Introduction to Accelerators

Lecture 1

Motivations

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Energy & Momentum units

- When we talk about the energy or momentum of individual particles, the Joule is inconvenient

- Instead we use the eV, the energy that a unit charge

$$e = 1.6 \times 10^{-19} \text{ Coulomb}$$

gains when it falls through a potential, $\Delta\Phi = 1$ volt.

$$1\, eV = 1.6 \times 10^{-19} \text{ Joule}$$

- For momentum we use the unit, eV/c, where c is the speed of light

Mass units

- We can use Einstein's relation,

$$E_o = mc^2$$

to convert rest mass to energy units (m is the rest mass)

- For electrons,

$$E_{o,e} = 9.1\text{x}10^{-31}\text{ kg x }(3\text{x}10^{8}\text{ m/sec})^2 = 81.9\text{x}10^{-15}\text{ J}$$
$$= 0.512\text{ MeV}$$

- For protons,

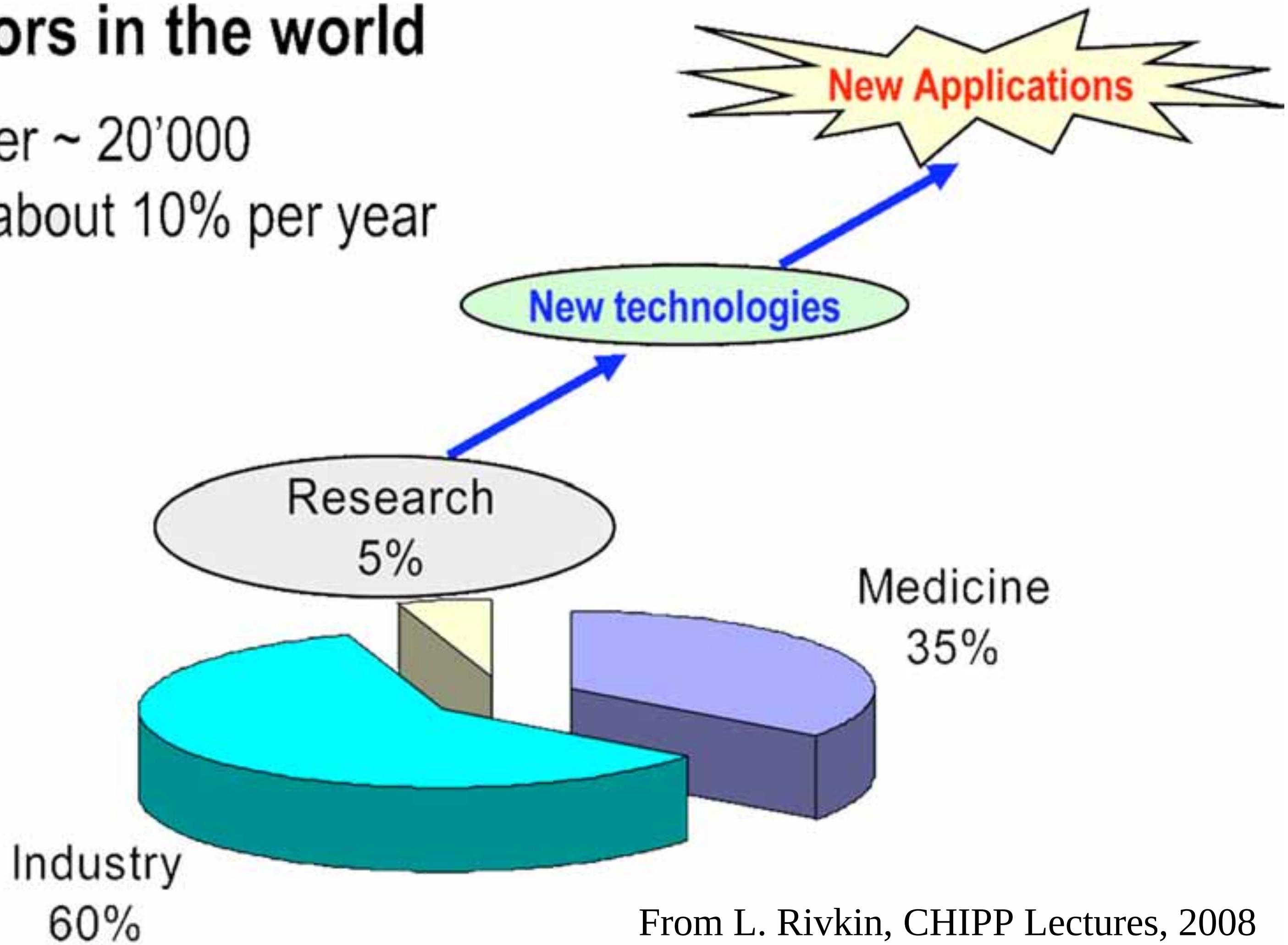
$$E_{o,p} = 938\text{ MeV}$$

Why do we build accelerators?

Research accounts for a small numebr

Accelerators in the world

Total number ~ 20'000
growing at about 10% per year



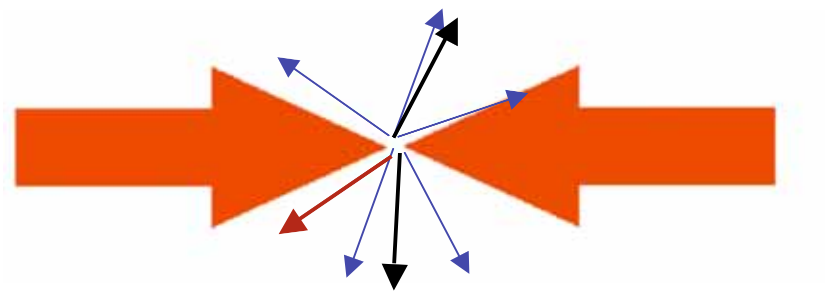
From L. Rivkin, CHIPP Lectures, 2008

What are these machines used for?

Category	**Number**
Ion implanters and surface modification	7’000
Accelerators in industry	1’500
Accelerators in non-nuclear research	1’000
Radiotherapy	5’000
Medical isotopes production	200
Hadrontherapy	20
Synchrotron radiation sources	70
Research in nuclear and particle physics	110
TOTAL	15’000

From L. Rivkin, CHIPP Lectures, 2008

Collide beams

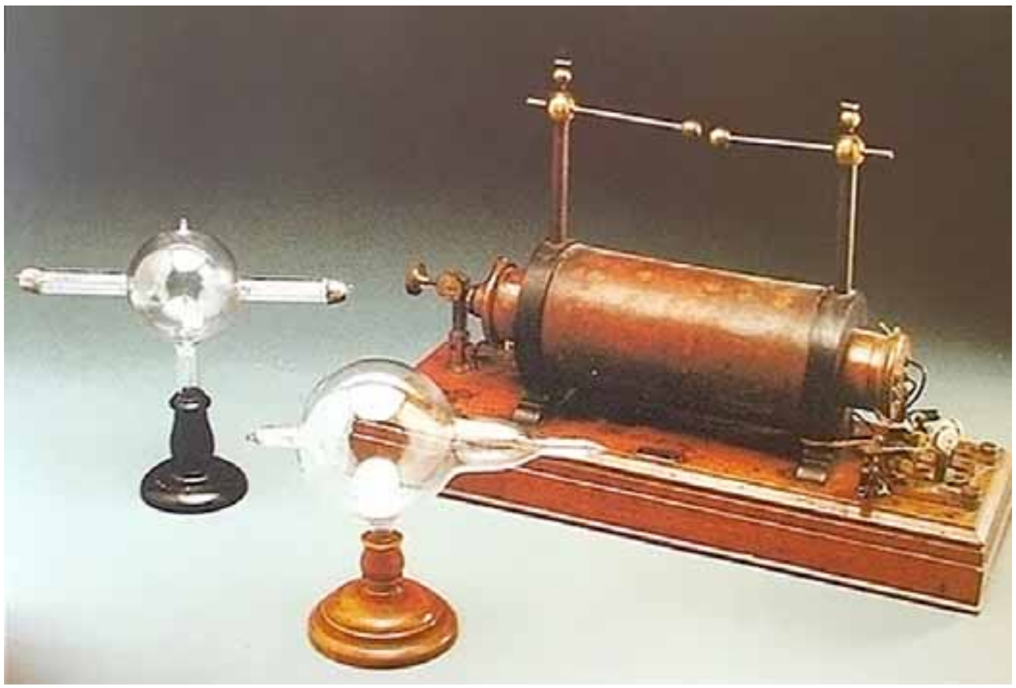


Figures of Merit (FOM):
Collision rate,
Energy stability,
Accelerating field

Examples: LHC, ILC, RHIC

What we know by direct observation

How can we understand the underlying structure of things?



Wilhelm Röntgen Discovered X-rays in 1895

How it all began

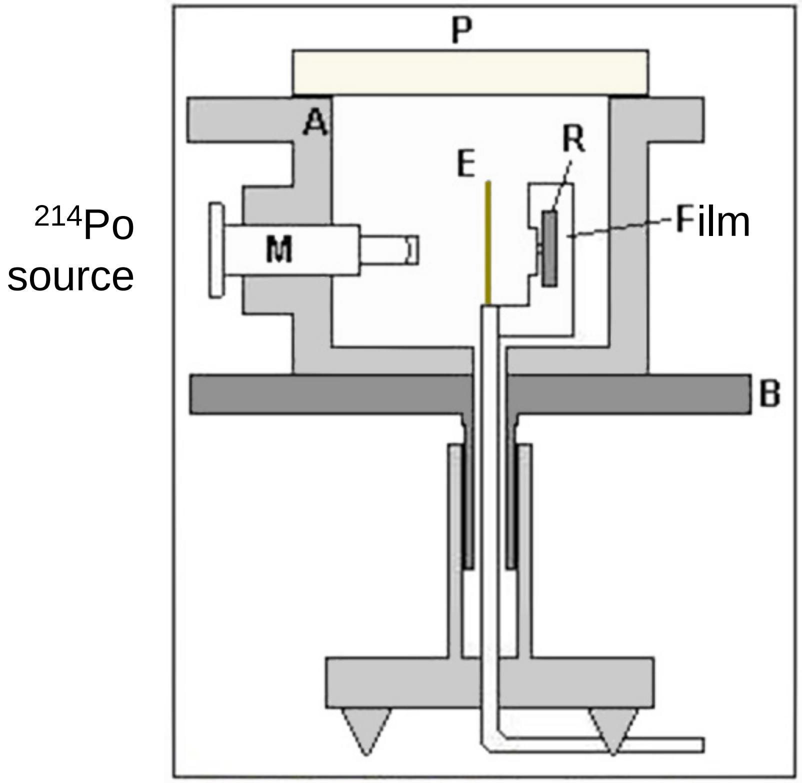


Fig1. Marsden-Geiger experiment.

Rutherford explains scattering of alpha particles on gold & urges … on to higher energy probes!

Why do we need high energy beams

- Resolution of "Matter" Microscopes
  - ➙ Wavelength of Particles (γ, e, p, ...) (de Broglie, 1923)

$$\lambda = h/p \quad = 1.2 \text{ fm} / \boldsymbol{p} \; [\text{ GeV/c}]$$

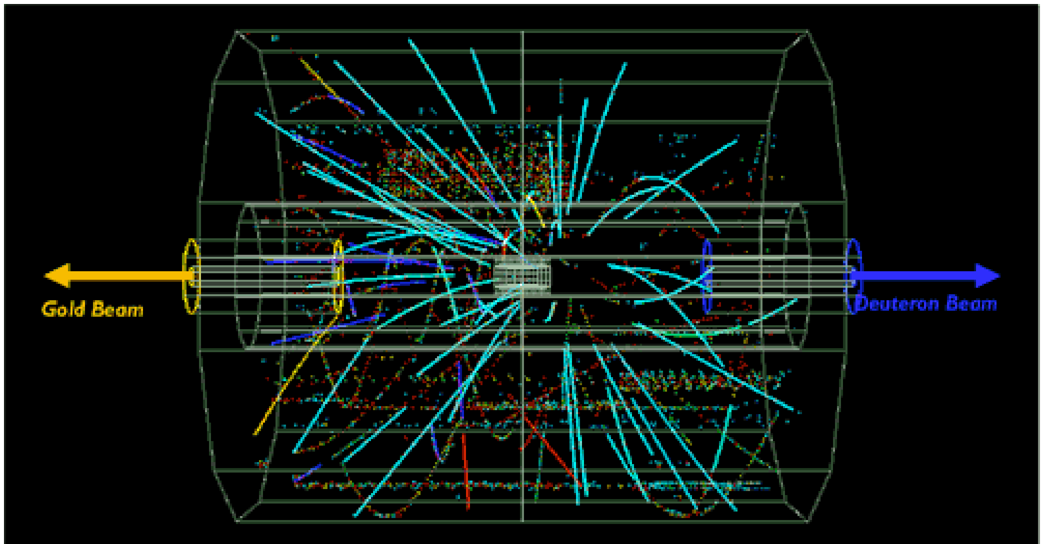
  - ➙ Higher momentum => shorter wavelength => better the resolution

- Energy to Matter
  - ➙ Higher energy produces heavier particles

$$E = mc^2 = \frac{m_o c^2}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma m_o c^2$$

- Penetrate more deeply into matter

Examples: Where we are today - Heavy ion collisions



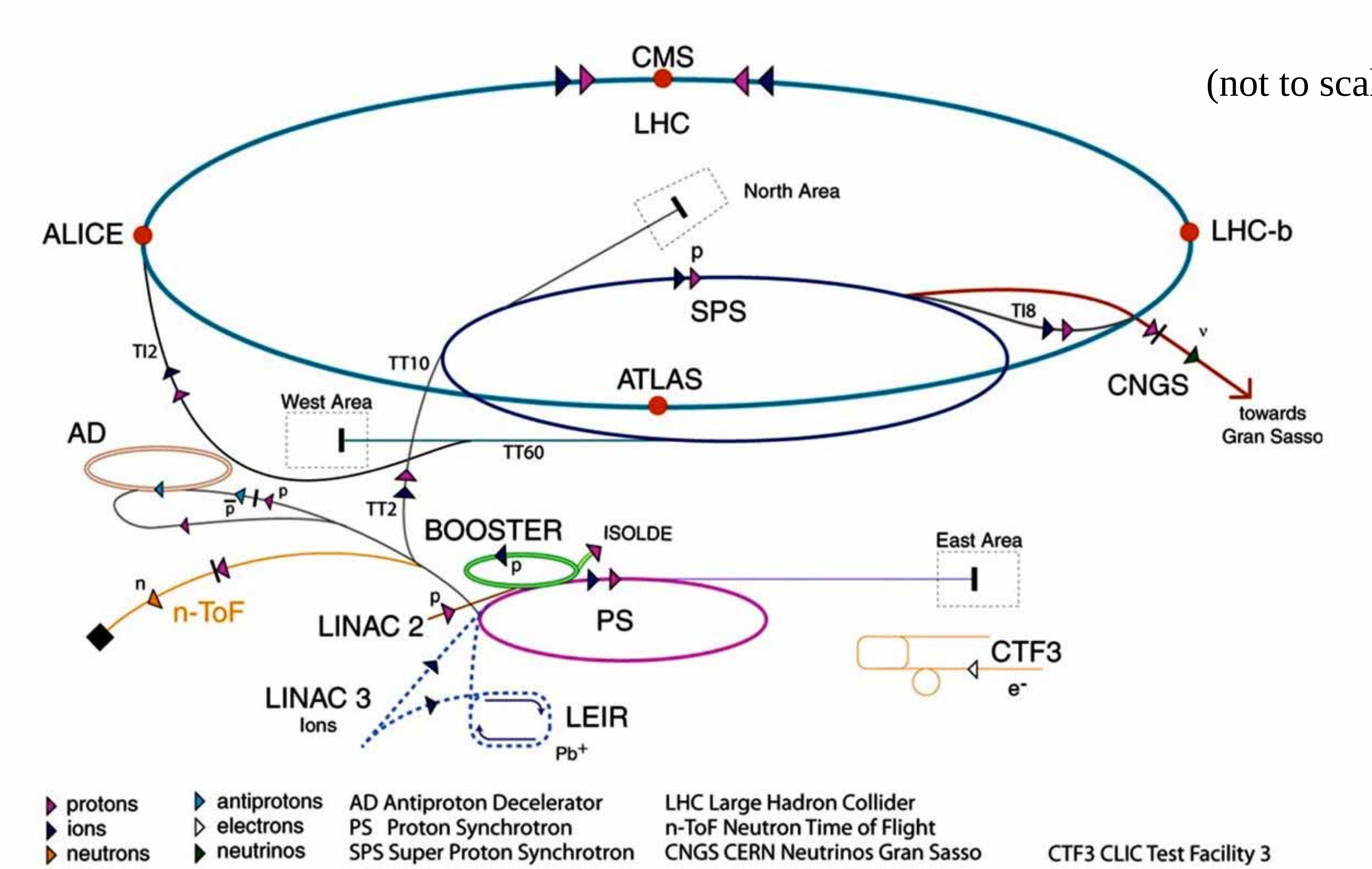
Brookhaven National Lab / RHIC-STAR Collaboration

