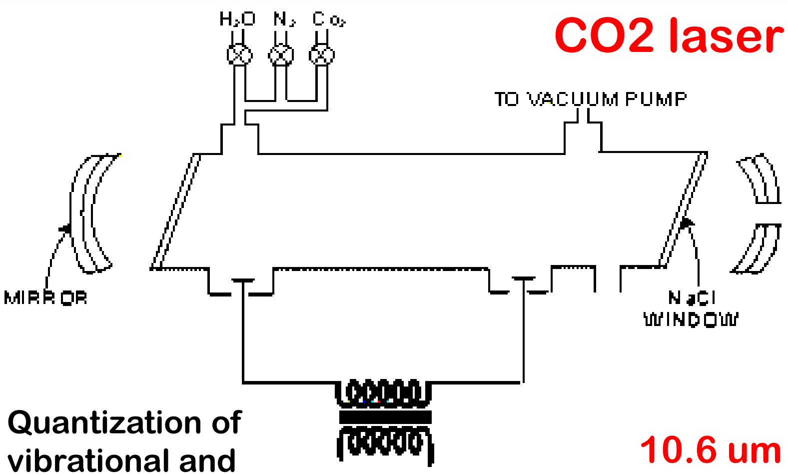


First laser
3-level



Ruby laser
694nm

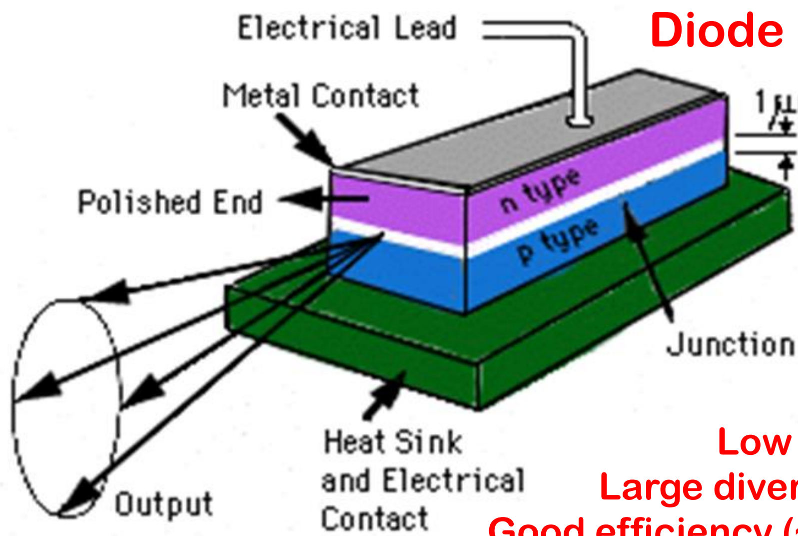
CO2 laser



Quantization of vibrational and rotational states of CO2 molecule

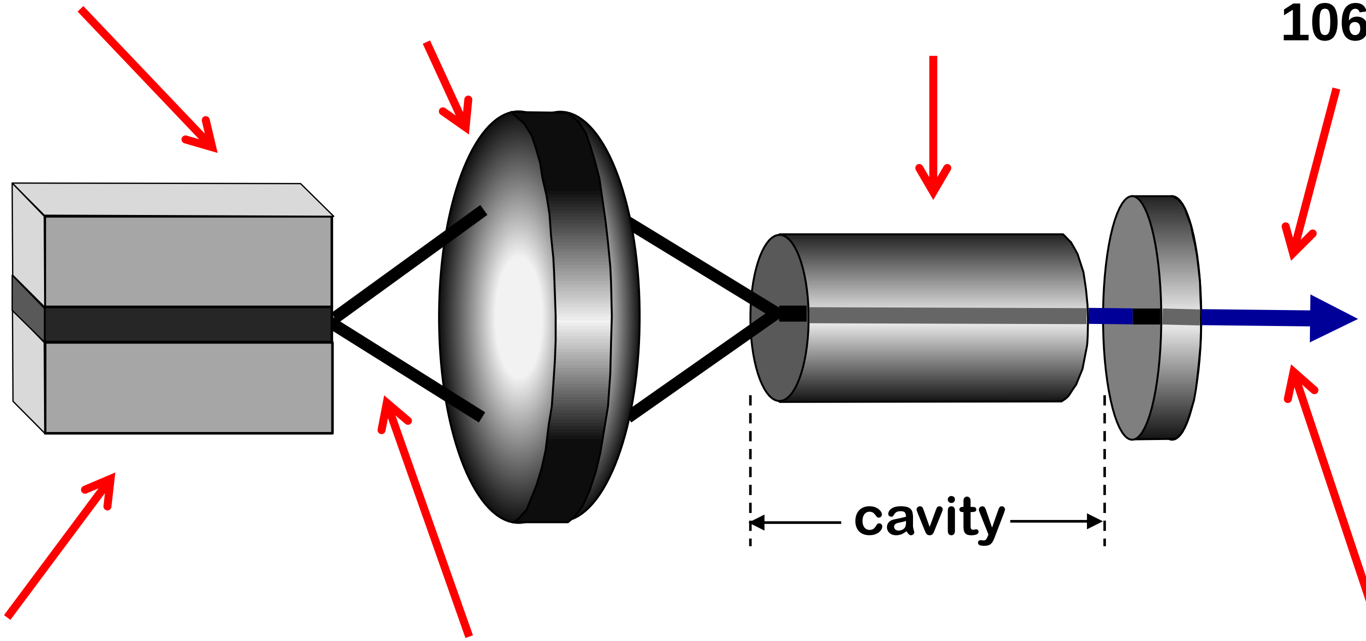
10.6 um
High power, kW in CW
Good efficiency (~ 30%)

Diode laser



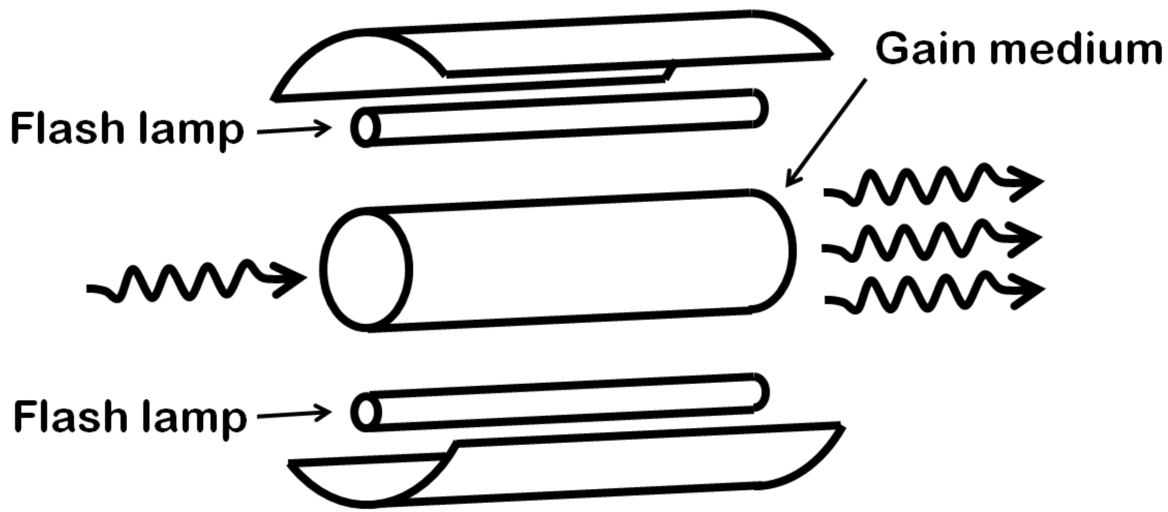
Low power
Large divergence
Good efficiency (~ 40%)

Diode laser – ideal for pumping



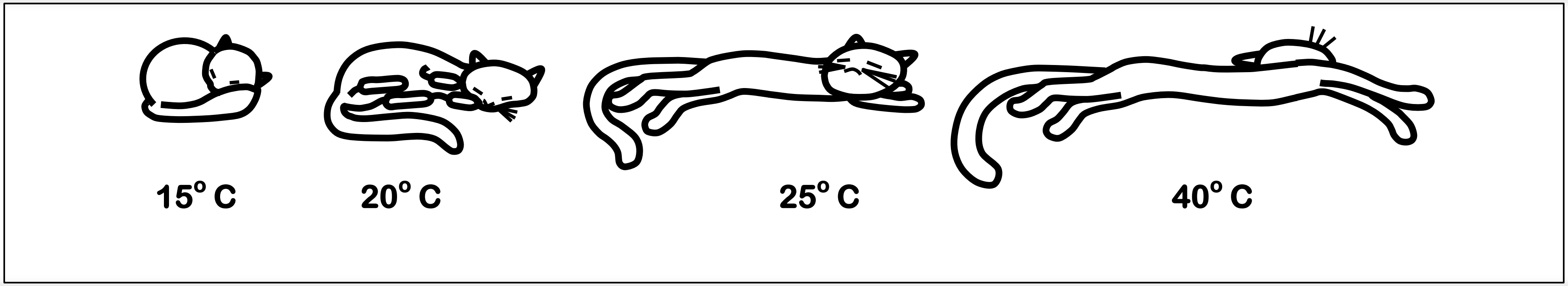
Nd:YAG neodymium-doped yttrium aluminium garnet; Nd:Y3Al5O12
Yb:YAG ytterbium-doped …

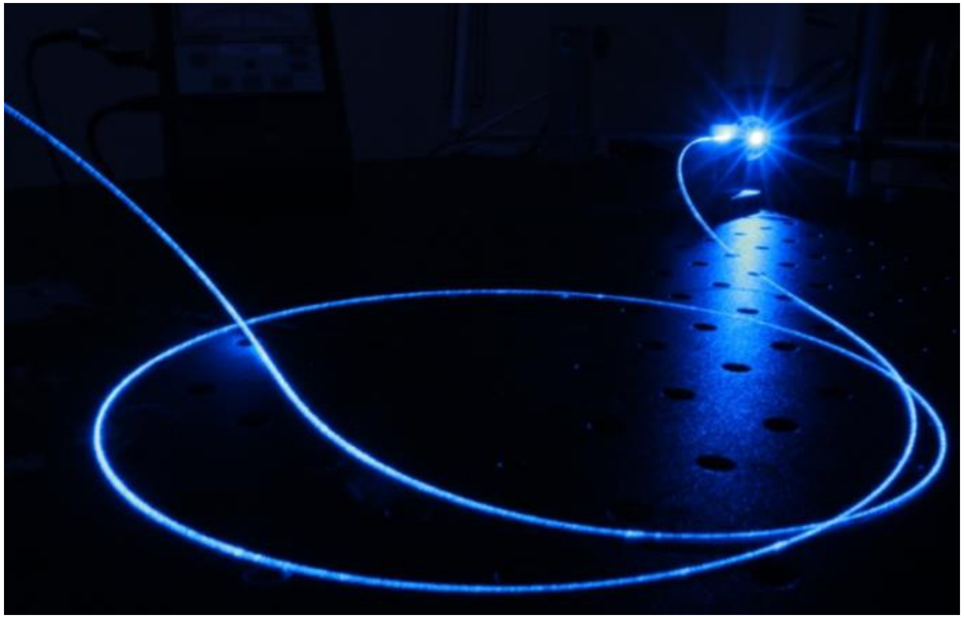
Laser amplifiers



Common principle: gain medium is pumped to produce gain for light at the wavelength of a laser made with the same material as its gain medium

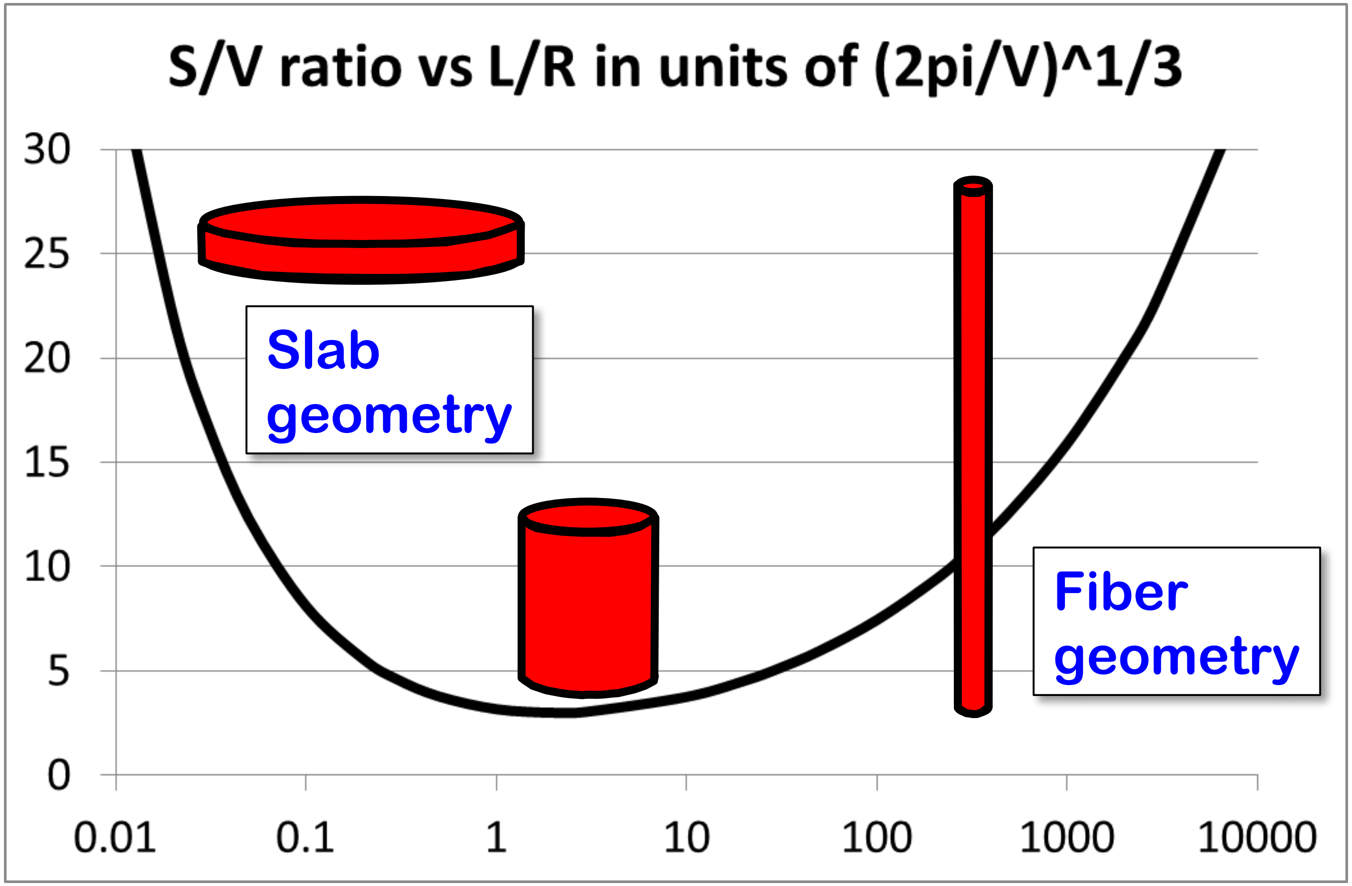
- **Ultra-short and ultra high power – challenges:**
  - **Ultra short – nonlinear effect in the medium**
  - **High power – heating the amplifier medium**
- **These challenges limit rep rate, power and efficiency**
  - **Some of the most powerful lasers fire just once per few hours!**
- **A lot of inventions in the field of light amplification**





Cats and fiber lasers are connected via a general inventive principle

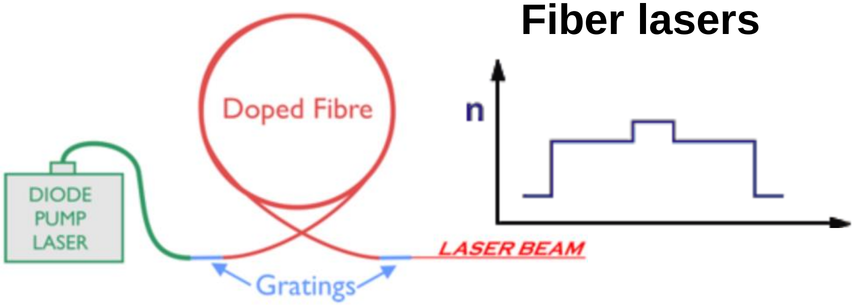
Fiber lasers and slab lasers



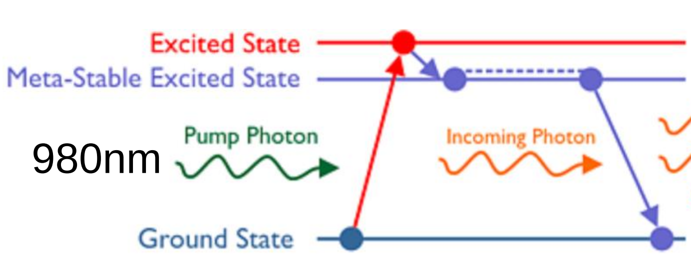
- **Fiber lasers and DiPOLE laser technology use the principle of larger surface to volume ratio**
  - **Possibility of high power, high rep rate, high efficiency**

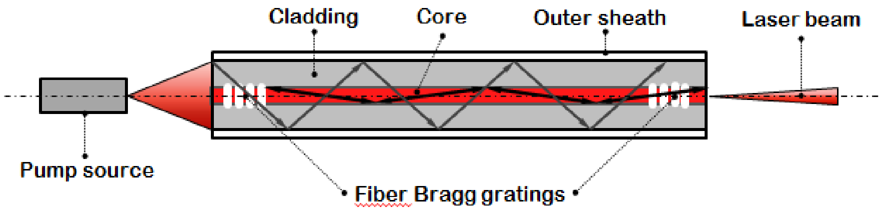
Fiber laser and DiPOLE lasers

Fiber lasers



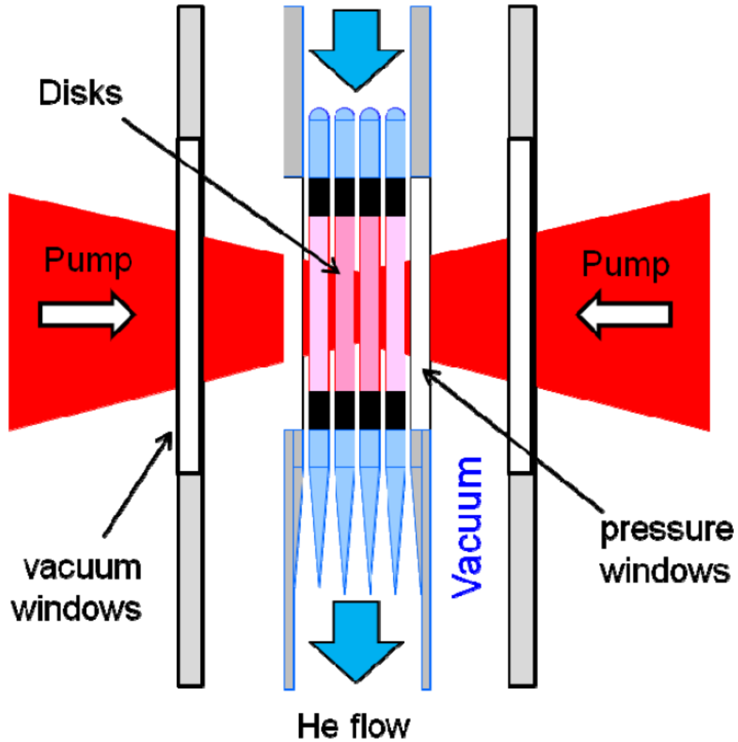
Diode pumped, Erbium-doped gain media





Bragg Gratings create reflections, acting as mirror
High efficiency, CW or sub-ps pulses
In CW mode – tens of kW (100 kW CW now!)
In pulsed mode – mJ in tens of kHz

DiPOLE = Diode Pumped Optical Laser Experiment – developed by CLF/RAL, UK



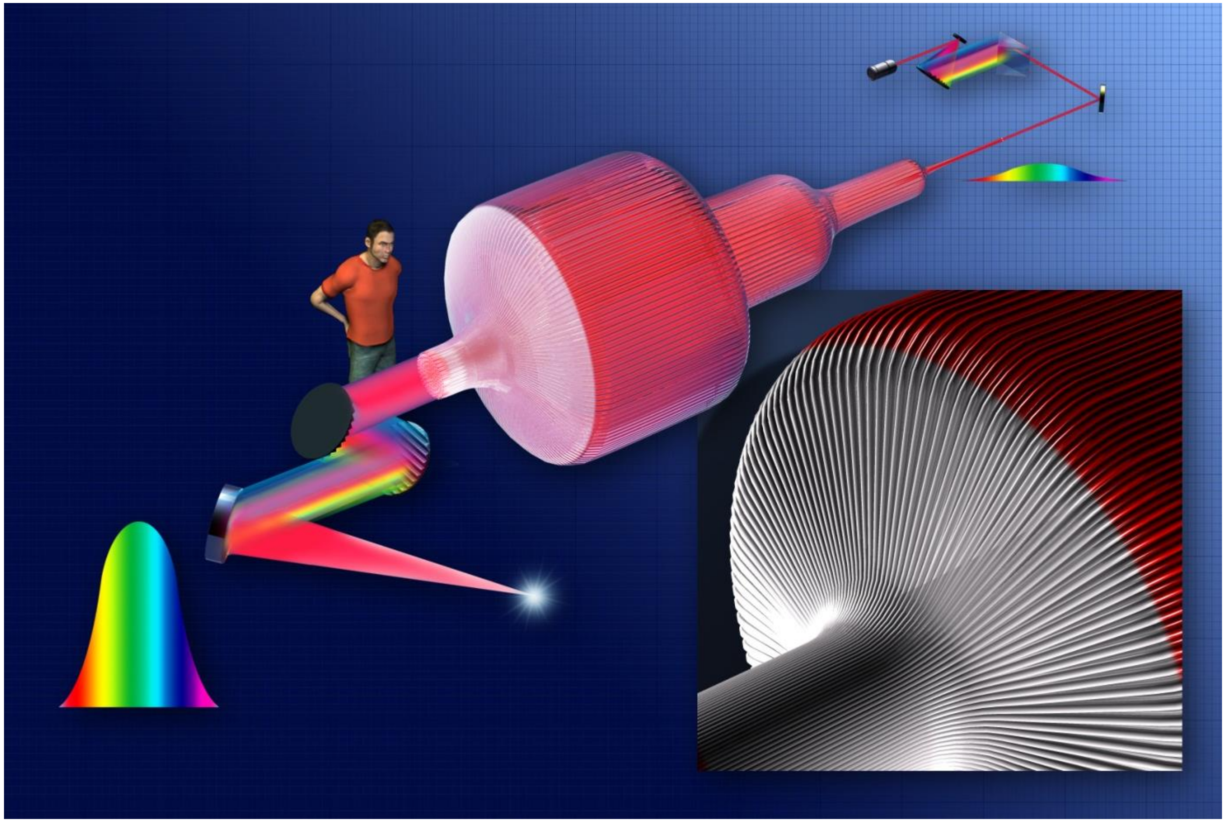
Cooled by cold He gas at 175K
Disks = Yb:YAG slabs
Aim to deliver kJ pulses at 10Hz
Pump at 939nm, radiate at 1030nm

A bit more about fiber lasers…

- Commercial fiber lasers reach 100 kW in CW
- Wall plug efficiency > 40%
- Photo below is from IPG Photonics

Laser combination

Research on combining many fibre lasers (short pulses!) together for high rep rate, high energy laser systems.

