Introduction to Particle Acc. including plasma acceleration

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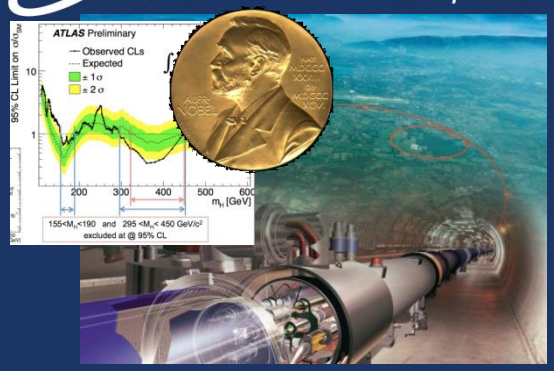
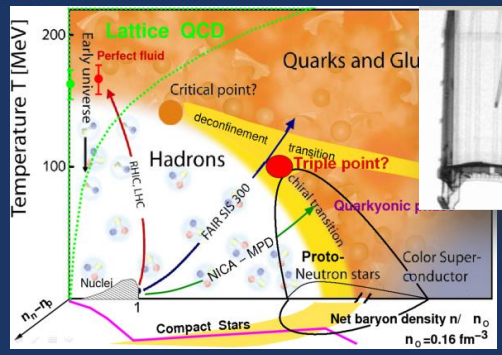
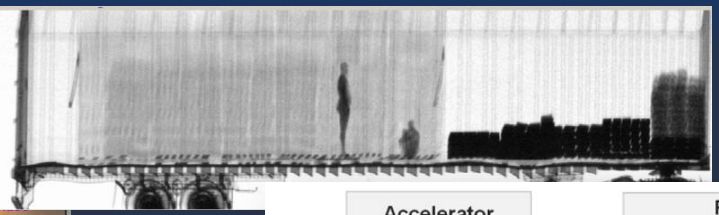
Discovery of the Higgs Boson – Step Closer to the Big Bang – what's next

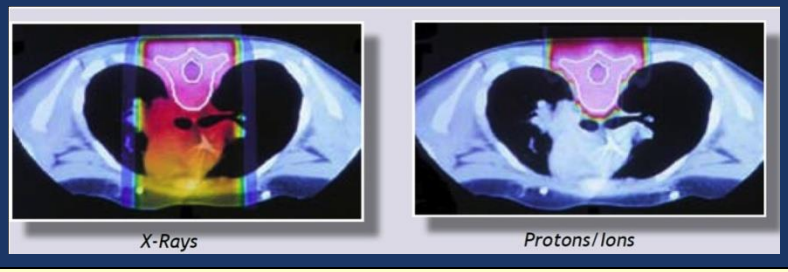
APPEAL-5
5th July 2014
organized by
CERN, JAI, STFC & University of Oxford

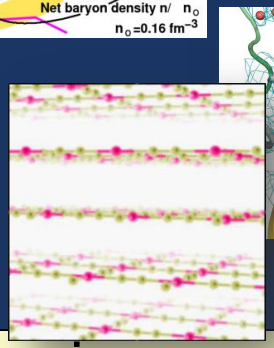
Accelerators for science and society

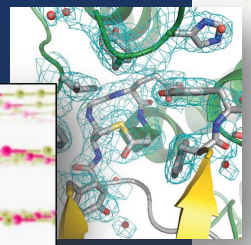


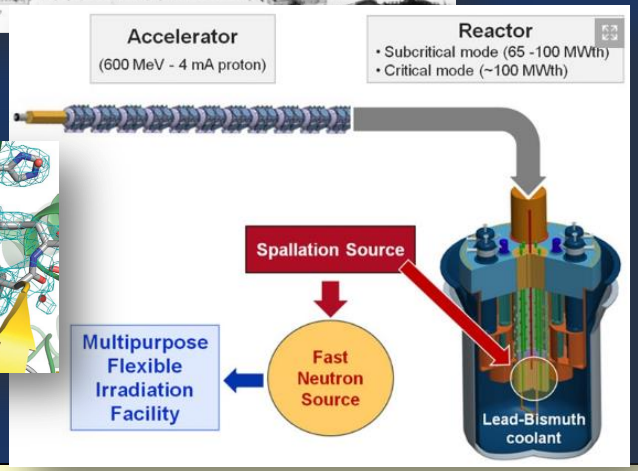












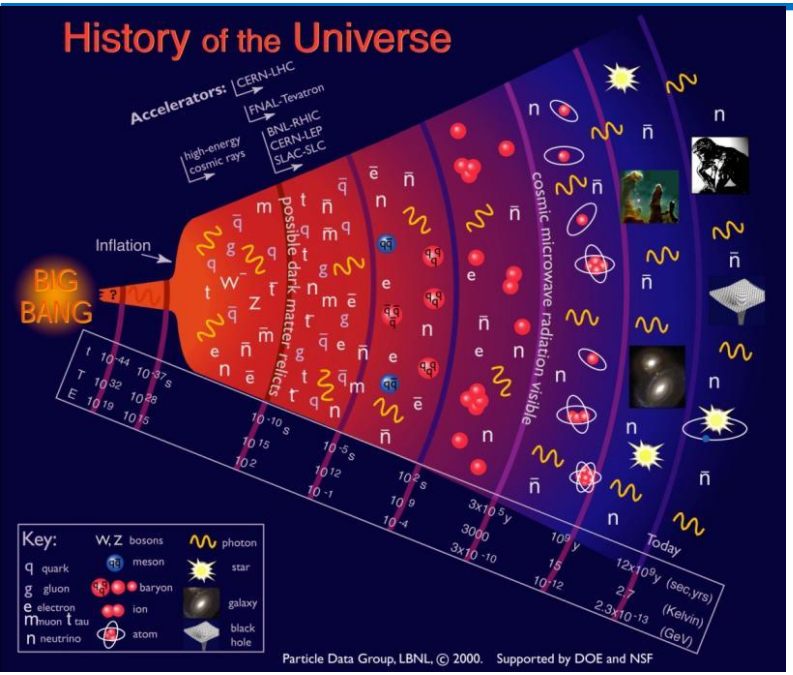
Accelerators: high energy physics, nuclear physics, healthcare, security, energy, life science, novel materials, industry, etc.

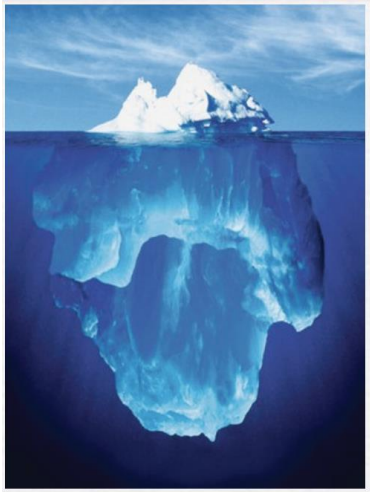
Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world

All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500B

The fraction of the Nobel prizes in Physics directly connected to accelerators is about 30%

Particle Accelerators – to study macro and micro world

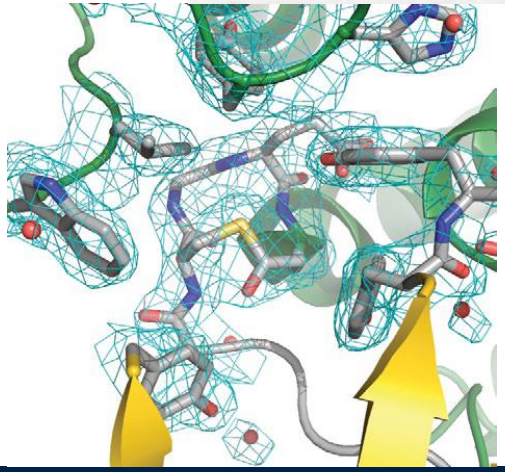


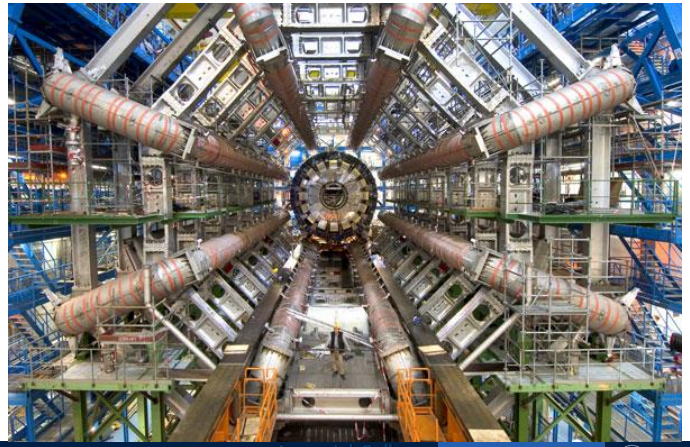


Known Matter

Unknown Matter

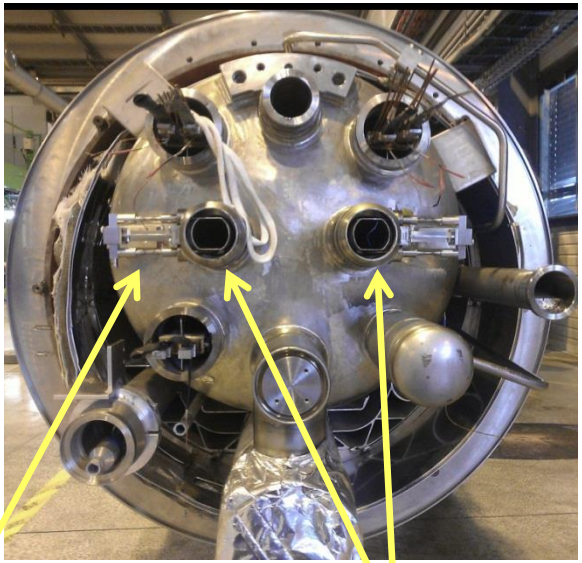
DARK MATTER & DARK ENERGY

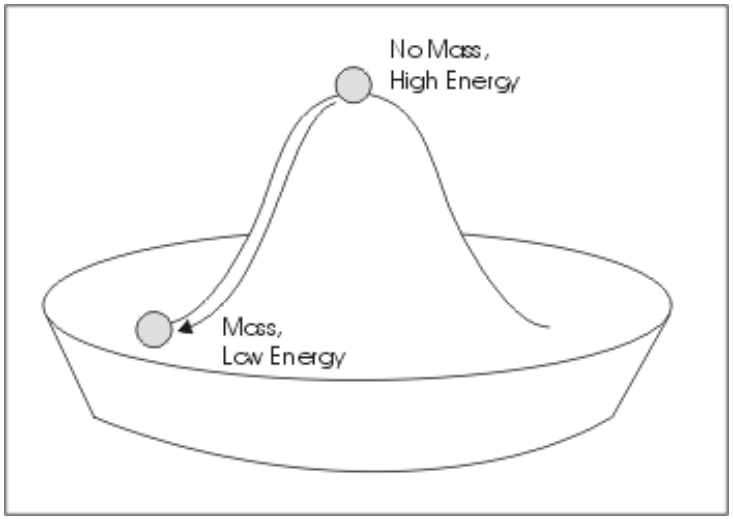




Large Hadron Collider

Peter Higgs and Francois Englert, Nobel prize 2013

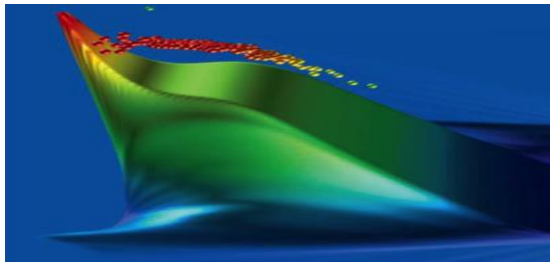




Accelerator science is attracting because…

- **Whether you are more inclined towards theory, or hardware development, or simulations, there are amazingly interesting tasks**

$$E_{x,y}^{1\to 2\to obs.plane} = E_{x,y}^{1} = \frac{1}{4\pi^2}\frac{iek}{\pi\gamma}\frac{e^{ikd}}{d}\frac{e^{ika}}{a}\iint_{x_2,y_2}\iint_{x_1,y_1}\begin{pmatrix}\dfrac{x_1}{\sqrt{x_1^2+y_1^2}}\\ \dfrac{y_1}{\sqrt{x_1^2+y_1^2}}\end{pmatrix}\times$$
$$K_1\left(\frac{k}{\gamma}\sqrt{x_1^2+y_1^2}\right)\exp\left[\frac{i\pi}{\lambda d}(x_1-x_2)^2+\frac{i\pi}{\lambda a}(x_2-\xi)^2\right]\times$$
$$\exp\left[\frac{i\pi}{\lambda d}(y_1-y_2)^2+\frac{i\pi}{\lambda a}(y_2-\eta)^2\right]dx_1dy_1dx_2dy_2.$$



- **Knowledge gained and developed has connections and applicable to surprisingly remote disciplines**

From stock market predictions

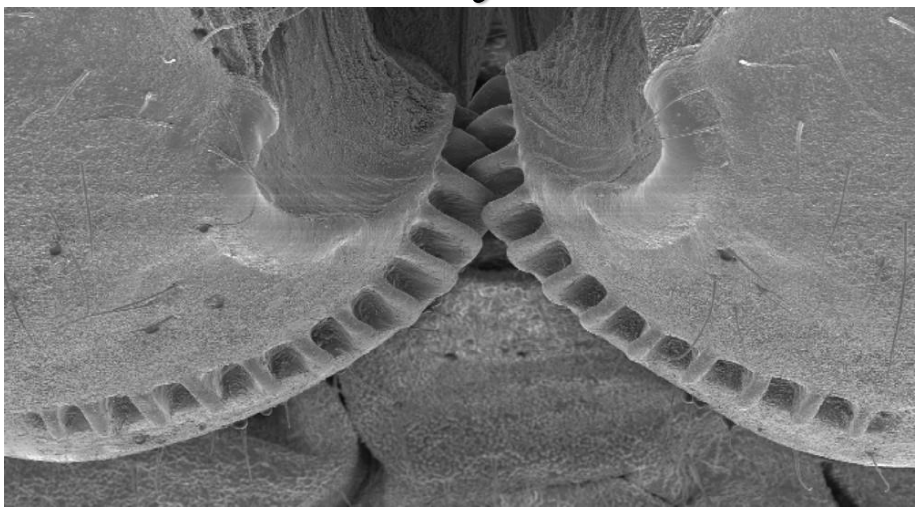
to

Planetary motions

Accelerator science and inventions…

- **Accelerator science demonstrate reach history of inventions, often inspired by the nature itself**

Gears invented by humans?

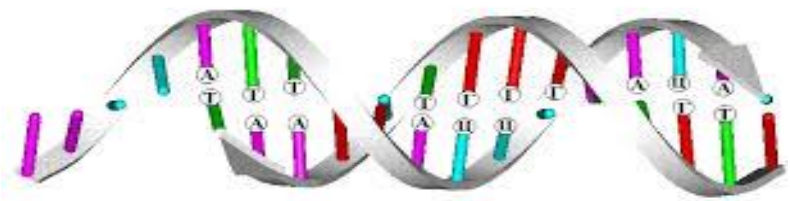


Insects are using gears for millions of years!

Interacting Gears Synchronize Propulsive Leg Movements in a Jumping Insect, Science, 13 Sep 2013, M.Burrows, G.Sutton

Muon Collider cooling channel

DNA



…was probably inspired by DNA shape

Accelerator science and inventions…

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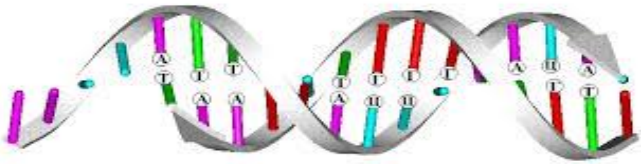
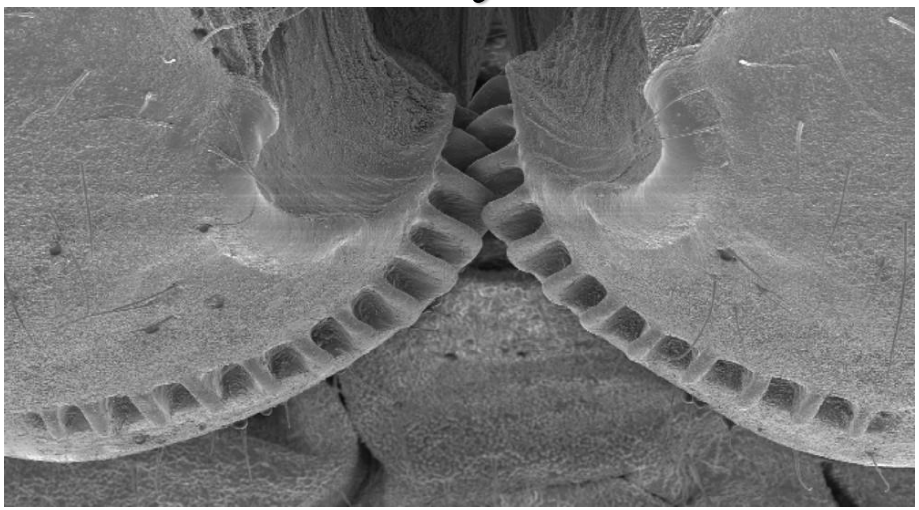
DNA



Gears invented by humans?



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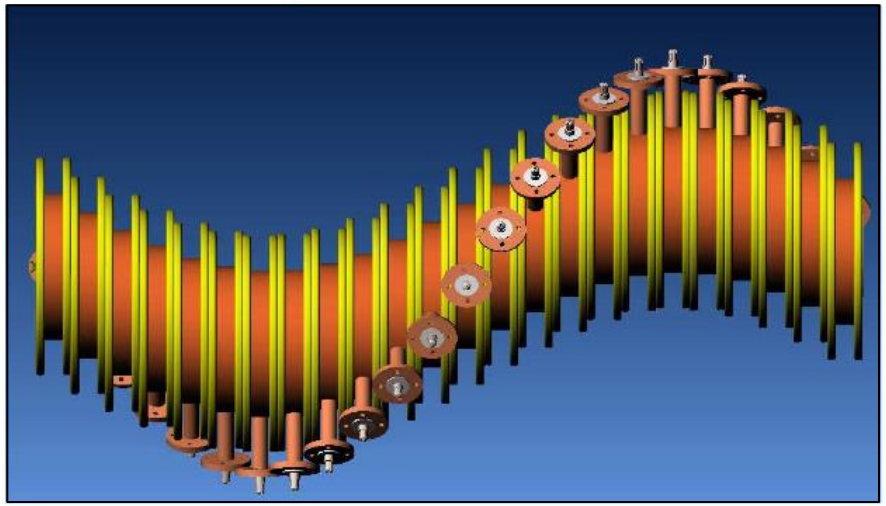
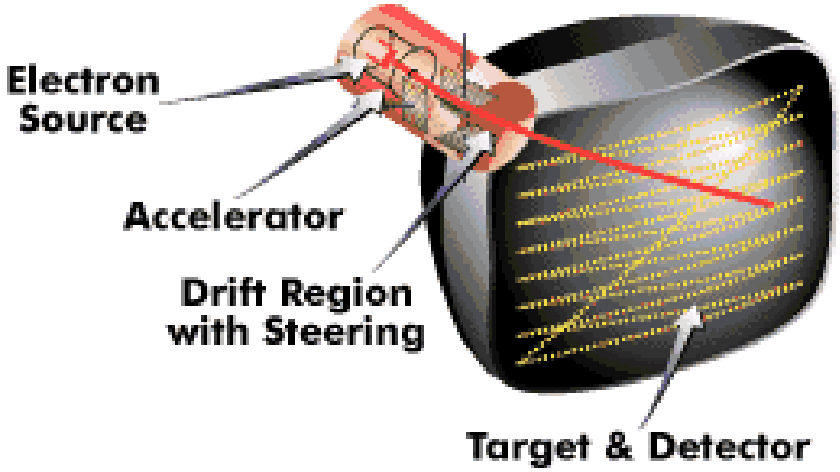
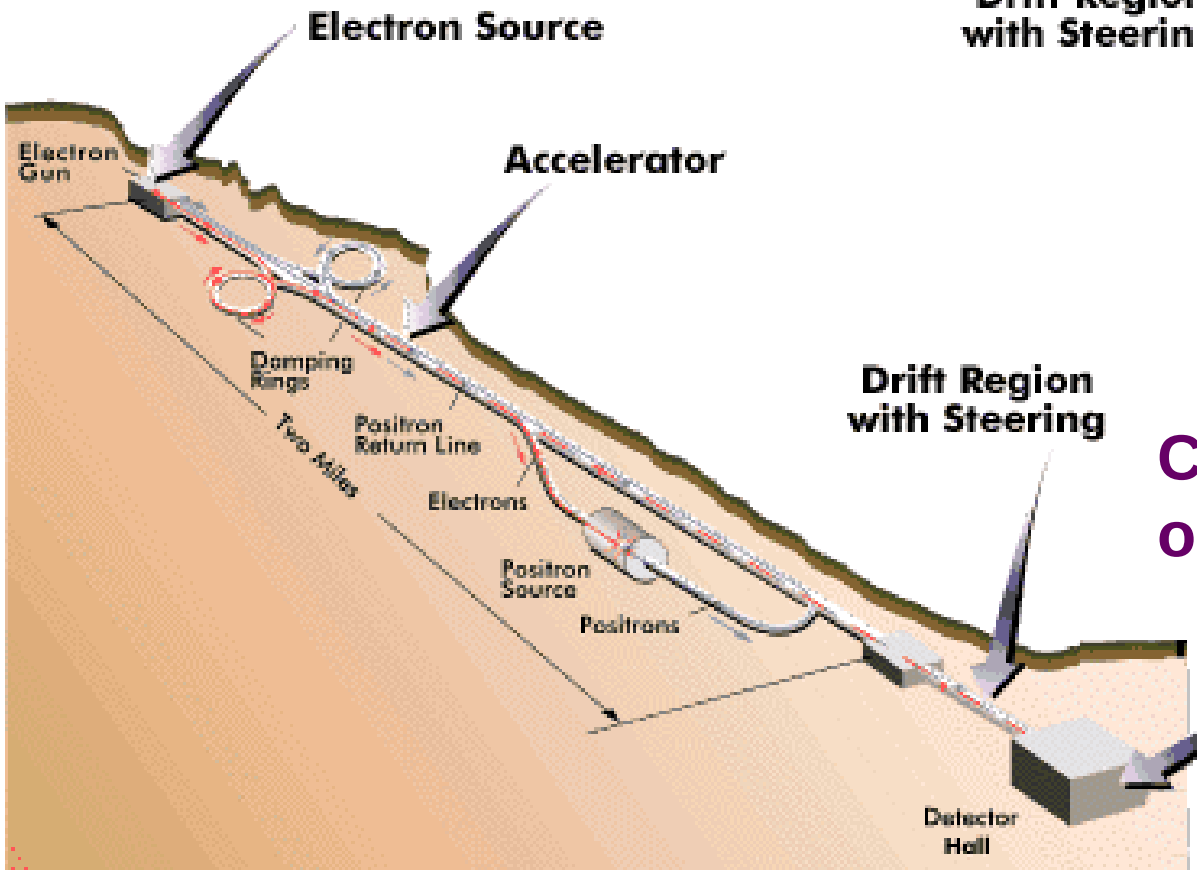


Integrated Helical Solenoid & RF cavities

Accelerators – similarities in small & large

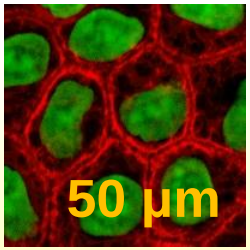
Internal workings of a TV or monitor





Cutaway view of the Linac

The structure of matter…



Extra magnification?