D - Au at RHIC

Next ALICE @ LHC

CERN Accelerator Complex

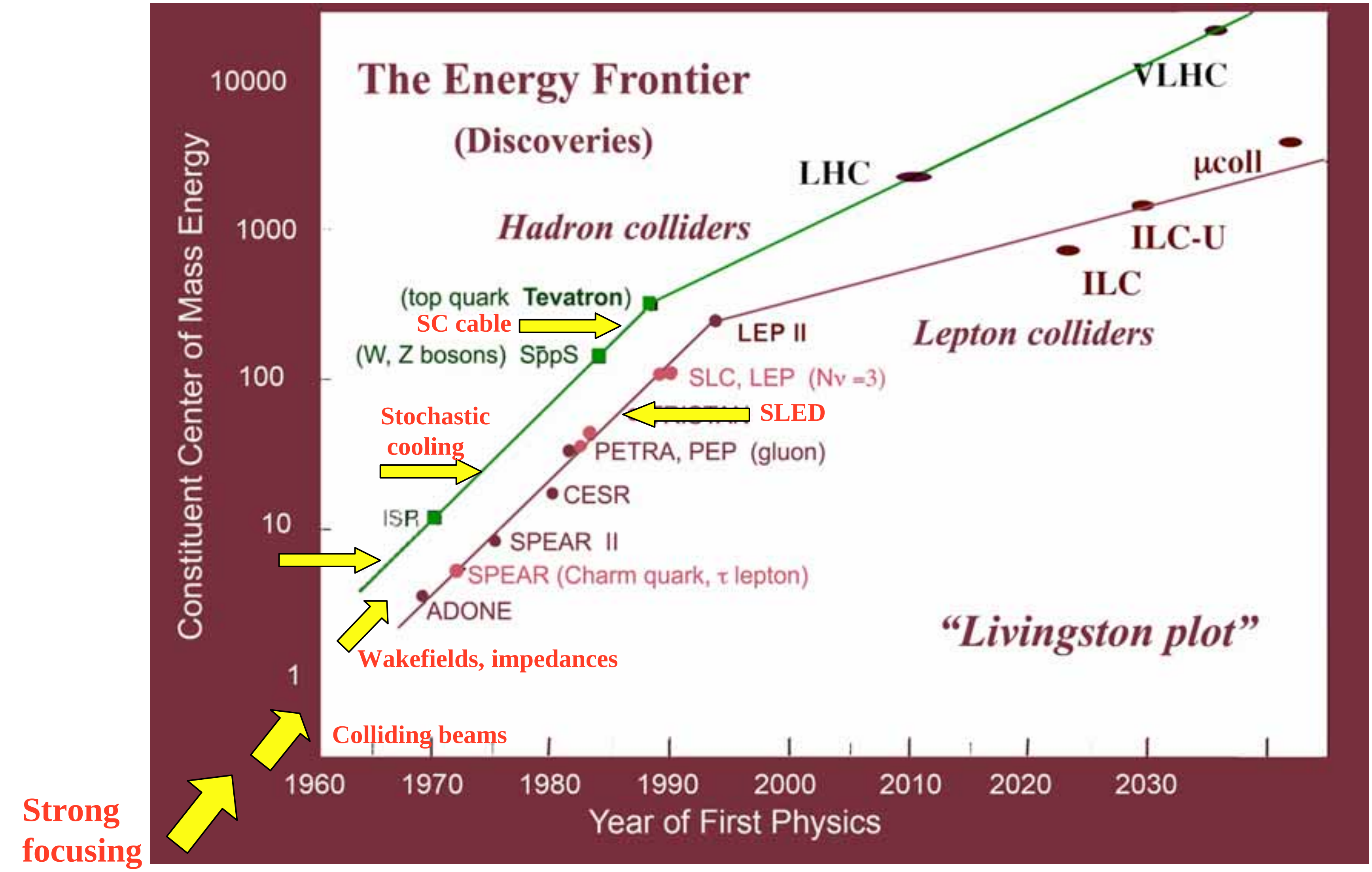
(not to scale)



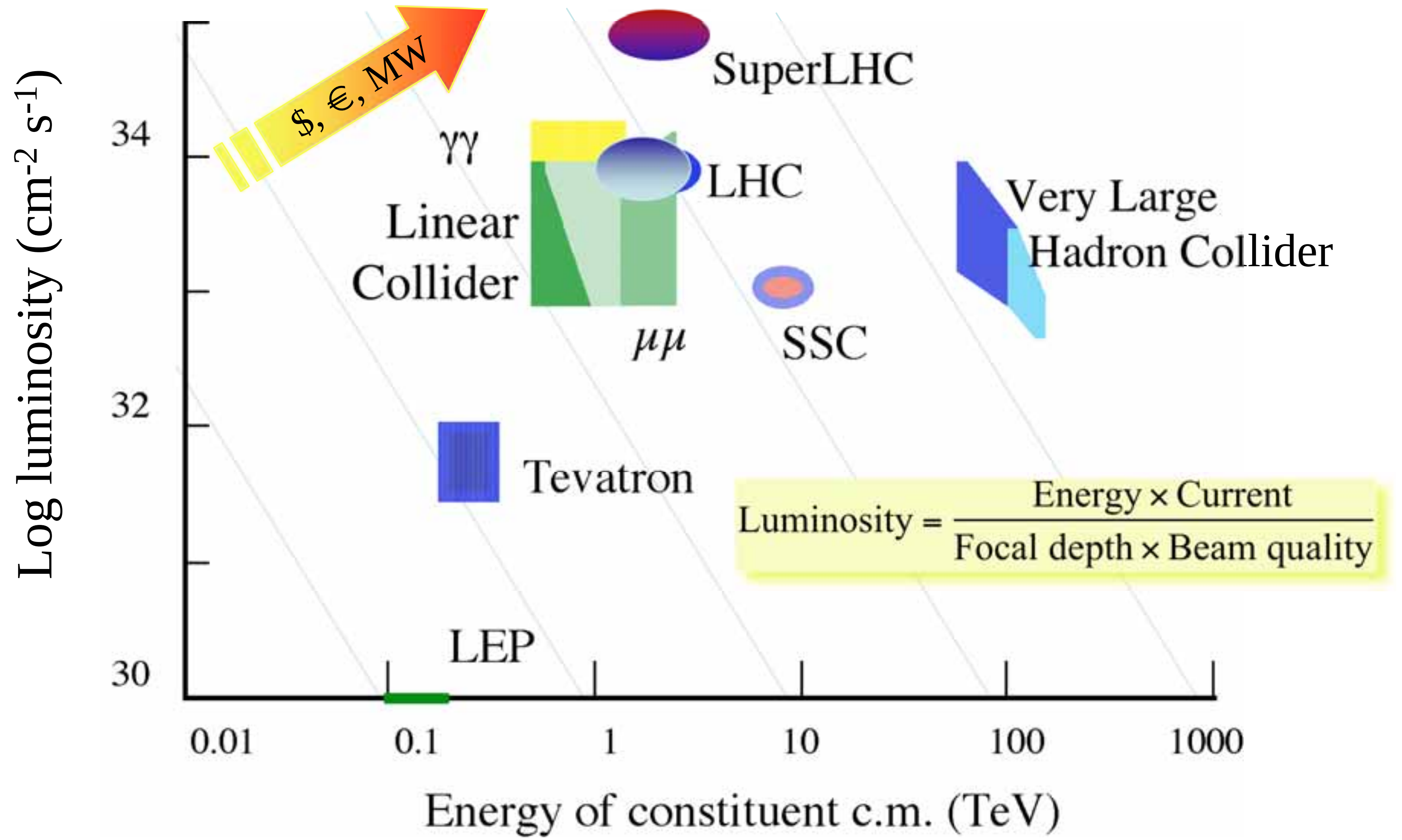
Inside the LHC tunnel

This goes on for 28 km!

Figure of Merit 1: Beam Energy ==> Energy frontier of discovery



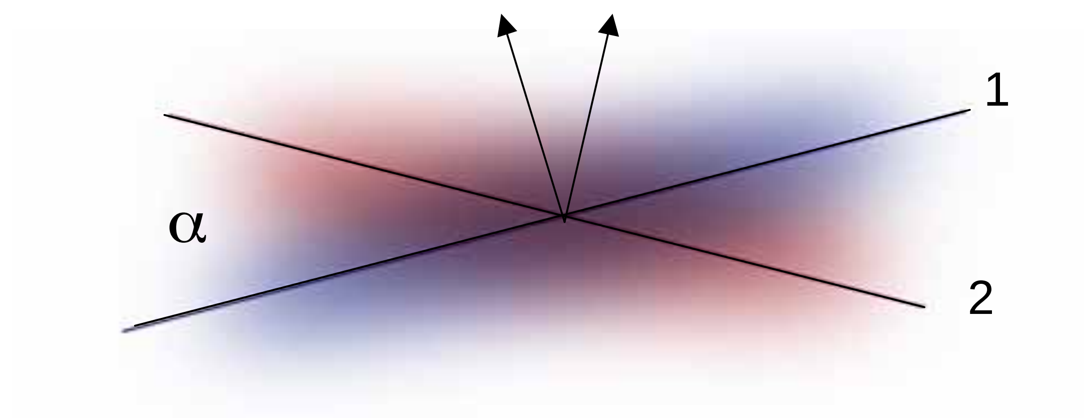
Example from High Energy Physics: Discovery space for future accelerators



High Energy Physics
Figure of Merit 2: Number of events

$$Events = Cross\text{-}section \times \langle Collision\ Rate \rangle \times Time$$

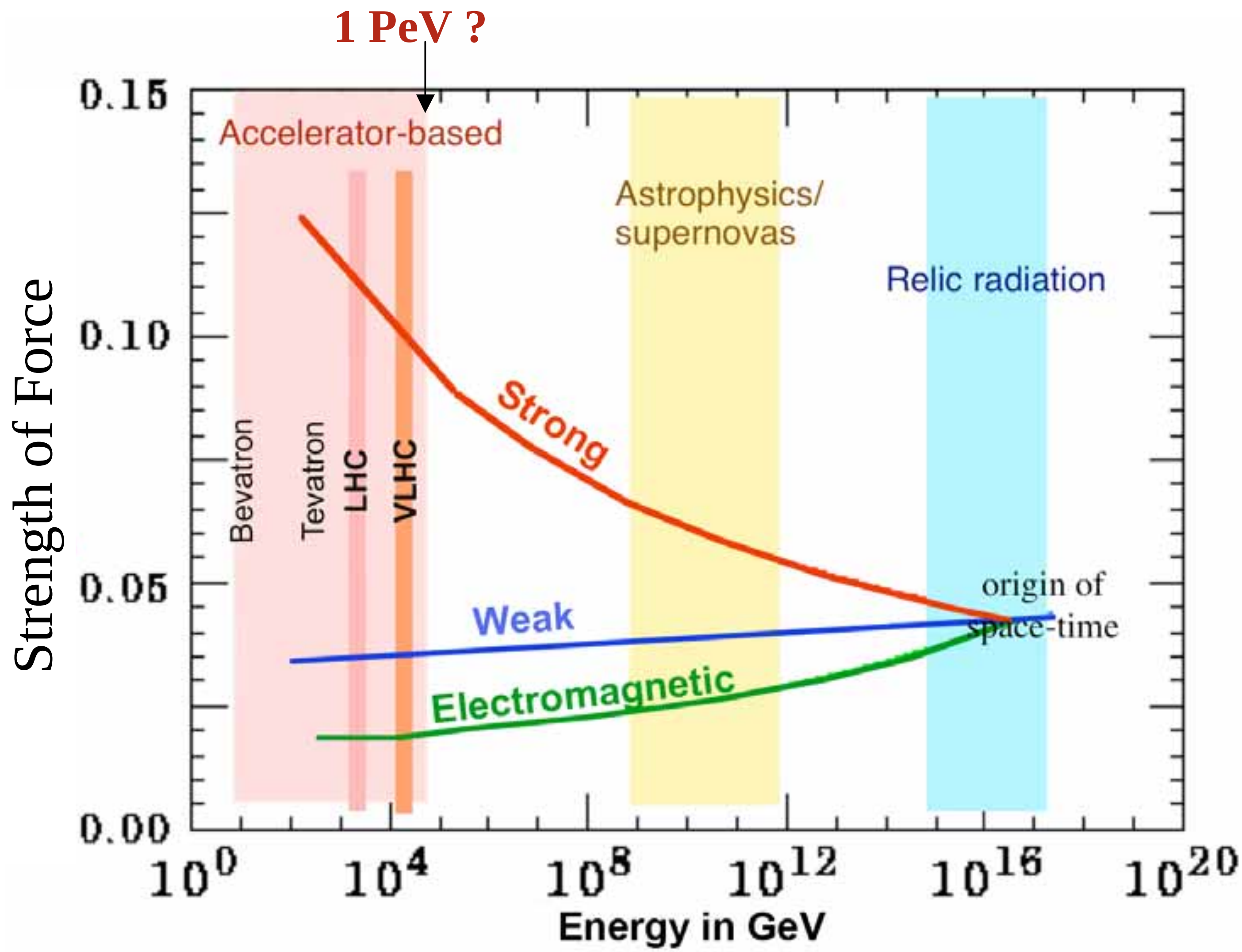
Beam energy: sets scale of physics accessible



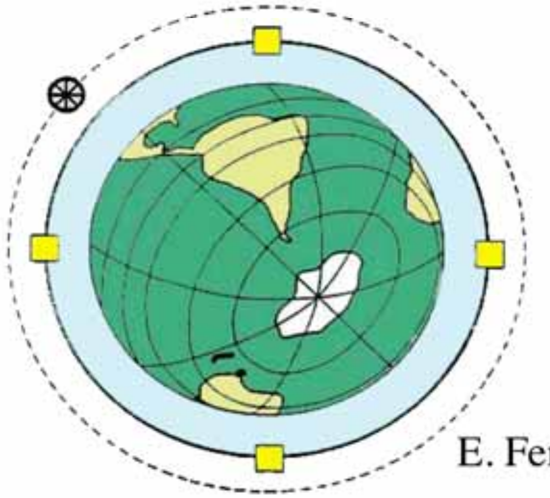
$$\text{Luminosity} = \frac{N_1 \times N_2 \times frequency}{Overlap\ Area} = \frac{N_1 \times N_2 \times f}{4\pi\sigma_x\sigma_y} \times Correction\ factors$$

We want large charge/bunch, high collision frequency & small spot size

How far can we go with this approach?



