Lecture 3
Applications of Accelerators

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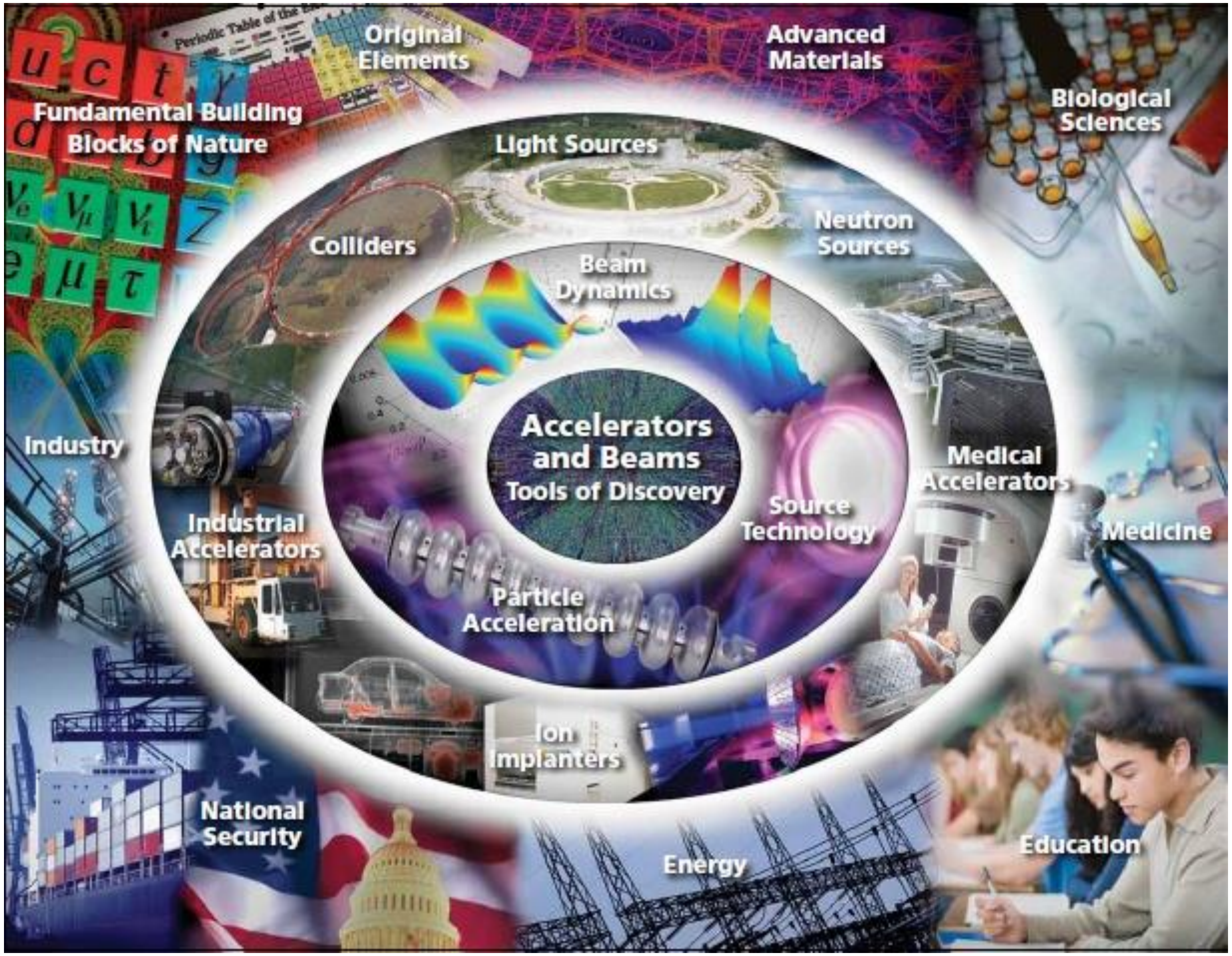
CERN & University of Oxford

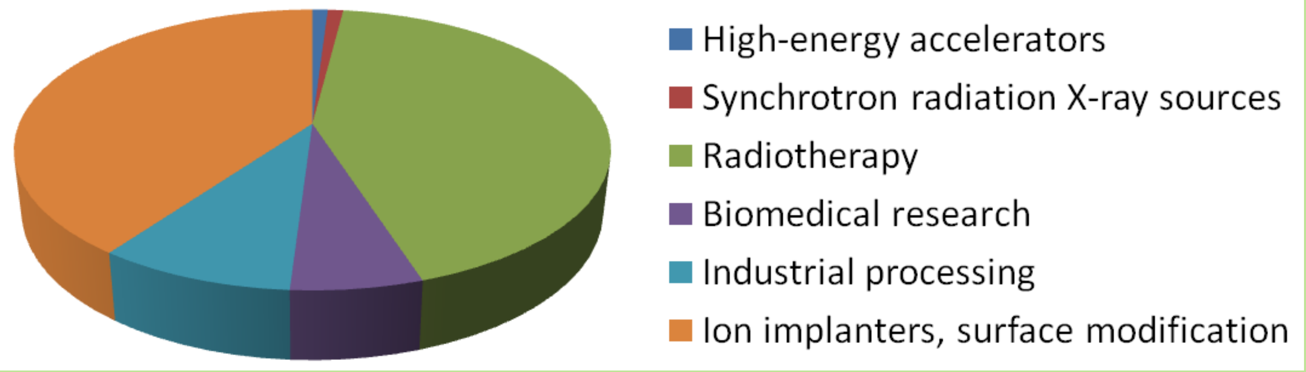
Graduate Accelerator Physics Course
John Adams Institute for Accelerator Science
11 October 2017

Introduction



Accelerators Worldwide

The number of accelerators worldwide exceed 20000



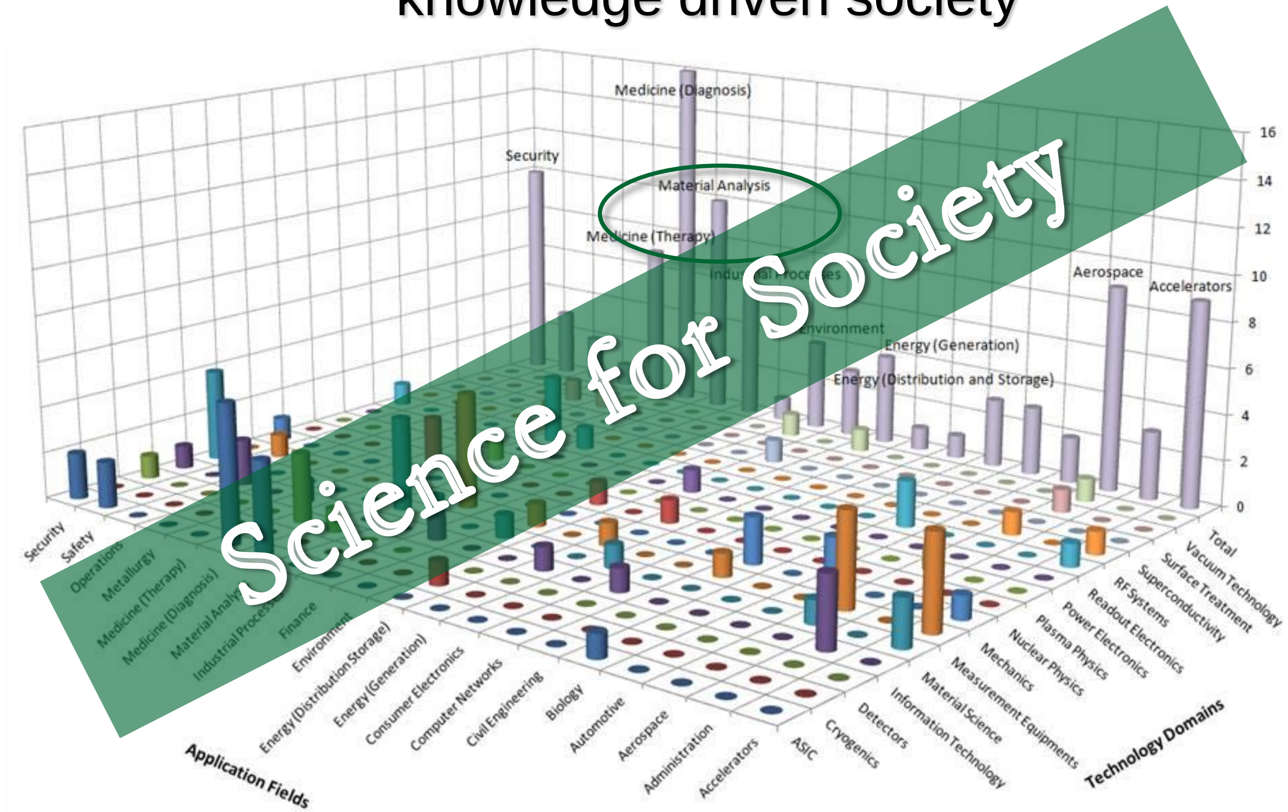
- Market for **medical and industrial** accelerators exceeds **$3.5 billion**. All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500 billion [1]

[1] http://www.acceleratorsamerica.org/

Accelerators are not only for high-energy physics

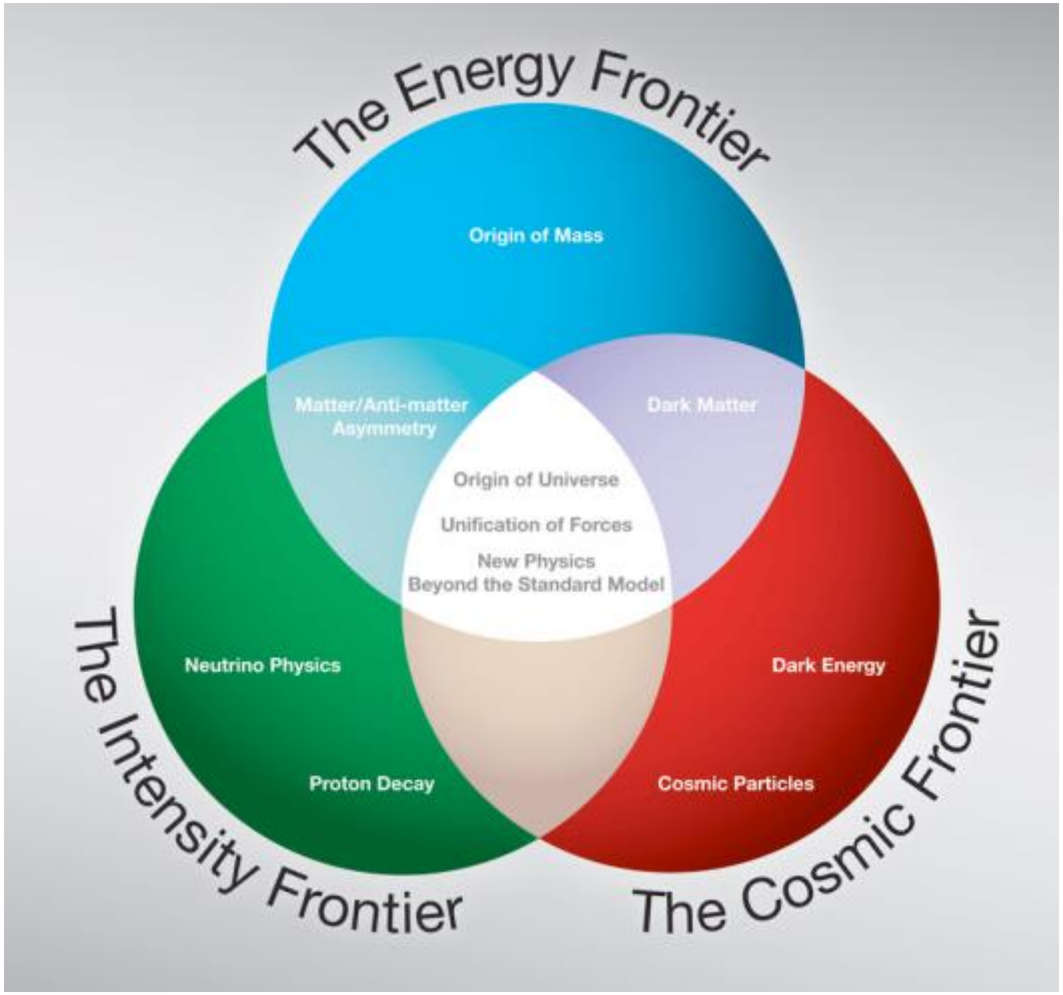
Technologies and Innovation

Cutting edge Research Infrastructures play a key role in a knowledge driven society

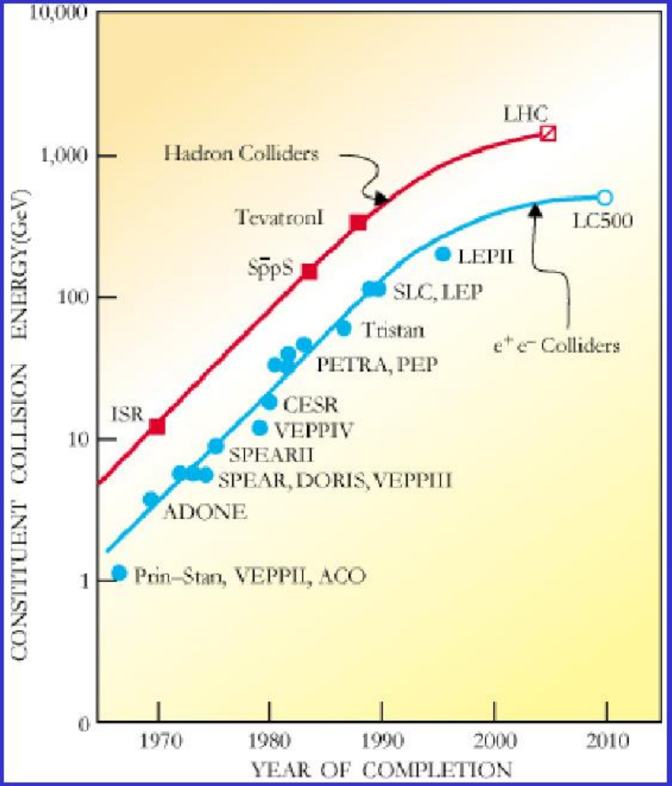


Knowledge is – and will be more and more –
the most precious resource for a sustainable development

Fundamental Building Blocks of Nature



Colliders – Energy vs. Time



M. Tigner: "Does Accelerator-Based Particle Physics have a Future?" Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

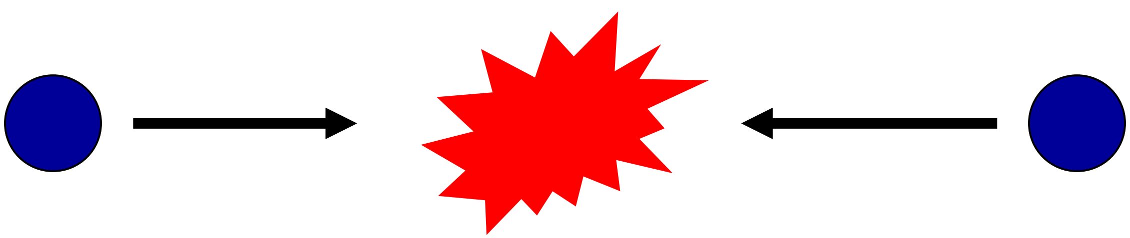
Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!

Not enough: Project cost increased by factor 200!

New technology needed…

Why Build Colliders?

- **Want to see constituents of matter .**
- **Smash matter together and look for the building blocks.**
- **Take small pieces of matter:**
  - **accelerate them to very high energy**
  - **crash them into one another**



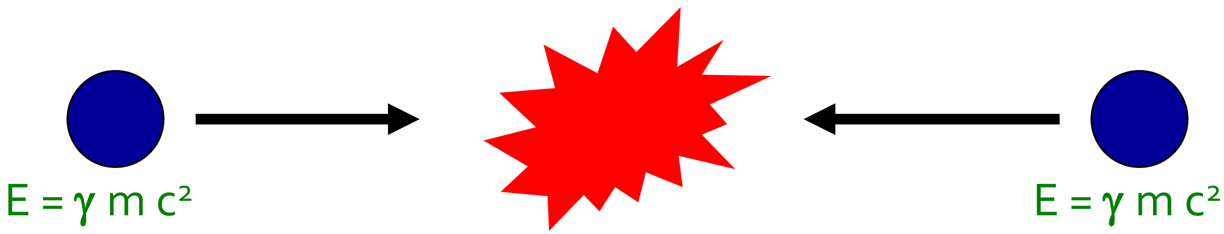
$E = mc^2 = \gamma m_0 c^2$

Higher energy produces more massive particles.

When particles approach speed of light, they get more massive but not faster.

Why Colliders?