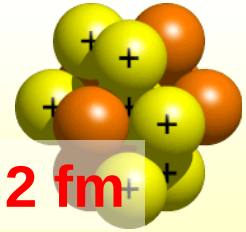
CELLS
Twenty per mm

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

Key Equation

$$\lambda = h/p$$

Momentum

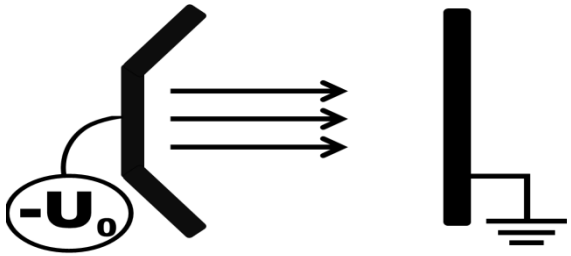
Planck Constant

De Broglie wavelength

See small? Large momentum

Acceleration of what and how

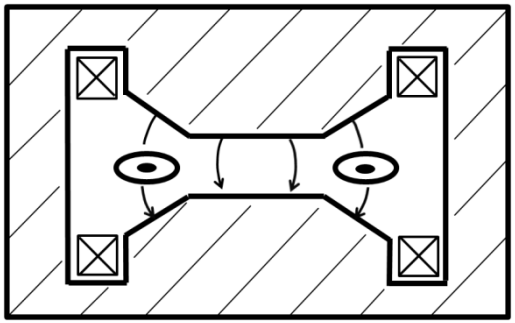
Beam of charged particles



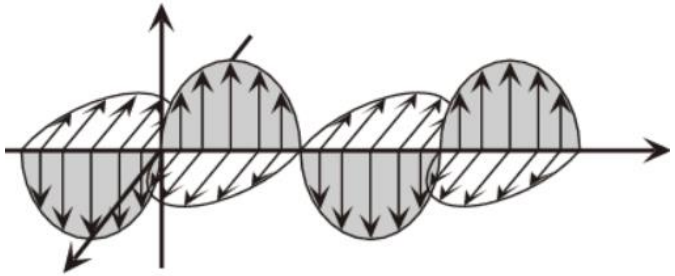
Electrostatic acceleration

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\int \vec{B} \cdot d\vec{S}$$

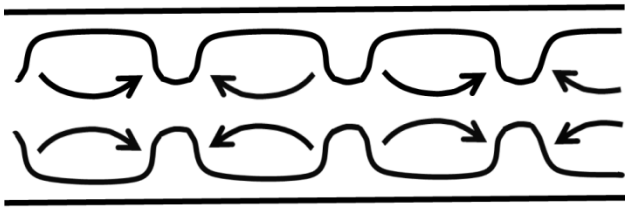
=>



Changing B => Curl E



=>

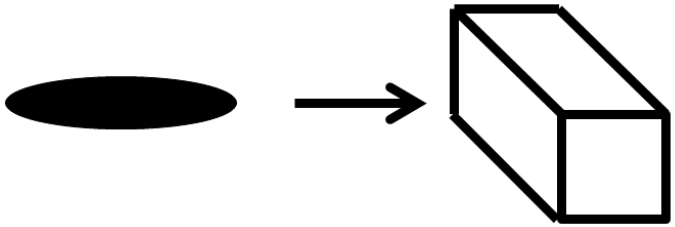


EM wave in space (cannot accelerate)

Accelerate with EM wave in structures

Why accelerate => uses of the beam

Beam

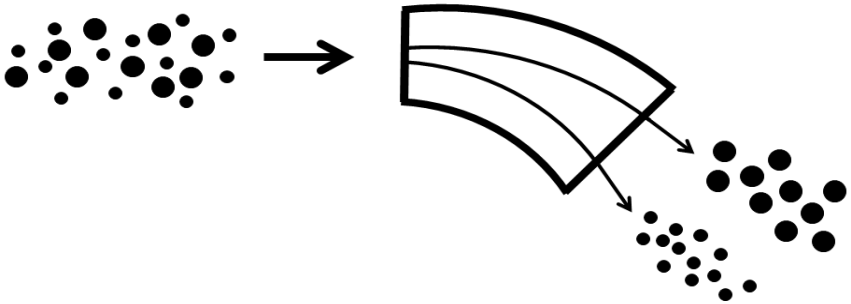


Its impact on a target

Beam

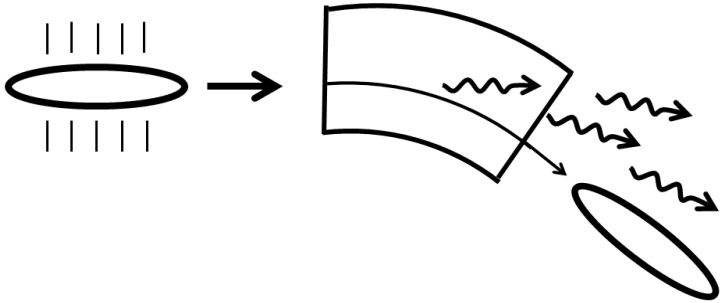
Collision with another beam

Beam



Characterisation of the beam

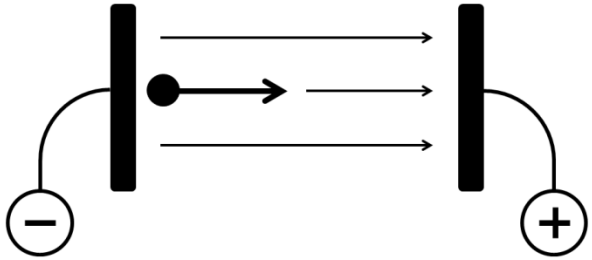
Beam



Generation of radiation

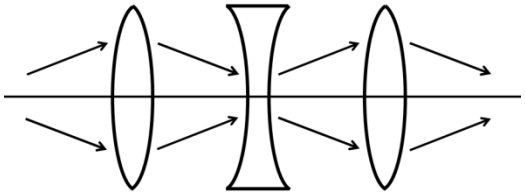
Uses => actions and characteristics

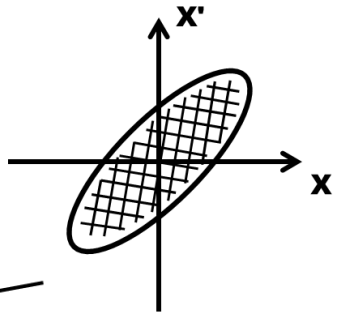
Acceleration



- Energy $E = \gamma mc^2$
- Rate of acceleration

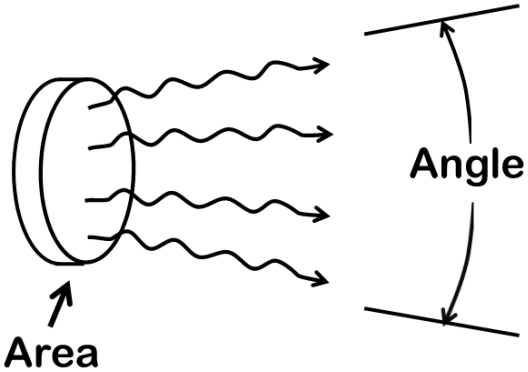
- Focusing
- Cooling





Sizes;
Phase-space volume - emittance ε (area in x-x' plane) – units m*rad
$\gamma\varepsilon$ is conserved => need of cooling

Generation of radiation

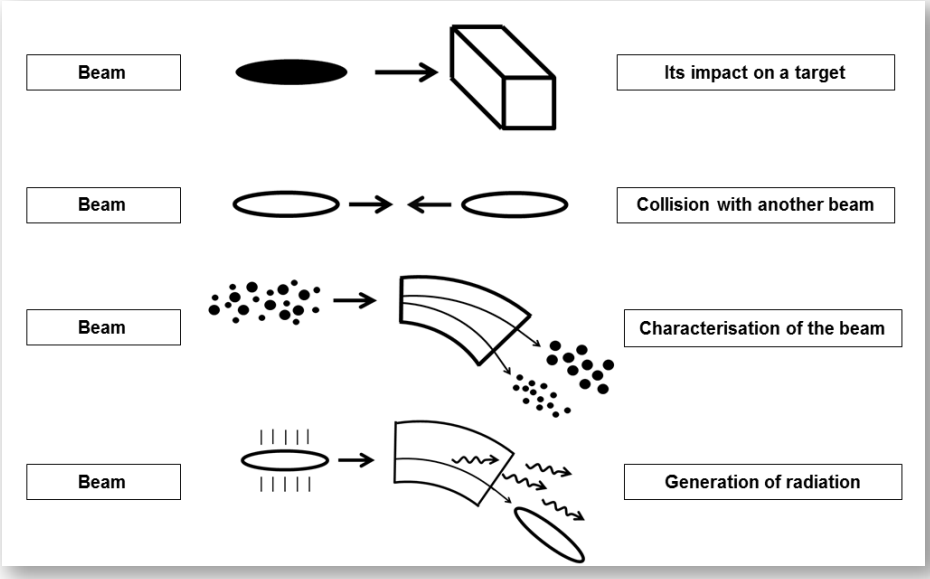


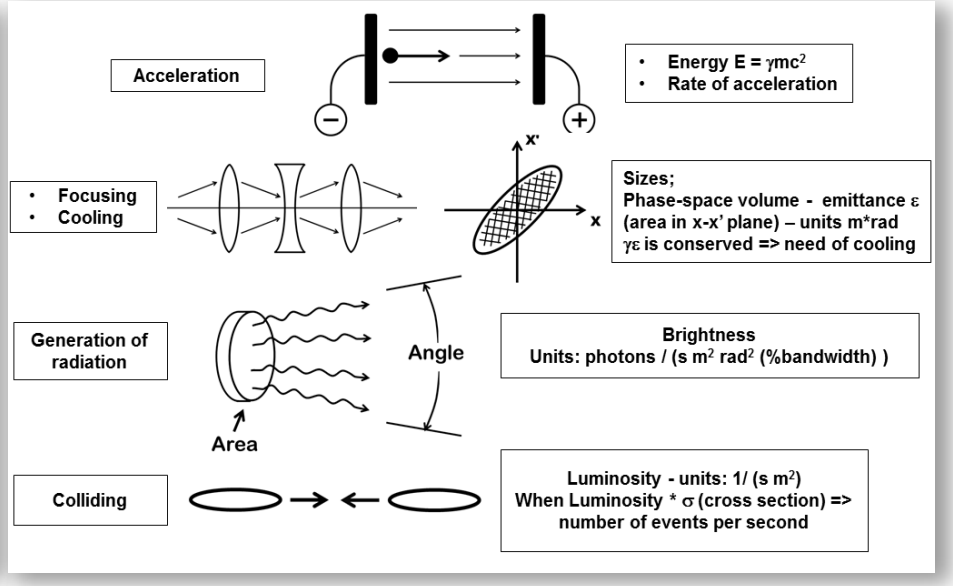
Brightness
Units: photons / (s m^2 rad^2 (%bandwidth))

Colliding

Luminosity - units: 1/ (s m^2)
When Luminosity * σ (cross section) => number of events per second

Uses & actions => evolution of accelerators

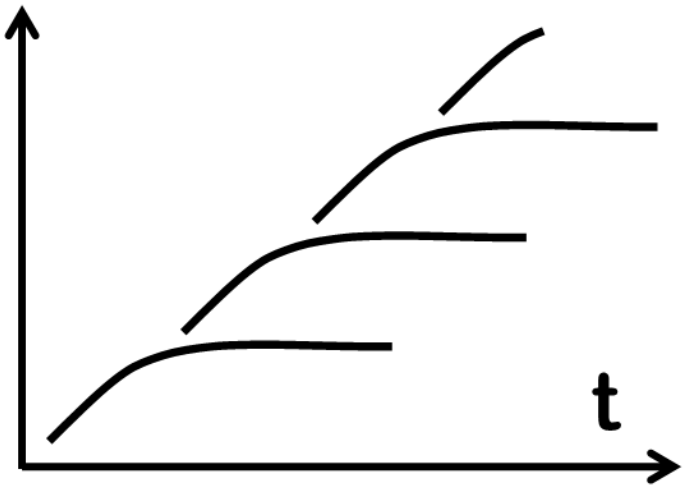


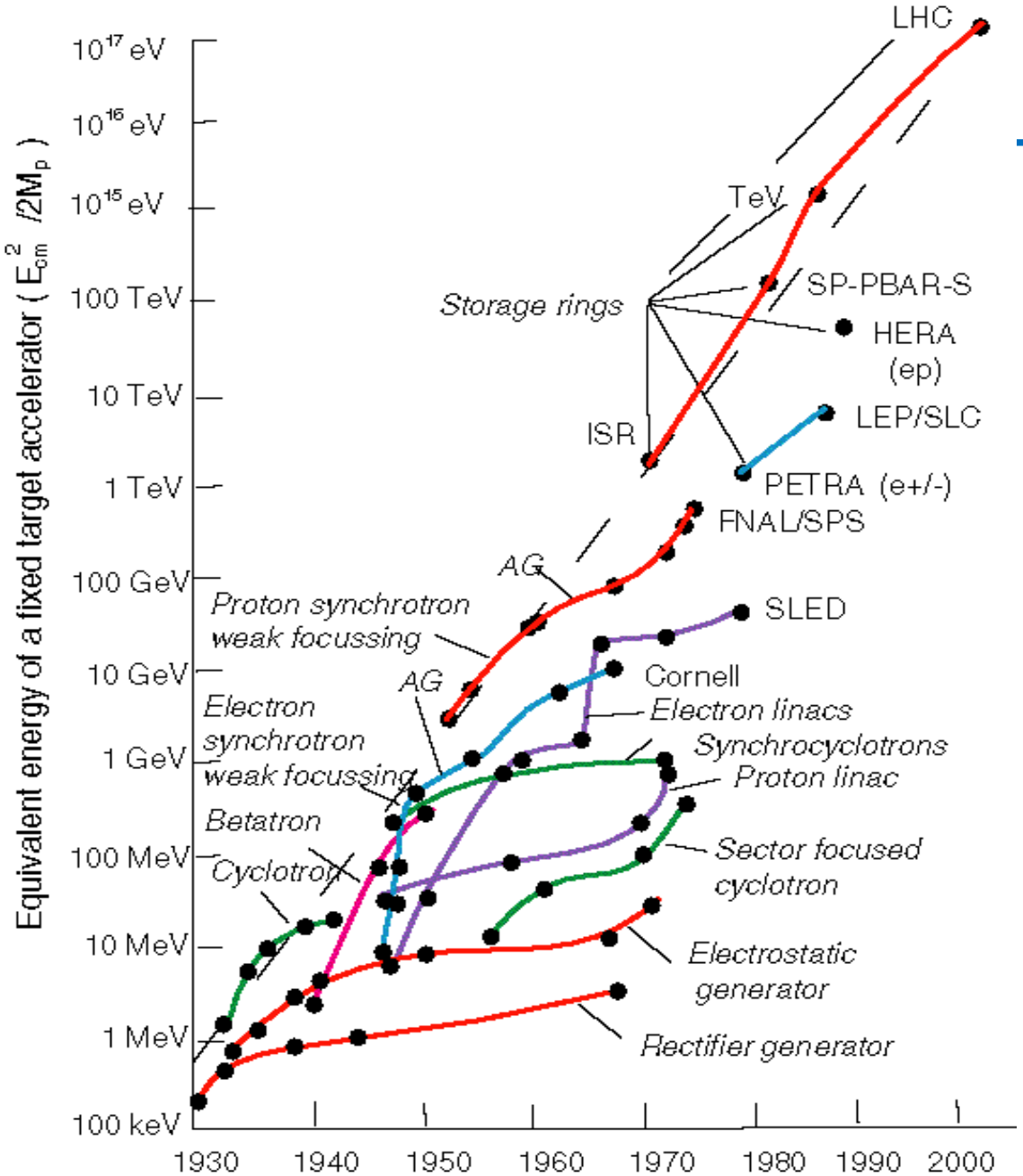


- **Increase of energy, mastering of acceleration**
  - **…accelerated species**
- **Smaller sizes - mastering of focusing and cooling**
- **Higher brightness – mastering of radiation generation**
- **…Luminosity**
- **…Applications**

"Livingston plot"

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

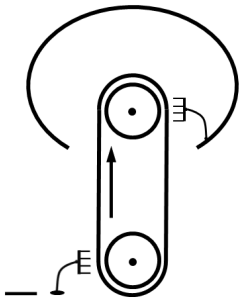




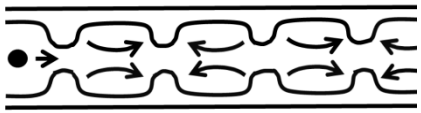
Selected discoveries & invention

- 1900 to 1925 radioactive source experiments à la Rutherford -> request for higher energy beams;
- 1928 to 1932 electrostatic acceleration ->
  - Cockcroft & Walton -> voltage multiplication using diodes and oscillating voltage (700 kV);
  - Van der Graaf -> voltage charging through mechanical belt (1.2 MV);
- 1928 resonant acceleration -> Ising establish the concept, Wideroe builds the first linac;
- 1929 cyclotron -> small prototype by Livingstone (PhD thesis), large scale by Lawrence;
- 1942 magnetic induction -> Kerst build the betatron;
- 1944 synchrotron -> MacMillan, Oliphant & Veksler invent RF phase stability (longitudinal focusing);
- 1946 proton linac -> Alvarez build an RF structure with drift tubes (progressive wave in 2π mode);
- 1950 strong focusing -> Christofilos patent alternate gradient concept (transverse strong focusing);
- 1951 tandem -> Alvarez upgrade the electrostatic acceleration concept and build a tandem;
- 1955 AGS -> Courant, Snider and Livingstone build the alternate gradient Cosmotron in Brookhaven;
- 1956 collective acceleration -> Veksler suggested collective acceleration of beams;
- 1956 collider -> Kerst discuss the concept of colliding beams;
- 1961 e^+e^- collider -> Touschek invent the concept of particle-antiparticle collider;
- 1967 electron cooling -> Budker proposes the e-cooling to increase the proton beam density;
- 1968 stochastic cooling -> Van der Meer proposes stochastic cooling to compress the phase space;
- 1970 RFQ -> Kapchinski & Telyakov build the radiofrequency quadrupole;
- 1971 FEL -> Madey developed a principle of a Free Electron Laser;
- 1979 plasma acceleration -> Tajima & Dawson proposes acceleration in plasma excited by laser;
- 1980 to now superconducting magnets -> developed in various labs to increase the beam energy;
- 1980 to now superconducting RF -> developed in various lab to increase the RF gradient;
- 1990 to now photon collider; crab waist collision; integrable optics… inventions continue…

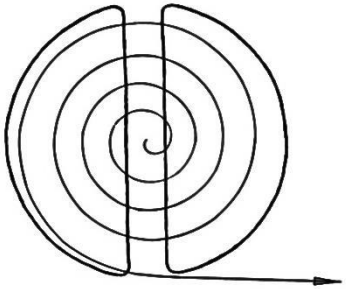
Selected inventions



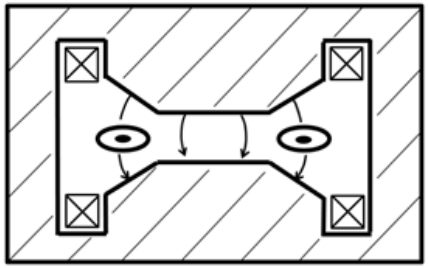
Electrostatic Acc.



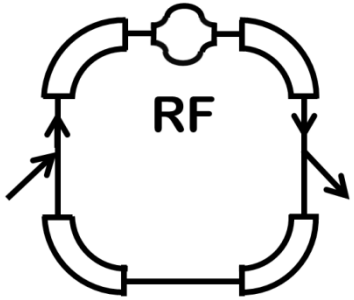
Resonant Linear Acc.