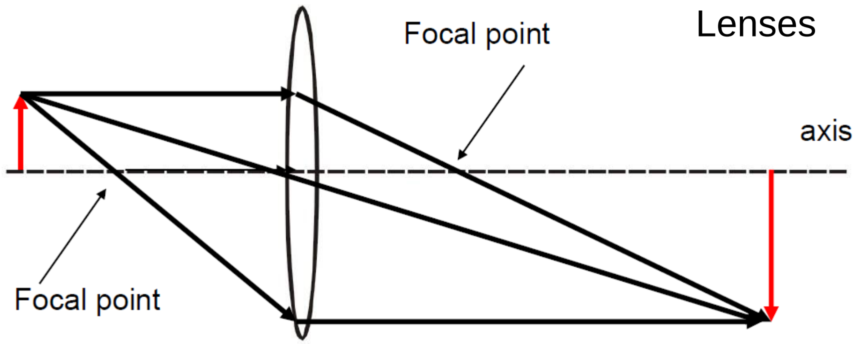


Phase control and combine 100s – 1000s fibres

"The future is fibre accelerators", Gerard Mourou, Bill Brocklesby,Toshiki Tajima & Jens Limpert, Nature Photonics 7, 258–261 (2013)

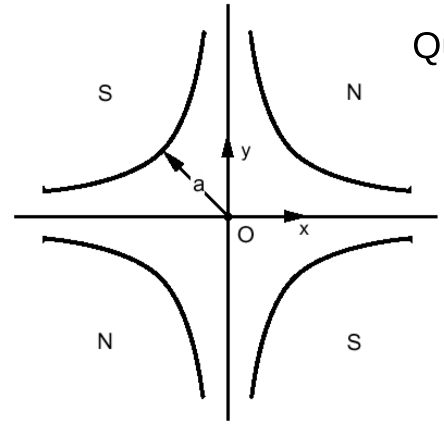
Beam and laser focusing

Lenses



Focus in both planes

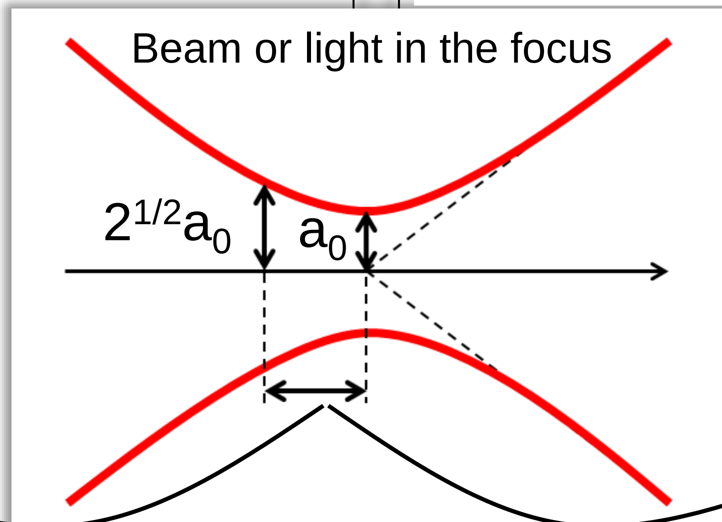
Quadrupole magnet



Focus in one plane, defocus in another:

$x' = x' + G\,x$

$y' = y' - G\,y$



Z_R

Rayleigh length

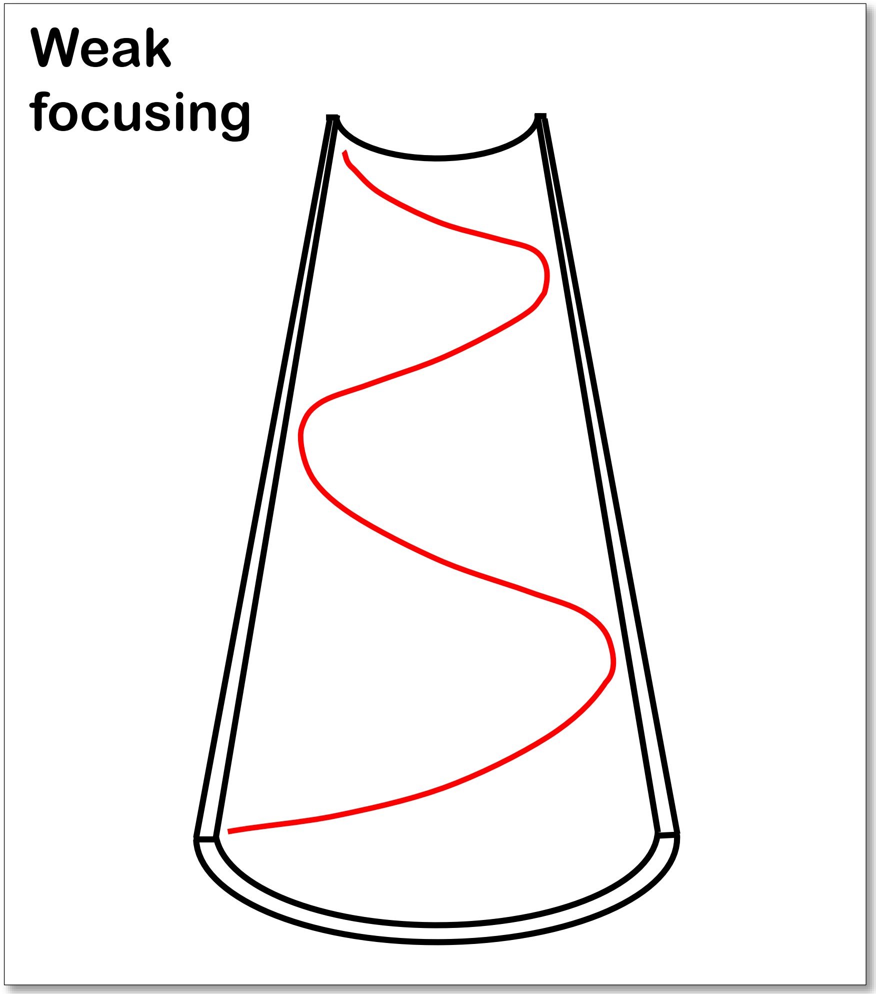
β_0

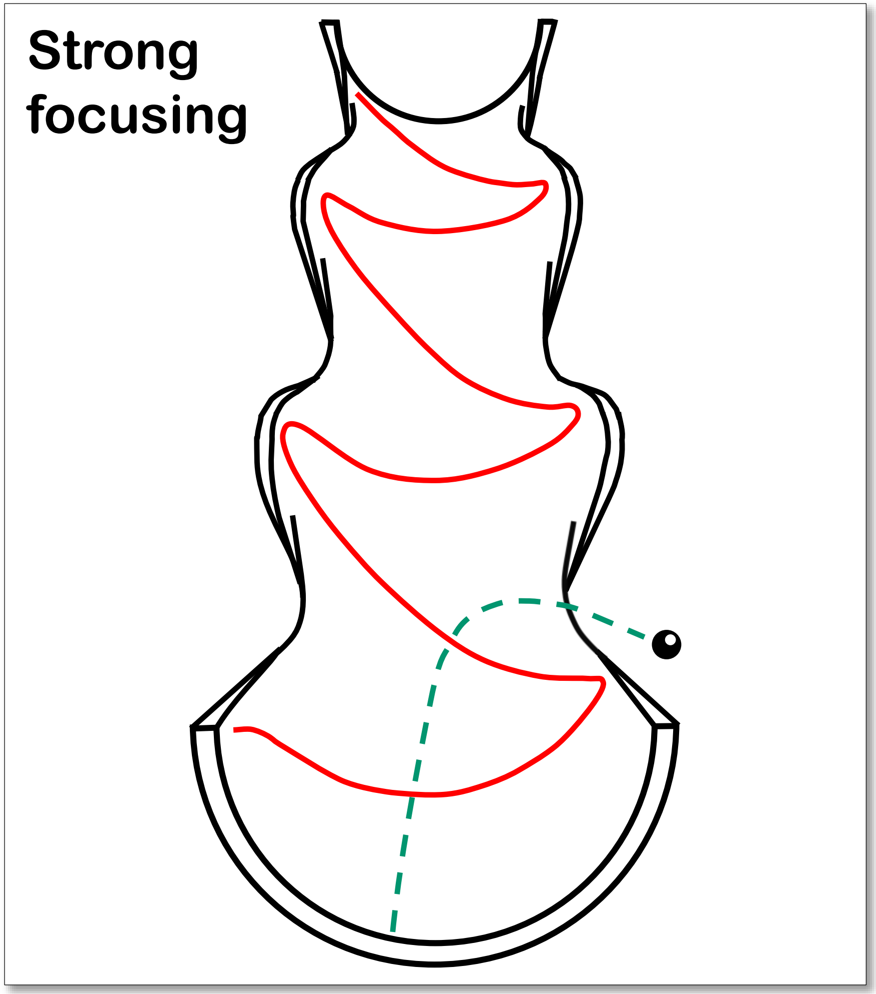
Twiss (beta) function in the focal point

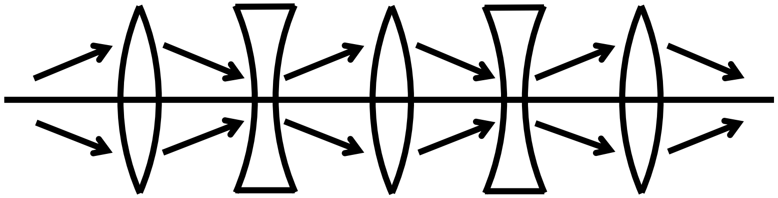
Light focusing lenses or mirrors

Beam focusing w magnets

Weak or strong focusing => chromaticity

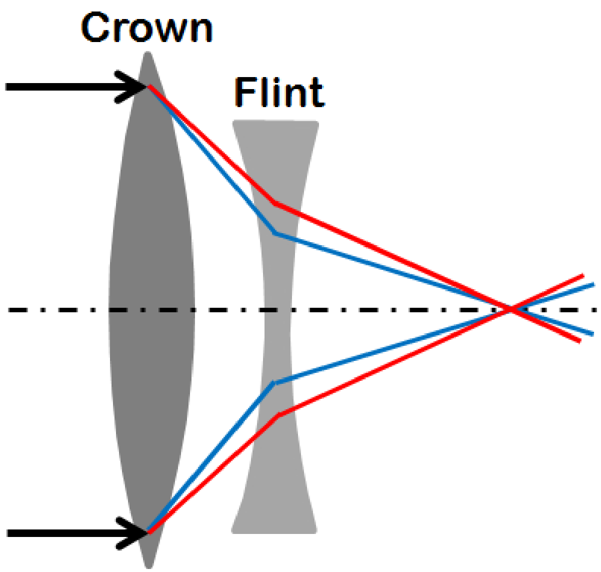






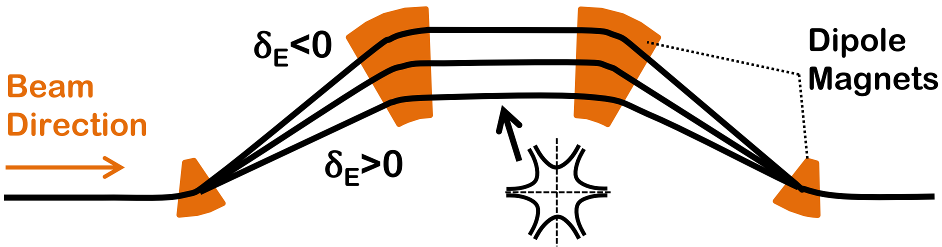
Aberrations for light and beam

For light, one uses lenses made from different materials to compensate chromatic aberrations



The use of a strong positive lens made from a low dispersion glass like crown glass coupled with a weaker high dispersion glass like flint glass can correct the chromatic aberration

For particle beams, chromatic aberrations compensated by nonlinear magnets placed in a dispersive region



Sextupole kick:

$x' = x' + S\,(x^2 - y^2)$

$y' = y' - S\,2xy$

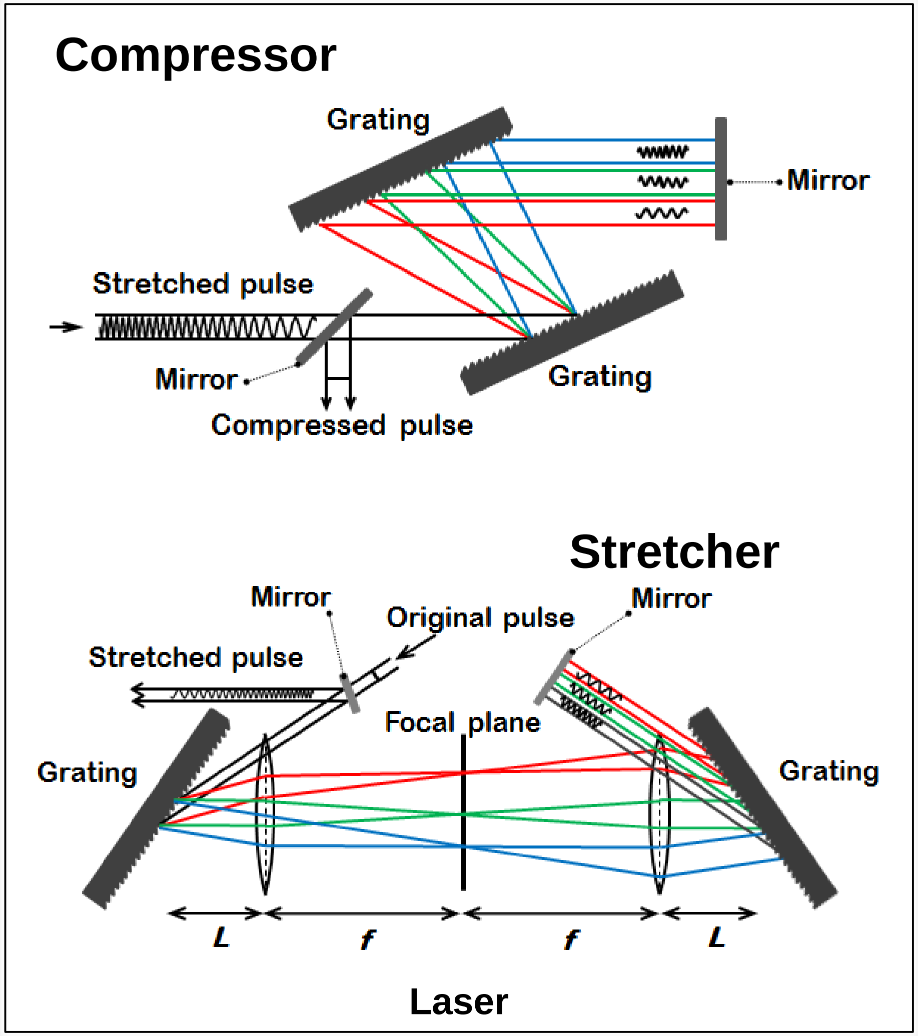
In dispersive region sextupole kick will contain energy dependent focusing:

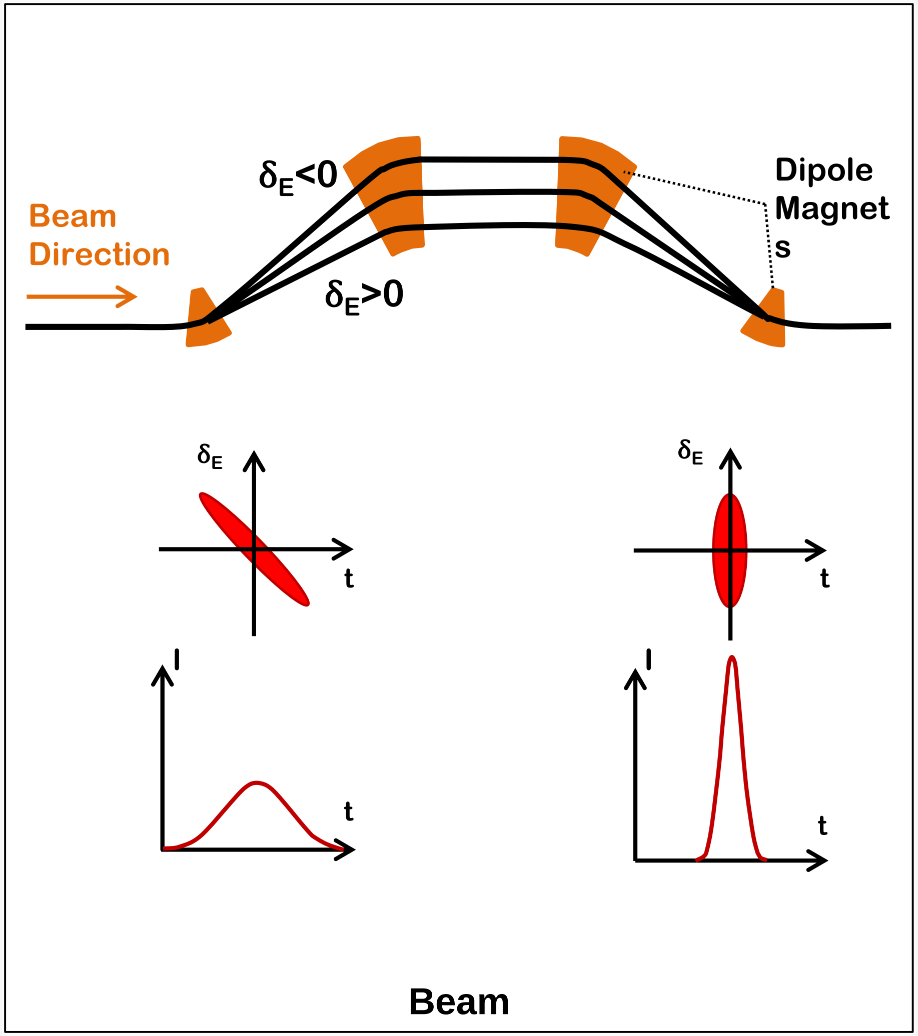
$x' \Rightarrow S\,(x+\delta)^2 \Rightarrow 2S\,x\,\delta + ..$

$y' \Rightarrow -S\,2(x+\delta)y \Rightarrow -2S\,y\,\delta + ..$

this can be used to arrange chromatic correction

Beam and laser bunch/pulse compression

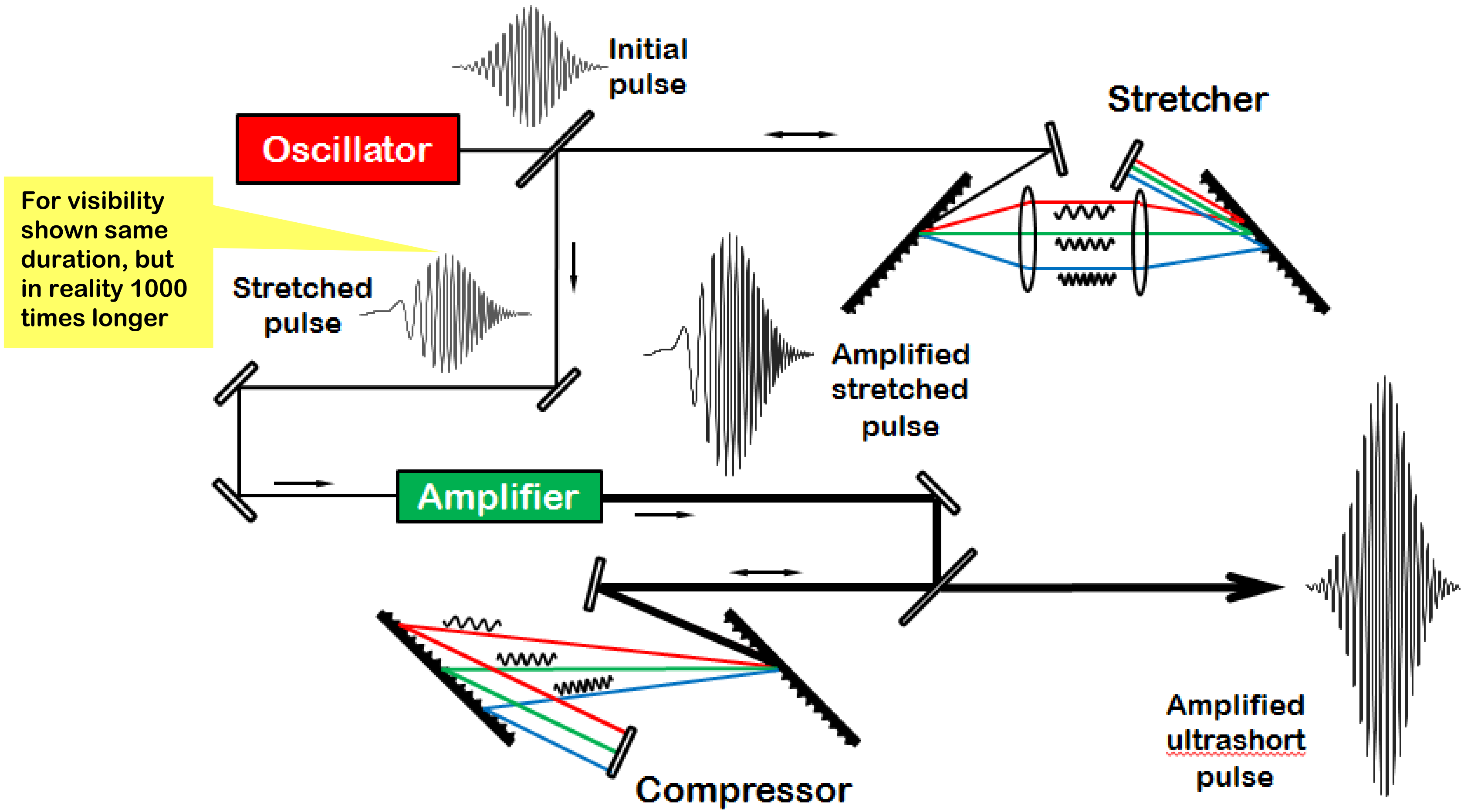




Both in laser and beam use z-Energy correlation to compress/stretch the pulse – one more general principle of AS-TRIZ

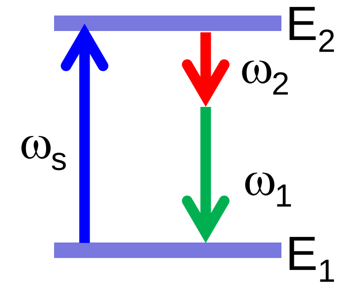
Telescope is needed inside stretcher to create "negative distance"

CPA – Chirped Pulse Amplification



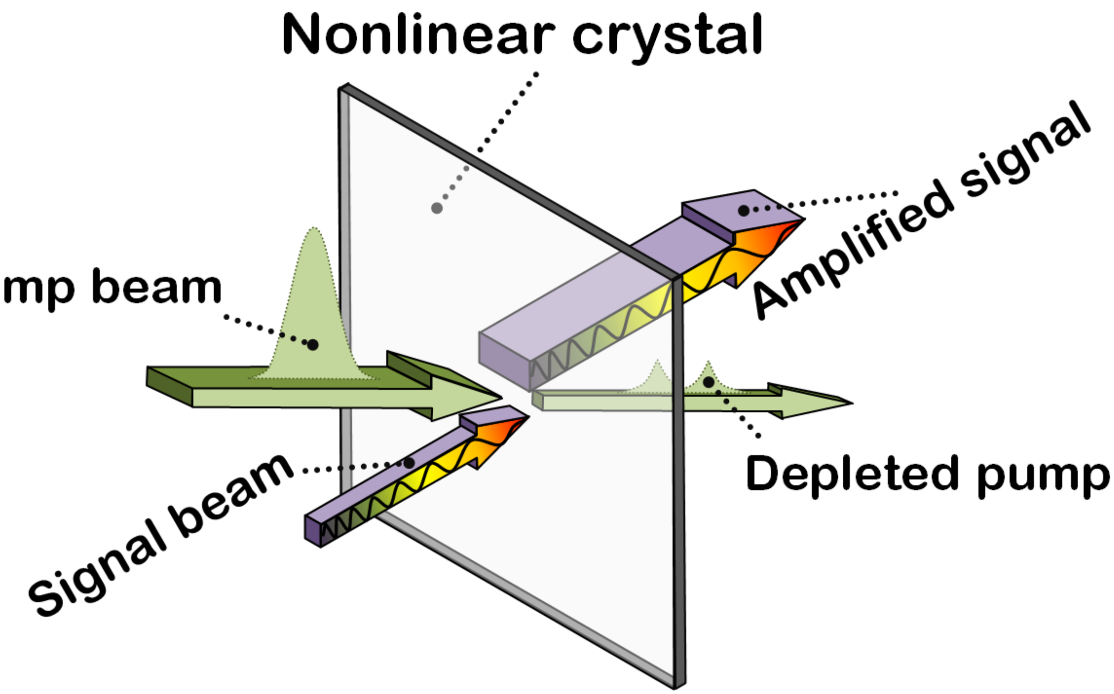
- **CPA: pulse stretching and compressing using time-energy correlation**

OPCPA – Optical Parametric CPA



Nonlinear crystal – optical parametric generation – input is ω_s, and output is ω_1 and ω_2, where $\omega_s = \omega_1 + \omega_2$

Optical parametric amplification – input is two beams, pump at ω_s and signal at ω_1. Output is amplified ω_1 beam and weakened ω_s beam, and additional idler beam at ω_2

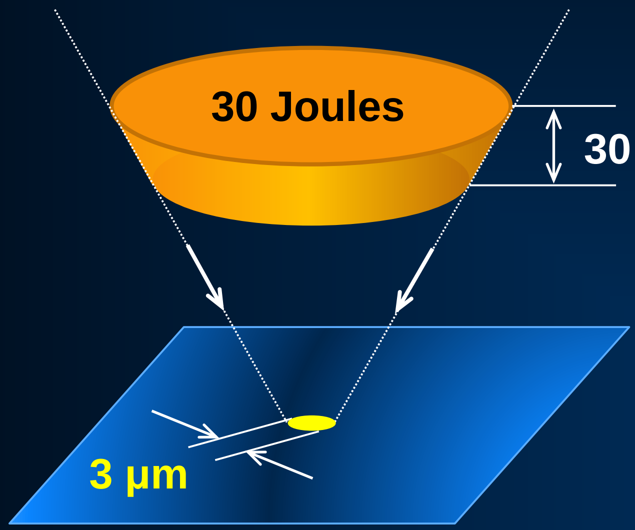


OPCPA scheme amplifies a frequency stretched "signal" pulse when a pump beam and a signal beam are present in a nonlinear crystal

CW to femtosecond
UV to TeraHertz
mW→TW→PW

Contemporary high-power lasers

... are impressive



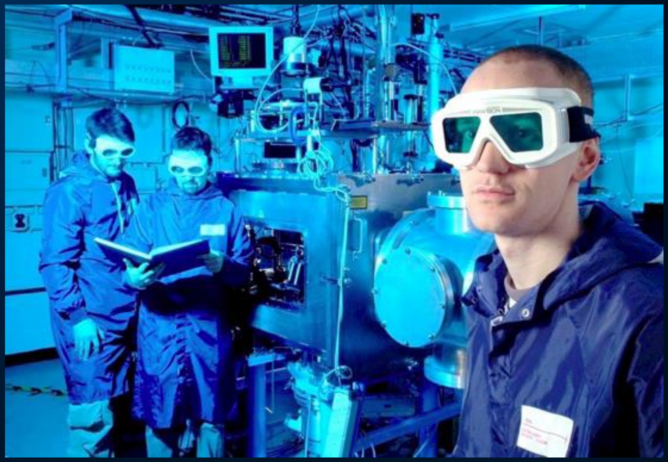
Peak power 10^{15} W

The power density at the focus is 10^{22} W/cm^2

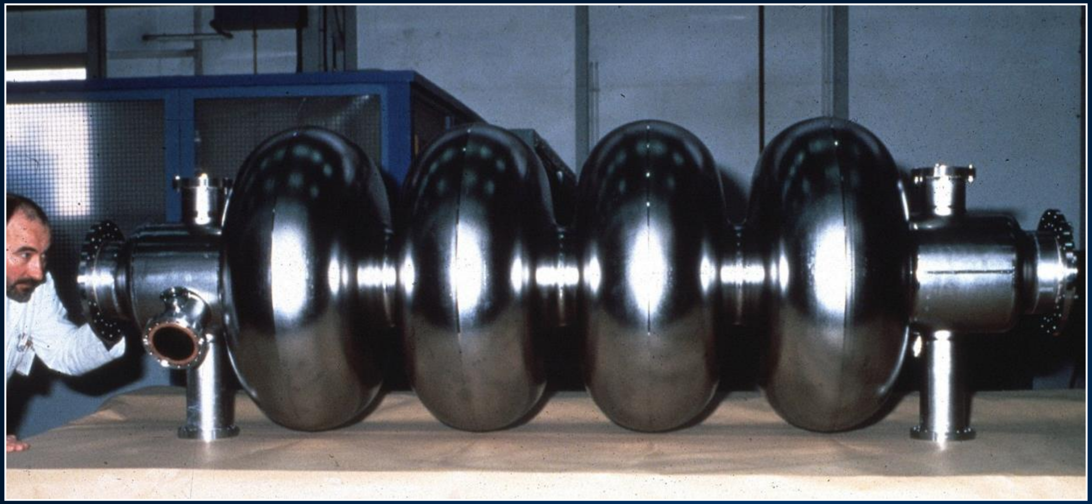
Laser of this power instantly ionizes any substance

Electrons carried along by the field of such a laser instantly become relativistic...

