Introduzione alla Fisica degli Acceleratori di Particelle

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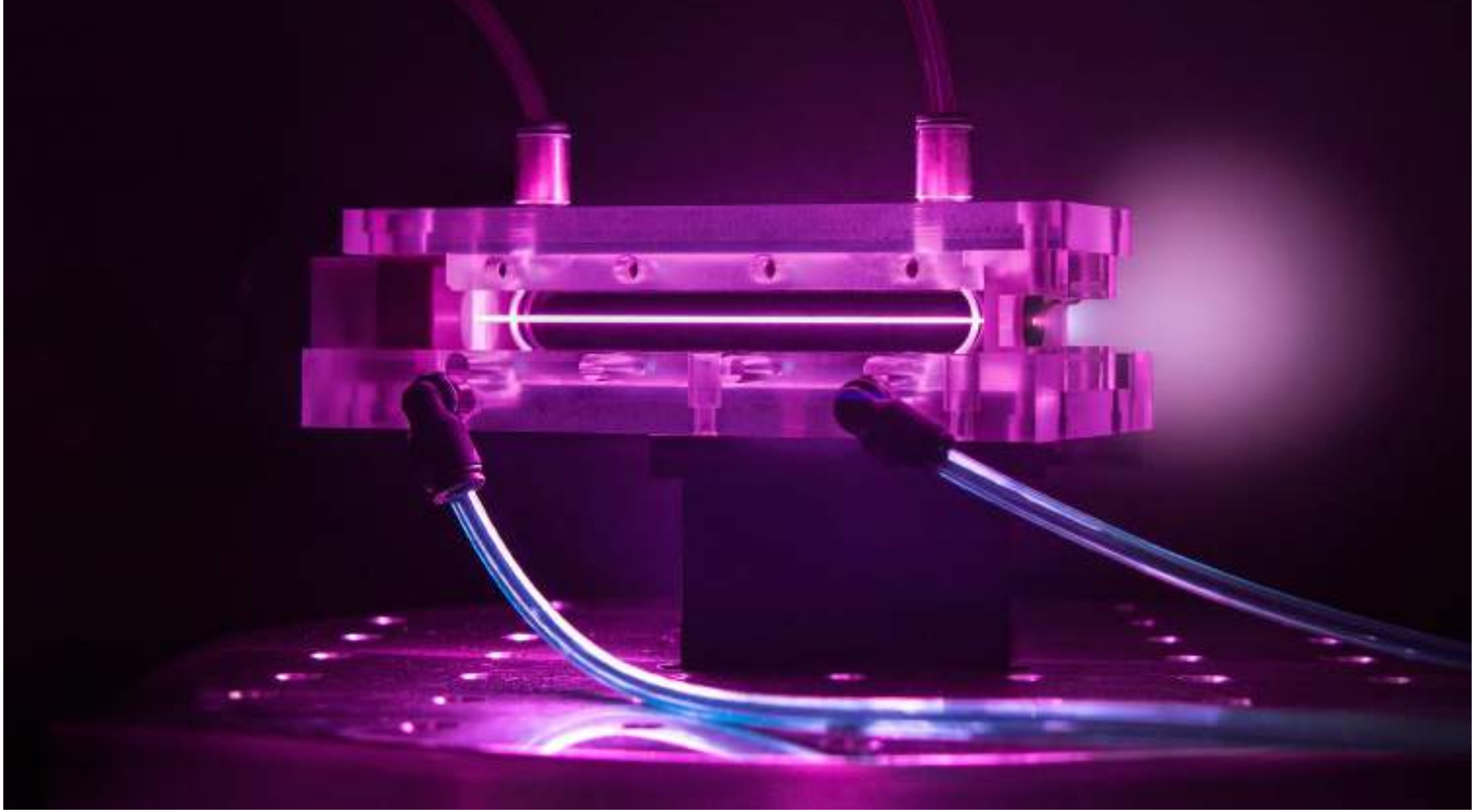
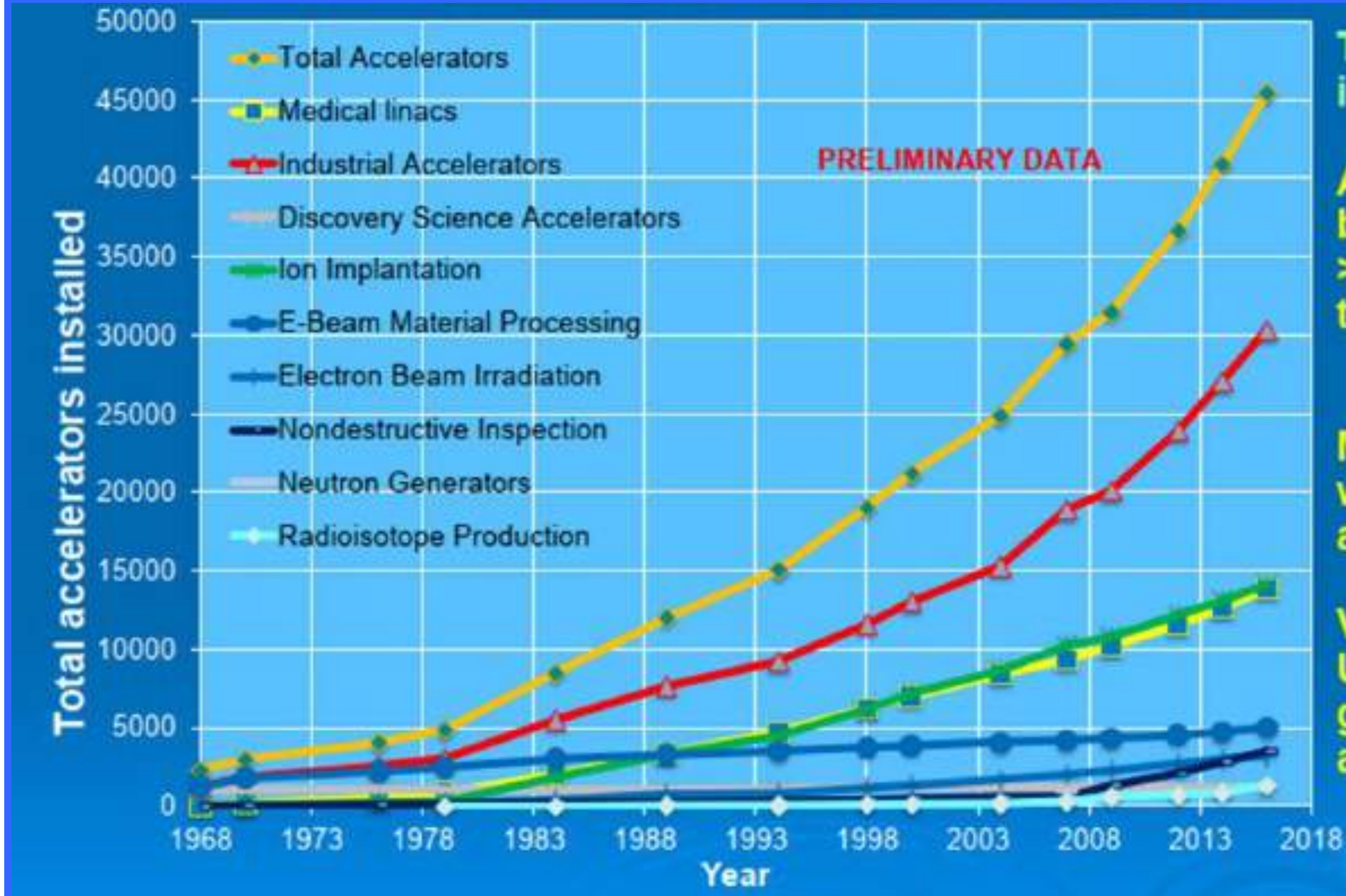


Accelerators installed worldwide



Total sales of accelerators is ~US$5B annually

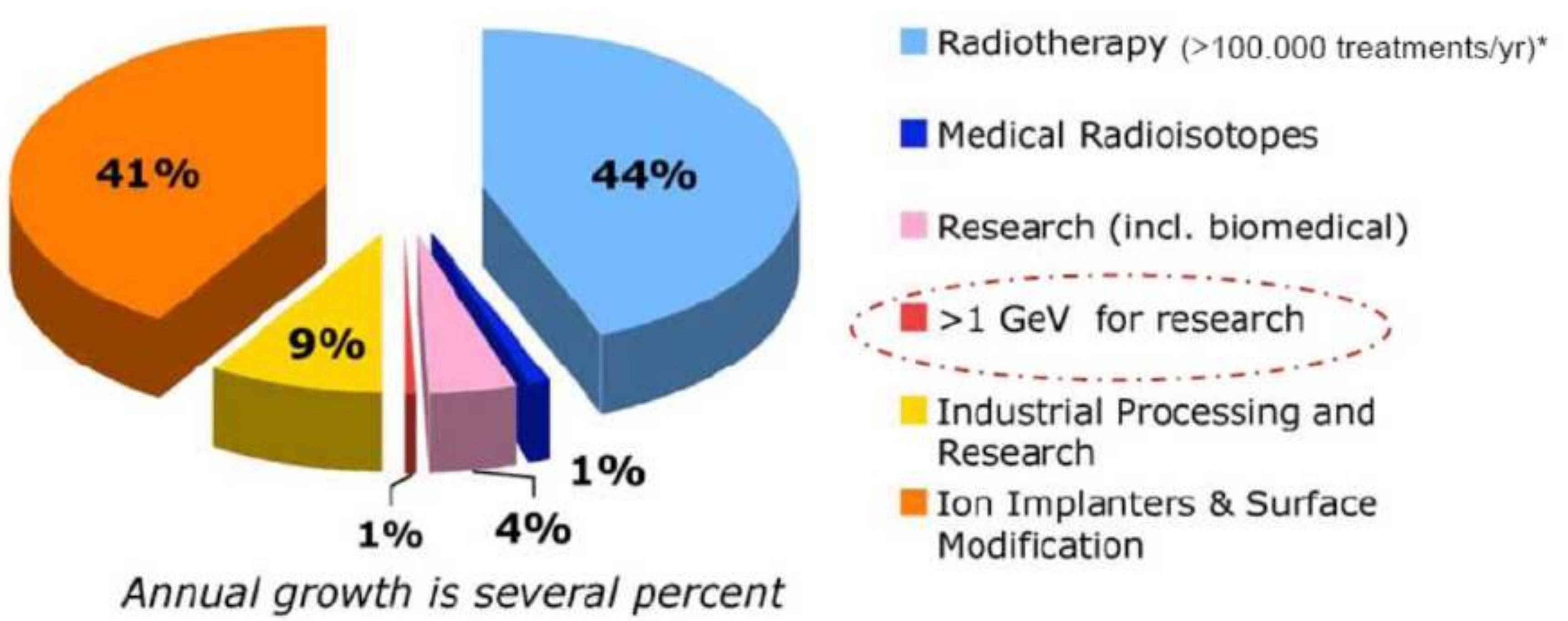
About 47,000 systems have been sold,
> 40,000 still in operation today

More than 100 vendors worldwide are in the accelerator business.

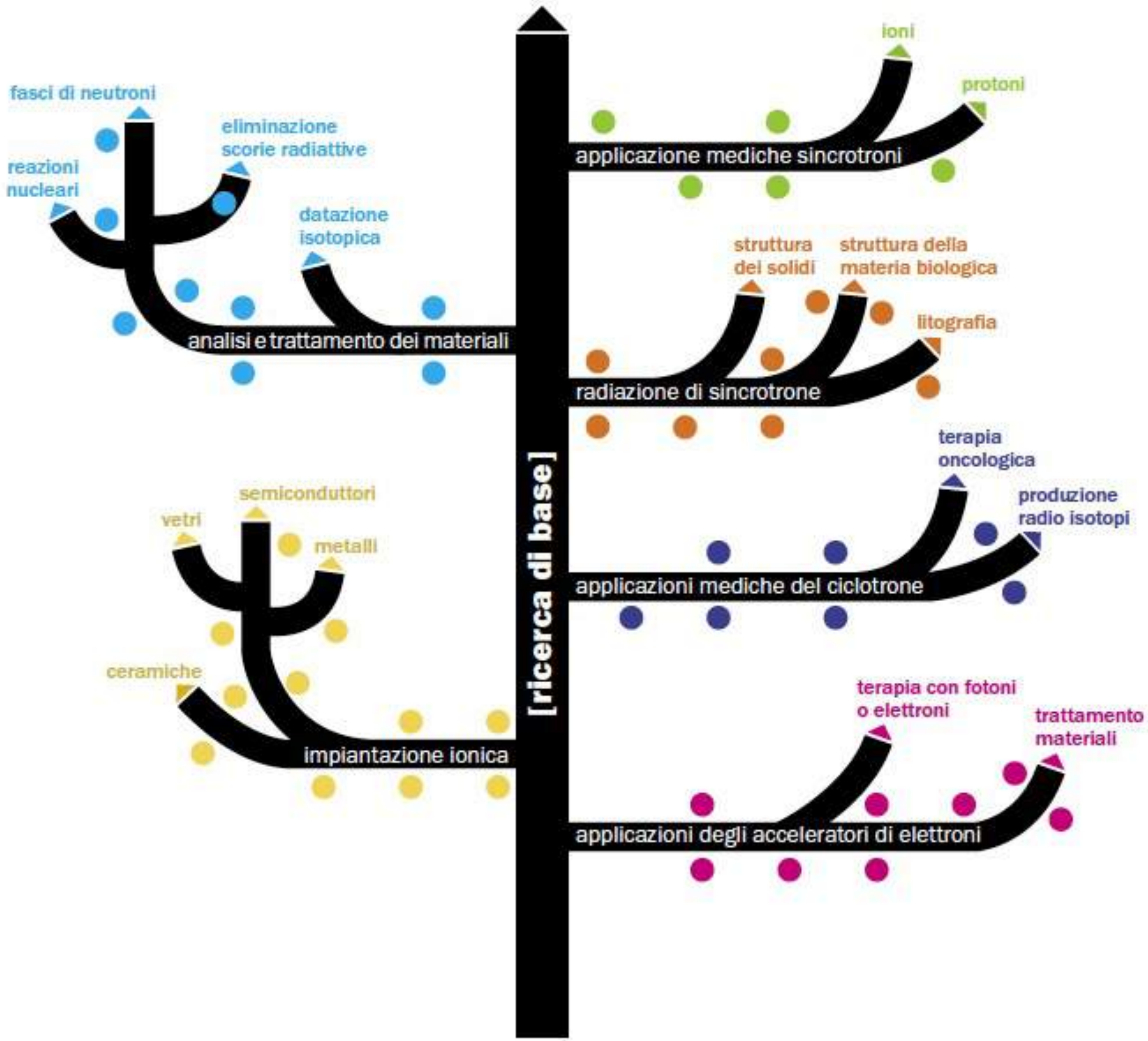
Vendors are primarily in US, Europe and Japan, but growing in China, Russia and India

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

Accelerators installed worldwide



-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011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eliminazione scorie radiattive
reazioni nucleari
datazione isotopica
applicazione mediche sincrotroni
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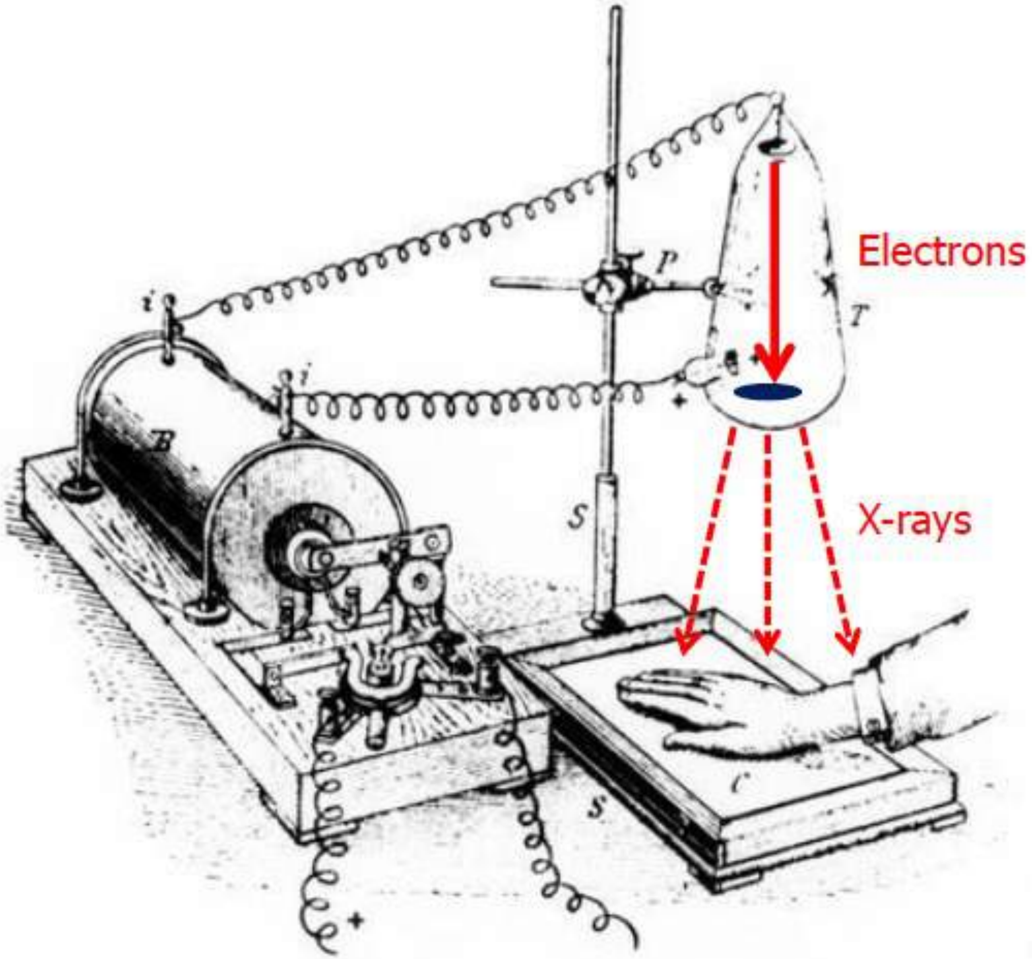
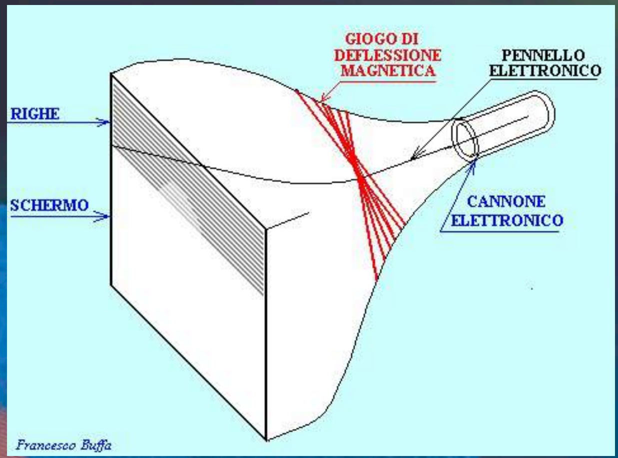
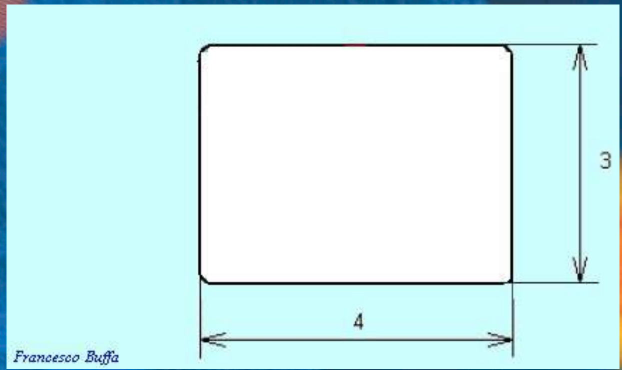
protoni
radiazione di sincrotrone
struttura dei solidi
struttura della materia biologica
litografia
applicazioni mediche del ciclotrone
terapia oncologica
produzione radio isotopi
impiantazione ionica
semiconduttori
vetri
metalli
ceramiche
applicazioni degli acceleratori di elettroni
terapia con fotoni o elettroni
trattamento materiali