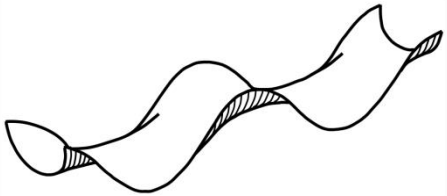
Cyclotron



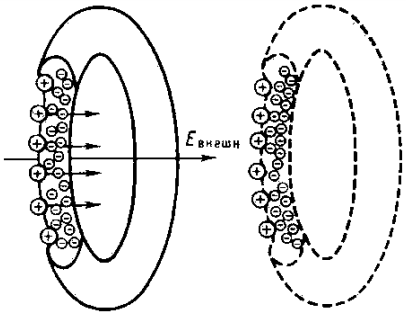
Betatron



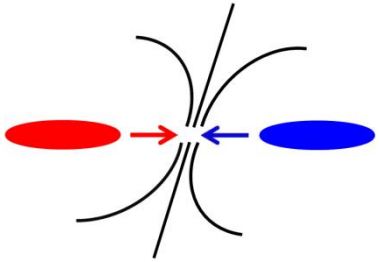
Synchrotron



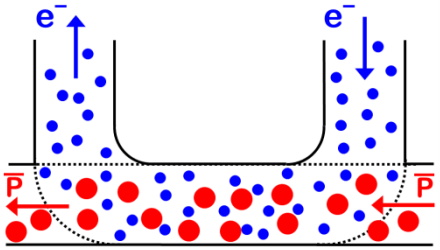
Strong focusing



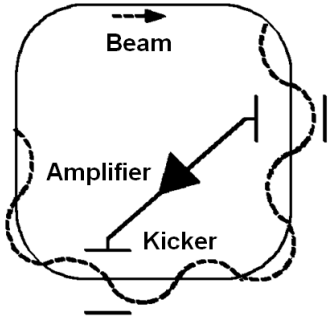
Collective acceleration



Colliders

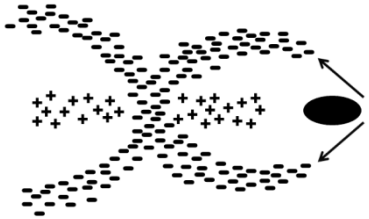


Electron cooling



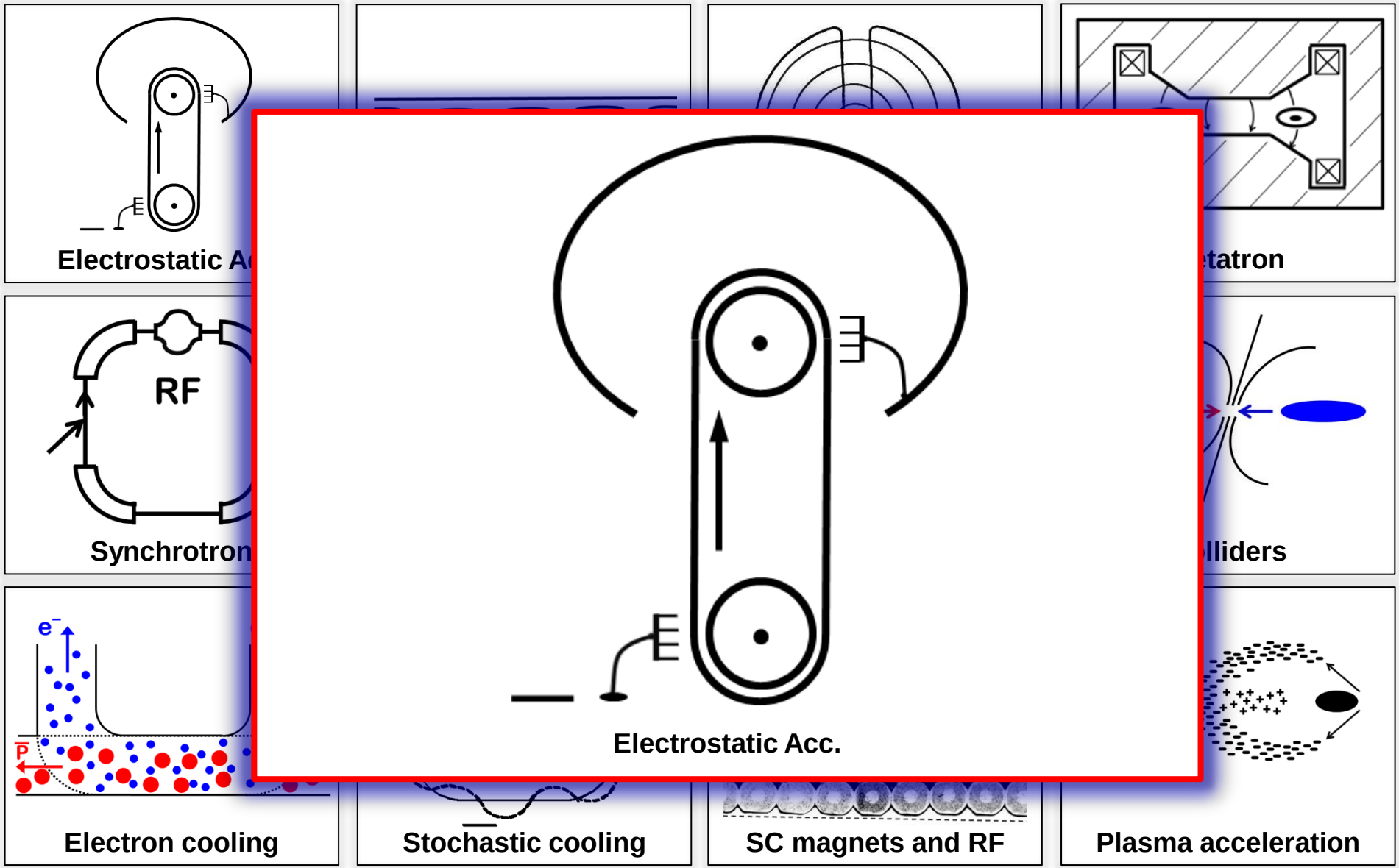
Stochastic cooling

SC magnets and RF



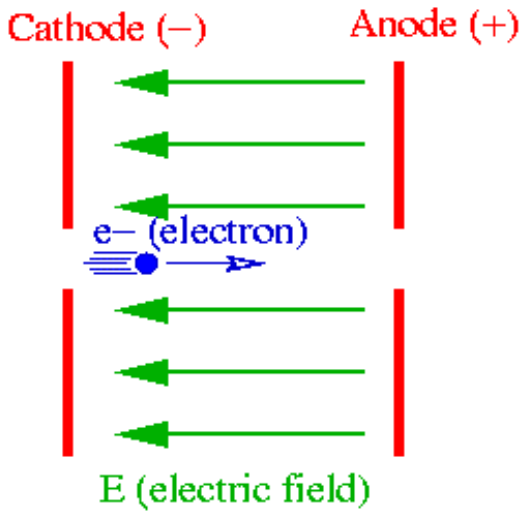
Plasma acceleration

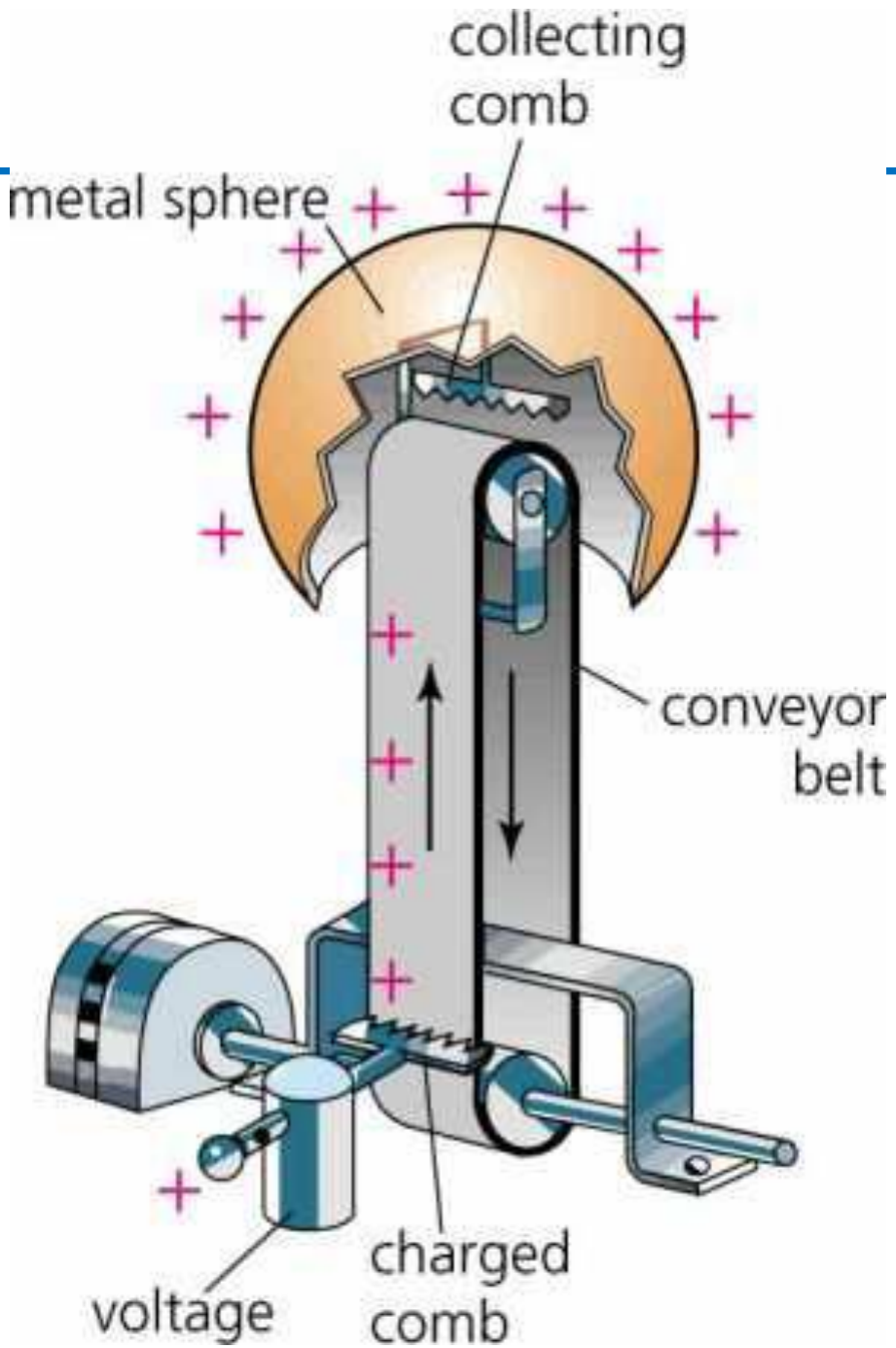
Selected inventions



Electrostatic accelerators

- **Example of electrostatic accelerators - "Van de Graaff"**

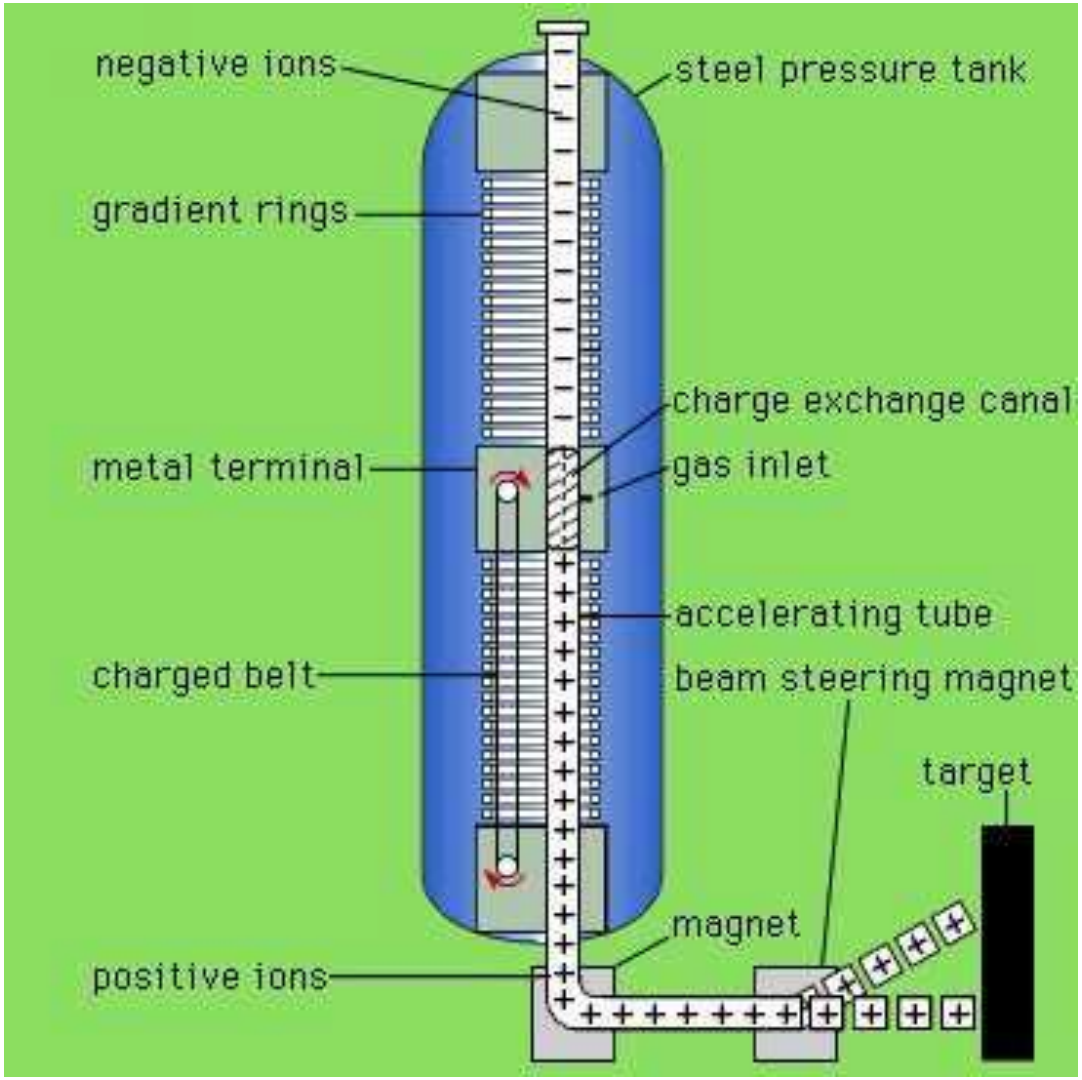




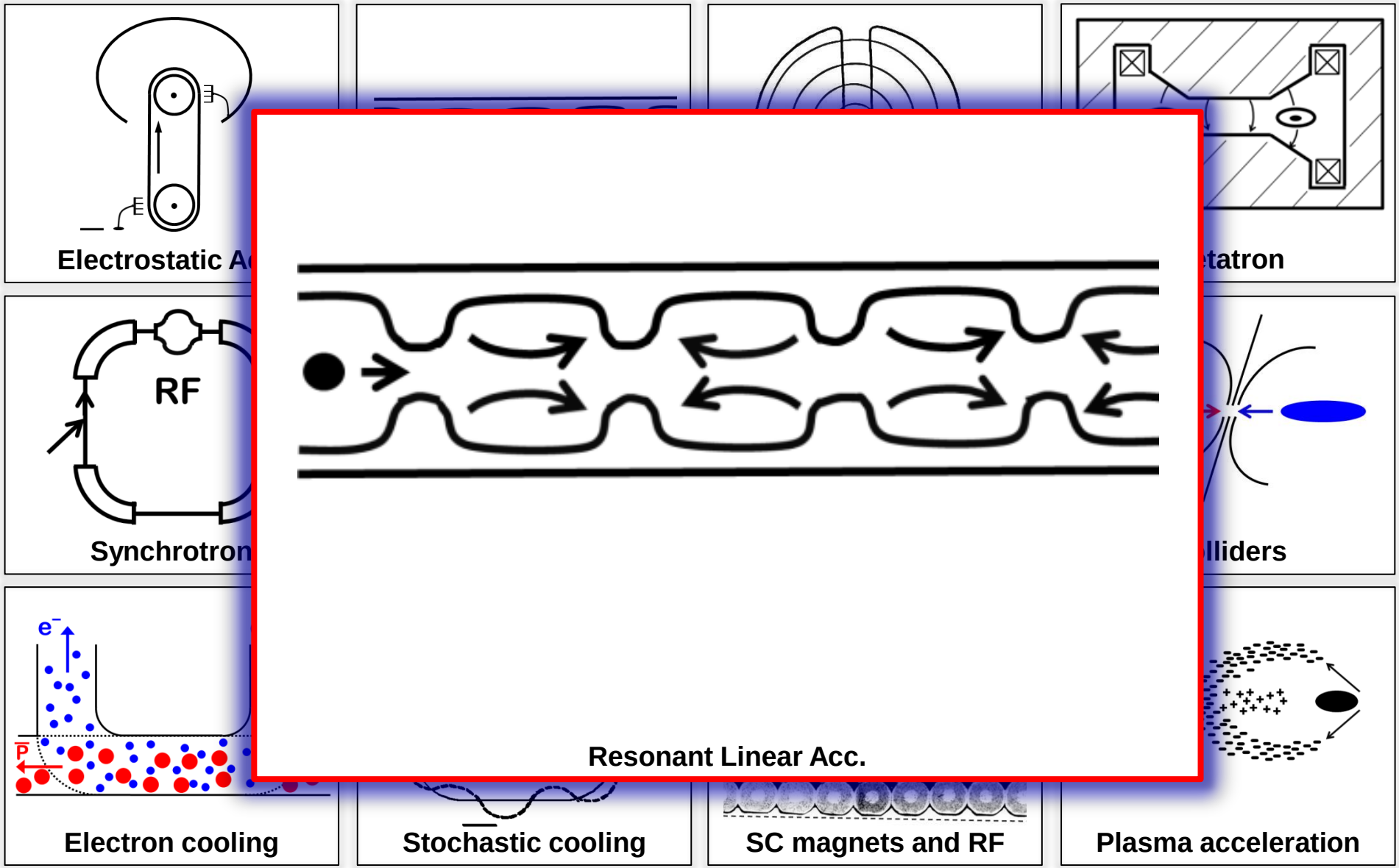
Electrostatic accelerators

- Example of electrostatic accelerators - “Van de Graaff”
- Tandem is a version with charge exchange in the middle

- With any electrostatic accelerators it is difficult to achieve energy higher than ~20MeV (e.g. due to practical limitations of the size of the vessels)

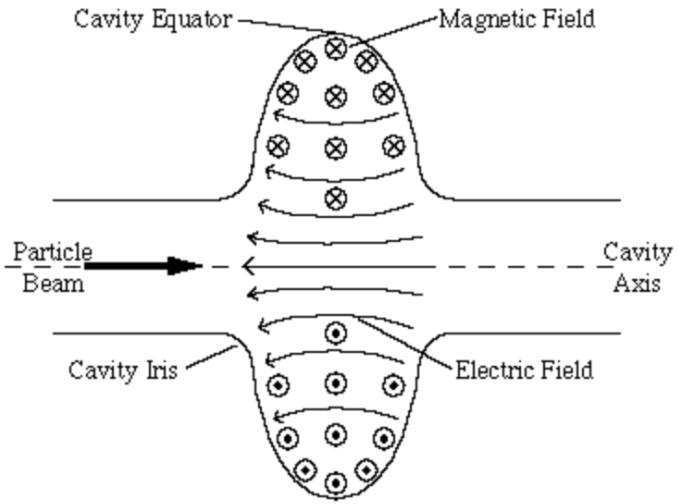


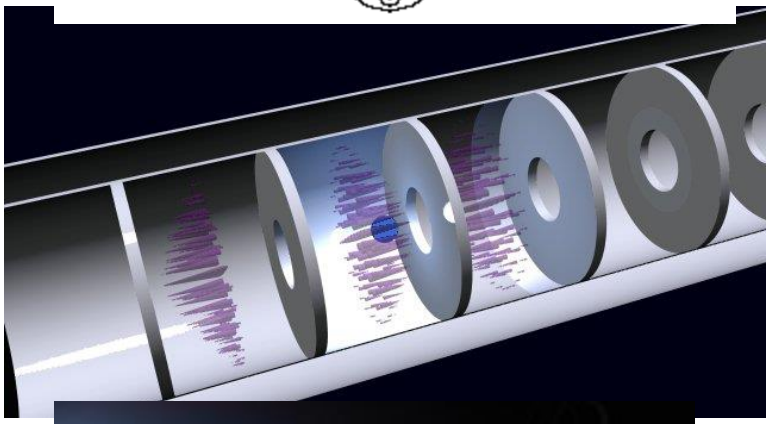
Selected inventions

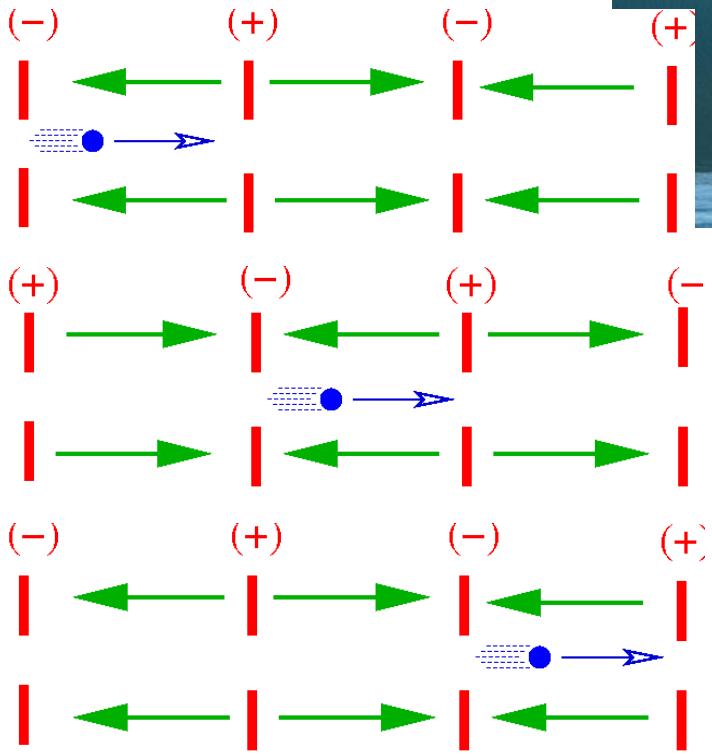


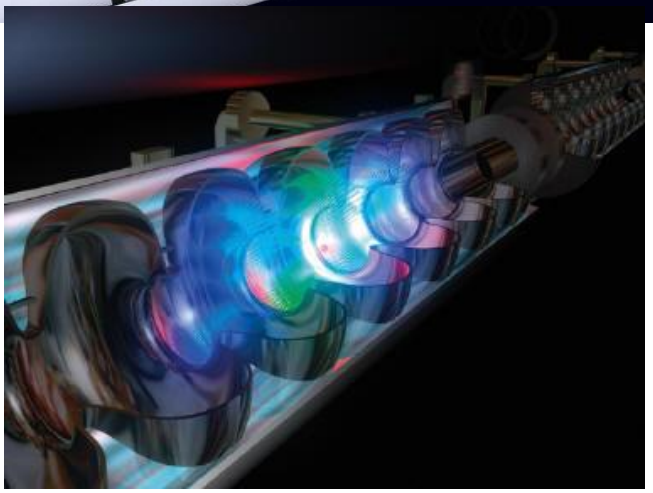
RF cavities

- ...are used in almost all modern accelerators...
- In RF cavity the particles “surf” on an electromagnetic wave that travels in the cavity

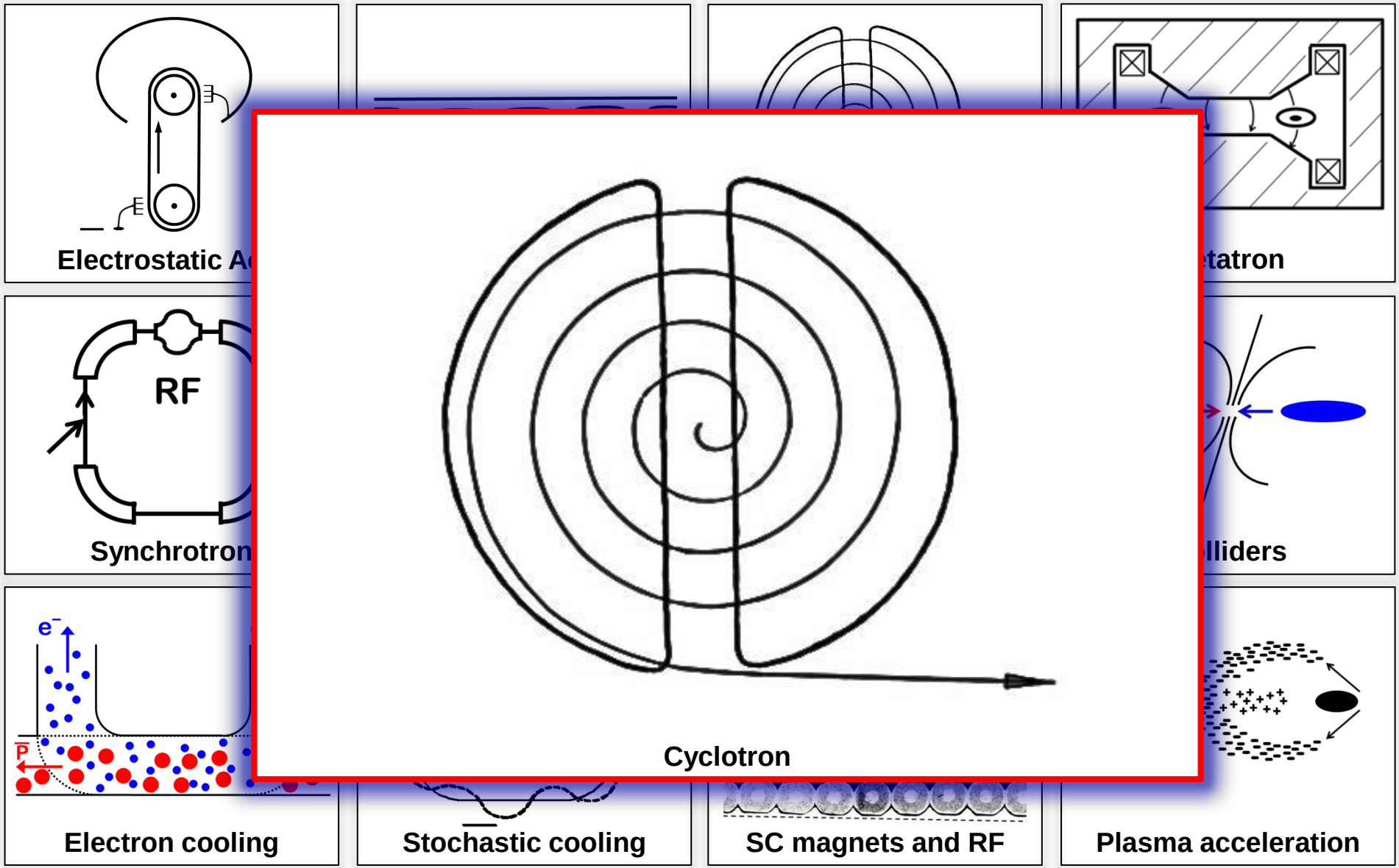






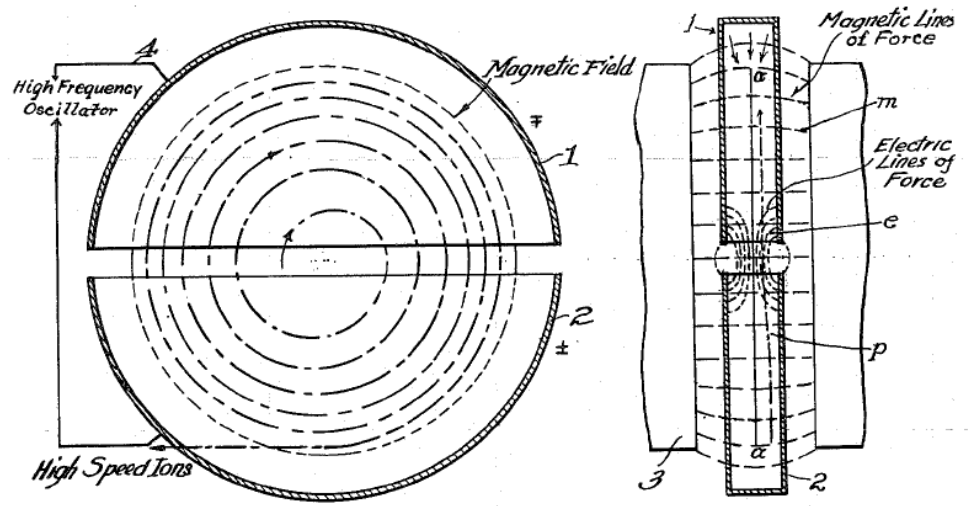


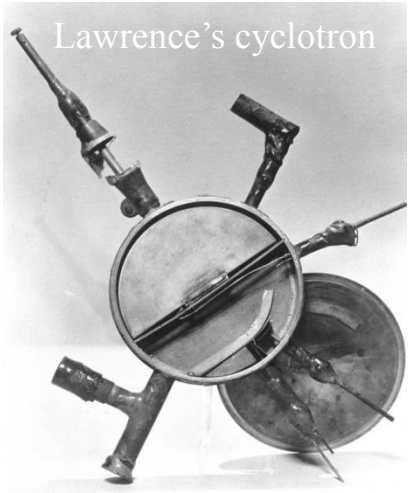
Selected inventions

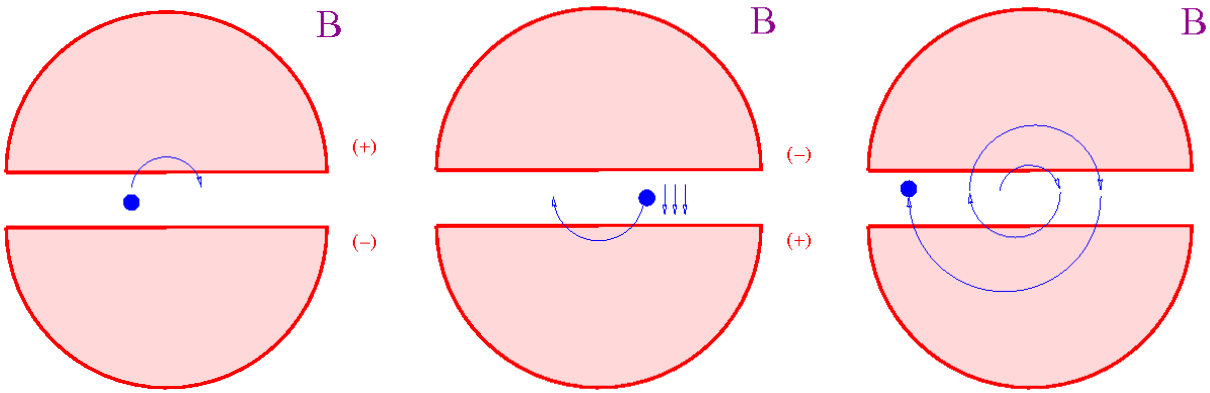


Cyclic accelerators

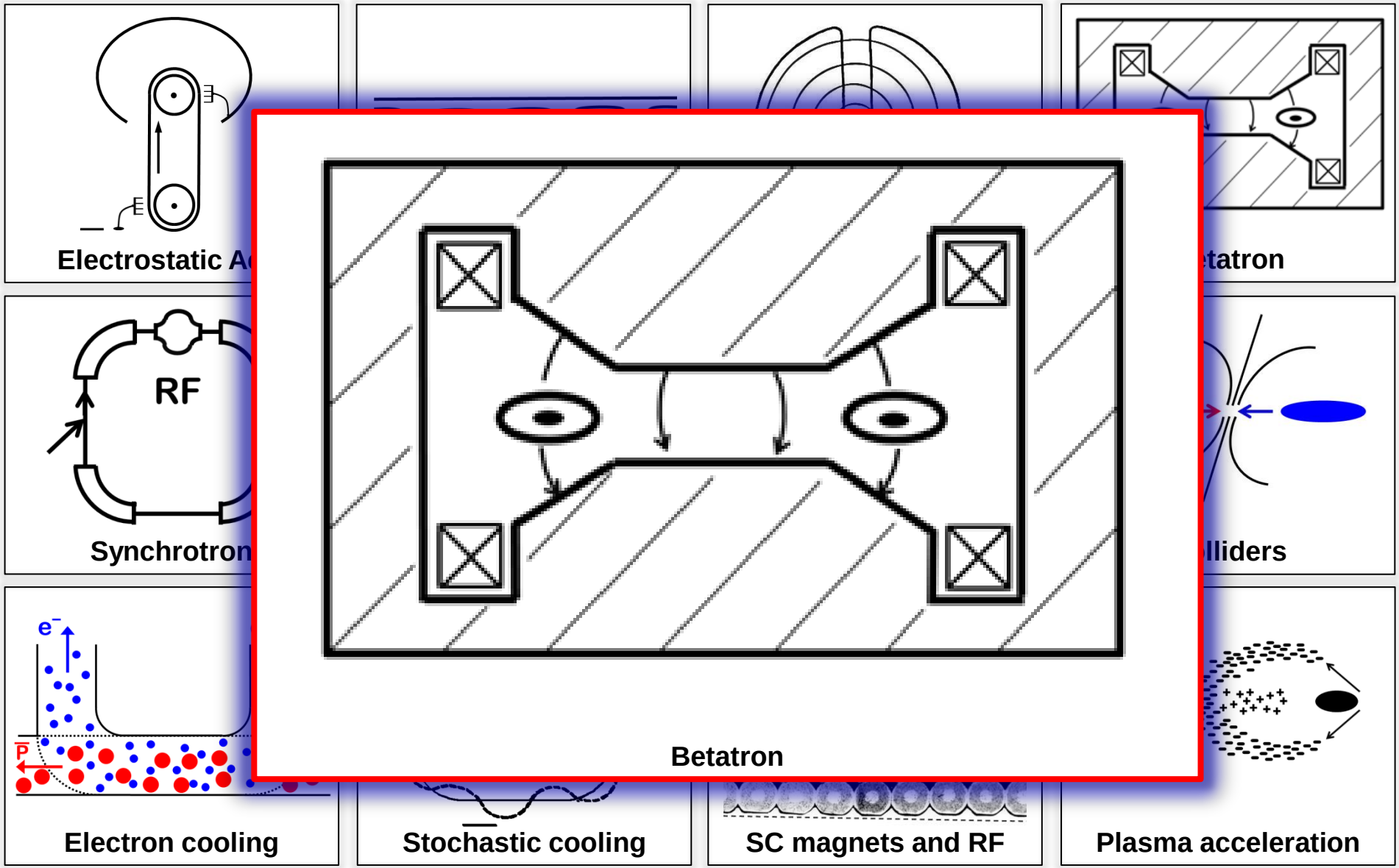
- **In 1931 Lawrence designed a "cyclotron", a circular device made of two electrodes placed in a magnetic field**
- **Cyclotrons can accelerate (e.g.) protons up to hundreds of MeV**



