From QCD to Hadrons and Nuclei

Advanced Subatomic Physics Course

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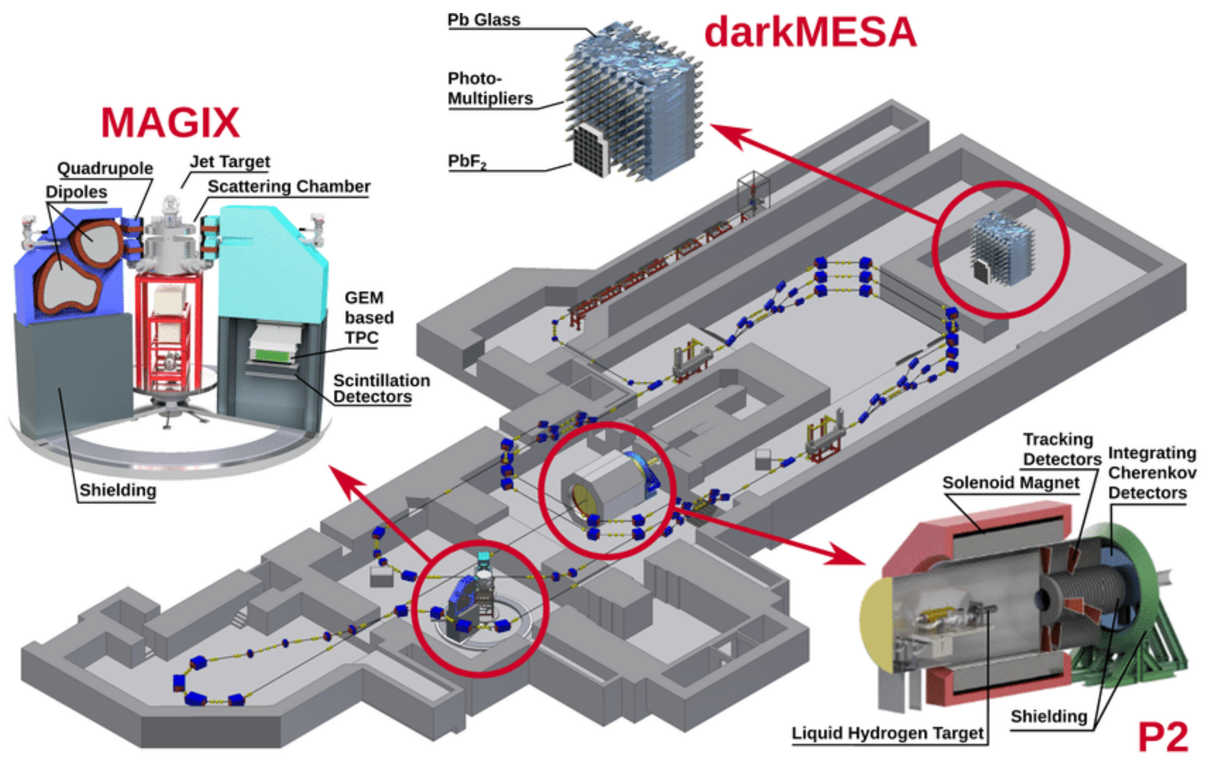
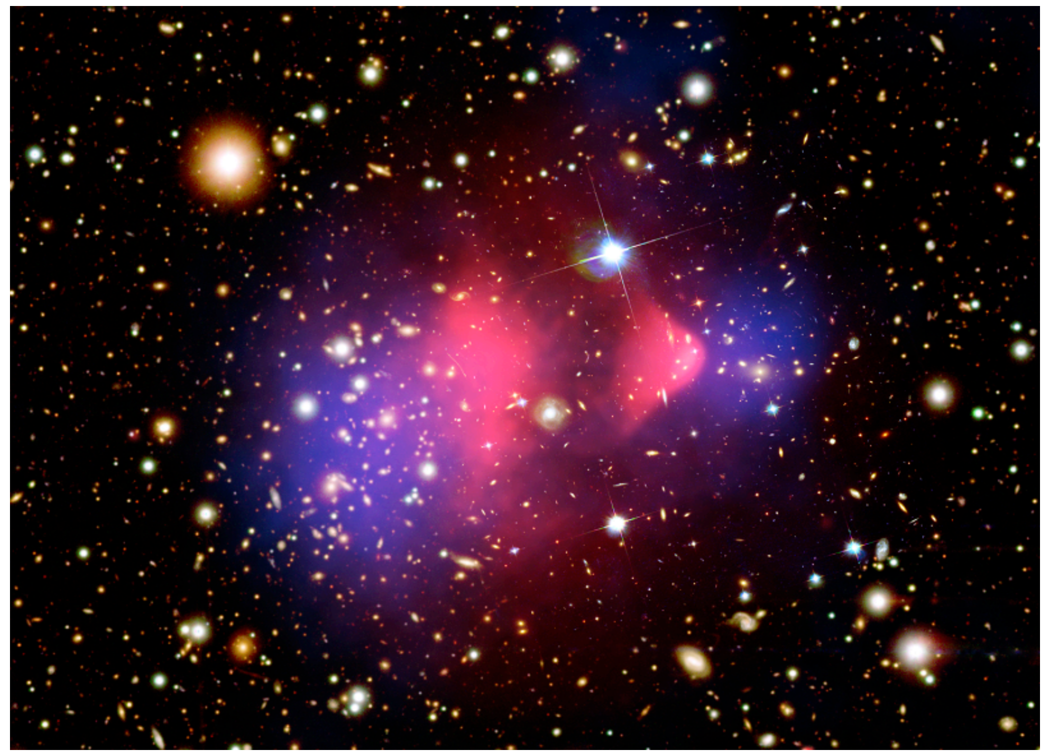
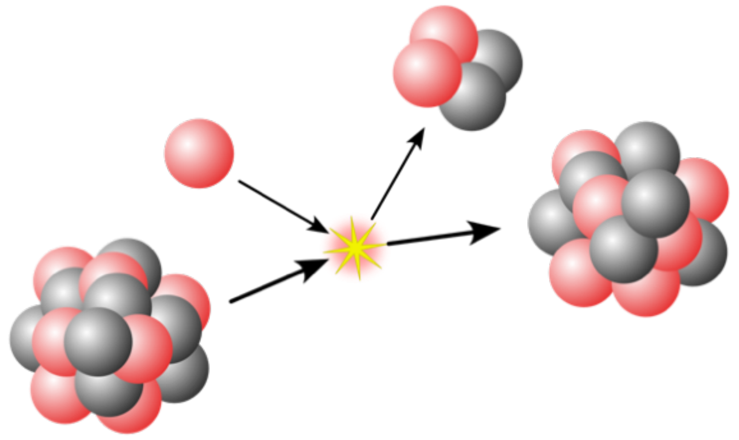
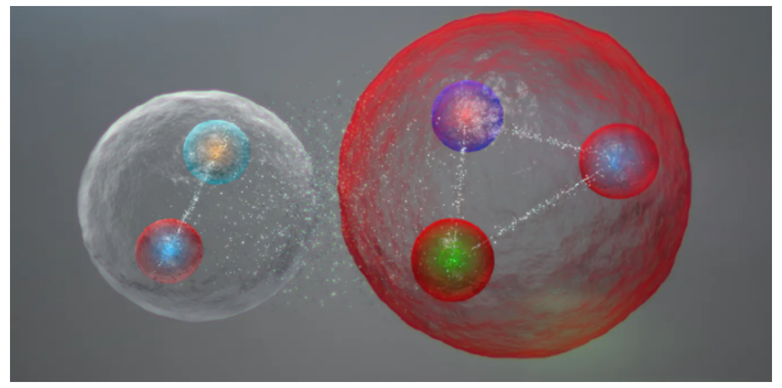








Sommersemester 2022

Syllabus

1. Introduction to strong interactions in the perturbative and non-perturbative regimes.
2. Hadrons and Nuclei
3. Electron and neutrino scattering experiments on hadrons and nuclei: form factors, elastic and inelastic scattering, resonances, deep inelastic physics.
4. Experimental methods and facilities with focus on MAMI and MESA at JGU Mainz.
5. Dark Matter
6. Search for dark matter with "intensity frontier" experiments, in particular, electron scattering experiments.
7. Search for dark matter with “direct detection” experiments with focus on argon.
8. Nuclear astrophysics and nuclear reactions of astrophysical relevance (in the Big Bang and stars).
9. Experiments for measuring astrophysical reactions with accelerators.
10. Discussion of a relevant published scientific paper on one of the topics discussed during the course.

Subatomic Physics with Electron beams

General Considerations:

* Electrons are purely electromagnetic probes.

* Since the EM interaction is well understood, if we investigate strongly-interacting systems with electrons, the interaction part is under control.

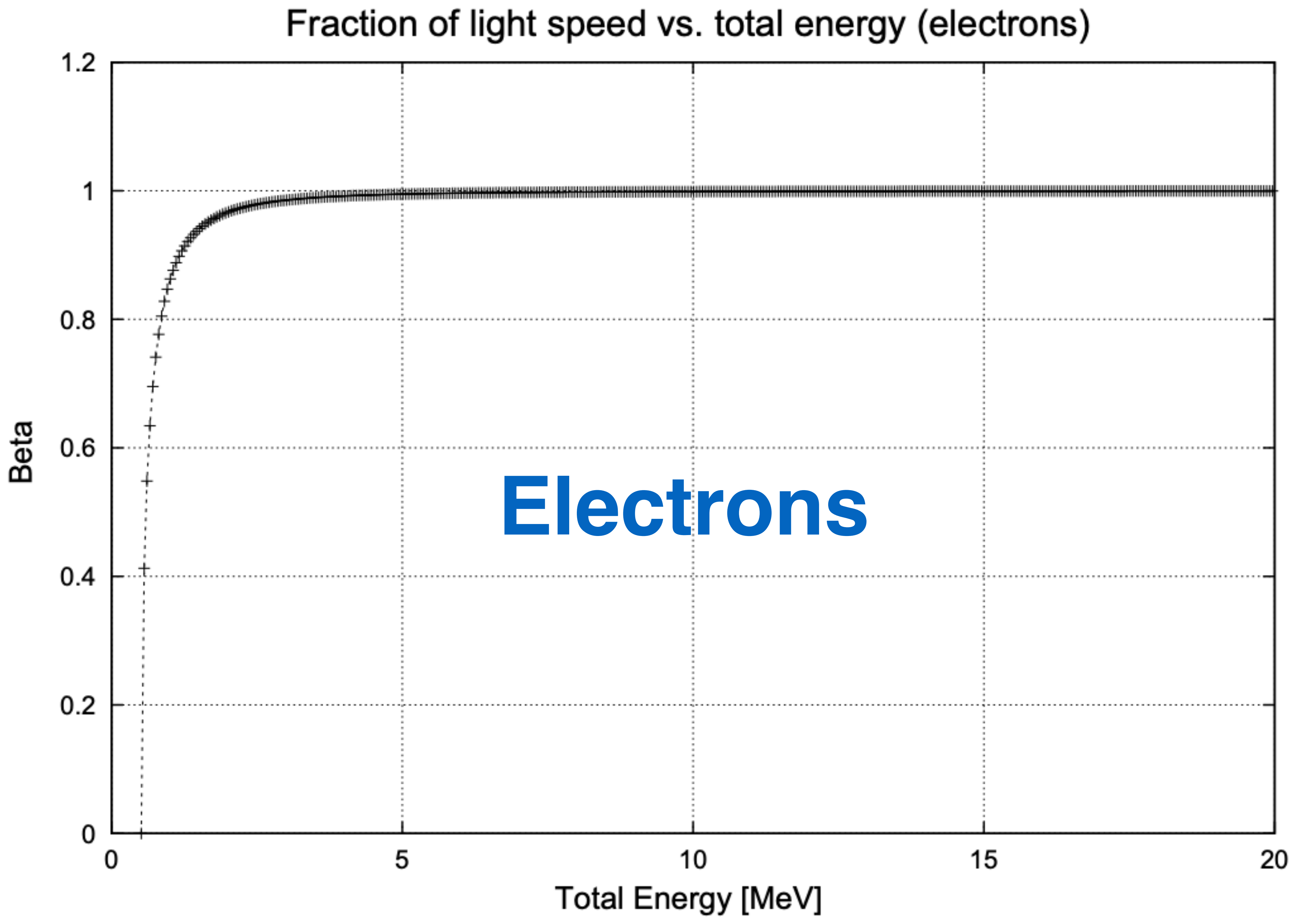
* Also in comparison with photons, exchanged energy and momentum can be both varied.