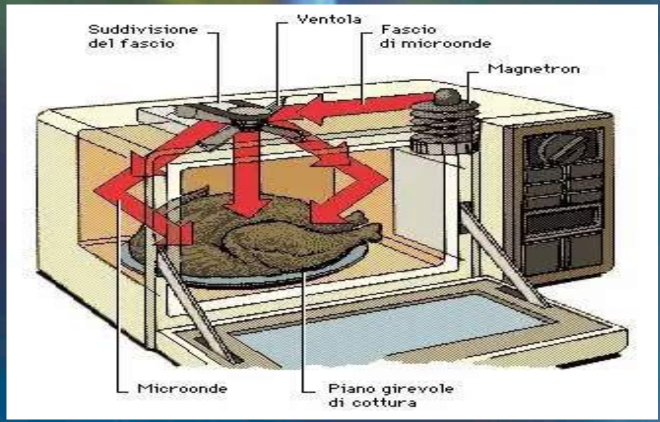
Roentgen 1896 – First radiograph of a hand

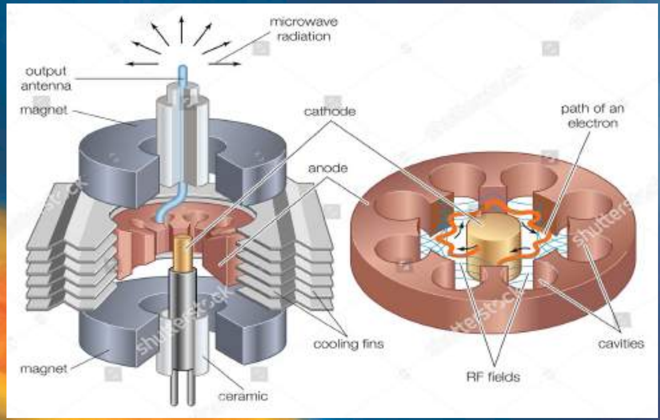


Acceleratori Domestici

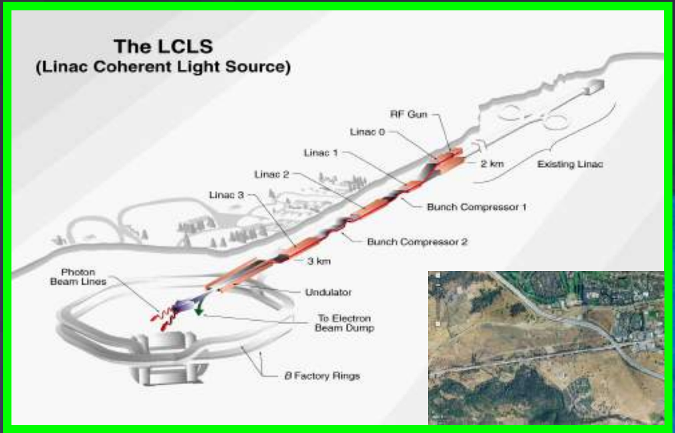


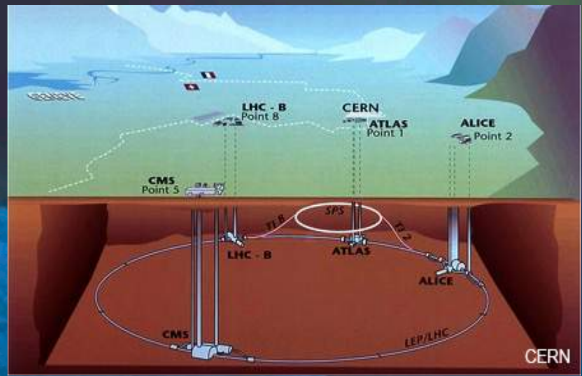


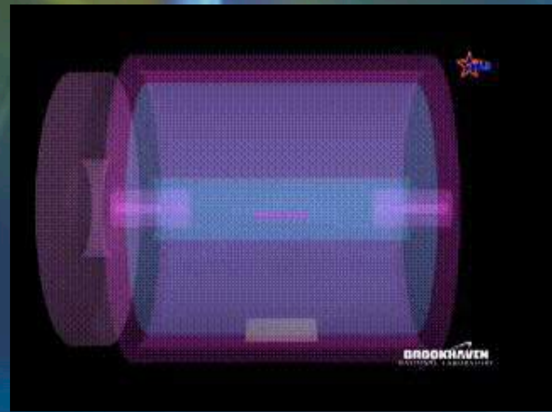


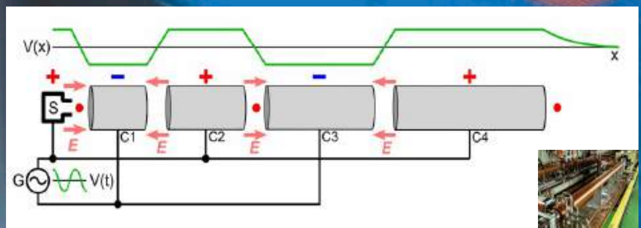


Acceleratori ad Alta Energia

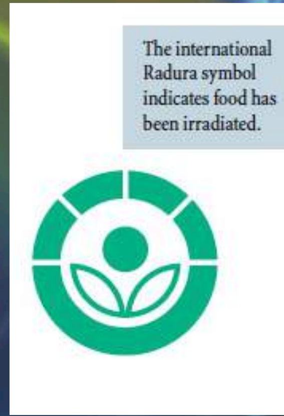


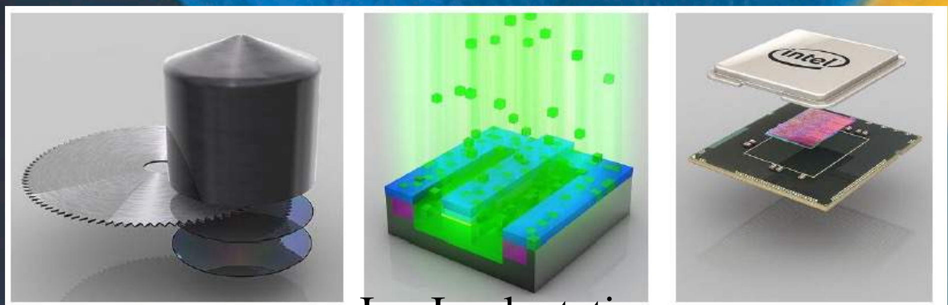




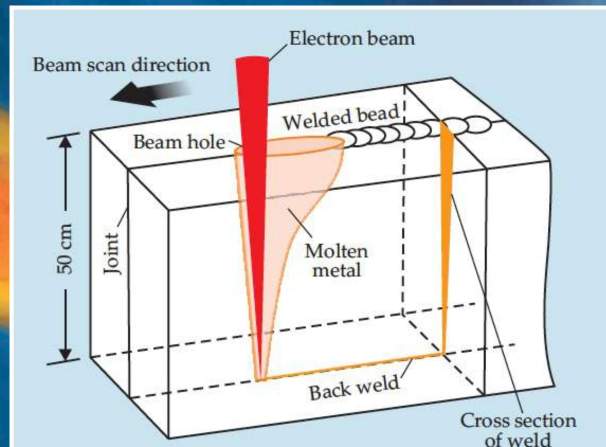


Acceleratori per l'Industria



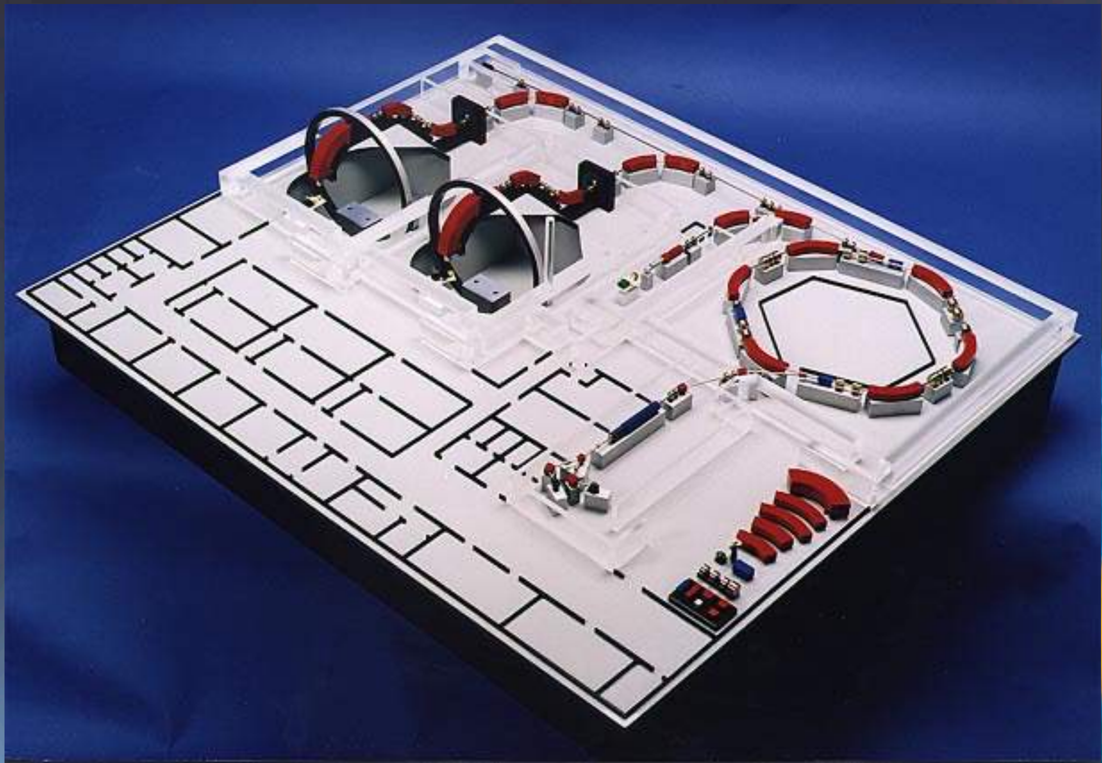


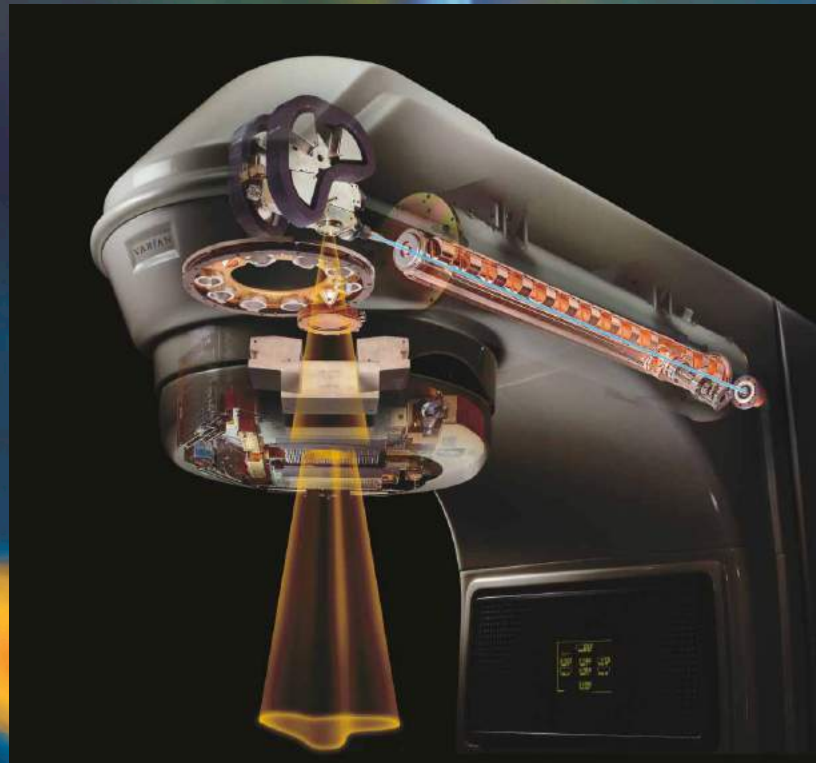
Images courtesy of Intel
Ion Implantation



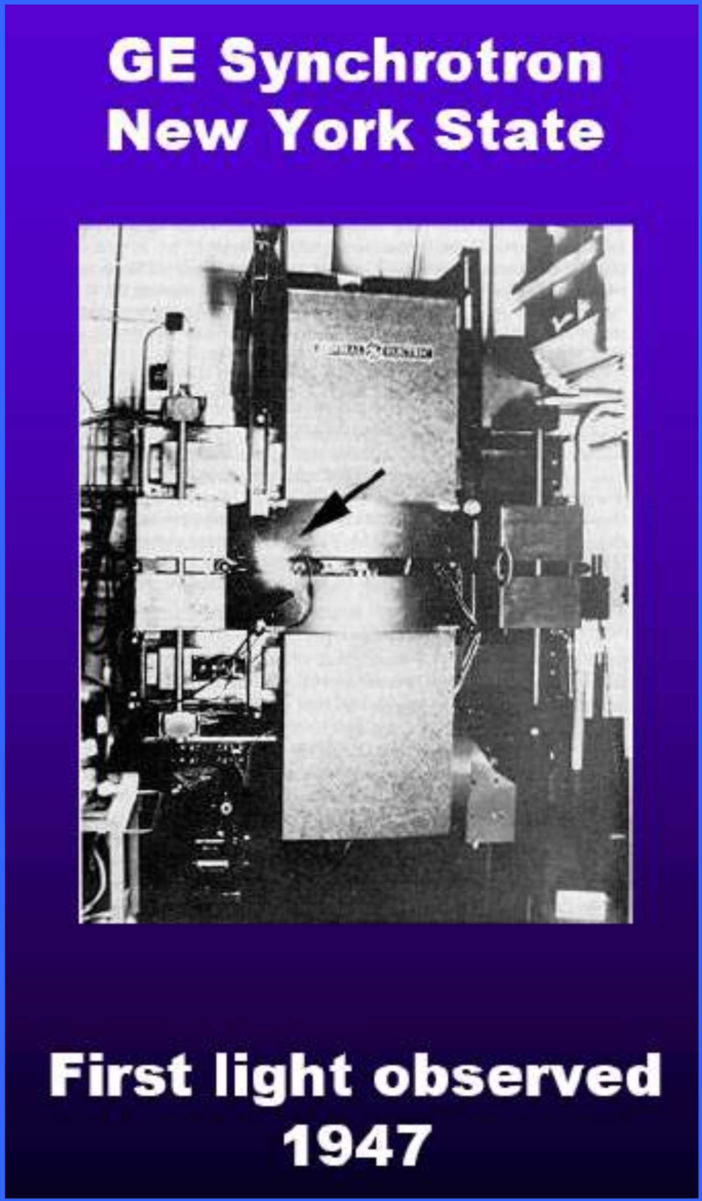
The beam business: Accelerators in industry
Robert W. Hamm, and Marianne E. Hamm
Citation: Physics Today **64**, 6, 46 (2011); doi: 10.1063/1.3603918

