Introduction to Accelerators III – Applications – E. Wilson

- **Low energy irradiation of material**
- **Dose and beam power**
- **Synchrotron light sources (ESRF)**
- **The cone of synchrotron radiation**
- **The spectrum**
- **The scale of things**
- **Diffraction**
  Lithography
- **Brightness**
- **Spallation source**
- **GSI – Ions Galore!**
- **HYOGO (JPN)- Ion beam medical center**
- **Energy amplifier**
- **Inertial confinement**
- **The development of accelerators**
- **Need for higher energy**
- **Center of mass *v.* Fixed target**
- **Luminosity**
- **CLIC**

Fig.

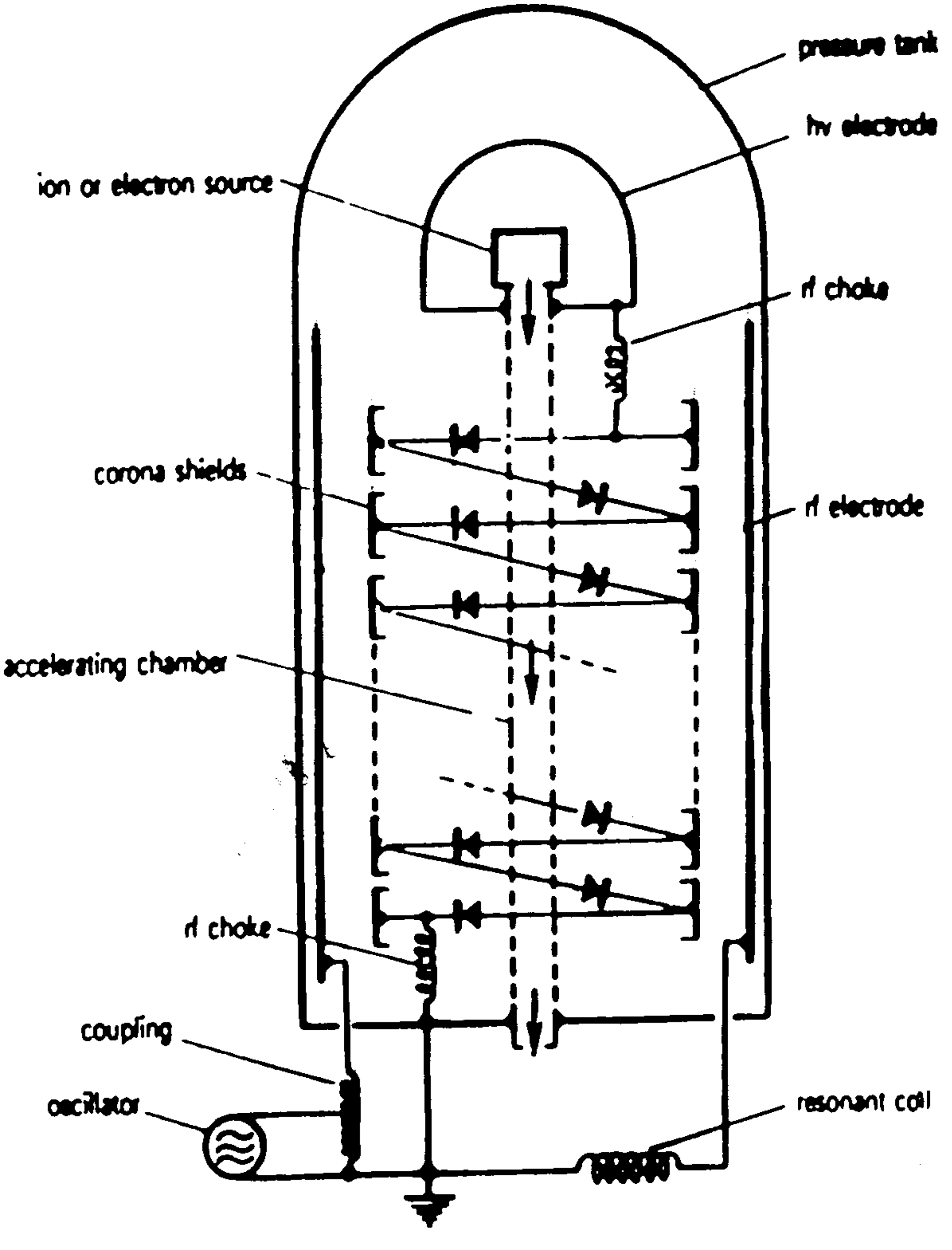
Accelerators world-wide

Table II – Particle accelerator family worldwide (items 2 to 6: lack of exact statistics, authors estimation only)

Category of accelerators	Number in use
(1) High Energy Accelerators	112
BIOMEDICAL ACCELERATORS	
(2) Radiotherapy	> 4000
(3) Research including Biomedical Research	800
(4) Medical Radioisotope Production	~ 200
(5) Accelerators in Industry	~ 1500
(6) Ion Implanters	> 2000
(7) Surface Modification Centres and Research	~ 1000
(8) Synchrotron Radiation Sources	~ 50
Total in 1994	~ 9962
TOTAL estimated for 1995	~10,000

Fig.

Dynamitron

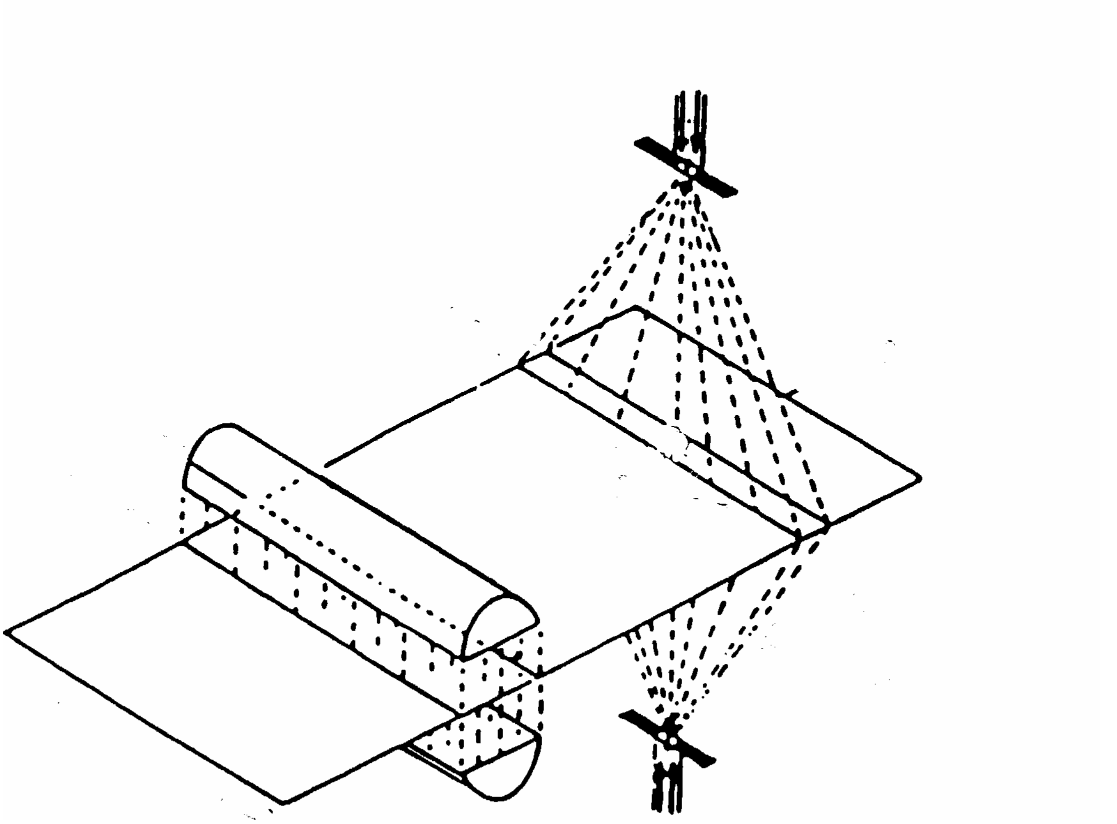


Dynam2.pct

Fig.

Low energy irradiation of material

- **Electrons are easy to produce, accelerate and shield**
- **Use an energy below the nuclear reaction threshold of 10 MeV. (7 MeV in some cases)**



$$\text{stopping power } = dE/dx \approx 1.8 \text{ MeV.cm}^2.\text{g}^{-1}$$

$$\text{maximum thickness} = \frac{1.5E}{(dE/dx)} \text{ g.cm}^{-2}$$

$$\approx 2.5 \text{ g.cm}^{-2} \text{ for } E = 3\,\text{MeV}$$

Fig. **Sharf 8.2.jpg**

Production line for sterilization

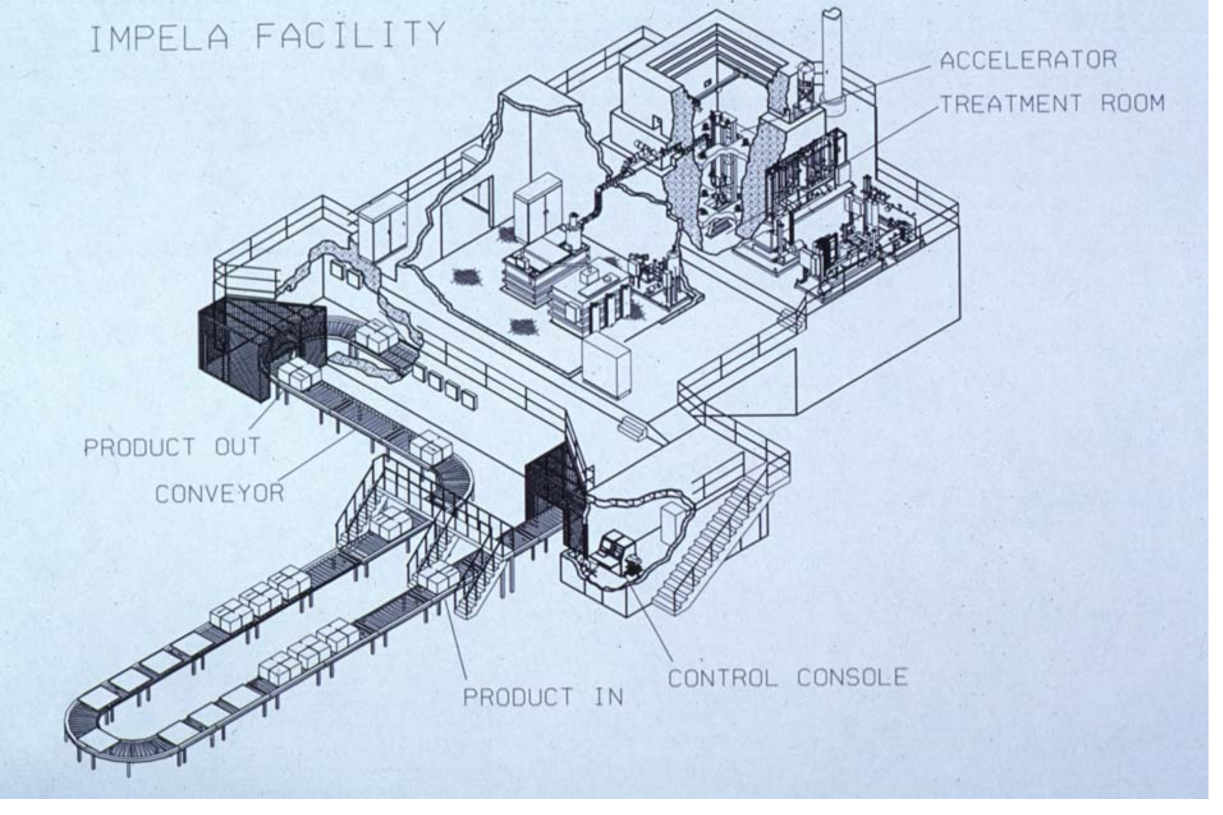


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Fig.

Dose and beam power

- **A milliamp of particles, each losing 2 MeV, passing through a 1 cm cube of material will for one second will deposit a total energy of**

$$10^{-3} \times 2\ 10^{6} = 2.10^{3}\ \text{Joules}$$

- **This corresponds to a (beam) power of 2 kW**
- **1 Gy is 1 Joule per kilo and if the density of the cube is 1 this will be a dose of**

$$10^{-3} \times 2\ 10^{3} = 2\ \text{Gy}$$

- **This is not much and we need several kGy to disinfect material say 100 kW for 20 seconds**
- **The dose would be the same for a thin film but we can use a lower energy and reach a much higher dose – 250 kGy to polymerize film.**

Fig.

