Science and Technology Facilities Council

Daresbury Laboratory

CI-ACC-101.2
Particle Accelerators – Types and Uses

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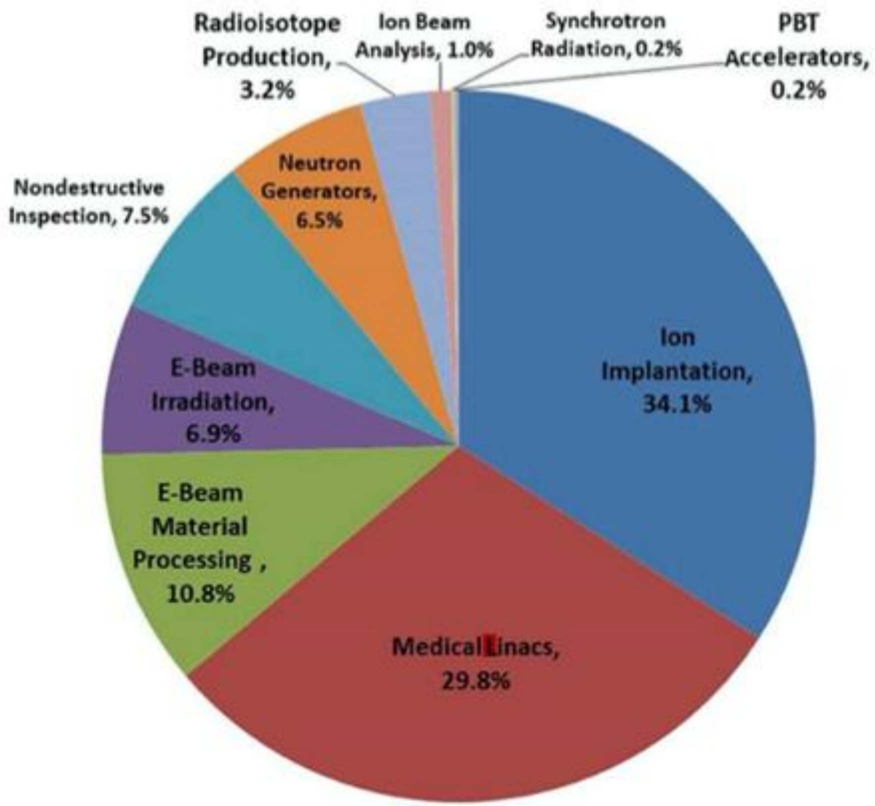
Cockcroft Institute Lecture Series

Types of Accelerator

- DC – simple vacuum tubes, VdGs
- Linacs – Wideroe, Alvarez, etc. etc.
- Cyclotrons, Synchrocyclotrons, Isochronous cyclotrons
- Betatrons, Induction Linacs, Induction Rings
- Synchrotrons, Storage Rings
- Microtrons, Rhodotrons
- FFAGs
- RFQs

- Novel Types– Plasma, Dielectric

- Particle Sources – Thermionic Guns, Photoguns, Ion Sources
- Secondary Sources – Neutrons (spallation, nuclear reactions), 'exotics' (pions, muons, antiprotons)



Doyle, McDaniel and Hamm 'The Future of Industrial Accelerators and Applications'
https://www.worldscientific.com/doi/abs/10.1142/S1793626819300068

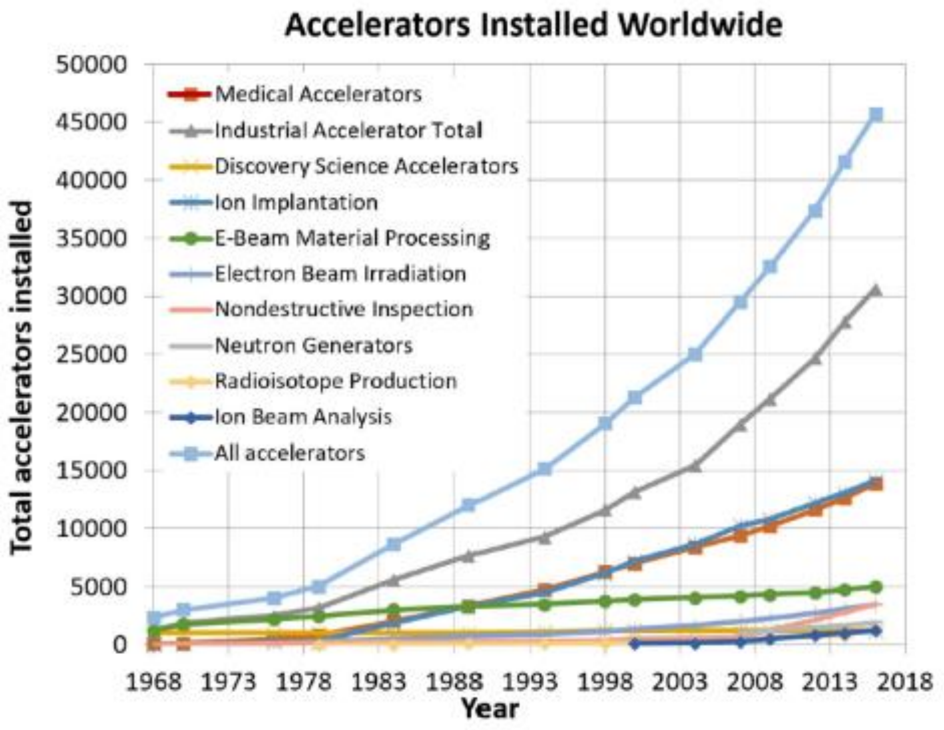
Nobel Prizes involving accelerator science

Haussecker, E.F., Chao, A.W. The Influence of Accelerator Science on Physics Research.
Phys. Perspect. **13,** 146 (2011).
https://doi.org/10.1007/s00016-010-0049-y

We show by using a statistical sample of important developments in modern physics that accelerator science has influenced 28% of post-1938 physicists and also 28% of post-1938 physics research. We also examine how the influence of accelerator science has evolved over time, and show that on average it has contributed to a physics Nobel Prize-winning research every 2.9 years.

1939	Ernest O. Lawrence
1951	John D. Cockcroft and Ernest T.S. Walton
1952	Felix Bloch
1957	Tsung-Dao Lee and Chen Ning Yang
1959	Emilio G. Segrè and Owen Chamberlain
1960	Donald A. Glaser
1961	Robert Hofstadter
1963	Maria Goeppert Mayer
1967	Hans A. Bethe
1968	Luis W. Alvarez
1976	Burton Richter and Samuel C.C. Ting
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg
1980	James W. Cronin and Val L. Fitch
1981	Kai M. Siegbahn
1983	William A. Fowler
1984	Carlo Rubbia and Simon van der Meer
1986	Ernst Ruska
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger
1989	Wolfgang Paul
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor
1992	Georges Charpak
1995	Martin L. Perl
2004	David J. Gross, Frank Wilczek, and H. David Politzer
2008	Makoto Kobayashi and Toshihide Maskawa

The growth in accelerator applications



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Accelerator Methods and Technologies

- Principles – electrodynamics, scattering, …
- Single-particle dynamics
- Multi-particle dynamics

- Lifecycle – production, injection, acceleration, transport, manipulation, extraction, delivery

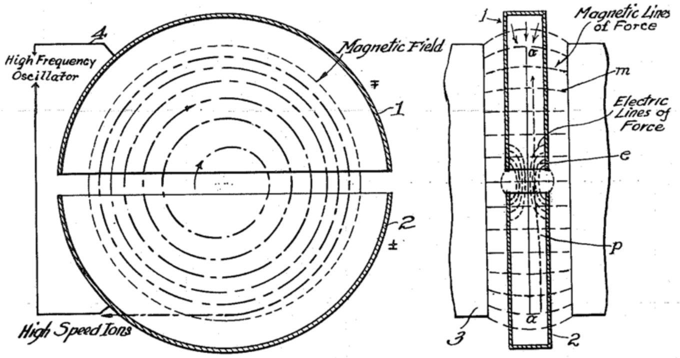
- Methods – analytic, simulation, MC

- Technology – sources, magnets, RF, plasma, laser, vacuum, diagnostics, radiation, geodesics, engineering, controls

- Discipline – electrodynamics, magnetism, surface science, radiofrequency engineering, FEA, nuclear physics, particle physics, software

- This is a multi-disciplinary institute

Cyclotrons



$$\frac{mv^2}{\rho} = qBv$$

$$B\rho = \frac{p}{q} = \frac{mv}{q} = \frac{\beta\gamma m_0 c}{q}$$

$$\omega = \frac{qB}{m} = \frac{qB}{\gamma m_0}$$

Constant as long as γ is small

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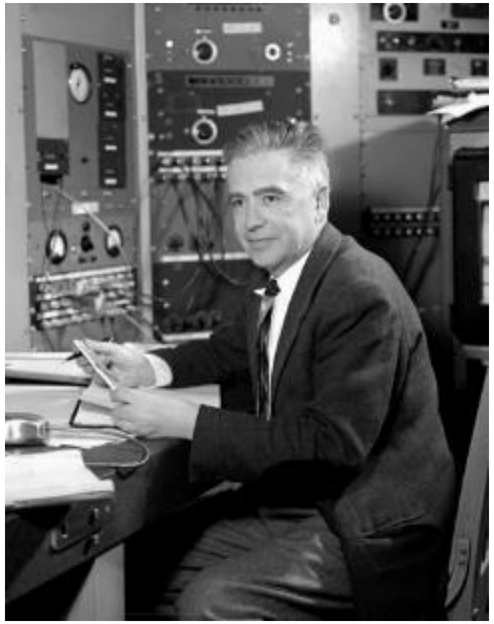
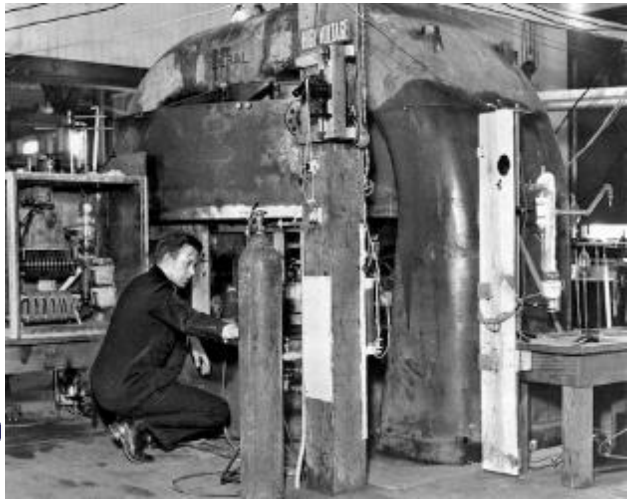
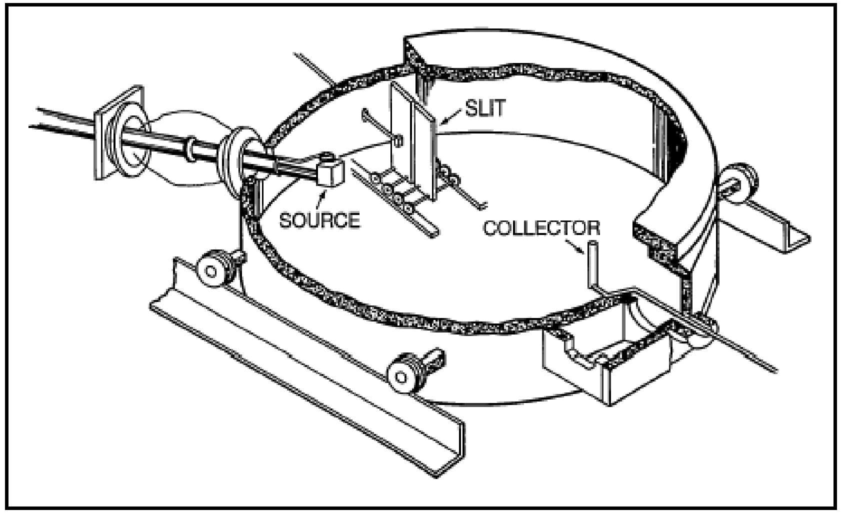
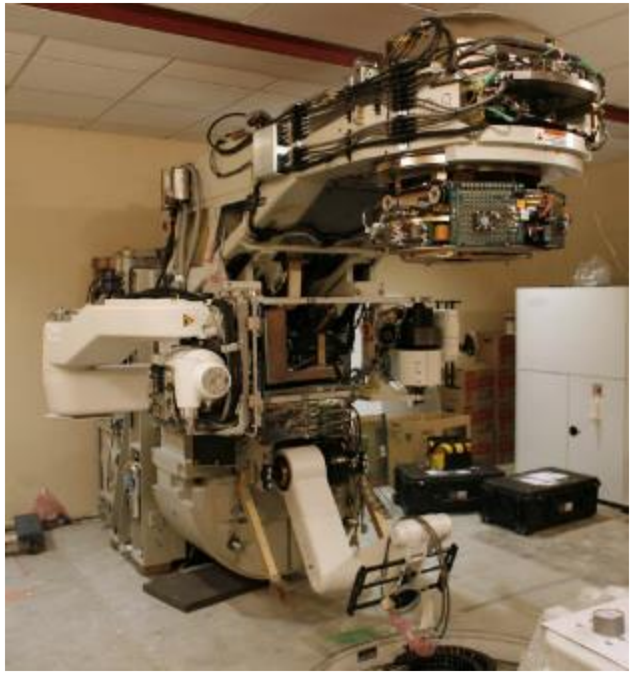
Emilio Segrè and the 37-inch cyclotron deflector foil

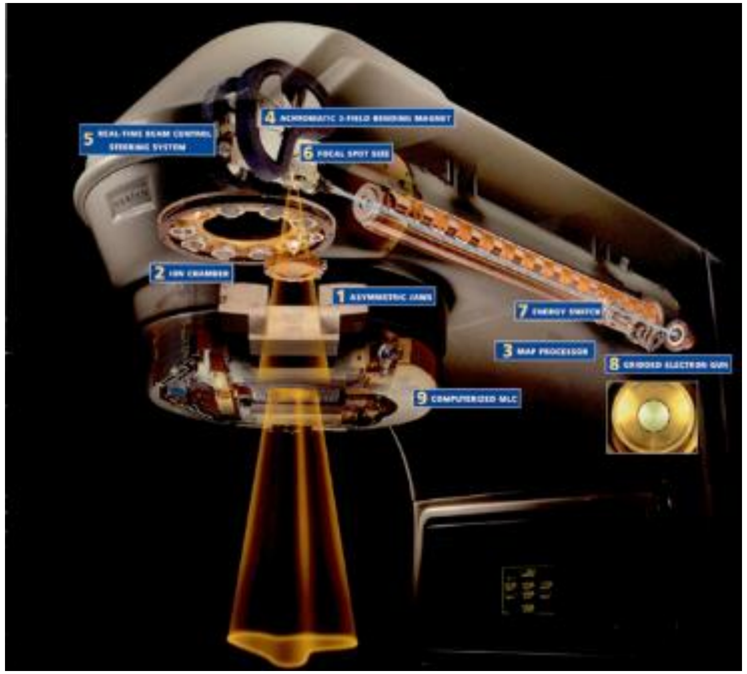


'In February 1937 I received a letter from Lawrence containing more radioactive stuff. In particular, it contained a molybdenum foil that had been part of the cyclotron's deflector. I suspected at once that it might contain element 43. The simple reason was that deuteron bombardment of molybdenum should give isotopes of element 43 through well-established nuclear reactions. My sample, the molybdenum deflector lip, had certainly been intensely bombarded with deuterons, and I noted that one of its faces was much more radioactive than the other. I then dissolved only the material of the active face, in this way achieving a first important concentration of the activity. '