Acceleratori per la medicina

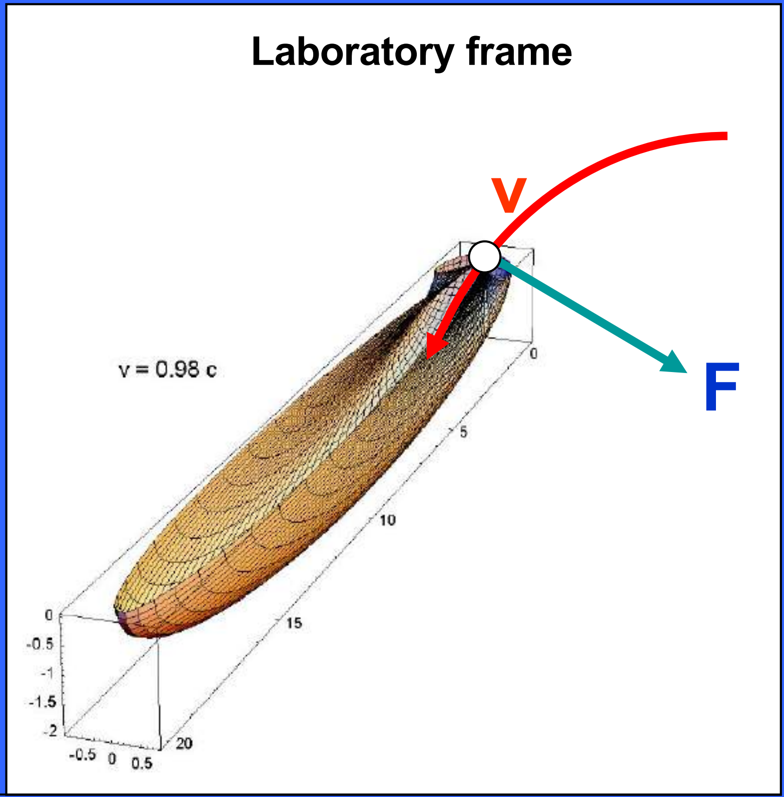




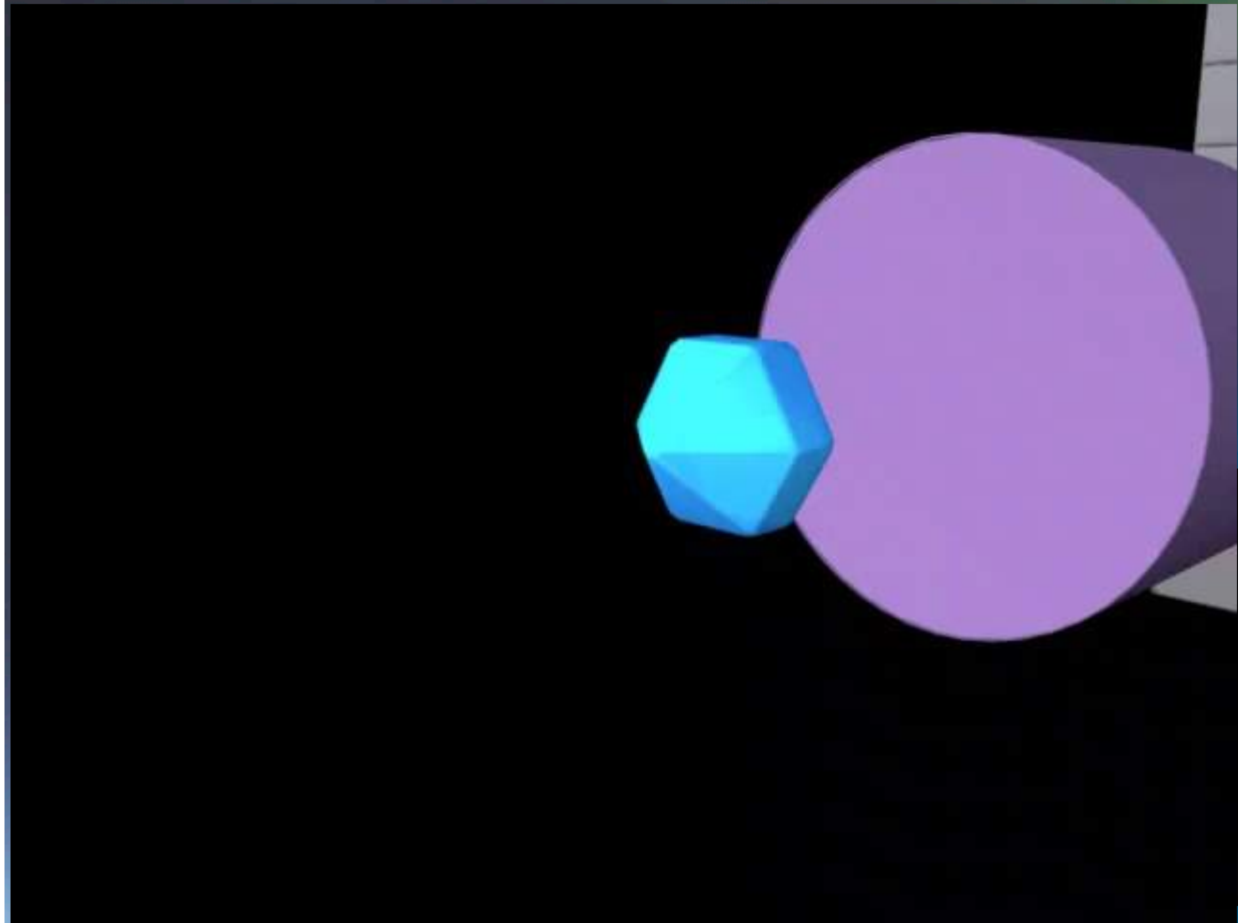
Synchrotron Radiation



$$P_\gamma = \frac{cC_\gamma}{2\pi} \cdot \frac{E^4}{\rho^2}$$



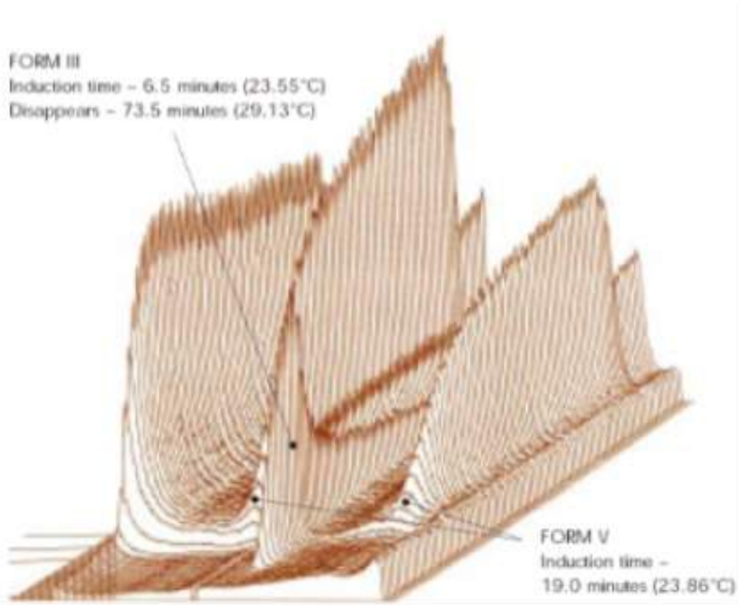
Acceleratori e Luce di Sincrotrone



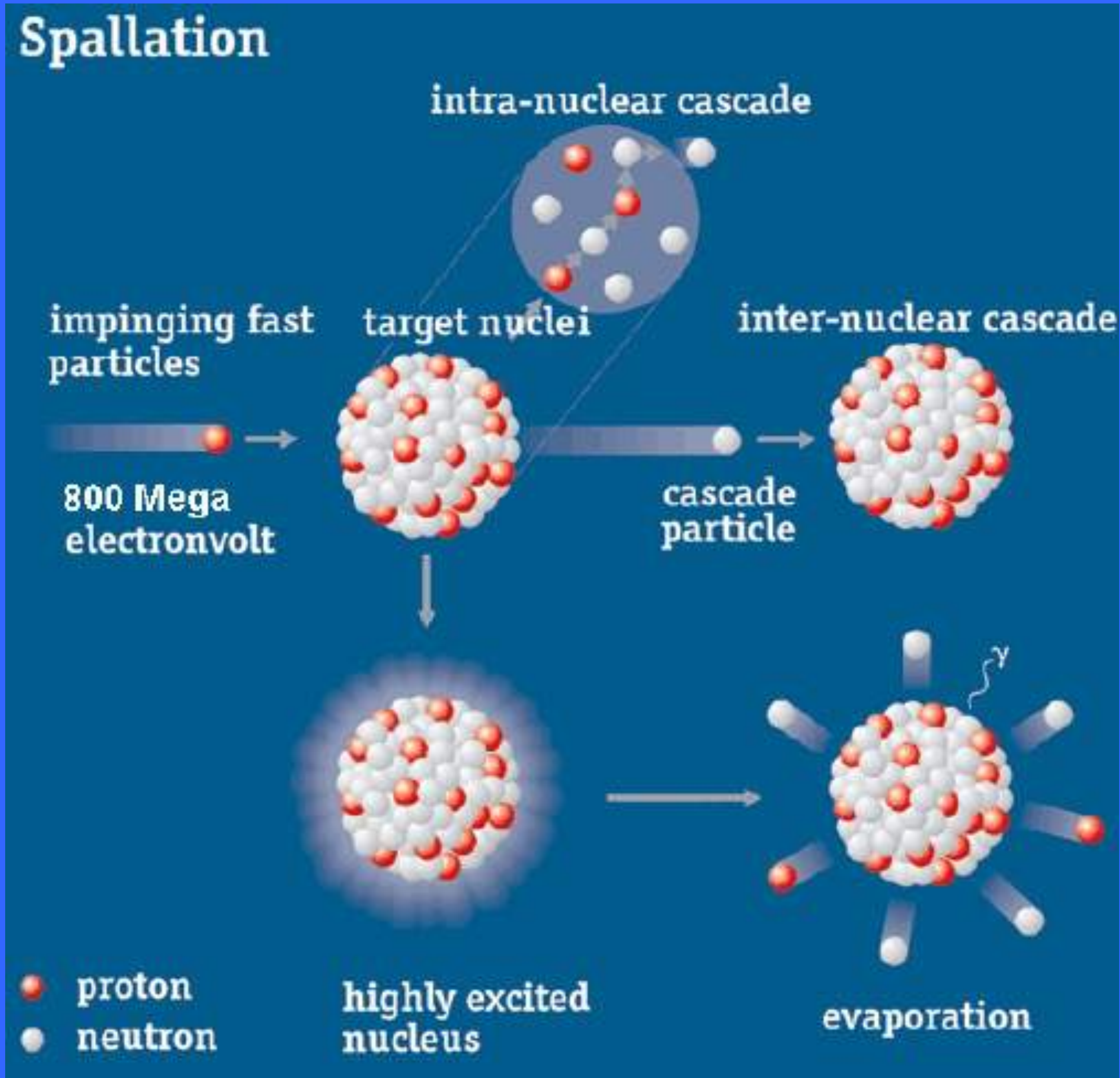
Prevent Chocolate Melting

Cadbury used X-rays from a particle accelerator to study how cocoa crystallises

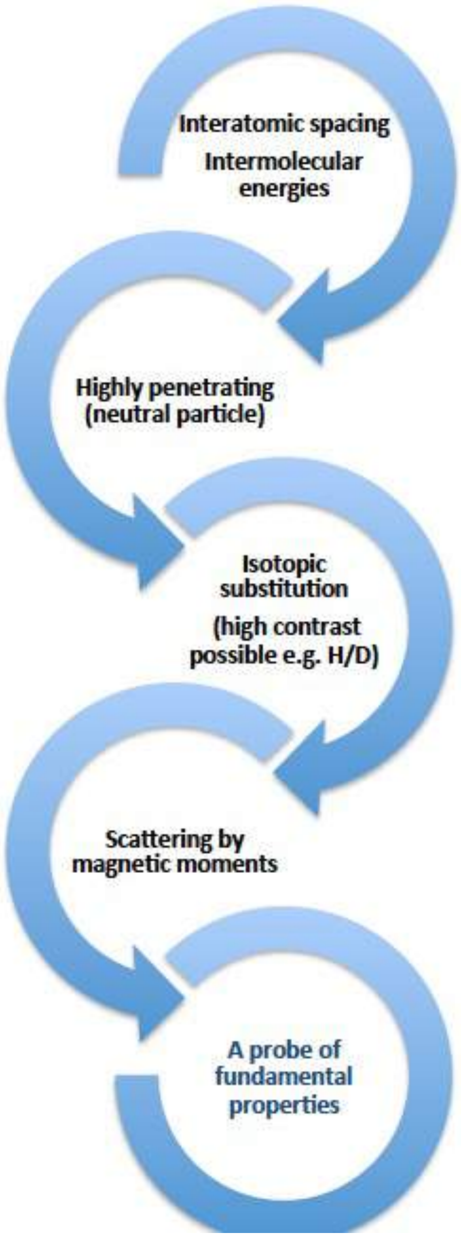
Of the six possible crystal forms, the fifth (form V) produces the best quality chocolate

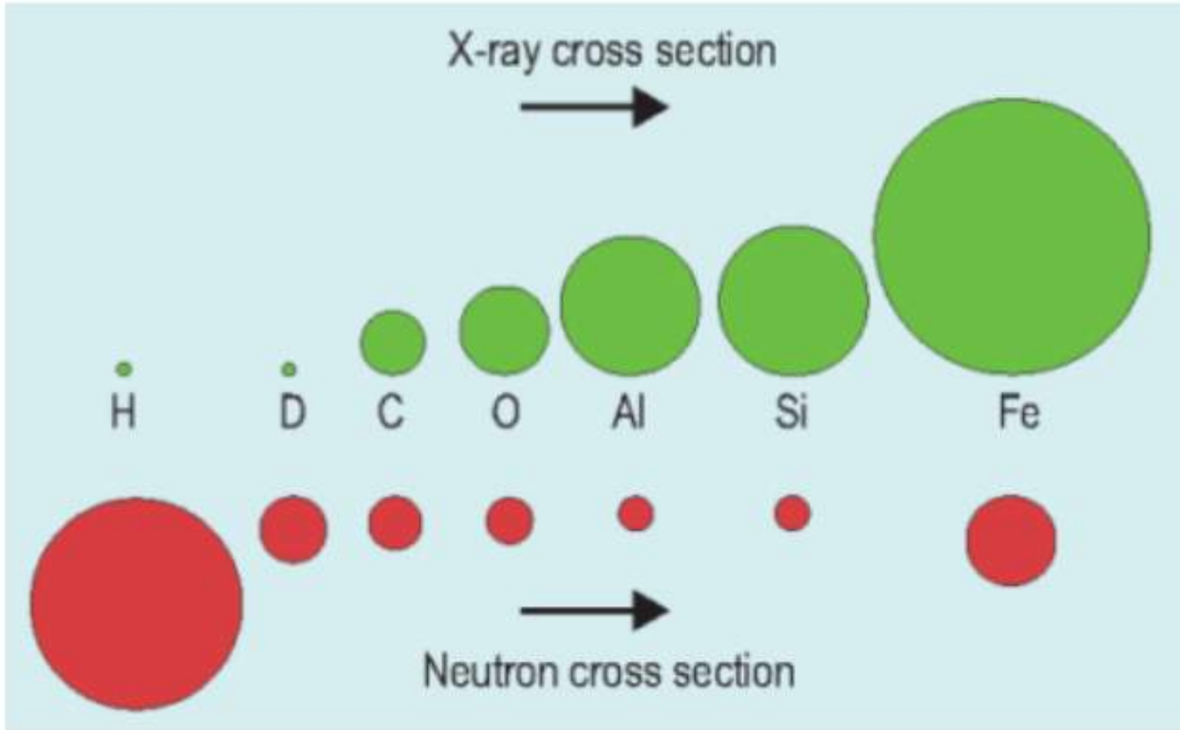


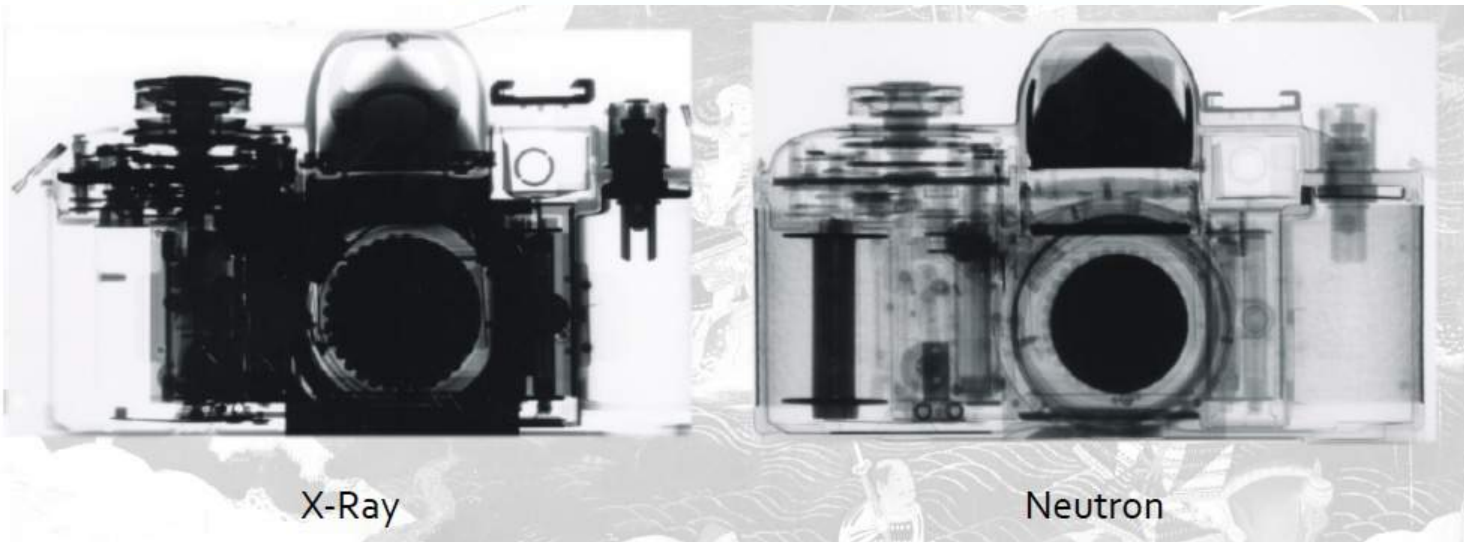
Neutron Sources



Relevant Neutron Properties







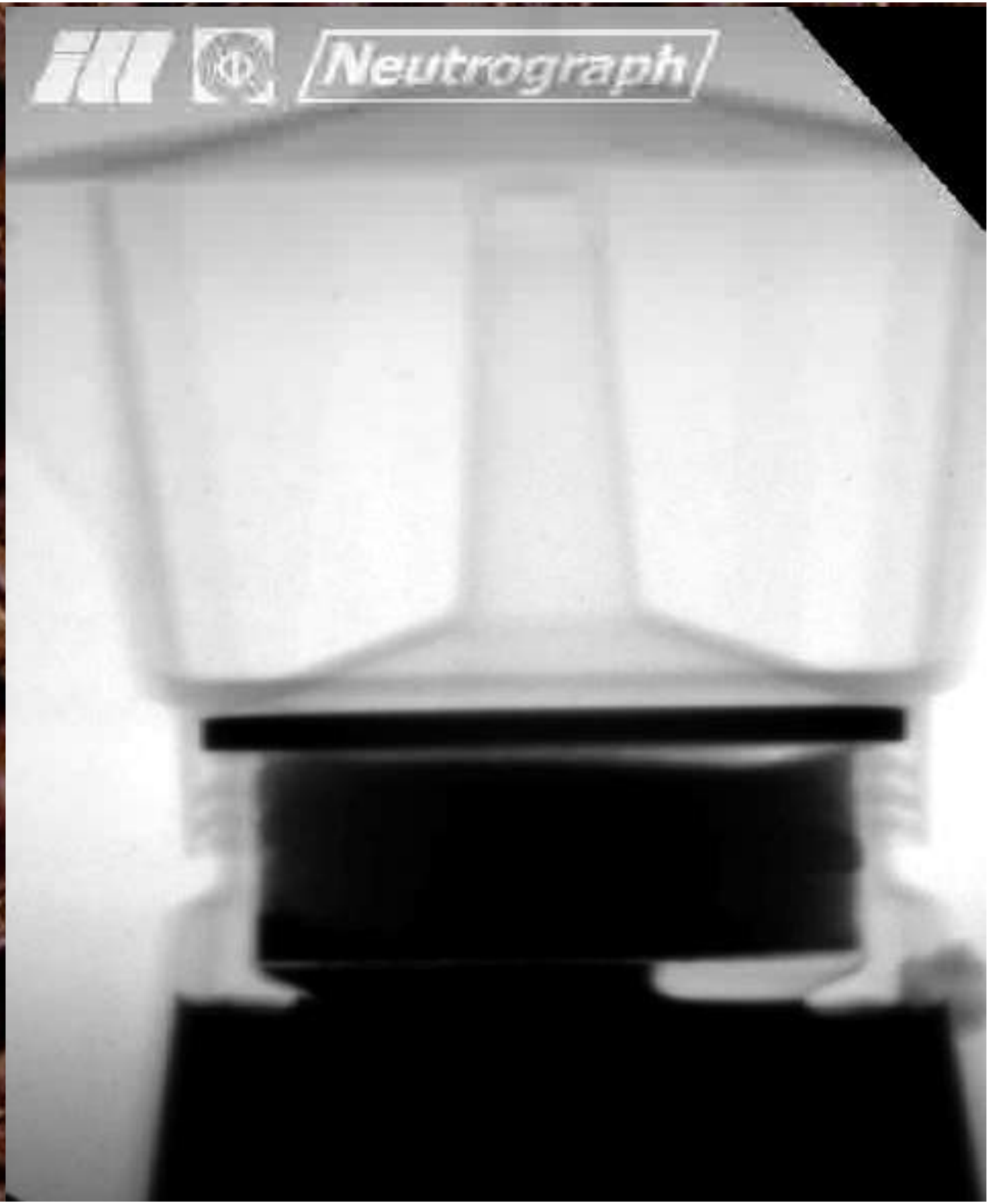
The special feature of Neutrograph is it's intensity together with a moderate collimation.

These properties allow the investigation of dynamic processes with an excellent time resolution and the transmittance through strongly absorbing and bulky materials.

A totally new spectrum of scientific and engineering applications could be developed.