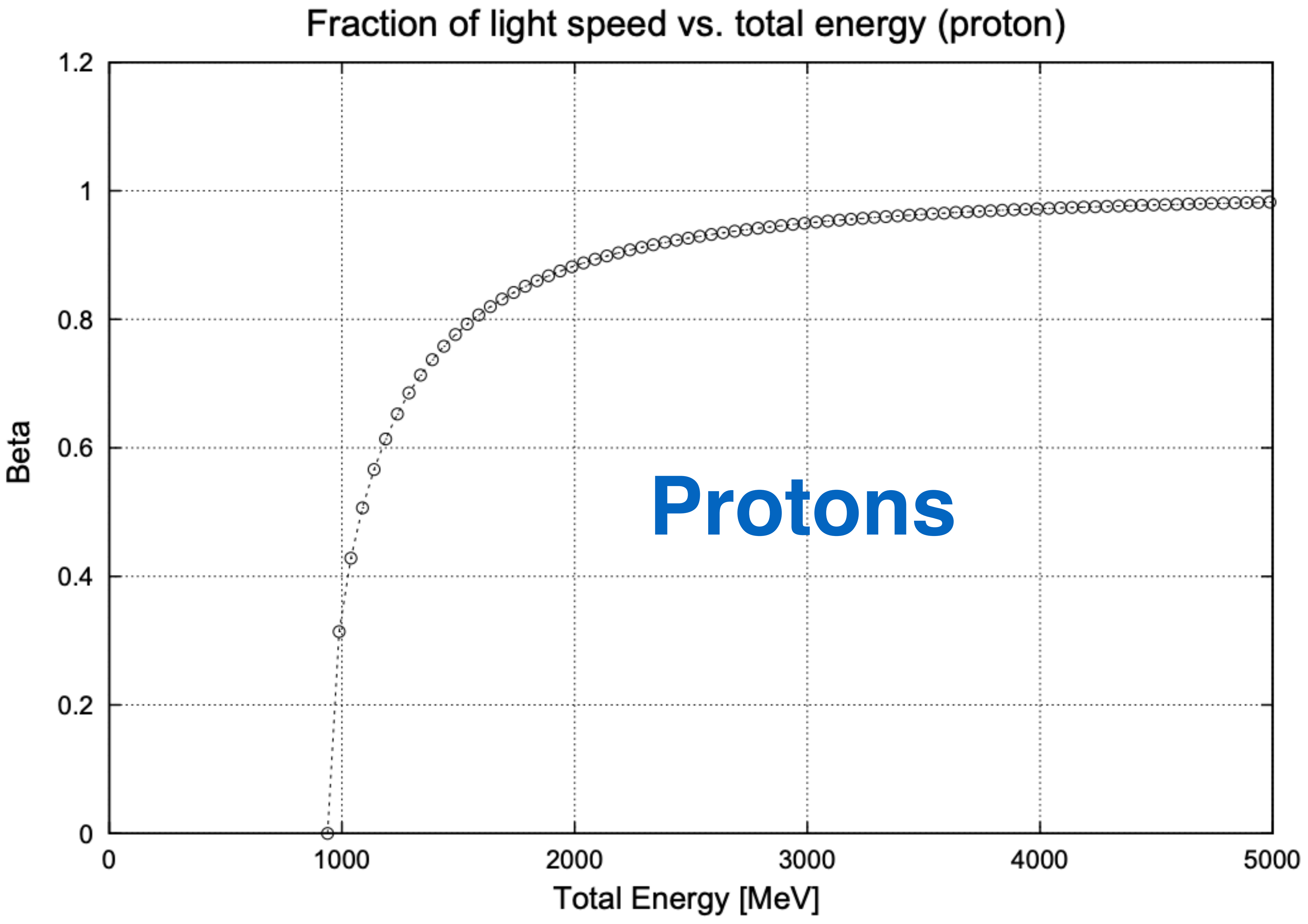
* In certain experimental situations, the light mass of the electron can limit its acceleration because of bremsstrahlung.

Subatomic Physics with Electron beams

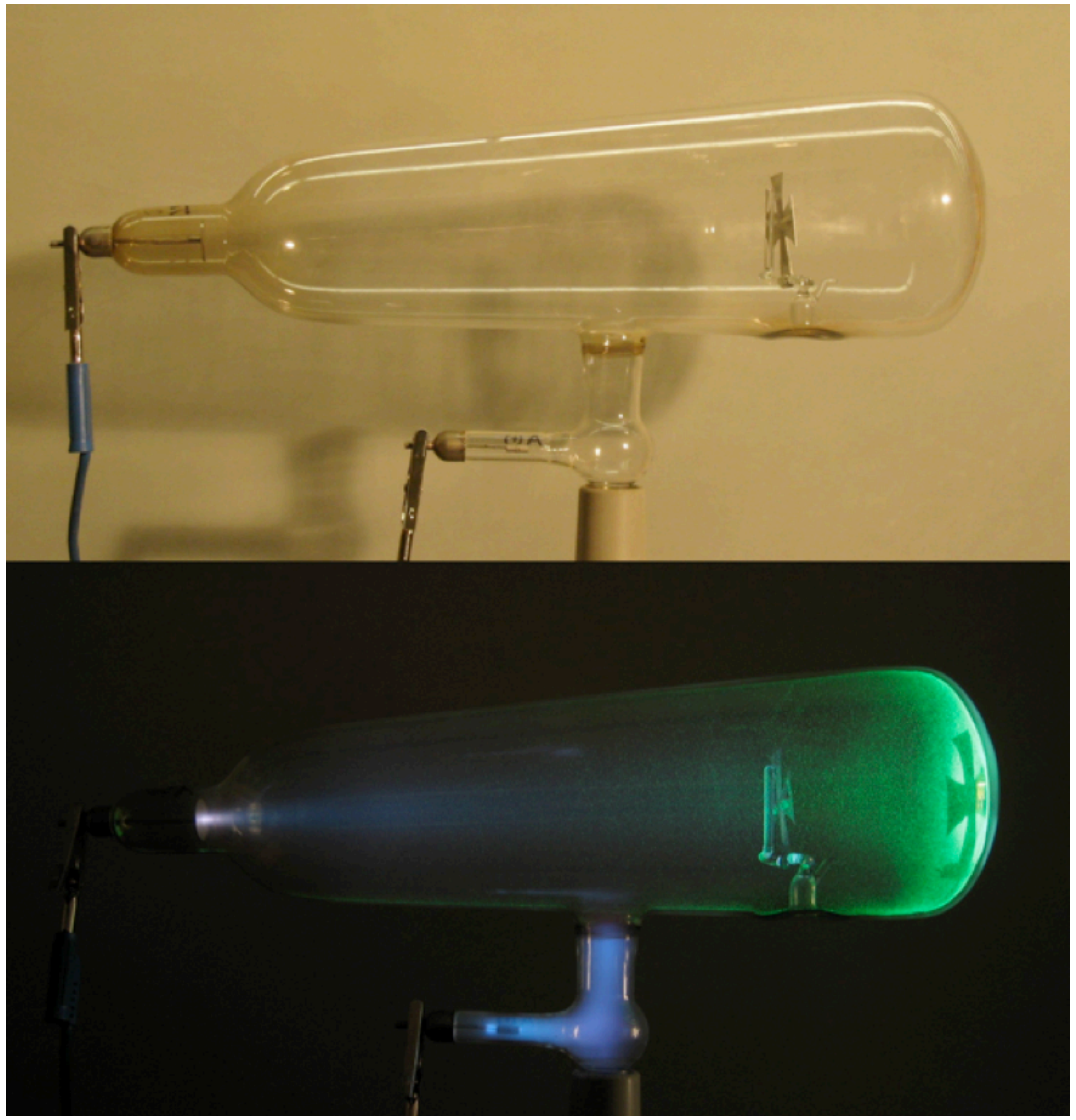
$$E = mc^2 = m_0 c^2 \gamma = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- Electrons become quickly relativistic and in practical situations their speed is v=c.
- This is not generally true for protons.