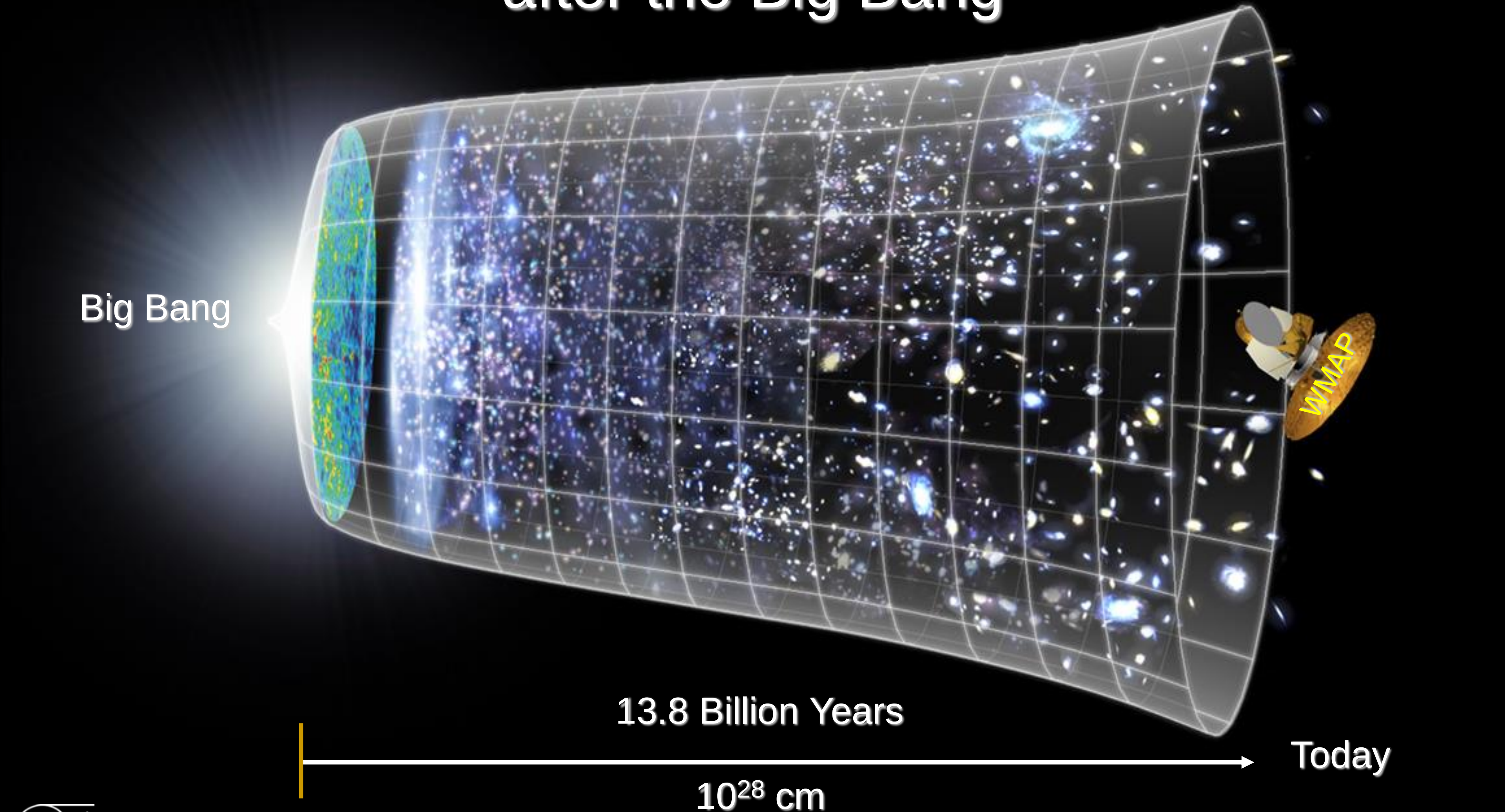
Only a tiny fraction of energy converted into mass of new particles
(due to energy and momentum conservation)



Entire energy converted into the mass of new particles

Scientific Challenge:

to understand the very first moments of our Universe after the Big Bang



Key Equation

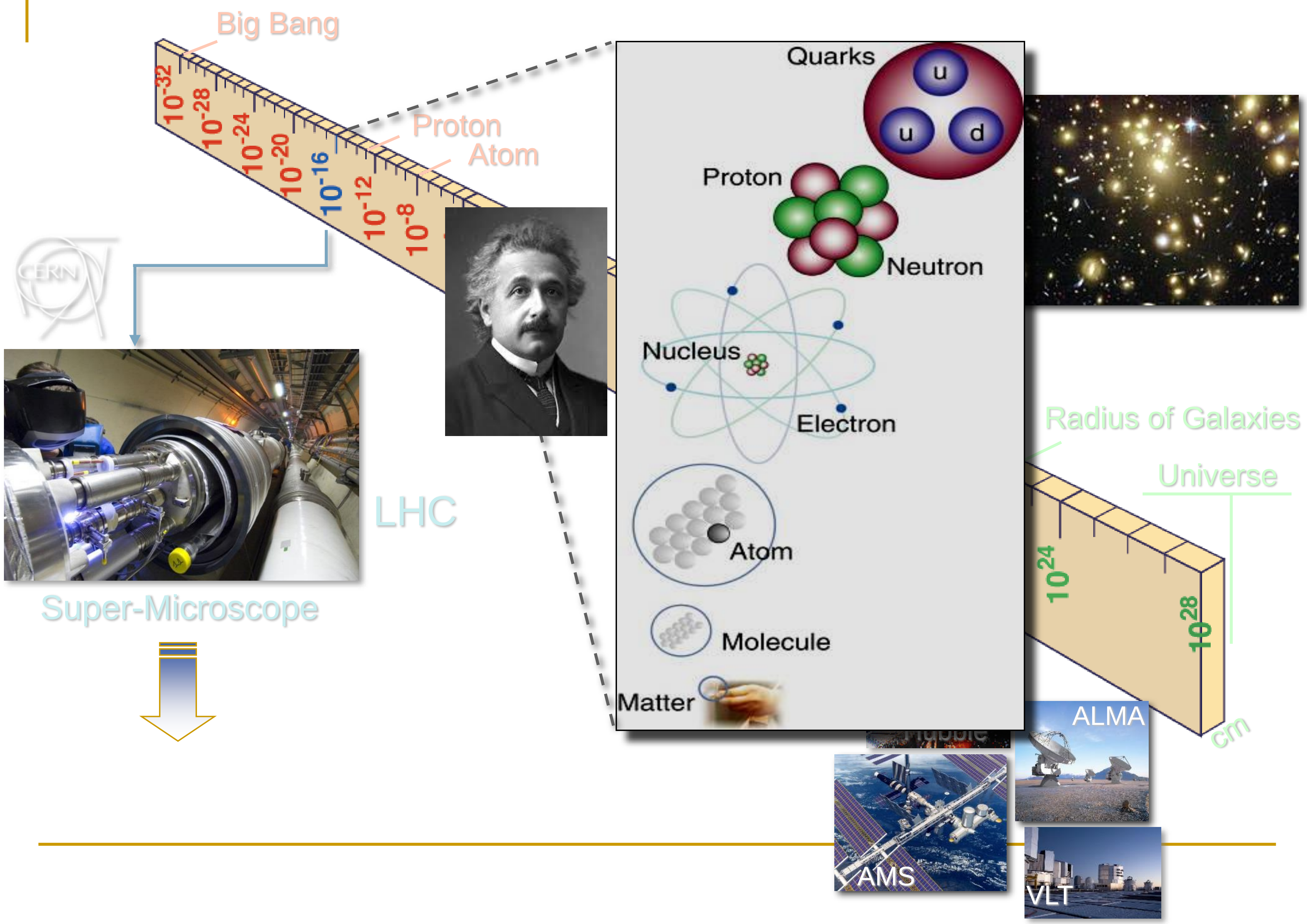
Momentum

$$\lambda = h / p \; (1.2 \text{ fm} / \text{p}\,[\text{GeV/c}]\,)$$

De Broglie wavelength

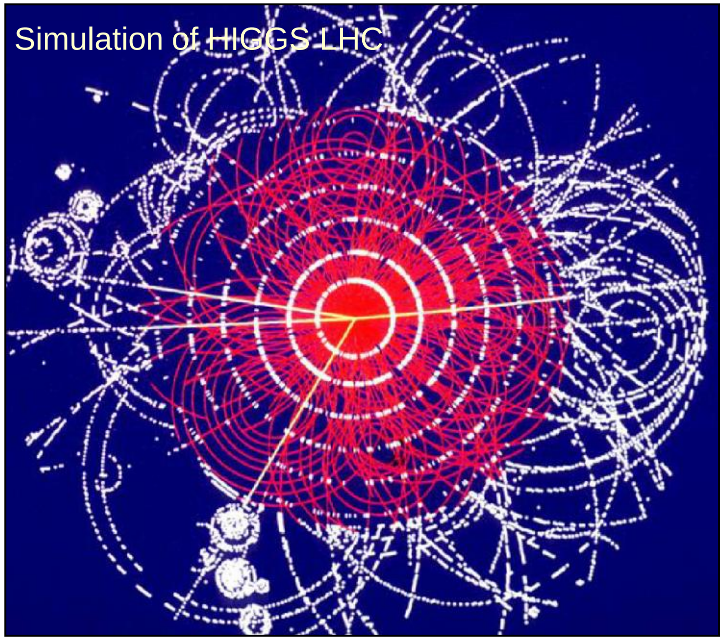
Planck Constant

De Broglie Wavelength
Wave-particle duality
For higher E, probe shorter distances inside matter

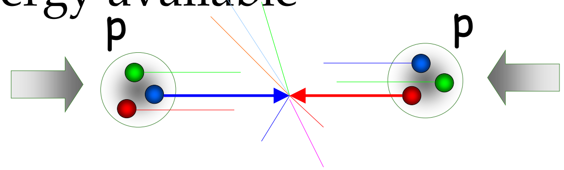


Big Bang
10^-32
10^-28
10^-24
10^-20
10^-16
10^-12
10^-8
Proton
Atom
Quarks
u
u
d
Proton
Neutron
Nucleus
Electron
Atom
Molecule
Matter
Radius of Galaxies
Universe
10^24
10^28
cm
LHC
Super-Microscope
ALMA
AMS
VLT

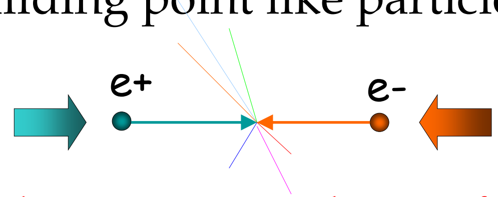
Collider Characteristics

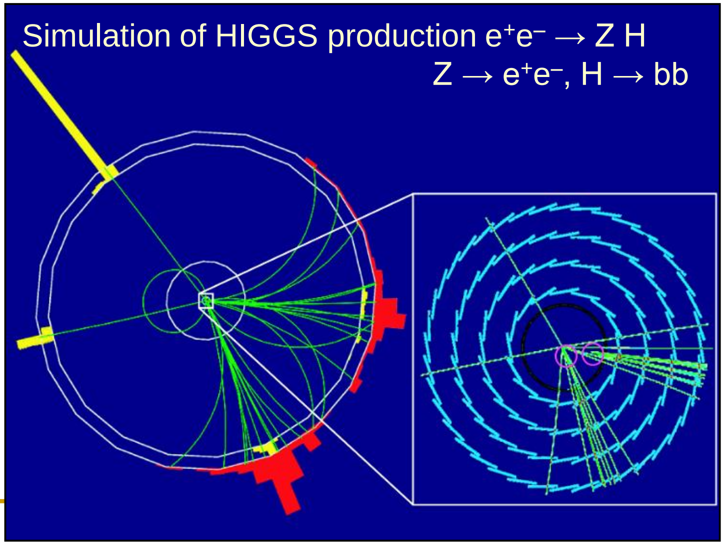


- Hadron collider at the frontier of physics
  - huge QCD background
  - not all nucleon energy available in collision



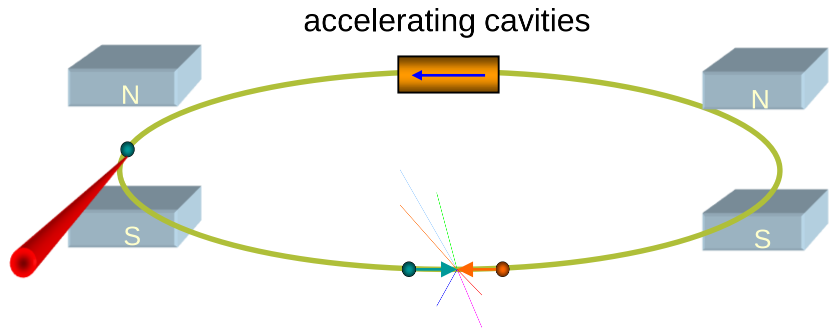
- Lepton collider for precision physics
  - well defined initial energy for reaction
  - Colliding point like particles





- Candidate next machine after LHC
  - e^+e^- collider
  - energy determined by LHC discoveries
  - study in detail the properties of the new physics that the LHC finds

Circular versus Linear Collider

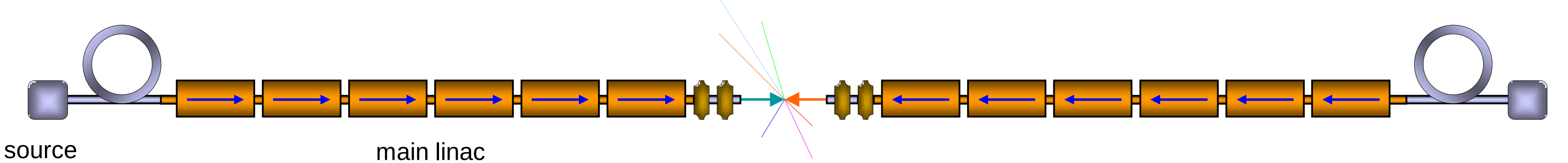


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



Linear Collider

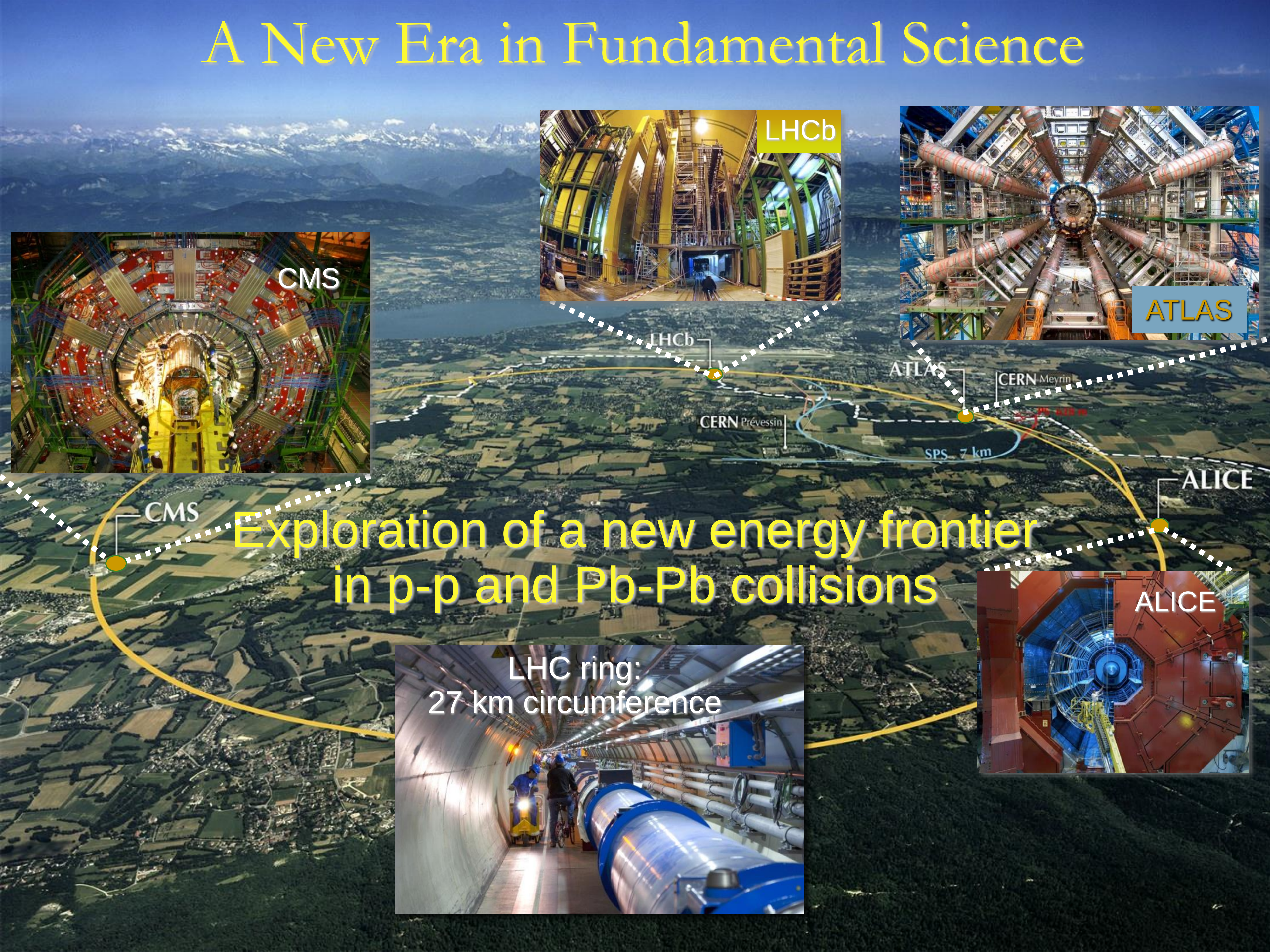
few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

A New Era in Fundamental Science

Exploration of a new energy frontier in p-p and Pb-Pb collisions



The LHC Arcs

The Predictable Future - *LHC Timeline*

2009 — Start of LHC

Run 1: 7 and 8 TeV centre-of-mass energy, luminosity ramping up to several 10^{33} cm^{-2} s^{-1}, ~25 fb^{-1} delivered

2013/14

LS1 - LHC shut-down to prepare … design energy and n…

…inal (10^{34} cm^{-2} s^{-1}, ~50 to 100 fb^{-1}) and …gy (13 and 14 TeV)

2018 — … injector and LHC upgrades to go to ultim…

Run 3: Ram… nominal, reaching ~100 fb^{-1} / year … fb^{-1}

~202… — LS3 – High-luminosity LHC (HL-LHC). New focusing magnets and CRAB cavities for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