Methods of analysis by scattering

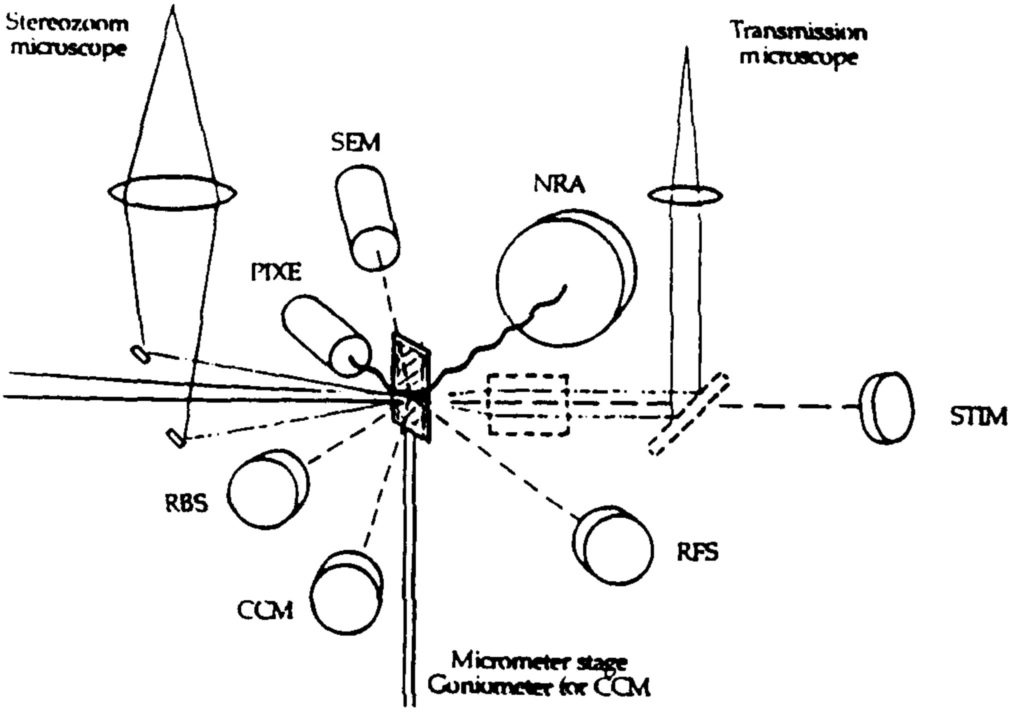
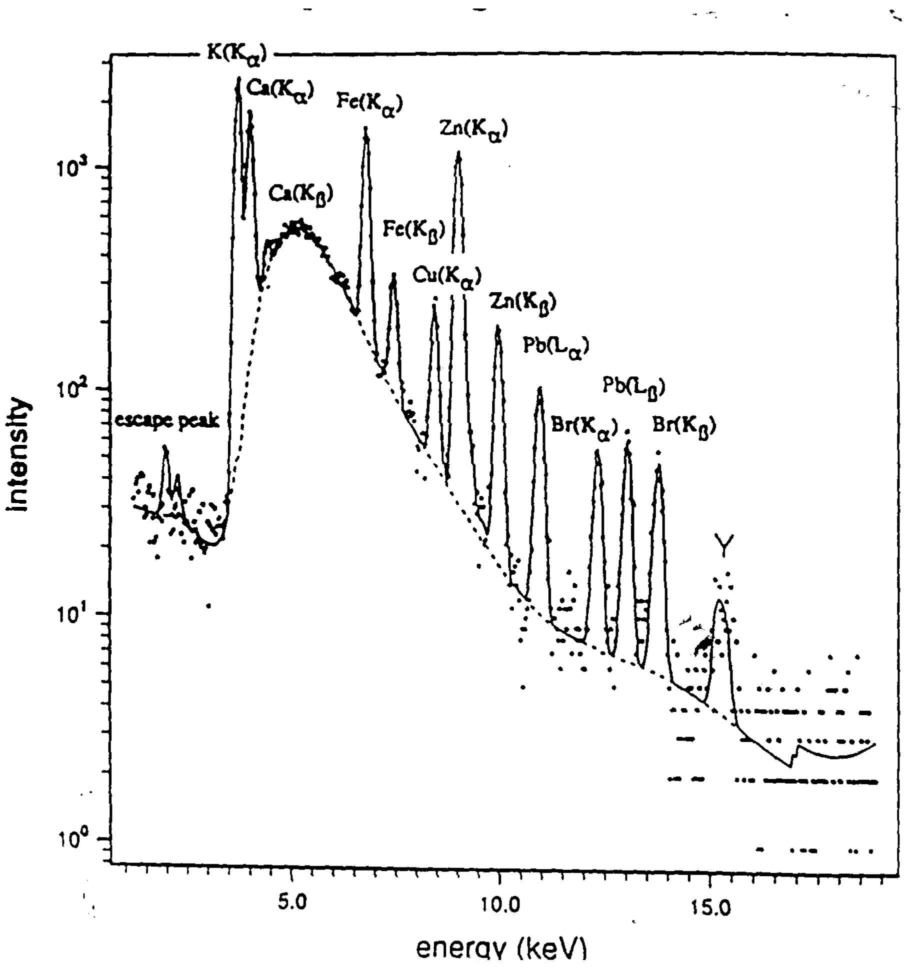


Fig.

Spectrum from PIXE analysis



PIXE.pct

Fig.

Scanning a lorry for drugs

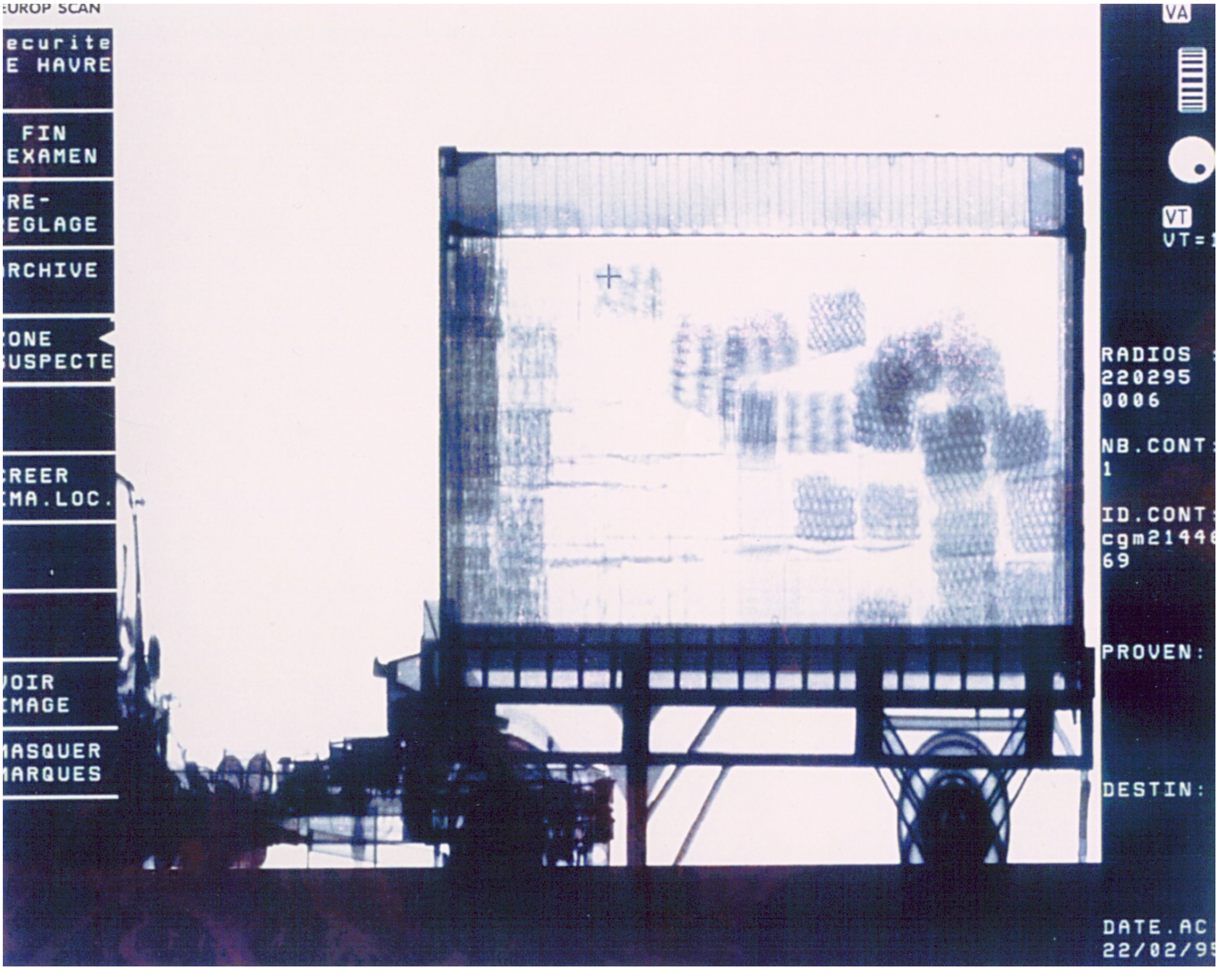


Fig.

Synchrotron light sources (ESRF)

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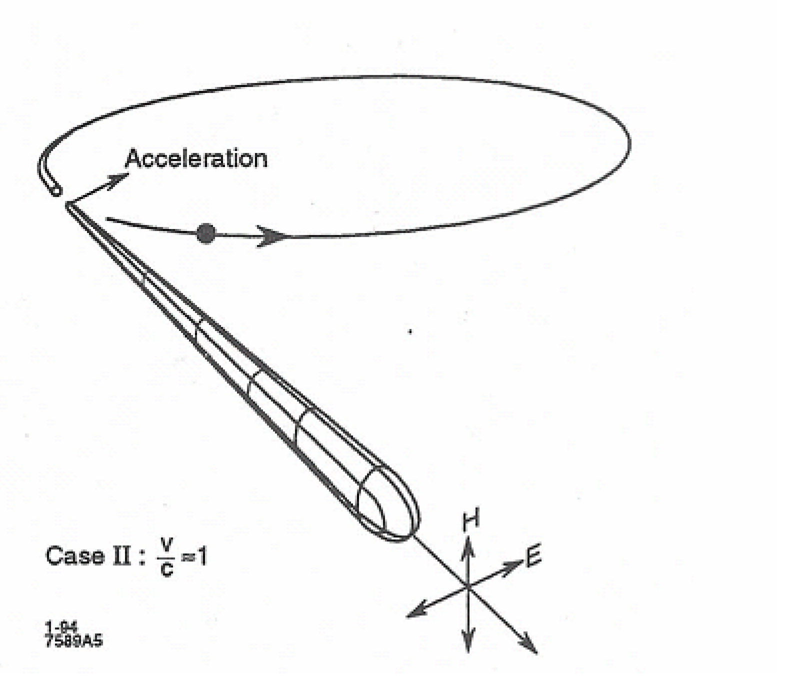
Fig.

The cone of synchrotron radiation



- **When an electron is bent in a circle it radiates synchrotron “light” along a tangent in a narrow cone (opening angle = 1/γ)**

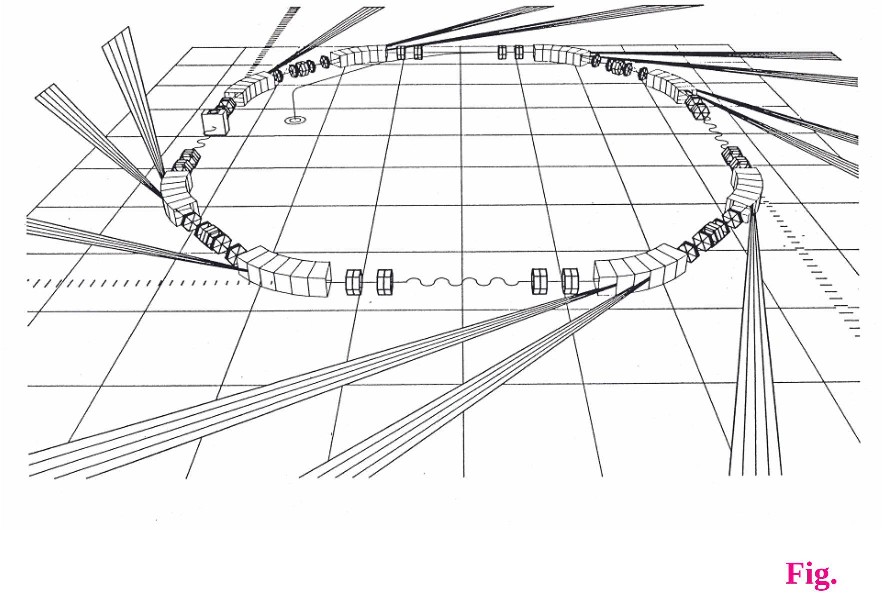
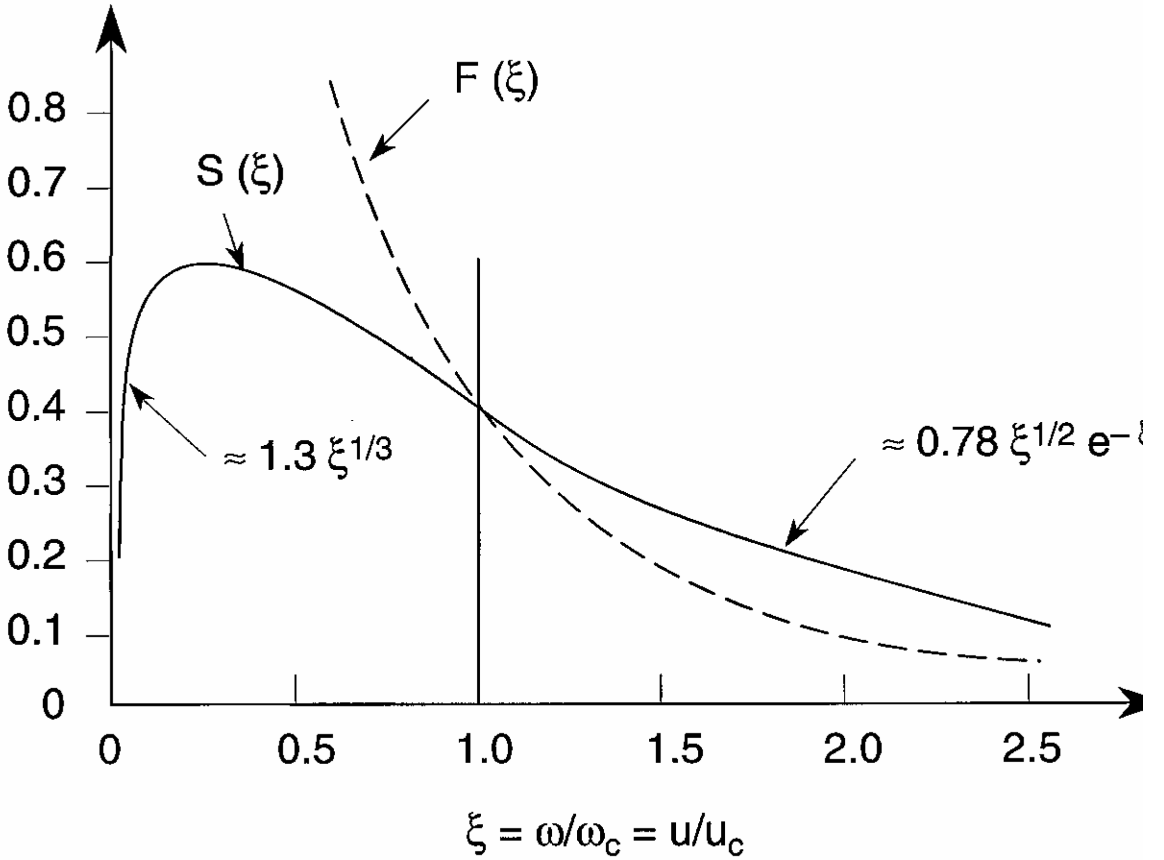


Fig.

