

Accelerator Physics for X-Rays

ESRF lectures by Boaz Nash, ASD

Lecture 1 : Fast electrons - *January 13, Auditorium 14-16h*

Acceleration methods : linear, circular

ESRF acceleration complex

Overview of different hardware elements

Lecture 2 : Surfing the ring - *January 27, Auditorium 14-16h*

History of storage rings and synchrotrons

Single particle dynamics in electron storage ring

Linear dynamics

Non-linear dynamics

Lecture 3: Collective survival - *February 24, Auditorium 14-16h*

Self interactions of electron beam

Quantum fluctuations and radiation damping

Impedance and instabilities

Beam lifetime

Lecture 4: Sculpting the electron beam - *March 10, Auditorium 14-16h*

Equilibrium emittance, bunch length and energy spread

Some lattice design considerations

Current ESRF vs. new machine

Lecture 5 : Let there be light ! - *March 31, Auditorium 14-16h*

Synchrotron radiation from bending magnets and undulators

Effect of electron beam distribution and orbit on radiation

Diffraction limit

Fast Electrons

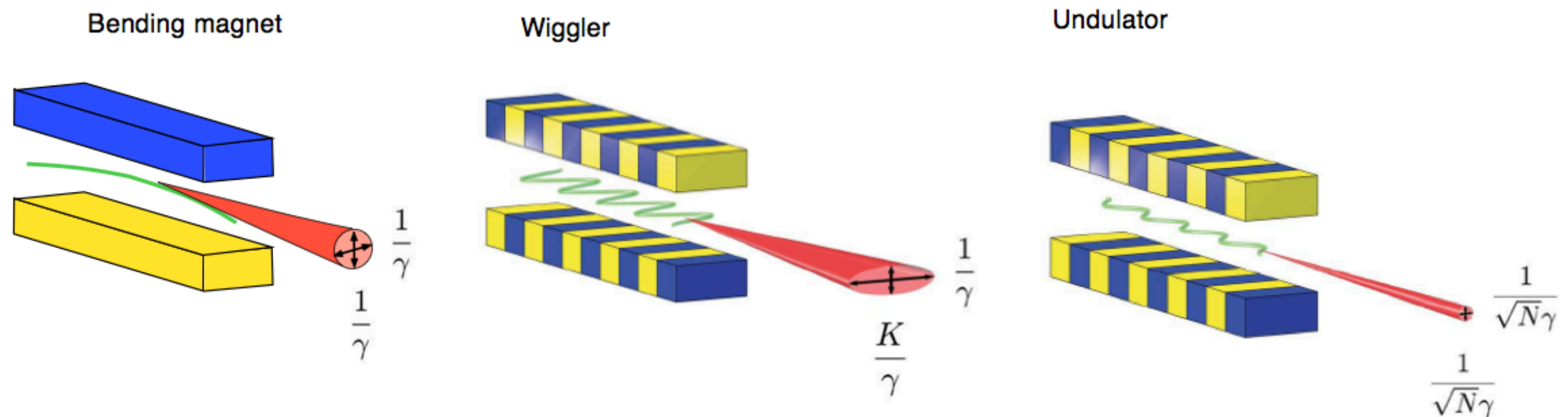
B. Nash

January 13, 2015

Outline

- Why fast electrons?
- How to get free electrons?
- Special relativity review
- Acceleration
 - --Electrostatic acceleration
 - --Acceleration with dynamic fields
- Configurations
 - --linear
 - --circular
- Synchrotrons
- ESRF Acceleration Complex

Why fast electrons for x-rays?



$$\lambda_c = \frac{4\pi m_e c}{3Bq\gamma^2}$$

$$\gamma = \frac{E}{m_e c^2}$$

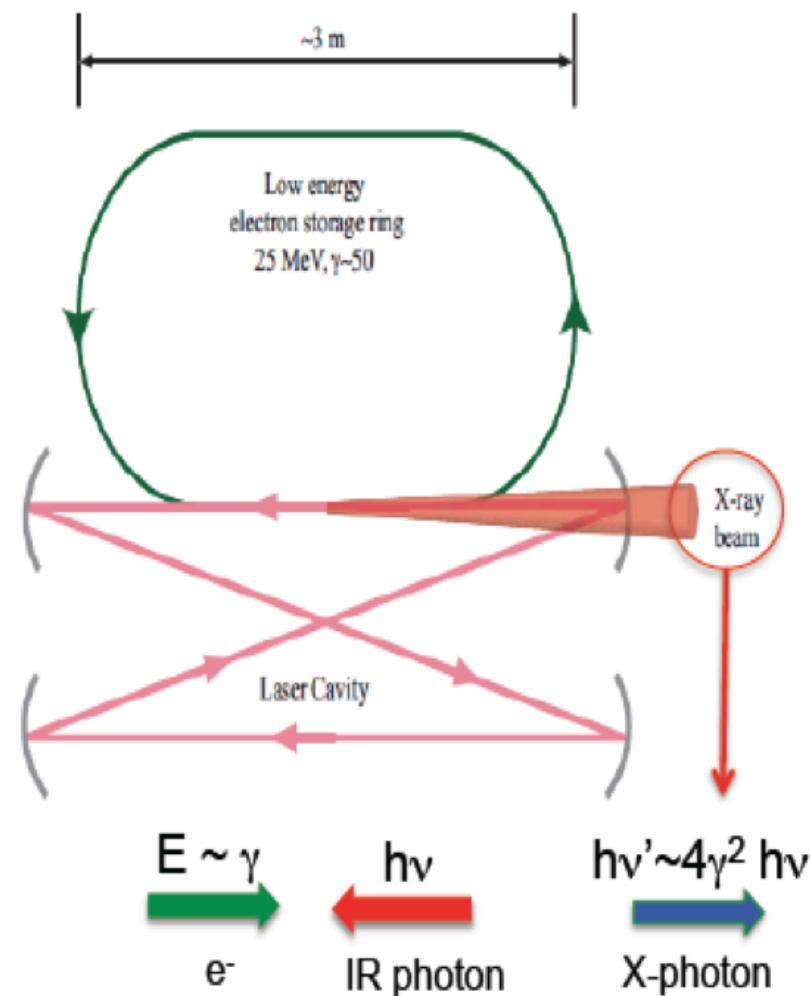
$$m_e = 9.1095 \times 10^{-31} \text{ kg} = 0.5109899 \times 10^6 \frac{\text{eV}}{c^2}$$

