Particle accelerators and applications

Philippe Lebrun
CERN, Geneva, Switzerland

Second African School of Fundamental Physics and its Applications
Kwame Nkrumah University of Science and Technology
Kumasi, Ghana, 15 July – 8 August 2012

Contents

- Accelerators for science
  - High-energy physics
  - Nuclear physics
  - Neutron science
  - Synchrotron light
  - New acceleration techniques
- Accelerators for society
  - Medical
  - Food and biological safety
  - Environment
  - Industry
  - Energy

Contents

- Accelerators for science
  - High-energy physics
  - Nuclear physics
  - Neutron science
  - Synchrotron light
  - New acceleration techniques
- Accelerators for society
  - Medical
  - Food and biological safety
  - Environment
  - Industry
  - Energy

High-energy particle collisions

probe matter at very small scale

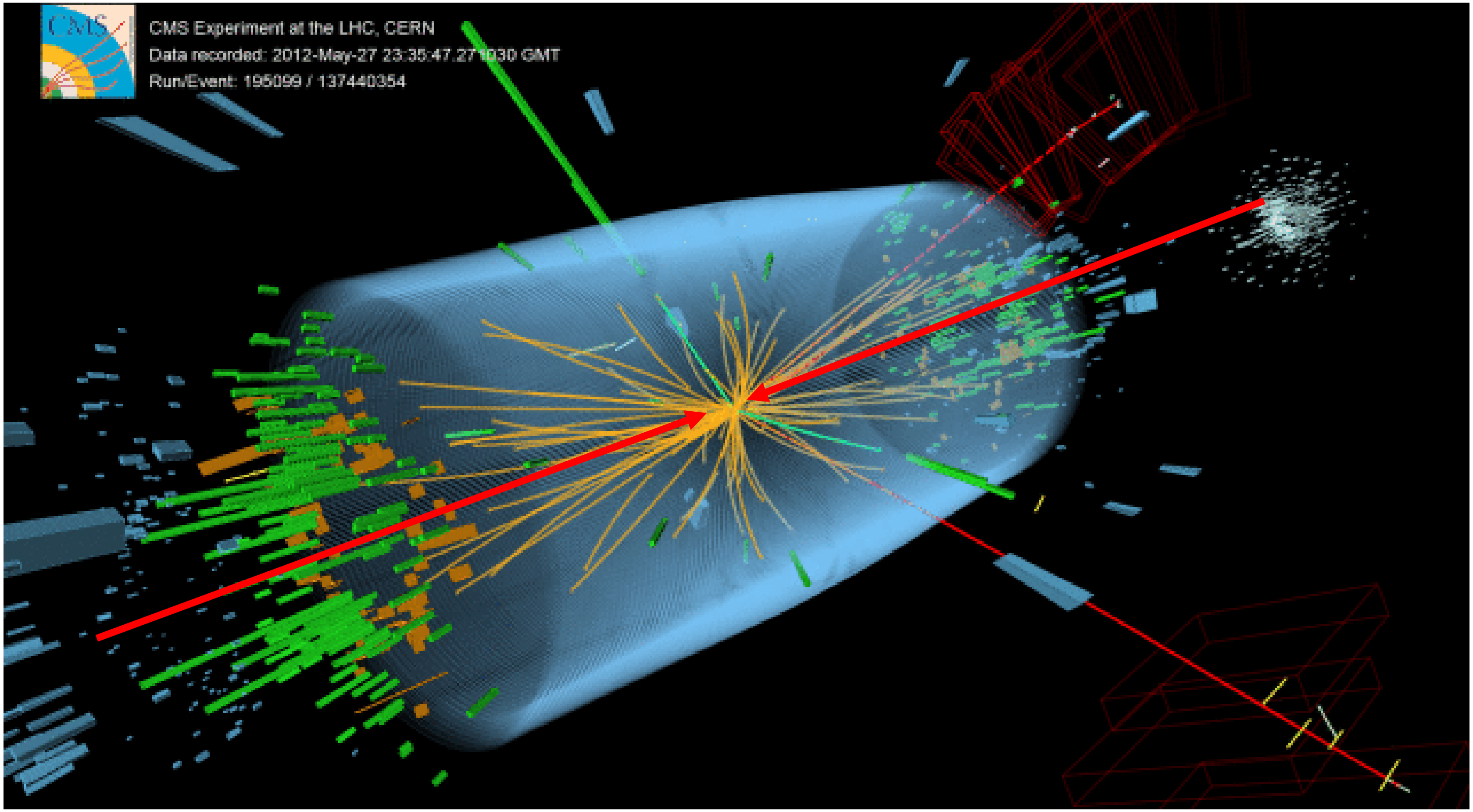
produce new, massive particles

De Broglie

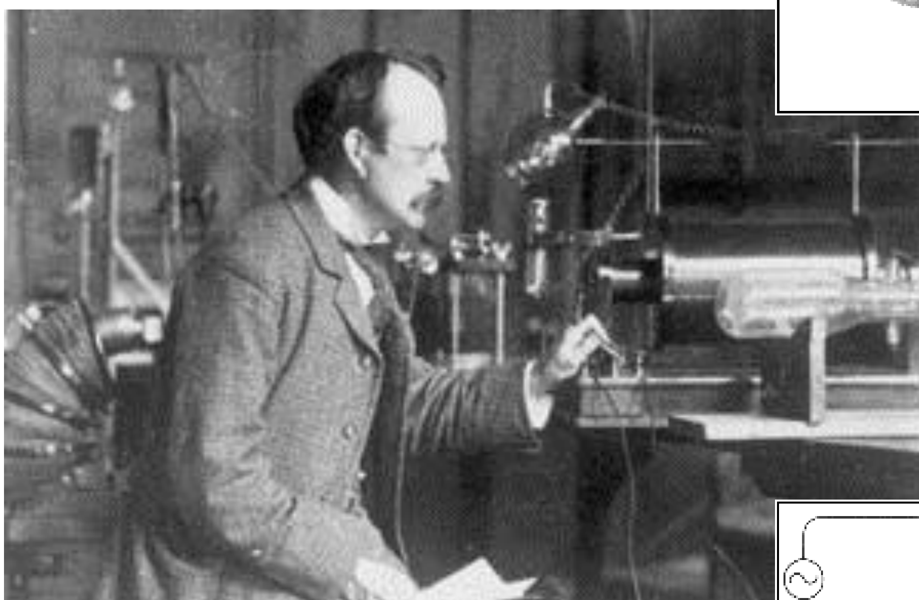
$E \sim 1/\lambda$

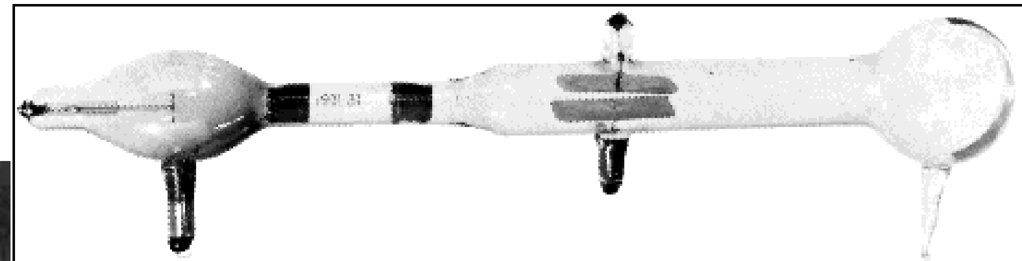
Einstein

$E = mc^2$

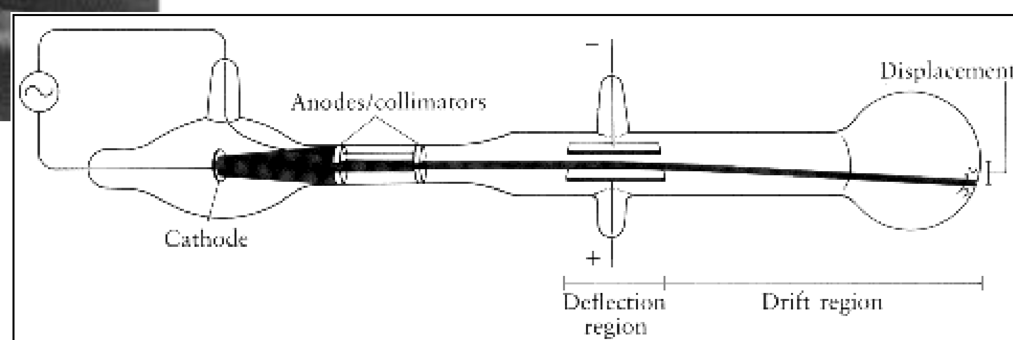


The first linear accelerator
Discovery of the electron by J.J. Thomson (1897)





Thomson's cathode ray tube accelerated electrons to a few keV and enabled measurement of their e/m ratio

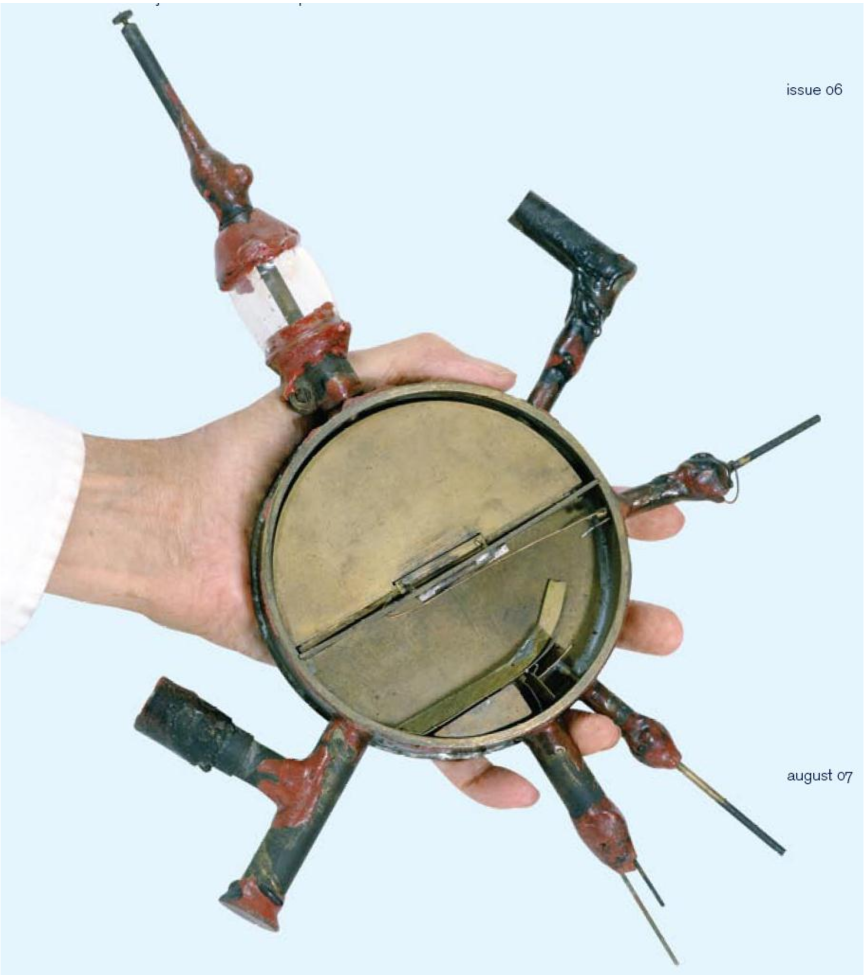


The 3 km SLAC linear accelerator/collider

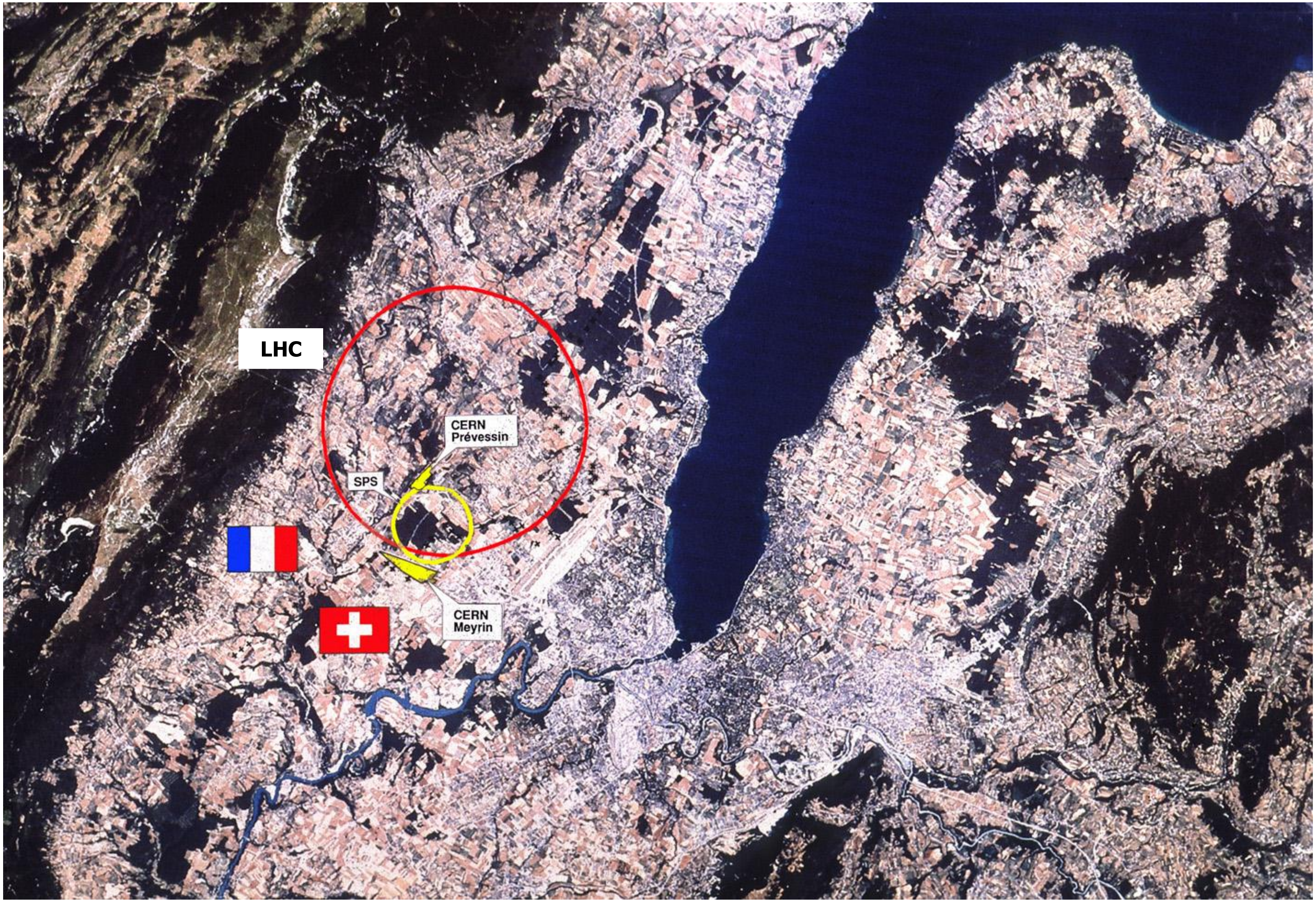
The first circular accelerator

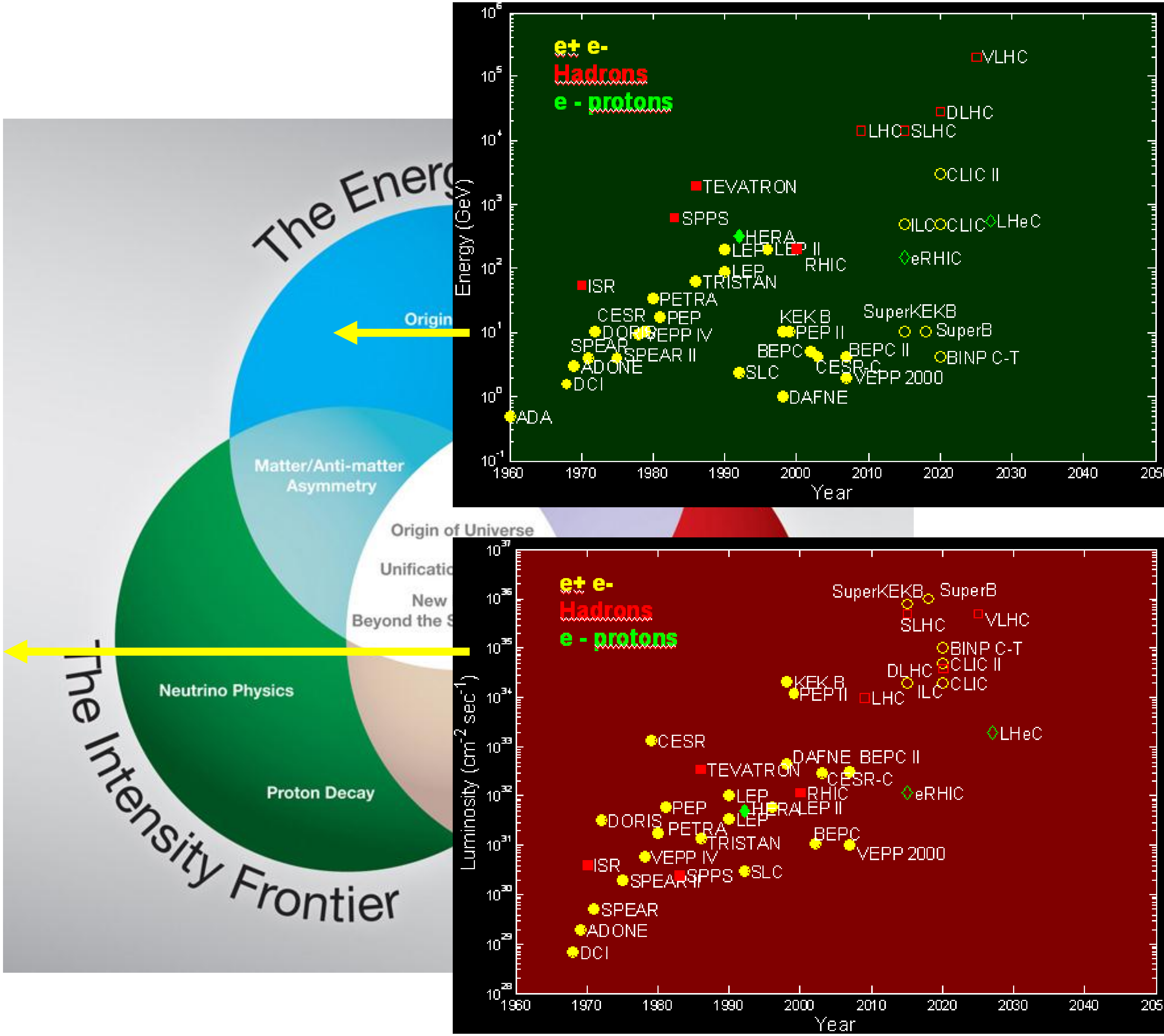
Lawrence and Livingston's 80 keV cyclotron (1930)

Ernest O. Lawrence



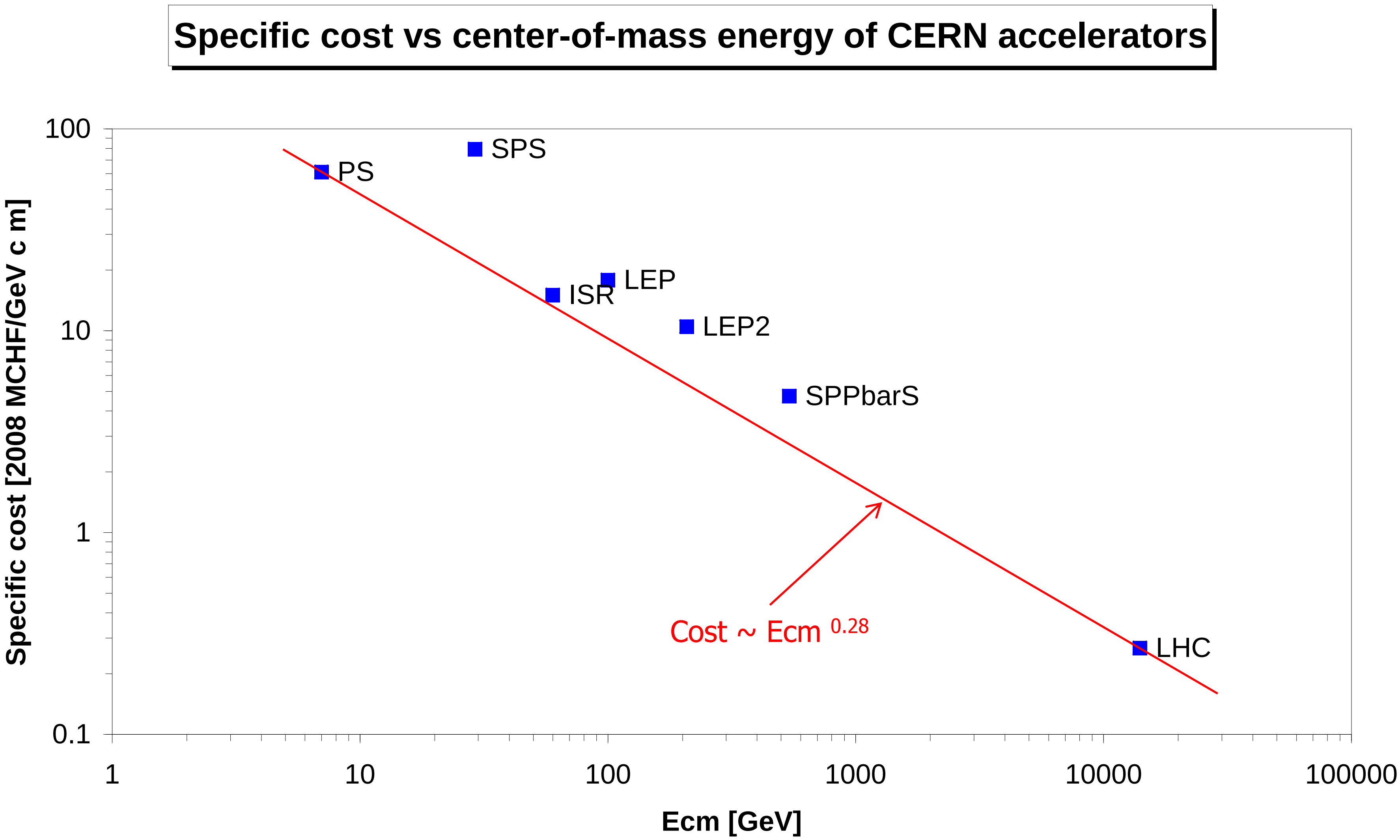
Over 80 years, x 10^5 in size, x 10^8 in energy!





