Fundamentals of Accelerators

Lecture 1

Motivations & policy

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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,

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

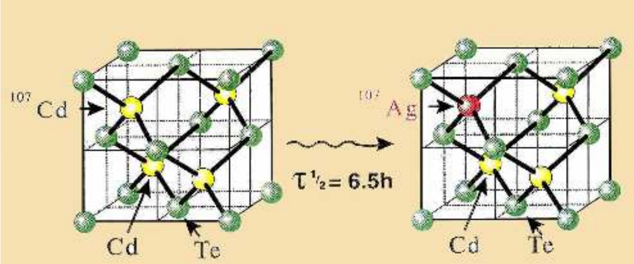
$$= 0.512\text{ MeV}$$

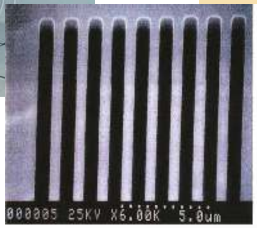
- For protons,

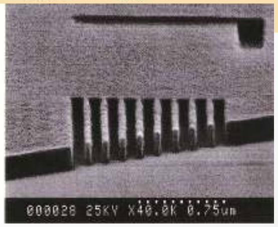
$$E_{o,p} = 938\text{ MeV}$$

Accelerators are the hallmark of highly technological societies

Medicine

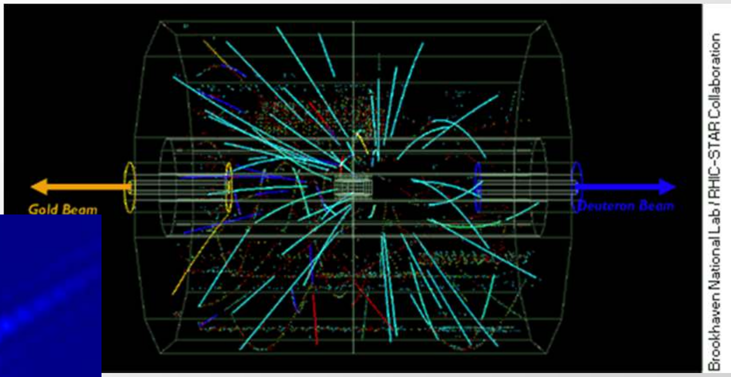




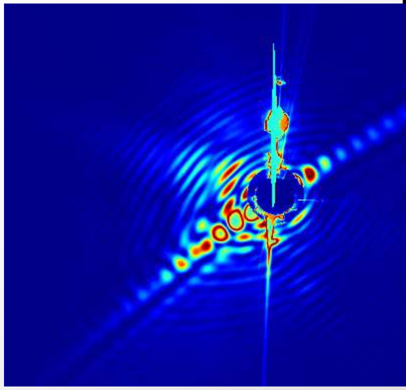


Materials

Basic Research



Brookhaven National Lab / RHIC-STAR Collaboration

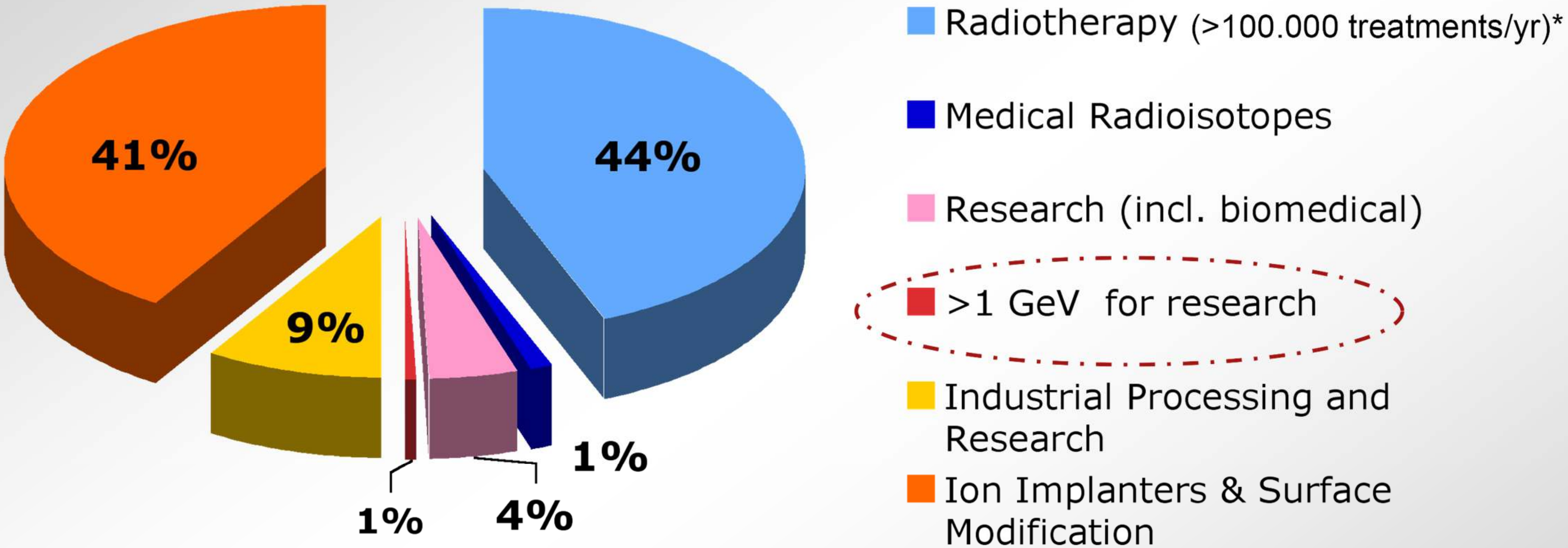


Exciting products…

exciting opportunities

Accelerators are big business
Academic researchers are "the 1%"

Number of accelerators worldwide
~ 26,000



Annual growth is several percent

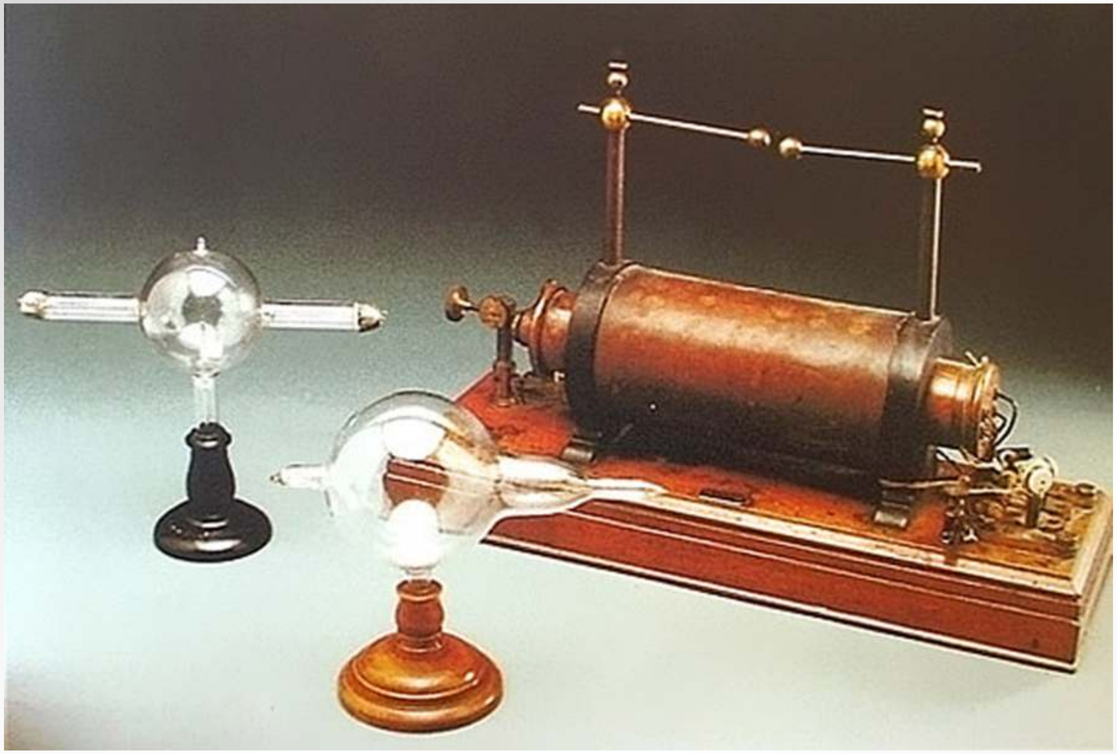
Sales >3.5 B$/yr
Value of treated good > 50 B$/yr **

Major research machines are a tiny fraction of the total, but…

Sources: W. Maciszewski & W. Scharf, L. Rivkin, * EPP2010, ** R. Hamm

Research: How can we understand the underlying structure of things?

The first "light source"



Wilhelm Röntgen discovered X-rays in 1895 by accelerating electrons

Motivations: How it all began

Paradigm 1: Fixed target experiments

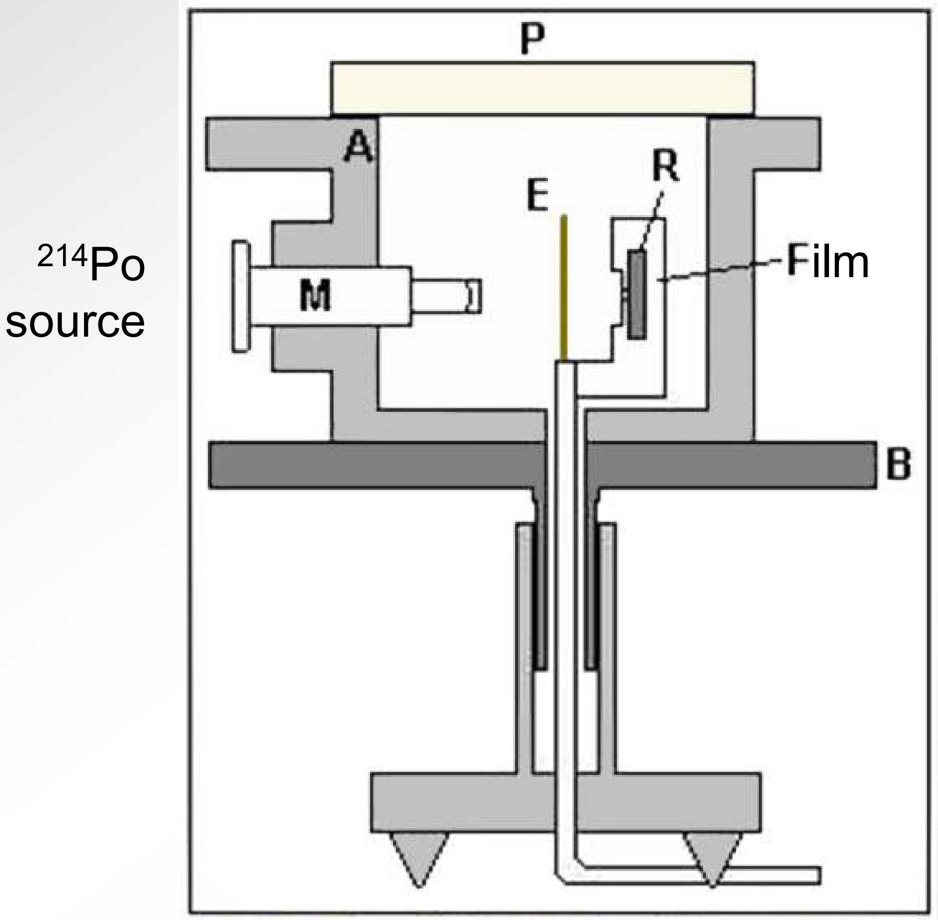


Fig1. Marsden-Geiger experiment.

Rutherford explains scattering of *alpha particles* on *gold* discovering the nucleus & urges … *On to higher energy probes!*

Rutherford articulated Figure of Merit 1

Particle (or photon) energy on target

Why we use energetic beams for research?

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

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

  - ➢ Higher momentum => shorter wavelength => better resolution

- ❖ Energy to Matter
  - ➢ Higher energy produces heavier particles

The advantage of the fixed target physics:
Figure of Merit 2

$$\frac{Events}{second} = \sigma_{process} \cdot \underbrace{Flux \cdot Target\ Number\ Density \cdot Path\ Length}_{Luminosity}$$

Typical values:

$Flux \sim 10^{12}$ - $10^{14}\ s^{-1}$

$Number\ density \sim \rho N_A Z/A \sim 5 \times 6 \times 10^{23} / 2$

$Path\ length \sim 10\ cm$

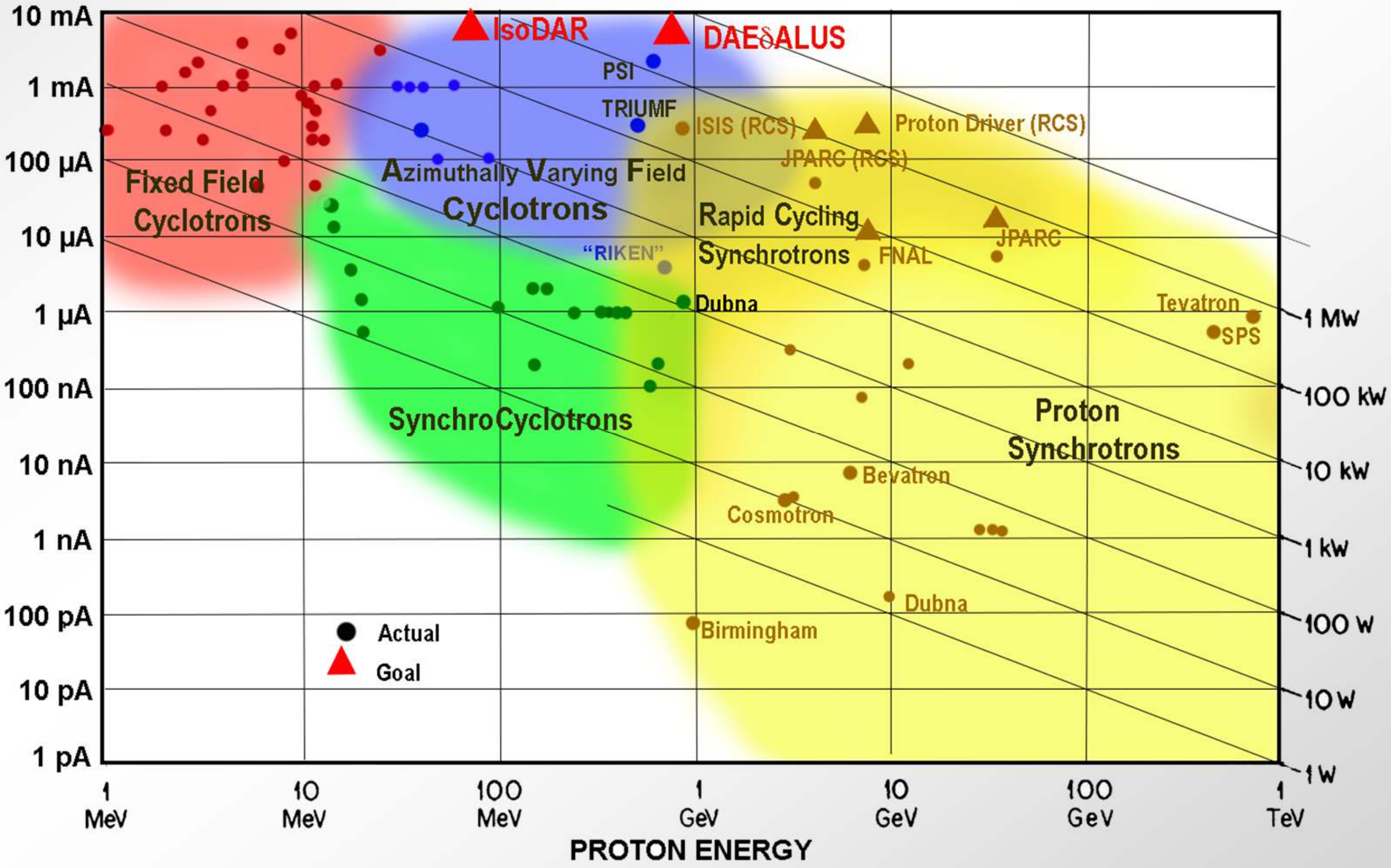
$Luminosity \sim 15 \times 10^{23} \times 10^{14} \sim 10^{36} - 10^{38}\ cm^{-2}s^{-1}$

Ideal for precision & rare process physics,

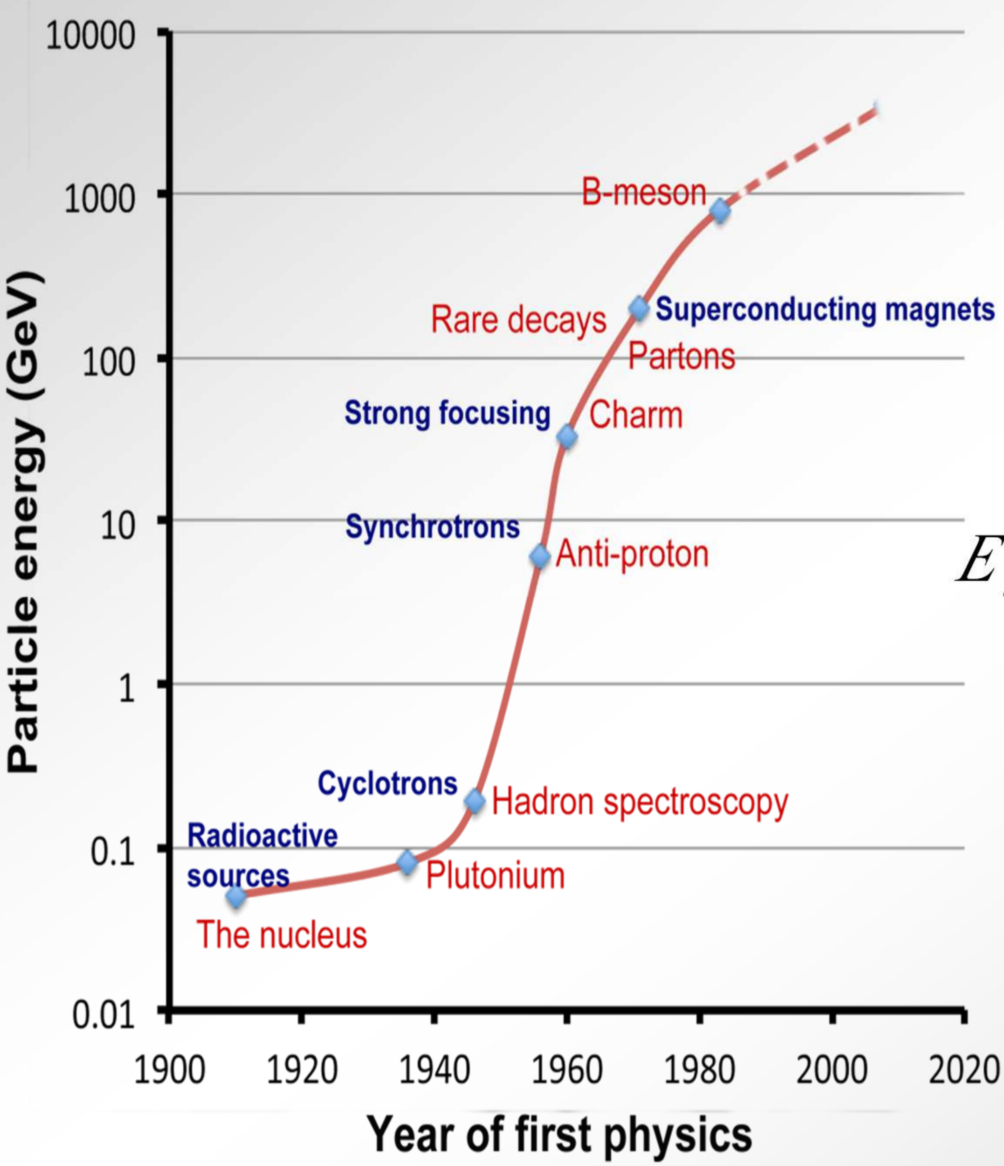
BUT how much energy is available for new physics

Fixed targets require high power beams

- ❖ For current < 5 mA, circular accelerators are economical
  - ➢ Current limit ~ 5 mA (space charge at injection) < Linac
  - ➢ Energy limit ~ 1 GeV << Linac potential
  - ➢ $$ per MW ~ 1/4 of Linac of same beam parameters



The fixed target paradigm has its limits



Invariance of

$$(p_1 + p_2)^\mu \bullet (p_1 + p_2)_\mu$$

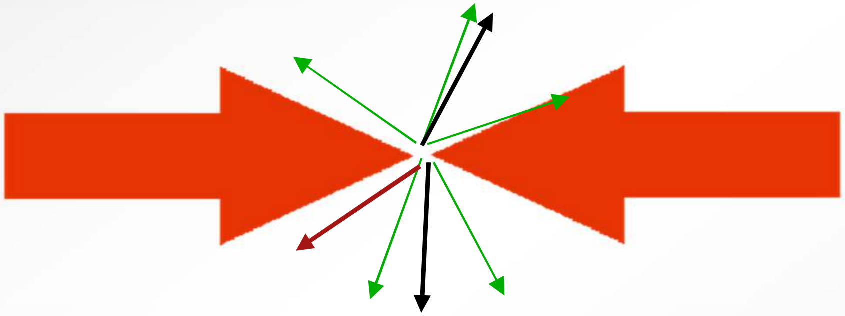
in Lorentz frames implies that

$$E_{cm} = \sqrt{m_1^2 + m_2^2 + 2m_2c^2E_{beam}}$$

$$\approx \sqrt{2mc^2E_{beam}} \quad \textit{for equal masses}$$

A great invention comes to the rescue (R. Wiederoe, 1943)

Collide beams !