$$\lambda = \frac{\lambda_0}{2\gamma^2}$$

$$B = \frac{F(\omega)}{4\pi^2 \sum_x \sum_{x'} \sum_z \sum_{z'}}$$

other important properties:
flux, emittance
flexible polarization,
coherence, and flexible spectrum

Detour: lower energy x-ray source?



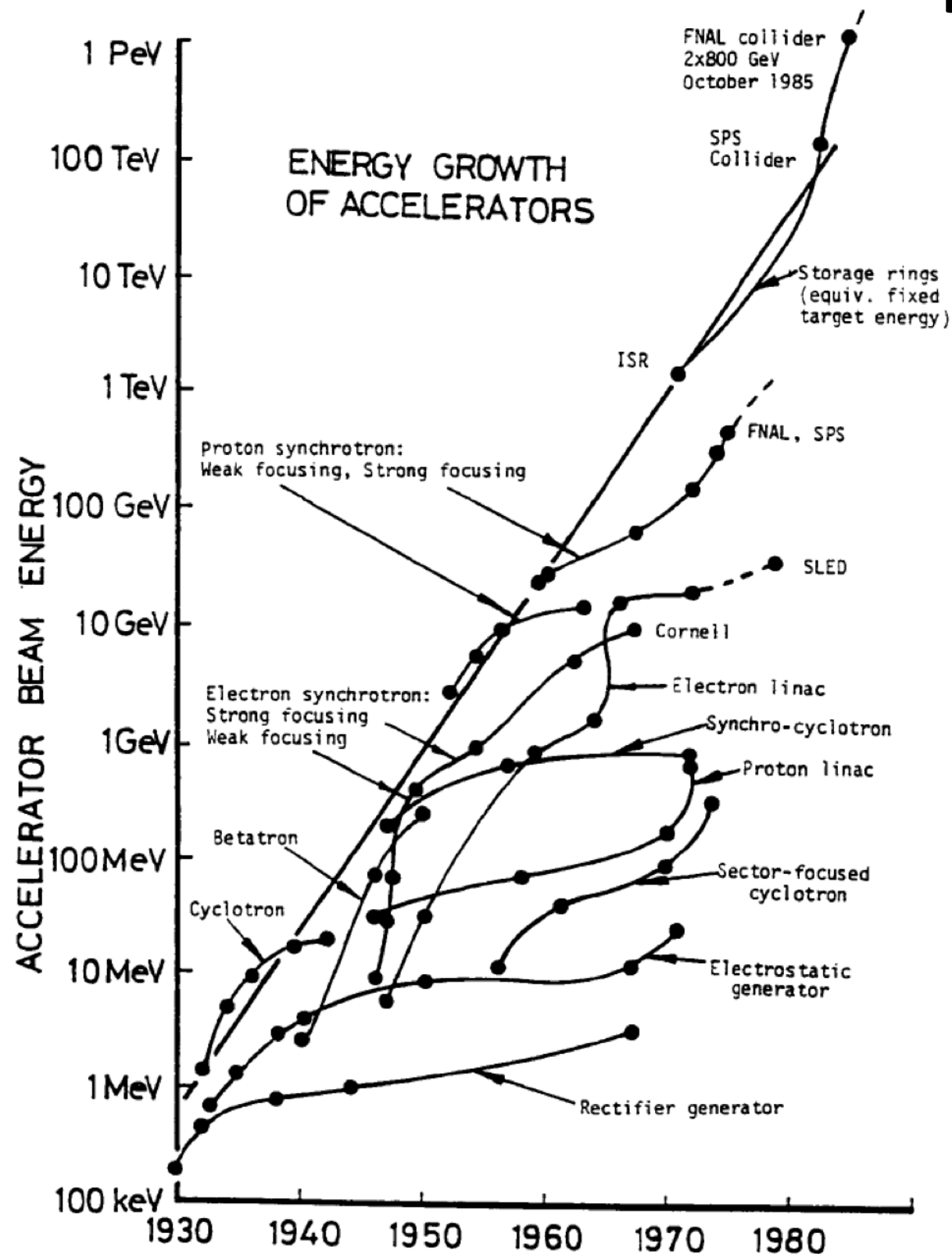
Electron beam frame: the photon energy $\approx 2\gamma h\nu$.
Laboratory frame: there is again a Doppler shift with a 2γ factor.

$\lambda = \frac{\lambda_0}{2\gamma^2}$ Can we make wavelength small?
Use laser with ~ 1 micron, then
we only need
 $\gamma=50$ for x-rays!