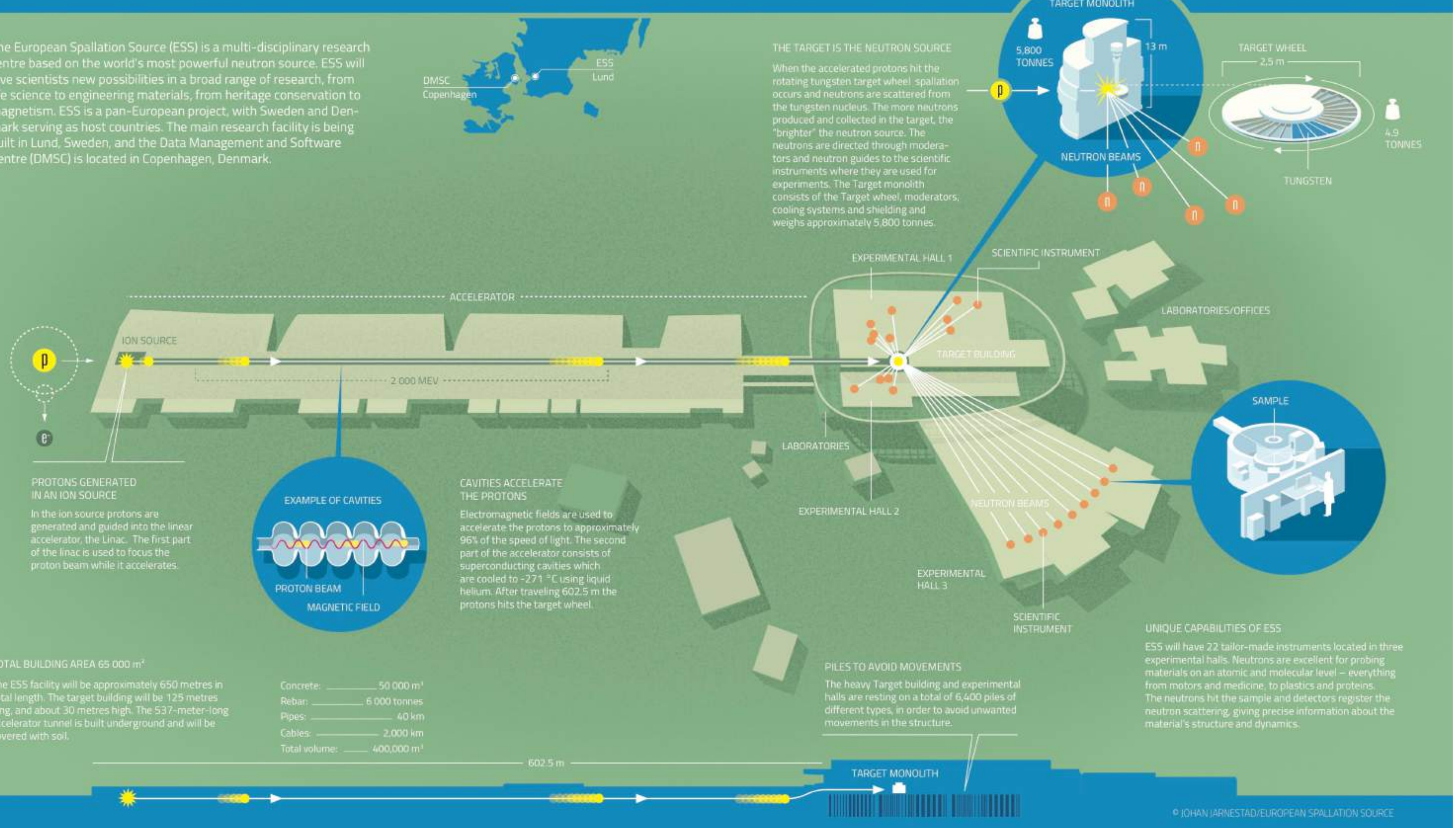
Among the experiments are investigations of heat exchangers and combustion engines, parts from aircrafts, fossils and historical heritage.

Institut Laue-Langevin (ILL) in Grenoble



European Spallation Source

The European Spallation Source (ESS) is a multi-disciplinary research centre based on the world's most powerful neutron source. ESS will give scientists new possibilities in a broad range of research, from life science to engineering materials, from heritage conservation to magnetism. ESS is a pan-European project, with Sweden and Denmark serving as host countries. The main research facility is being built in Lund, Sweden, and the Data Management and Software Centre (DMSC) is located in Copenhagen, Denmark.



THE TARGET IS THE NEUTRON SOURCE

When the accelerated protons hit the rotating tungsten target wheel spallation occurs and neutrons are scattered from the tungsten nucleus. The more neutrons produced and collected in the target, the "brighter" the neutron source. The neutrons are directed through moderators and neutron guides to the scientific instruments where they are used for experiments. The Target monolith consists of the Target wheel, moderators, cooling systems and shielding and weighs approximately 5,800 tonnes.

PROTONS GENERATED IN AN ION SOURCE

In the ion source protons are generated and guided into the linear accelerator, the Linac. The first part of the linac is used to focus the proton beam while it accelerates.

CAVITIES ACCELERATE THE PROTONS

Electromagnetic fields are used to accelerate the protons to approximately 96% of the speed of light. The second part of the accelerator consists of superconducting cavities which are cooled to -271 °C using liquid helium. After traveling 602.5 m the protons hits the target wheel.

TOTAL BUILDING AREA 65 000 m²

The ESS facility will be approximately 650 metres in total length. The target building will be 125 metres long, and about 30 metres high. The 537-meter-long accelerator tunnel is built underground and will be covered with soil.

Concrete:	50 000 m³
Rebar:	6 000 tonnes
Pipes:	40 km
Cables:	2,000 km
Total volume:	400,000 m³

PILES TO AVOID MOVEMENTS

The heavy Target building and experimental halls are resting on a total of 6,400 piles of different types, in order to avoid unwanted movements in the structure.

UNIQUE CAPABILITIES OF ESS

ESS will have 22 tailor-made instruments located in three experimental halls. Neutrons are excellent for probing materials on an atomic and molecular level – everything from motors and medicine, to plastics and proteins. The neutrons hit the sample and detectors register the neutron scattering, giving precise information about the material's structure and dynamics.

Area	Application	Beam	Accelerator	Beam energy/MeV	Beam current/ mA	Number
Medical	Cancer therapy	e	linac	4-20	10^{-2}	>14000
		p	cyclotron, synchrotron	250	10^{-6}	60
		C	synchrotron	4800	10^{-7}	10
	Radioisotope production	p	cyclotron	8-100	1	1600
Industrial	Ion implantation	B, As, P	electrostatic	< 1	2	>11000
	Ion beam analysis	p, He	electrostatic	<5	10^{-4}	300
	Material processing	e	electrostatic, linac, Rhodatron	≤10	150	7500
	Sterilisation	e	electrostatic, linac, Rhodatron	≤10	10	3000
Security	X-ray screening of cargo	e	linac	4-10	?	100?
	Hydrodynamic testing	e	linear induction	10-20	1000	5
Synchrotron light sources	Biology, medicine, materials science	e	synchrotron, linac	500-10000		70
Neutron scattering	Materials science	p	cyclotron, synchrotron, linac	600-1000	2	4
Energy – fusion	Neutral ion beam heating	d	electrostatic	1	50	10
	Heavy ion inertial fusion	Pb, Cs	Induction linac	8	1000	Under development
	Materials studies	d	linac	40	125	Under development
Energy – fission	Waste burner	p	linac	600-1000	10	Under development
	Thorium fuel amplifier	p	linac	600-1000	10	Under development
Energy – bio-fuel	Bio-fuel production	e	electrostatic	5	10	Under development
Environmental	Water treatment	e	electrostatic	5	10	5
	Flue gas treatment	e	electrostatic	0.7	50	Under development

Ultra-precise microscopy

- Probing particles are required for studies of the elementary constituents
- The associated de Broglie wavelength λ of a probing particle defines the minimum object size that can be resolved.

$$\lambda = \frac{h}{p} = h \times \frac{c}{E} \quad \text{with} \begin{cases} h = 4 \times 10^{-15} \text{ eVs} & \text{(Plank constant)} \\ p = \text{momentum}, \ E = \text{energy} \end{cases}$$

Resolving Smaller Objects Requires Higher Momentum Probe Particles

Example of probe wavelength

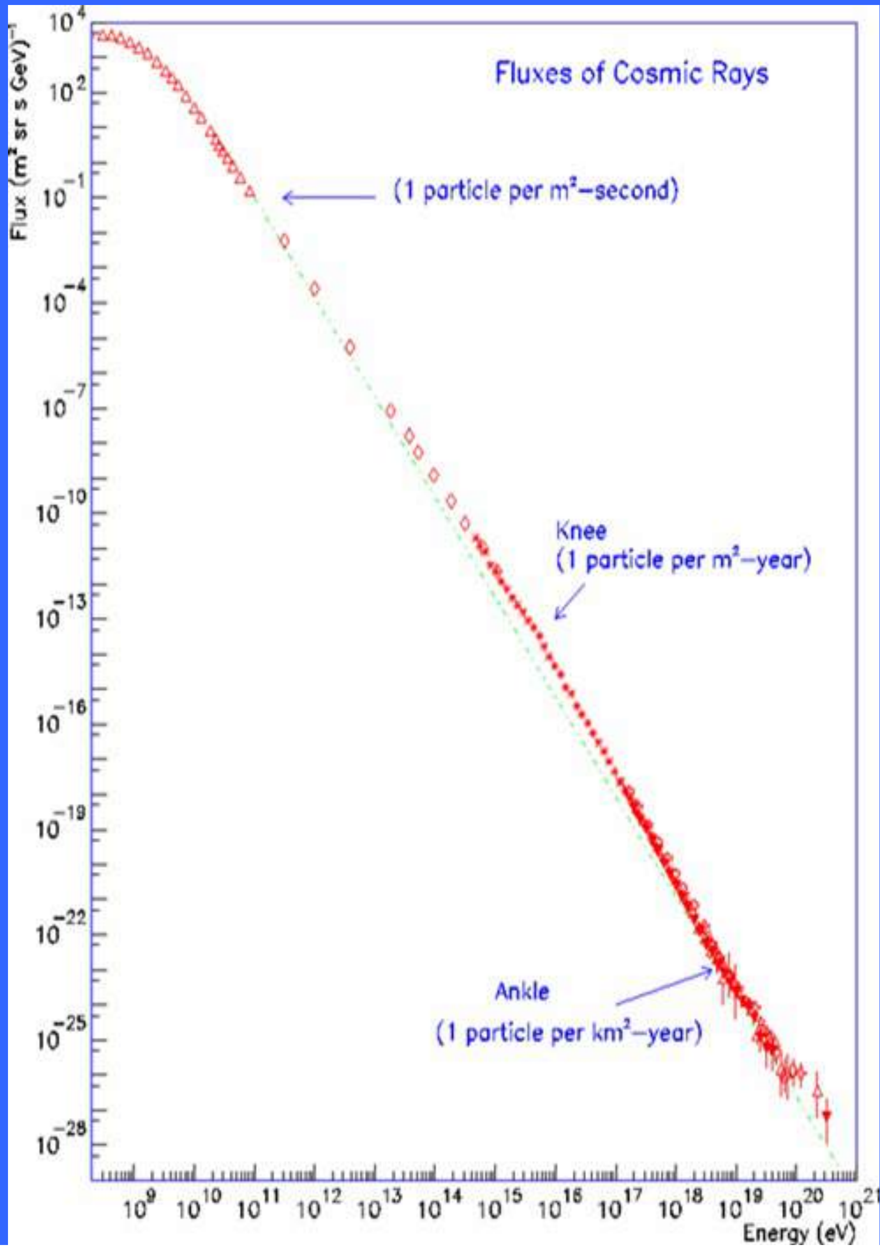
- electrons with p = 1 keV/c $\Rightarrow$ l = h/p = 4×10^{-12} m
- photons with E = 1 keV $\Rightarrow$ l = $h\times c/E$ ~ 1.2×10^{-9} m.

➔ electrons have ~ 300 times better resolution than photons (electron-microscopy !)

Typical microscopic sizes

- Atom 10^{-10} m
- Nucleus 10^{-14} m
- Proton 10^{-15} m
- Quark 10^{-19} m

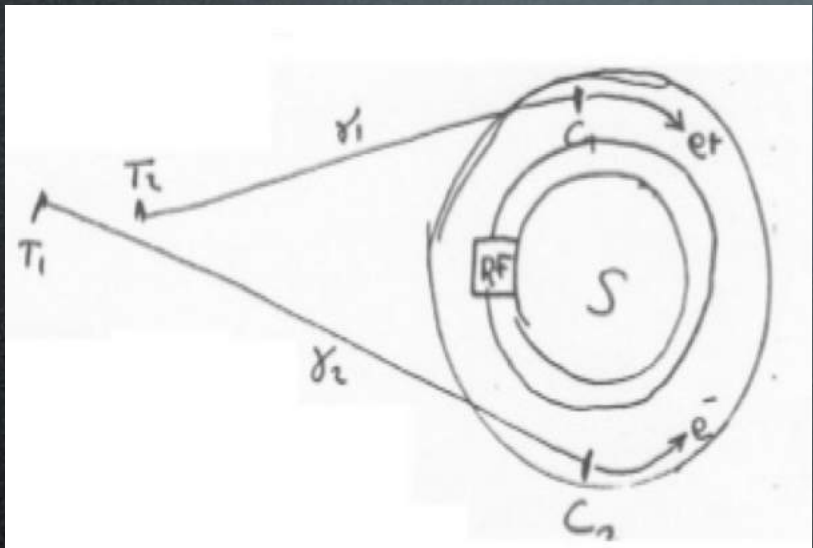
Cosmos is able to accelerate particles …but in uncontrolled conditions



GeV TeV PeV EeV ZeV

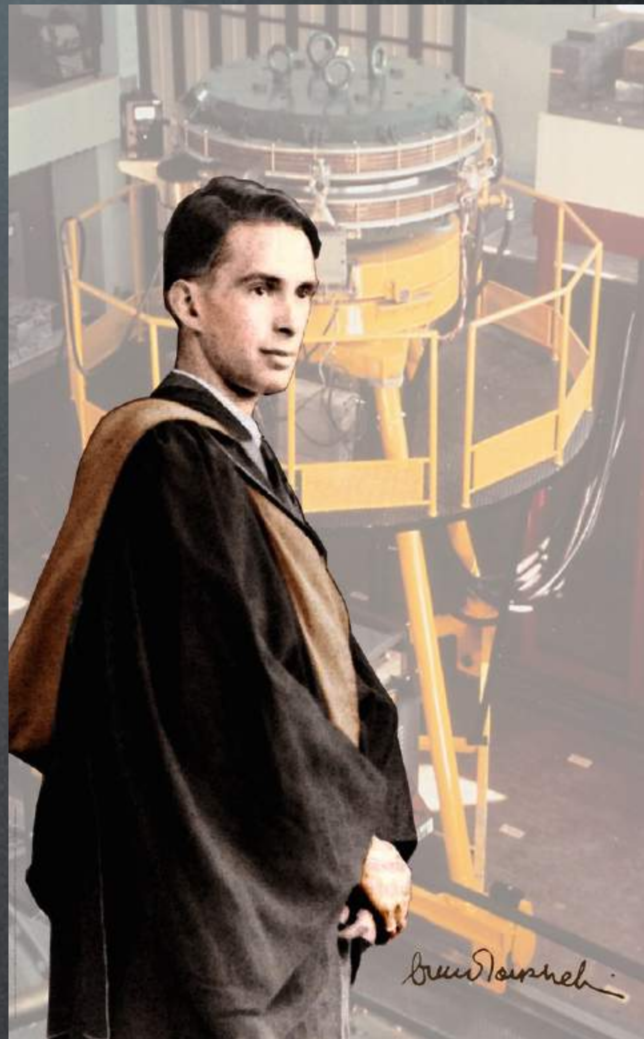
Touschek's Anello Di Accumulazione (ADA)

1961 the first e+e- Collider

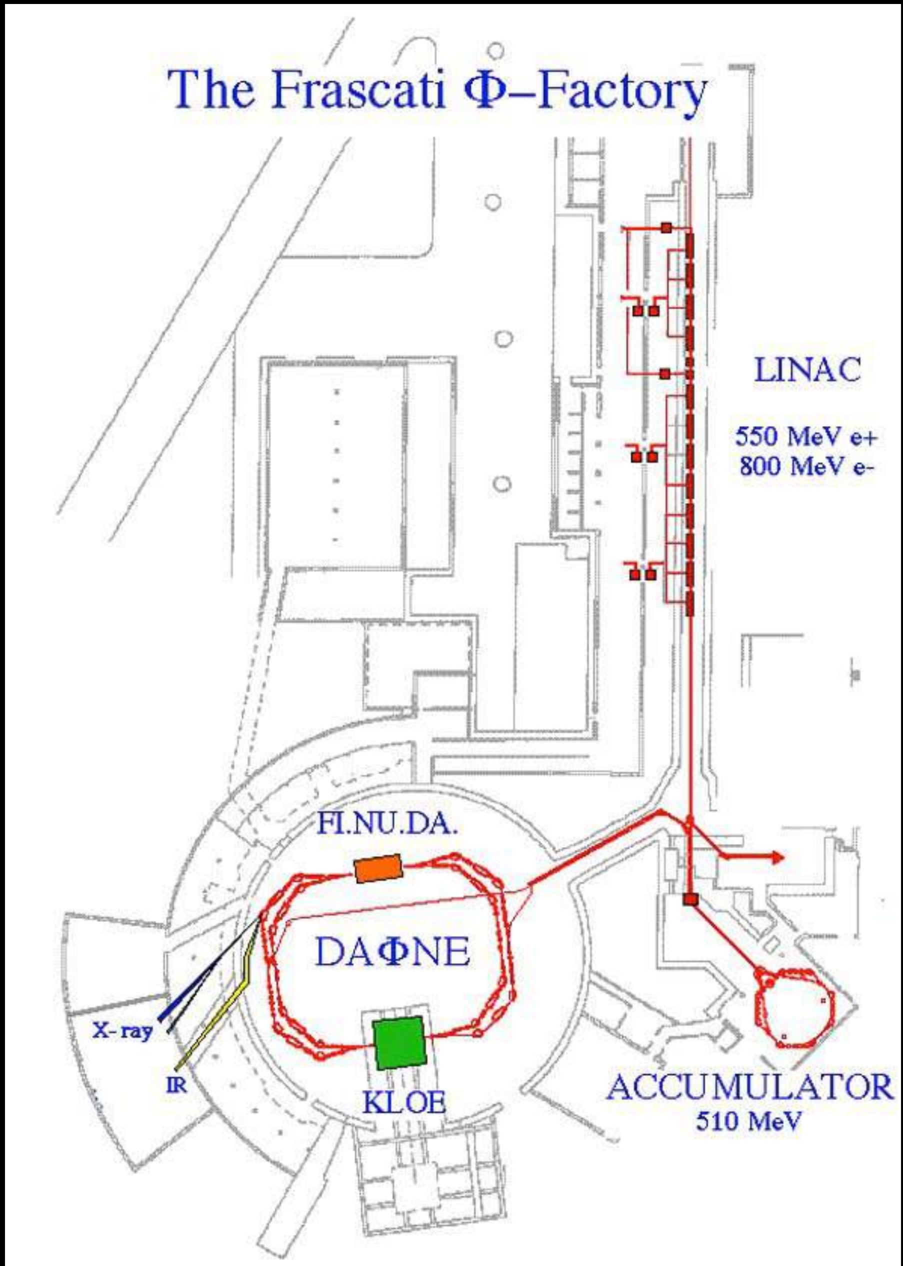


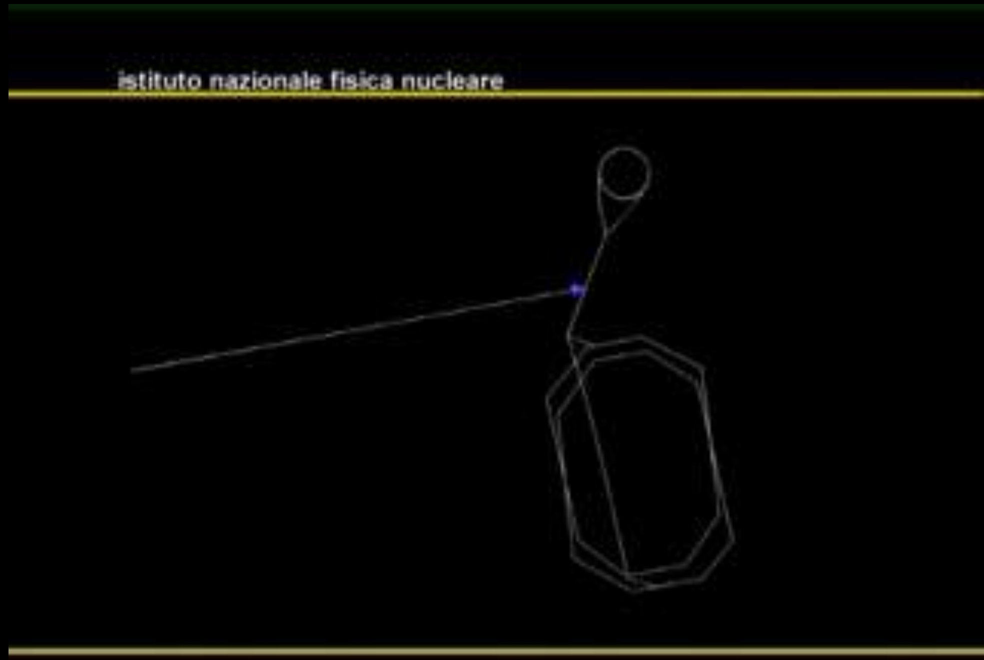
$$E_{CM} \approx \sqrt{2E_1 m_2}$$

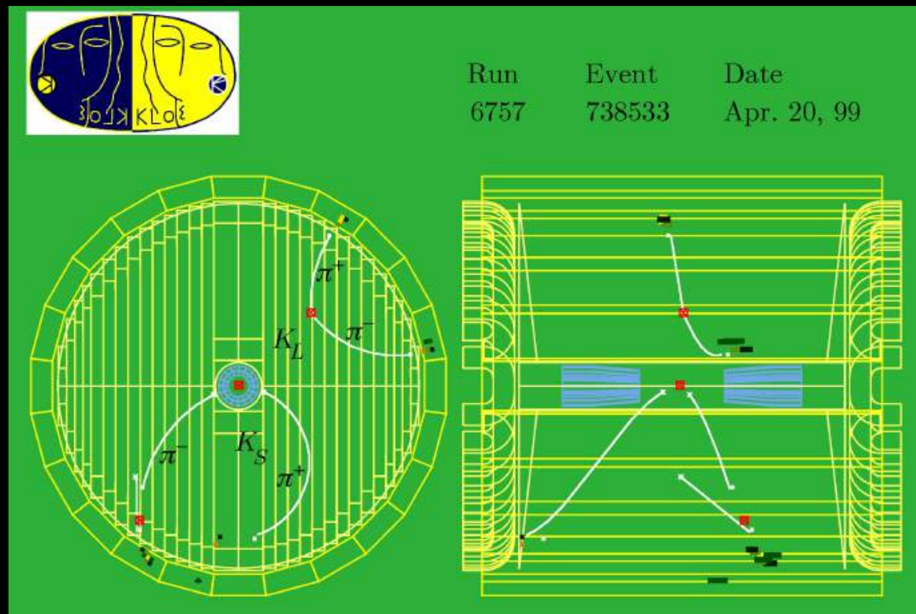
$$E_{CM} \approx 2E$$



Collider e+ e- DAFNE (INFN)