The spectrum



- **Spectrum is broad and looks the same when normalized to**

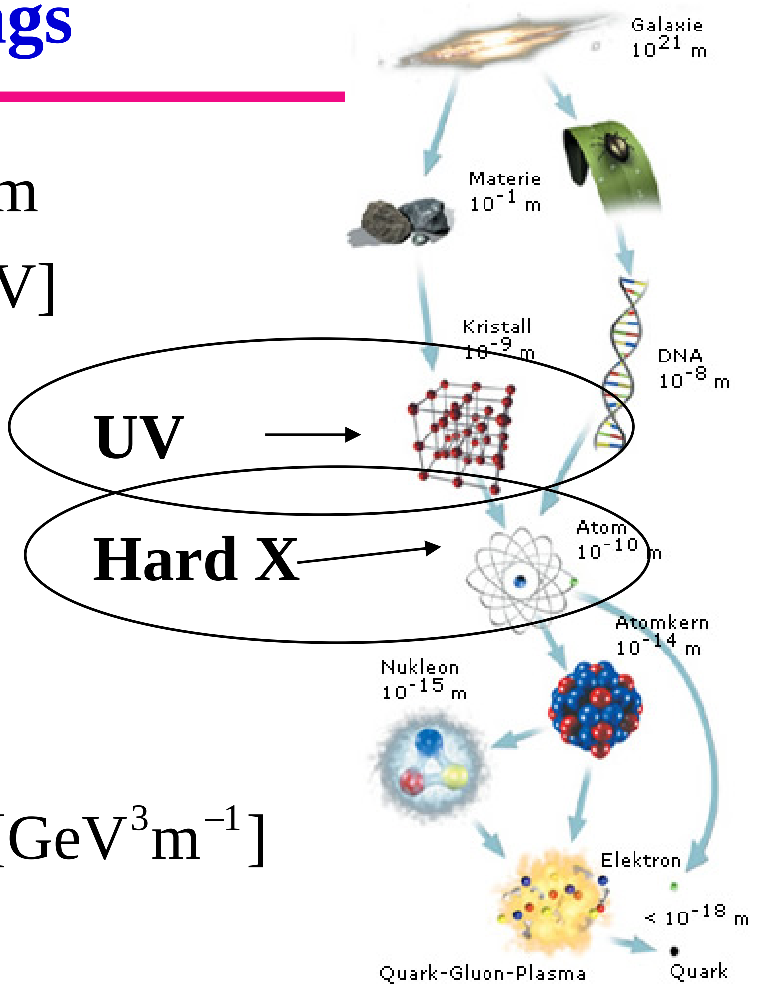
$$u_c = \hbar\omega_c = \frac{3}{2}\frac{\hbar c\gamma^3}{\rho}$$

- **Every quantity is normalized to the frequency of a characteristic quantum which is proportional to** u_c

Fig.

The scale of things

$$1\,\text{angstrom} = 10^{-10}\ \text{m}$$
$$= 12.4/E_{photon}\quad [\text{MeV}]$$

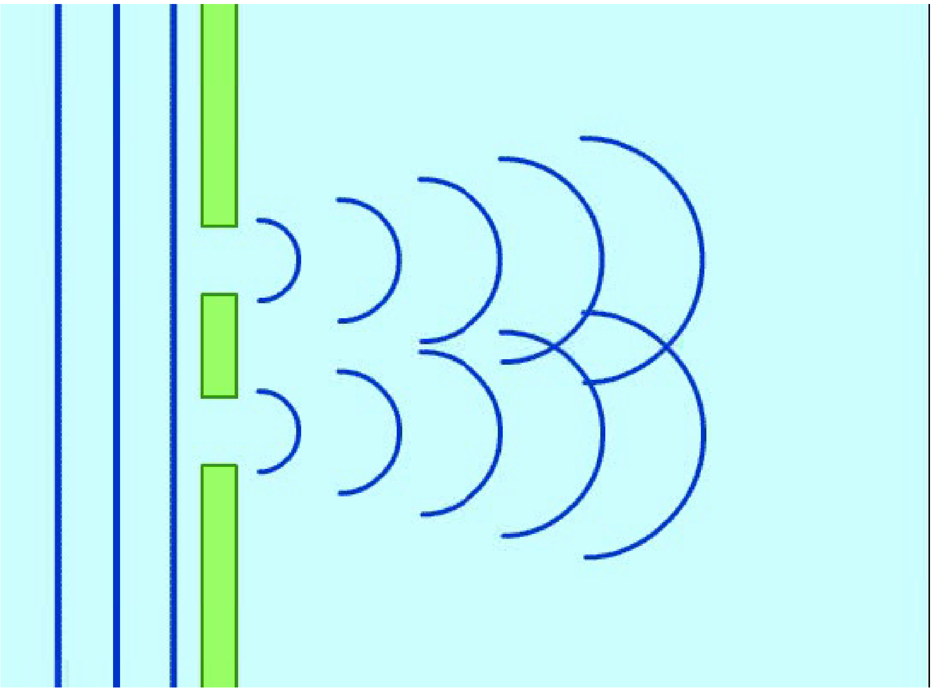


$$E_{photon} = 2218\,\frac{E^3_{beam}}{r}\,[\text{GeV}^3\text{m}^{-1}]$$

	Energy [GeV]	**Photon [keV]**	**λ [A]**	
BESSY-I	**0.8**	**0.64**	**19.4**	**UV**
HELIOS	**0.7**	**1.5**	**8.5**	**UV**
SRS	**2.0**	**3.2**	**3.9**	**Hard X**
ESRF	**6.0**	**20.7**	**0.60**	**Hard X**
LEP	**50.0**	**88.5**	**0.14**	**Hard X**

Fig.

Diffraction



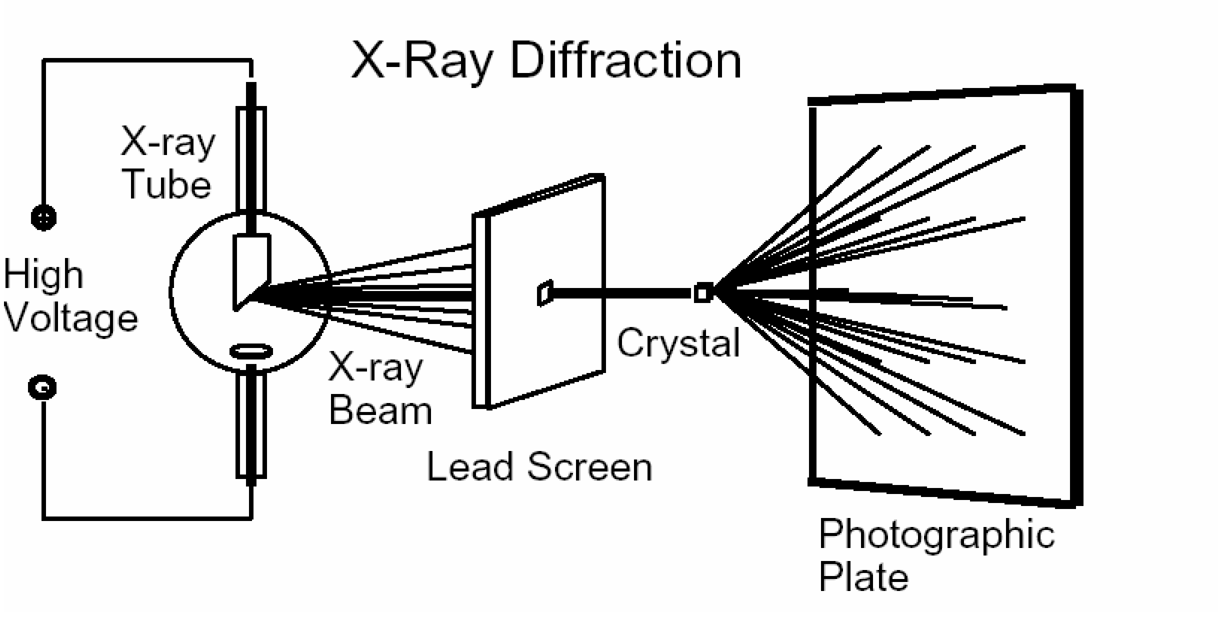


Fig.

Diffraction experiment (synch.rad)