Already used to solve protein structure!
X-Ray Structure determination of the Glycine Cleavage System Protein H of *Mycobacterium tuberculosis* Using An Inverse Compton Synchrotron X-Ray Source
J Struct Funct Genomics
Abendroth et. al. (2010)

Issues for comparison:
larger emittance
lower total current

Drivers for Accelerator Development



Livingston plot, 1985

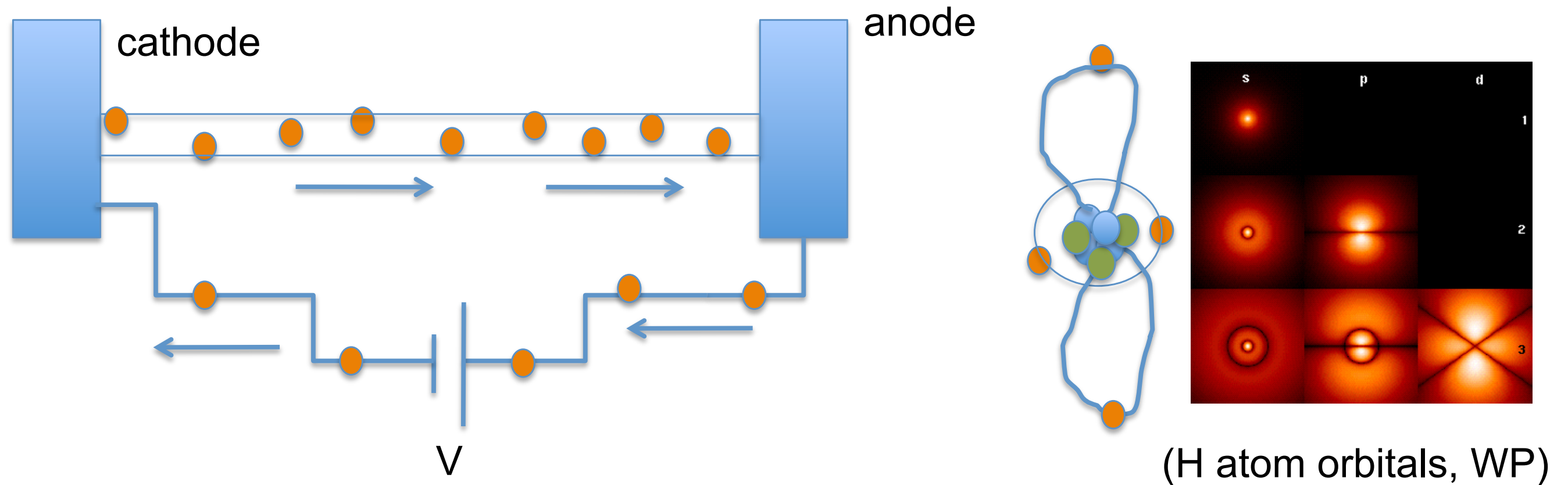
accelerator technology pushed due to nuclear physics and eventually high energy physics

Synchrotron radiation sources came as a spin off of this development

- 1st gen: used parasitically
- 2nd gen: dedicated, ~1970's
- 3rd gen: optimized, emittance, optics

(Livingston and Blewitt, 1985)

How to get free electrons?



Normally electrons are trapped in atomic orbitals
or flowing in a metal circuit.