The Frascati Φ–Factory
LINAC
550 MeV e+
800 MeV e-
FI.NU.DA.
DAΦNE
X-ray
IR
KLOE
ACCUMULATOR
510 MeV


istituto nazionale fisica nucleare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6757
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738533
Date
Apr. 20, 99
π^+
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K_L
K_S
π^-
π^+

Historical Milestones

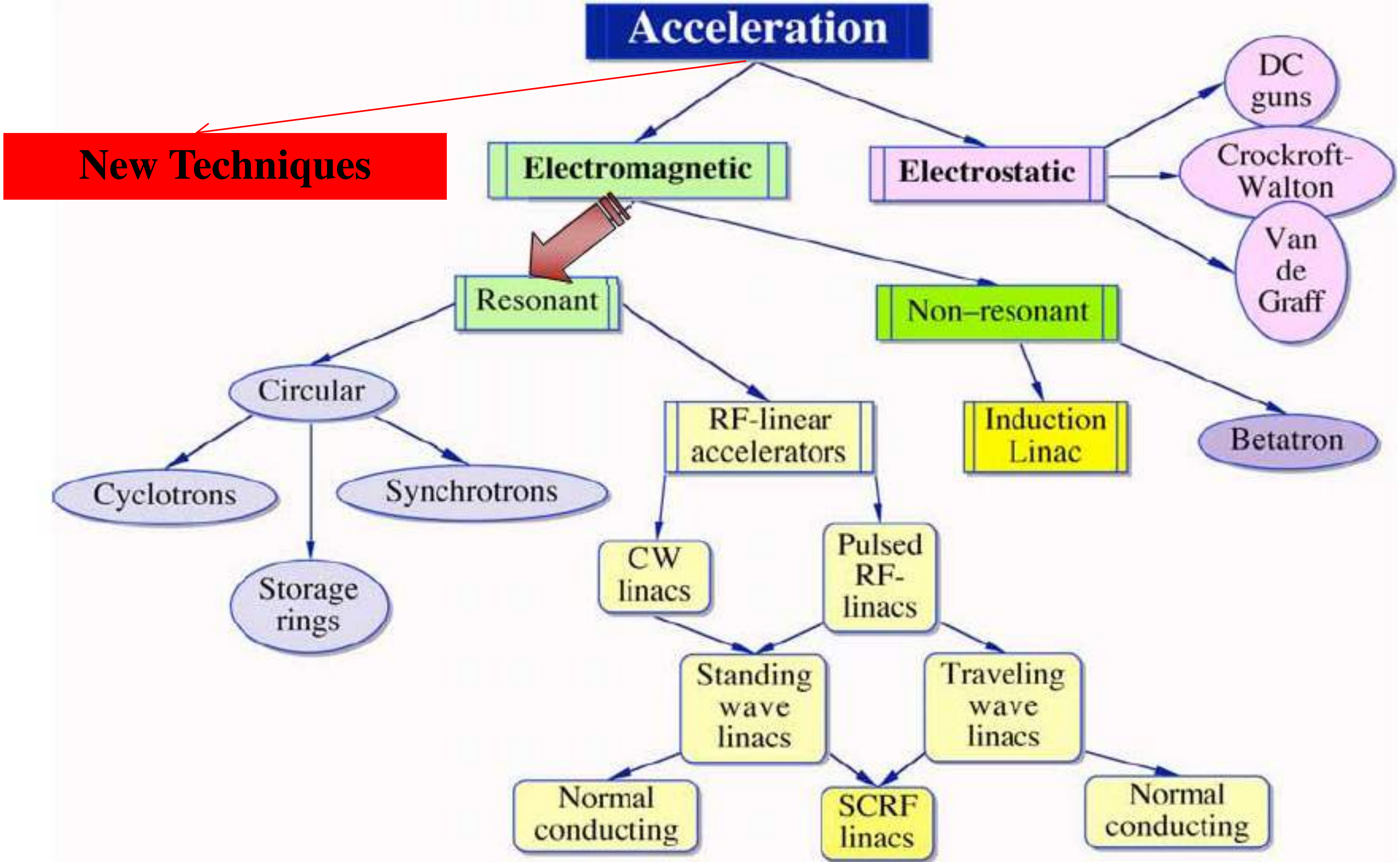
- 1900 to 1925 radioactive source experiments à la Rutherford -> request for higher energy beams;
- 1928 to 1932 electrostatic acceleration ->
  - Cockcroft & Walton * -> voltage multiplication using diodes and oscillating voltage (700 kV);
  - Van der Graaf -> voltage charging through mechanical belt (1.2 MV);
- 1928 resonant acceleration -> Ising establish the concept, Wideroe builds the first linac;
- 1929 cyclotron ->
  - small prototype by Livingstone (PhD thesis), large scale by Lawrence**;
- 1942 magnetic induction -> Kerst build the betatron;
- 1944 synchrotron -> MacMillan, Oliphant and Veksel invent the RF phase stability (longitudinal focusing);
- 1946 proton linac -> Alvarez build an RF structure with drift tubes (progressive wave in 2π mode);
- 1950 strong focusing -> Christofilos patent the alternate gradient concept (transverse strong focusing);
- 1951 tandem -> Alvarez upgrade the electrostatic acceleration concept and build a tandem;
- 1955 AGS -> Courant, Snider and Livingstone build the alternate gradient Cosmotron in Brookhaven;
- 1956 collider -> Kerst discuss the concept of colliding beams;
- 1961 e^+e^- collider -> Touschek invent the concept of particle-antiparticle collider;
- 1967 electron cooling -> Budker proposes the e-cooling to increase the proton beam density;
- 1968 stochastic cooling ->
  - Van der Meer*** proposes the stochastic cooling to compress the phase space;
- 1970 RFQ -> Kapchinski & Telyakov build the radiofrequency quadrupole;
- 1980 to now superconducting magnets -> developed in various laboratories to increase the beam energy;
- 1980 to now superconducting RF -> developed in various lab to increase the RF gradient.

* Nobel 1951

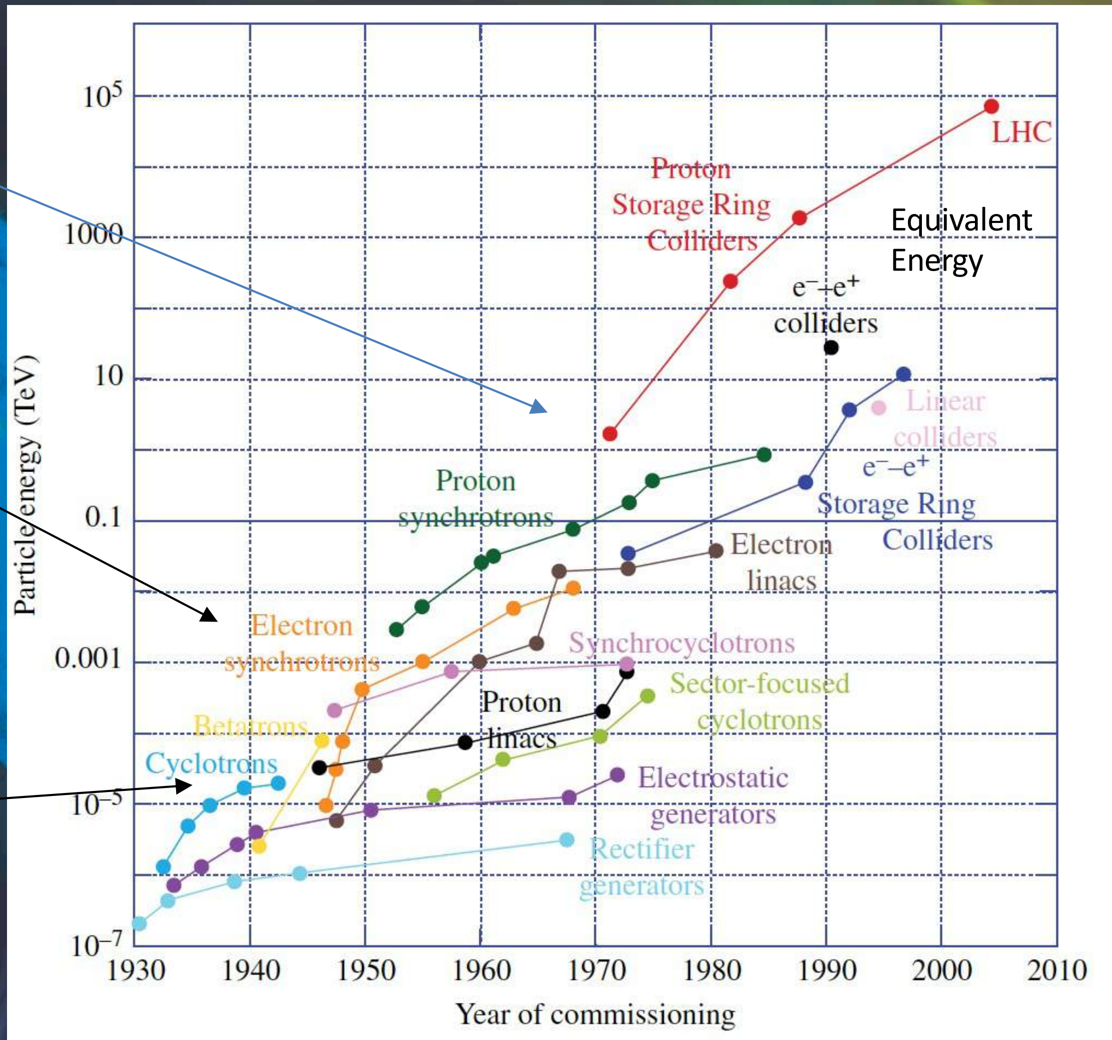
** Nobel 1939

*** Nobel 1984

Accelerator Configurations

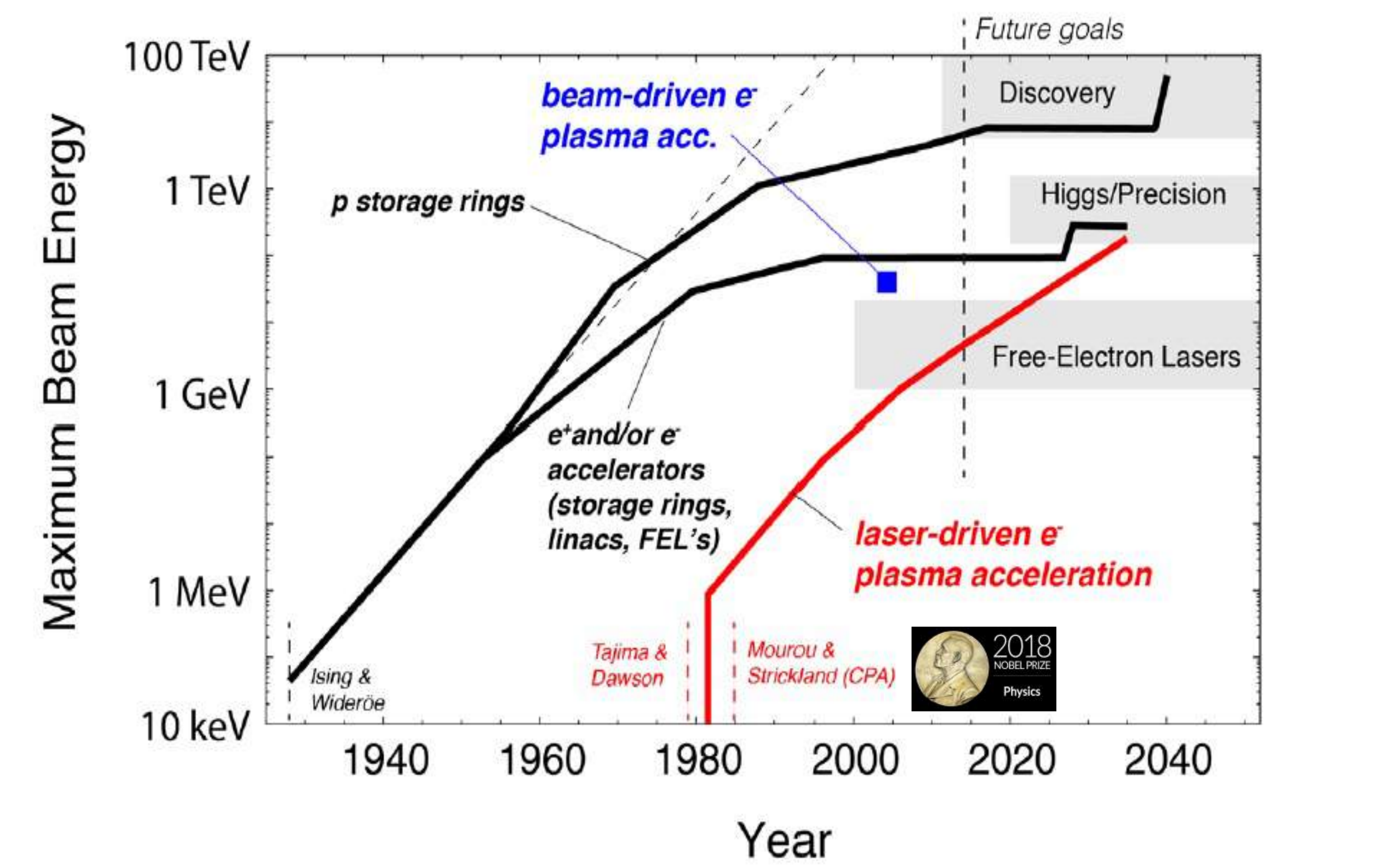


Il diagramma di Livingstone

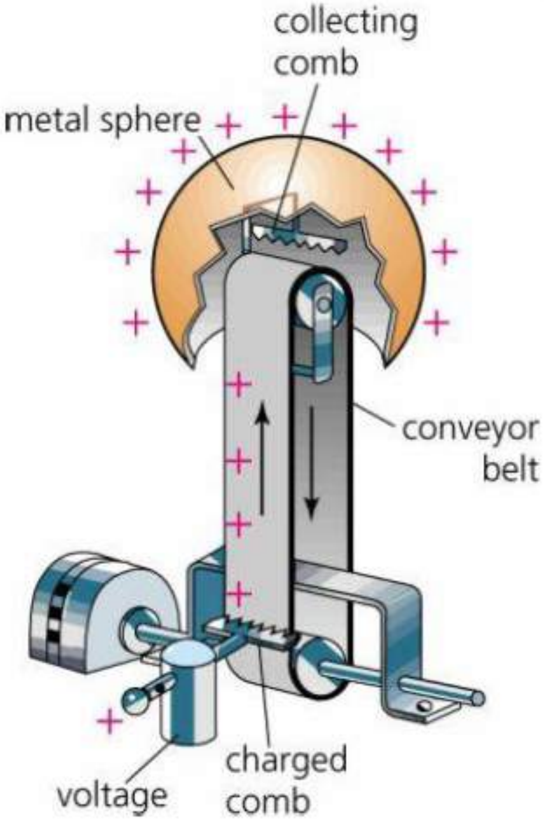


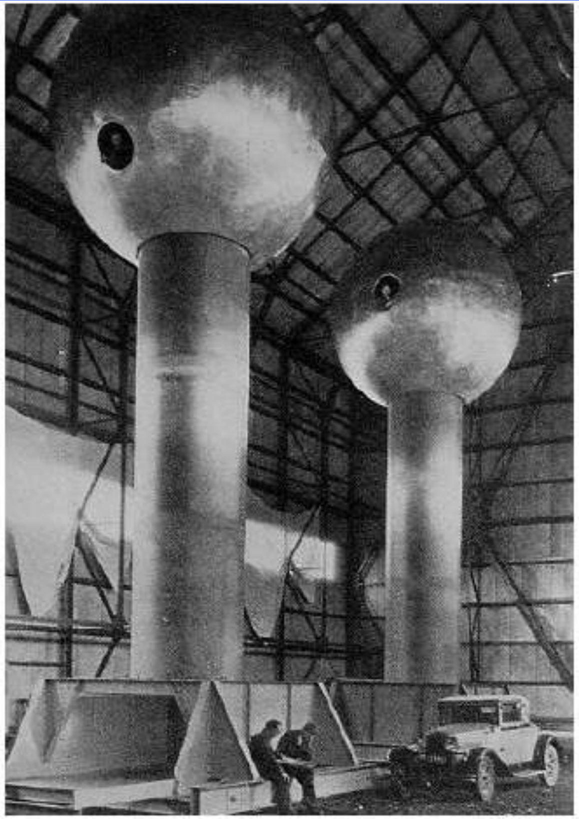
Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

Recent sign of saturation?