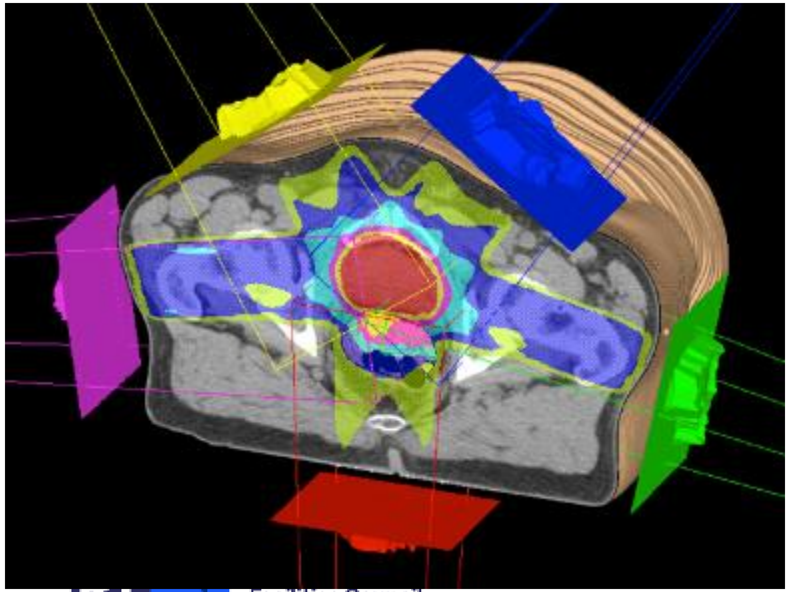


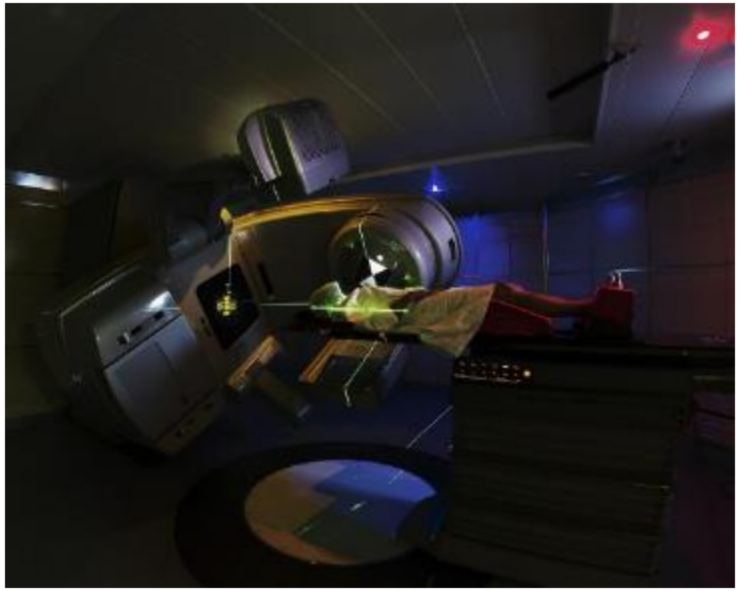






HSL/Jeniffer Caetano





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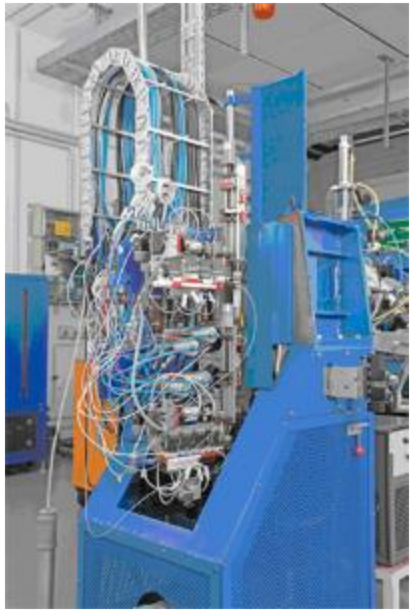
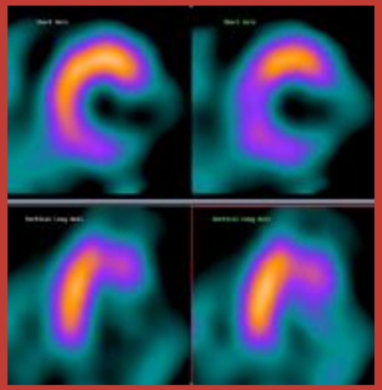
A modern isotope cyclotron



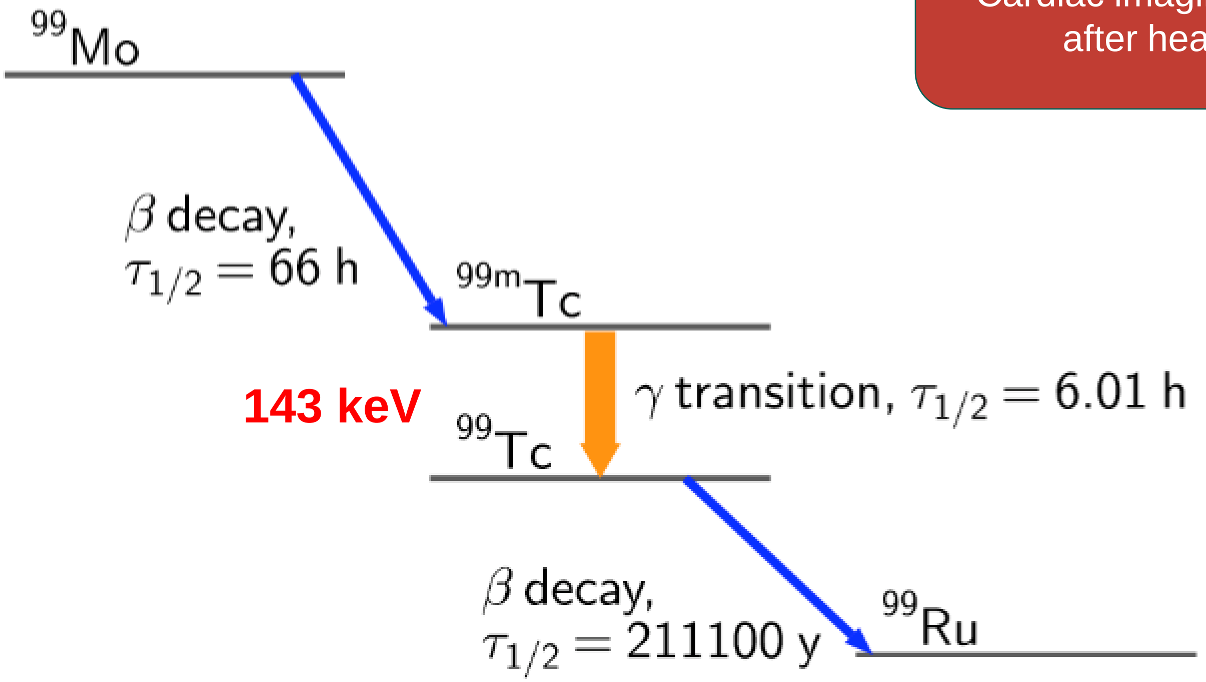
Nuclide	F-18	C-11	N-13	O-15	Ge-68
Half-Life	110min	20.5m	10m	2m	275d
Positron (keV)	630	960	1200	1730	1900
Gammas (keV)	511(2)	511	511	511	511

Mo-99/Tc-99m/Tc-99

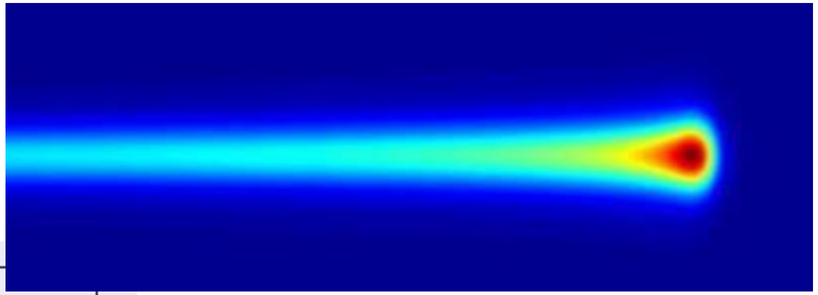
30 Million procedures a year



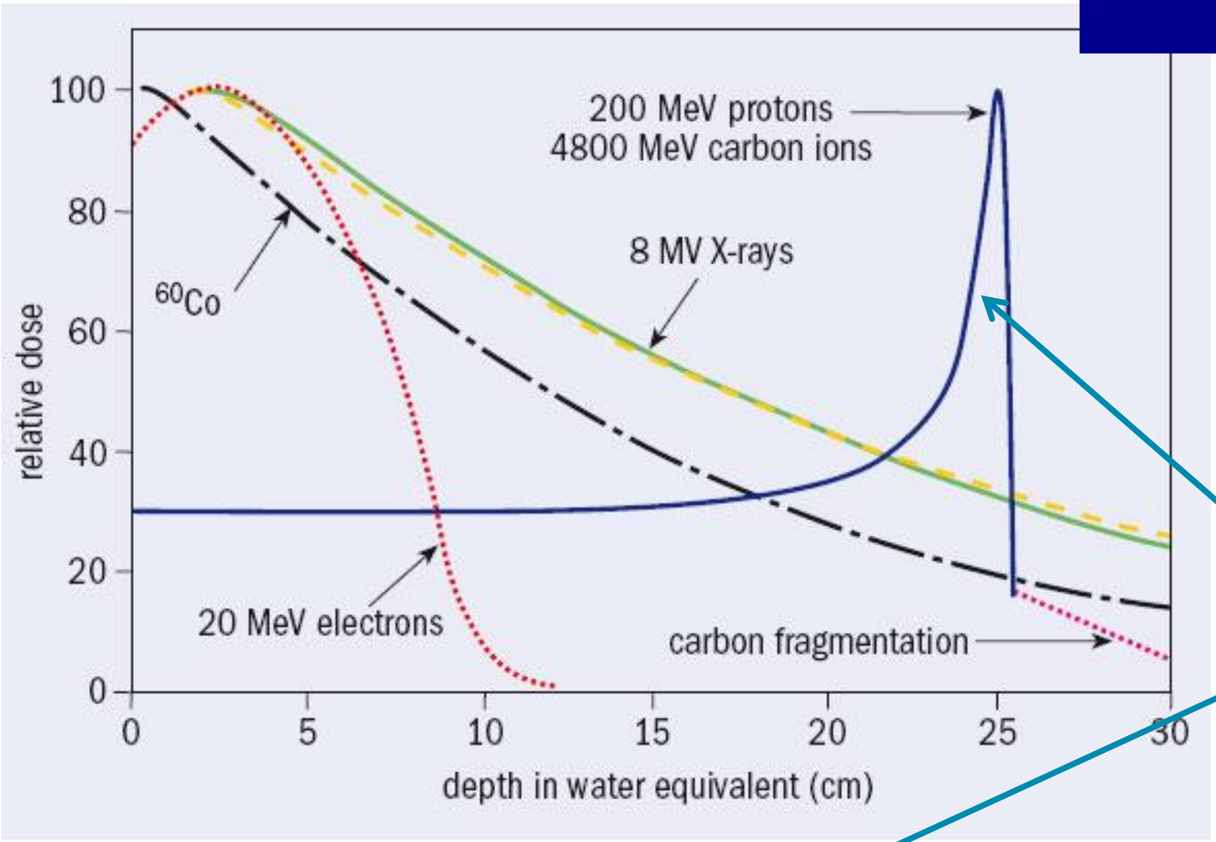
Cardiac imaging to diagnose after heart attacks



The magic Bragg peak



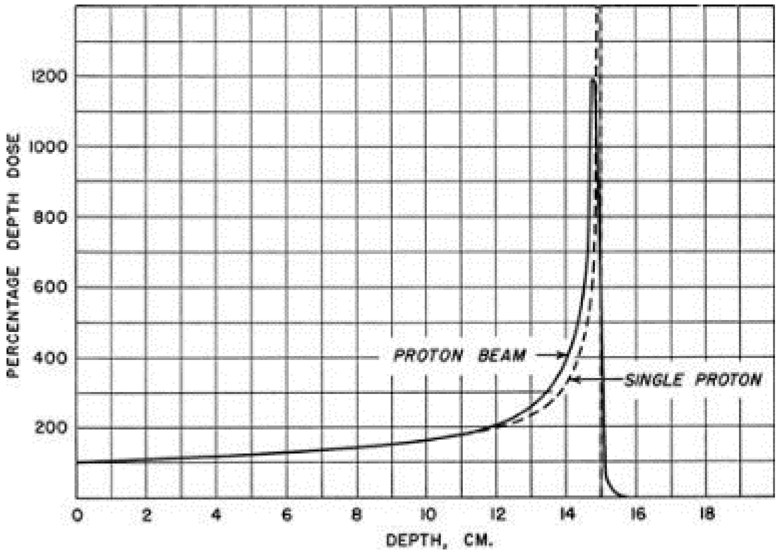
Also transverse scattering (MCS)



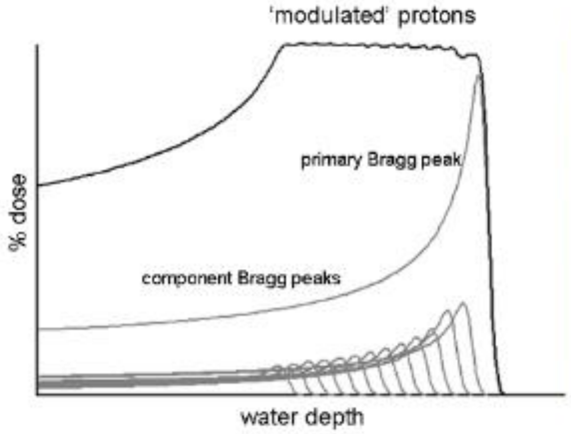
Rate of slowing inverse to energy; gives a peak at the end of range

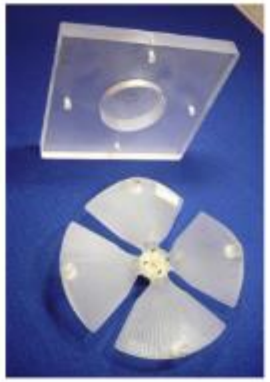
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Spreading out the peak



The original picture from R. R. Wilson's paper on proton therapy. (*Radiology* **47**, 487–491, 1946)

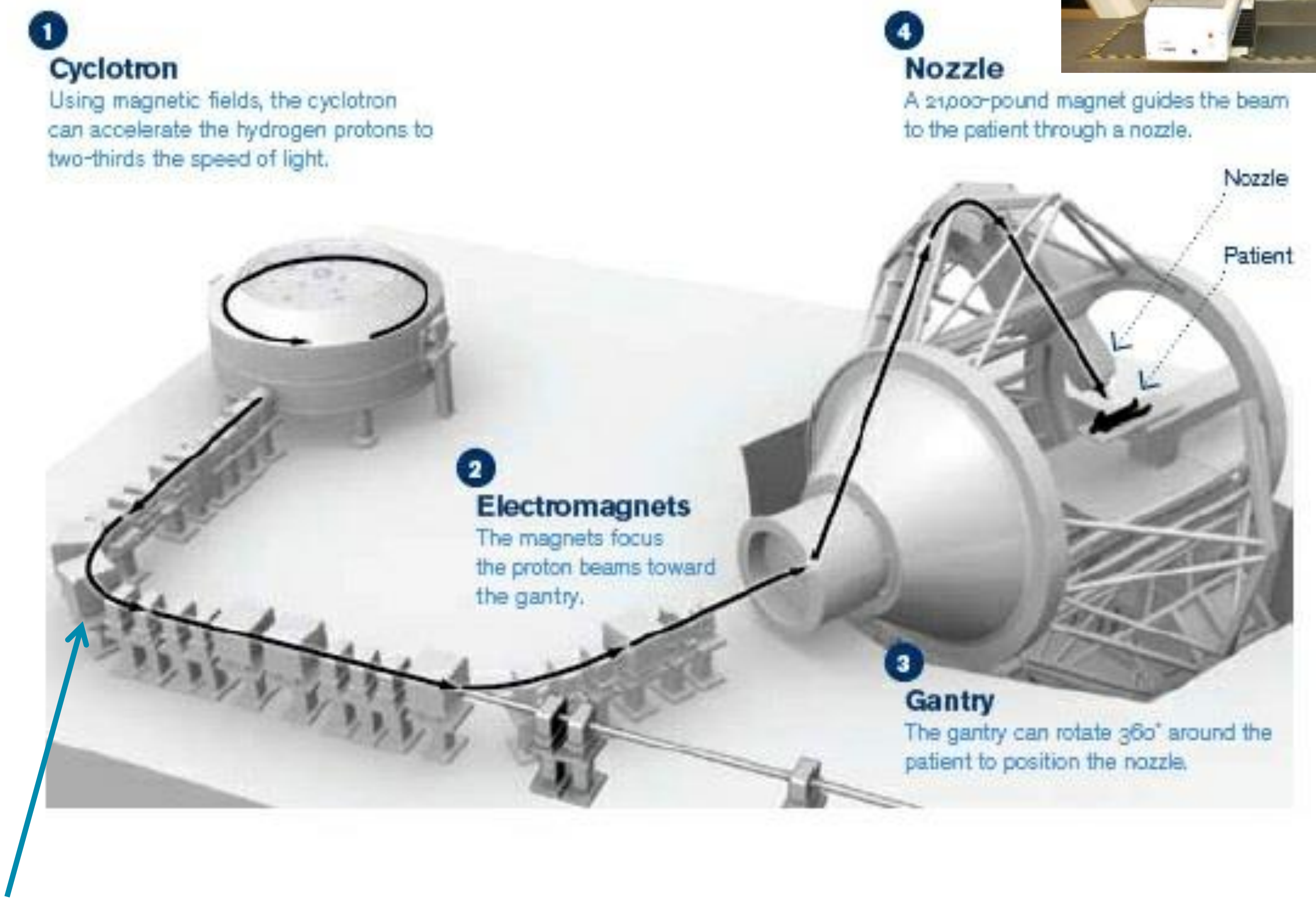




Intrinsic - straggling

Deliberate – range modulating

From source to patient



Energy selection + variable absorber

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ISIS Spallation Neutron Source

https://www.sciencedirect.com/science/article/pii/S0168900218317820

		Target Station 1	Target Station 2
Synchrotron injection energy	70 MeV		
Synchrotron extraction energy	800 MeV		
Proton beam current	~225 μA	~180 μA	~45 μA
Beam pulse repetition rate	50 pps	40 pps	10 pps
Proton beam power	~180 kW		
Operational days per year	~200		
Tungsten target configuration		Multi-plate	'Solid' cylinder
No. of neutron instruments		17	10
No. of muon instruments		5	
No. of user visits	2278 (in 2017)		
No. of journal publications	486 (in 2017)		