If $m_1 = m_2$ and if $E_1 = E_2 = E$

$$E_{cm} = 2\ E$$

The full kinetic energy of both particles is now available to physical processes

The next big step was the ISR at CERN

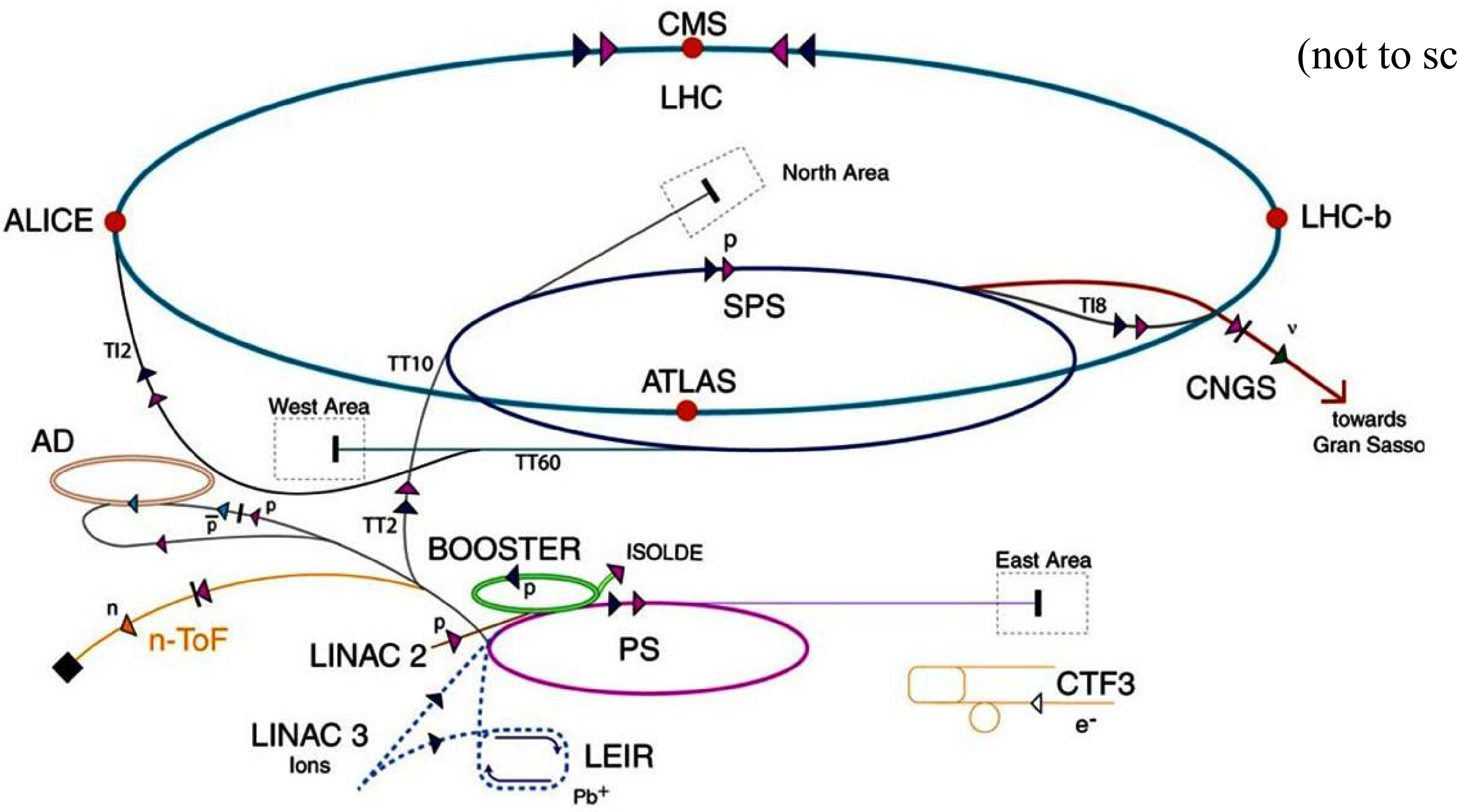
- 30 GeV per beam with > 60 A circulating current
  - Required extraordinary vacuum (10^{-11} Torr)
  - Great beam dynamics challenge - more stable than the solar system
- Then on to the 200 GeV collider at Fermilab (1972) and …

- The Sp$\bar{p}$S at CERN
  - *Nobel invention:* Stochastic cooling
- Then the Tevatron
  - Required a *major technological invention*

First machine to exploit superconducting magnet technology

The largest research accelerator: CERN Accelerator Complex (LHC)

(not to scale)



▶ protons
▶ ions
▶ neutrons

▶ antiprotons
▷ electrons
▶ neutrinos

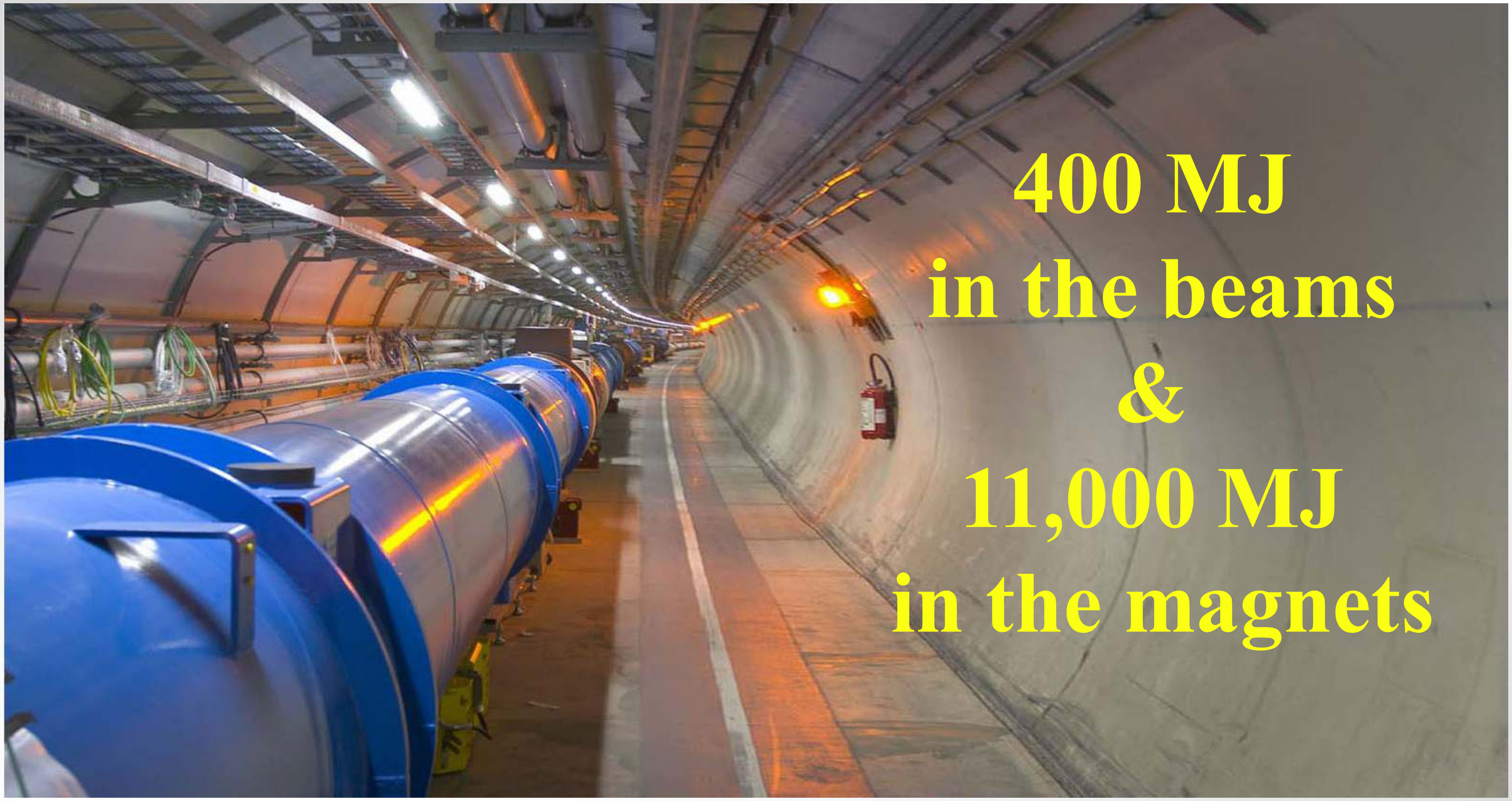
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3

The future of HEP runs through CERN

“Après moi, le déluge”


400 MJ
in the beams
&
11,000 MJ
in the magnets

- LHC upgrades rely on advances in magnet technology
  - Luminosity upgrade - very high gradient, Nb_3Sn quads
  - Super LHC (energy upgrade) - very high field dipoles

9 min

What sets beam size ?

- Strength (depth of focus) of lens at interaction point, β*
- Distribution of positions & transverse momenta of beam particles (emittance), ε

$$\sigma_{x,y} = \sqrt{\ _{x,y}\ ^{*}}$$

$$\text{Luminosity} = \frac{N_1 \times N_2 \times f}{4\pi\sqrt{\ ^{*}_{x}\ ^{*}_{y}\ _{x}\ _{y}}} \times \text{Pinch effect} \times \textit{angle correction}$$

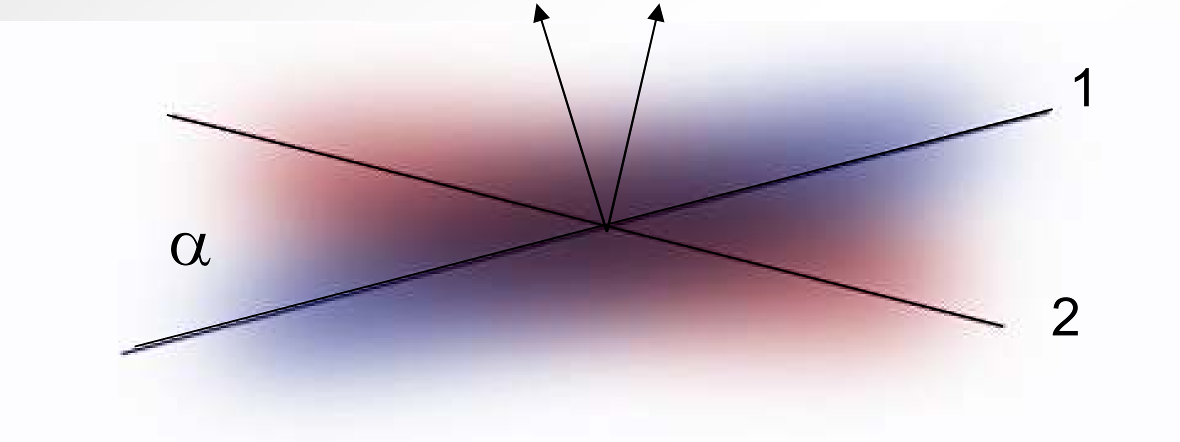
- For simplicity say ε and β* are equal for x and y

$$\text{Luminosity} = \frac{N_1 \times N_2 \times f}{4\pi\ ^{*}_{x}\ _{x}} \times H_D \times \textit{angle correction}$$

This looks too good to be true!
What about the luminosity?

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

Beam energy: sets scale of physics accessible

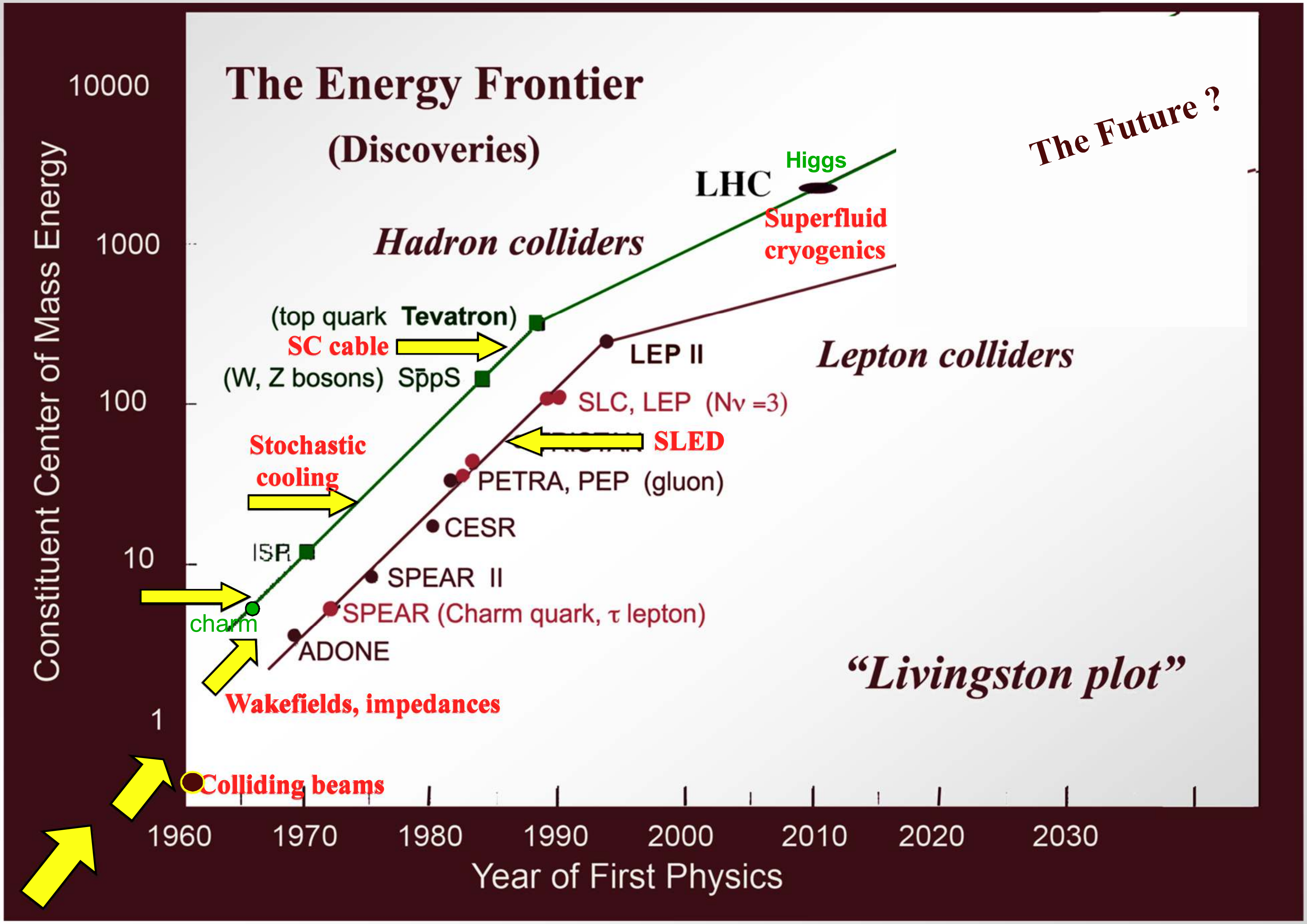


$$\text{Luminosity} = \frac{N_1 \times N_2 \times frequency}{Overlap\ Area} = \frac{N_1 \times N_2 \times f}{4\pi\sigma_x\sigma_y} \times Correction\ factors$$

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

$$Luminosity \sim 10^{31} - 10^{34}\ cm^{-2}s^{-1}$$

Energy frontier is extended
by inventions in accelerator technology (in red)

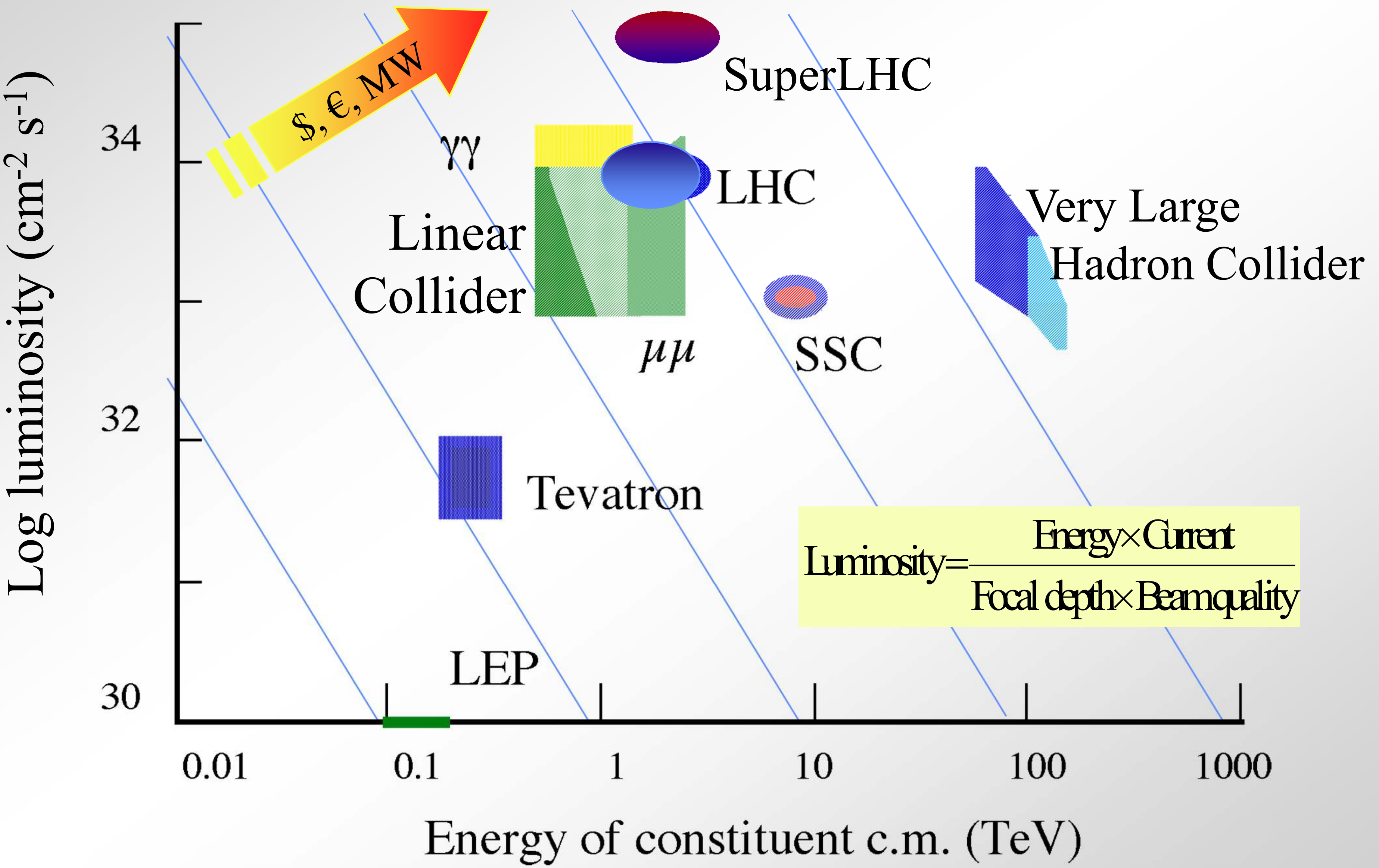


Strong focusing

10 minute exercise:

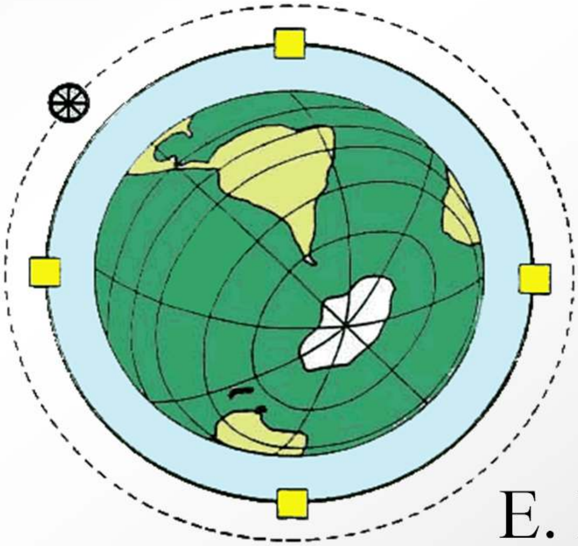
Show explicitly that the expression for
collider luminosity
is equivalent to the expression for
fixed target luminosity.

Example from High Energy Physics: Discovery space for future accelerators



$$\text{Luminosity} = \frac{\text{Energy} \times \text{Current}}{\text{Focal depth} \times \text{Beam quality}}$$

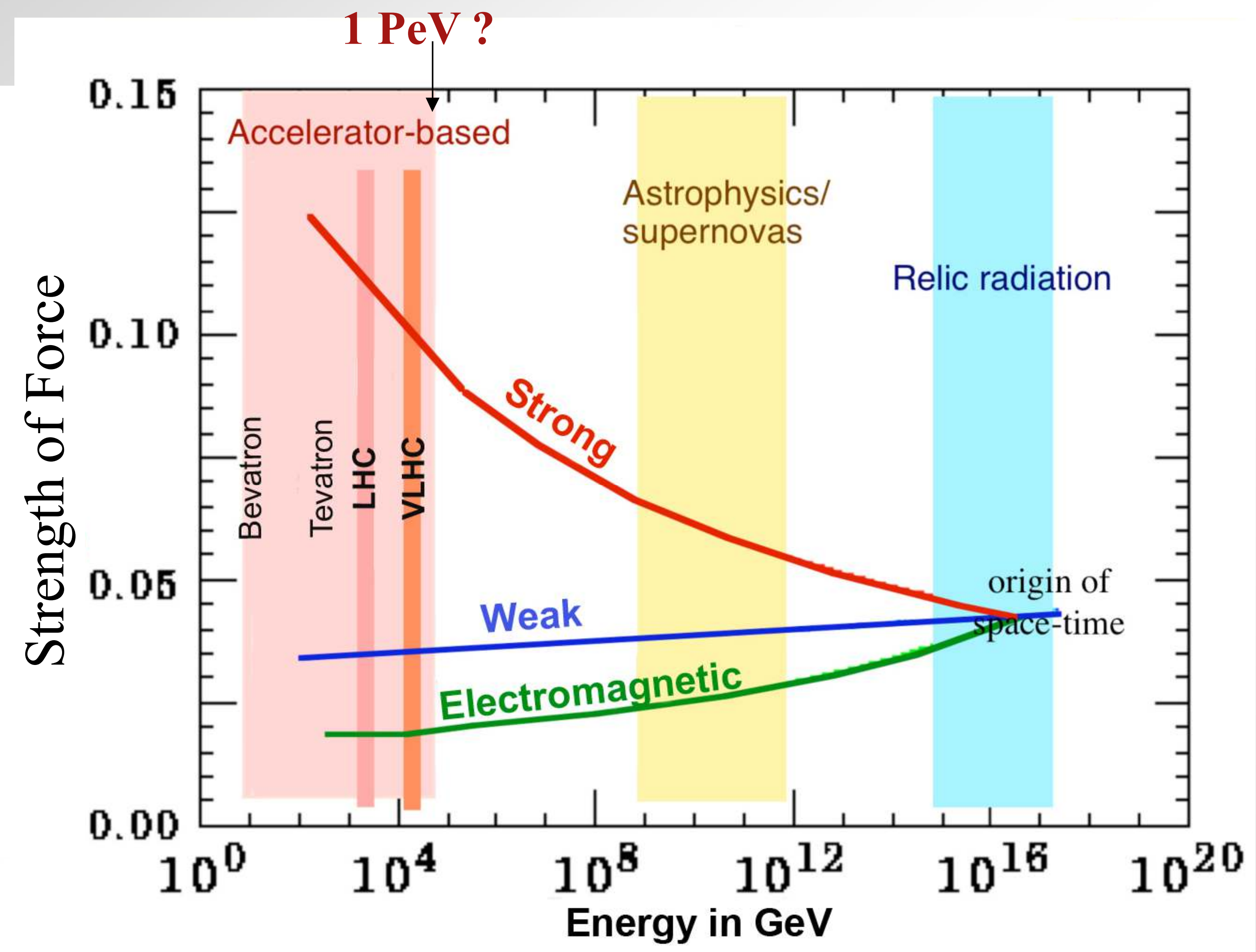
Limits
of
accelerator-based HEP



E. Fermi

15 mi

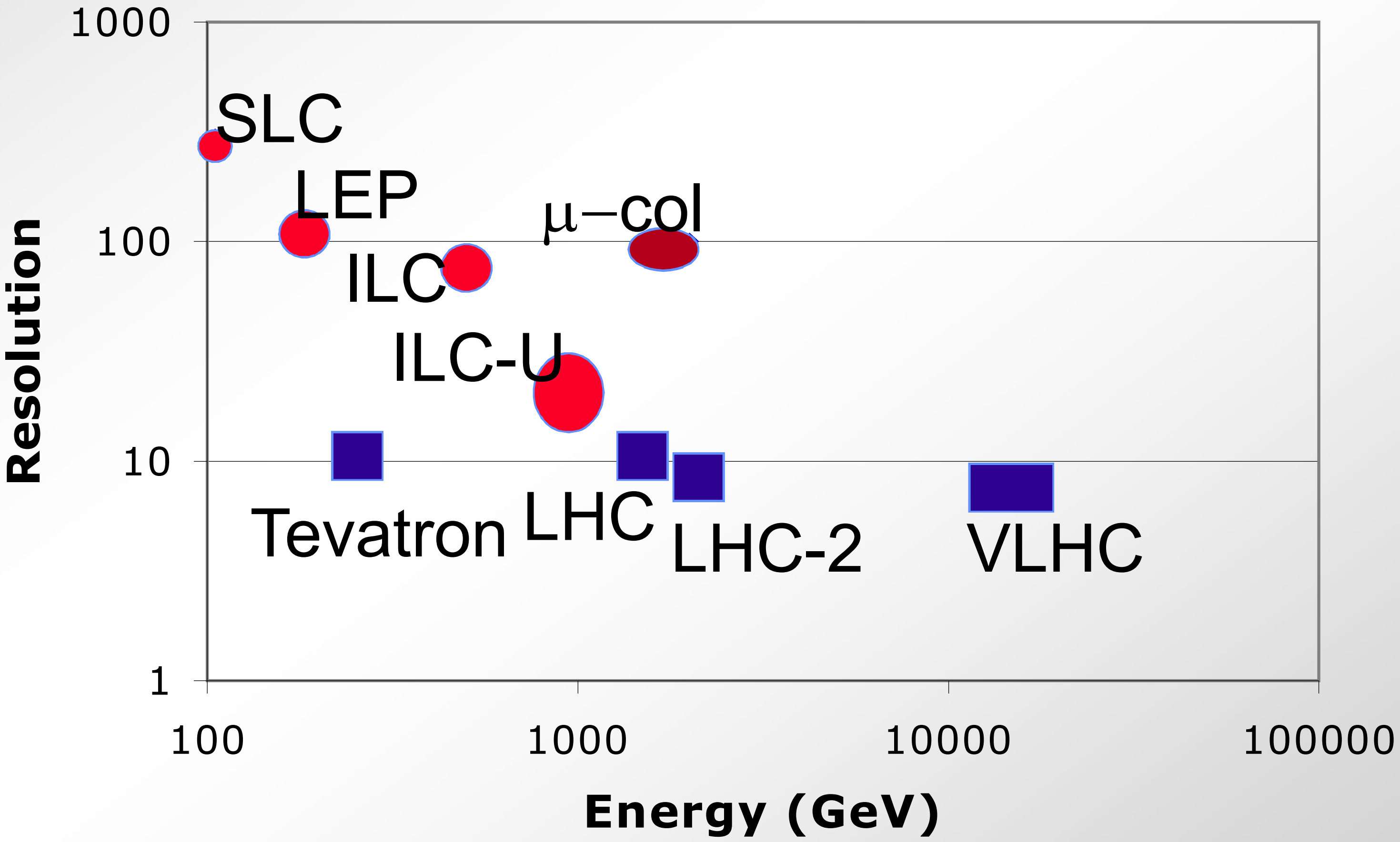
How far can we go with this approach?