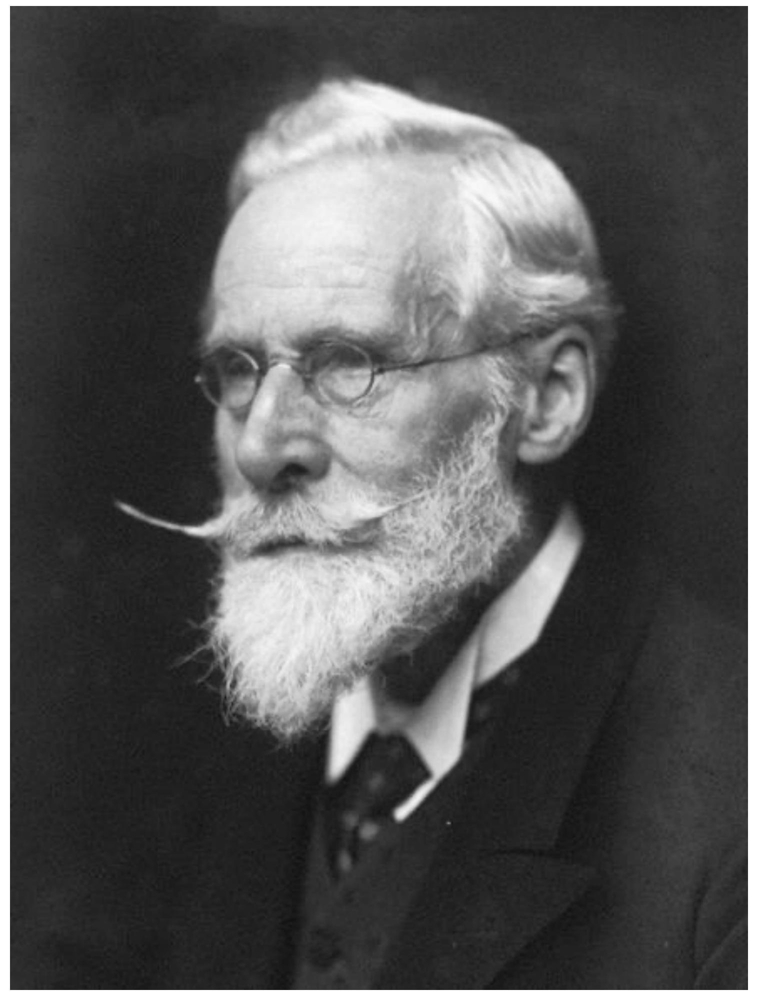




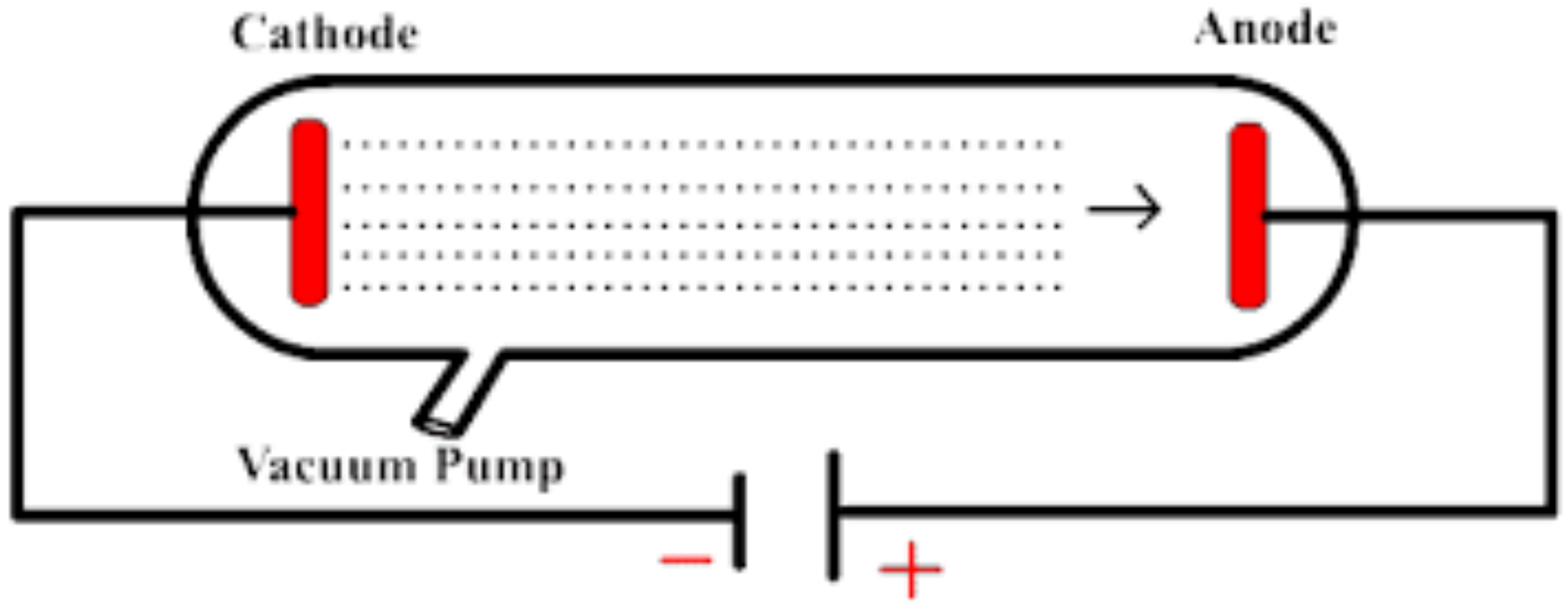
Electron Accelerators



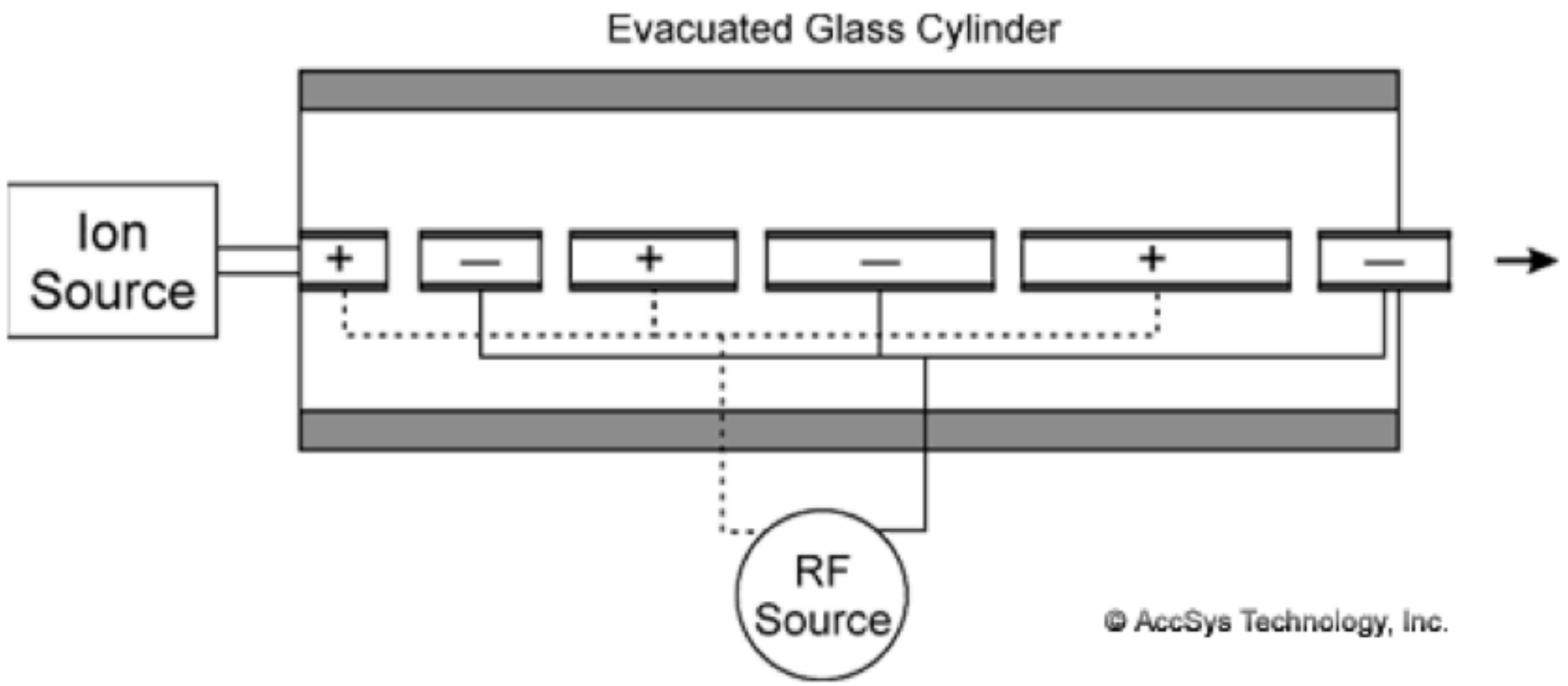
- W. Crookes (UK, 1832-1919)
- The Crookes Tube (mid-800s).
- Allowed X-ray discovery by Röntgen
- Deflection of electrons by E/B fields

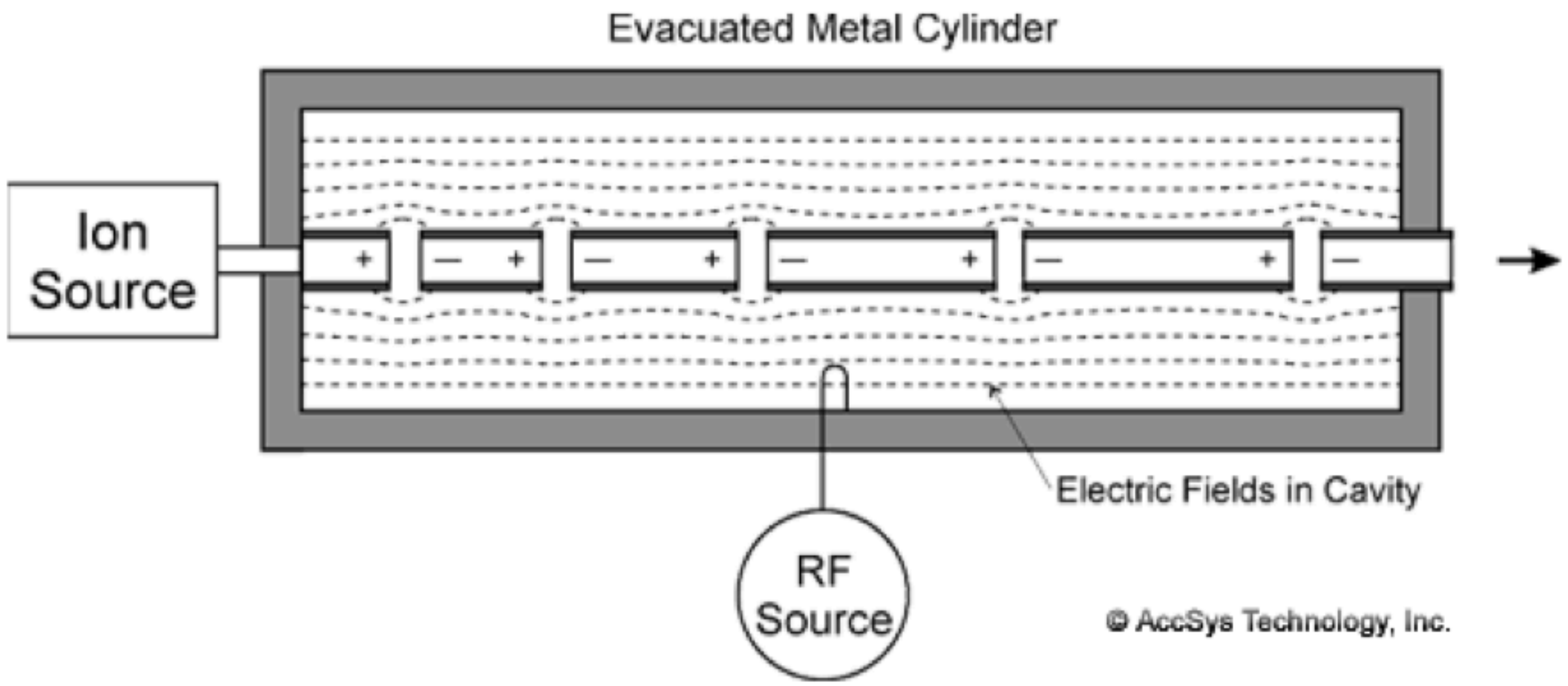


Functioning principle:



Electron Accelerators



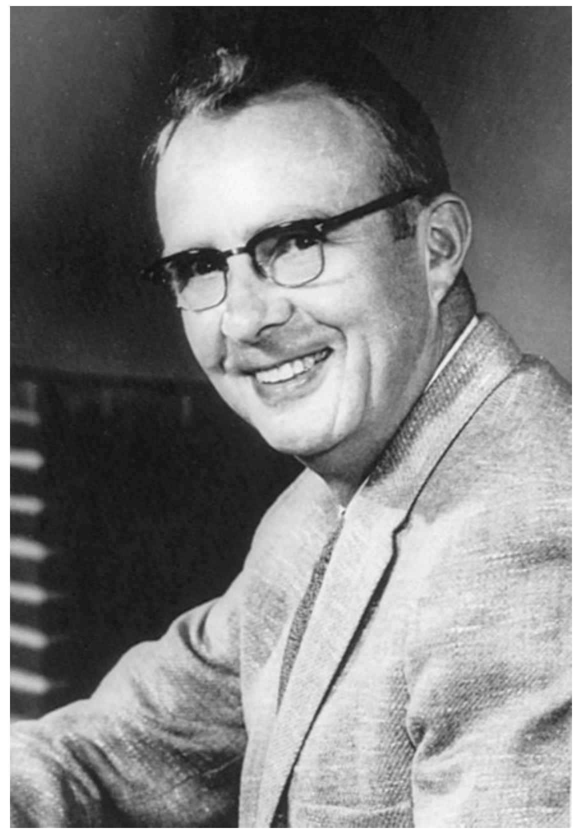


Rolf Widerøe (1902-1996)

No voltage pulses, but RF!
Section increasing with β.