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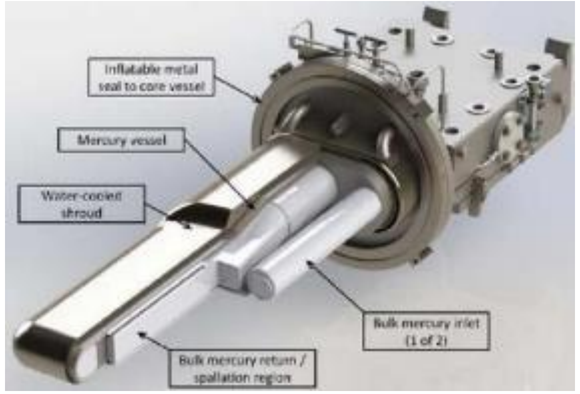
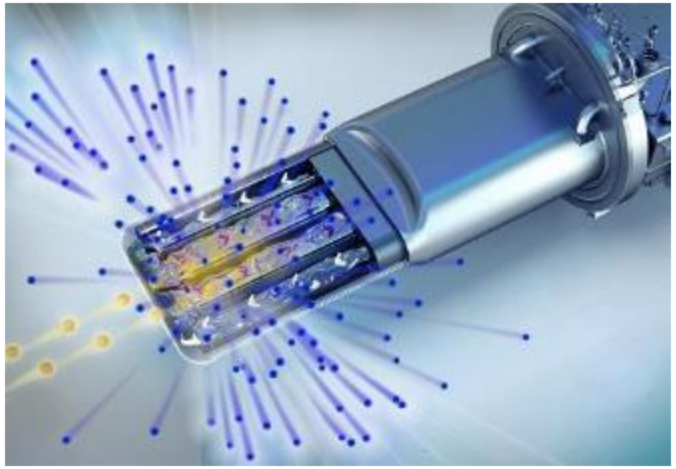
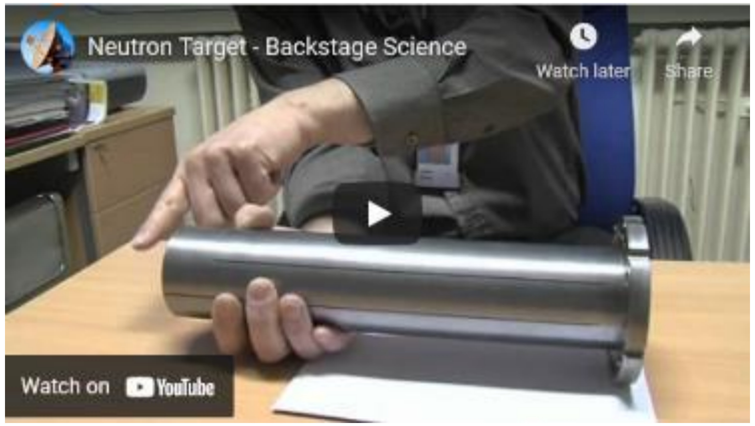
Spallation Targets

SNS (Oak Ridge) 1 MW
liquid mercury target

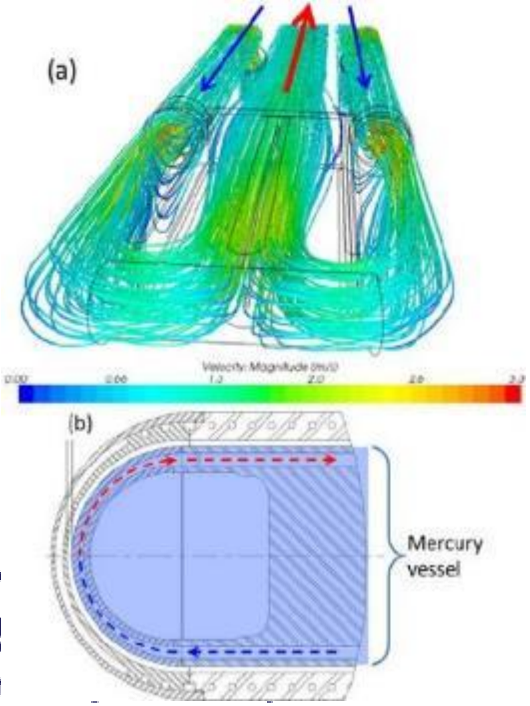


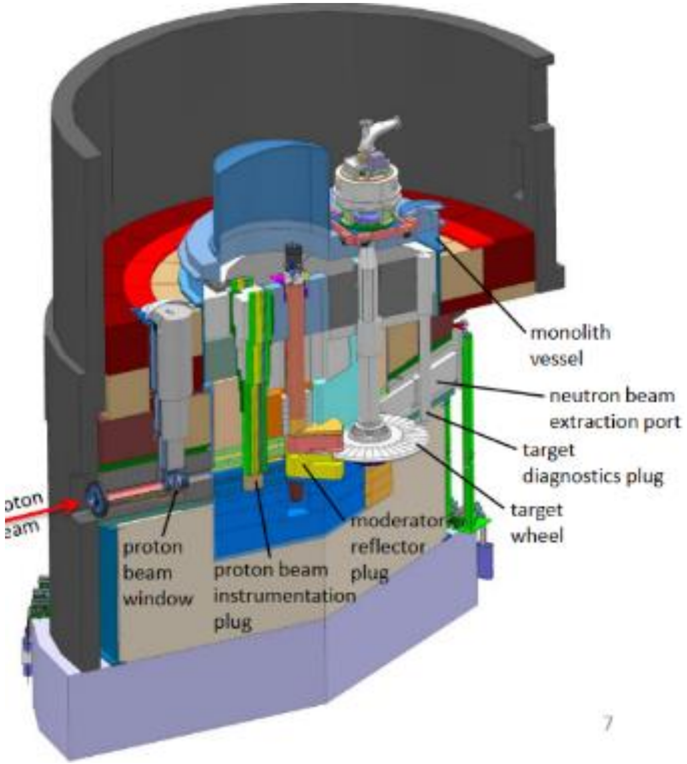




https://www.youtube.com/watch?v=Vopxry2Jq8c

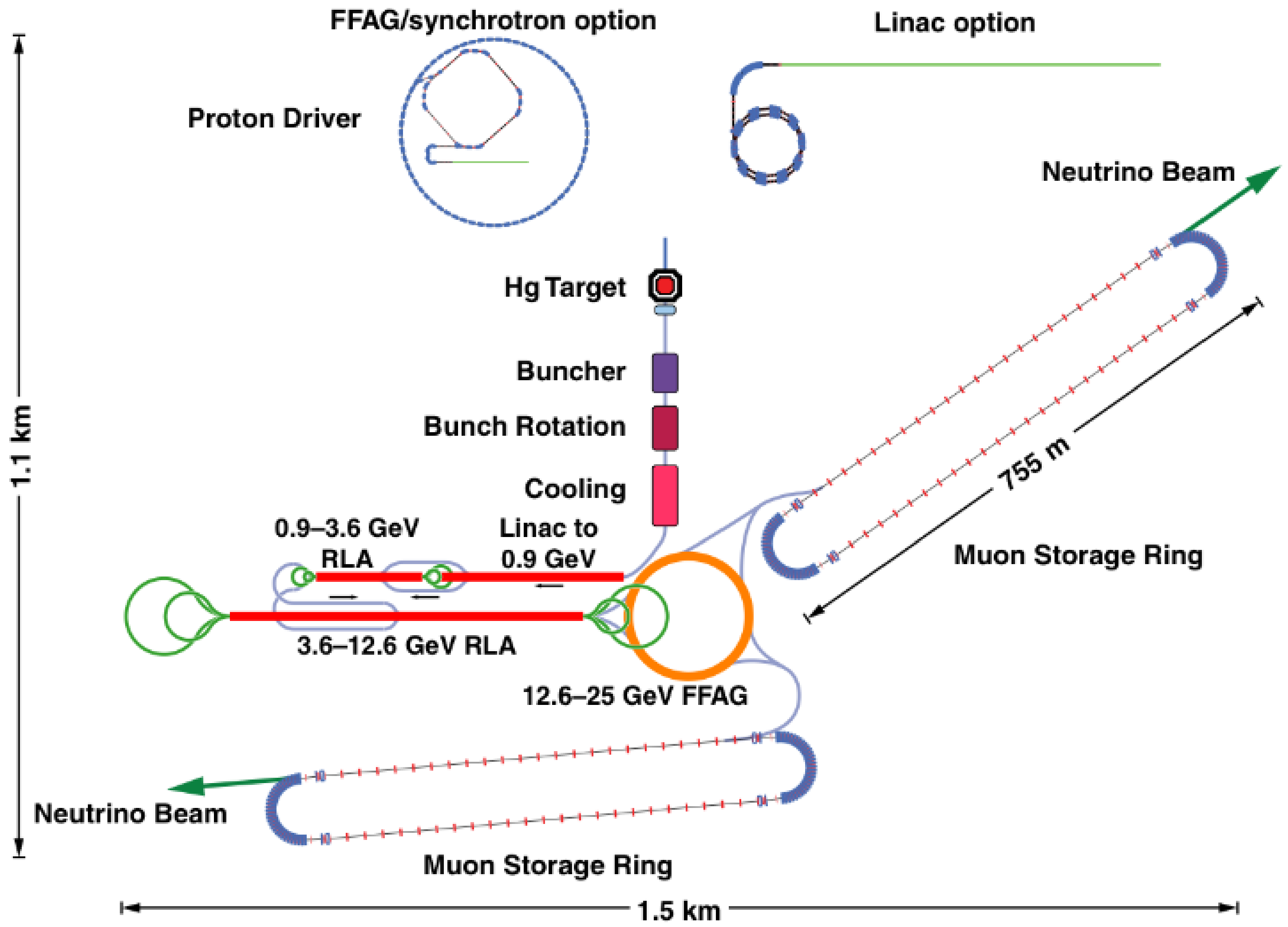
ISIS 160 kW solid W target



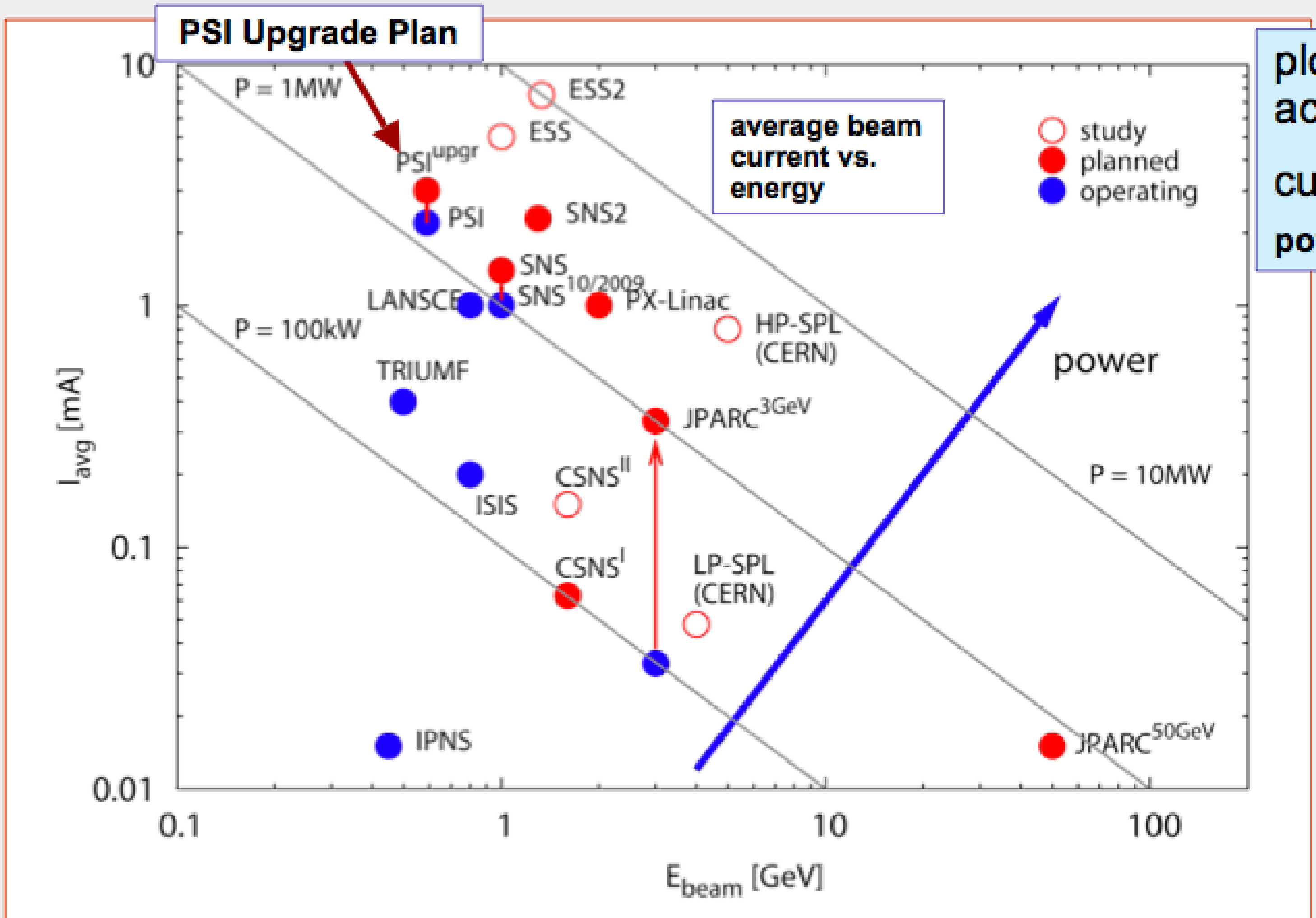


ESS 5 MW solid rotating W target

Neutrino Factory



Proton Driver Power



plot: selected accelerators

current vs. energy

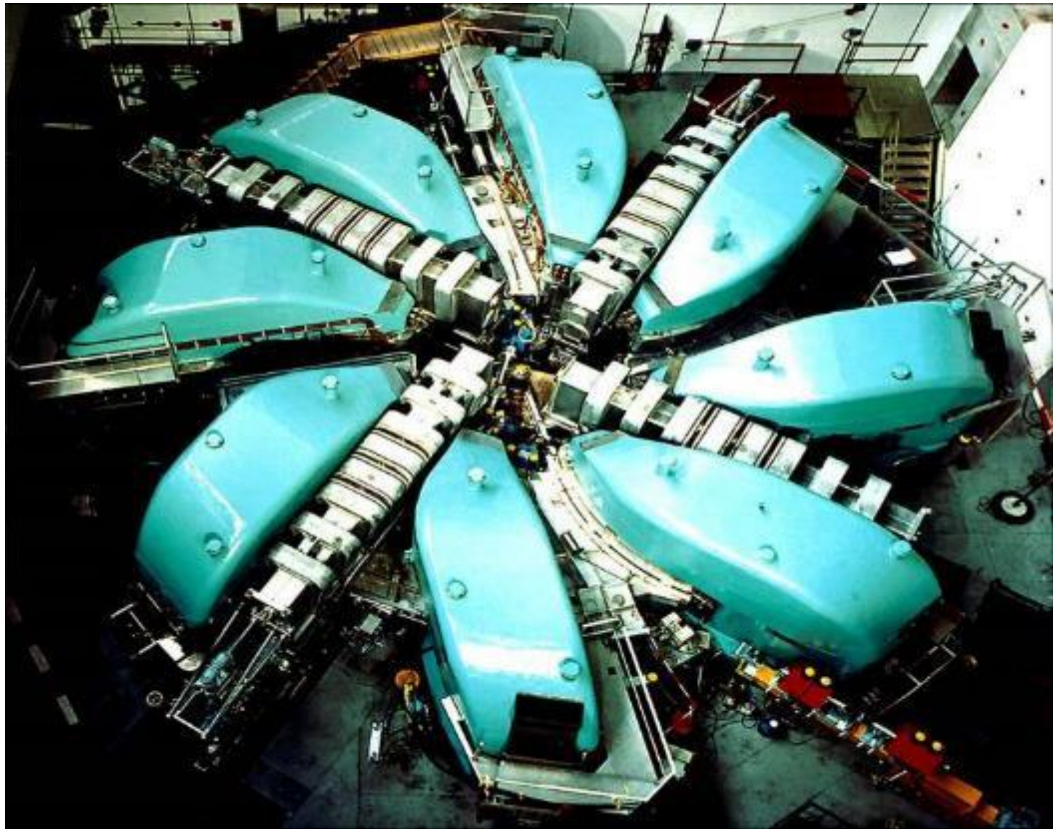
power ∝ current·energy

PSI Parameters: [2.2mA, 1.3MW] → [3mA, 1.8MW]