>2035

Study of the properties of the Higgs Boson & physics beyond the Standard Model

LHC results will guide the way at the energy frontier

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

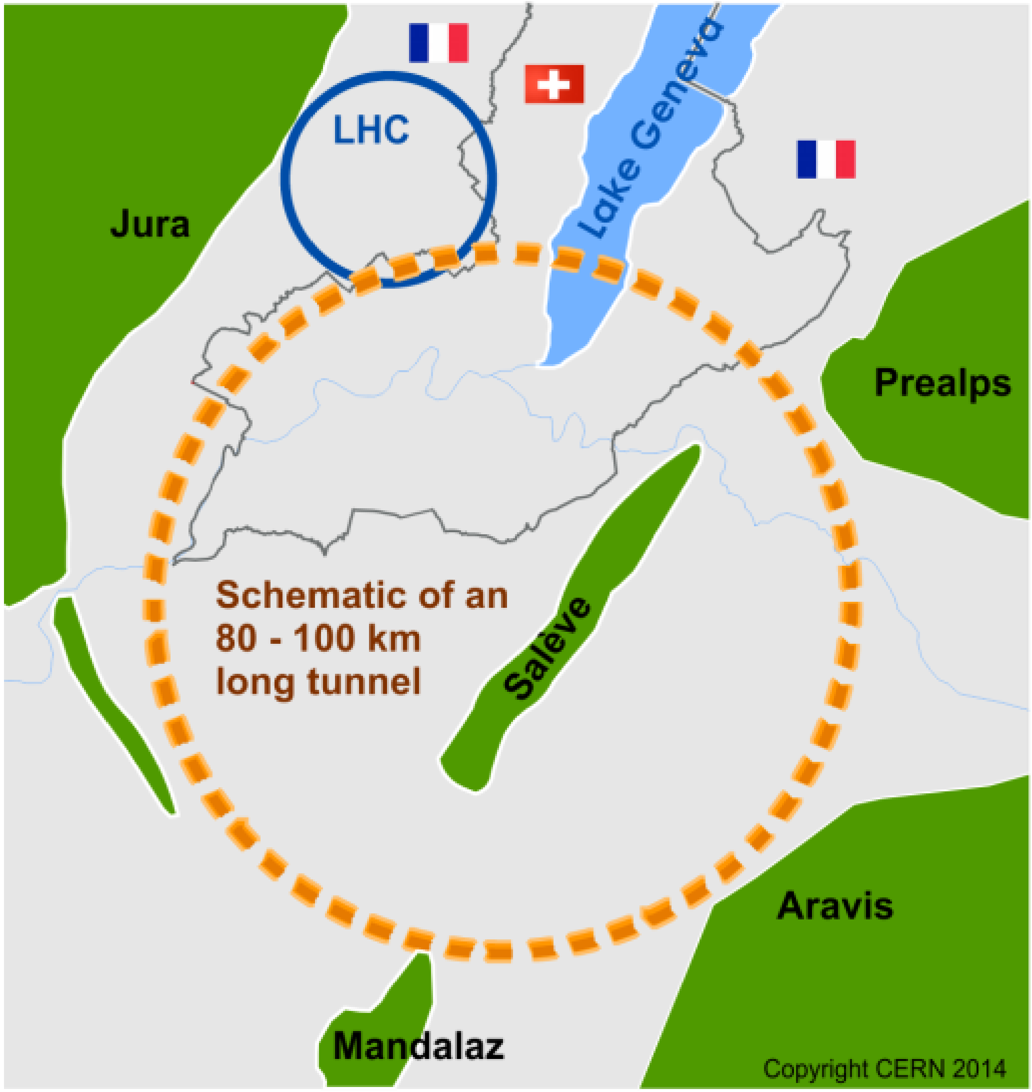
•***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

•***e$^+$e$^-$* collider (*FCC-ee*)** as potential intermediate step

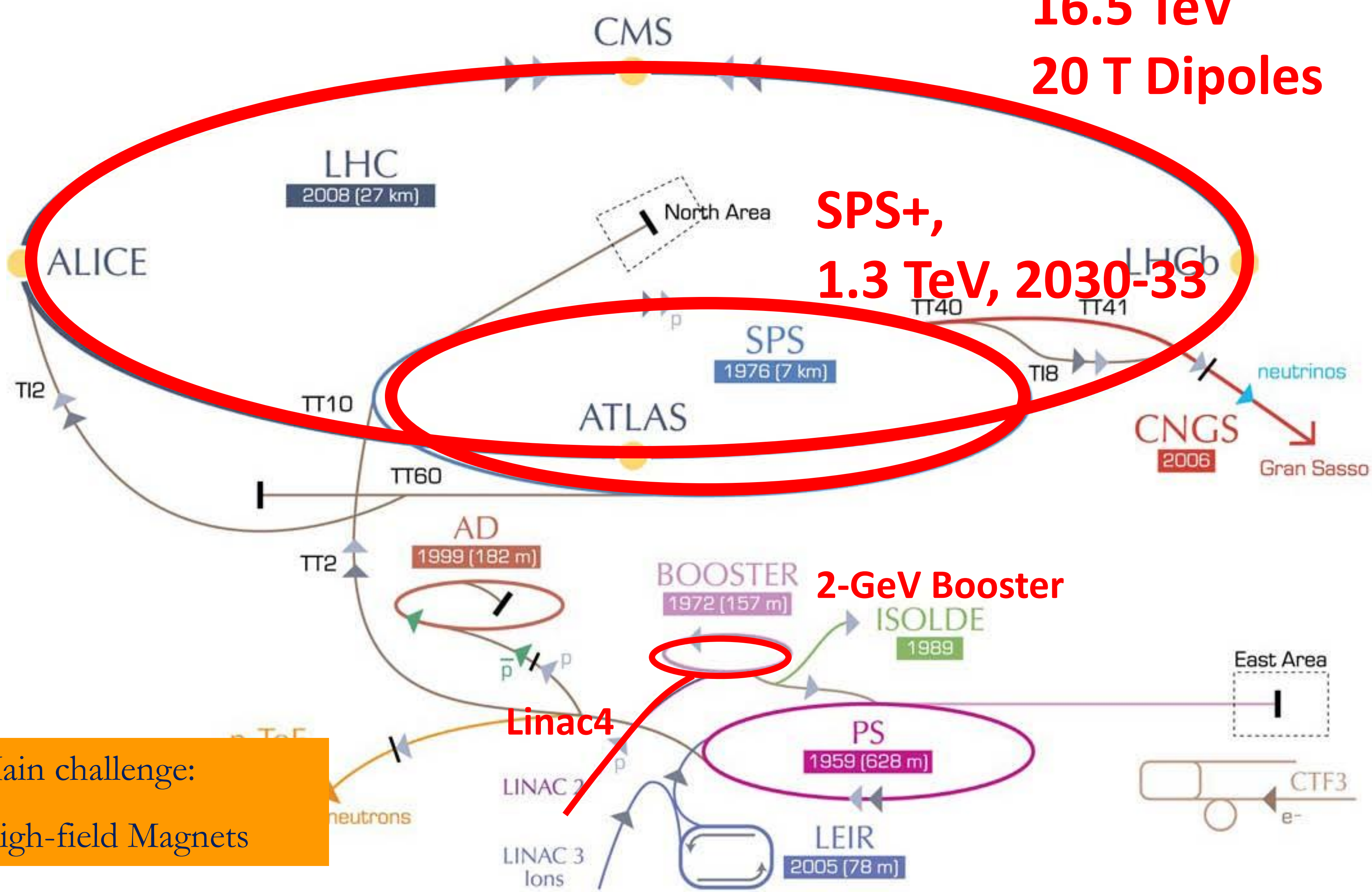
•***p-e* (*FCC-he*) option**

•**80-100 km infrastructure** in Geneva area



High-Energy LHC (HE-LHC)?

HE-LHC >2035
16.5 TeV
20 T Dipoles

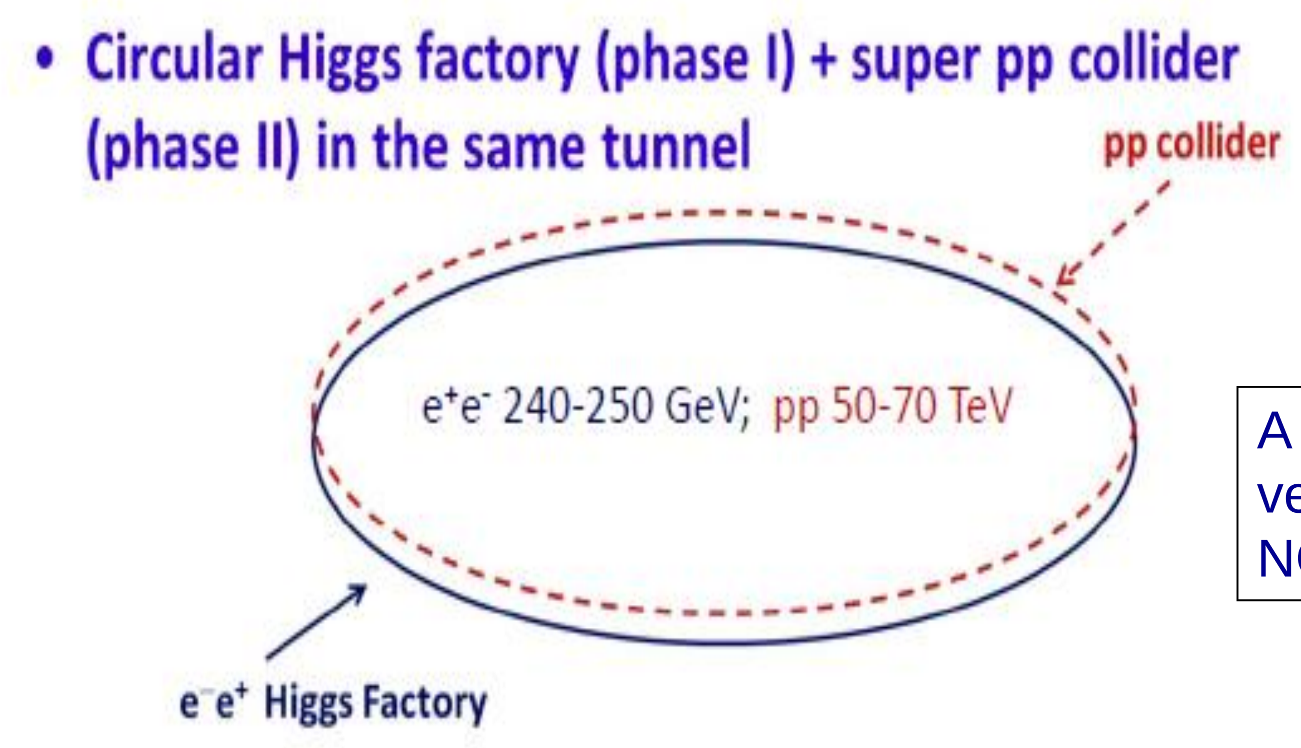


Main challenge:

High-field Magnets

CEPC+SppC

- For about 8 years, we have been talking about “What can be done after BEPCII in China”
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012

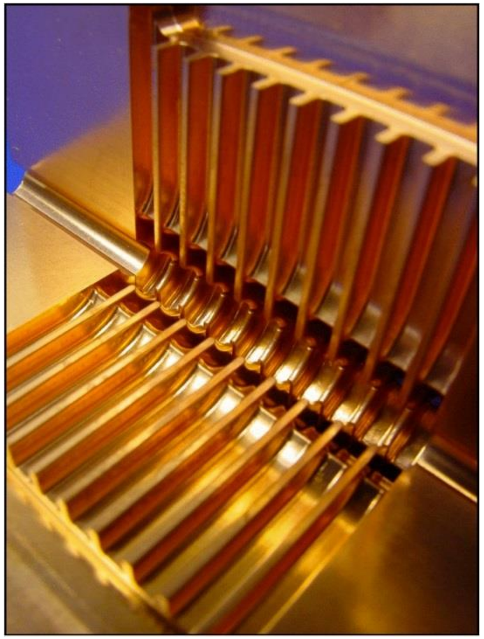


Yifang Wang
Feb. 2014

A 50-70 km tunnel is very affordable in China NOW

ILC (and the Compact Linear Collider CLIC)

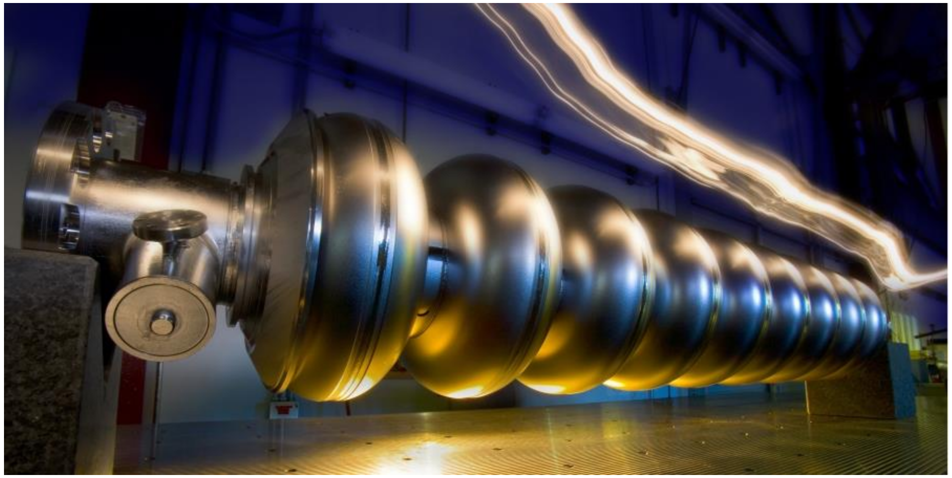
CLIC



•2-beam acceleration scheme at room temperature
•Gradient 100 MV/m
•$\sqrt{s}$ up to 3 TeV
•Physics + Detector studies for 350 GeV - 3 TeV

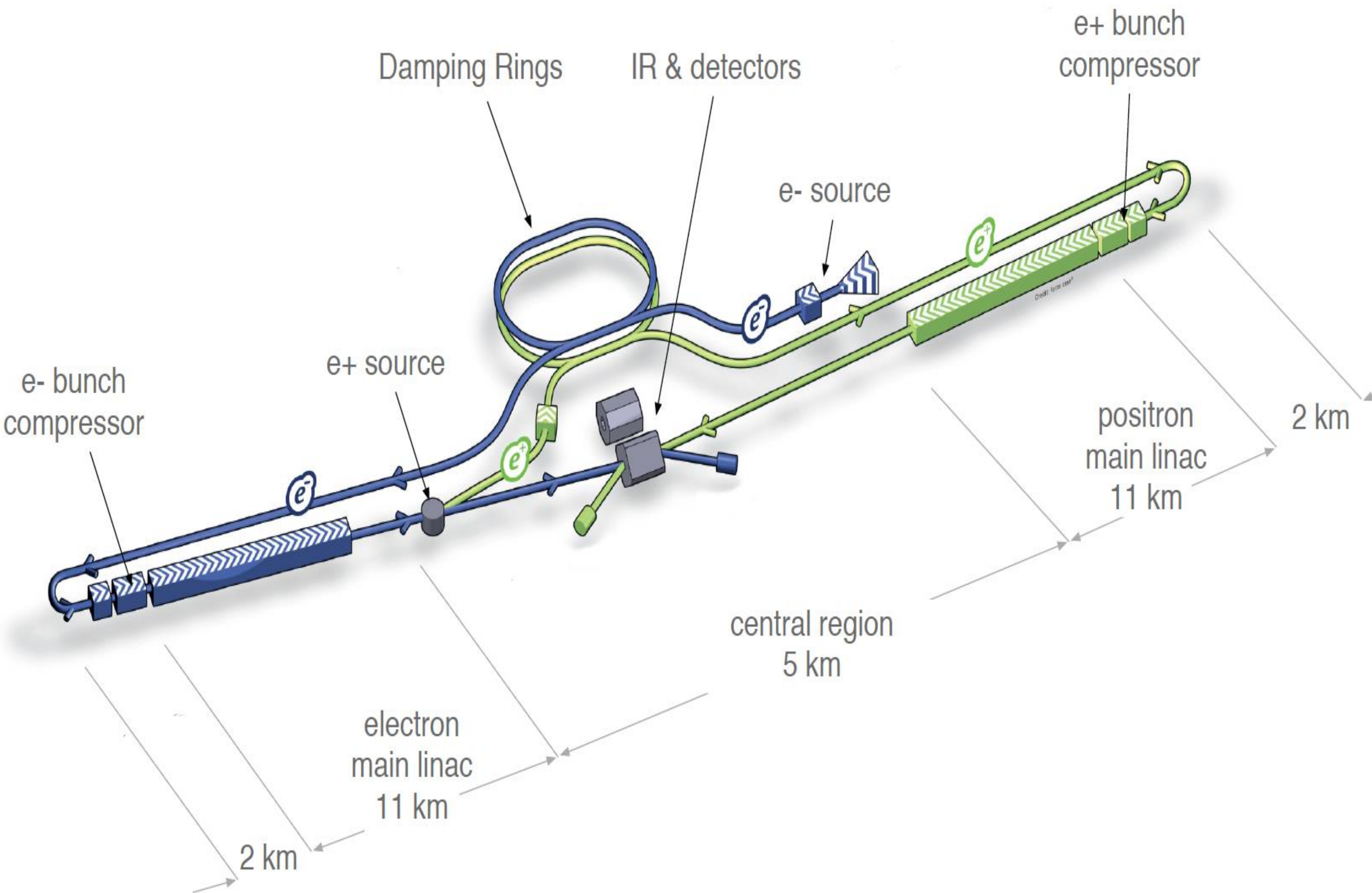
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