Limits of accelerator-based HEP

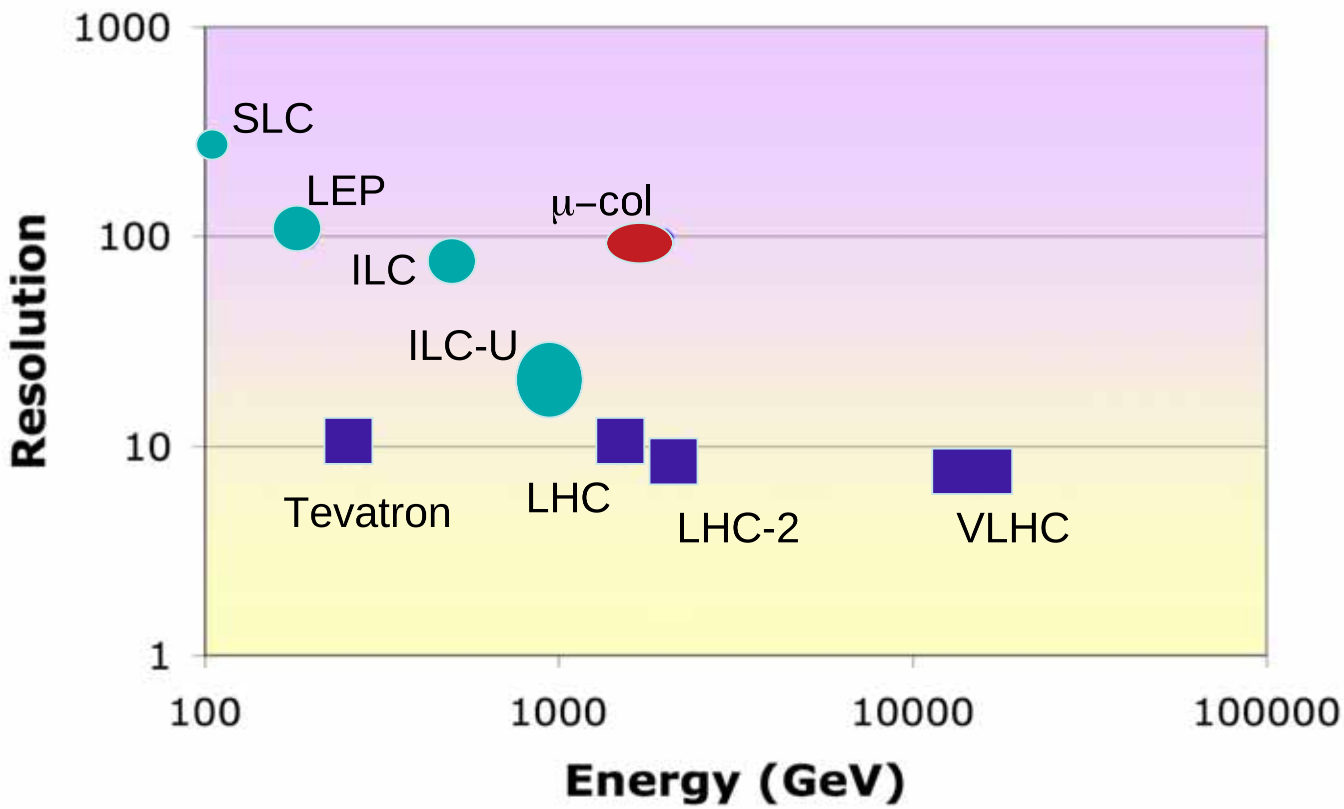


15 min

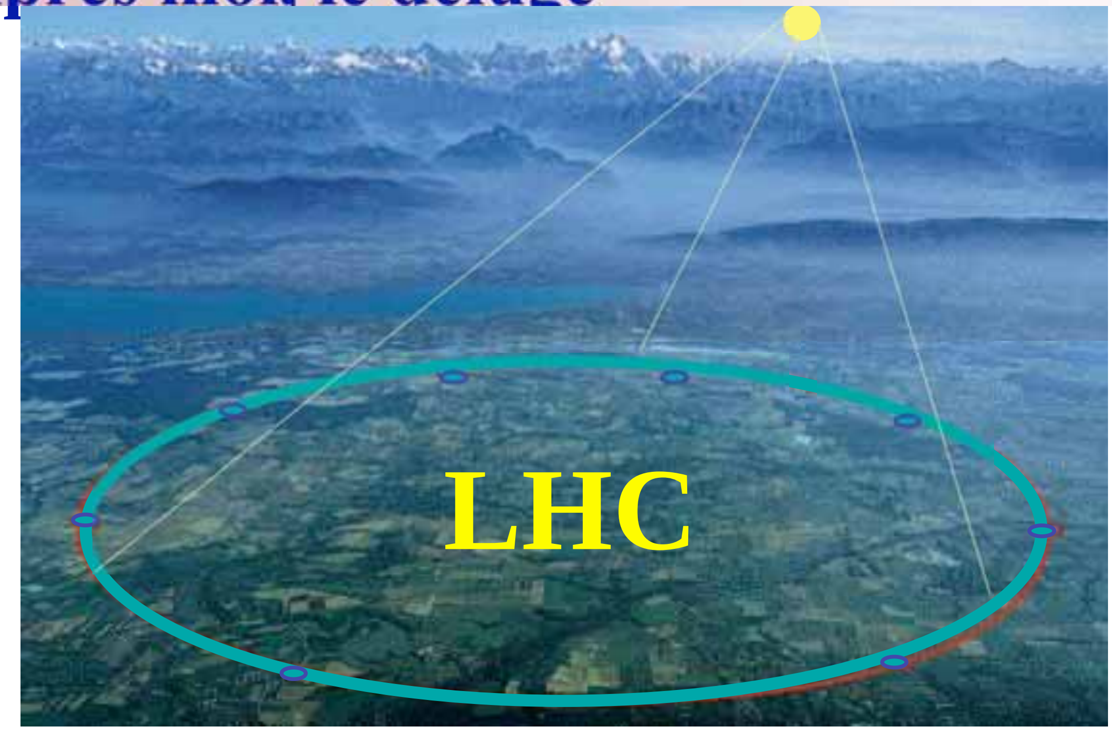
How big is a PeV collider?

FoM 3: Resolution (Energy/ΔEnergy)

- Intertwined with detector & experiment design
  - → In hadron colliders: production change, parton energy distribution
  - → In lepton colliders: energy spread of beams (synchrotron radiation)



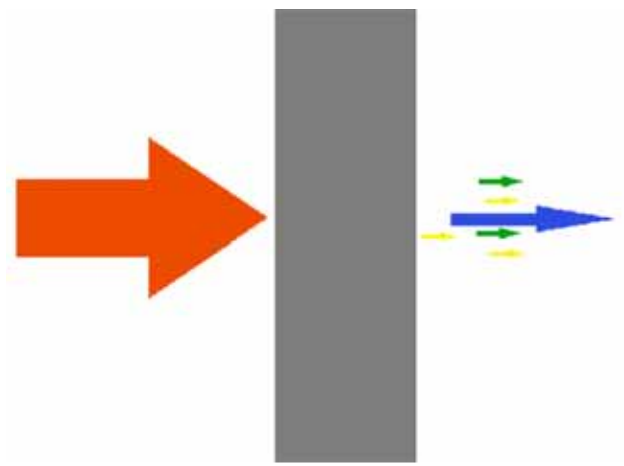
The future of HEP runs through CERN
"Après moi, le déluge"



- LHC upgrades rely on advances in magnet technology
  - → Reliability upgrade (2013) - replace IR Quads & collimators
  - → Luminosity upgrade - very high gradient, Nb_3Sn quads
  - → Super LHC (energy upgrade) - very high field dipoles

9 min

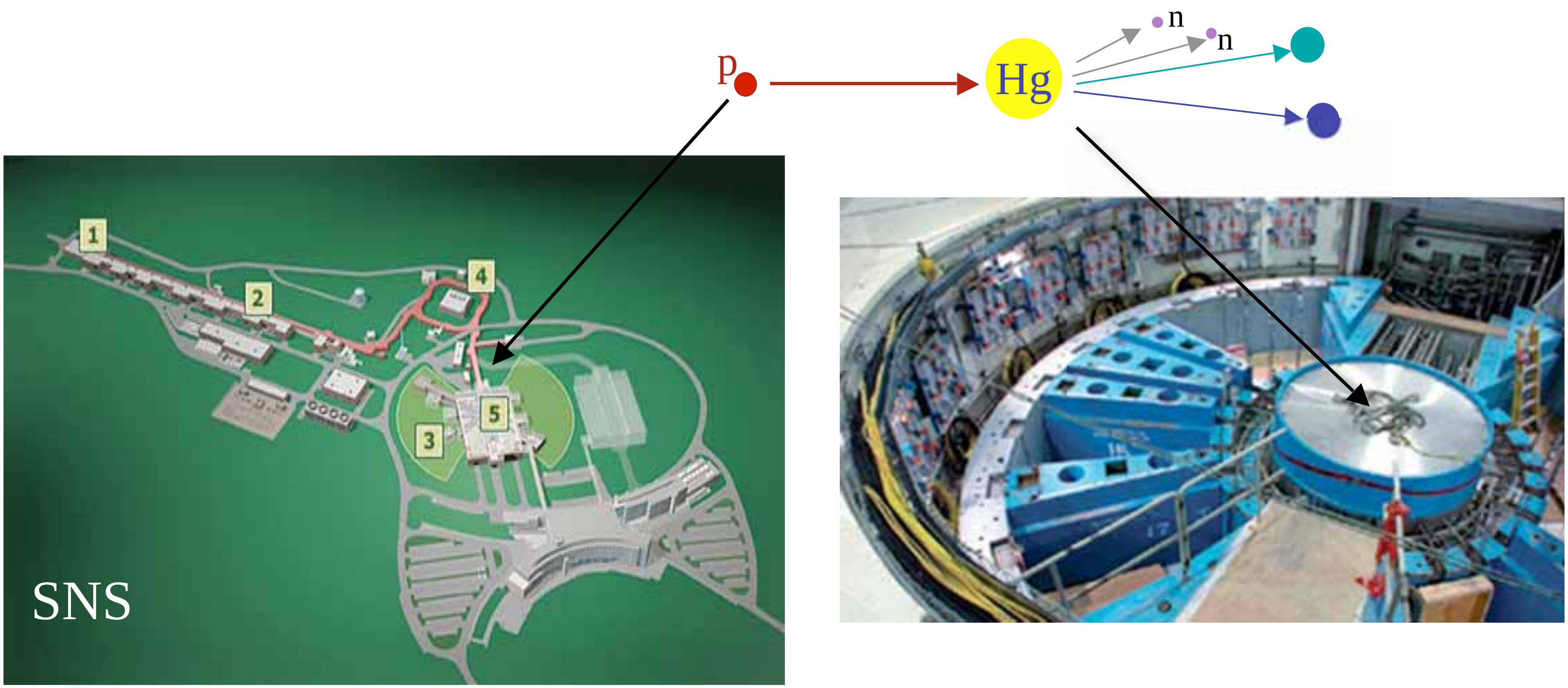
Secondary beams



FOM: Secondaries/primary

Examples: spallation neutrons for condensed matter physics, neutrino beams for high energy physics, rare isotopes

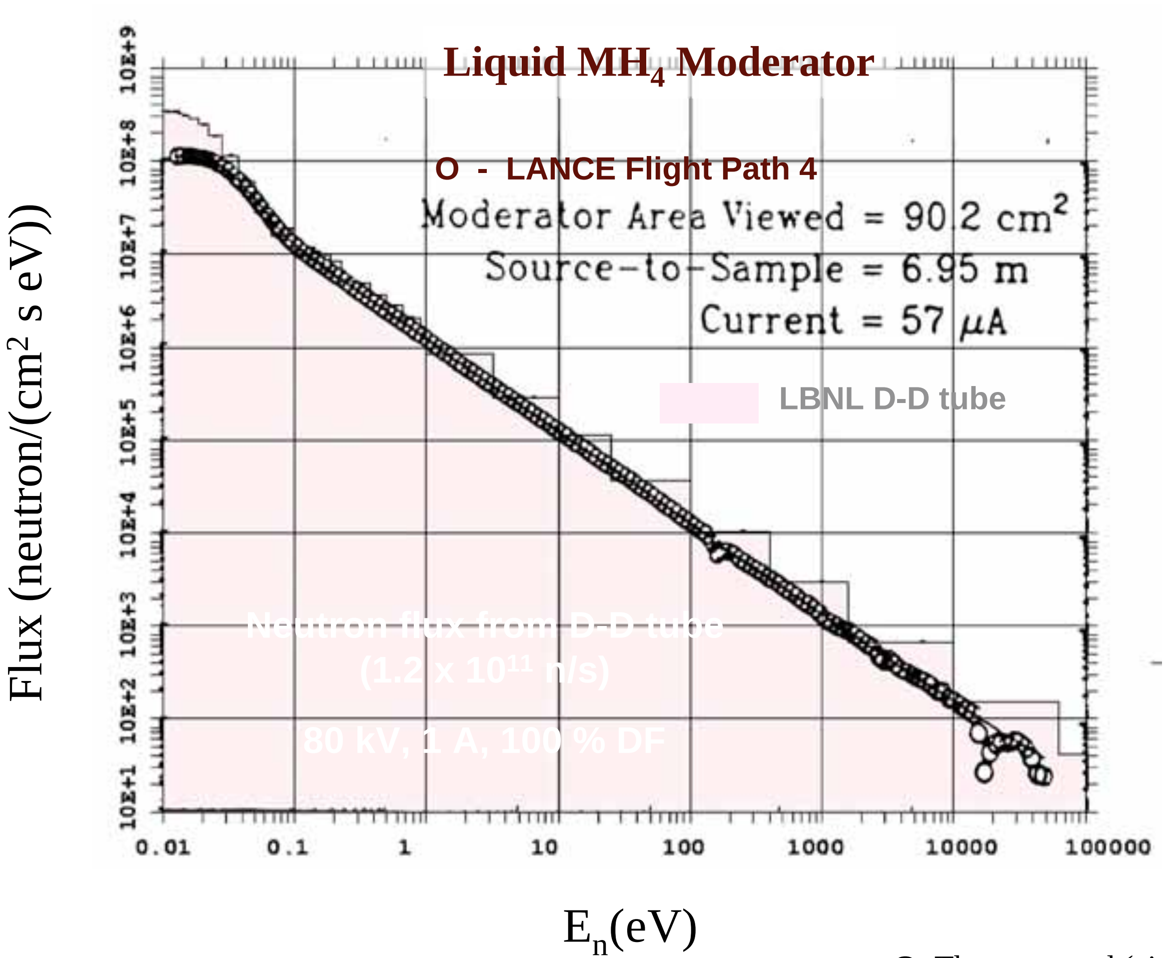
Example: The Spallation Neutron Source

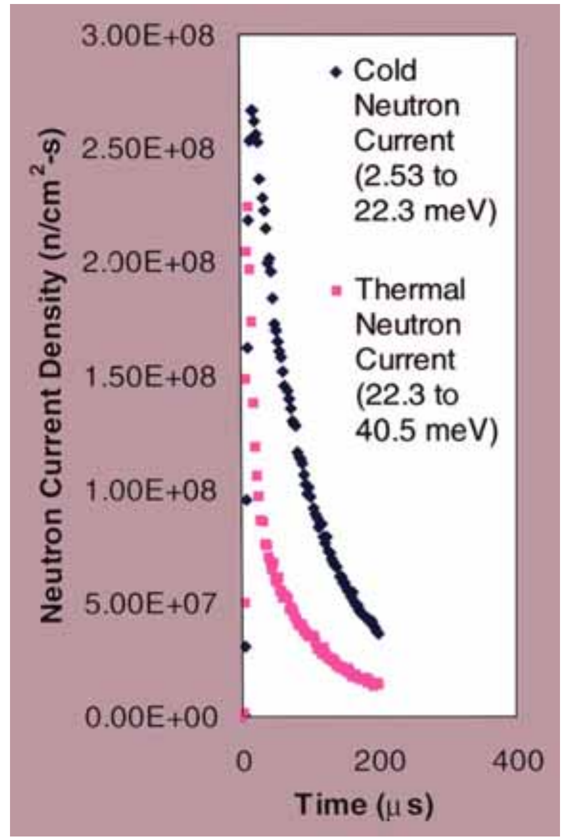


1 GeV, 35 mA of protons,
6% duty factor

1 MW liquid Hg target
$>10^{17}$ n/sec

Figures of Merit: Spectrum & time structure





O The measured (circles) neutron flux v. neutron energy

Ref: Paul E. Koehler, Nucl. Instrum. Meth. A292, 541 (1990)

FOM: Flux, Joules per secondary particle

1MW SNS (1 GeV, 60 Hz)

Protons per pulse ≈ 10^{14}

Neutrons per pulse ≈ 20 x 10^{14} = 2 x 10^{15}

Rate = 60 Hz ==> yield ≈ 10^{17} n/s.