Electrostatic Accelerator: Van de Graff



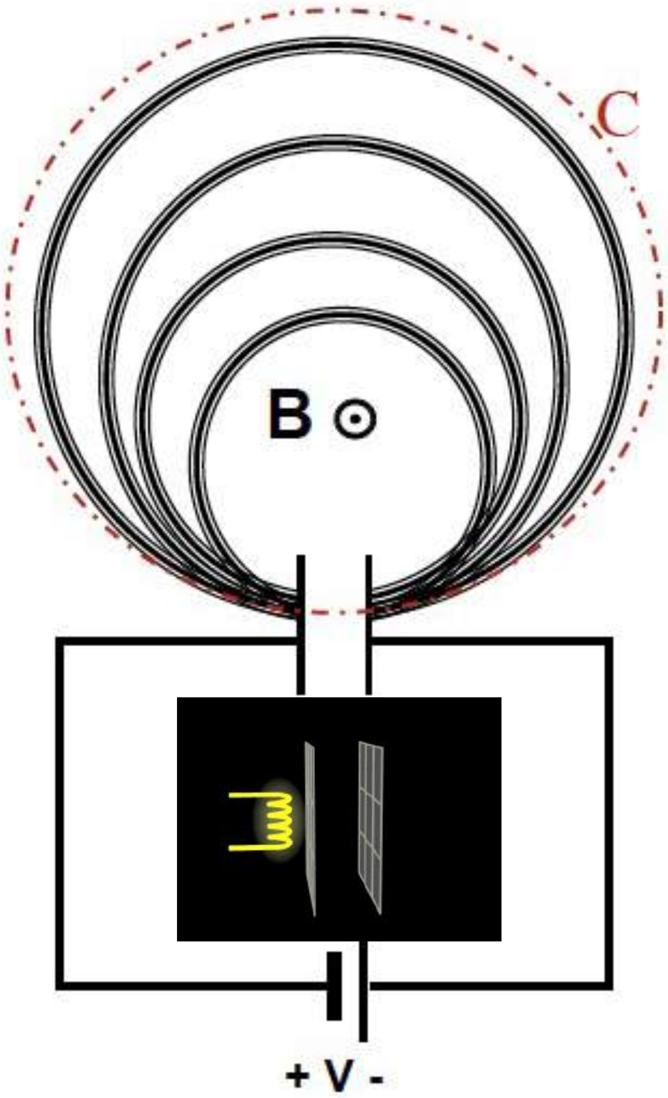


7 MV Van de Graaf at MIT (1933)

R.J. Van de Graaf

- Electric charges are transported mechanically on an insulating belt
- Stable, continuous beams, practical limit 10 - 15 MV

Possible Higher energy DC accelerator?



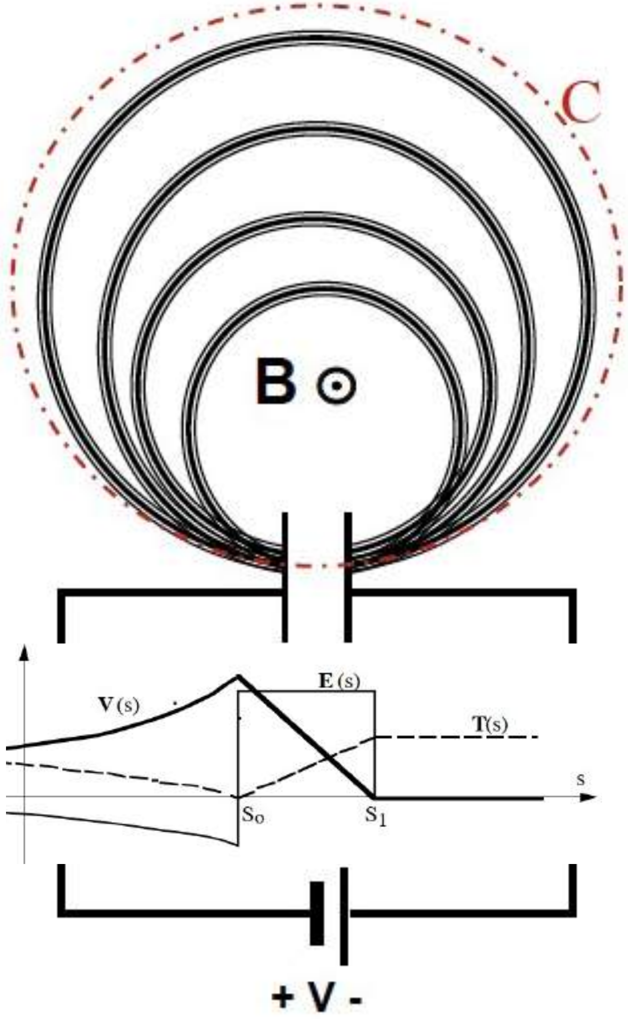
$$F_{Lorentz} = q\,v\,B = F_{centripital} = \frac{mv^2}{\rho}$$

$$\Rightarrow \rho = \frac{mv}{qB} = \frac{p}{qB}$$

$$\rho(\mathrm{m}) = 3.34\left(\frac{p}{1\ \mathrm{GeV/c}}\right)\left(\frac{1}{q}\right)\left(\frac{1\ \mathrm{T}}{B}\right)$$

$T=q\Delta V$

Forbidden by Maxwell



$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

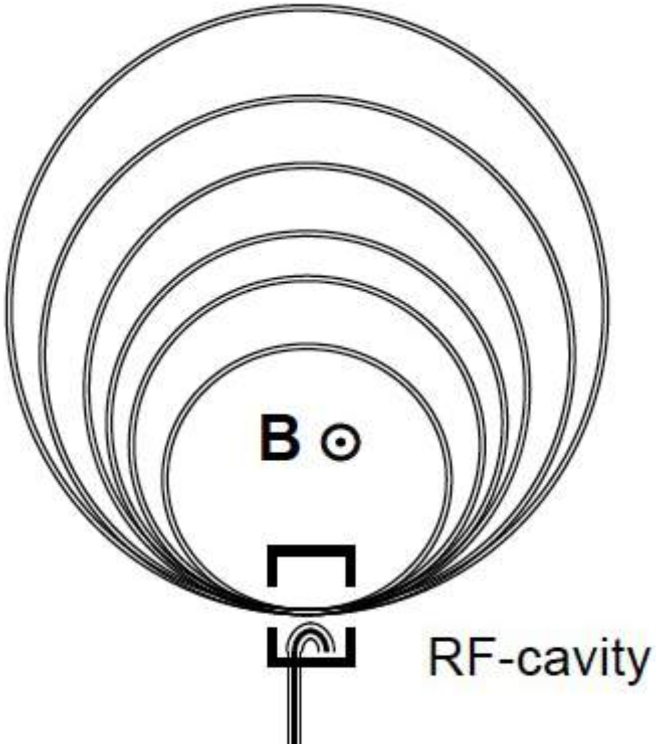
or in integral form

$$\oint_C \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot \mathbf{n}\, da$$

∴ **There is no acceleration without time-varying magnetic flux**

$\Delta V_T = 0$

B can vary in a RF cavity



$$E_z = E_0 J_0(k_r r) \cos \omega t$$

$$B_\theta = -\frac{E_0}{c} J_1(k_r r) \sin \omega t$$

Note that inside the cavity
dB/dt ≠ 0

However,

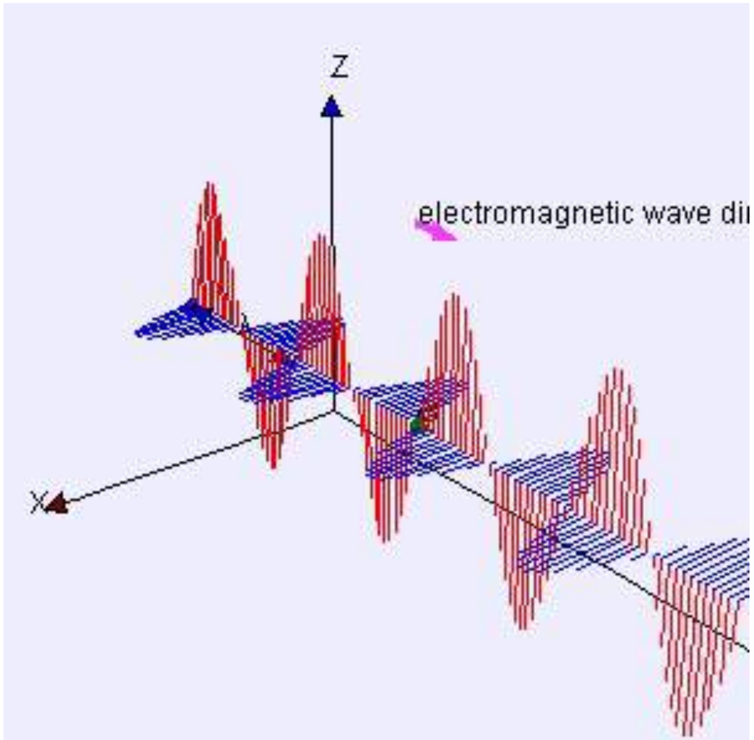
Synchronism condition:
$\Delta\tau_{rev} = N/f_{rf}$

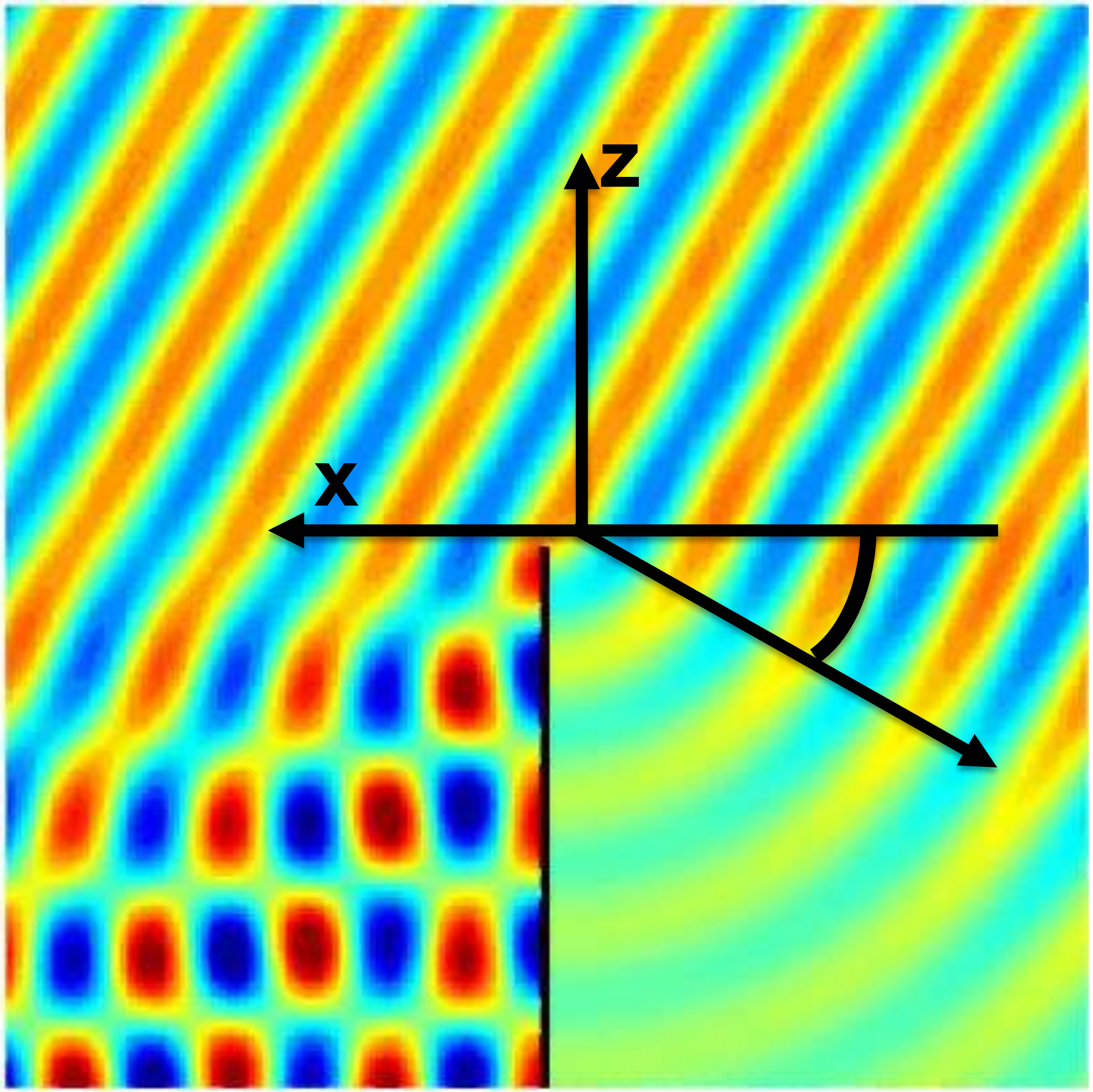
Lawson-Woodward Theorem

(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

The theorem assumes that
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,

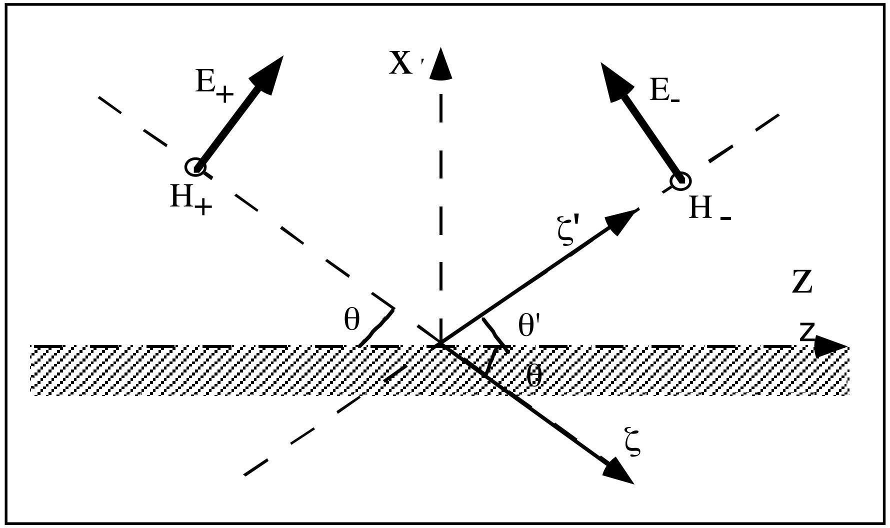



z
x

Reflection of plane waves

Plane wave reflected by a perfectly conducting plane

$$\sigma = \infty$$



In the plane xz the field is given by the superposition of the incident and reflected wave:

$$E(x,z,t) = E_+(x_o,z_o,t_o)e^{i\omega t - ik\zeta} + E_-(x_o,z_o,t_o)e^{i\omega t - ik\zeta'}$$

$$\zeta = z\cos\theta - x\sin\theta \qquad \zeta' = z\cos\theta' + x\sin\theta'$$

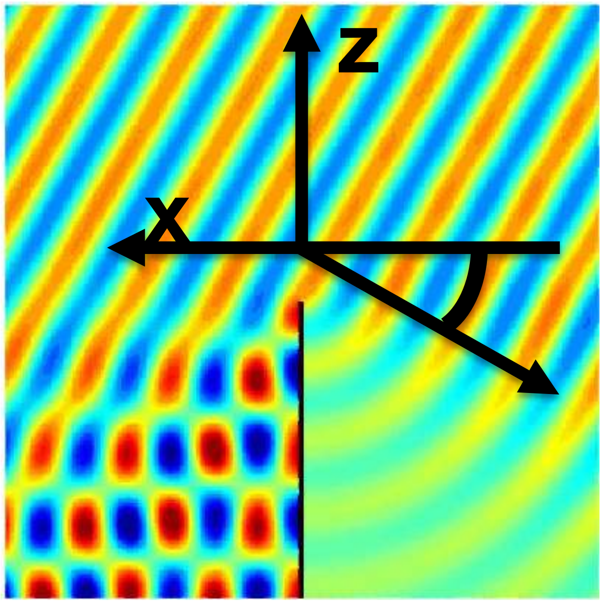
And it has to fulfill the boundary conditions (no tangential E-field)

Reflection of plane waves (a first boundary value problem)

Taking into account the boundary conditions the longitudinal component of the field becomes:

$$E_z(x,z,t) = (E_+ \sin\theta) e^{i\omega t - ik(z\cos\theta - x\sin\theta)} - (E_+ \sin\theta) e^{i\omega t - ik(z\cos\theta + x\sin\theta)}$$

$$= 2iE_+ \sin\theta \sin(kx\sin\theta) e^{i\omega t - ikz\cos\theta}$$



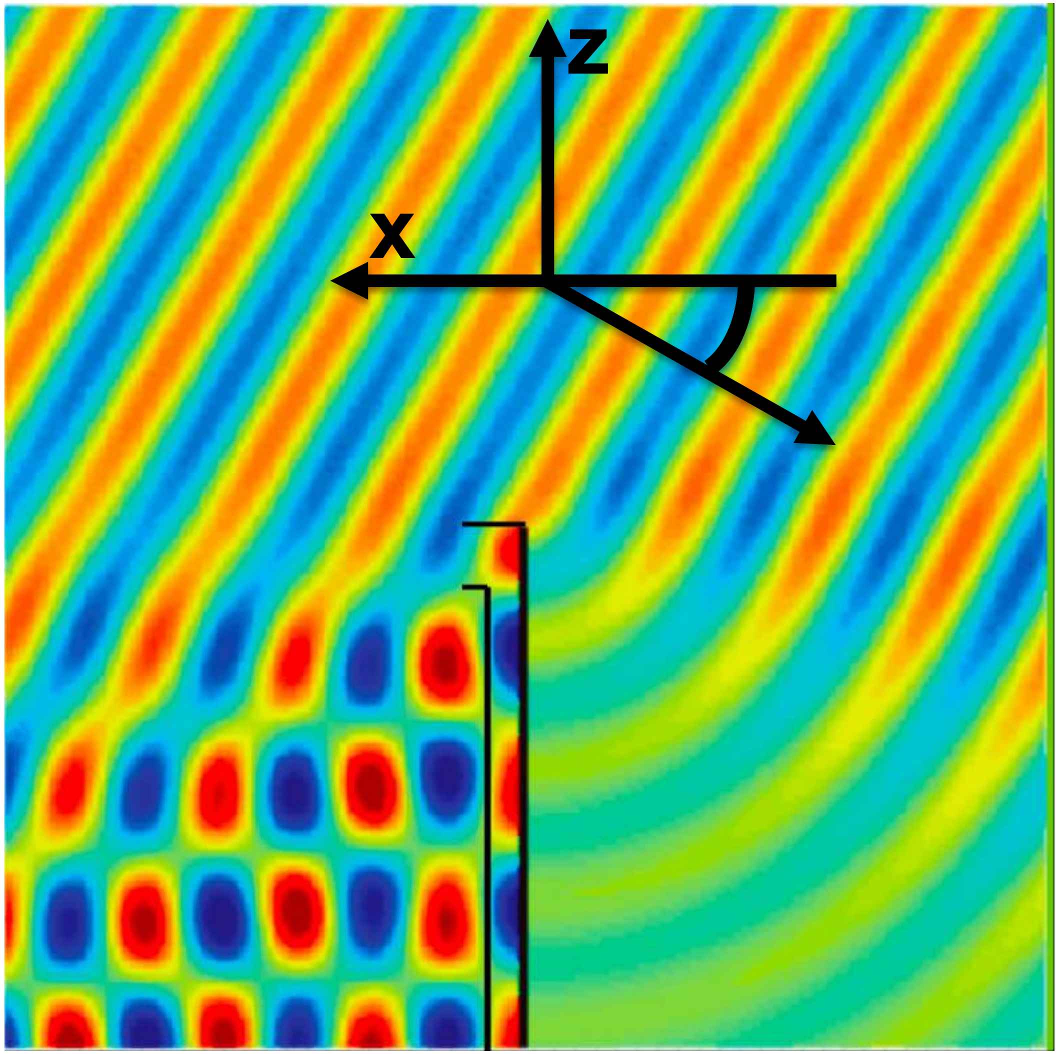
Standing Wave pattern (along x)