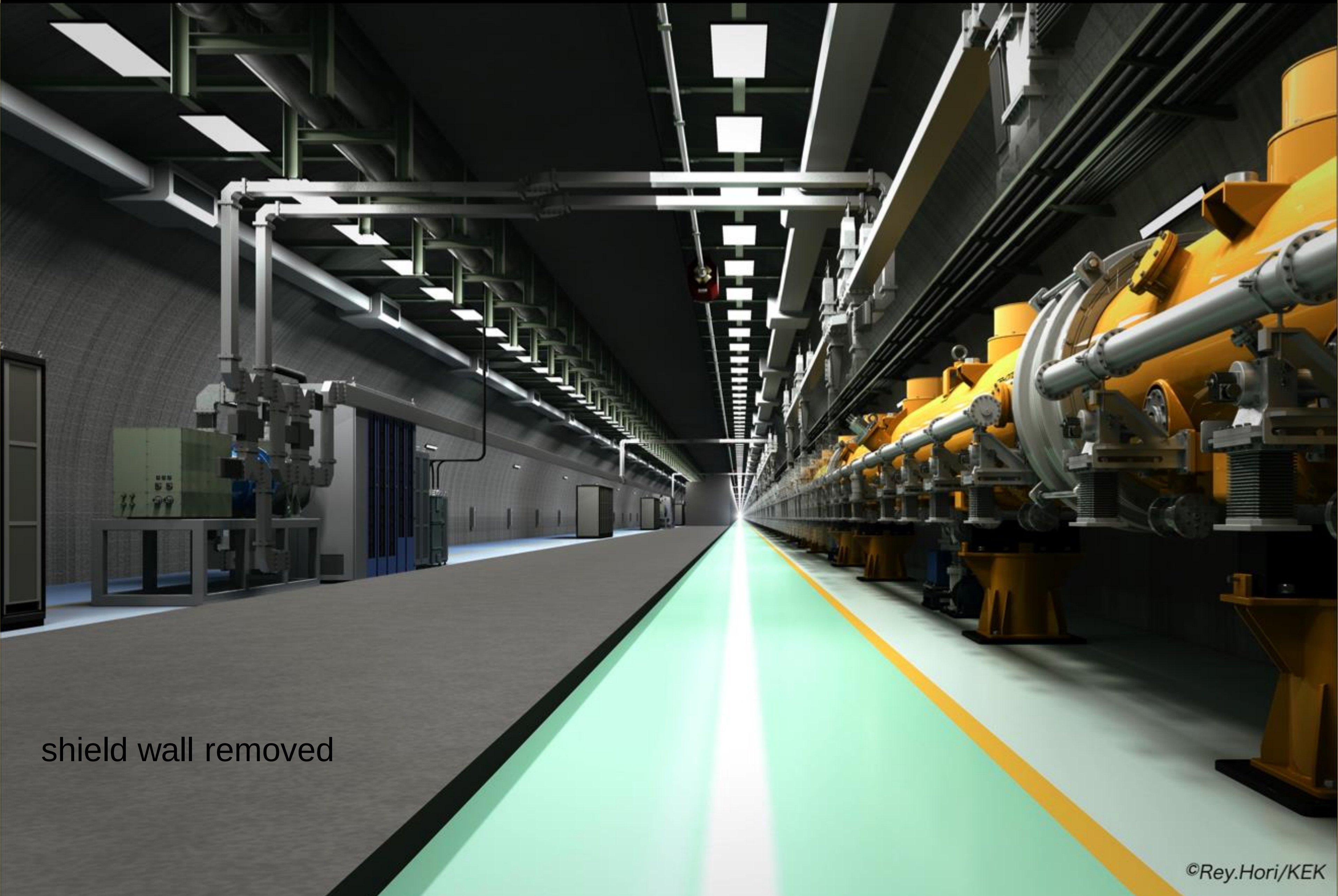
ILC



•Superconducting RF cavities (like XFEL)
•Gradient 32 MV/m
•$\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
•Focus on ≤ 500 GeV, physics studies also for 1 TeV

The International Linear Collider

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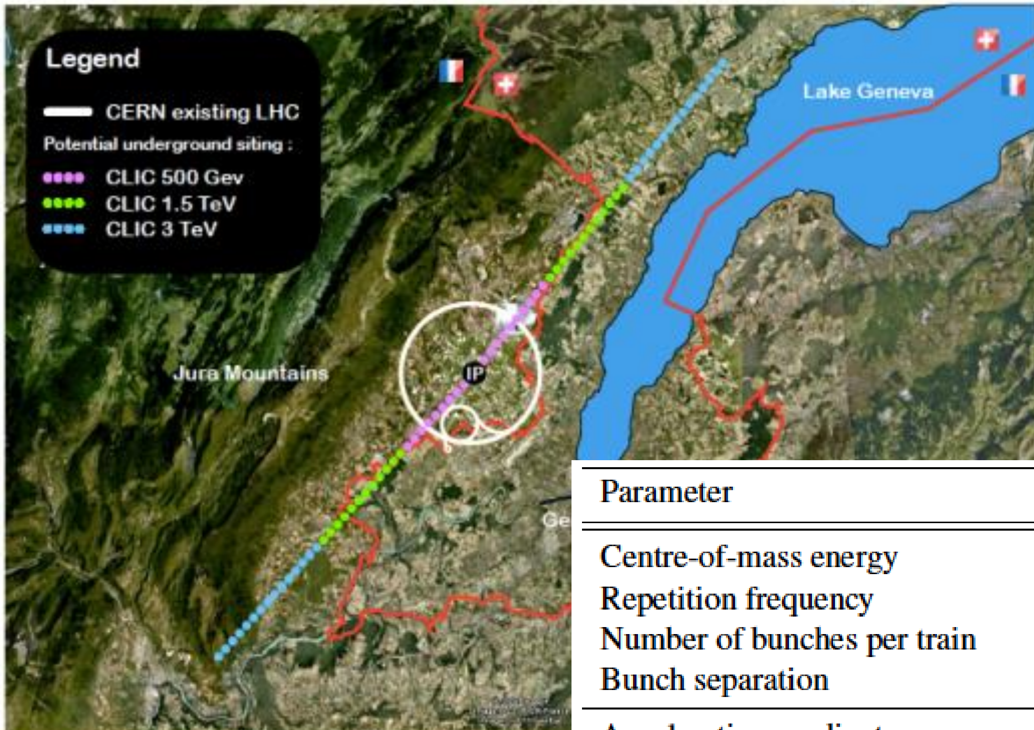
CLIC Implementation



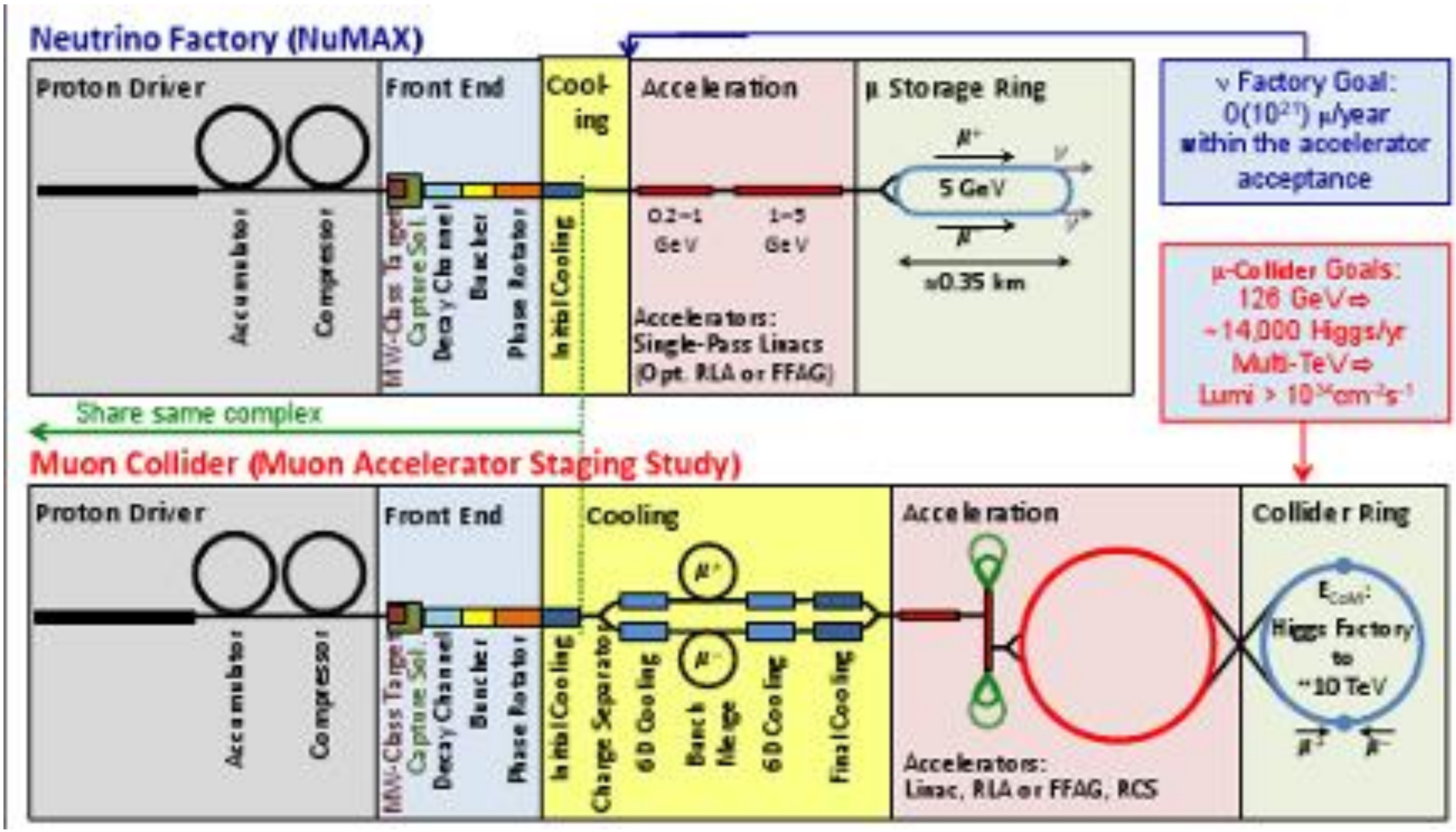
← Possible lay-out near CERN

↓ CLIC parameters

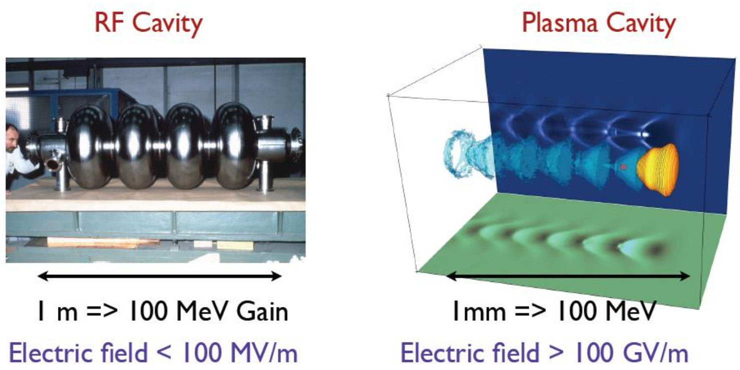
Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

Note: the design is currently being re-optmised, e.g. to include 350 GeV as the first stage

Muon Collider (?)



Plasma Accelerators



V. Malka *et al.*, Science **298**, 1596 (2002)

e.g. AWAKE at CERN

Demonstration experiment to verify novel technique of p-driven plasma wakefield acceleration

Plasma accelerators:

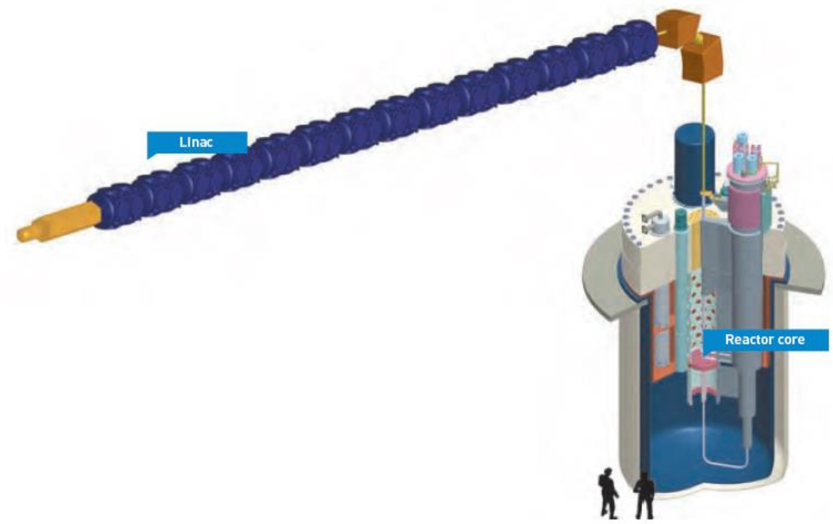
Transform transverse fields into longitudinal fields.

Significantly higher accelereating gradients than conventional RF.

- **Laser driven**
- **e- driven**
- **p driven**
- **Dielectric wakefields**

Accelerators for Energy

- Accelerator-Driven Subcritical System (ADSR)
  - External source of neutrons to drive sub-critical reactor loaded with non-fissile fuel such as ^{232}Th.
  - Neutrons produced by high-power proton beam through spallation, breeding ^{233}U causing it to fission.
  - Cannot support self-sustaining chain reaction.
  - ^{232}Th is widely-available natural resource.
  - Released thermal power is 100 times that of beam energy.
  - Turning off the accelerator stops the fission reaction.



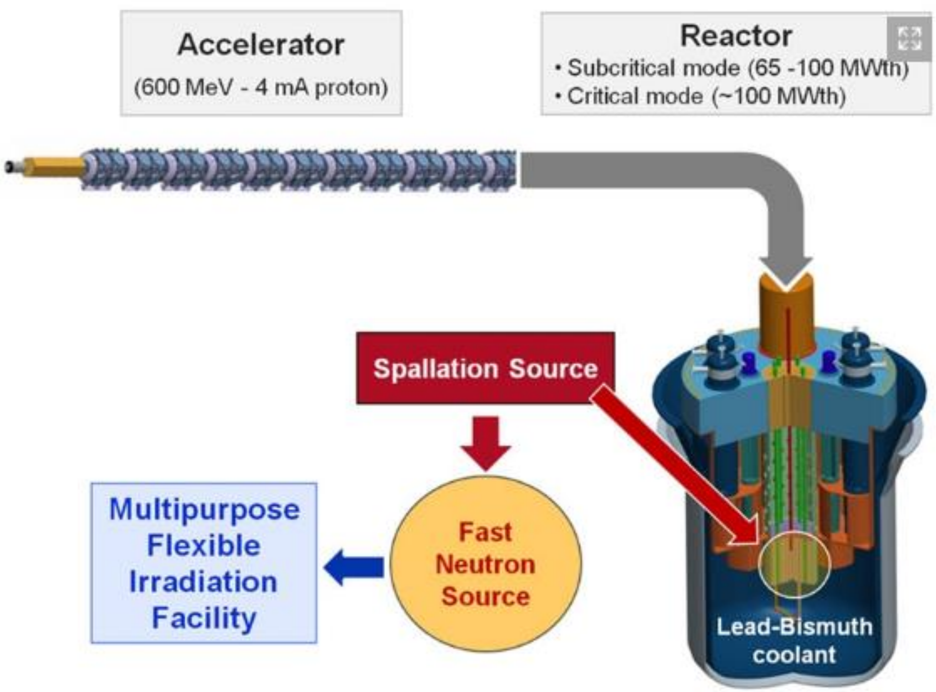
Use of Th instead of U produces less actinides.

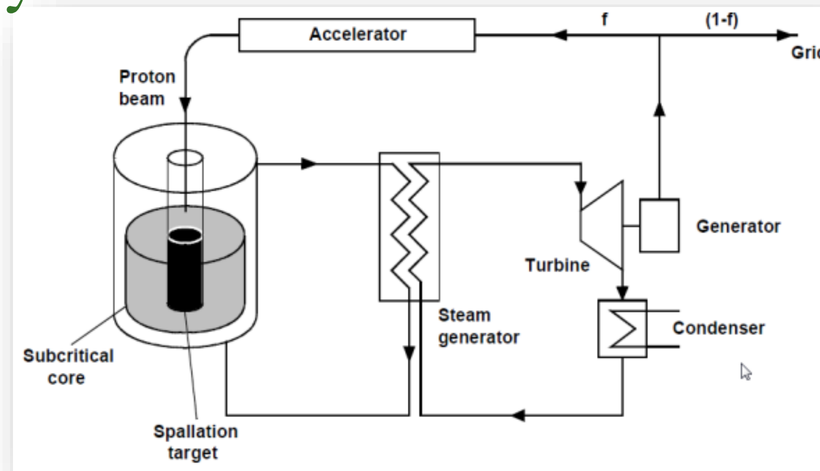
The cycle produces much less long-lived radioactive waste (e.g. Pu).

Enough Th is available to sustain such systems for 10 centuries.