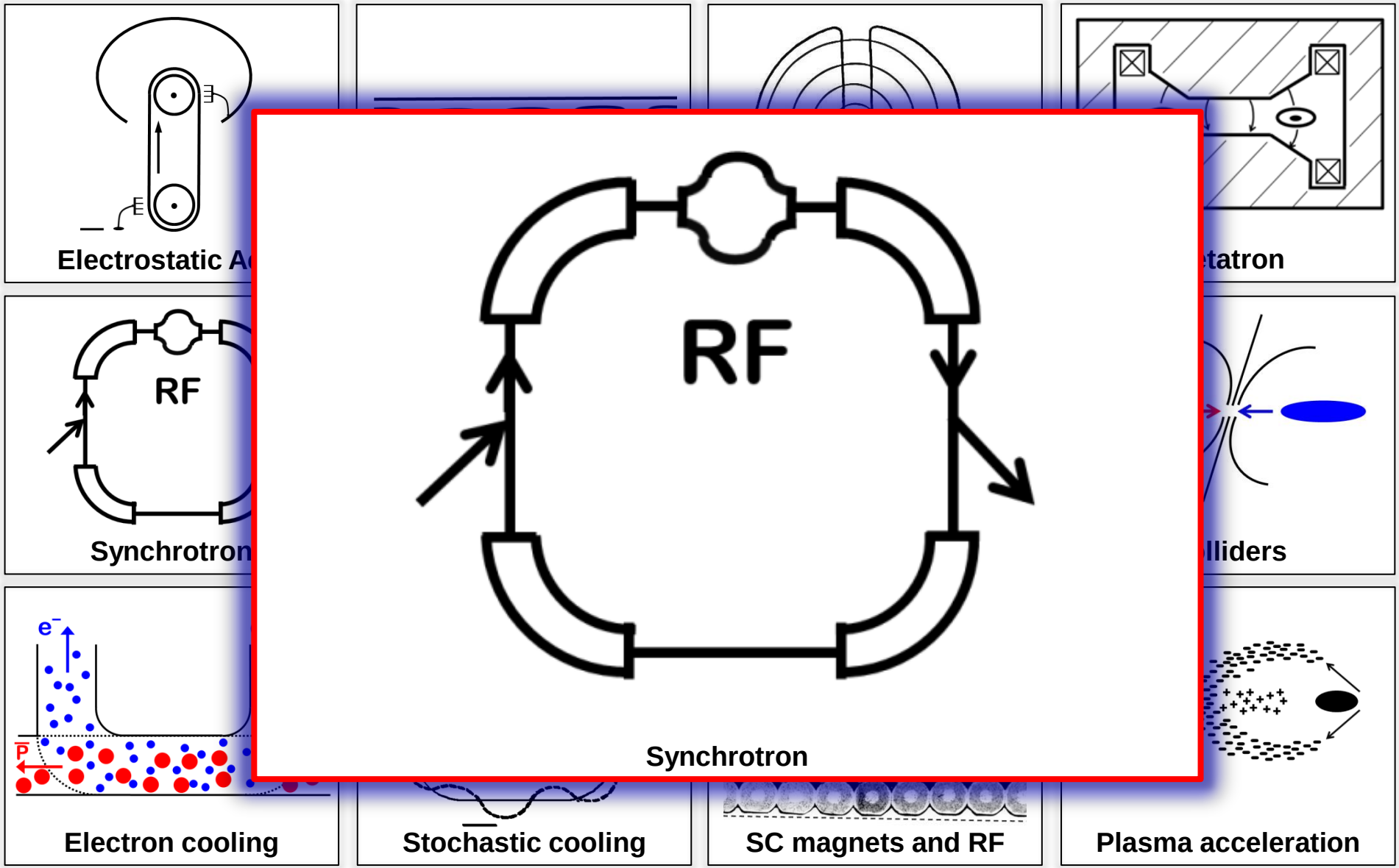




Selected inventions

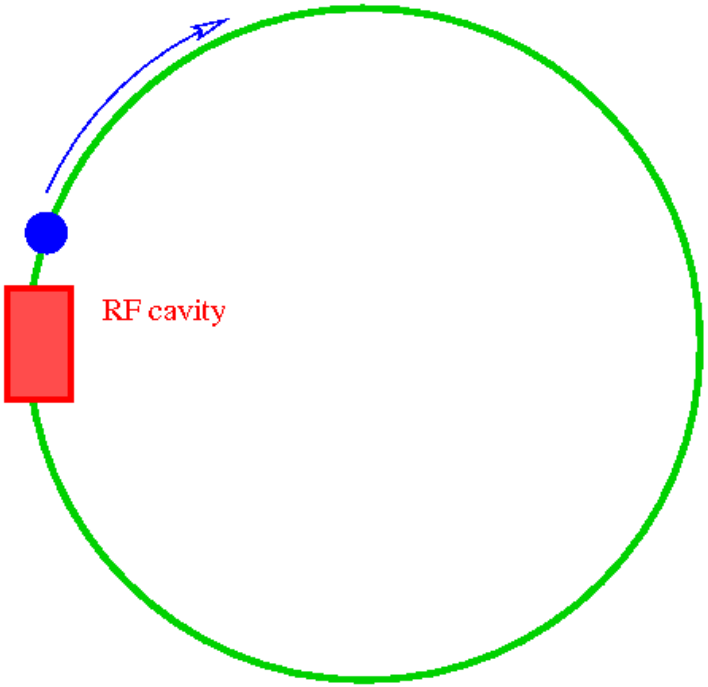


Selected inventions

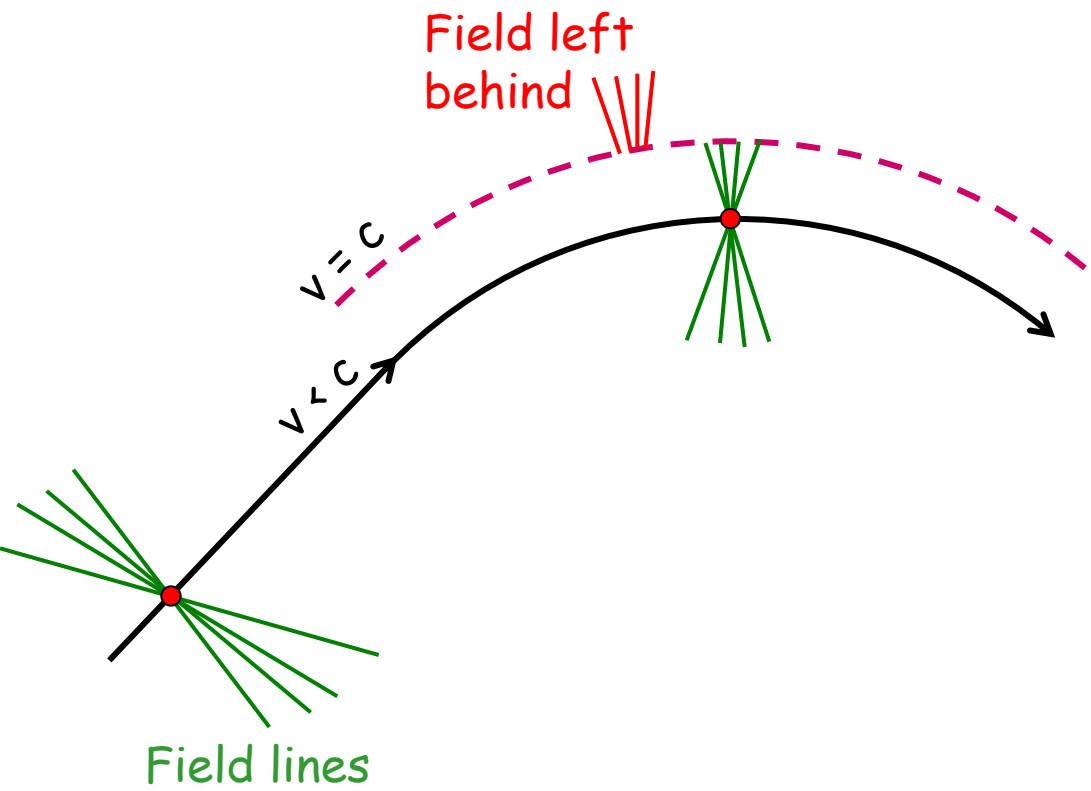


Synchrotrons

- Synchrotrons can accelerate to very high energy
- E.g., LHC is synchrotron
- Limitation of synchrotrons (especially for electrons) is due to "synchrotron radiation"



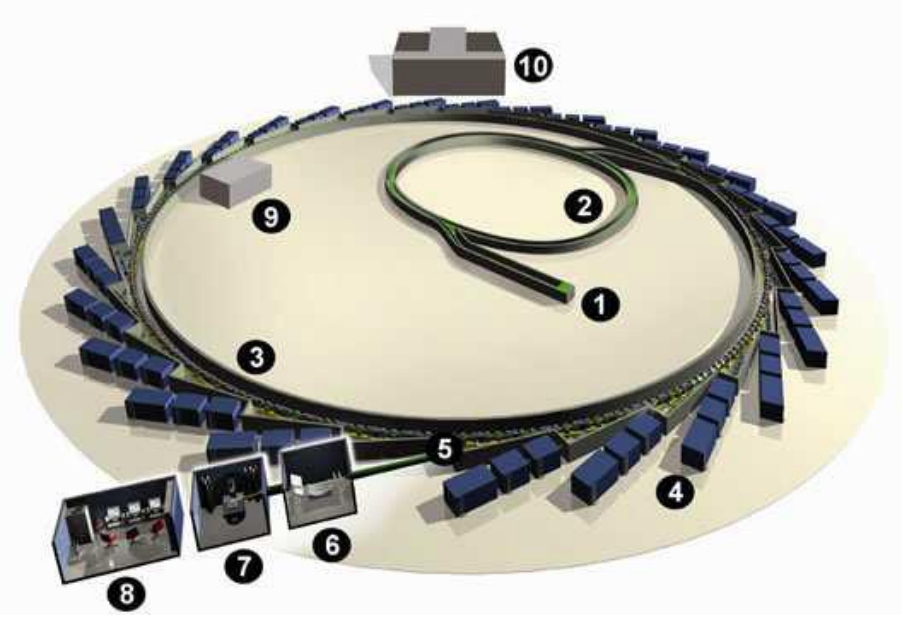
Synchrotron radiation

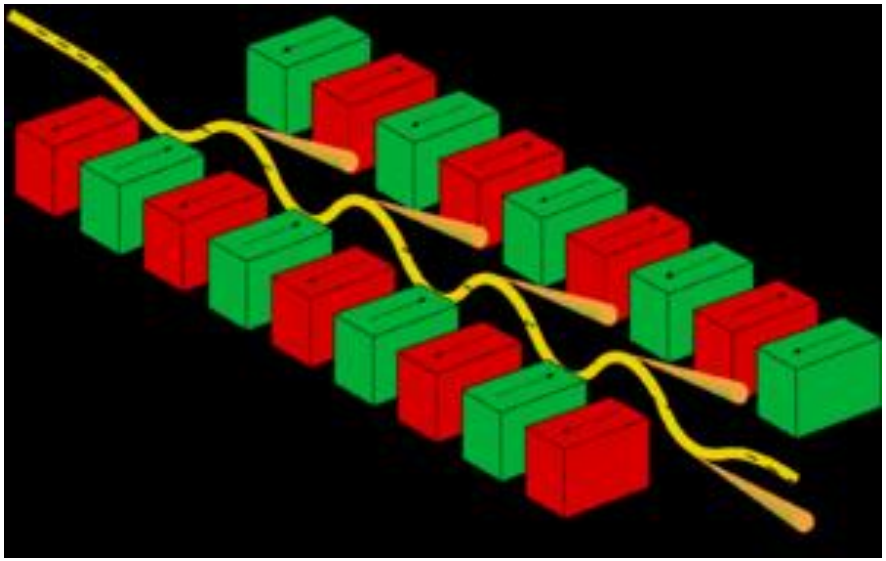


- **Caused by field "left behind" during motion on a curved trajectory**
- **Energy loss per meter is proportional to γ^4 and to $1/R^2$**
- **Can be both harmful and useful**

Good use of synchrotron radiation

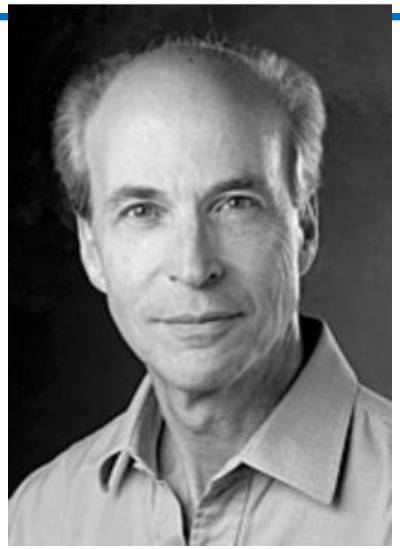
- Synchrotron radiation light sources exploit this feature to create scientific instruments
- Example – Diamond light source
- Special magnets (undulators) are inserted to further enhance the synchrotron radiation





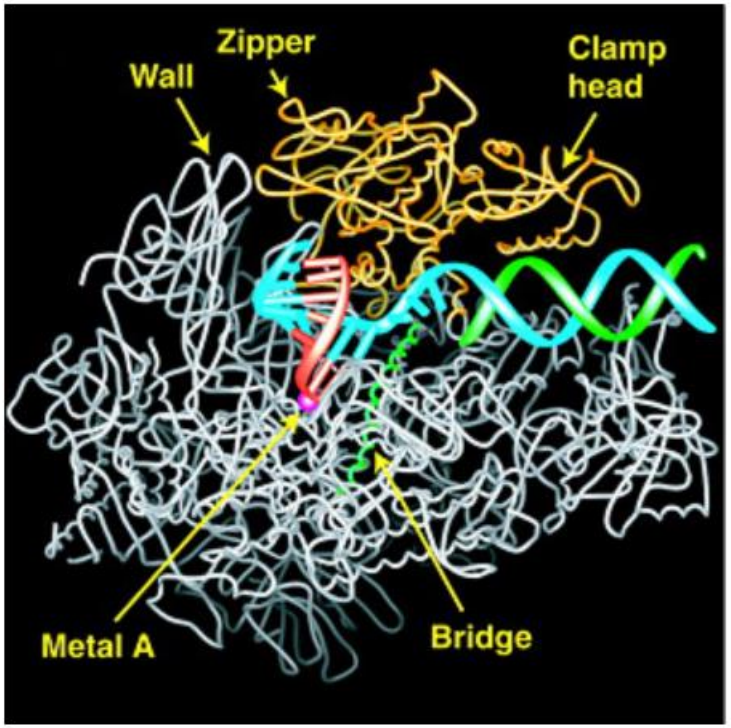
The Nobel Prize in Chemistry 2006

Roger D. Kornberg



Roger Kornberg's Nobel Prize-winning determination of the structure of RNA polymerase has been described as a "technical tour de force." The key to the visualization of this fundamental biological molecule in action was synchrotron radiation, supplied by the powerful X-ray crystallography instruments at the Stanford Synchrotron Radiation Laboratory.

Science



The transcription process visualized by Roger Kornberg and his colleagues in his X-ray crystallography studies published online April 19, 2001, in *Science*. The protein chain shown in grey is RNA polymerase, with the portion that clamps on the DNA shaded in yellow. The DNA helix being unwound and transcribed by RNA polymerase is shown in green and blue, and the growing RNA stand is shown in red.

24 Nobel Prizes in Physics that had direct contribution from accelerators (table as of 2010)

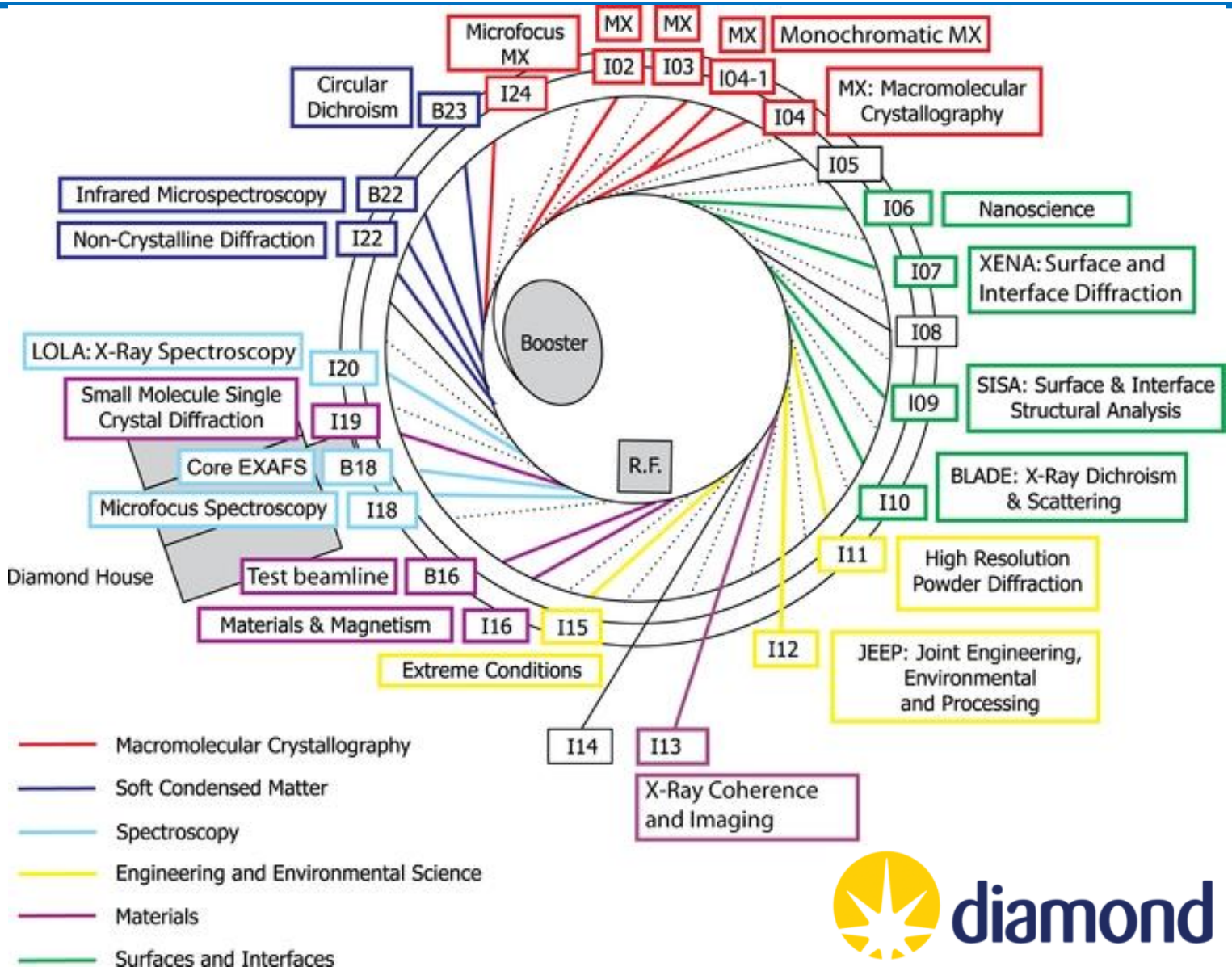
Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & published in the Physics in Perspective Journal, Dec 2010.

Diamond: synchrotron source of X-rays

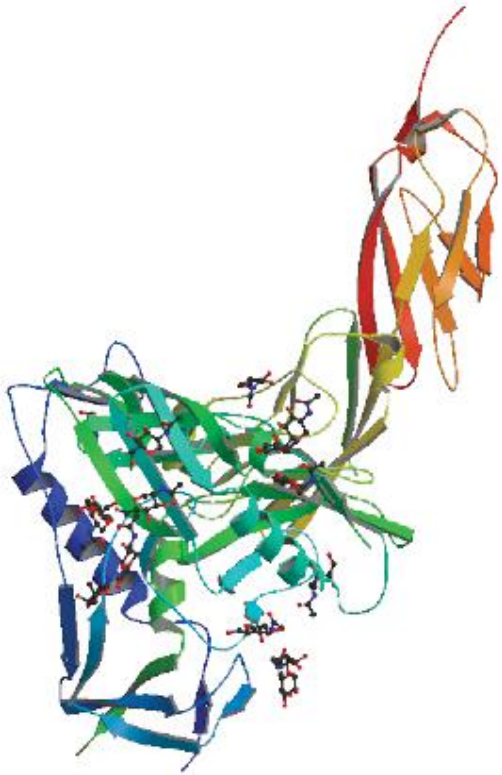
Diamond Light Source, Harwell Science and Innovation Campus, UK

Diamond beamlines

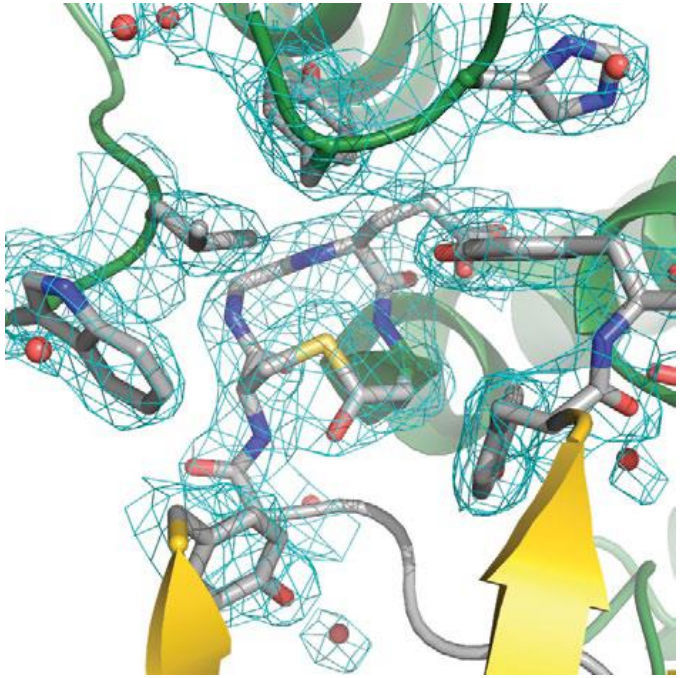


diamond

Protein structure revealed by light sources



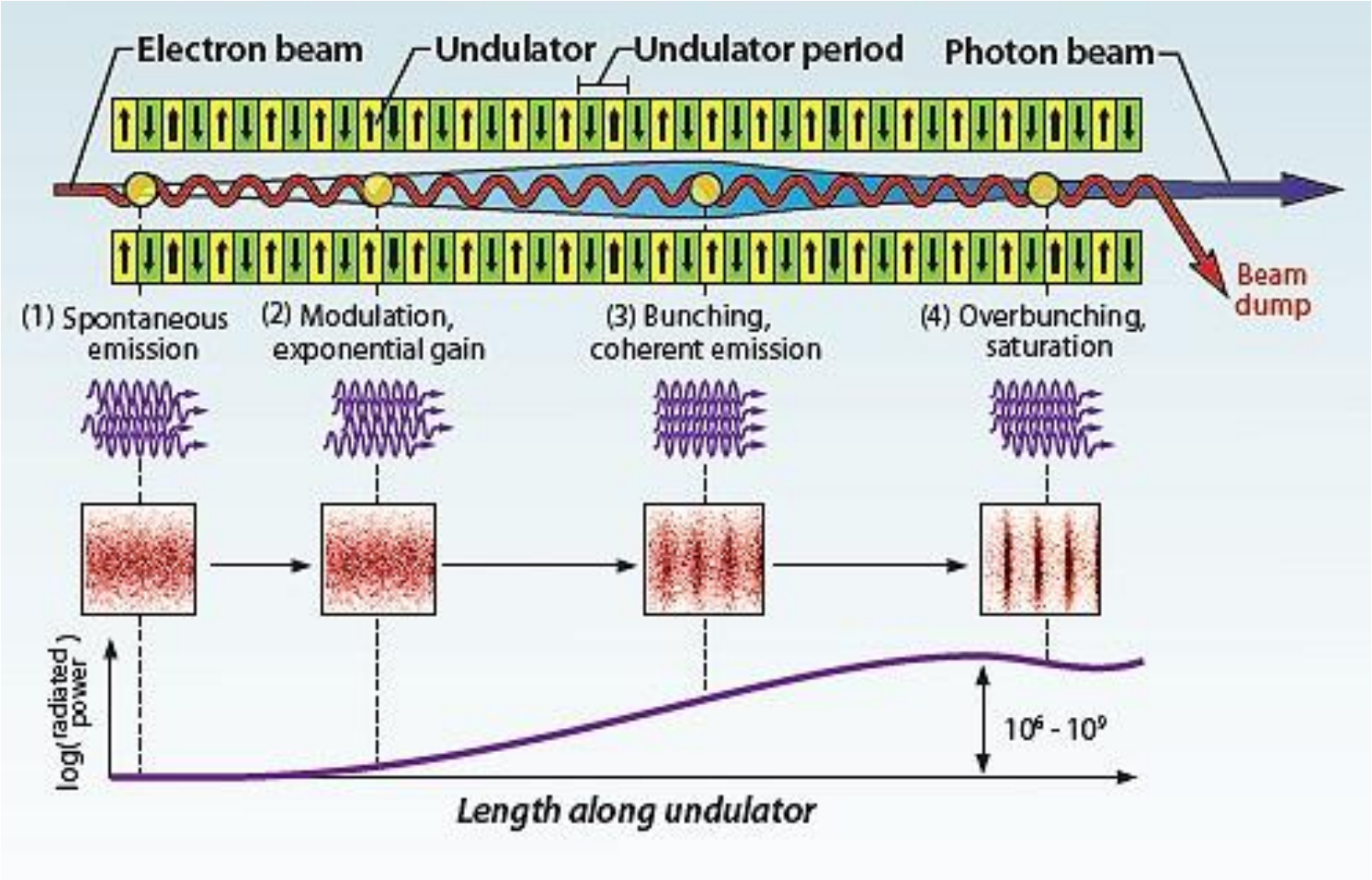
HIV glycoprotein



mosquito immune system

yeast enzyme

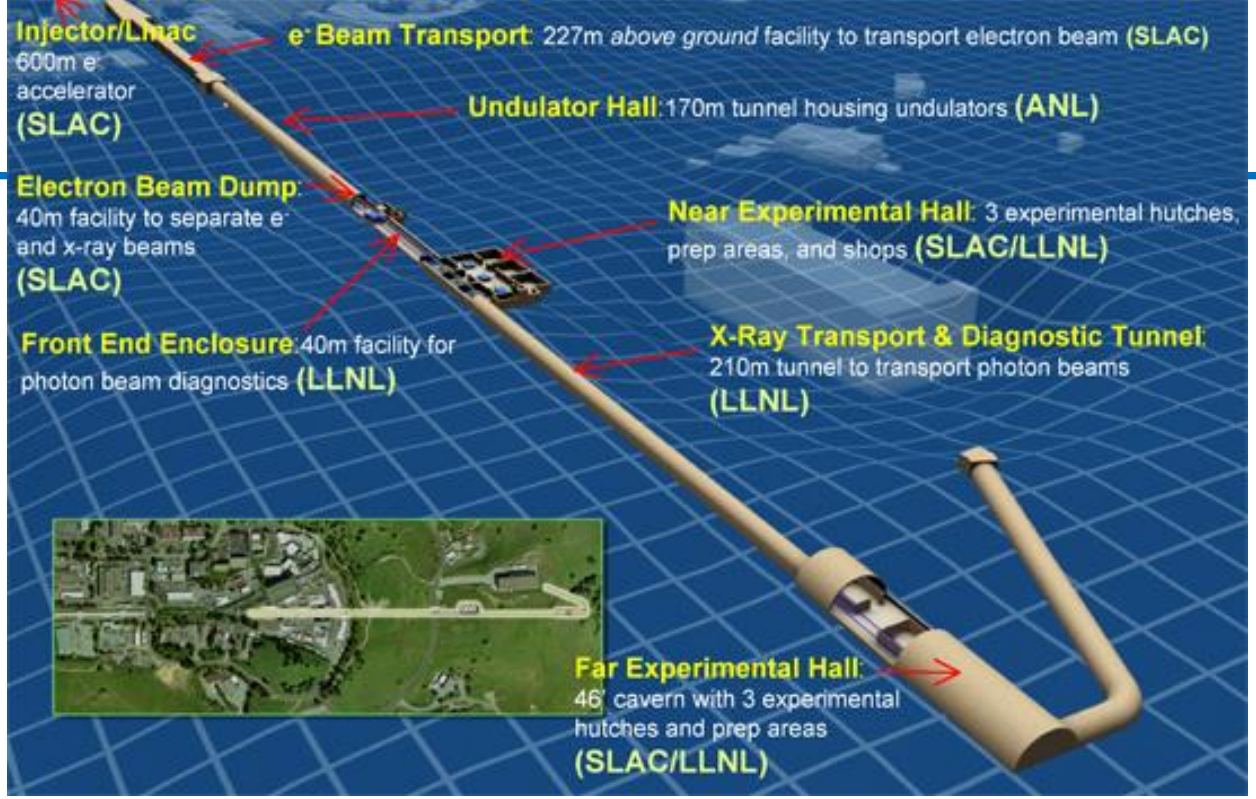
4th generation light source – Free Electron Laser