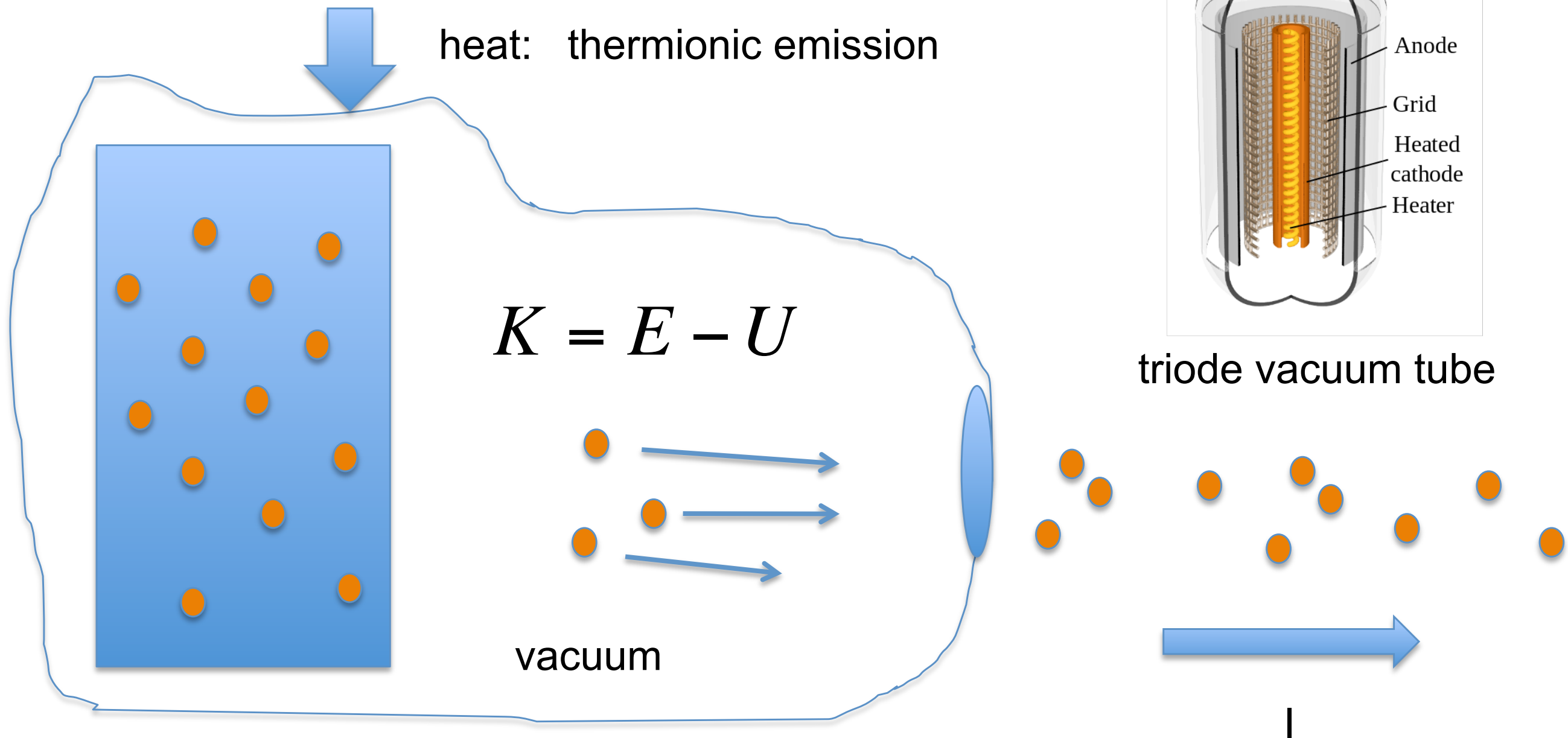


Some tungsten.

How to get free electrons?

add energy E photons: photoelectric effect

heat: thermionic emission



Brief review of relativity



electron moving with velocity v

define $\beta = \frac{v}{c}$

← speed of light

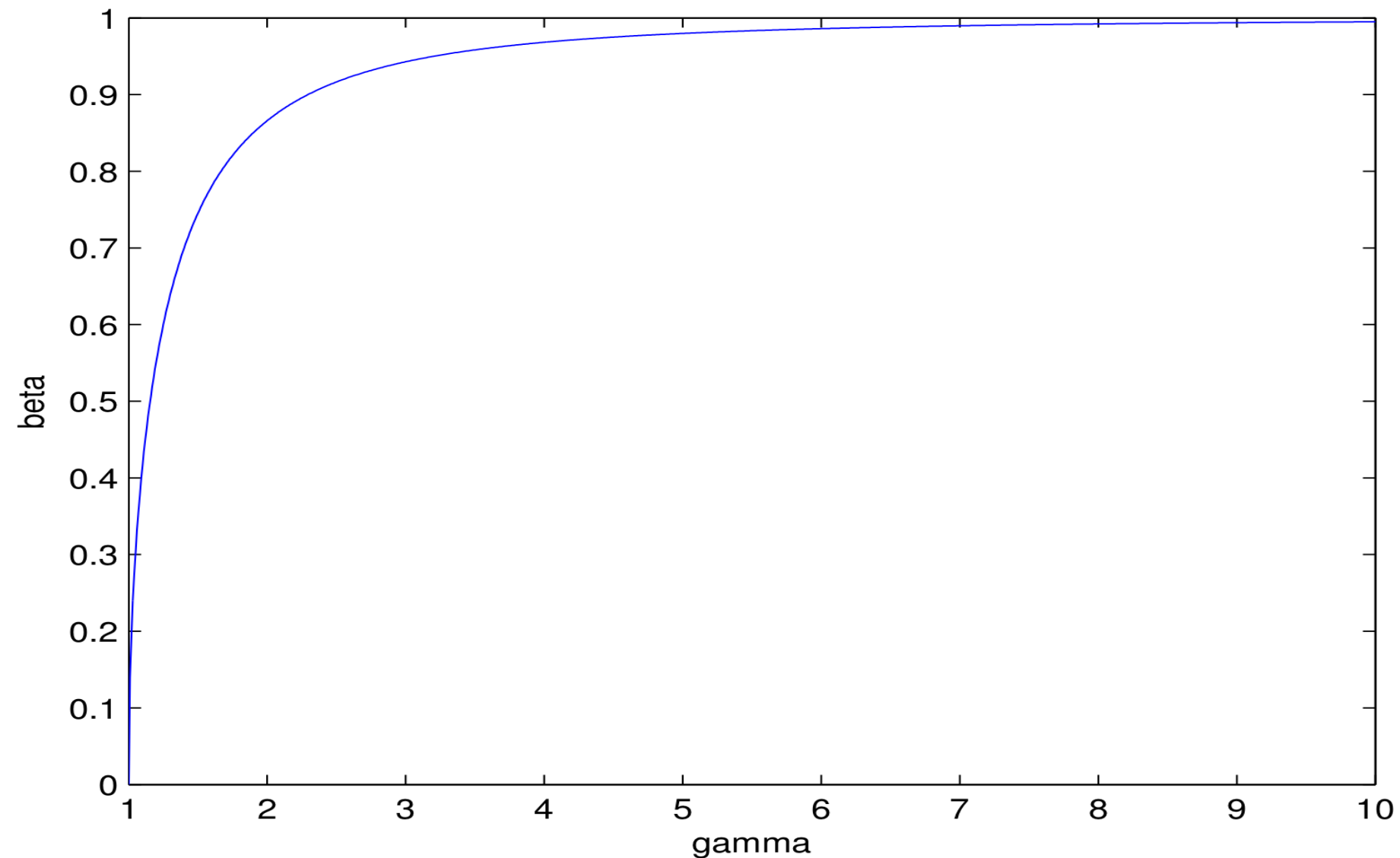
$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$
$$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$E = \gamma mc^2 \quad \longrightarrow \quad \gamma = \frac{E[\text{MeV}]}{0.5109989} = 1.96 \times E[\text{MeV}]$$