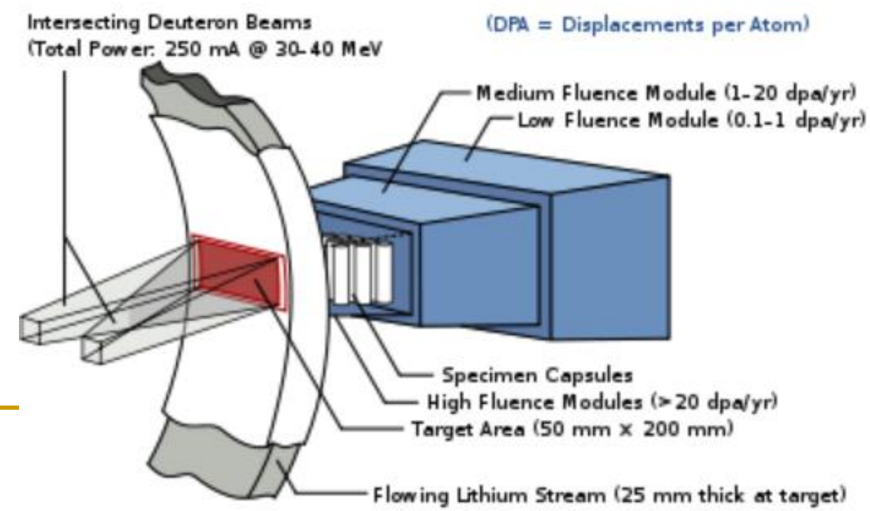
Accelerators for Energy

Accelerators can drive next-generation reactors (ADSR) that burn non-fissile fuel, such as thorium





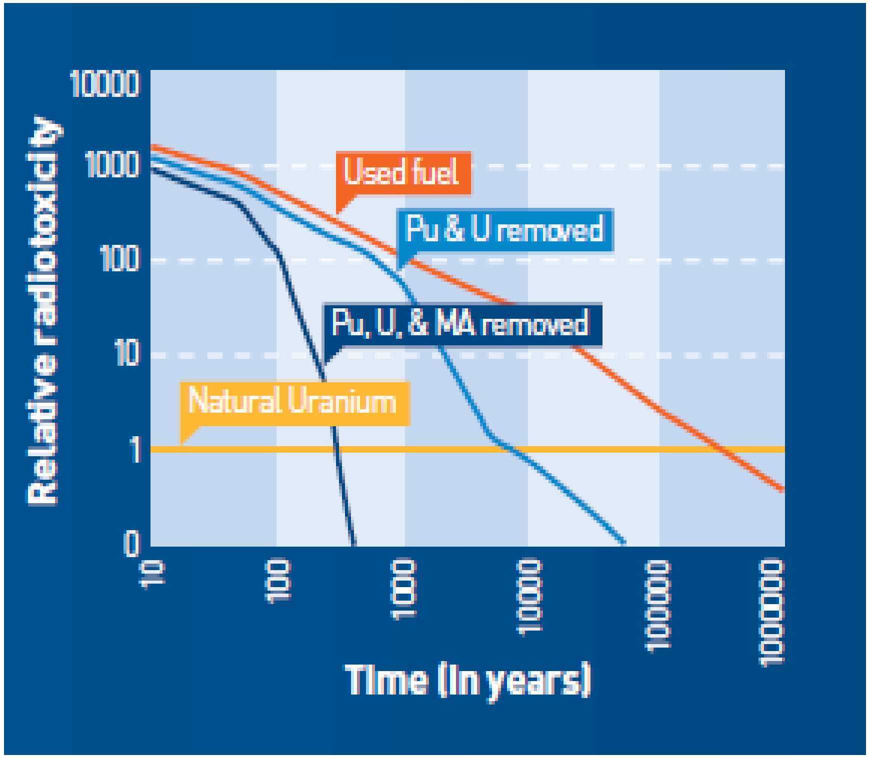
MYRRHA: Multi-purpose hybrid research reactor for high-tech applications, conceived as an accelerator driven system



International Fusion Material Irradiation Facility (IFMIF)

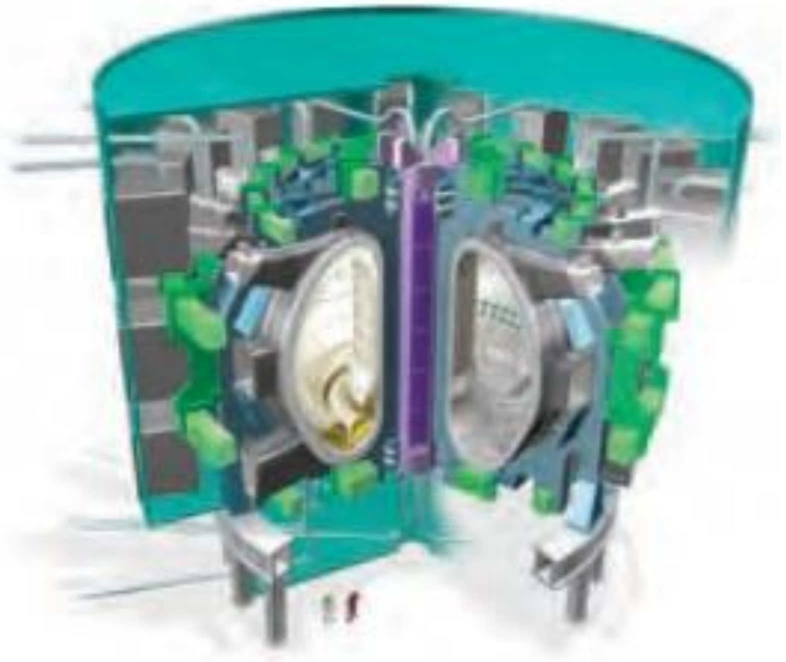
Accelerators for Energy

- ADSR & Radioactive Waste Transmutation
  - ADSR neutrons interact with surrounding fuel material containing separated long-lived isotopes.
    - Transmute these isotopes into shorter-lived products.



Accelerators for Energy

- International Thermonuclear Experimental Reactor (ITER)
  - Ion beams to be part of plasma heating techniques for fusion
    - Provide high current drive efficiency required magnetic confinement fusion facilities.
    - Required tens of A of ion current at 1 MeV kinetic energy.

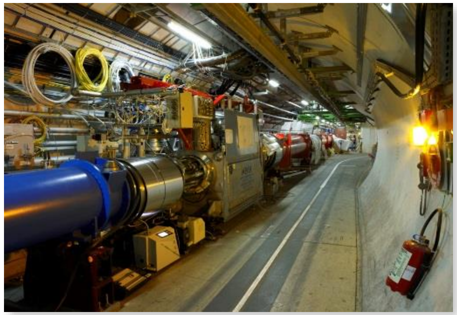


Accelerators for the Environment

- CLOUD experiment at the CERN PS
  - Experiment using cloud chamber to study possible link between cosmic-rays and cloud formation.
    - Studies suggest that cosmic- rays may have an influence on the amount of cloud cover through the formation of new aerosols (tiny particles suspended in the air that seed cloud droplets).
  - Understanding the underlying microphysics in controlled laboratory conditions is a key to unraveling the connection between cosmic-rays, clouds and climate.
  - First time high-energy physics accelerator used to study atmospheric and climate science.

Medical Application as an Example of Particle Physics Spin-off

Combining Physics, ICT, Biology and Medicine to fight cancer



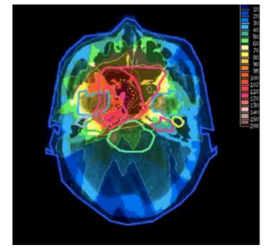
Accelerating particle beams

~30'000 accelerators worldwide

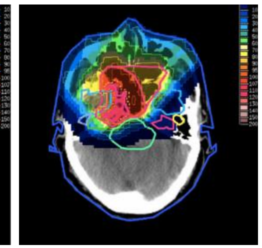
~17'000 used for medicine

Hadron Therapy

Protons
light ions



X-ray

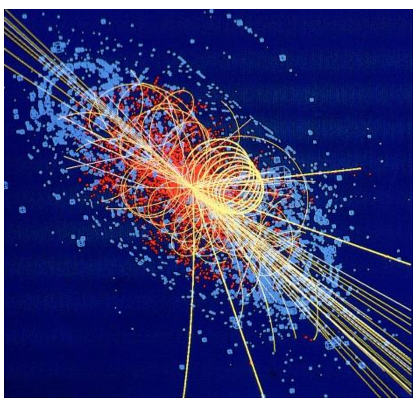


protons

Leadership in Ion Beam Therapy now in Europe and Japan

>100'000 patients treated worldwide (45 facilities)

>50'000 patients treated in Europe (14 facilities)

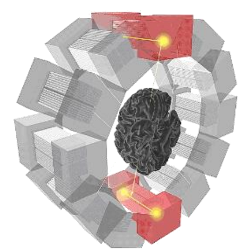


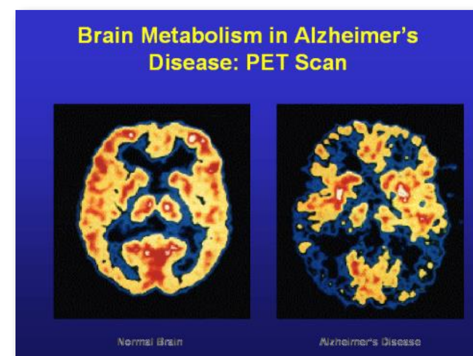
Detecting particles

Imaging

Clinical trial in Portugal, France and Italy for new breast imaging system (ClearPEM)

PET Scanner





Accelerators for Medical Use

- Production of radionuclides with (low-energy) cyclotrons
  - Imaging
  - Therapy
- Electron linacs for conventional radiation therapy.
- Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u 12C-ions).

Accelerators for Medicine

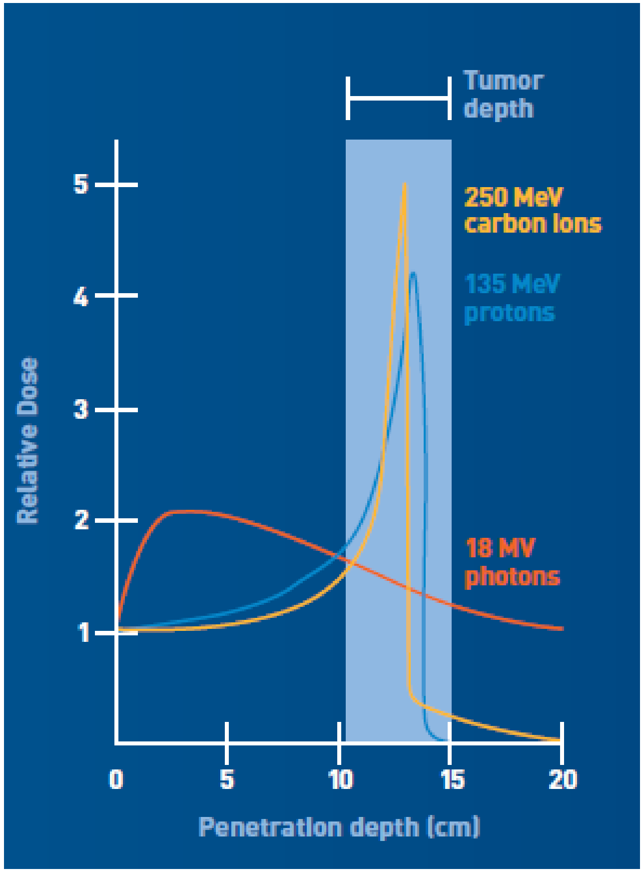
- Medical Therapy
  - X-rays have been used for decades to destroy tumours.
  - For deep-seated tumours and/or minimizing dose in surrounding healthy tissue use hadrons (protons, light ions).
  - Accelerator-based hadrontherapy facilities.

Accelerator cancer therapy

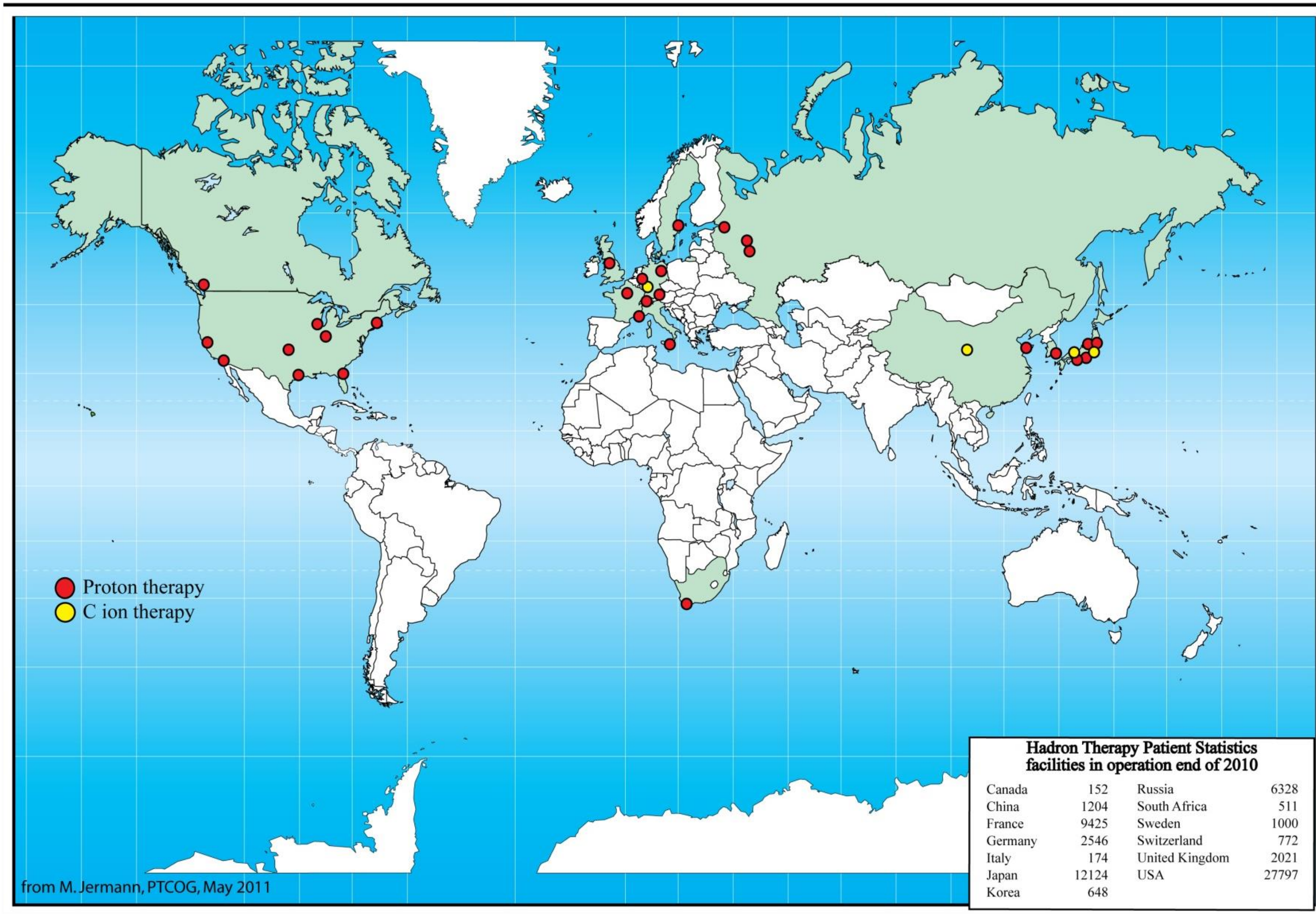
Loma Linda Proton Treatment Centre
Constructed at FNAL

Accelerators for Medicine

Photons, Protons and Light Ions



Centers for HADRON Therapy in operation end of 2010



Canada	152	Russia	6328
China	1204	South Africa	511
France	9425	Sweden	1000
Germany	2546	Switzerland	772
Italy	174	United Kingdom	2021
Japan	12124	USA	27797
Korea	648		

Worldwide: 30 centres (4 have C-ions): ~ 65’000 patients

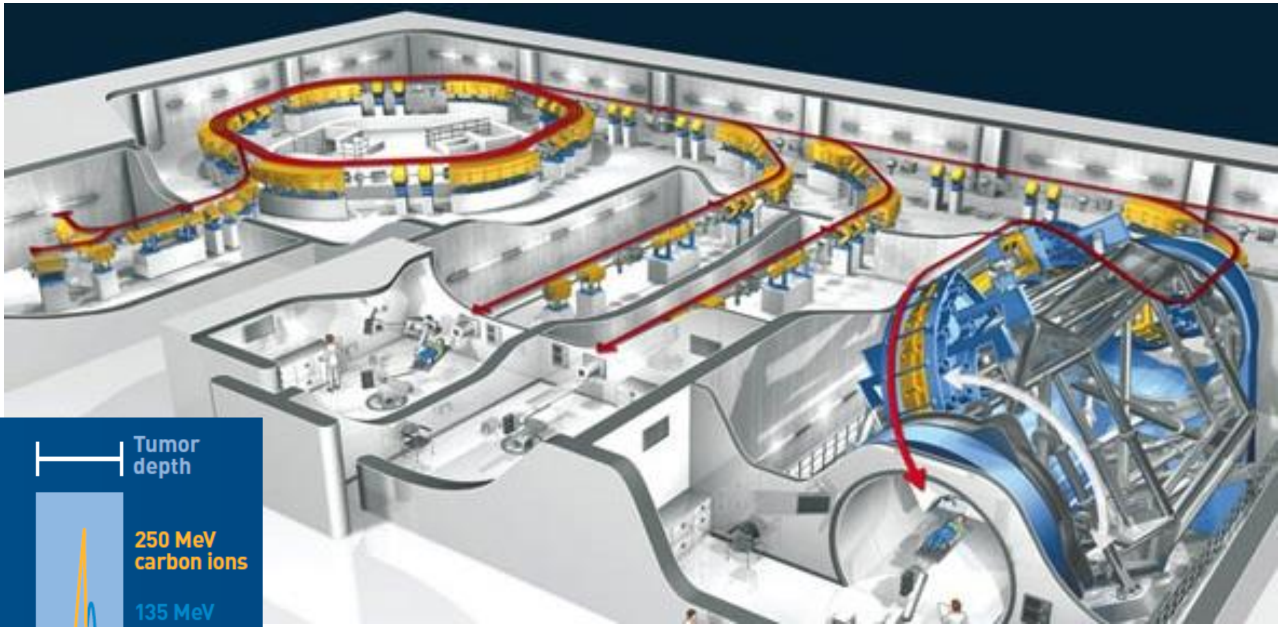
Europe: 9 centres (with C-ions at GSI and Heidelberg): ~ 16’000 patients