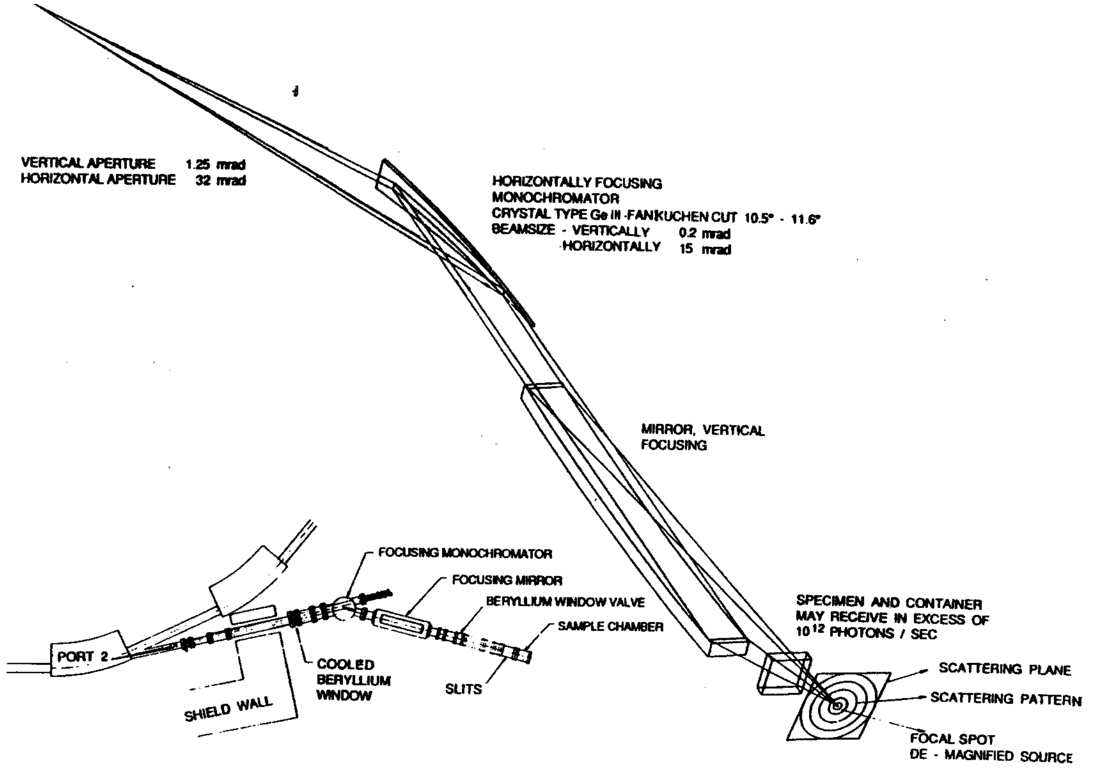


Fig. 2 Practical implementation of X-rav lens

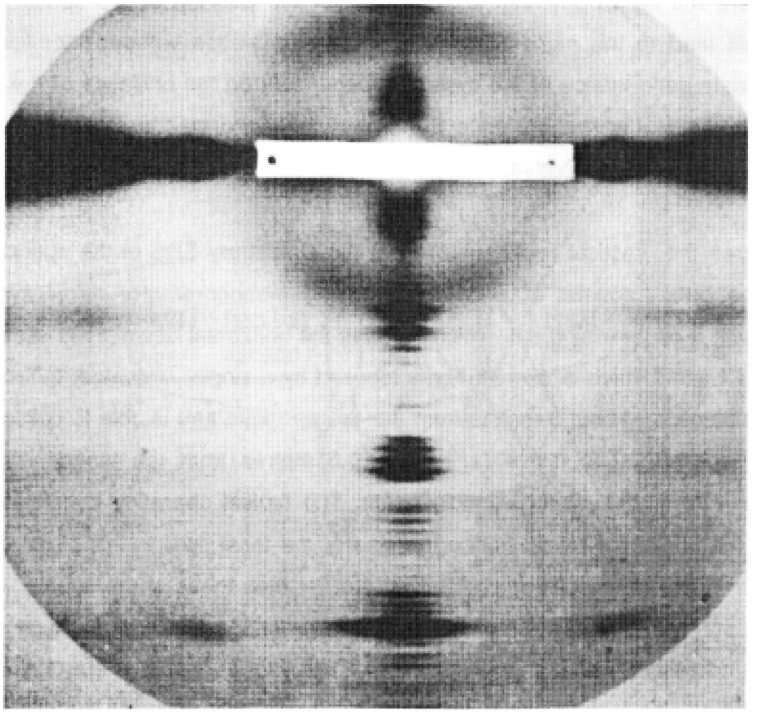
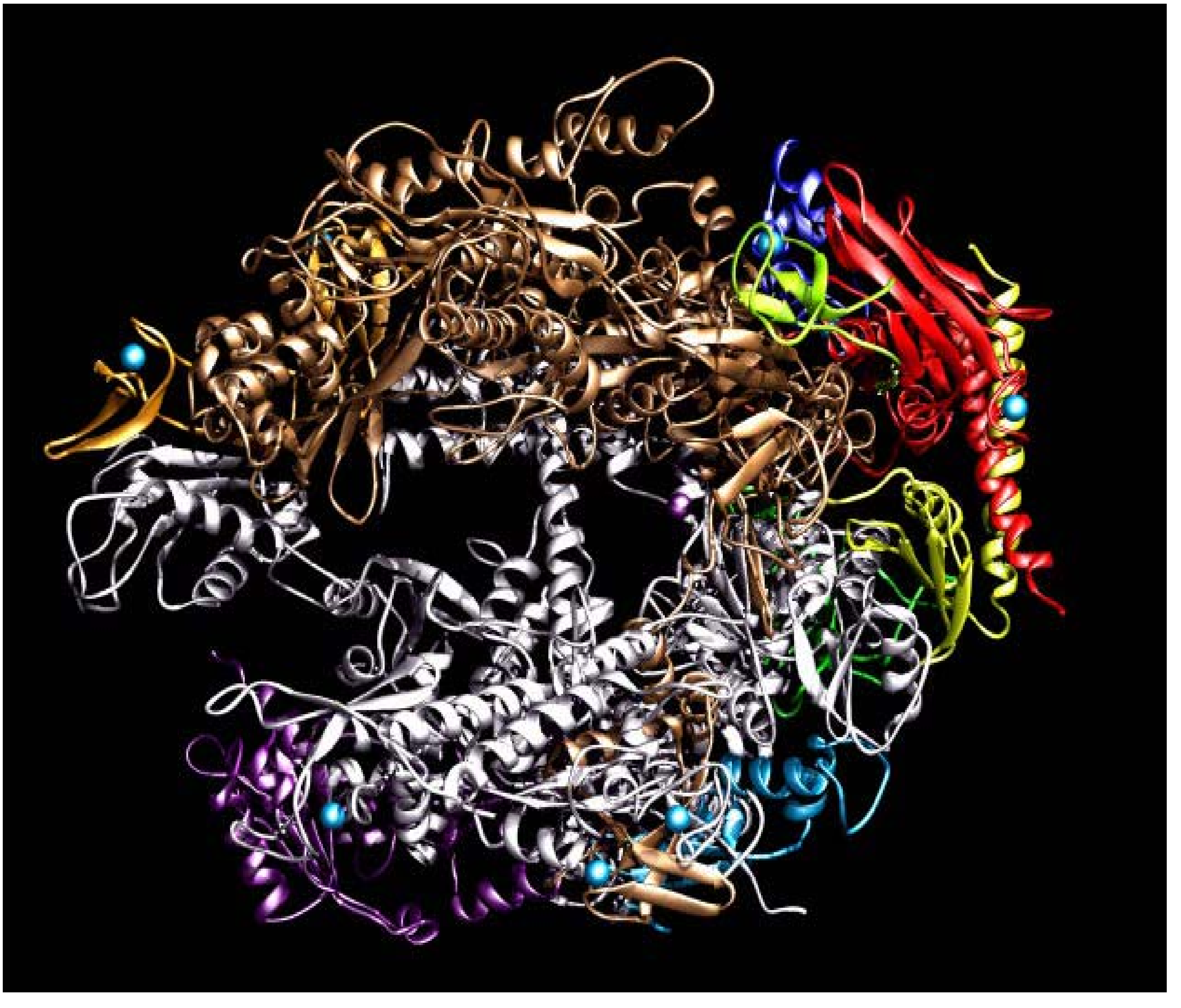


Fig. 3 Diffraction diagram from frog semitendinosus muscle

Diff-phot.pct
Diff-diag.pct

Fig.

A very complex molecule



- **RNA Polymerase – the structure that enables the code for each protein to be used to make each protein**

Fig.

Lithography in practice

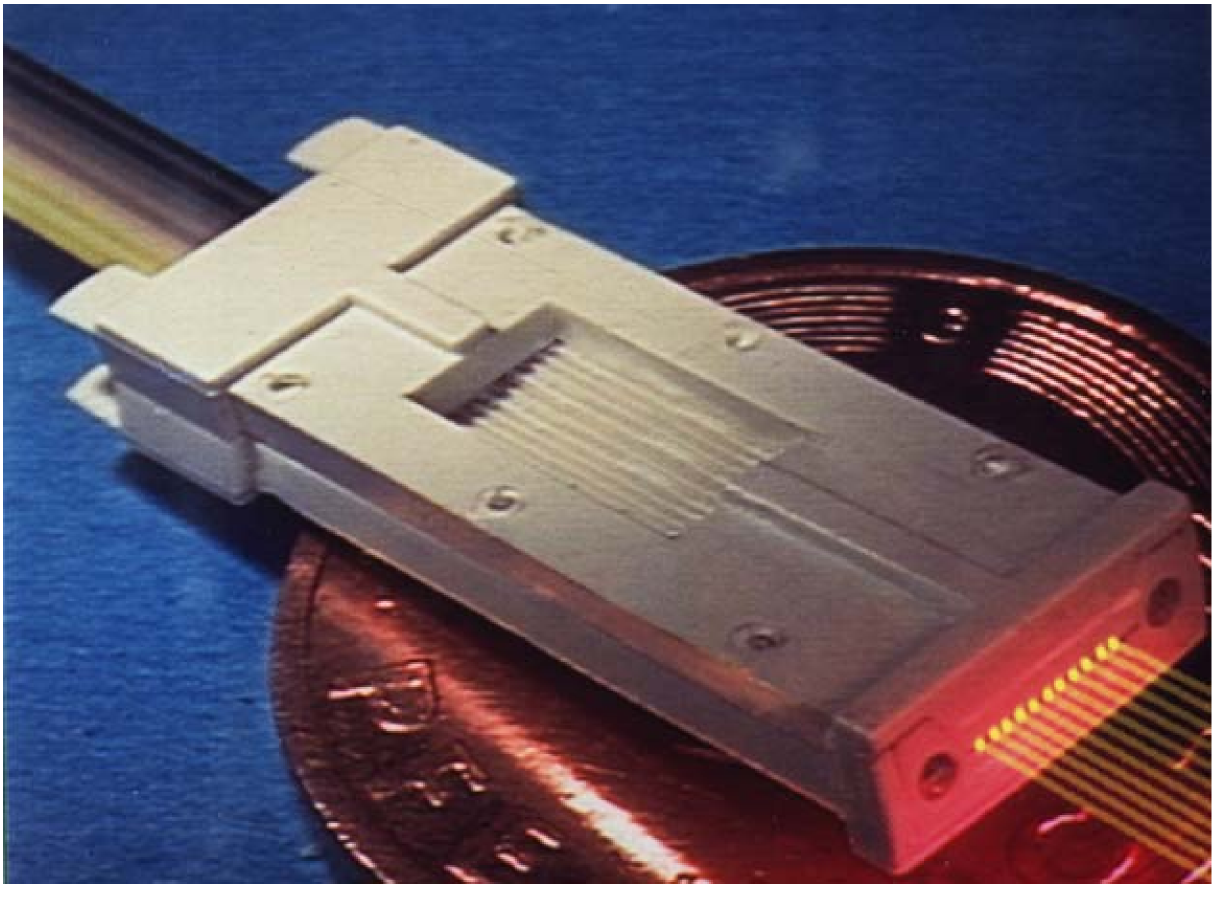


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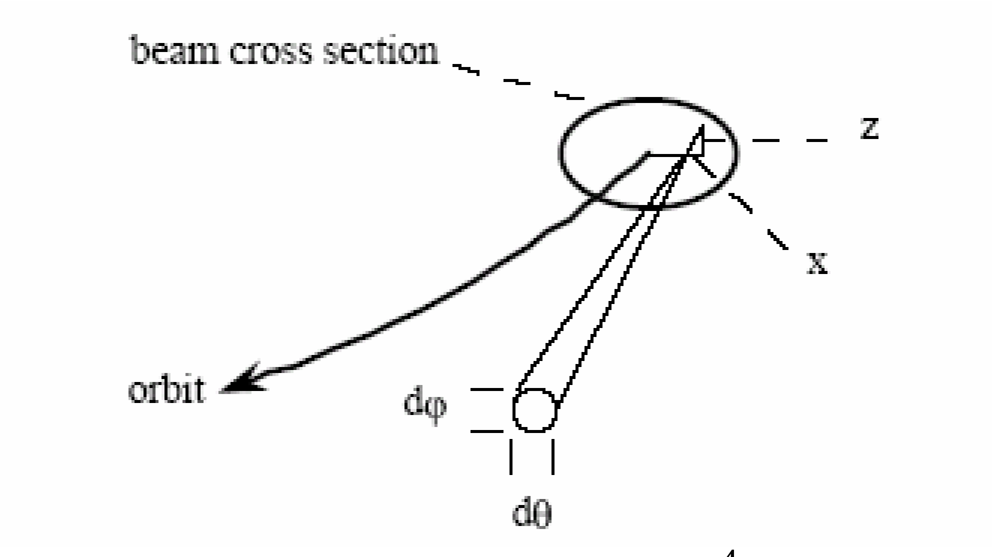
Fig.

Brightness (importance of small emittance)



$$\text{Brightness} = \frac{d^4}{dx\,dz\,d\theta\,d\phi}$$

$$= \frac{dF/d\theta}{2.36\sigma_x 2.36\sigma_z 2.36\sigma_\gamma}$$

where $dF/d\theta$ is the vertically integrated flux

$$\sigma_\gamma \approx \frac{1}{2\gamma}$$

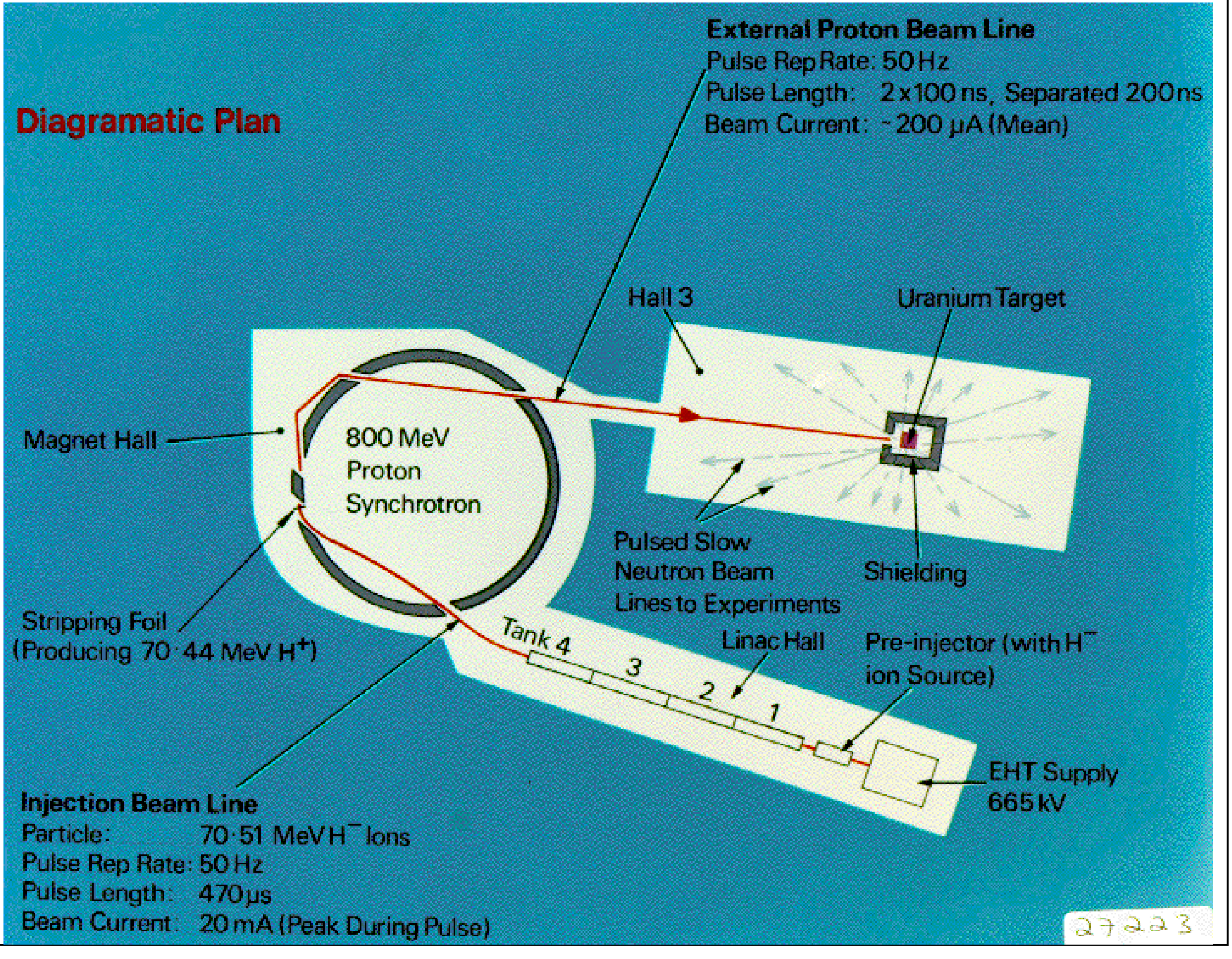
- **Brightness is measured in :**

  photons/sec/mm^2 / mr^2 / 0.1% bandwidth

- **Wigglers and undulators enhance this!**

Fig.