Applications:

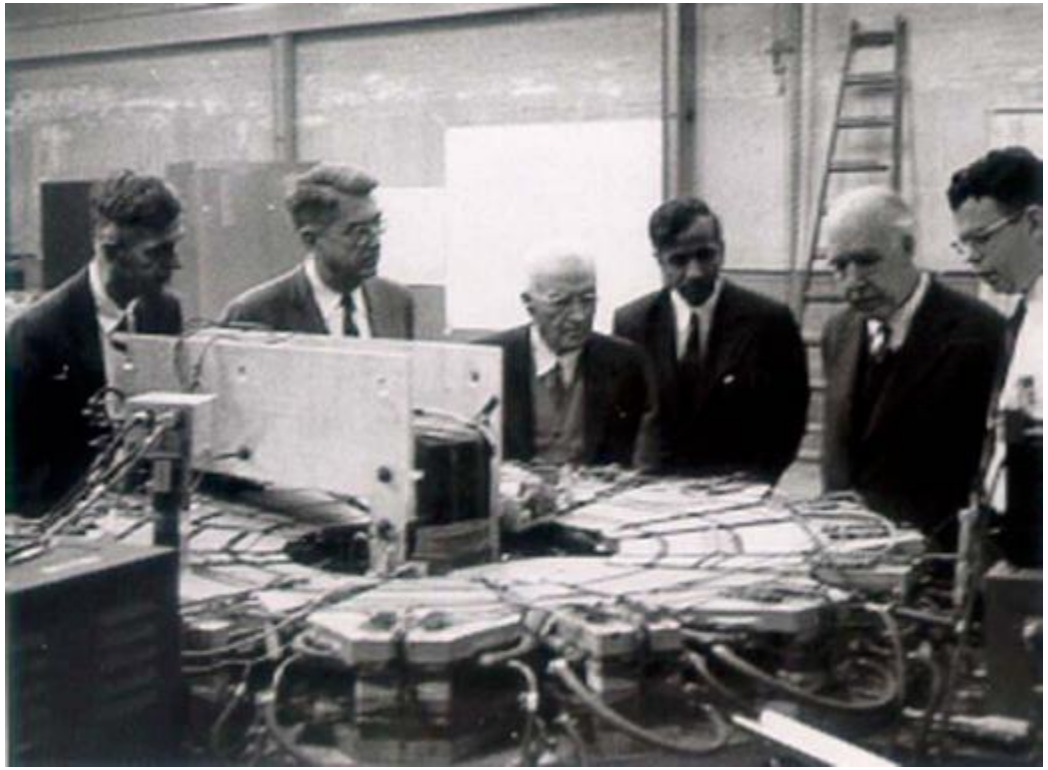
- High-intensity physics
- Fusion materials testing
- ADSRs
- Tritium production

The PSI Cyclotron – (still) the world's highest power accelerator (1.3 MW)

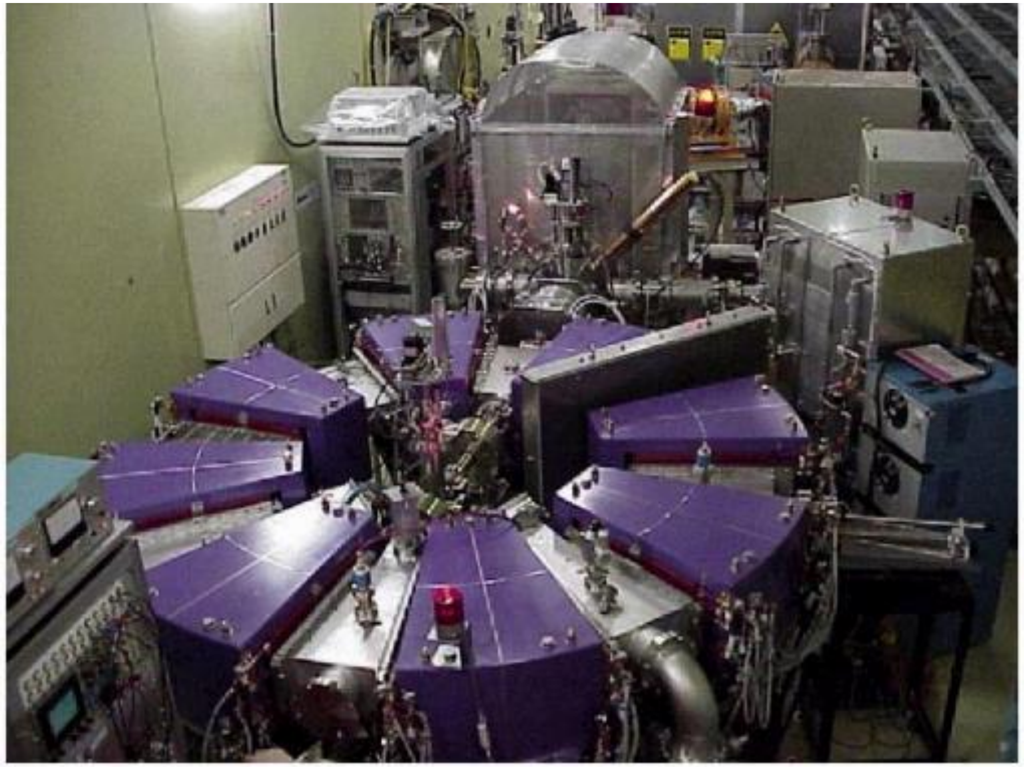


- p+ 590 MeV
- 2 mA
- (Zurich, Switzerland)

FFAGs – Fixed Field, Alternating Gradient



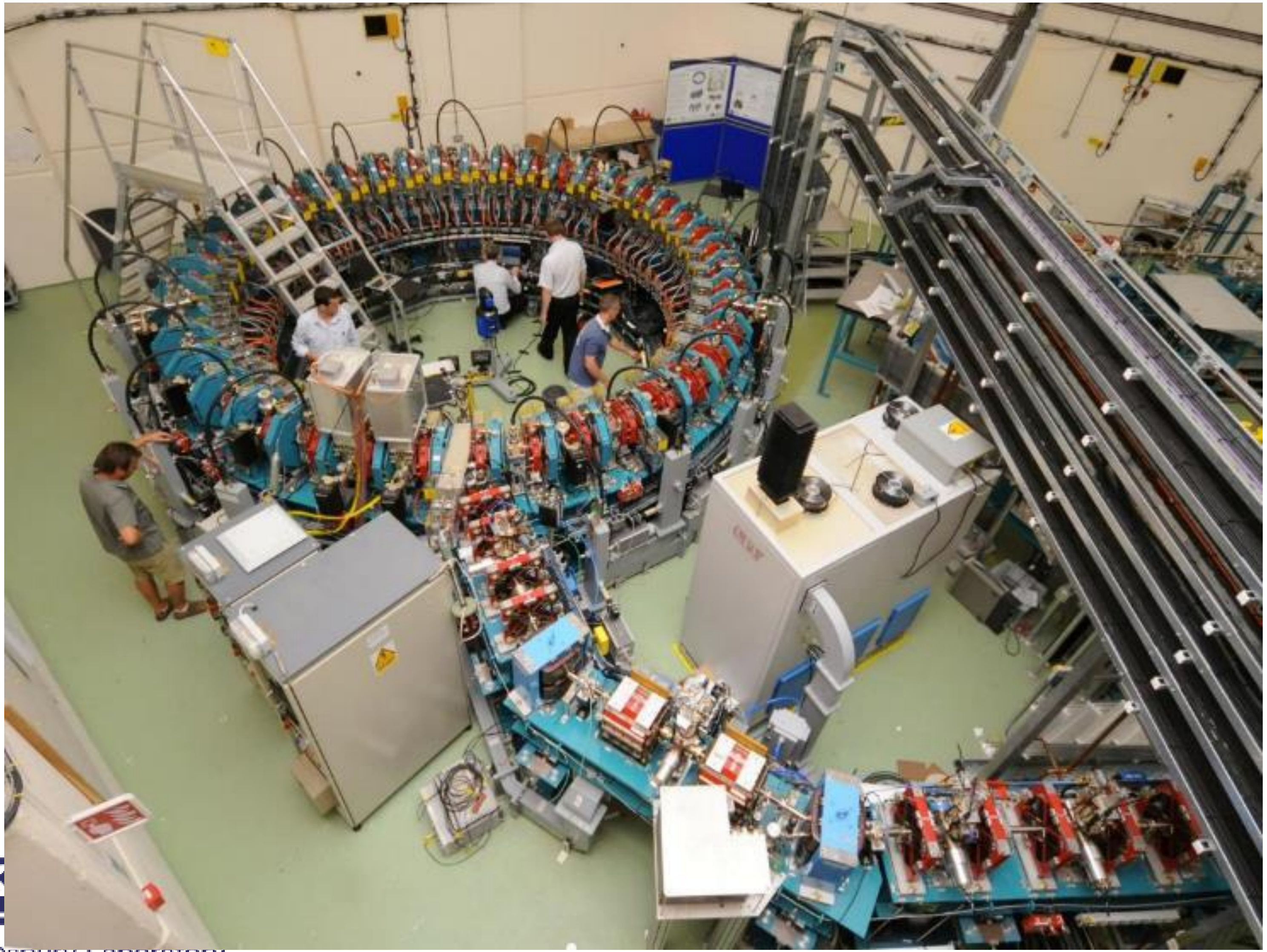
MURA, 1956 – a variant of the betatron

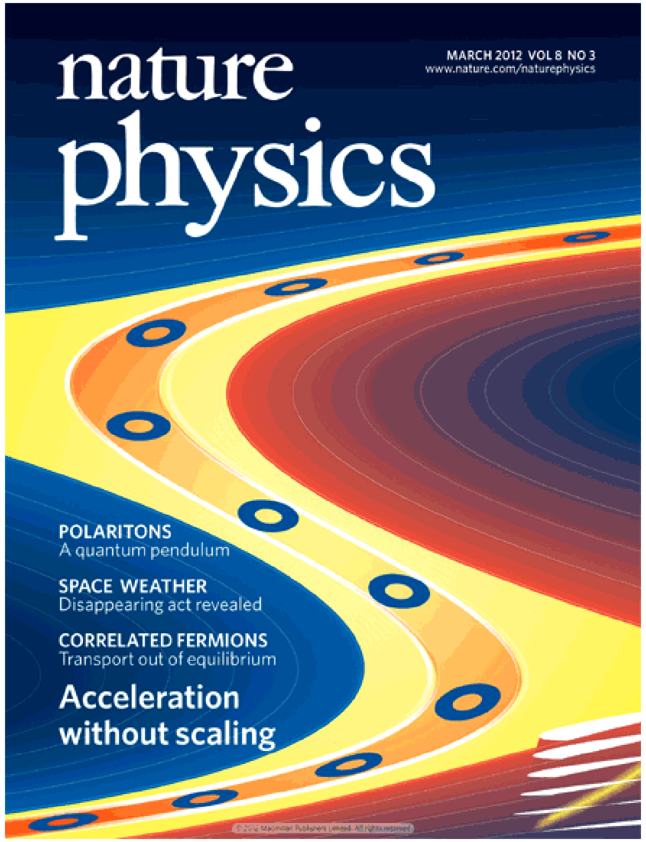


KEK, 2000. First proton FFAG

Unique Selling Point: Rapid acceleration without rapidly varying the dipole fields, but to a higher energy than possible with a cyclotron
Useful for accelerating unstable particles (e.g. muons)

EMMA – the first NS-FFAG





- Gives a larger energy range
- First one built by Daresbury/CI
- CBETA recently demonstrated at Cornell Uni

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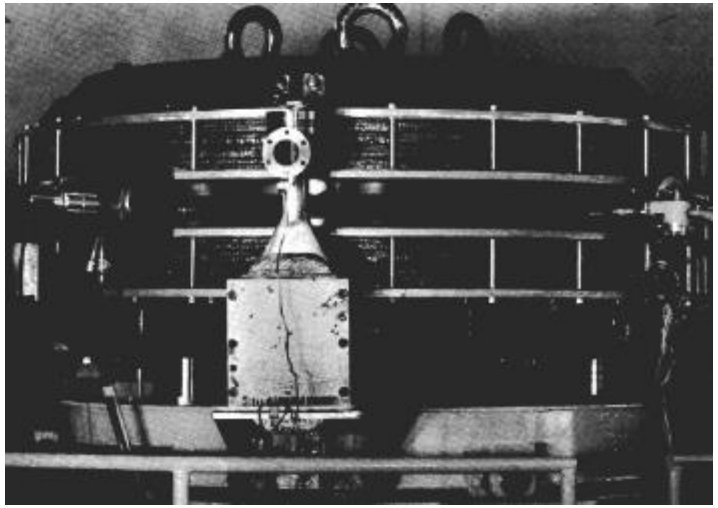
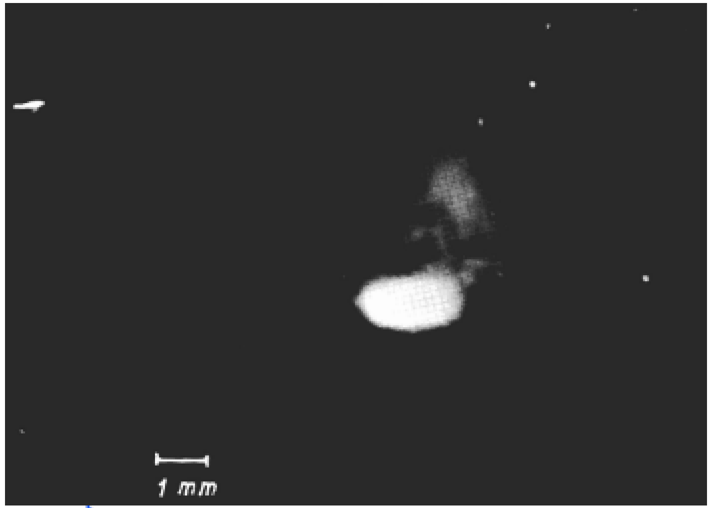
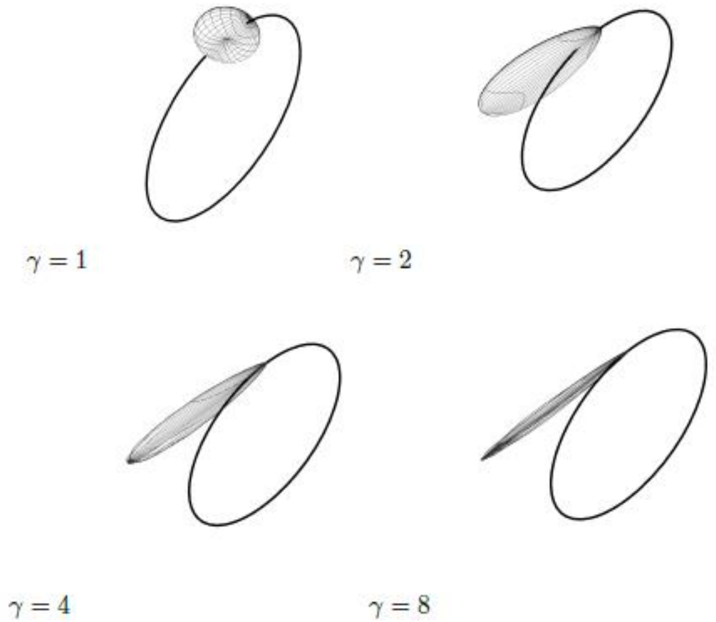
ADA – the first electron storage ring







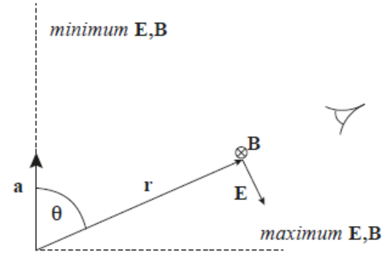


FIGURE 6.5 Illustration of how the magnitude of the emitted electric and magnetic fields vary with observation angle θ.