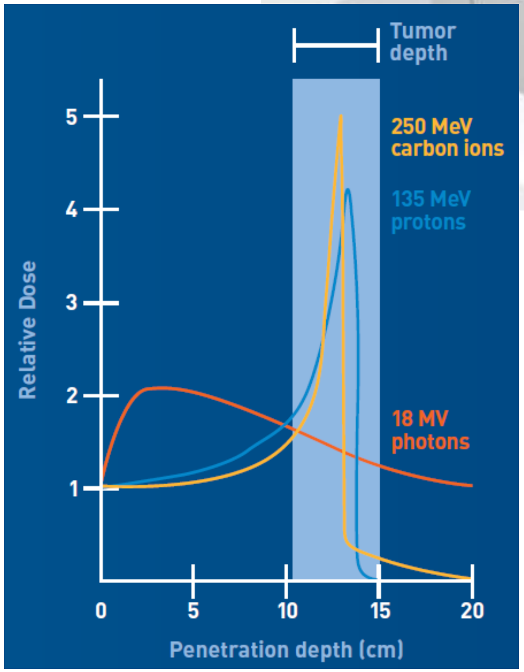
The Clatterbridge Centre for Oncology

Established 1989 – 60 MeV protons

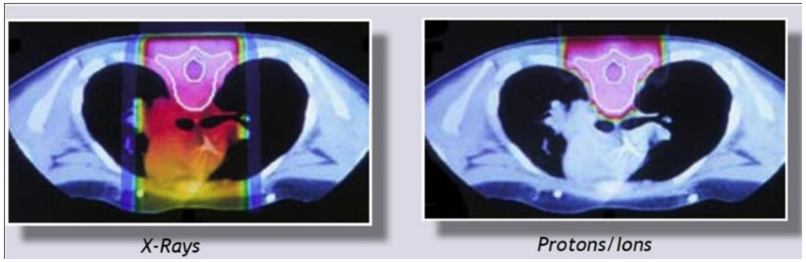
First hospital-based proton therapy – more than 1400 patients with ocular melanoma

Radiotherapy with Ions





Heidelberg Ion Therapy Facility (protons & carbon)

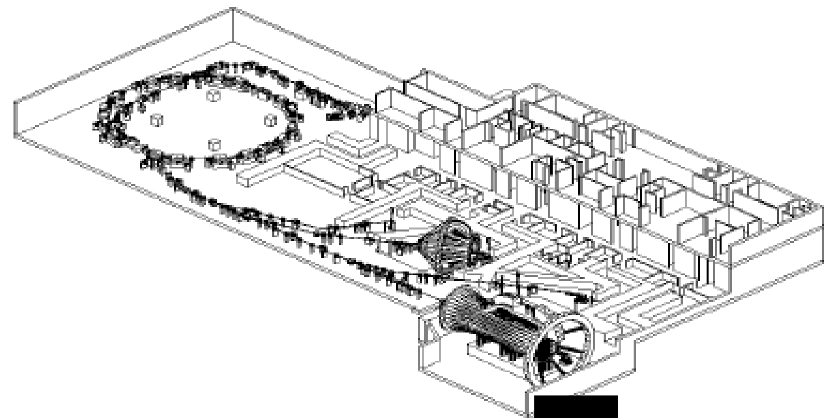


Cancer therapy with x-rays and protons or heavier ions

PIMMS Study 2000

CERN in collaboration with INFN and TERA

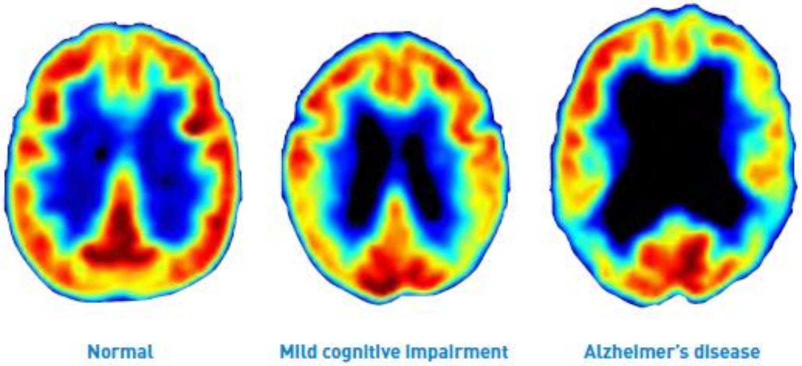
has led to:



Accelerators for Medicine

- Medical Imaging
  - Radioisotopes have become vital components in medicine.
    - Produced at reactors or accelerators.
  - Positron Emission Tomography (PET)
    - Requires positron emitter ^{18}F
  - ^{99}Mo / ^{99m}Tc
    - 100 kW of 200 MeV protons impinging on depleted U target produce neutrons.
    - Neutrons targeted on low-enriched U thus producing ^{99}Mo.

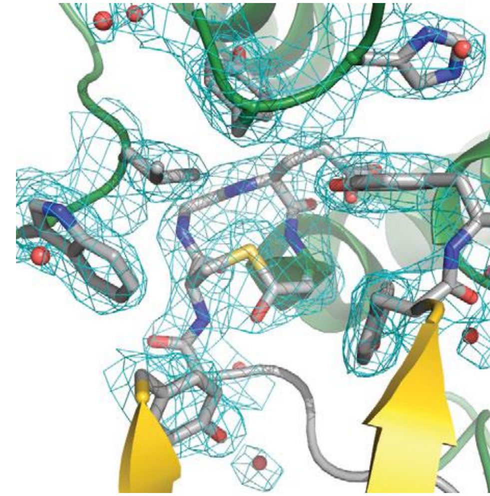
Bone scans indicating increased ^{99m}Tc intake due to cancer growth



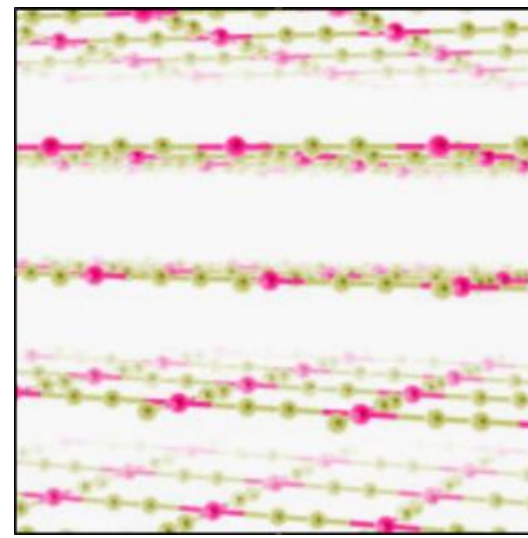
PET Scan

Neutrons & X-rays

Protein structure revealed with help of light sources



ISIS and Diamond neutron and X-ray sources
Harwell, UK



2-d material (graphene)

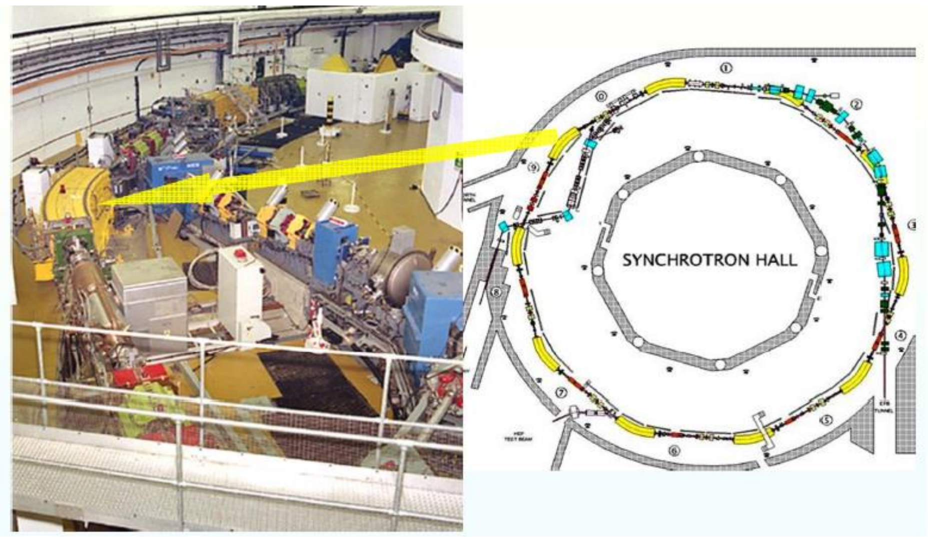
Neutron and X-ray imaging essential for studies of proteins and advanced materials.

diamond

Science & Technology Facilities Council

Accelerators for Neutron Science

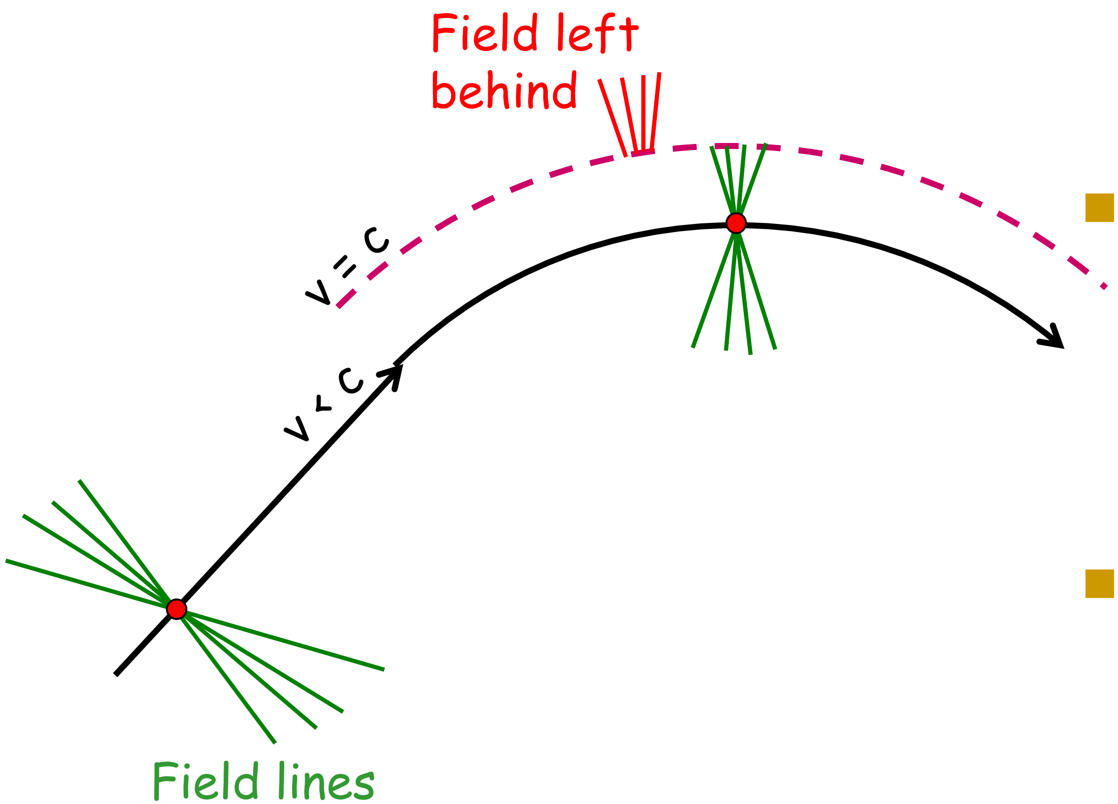
- Penetrate deep inside materials since they are deflected only from the nuclei of atoms.
- Statistical observation of deflected neutrons at various positions after the sample can be used to find the structure of a material.
- Loss or gain of energy by neutrons can reveal the dynamic behaviour of parts of a sample, for example dynamic processes of molecules in motion.



ISIS Spallation Facility (800 MeV) at RAL

+ new European Spallation Source (ESS) in Lund

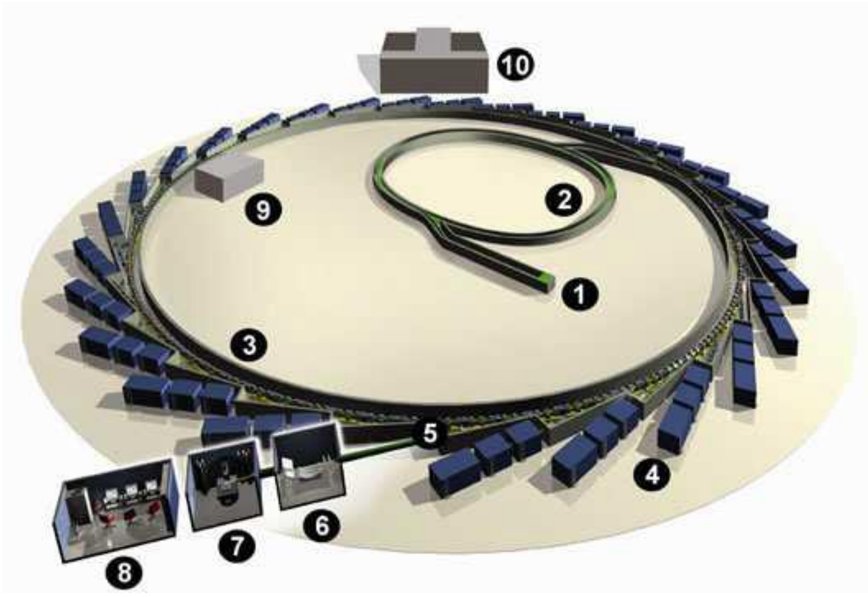
Synchrotron Radiation

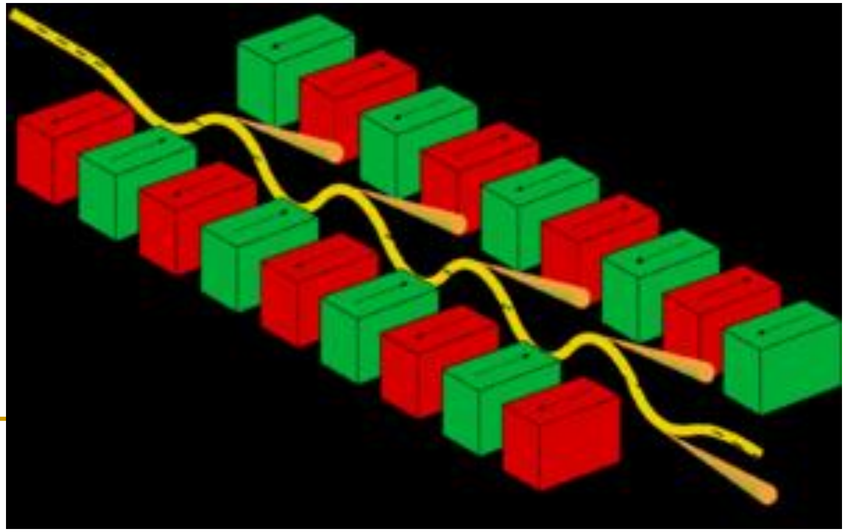


- Caused by field "left behind" during motion in a curved trajectory.
- Energy loss per meter is proportional to γ^4 and to $1/R^2$
- Can be both a nuisance and useful.