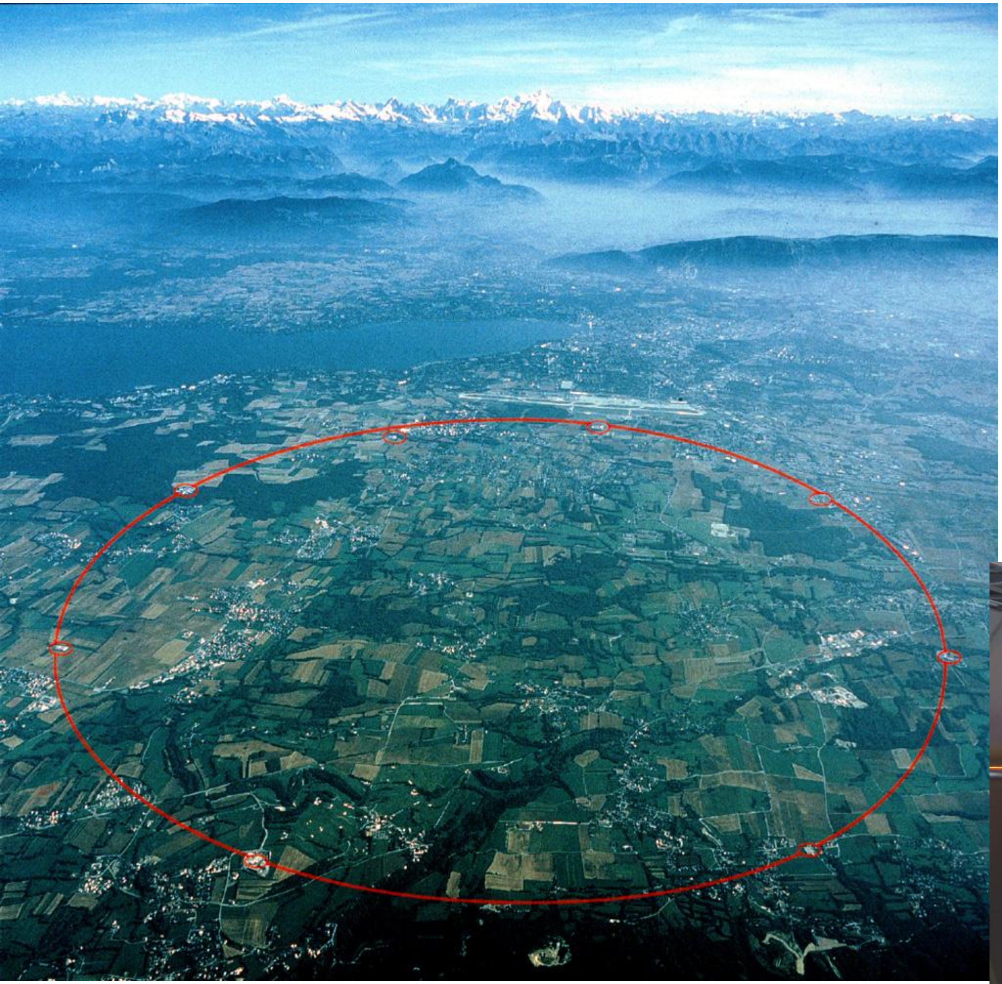
The Intensity Frontier
Origin
Matter/Anti-matter Asymmetry
Origin of Universe
New
Neutrino Physics
Proton Decay
e+ e-
Hadrons
e - protons
Energy (GeV)
Year
VLHC
DLHC
LHC
SLHC
CLIC II
TEVATRON
SPPS
HERA
LEP
LEP II
RHIC
ILC
CLIC
LHeC
eRHIC
ISR
TRISTAN
PETRA
CESR
PEP
DORIS
VEPP IV
SPEAR
SPEAR II
ADONE
DCI
ADA
KEK B
PEP II
SuperKEKB
SuperB
BEPC
BEPC II
CESR-C
BINP C-T
SLC
VEPP 2000
DAFNE
Luminosity (cm^{-2} sec^{-1})

A sustained decrease in specific cost



The LHC at CERN

High-energy, high-luminosity particle collider

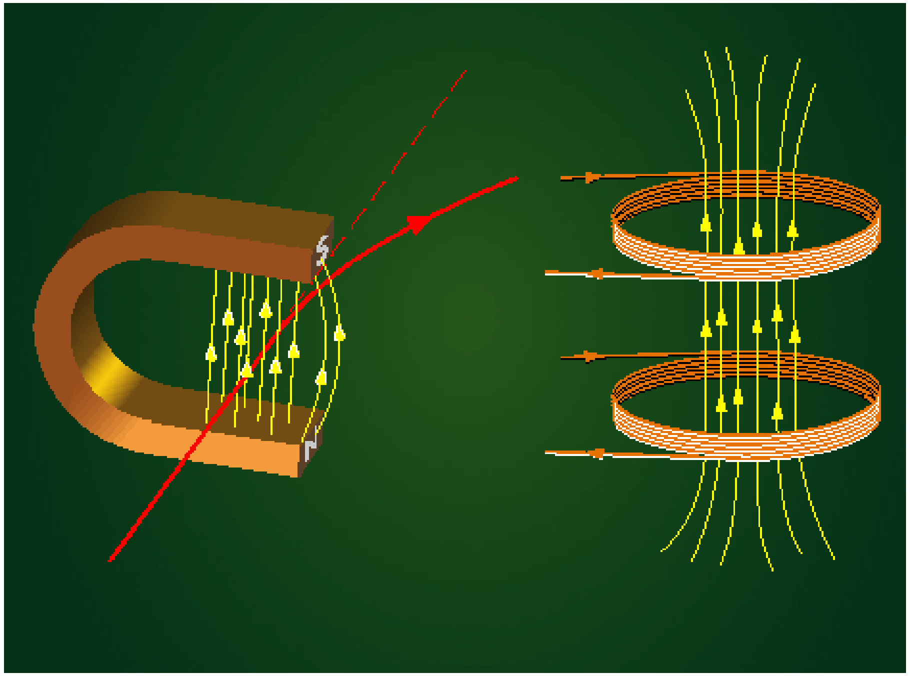


E_{beam}	7 TeV
Luminosity	$2\ 10^{34}\ cm^{-2}.s^{-1}$
Circumference	26.7 km
Bending field	8.3 T
Superconductor	Nb-Ti @ 1.9 K

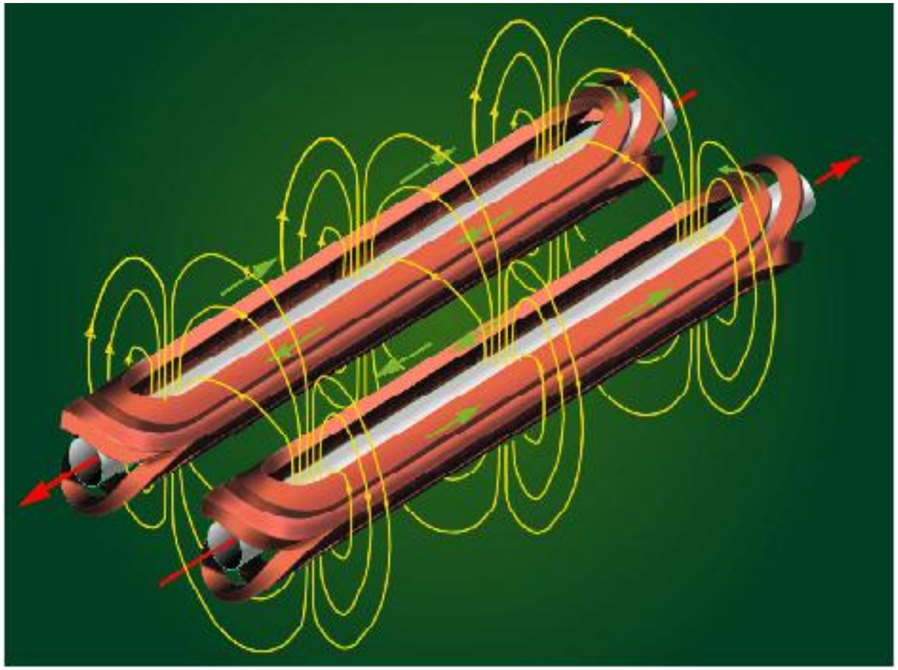
1232 SC dipoles, 400 SC quadrupoles

120 tons helium (of which 80 superfluid)

Superconducting magnets for particle accelerators



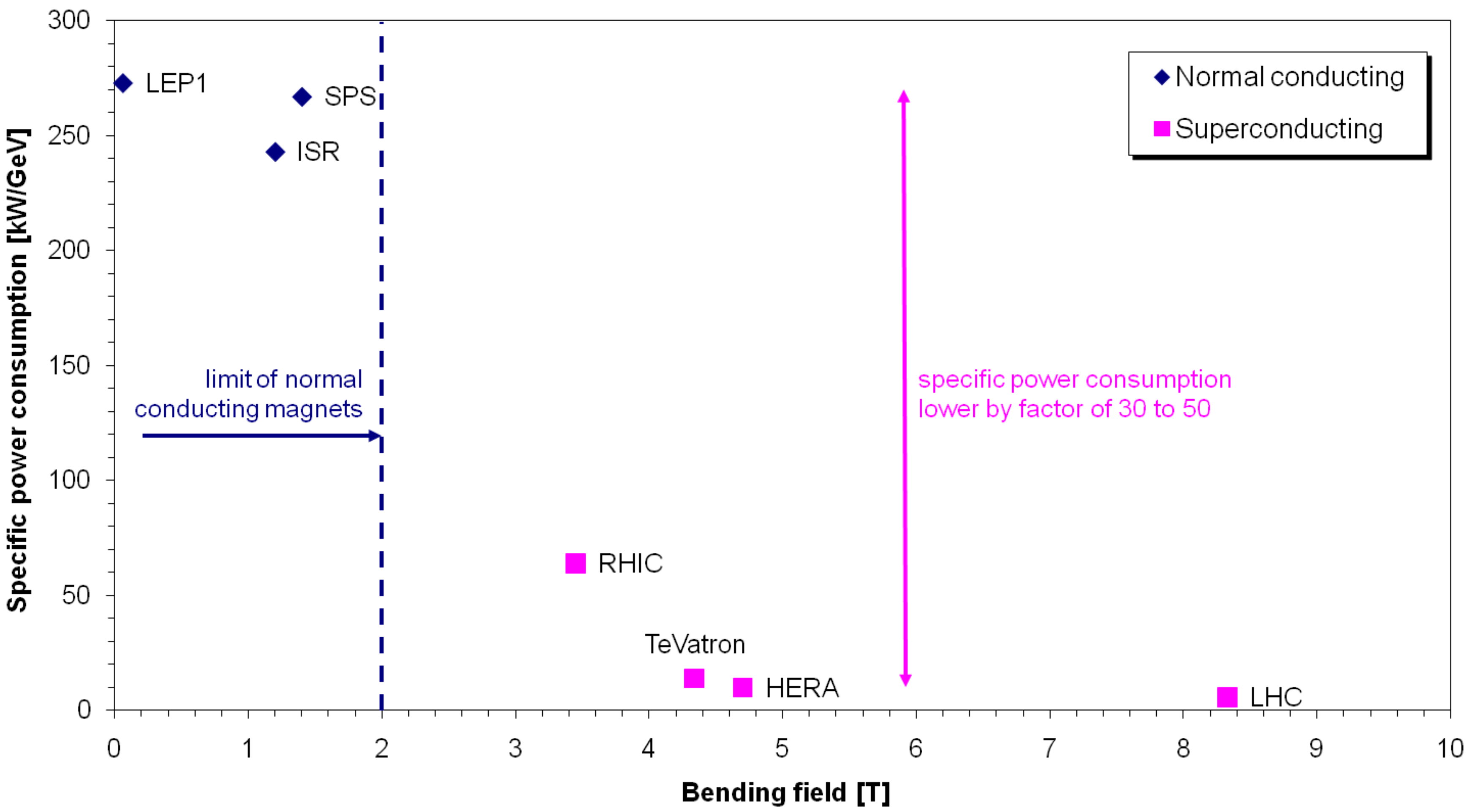
In a particle accelerator, electromagnets produce fields for guiding and focussing the beams



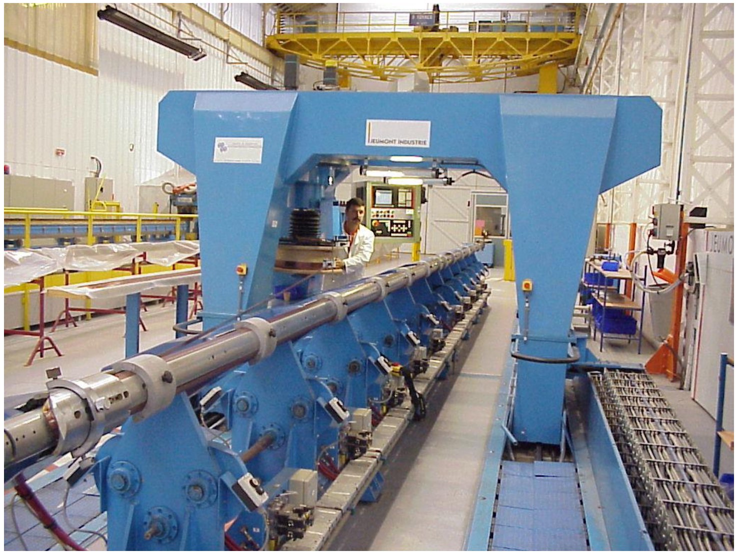
Superconducting magnet coils fit along the beam pipes to produce a high magnetic field in the useful volume

Superconductivity permits to produce higher fields for reducing the size and the electrical energy consumption of accelerators

Energy efficiency through advanced magnet technology
Specific power consumption of particle colliders



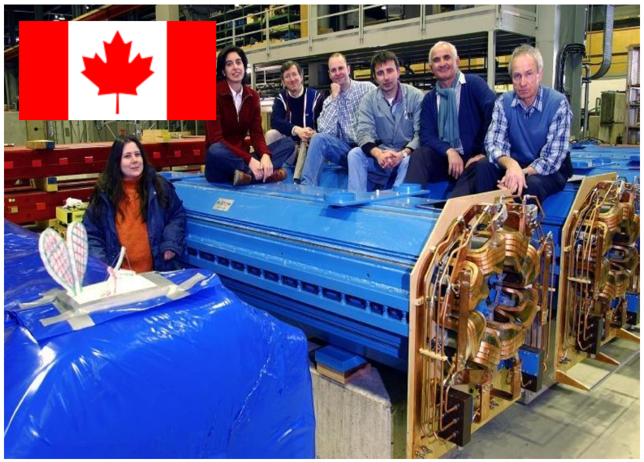
Manufacturing in industry of LHC superconducting magnets

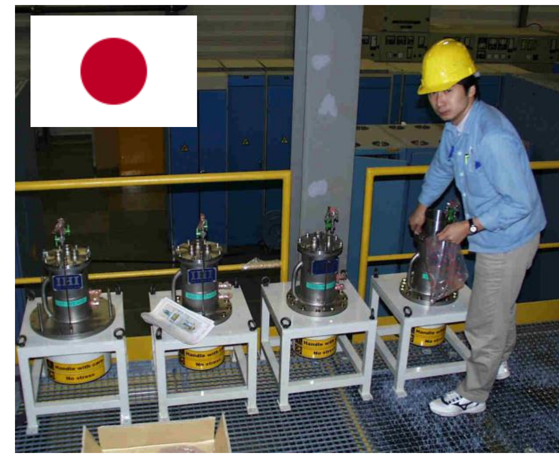


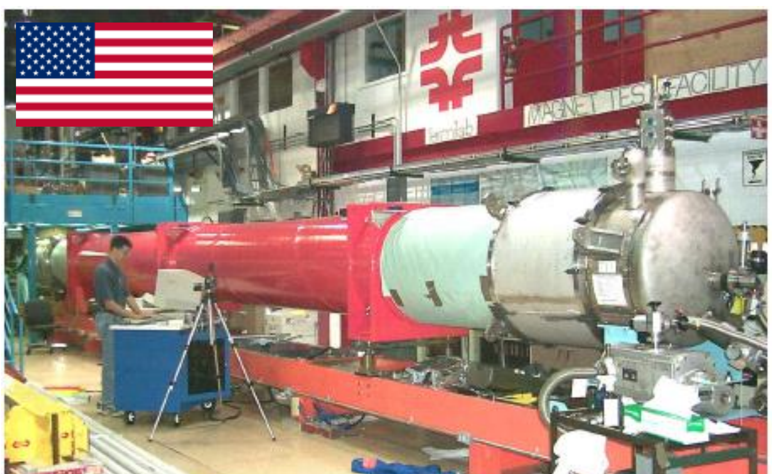
Final assembly at CERN of LHC superconducting magnets in their cryostats

High-energy accelerators are now global projects

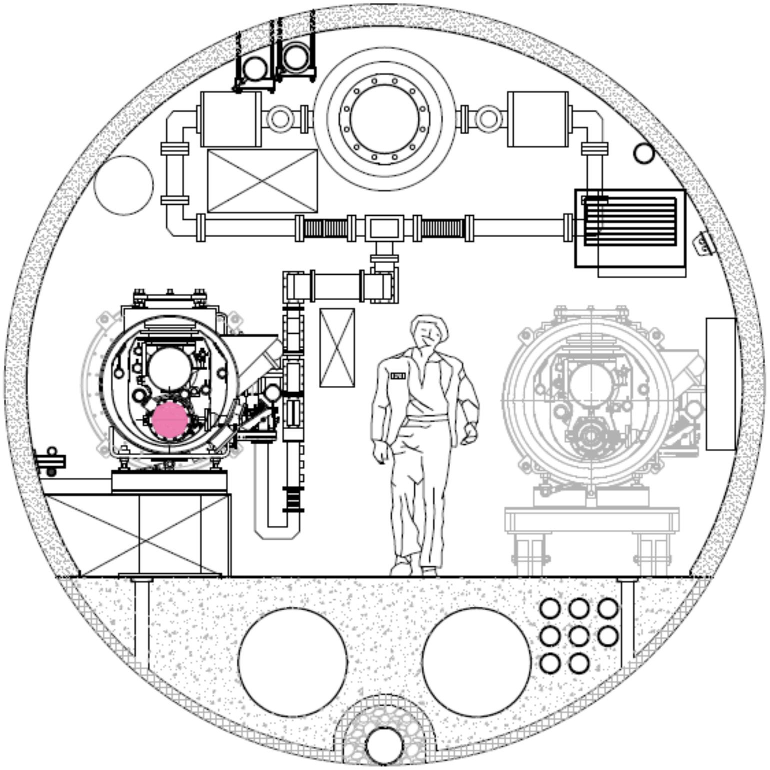
In-kind contributions to the LHC from CERN non-member states







International Linear Collider (ILC) study



e+ e- linear collider

Collision energy 500 GeV c.m. initially, later upgrade to ~1 TeV c.m.