Luis Alvarez (1911-1988)

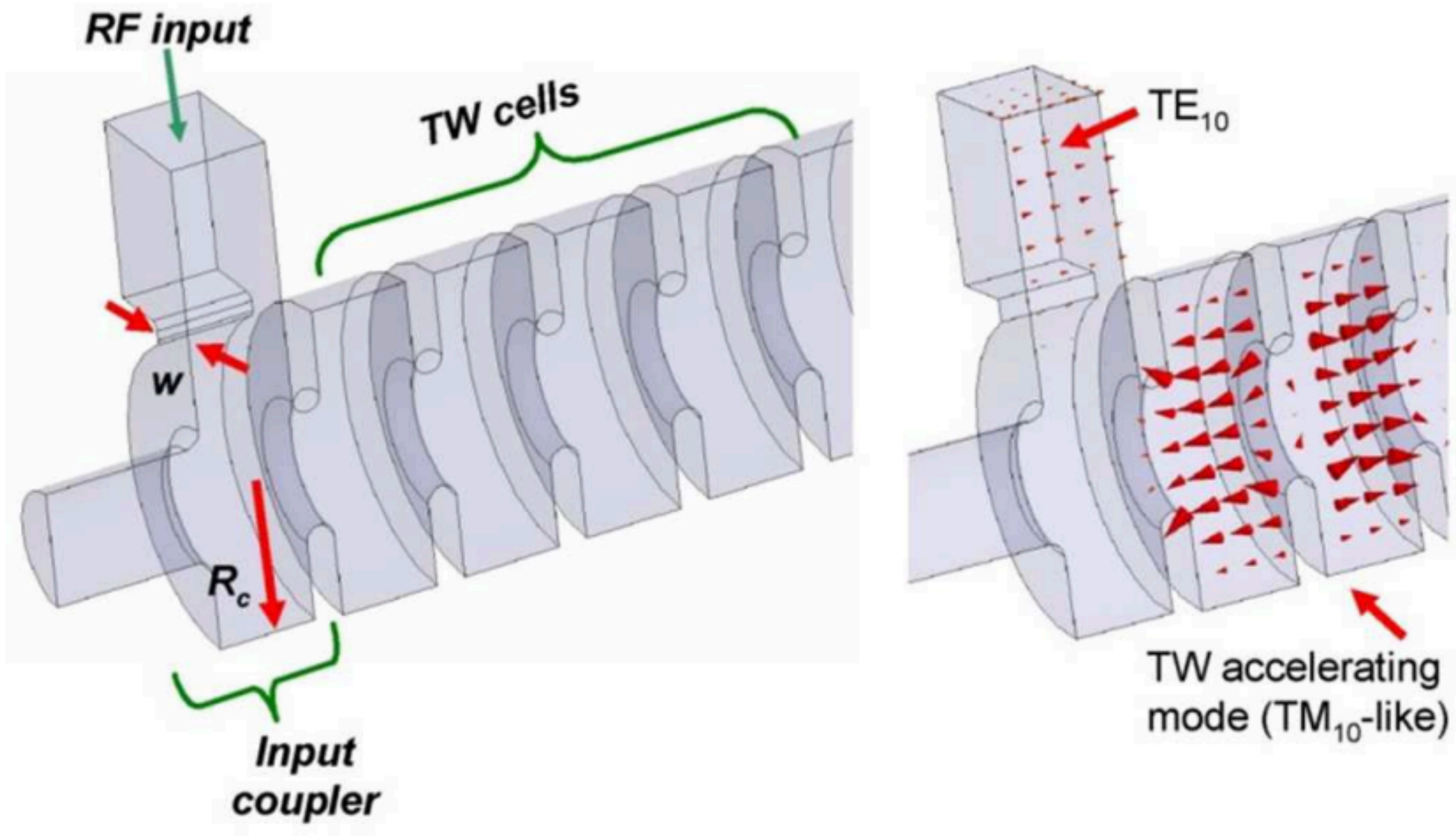
Standing wave cavity resonator.
Tubes shielding the particle during deceleration cycle.
Higher frequency possible.



What about electrons? They have effectively $\beta = 1$.

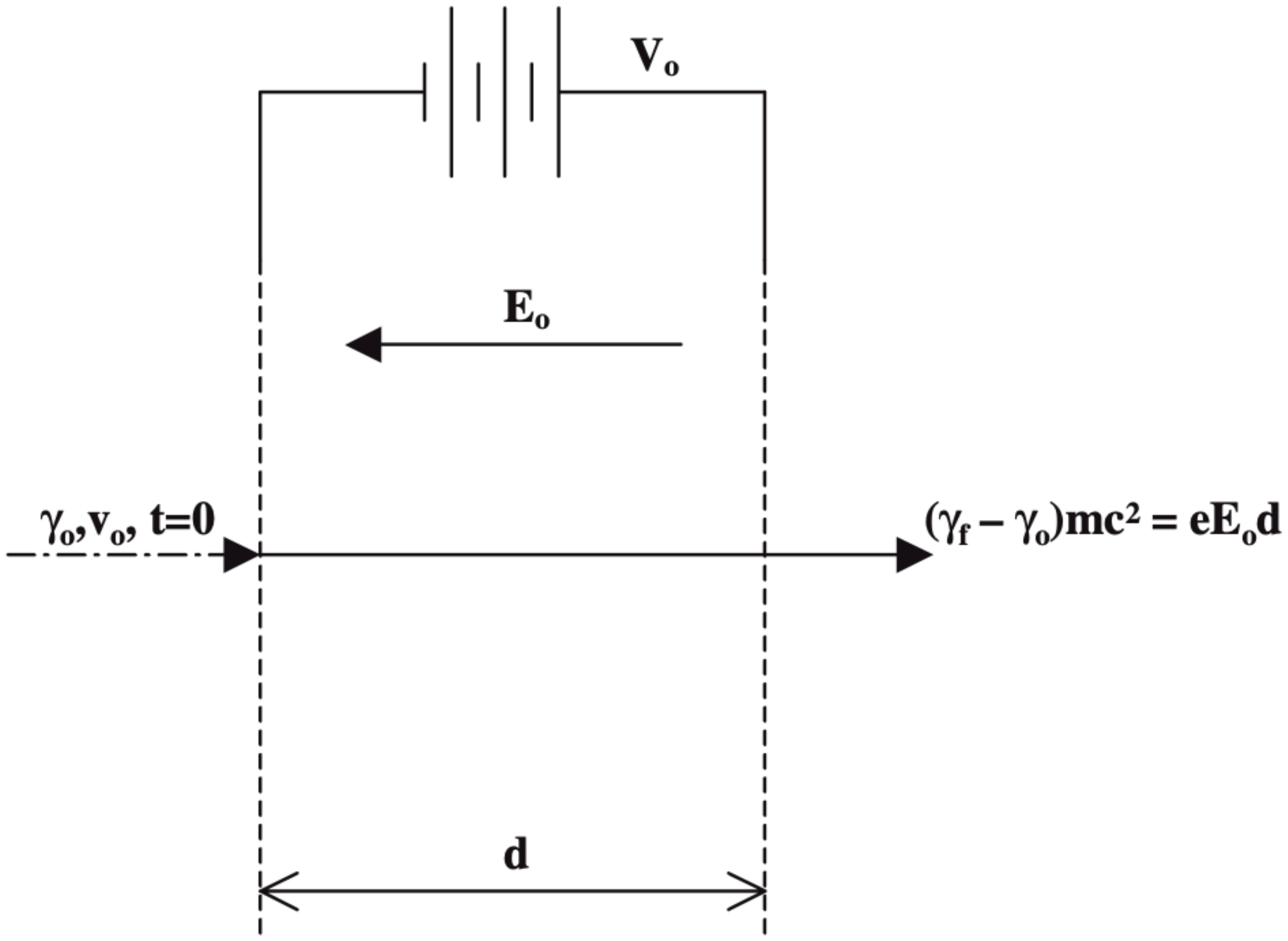
Electron Accelerators

William Hansen and collaborators.
First e-cavity, Stanford, 1947.



Electron Accelerators

Acceleration by a uniform electron field



Relativistic force law (Lorentz)

$$\frac{d(mv\gamma)}{dt} = -e(E + v \times B)$$

Relativistic force law (Lorentz)

$$\frac{d(\beta\gamma)}{dt} = \frac{e}{mc}E_0 \qquad E_0 = \frac{V_0}{d}$$

Solving the equation:

$$\beta\gamma = \frac{e}{mc}E_0 t + \beta_0\gamma_0$$

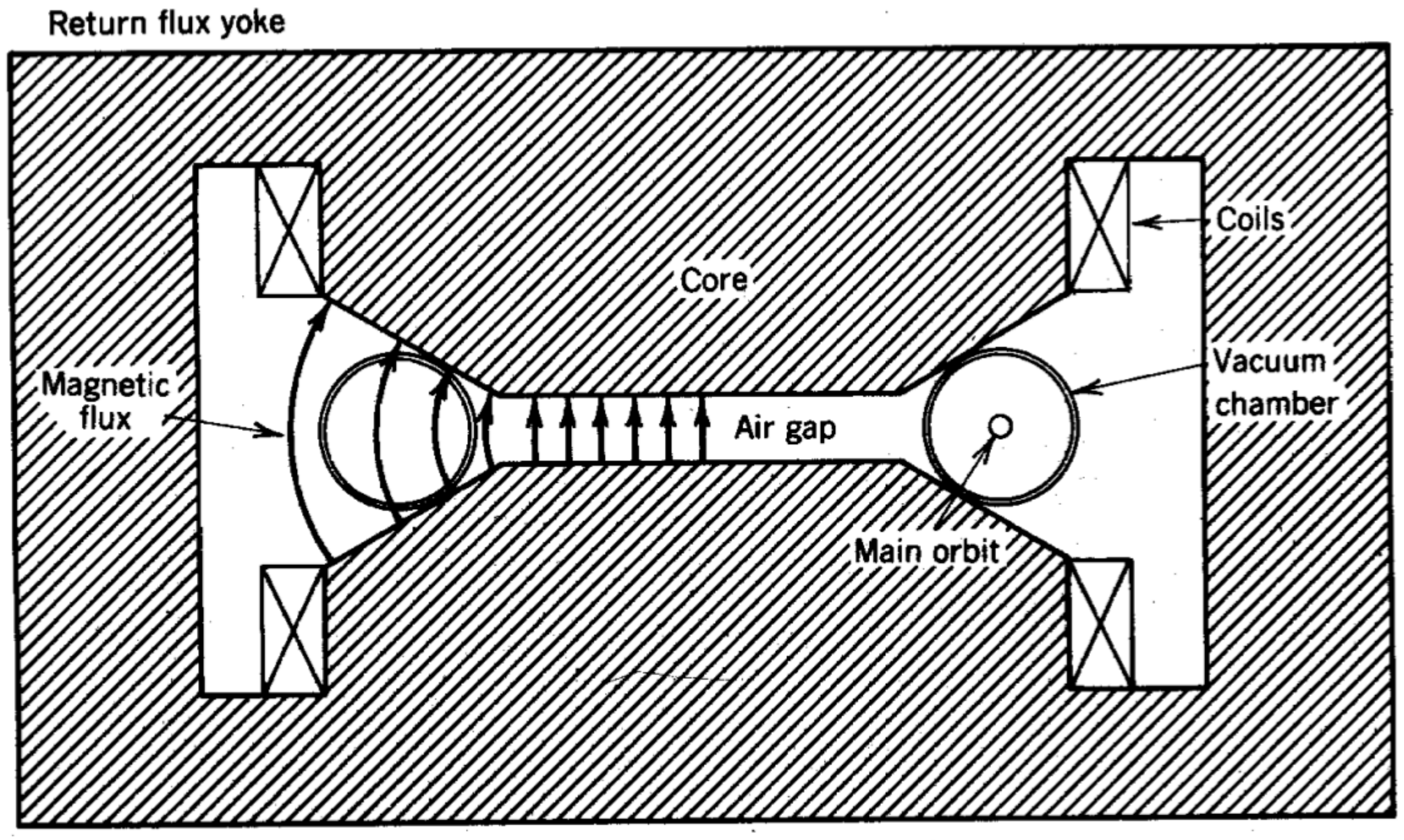
In the ultra-relativistic case, it is which rises linearly, not the velocity.