…although conventional resonators usually used for such acceleration

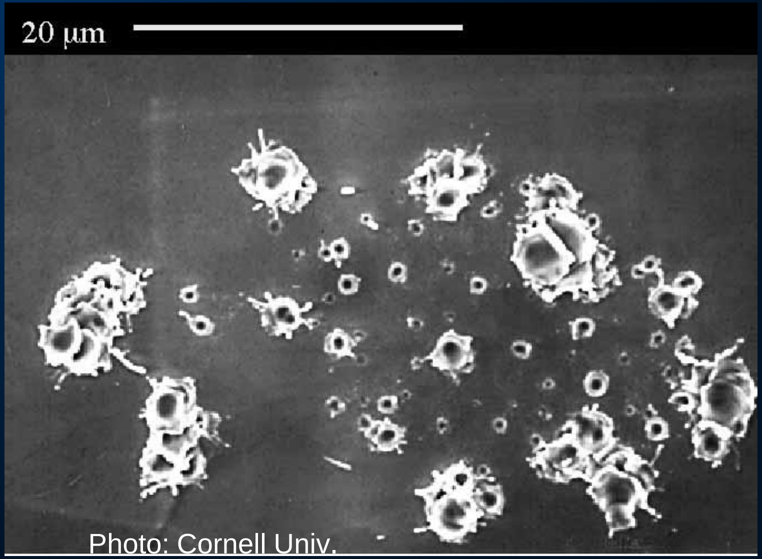


Limits of resonators for acceleration



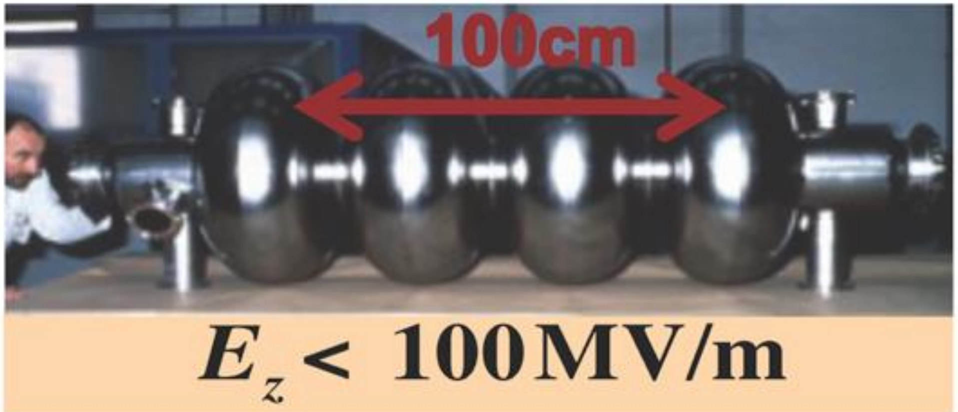
Superconducting Nb accelerating structures

Conventional, Cu

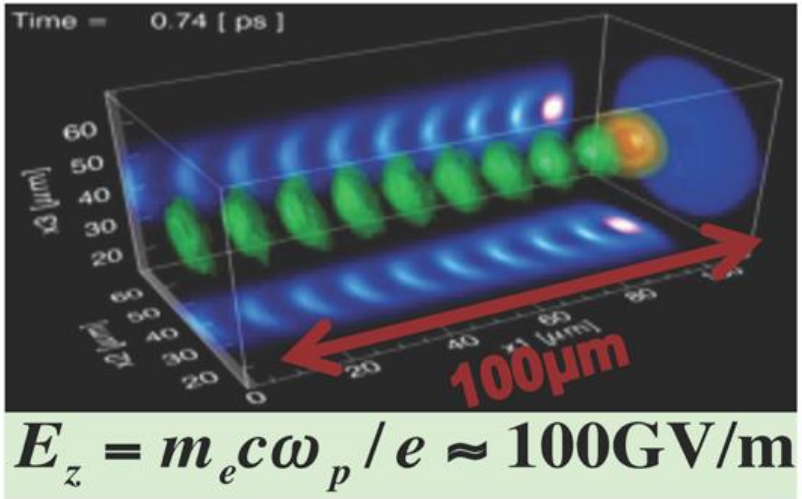


Problem:
As rate of E change (accelerating gradient) increases, the surface of cavities get damaged by occasional breakdowns

Lasers and particle acceleration



Accelerating structure, metal (normal conductive or super-conductive)



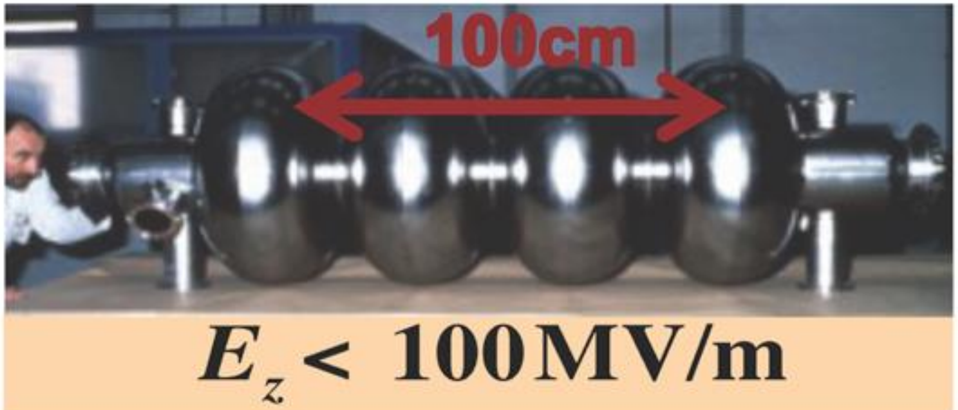
"Accelerating structure" produced on-the-fly in plasma by laser pulse

Solution:

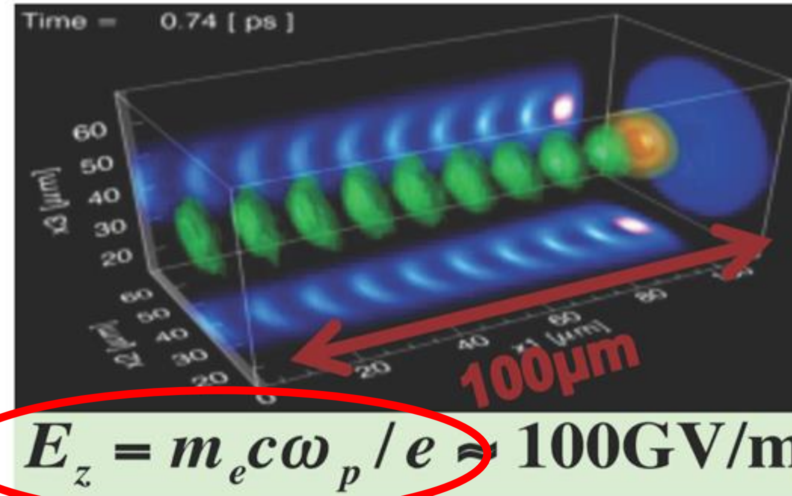
Apply this inventive AS-TRIZ principle:

- **"Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)"**

Lasers and particle acceleration



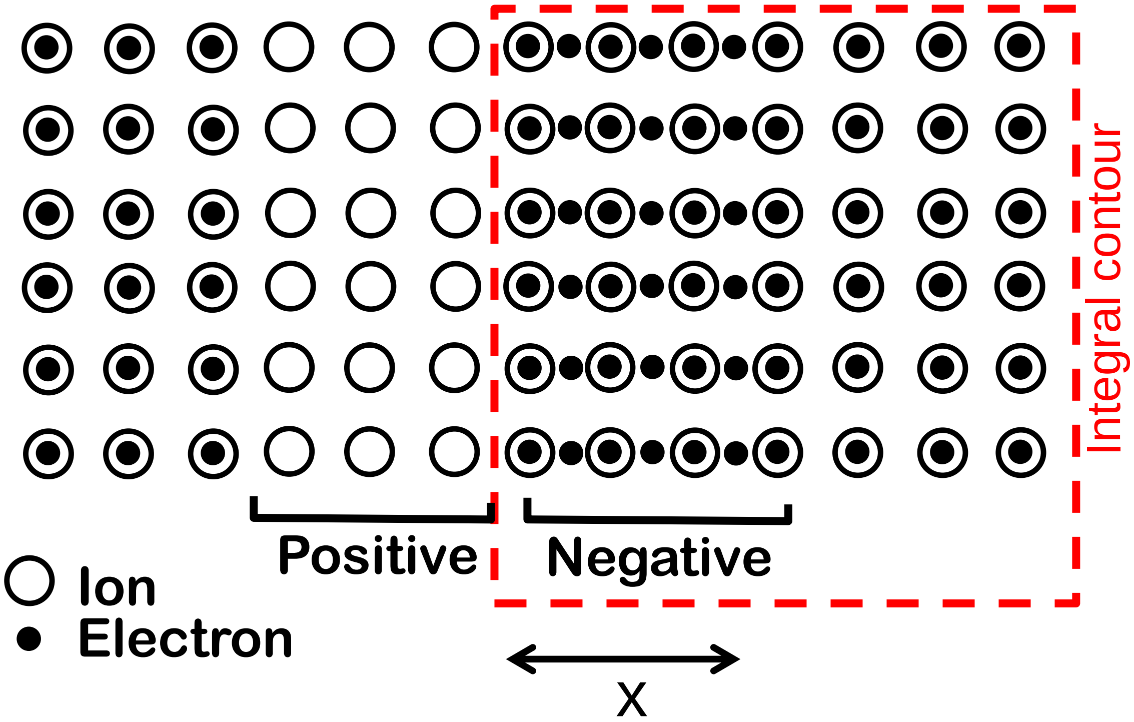
Accelerating structure, metal (normal conductive or super-conductive)



“Accelerating structure” produced on-the-fly in plasma by laser pulse

- **Let’s derive the max possible accelerating field**

Plasma oscillations



Derive ω_p

$$\oint\!\!\oint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho dV$$

$$E = \frac{nex}{\varepsilon_0}$$

$$F = m\frac{d^2x}{dt^2} = -eE = -\frac{ne^2x}{\varepsilon_0}$$

Oscillation frequency: $\omega_p^2 = \frac{ne^2}{\varepsilon_0 m}$

use: $r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$ to rewrite as: $\omega_p^2 = 4\pi n c^2 r_e$

Useful formula $f_p \sim 9000\, n^{1/2}$ (n in cm^{-3})

Equations and units

SI

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \qquad \oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho dV$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \qquad \oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \mu_0 \varepsilon_0 \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S}$$

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Gauss-cgs

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} \right)$$

$$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right)$$

Microscopic Maxwell equations and Lorentz force in SI and Gaussian-cgs units

The SI units are the standard, but Gaussian units are more natural for electromagnetism. Advice: deriving the formula, instead of writing for example *e* or *h*, express the end result via more natural quantities ($m_e c^2$, r_e, λ_e, α, etc.)

SI

$$r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2}$$

$$\alpha = \frac{e^2}{(4\pi\varepsilon_0)\hbar c}$$

$$r_e \approx 2.82 \cdot 10^{-15} m$$

$$\alpha \approx 1/137$$

$$\lambda\!\!\!^{-}_e = r_e / \alpha \approx 3.86 \cdot 10^{-13} m$$

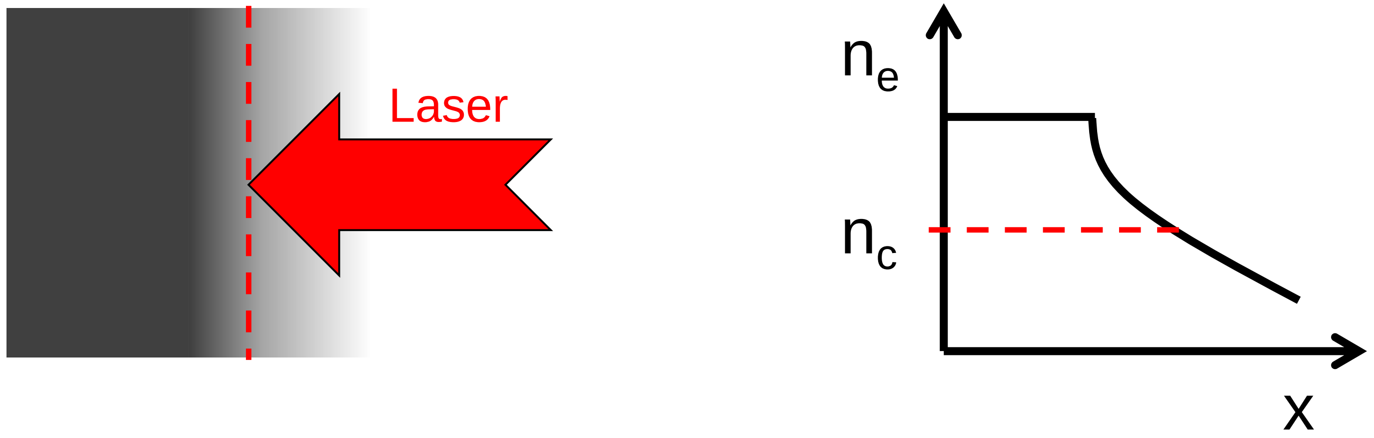
Gauss

$$r_e = \frac{e^2}{m_e c^2}$$

$$\alpha = \frac{e^2}{\hbar c}$$

Critical density and surface

When laser hits a target its surface is heated, and plasma is formed
Plasma expands into the vacuum, and its density drops



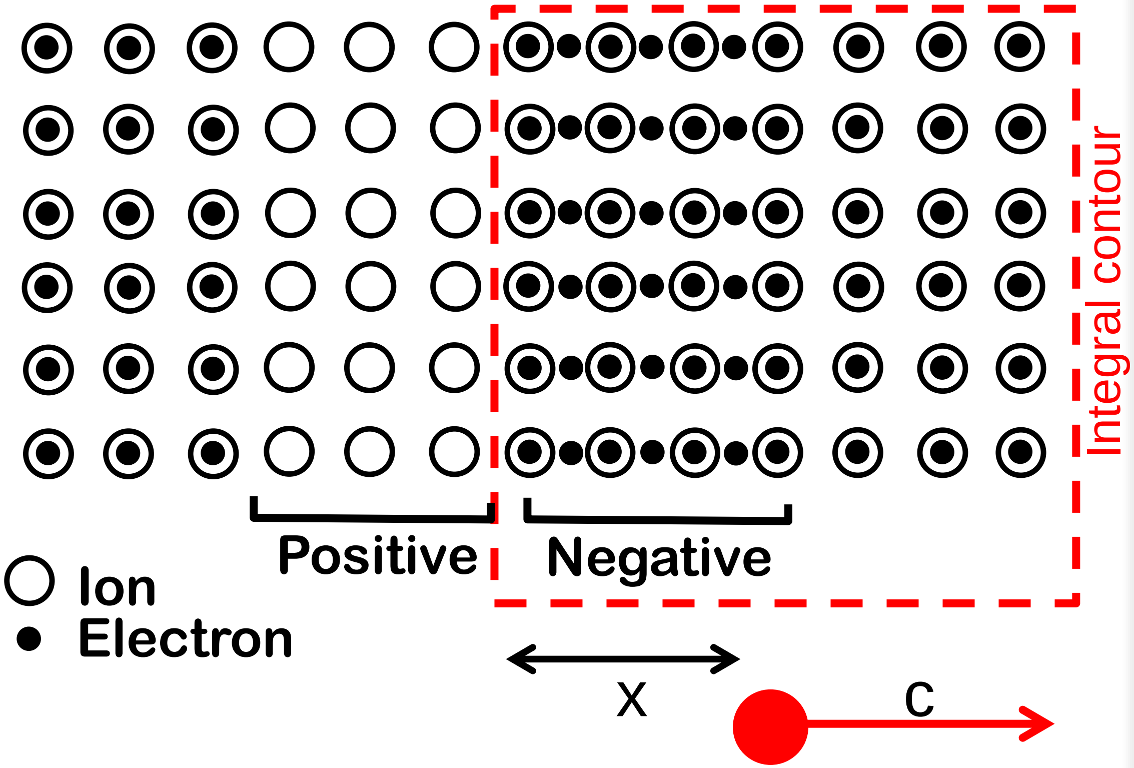
If ω_p is larger than laser frequency ω, then the plasma electrons can move fast enough to screen the laser

Therefore, laser penetrates only to the point where $\omega_p < \omega$

$$n_c = \omega^2 / (4\pi c^2 r_e)$$

The critical density is thus

Maximum field in plasma



Recall how we derived ω_p

$$\oint\!\!\oint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega}\rho dV \qquad E = \frac{nex}{\varepsilon_0}$$

$$F = m\frac{d^2x}{dt^2} = -eE = -\frac{ne^2x}{\varepsilon_0}$$

Oscillation frequency: $\omega_p^2 = \frac{ne^2}{\varepsilon_0 m}$

use: $r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$

to rewrite as: $\omega_p^2 = 4\pi n c^2 r_e$

Assume wave is excited by object moving with c

If total charge separation achieved in plasma, max field estimated taking $x \sim \lambda_p \sim \frac{c}{\omega_p}$

Thus $E_{max} \sim \frac{nec}{\varepsilon_0\omega_p} = \frac{mc\omega_p}{e}$ or $eE_{max} \cong mc^2\frac{\omega_p}{c}$

Use $f_p \sim 9000\, n^{1/2}$ (n in cm^{-3}) $\longrightarrow$ $eE_{max} \approx 1\frac{eV}{cm}\cdot n^{1/2}(cm^{-3})$

1 GeV/cm for plasma 10^{18} cm^{-3}

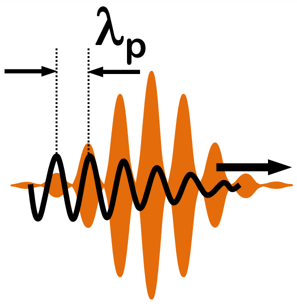
How to excite plasma

- **We see that GeV/cm require plasma with $n=10^{18}$ cm^{-3}**

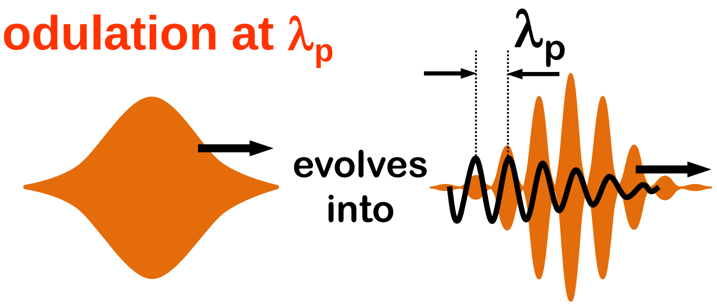
$$\lambda_p = \frac{c}{f_p} \quad \rightarrow \quad \lambda_p \approx 0.1mm\sqrt{\frac{10^{17}\,cm^{-3}}{n}}$$

- **Thus, short sub-ps pulses needed for plasma excitation**
- **In absence of short laser pulses other methods suggested:**

- **Plasma Beat Wave Accelerator (PBWA)**
  - **Two laser pulses of closer frequencies beat at ω_p**



- **Self-Modulated Laser Wakefield Accelerator (SMLWFA)**
  - **Instability in a long laser pulse cause modulation at λ_p**

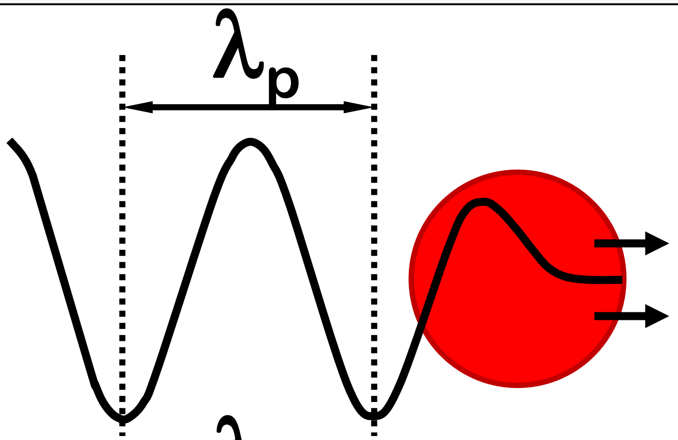


J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

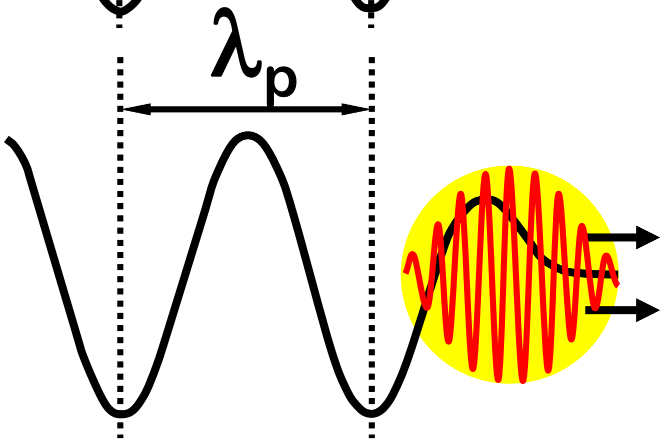
How to excite plasma

- **Availability of short sub-ps pulses of laser or beams stimulated rapid progress of plasma acceleration**

- **Plasma Wakefield Accelerator (PWFA)**
  - A short high energy particle bunch



- **Laser Wakefield Accelerator (LWFA)**
  - A short laser pulse of <u>high intensity</u>



Laser pulse of high intensity

Laser intensity (in vacuum)

$$I = \frac{1}{2}\varepsilon_0 E_{max}^2 c \qquad \text{(SI)}$$

$$I = \frac{1}{8\pi} E_{max}^2 c \qquad \text{(Gaussian)}$$

Fields in practical units:

$$E_{max}\left[\left(\frac{V}{cm}\right)\right] \cong 2.75\times 10^9 \left(\frac{I}{10^{16} W/cm^2}\right)^{1/2}$$

$$B_{max}[Gauss] \cong 9.2\times 10^6 \left(\frac{I}{10^{16} W/cm^2}\right)^{1/2}$$

(useful to remember that 300 V/cm is ~same as 1 Gauss)

Compare with field in a hydrogen atom. Bohr radius and field:

$$a_B = \frac{\hbar^2}{me^2} = 5.3\times 10^{-9}\,cm$$

$$E_a = \frac{e}{a_B^2} = \frac{e}{4\pi\varepsilon_0 a_B^2} \approx 5.1\times 10^{11}\,\frac{V}{m}$$

(Gaussian) (SI)

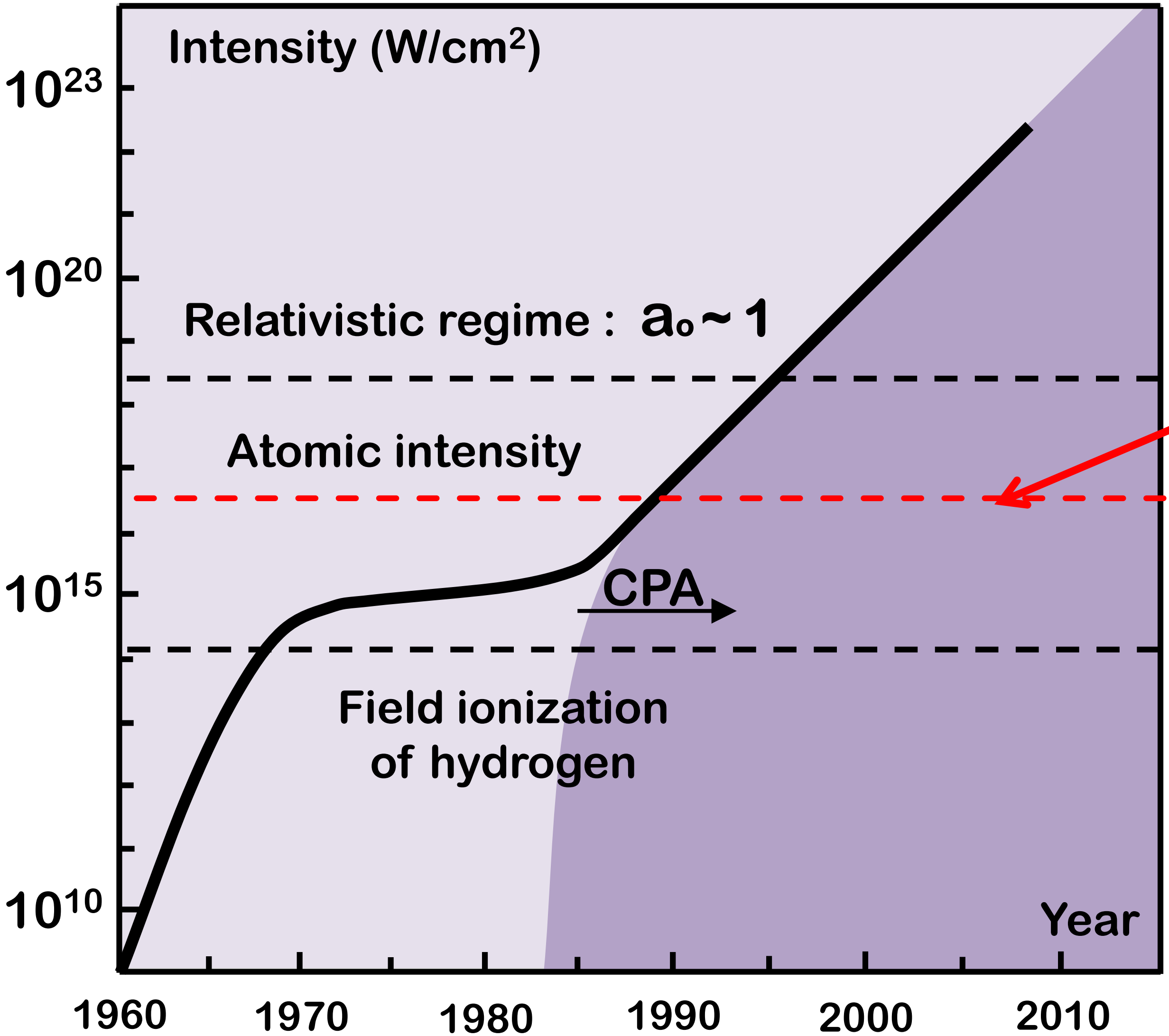
(Recall $\varepsilon_0 \approx 8.8\cdot 10^{-12}\,\frac{A^2\cdot s^4}{kg\cdot m^3}$)

Atomic intensity

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times 10^{16}\,\frac{W}{cm^2}$$