Overall length 31 km

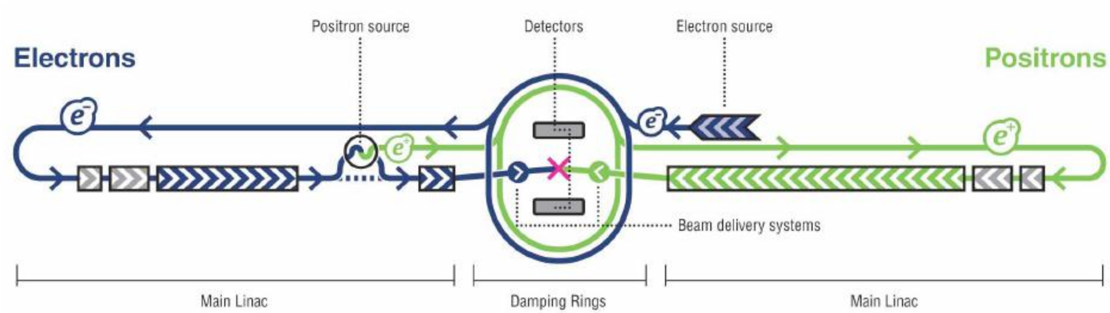
Key technology: SC RF cavities

Global Design Effort

No central laboratory

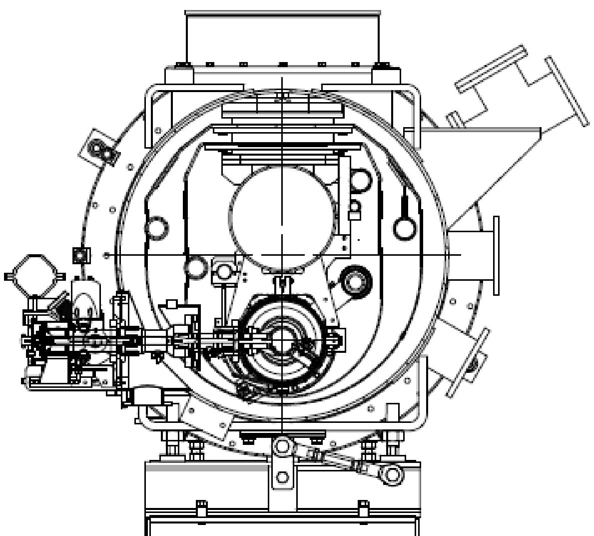
World-wide collaboration

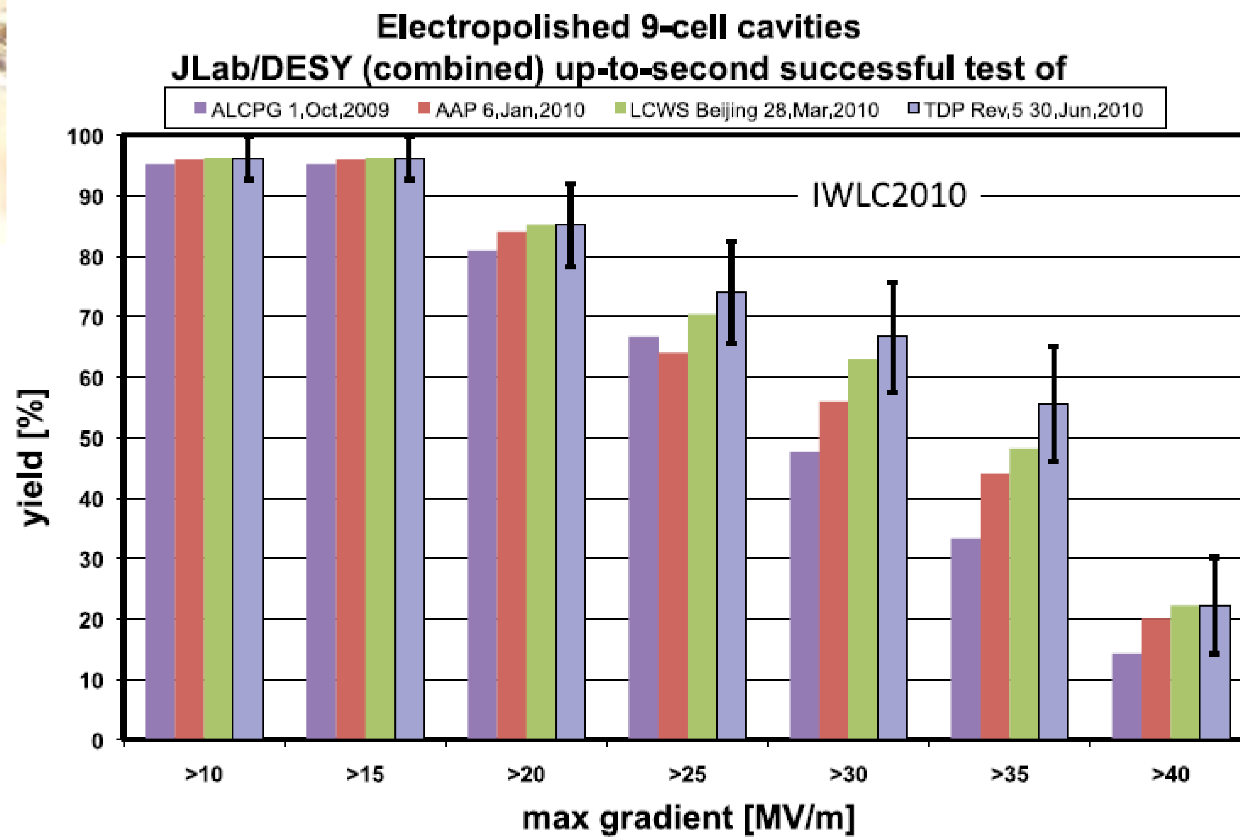
Site-specific studies conducted on sample sites



16 000 Nb superconducting cavities at 1.3 GHz

Operating gradient 31.5 MV/m



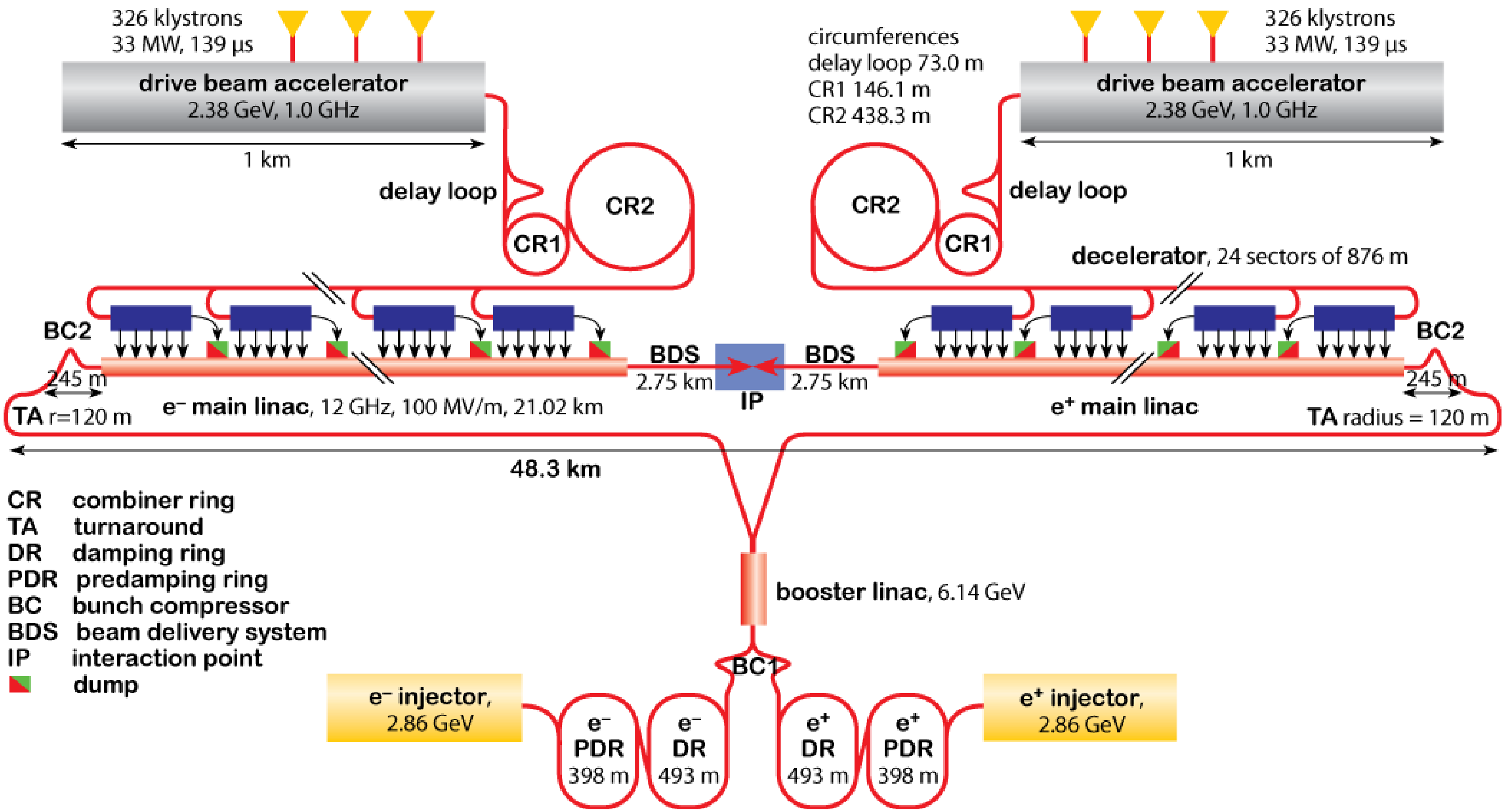


Compact Linear Collider (CLIC) study

Key technology: two-beam acceleration, multi TeV

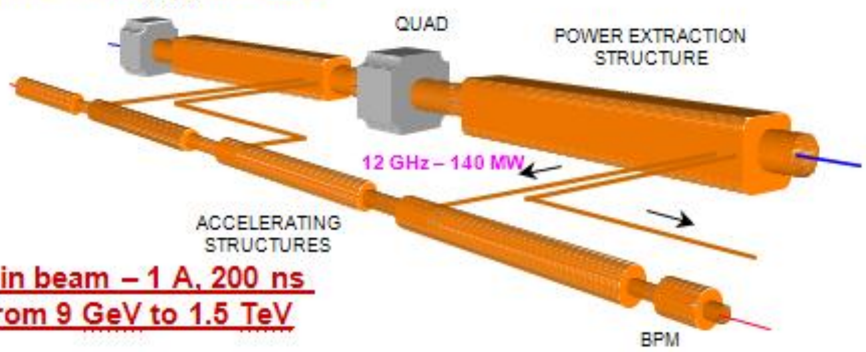
Accelerating gradient: 80 to 100 MV/m

World-wide collaboration with CERN as home laboratory

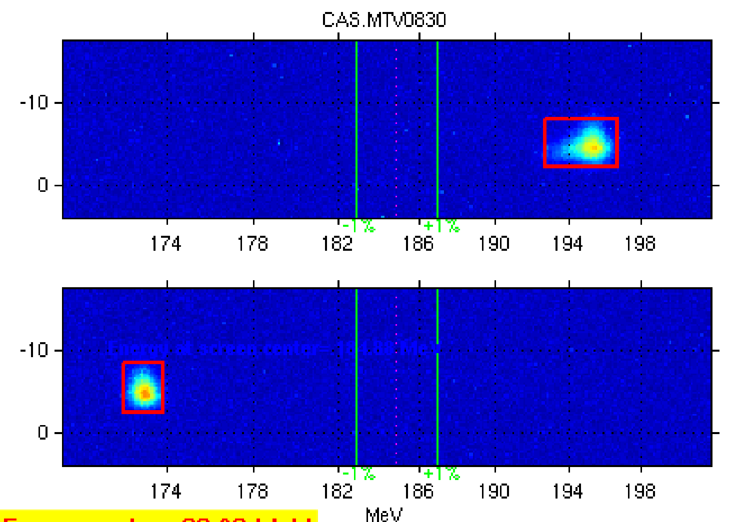


CLIC two-beam test facility at CERN

Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV



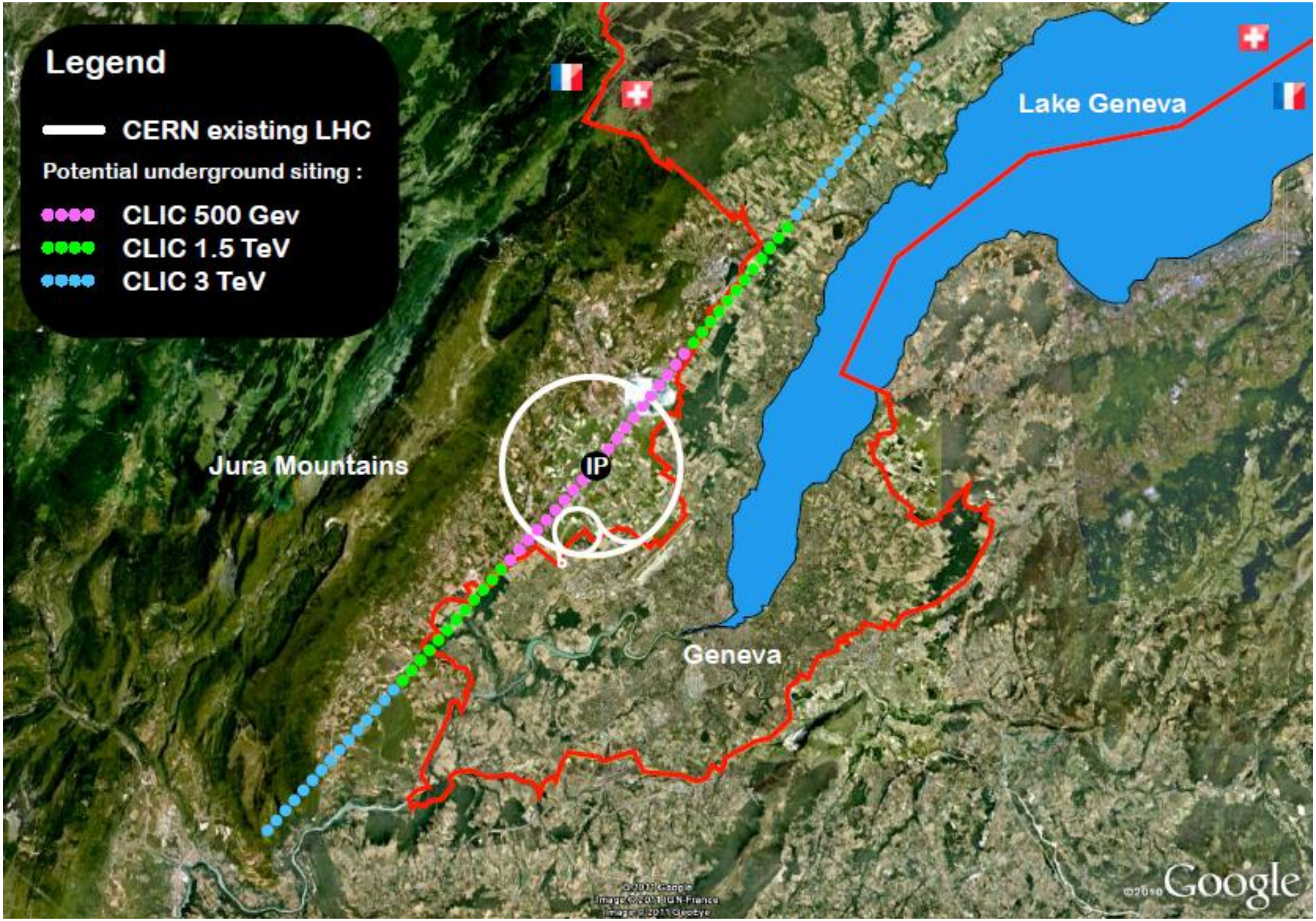
Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV



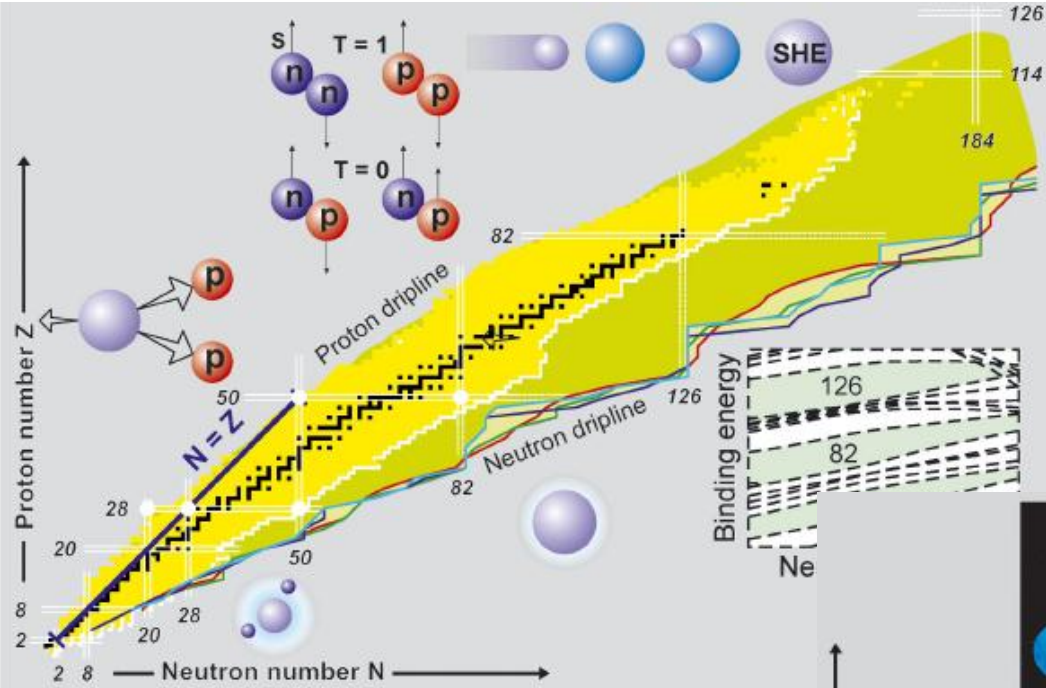
Energy gain = 23.08 MeV

Corresponding to a gradient of 106 MV/m

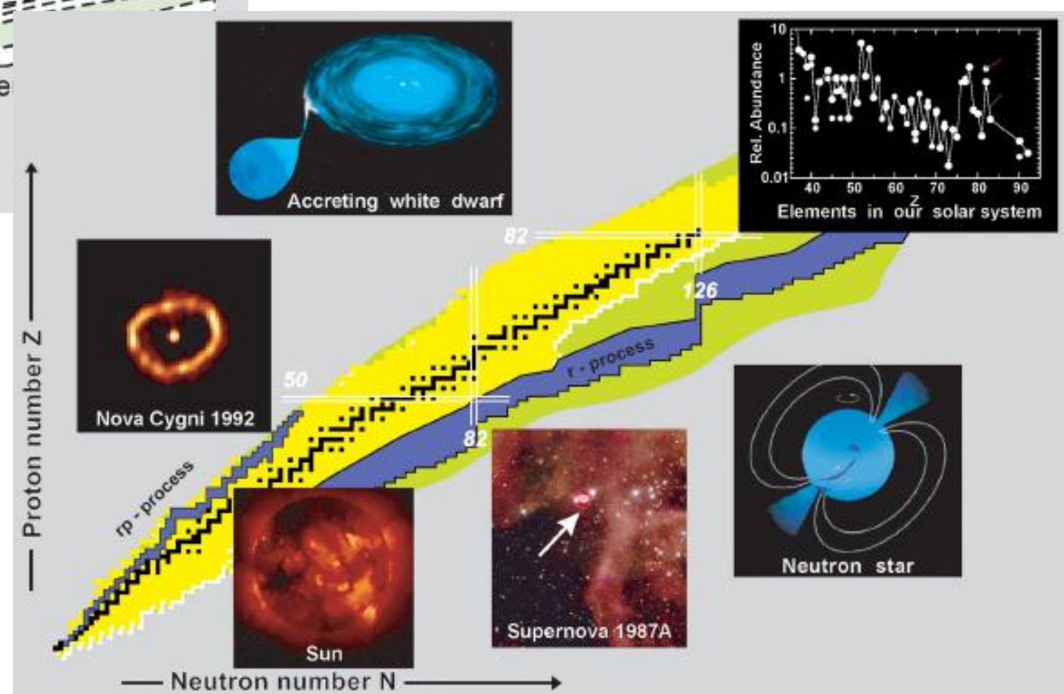
Possible layout of the Linear Collider near CERN