Electron Accelerators

* Klystrons introduced in 1937 (Varian Brothers). Fundamental for Radar technology.
* After the first “tubes”, D.W. Kerst and R. Serber develop the Betatron (1941)
* Rising the energy implied an unsustainable mass of the magnets.
* Veksler (USSR) and McMillan (USA) discover the phase stability concept.
* Invention of the synchrotron.

Electron Accelerators

The Betatron



Donald W. Kerst
(1911-1993)

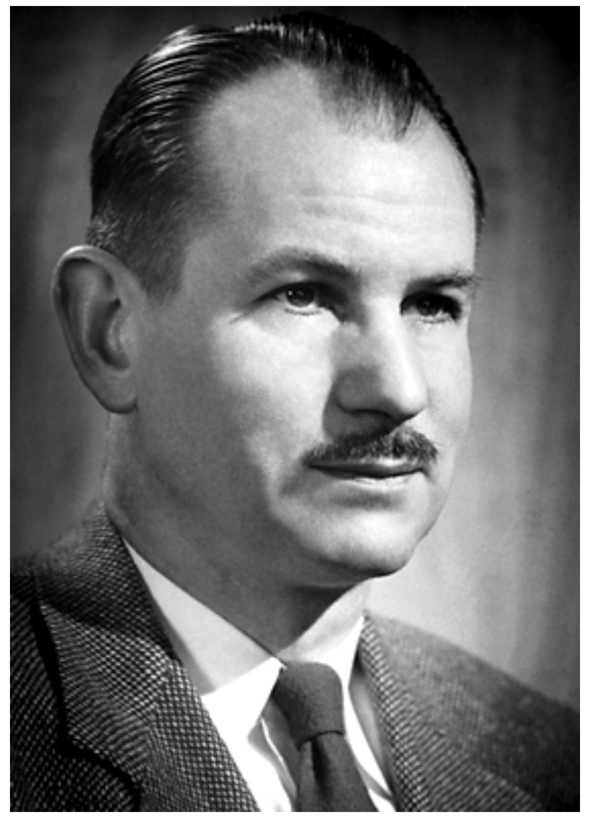
Robert Serber
(1909-1997)

A varying magnetic field induces an accelerating electric field in a toroidal vacuum chamber.
The magnetic field keeps the electrons in a stable orbit.
The shape of the magnet favours focussing (stability) of the orbits.

35 MeV Betatron

Electron Accelerators

V.I. Veksler
1907-1966



Edwin M. McMillan
(1907-1991)

Phase Stability Principle

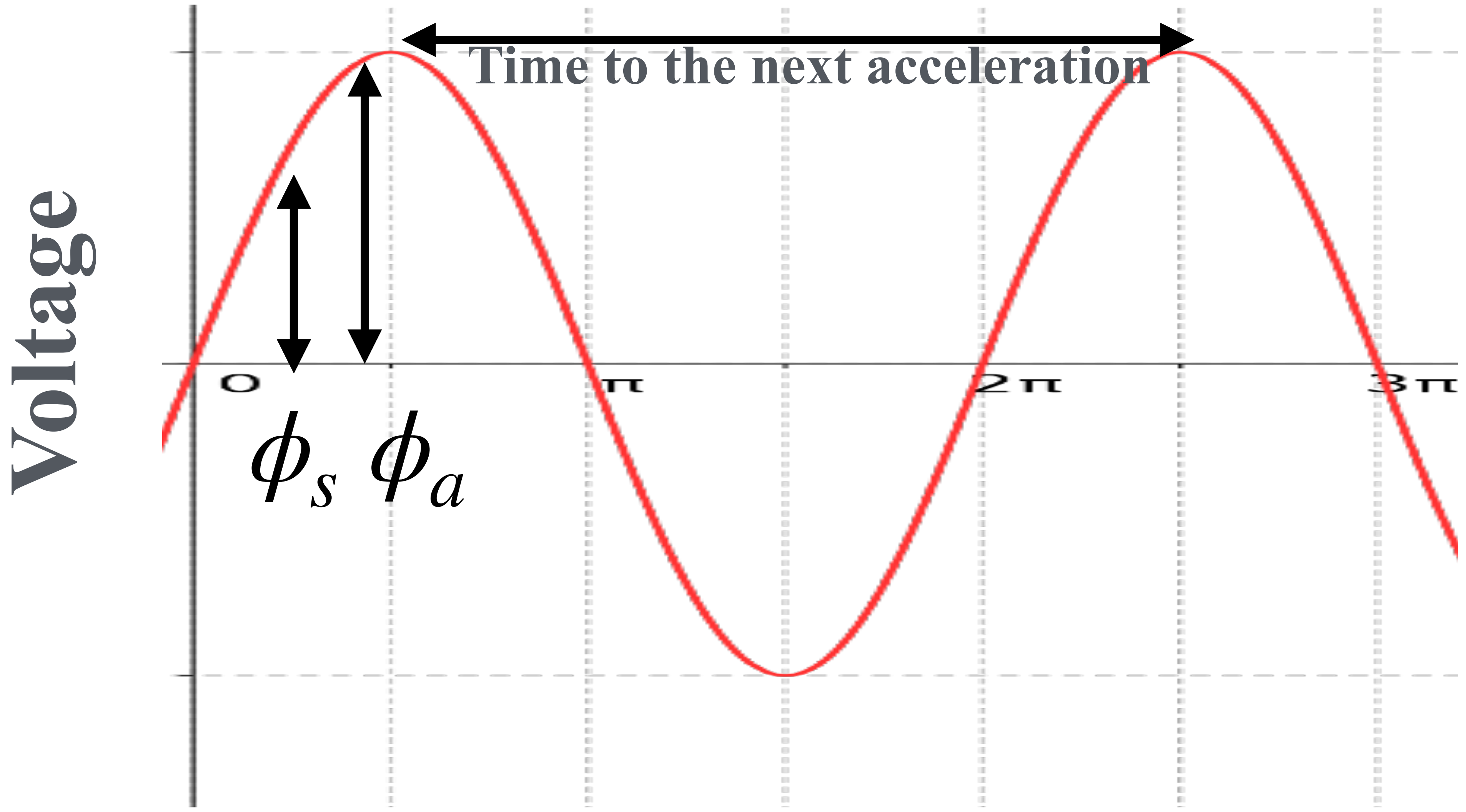
The PSP is a result proving that particles will remain stably in phase with the accelerating RF while in a circular orbit.

Two approaches:

Constant B, varying R : **Synchrocyclotrons**

Constant R, varying B : **Synchrotrons**.

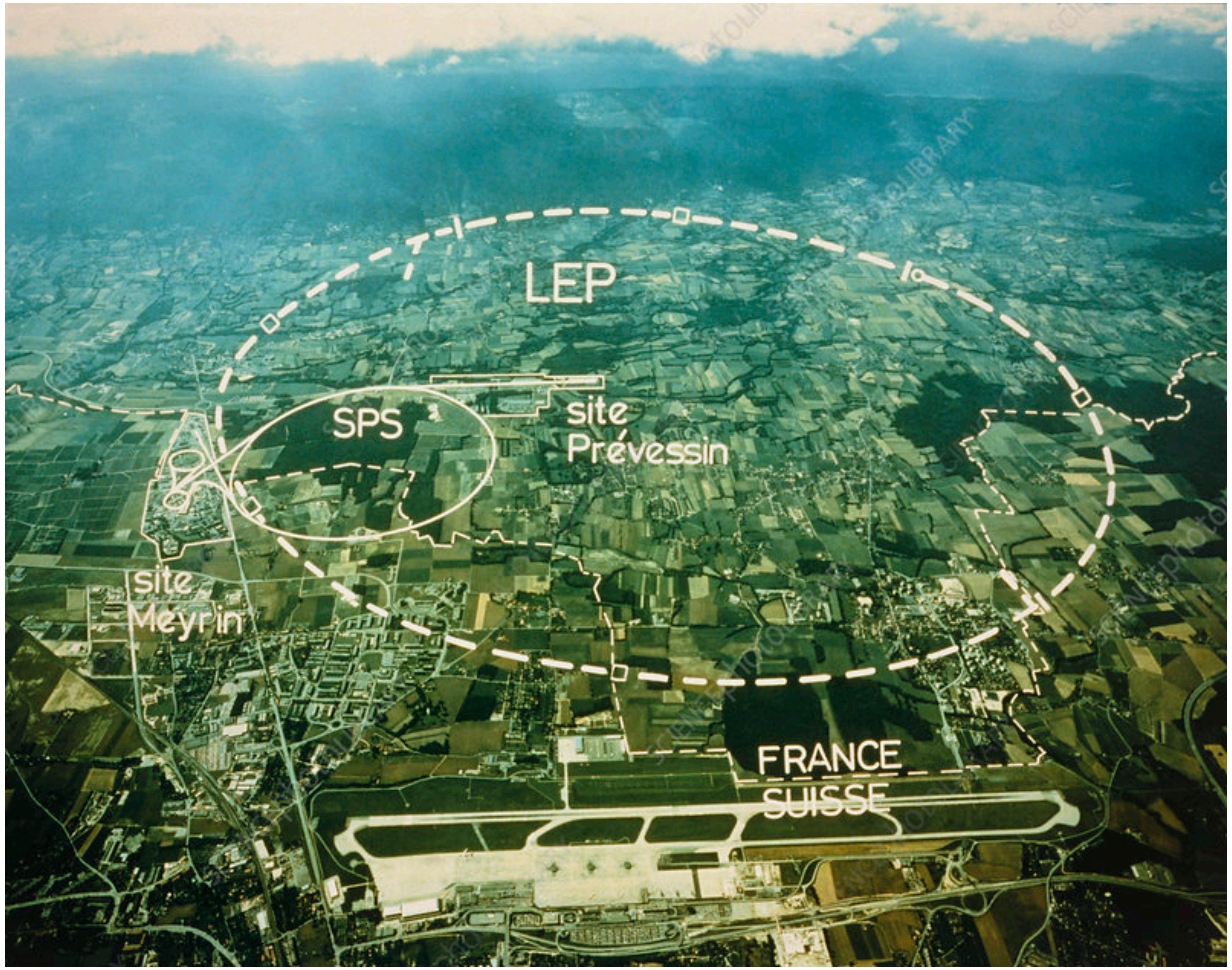
There is only one exact phase for which particles remain in phase with the RF.
PSP guarantees that also the "neighbouring" particles remain stable:



If $\phi_s < \pi/2$, a particle with $\phi_a > \phi_s$ will gain more energy: even if "late", it will "catch up". The converse is also true and the longitudinal motion is stable.
Another key idea is **strong focussing**.