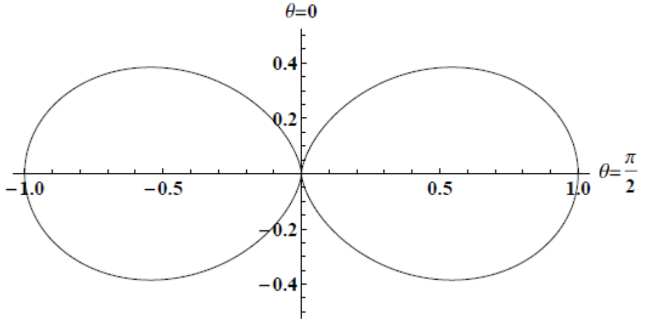
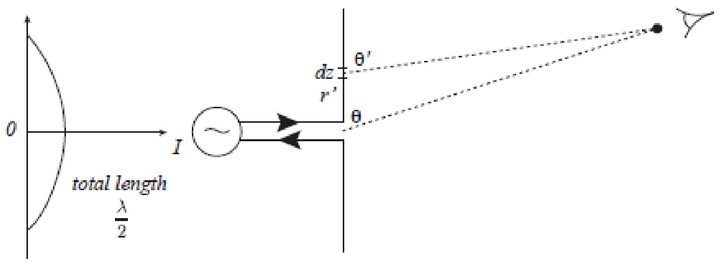


FIGURE 6.6 2D illustration of how the magnitude of the Poynting vector **S** (here shown as the distance of the solid from the origin, for any given angle θ) varies with observation angle θ.



ABCO Section 6.1.2

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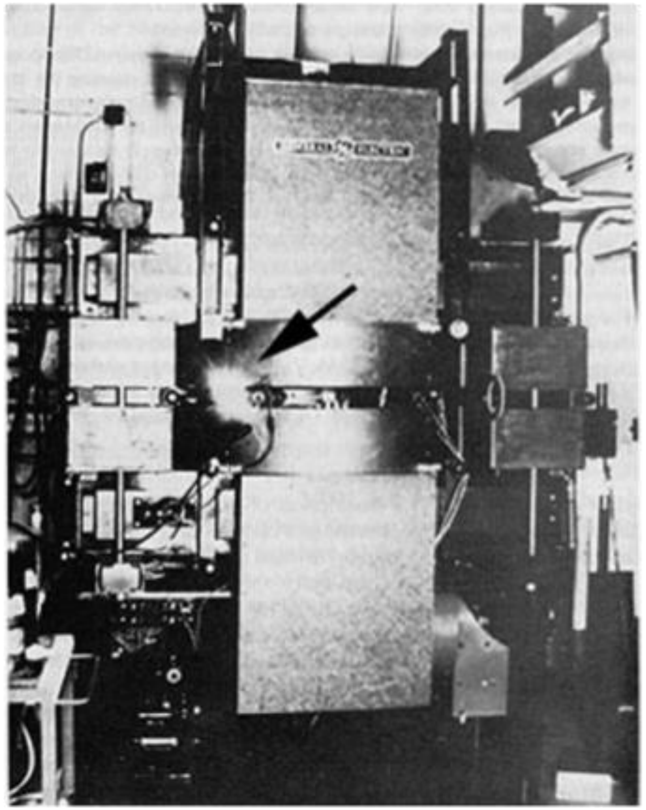


'If the accelerator tube of the 100-MeV betatron at Schenectady had not been opaque, the visual observation would probably have been made three years earlier by Westendorp or Blewett soon after the publication of your letter to the Physical Review (Phys. Rev. 65:343, 1944). Unfortunately they were not able to see through the silvered wall of the betatron donut.

The General Electric Synchrotron

$$P = \frac{e^2 c \gamma^4}{6\pi\epsilon_0\rho^2}, \langle\epsilon\rangle = \frac{8\sqrt{3}}{45}\frac{\hbar c\gamma^3}{\rho}, U_0 = \frac{e^2\gamma^4}{3\epsilon_0\rho}.$$

$$N_\gamma = \frac{U_0}{\langle\epsilon\rangle} = \frac{45}{8\sqrt{3}}\frac{2}{3}\frac{\rho}{\hbar c\gamma^3}\frac{e^2\gamma^4}{3\epsilon_0\rho}.$$

$$N_\gamma = \frac{5\pi}{\sqrt{3}}\alpha\gamma \simeq 0.0662\gamma.$$

$$P_{\text{total}}\ [\text{kW}] = 88.4\frac{E\ [\text{GeV}]^4 I_b\ [\text{A}]}{\rho\ [\text{m}]}.$$ for electrons

Beam Equilibrium

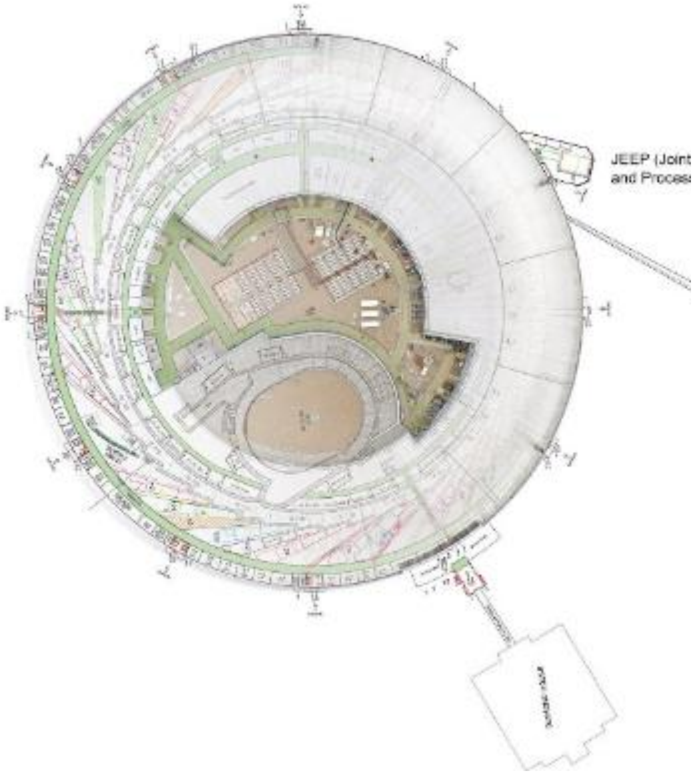
ABCO Section 6.4

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2} \quad \epsilon_y \simeq \kappa \epsilon_x$$

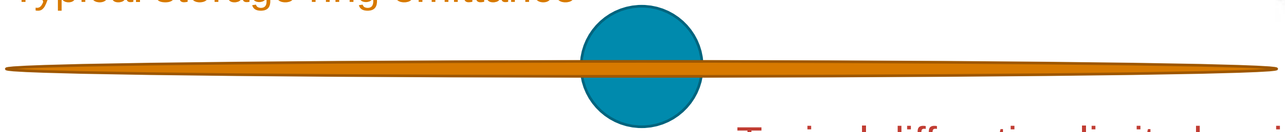
$$I_5 = \oint \frac{H(s)}{|\rho(s)^3|} ds \quad I_2 = \oint \frac{1}{\rho(s)^2} ds$$

$$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

$$C_q = 55\hbar c / 32\sqrt{3} m_e c^2$$



Typical storage ring emittance



Typical diffraction-limited emittance (depends on λ)

Example 6.10

Average photon energy emitted from an electron storage ring

The DIAMOND Light Source in Oxfordshire is the UK's national synchrotron radiation production facility, and one of the brightest such sources on the planet; it is used by thousands of researchers each year. Like all such sources the magnetic field is more complex than being just a single, uniform field B, but there are dipole magnets in which the electrons are bent so that they can be stored; DIAMOND is therefore a *storage ring*

The electrons in DIAMOND are maintained at a kinetic energy $K = 3$ GeV, and pass through dipole magnets that give a field of 1.4 T, which corresponds to a bending radius $r = 7.1$ m; note that the circumference L of the storage ring is not $L = 2\pi r$, since not all of the path taken by the electrons has a bending field B applied. In fact, in most storage rings only a small fraction of the particle path has dipole field. The word 'circumference' when used for storage rings is therefore a bit of a misnomer; by 'circumference' we mean the total distance travelled by the particle in one orbital period. In DIAMOND, the circumference $L = 561.6$ m, so that the revolution period is $\tau_r = L/c \simeq 1.87\ \mu$s.

Hence the critical energy of the photons (emitted by the electrons within the dipoles) is $E_{crit} = 8.3$ keV. The average photon energy is $\langle E_\gamma \rangle = 2.8$ keV.

Example 6.11

Synchrotron radiation power and number of photons from an electron storage ring

Of course, there isn't just one electron orbiting in DIAMOND. Knowing that an ammeter placed at any point in the storage ring measures a typical passing current of 300 mA and that obviously $I \equiv \Delta Q/\Delta t$, the total charge in the storage ring ΔQ is

$$\Delta Q = I \Delta t = \frac{IL}{c} \tag{6.54}$$

where the circumference is $L = 561.6$ m, and $\Delta t = \tau_r$. The number of electrons is then just

$$N_e = \frac{\Delta Q}{e} \simeq 3.5 \times 10^{12} \tag{6.55}$$

for a current of 300 mA.

By comparing the synchrotron radiation power to the revolution period, we can straightforwardly obtain that the energy loss per orbit revolution is

$$U_0 = \frac{e^2\gamma^4}{3\epsilon_0 r} \simeq 1.0 \text{ MeV}. \tag{6.56}$$

The total power radiated by each electron is $P_e = 86$ nW, but since there are $\sim 10^{12}$ electrons the total power emitted is $P_{total} = N_e P_e \simeq 300$ kW. This is a simply enormous power. Synchrotron radiation facilities such as DIAMOND are the only known method of producing such a large quantity of X-ray photons; they are one of the brightest artificial sources of photons.

Knowing the energy lost per turn and the average photon energy, we can easily calculate the number of photons emitted by each electron as it executes a single orbit. This is

$$N_\gamma = \frac{U_0}{\langle E_\gamma \rangle} \simeq \frac{2}{3}\frac{e^2}{\epsilon_0 \hbar c}\gamma = \frac{2}{3} 4\pi\alpha\gamma = \frac{8\pi}{3}\alpha\gamma, \tag{6.57}$$

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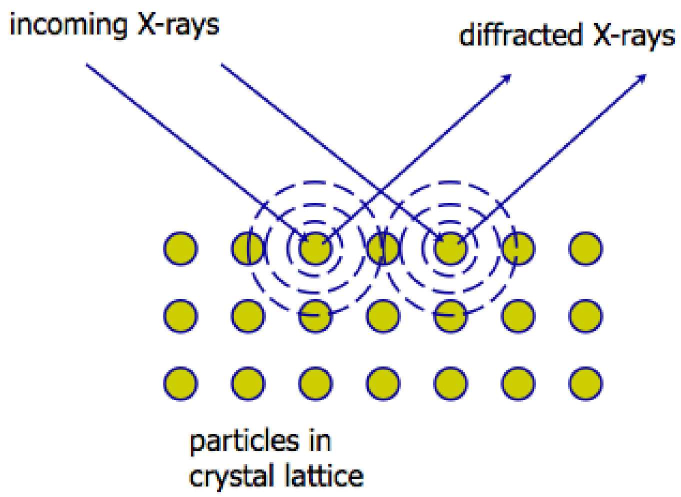
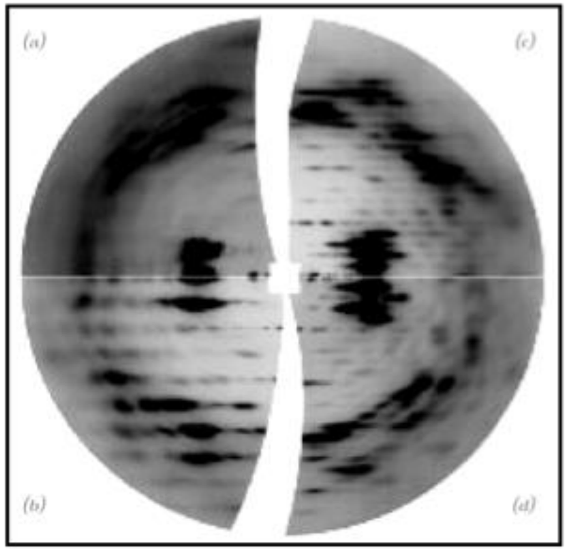
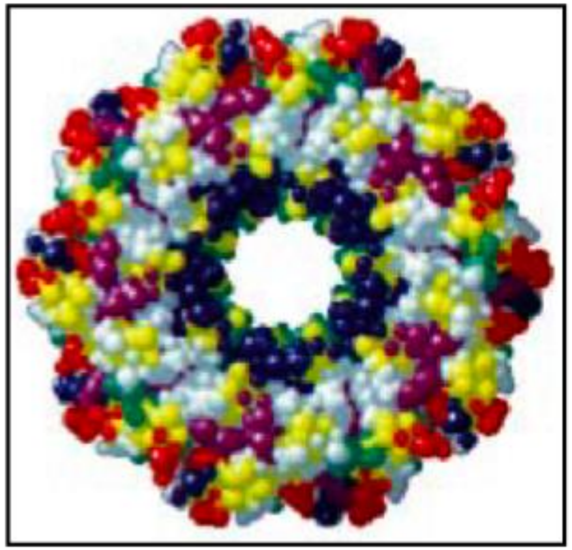
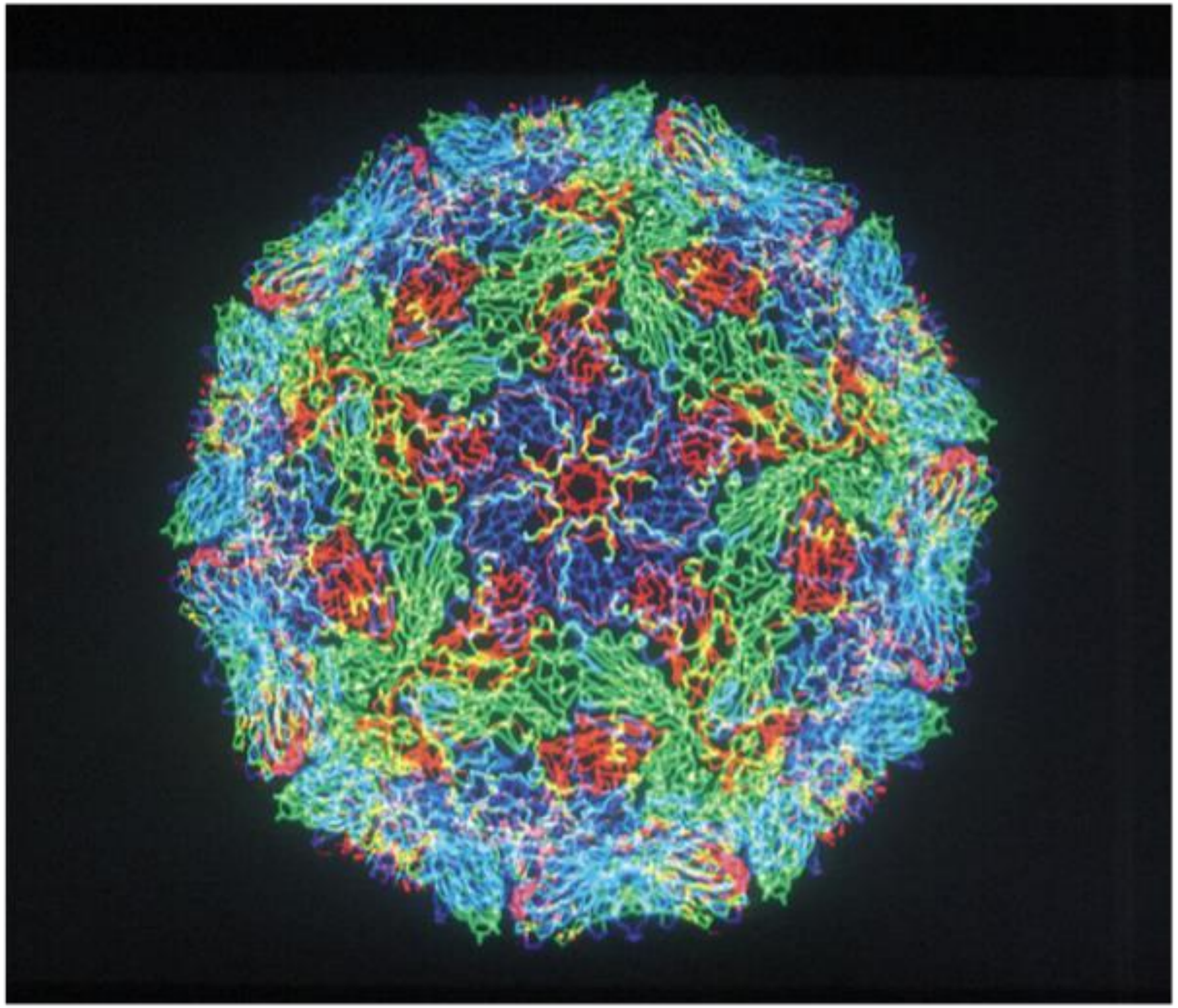
Insertion Devices