A laser with intensity higher than that will ionize gas immediately

Laser intensity

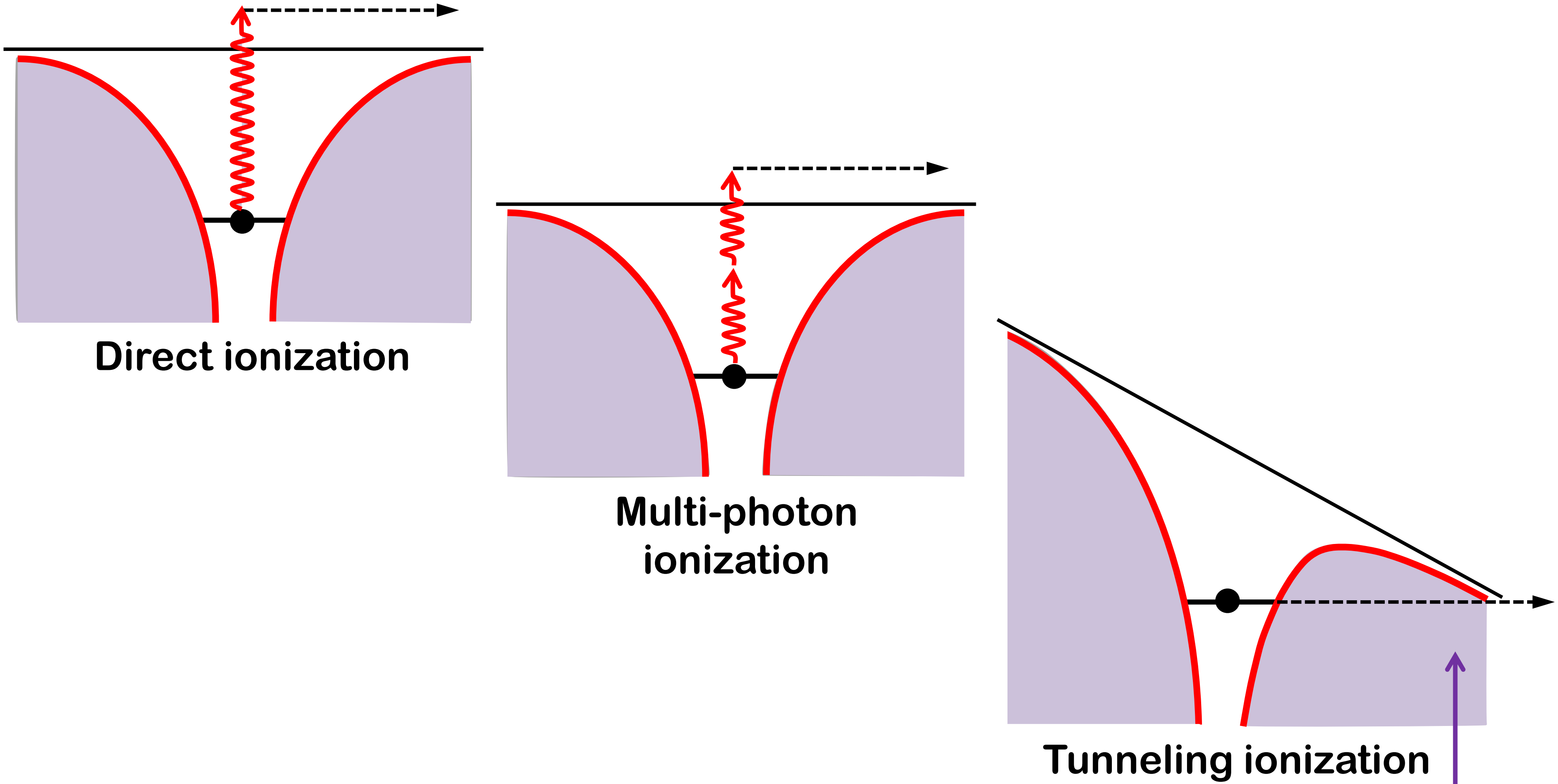


Progress in peak intensity since laser invention in 1960

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times10^{16}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$$

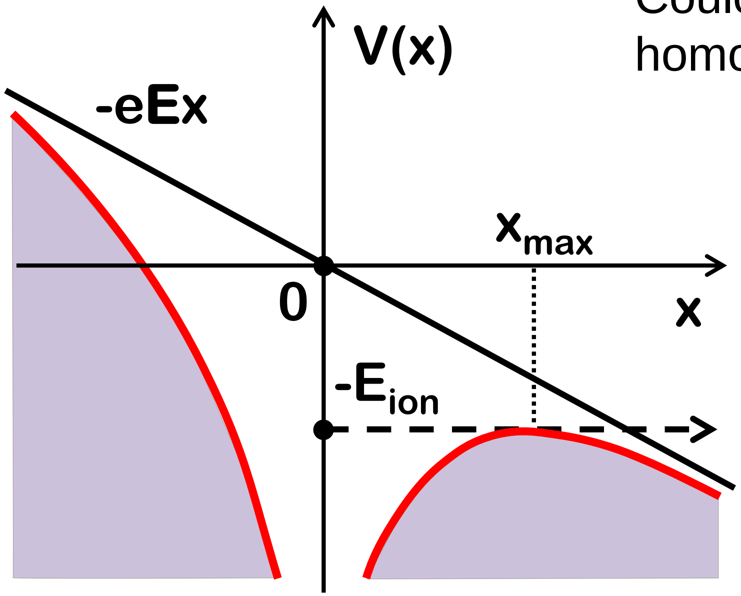
- **In fact, Ionization can occur well below this threshold due to:**
  - **multi-photon effects;**
  - **tunneling ionization**

Types of ionization



With even more laser intensity – barrier suppression ionization (BSI)

Laser intensity for barrier suppression ionization



Coulomb potential of hydrogen atom distorted by homogeneous field ε:

$$V(x) = -\frac{e^2}{x} - e\varepsilon x$$

Find position of the maximum:

$$x_{max} = (e/\varepsilon)^{1/2}$$

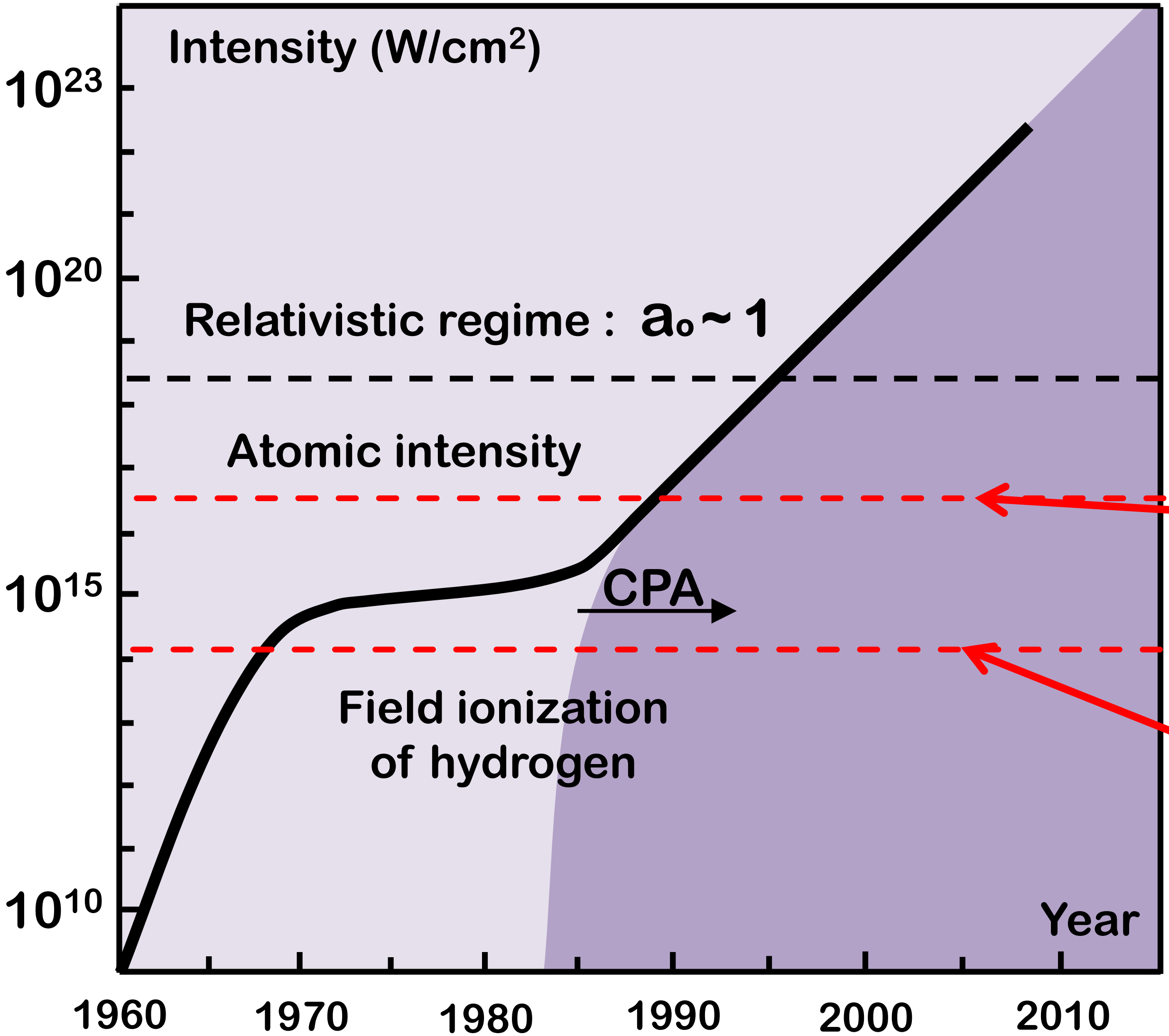
Equate potential value at max to hydrogen ionization potential

$$V(x_{max}) = 2(e^3\varepsilon)^{1/2} \qquad = \qquad E_{ion} = \frac{e^2}{2a_B} \approx 13.6\text{eV}$$

The critical field for hydrogen is therefore $\varepsilon_c = \frac{e}{16a_B^2} = \frac{E_a}{16}$

Which corresponds to intensity $I_c = \frac{I_a}{256} \approx 1.4 \cdot 10^{14}\ \text{W}/\text{cm}^2$

Laser intensity



Progress in peak intensity since laser invention in 1960

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times10^{16}\ \frac{W}{cm^2}$$

$$I_c = \frac{I_a}{256} \approx 1.4\cdot10^{14}\,W/cm^2$$

Normalized vector potential

The laser field can be written in terms of the vector potential of the laser field A as

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{c\partial t}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

For linearly polarized field

$$\mathbf{A} = A_0 \cos(kz - \omega t)\mathbf{e}_\perp$$

We see that $E_0 = \frac{A_0 \omega}{c}$

Compare momentum gained by e- in one cycle of laser field $e\,E\,\Delta t \cong \frac{eE}{\omega}$ with $m_e c$

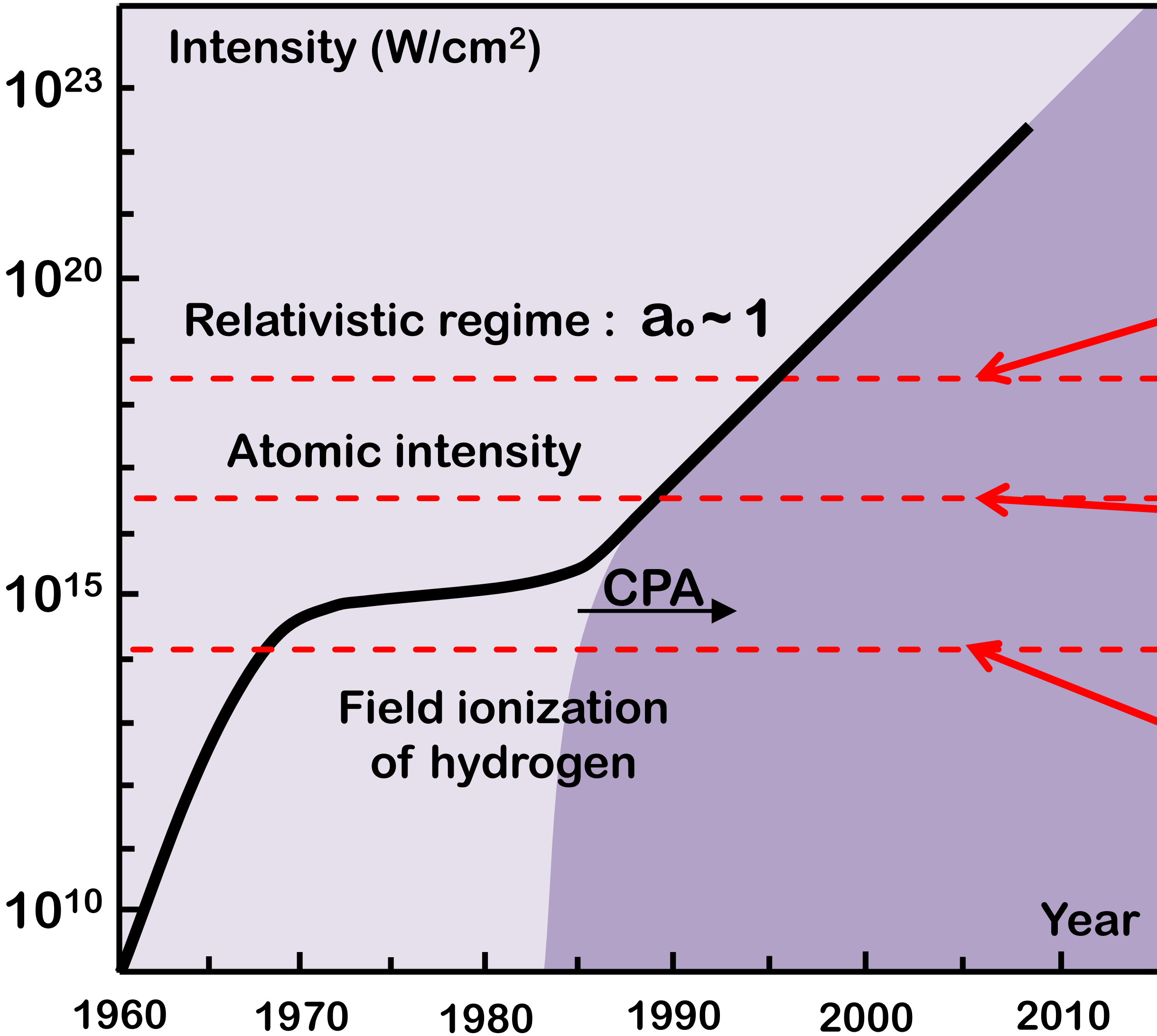
We see that it is useful to define the normalized vector potential as $\mathbf{a} = \frac{e\mathbf{A}}{m_e c^2}$ with amplitude $a_0 = \frac{eE_0}{m_e \omega c}$

The amplitude a_0 will indicate if the electron motion in laser field relativistic

$a_0 \gg 1$ – relativistic, $a_0 \ll 1$ – non relativistic

In practical units $a_0 \approx \left(\frac{I[W/cm^2]}{1.37 \cdot 10^{18}}\right)^{\frac{1}{2}} \cdot \lambda[\mu m]$ where $\lambda = \frac{2\pi c}{\omega}$

Laser intensity



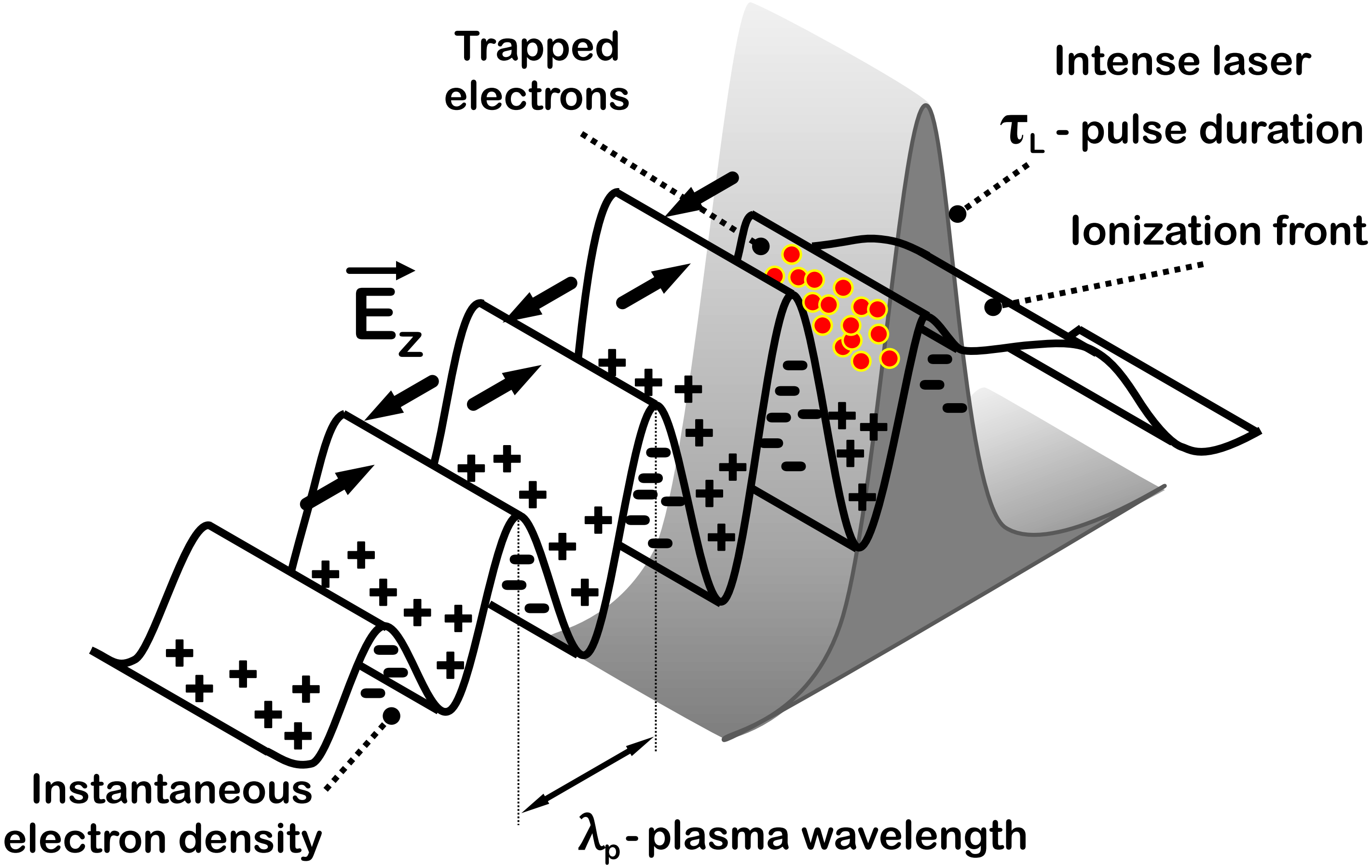
a_0 ~1 for red laser

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times 10^{16} \frac{W}{cm^2}$$

$$I_c = \frac{I_a}{256} \approx 1.4\cdot 10^{14} W/cm^2$$

Progress in peak intensity since laser invention in 1960

Laser acceleration - conceptually



- **Note in particular**
  - **Ionization front starting at the front tail of laser**
  - **Laser pulse length similar of shorter than plasma wavelength**
  - **Electrons trapped in the first bubble**

Formation of bubble – ponderomotive force

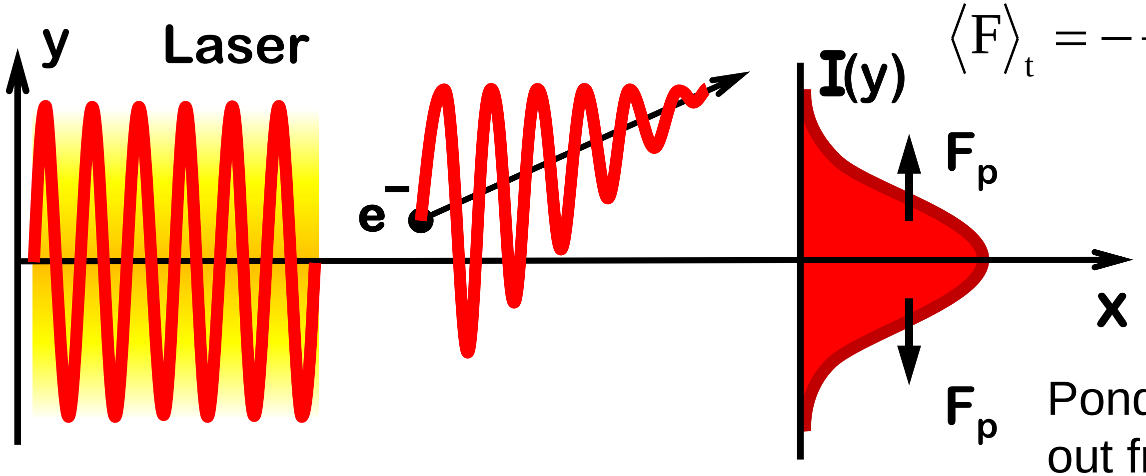
First, assume laser field homogeneous: $$E = E_0 \cos(\omega t)$$

Motion of electron: $$\ddot{y} = \frac{F}{m} = \frac{eE}{m} \quad \Rightarrow \quad y = -\frac{eE_0}{m\omega^2}\cos(\omega t)$$

Now, assume E has gradient in y: $$E = E_0(y)\cos(\omega t) \approx E_0 \cos(\omega t) + y\frac{\partial E_0}{\partial y}\cos(\omega t)$$

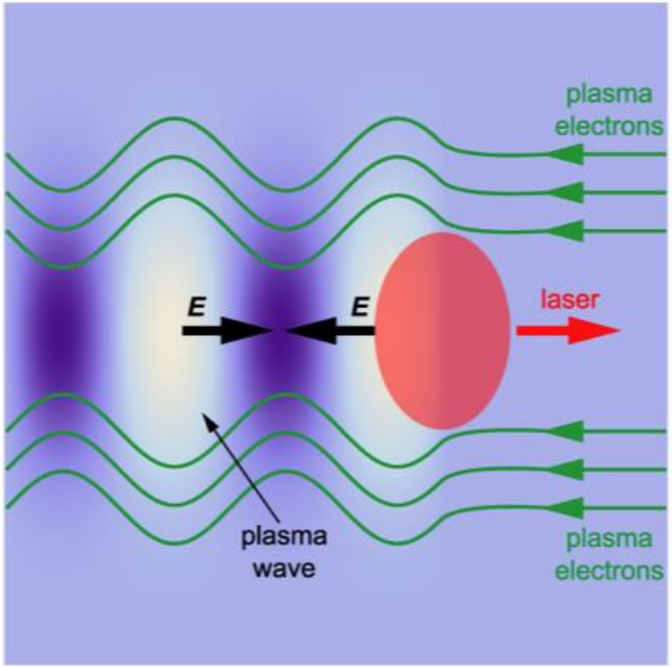
Find time average of force acting on e-: $$\langle F \rangle_t = \left\langle -\frac{eE_0}{m\omega^2}\cos(\omega t)\cdot\frac{\partial E_0}{\partial y}\cos(\omega t)\right\rangle_t$$

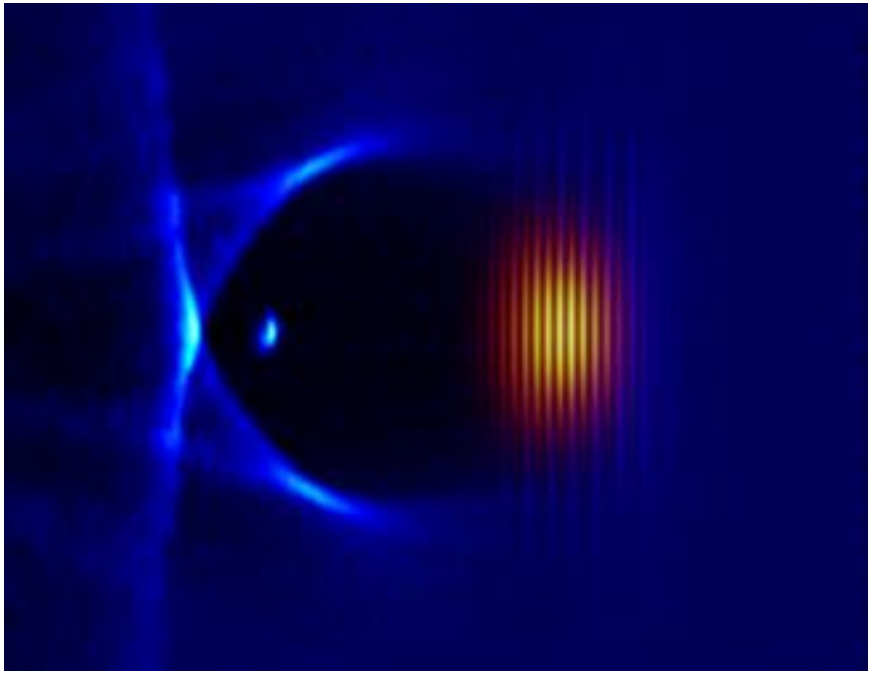
$$\langle F \rangle_t = -\frac{e^2}{2m\omega^2}E_0\frac{\partial E_0}{\partial y} = -\frac{e^2}{4m\omega^2}\frac{\partial E_0^2}{\partial y}$$



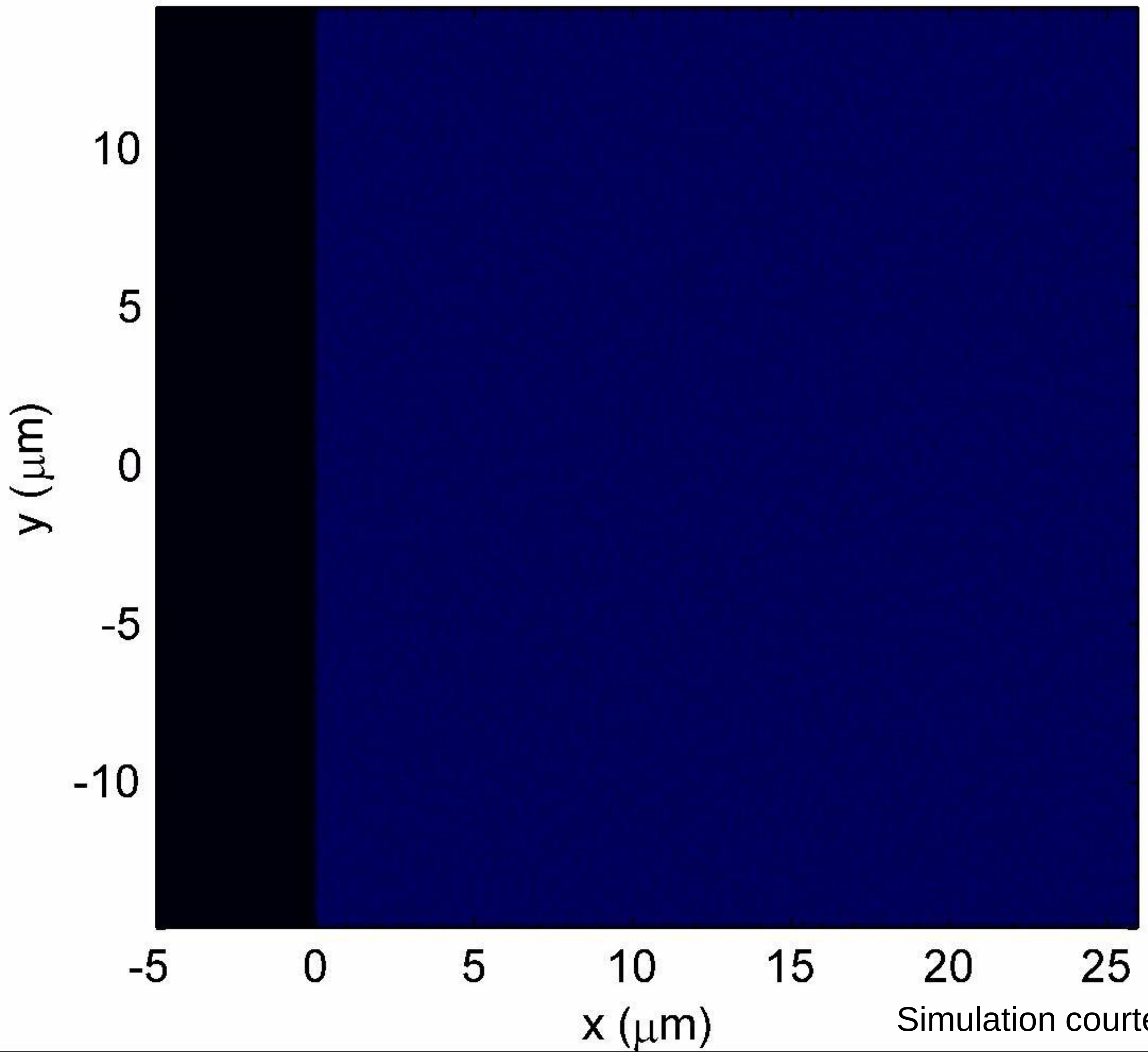
Ponderomotive force pushes electrons out from the high intensity region