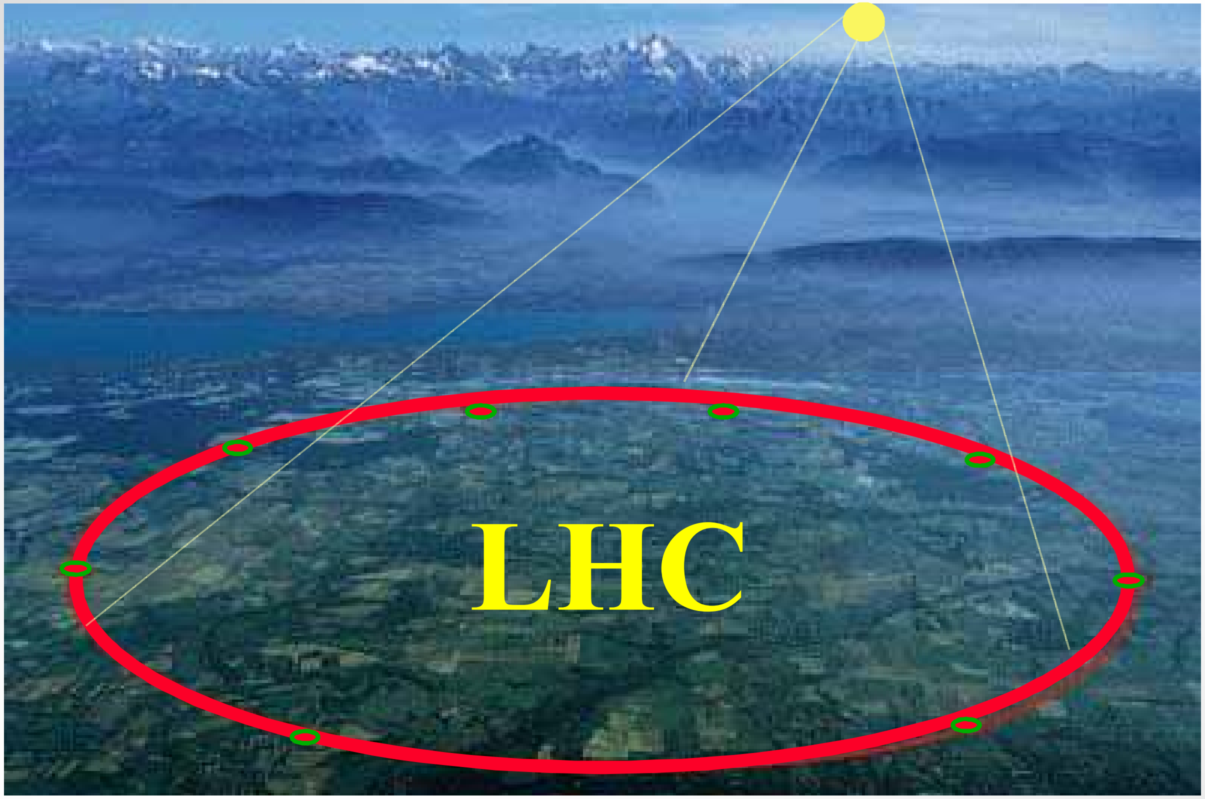
How big is a PeV collider?

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"

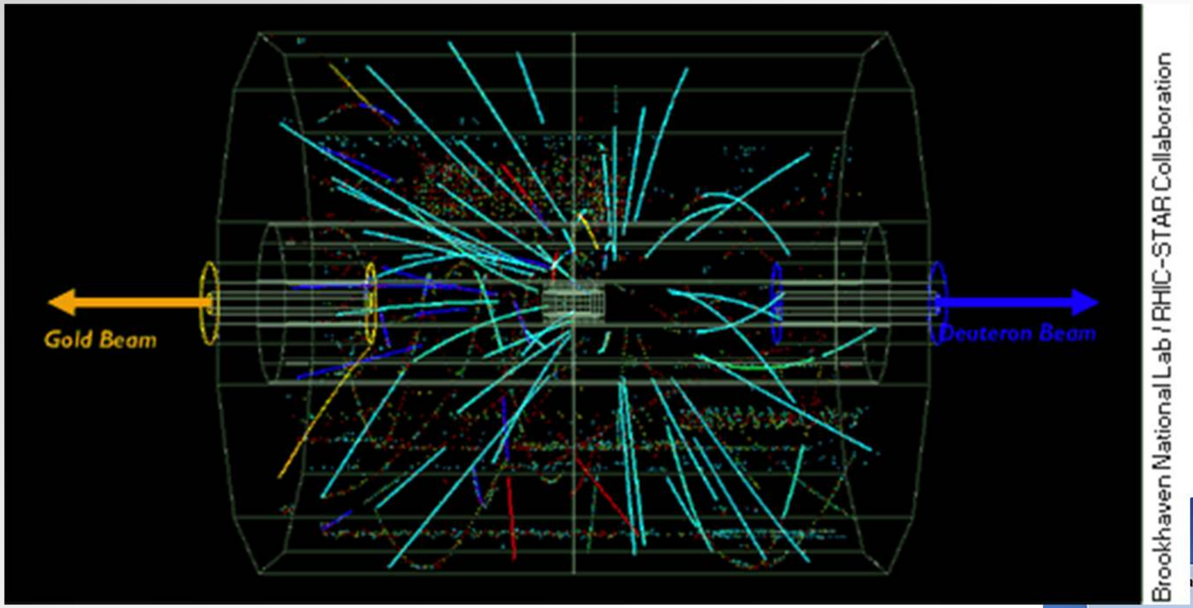


- ☐ LHC upgrades rely on advances in magnet technology
  - ☐ Reliability upgrade (2013) - replace IR Quads & collimators
  - ☐ Luminosity upgrade - very high gradient, Nb_3Sn quads
  - ☐ Super LHC (energy upgrade) - very high field dipoles

9 min

Nuclear Physics

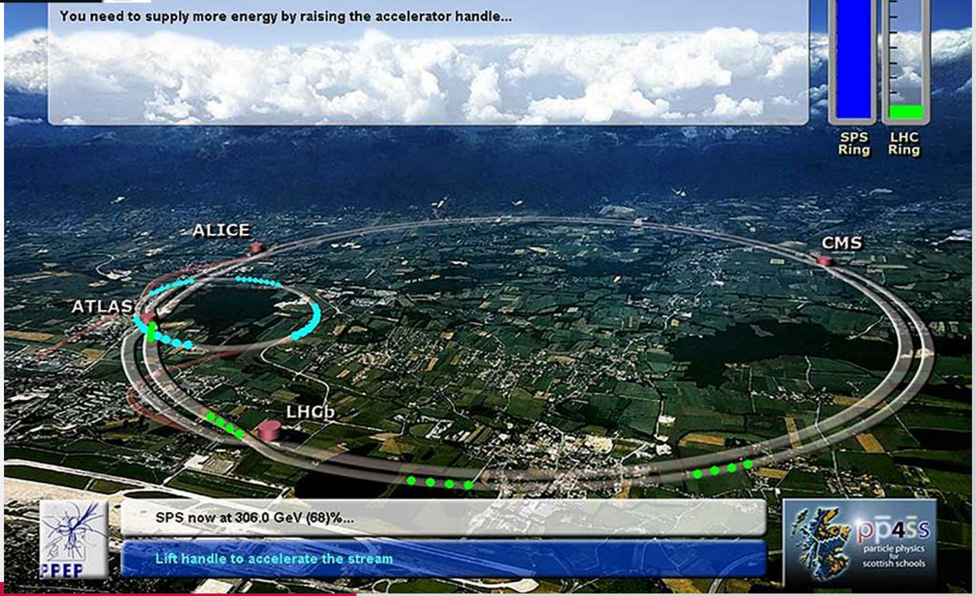
High energy studies of QCD:
Heavy ion collisions using synchrotrons



Brookhaven National Lab / RHIC-STAR Collaboration

D - Au at RHIC
==> Nuclear superfluid

LHC: The Large Hadron Collider



ave not yet been accelerated to their full energy.

You need to supply more energy by raising the accelerator handle...

SPS now at 306.0 GeV (68)%...

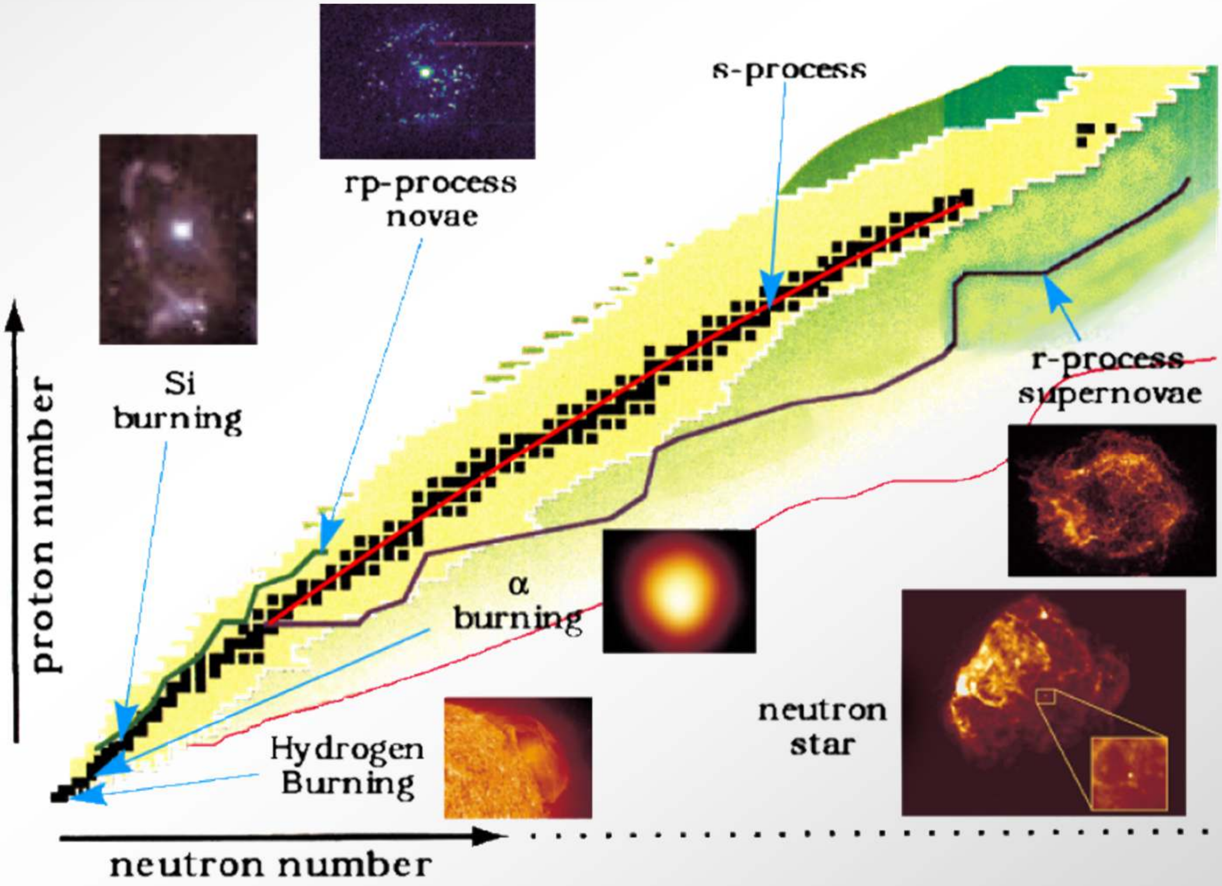
Lift handle to accelerate the stream

Next ALICE @ LHC
==> Quark-gluon plasma

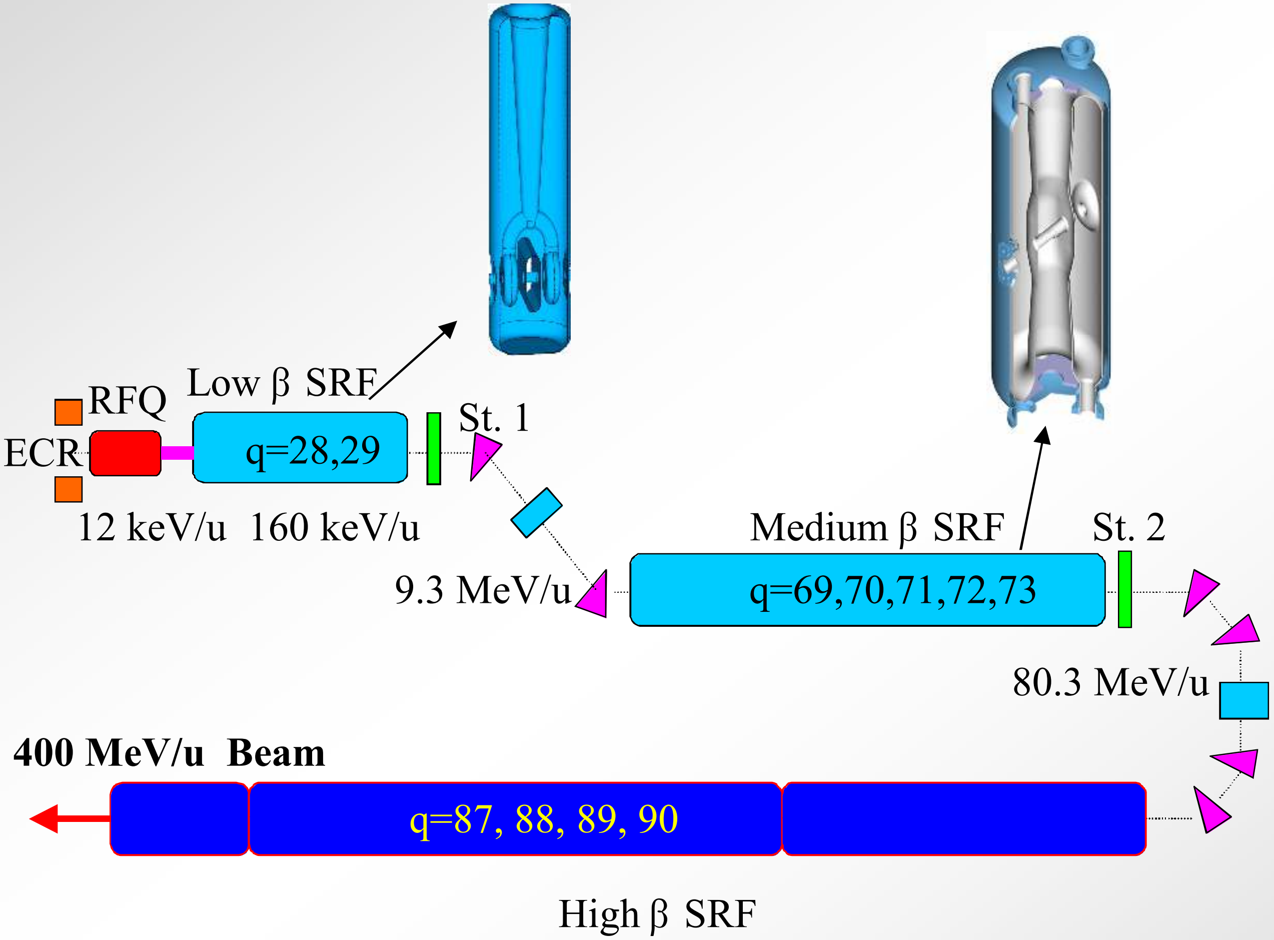
Nuclear Astrophysics - Nature of Hadronic Matter: Radioactive Beam Facilities

a Explore nuclear structure & reactions involving nuclei far from the valley of stability

  Ù These nuclei participate in explosive nucleo-synthesis in novae, x-ray bursts, and supernovae via rapid proton and neutron capture



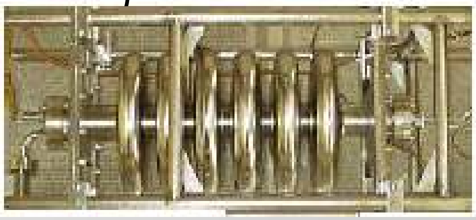
Superconducting linac structures for radioactive beam accelerator (FRIB)



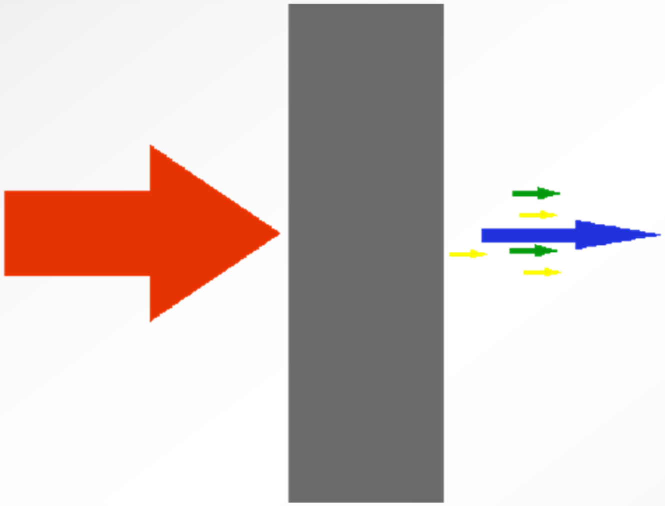
β = 0.81

β = 0.61

β = 0.5

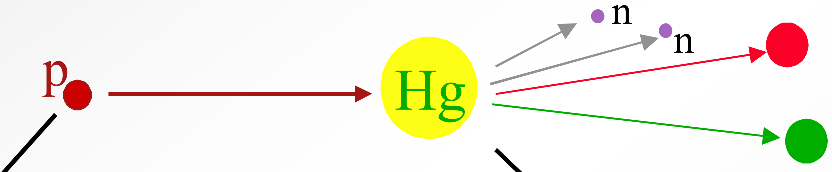


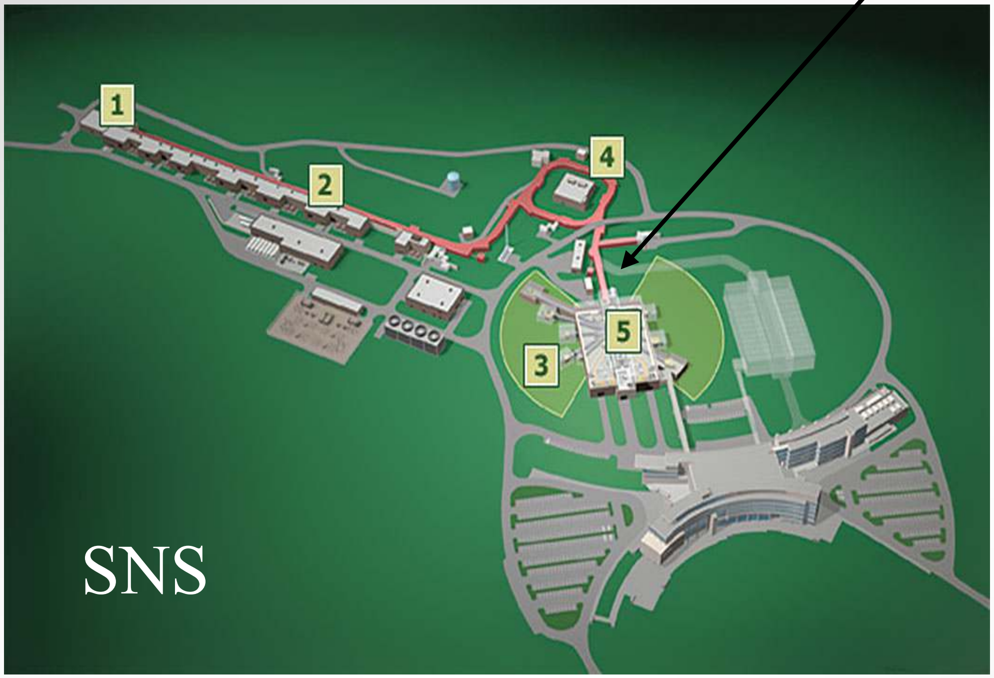
Neutron science with accelerators



FOM: Neutrons/proton, neutron beam brightness

Example: The Spallation Neutron Source
at Oak Ridge National Laboratory

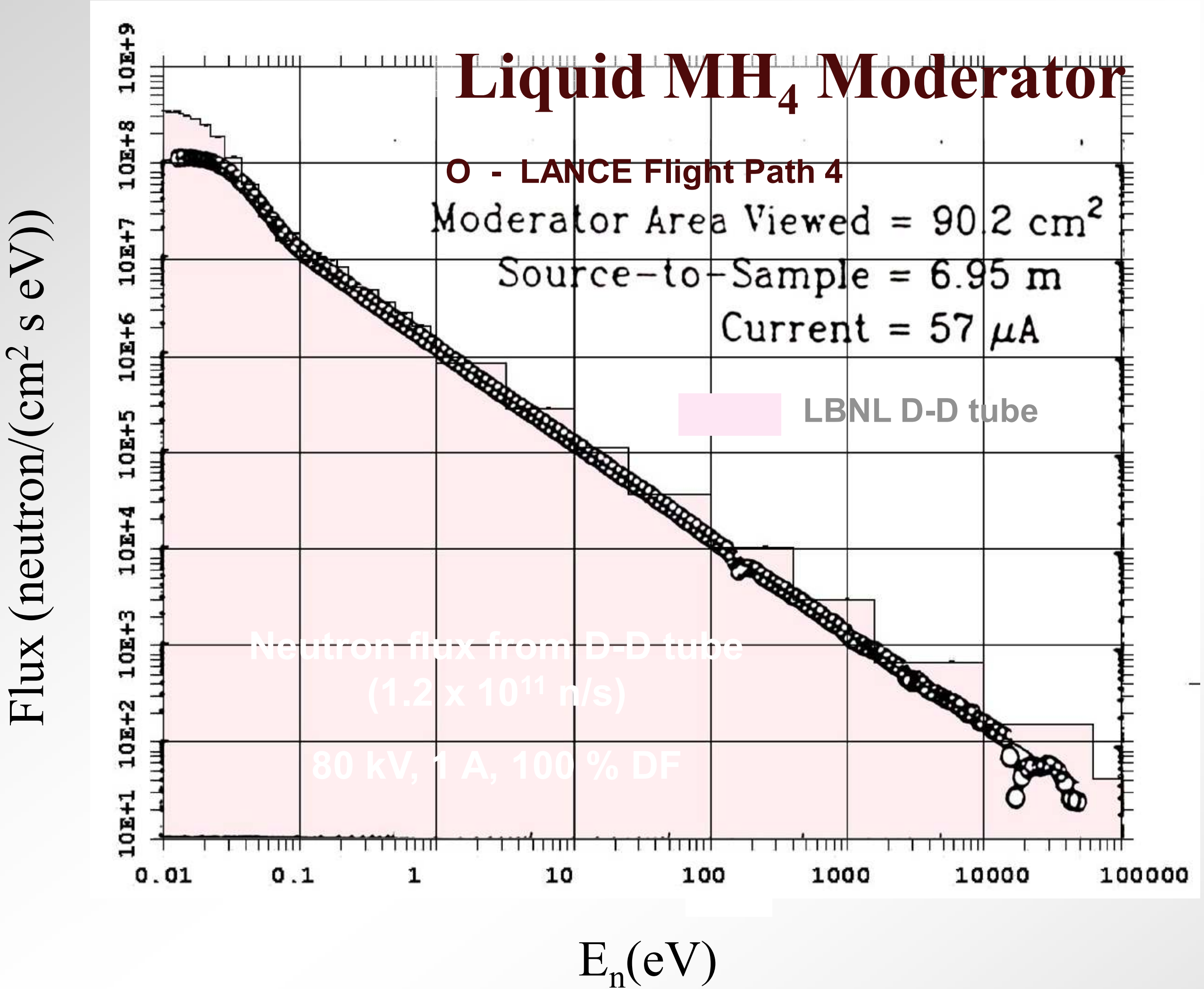


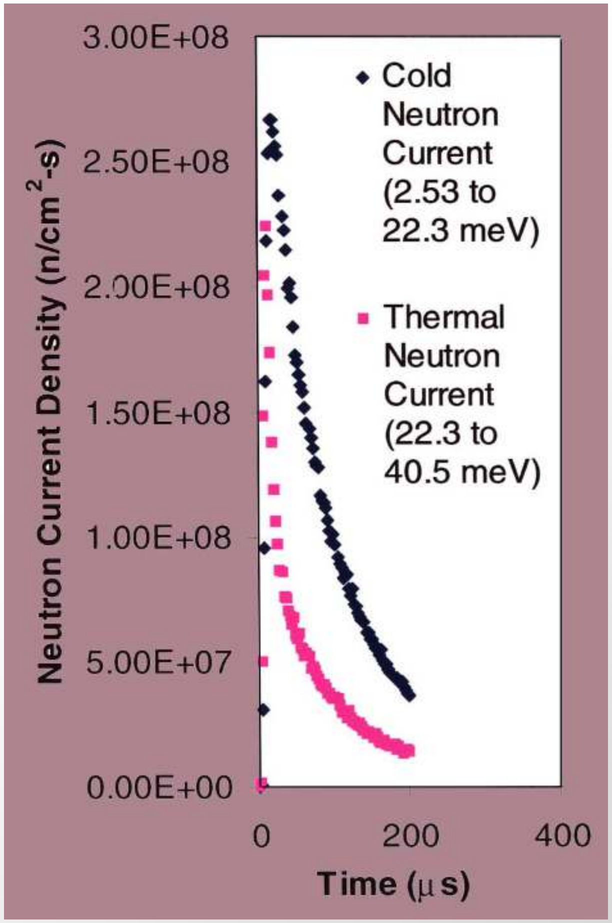


1 GeV, 35 mA of protons,
6% duty factor

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

Figures of Merit: Spectrum & time structure

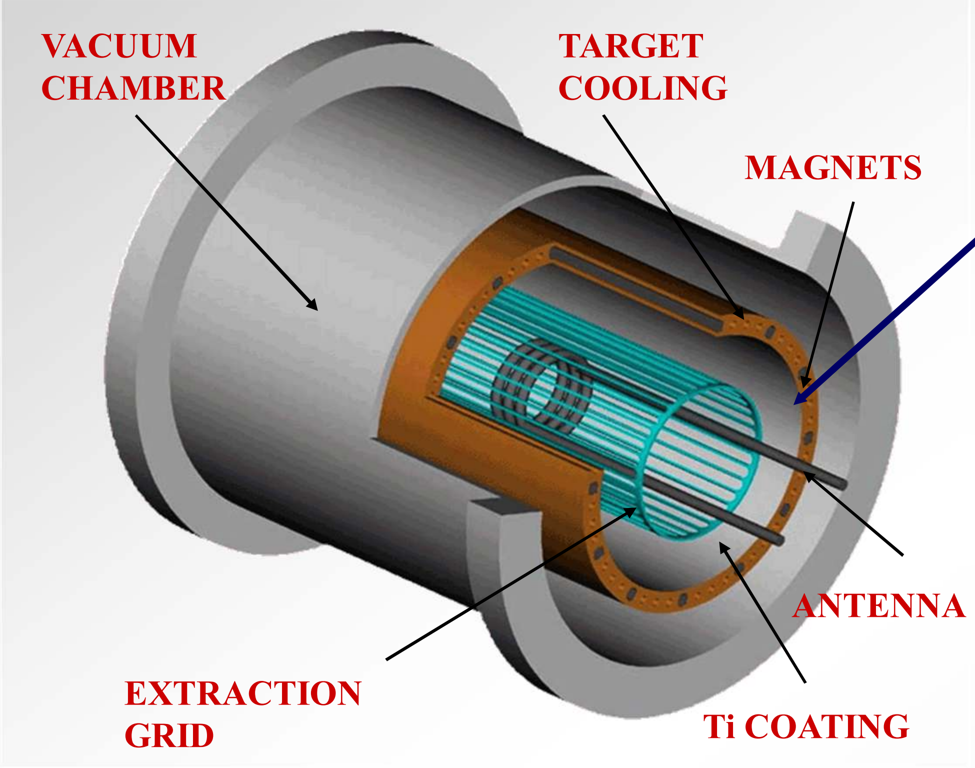




O The measured (circles) neutron flux v. neutron energy

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

Coaxial design increases target area in small volume source



TARGET CHAMBER

Length	26cm
Diameter	28cm
Weight	40lb

For D-D neutron output ~ 1.2 x 10^{12} n/s
For D-T neutron output ~ 3.5 x 10^{14} n/s
@ 80 kW of beam, 10% d.f.