Kinetic energy:

$$E_k = (\gamma - 1)mc^2 \quad \longrightarrow \quad E_k = \frac{1}{2}mv^2, \quad \text{for } \beta \ll 1$$

Relativity (2)

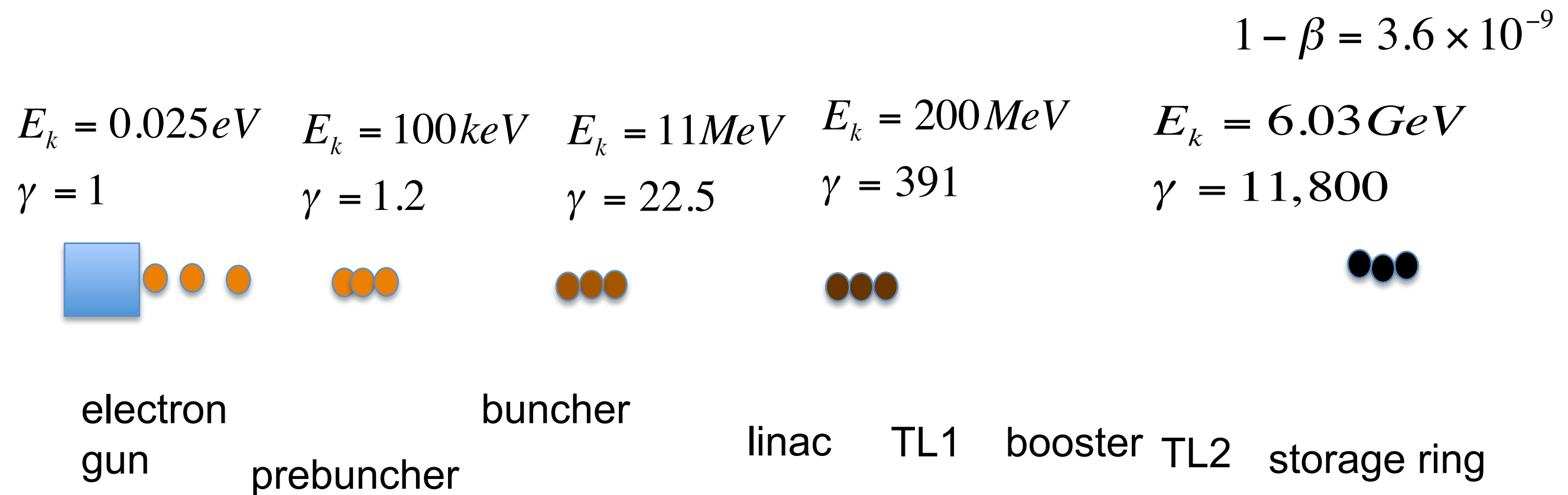


Note that for $\gamma > 5$,
velocity increase becomes
negligible

However, effects as γ gets large:
length contraction
time dilation



preview: ESRF Acceleration Complex



Acceleration



How to accelerate?