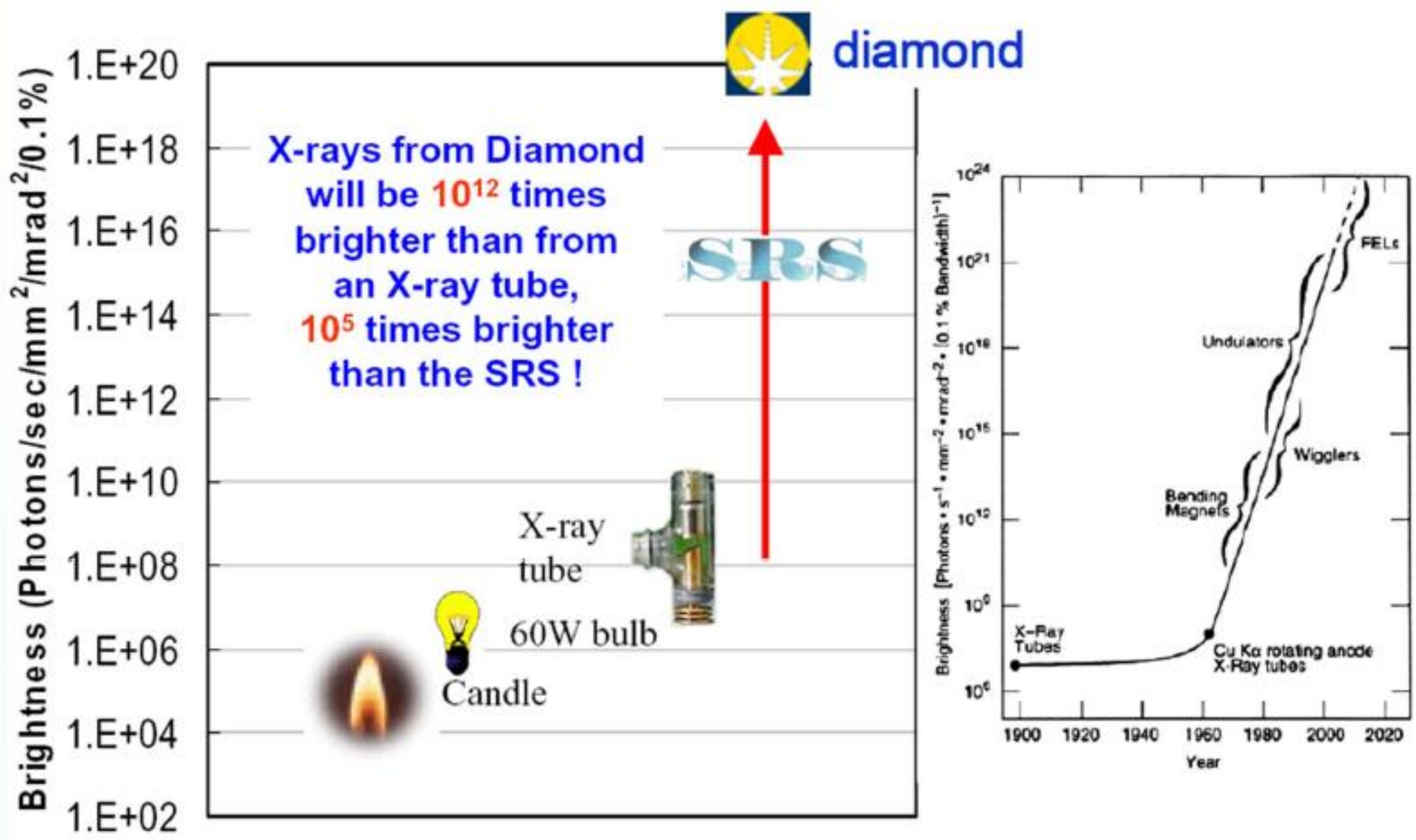
Use of Synchrotron Radiation

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





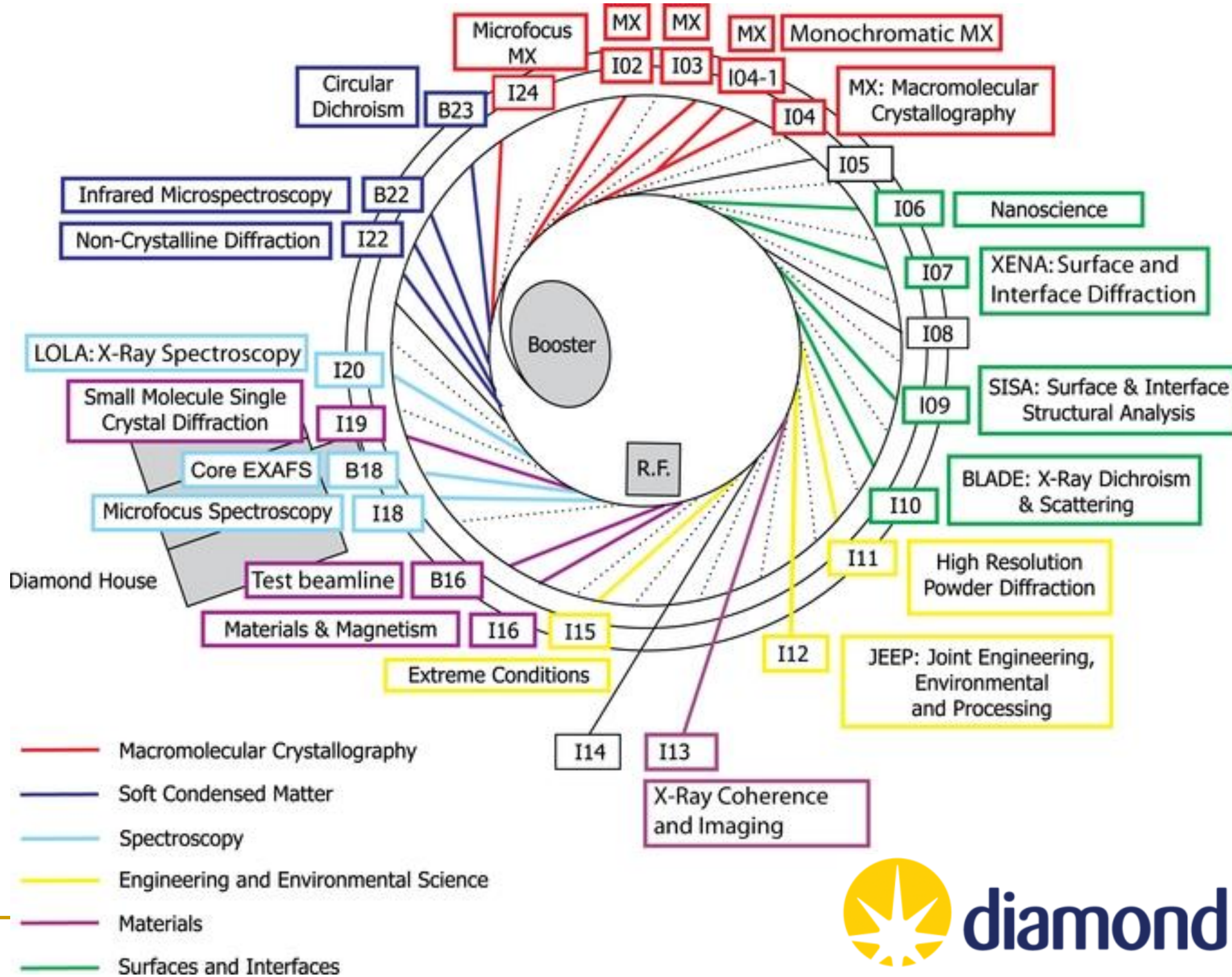
Accelerators for Synchrotron Light



Synchrotron Source of X-rays

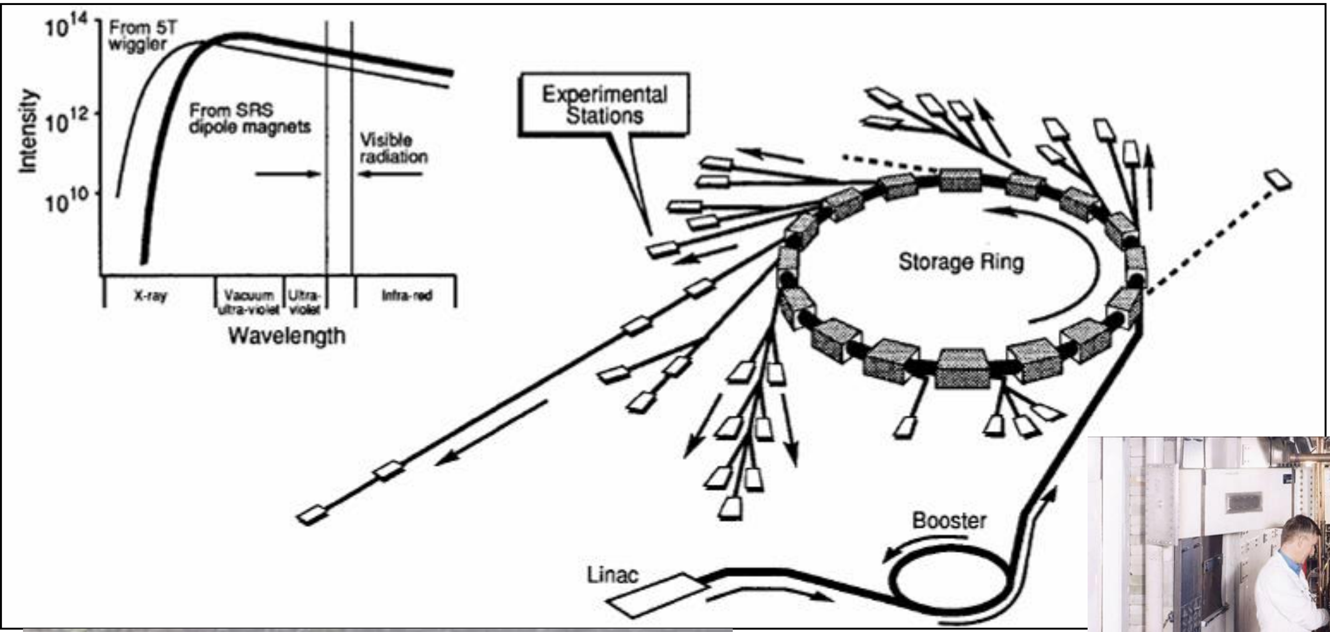
Diamond Light Source
Harwell Science and Innovation Campus, UK

Diamond Beamlines



diamond

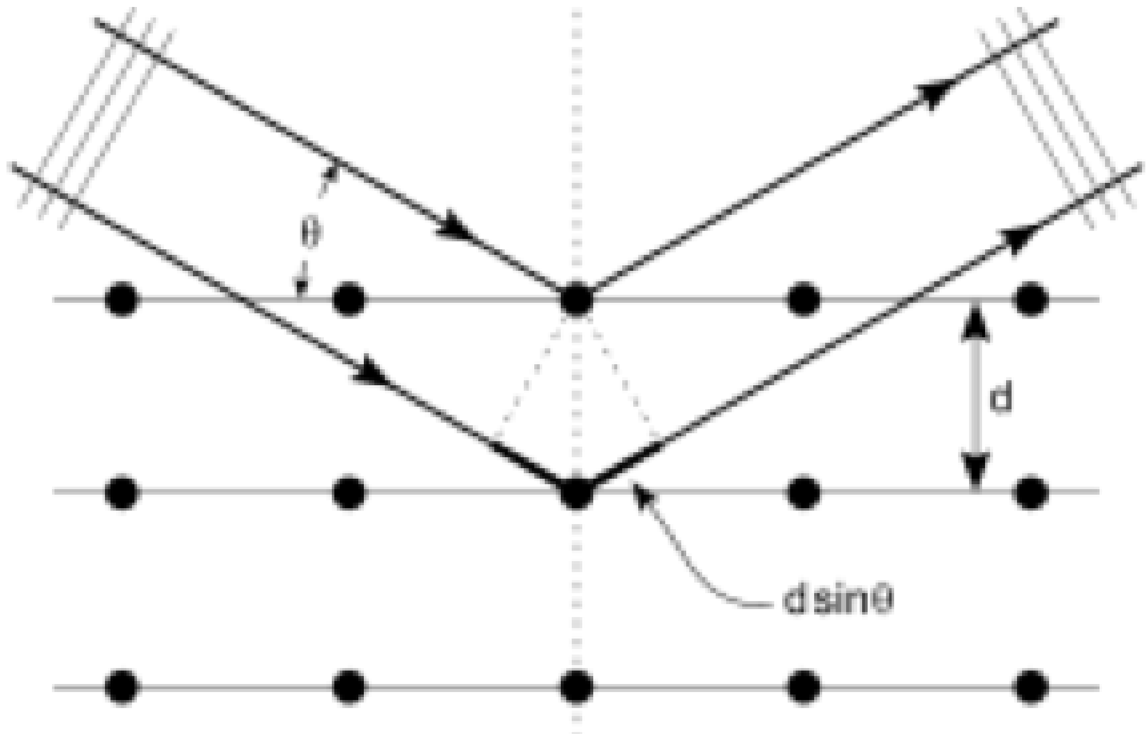
Accelerator X-ray Sources



SRS
Daresbury, UK

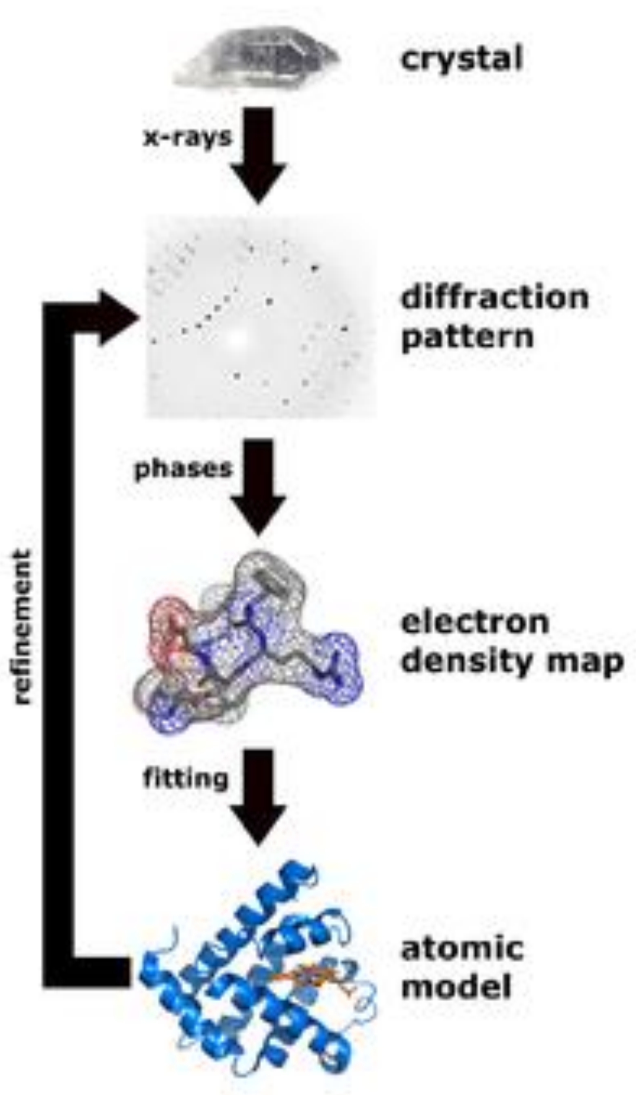
X-ray Diffraction

Max von Laue
1914 Nobel Prize:
'For his discovery of the diffraction of X-rays by crystals'



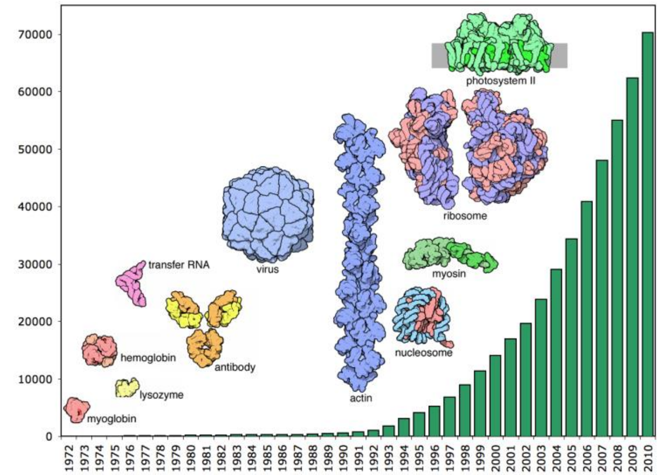
Constructive interference:
$2\ d\ \sin\theta = n\ \lambda$

X-ray Diffraction Today

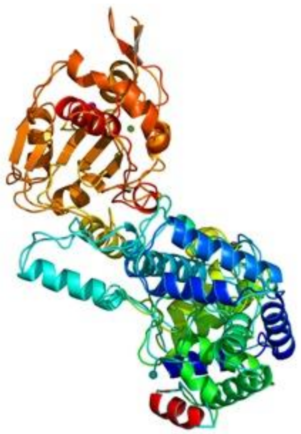


Accelerators for Synchrotron Light

- Protein Structures
  - Proteins are biological molecules involved in almost every cellular process.
  - The protein is produced, crystallised and illuminated by X-rays. The interactions between the X-rays and the crystal form a pattern that can be analysed to deduce the protein structure.
  - Over 45,000 structures have been solved by the worldwide synchrotron community.

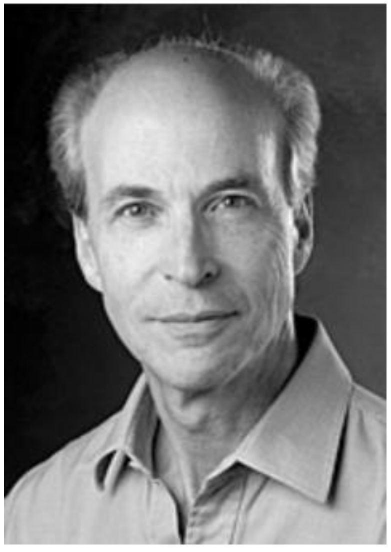


Protein Data Bank



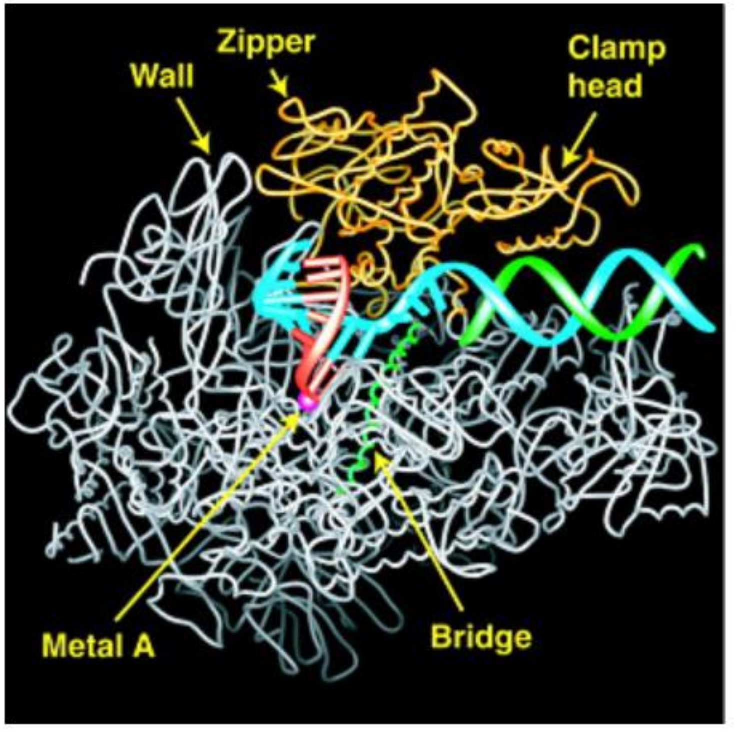
The trimer of the Lassa nucleoprotein, part of the Lassa virus

The Nobel Prize in Chemistry 2006
Roger D. Kornberg



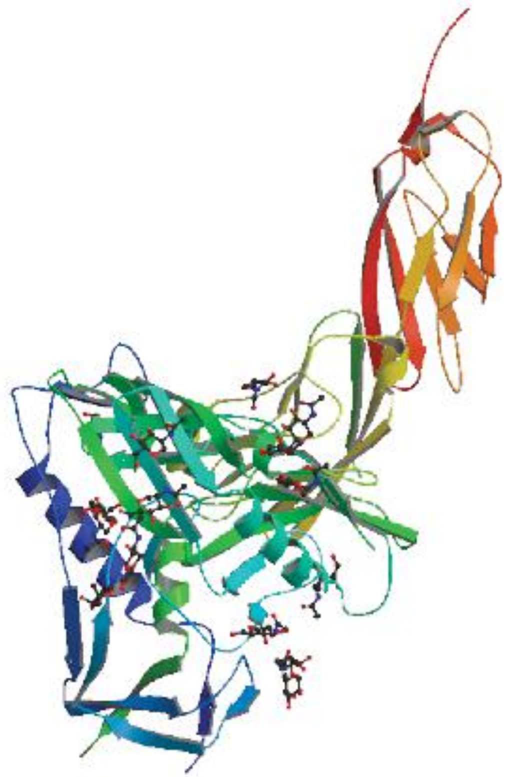
Roger Kornberg's Nobel Prize-winning determination of the structure of RNA polymerase has been described as a "technical tour de force." The key to the visualization of this fundamental biological molecule in action was synchrotron radiation, supplied by the powerful X-ray crystallography instruments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