Nuclear physics and astrophysics

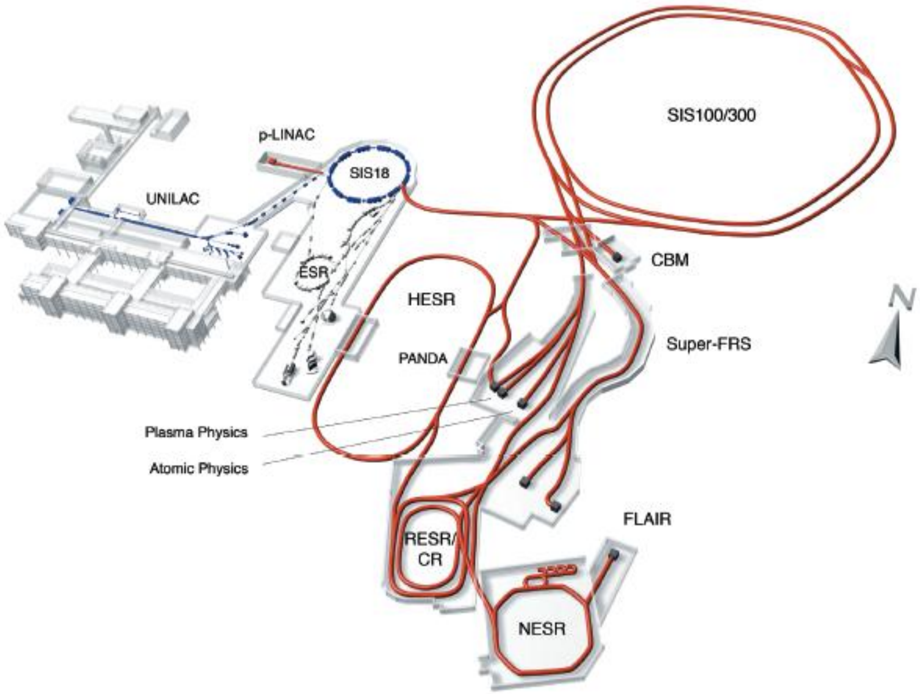


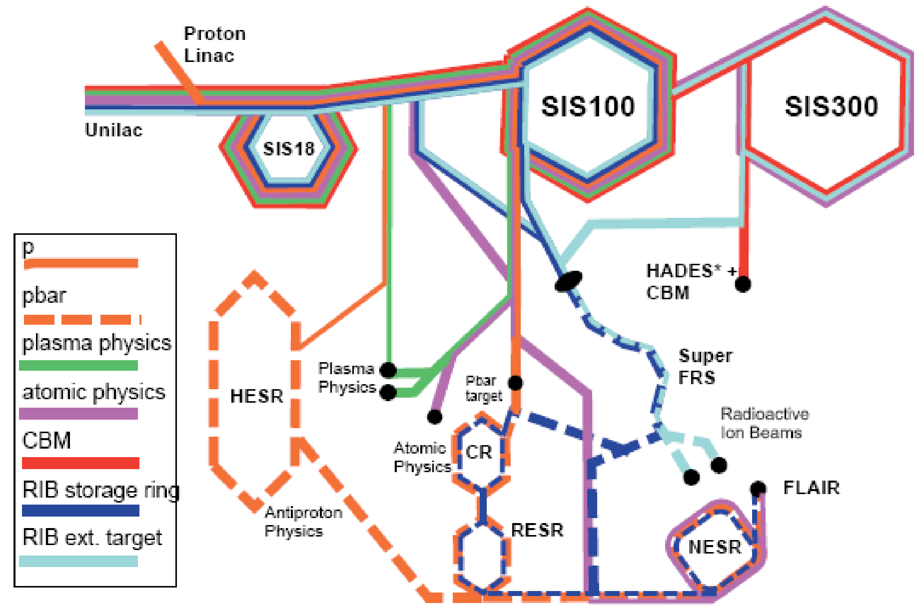
Exploring the confines of the valley of nuclear stability



Studying astrophysical processes in the laboratory

FAIR at GSI, Darmstadt (Germany)



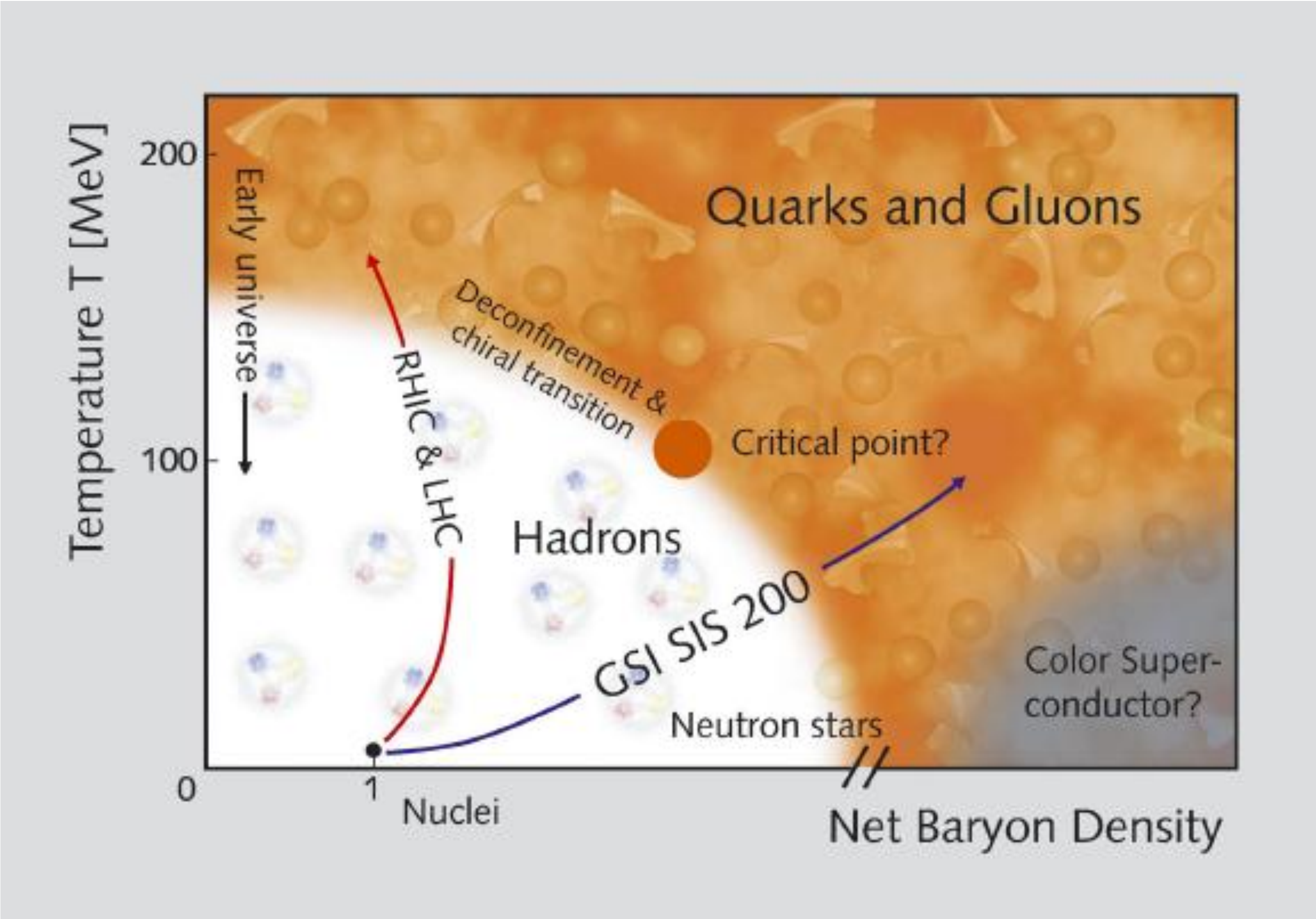


Facility for Antiproton & Ion Research

Complex of synchrotrons and storage rings using superconducting magnets

Subproject	Numbers of sc magnets
SIS 100	449
SIS 300	444
HEBT	187
SuperFRS	180
CR	48
HESR	320
MTF	2*

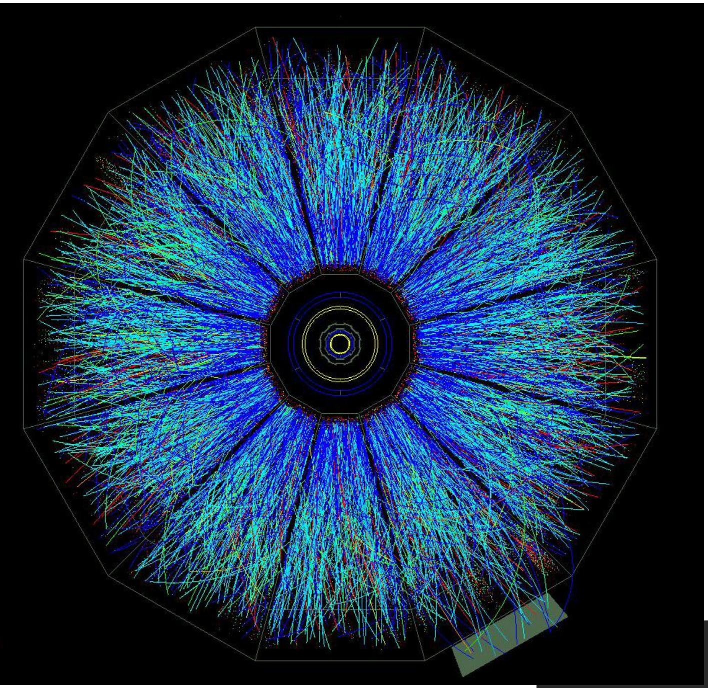
Exploring the quark-gluon phase diagram



RHIC at Brookhaven National Lab (USA)

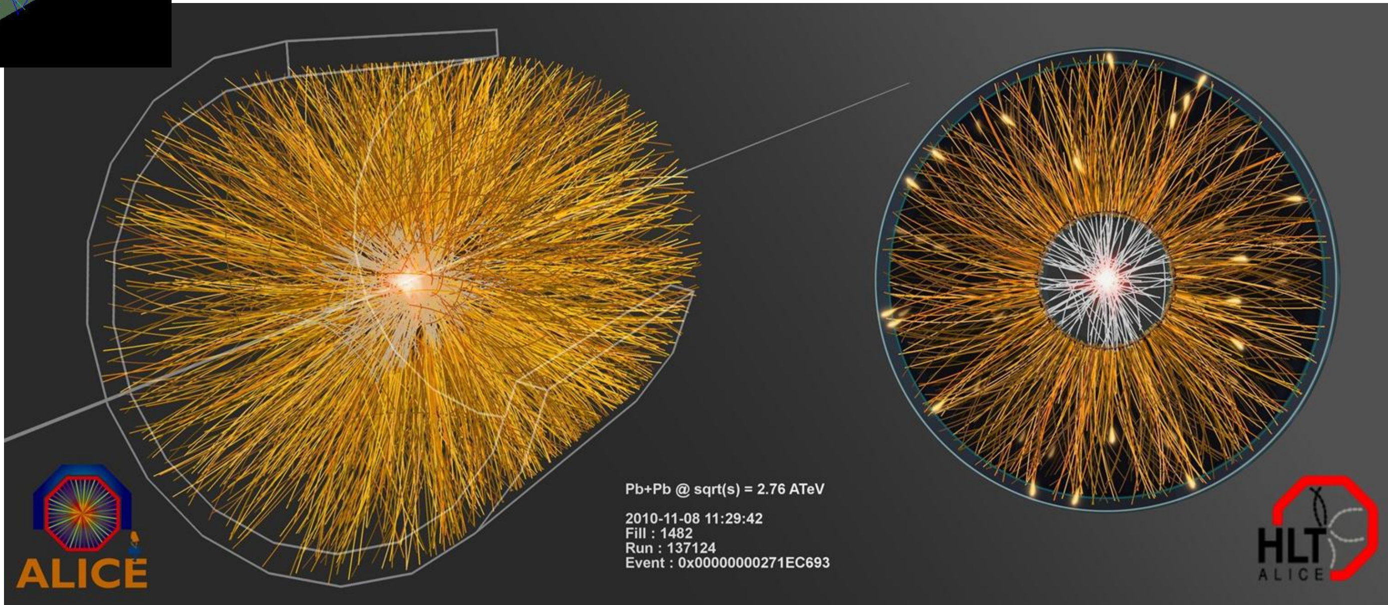
Proton and ion collider, typical energy 200 GeV/nucleon

Heavy ion collisions at RHIC and LHC



Colliding beams of Au atoms at RHIC ($\sqrt{s}$ = 60 GeV)
STAR experiment

Colliding beams of Pb atoms at LHC ($\sqrt{s}$ = 2.76 TeV)
ALICE experiment



Superconducting cyclotron at VECC, Kolkata (India)

80 MeV/nucleon (light ions)

10 MeV/nucleon (heavy ions)

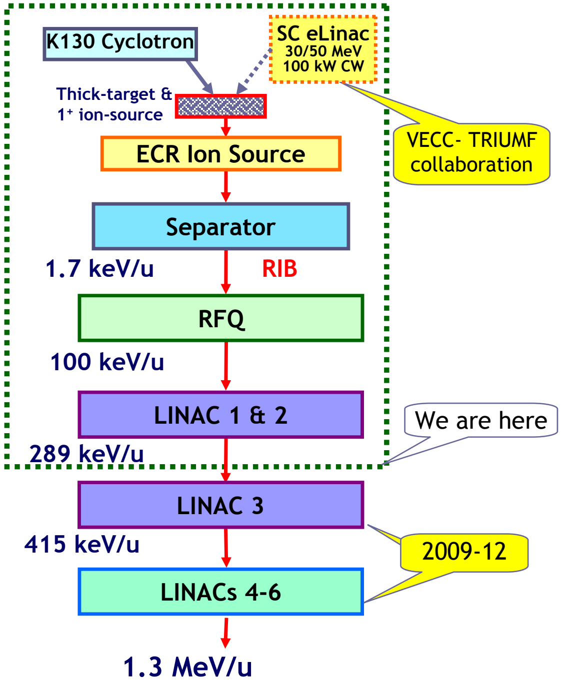
RF system 9-27 MHz

Max Dee voltage 80 kV

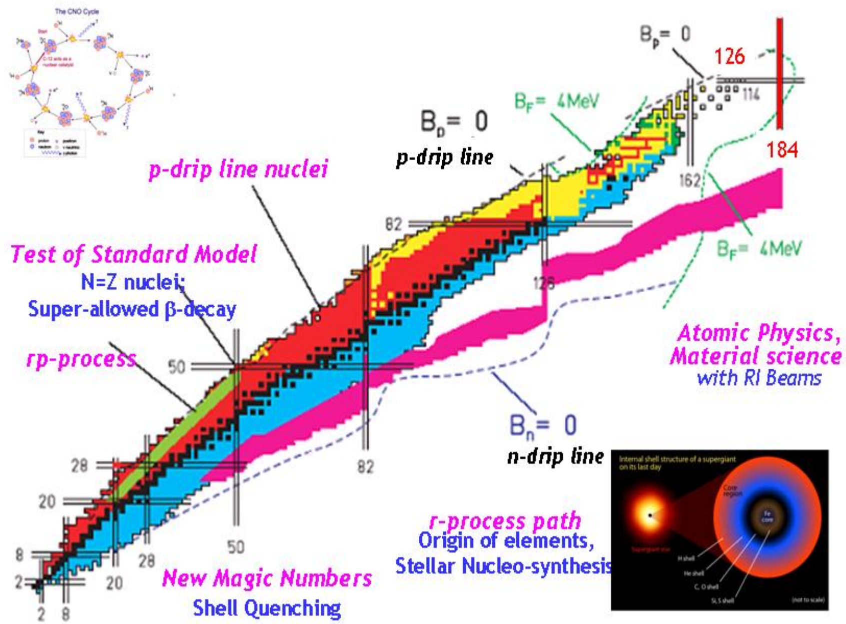
Magnetic field 5 T

In operation

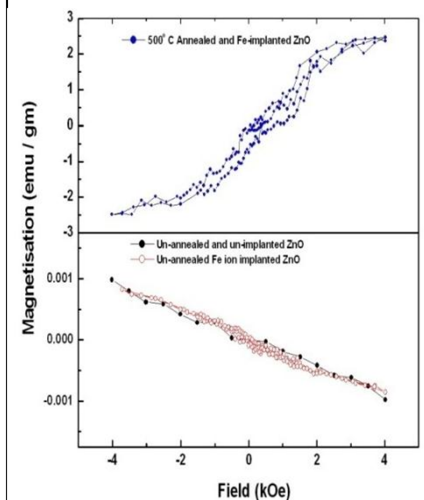
RIB project at VECC, Kolkata (India)

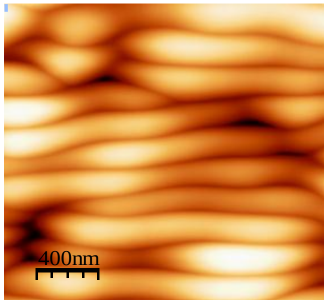


Schematic Layout of RIB Facility



29 keV/u Fe ion-implantation in ZnO room temp ferromagnetism enhancement by 2 orders





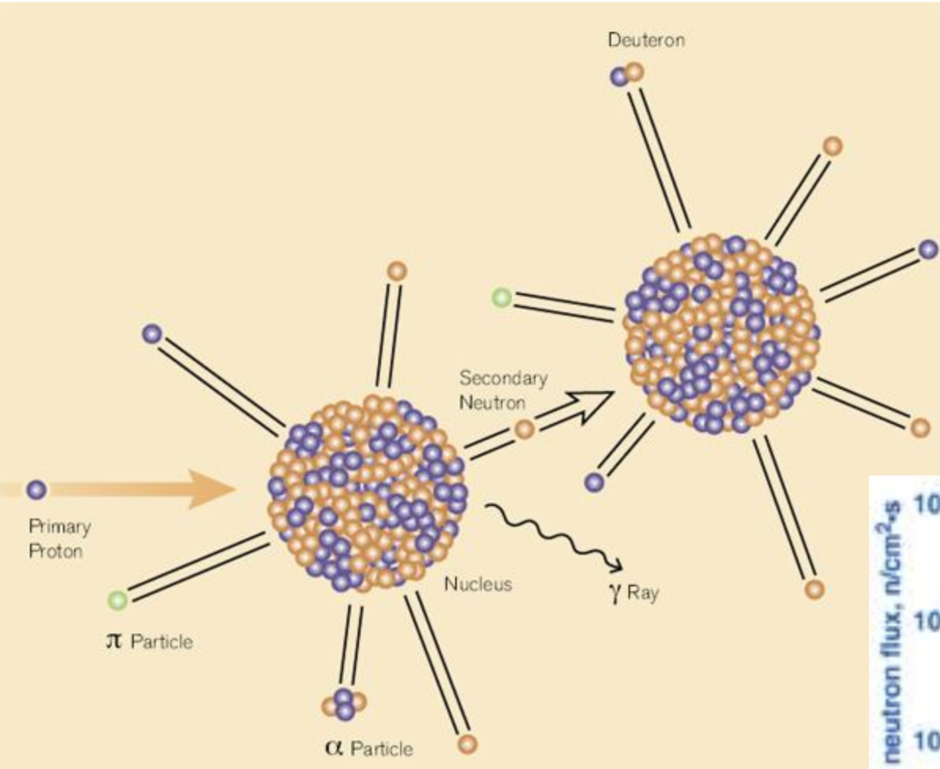
Coulomb sputtering of Si nano-structures by Ar^{8+} ion bombardment