Laser-Driven Plasma Acceleration





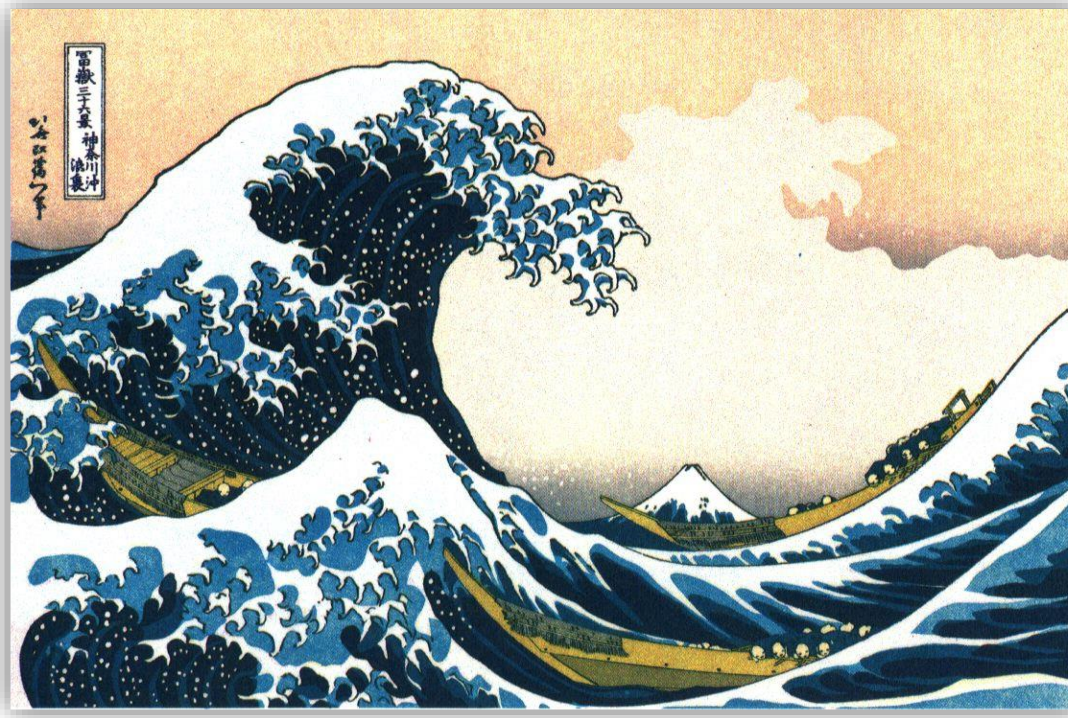
- Ponderomotive force of short (50fs), intense (10^{18} W cm^{-2}) laser pulse expels plasma electrons while heavier ions stay at rest
- Electrons attracted back to ions, forming a bubble (blow-out regime) and setting up plasma wave which trails laser pulse
- Electric fields within plasma wave of order 100 GV/m formed



Simulation courtesy Prof Simon Hooker

How e- gets into the bubble – wave breaking

- **Wave breaking**
  - **Self-injection of background plasma electrons to the wake when some particles outrun the wake**

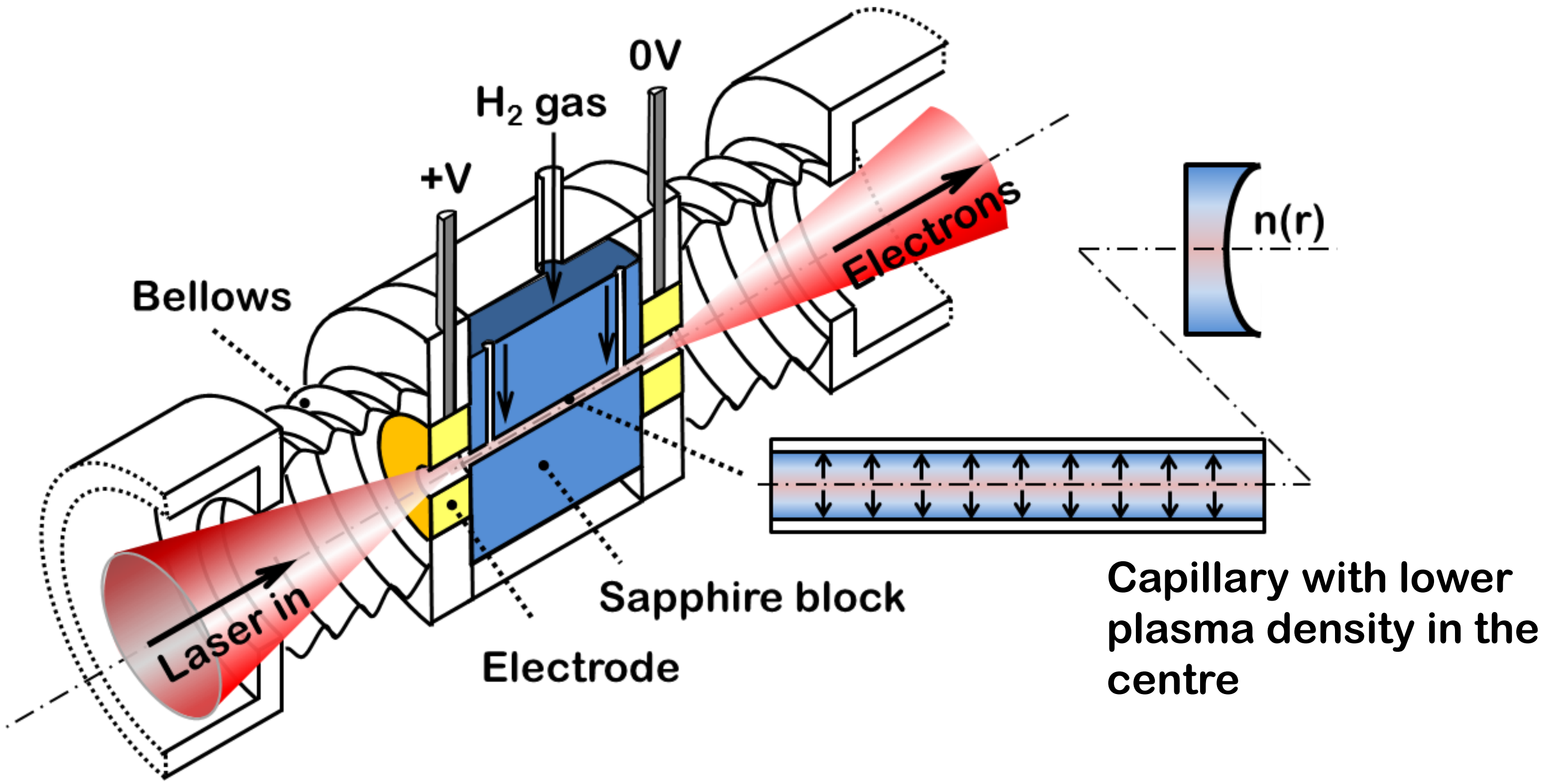


- **Other methods**
  - **External injection (difficult for so short bunches)**
  - **Methods which involve two laser pulses and mix of two gases with different ionization potential**

Importance of laser guidance

- **As laser propagates through the gas/plasma, several competing effects are important**
  - **Dephasing**
  - **Depletion**
  - **Longitudinal compression by plasma waves**
  - **Self focusing**
    - **Including relativistic effect – electrons of plasma at centre become relativistic and have higher mass**
  - **Diffraction**
    - **Small laser beam (~30μm) will diffract very fast**
    - **Includes ionization caused diffraction (centre where intensity is higher ionized first)**
- **A possible solution – create a channel with plasma density profile n(r) to guide laser**
  - **A particular solution – capillary discharge channel developed in Oxford**

Importance of laser guidance

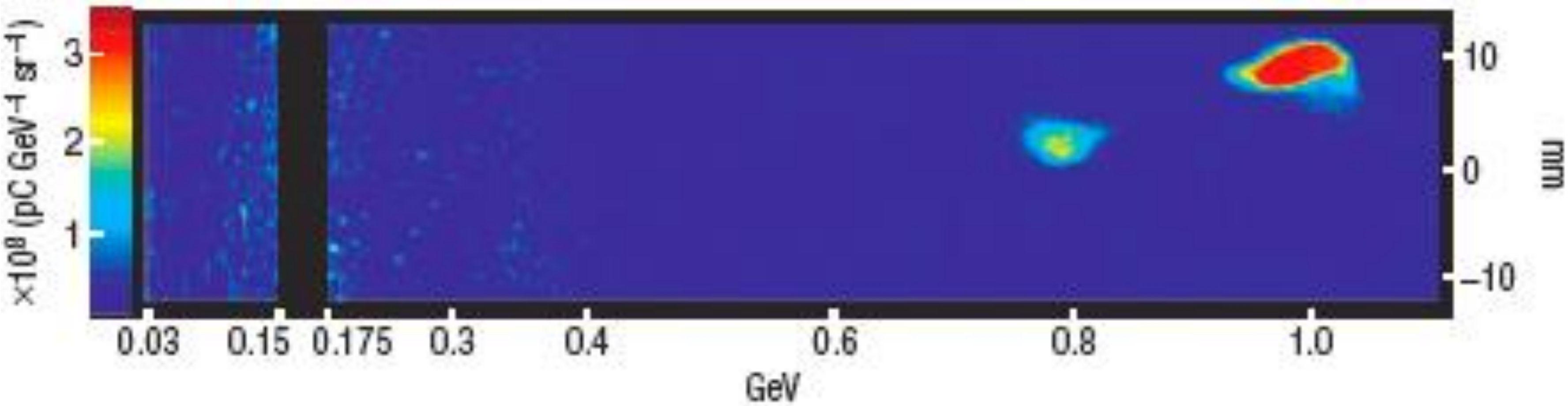


Capillary channel designed by Prof Simon Hooker

- **Capillary channel allowed exceeding 1GeV laser plasma acceleration for the first time**

First ever 1 GeV from laser plasma accelerator

- **1 GeV acceleration & monoenergetic beam**
  - **Use of guiding capillary was essential**

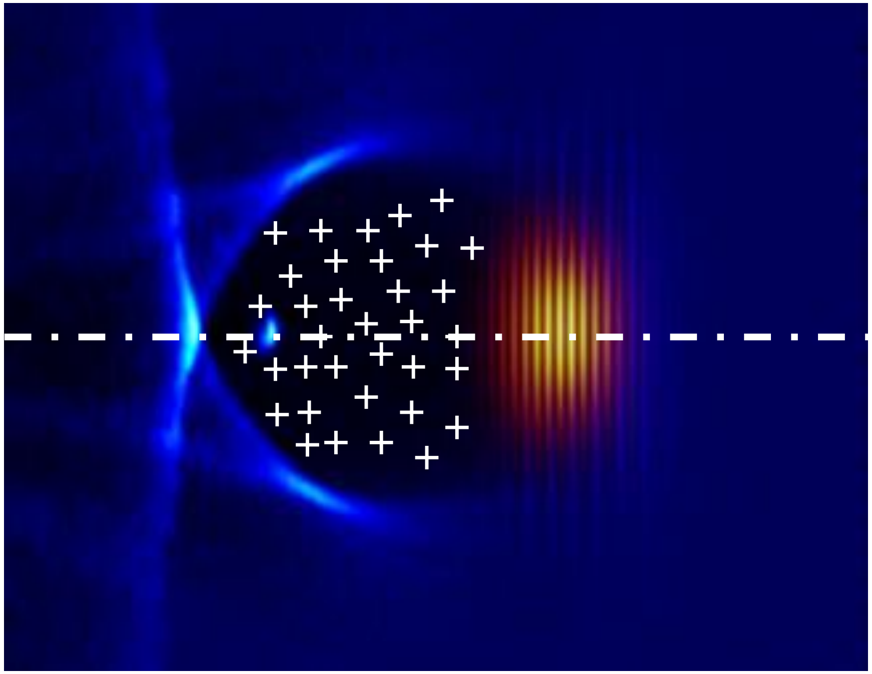


1GeV acceleration in just 3cm of plasma

W. Leemans, B. Nagler, A. Gonsalves, C. Toth, K. Nakamura, C. Geddes, E. Esarey, C. B.Schroeder, & S. Hooker, ***Nature Physics*** 2006

Plasma density 2.7×10^{18} cm^{-3}, 40 TW laser with 1018 W/cm^2

Transverse fields in the bubble

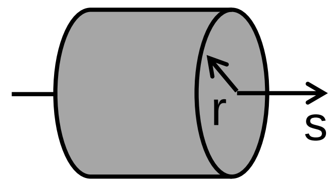


The ions are heavy and are inside of the bubble. They produce focusing force.

$$\oint \mathbf{E} \cdot d\mathbf{S} = 4\pi \int \rho dV$$

(Gaussian)

Assume cylindrical symmetry



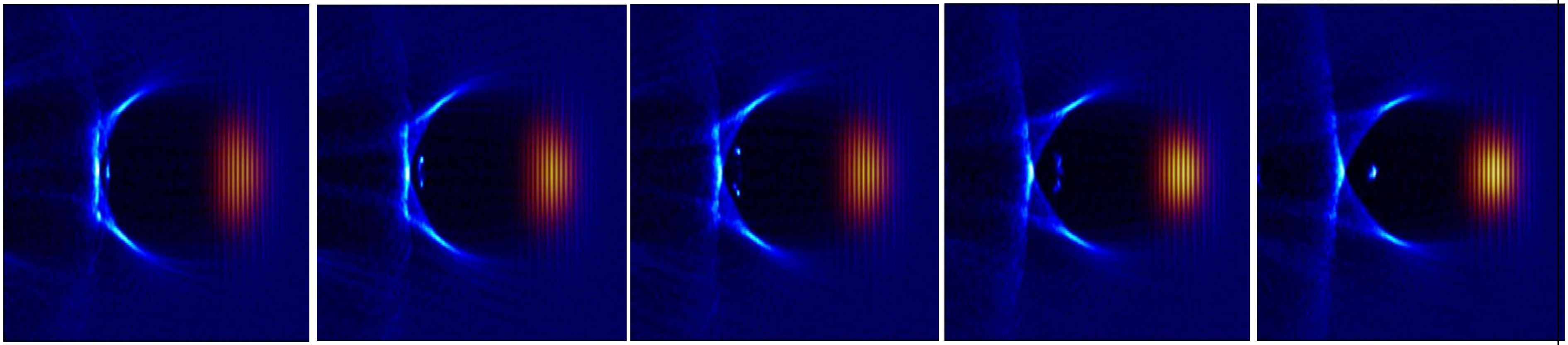
Focusing force $eE = 2\pi n e^2 r$

Assume electron is relativistic with γ

It will oscillate in this field as $$\frac{d^2 r}{ds^2} = \frac{2\pi n e^2 r}{\gamma m c^2} = \frac{\omega_p^2}{2\gamma c^2} r$$

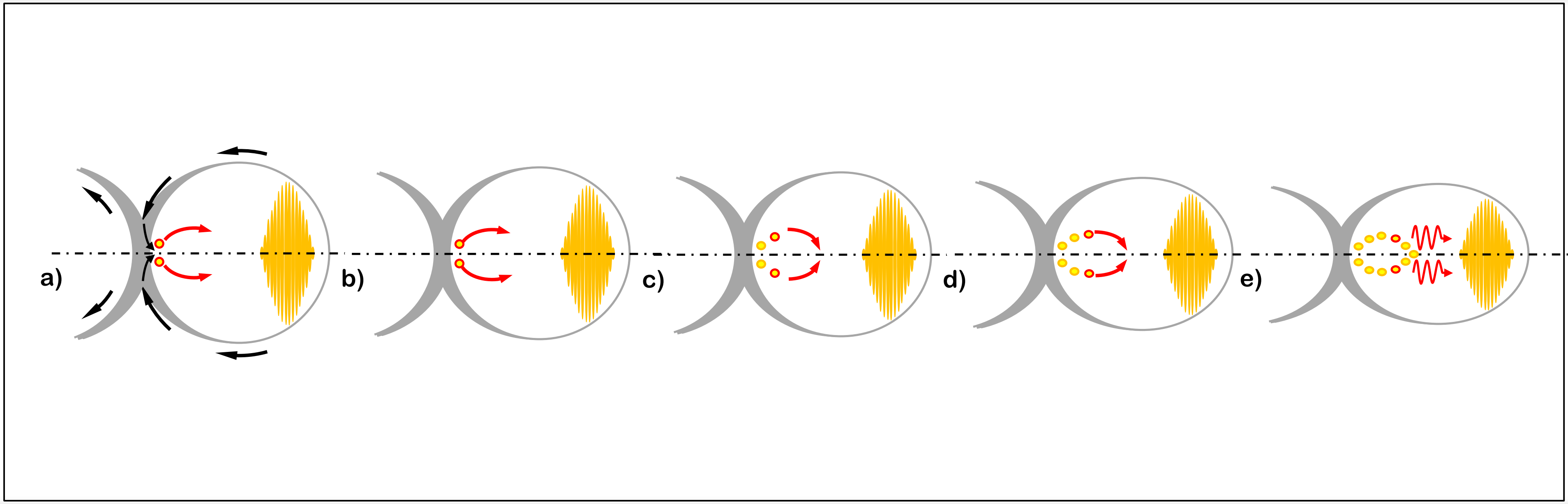
The period of oscillation is therefore $\lambda = \sqrt{2\gamma}\ \lambda_p$

Betatron radiation



- **Strong radial electric field within plasma wave cause transverse oscillation of electron bunch**
- **Generates bright betatron radiation in 1- 100 keV range**
- **Let's estimate parameters of this radiation**

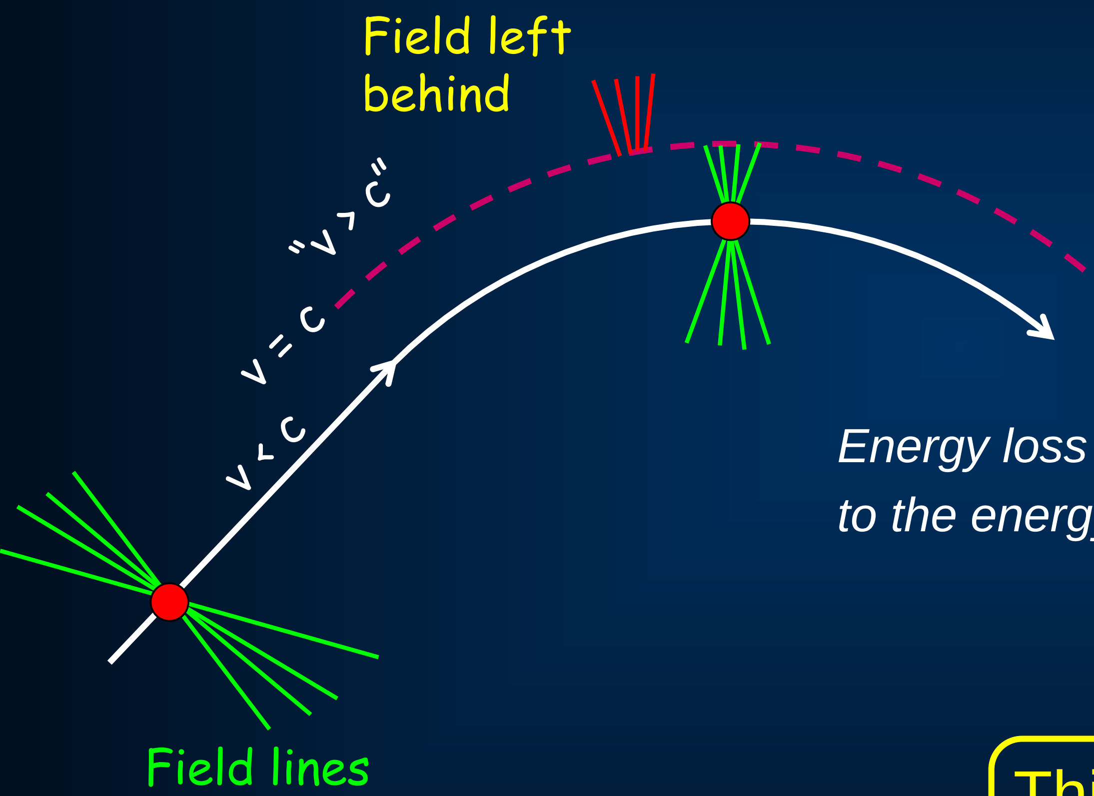
Betatron radiation



- **Strong radial electric field within plasma wave cause transverse oscillation of electron bunch**
- **Generates bright betatron radiation in 1- 100 keV range**
- **Let's estimate parameters of this radiation**

Synchrotron Radiation (SR)

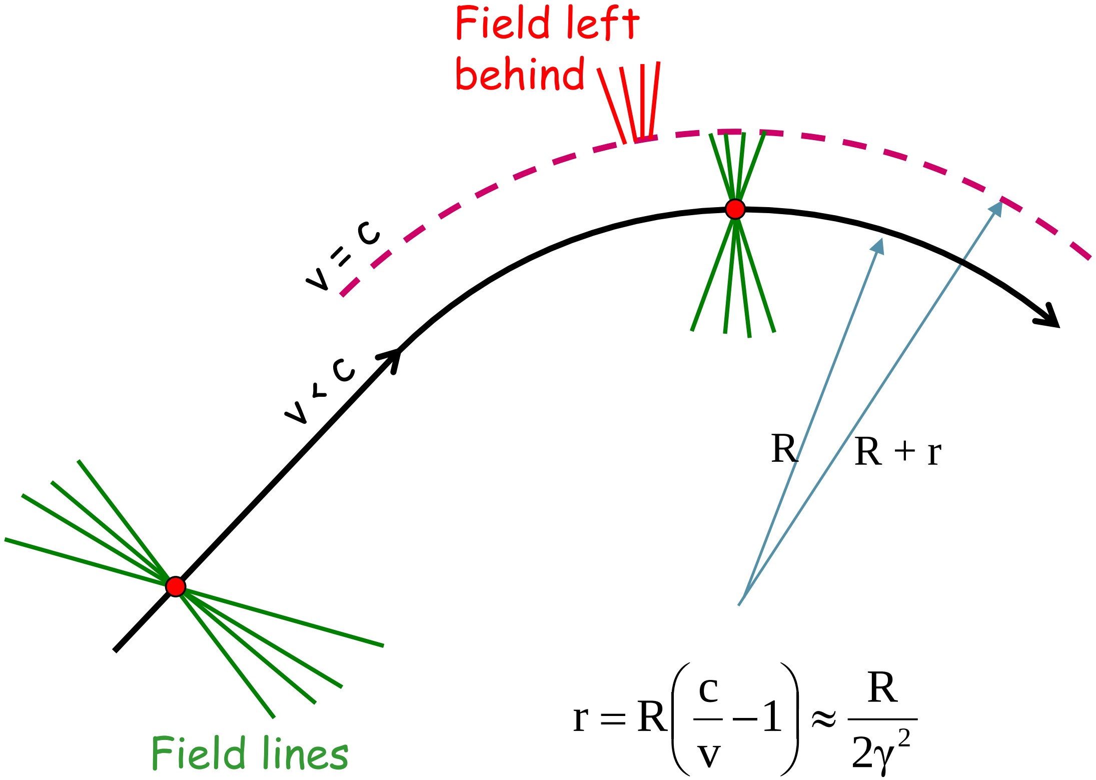
SR caused by leaving part of fields behind when the beam moves along the curve



Energy loss per meter is proportional to the energy in the 4th degree

This radiation can be harmful and beneficial

Synchrotron radiation *on-the-back-of-the-envelope* – power loss

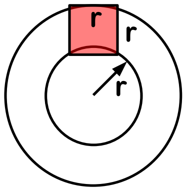


$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2 \, dV$$

The field $E \approx \frac{e}{r^2}$ the volume $V \approx r^2 \, dS$



Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

Substitute $r \approx \frac{R}{2\gamma^2}$ and get an estimate:

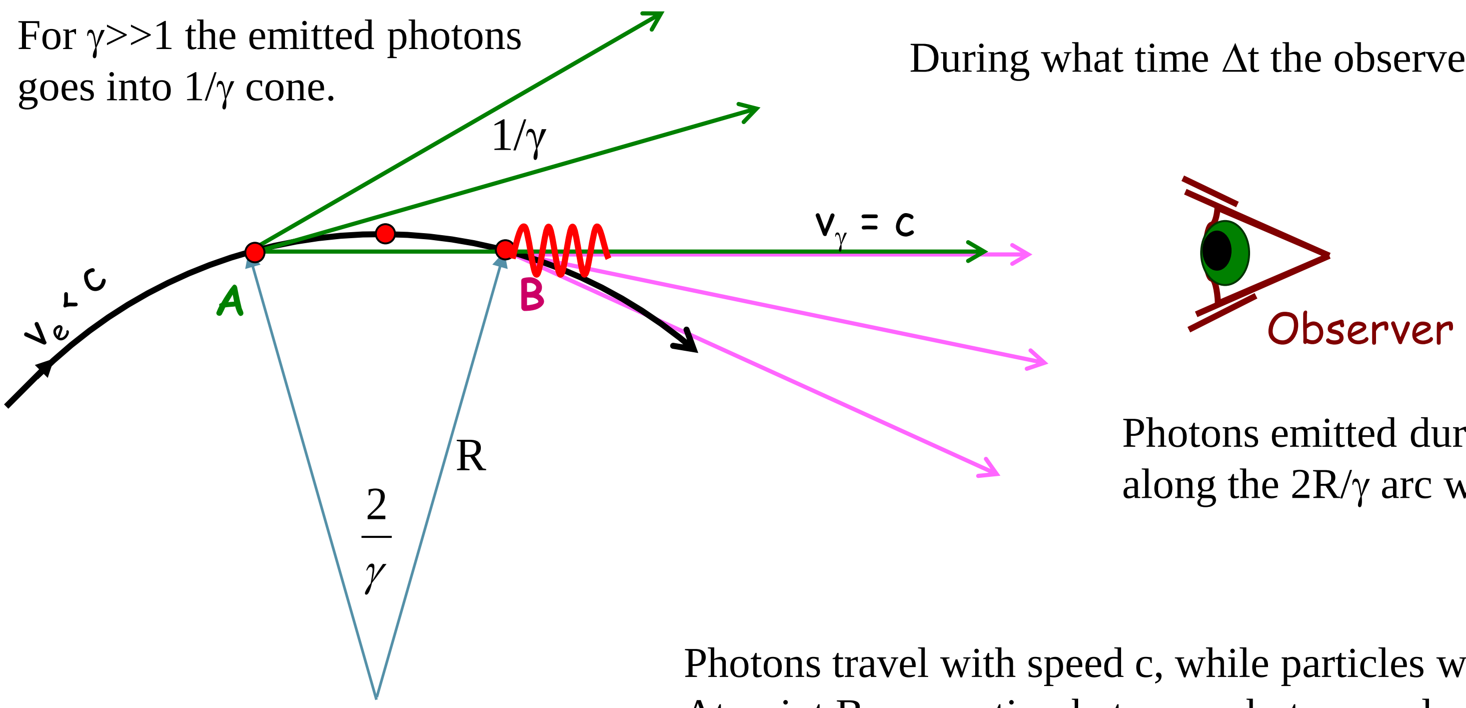
$$\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}$$

Gaussian units on this page!