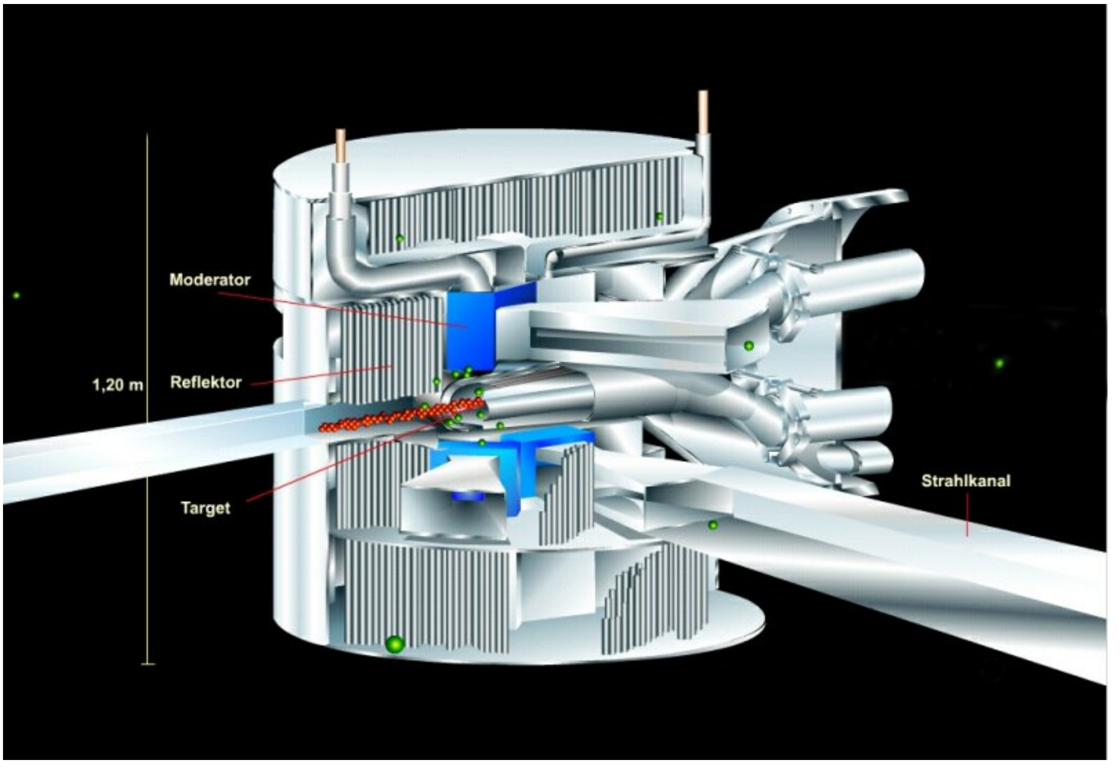
ISIS



Diagramatic Plan
External Proton Beam Line
Pulse Rep Rate: 50 Hz
Pulse Length: 2 x 100 ns, Separated 200 ns
Beam Current: ~200 μA (Mean)
Hall 3
Uranium Target
Magnet Hall
800 MeV
Proton
Synchrotron
Pulsed Slow
Neutron Beam
Lines to Experiments
Shielding
Stripping Foil
(Producing 70·44 MeV H+)
Tank 4
3
2
1
Linac Hall
Pre-injector (with H⁻
ion Source)
EHT Supply
665 kV
Injection Beam Line
Particle: 70·51 MeV H⁻ Ions
Pulse Rep Rate: 50 Hz
Pulse Length: 470 μs
Beam Current: 20 mA (Peak During Pulse)
27223

Fig.

Spallation source (ESS)



Average Beam Power: 2 x 5 MW

Average Neutron Flux :3.1 x 10^{14} n/cm2s

Pulse frequency = 16 2/3 Hz

Neutron pulse length = 2 Milliseconds

Mean Power = 5 MW

Target material = mercury

Max. Neutron flux = 1 x 10^{16} n/cm2s

◆ Compare with ISIS

Proton energy: 0.800 GeV

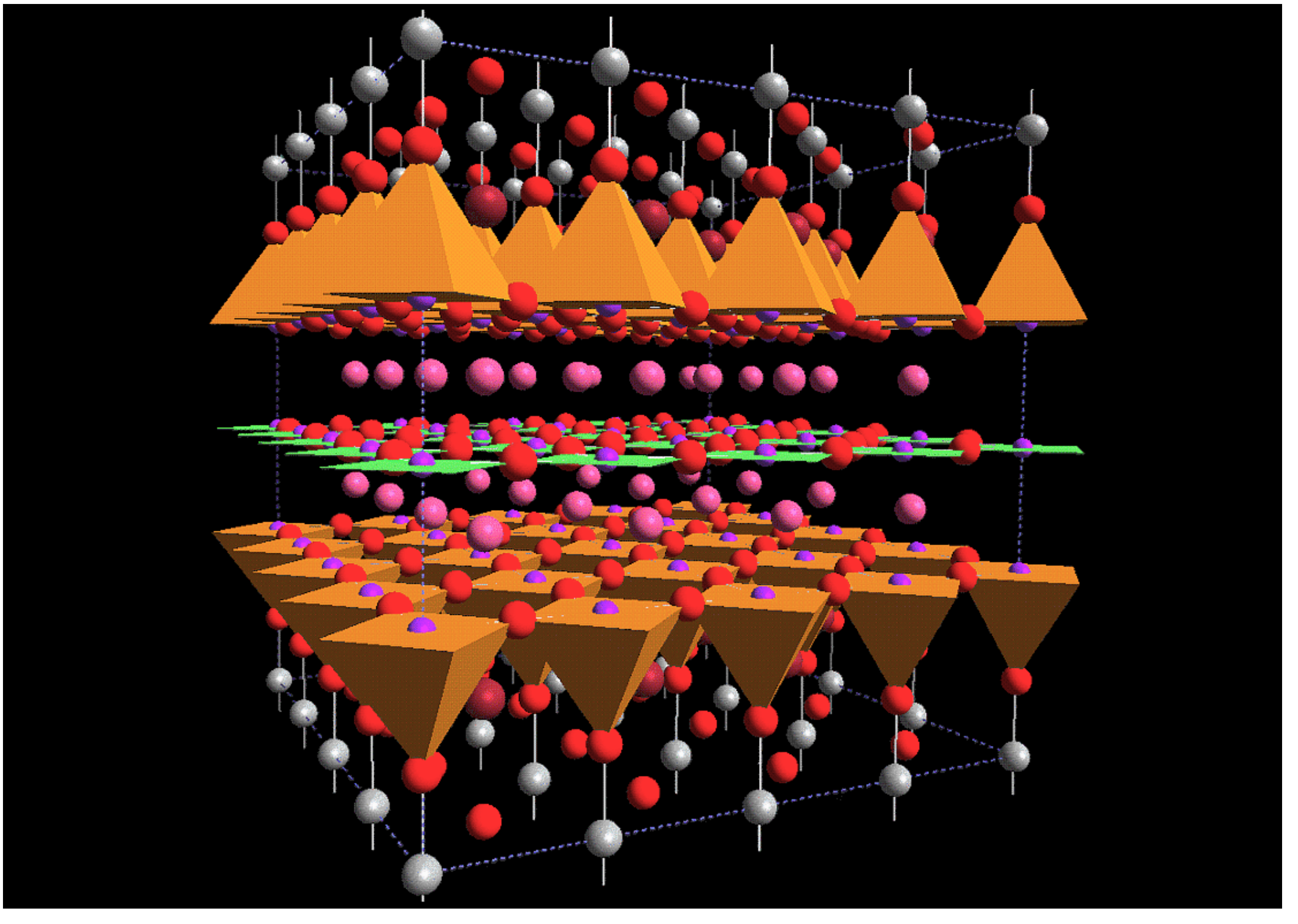
Protons per second: 2.5 x 10^{13} x 50 Hz = 1.3x10^{15}

Current = Charge/sec:x1.3x 10^{15} x 1.6 x 10^{-19} =0.2 mA

Mean Power = 0.2 mA x 800 MeV = 0.16 MW

Fig.

High temperature superconductor



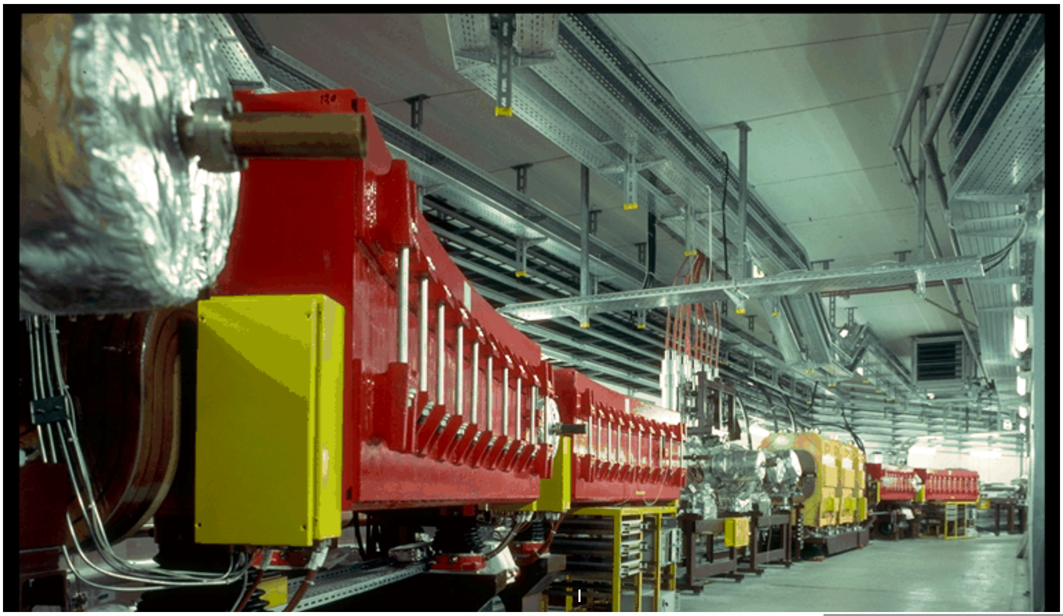
Crystal structure of the 90K $YBa_2Cu_3O_7$ superconductor

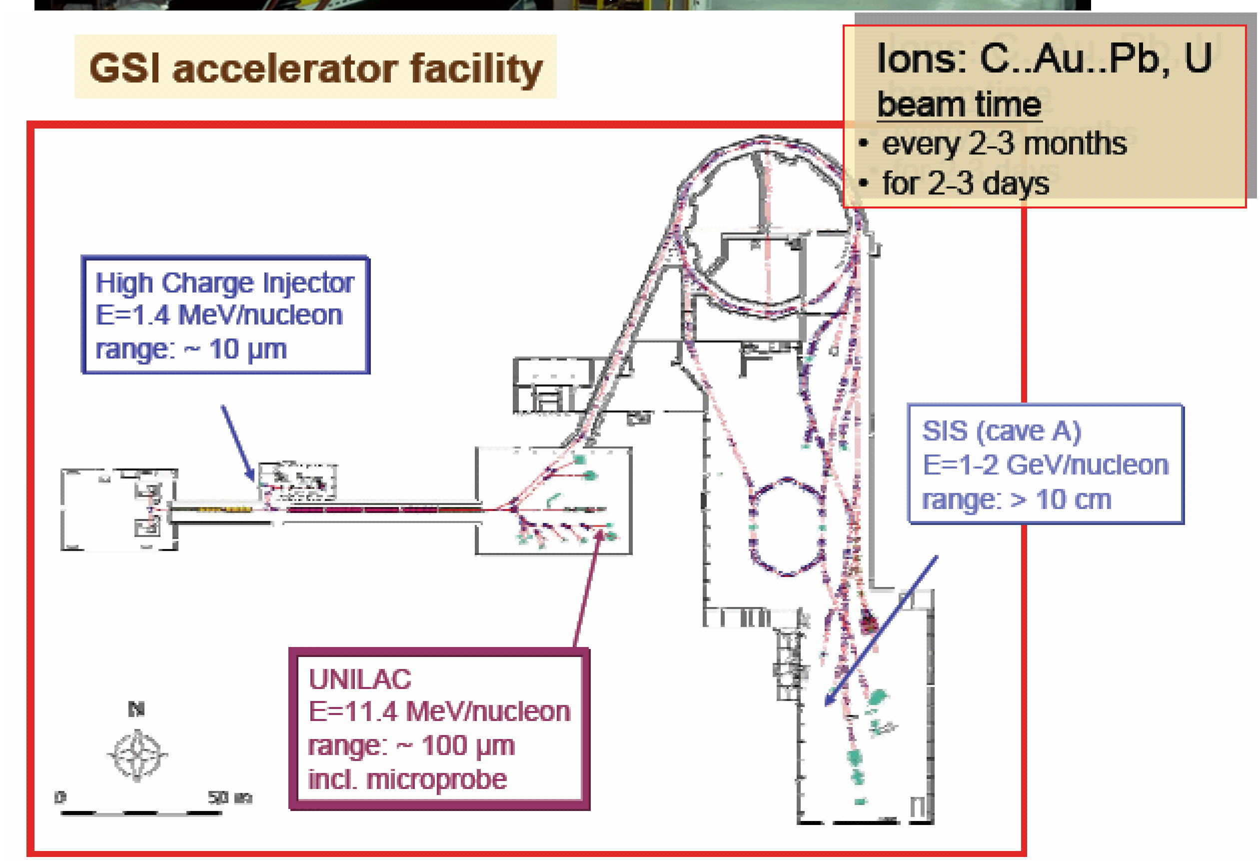
HgBa2CuO4.Color-PICT

Fig.