Science

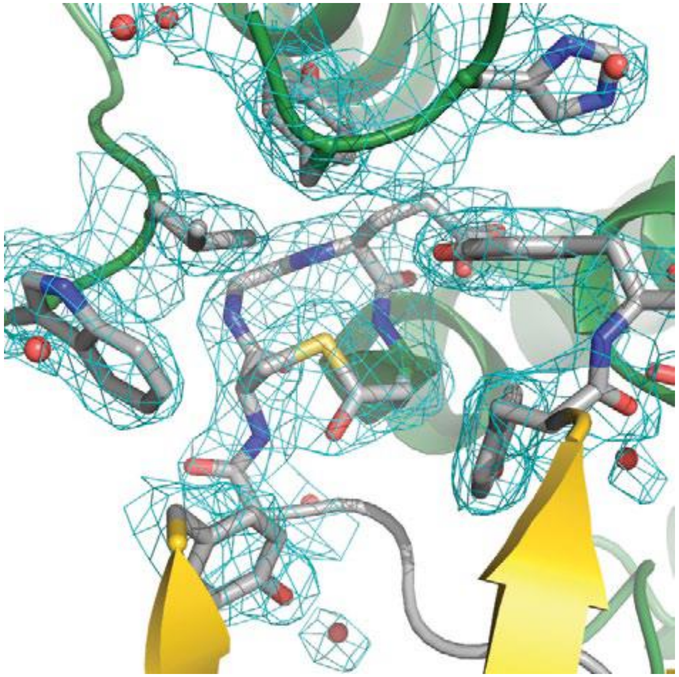


The transcription process visualized by Roger Kornberg and his colleagues in his X-ray crystallography studies published online April 19, 2001, in *Science*. The protein chain shown in grey is RNA polymerase, with the portion that clamps on the DNA shaded in yellow. The DNA helix being unwound and transcribed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

Protein Structure Revealed by Light Sources



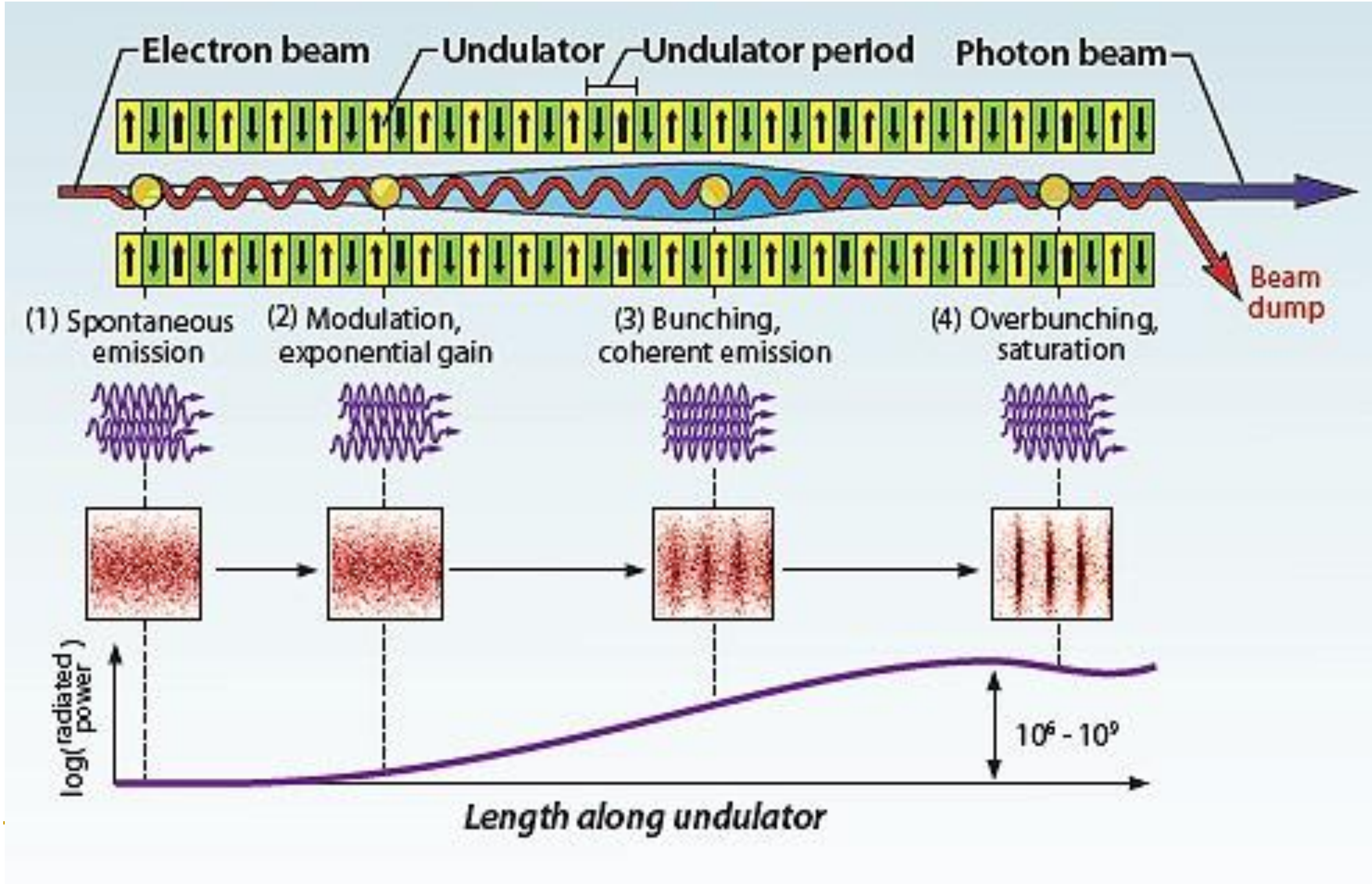
HIV glycoprotein



mosquito
immune system

yeast enzyme

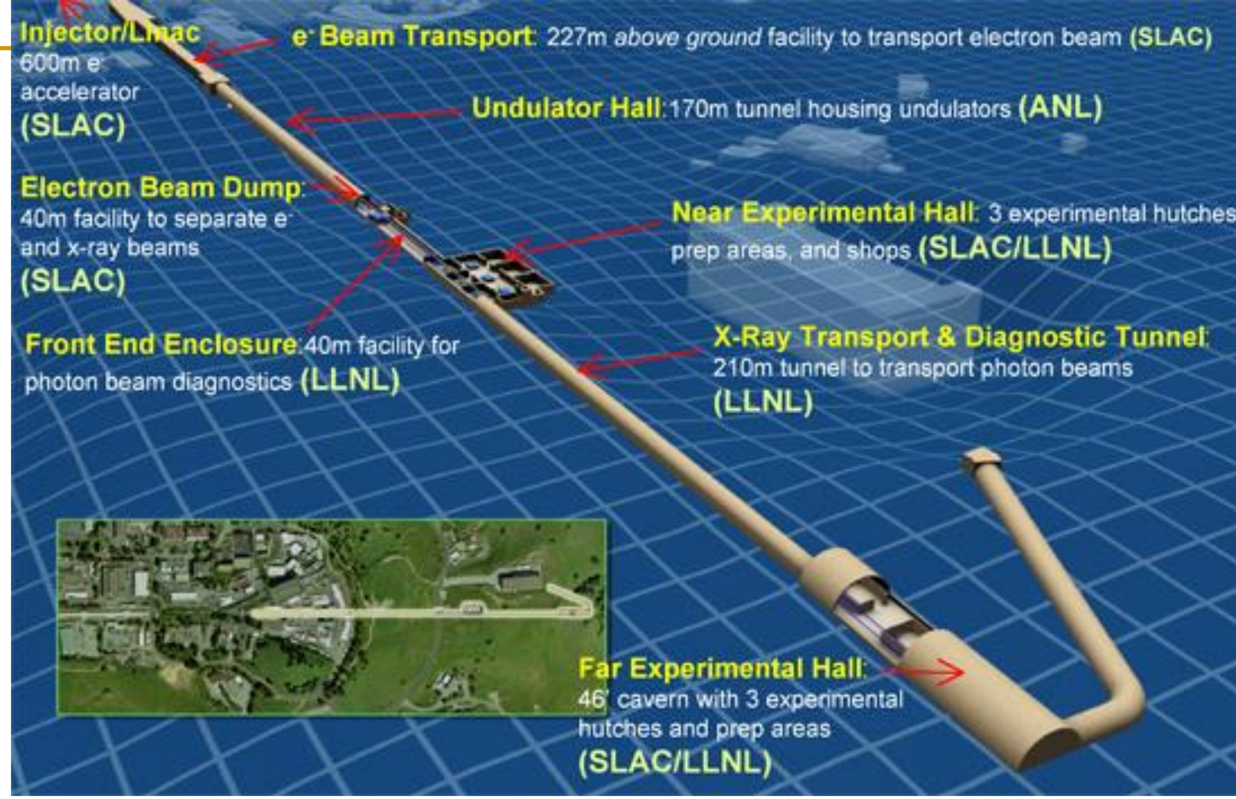
4^{th} Generation Light Source – Free Electron Laser

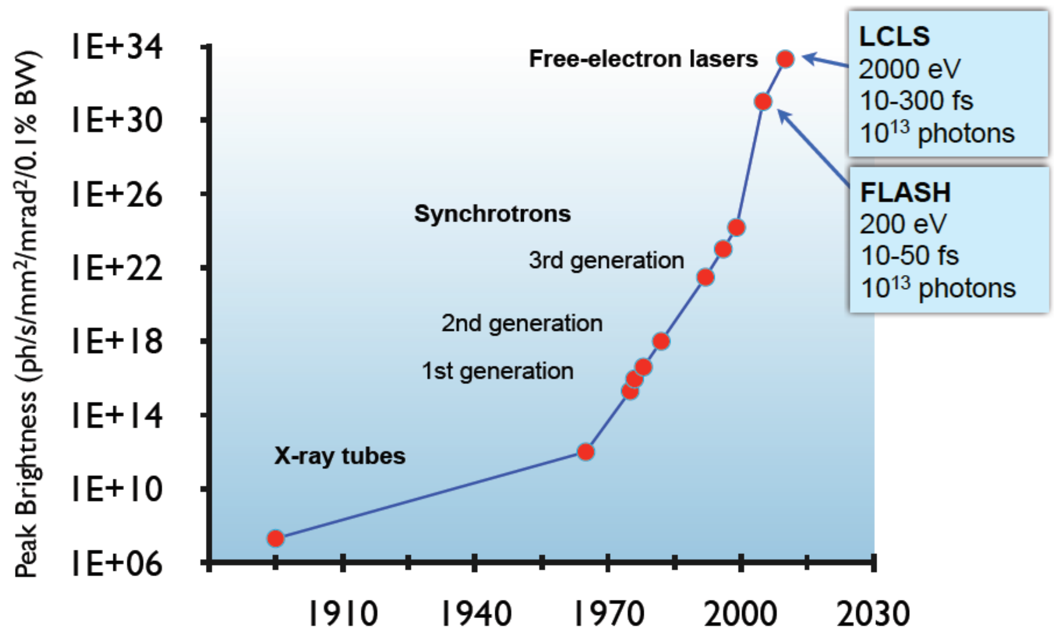


4th Generation Light Source –

X-ray FEL-

LCLS at SLAC



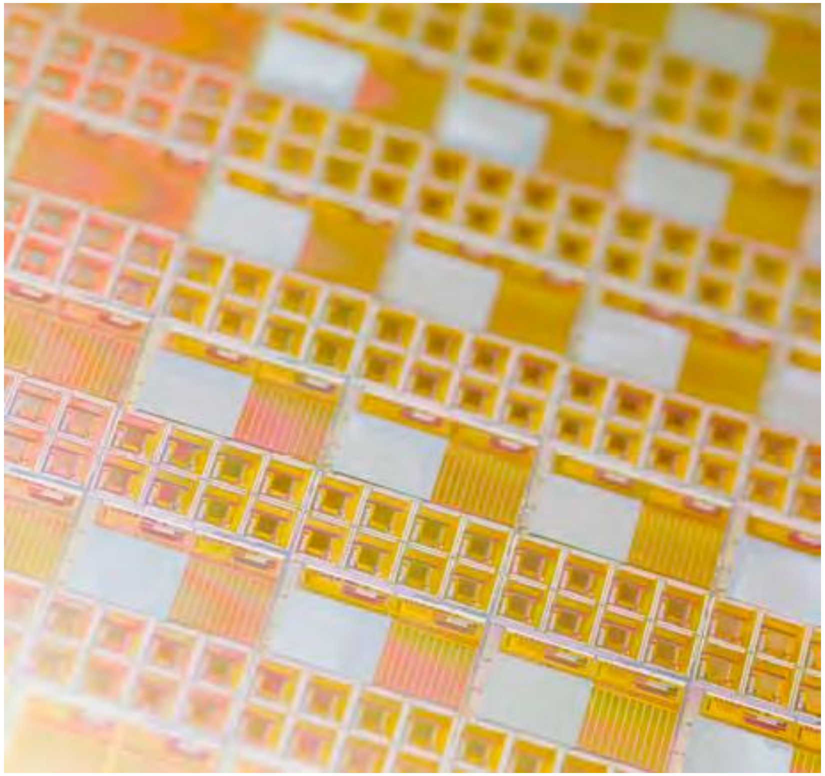


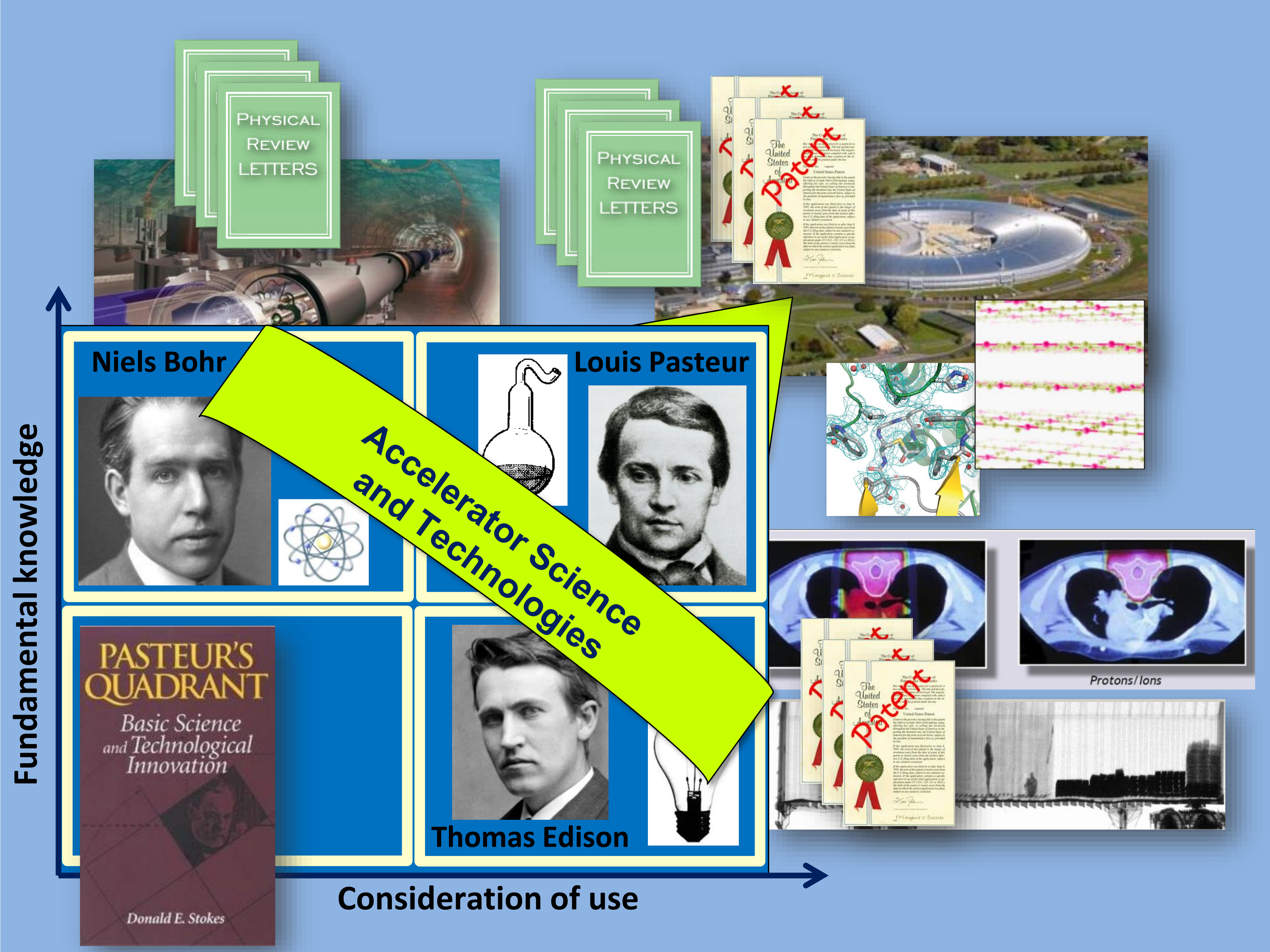
Ion Beam Implantation

- Ion implantation in semiconductor manufacture
- Typical semiconductor fabrication:
  140 operations, 70 involving ion implantation at specific sites in crystal
- Ions accelerated to modest energies

  Depth of implant controlled by ion beam energy: typically 2 → 600 keV

Ion Beam Implantation Products




Physical Review Letters
Physical Review Letters
Patent
Patent
Niels Bohr
Louis Pasteur
Accelerator Science and Technologies
Thomas Edison
Pasteur's Quadrant
Basic Science and Technological Innovation
Donald E. Stokes
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Consideration of use