Lorentz Force Law

$$\frac{d\vec{P}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

accelerate

bend

$$\vec{P} = \gamma m \vec{v}$$

For constant E field: $\vec{P}(t) = \vec{P}_0 + q\vec{E}t$

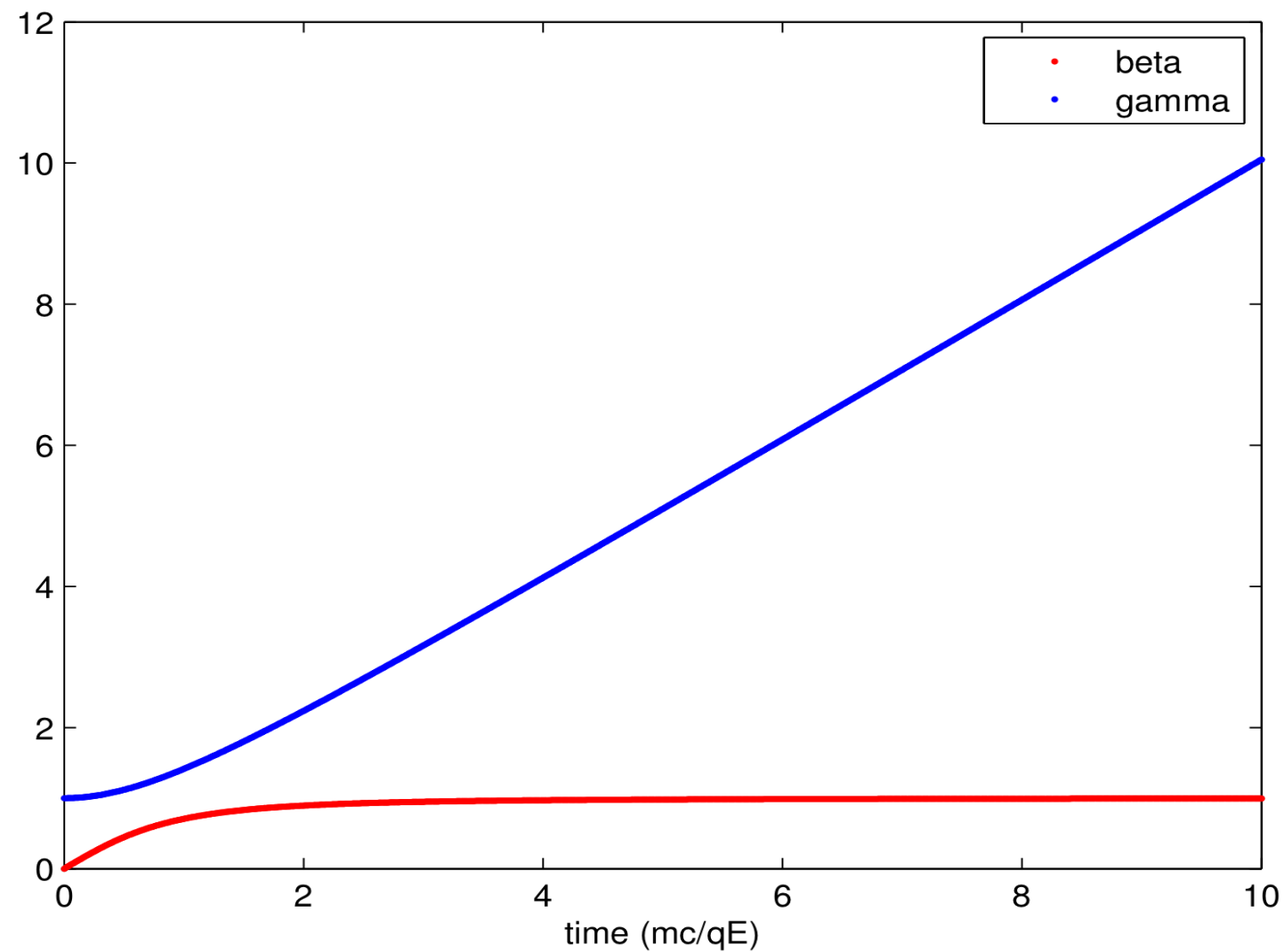
Acceleration

$$\vec{P}(t) = \vec{P}_0 + q\vec{E}t$$

$$\vec{P} = \gamma m \vec{v}$$

$$\beta(t) = \frac{\gamma_0 \beta_0 + \frac{qE}{mc} t}{\sqrt{1 + (\gamma_0 \beta_0 + \frac{qEt}{mc})^2}}$$

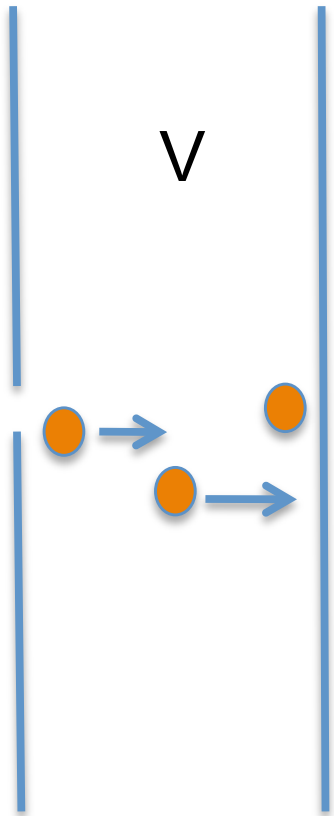
$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$



Electrostatic Acceleration

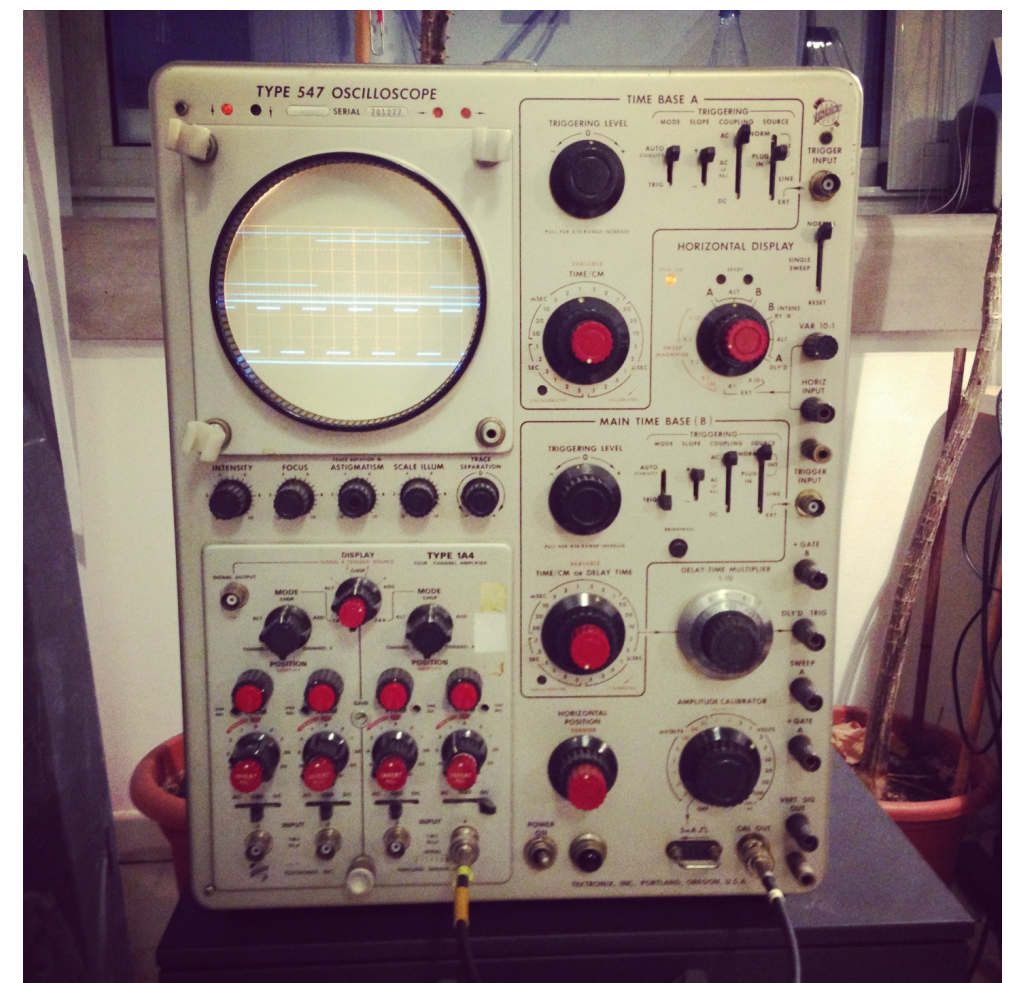


analog
TV



$$V = \int \vec{E} \cdot d\vec{s}$$

analog
oscilloscope
Tektronix 547
(~1968)