GSI – Ions galore!

View along the SIS accelerator ring, which can accelerate the ions coming from the UNILAC to 90% of the speed of light.





Ion- beam surface treatment

Setup for surface treatment of artificial knee joint by low energy ion implantation. Collaboration Aesculap and Technical University Darmstadt

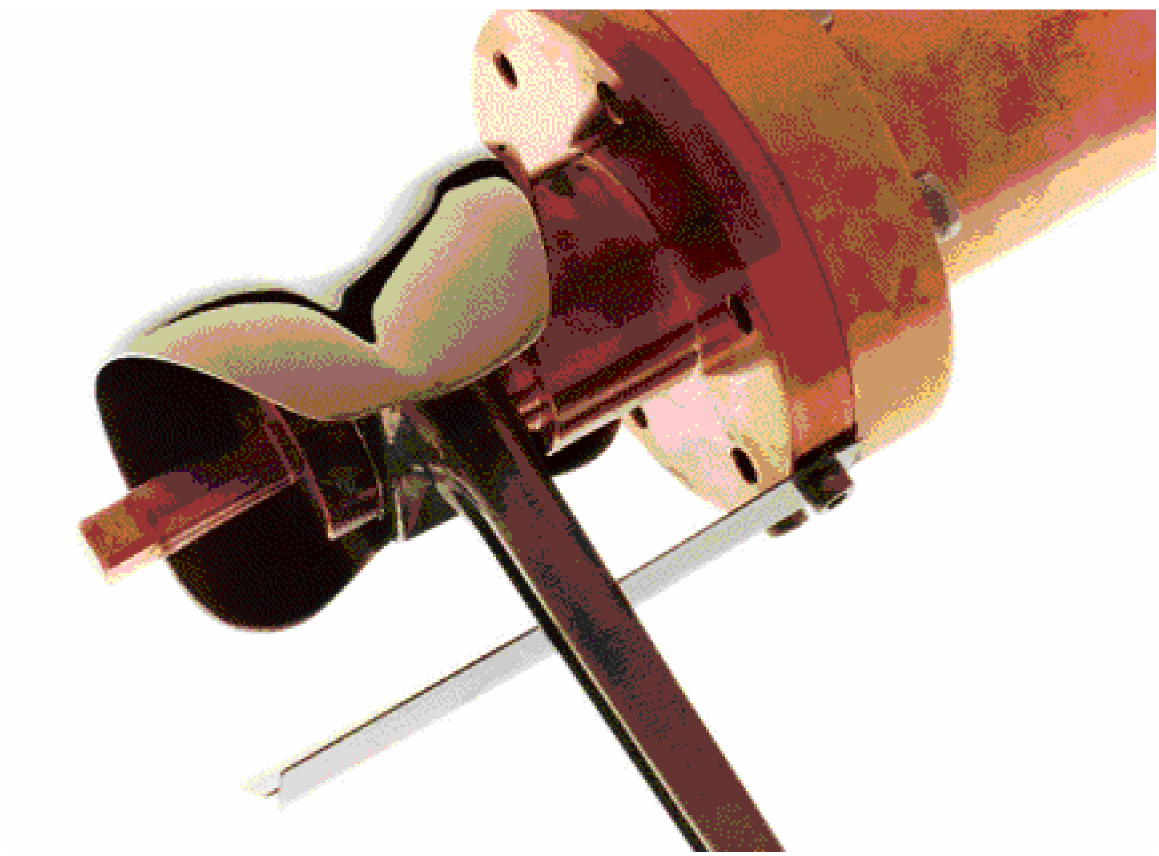
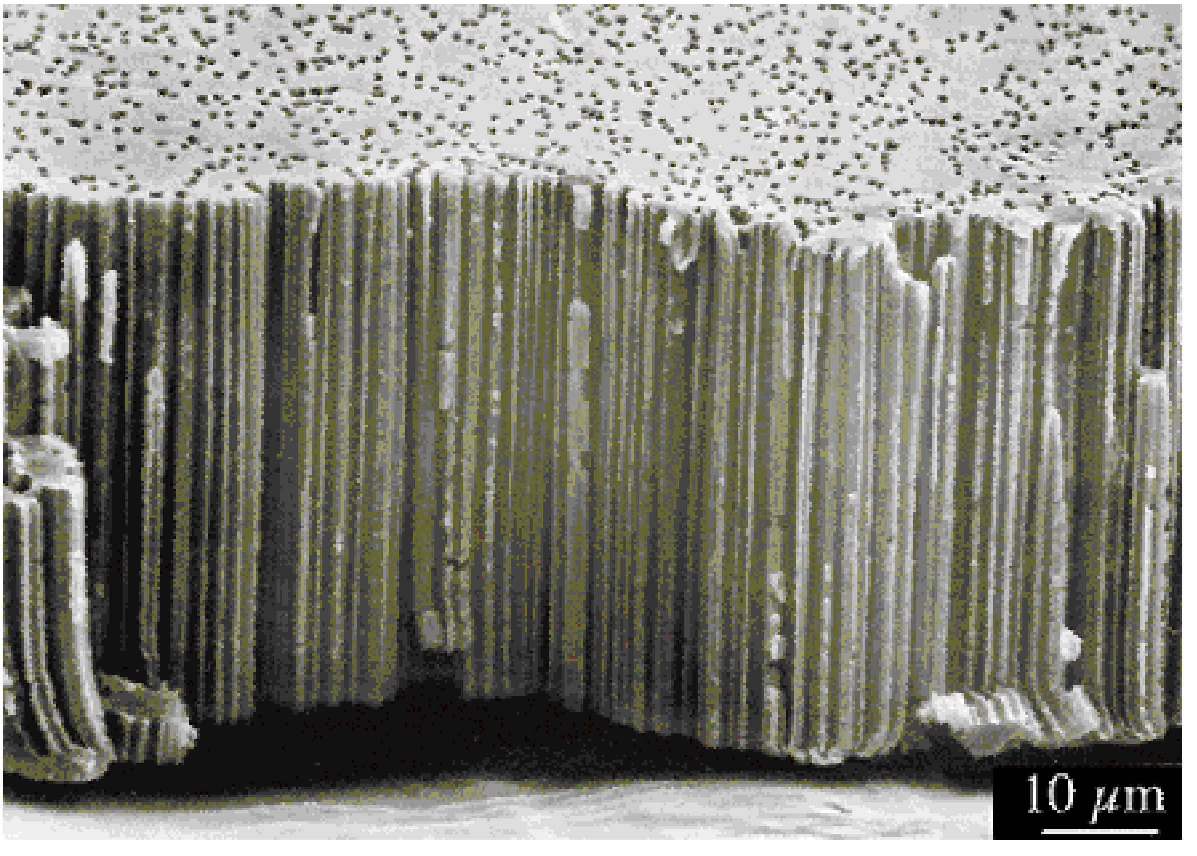


Fig.

Kniegelenk.gif

Membranes made with ion-beams

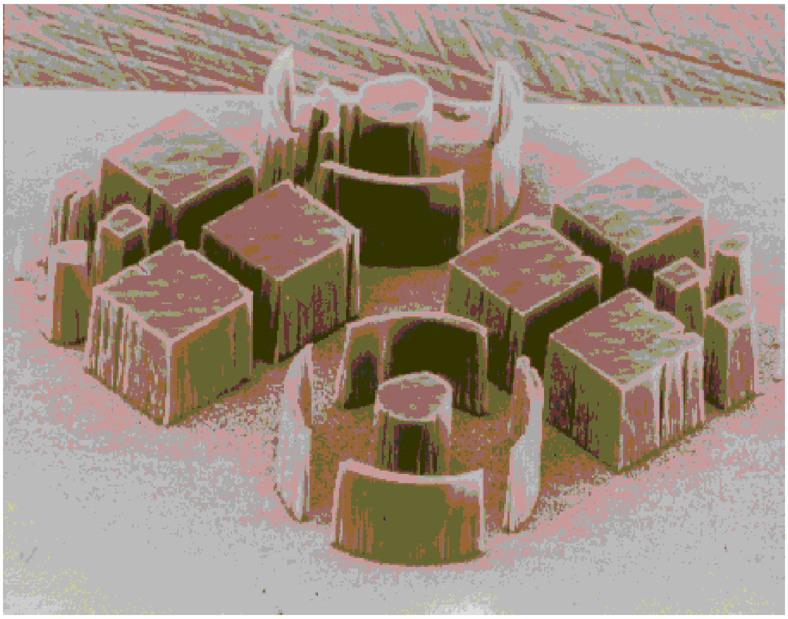
The damage produced by the heavy ions along the track in the material can be used to develop pores. With this technique tracks in many polymers, crystalline insulators, glasses, semi-conductors and recently amorphous metals are etcheable.

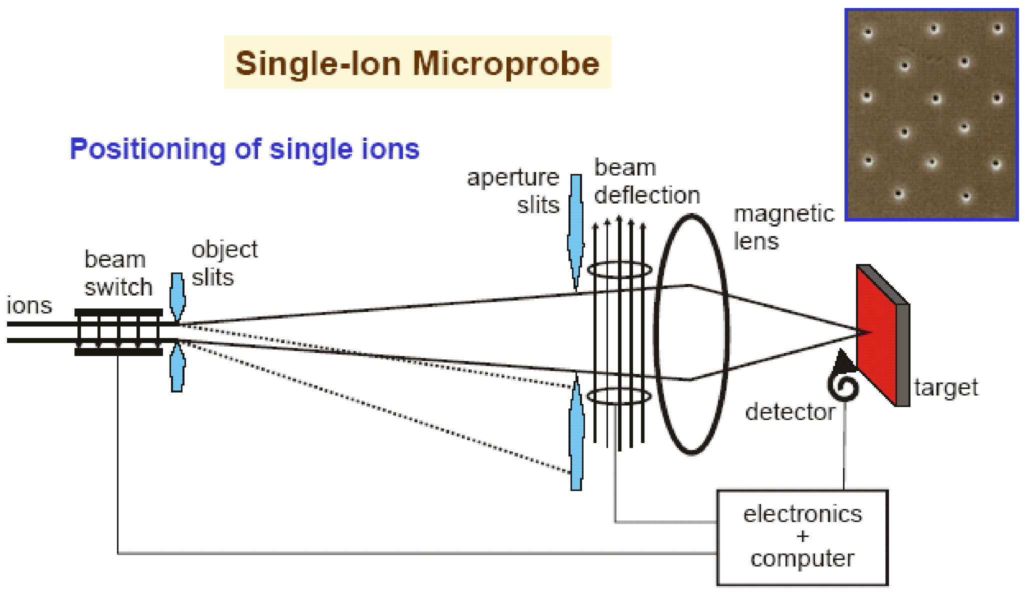


Etched ion tracks in polymer foil. The pore density is 10 million per cm^2. By ion track etching it is possible to produce membranes with track diameter from 10 nm up to 10 μm and densities from 1 to 10^9 pores per cm^2.