E/neutron = 1 MW/10^{17} n/s ≈ 10^{-11} J/n

Overall efficiency for accelerator system ~ 2%

==> ~ 5x10^{-10} J/n

D-T neutron tube (120kV, 1 A ⇒ 10^{14} n/s)

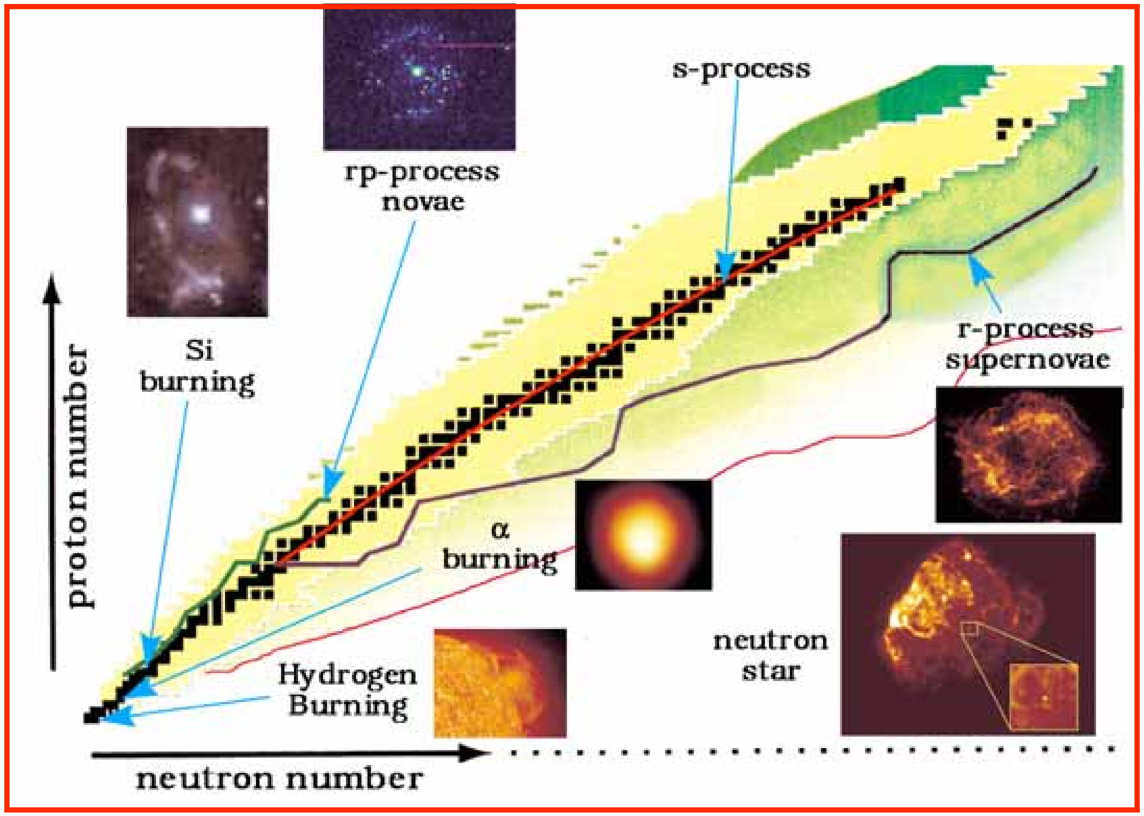
E/neutron ≈ 120 kW/10^{14} n/s ≈ 10^{-9} J/n

DC power supply efficiency > 85%

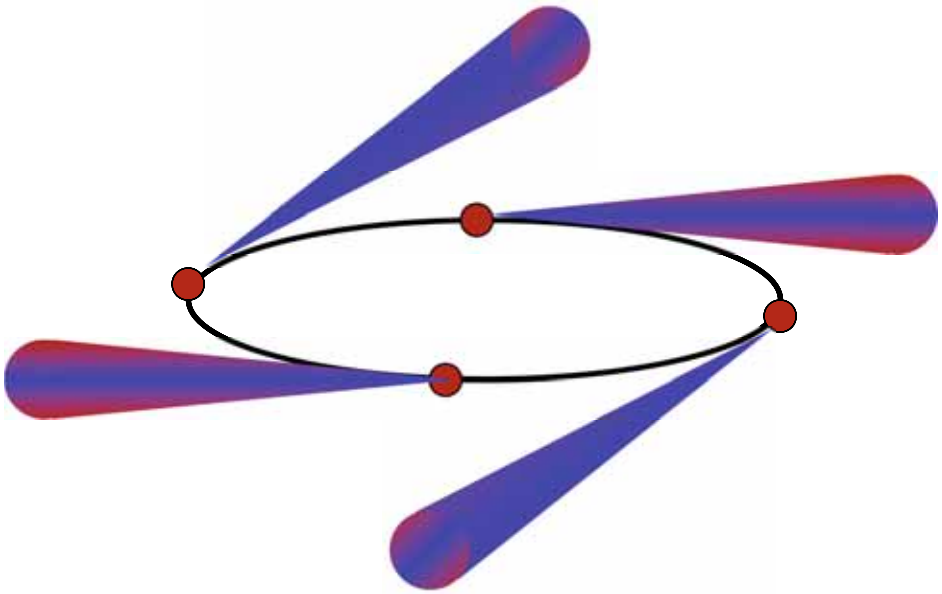
==> ≈ 10^{-9} J/n

Nuclear Astrophysics: Radioactive Beam Facilities

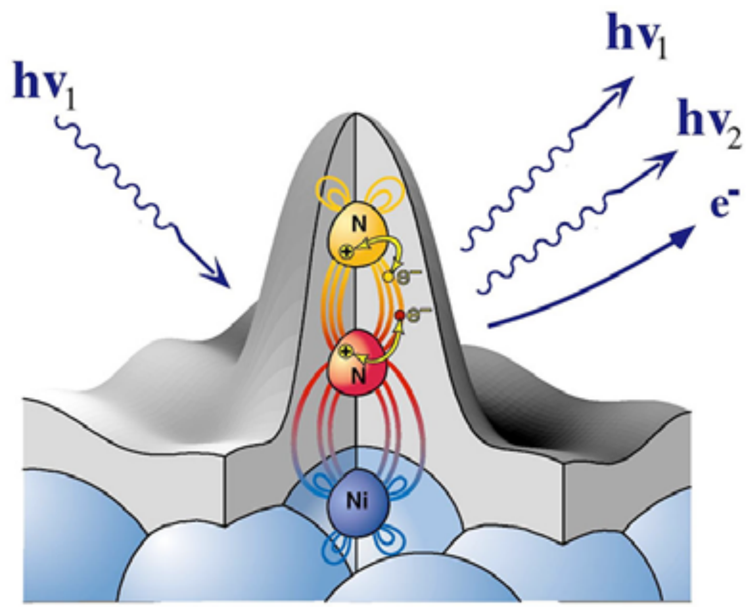
- Explore nuclear structure & reactions involving nuclei far from the valley of stability
  - ➙ These nuclei participate in explosive nucleo-synthesis in novae, x-ray bursts, and supernovae via rapid proton and neutron capture



Synchrotron light source



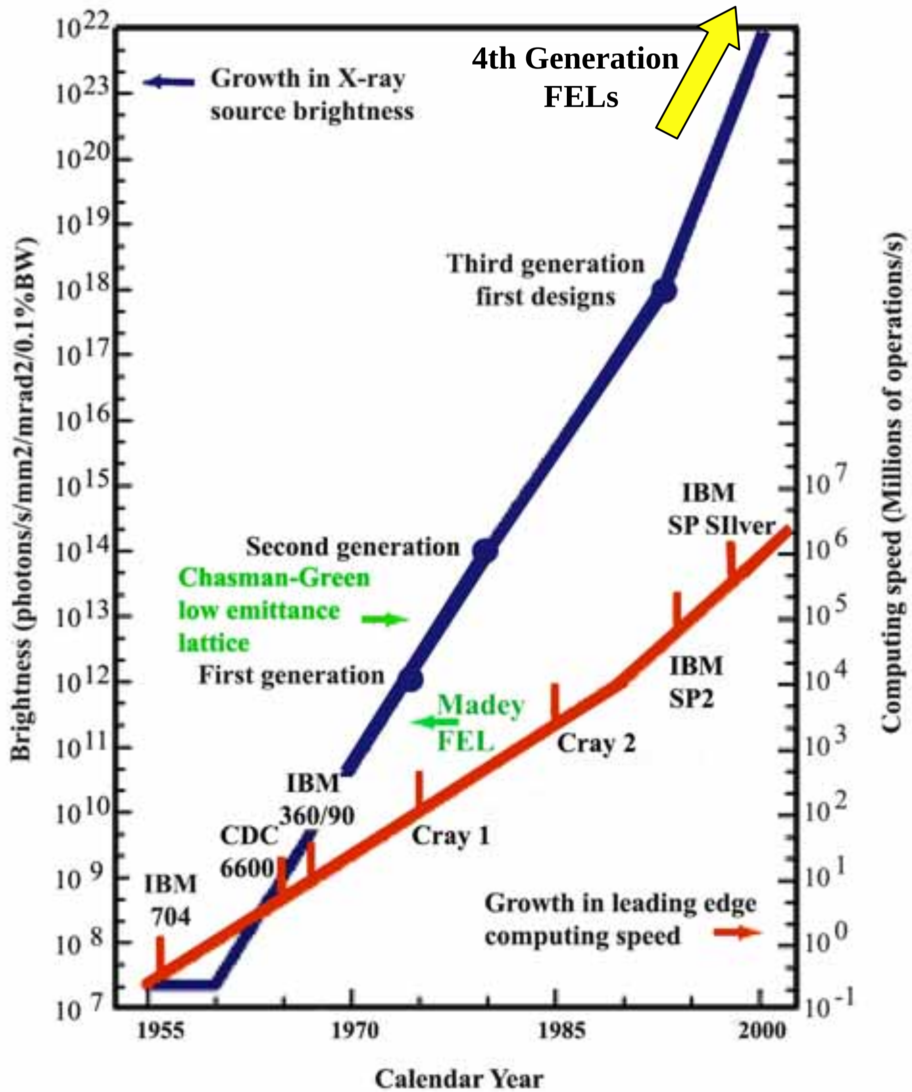
- Science with X-rays
  - Microscopy
  - Spectroscopy



FOM: Brilliance v. λ

$B = ph/s/mm^2/mrad^2/0.1\%BW$

Progress in X-ray source brightness



Coherent Imaging: TwinMic on BACH-ELETTRA

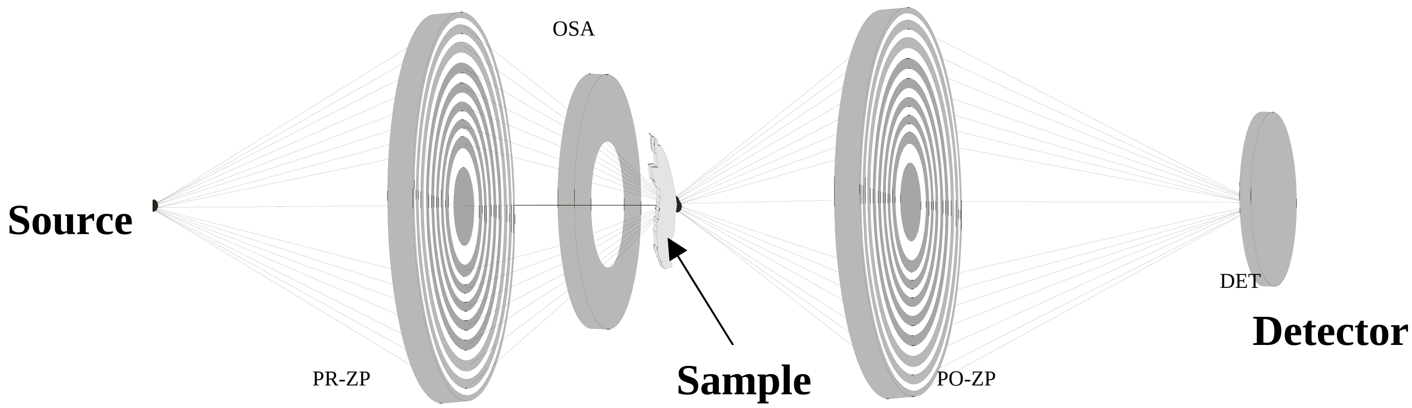


Figure . Optical scheme of TwinMic.

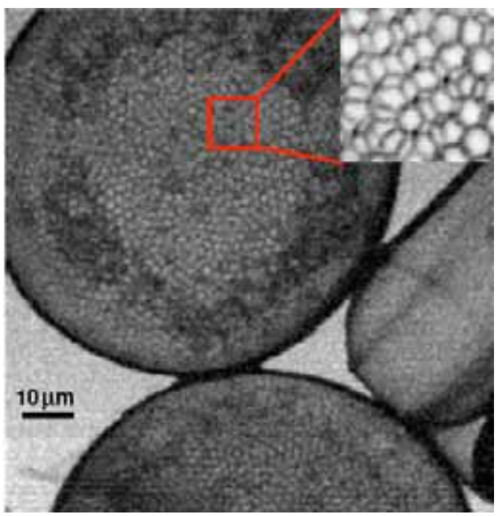


Figure 3. Scanning mode

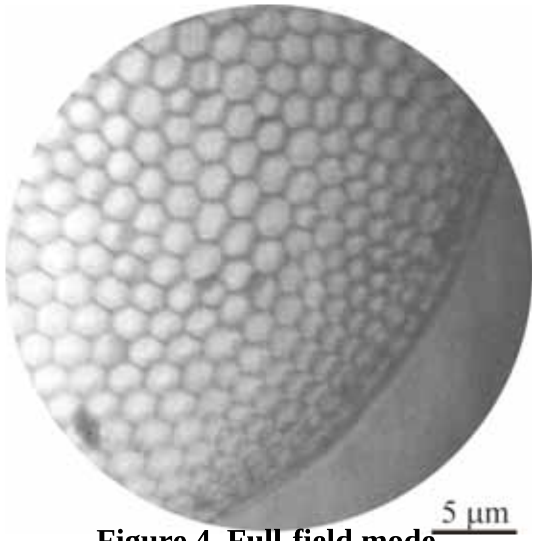
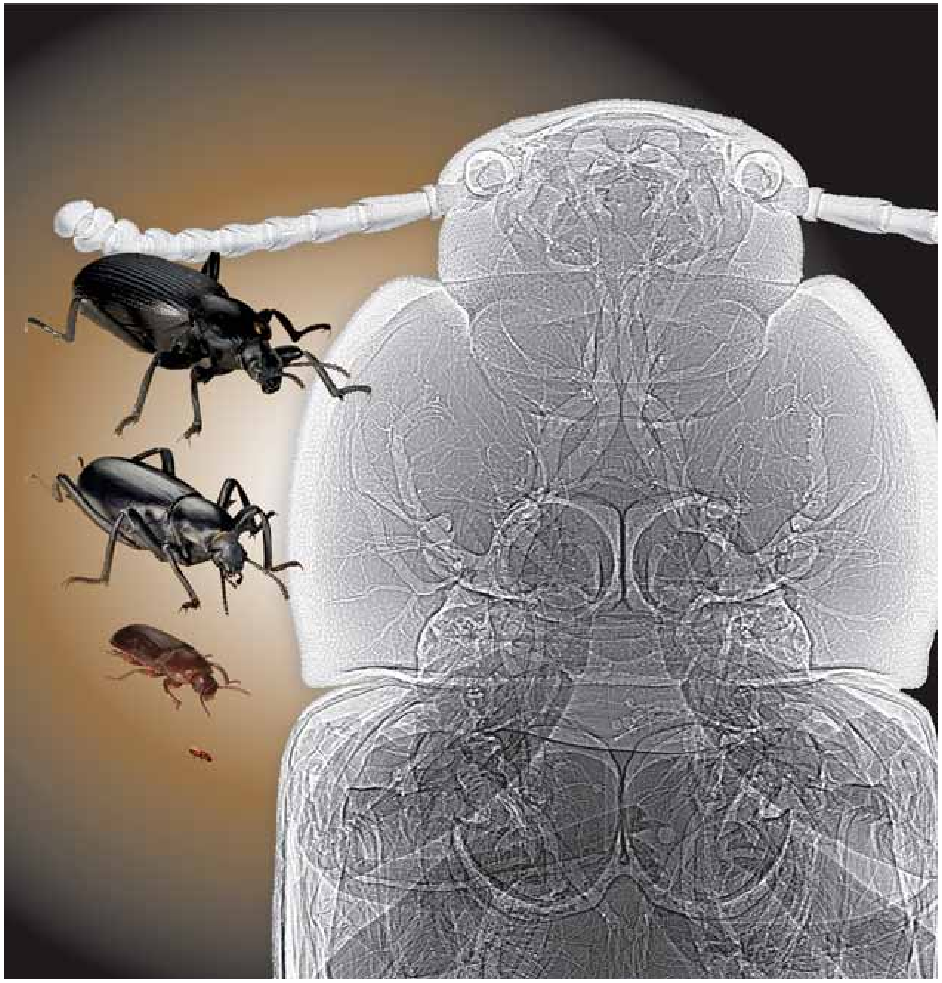


Figure 4. Full-field mode.