Limiting parameter is power density on target

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

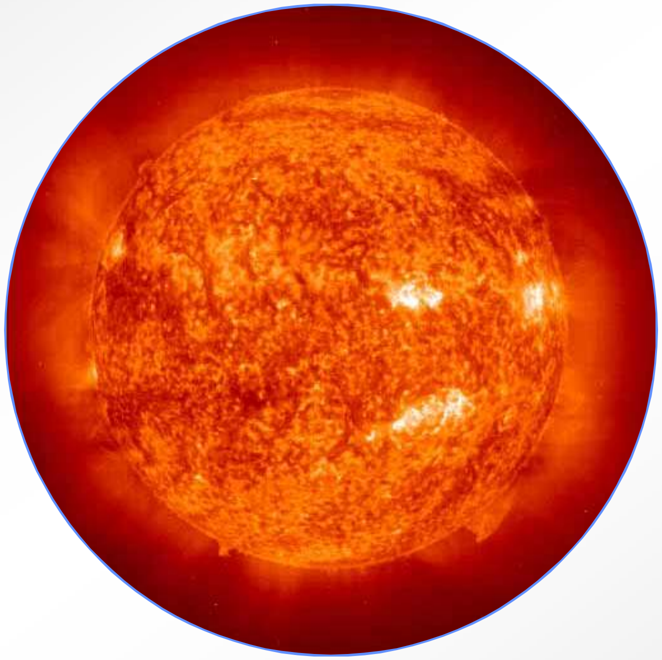
D-T neutron tube (120kV, 1 A ⇒ 10^{14} n/s)

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

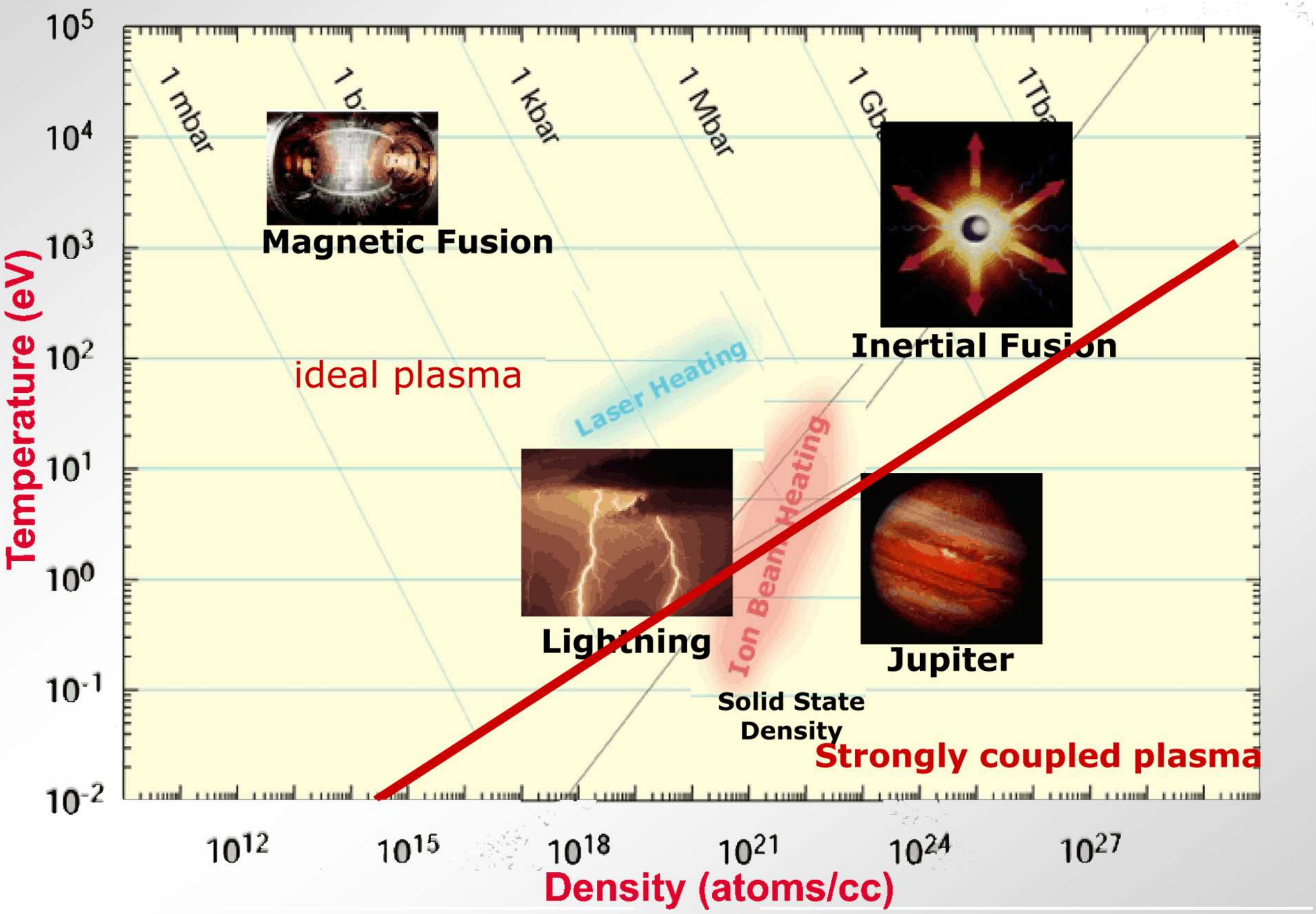
DC power supply efficiency > 85%

==> ≈ 10^{-9} J/n

Ion beams to produce fusion energy



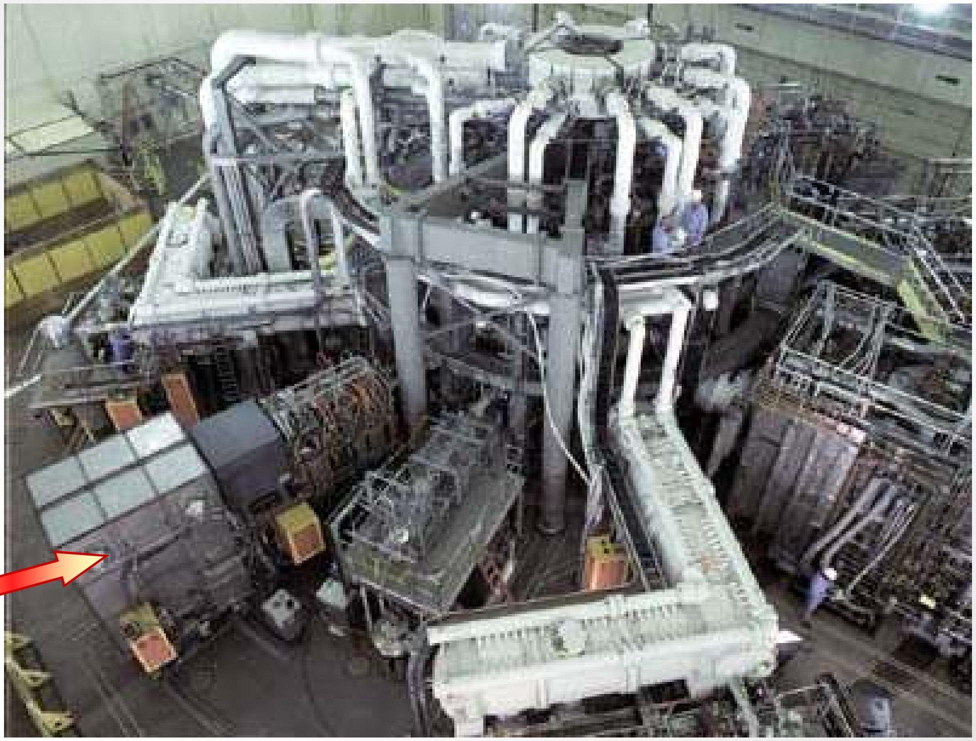
Matter in extreme conditions can be driven by intense heavy ion beams



27 mi

Beams can heat fusion plasmas in tokomaks

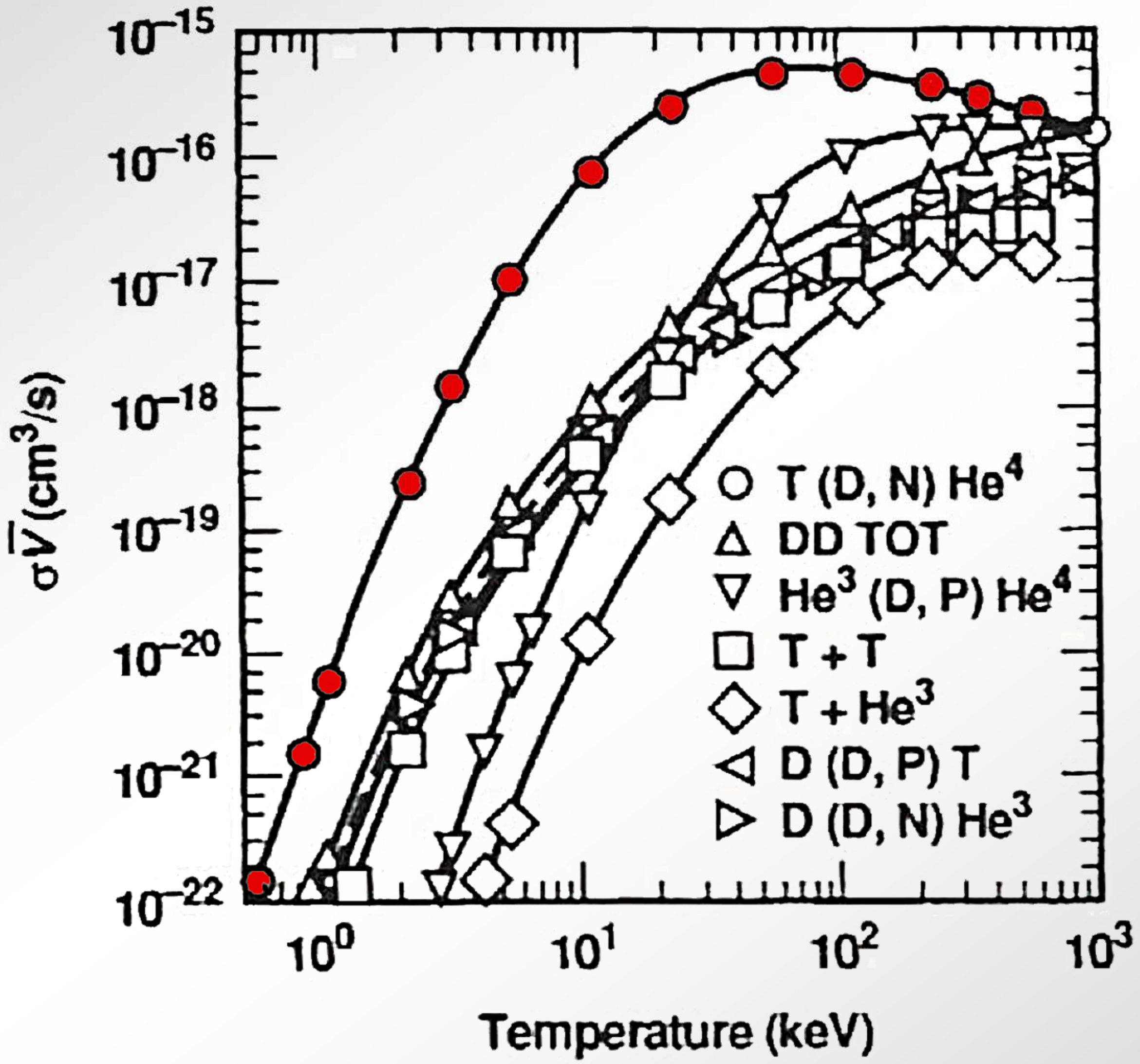
- Example: neutral beams for TFTR at Princeton



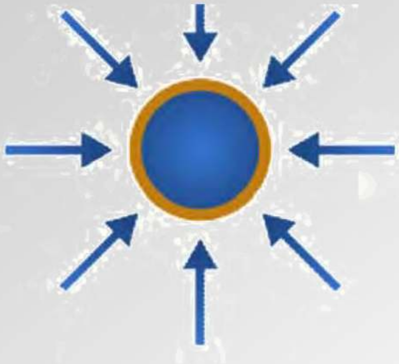
Neutral beam injectors

- ITER will require 60 MW of neutral beam heaters

Thermonuclear reaction rates



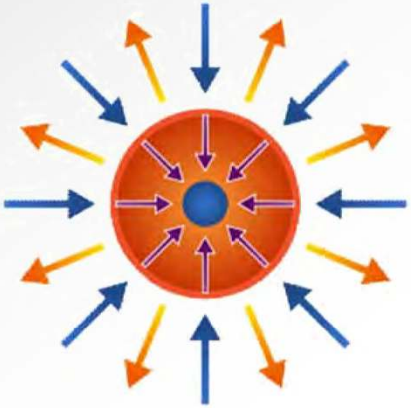
How accelerators can produce fusion power



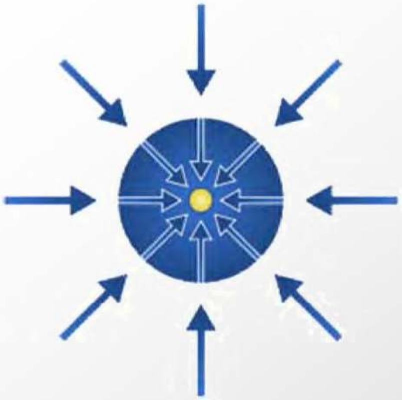
input energy quickly heats surface of fuel capsule

~10mg DT
$\rho \sim 0.5$ mg/cm^3
(ρ-r 0.03-3 g/cm^2)

Compression ratio up to 30:1



fuel is compressed isentropically by rocket-like blowoff of hot surface material



compressed fuel core ("hotspot") reaches density and temperature needed for ignition

ρ ~100 g/cm^3 (hotspot)
T ~ 5-12 keV
(ρ-r ~ 0.2-0.5 g/cm^2)

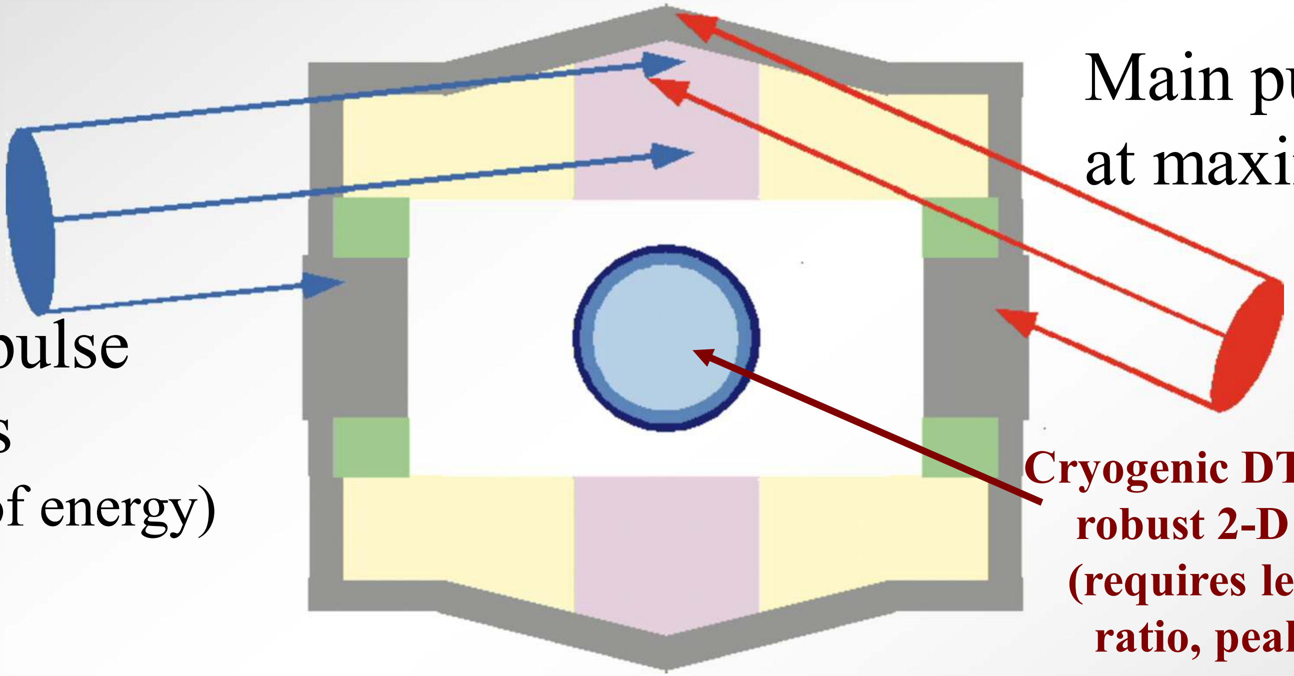
ρ ~400-800 g/cm^3 (fuel)
T << 5 keV

thermonuclear burn spreads quickly through compressed fuel

0.5-2 GJ
~50ps

Source: W. Sharp

Indirect drive: Target design is a variation of the distributed radiator target (DRT)



Main pulse beams at maximum angle

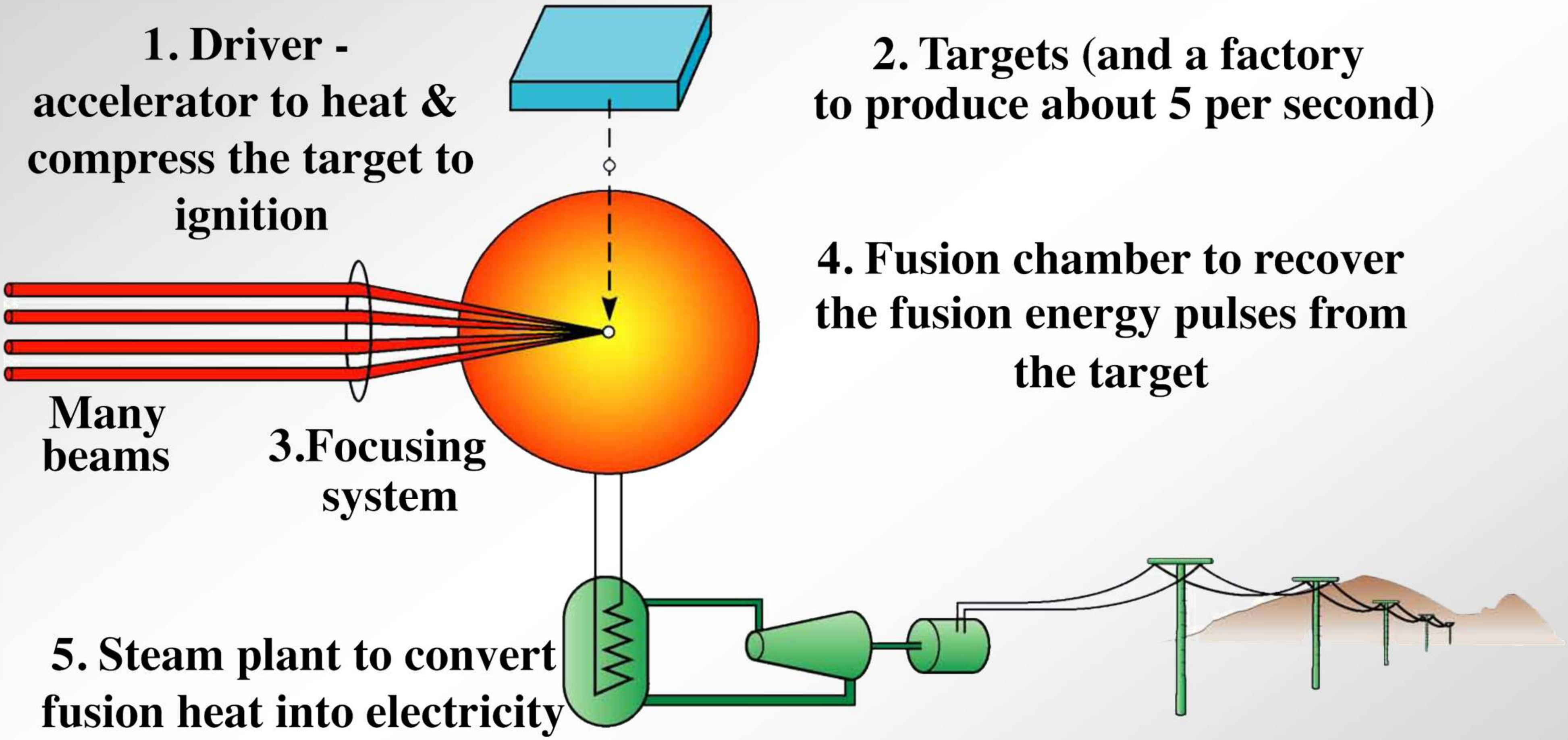
Foot pulse beams
(40% of energy)

Cryogenic DT fuel capsule has robust 2-D hydrostability (requires less convergence ratio, peak density, and ablator/ice smoothness than NIF)

New design allows beams to come in from larger angle, ~ 24° off axis.

Yield = 400 MJ, Gain = 57 at $E_{driver} = 7$ *MJ*

The inertial fusion power plant



1. Driver - accelerator to heat & compress the target to ignition

2. Targets (and a factory to produce about 5 per second)

Many beams

3.Focusing system

4. Fusion chamber to recover the fusion energy pulses from the target

5. Steam plant to convert fusion heat into electricity

Beam requirements for HIF

- Representative set of parameters for indirect-drive targets
  - ~ 5 Megajoules of beam energy
  - ~500 Terawatts of beam power ==> tens of kA
  - beam pulse length ~ 10 ns
  - range 0.02 - 0.2 g/cm^2
  - focus such a large beam to a spot of ~1-5 mm radius
  - desired focal length ~6 m (maximum chamber size
- Basic requirements ==> certain design choices
  - parallel acceleration of multiple beams
  - acceleration of needed charge in a single beam is uneconomical
  - emittance required to focus single large beam extremely difficult

Requires a new class of accelerator

The new radiation science:
The Ultra-fast & Ultra-bright

"Big Questions "

Can we image single molecules?

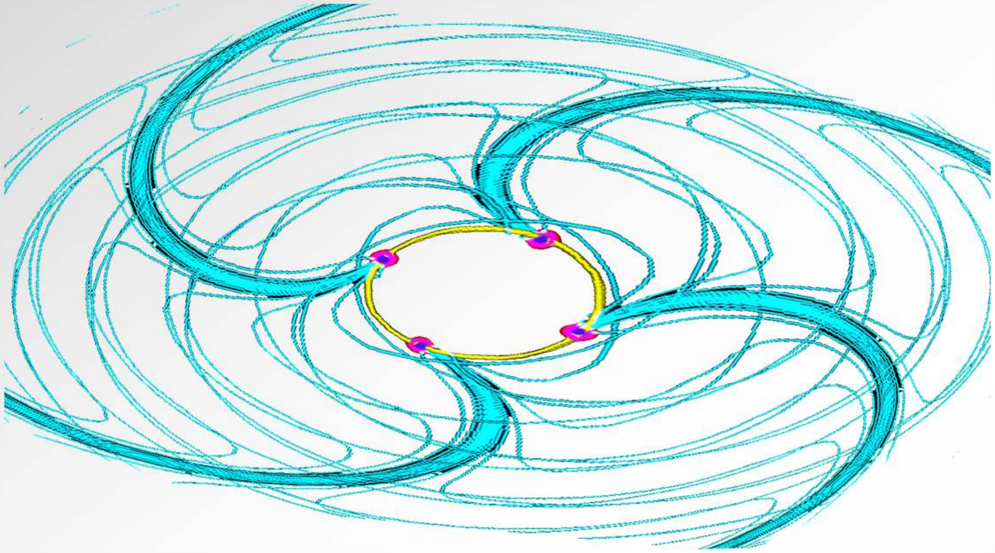
Can we make molecular movies of chemical reactions?