Guided wave pattern (along z)

The phase velocity is given by

$$v_{\phi z} = \frac{\omega}{k_z} = \frac{\omega}{k\cos\theta} = \frac{c}{\cos\theta} > c$$

From reflections to waveguides



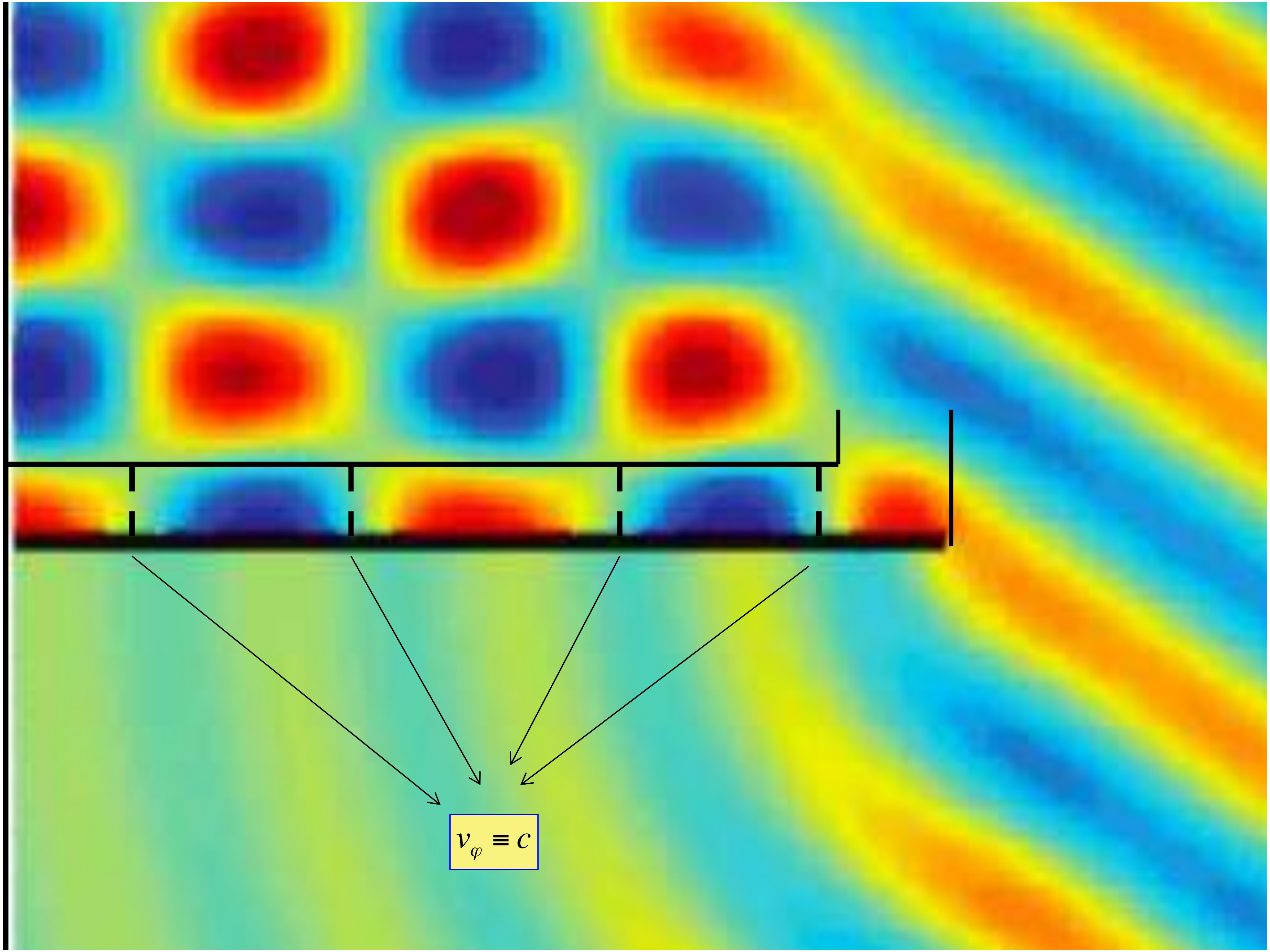
Put a metallic boundary where the field is zero at a given distance from the wall.

Between the two walls there must be an integer number of half wavelengths (at least one).

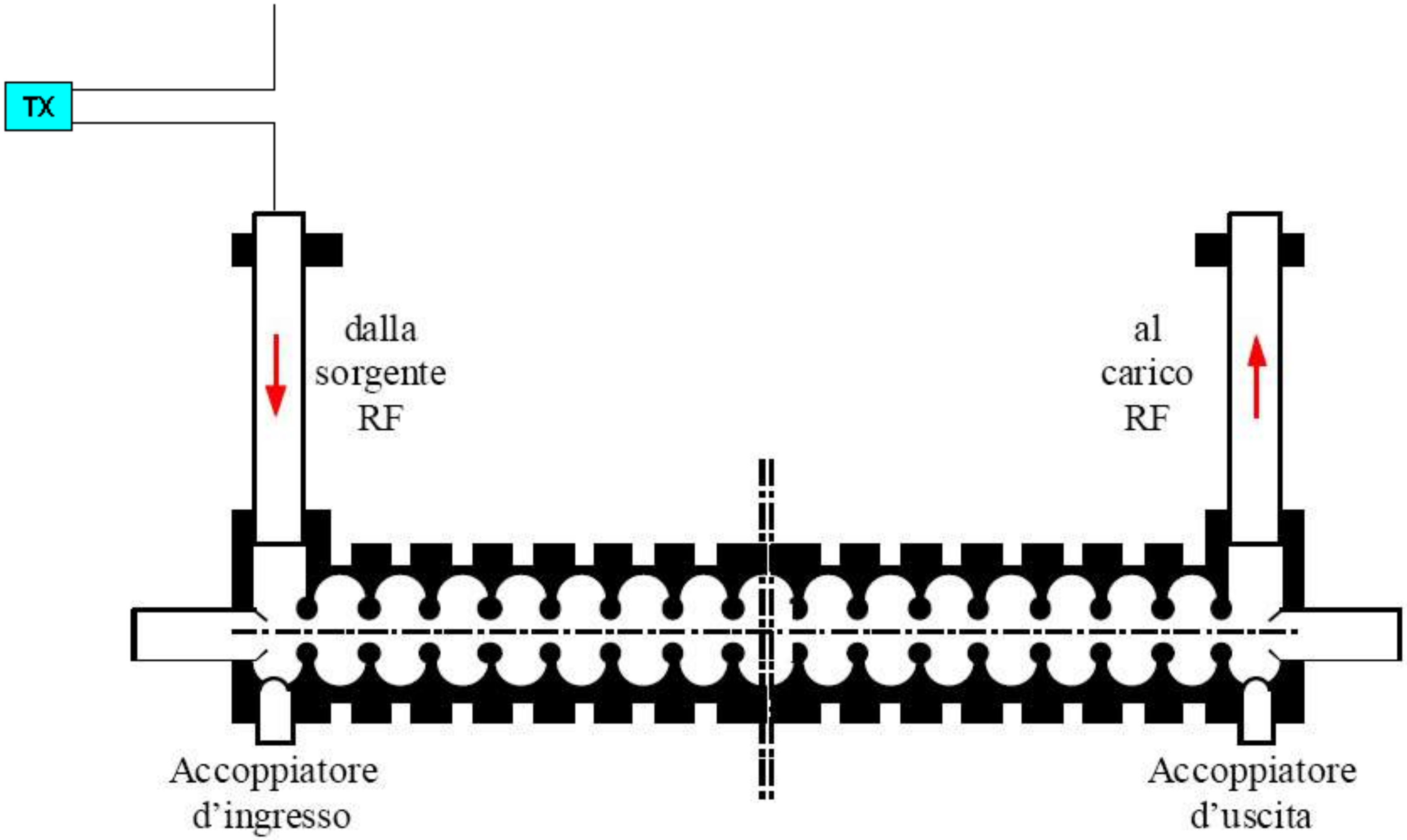
For a given distance, there is a maximum wavelength, i.e. there is **cut-off frequency**.

$$v_{\phi z} = \frac{\omega}{k_z} = \frac{\omega}{k\cos\theta} = \frac{c}{\cos\theta} > c$$

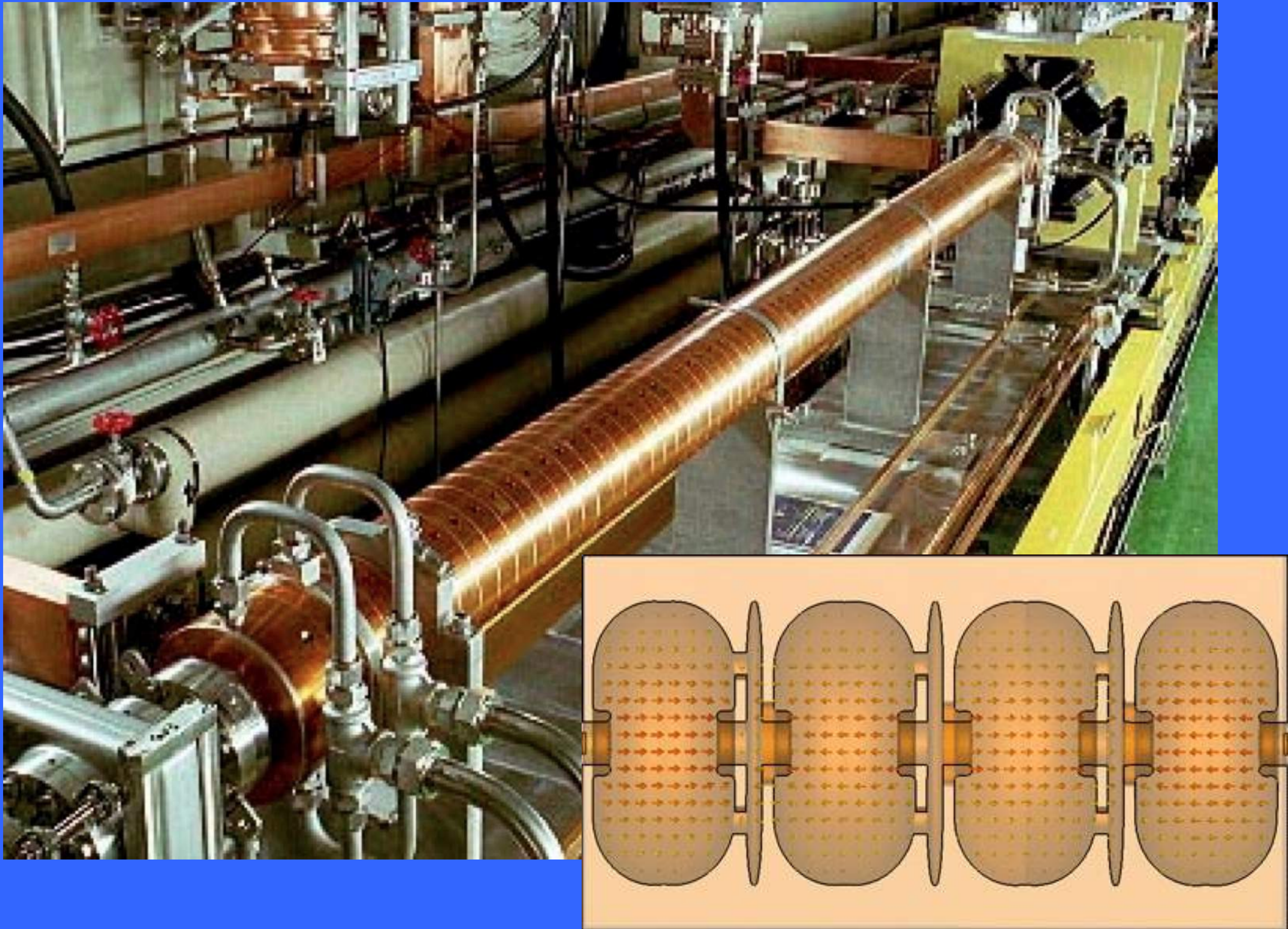
→ It can not be used as it is for particle acceleration


$v_{\varphi} \equiv c$

Electromagnetic waveguides



Conventional RF accelerating structures



We must slow down the wave propagation

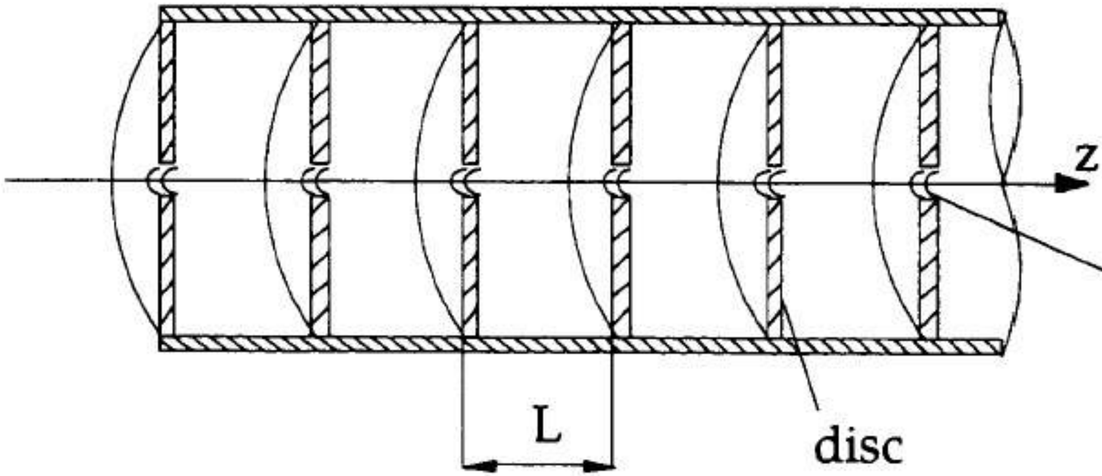
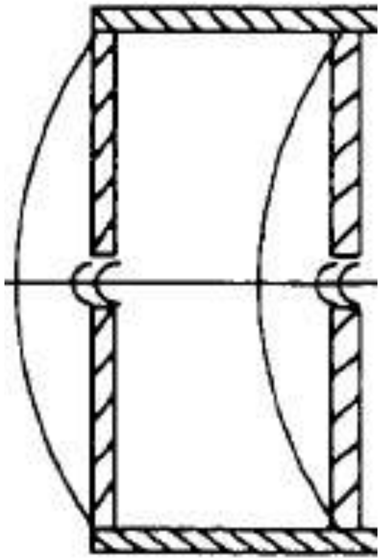


Fig. 6 Disc-loaded cavity (schematic)

In order to slow down the waves we have to load the cavity by introducing some periodic obstacle into it

$$\frac{\partial^2 E_z}{\partial z^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{\partial^2 E_z}{\partial r^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} = 0$$



$$E_z = E_0 J_0(k_r r) \cos \omega t$$

$$B_\theta = -\frac{E_0}{c} J_1(k_r r) \sin \omega t$$

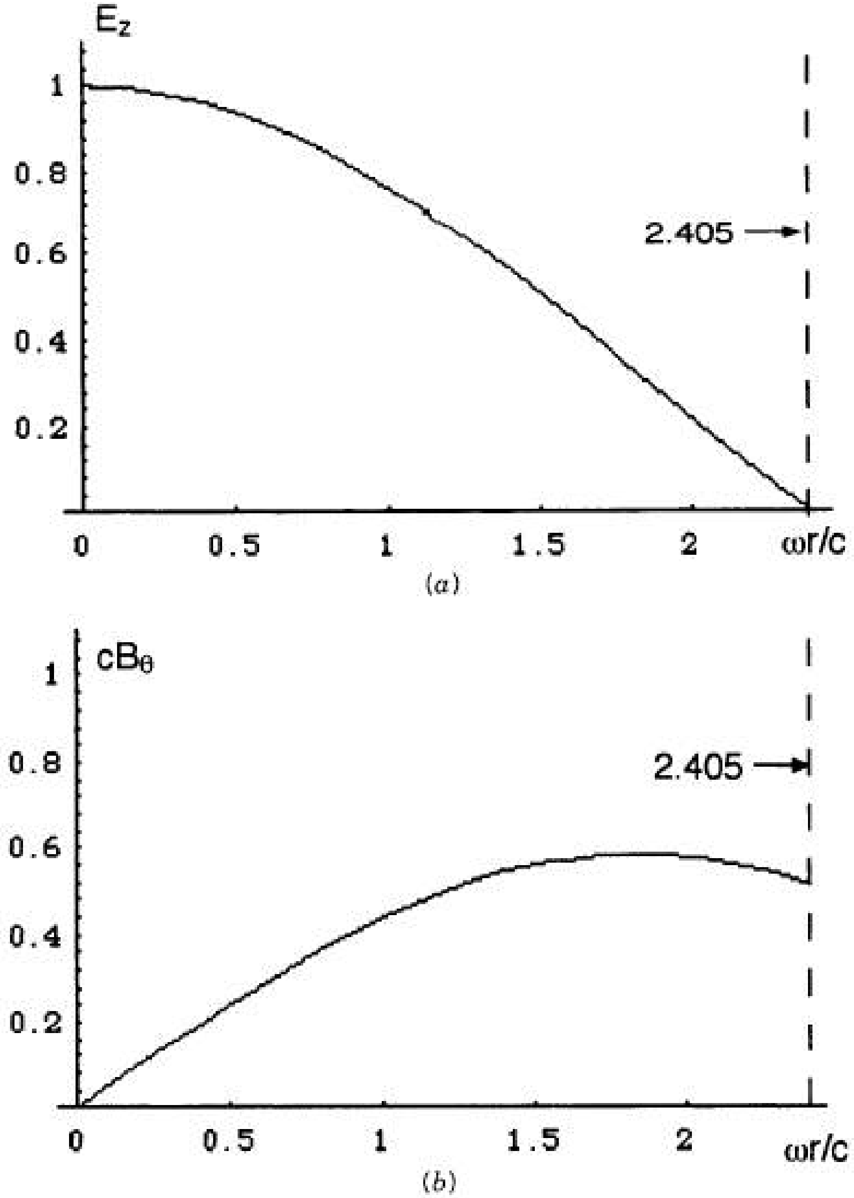
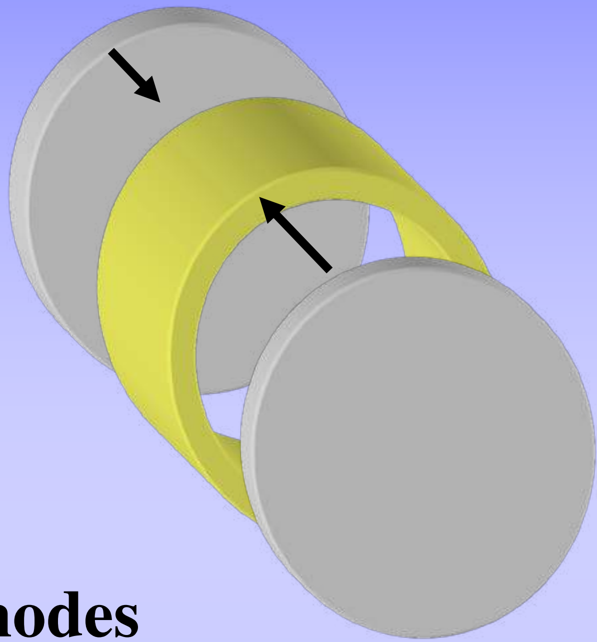


Figure 1.17 Fields for a TM_{010} mode of a cylindrical (pillbox)-cavity resonator.