Fig. quartz_MITE.gif

Quartz micro machining by control of ion track etch access





fluence= ions per area [ions / cm^2]

1 ion/sample-single pore membrane

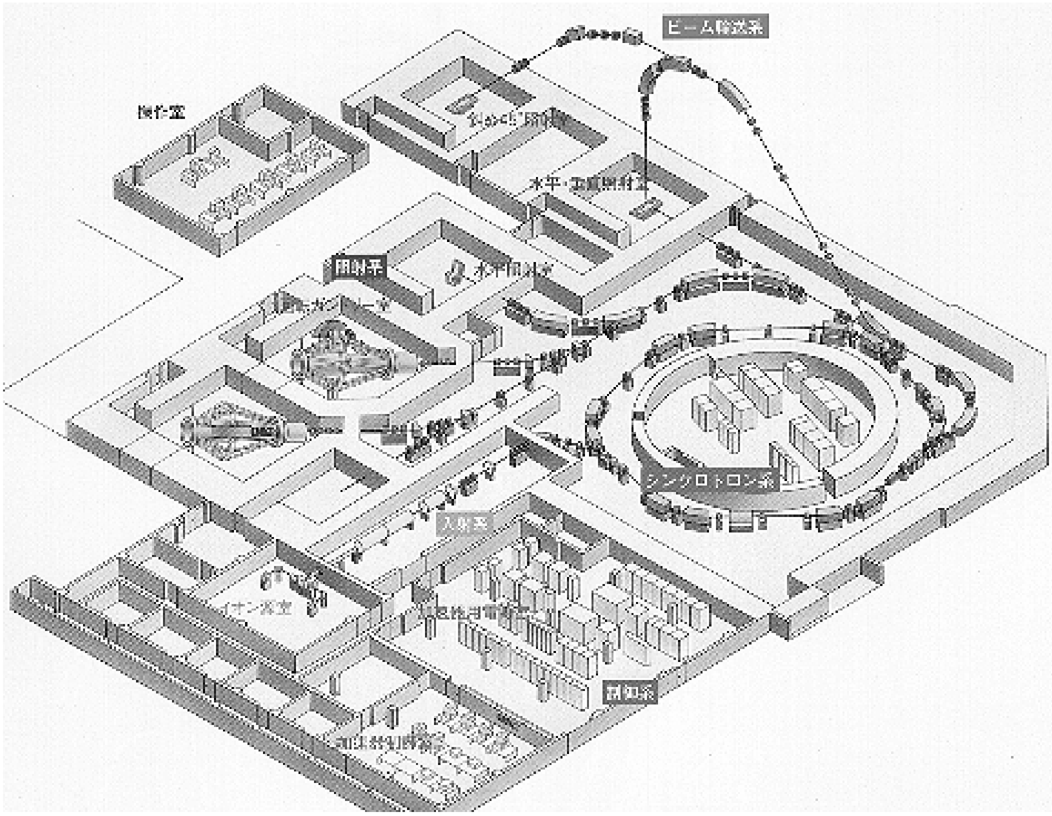
10^6…10^{10} ions/cm^2-etching

10^9…10^{11}ions/cm^2 -single track regime

10^{11} 10^{14}ions/cm^2 -overlapping tracks

Fig. quartz_MITE.gif

HYOGO (JPN)- Ion beam medical center



Particle species	p, He and C
Beam energy for p and He [MeV/u]	70 - 230
Beam energy for C [MeV/u]	70 - 320
Beam spill length [ms]	400
Repetition rate for He and C [Hz]	0.5

- **Beam intensity is typically 10^{10} ppp**
- **The tumor is "painted " with beam**
- **Depth modulation = energy loss absorber**
- **Slow extraction must be ripple free.** fig.

Depth in tissue

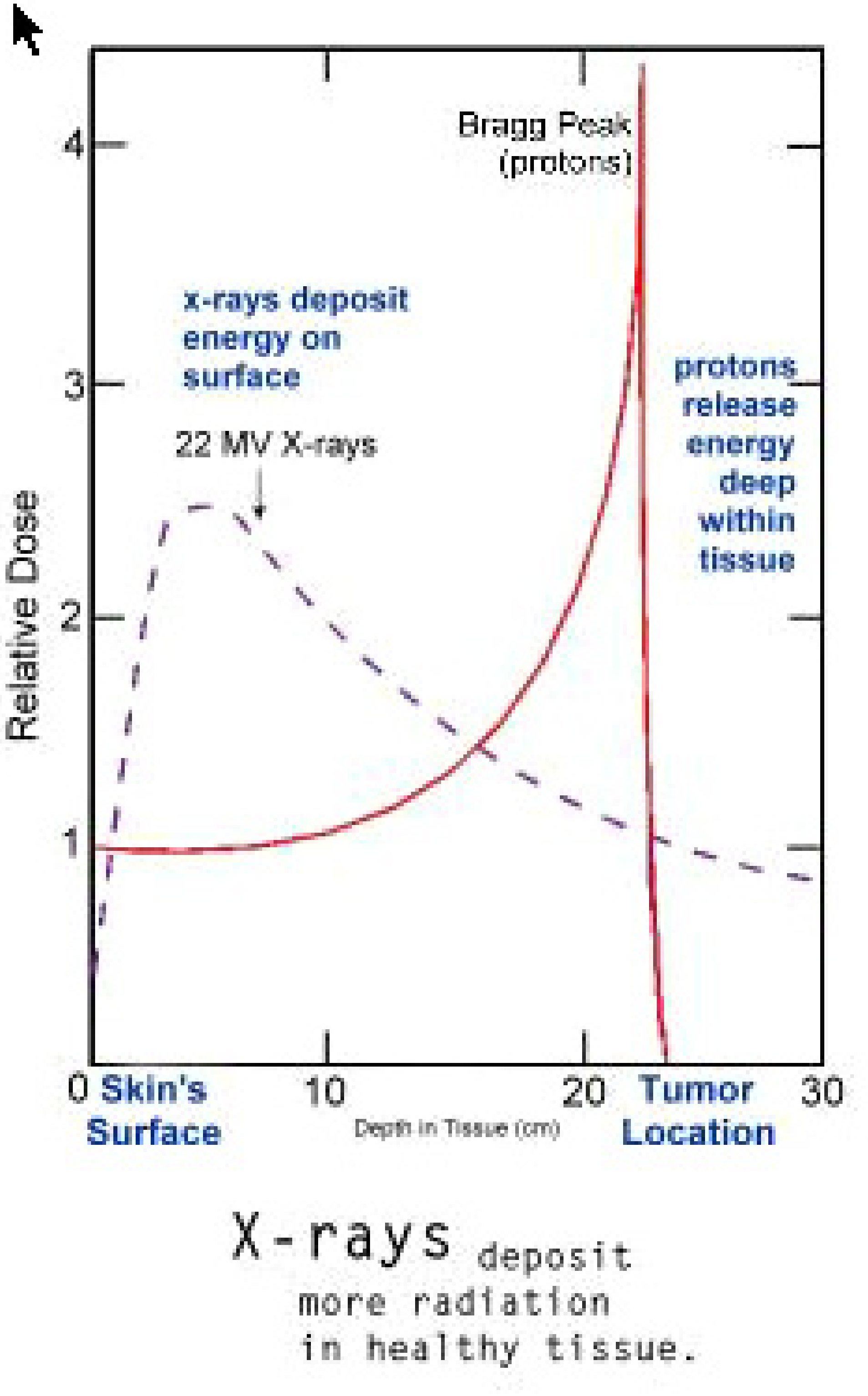


Fig.

Lawrence's Cyclotron

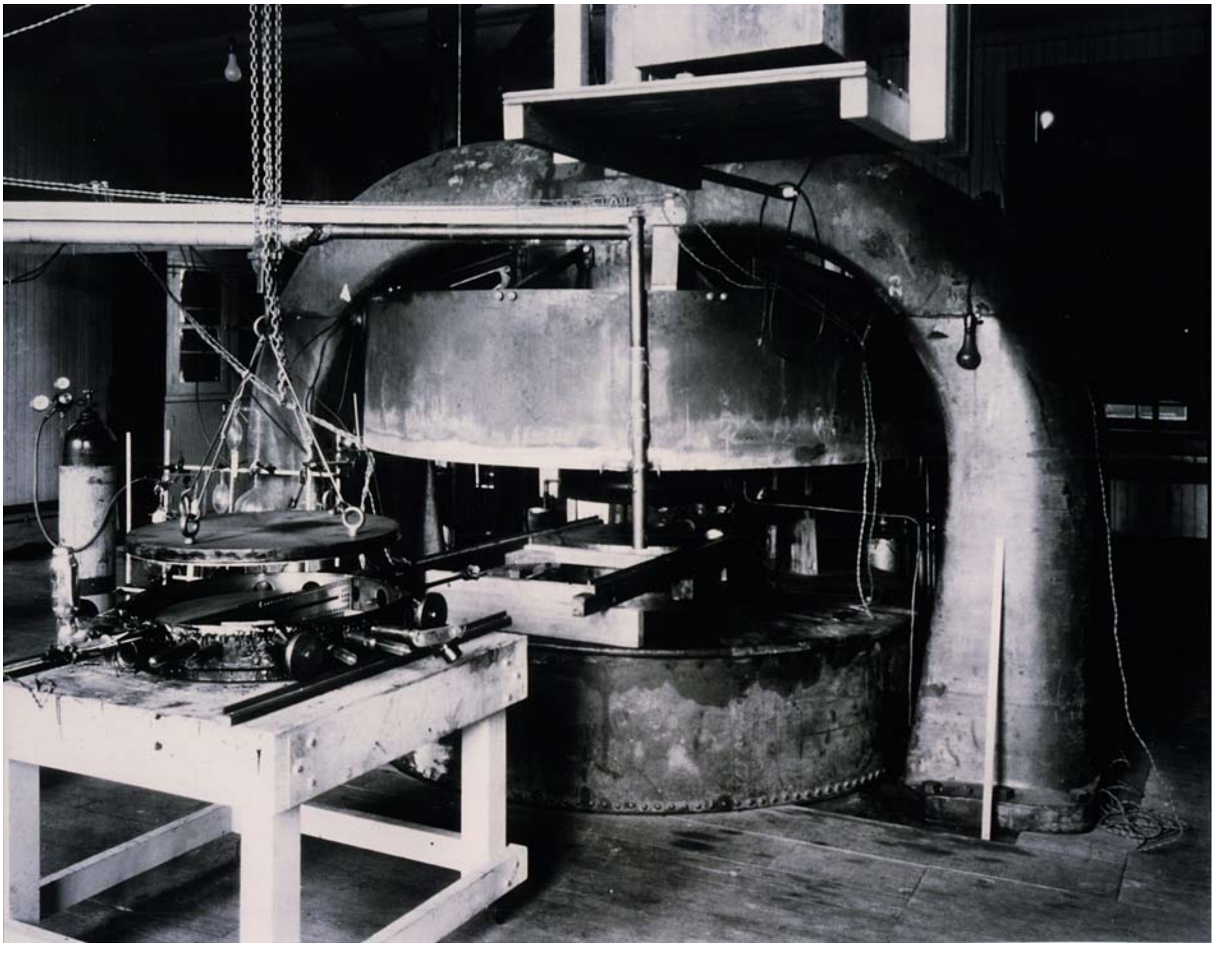


Fig.

Isotopes for PET

PET PRODUCTION

Radionuclide	Nuclear Reaction	Chemical Form	Beam Current	Irradiation Time	Yield mCi
C-11	$^{14}N(p,a)^{11}C$	CO 2	50 µA	30 min	3000
N-13	$^{16}O(p,a)^{13}N$	NH 3	30 µA	30 min	450
O-15	$^{14}N(d,n)^{15}O$	O 2	50 µA	6 min	1200
F-18	$^{18}O(p,n)^{18}F$	HF	30 µA	60 min	1000

petiso.pct

Fig.

Energy amplifier

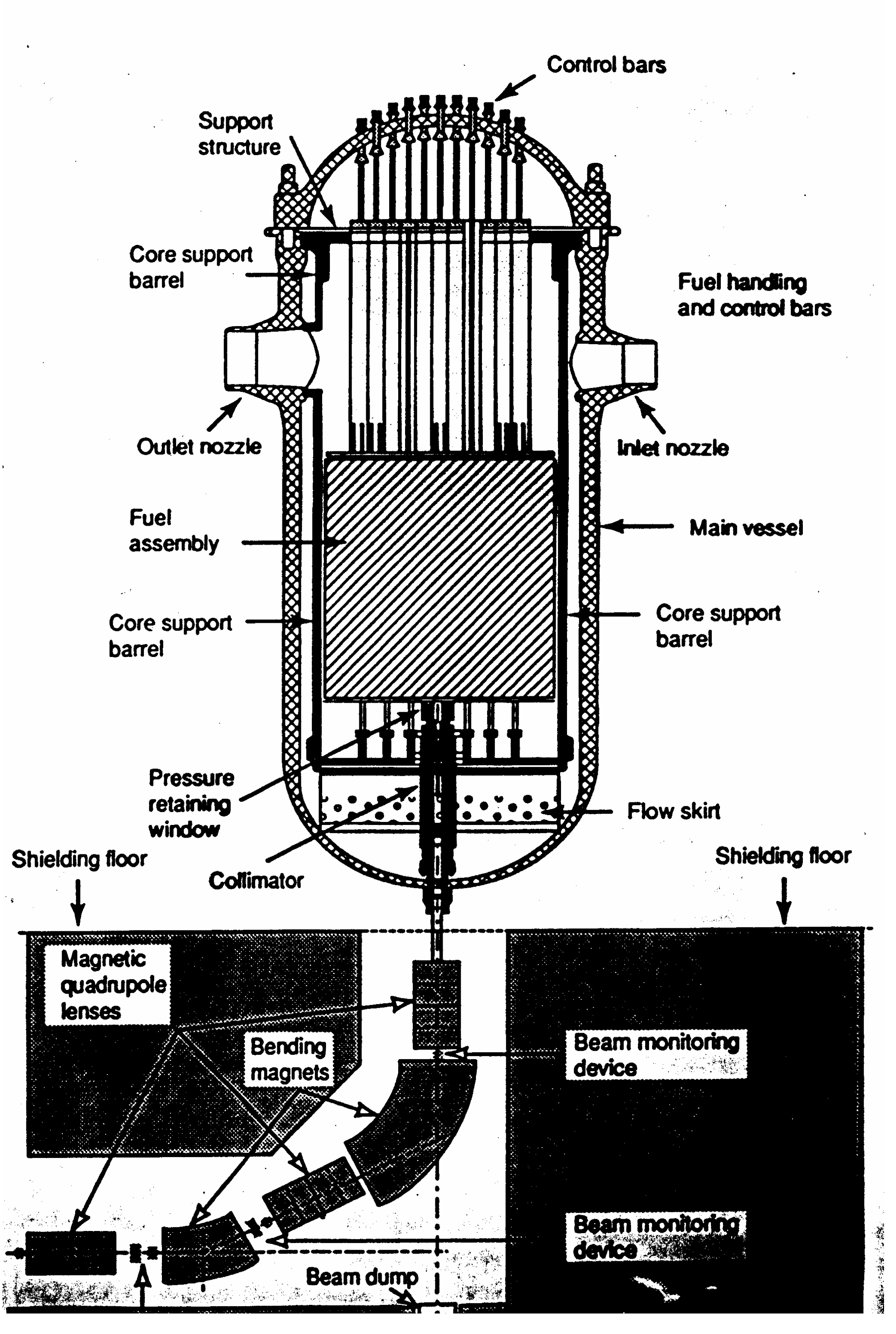


Fig.