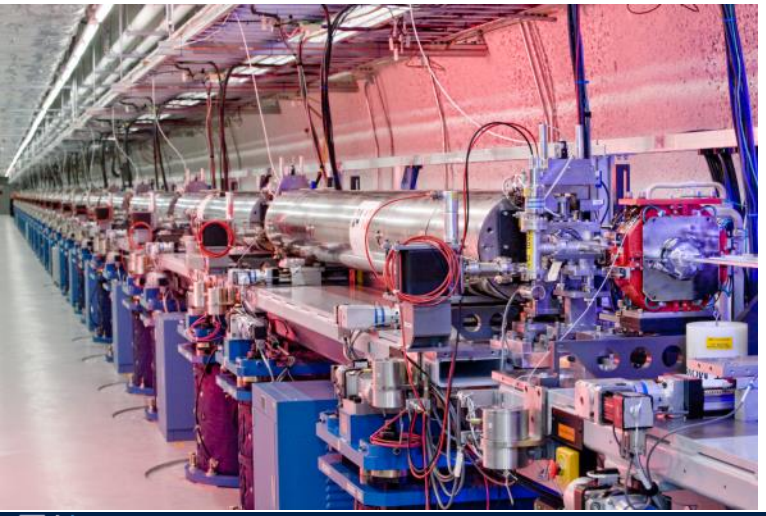


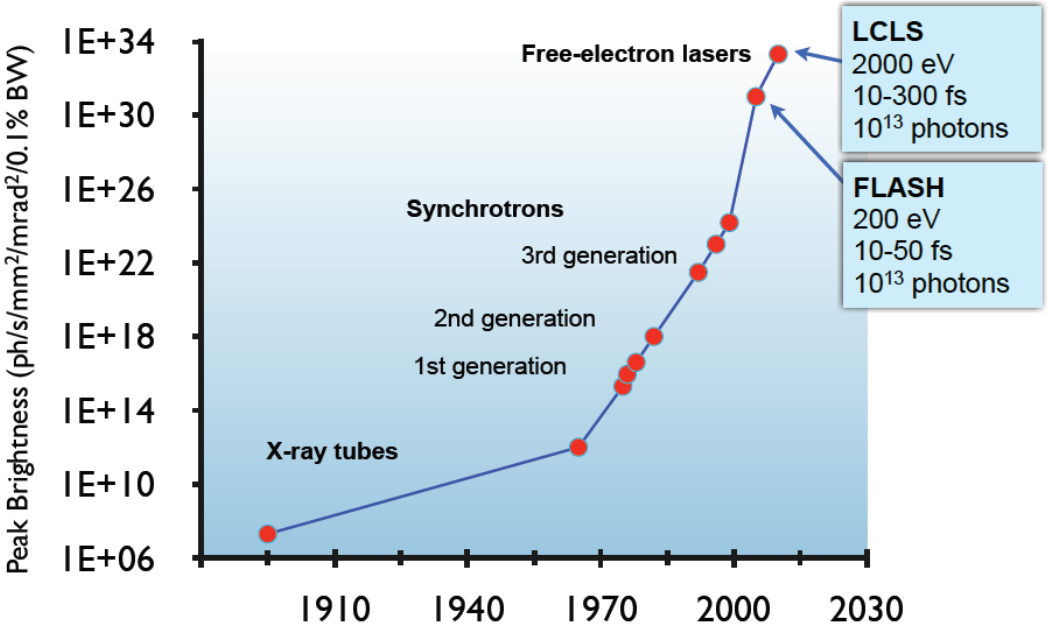
4th generation light source –

X-ray FEL-

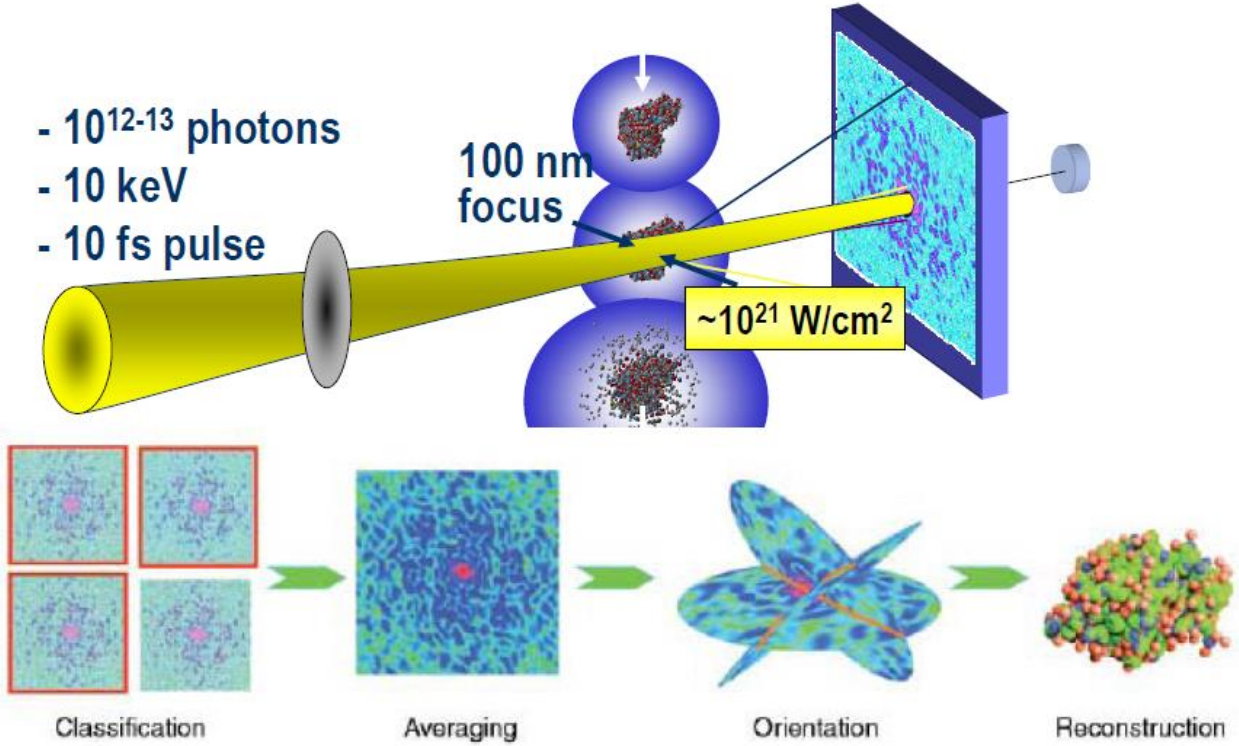
LCLS at SLAC



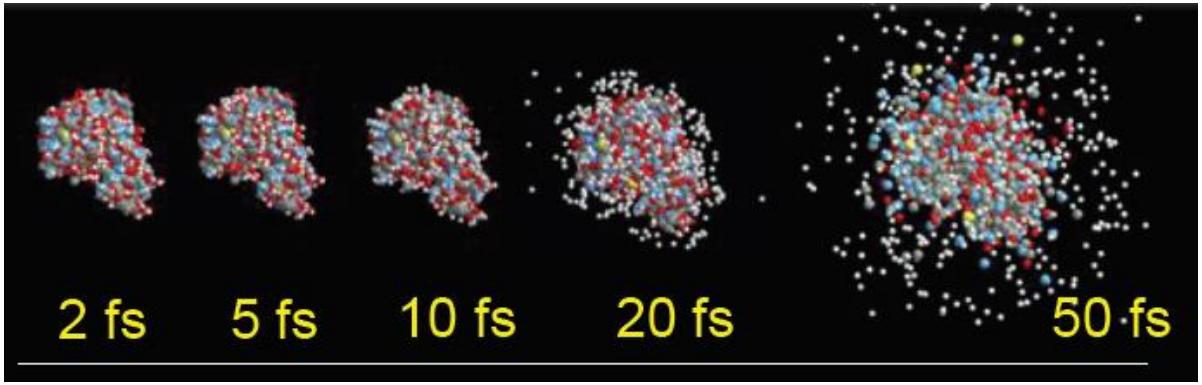




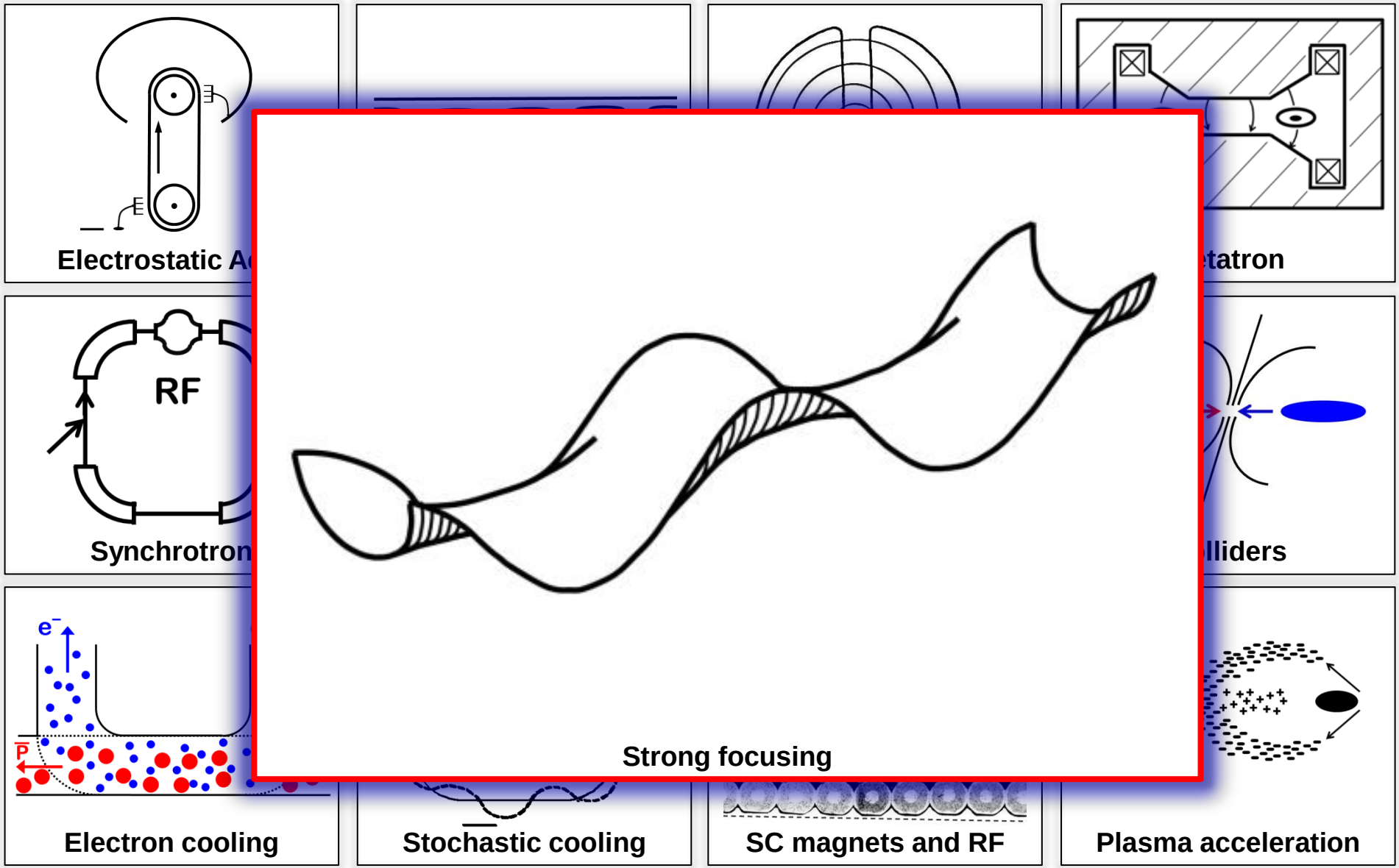
Coherent diffractive imaging of single particles



Calculations. in vacuum Neutze et al., Nature 2000 Chapman, Gaffney Science 2007

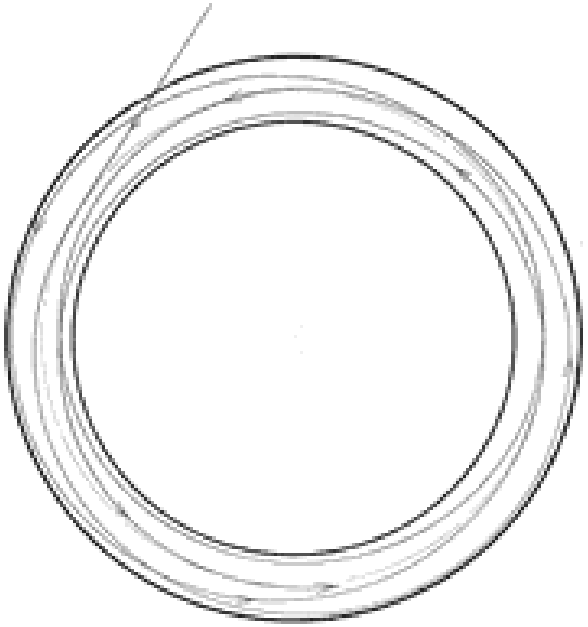


Selected inventions



Focusing

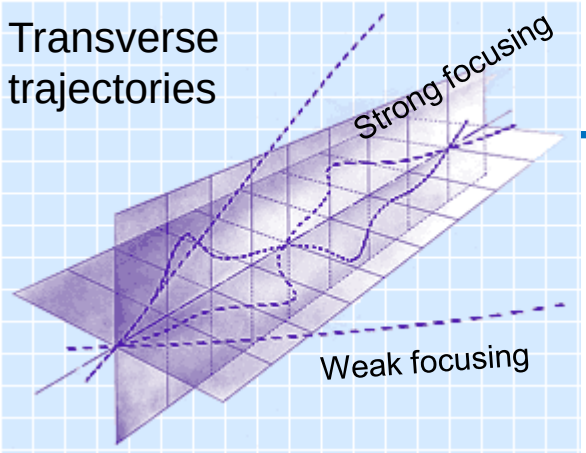
- **Focusing is needed to confine the orbits**
- **First accelerators had "weak focusing" – when focusing period was larger than the perimeter**



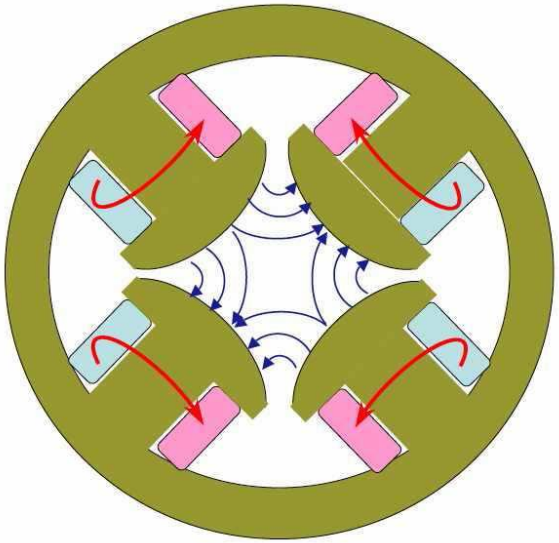
Weak focusing accelerator

10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for his time. Its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world

- **“Strong focusing” alternates focusing-defocusing forces (provided by quadrupoles) to give overall focusing in both X & Y planes**



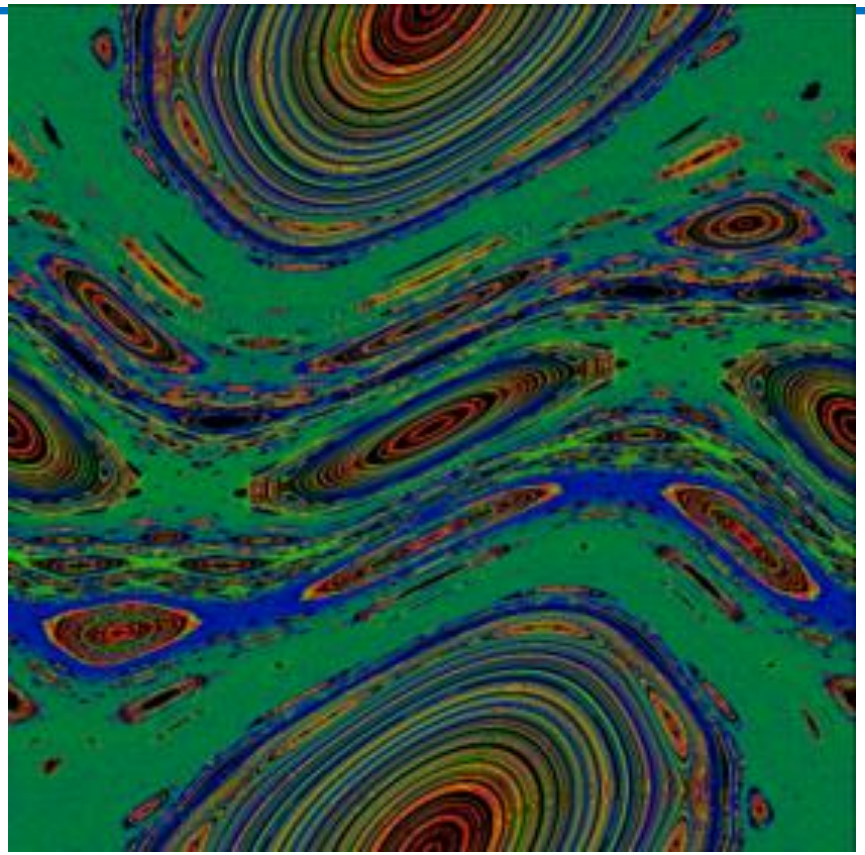
Strong focusing allow use of more compact magnets, thus achieving many times larger energy with the same cost

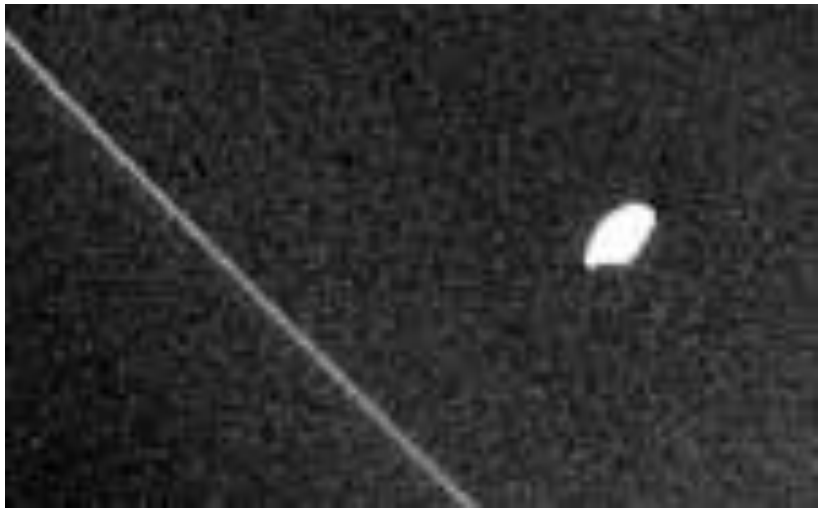


CERN's Proton Synchrotron, the first operating strong-focusing accelerator

200-m diameter ring, weight of magnets 3,800 tons

Chaos Seen in Movement of Ring-Herding Moons of Saturn October 11, 2002

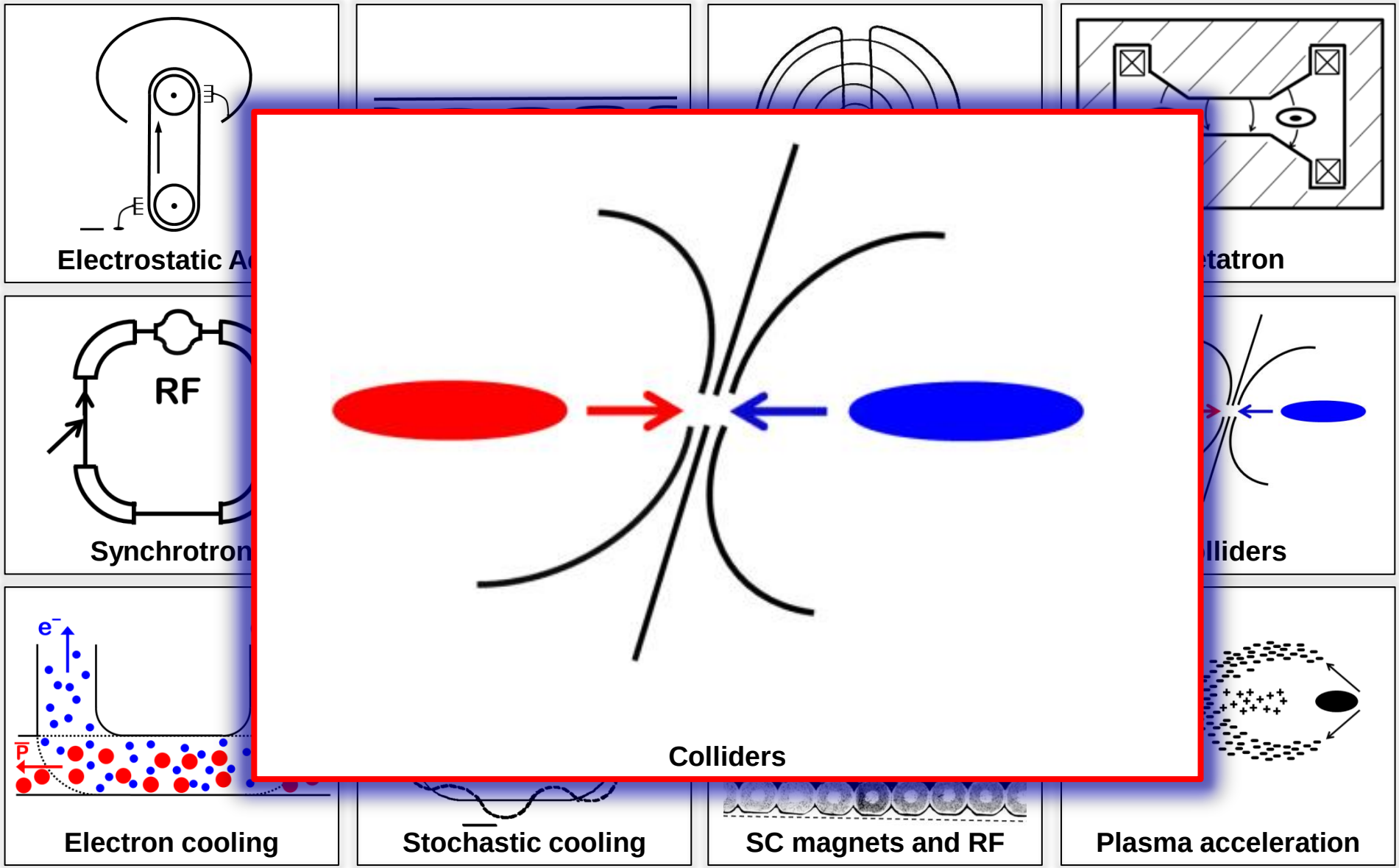




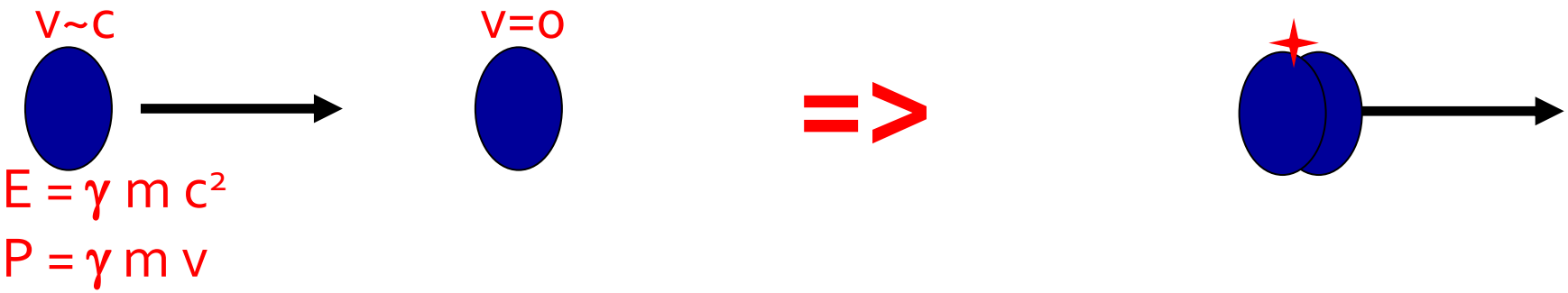
Saturn's F ring and Prometheus

Orbits in accelerator, dynamical system, often exhibit chaotic dependence

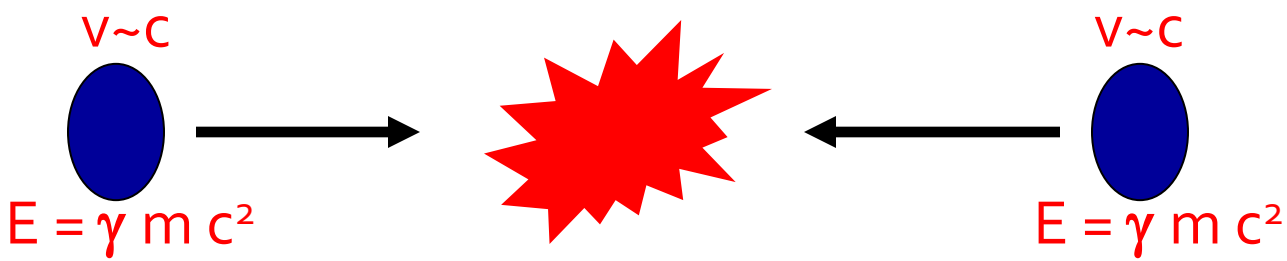
Selected inventions



Why colliders?