What Keeps Bugs from Being Bigger?

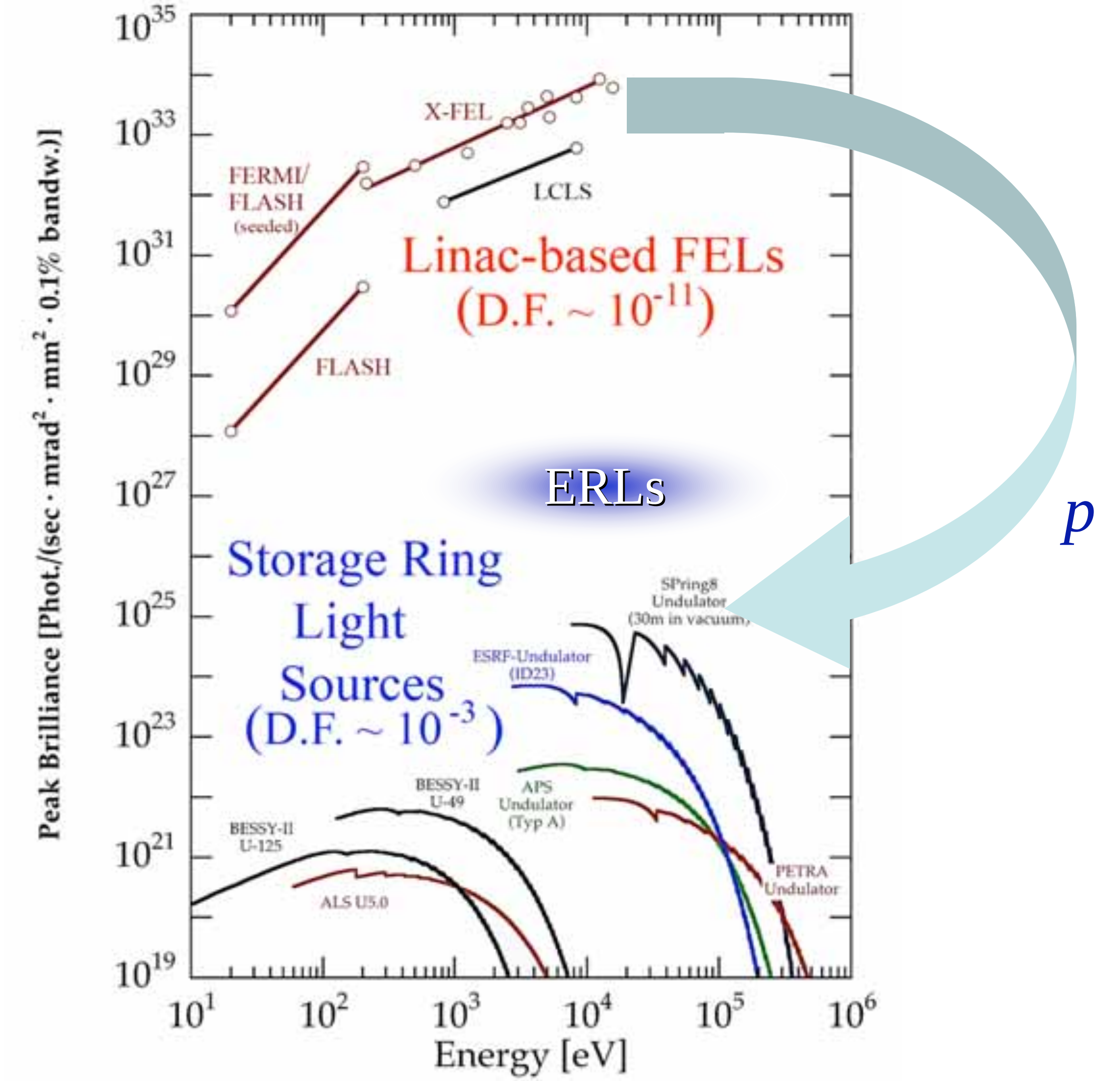
Does the tracheal system limit the size of insects?

Research* at the Argonne Advanced Photon Source (APS) explains what limits size in beetles: the constriction of tracheal tubes leading to legs.



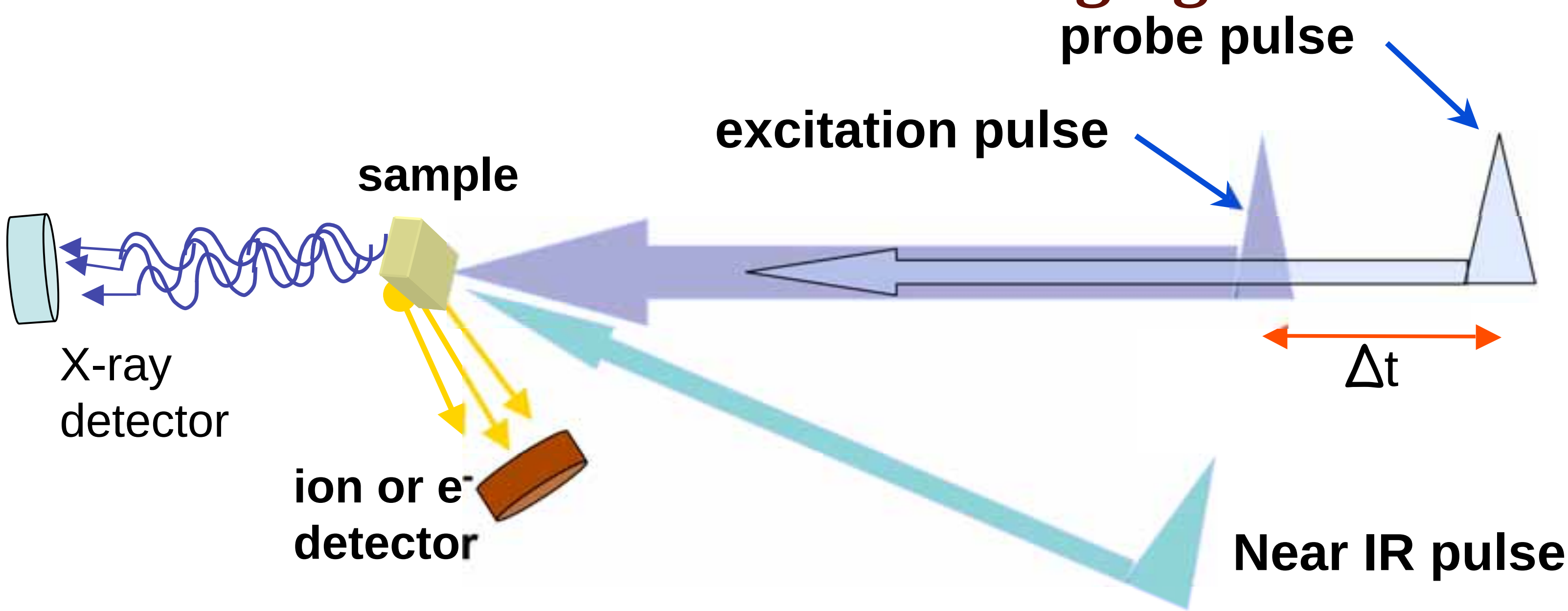
* Alexander Kaiser, C. Jaco Klok, John J. Socha, Wah-Keat Lee, Michael C. Quinlan, and Jon F. Harrison, " Increase in tracheal investment with beetle size supports hypothesis of oxygen limitation on insect gigantism," Proc. Nat. Acad. Sci. USA **104**(32), 13198 (August 7, 2007).

FOM 1 from condensed matter studies: Light source brilliance v. photon energy



Duty factor correction for pulsed linacs

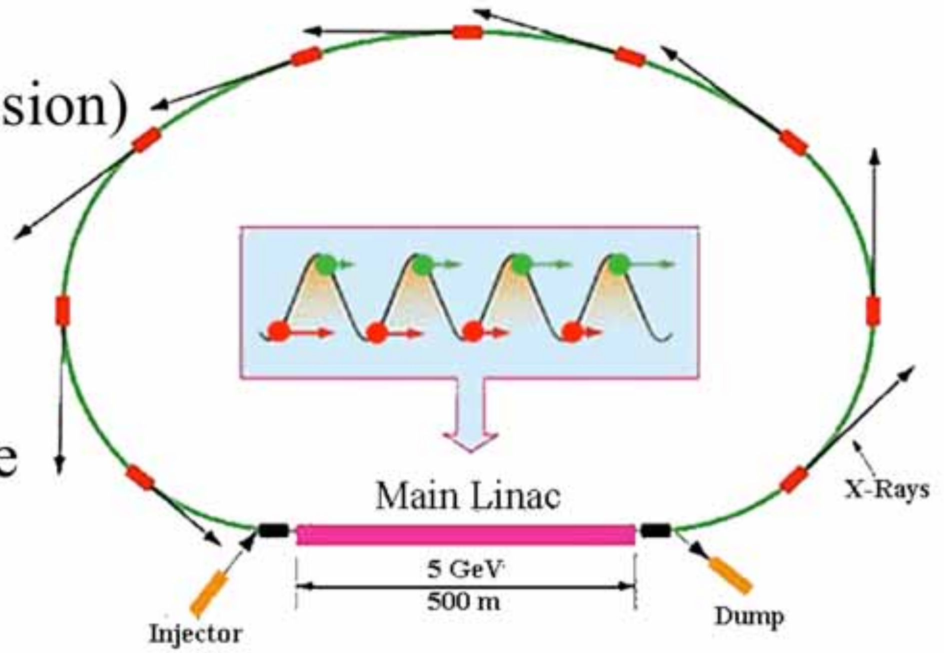
Pump-probe experiment concept for ultra-fast science and/or imaging



- Pulses can be x-rays, VUV, electrons or ions
- Requires control/measurement of Δt with a resolution << x-ray pulse duration (possibly as small as 100 attoseconds)

Matter to energy: Energy Recovery Linacs (Hard X-rays ==> ~ 5 GeV electrons)

Synchrotron light source
(pulsed incoherent X-ray emission)



Pulse rates – kHz => MHz

X-ray pulse duration ~ 1 ps

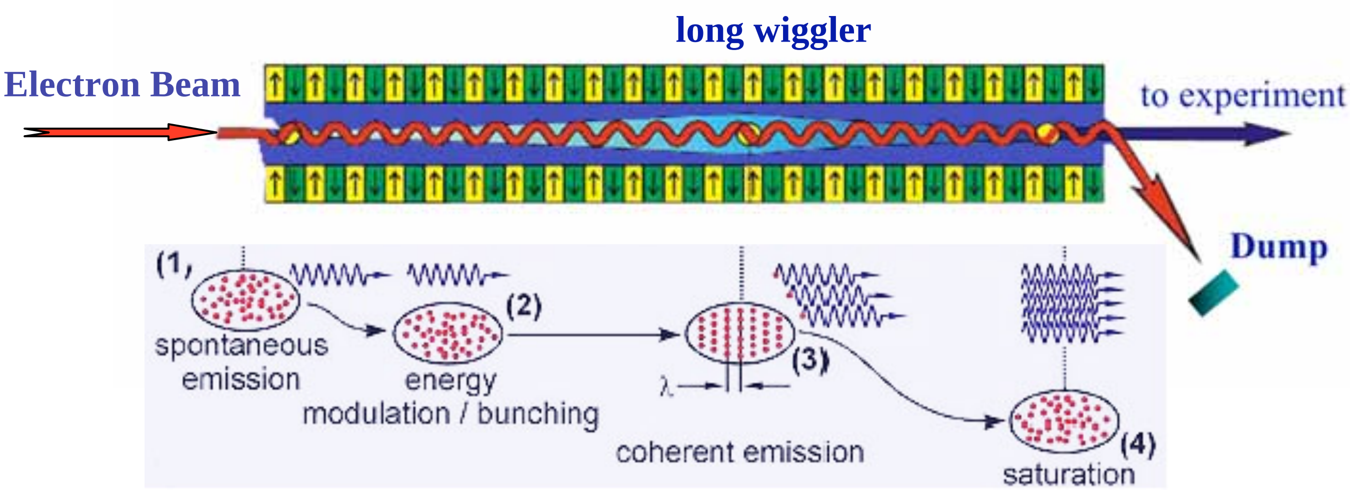
High average e-beam brilliance
& e-beam duration ~ 1 ps

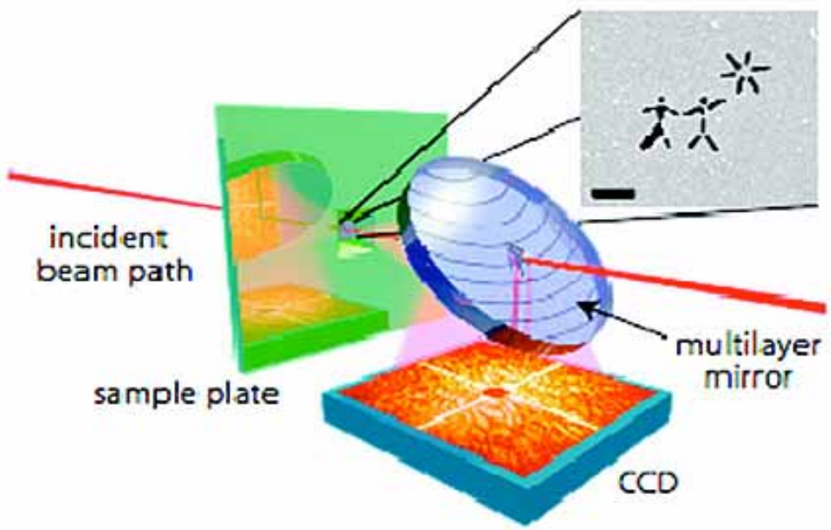
⇒ One pass through ring
⇒ Recover beam energy
⇒ High efficiency