Compare with exact formula: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$

Synchrotron radiation *on-the-back-of-the-envelope* –photon energy

For γ>>1 the emitted photons goes into 1/γ cone.



During what time Δt the observer will see the photons?

Photons emitted during travel along the 2R/γ arc will be observed.

Photons travel with speed c, while particles with v.
At point B, separation between photons and particles is

$$dS \approx \frac{2R}{\gamma}\left(1-\frac{v}{c}\right)$$

Therefore, observer will see photons during $\Delta t \approx \frac{dS}{c} \approx \frac{2R}{c\gamma}(1-\beta) \approx \frac{R}{c\gamma^3}$

Estimation of characteristic frequency $\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}$

Compare with exact formula: $\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$

Synchrotron radiation *on-the-back-of-the-envelope* –number of photons

We estimated the rate of energy loss : $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ And the characteristic frequency $\omega_c \approx \frac{c\gamma^3}{R}$

&

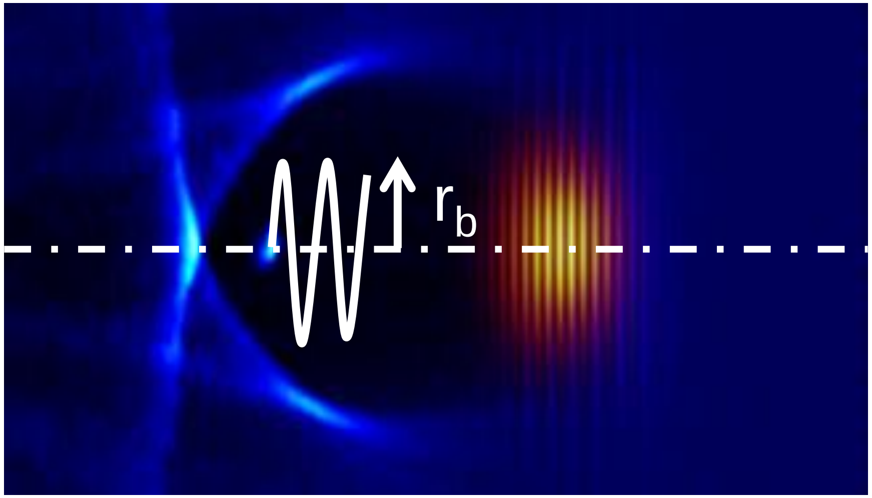
The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R}\lambda_e mc^2$ where $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

=>

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ (per angle θ : $N \approx \alpha\gamma\theta$)

Gaussian units on this page!

Estimations of betatron radiation



We found that relativistic electron with γ will oscillate in the field of ions as

$$\frac{d^2 r}{ds^2} = \frac{2\pi n e^2 r}{\gamma m c^2} = \frac{\omega_p^2}{2\gamma c^2} r$$

period of oscillation is $\lambda = \sqrt{2\gamma}\ \lambda_p$

If amplitude of oscillation is r_b then the radius of curvature of the trajectory is

$$R = \frac{\lambda^2}{4\pi^2 r_b}$$

Substitute and get the radius of curvature as $R = \dfrac{\gamma \lambda_p^2}{2\pi^2 r_b}$

Substitute into $\omega_c = \dfrac{3}{2}\dfrac{c\gamma^3}{R}$ and get estimation of radiation wavelength

$$\lambda_c = \frac{\lambda_p^2}{3\pi\gamma^2 r_b}$$

Use $\dfrac{dN}{dS} \approx \dfrac{\alpha\gamma}{R}$ to estimate N_γ photons emitted per λ

$$N_\gamma \approx \sqrt{2\gamma}\ 2\pi^2 \alpha \frac{r_b}{\lambda_p}$$

Assume 1GeV (γ=2E3), λ_p=0.03mm, r_b=0.001mm => λ_c=0.25 A or ~50 keV and N_γ per λ is ~0.3

Many hard photons!

Importance of back-of-envelope estimations

- **They are important because**
  - **they help to understand things better - obvious**
  - **but even more important: they allow to improve cross-disciplinary understanding of scientists from different fields, like biology and physics**

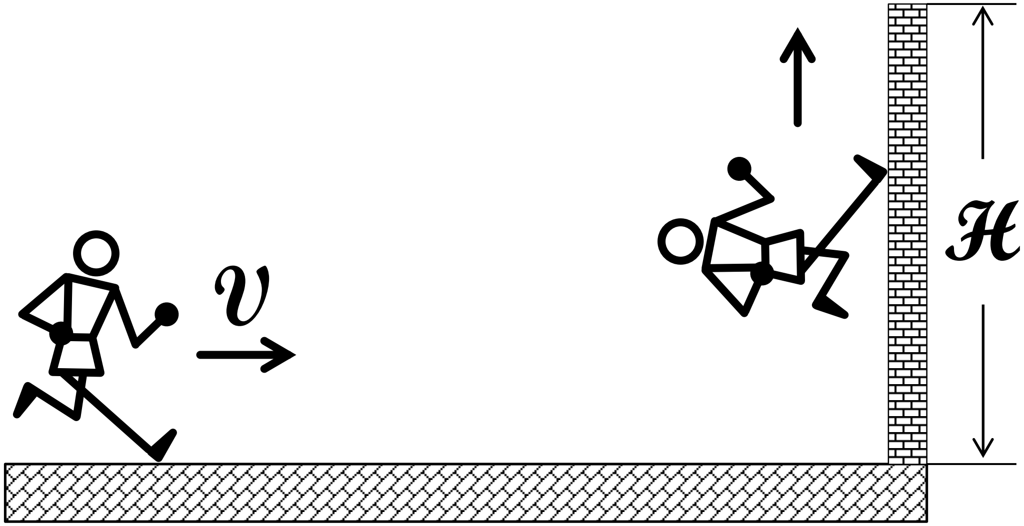
- **To train yourself on back-of-envelope estimations one can consider various questions**
- **They do not have to be necessarily serious ;-)**
- **But the estimates should be based on a physical effect that is considered most important for a given question**

Importance of back-of-envelope estimations

- **They are important because**
  - **they help to understand things better - obvious**
  - **but even more important: they allow to improve cross-disciplinary understanding of scientists from different fields, like biology and physics**

- **What speed V is needed to reach height H and get to other side of the wall?**

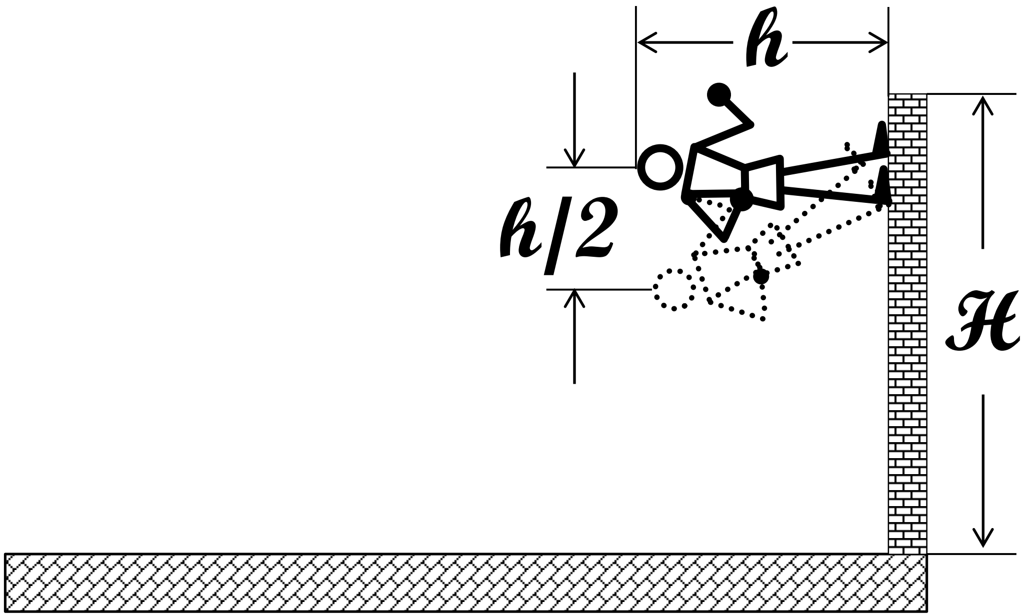
;-)



Importance of back-of-envelope estimations

- **Estimate by requiring that during run along the wall the head would not fall to lower than half the height of the person…**

;-)



You will then find
$V=H\,(g/h)^{1/2}$

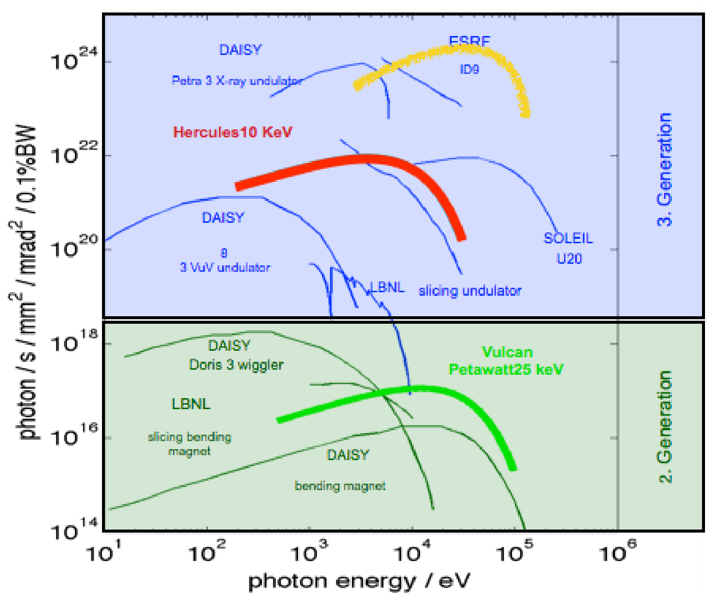
or, for H=2m

V~4.7 m/s

Compact laser plasma radiation sources

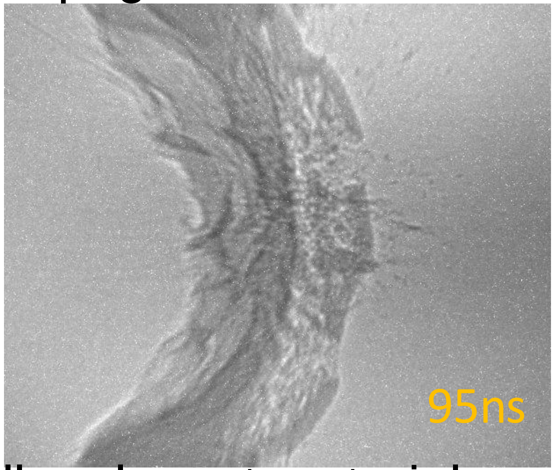
Gemini betatron x-ray source now > **10^{24}** photons per (mm^2 $mrad^2$ sec 0.1%BW)

Gemini 2015

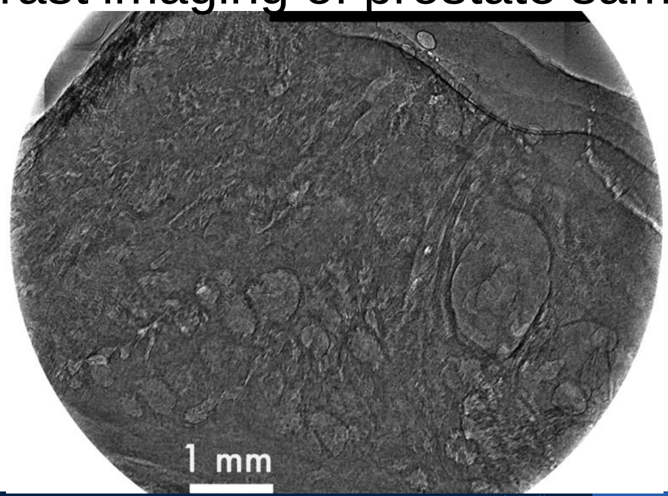


other light sources from A. Rousse *et al*, EPJD, 2008

Used for imaging fast phenomena; e.g. shock propagation in dense material.



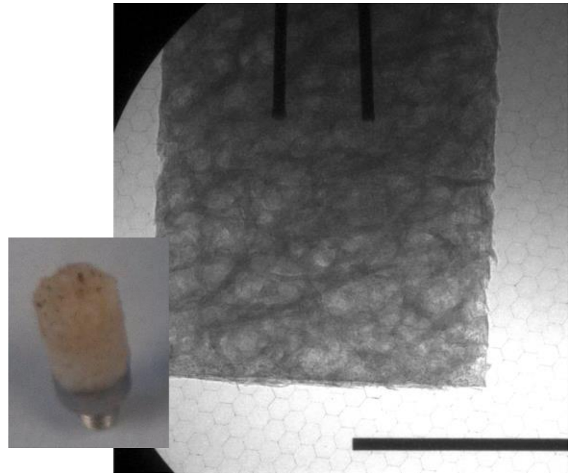
medically relevant material; e.g. phase contrast imaging of prostate sample



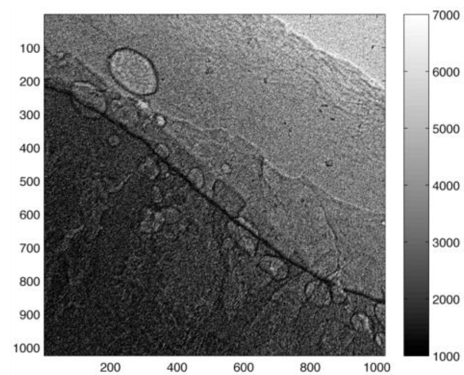
Medical application of laser-acc. particles

- **Betatron radiation could prove to be an interesting source for medical radiography**
  - **Small source size and collimated beam allows for high resolution phase contrast imaging of soft tissue, e.g. breast, prostate…**
  - **Hard photon energy with small source size allows for high resolution imaging of bone, biological samples**

Z.Najmudin, et al

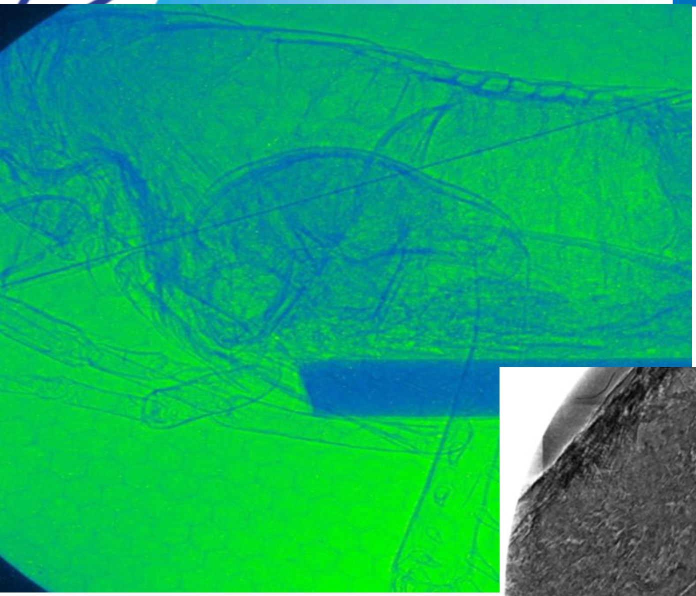


X-ray radiograph of femural bone sample (left, and photo inset) tomographically reconstructed (right)



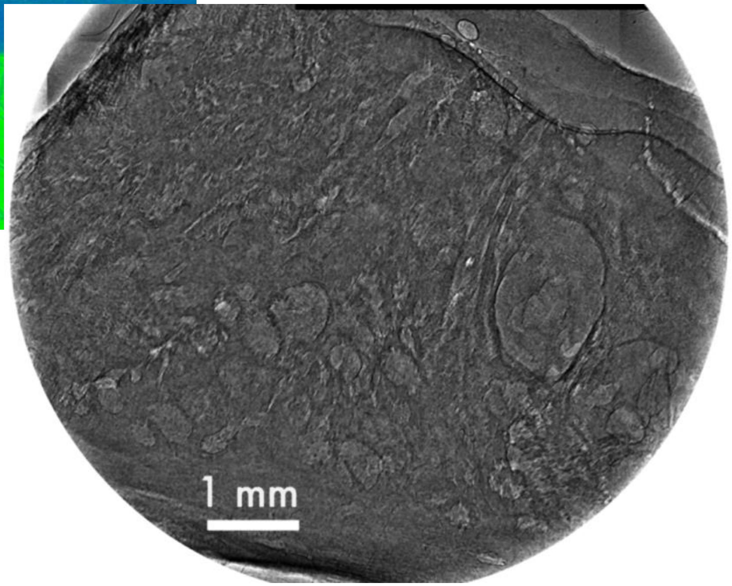
Phase-contrast imaging of prostate (left) and tomograph of pre-natal mouse (right)

LP acceleration for medicine



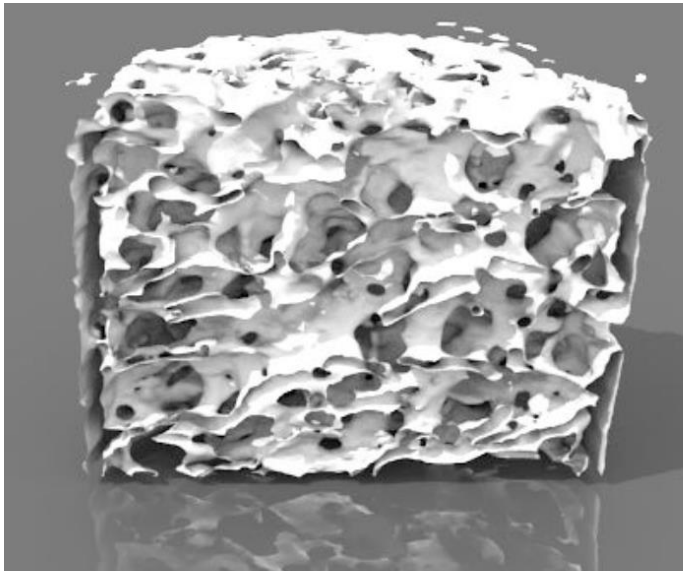
Imaging with Gemini laser-plasma acceleration and betatron radiation

Small size of emitting area => use of phase contrast technique => many applications in medical imaging



Lopes N. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. In Preparation (2014).

Bone tomography

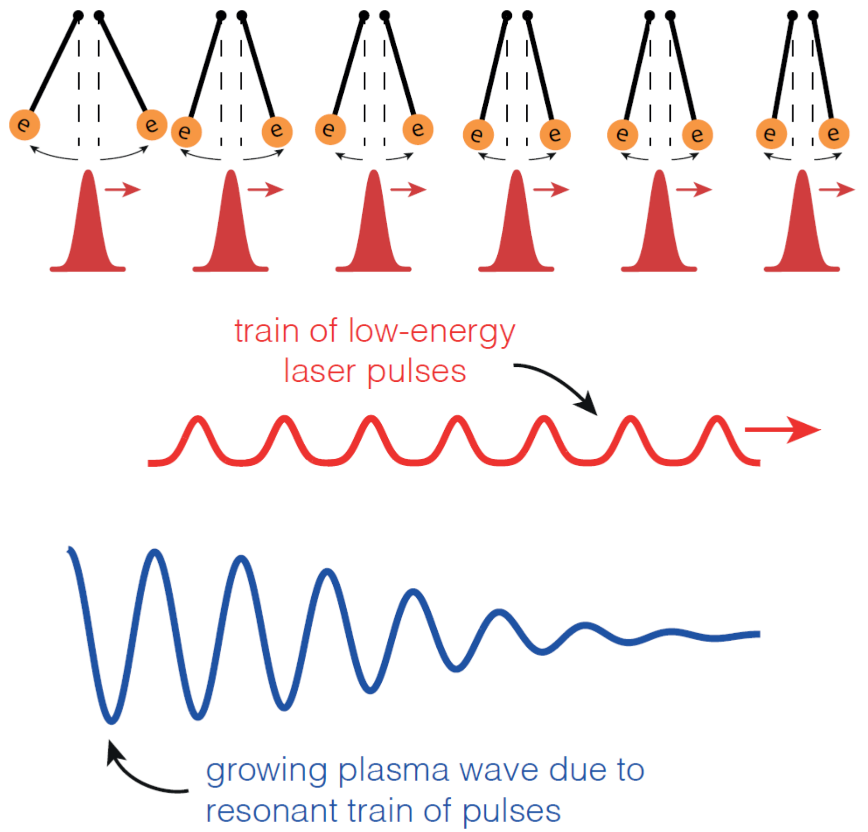


Cole J. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. Submitted (2014).

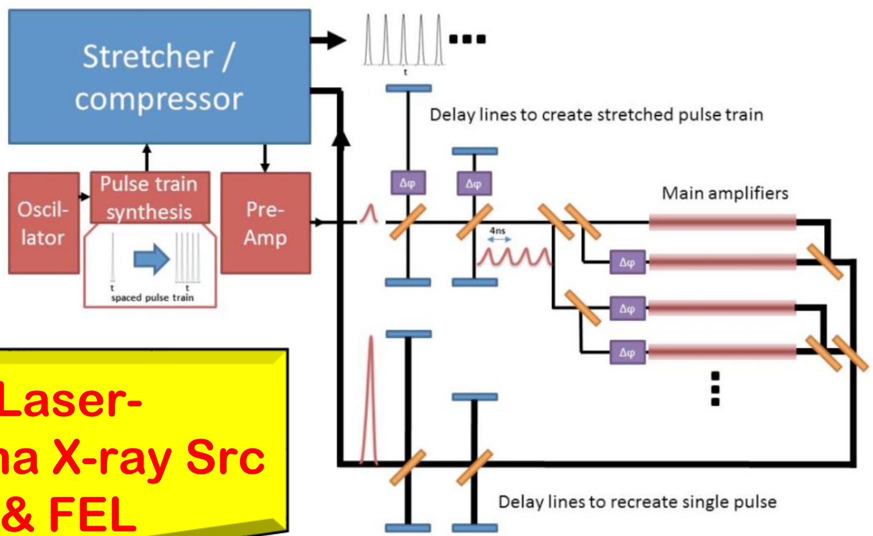
Z.Najmudin, et al

Challenge of efficiency & repetition rate

- Use a train of pulses separated by plasma period to resonantly excite wakefield – MP-LWFA
- Energy stored efficiently in plasma wave
- Can tune pulse separation to avoid saturation (unlike beat-wave scheme)



S.Hooker, R.Bartolini, S.Mangles, A.Tünnermann, L.Corner, J.Limpert, A.Seryi, R.Walczak. Jan 30, 2014, J.Phys. B47 (2014) 234003



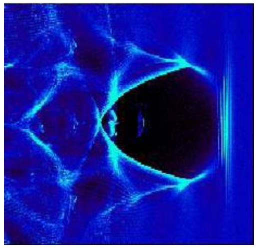
Laser-Plasma X-ray Src & FEL

- Fibre lasers: ~kW <u>average</u> power at wall-plug efficiencies > 20%
- Fibre lasers can generate trains of short pulses

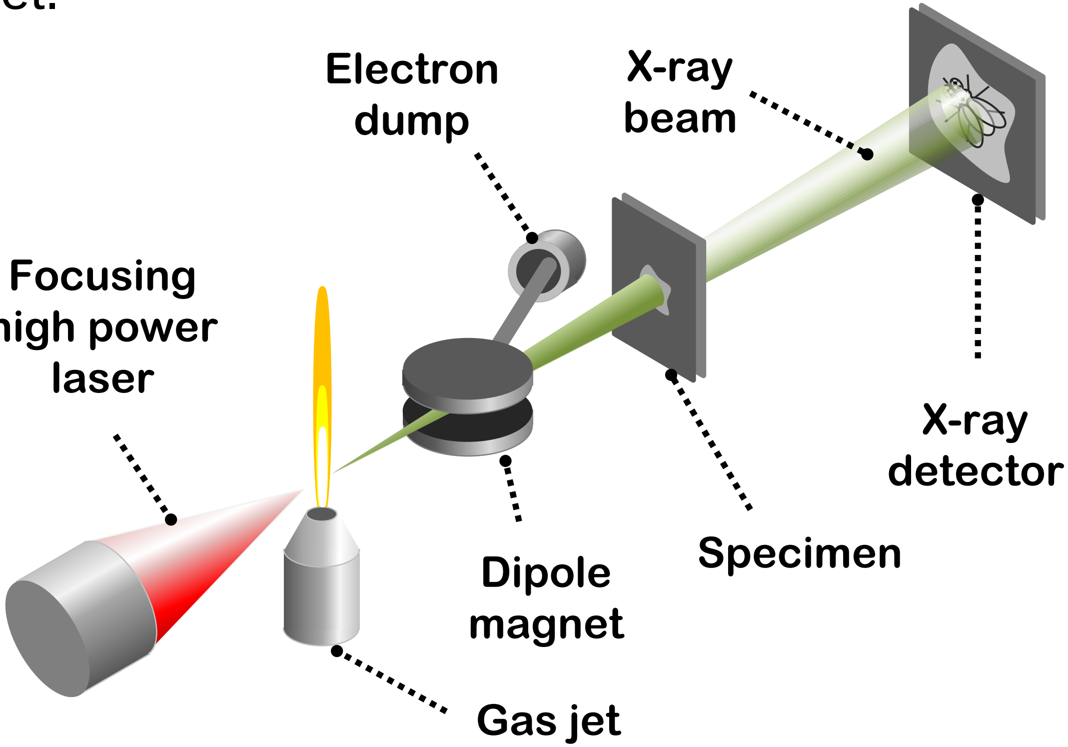
Laser Plasma accelerator

Modern synchrotrons (light sources) are big machines (several 100s meters)

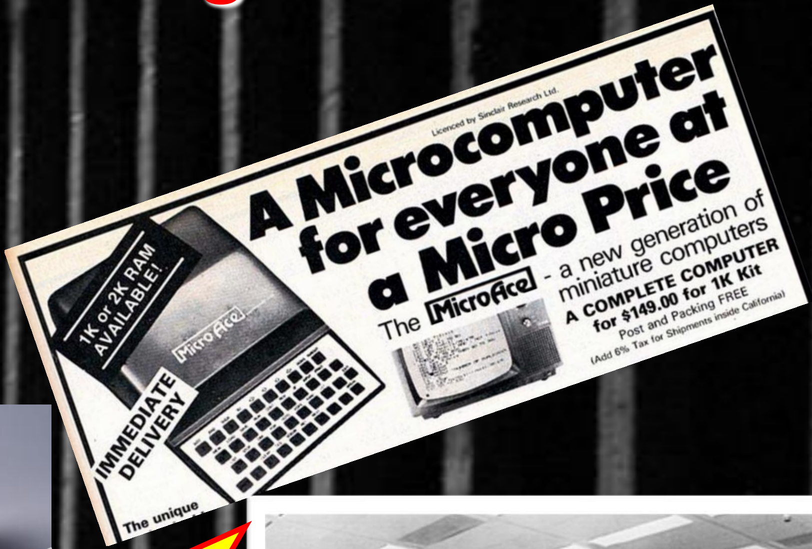
Similar electron energies can be reached in a much more compact accelerator using the “wake” created by a laser in a gas jet.