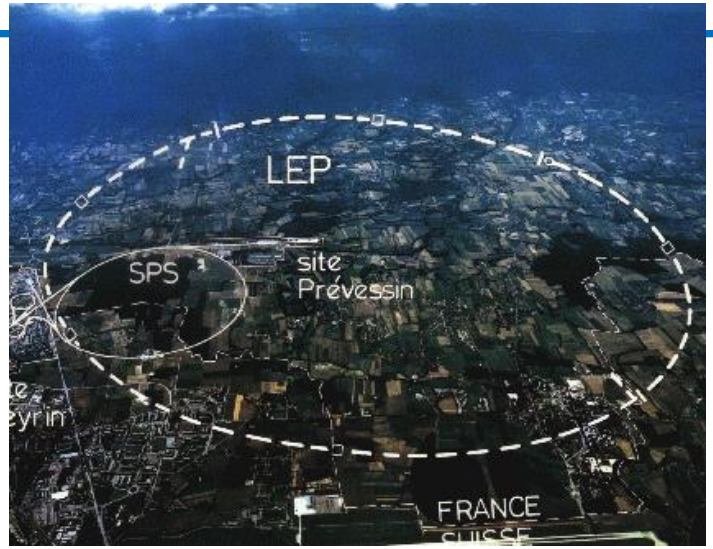


Only a tiny fraction of energy converted into mass of new particles
(due to energy and momentum conservation)