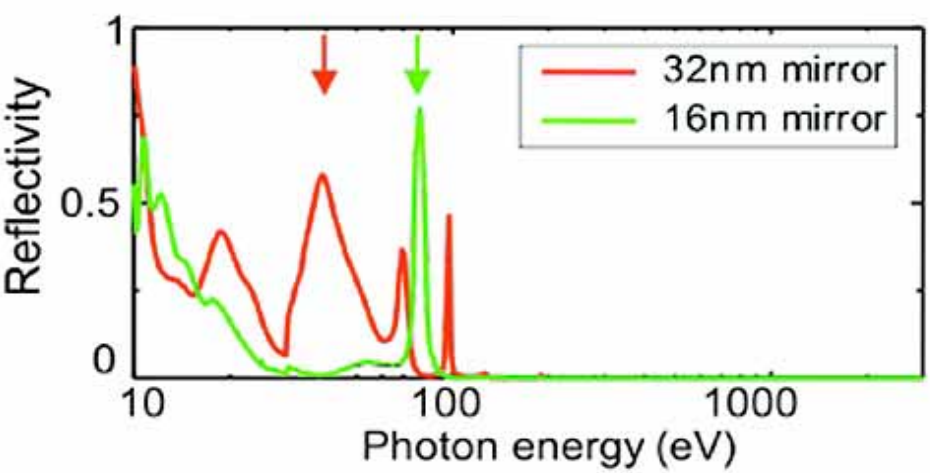
⇒ **SC RF**

Pulse duration limited by CSR

Even higher peak brightness requires coherent emission ==> FEL







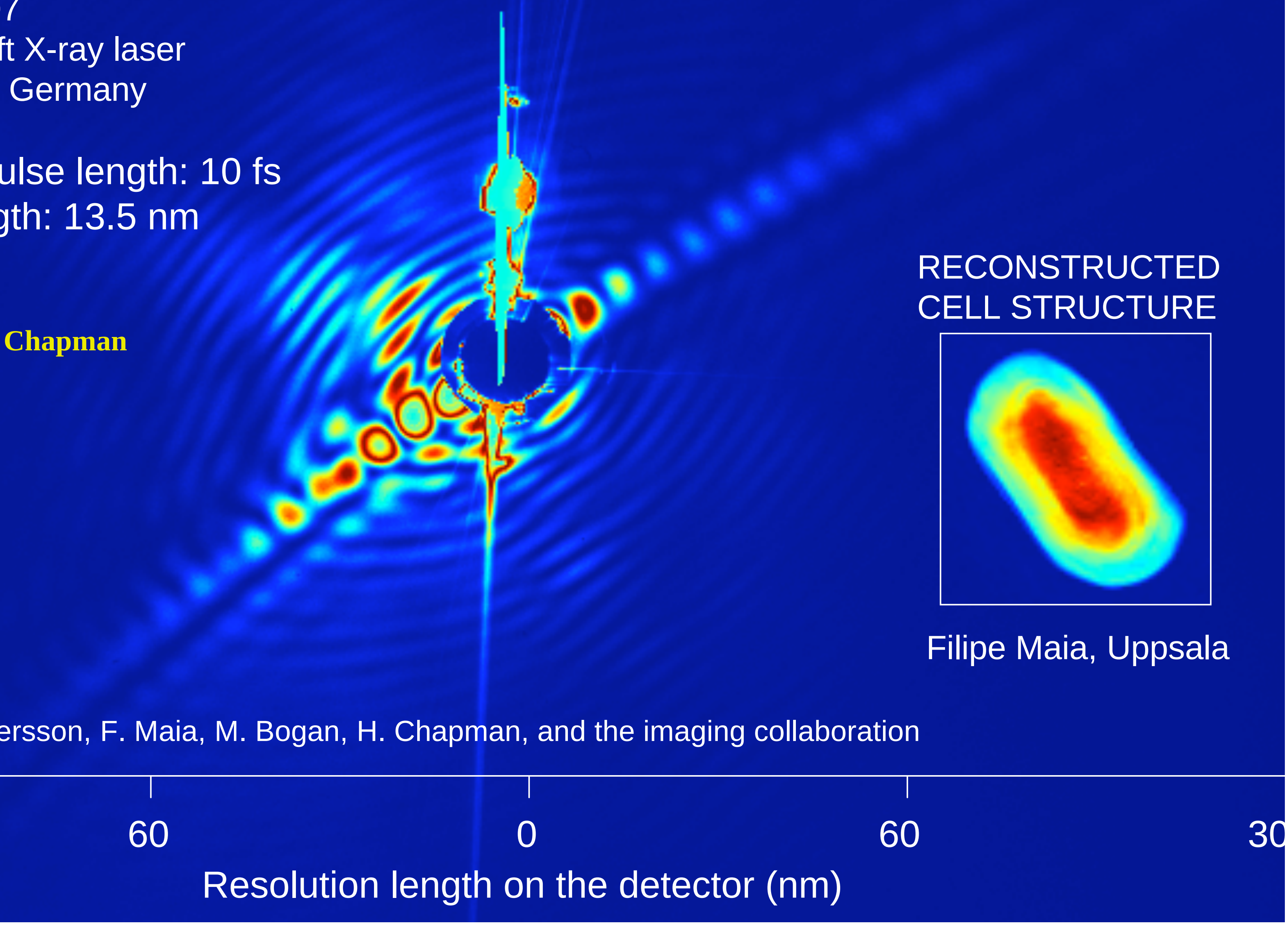
FIRST FLASH DIFFRACTION IMAGE OF A LIVE PICOPLANKTON

March 2007
FLASH soft X-ray laser
Hamburg, Germany

FLASH pulse length: 10 fs
Wavelength: 13.5 nm

Thanks

J.Hajdu and H. Chapman

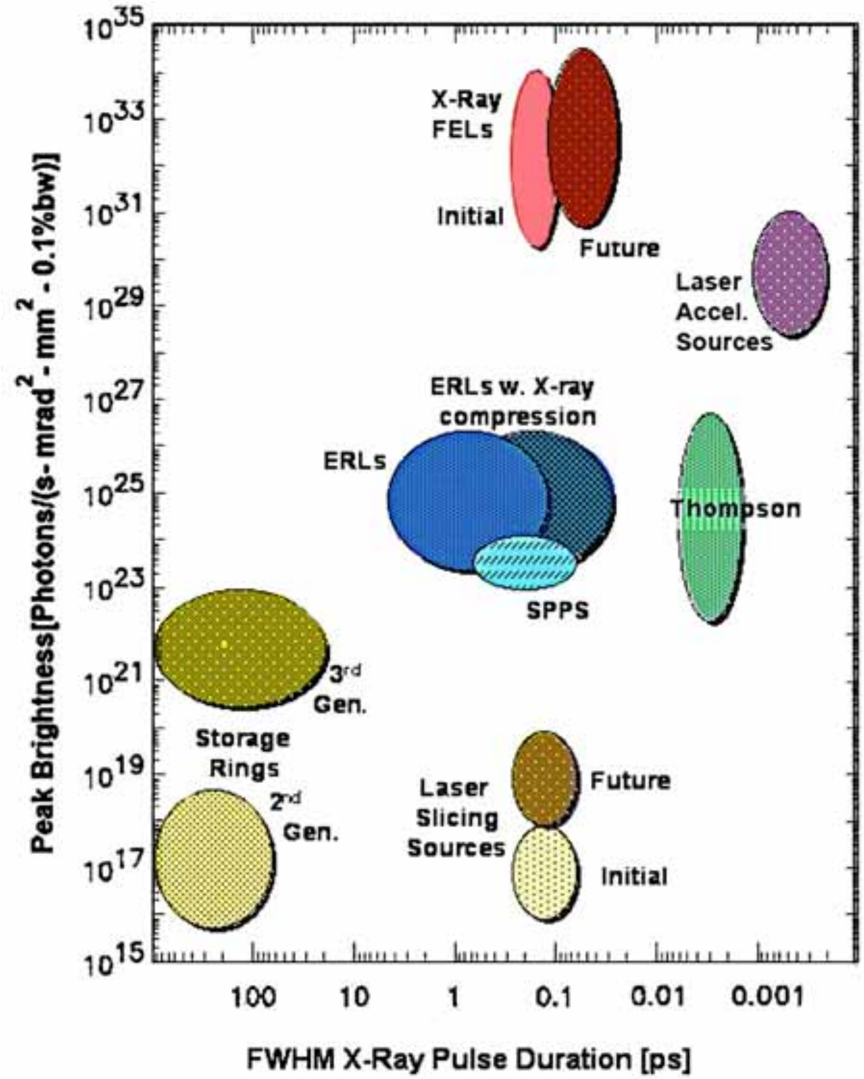


RECONSTRUCTED CELL STRUCTURE

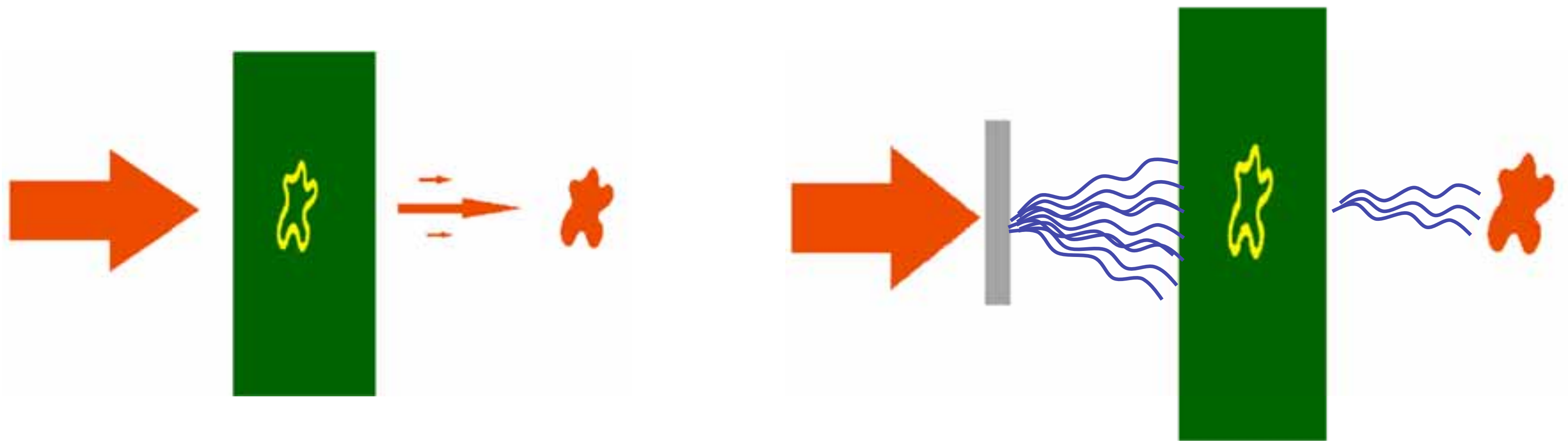
Filipe Maia, Uppsala

J. Hajdu, I. Andersson, F. Maia, M. Bogan, H. Chapman, and the imaging collaboration

FOM 2 from condensed matter studies: Ultra-fast light sources

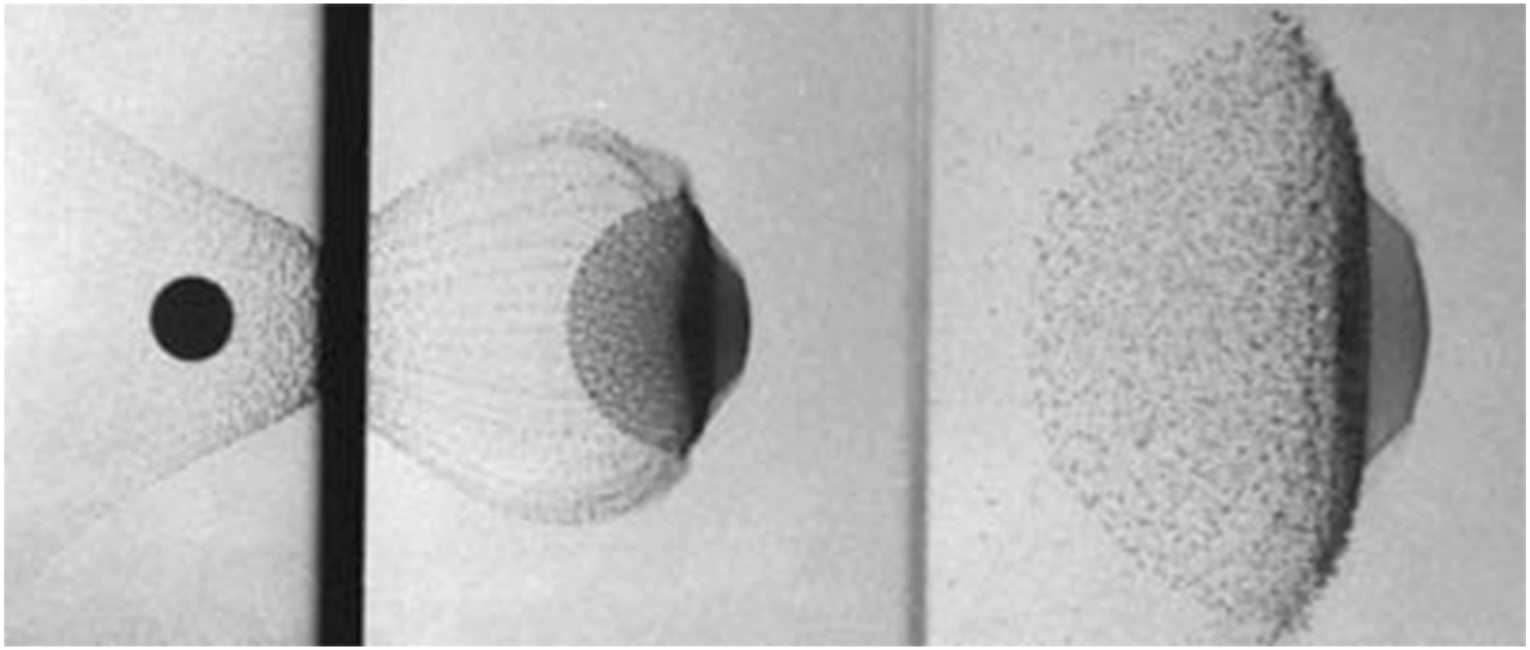


Radiography



FOM: Signal/noise ==> Dose at 1 m & resolution (x,t)

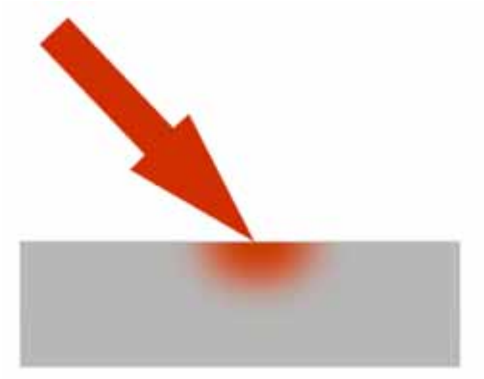
Example: Flash radiography



Debris cloud produced
by an Al sphere impacting
a thin AL shield at hypervelocity.