Can we "stop electrons in their tracks"?

Synchrotron radiation science
(~ 70 facilities world-wide)

Synchrotron light source

Calculated electric field lines from 4 bunches in circular orbit



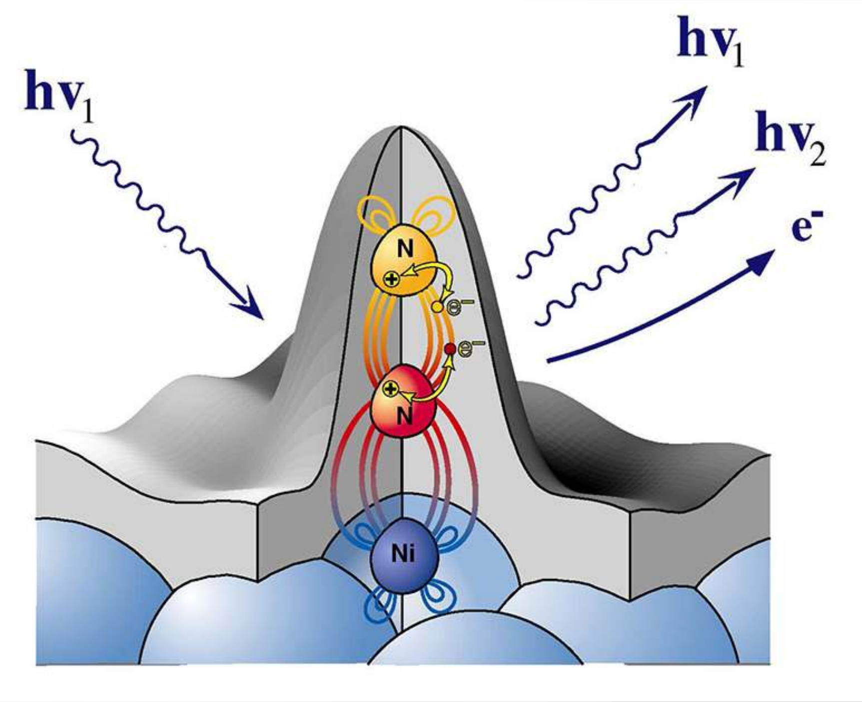
In practice the vacuum chamber cuts out all but the 1/γ cone

FOM: Brilliance v. λ

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

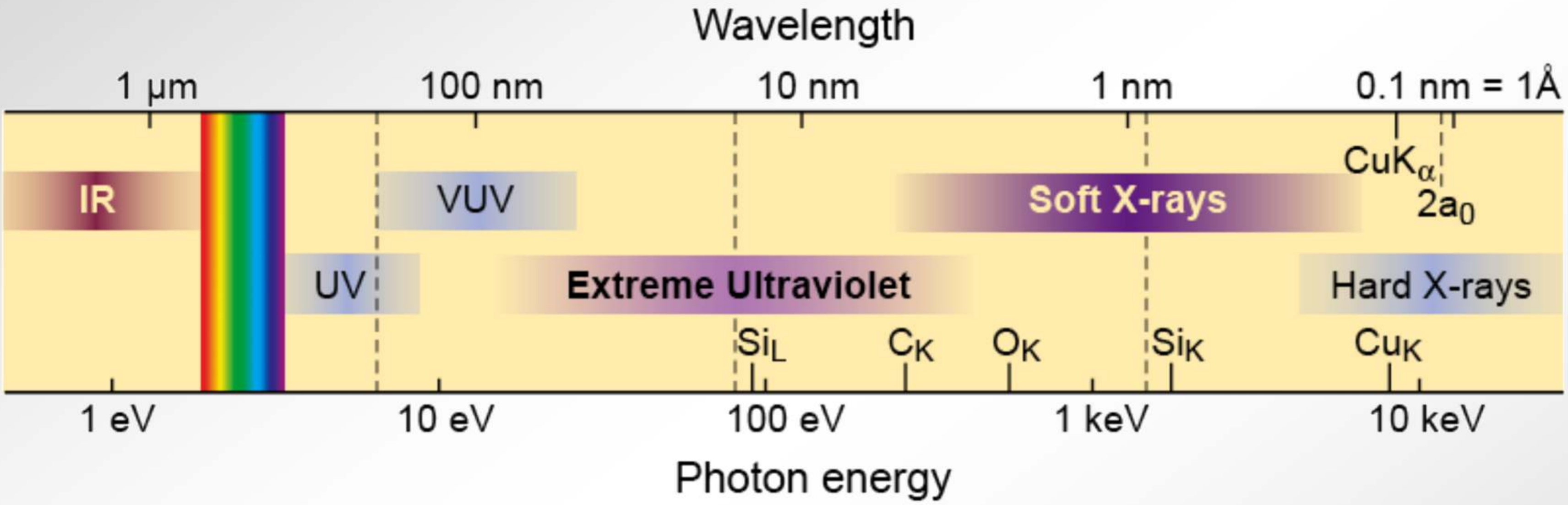
☐ Science with X-rays

- Microscopy
- Spectroscopy



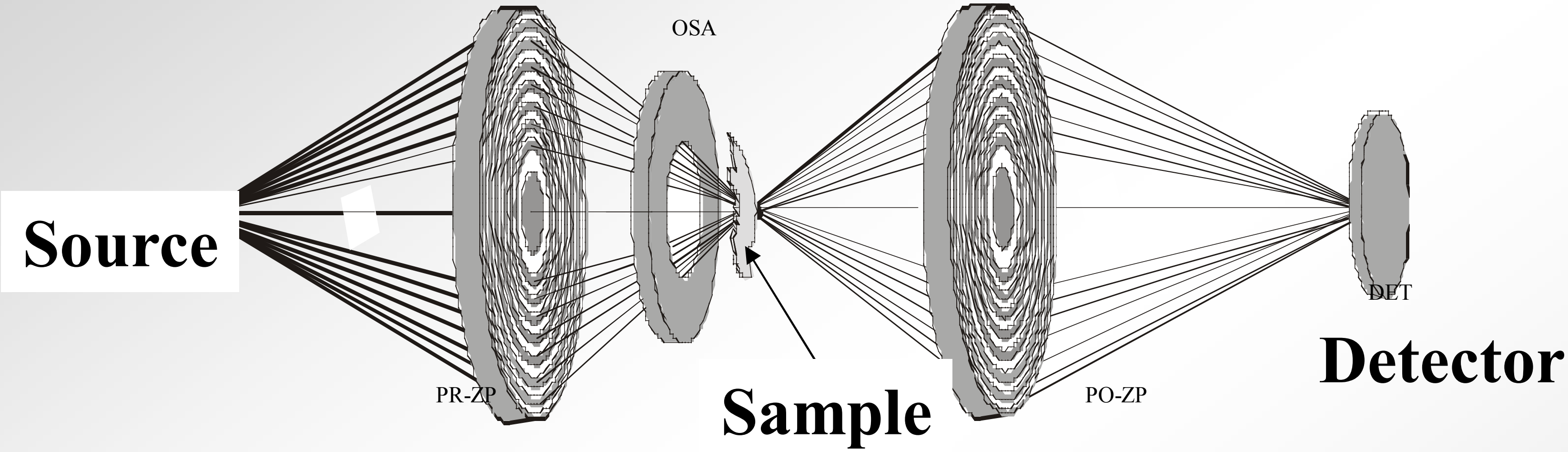
These facilities enable fixed target experiments with photons

Spectrum available using SR



- **See smaller features**
- **Write smaller patterns**
- **Elemental and chemical sensitivity**

Coherent Imaging:
TwinMic on BACH-ELETTRA



Source

Sample

Detector

Figure . Optical scheme of TwinMic.

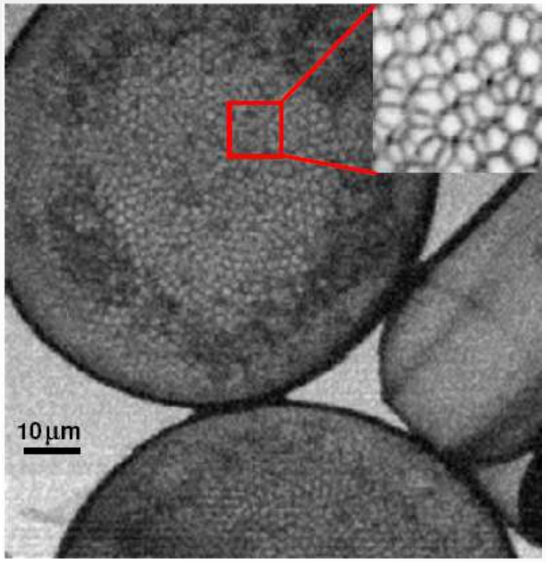


Figure 3. Scanning mode

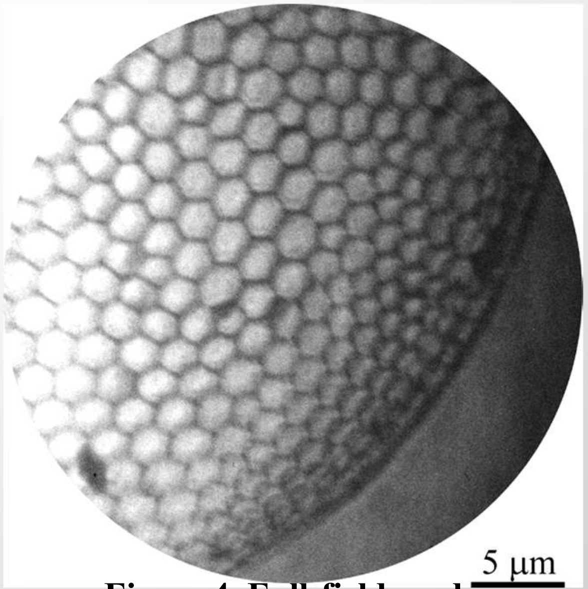


Figure 4. Full-field mode.

What Keeps Bugs from Being Bigger?

Does the tracheal system limit the size of insects?

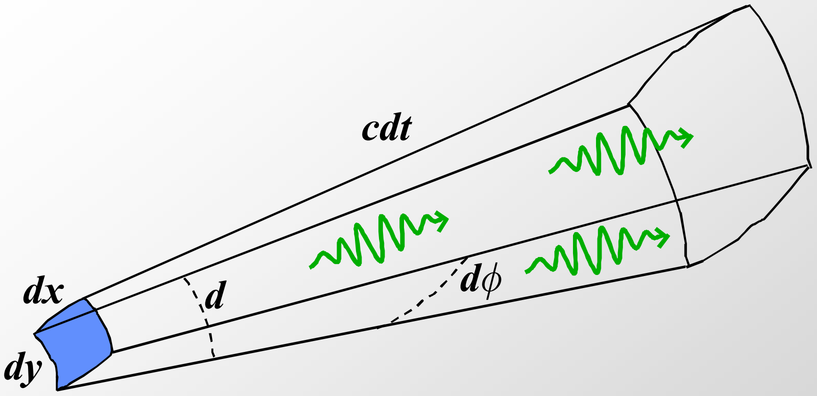
Research* at the Argonne Advanced Photon Source (APS) explains what limits size in beetles: the constriction of tracheal tubes leading to legs.

* 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).

Brightness of a Light Source

- Brightness is a principal characteristic of a particle source
  - Density of particle in the 6-D phase space
- Same definition applies to photon beams
  - Photons are bosons & the Pauli exclusion principle does not apply
  - Quantum mechanics does not limit achievable photon brightness

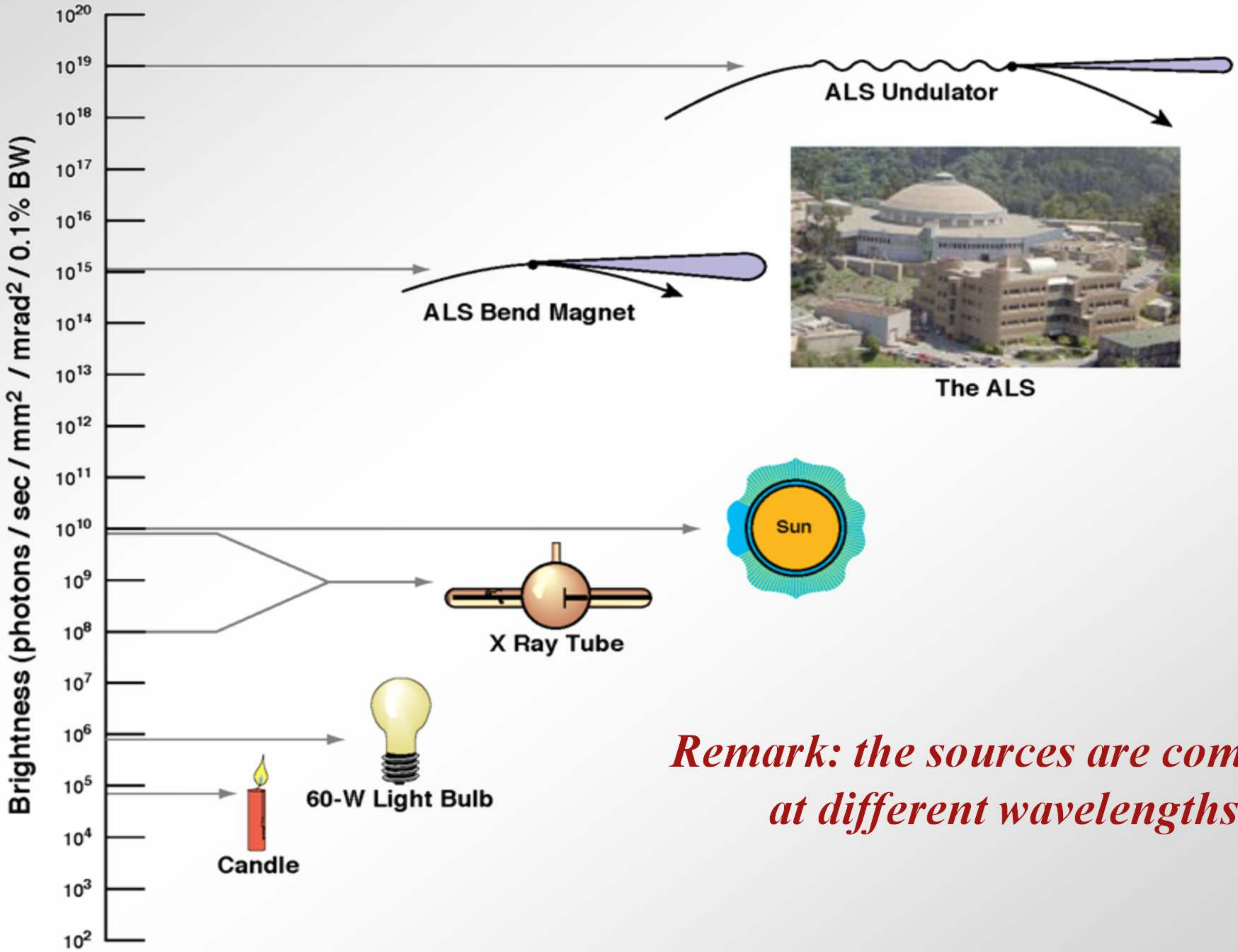
$$\textbf{Brightness} = \frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$$



$$\textbf{Flux} = \frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec}}$$

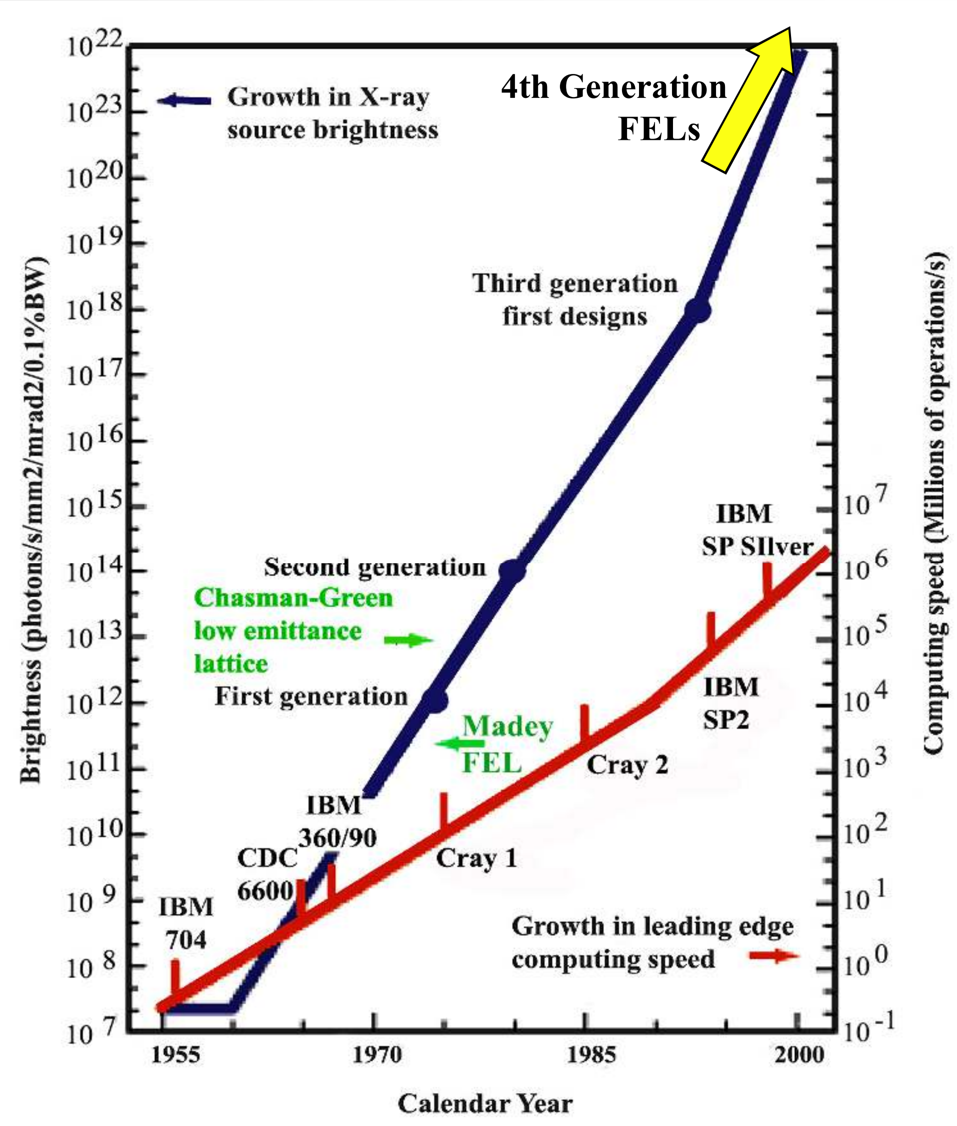
$$Flux = \frac{dN}{d\lambda} = \int Brightness\, dS\, d\Omega$$

How bright is a synchrotron light source?



Remark: the sources are compared at different wavelengths!

Progress in X-ray source brightness

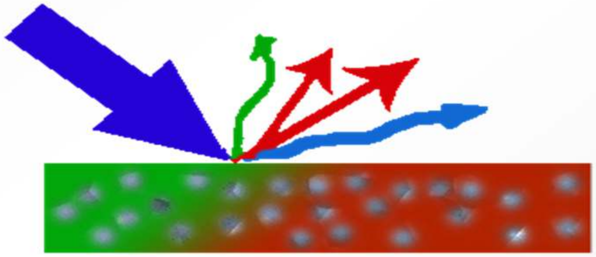


Studying ultra-fast processes requires another great invention: FEL

Grand challenge science with X-rays

Two general modes of experiments

- Image molecular structures with *atomic resolution*
  - "Diffract before destroy"
- Unprecedented studies of dynamics parameters combining spectroscopy & diffraction using X–rays
  - Typically "pump-probe"



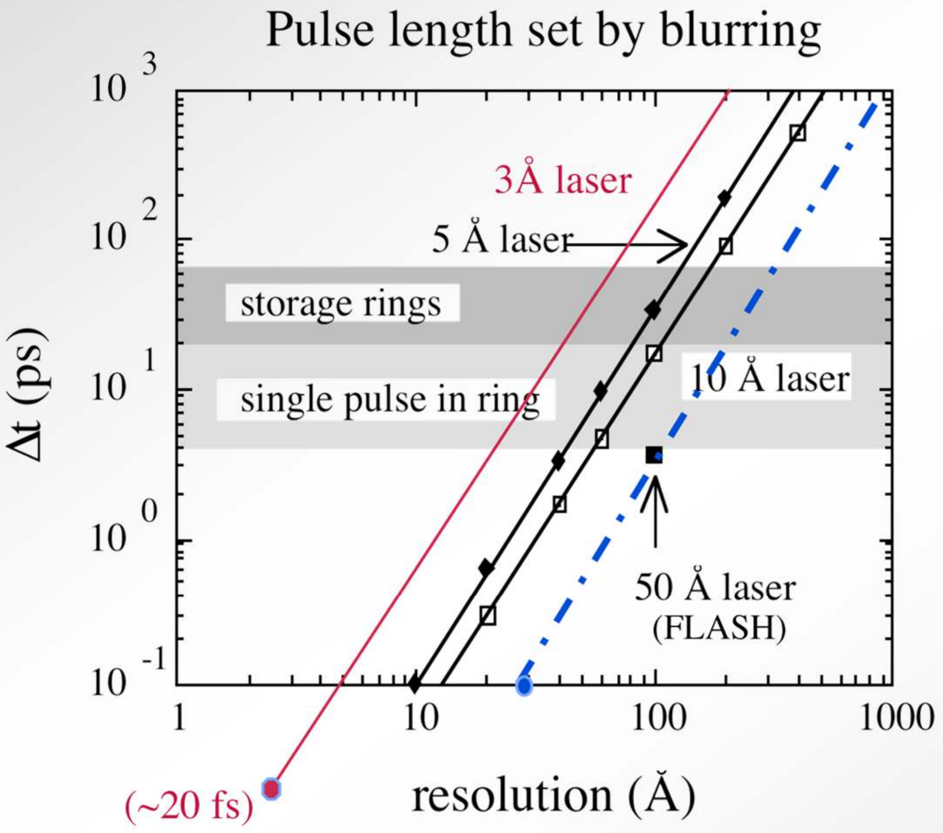
Figures of Merit:

Brilliance v. λ (B = ph/s/mm^2/mrad^2/0.1%BW)

Time structure of x-ray pulses

Diffract before destroy:
Ultra-fast imaging => Sub-100 fs & >10 GW pulses

- Simple calculation of molecular imaging
  - Updated from “SLAC-lite” calculations (Barletta, 1993)


Pulse length set by blurring

(Solem model)