Accelerator technology for RIB

RIB site today

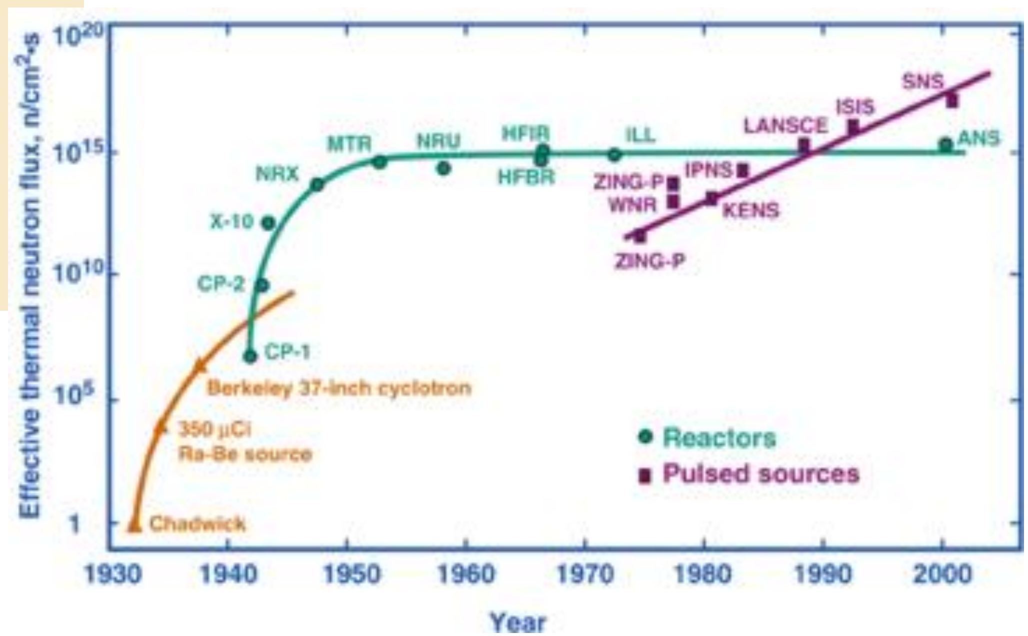
G. Pal

Accelerator-based neutron sources complementary of nuclear reactors



Producing neutrons by spallation

Evolution of neutron source performance



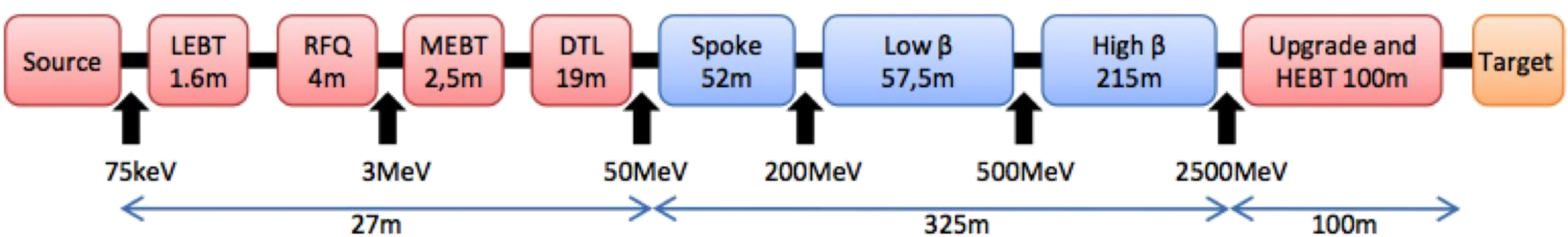
The Spallation Neutron Source (SNS), Oak Ridge, USA

Proton beam power	1.4 MW
Proton beam energy	1 GeV
Average beam current	1.4 mA
Pulse repetition rate	60 Hz
RF frequency	805 MHz
Peak field	27.5/35.0 MV/m
Q0	$> 5 \, . \, 10^9$
Linac length	157 m

European Spallation Source, Lund (Sweden)

EUROPEAN SPALLATION SOURCE

5 MW long pulse source
- ≤2 ms pulses
- ≤20 Hz
- Protons (H+)
- Low losses
- High reliability, >95%
- 2.5 GeV



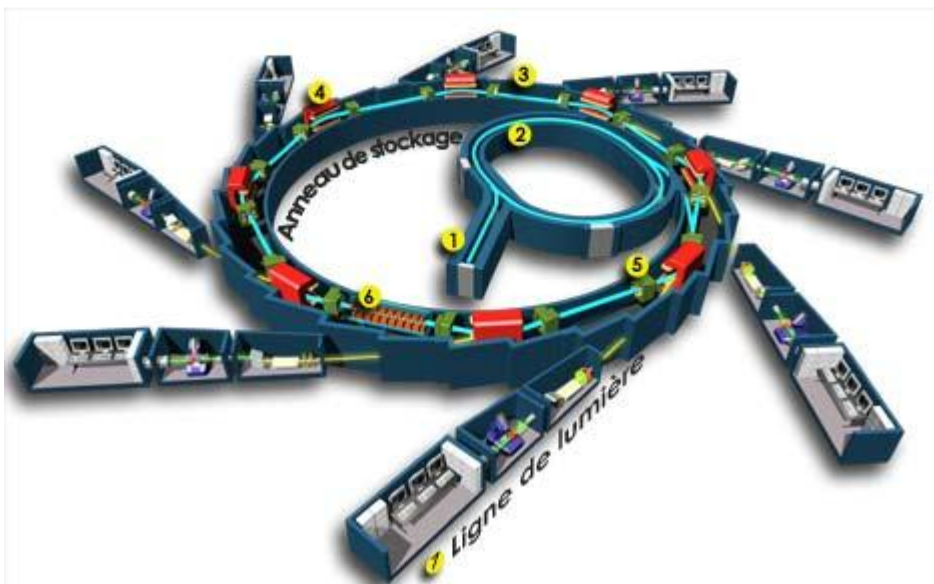
Synchrotron light sources

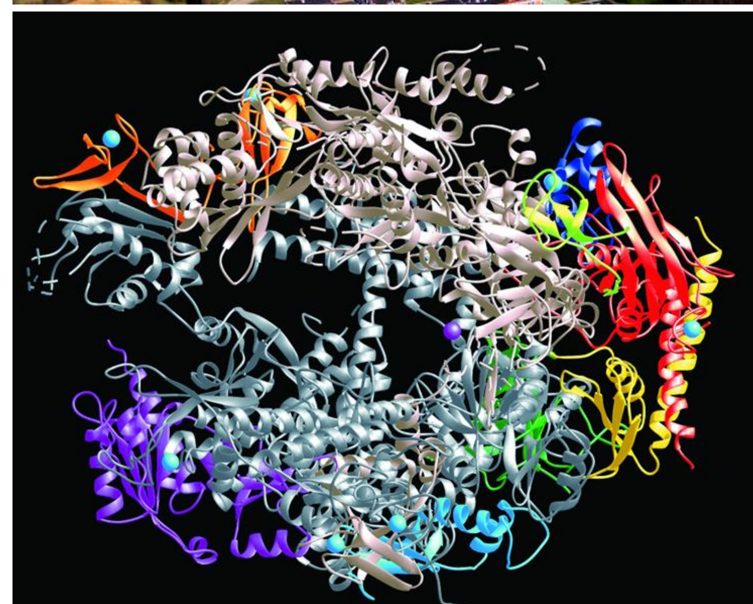
50 synchrotron ring light sources in 29 countries

About 60'000 users world wide

INDUS-2, Indore (India)

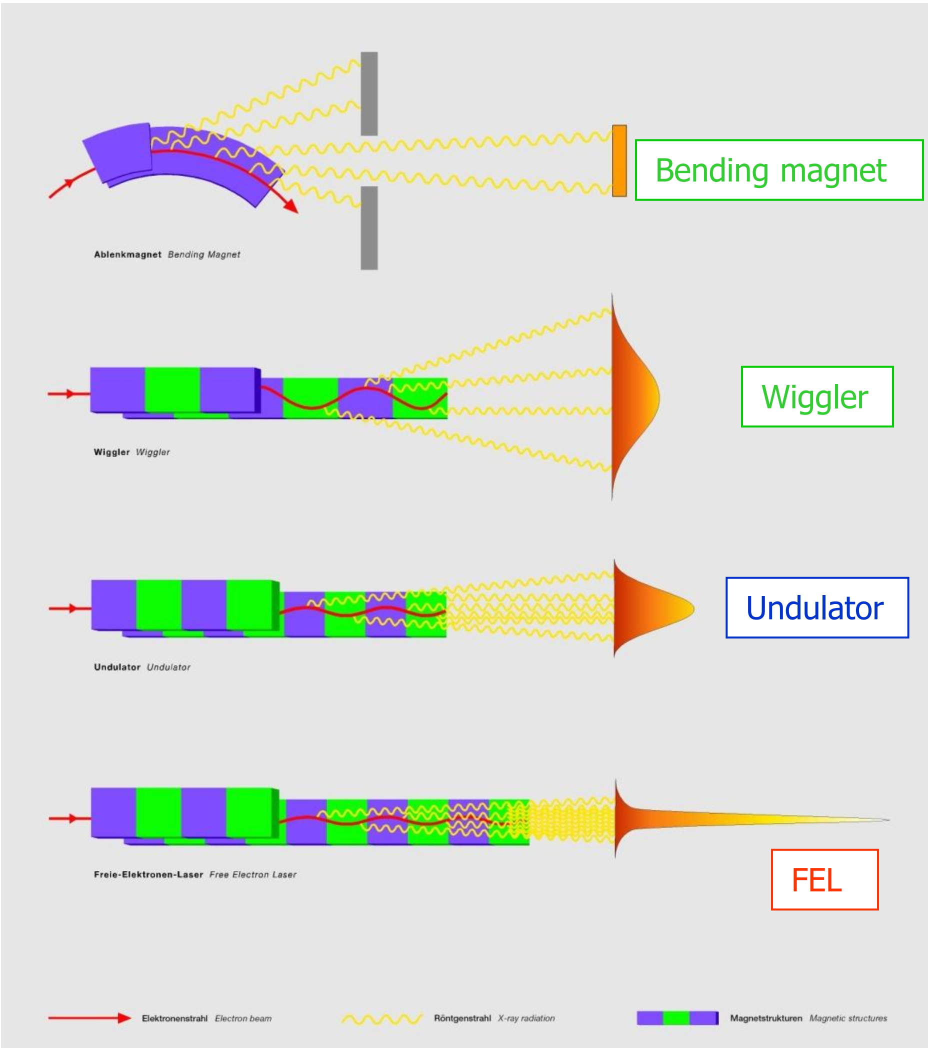
SOLEIL, Saclay (France)

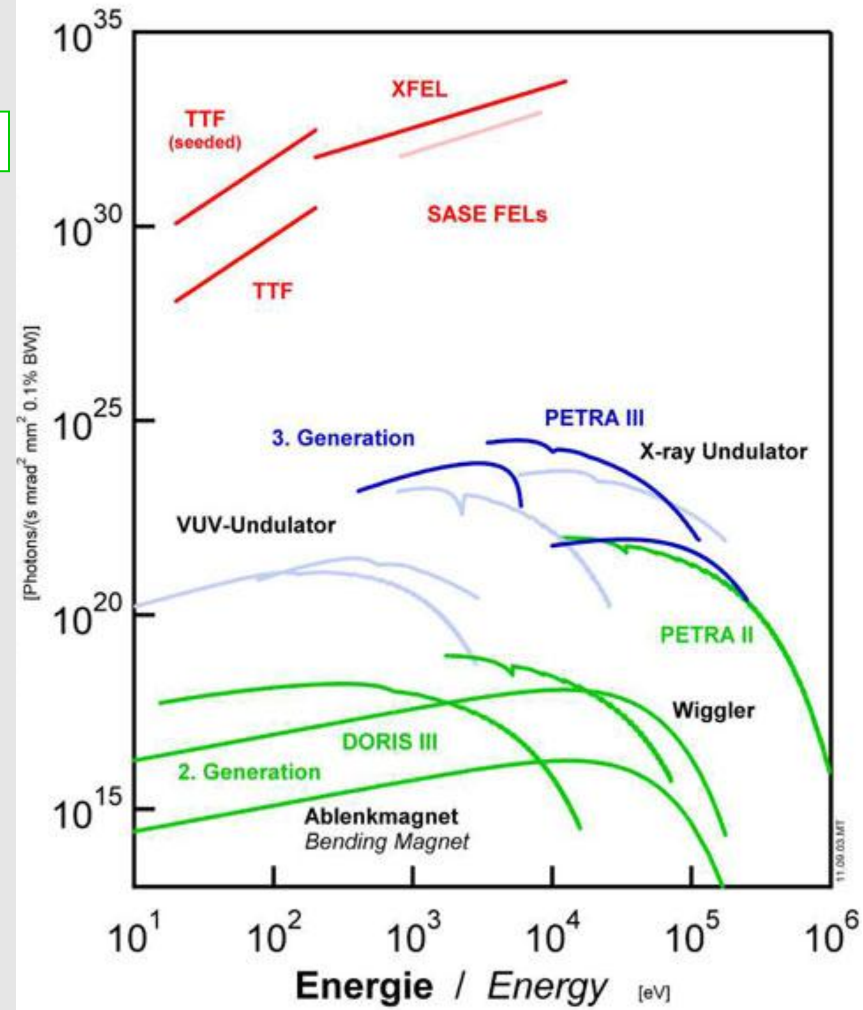




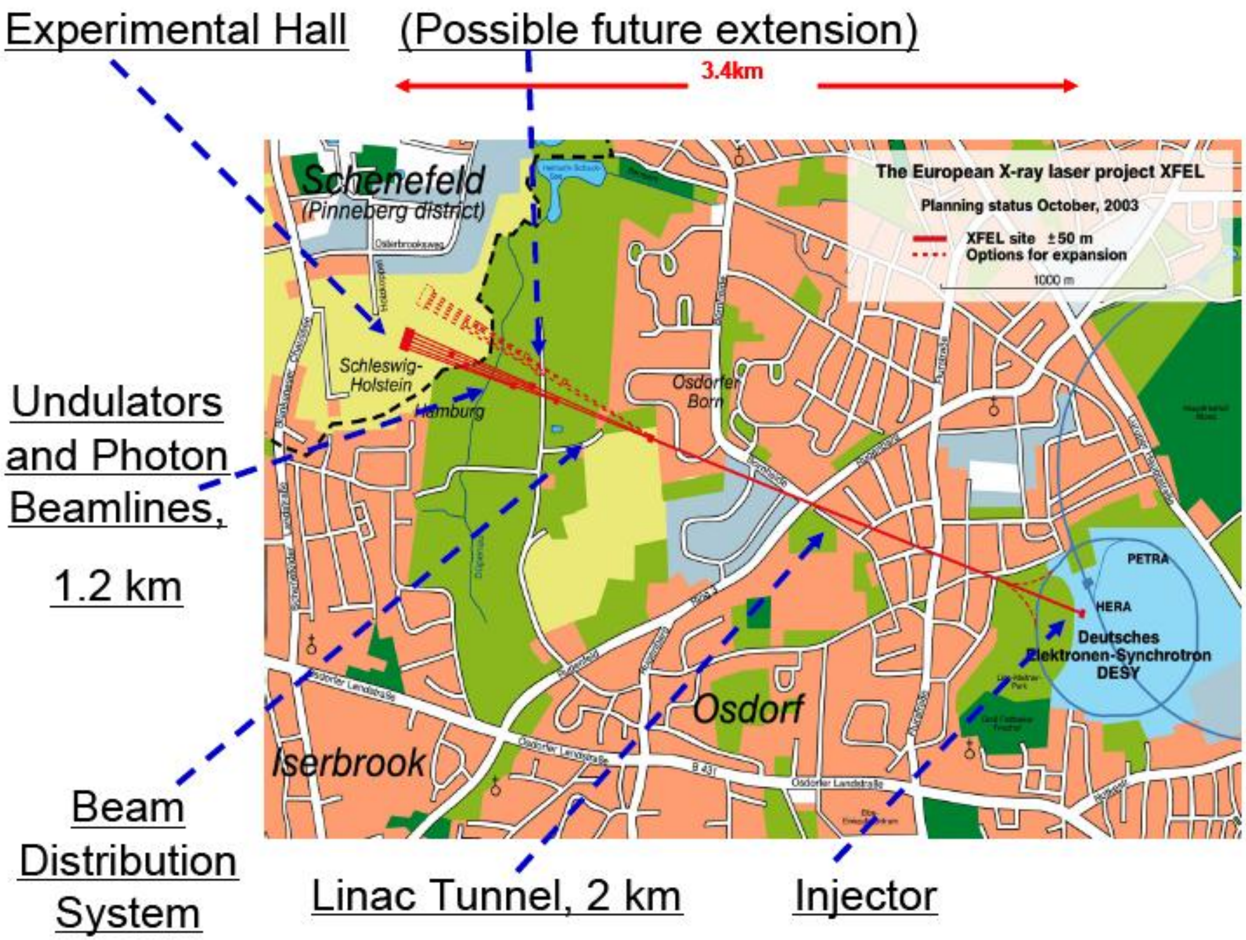
Protein structure analysed by x-ray diffraction

Synchrotron light, from bending magnets to FEL





European X-FEL, DESY, Hamburg (Germany)



Very brilliant, ultra-short (100 fs) pulses of X-rays down to 0.1 nm

Based on s.c. e linac

Beam energy 17.5 GeV

Beam power 600 kW

Linac length 1.7 km

Scientific applications of the European X-FEL

Atoms, ions, molecules, and clusters
- Multiple ionization/multiphoton events
- Creation and spectroscopy of excited states (hollow atoms, Rydberg & Laser states, ...)
- Dynamics, elec. & geom. structure of cluster

Plasma physics
- Generation of solid-density plasmas
- Plasma diagnostics

Condensed-matter physics
- Ultrafast dynamics
- Electronic structure
- Disordered materials & soft matter

Materials sciences
- Dynamics of hard materials
- Structure and dynamics of nanomaterials

Chemistry
- Reaction dynamics in solid, liquid systems
- Analytical solid-state chemistry
- Heterogenous catalysis

Structural biology
- Single particle/molecule imaging
- Dynamics of biomolecules

Optics and nonlinear phenomena
- Nonlinear effects in atoms and solids
- High field science

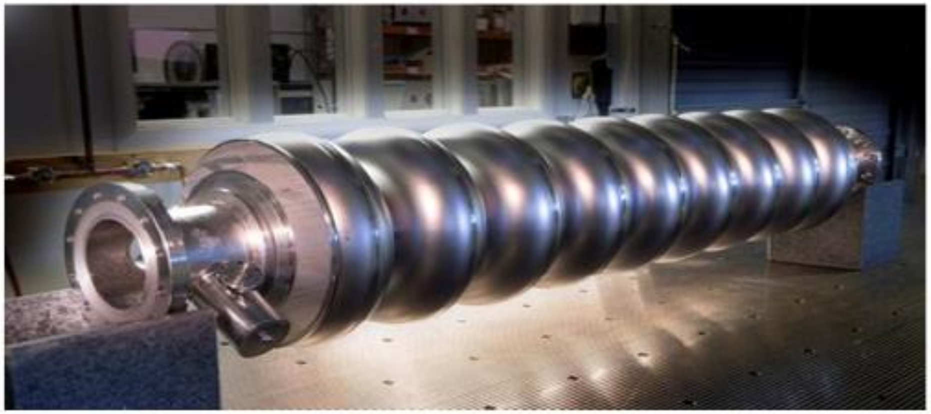
Ultrashort pulses | Pulse intensities | Coherence | Average brilliance