Source:. http://www.udri.udayton.edu/NR/exeres/9E82E5F2-AC29-4467-8F15-0E5A7FEA48F3.htm

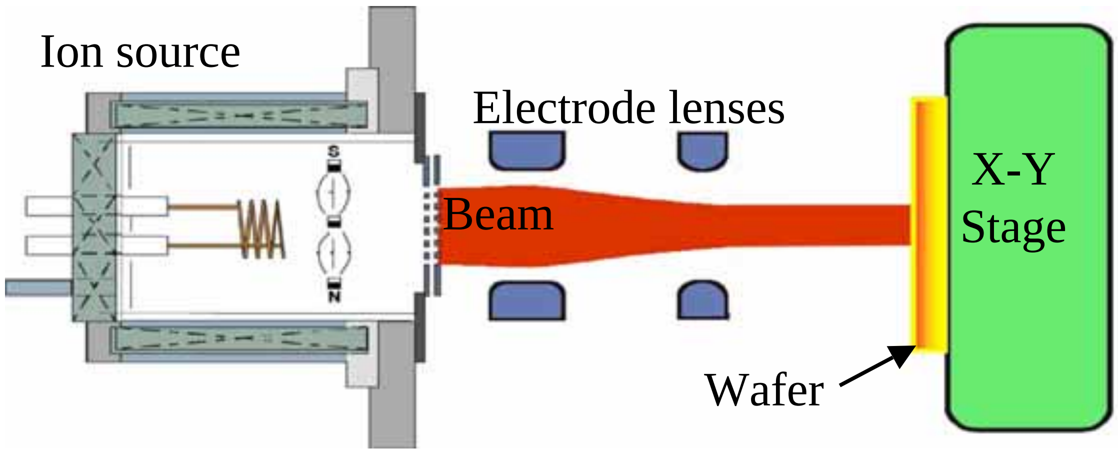
Alter matter



FOM: process time
process efficiency

Ion implantation is essential in semi-conductor production

- Ions prepare Si wafers for further processing finally yielding integrated circuit chips
  - ➙ > 1 B$/year business in semi-conductor "machine tools"



- Emerging areas
  - ➙ Flat-panel video displays
  - ➙ Ultra-high density electronics

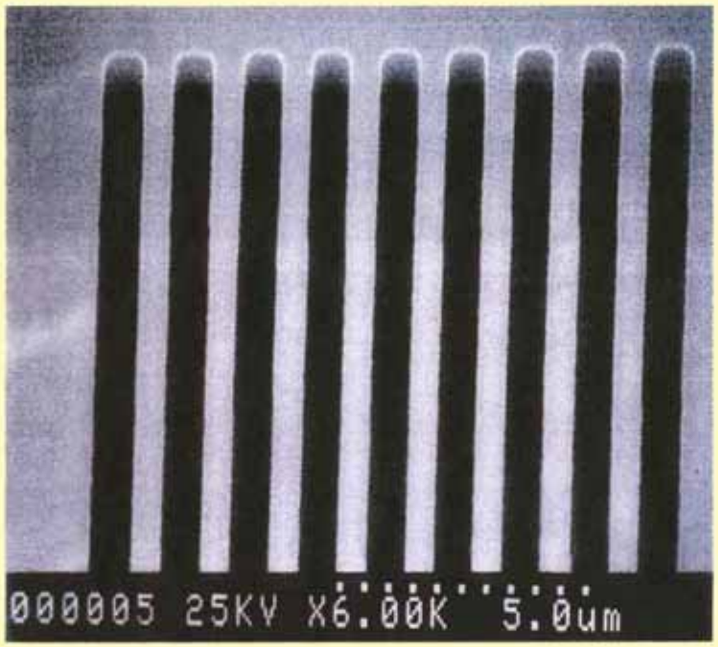
Example of ion beam lithography

in 180 nm Shipley DUV resist UVIIHS

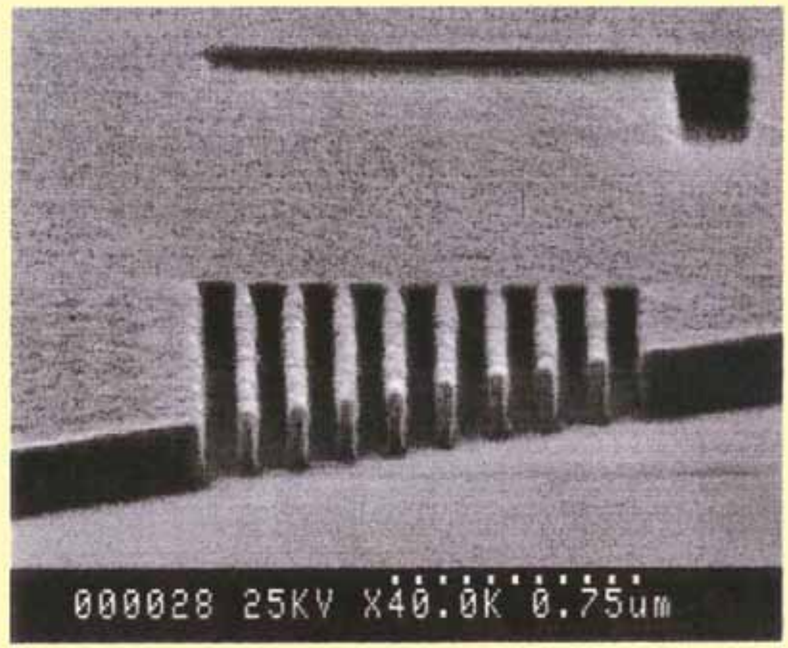
W. Bruenger
FhG ISiT
Nov 1999

75 keV He+ ions
0.46 µC/cm2
exposure dose

Stencil Mask

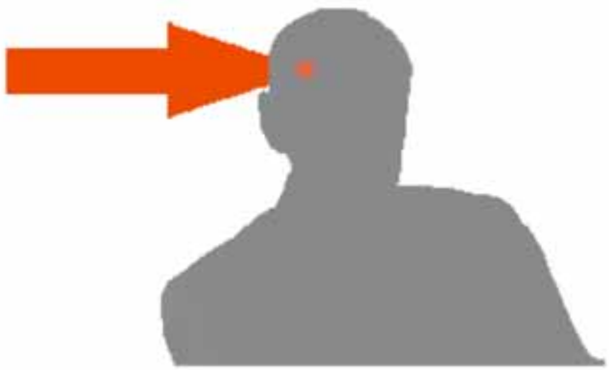


Wafer



650 nm L/S → 8.7x reduction → 75 nm L/S

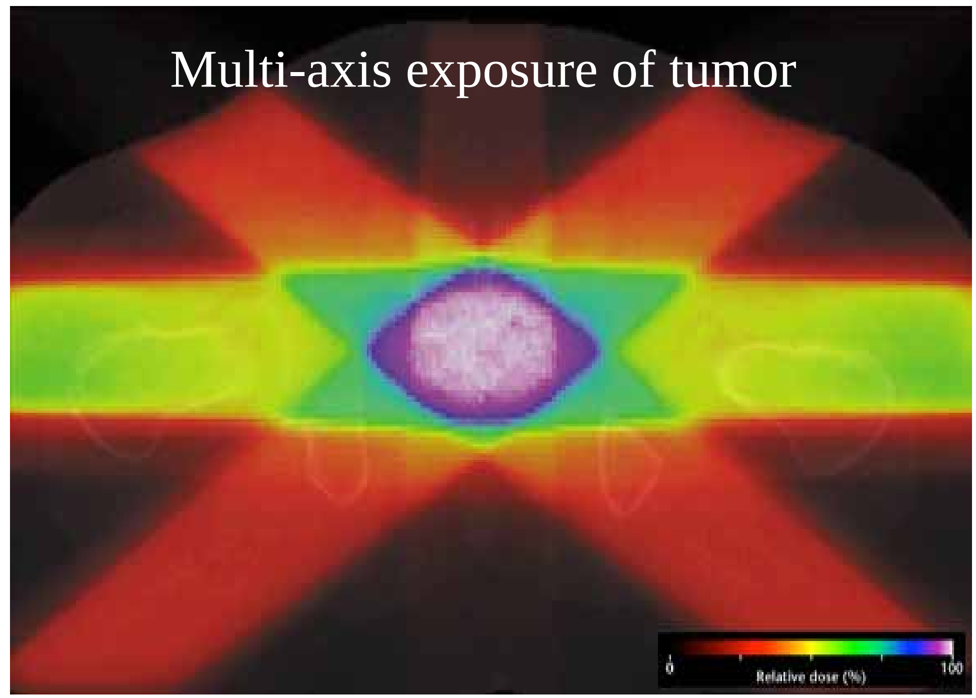
Therapy



FOM: treatment time
tumor control probability
precision beam control

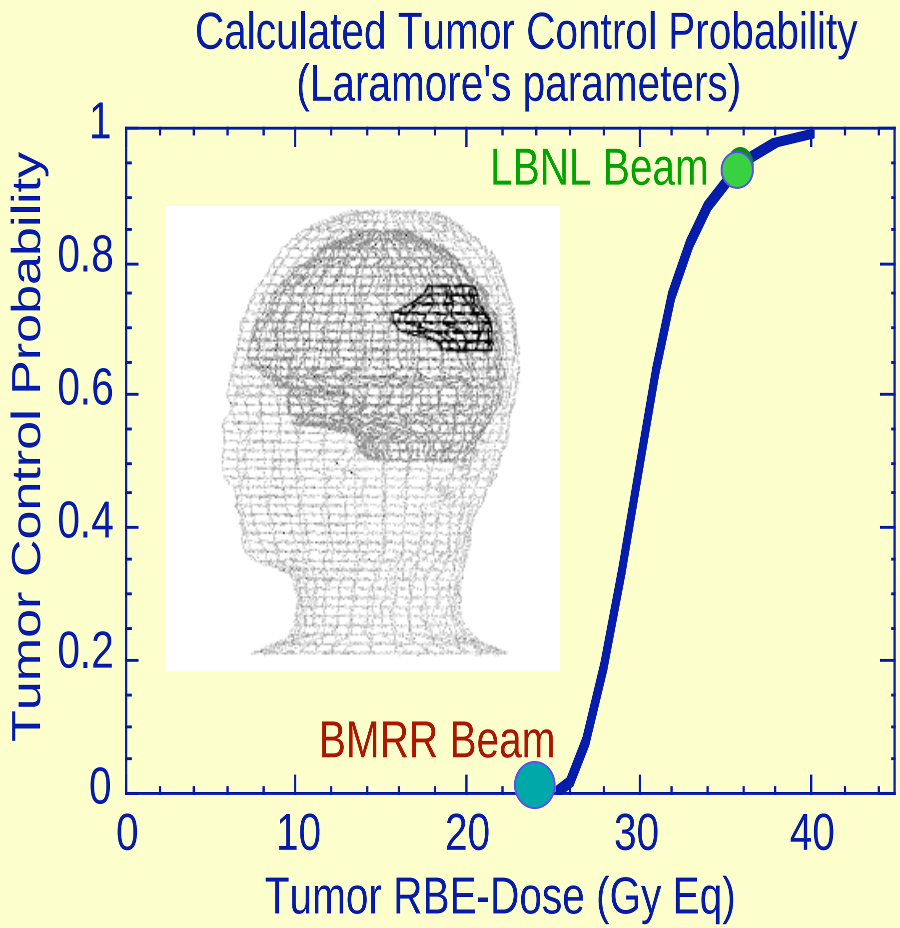
Example: Conformal therapy

Challenge: Kill the tumor cells w/o killing healthy tissue



Gamma rays from electron linac

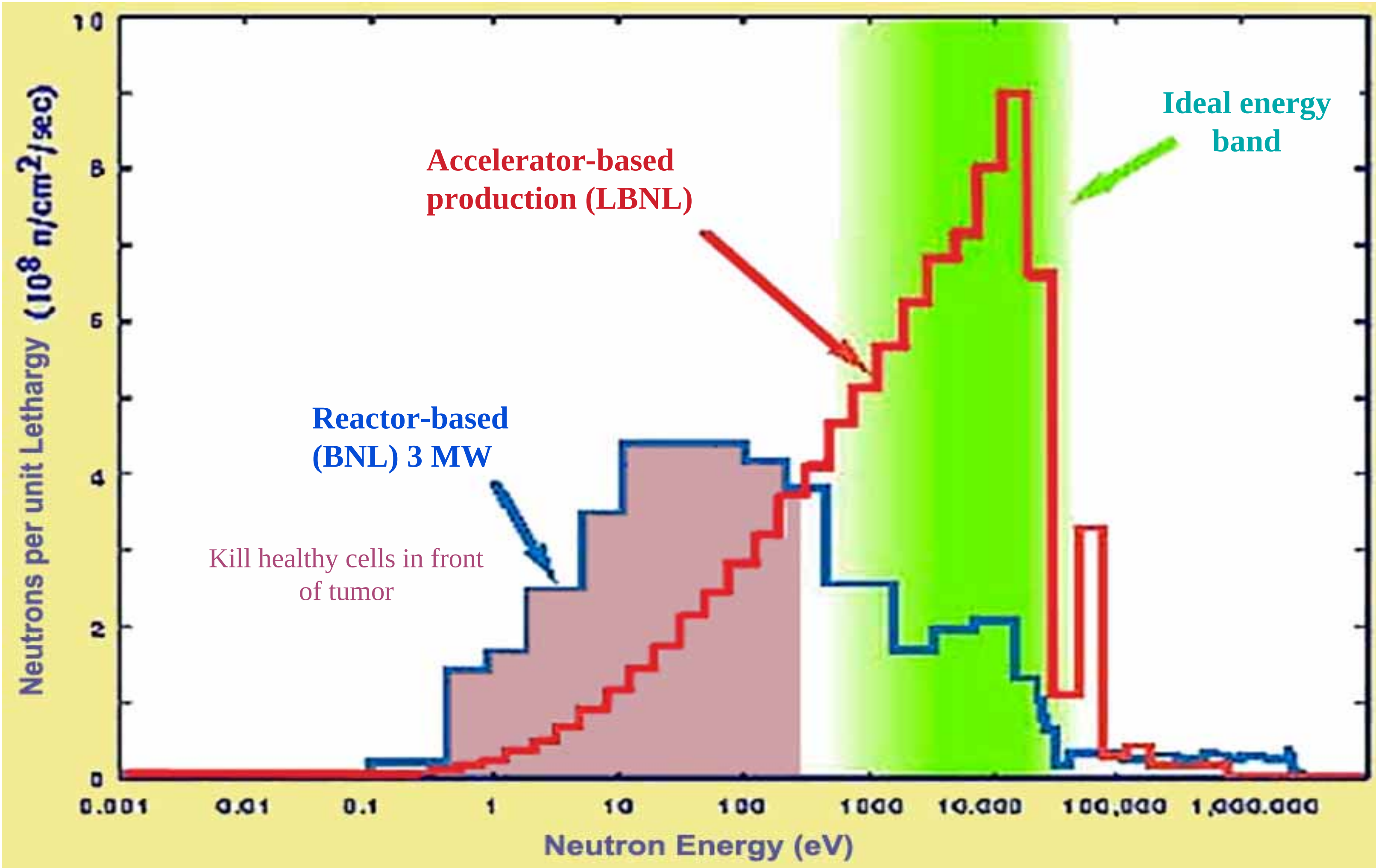
FOM - Tumor control probability



Dots indicate tumor doses near midline of brain for BMRR and LBNL Beams (for specific head, treated to maximal normal tissue dose)

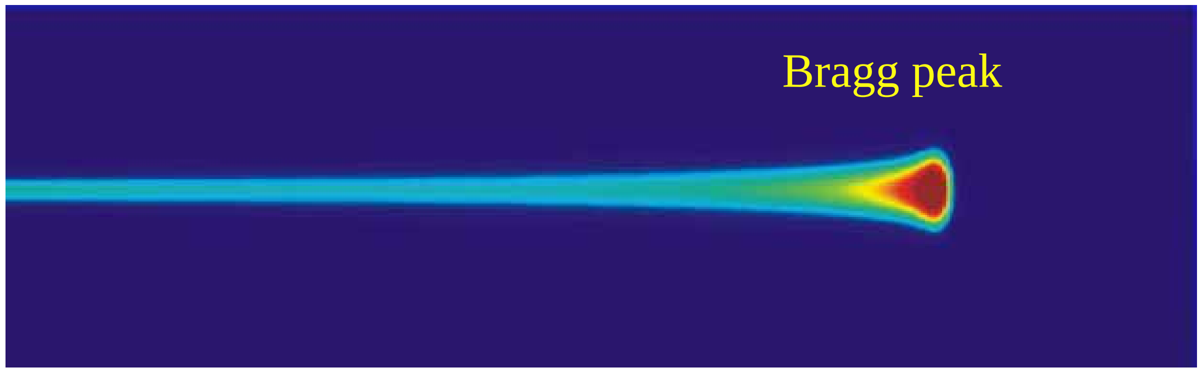
Control of gliobastoma multiformae with neutron capture therapy

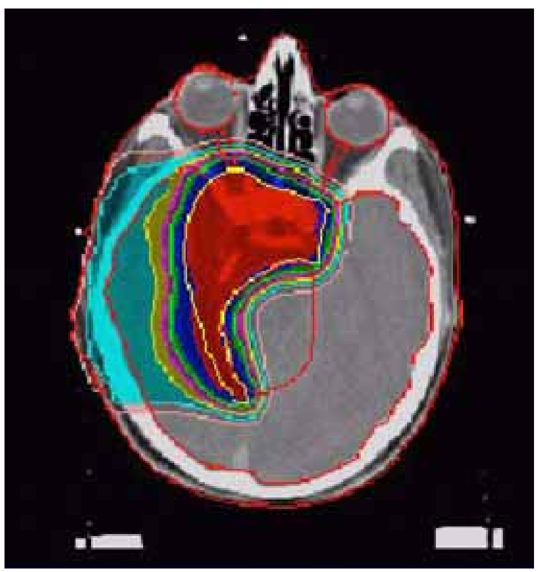
What's the difference between the beams?