Charged particle species

Given particle has charge $q=Ze$ and mass m

$$\Delta E = ZeV$$

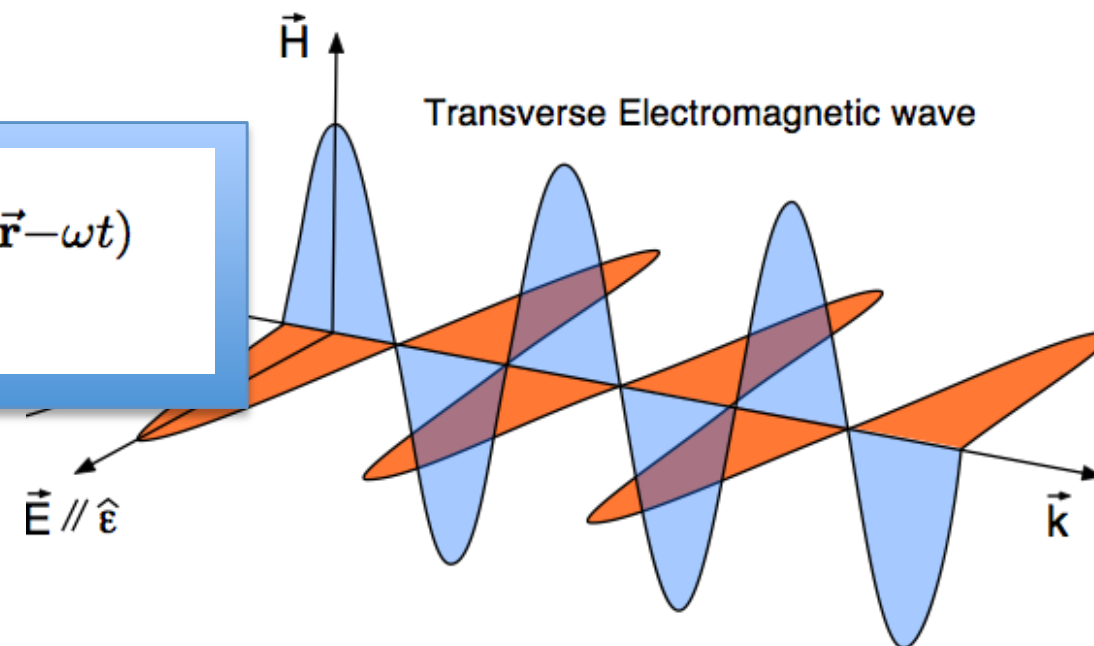
$e = -1.602176565(35) \times 10^{-19}$ Coulombs

For electrons, its very simple:
1 volt changes energy by 1 electron volt

Acceleration with dynamic fields

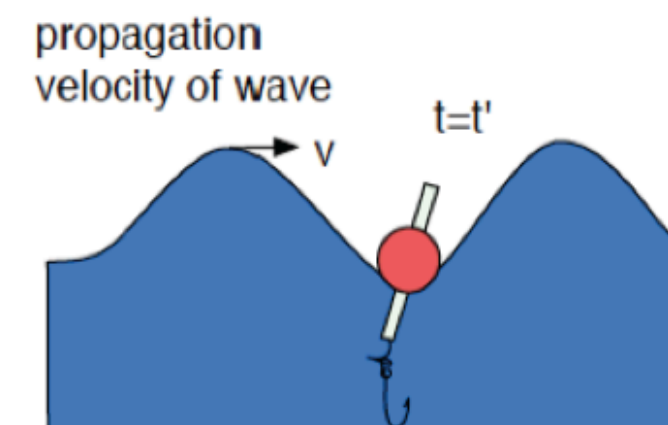
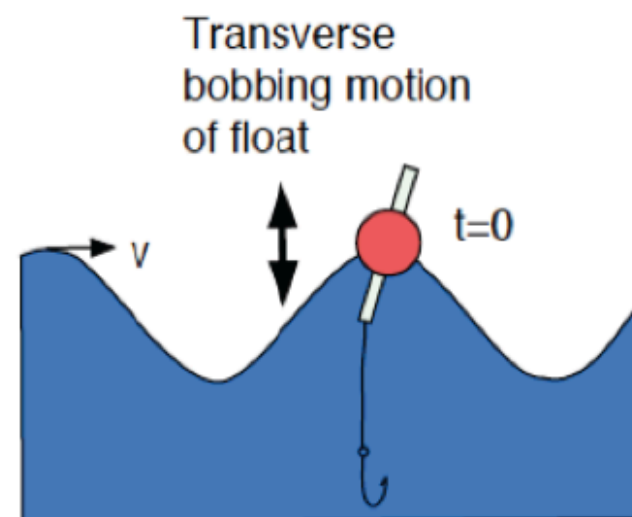
Idea:
use electric field from EM radiation?

$$\vec{E}(\vec{r}, t) = \hat{\epsilon} E_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)}$$