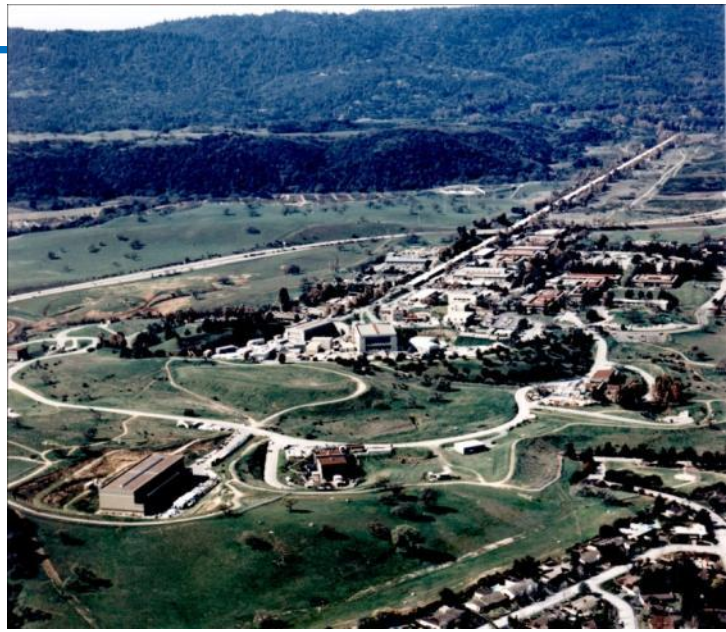


Entire energy converted into the mass of new particles

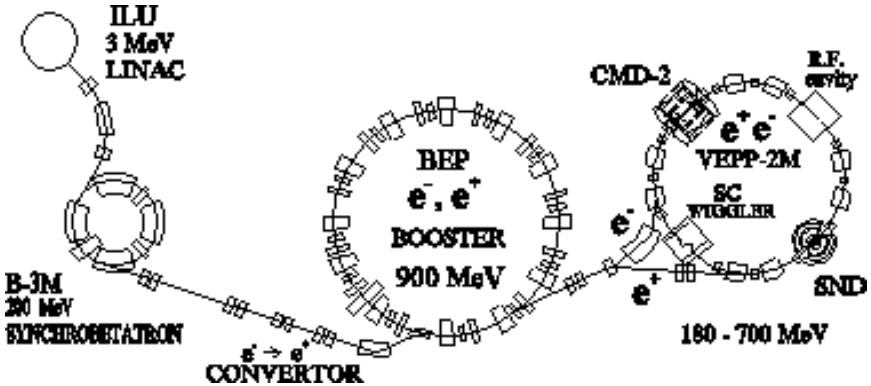
LEP Collider, CERN



SLAC Linear Collider



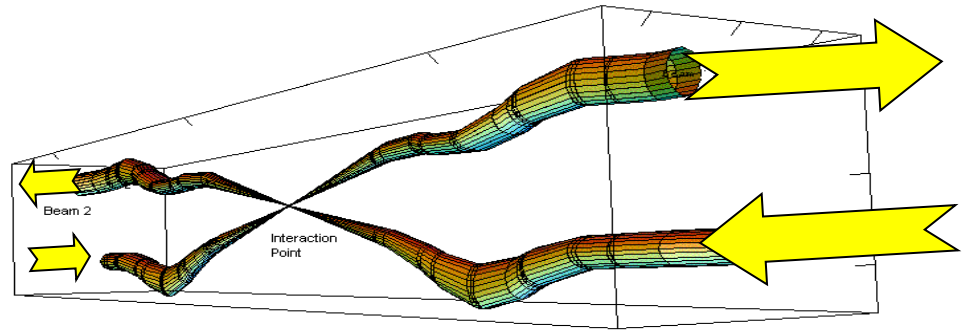
VEP Colliders
BINP, Novosibirsk



Tevatron collider, Fermilab

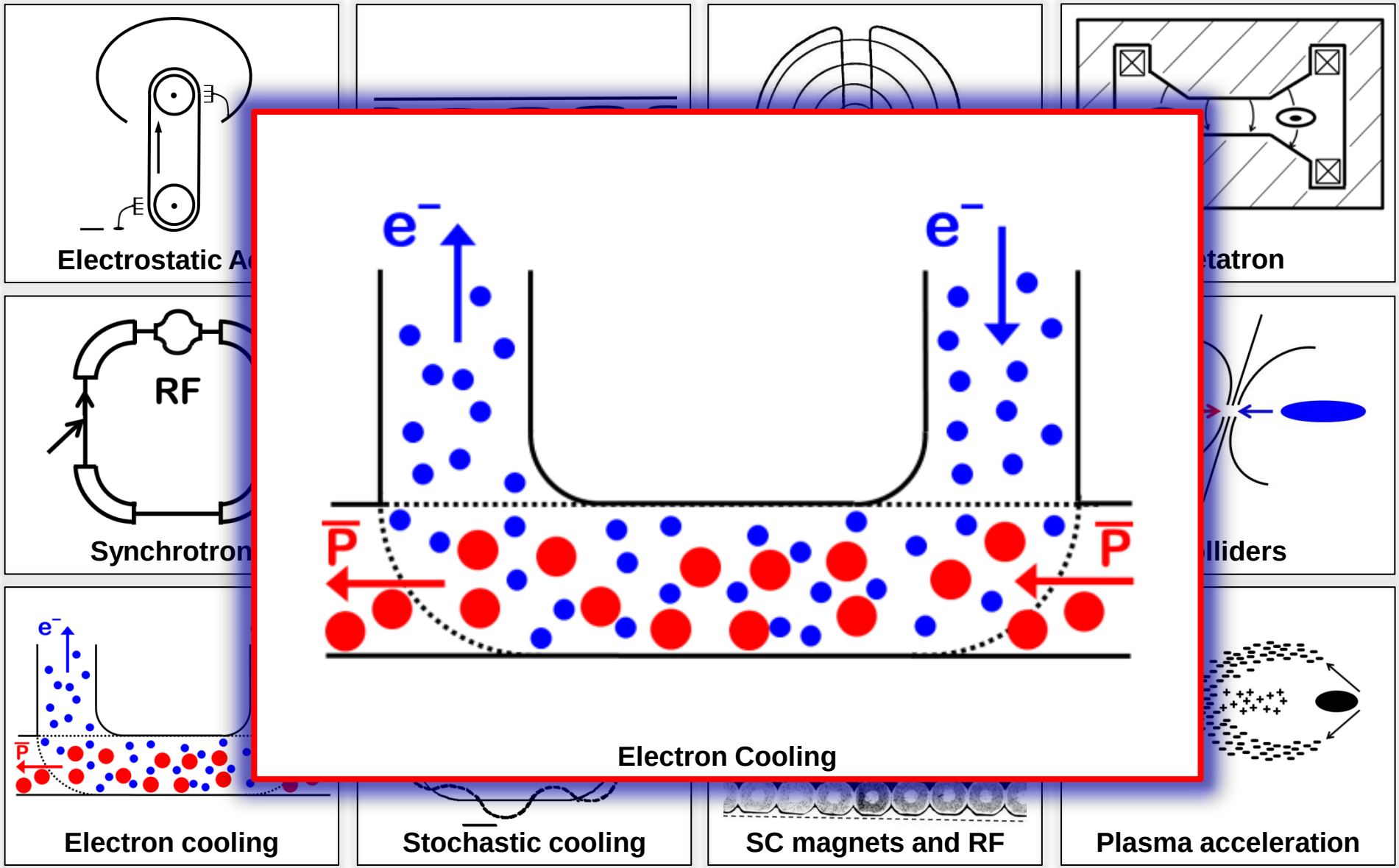
LHC collision points

At four places the beams intersect

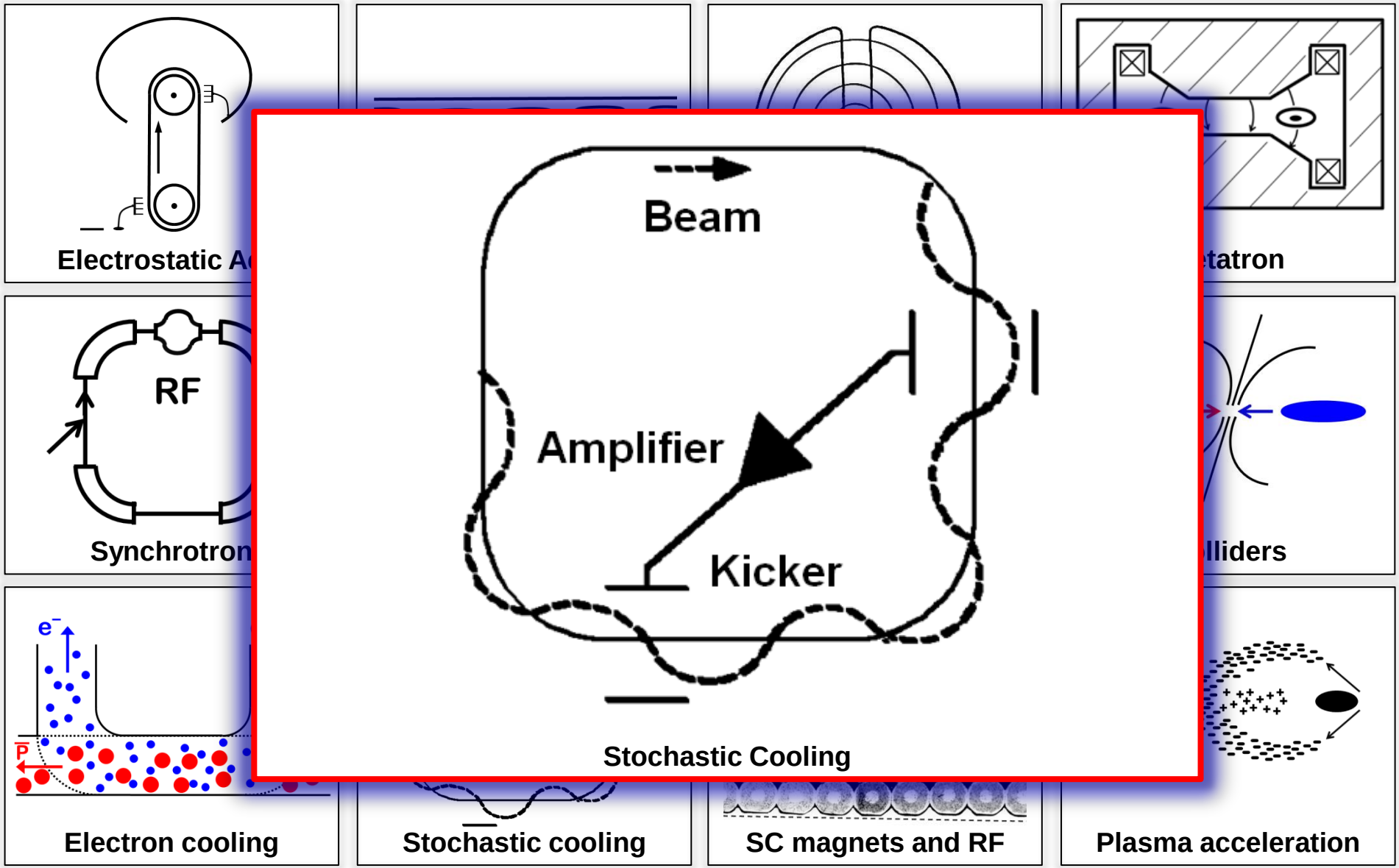


Relative beam sizes around IP1 (Atlas) in collision

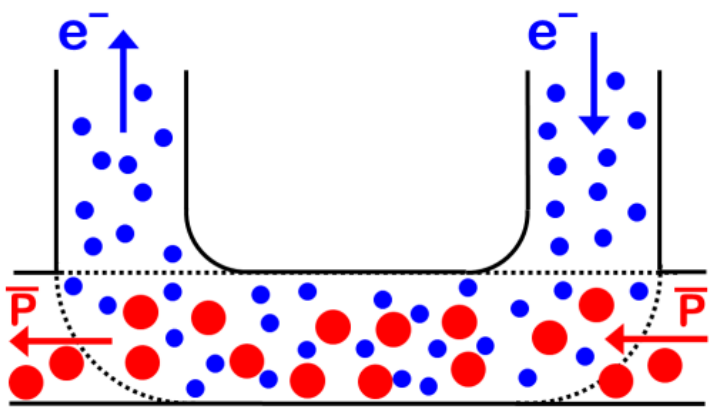
Selected inventions



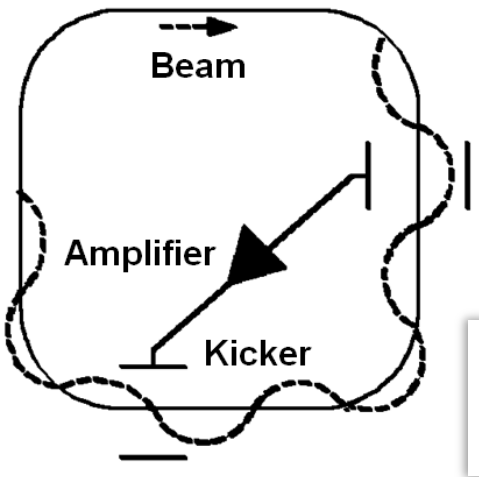
Selected inventions



Beam cooling



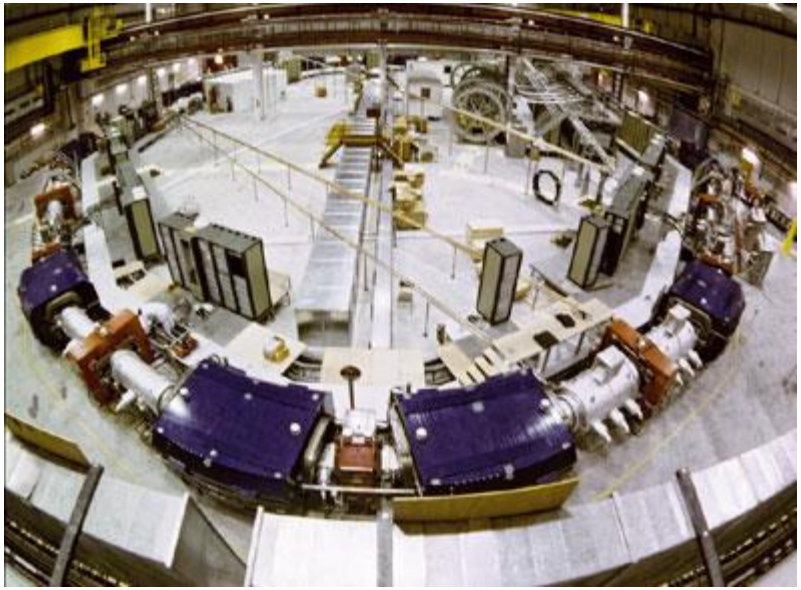
Electron cooling



Nobel of 1984 for discovery of W and Z Bosons

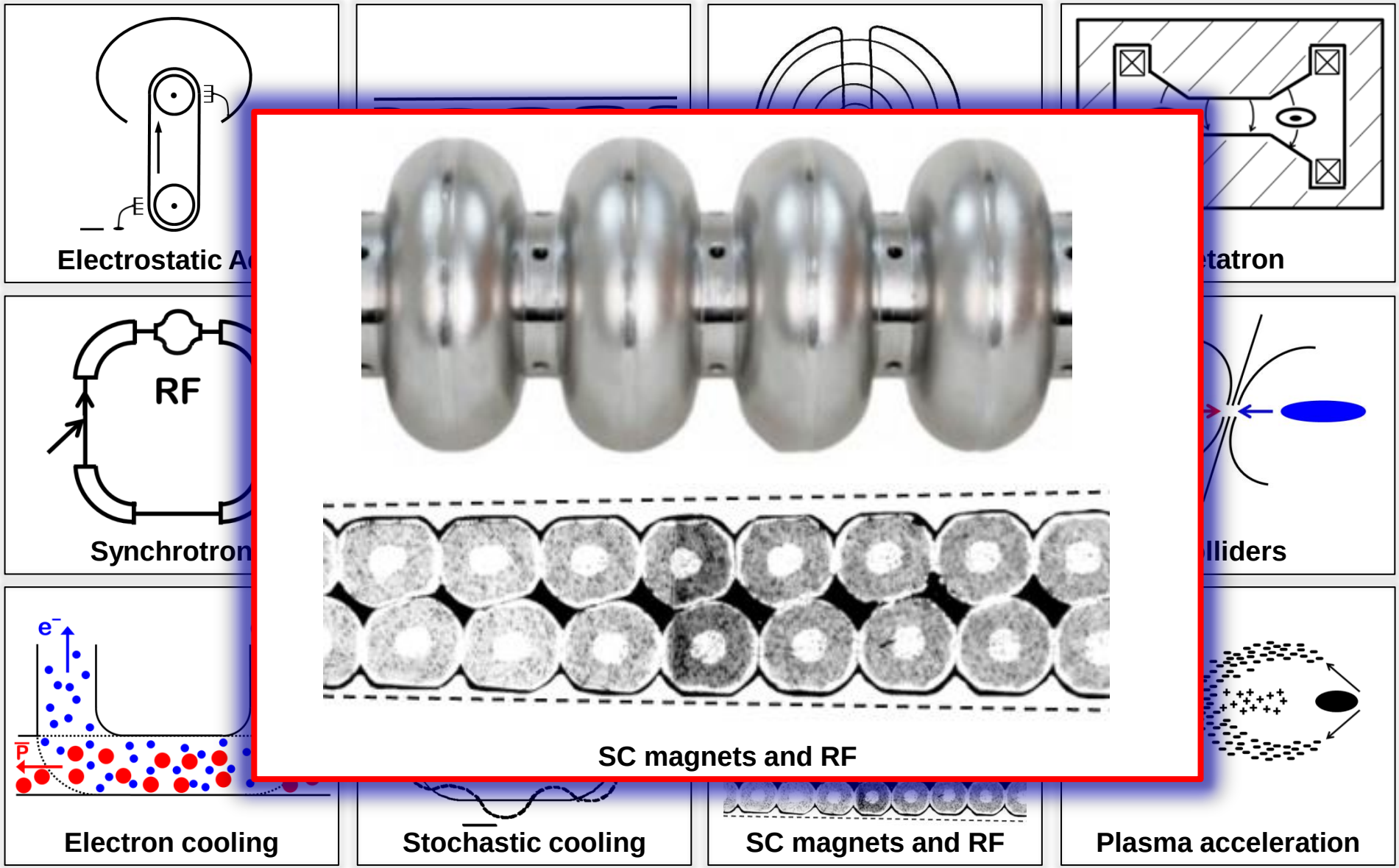
stochastic

Fist e-cooler at BINP

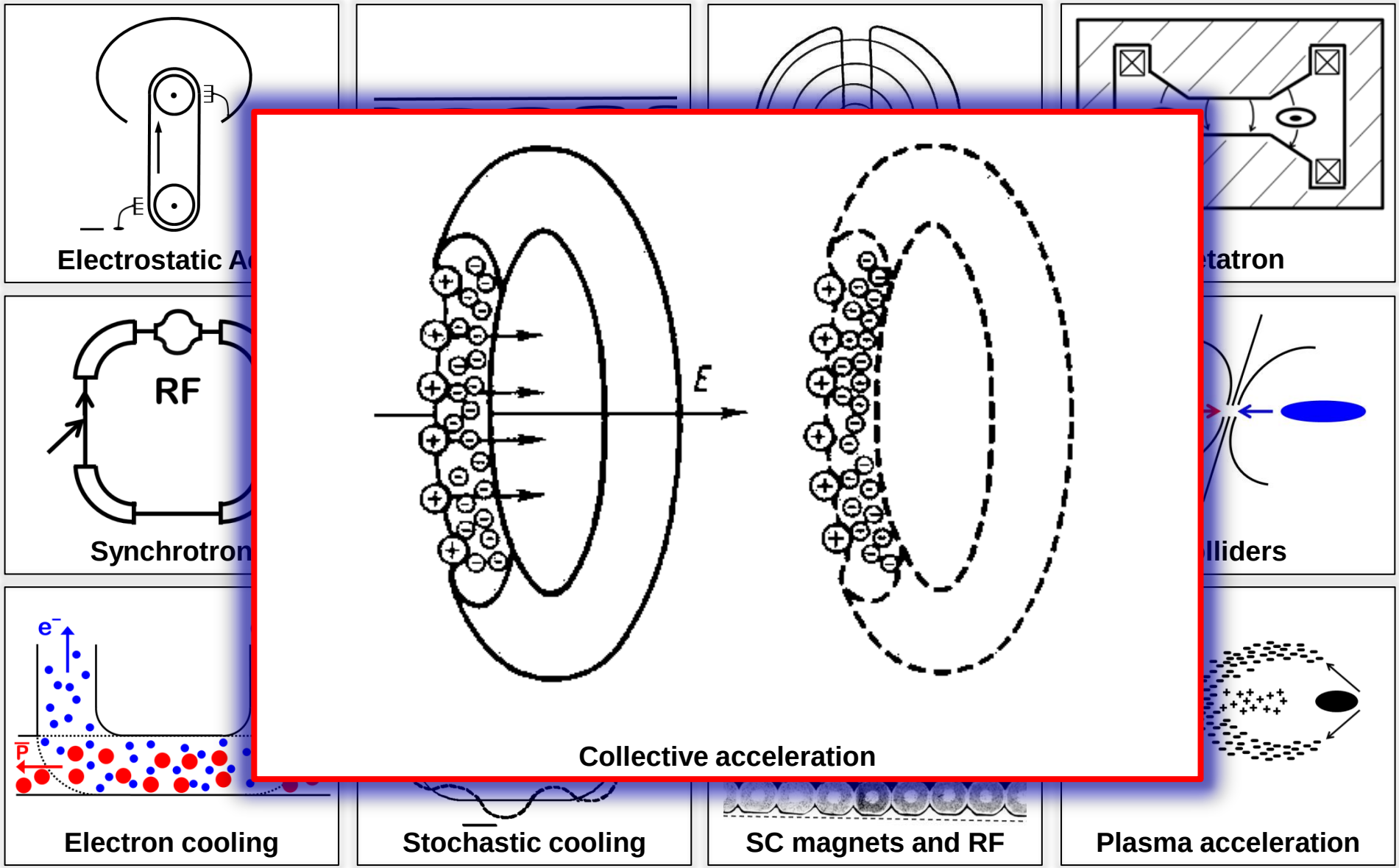


Antiproton accumulator at CERN

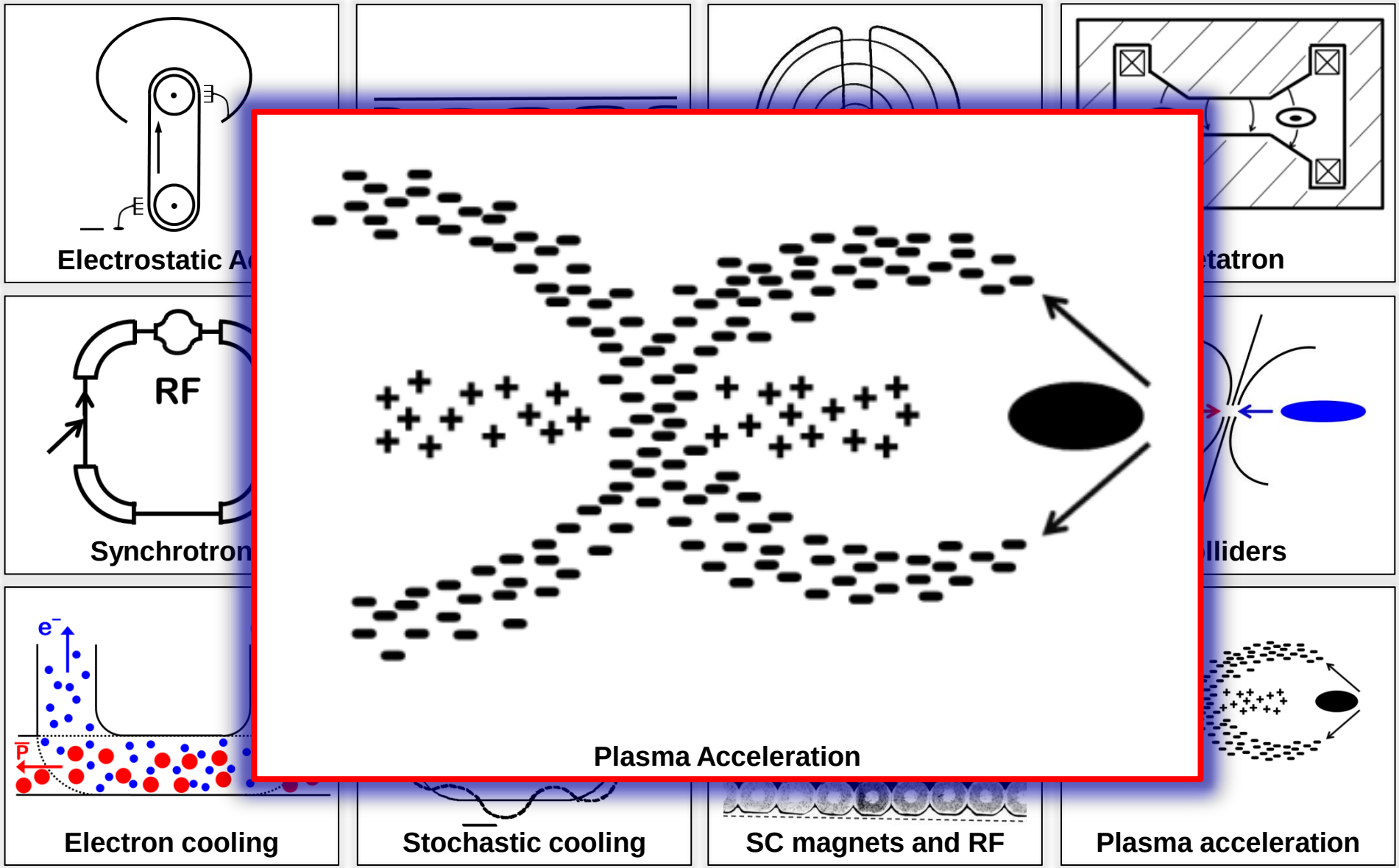
Selected inventions



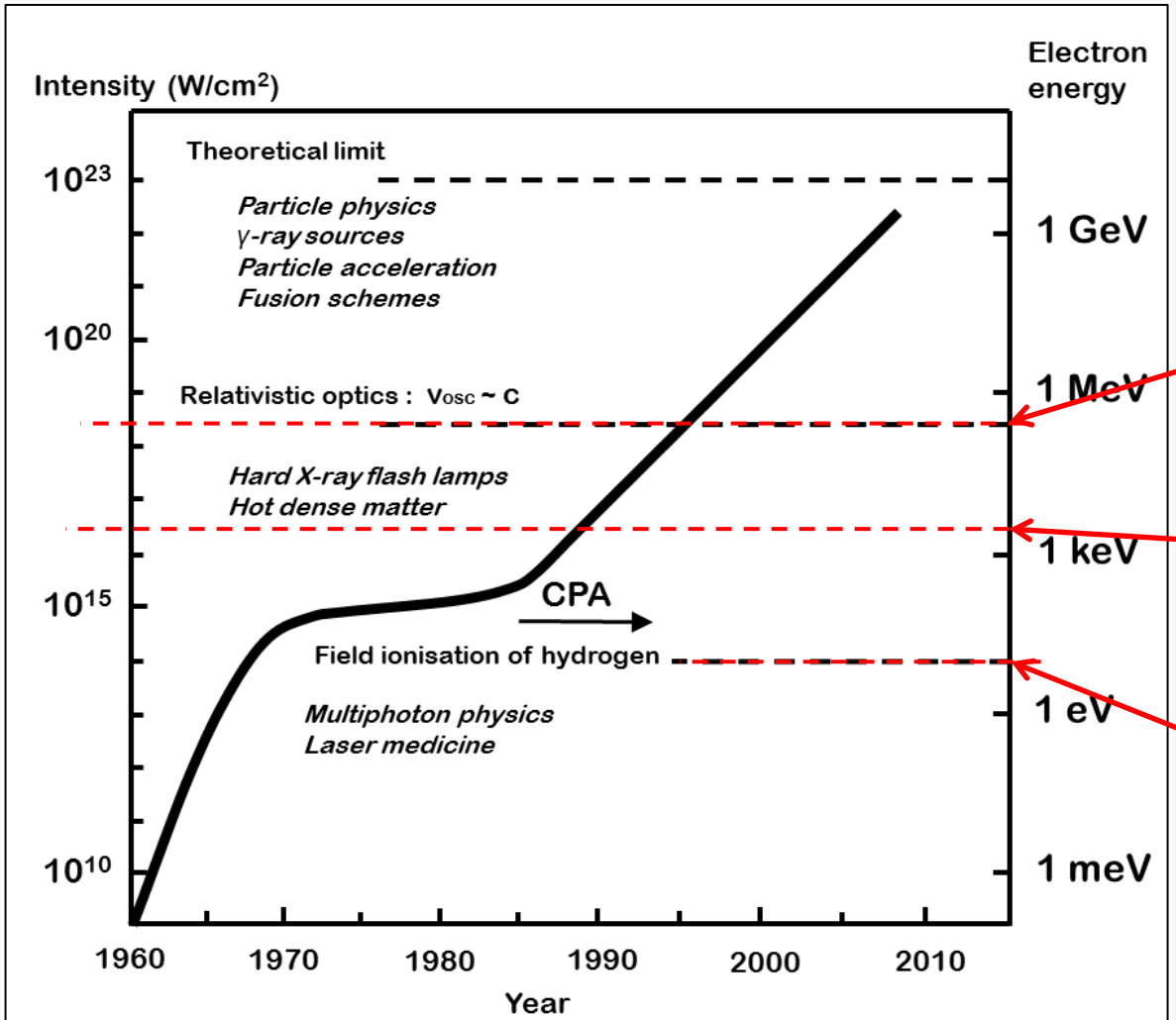
Selected inventions



Selected inventions



Laser intensity



Progress in peak intensity since laser invention in 1960 (after Paul Gibbon, ICP, 2005)

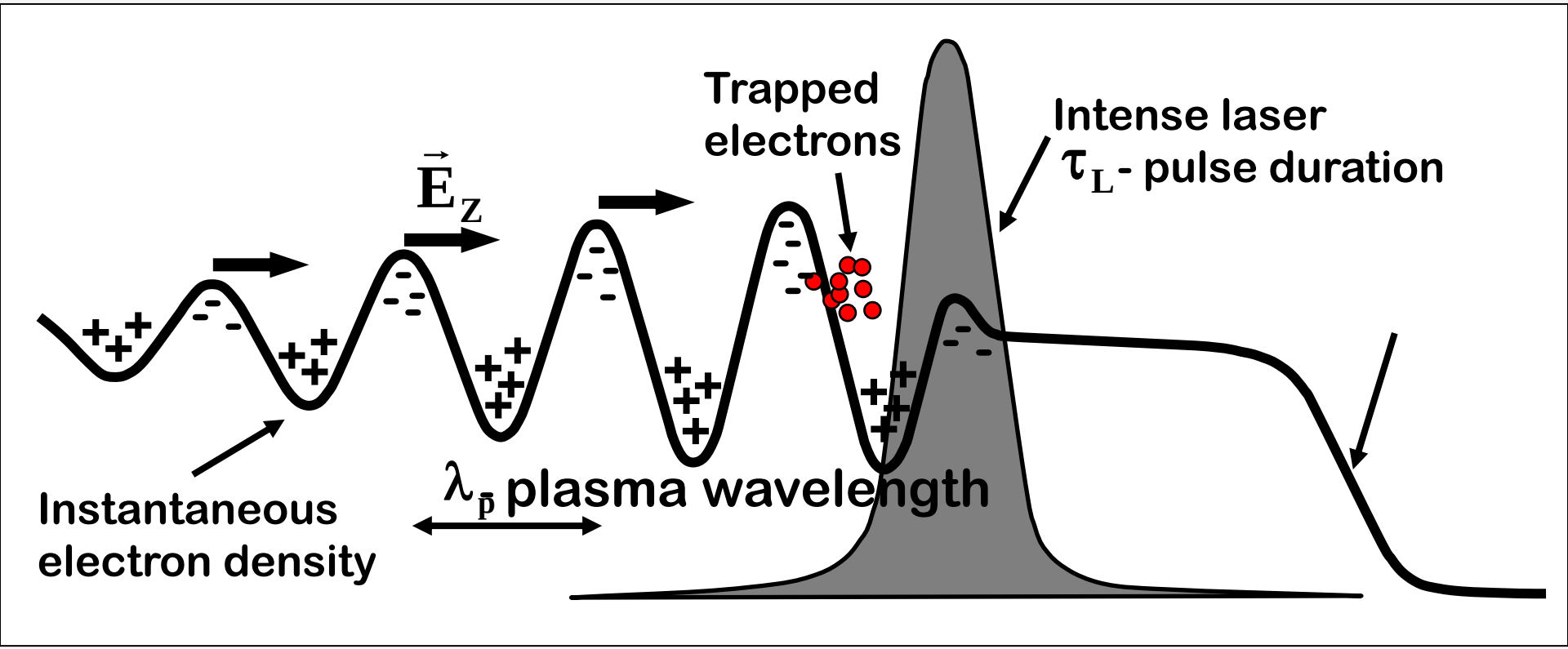
a_0 ~1 for red laser

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

Atomic intensity

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

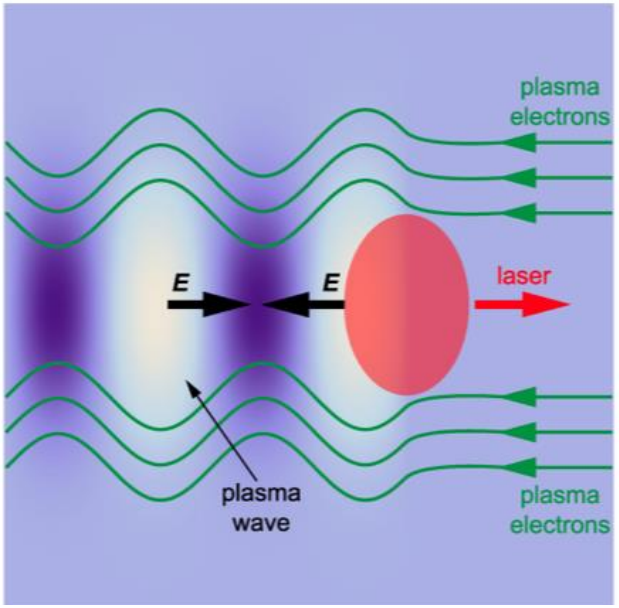
Laser acceleration - conceptually

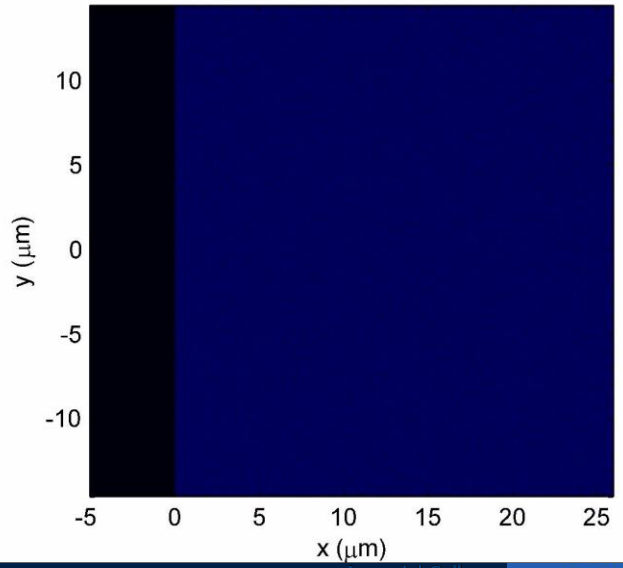


- **Note in particular**
  - Ionization front starting at the front tail of laser
  - Laser pulse length similar of shorter than plasma wavelength
  - Electrons trapped in the first bubble

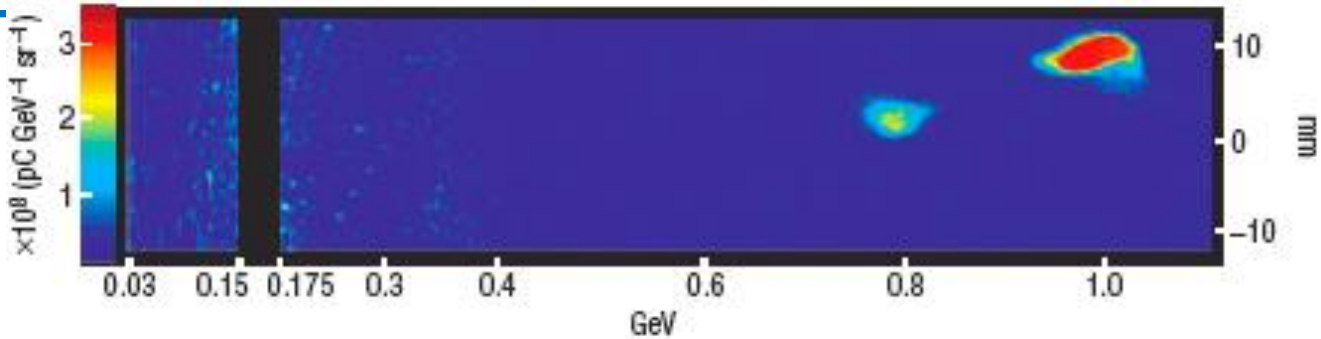
Laser-Driven Plasma Accelerators

- Ponderomotive force of short (50fs), intense (10^{18} W cm^{-2}) laser pulse expels plasma electrons
- This sets up plasma wave which trails laser pulse
- Electric fields within plasma wave of order 100 GV/m formed
- 3 to 4 <u>orders of magnitude</u> bigger than in conventional accelerator!



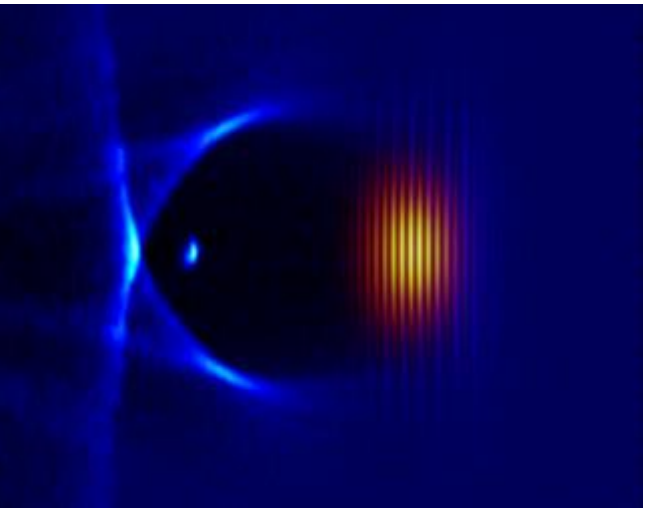


Laser-Plasma Acceleration



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



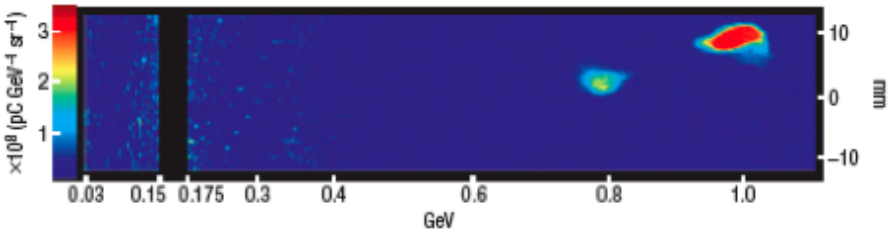
← **Simulation of laser-plasma acceleration**

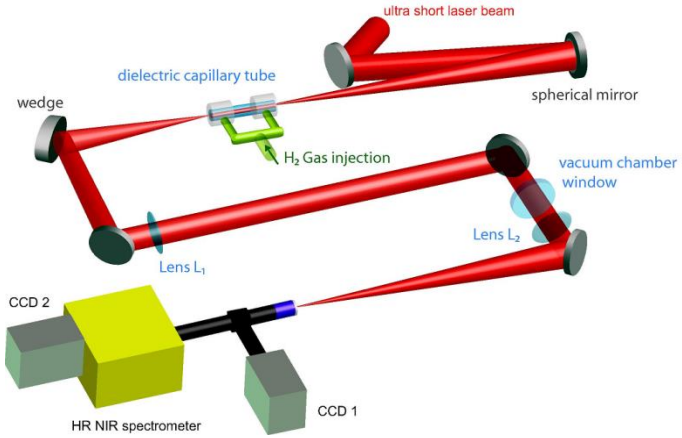
Rapid progress in beam energy achieved with laser-plasma acceleration shows that the synergy of accelerators, laser and plasma is revolutionizing the field of accelerator science

Rapid progress is being made …

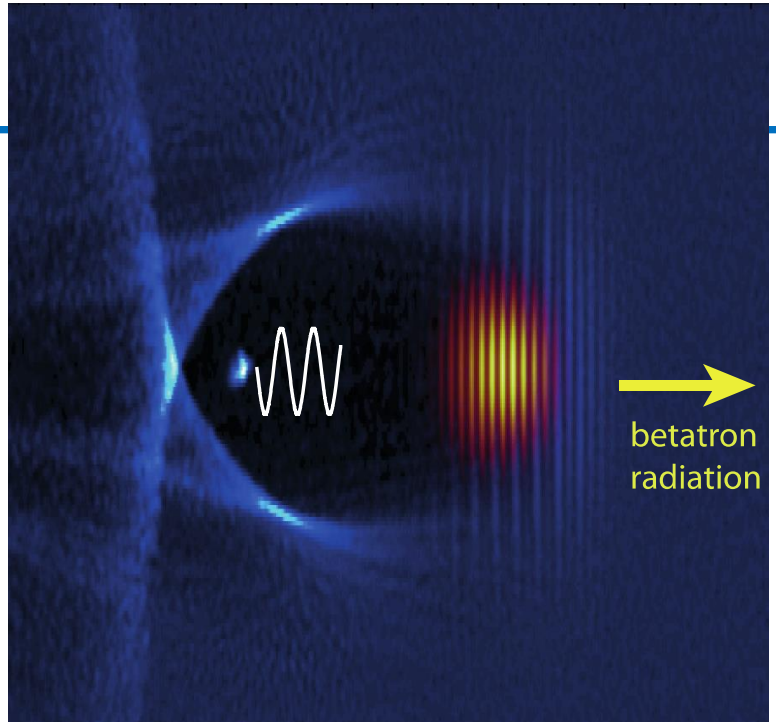
- 2004: First quasi-monoenergetic beams generated (IC, LBNL, LOA)
- 2006 First GeV beams generated (Oxford & LBNL)
- 2008 Generation of visible radiation in undulator (Strathclyde & Jena)
- 2009 Measurement of E_zL ~ 1 GeV in weakly nonlinear regime (LPGP, Strathclyde, Lund, JIHT)
- 2009: Generation of extreme UV radiation in undulator (MPQ & Oxford)
- 2011: Biological imaging with betatron radiation (IC, Michigan & MPQ)

The Economist



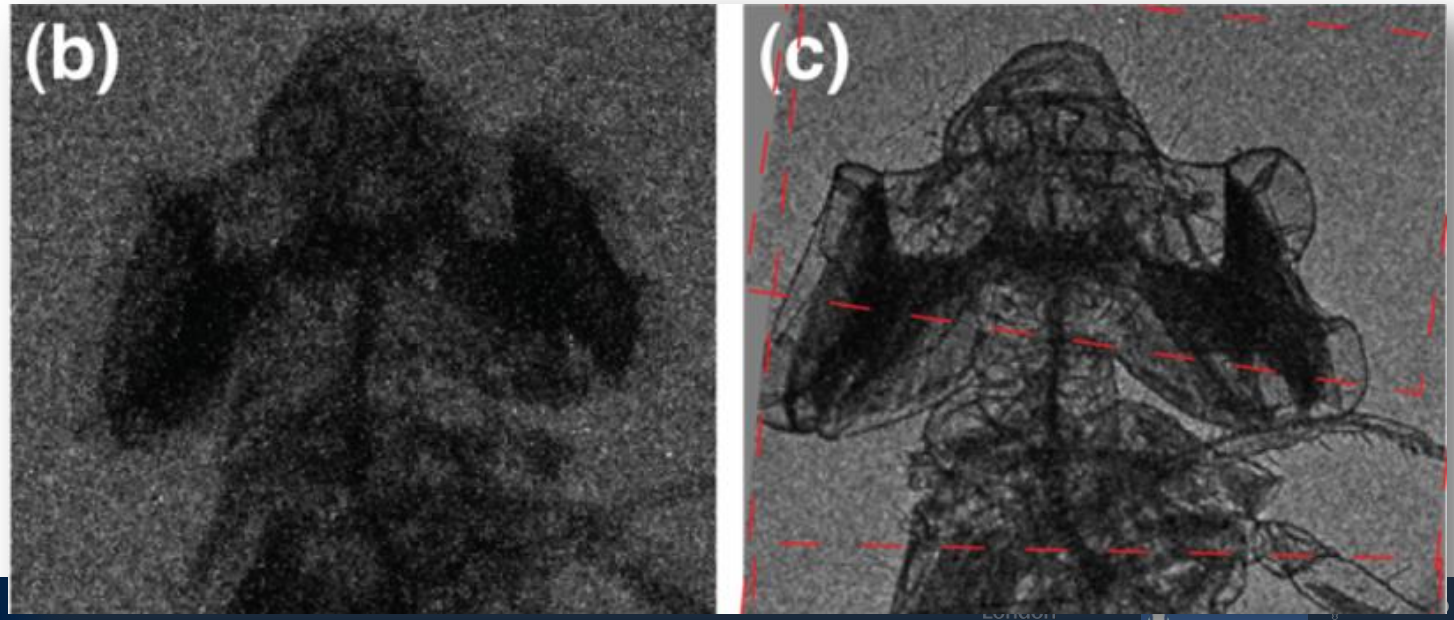


Betatron radiation sources

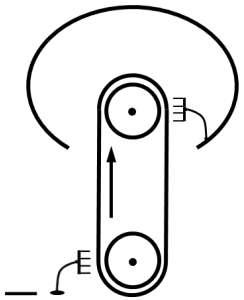


- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates very bright **betatron radiation** in 1- 100 keV range

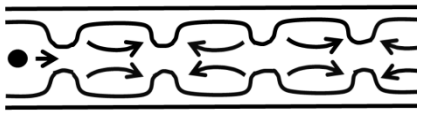
S. Kneip et al., Appl. Phys. Lett. **99, 093701 (2011)**



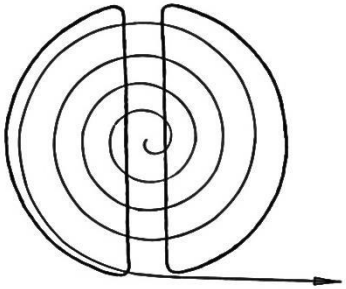
Selected inventions



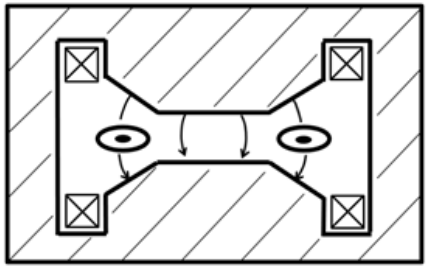
Electrostatic Acc.



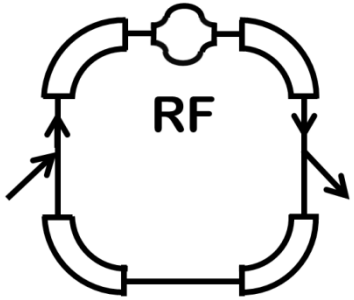
Resonant Linear Acc.



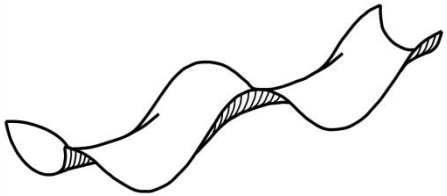
Cyclotron



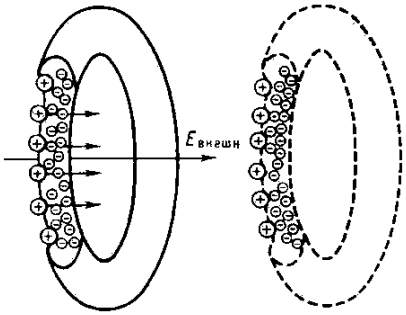
Betatron



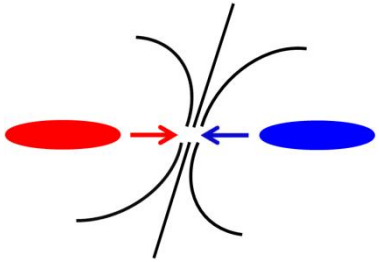
Synchrotron



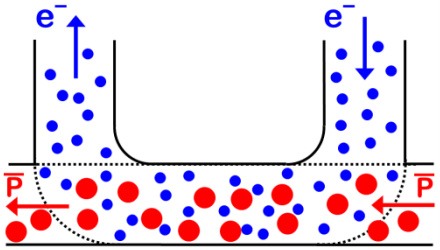
Strong focusing



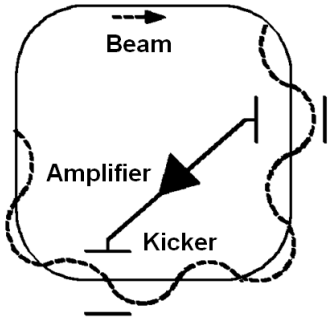
Collective acceleration



Colliders

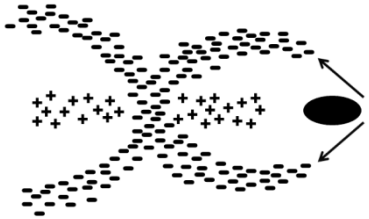


Electron cooling



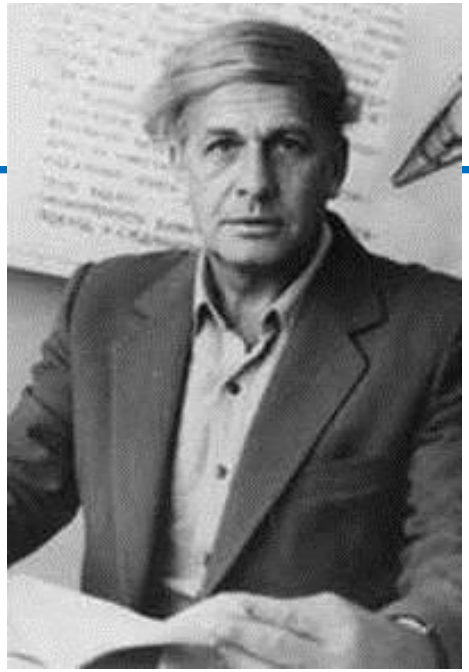
Stochastic cooling

SC magnets and RF



Plasma acceleration

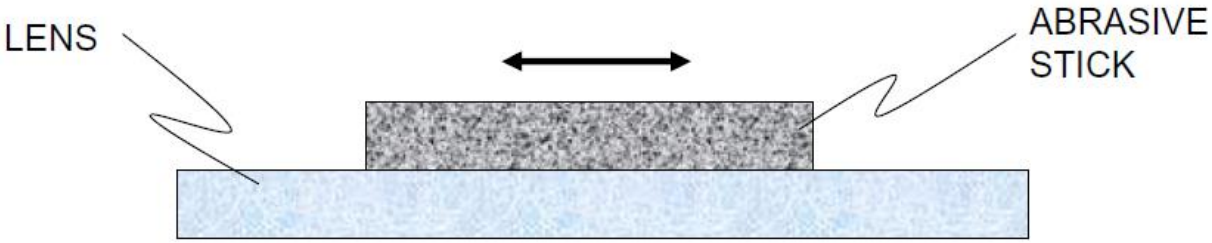
How to invent – TRIZ



Genrikh Altshuller (aka Altov)1926-1998

- **TRIZ = Theory of Inventive Problem Solving**
- **Developed by Genrikh Altshuller**
  - **Work in patent office in 1946**
  - **Analysed 2.5 mlns patents, discovered patterns and identified what makes a patent successful**
  - **Formulated TRIZ in 1956-1985**
- **Four key discoveries of TRIZ:**
  - **The <u>same Problems and Solutions</u> appear again and again but in <u>different industries</u>**
  - **There is a recognisable <u>Technological Evolution path</u> for all industries**
  - **Innovative patents, (23% of total) used science/engineering theories <u>outside their own area/industry</u>**
  - **An Innovative Patent <u>uncovers and solves contradictions</u>**