J. Hajdu

Converting the SLAC linac:
the LCLS FEL at Stanford, USA

New acceleration techniques: near-field accelerators

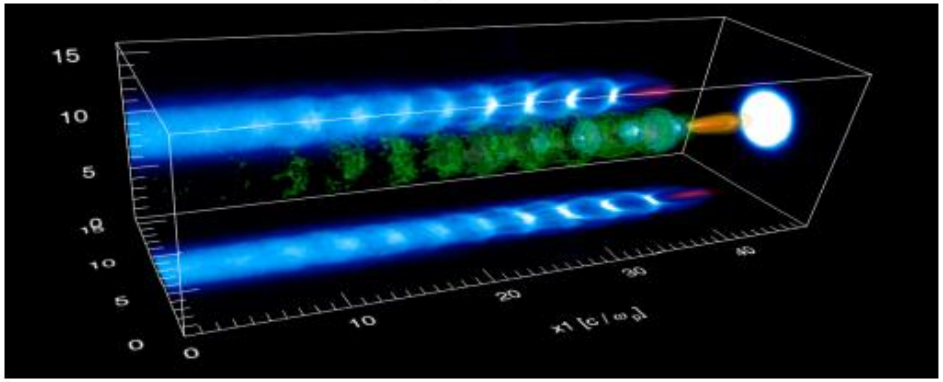
Conventional cavity: meter scale



Accelerating Gradient

10 - 40 MV/m

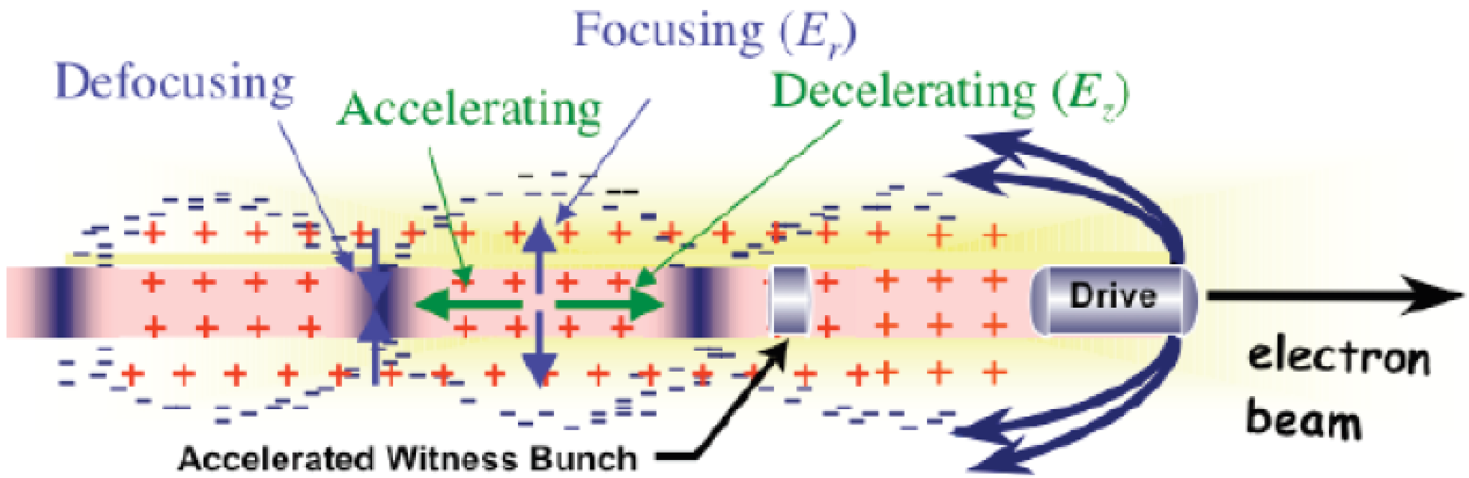
Plasma Technology: 100 micron scale



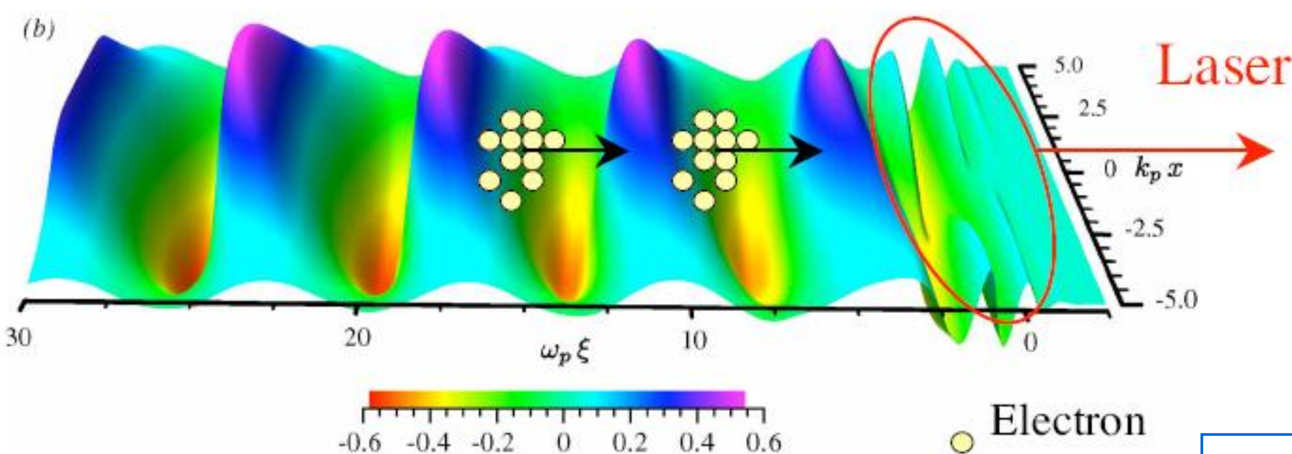
10 - 100 GV/m

W. Brinkmann

Beam driven plasma acceleration



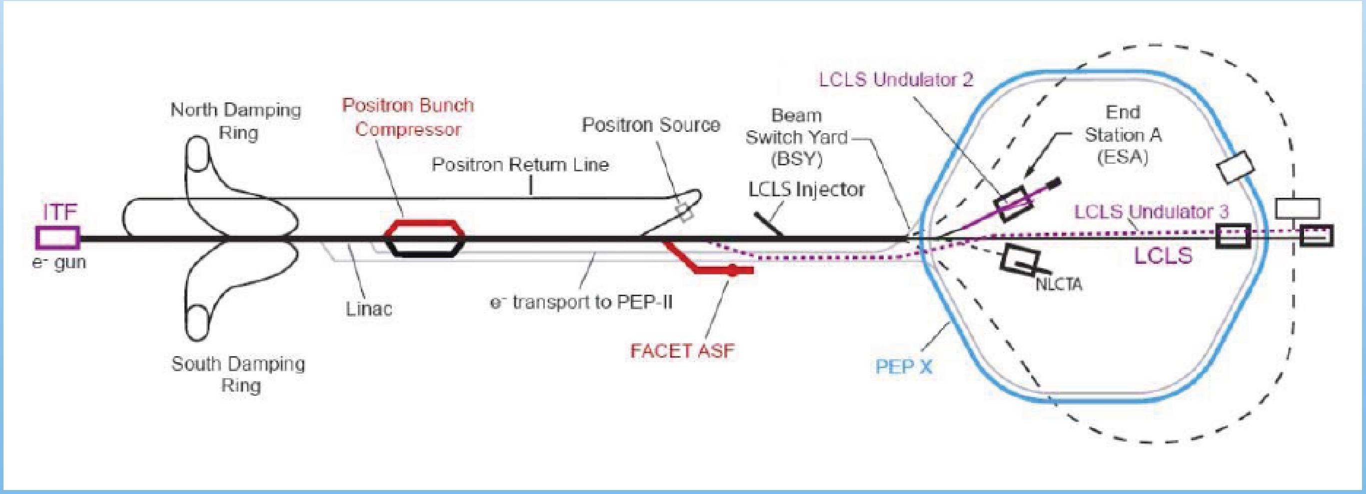
Laser driven plasma acceleration



M. Tigner

FACET: Facility for Advanced Accelerator Experimental Tests

- Will address critical issues of a single stage
- Uses the SLAC injector complex and 2/3 of the SLAC linac to deliver electrons and positrons



Pluridisciplinary training & education

Contents

- Accelerators for science
  - High-energy physics
  - Nuclear physics
  - Neutron science
  - Synchrotron light
  - New acceleration techniques
- Accelerators for society
  - Medical
  - Food and biological safety
  - Environment
  - Industry
  - Energy

NAE Grand Challenges for the 21st Century

Make solar energy economical

Provide energy from fusion

Develop carbon sequestration methods

Manage the nitrogen cycle

Provide access to clean water

Restore and improve urban infrastructure

Advance health informatics

Engineer better medicines

Reverse-engineer the brain

Prevent nuclear terror

Secure cyberspace

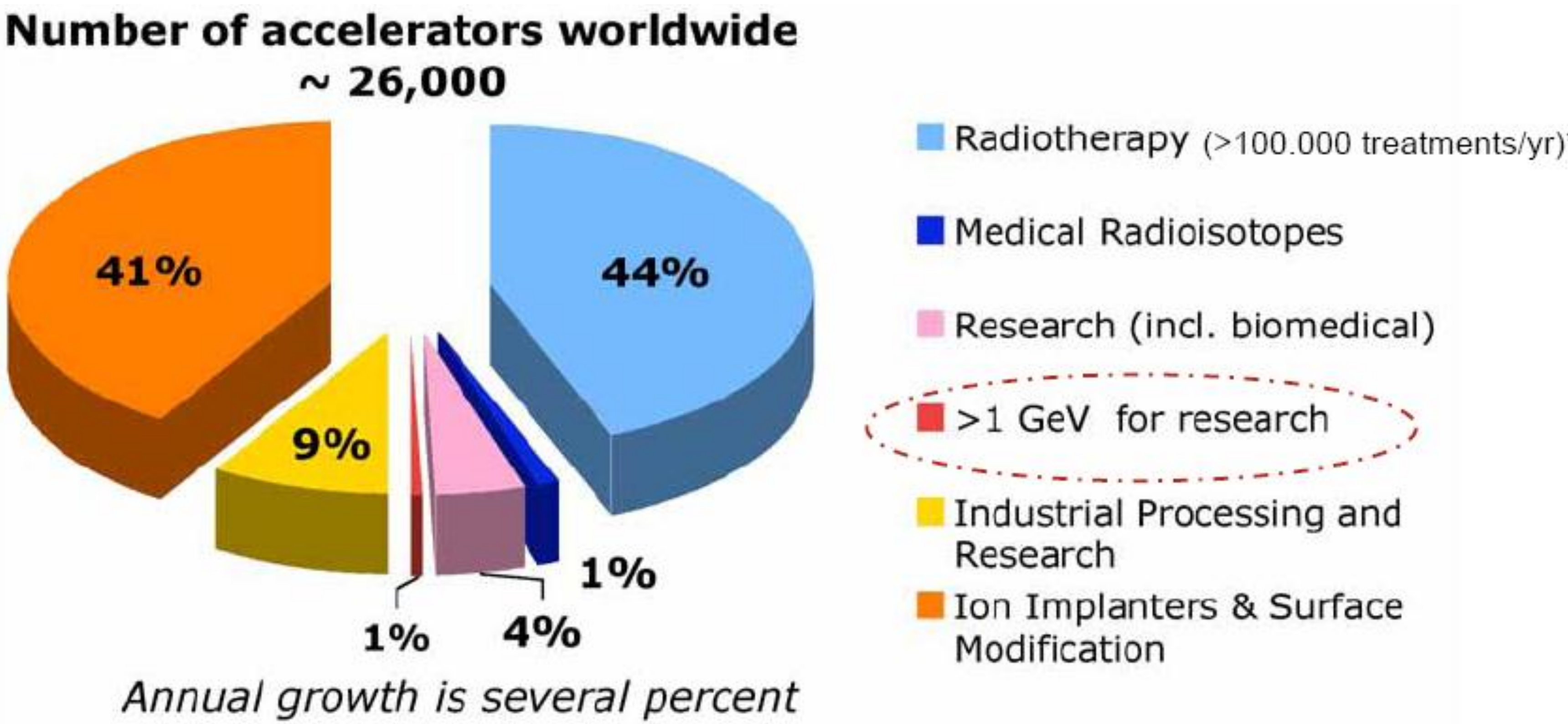
Enhance virtual reality

Advance personalized learning

Engineer the tools of scientific discovery

T. Katsouleas

Accelerators are big business



Sales >3.5 B$/yr

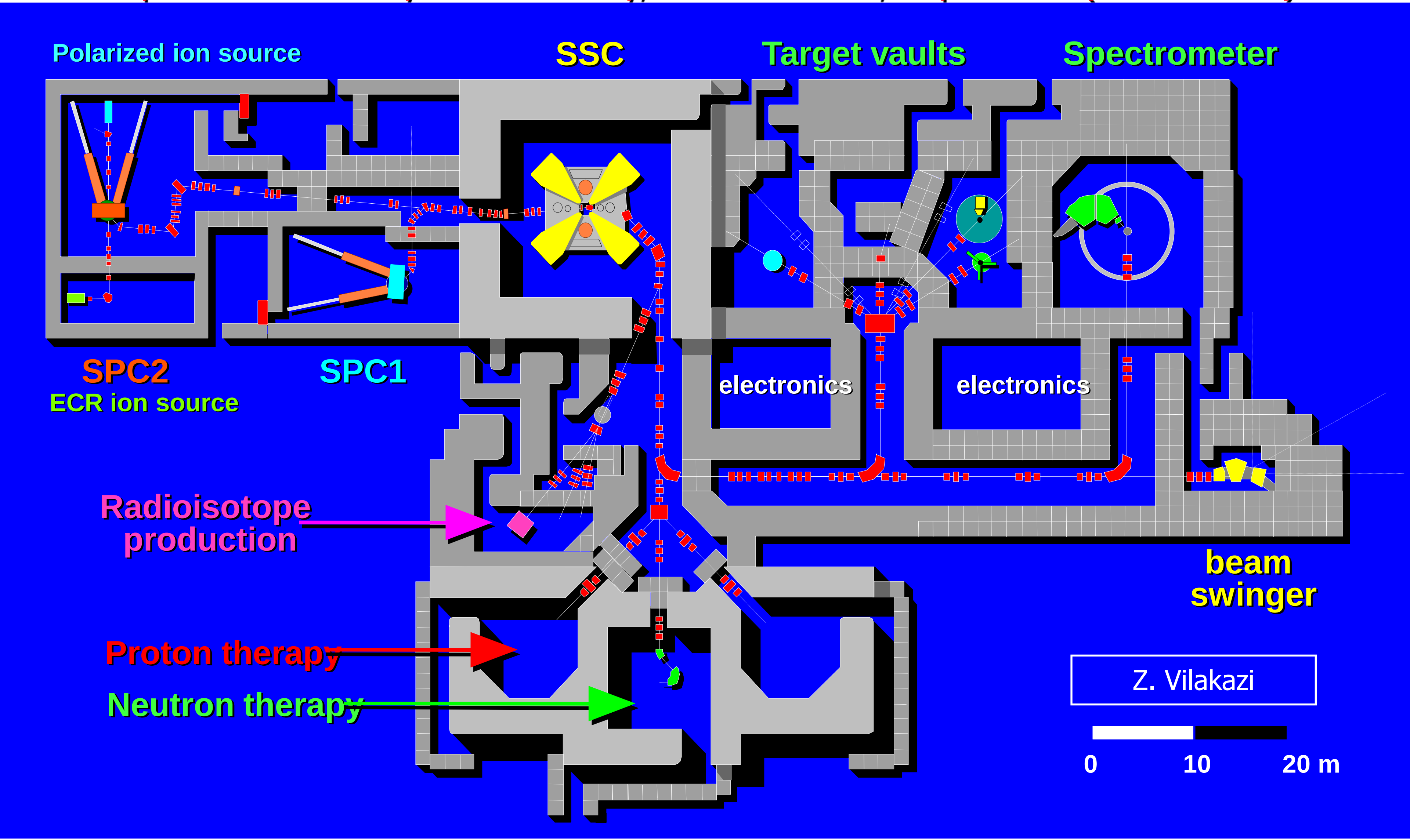
Value of treated good > 50 B$/yr **

W. Barletta

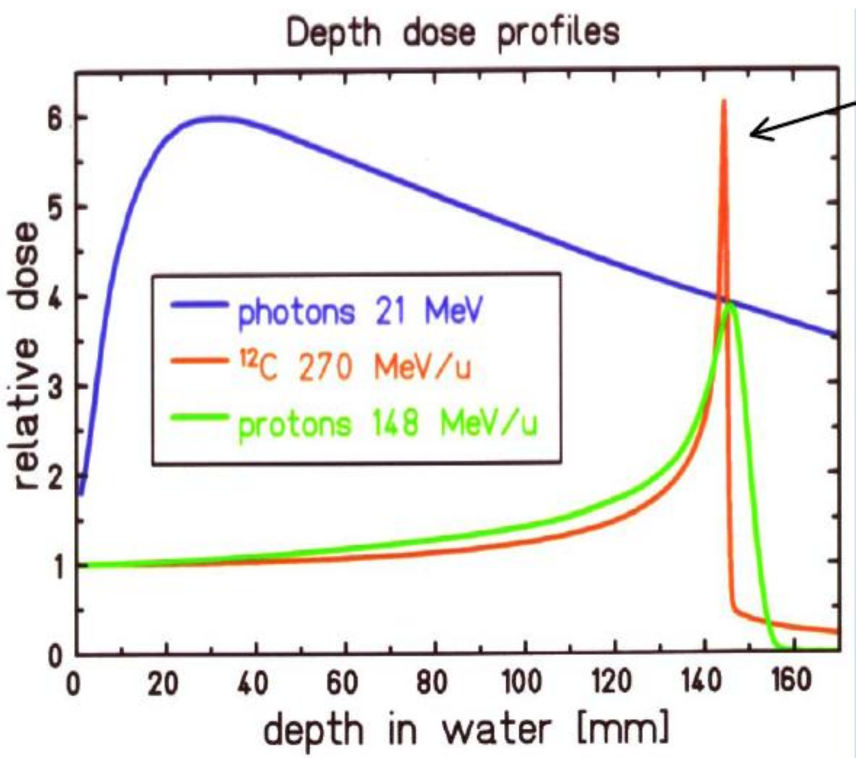
Medical accelerators

Radioisotope production & particle therapy

Separated-Sector Cyclotron Facility, iThemba Labs, Cape Town (South Africa)

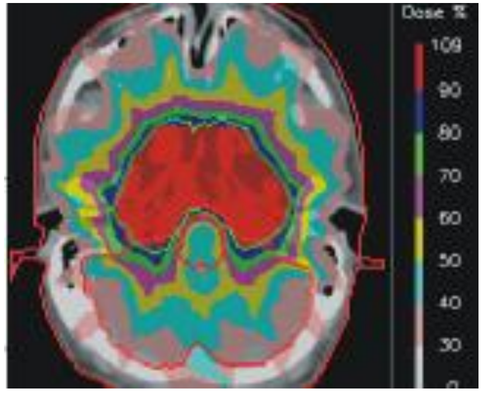


Accelerators for tumor treatment by particle therapy
30 centers worldwide, >100'000 patients treated