Inertial confinement

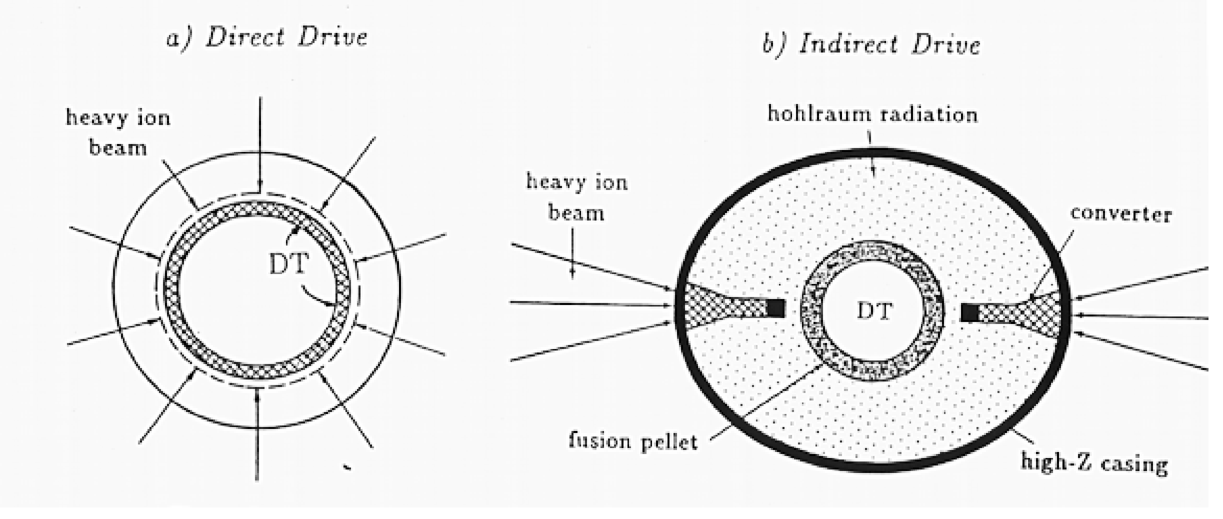


Fig.

The history of accelerators

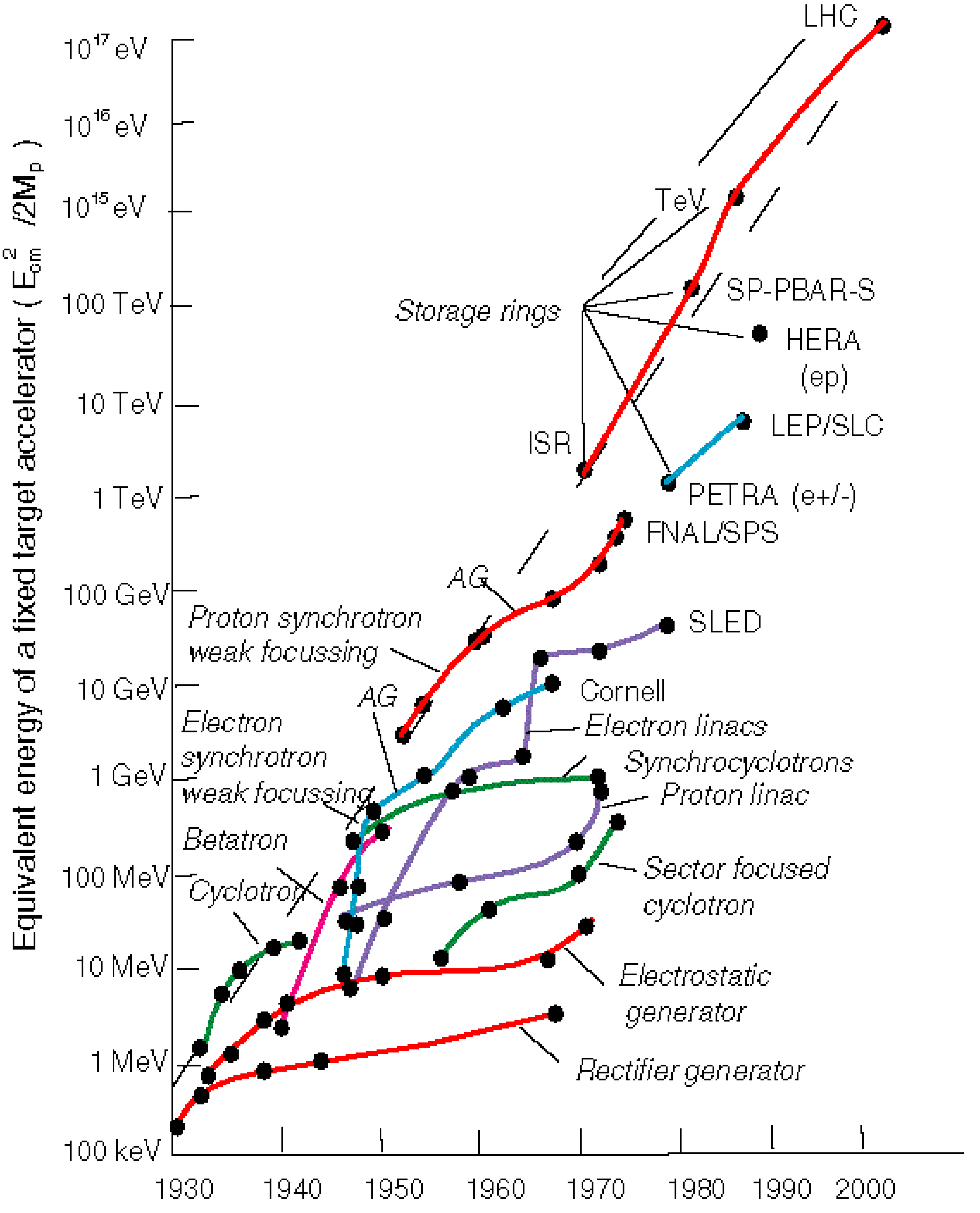


Fig.

Need for Accelerators

Why do we need accelerators? (2)

Resolution of "Matter" Microscopes:

Wavelength of Particles (Photon, Electron, Proton, ...): (de Broglie, 1923)

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

The higher the momentum, the shorter the wavelength, the better the resolution

Energy to Matter:

Einstein (1905):

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

Higher energy means we can produce more massive particles

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

3

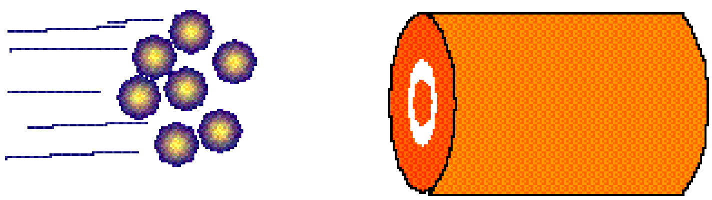
Fig.

Center of mass *v.* Fixed target

W = Energy available in center-of-mass for making new particles

For fixed target :

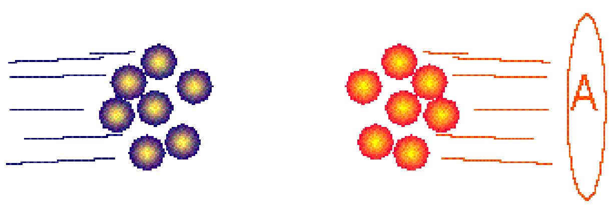
$$E_{c.m.} \cong \sqrt{2 m_T E_B}$$



... and we rapidly run out of money trying to gain a factor 10 in c.m. energy

But a storage ring , colliding two beams, gives:

$$E_{c.m.} \cong 2\ E_B$$

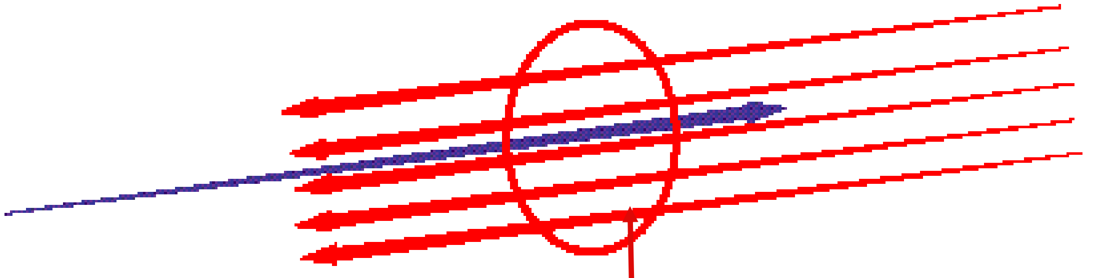


Problem: Smaller probability that accelerated particles collide .... "Luminosity" of a collider

$$L = N_1 N_2 \frac{1}{A} \frac{\beta c}{2\pi R} \approx 10^{29} \ldots 10^{34}\, cm^{-2} s^{-1}$$

Fig.

Luminosity



- Imagine a blue particle colliding with a beam of cross section area - A
- Probability of collision is $\frac{\sigma}{A} \cdot N$
- For N particles in both beams $\frac{\sigma}{A} \cdot N^2$
- Suppose they meet *f* times per second at the revolution frequency

$$f_{rev} = \frac{\beta c}{2\pi R}$$

- Event rate $\frac{f_{rev} N^2}{A} \cdot \sigma$

Make big

e.g. 10^{-25}

Make small

LUMINOSITY $\approx 10^{30}$ to 10^{34} $\left[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\right]$

CLIC SCHEME

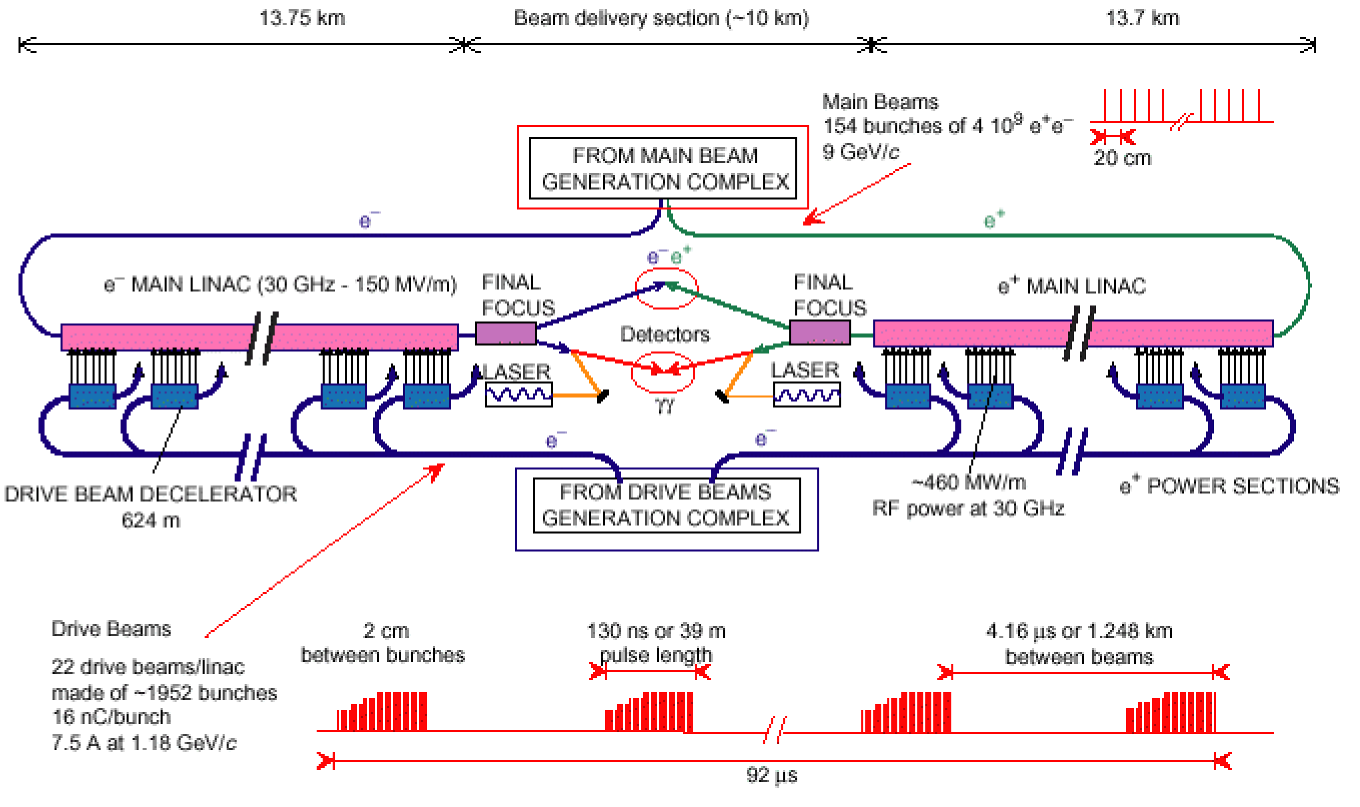


Fig.

Summary of lecture:
III – Applications – E. Wilson

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Fig.