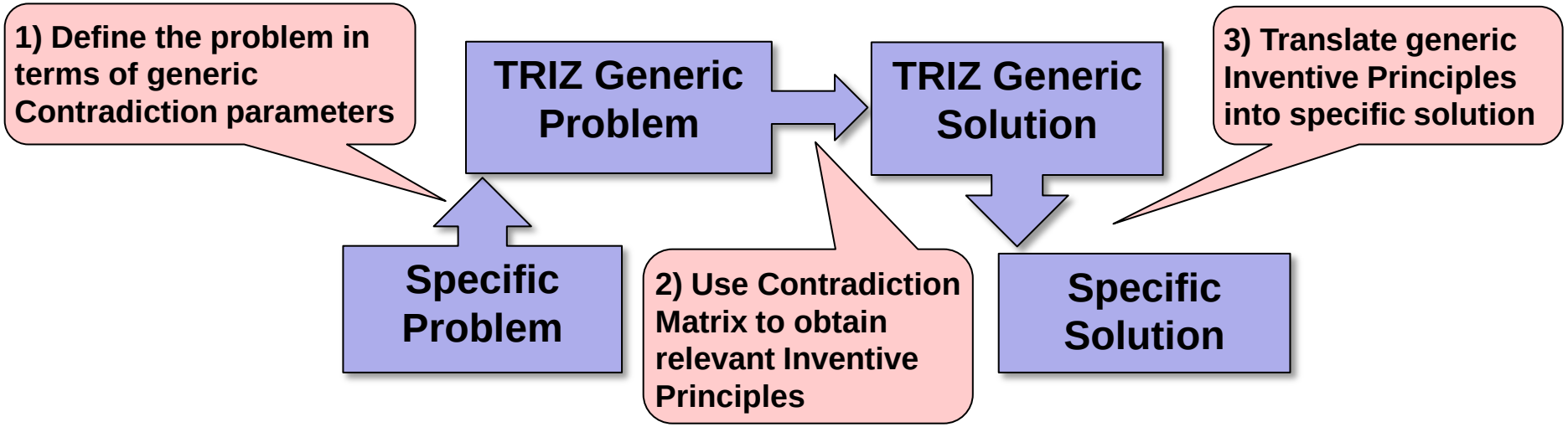
TRIZ in action - example



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

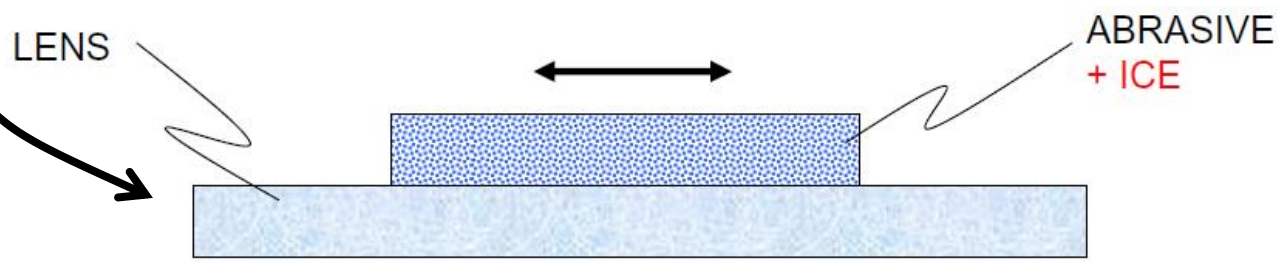
Has anyone else solved such contradiction?



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

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/

TRIZ Principles and Contradiction matrix

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

Elements of TRIZ contradiction matrix

1. Weight of moving object
2. Weight of stationary
3. Length of moving object
4. Length of stationary
5. Area of moving object
6. Area of stationary
7. Volume of moving object
8. Volume of stationary
9. Speed
10. Force (Intensity)
11. Stress or pressure
12. Shape
13. Stability of the object
14. Strength
15. Durability of moving obj.
16. Durability of non moving obj.
17. Temperature
18. Illumination intensity
19. Use of energy by moving
20. Use of energy by stationary
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

TRIZ 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

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**
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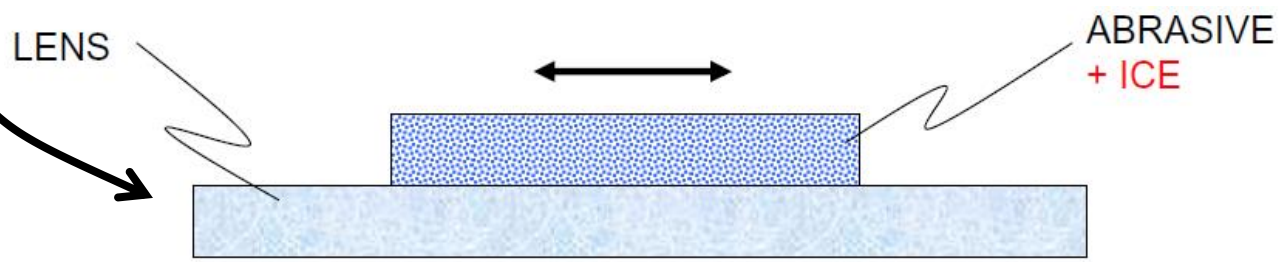


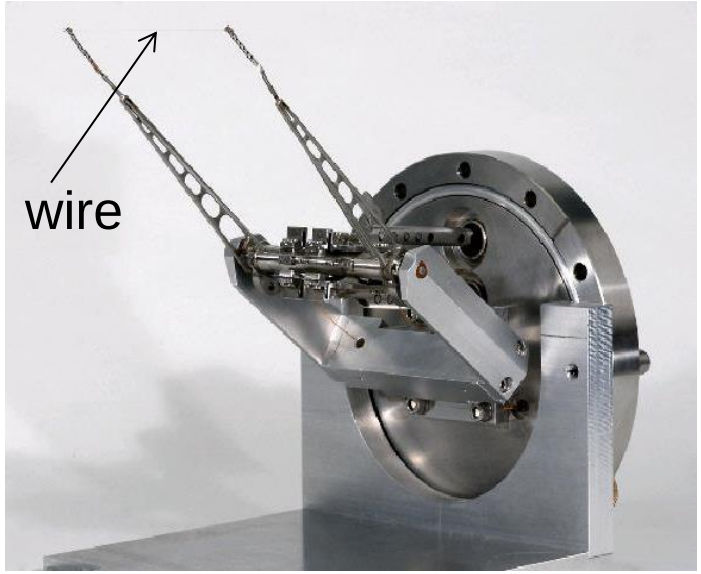
Abrasive + Ice - Inventive Principle 'Phase Transition'

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

TRIZ => Accelerator Science

- **TRIZ created for engineering**
- **But the methodology is universal, and can be applied to science!**
  - **In particular to Accelerator Science**
- **TRIZ => Accelerator Science**
  - **Is being developed right now in JAI**
  - **Specific AS-TRIZ Principles and Contradiction Matrix are being built**
  - **AS-TRIZ planned to become part of Accelerator training in JAI**

AS-TRIZ examples



Beam profile monitor with tungsten or carbon wire

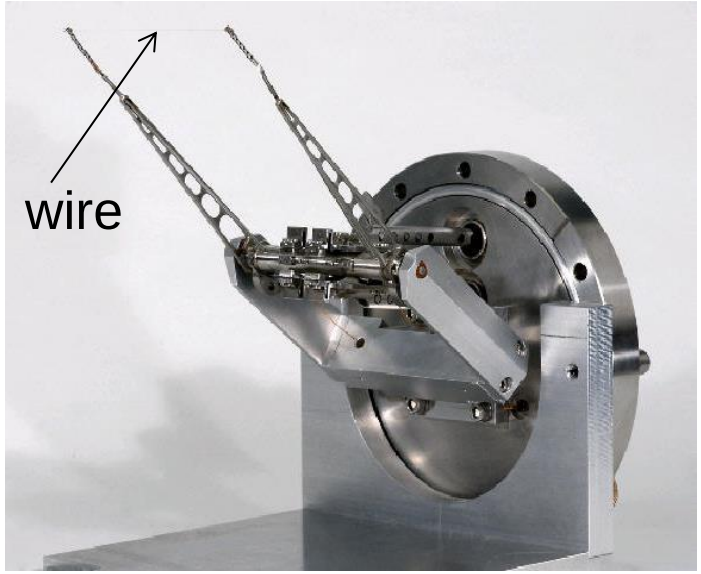
Problem:

As intensity of the beam increase, the wire get damaged after a single use

Contradiction:

To be improved: INTENSITY,
What gets worse: INTEGRITY

AS-TRIZ examples



Beam profile monitor with tungsten or carbon wire

Problem:

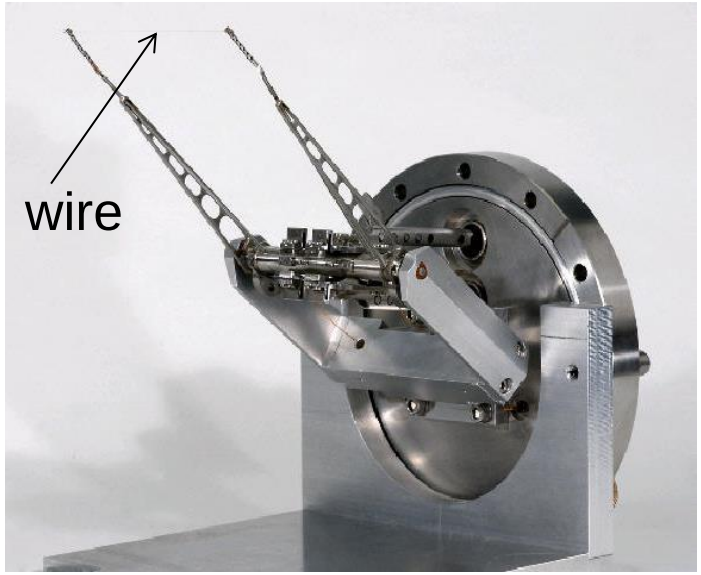
As intensity of the beam increase, the wire get damaged after a single use

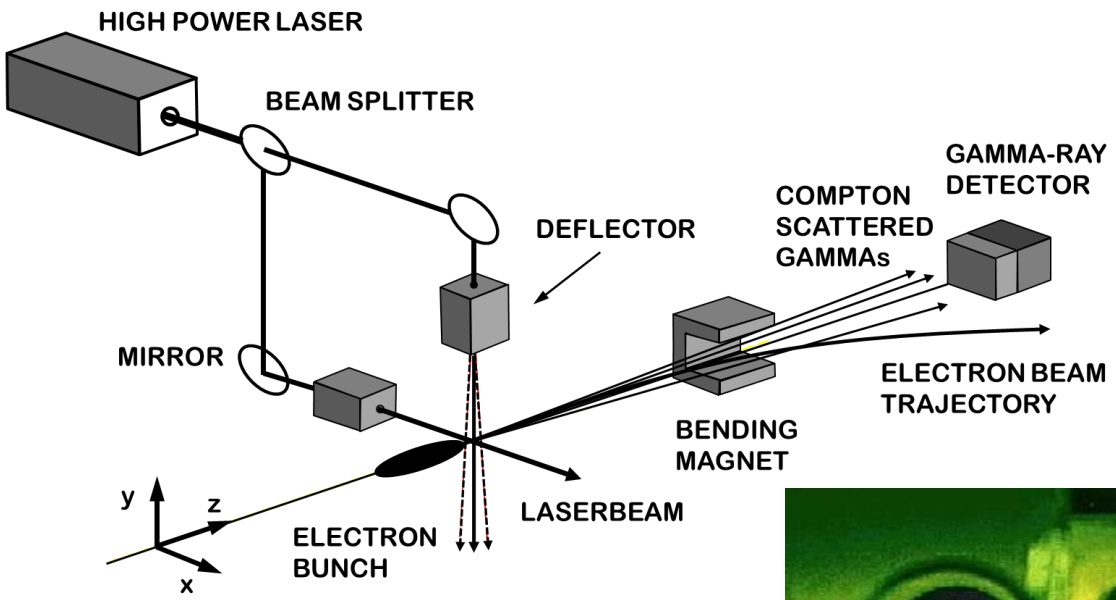
Contradiction:

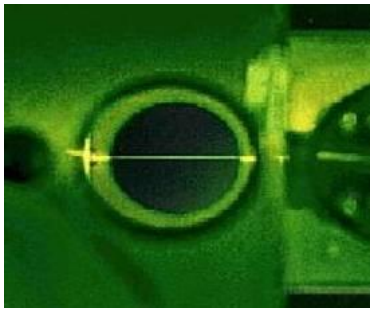
To be improved: INTENSITY,
What gets worse: INTEGRITY

- **One of emerging AS-TRIZ principles**
  - **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

AS-TRIZ examples







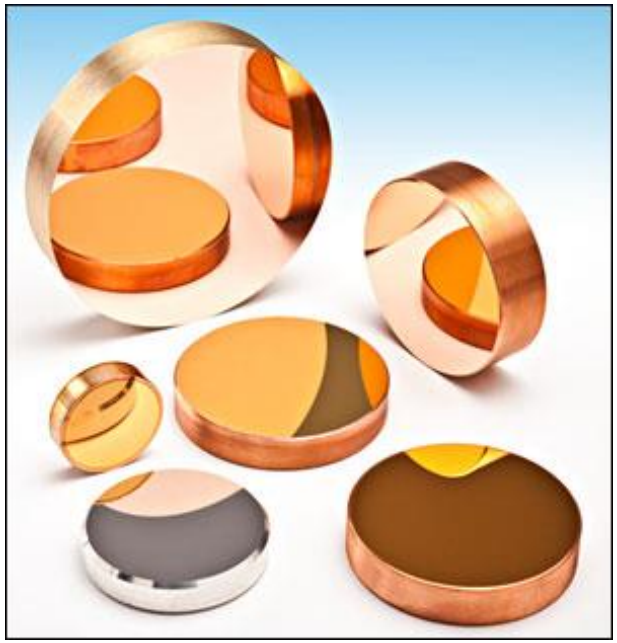
Beam profile monitor with tungsten or carbon wire

Beam profile monitor with laser beam as the "wire"

Solution:

- **One of emerging AS-TRIZ principles**
  - **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

AS-TRIZ examples



Standard glass mirror

Problem:

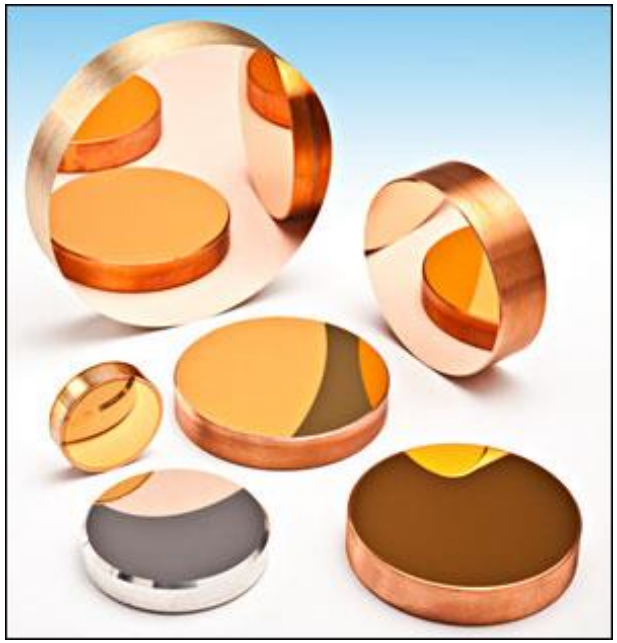
As intensity of the laser increase, the mirror can get damaged

Contradiction:

To be improved: INTENSITY,
What gets worse: INTEGRITY

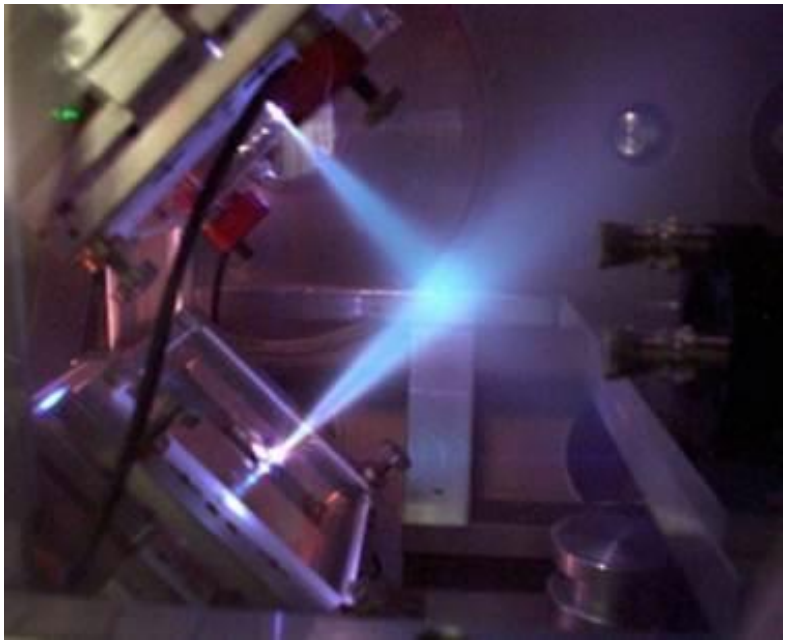
- **One of emerging AS-TRIZ principles**
  - **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

AS-TRIZ examples



Standard glass mirror

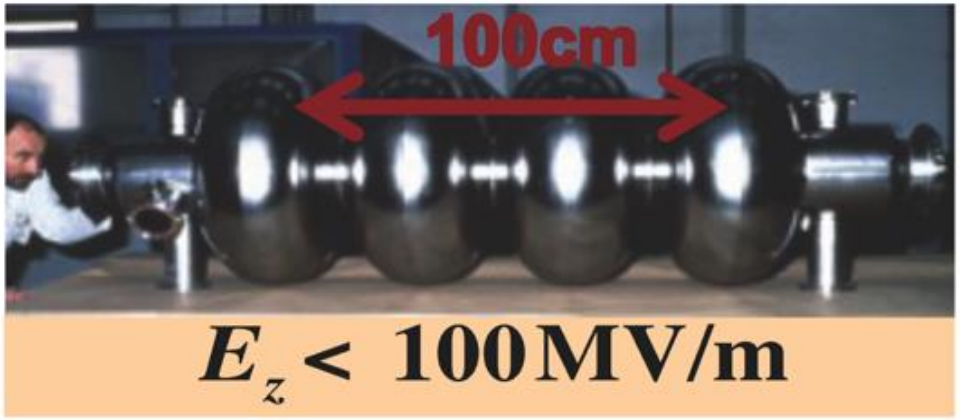
Solution:



Plasma mirror: a laser beam is focused on a piece of glass or gas. It will be transmit until it reach enough intensity and produce a plasma. At that moment, the reflective index change, the beam is then reflected on the free electron.

- **One of emerging AS-TRIZ principles**
  - **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

AS-TRIZ examples



Problem:

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

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

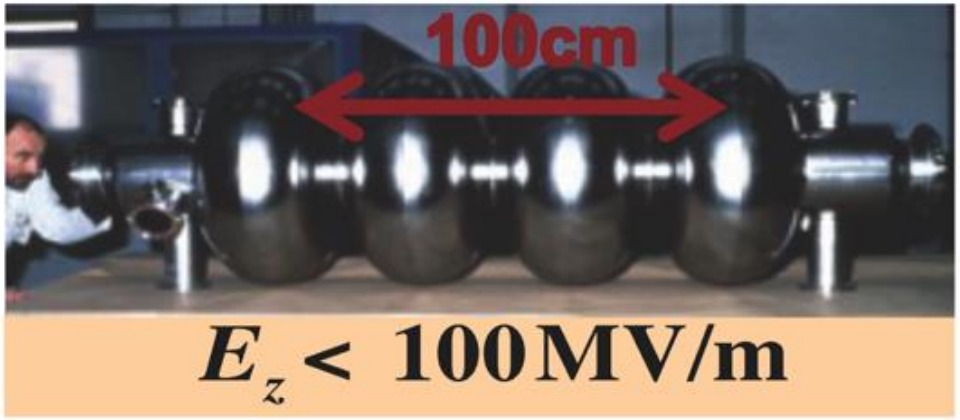
Contradiction:

To be improved: Rate of E change,

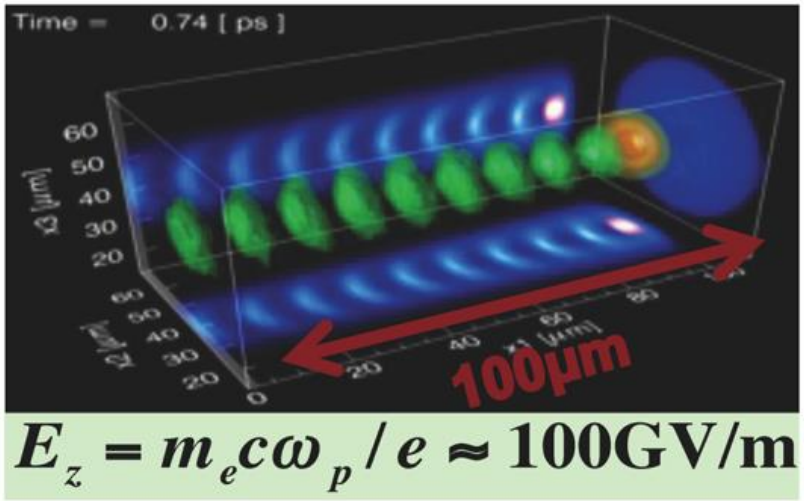
What gets worse: INTEGRITY

- **One of emerging AS-TRIZ principles**
  - **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

AS-TRIZ examples



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



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

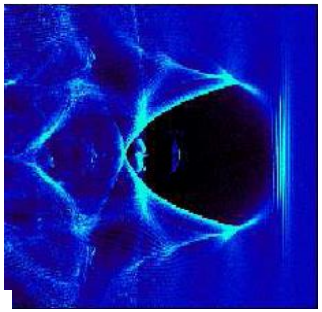
Solution:

- **One of emerging AS-TRIZ principles**
  - **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

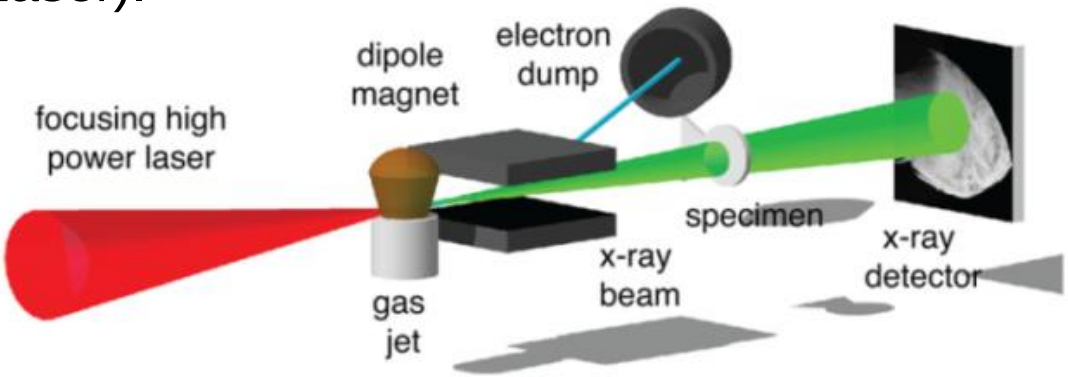
Laser Plasma accelerator

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

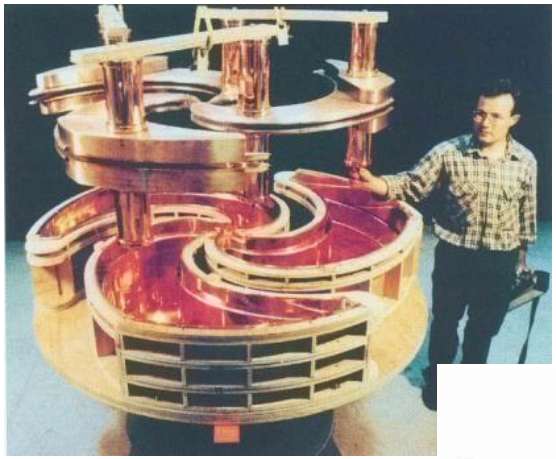
Similar electron energies can be reached in a much more compact accelerator using the “wake” created by a laser in a gas jet.



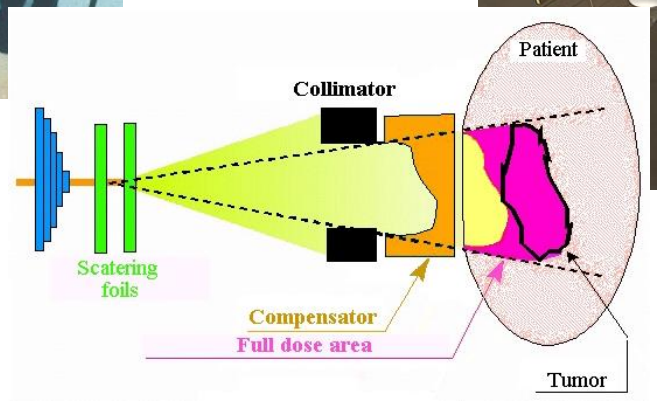
This could be used to build an accelerator compact enough to fit in several tens of meters space but powerful enough to be used as a light source (Free Electron Laser).



Laser acceleration of protons - motivation



RF cavity of the TERA compact protontherapy superconducting cyclotron



Heidelberg Ion-Beam Therapy Center

- **Proton therapy systems require 250 MeV protons**
- **Such systems, especially the beam delivery gantries, are large and expensive**
- **Desire to create compact laser –plasma acceleration proton therapy systems is one of main motivations of plasma acceleration of protons**

Summary

- Accelerator science – needed everywhere
- Acc. Science – rich history of inventions
- Next generation of accelerators and colliders are developed
- Applications of accelerators – many existing and new are coming
- New methods of acceleration getting to practical use
- New science instruments based on plasma acceleration are coming…