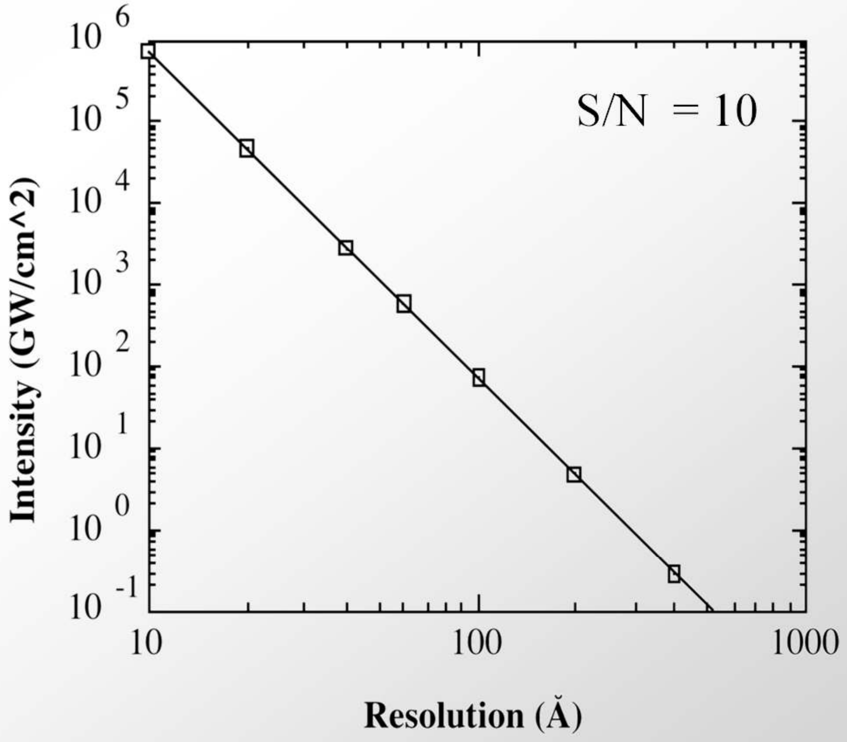
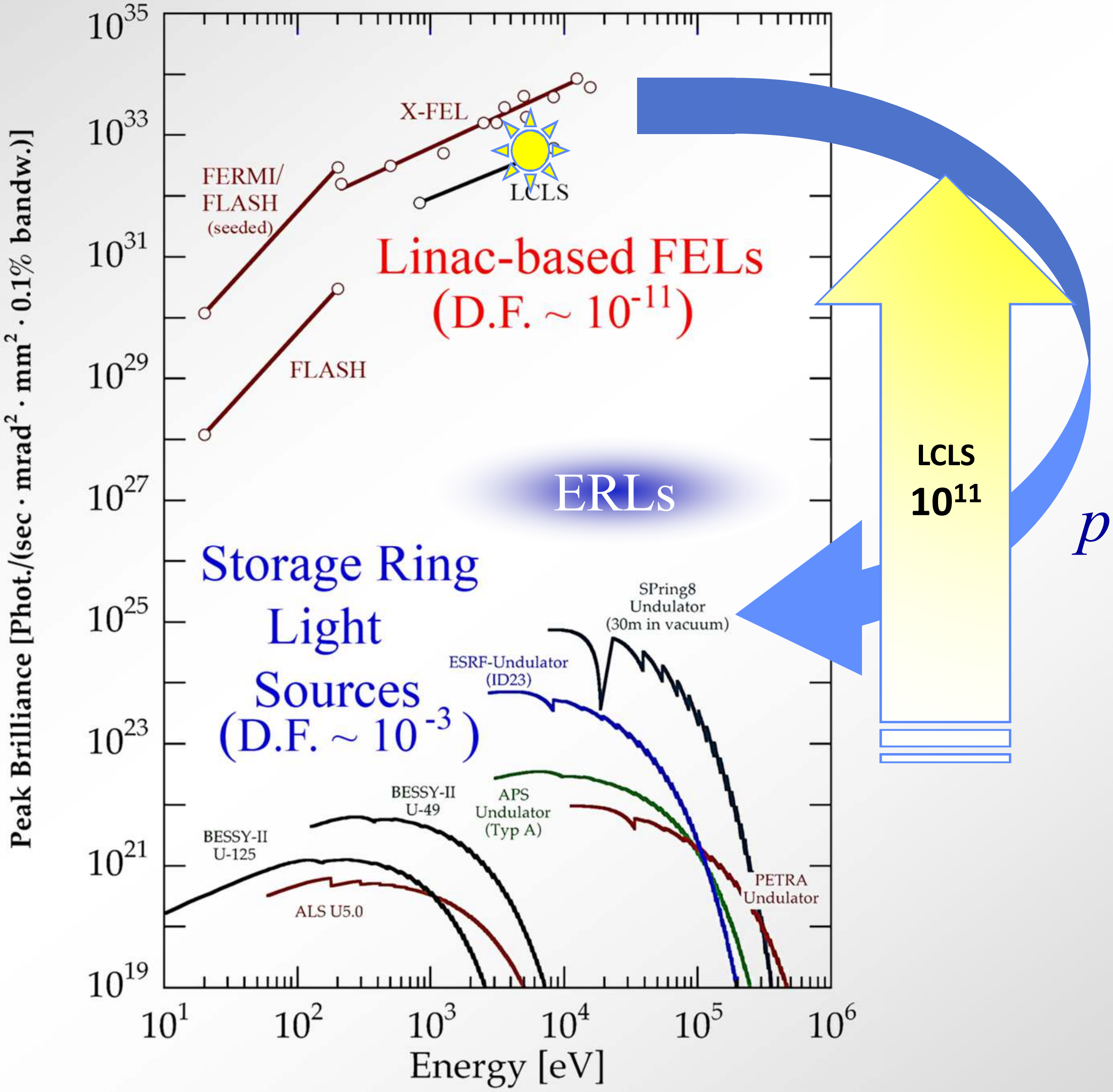


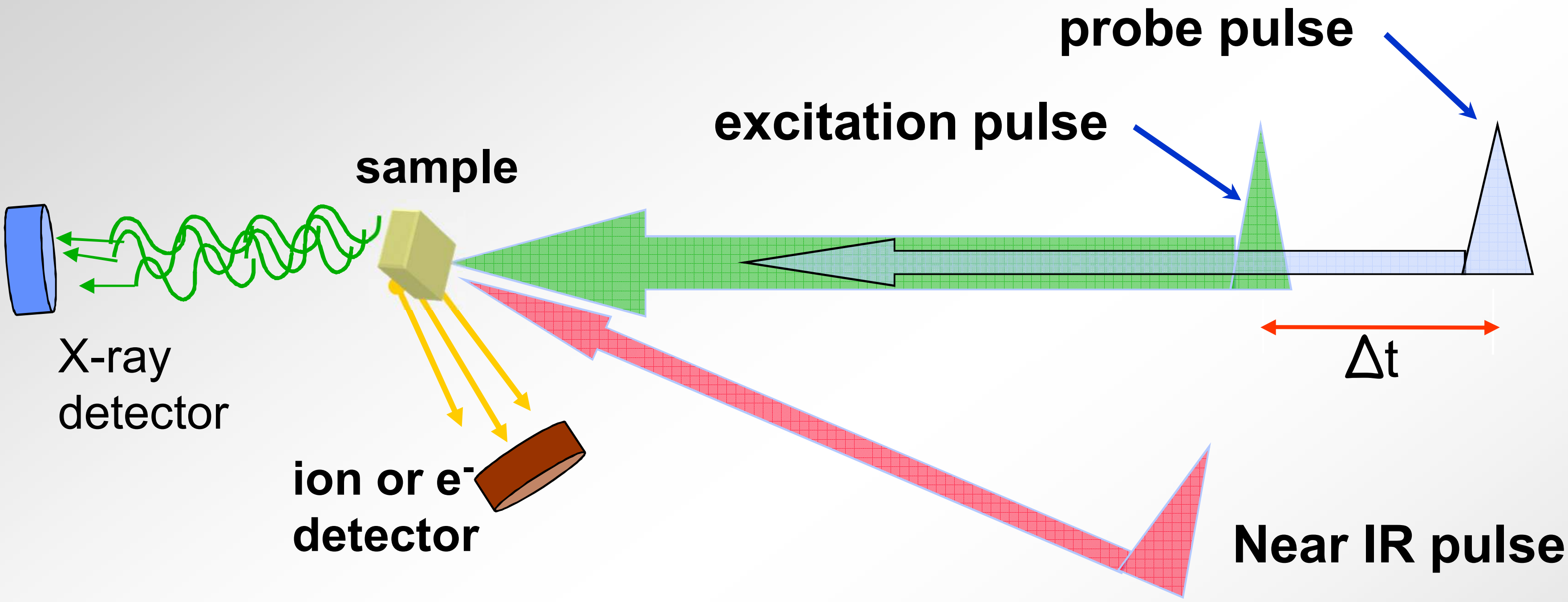
Figure of Merit:
Light source brilliance v. photon energy



Duty factor correction for pulsed linacs

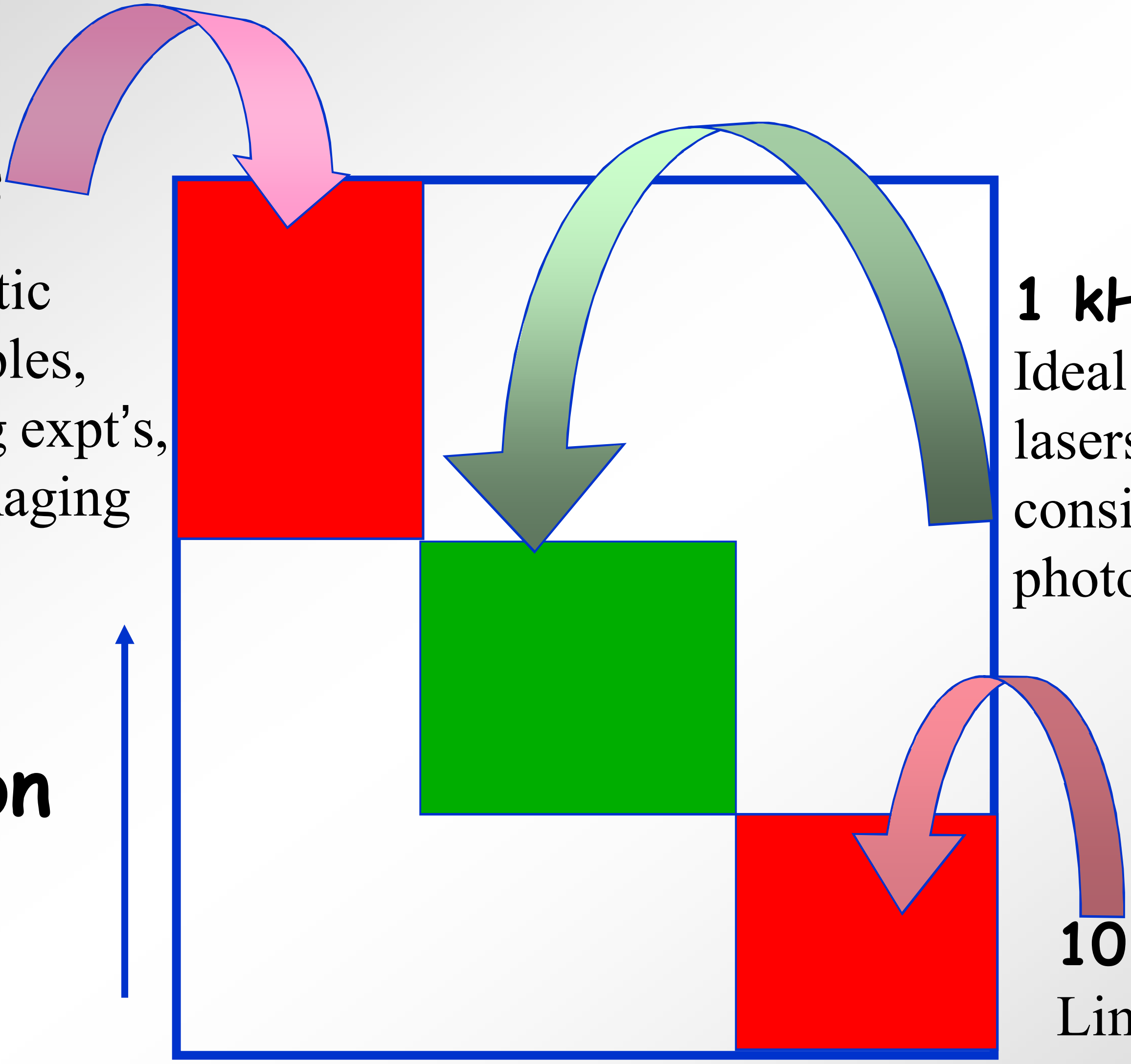
Pump-probe experiment concept

for ultra-fast science and/or imaging



- Pulses can be x-rays, VUV, electrons or ions
- Control/measure Δt with a resolution << x-ray pulse duration
  - Possibly as small as 300 attoseconds

Repetition rate vs. pulse energy



MHz-GHz, nJs

Limited by acoustic velocities in samples, good for counting expt's, photoemission imaging

1 kHz-1 MHz, μJs

Ideal match to ultrafast lasers & sample considerations, single photon regime

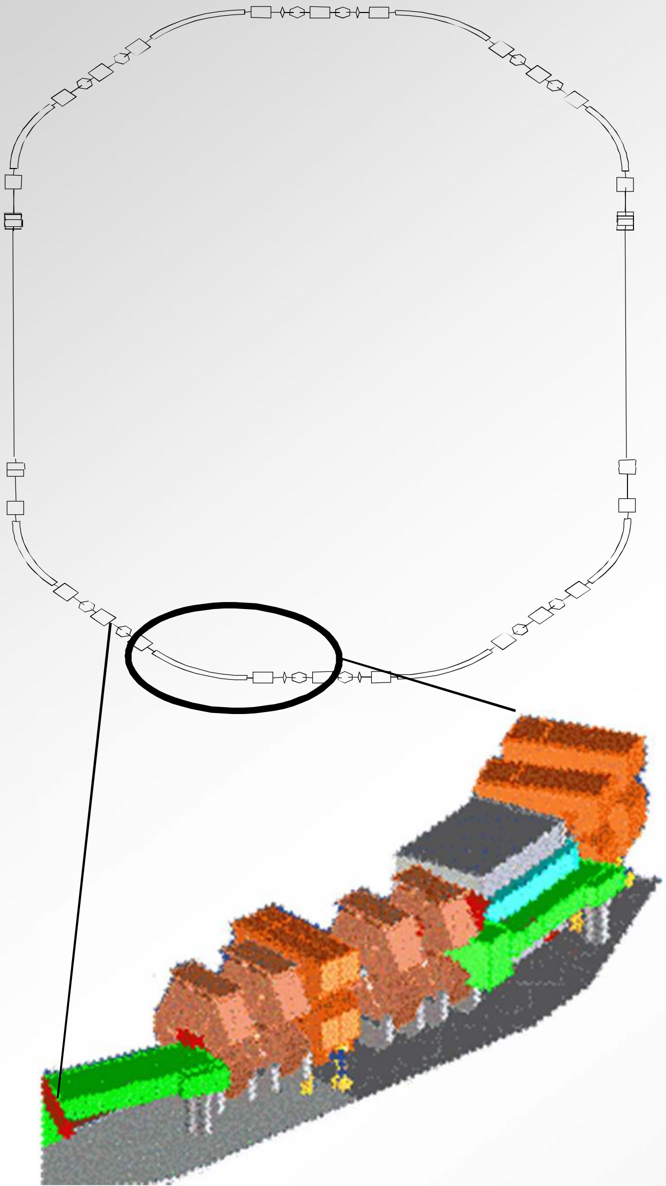
10-100Hz, mJs,

Limited by sample damage, many high field effects

Repetition rate

Pulse energy

Approach 1:
Diffraction limited storage rings



- 100 x brighter than existing rings
  - Ideal for structural studies
  - Extremely stable, Many simultaneous users

The U.S. needs a diffraction limited,

hard X-ray source to remain competitive

BUT cannot access ultra-fast processes

- Pulse length in rings (2p - 50 ps) is set by
  - Natural energy spread
  - Coherent synchrotron radiation
  - Instabilities

These effects take many revolutions
to spoil the beam

==> Discard the beam after using

Approach 2: Energy Recovery Linacs
(Hard X-rays ==> ~ 5 GeV electrons)

Synchrotron light source
(pulsed incoherent X-ray emission)

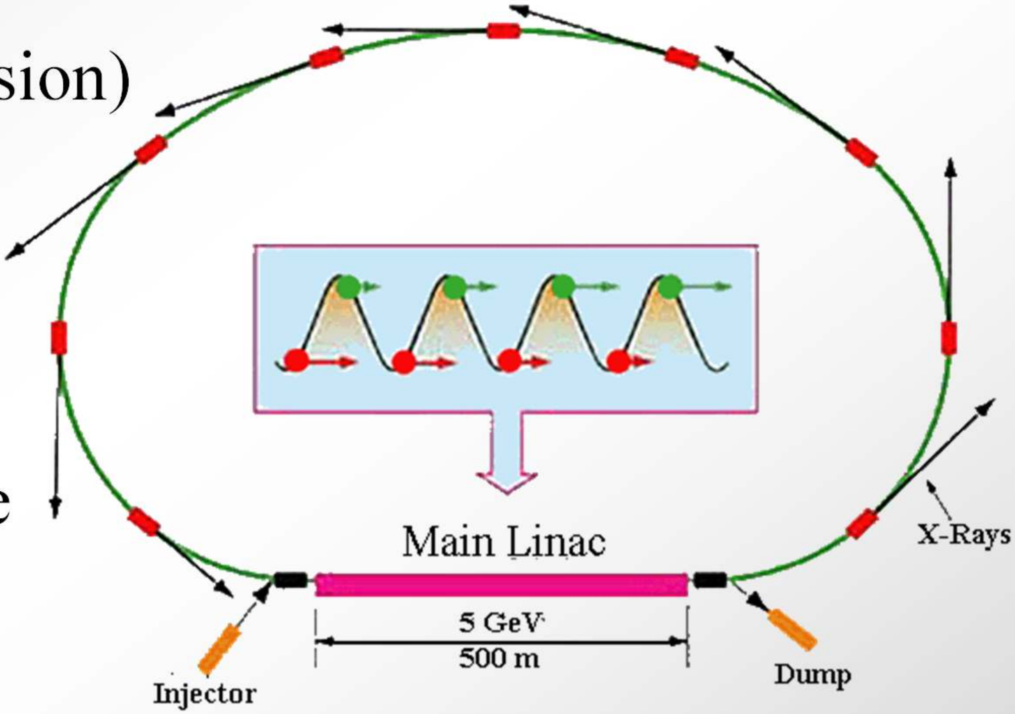
Pulse rates – kHz => MHz

X-ray pulse duration ~ 1 ps

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

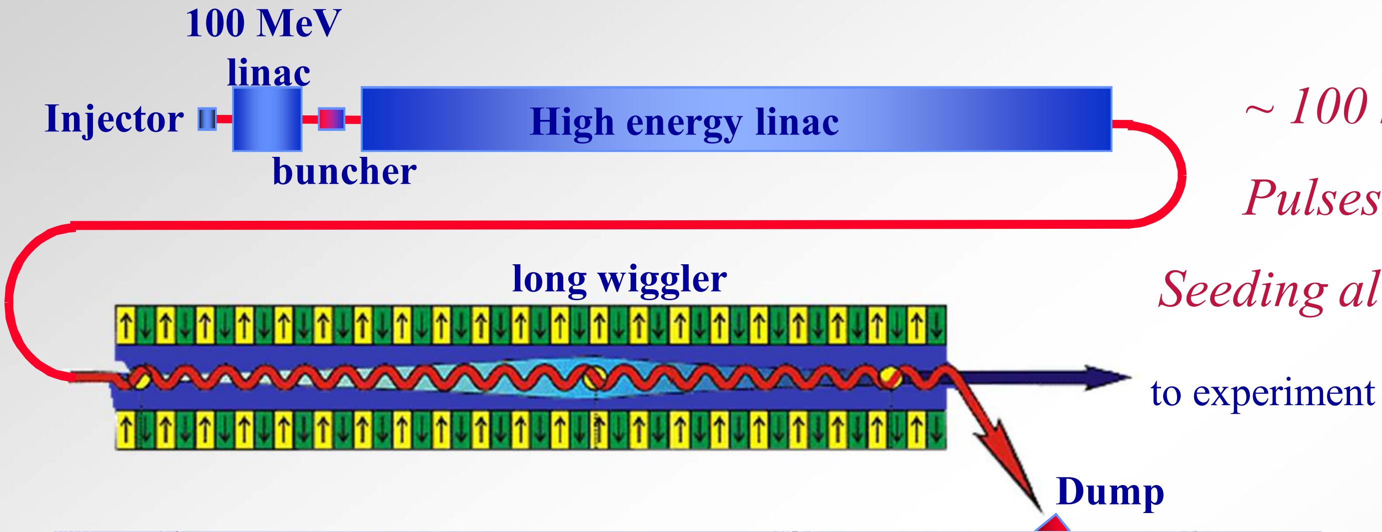
⇒ One pass through ring
⇒ Recover beam energy
⇒ High efficiency

⇒ Superconducting RF optimized for CW operation



Pulse duration & ΔE limited (> 50 fs at 0.1% bandwidth) by coherent synchrotron radiation in the arcs

Approach 3: fs pulses & highest brightness
Coherent emission ==> FEL



100 MeV linac

Injector

buncher

High energy linac

long wiggler

to experiment

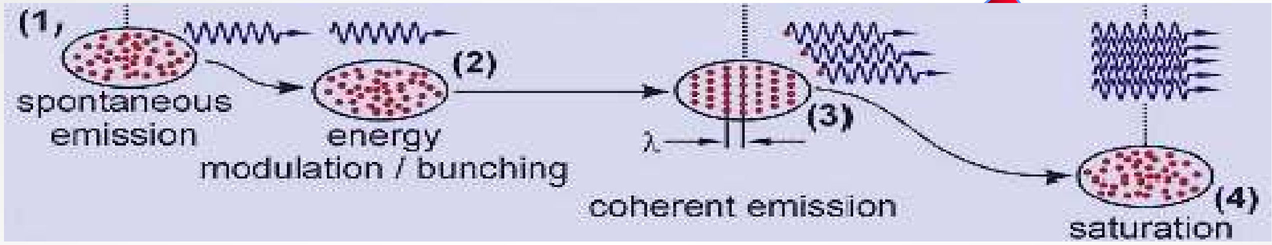
Dump

For SCRF linacs

~ 100 kHz to >1 MHz practical

Pulses length of ~ 1 fs practical

Seeding allows for full phase coherence



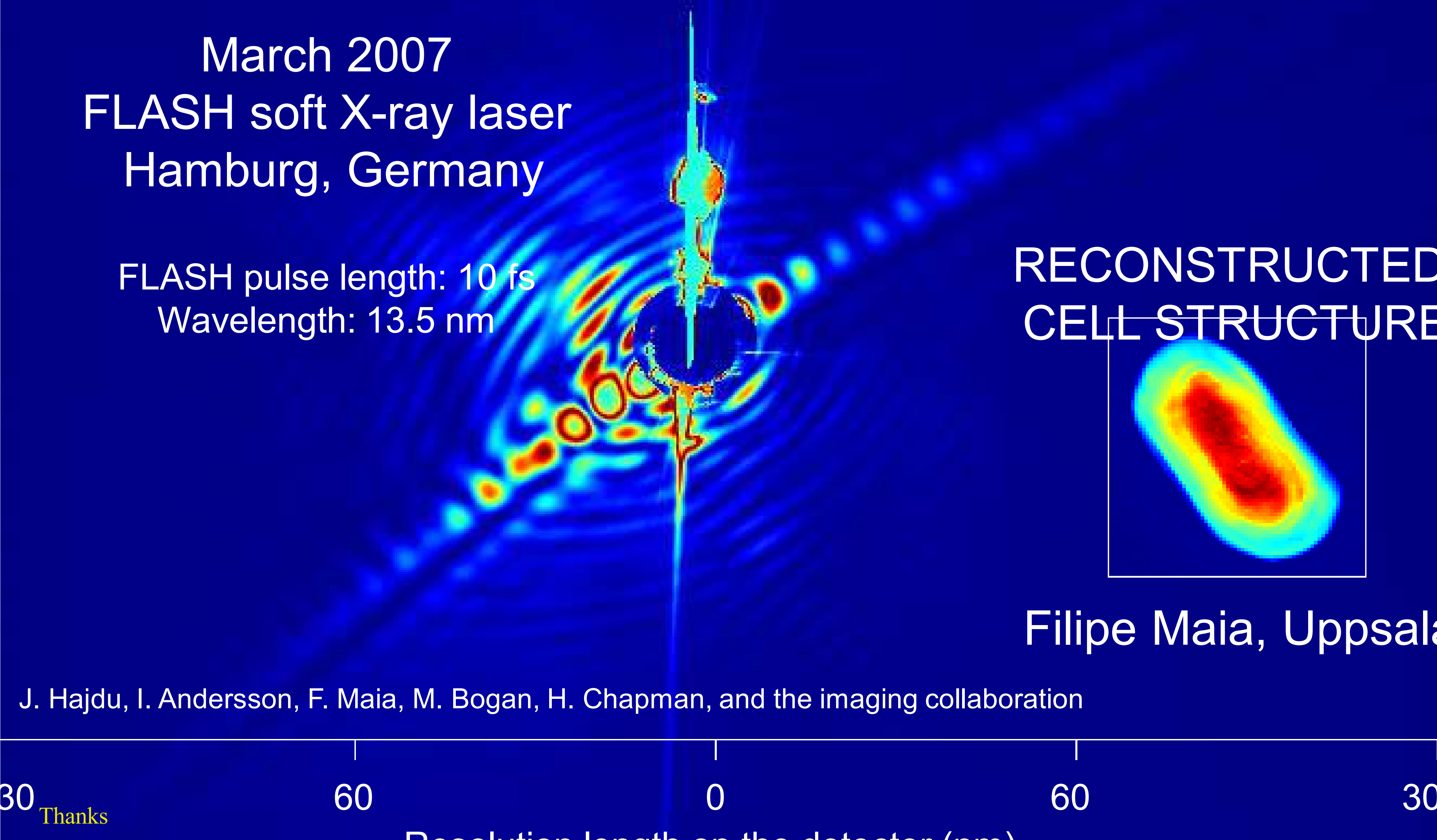
$$\rho = \frac{1}{\gamma}\left(\frac{a_w\,\omega_p}{4\,c\,k_w}\right)^{2/3} \propto \frac{I^{1/3}\,B^{2/3}\,\lambda_w^{4/3}}{\gamma}$$

High rep rate FEL meets the challenge of the "Big Questions"

IF we know how to seed the FEL

First X-ray diffraction image of a live picoplankton

(FLASH FEL in Hamburg)