This could be used to build an accelerator compact enough to fit in several tens of meters space but powerful enough to be used as a light source – betatron X-ray and eventually an FEL



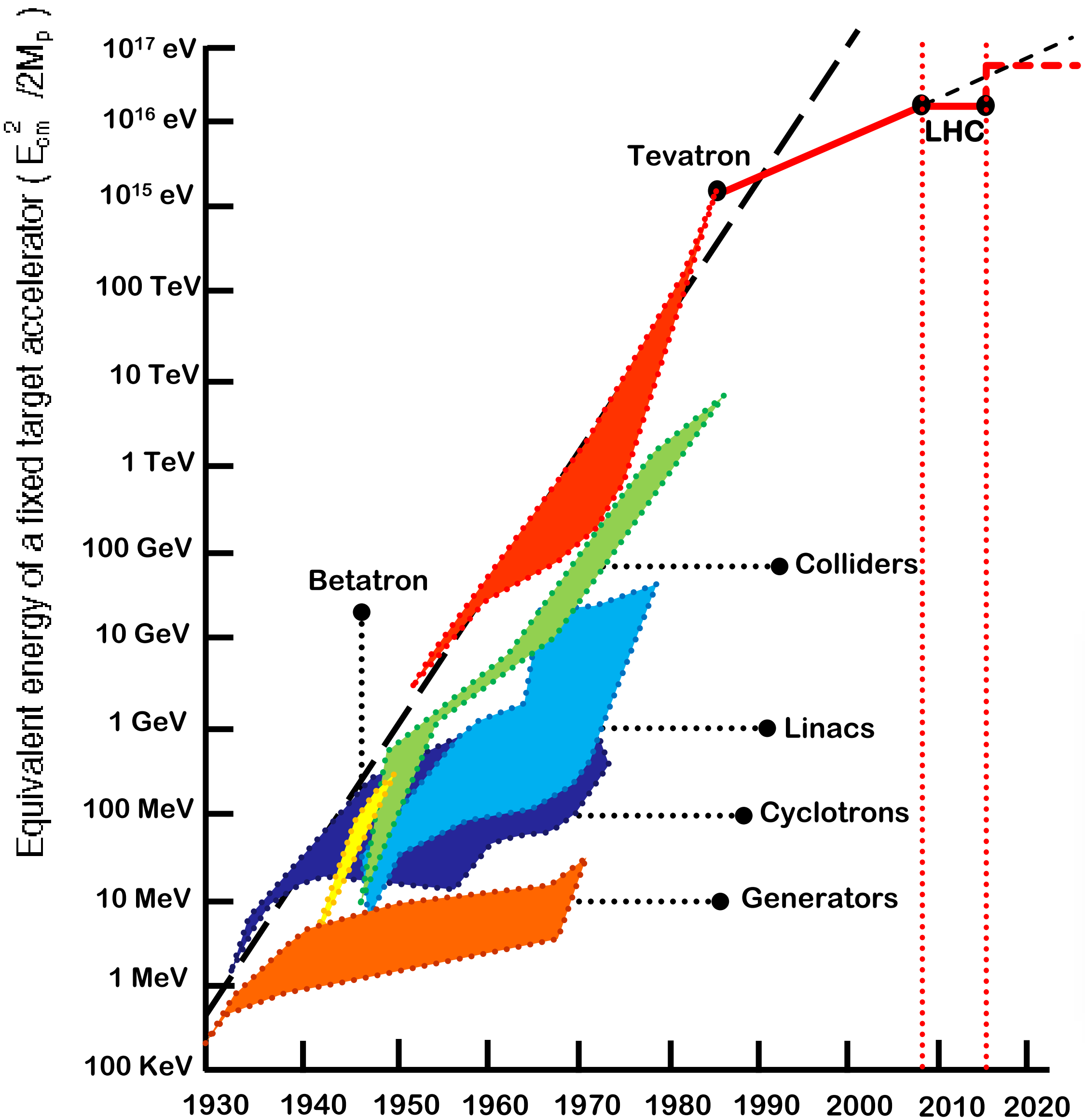
Evolution of computers and light sources



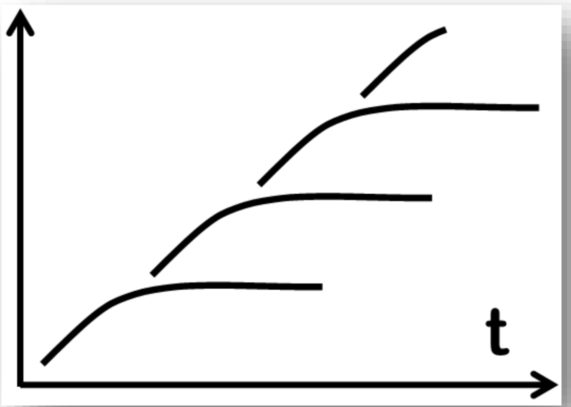
"IBM bringing out a personal computer would be like teaching an elephant to tap dance" cca. 1981

Evolution of computers and light sources

Motivation

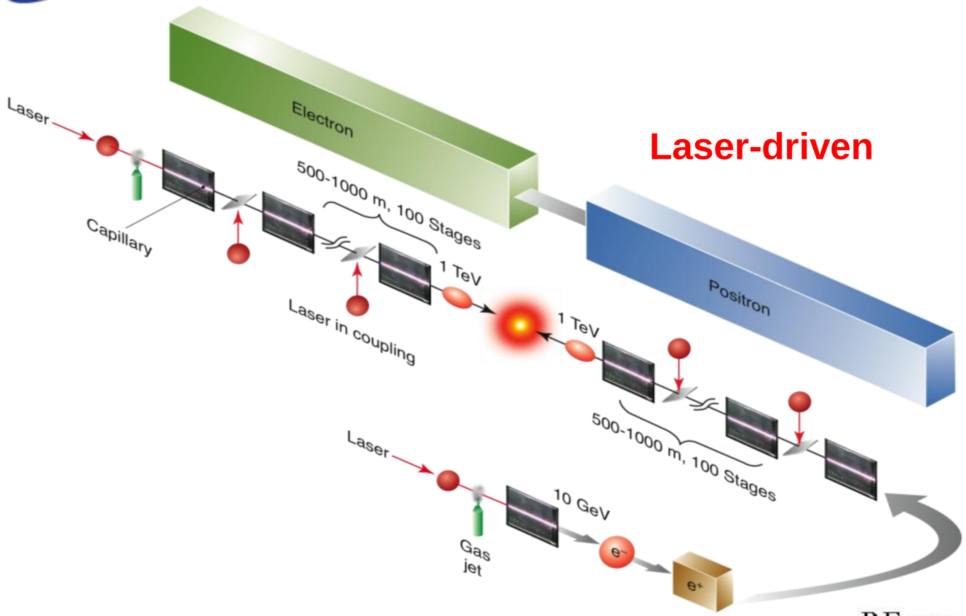


- “Livingston plot” shows great history of accelerators and <u>great inventions</u>
- … and shows signs of the need for the next revolution in accelerator technology



Concepts of plasma acceleration based colliders

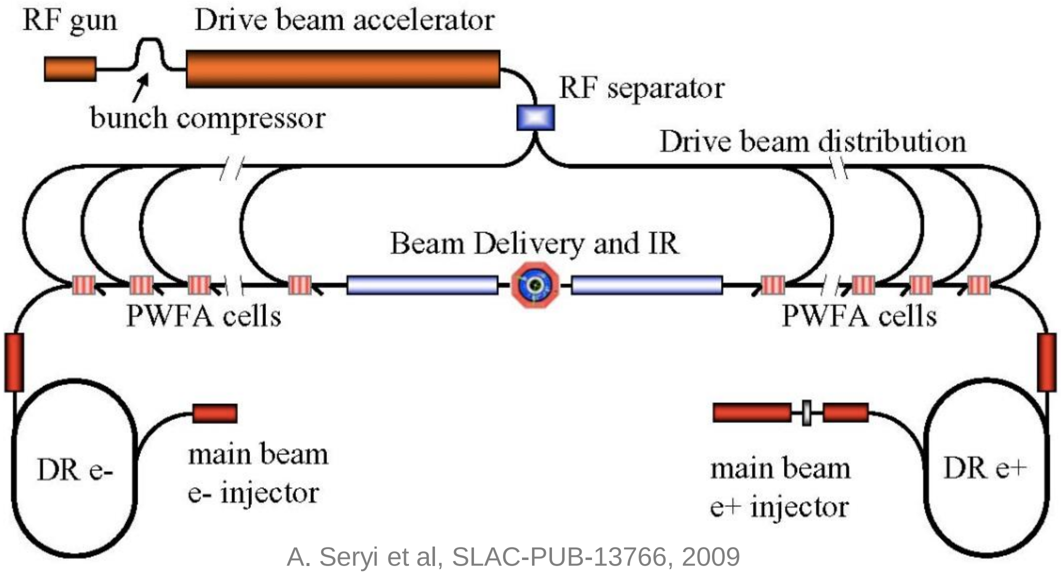
Laser-driven



Esarey et al, Rev. Mod. Phys. (2009)

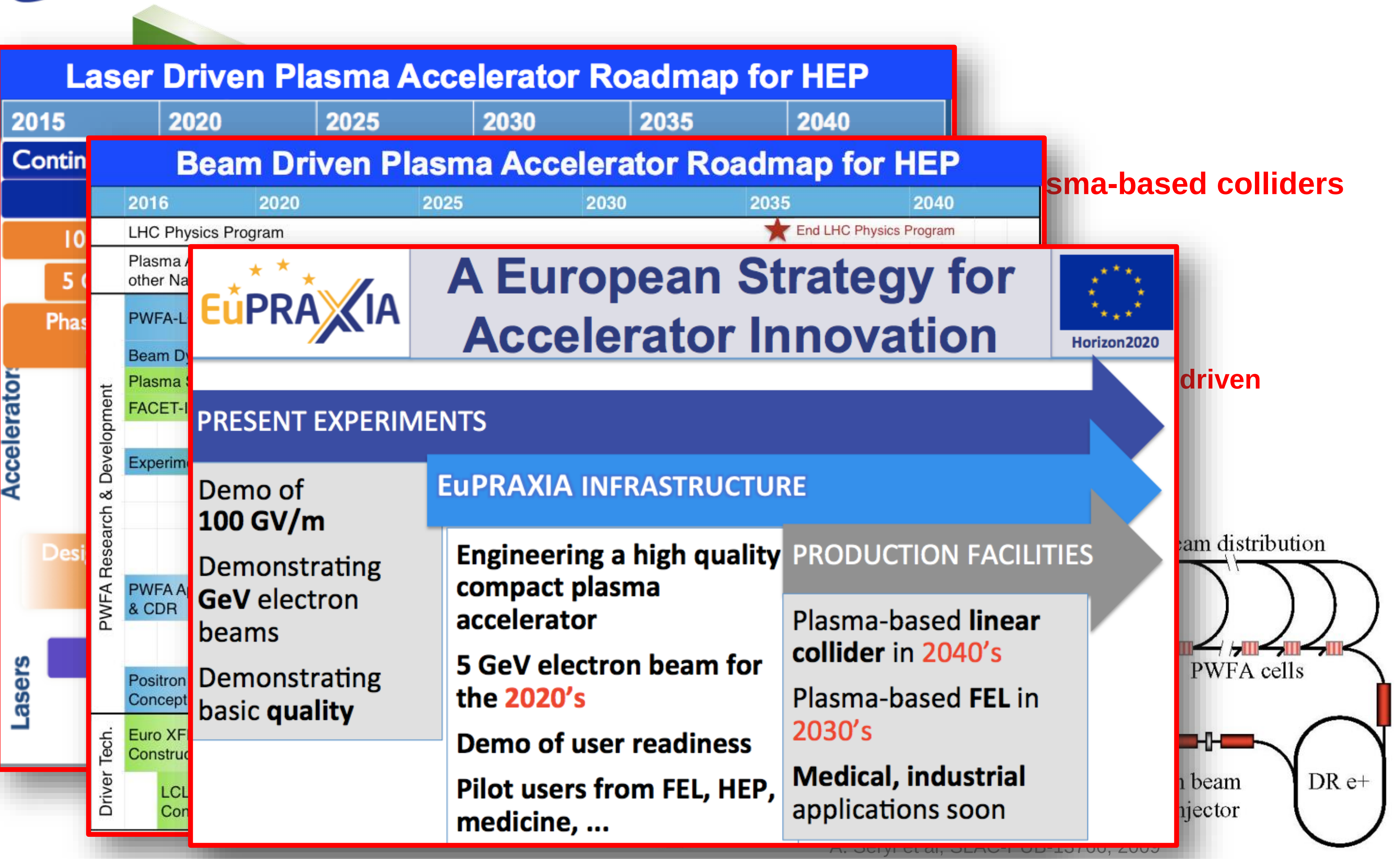
Can the next collider be based on plasma acceleration?

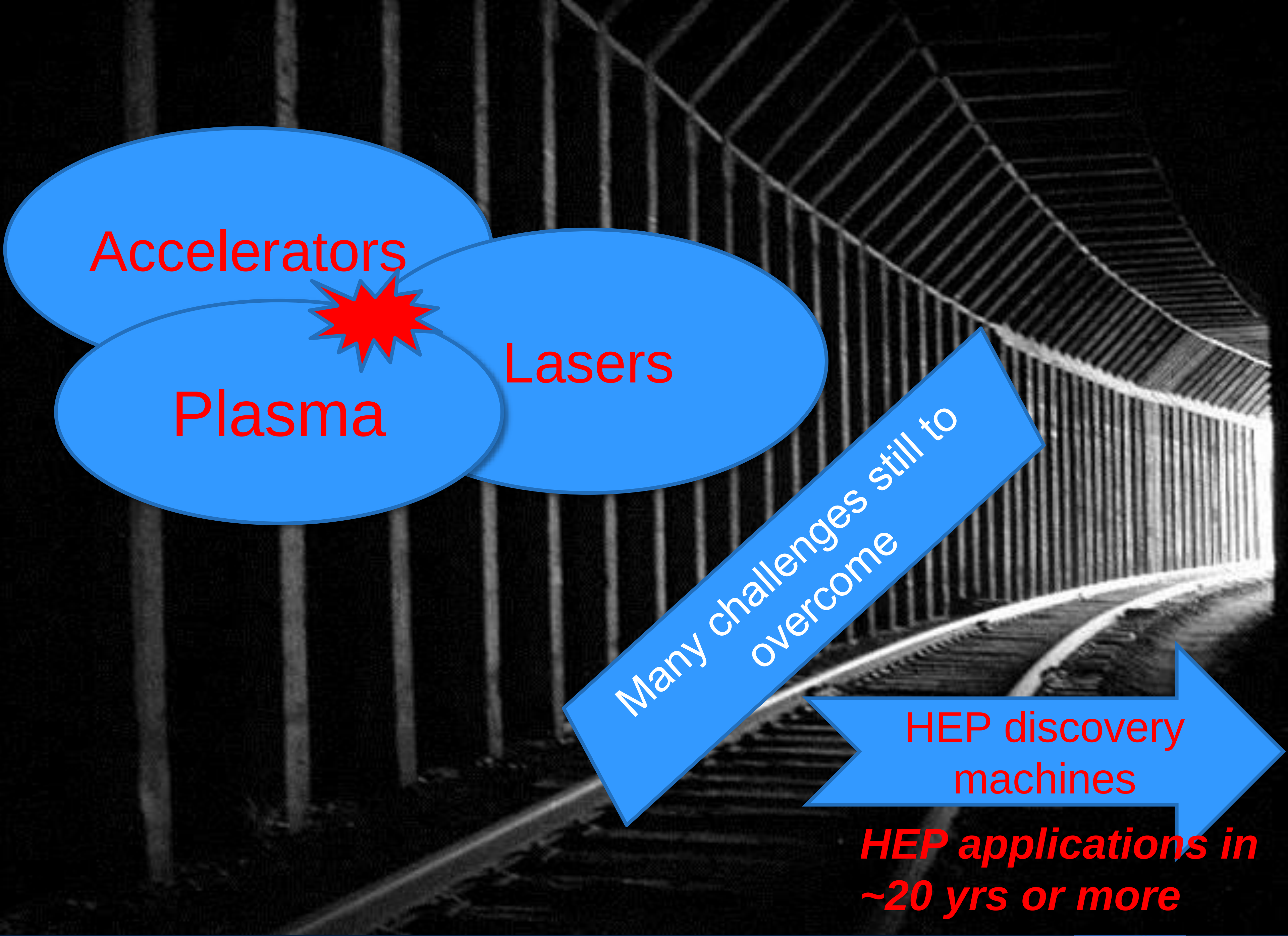
Beam-driven

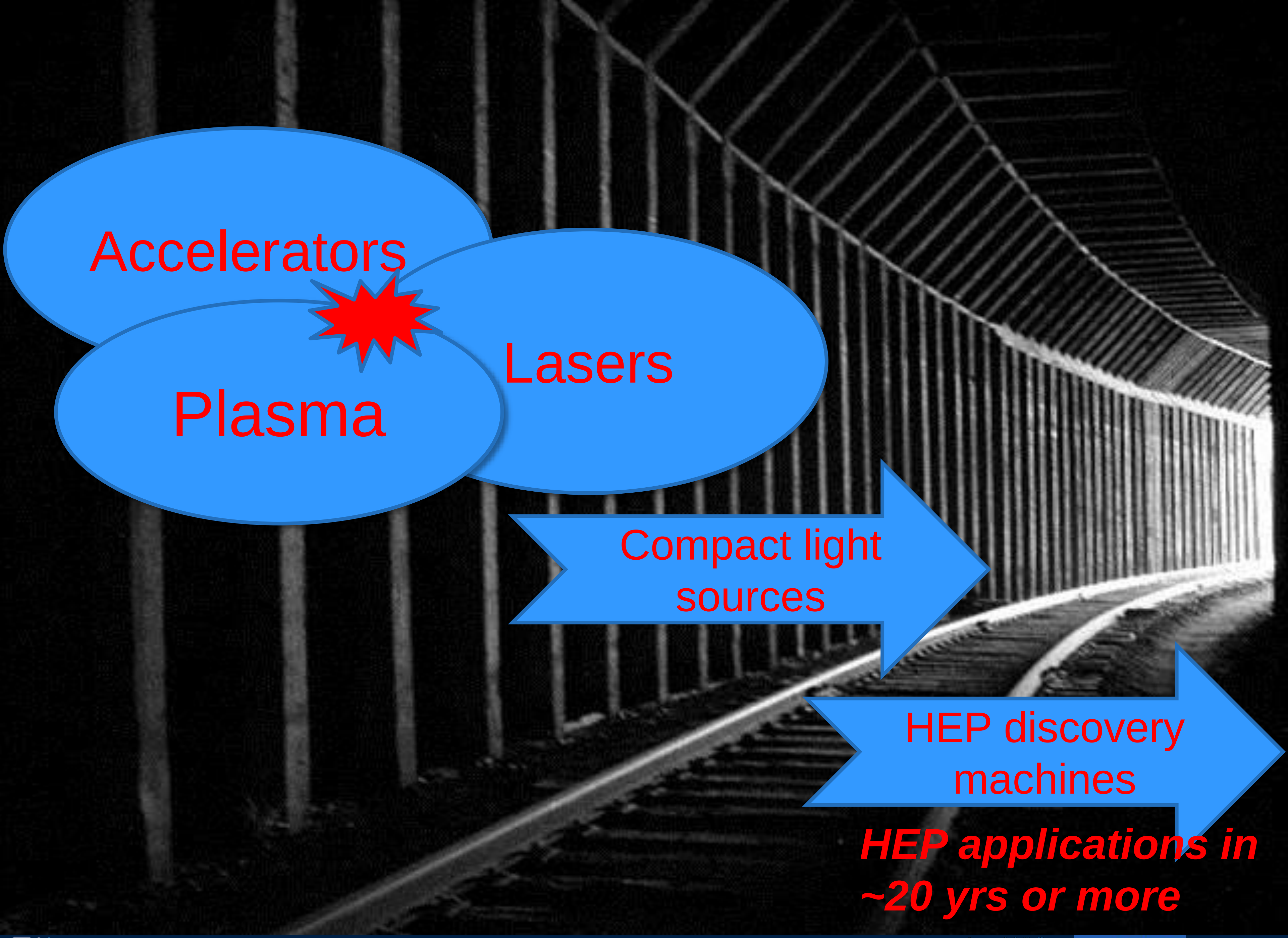


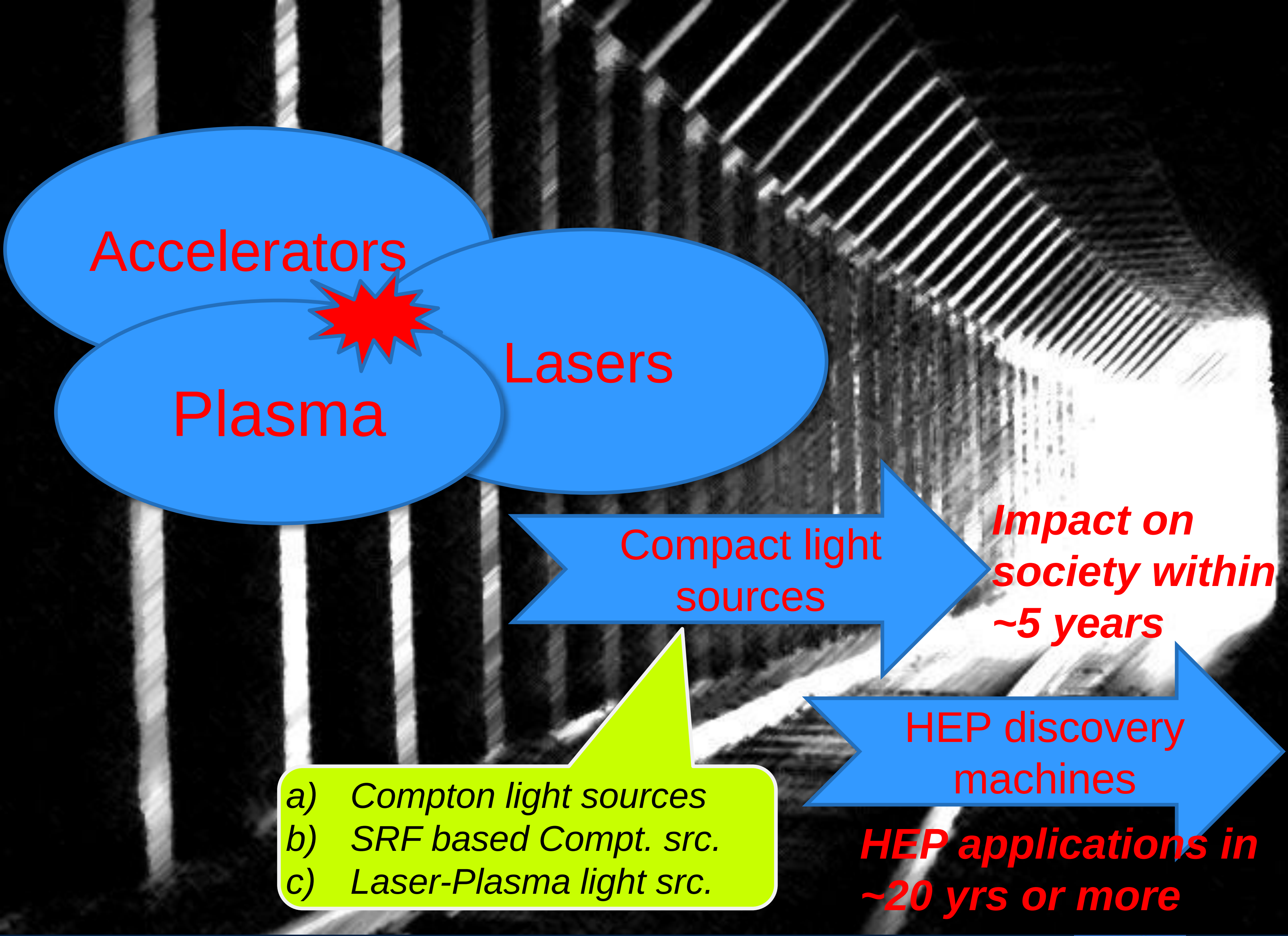
A. Seryi et al, SLAC-PUB-13766, 2009

Advanced accelerator community developing roadmaps toward plasma-based collider in 2040