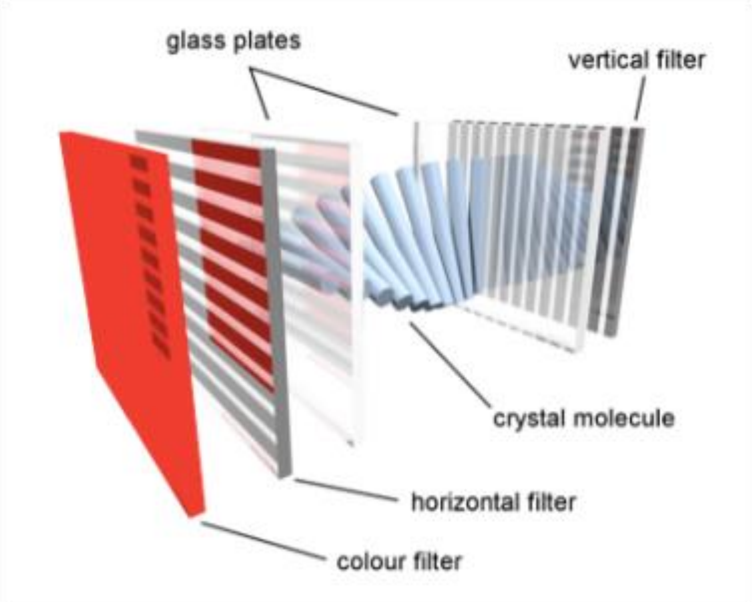
X-ray diffraction

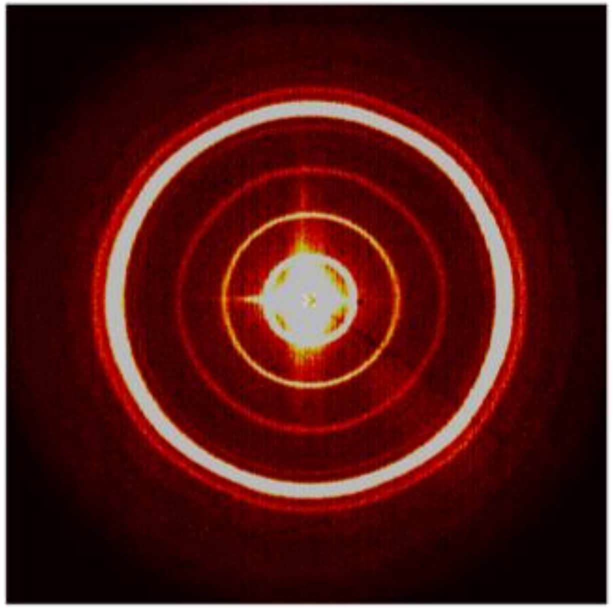


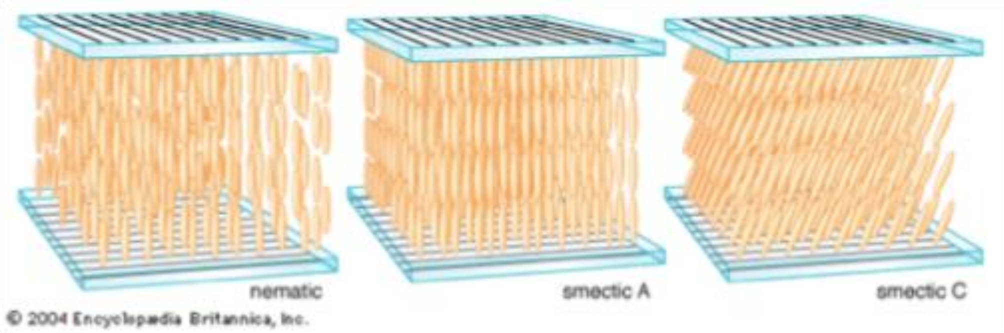




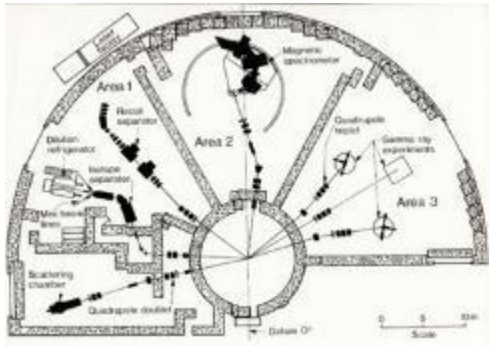
Foot and Mouth Virus

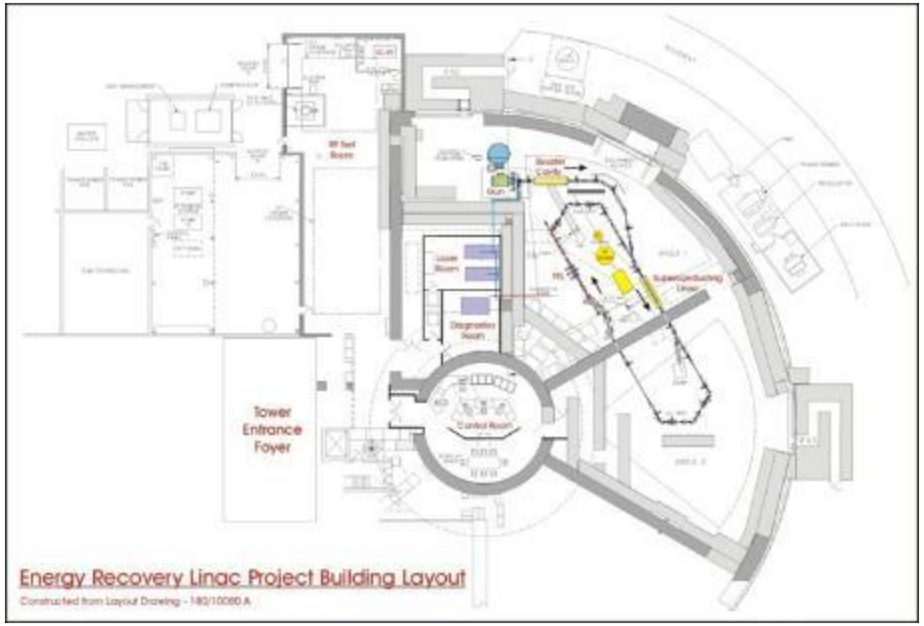

glass plates
vertical filter
crystal molecule
horizontal filter
colour filter



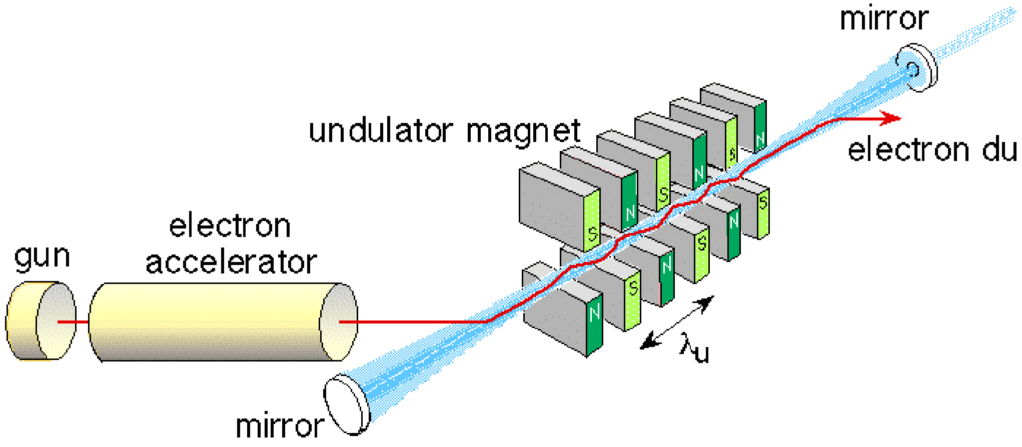

nematic
smectic A
smectic C
© 2004 Encyclopædia Britannica, Inc.

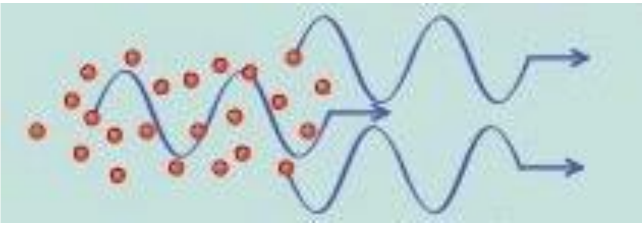
ALICE in Daresbury Tower





Oscillator Free Electron Laser (FEL) Principle

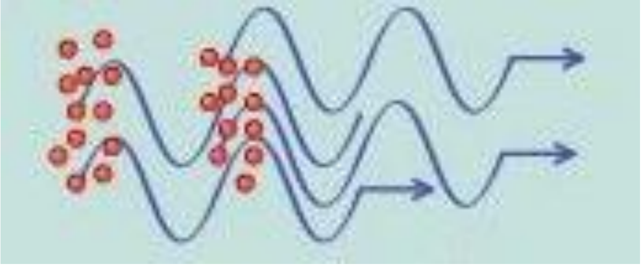




Incoherent emission:

Synchrotron Radiation

Intensity ~ N_e



Coherent emission:

Free-Electron Laser (FEL)

Intensity ~ N_e^2

- relativistic electron beam passes through periodic magnetic field - radiates
- mirror feeds spontaneous emission back onto the beam
- spontaneous emission enhanced by stimulated emission

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left[1 + \frac{K^2}{2} + \gamma^2\theta^2\right]$$

where:

$n = 1,2,3...$

$\gamma = \frac{E}{m_0c^2}, \quad K = 0.934B_0\lambda_u$

λ_u is the undulator period

(B_0 is in Tesla and λ_u is in cm)

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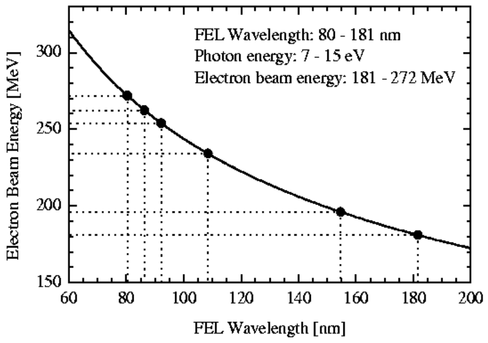
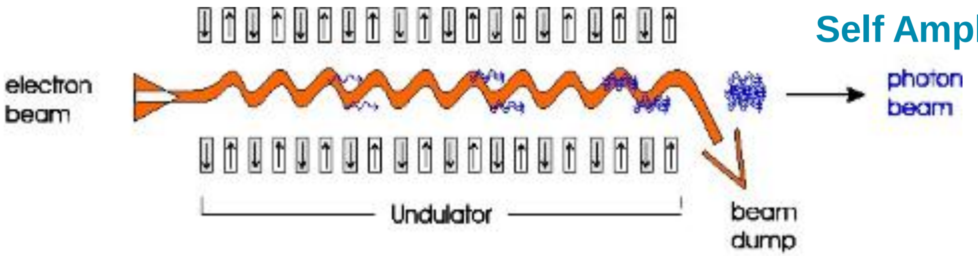
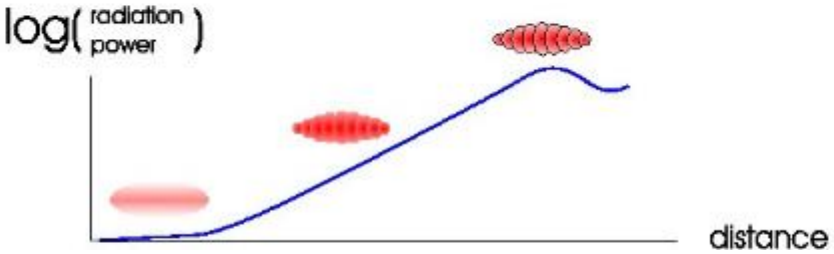
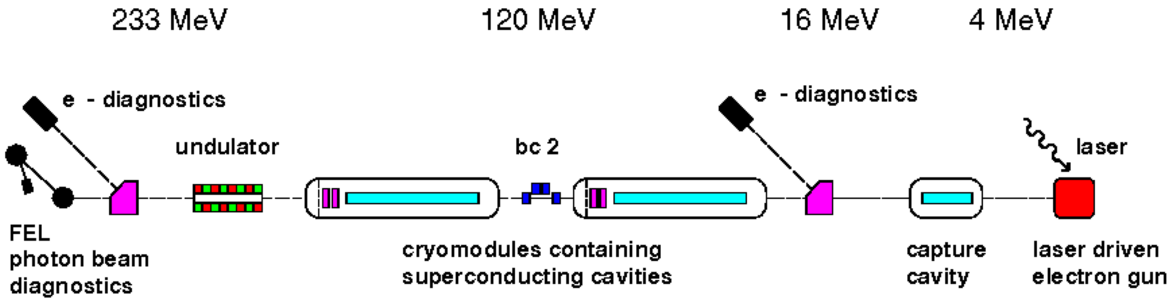
High Gain FEL - Single Pass SASE





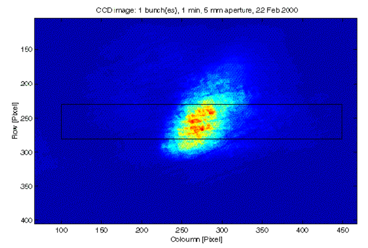
Self Amplified Spontaneous Emission (SASE)

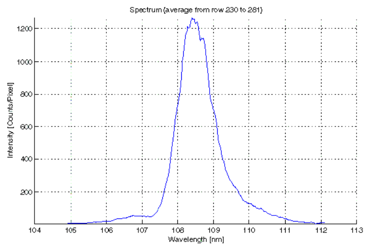


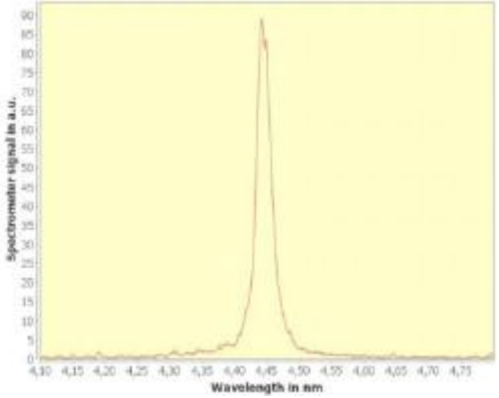


First SASE demonstration at TTF (FLASH), DESY, 2000

- electrons start emitting incoherent radiation
- radiation from the tail of the bunch interacts with electrons nearer the front, causing the electrons to bunch on the scale of the radiation wavelength
- due to the bunching, the electrons emit more coherently
- more radiation → more bunching → more radiation … *an instability*
- radiation power grows exponentially







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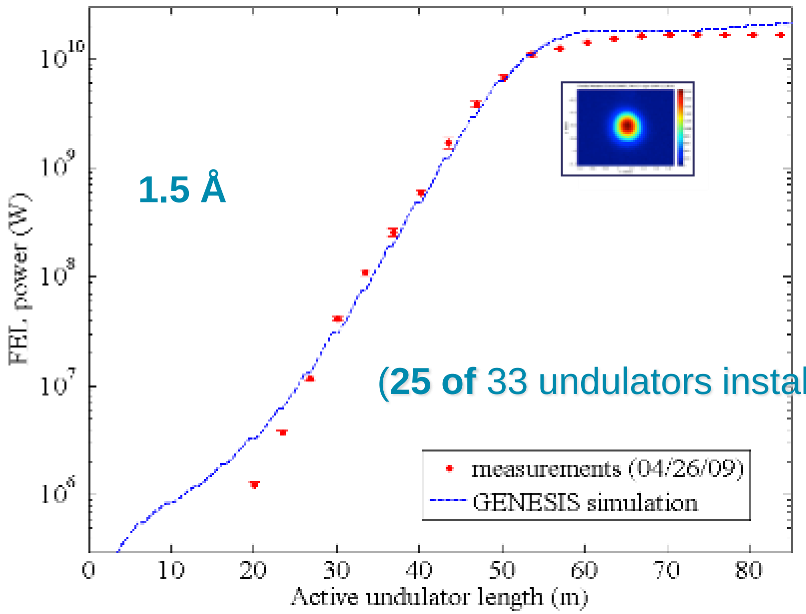
Need for very high peak currents ~ kA

June 2010 achieved 4.5 nm at 1.2 GeV

X-Ray Free-Electron Lasers



1.5 Å

(25 of 33 undulators installed)

14 GeV

$ge_{x,y}$ = 0.4 *mm* (slice)

I_{pk} = 3.0 kA

s_E/E = 0.01% (slice)