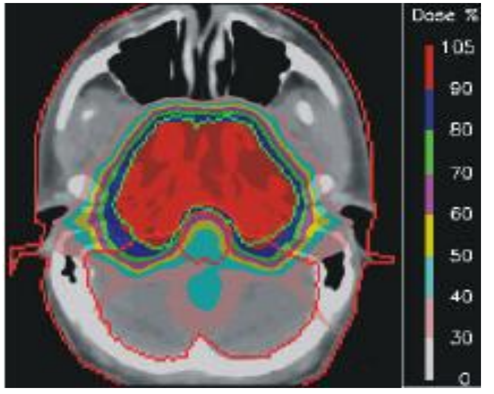


Bragg peak

9 X-ray fields



4 proton fields

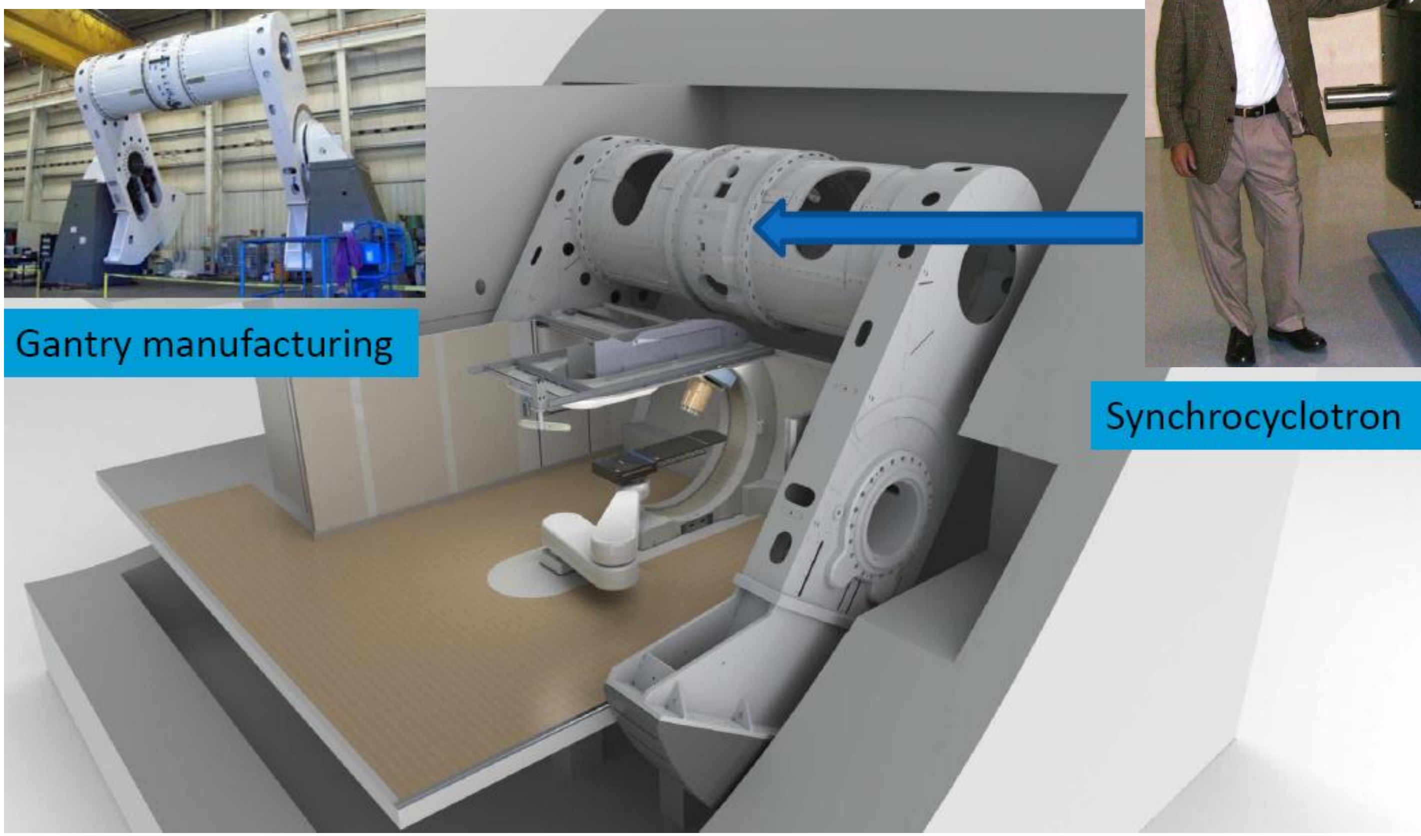


Better targeting of tumor
with hadron beams

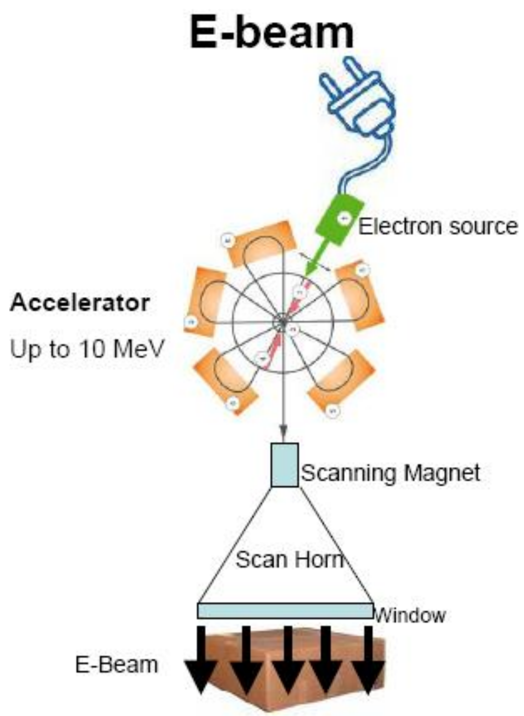
HIT particle therapy center in Heidelberg, Germany

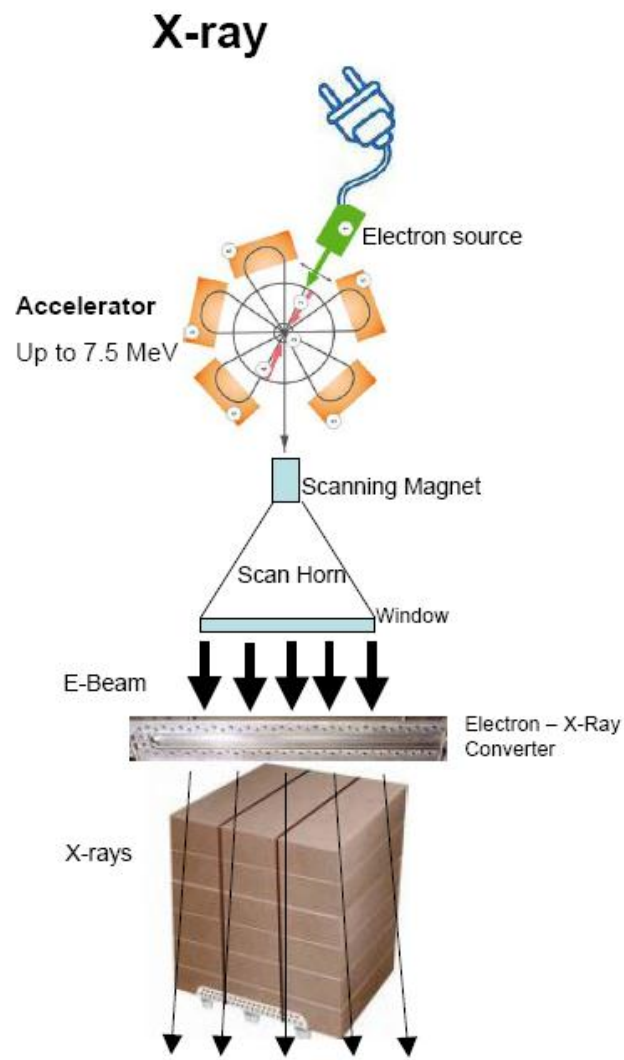
Compact superconducting synchrocyclotron for hadron therapy
(*Still River Systems*)

- 250 MeV protons
- 20 t mass allowing integration in gantry
- cooled by cryocoolers (no liquid helium)



Accelerators for sterilization by irradiation





Y. Jongen

Food irradiation

- **Low Dose Applications (< 1kGy)**
  - **Phytosanitary** Insect Disinfection for grains, papayas, mangoes, avocados...
  - **Sprouting Inhibition** for potatoes, onions, garlic...
  - **Delaying of Maturation**, parasite disinfection.

- **Medium Dose Applications (1 – 10 kGy)**
  - **Control of Foodborne Pathogens** for beef, eggs, flounder-crab-meat, oysters...
  - **Shelf-life Extension** for chicken and pork, low fat fish, strawberries, carrots, mushrooms, papayas...
  - **Spice Irradiation**

- **High Dose Applications (> 10 kGy)**
  - **Food sterilization** of meat, poultry and some seafood is typically required for hospitalized patients or astronauts.

Y. Jongen

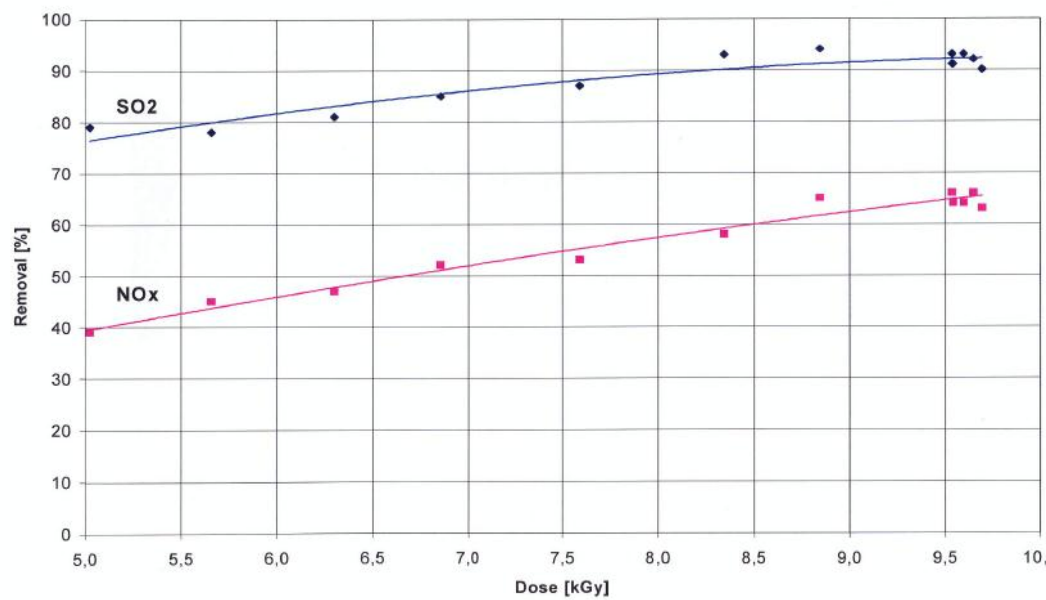
Environmental safety

Flue gas treatment

Dry scrubbing process for simultaneous removal of SO_2, NO_x and volatile organic compounds

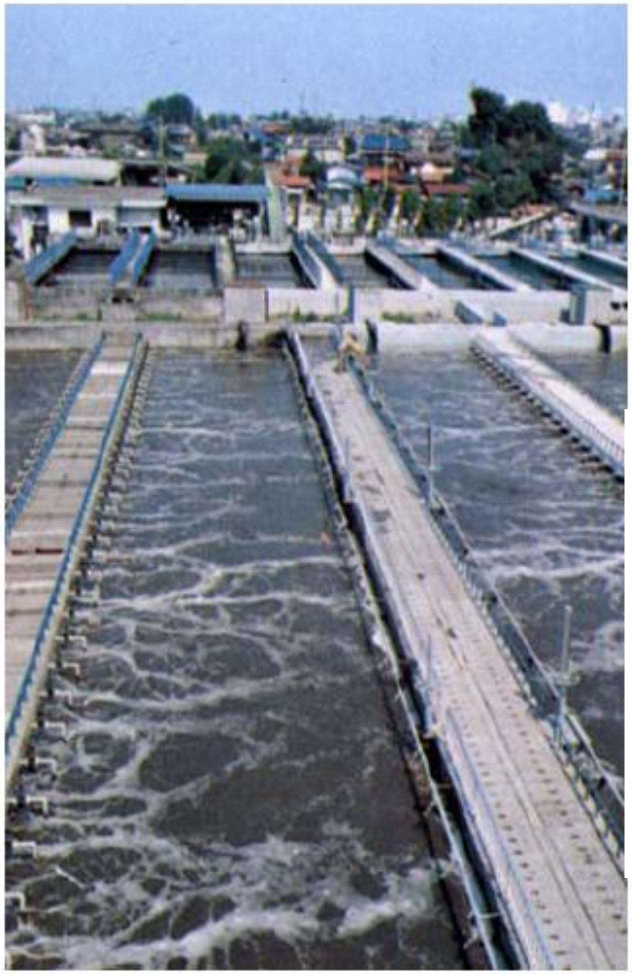
Creation of free radicals by radiolysis

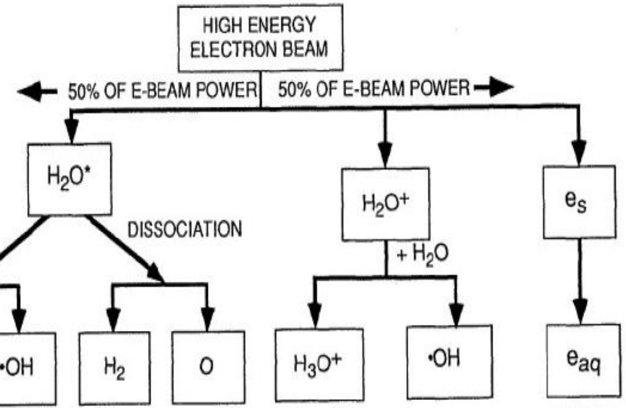
Efficient and clean alternative to chemical processes such as wet flue gas desulphuration and selective catalytic reduction (no waste generated)

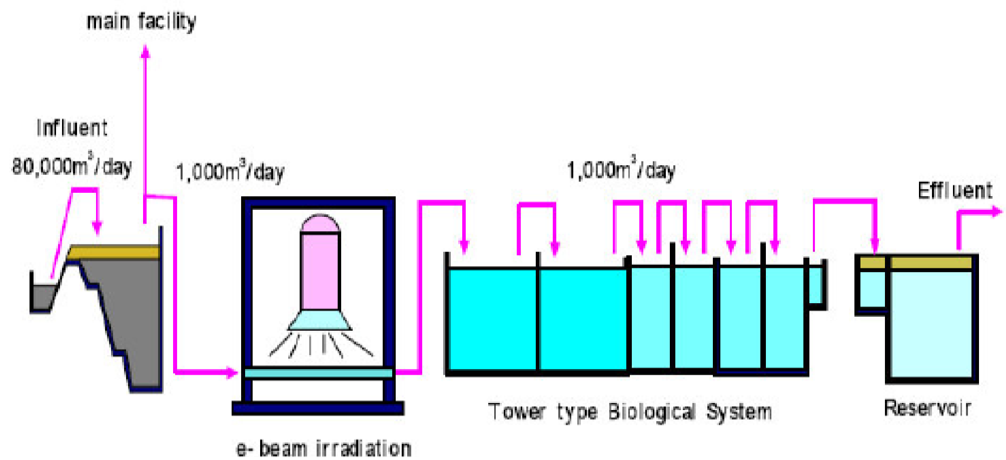


Environmental safety

Liquid effluents treatment





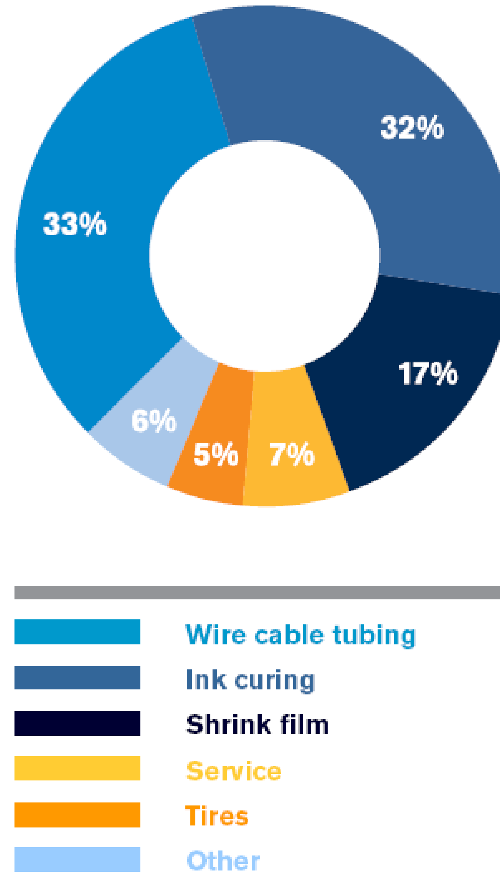


1000 m^3/day pilot plant at Daegu (South Korea)

Polymer crosslinking by e-beams

- **Wires** stand higher temperature after irradiation
- **Pipes** for central heating and plumbing
- **Heatshrink elastomers** are given a memory

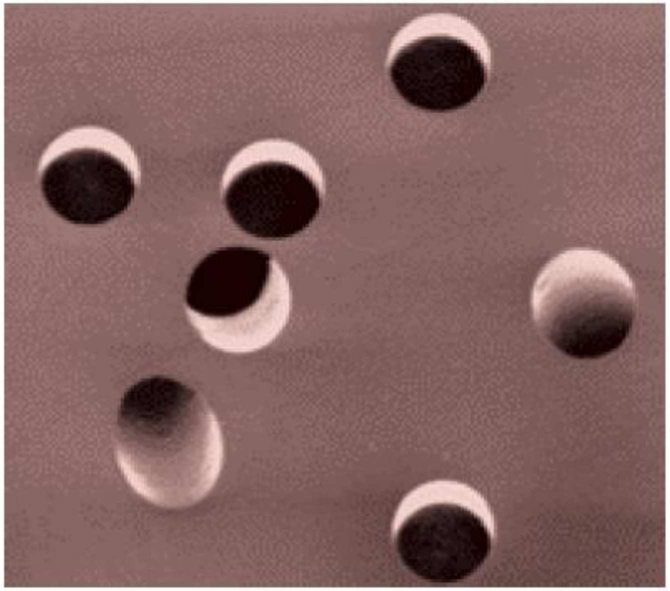
Markets for industrial electron beams total $50 billion per year.
Image source: IAEA Working Material on Industrial Electron Beam Processing

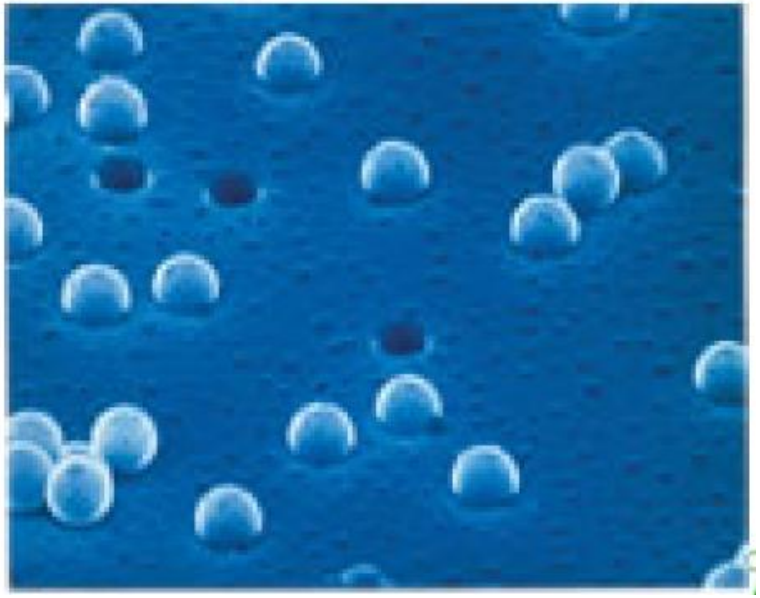


Y. Jongen

Microfiltration membranes by heavy ion beams

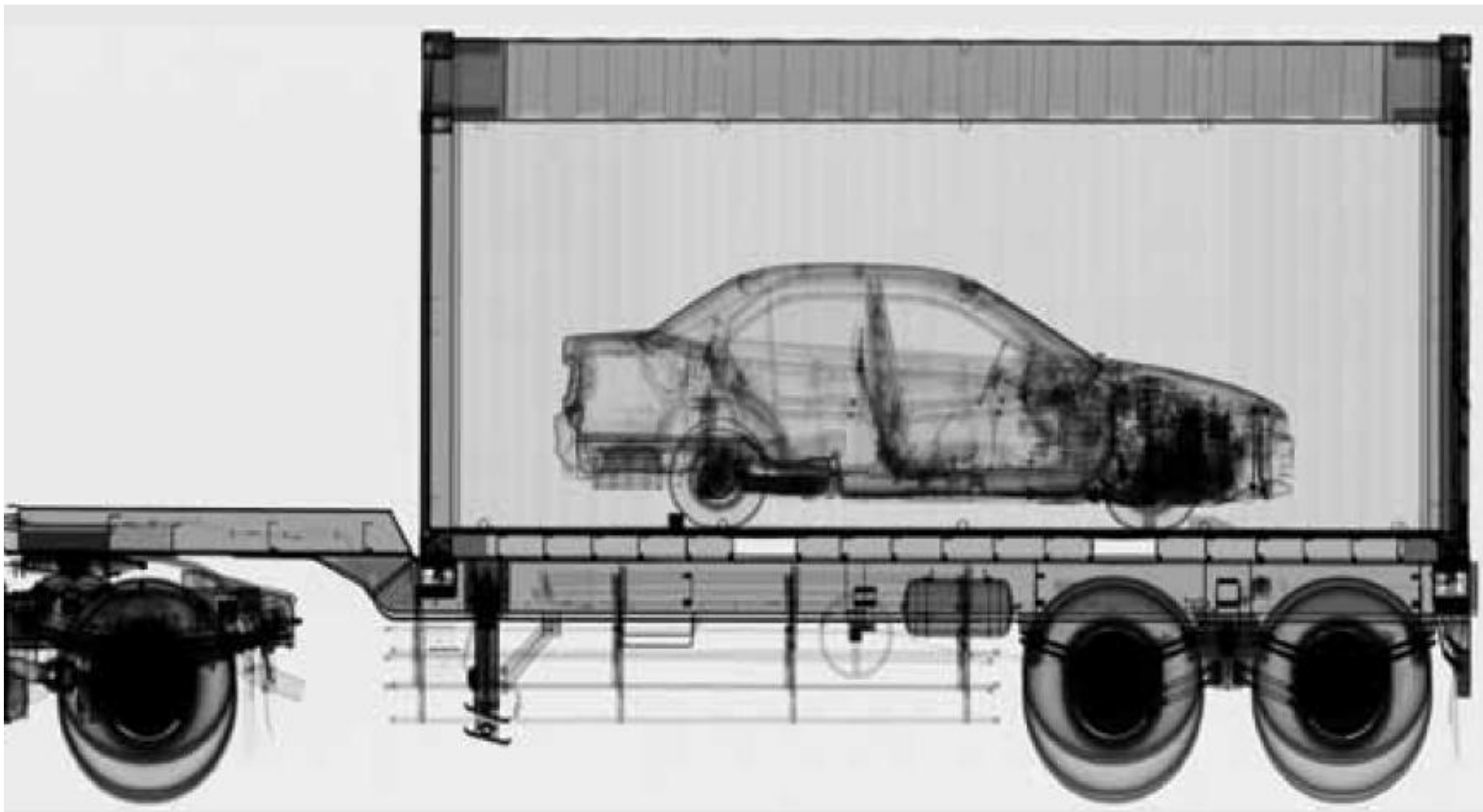
- Heavy ion beams are used to produce track-etched microfiltration membranes, commercialized i.a. under the brand name "Cyclopore"
- In these membranes, tracks of slow, heavy ions crossing a sheet of polymer are chemically etched, giving cylindrical pores of very accurate diameter