Electron Accelerators

First synchrotron for electrons: Berkeley 300MeV.
Latest, highest energy synchrotron: **LEP** at CERN (1989-2000):



Maximum energy	209 GeV
Maximum current	6.2 mA
Maximum luminosity	$1\times10^{32}/(\mathrm{cm}^2\cdot\mathrm{s})$
Circumference	26659 m

Electron Accelerators

Relevant limiting factor: Synchrotron radiation

Energy lost per turn in one revolution of radius R:

$$\delta E = \frac{4\pi}{3}\frac{e^2}{R}\beta^3\gamma^4$$

For high-energy electrons:

$$\delta E(MeV) \approx \frac{0.0885}{R(m)} \cdot E^4(GeV)$$

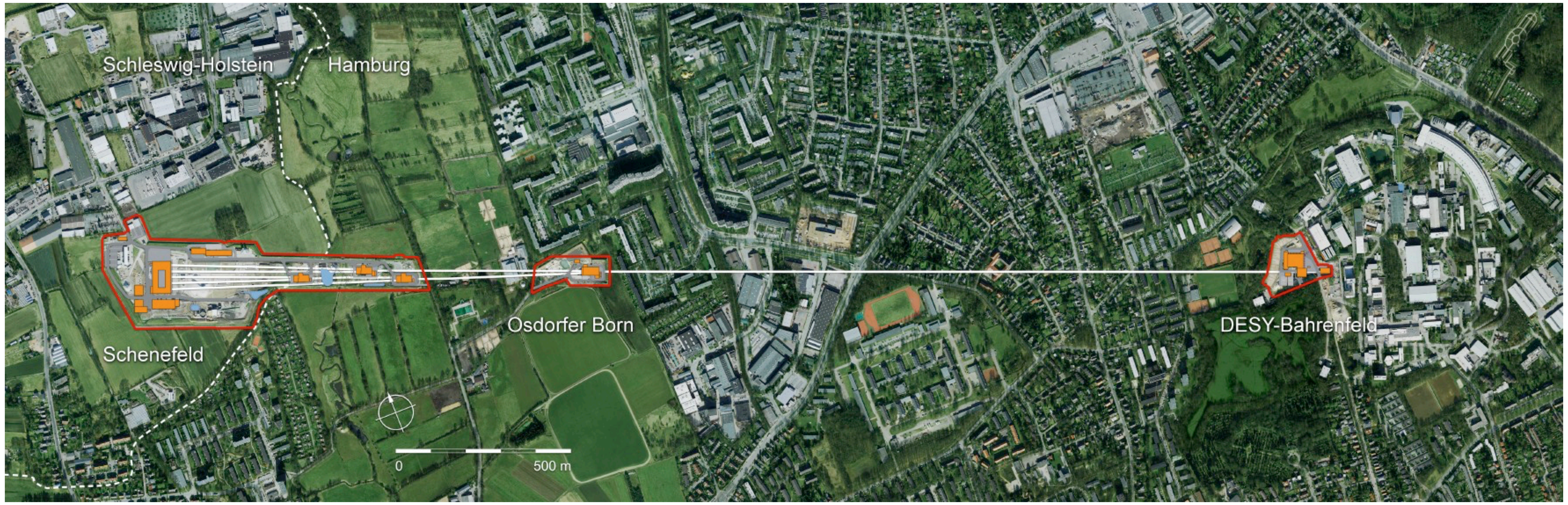
For LEP (try to do the calculation), few tens of MeV lost per turn.
Energy loss reduced only linearly with the radius!

Electron Accelerators

Linear Accelerators

SLAC
3.2 km length
50 GeV max. energy
Decommissioned in 2000.
Many discoveries:
- charm quark
- quark structure
- tau lepton

European XFEL
3.4 km length
17.5 GeV max. energy



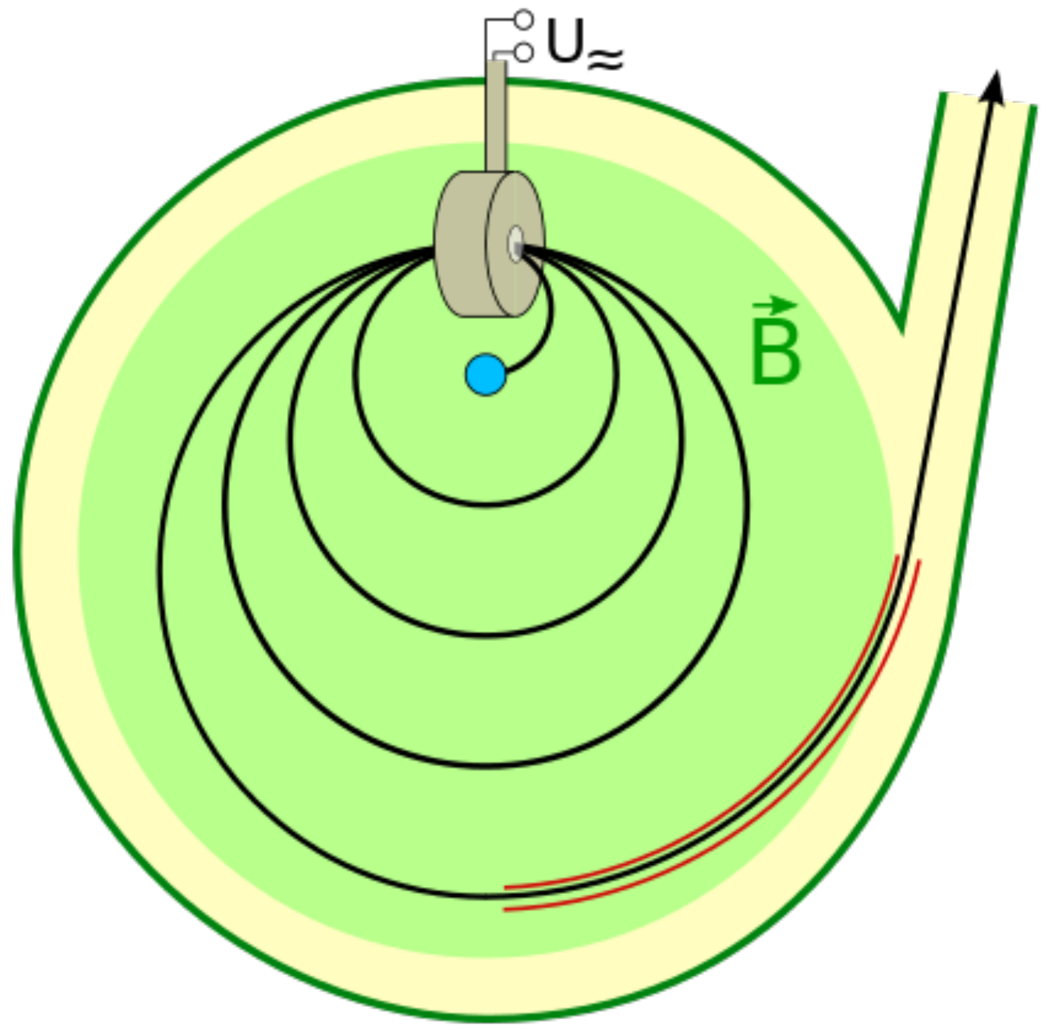
Electron Accelerators

Linear Accelerators + Recirculation: Microtrons & ERLs

Microtron

Proposed for the first time by Veksler in 1944.

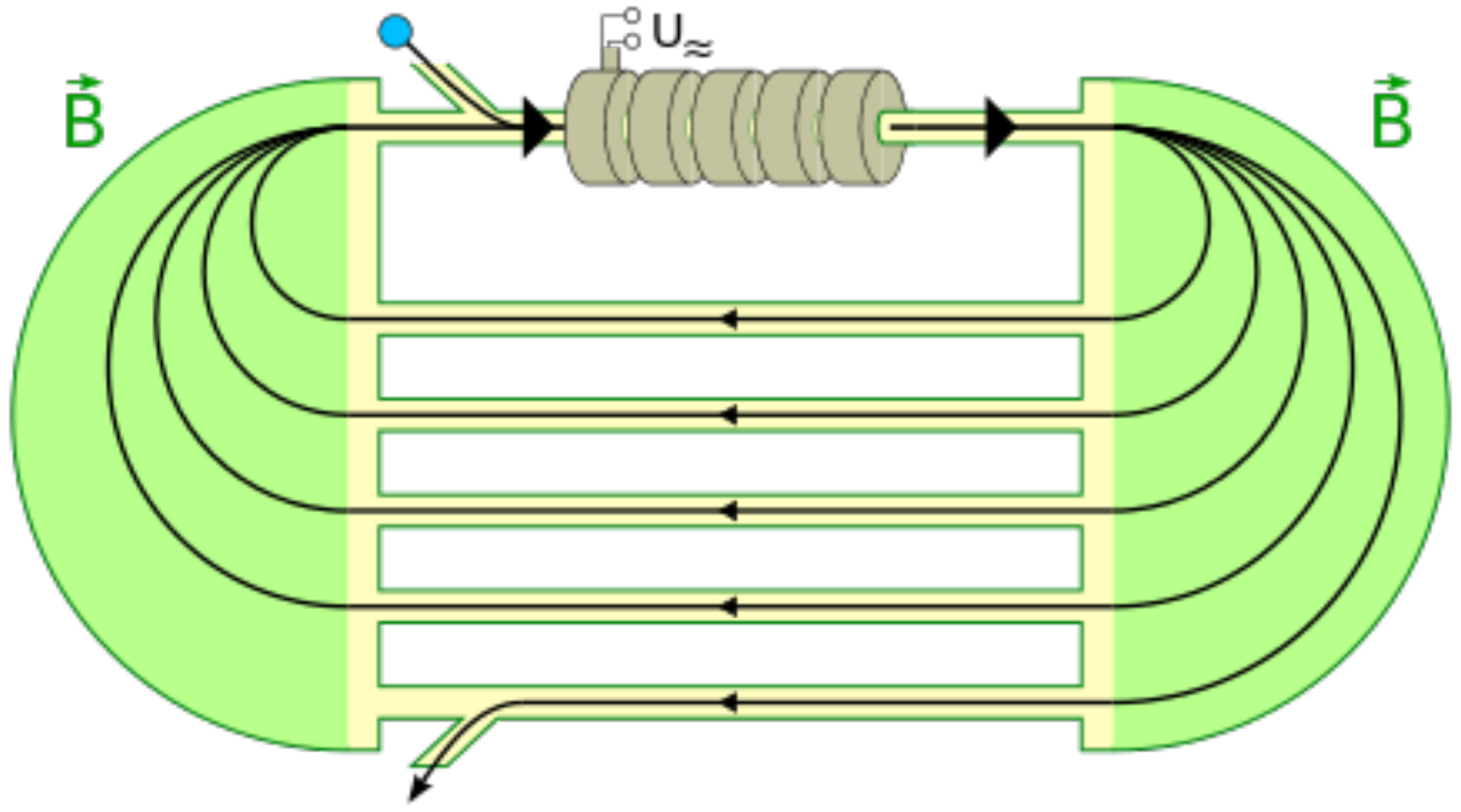
First Microtron built: NRC Canada in 1947 (4.6 MeV)