Linac Coherent Light Source

Use of 1/3 SLAC Linac

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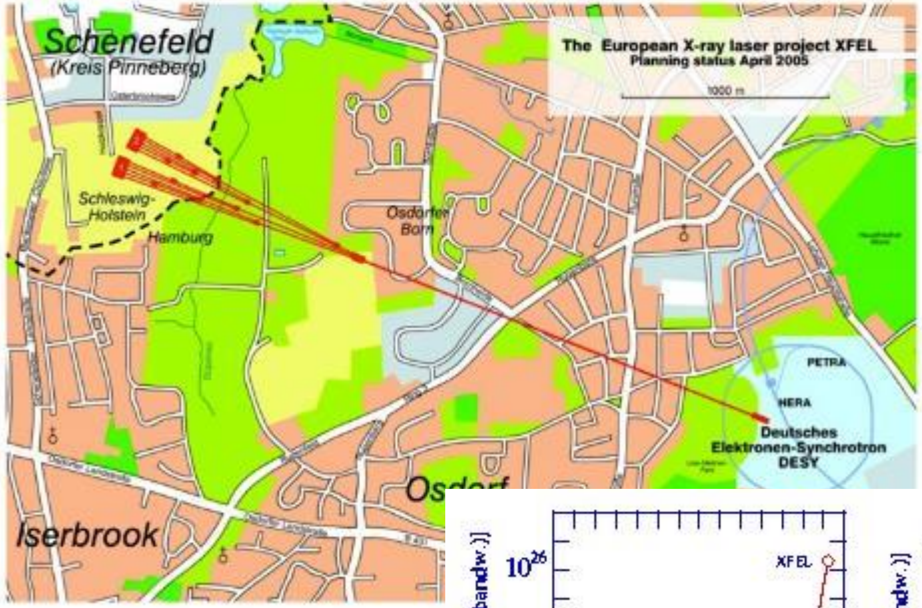
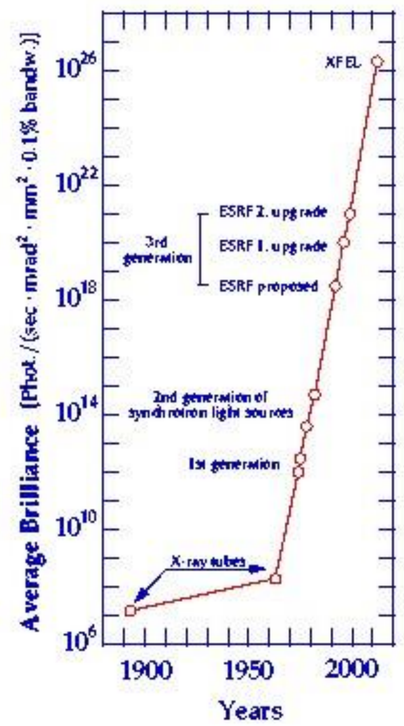
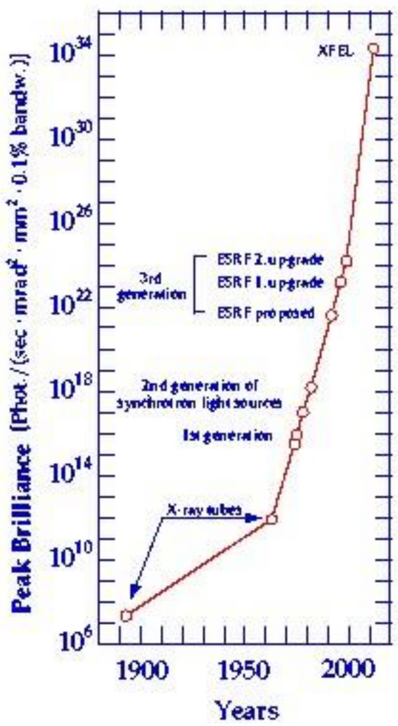
Europe's Answer: XFEL







Performance Goals for the Electron Beam	
Beam Energy Range	10 - 20 GeV
Emittance (norm.)	1.4 mrad · mm
Bunch Charge	1 nC
Bunch Length (1σ)	80 fs
Energy-Spread (uncorrelated)	<2.5 MeV rms
Main Linac	
Acc. Gradient @ 20 GeV	23 MV/m
Linac Length	approx. 1.5 km
Beam Current (max)	5 mA
Beam Pulse Length	0.65 ms
# Bunches p. Pulse (max)	3250
Bunch Spacing (min)	200 ns
Repetition Rate	10 Hz
Avg. Beam Power (max)	650 kW

Performance Goals for SASE FEL Radiation	
photon energy	15 – 0.2 keV
Wavelength	0.08 – 6.4 nm
peak power	10 – 20 GW
average power	40 – 80 W
number photon per pulse	$0.5 – 4 \times 10^{12}$
peak brilliance	$2.5 – 0.08 \times 10^{33}$*
average brilliance	$1 – 0.03 \times 10^{25}$ *

* in units of photons / (s mrad² mm² 0.1% bw)

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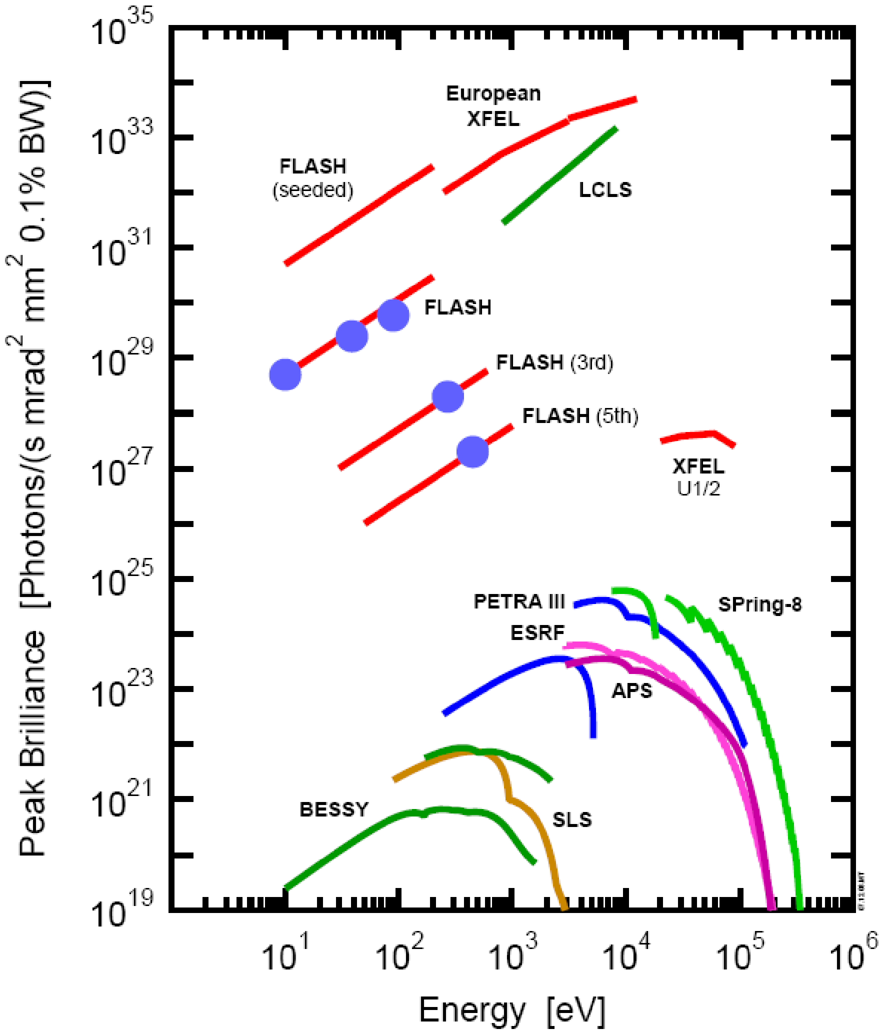
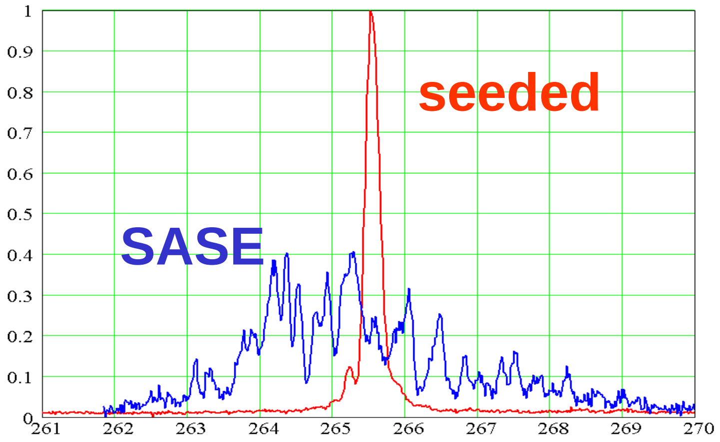
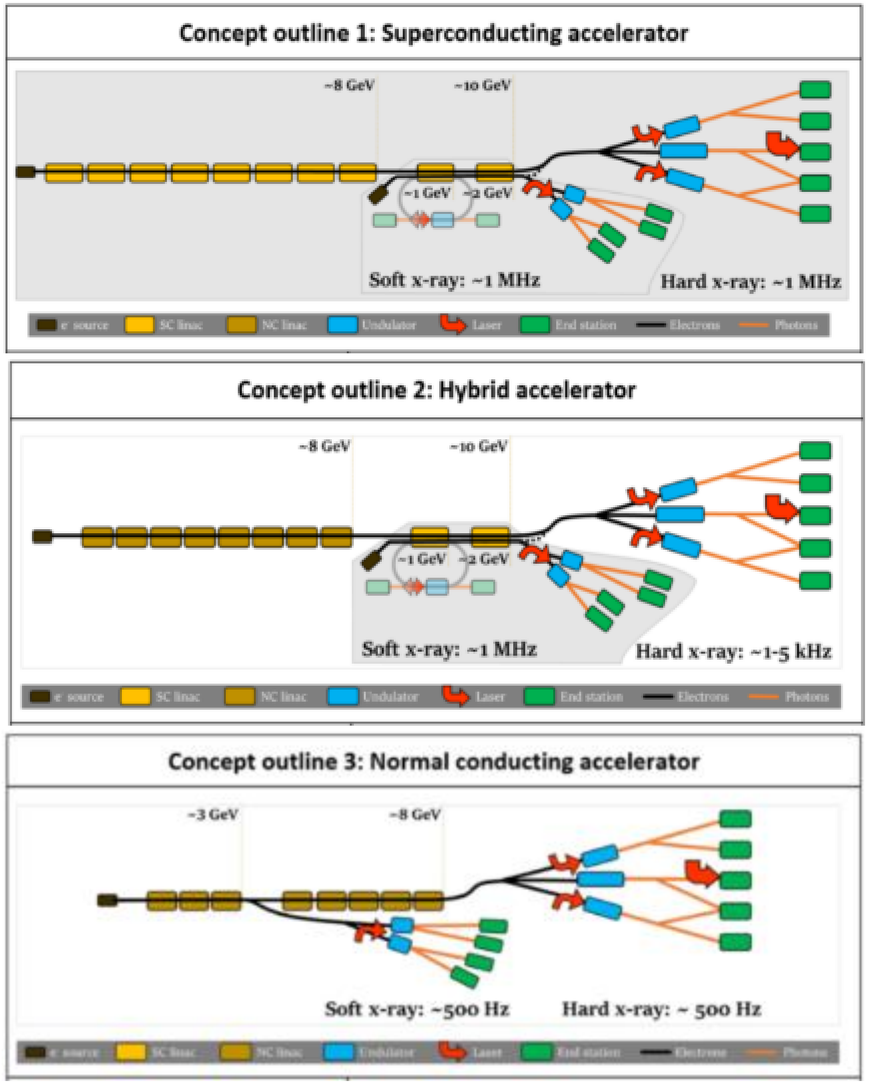
Comparison of 3rd and 4th Generation Sources

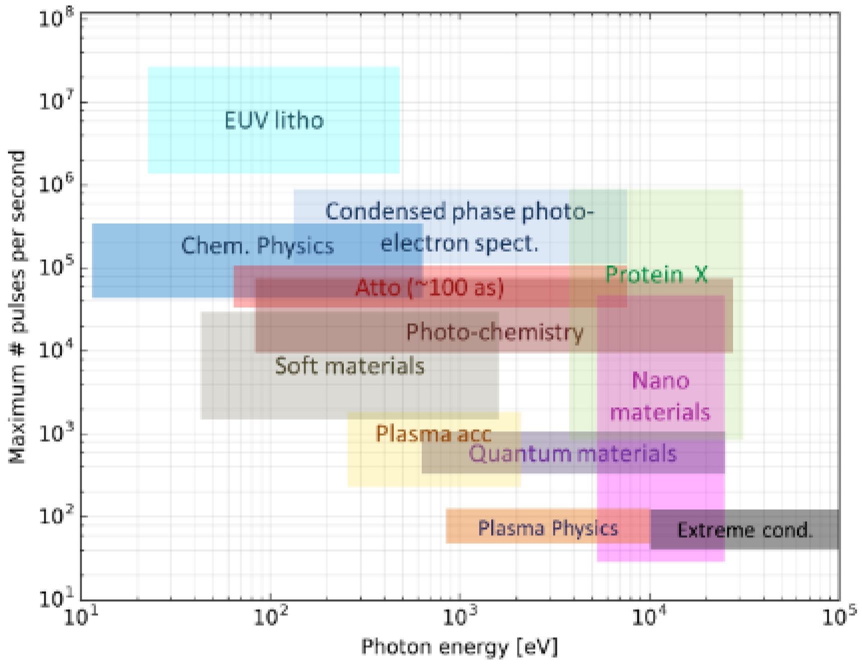




Seeding is very important for FEL beam quality

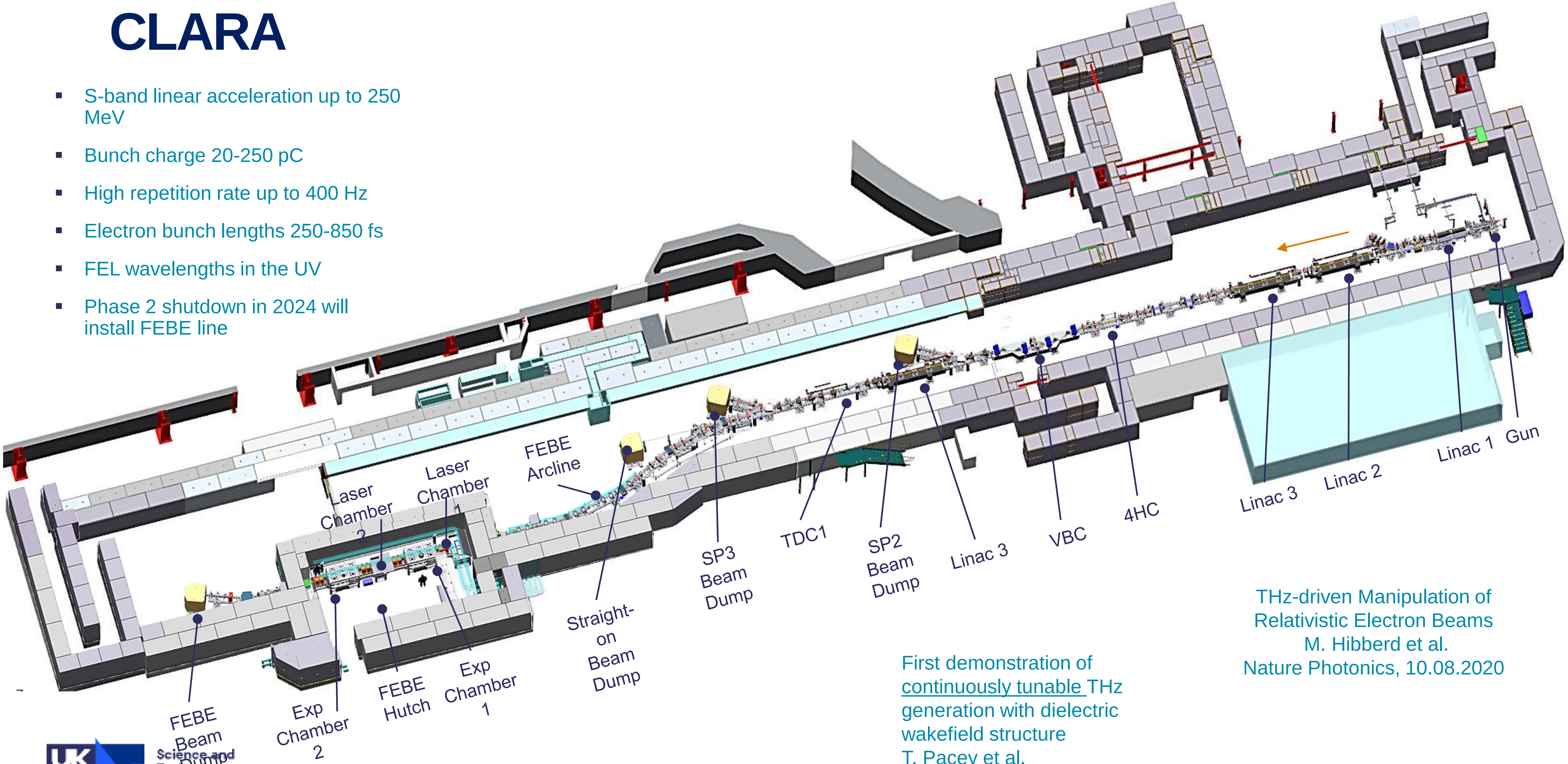
UK FEL


Concept outline 1: Superconducting accelerator
~8 GeV
~10 GeV
~1 GeV
~2 GeV
Soft x-ray: ~1 MHz
Hard x-ray: ~1 MHz
e source
SC linac
NC linac
Undulator
Laser
End station
Electrons
Photons
Concept outline 2: Hybrid accelerator
~8 GeV
~10 GeV
~1 GeV
~2 GeV
Soft x-ray: ~1 MHz
Hard x-ray: ~1-5 kHz
e source
SC linac
NC linac
Undulator
Laser
End station
Electrons
Photons
Concept outline 3: Normal conducting accelerator
~3 GeV
~8 GeV
Soft x-ray: ~500 Hz
Hard x-ray: ~ 500 Hz


Maximum # pulses per second
Photon energy [eV]
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
EUV litho
Condensed phase photo-electron spect.
Chem. Physics
Protein X
Atto (~100 as)
Photo-chemistry
Soft materials
Nano materials
Plasma acc
Quantum materials
Plasma Physics
Extreme cond.