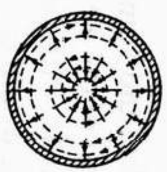
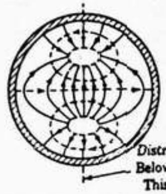
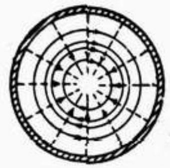
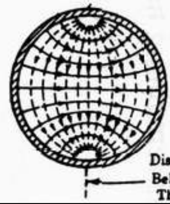
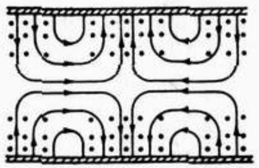
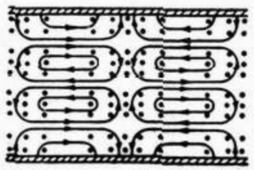
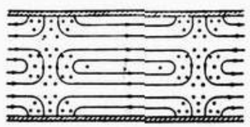
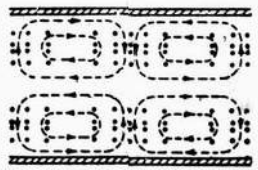
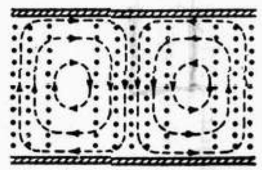
Analytical field solutions: the Pill-box cavity

In the simplest cases the mode field configuration can be calculated analytically, while in almost all practical cases the solutions are computed numerically by means of dedicated computer codes.

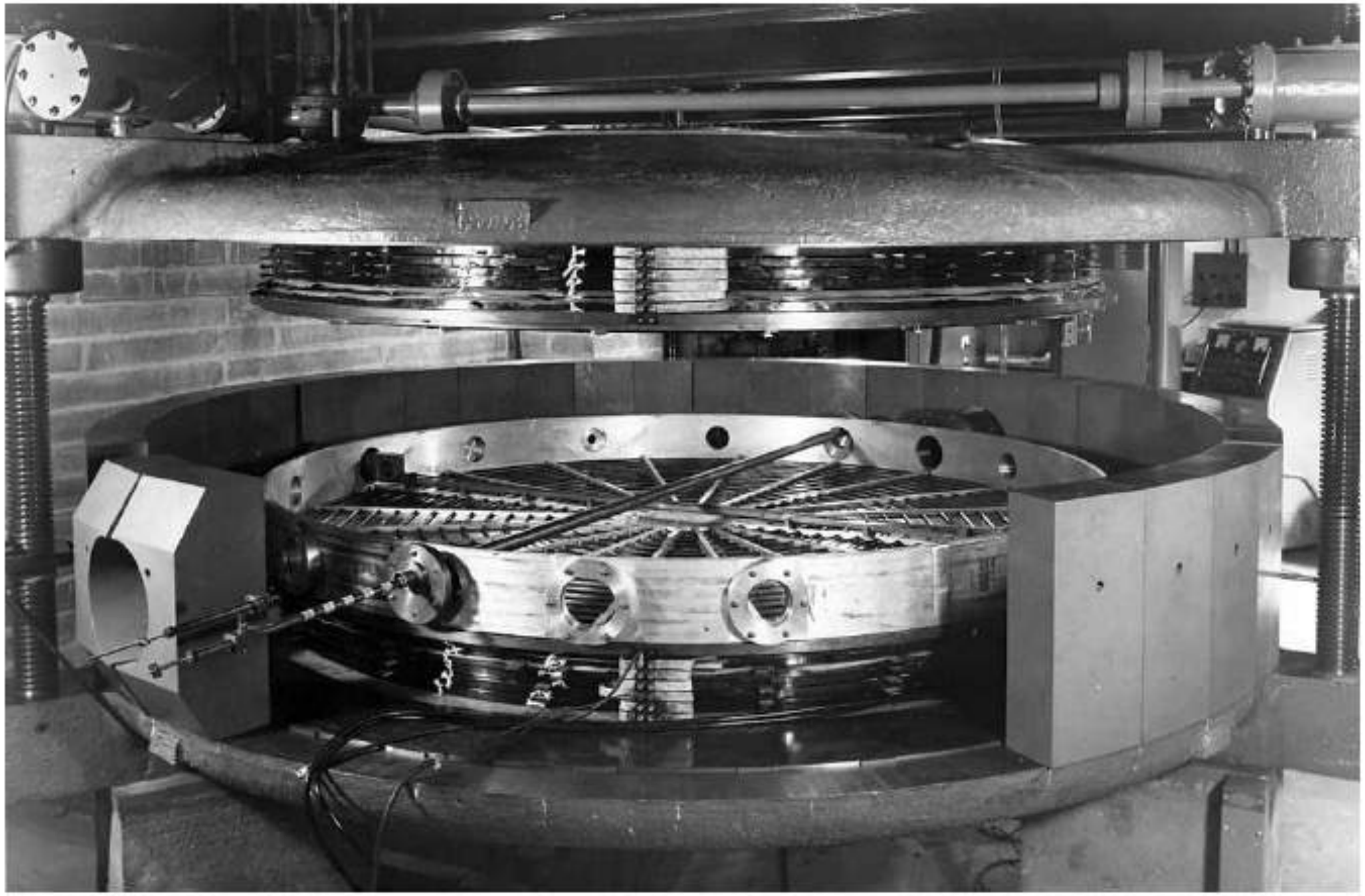
One of the most interesting didactical case is the cylindrical or ‗pill-box" cavity. The pill-box cavity can be seen as a piece of circular waveguide short-circuited at both ends by metallic plates.



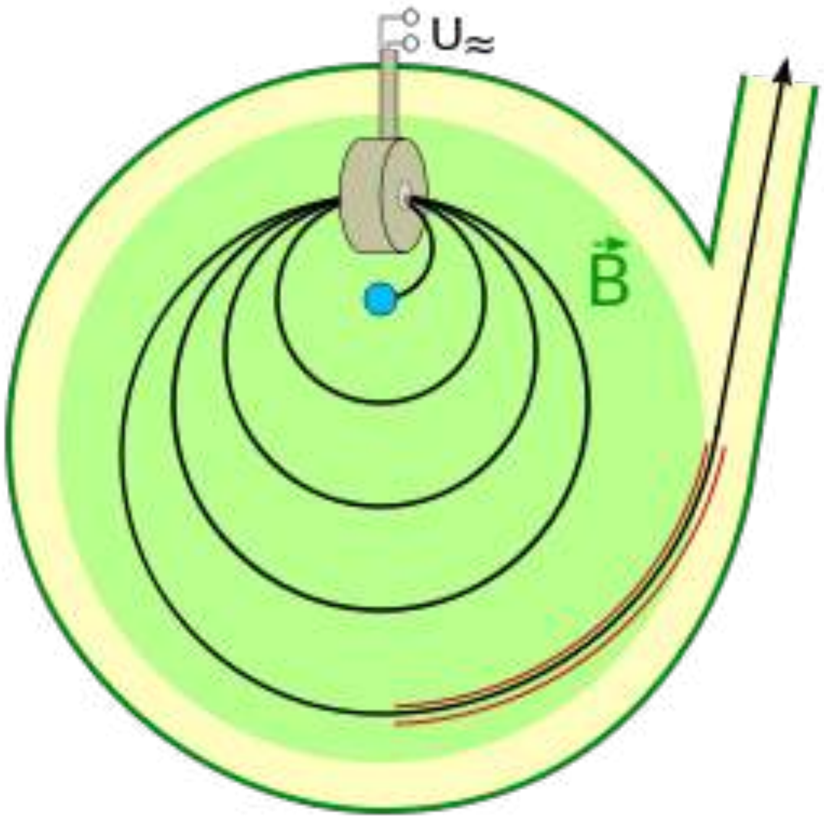
Circular waveguide modes

Wave Type	TM_{01}	TM_{02}	TM_{11}	TE_{01}	TE_{11}
Field distributions in cross-sectional plane, at plane of maximum transverse fields			 Distributions Below Along This Plane		 Distributions Below Along This Plane
Field distributions along guide					

28 MeV Microtron at HEP Laboratory University College London



Microtron - Synchronization



$$t_i = \frac{2\pi R_i}{v_i}$$

$$e v_i B = m_i \frac{v_i^2}{R_i}$$

$$R_i = \frac{v_i m_i c^2}{e c^2 B} = \frac{v_i}{e c^2 B} E_i$$

$$\Delta t = t_{i+1} - t_i = \frac{2\pi}{e c^2 B}\left(E_{i+1} - E_i\right) = \frac{2\pi}{e c^2 B} \Delta E$$

Energy gain/revolution

$$\Delta t = t_{i+1} - t_i = \frac{2\pi}{ec^2 B}\left(E_{i+1} - E_i\right) = \frac{2\pi}{ec^2 B}\Delta E$$

$$\Delta t = \frac{k}{\nu_{RF}} = \frac{2\pi}{ec^2 B}\Delta E$$

$$\boxed{\Delta E = k\frac{ec^2 B}{2\pi\nu_{RF}}}$$

- In a microtron, due to the electrons' increasing momentum, the particle paths are different for each pass. The time needed for that must be an integer multiple k of the RF period. The allowed energy gain/pass must fulfill the above condition.

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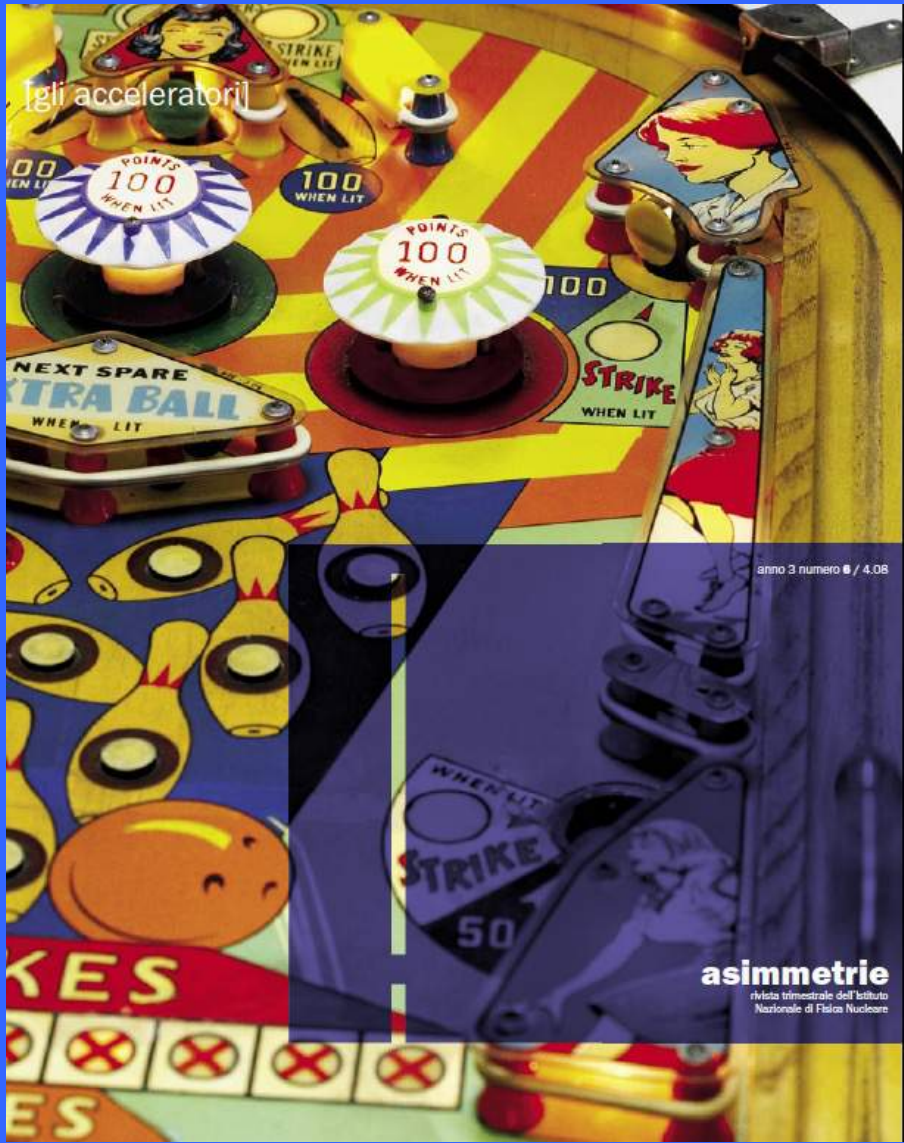

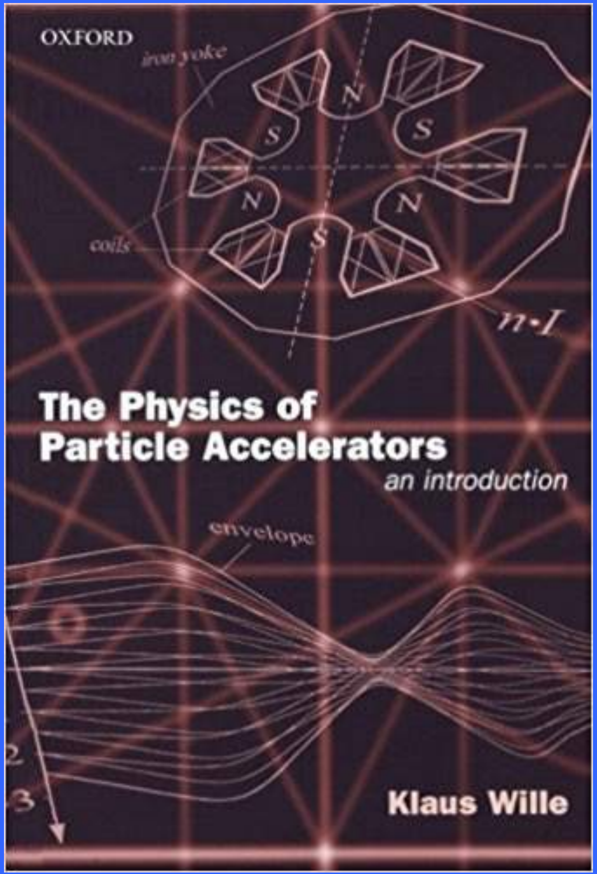
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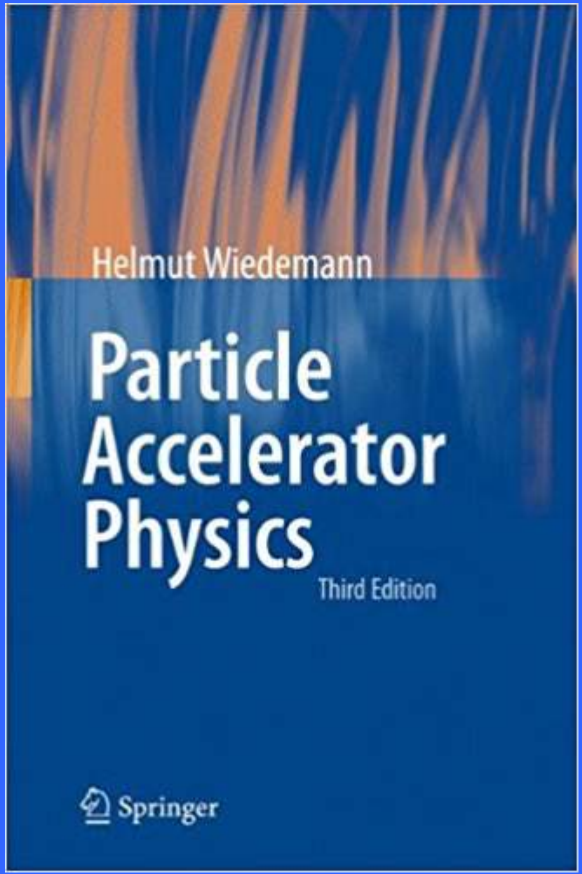
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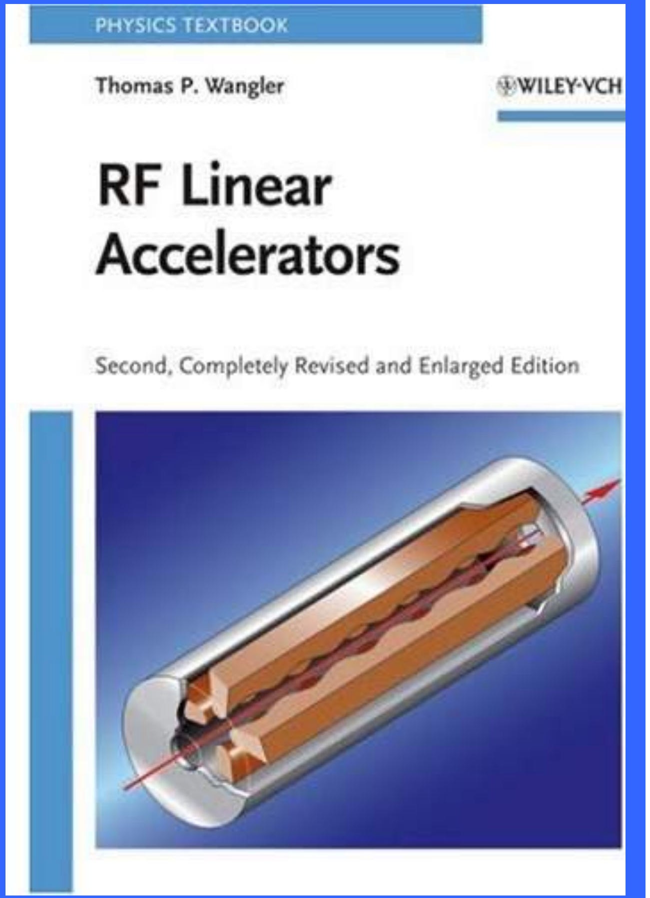
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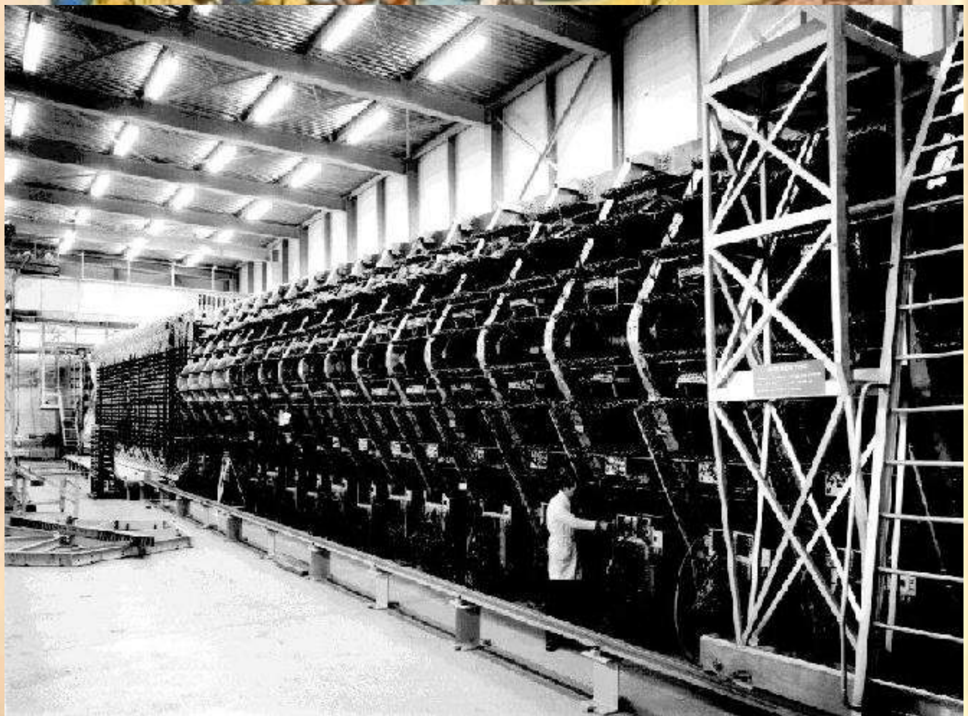


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