March 2007
FLASH soft X-ray laser
Hamburg, Germany

FLASH pulse length: 10 fs
Wavelength: 13.5 nm

RECONSTRUCTED
CELL STRUCTURE

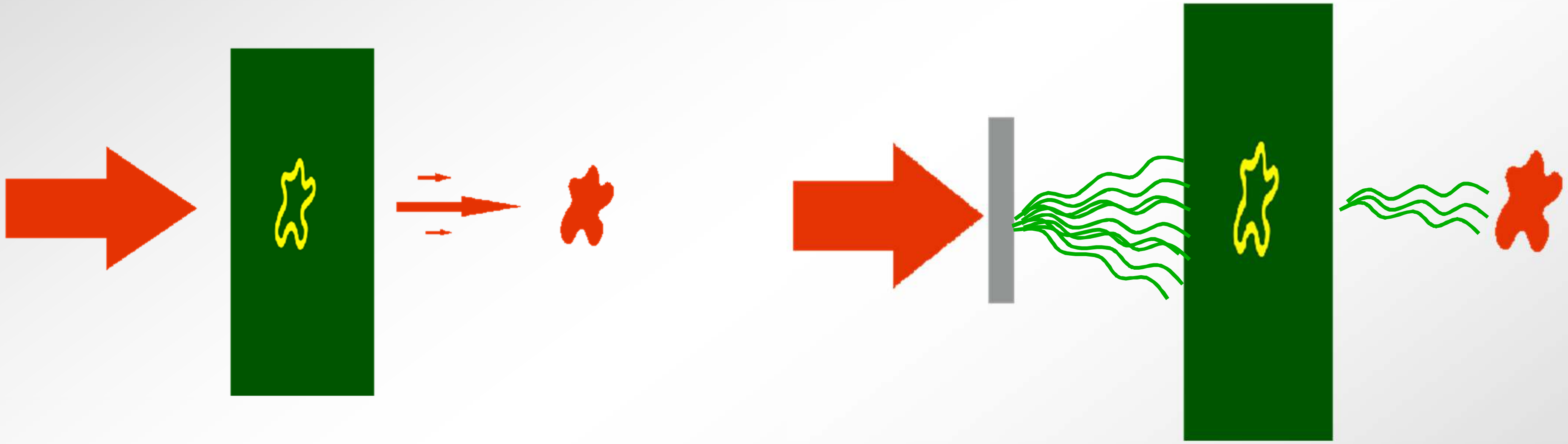
Filipe Maia, Uppsala

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

Thanks
J.Hajdu and H. Chapman

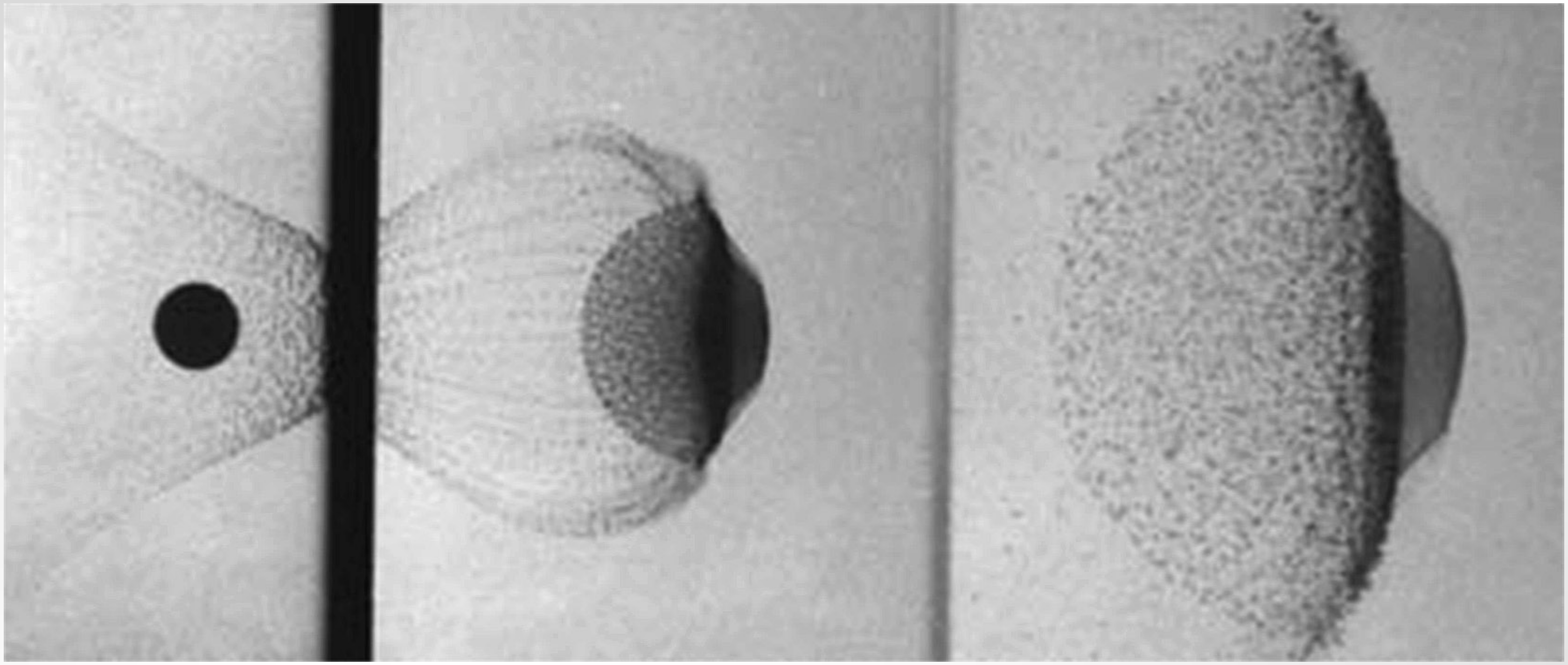
Uses of beams: looking through matter

Radiography



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

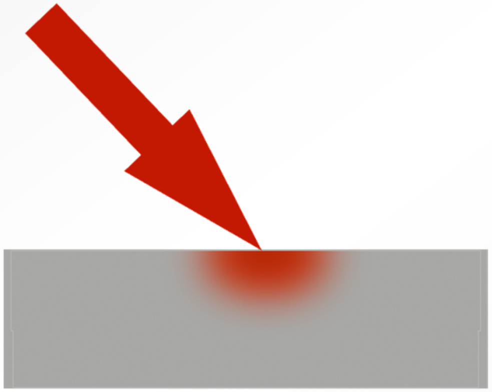
Example: Flash radiography



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

Industrial uses of beams

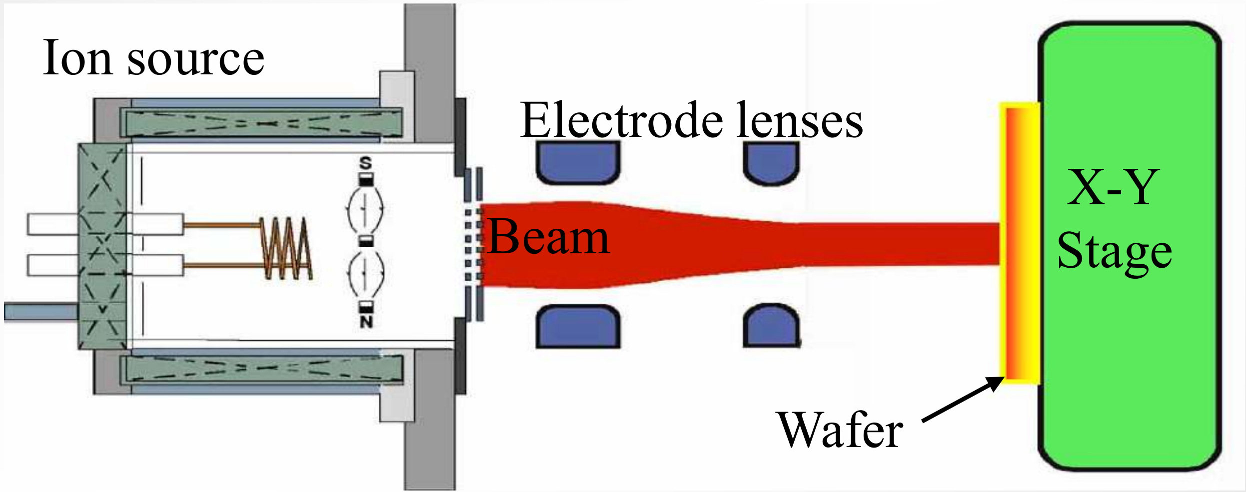


Alter matter,
induce chemistry

FOM: process time
process efficiency

Ion implantation is essential in semi-conductor production

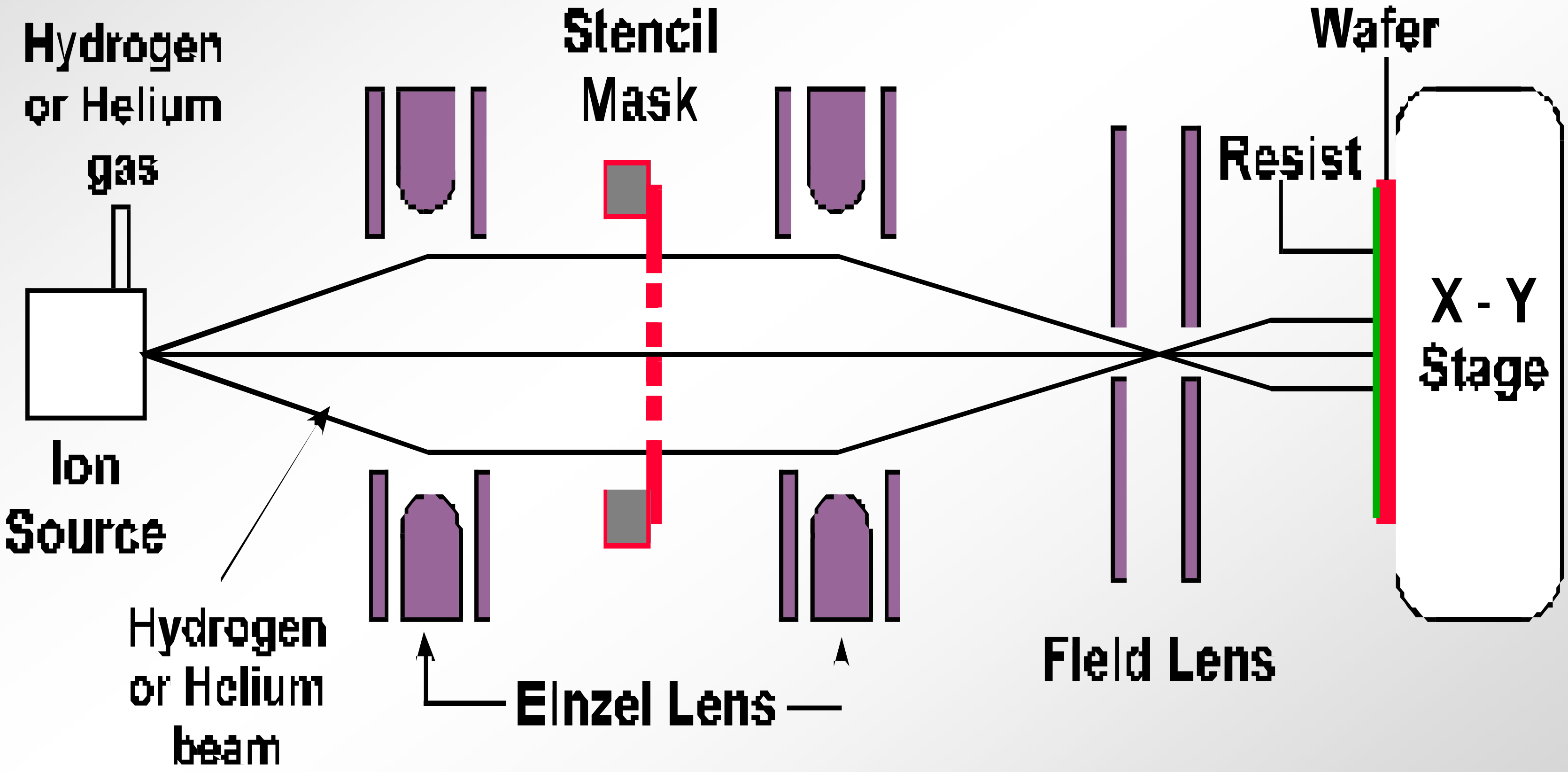
- Ions prepare Si wafers for further processing finally yielding integrated circuit chips
  - > 1 B$/year business in semi-conductor "machine tools"



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

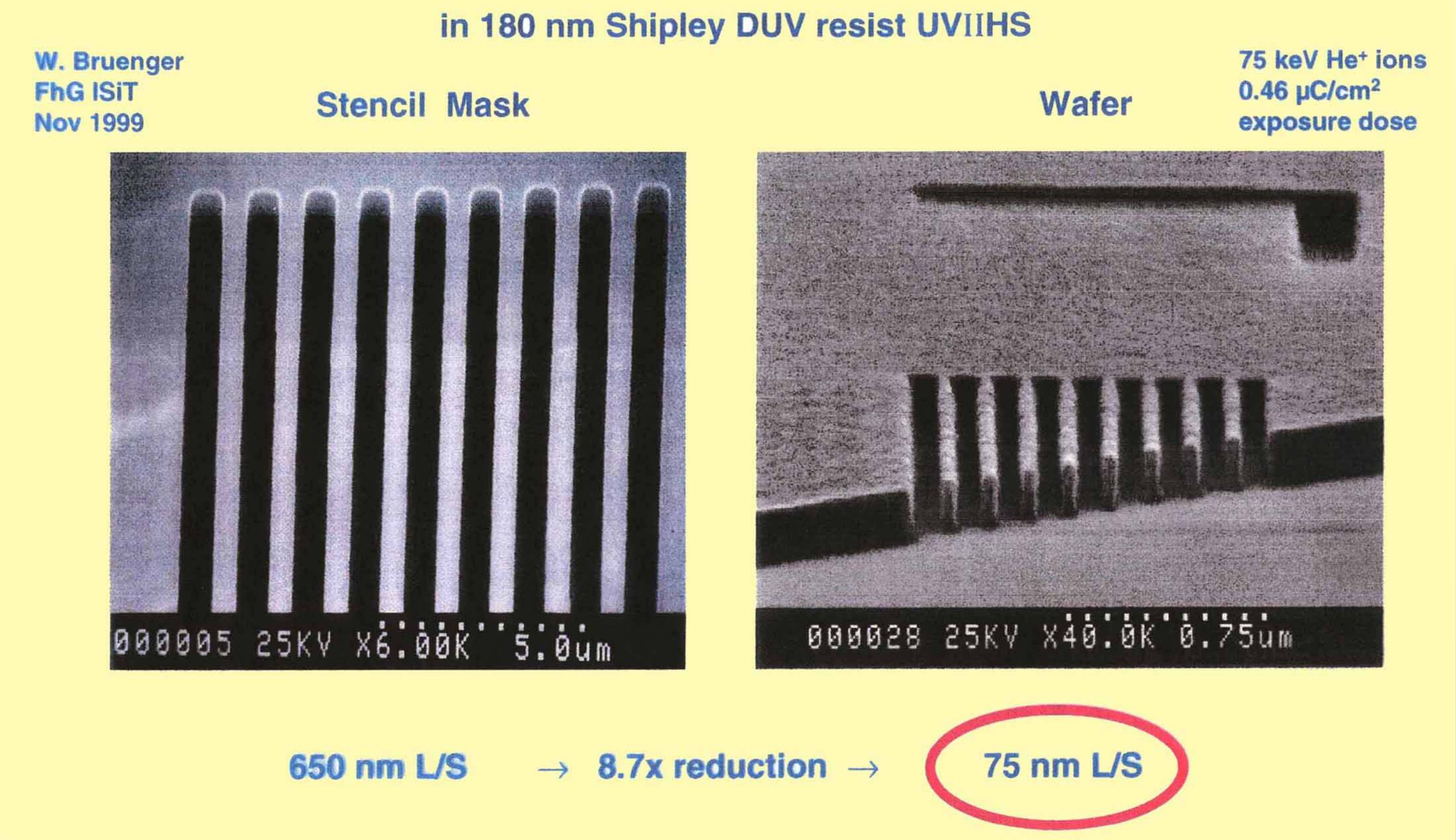
Ion Projection Lithography

- In conventional optical lithography the ion beam is replaced with a bright light source



- The Si wafer is coated with a photo-sensitive material (resist)

Future industrial applications: Ion beam lithography



in 180 nm Shipley DUV resist UVIIHS

W. Bruenger
FhG ISiT
Nov 1999

Stencil Mask

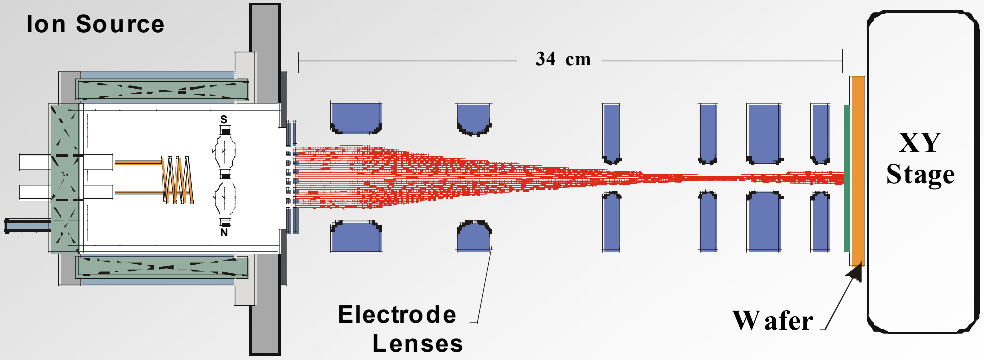
Wafer

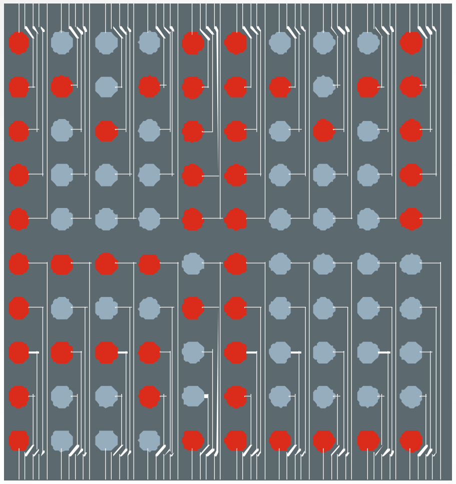
75 keV He⁺ ions
0.46 μC/cm²
exposure dose

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

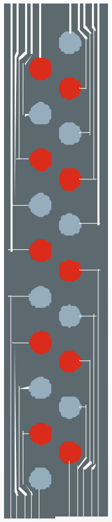
Writing with a million beams:

Maskless Micro-Beam Reduction Lithography



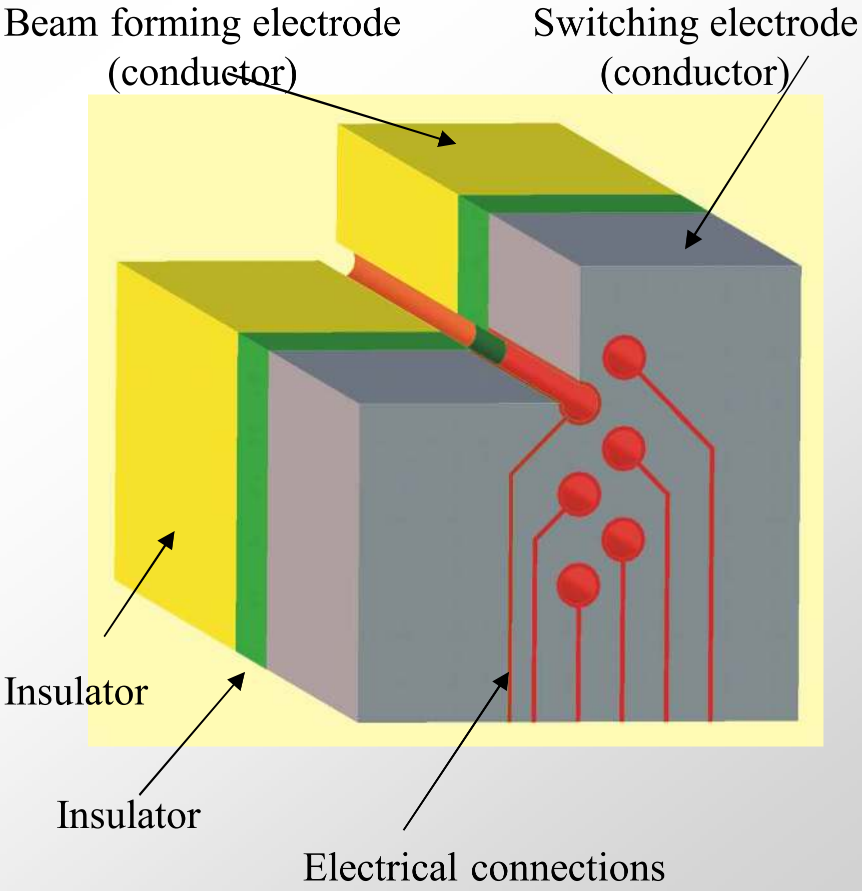


Direct projection



Projection and scanning

Universal Pattern Generator Electrode Layout



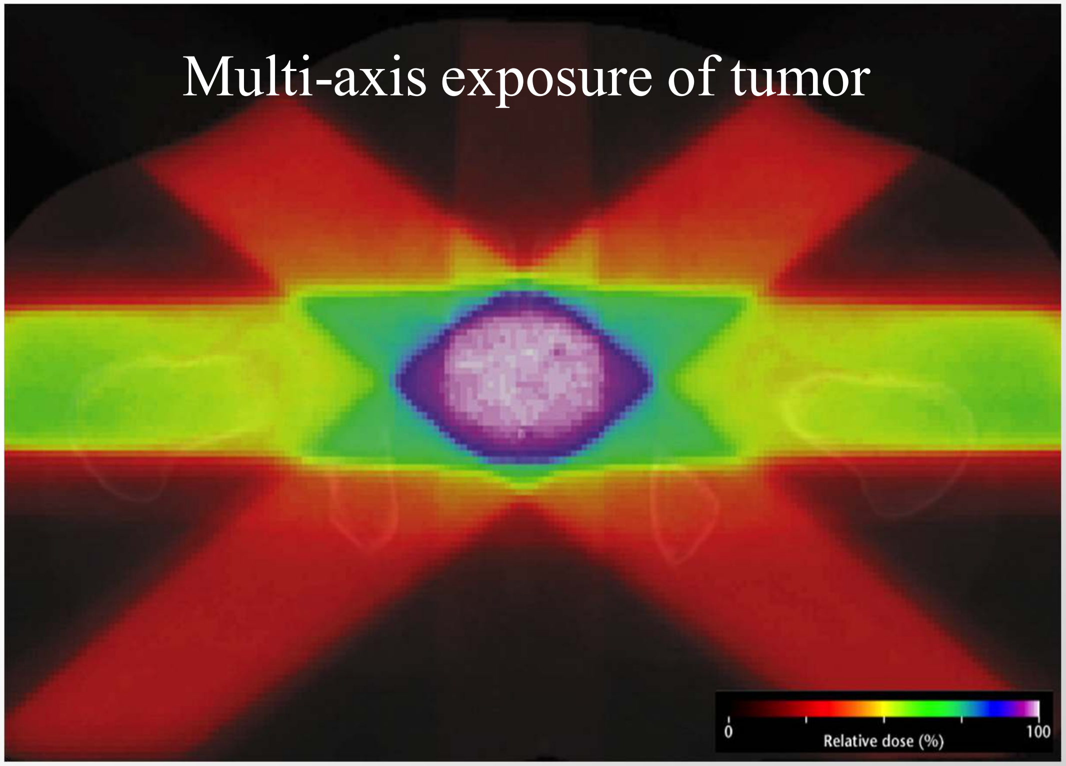
Therapeutic uses of beams

Therapy

FOM: treatment time
tumor control probability
precision beam control

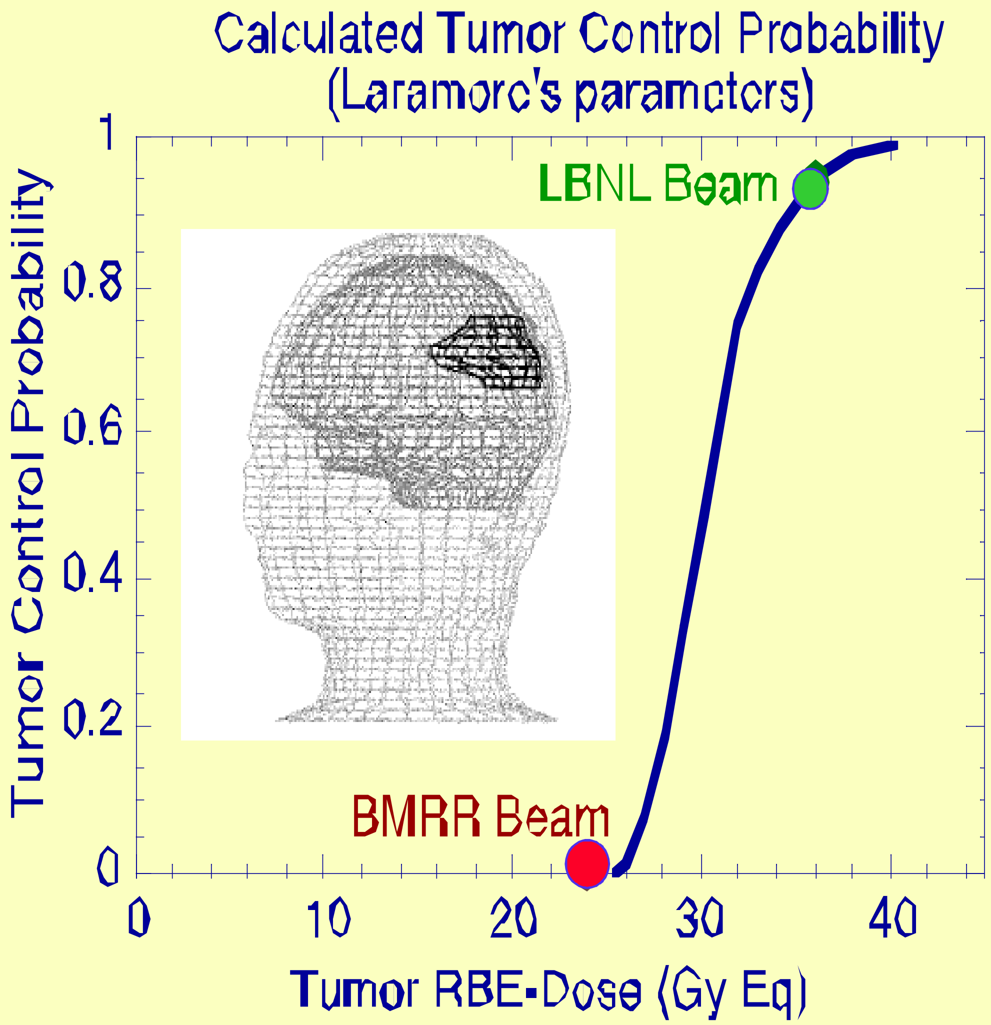
Example: Conformal therapy

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


Multi-axis exposure of tumor

Gamma rays from electron linac

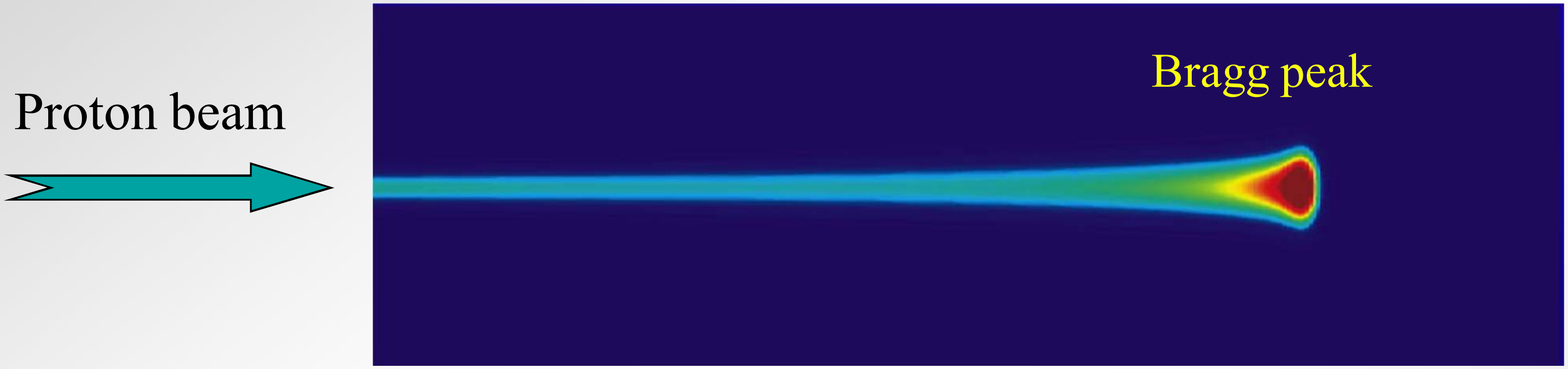
FOM - Tumor control probability



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

Tumor control with hadron beams



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

Extracts from Comments from the Office of Science

BESAC

27 February 2014

Patricia M. Dehmer
Acting Director, Office of Science
U.S. Department of Energy

Outline

- Reflections on prioritization of science & scientific facilities
- Reflections on the impact of the BESAC Report on “Future X-Ray Light Sources”