Racetrack Microtron

E.M. Moroz and A. Roberts in1958

First built: University of Western Ontario, 1961, 5MeV



Electron Accelerators

Resonance condition

Revolution time in constant magnetic field: $T = \frac{2\pi m}{eB} = \frac{2\pi E_T}{eBc^2}$ $\quad E_T = mc^2$

Energy after n turns: $E_n = E_0 + E_f + n\Delta E$

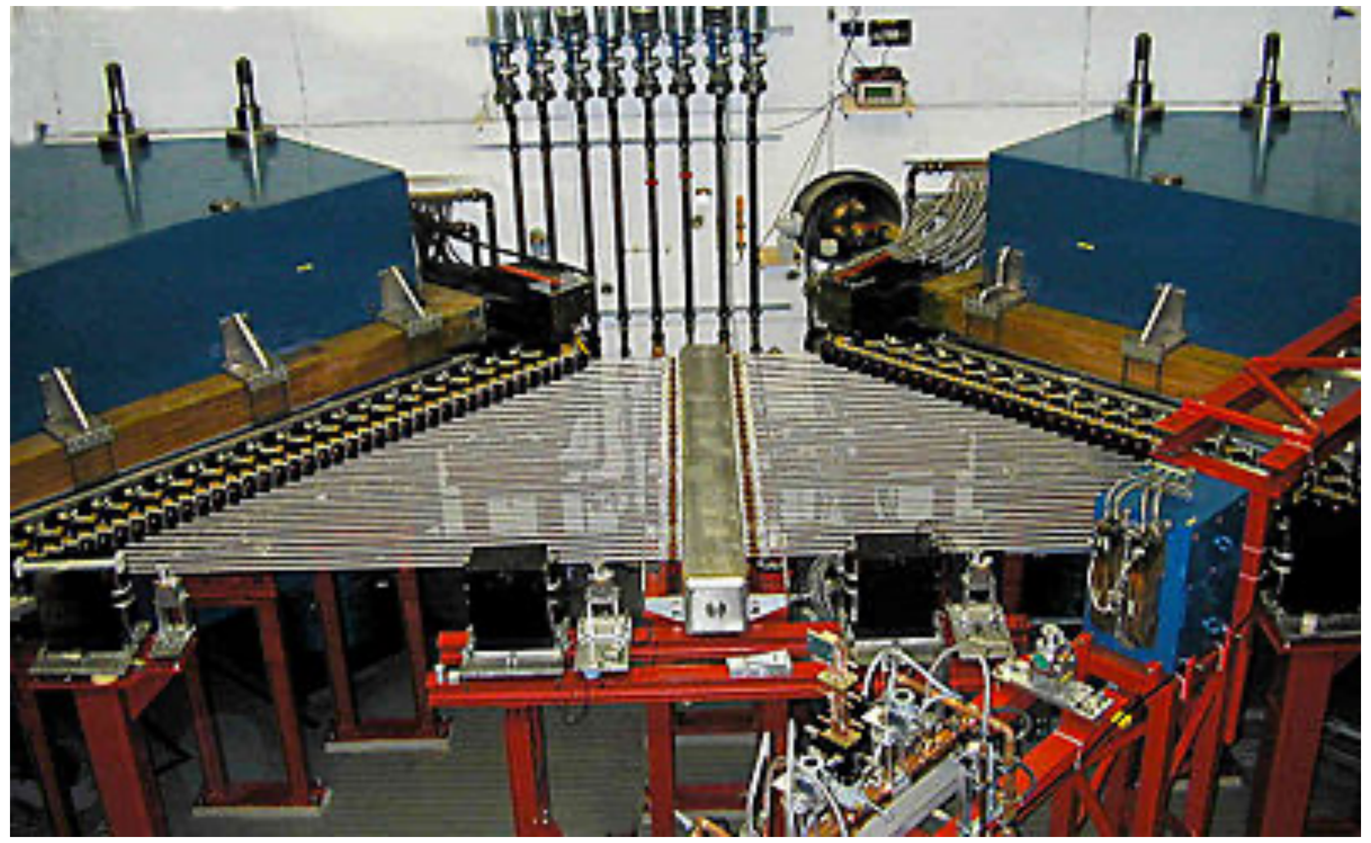
$$T_n = \frac{2\pi}{eBc^2}(E_0 + E_f + n\Delta E)$$

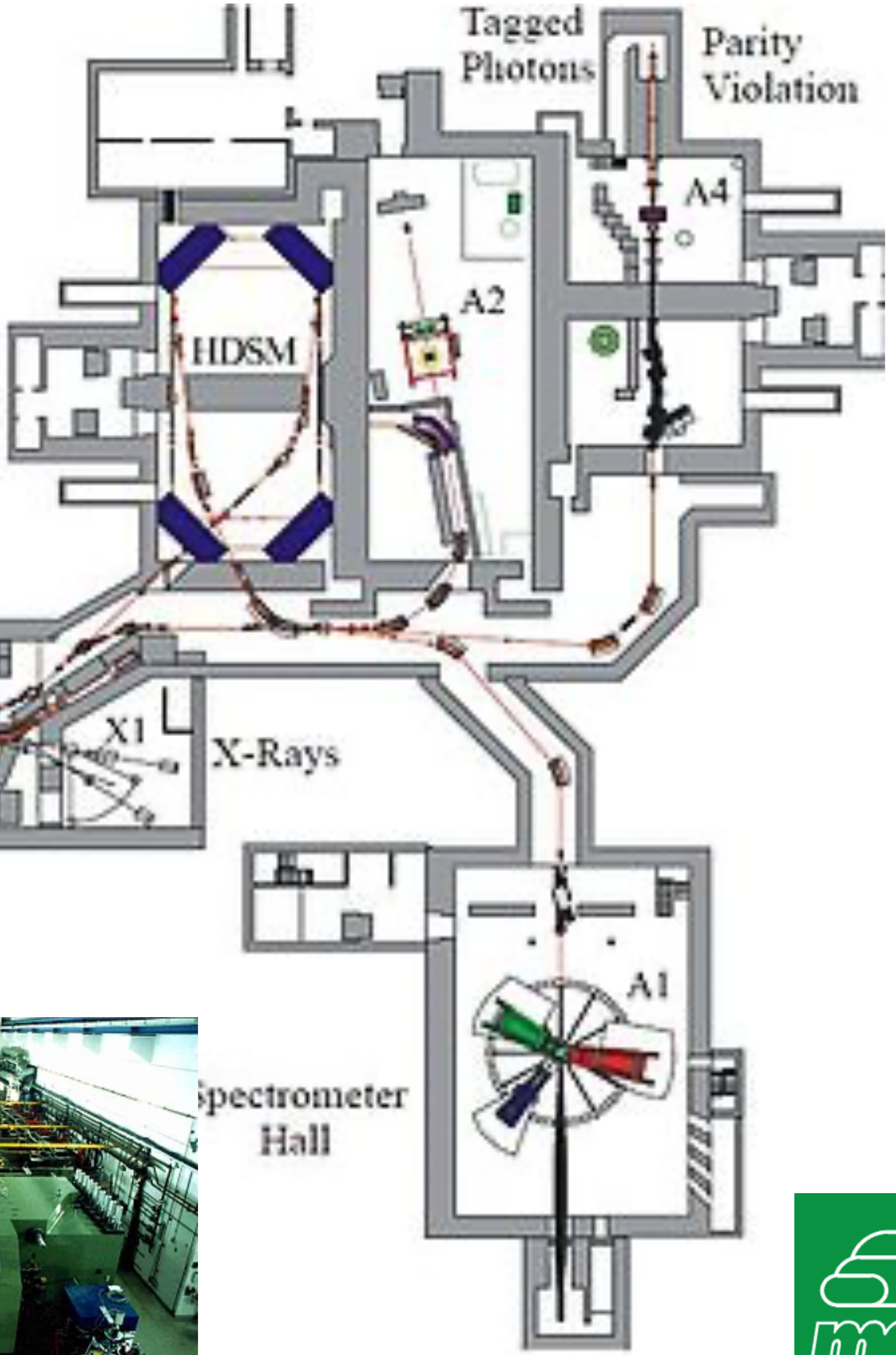
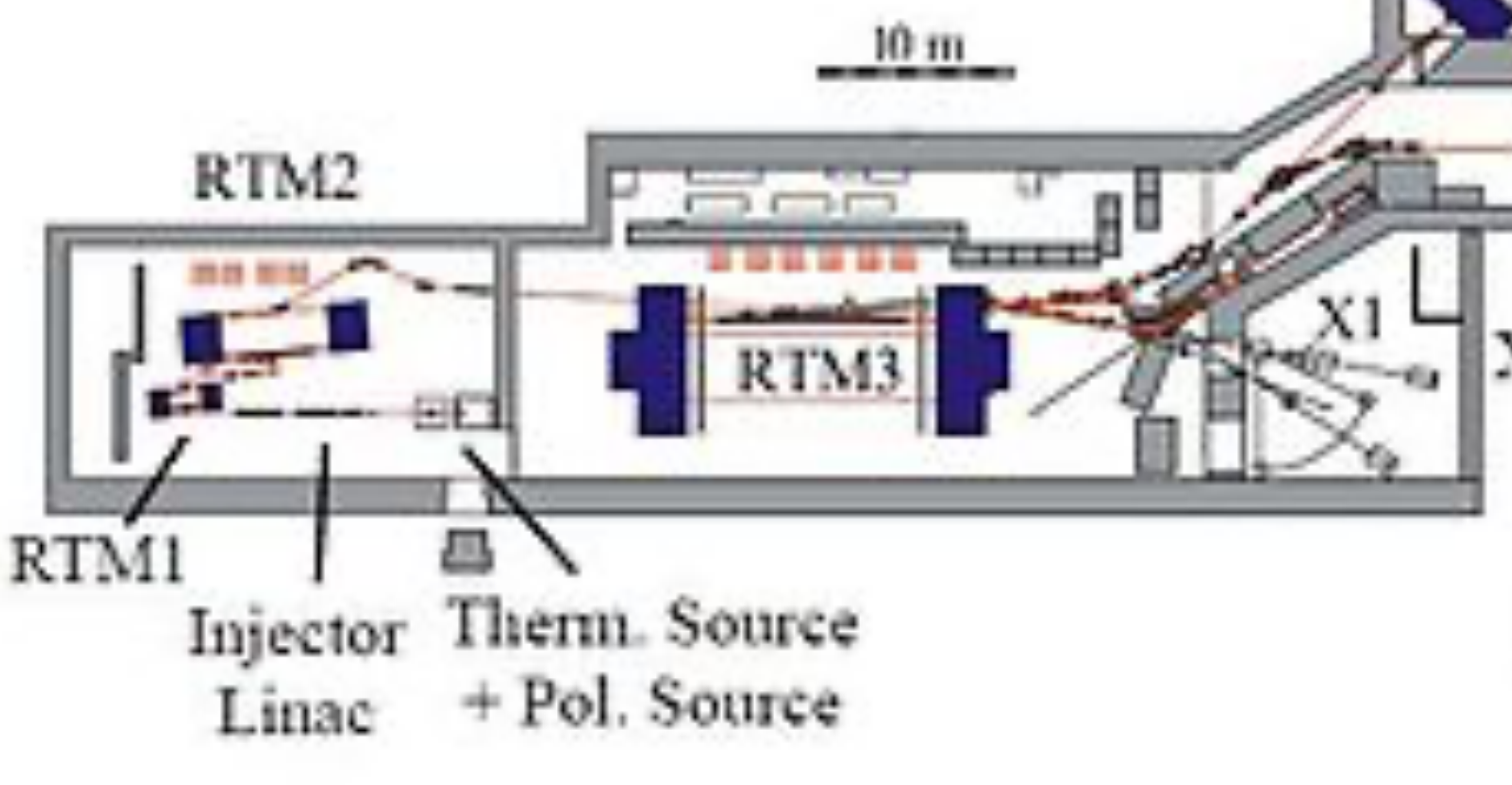
Time difference between 2 turns must match RF time:

$$\Delta T = T_{n+1} - T_n = \frac{2\pi \Delta E}{eBc^2} = bT_{RF}$$

Electron Accelerators

The MAMI Accelerator

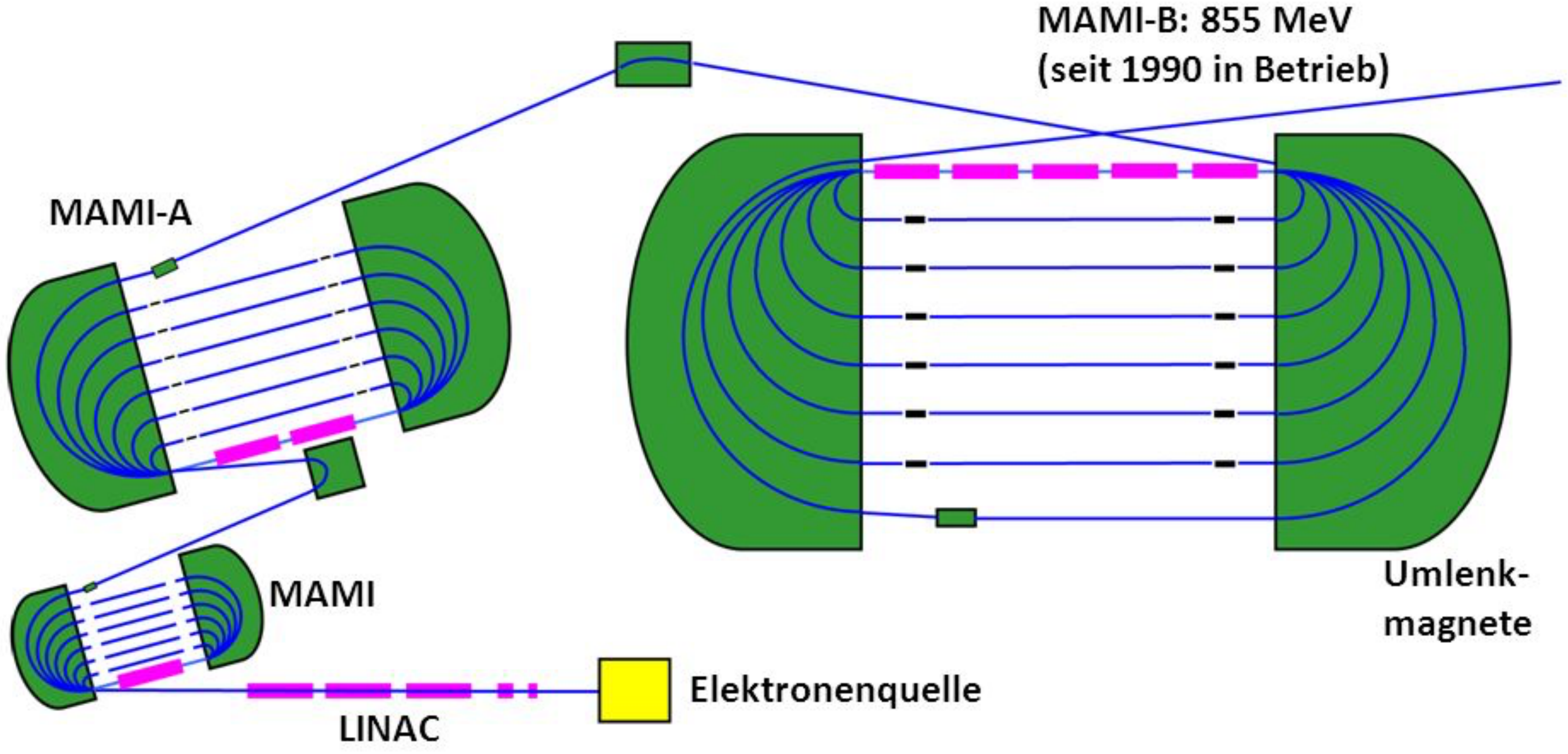


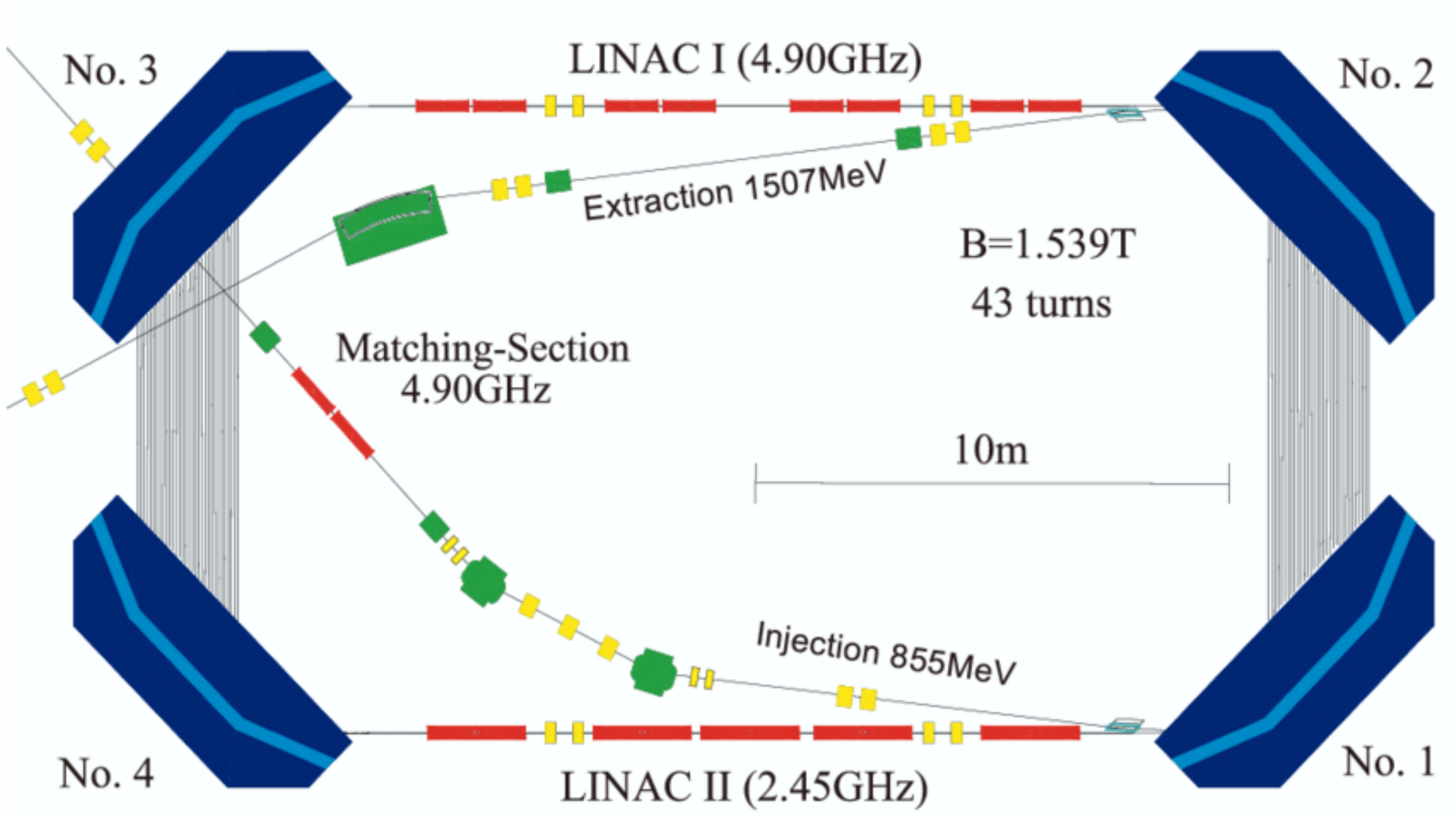



Electron Accelerators

Static coherence condition: $$L_1 = k \cdot \lambda_{rf} = \frac{2\pi(E_{Inj} + \Delta E)}{ecB} + 2d$$

Dynamic resonance condition: $$L_{i+1} - L_i = 2\pi \Delta R = n \cdot \lambda_{rf}$$





Electron Accelerators

		Injector	RTM1	RTM2	RTM3	HDSM
General						
injection / extraction energy (total)	[GeV]	$0.511/3.97 \cdot 10^{-3}$	$3.97/14.86 \cdot 10^{-3}$	$14.86/180 \cdot 10^{-3}$	0.180 / 0.855	0.855 / 1.5
number of turns		–	18	51	90	43
total power consumption	[kW]	92	92	220	650	1400
Rf-System						
energy resp. energy gain / turn	[MeV]	3.5	0.599	3.24	7.50	16.58-13.66
frequency	[GHz]	2.4495	2.4495	2.4495	2.4495	4.8990|2.4495
linac length (electrically)	[m]	4.93	0.80	3.55	8.87	8.57|10.1
number of sections / klystrons		3 / 1	1 / 1	2 / 2	5 / 5	8/4|5/5
power dissipation / beam power	[kW]	33.2 / 0.35	7.9 / 1.1	48.4/16.6	102.5 / 67.5	299 / 65
power consumption	[kW]	90	90	180	450	1000 [a]
Magnet-System						
flux density (within the gap)	[T]	–	0.1026	0.5550	1.2842	1.53-0.95
gap height	[cm]	–	6	7	10	8.5-13.9
min./max. deflection radius	[m]	–	0.129-0.482	0.089-1.083	0.467-2.216	2.23-4.60
iron / copper weigth of the magnets	[t]	–	4 / 0.2	90 / 2.3	900 / 11.6	1000 / 27.4
number of corrector magnets		40	72	204	360	$2 \cdot 172 + 2 \cdot 6$
number of quadrupoles and solenoids		20	2	4	4	$2 \cdot 4$
power consumption	[kW]	2	2	40	200	400
Beam-Parameters						
energy spread (1σ)	[keV]	1.2	1.2	2.8	13	110 [b]
norm. emittance hor. / vert. (1σ)	$[\pi \cdot 10^{-6}\ \mathrm{m}]$	0.05 / 0.04	0.07 / 0.07	0.25 / 0.13	13 / 0.84	27 [b] / 1.2 [b]
standard-energies for experiments				180MeV	195-855MeV in steps of 15MeV	0.855-1.5GeV in steps of ca. 15MeV

Electron Accelerators