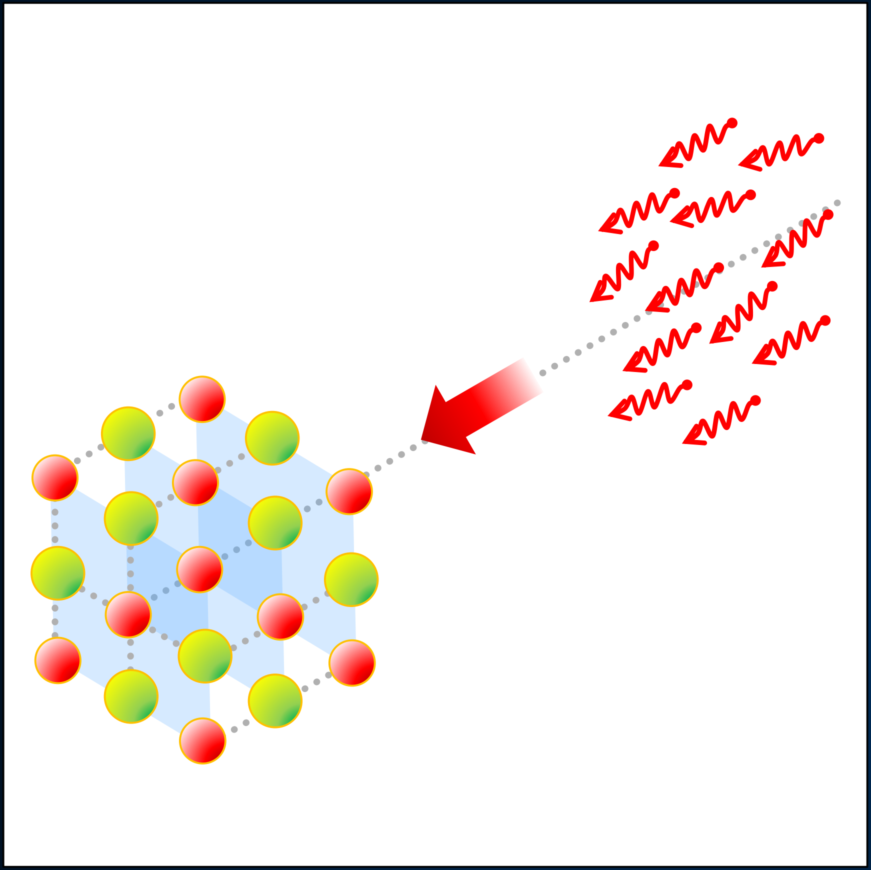


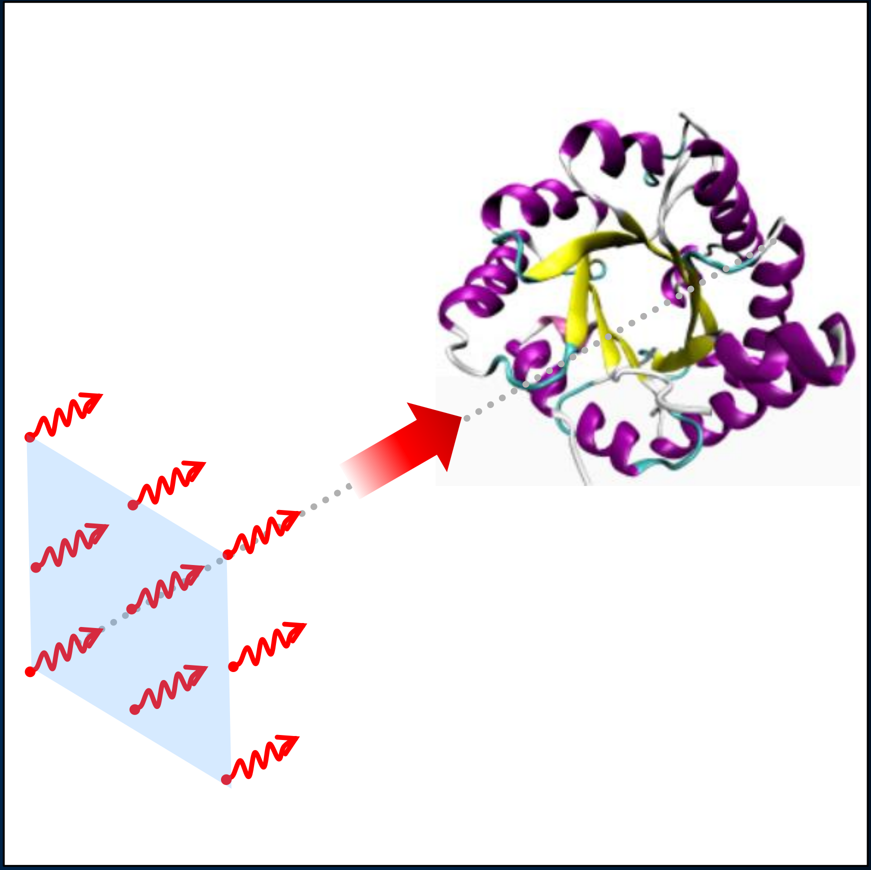

Accelerators
Lasers
Plasma
Many challenges still to overcome
HEP discovery machines
HEP applications in ~20 yrs or more


Accelerators
Lasers
Plasma
Compact light sources
HEP discovery machines
HEP applications in ~20 yrs or more


Accelerators
Lasers
Plasma
Compact light sources
Impact on society within ~5 years
HEP discovery machines
HEP applications in ~20 yrs or more
a) Compton light sources
b) SRF based Compt. src.
c) Laser-Plasma light src.

From 3-rd to 4-th generation (FEL)

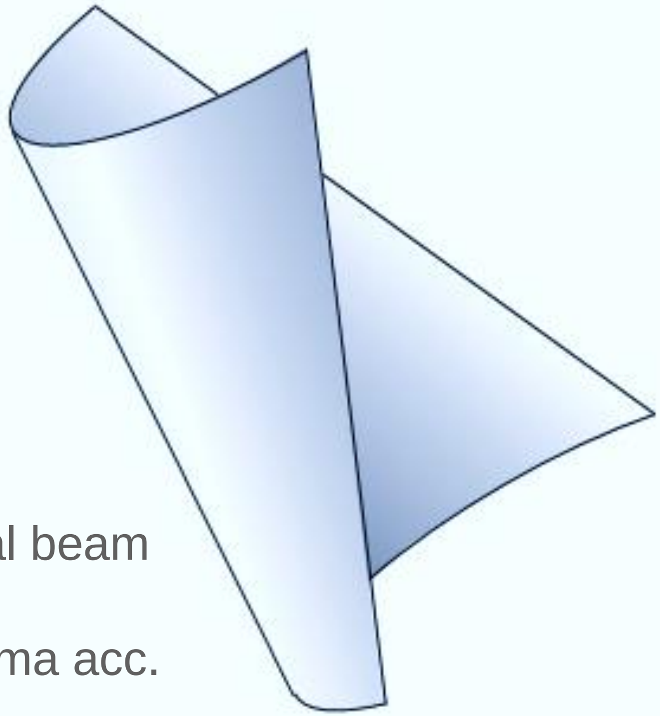




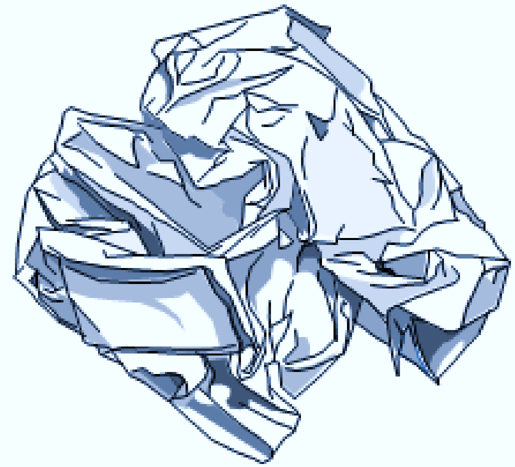
Era of studies of crystal structures by incoherent sources of X-rays → Era of studies of non-crystalline structures by coherent sources of X-rays

…and also this is an inventive principle "system-antisystem"

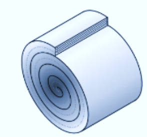
Challenge of low-size, large divergence beams



Initial beam from plasma acc.



Filamentation – poorly matched beam



Well matched beam

Using laser-plasma accelerated beam for FEL require not only achieving low $\Delta E/E$ beam, but also properly capturing and handling the large-divergence beam which is typically produced by plasma acceleration

Further evolution of light sources

Let's assume that laser-plasma FEL is working

What are long-terms perspectives and evolution of light sources then?

Let's first look at TRIZ general laws of evolution

Laws of technical system evolution
(standard TRIZ)

Static Laws

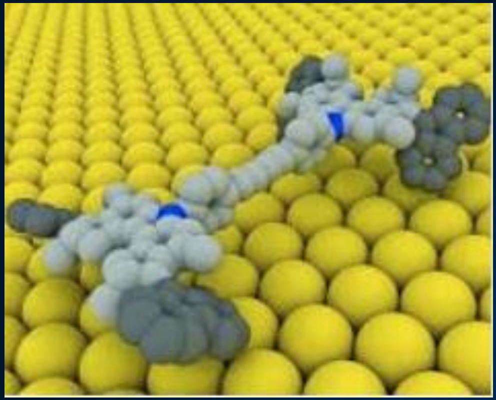
Kinematic laws

Dynamic laws

Laws of technical system evolution (standard TRIZ)

- **Static Laws**
  - **The law of the completeness of the parts of the system**
    - **4 parts: engine, transmission, working unit, control element**
  - **The law of energy conductivity of the system**
    - **every technical system is a transformer of energy and it should circulate freely and efficiently through its 4 main parts**
  - **The law of harmonizing the rhythms of parts of the system**
    - **frequencies of periodicity of parts and movements of the system should be in synchronization with each other**

Nobel prize 2016 – molecular machines



Pierre Sauvage, J. Fraser Stoddart, and Ben L. Feringa, Chemistry Nobel Prize 2016

Compare this with laws of technical system evolution

that were developed for TRIZ in 20th century

- Static Laws
  - The law of the completeness of the parts of the system
    - 4 parts: engine, transmission, working unit, control element
  - The law of energy conductivity of the system
    - every technical system is a transformer of energy and it should circulate freely and efficiently through its 4 main parts

These laws allow to predict what parts of molecular machine would be invented next

Laws of technical system evolution (standard TRIZ)

- **Dynamic laws**
  - **Transition from macro to micro level**
    - **development of working organs proceeds initially on a macro and then more and more on a micro level**
  - **Increasing involvement of fields in systems**
    - **the fields evolve from mechanical fields to electro-magnetic fields**

Laws of technical system evolution (standard TRIZ)

- **Kinematic laws**
  - **Law of increasing the degree of ideality of the system**
    - **ideality is a qualitative ratio between all desirable benefits of the system and its cost or other harmful effects**
  - **The law of uneven development of parts of a system**
    - **different parts of technical system will evolve differently, leading to the new technical and physical contradictions**
  - **The law of transition to a super-system**
    - **a system exhausting possibilities of further significant improvement is included in a super-system as one of its parts**

Understanding where we are

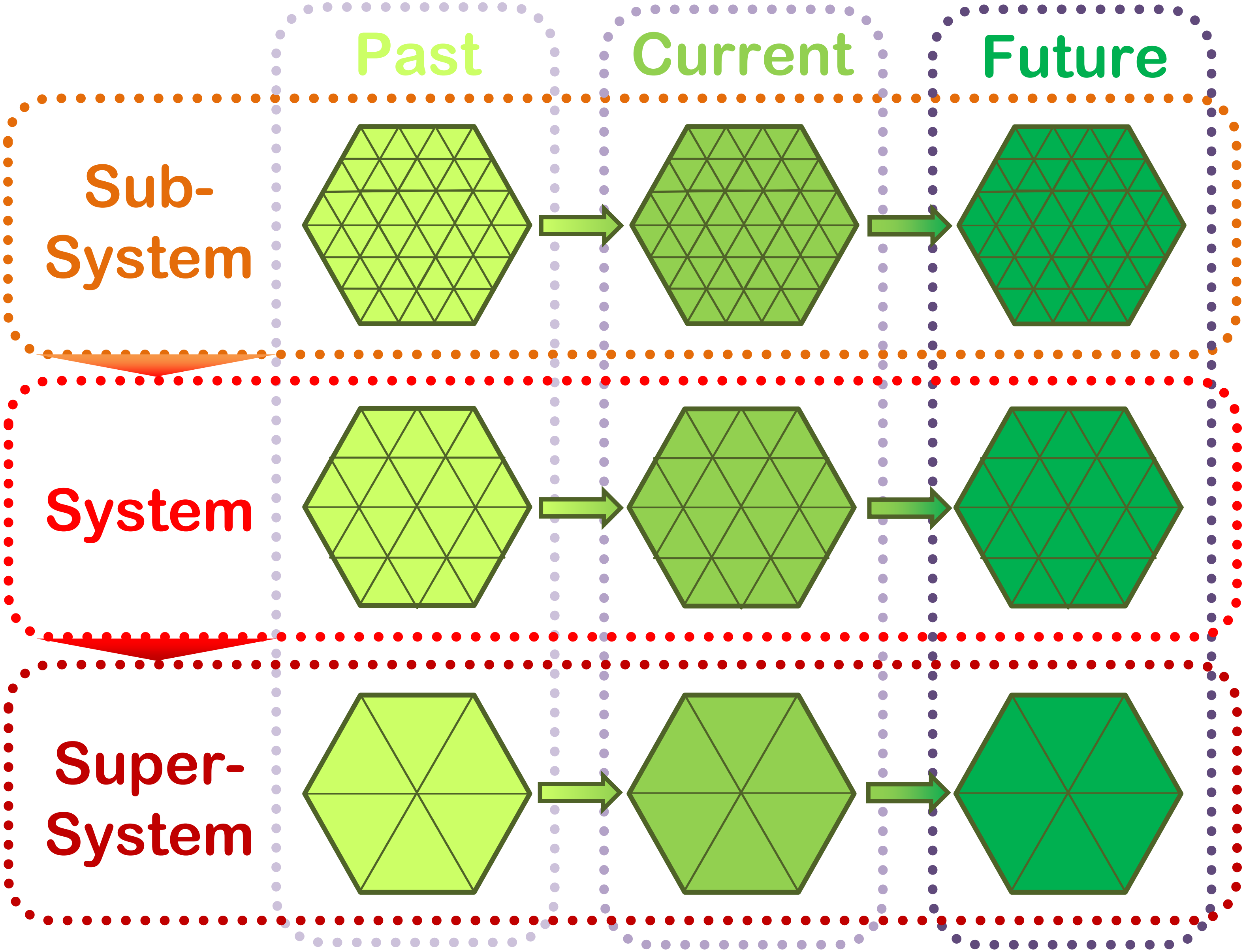
- **In time**
  - **past, now, future**
- **In space**
  - **sub-system, system, super-system**

together with

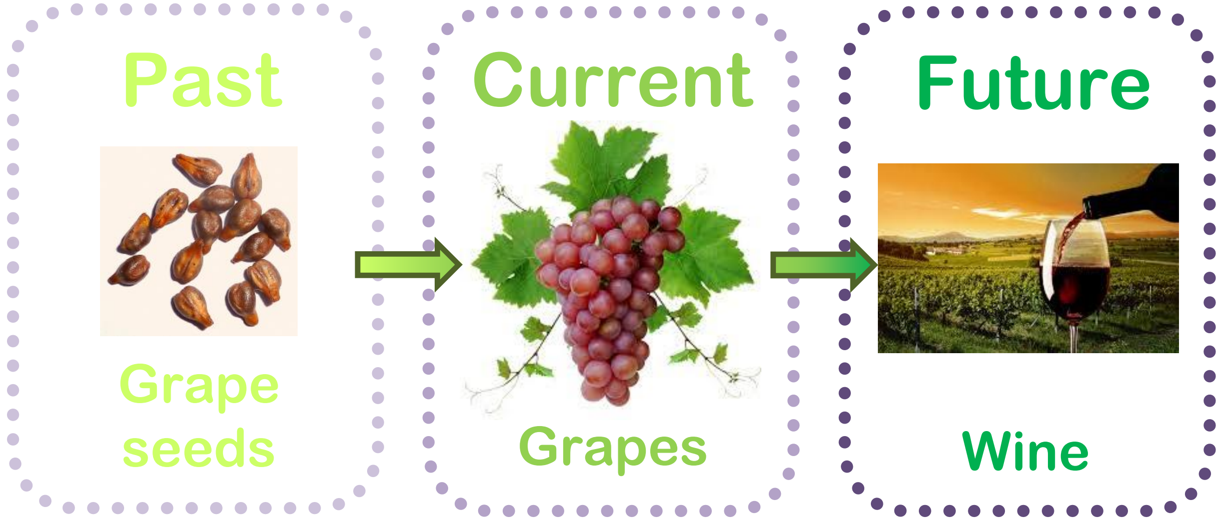
The law of transition to a super-system

will help to make predictions about evolution of scientific instruments

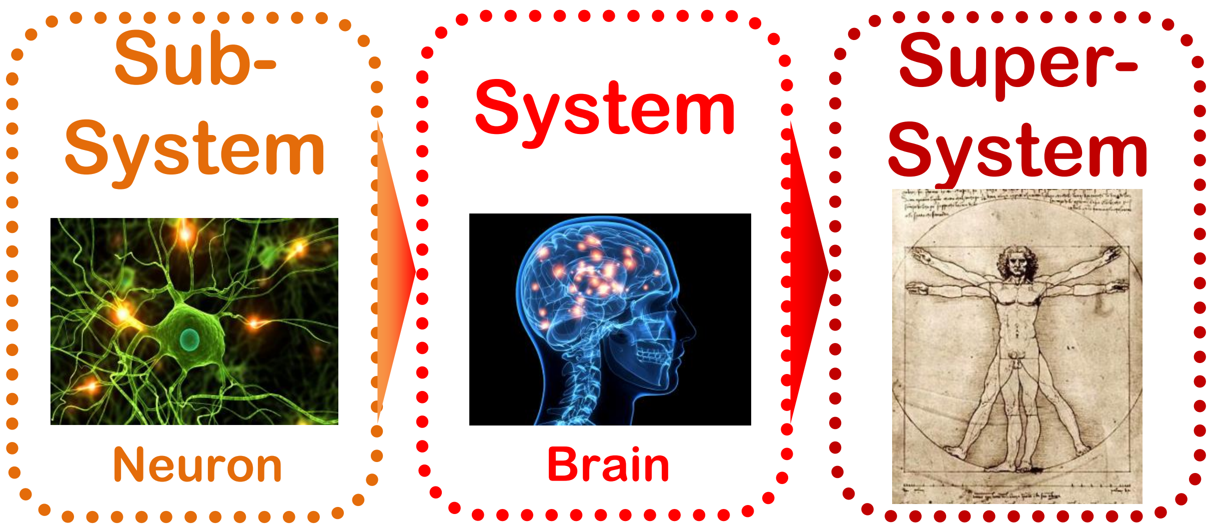
Understanding where we are



Understanding where we are



Examples



Understanding where we are

Past

Grape seeds

Current

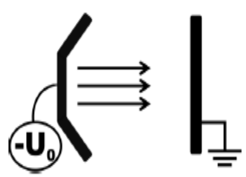
Grapes

Future

Wine

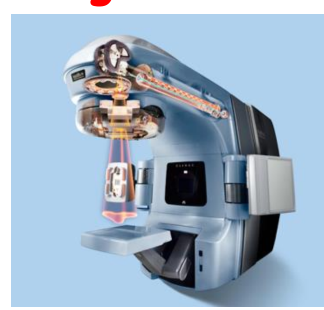
Examples

Sub-System



Electron gun

System



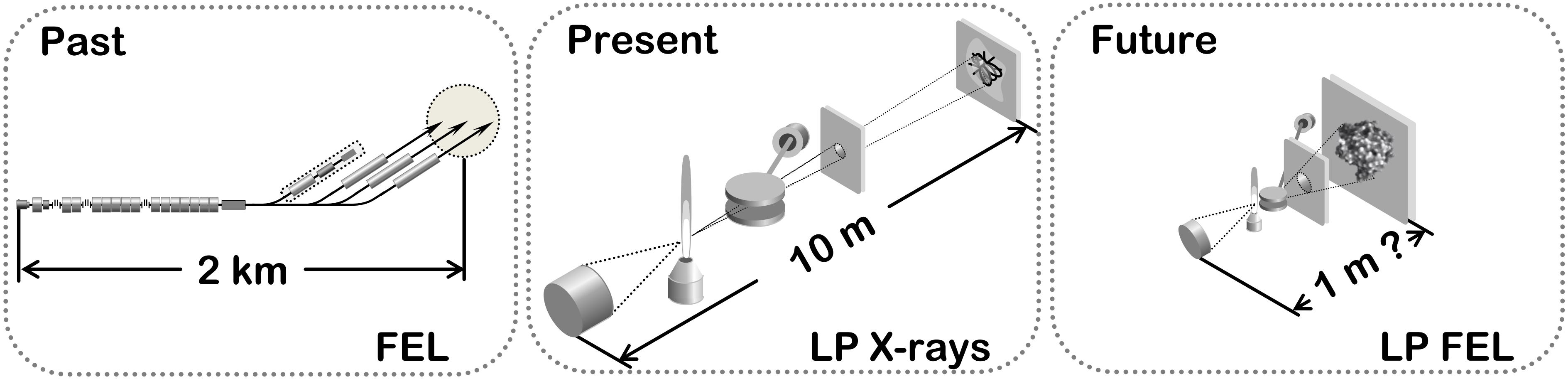
X-rays

Super-System

Hospital

FEL evolution forecast

- In time



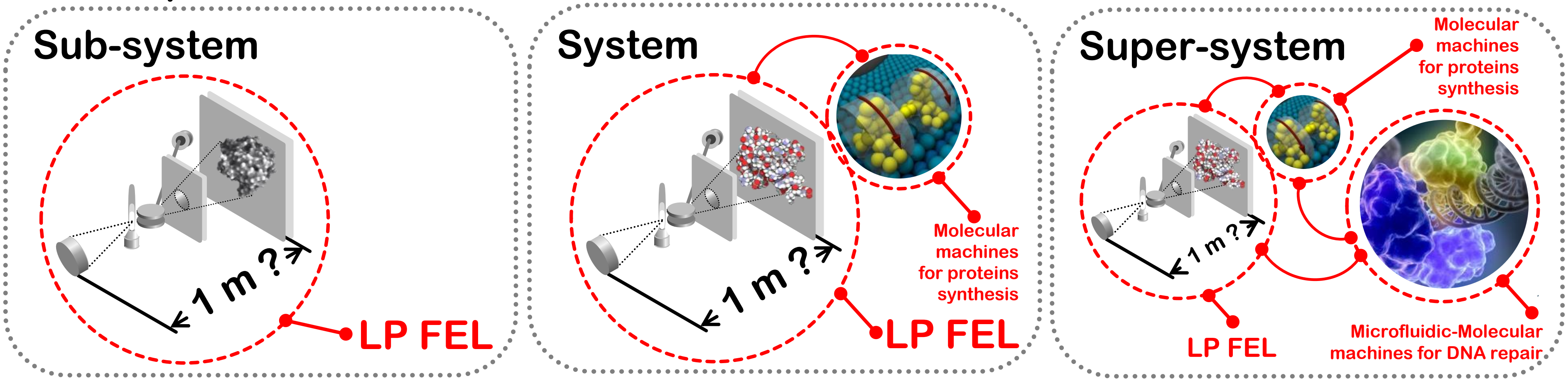
FEL will be so compact and developed that it can become part of another system, and that system in turn part of super-system

FEL becomes part of other system

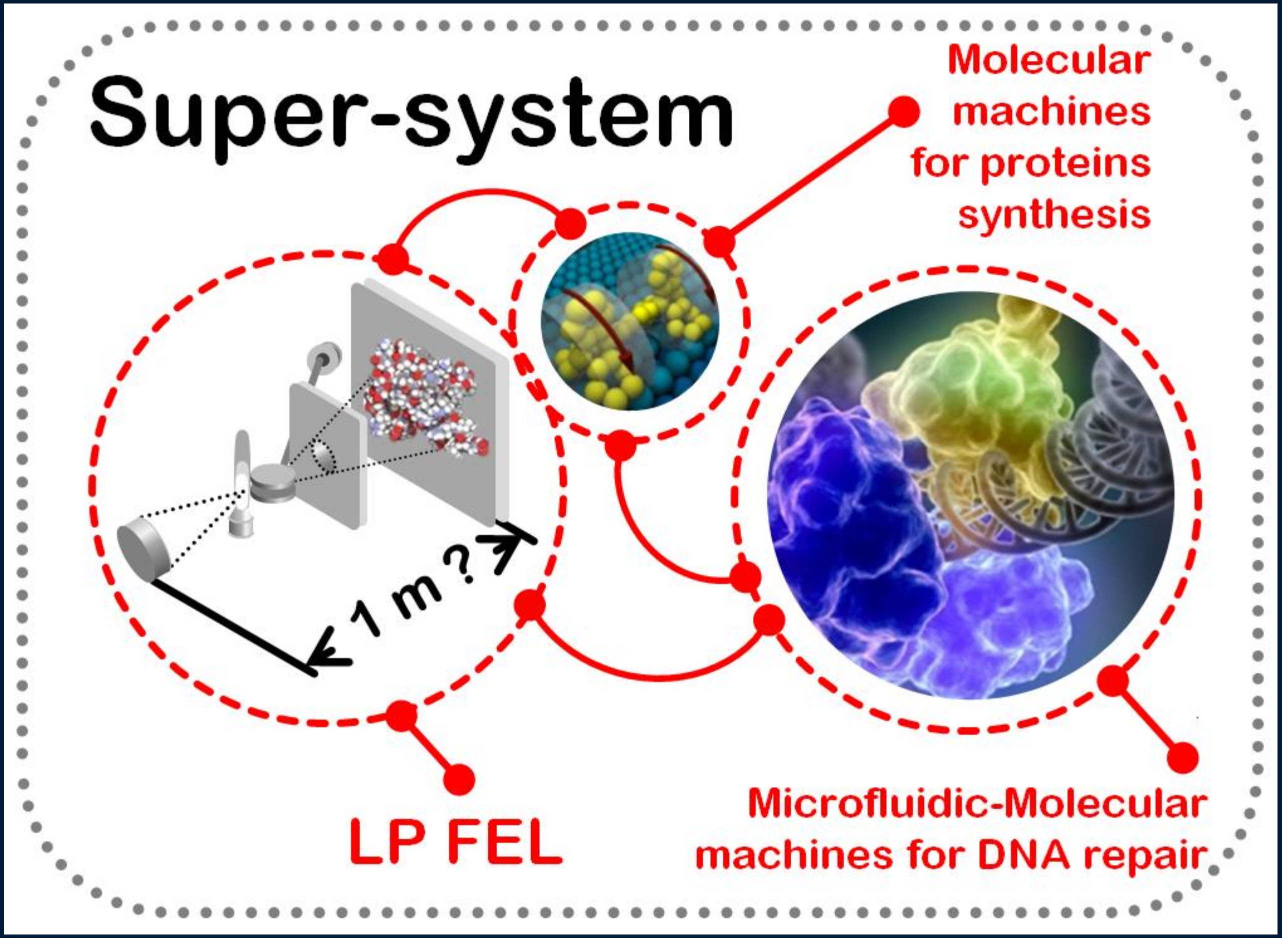
FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair

FEL is part of system where it analyses proteins synthesized by molecular machine

- In space



Let's make this dream a reality!



Laser plasma FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair

Thank you for your attention!

And thanks to may colleagues for materials used in this presentations