Tumor control with hadron beams

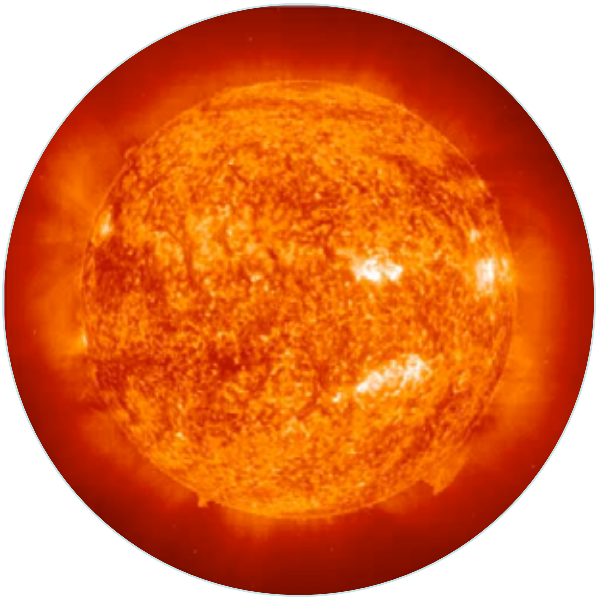
Proton beam



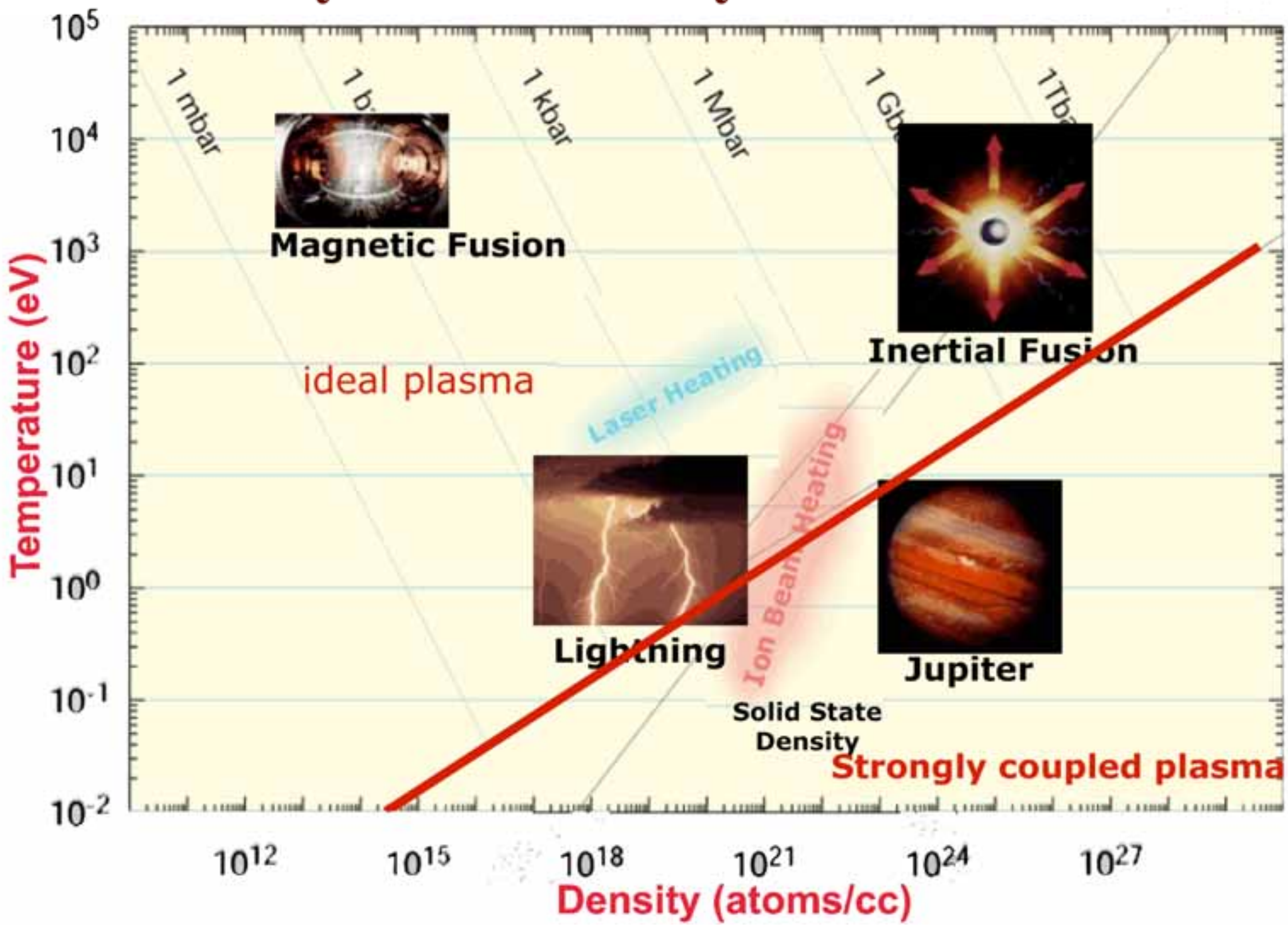


Hadron therapy allows for the best treatment of deep tumors with minimized dose to healthy tissue

Ion beams to produce fusion energy

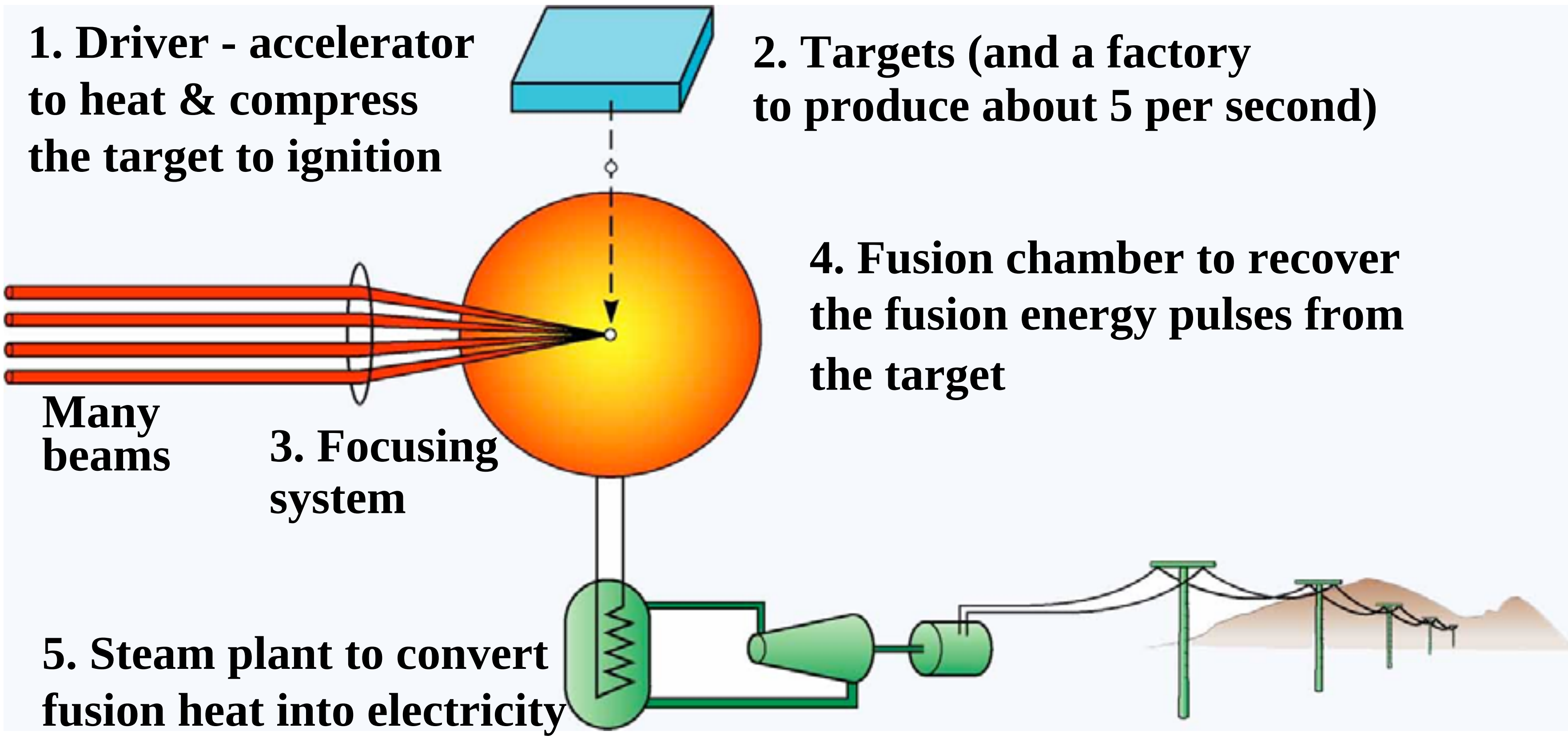


Matter in extreme conditions can be driven by intense heavy ion beams



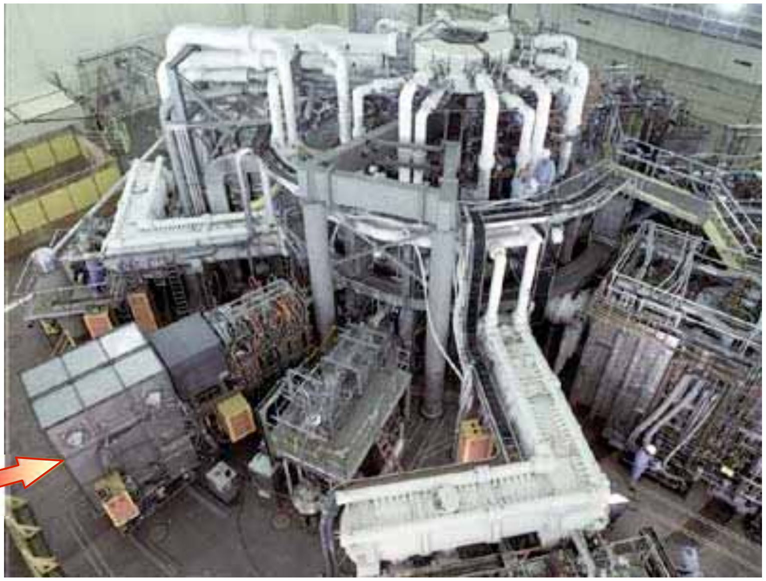
27 min

The inertial fusion power plant



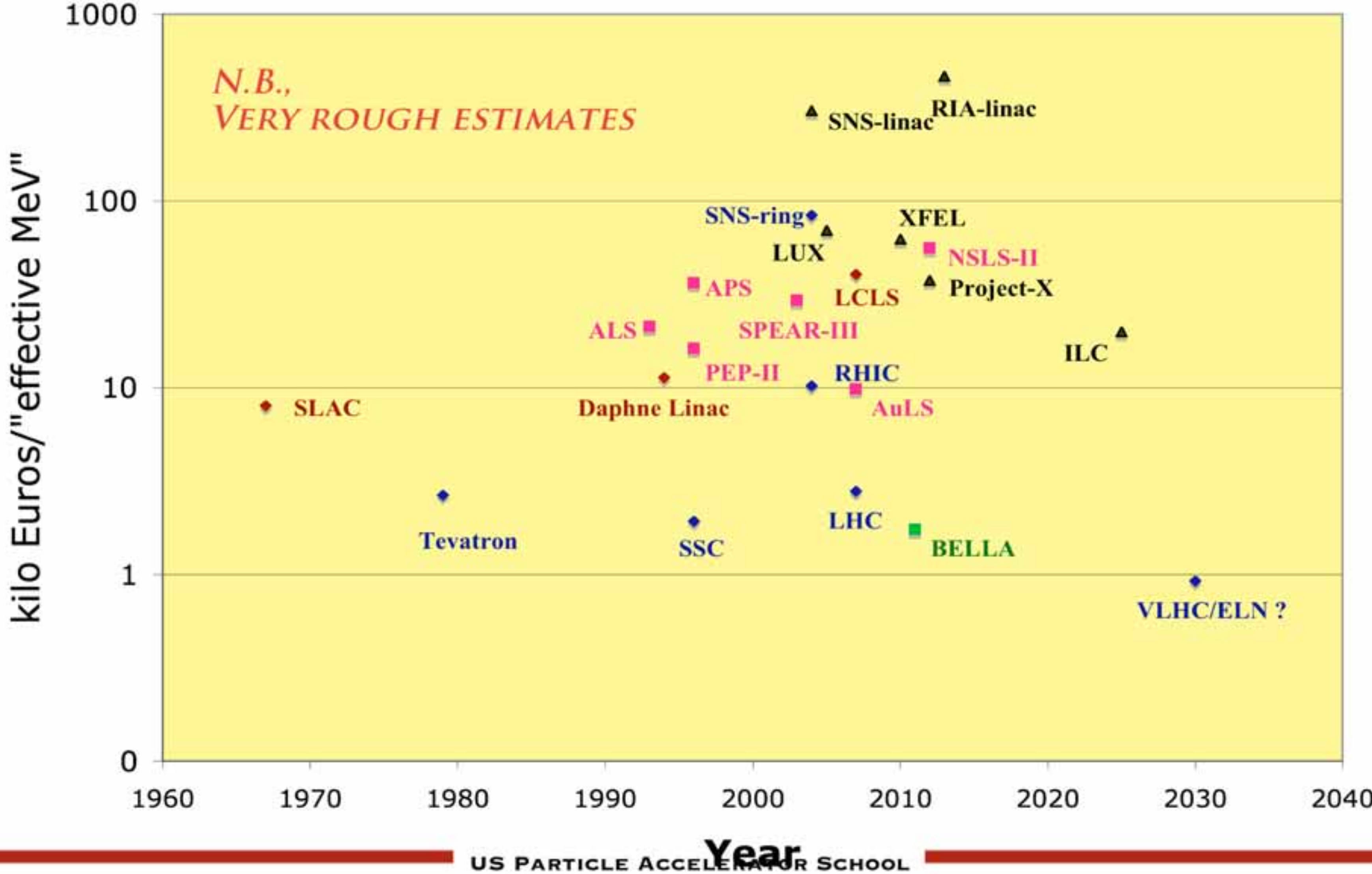
Beams to heat fusion plasmas

- Example: neutral beams for TFTR at Princeton



- ITER will require 60 MW of neutral beam heaters

How much do these things cost?



Just what are these beams?

That's the next lecture