CLARA

- S-band linear acceleration up to 250 MeV
- Bunch charge 20-250 pC
- High repetition rate up to 400 Hz
- Electron bunch lengths 250-850 fs
- FEL wavelengths in the UV
- Phase 2 shutdown in 2024 will install FEBE line



First demonstration of continuously tunable THz generation with dielectric wakefield structure
T. Pacey et al.
PRAB 22, 091302, 2019

THz-driven Manipulation of Relativistic Electron Beams
M. Hibberd et al.
Nature Photonics, 10.08.2020

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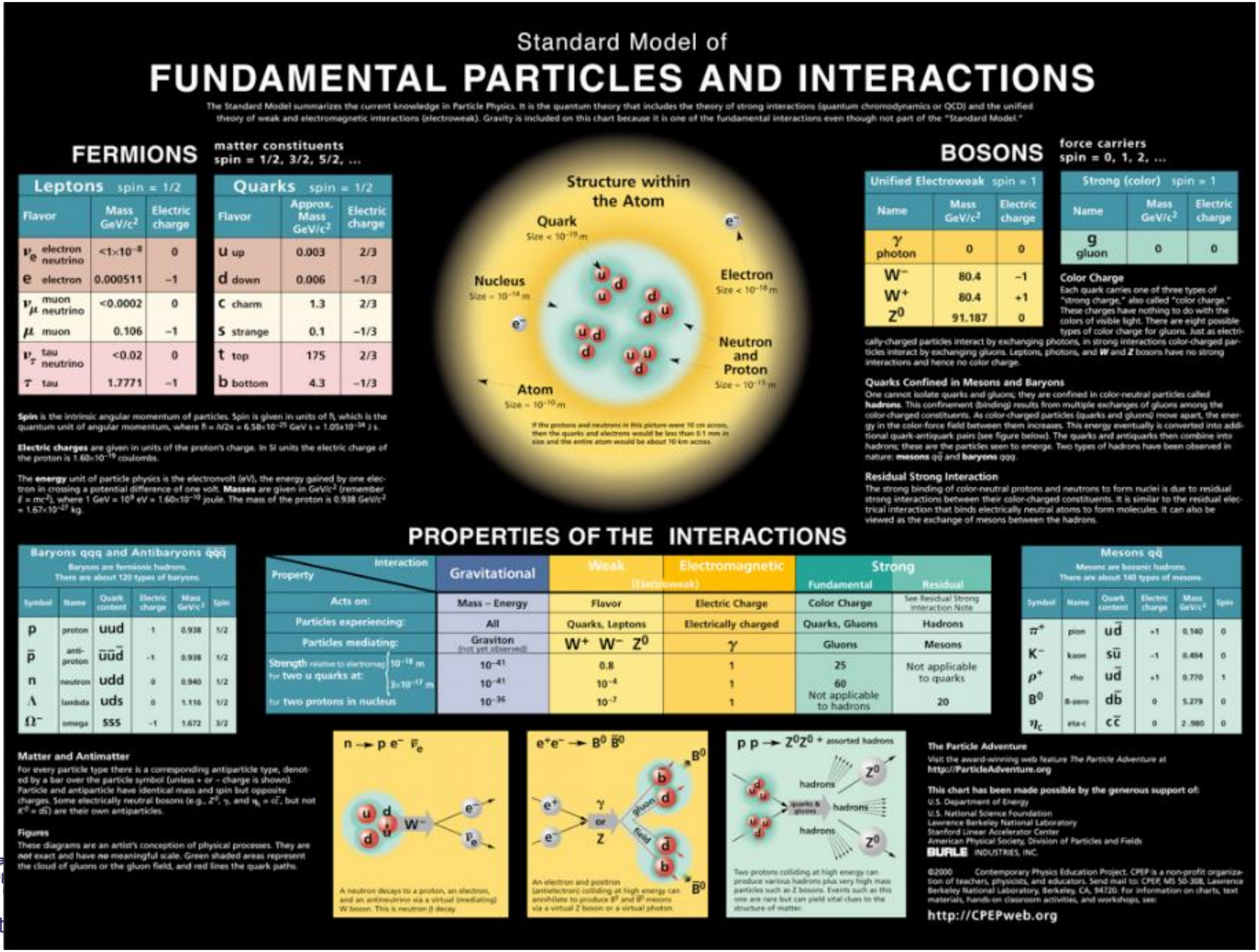

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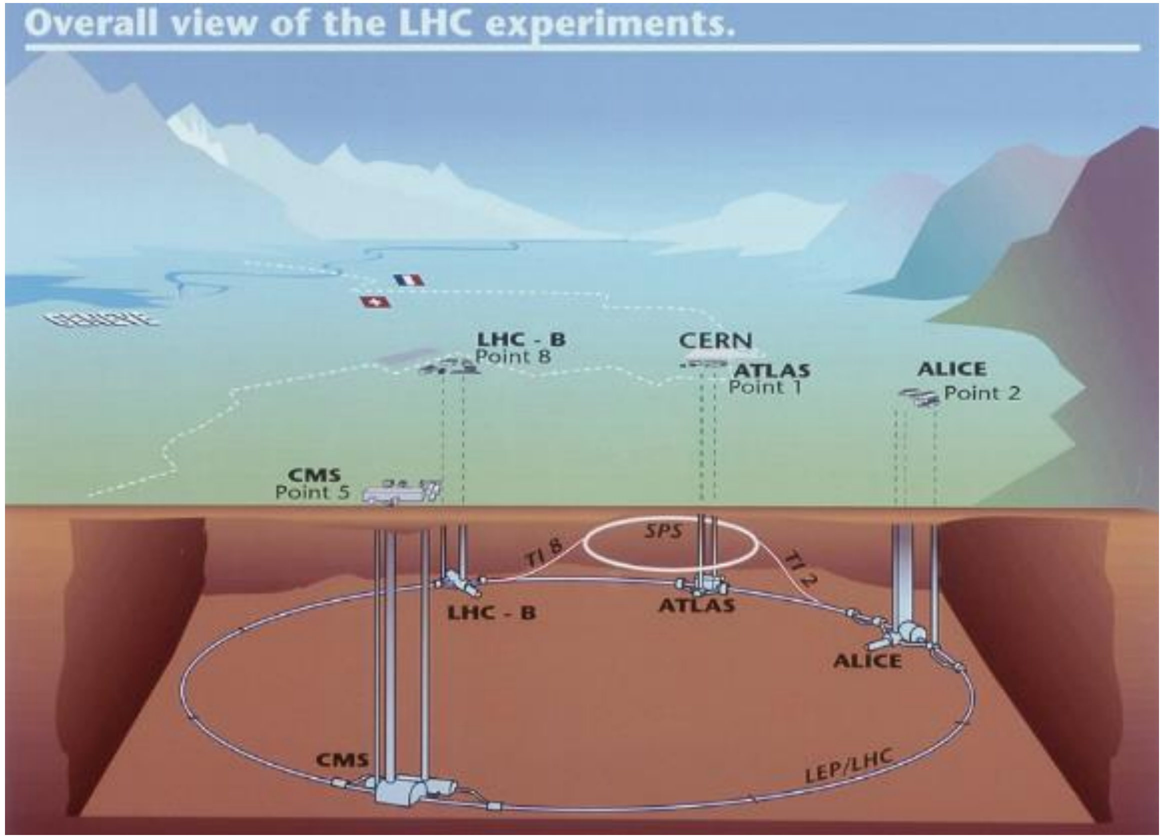
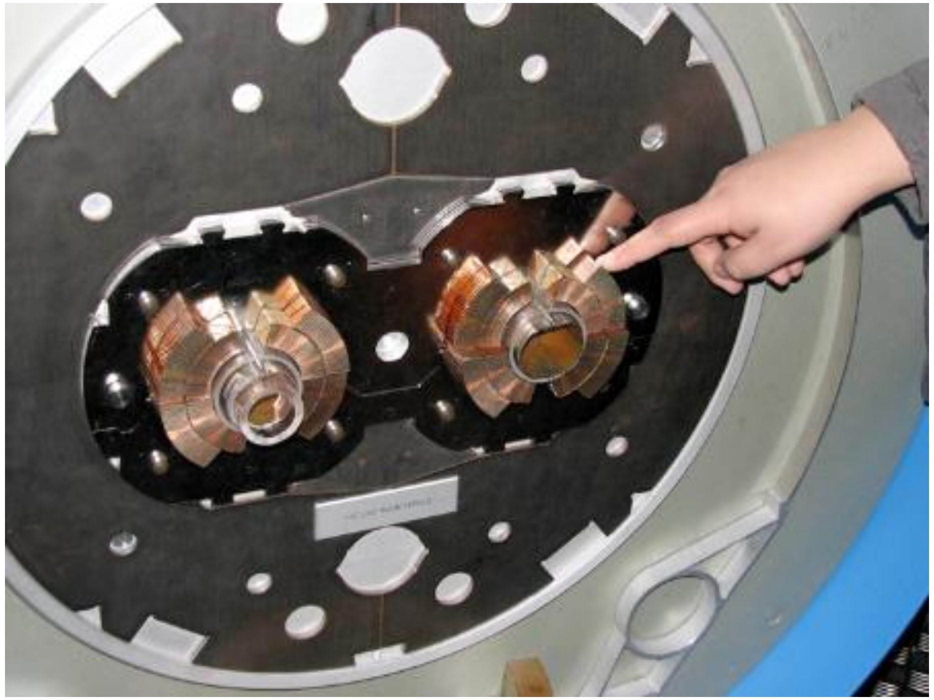
LHC

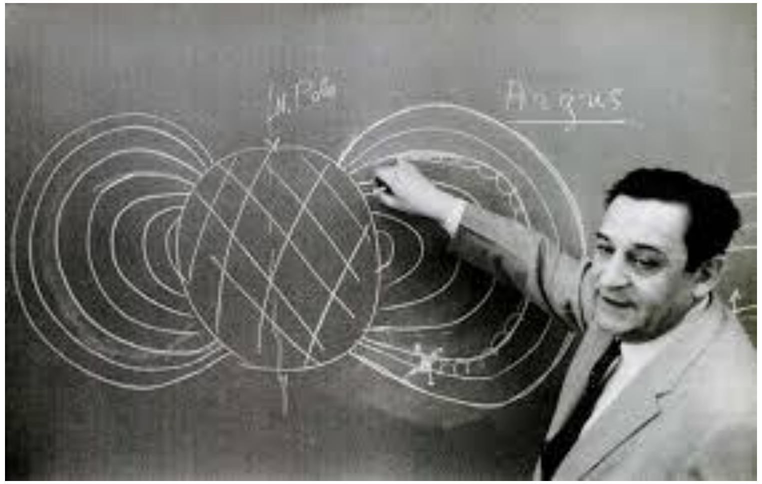

LHCb
ATLAS
CERN
SUISSE
FRANCE
CMS
ALICE
SPS 7 km
LHC 27 km

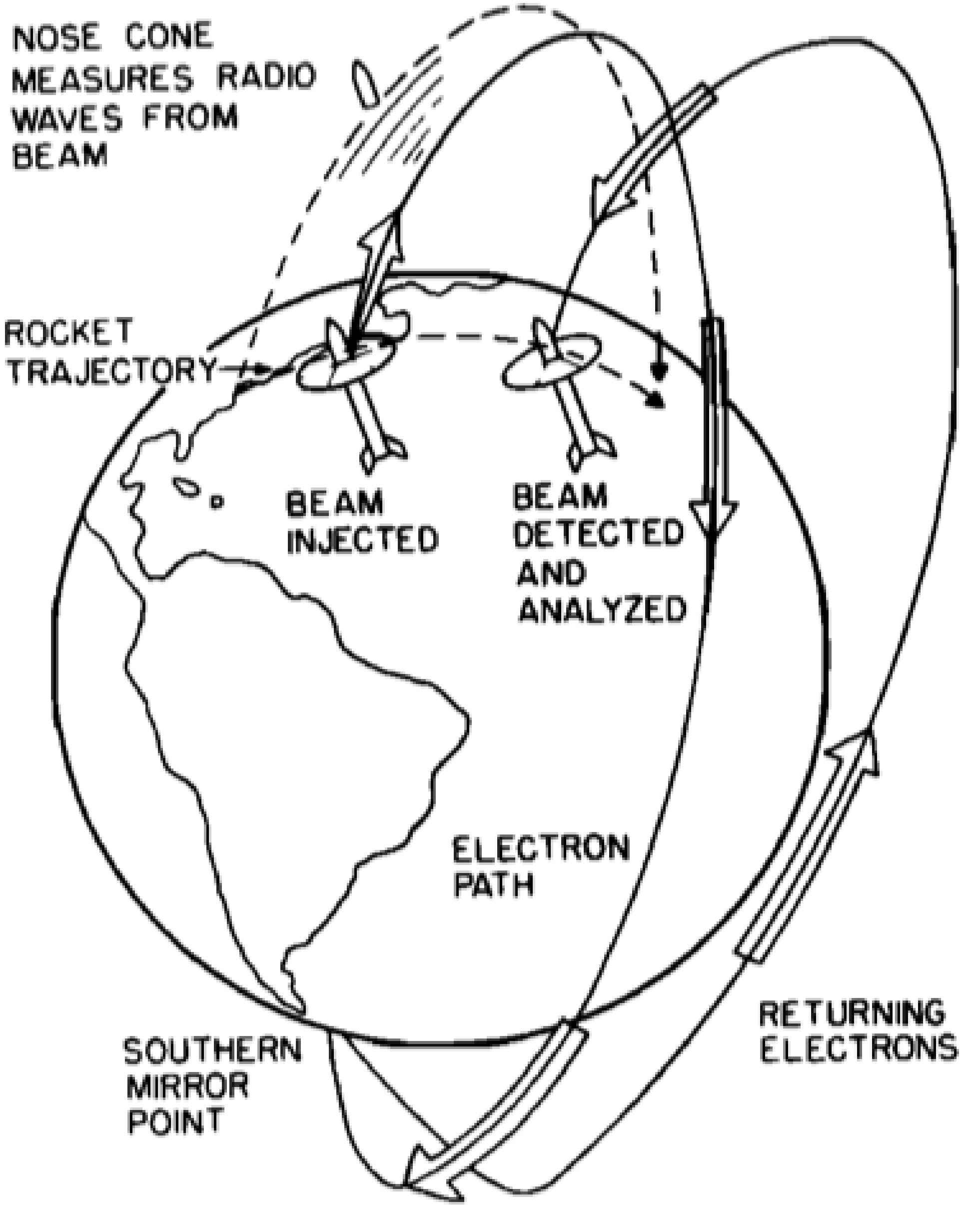

Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC



Circumference	26659 m
Dipole temperature	1.9 K
Lattice	FODO
Number of arcs/straights	8
Cells per arc	23
Number of magnets	9300
Nominal collision energy	7 TeV/c
Peak dipole field/current	8.33 T/11800 A
Stored energy in beam	360 MJ
Number of bunches per beam	2808
Number of protons per bunch	1.15 x 10^11
Number of turns per sceond	11245
Collisions per second	600 million

Think Big!




NOSE CONE MEASURES RADIO WAVES FROM BEAM
ROCKET TRAJECTORY
BEAM INJECTED
BEAM DETECTED AND ANALYZED
ELECTRON PATH
SOUTHERN MIRROR POINT
RETURNING ELECTRONS