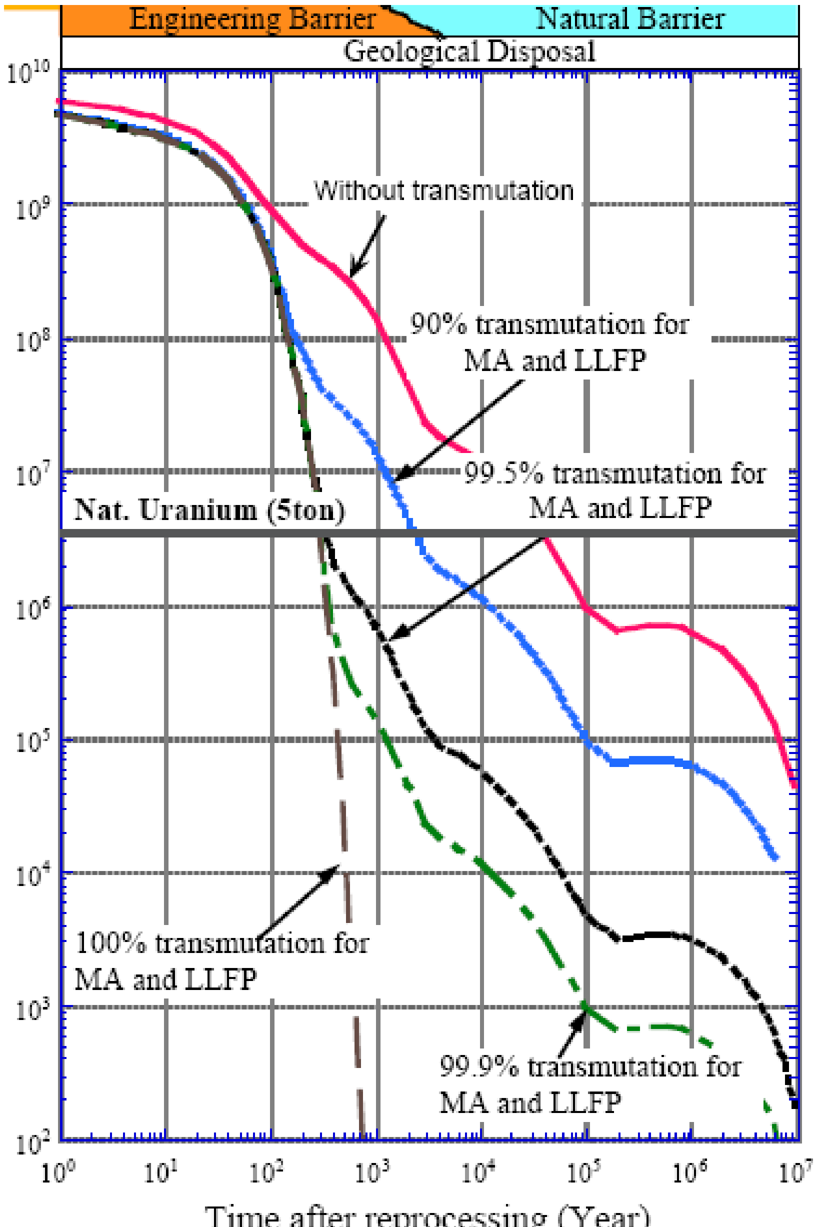




Y. Jongen

High-energy (MeV) X-rays scan shipping containers





LLFP: long-lived FP ($T_{1/2}$ >30years)

MA: minor actinide

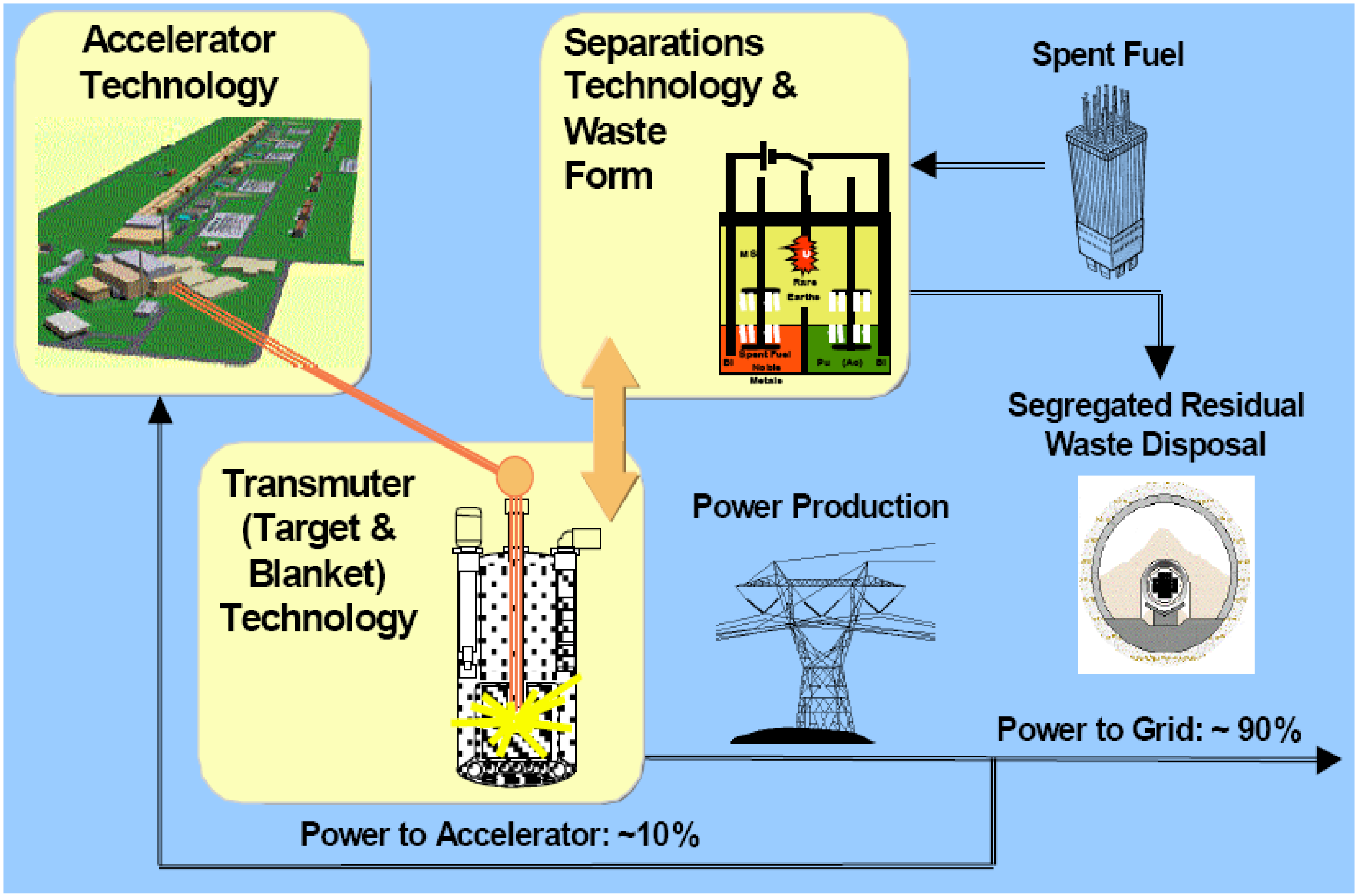
Nuclear waste transmutation

reduces activity of MA and LLFP

alleviates the long-term storage problem

R. Sheffield

ADS for nuclear waste transmutation



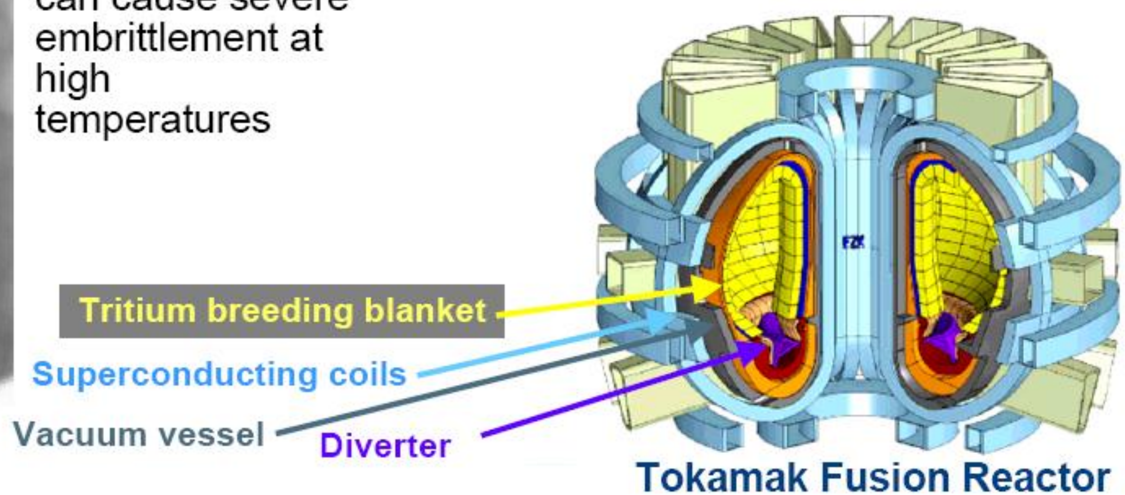
R. Sheffield

The challenge of materials for nuclear fusion

Requirements for fusion materials:

- Low activation: shallow burial after 100 years desired, limits candidate elements
- Withstand fusion fluxes: maintain strength, ductility, structural integrity for 2 MW/m^2-s (10^{18} neutrons/m^2-s)
- Long lifetime: 5-10 years for full power operation with wall load of 2 MW/m^2; 1.5-3 x 10^{26} n/m2

He bubbles on grain boundaries can cause severe embrittlement at high temperatures



R. Sheffield

IFMIF
a facility for testing materials under high neutron flux

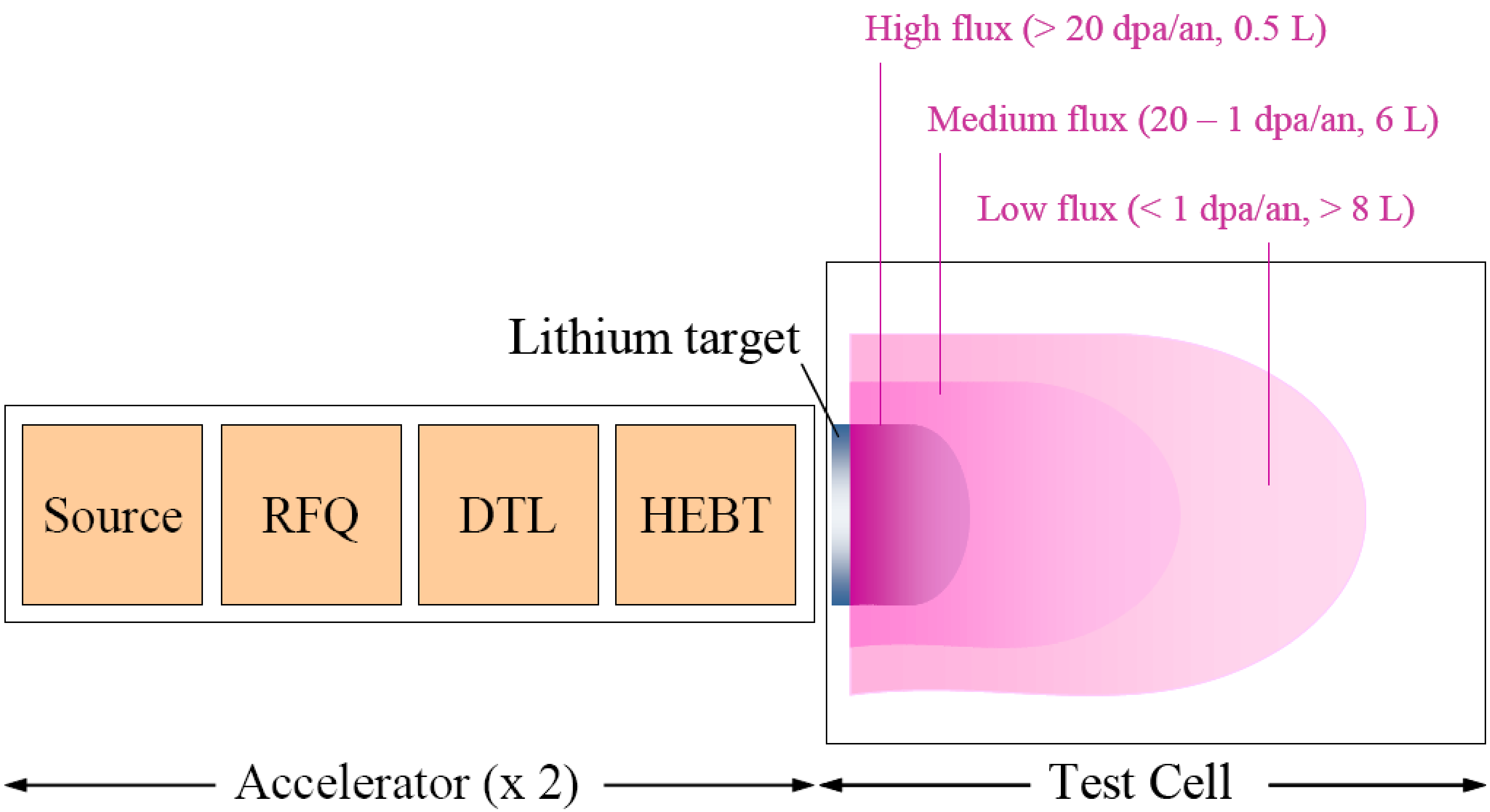
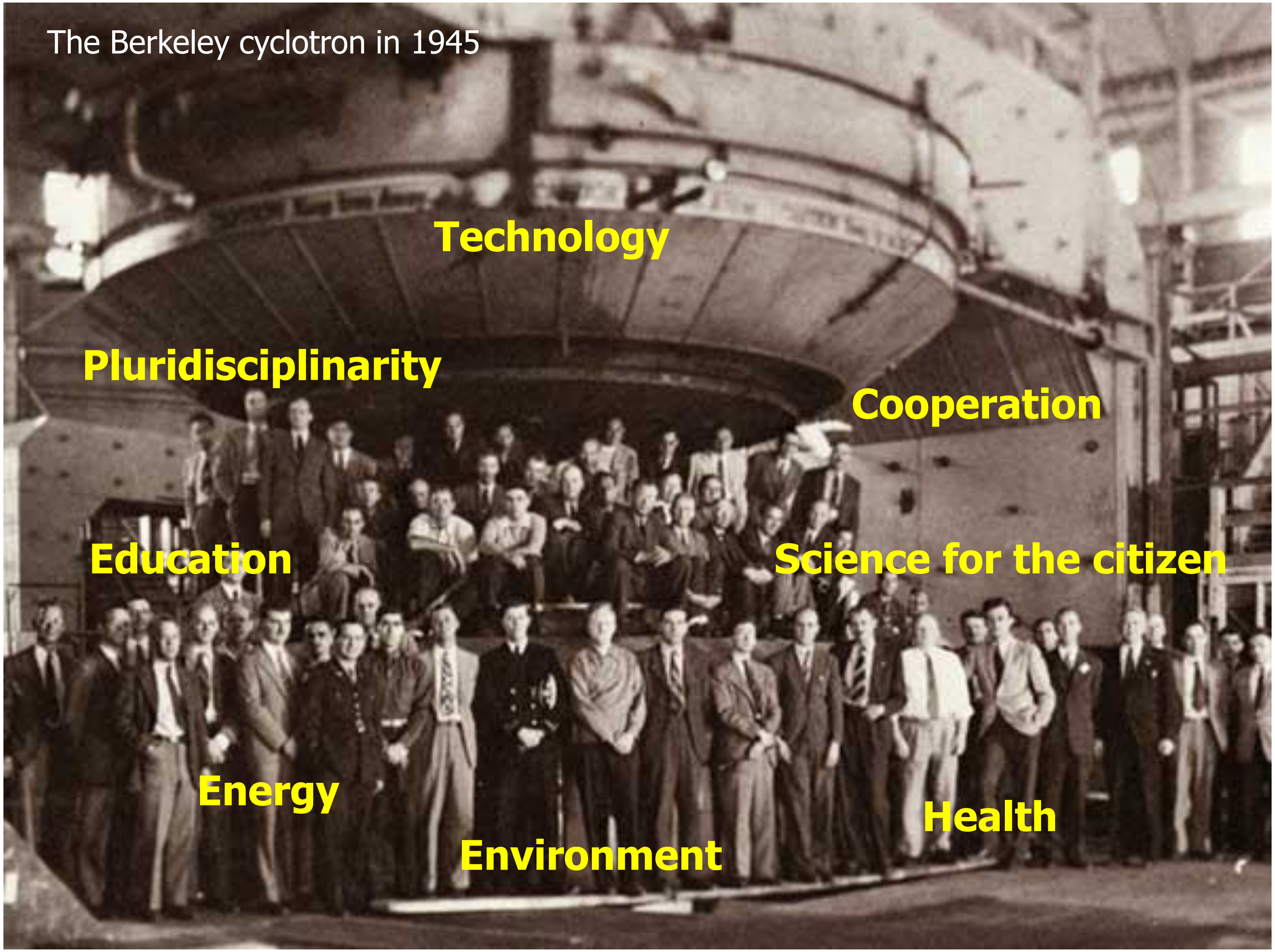


Figure 1: Principle of IFMIF: the two accelerators bring the deuteron beams (125 mA each) to an energy of 40 MeV. The neutrons produced by their interaction with a liquid lithium flow irradiate three sets of volumes called High Flux Test Module, Medium Flux Test Module and a low flux region.

Benefits of accelerator science and technology



Conclusion

- Particle accelerators, invented as the discovery instruments of basic science, have developed to become the workhorses of applied science and the tools of societal applications in medicine, health, environmental protection, energy and industry
- Development of particle accelerators cross-stimulated progress in a variety of advanced technologies, providing opportunities for training and education in engineering & science and promoting global cooperation
- The societal impacts of such powerful instruments as particle accelerators must be explained, understood and democratically accepted for the benefit of mankind

If information and knowledge are central to democracy, they are the conditions for development

Kofi Annan