Scientific User Facilities of the Office of Science

Office of Science

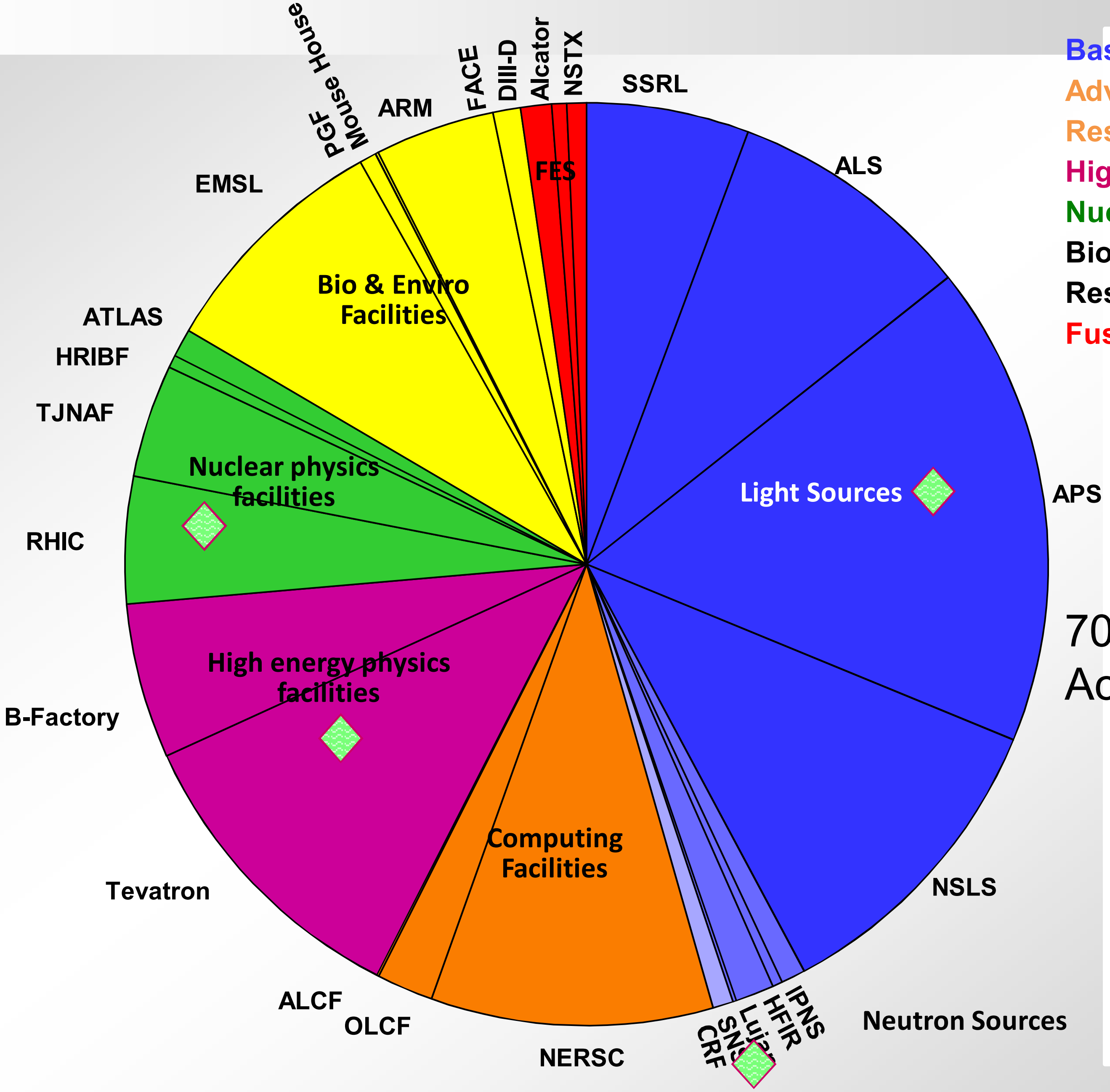
Support for Researchers

- **~22,000** Ph.D. scientists, graduate students, undergraduates, engineers, & support staff at **>300** institutions.
- **47%** of Federal support of **basic research in the physical sciences** & key components of the Nation’s basic research in biology and computing.
- Research that led to > **100 Nobel Prizes** during the past 6 decades — **>20** in the past **10** years.

Support for Scientific User Facilities

- World’s largest collection of scientific user facilities to ~28,000 users each year.

Distribution of Users at the SC Facilities 2007

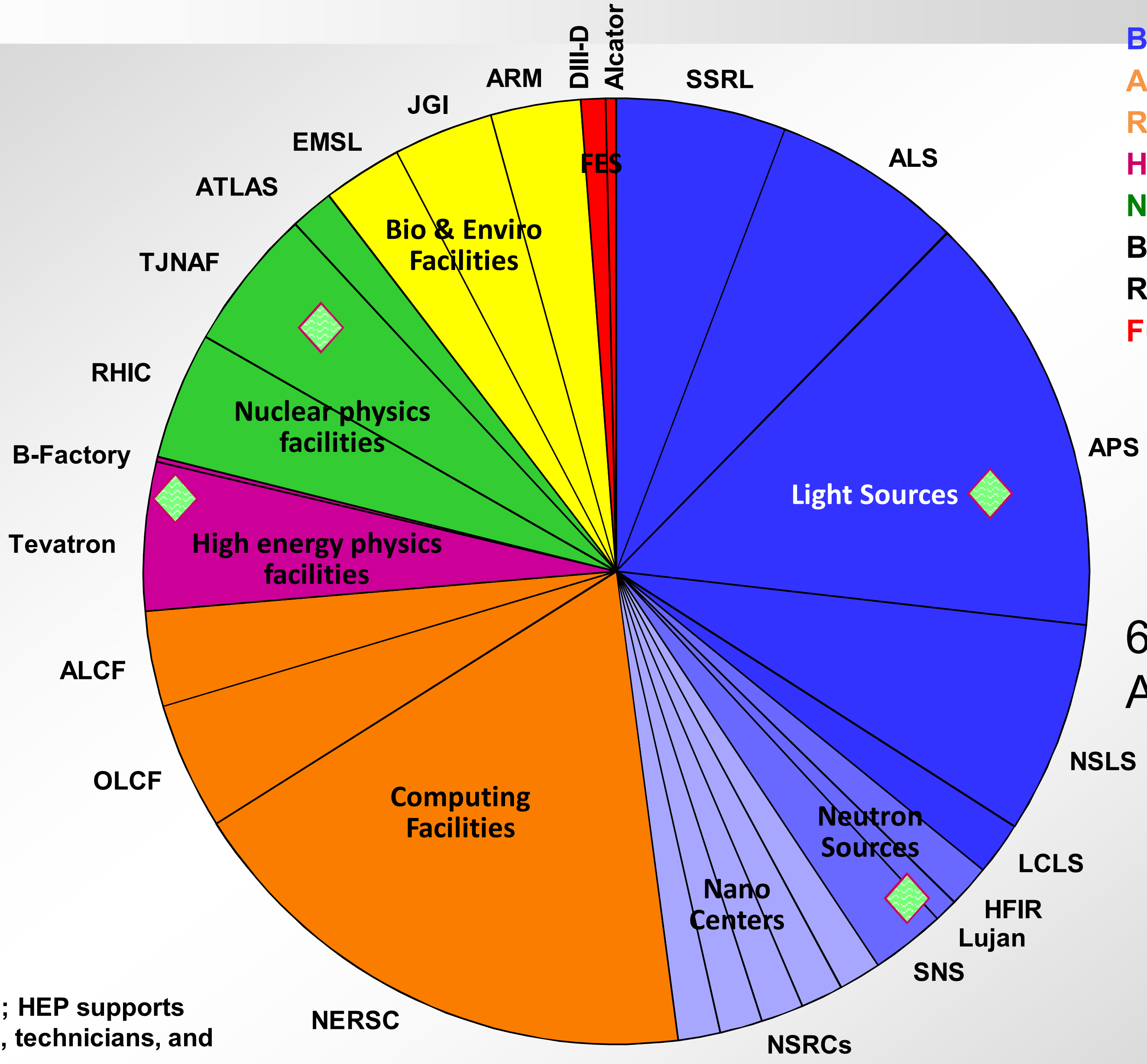


Basic Energy Sciences
Advanced Scientific Research Computing
High Energy Physics
Nuclear Physics
Biological & Environmental Research
Fusion Energy Sciences

70% used ◆ Accelerators

Distribution of Users at the ~30 SC Facilities 2013

Nearly ¾ of users do their work at ASCR or BES facilities

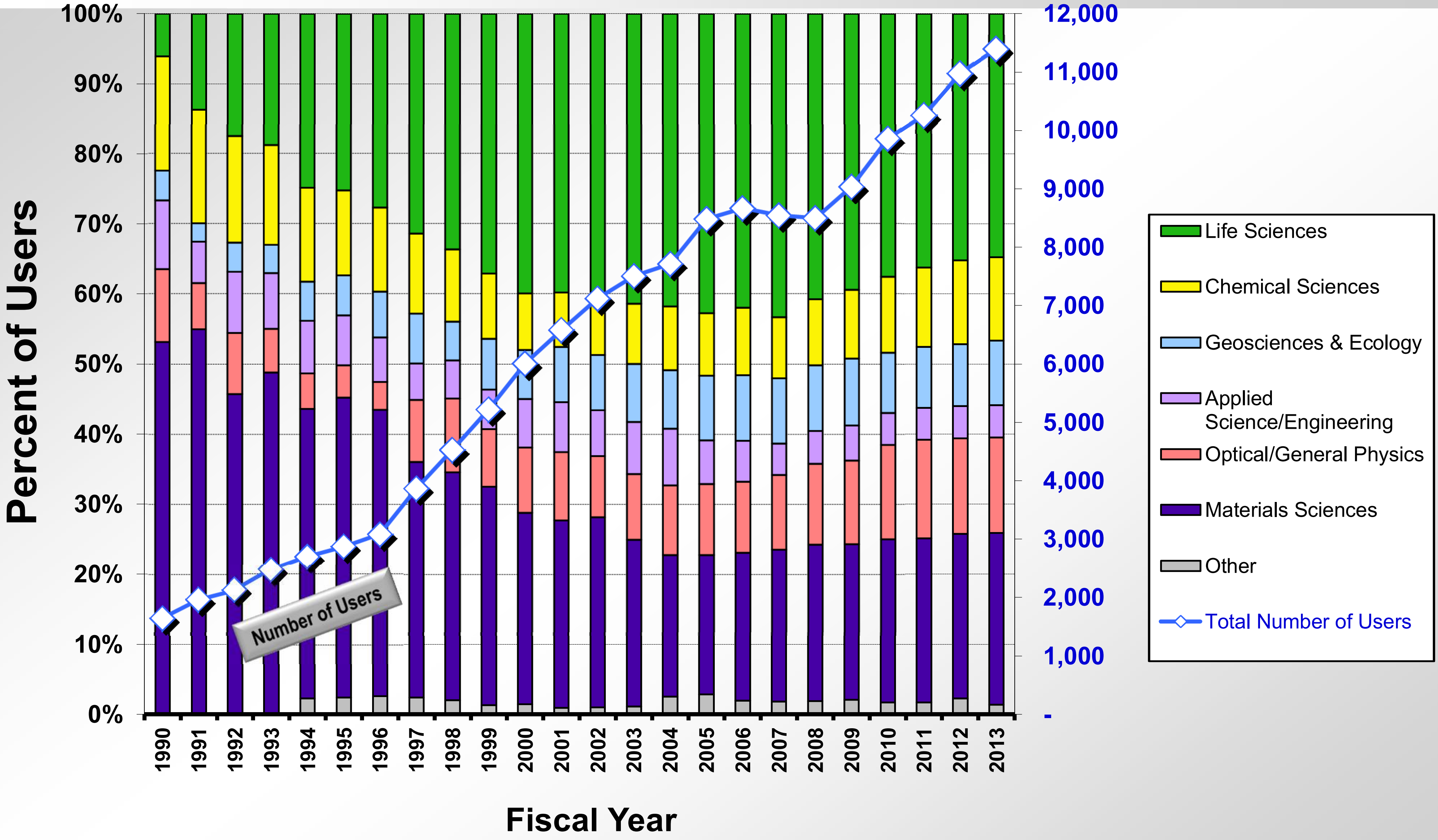


Basic Energy Sciences
Advanced Scientific Research Computing
High Energy Physics
Nuclear Physics
Biological & Environmental Research
Fusion Energy Sciences

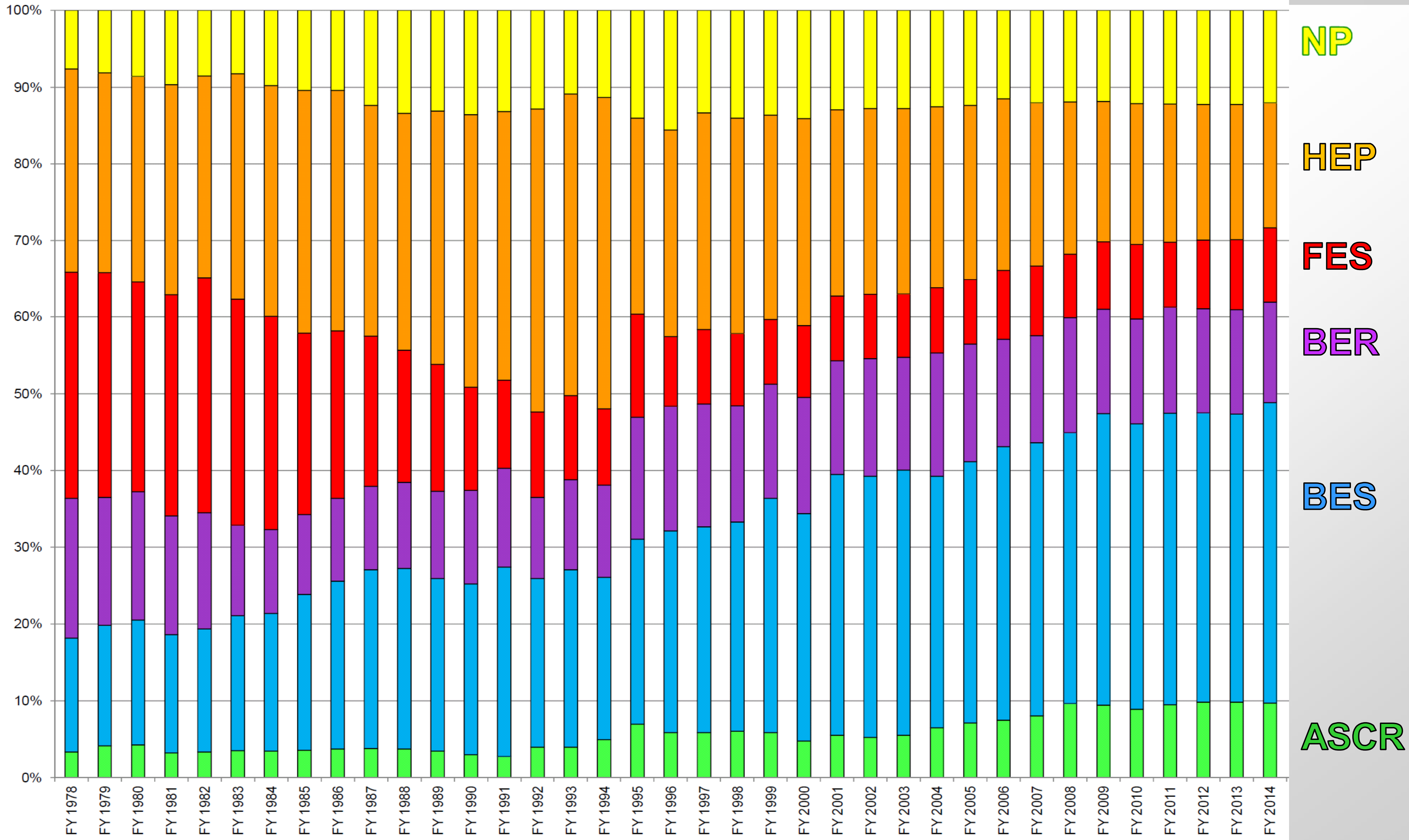
60% use ◆ Accelerator-based

Does not include LHC; HEP supports about 1,700 scientists, technicians, and engineers at the LHC.

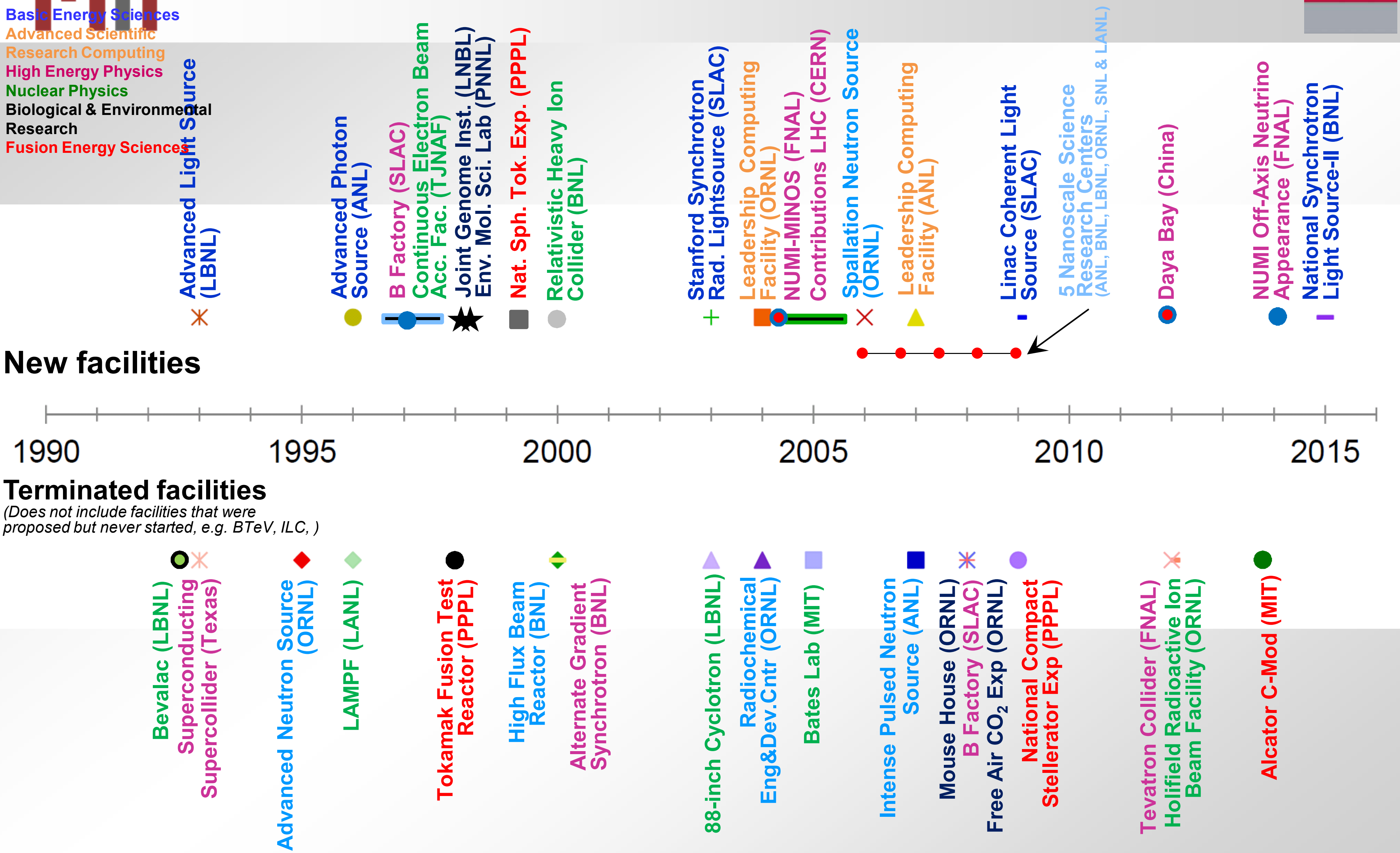
Users by Discipline at the Light Sources



Major SC Program Funding (% of total) FY 1978-2014



A Summary of Terminated and New Major Facilities 1990-2015



Basic Energy Sciences
Advanced Scientific Research Computing
High Energy Physics
Nuclear Physics
Biological & Environmental Research
Fusion Energy Sciences

New facilities

- Advanced Light Source (LBNL)
- Advanced Photon Source (ANL)
- B Factory (SLAC)
- Continuous Electron Beam Acc. Fac. (TJNAF)
- Joint Genome Inst. (LNBL)
- Env. Mol. Sci. Lab (PNNL)
- Nat. Sph. Tok. Exp. (PPPL)
- Relativistic Heavy Ion Collider (BNL)
- Stanford Synchrotron Rad. Lightsource (SLAC)
- Leadership Computing Facility (ORNL)
- NUMI-MINOS (FNAL)
- Contributions LHC (CERN)
- Spallation Neutron Source (ORNL)
- Leadership Computing Facility (ANL)
- Linac Coherent Light Source (SLAC)
- 5 Nanoscale Science Research Centers (ANL, BNL, LBNL, ORNL, SNL & LANL)
- Daya Bay (China)
- NUMI Off-Axis Neutrino Appearance (FNAL)
- National Synchrotron Light Source-II (BNL)

Terminated facilities

(Does not include facilities that were proposed but never started, e.g. BTeV, ILC,)

- Bevalac (LBNL)
- Superconducting Supercollider (Texas)
- Advanced Neutron Source (ORNL)
- LAMPF (LANL)
- Tokamak Fusion Test Reactor (PPPL)
- High Flux Beam Reactor (BNL)
- Alternate Gradient Synchrotron (BNL)
- 88-inch Cyclotron (LBNL)
- Radiochemical Eng&Dev.Cntr (ORNL)
- Bates Lab (MIT)
- Intense Pulsed Neutron Source (ANL)
- Mouse House (ORNL)
- B Factory (SLAC)
- Free Air CO_2 Exp (ORNL)
- National Compact Stellerator Exp (PPPL)
- Tevatron Collider (FNAL)
- Holifield Radioactive Ion Beam Facility (ORNL)
- Alcator C-Mod (MIT)