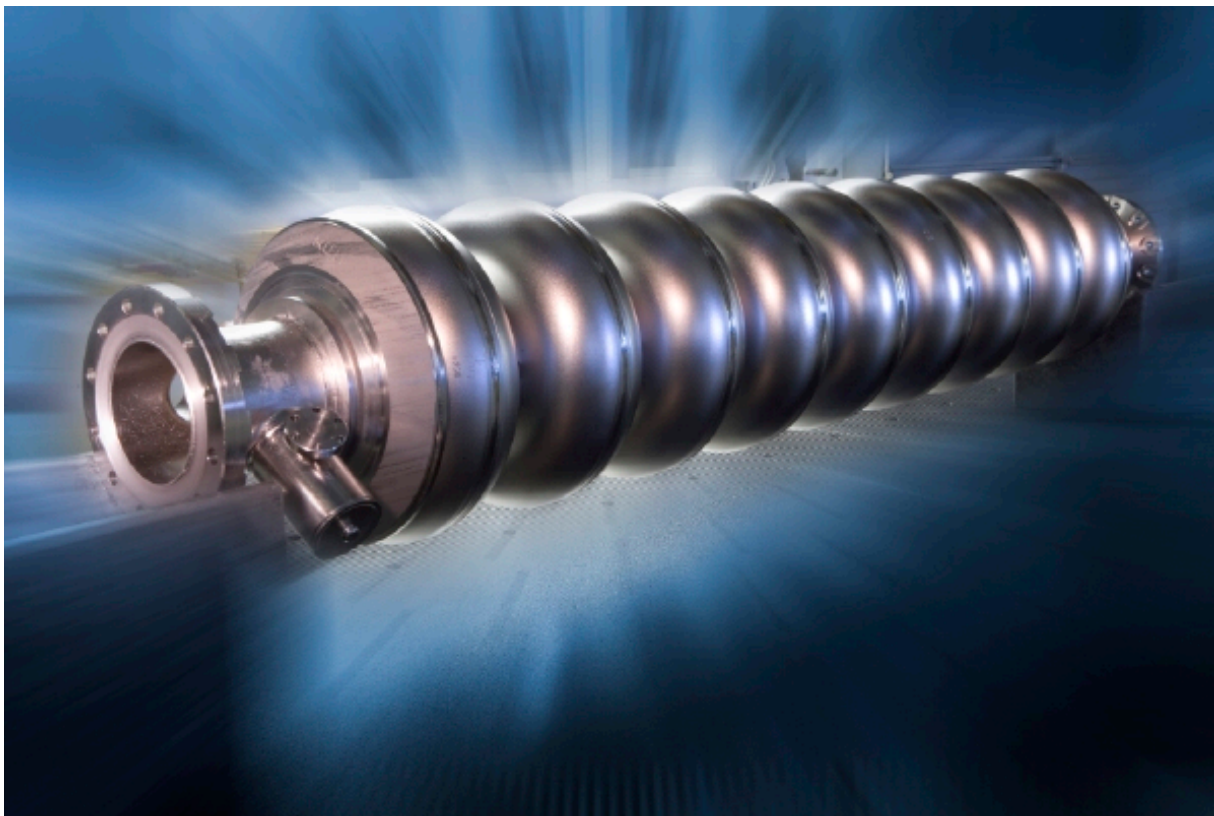
The problem:
averaged over a period,
the plane wave does no work!

like floater bobbing in a pool
of water with wave motion.



Acceleration with dynamic fields (2)

Solution: Use a conducting cavity to change boundary conditions and create a longitudinal electric field.



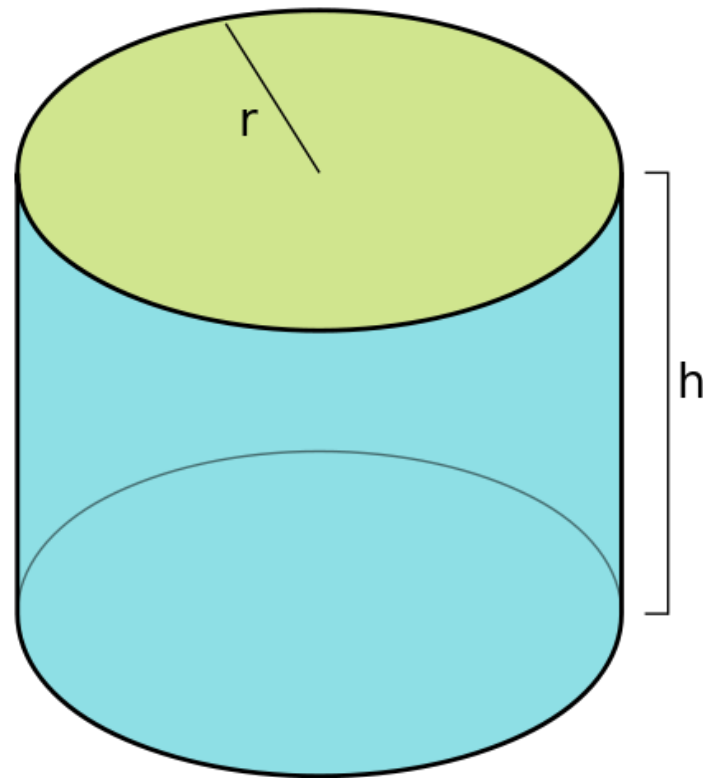
Niobium cavity structure from ILC

$$E^{\parallel} = 0$$

$$B^{\perp} = 0$$

With these boundary conditions we find configurations with longitudinal electric fields TE, TM, TEM.

Acceleration with dynamic fields



consider cylindrical cavity of radius b

TM_{010} (cut-off wave number gives min freq.)

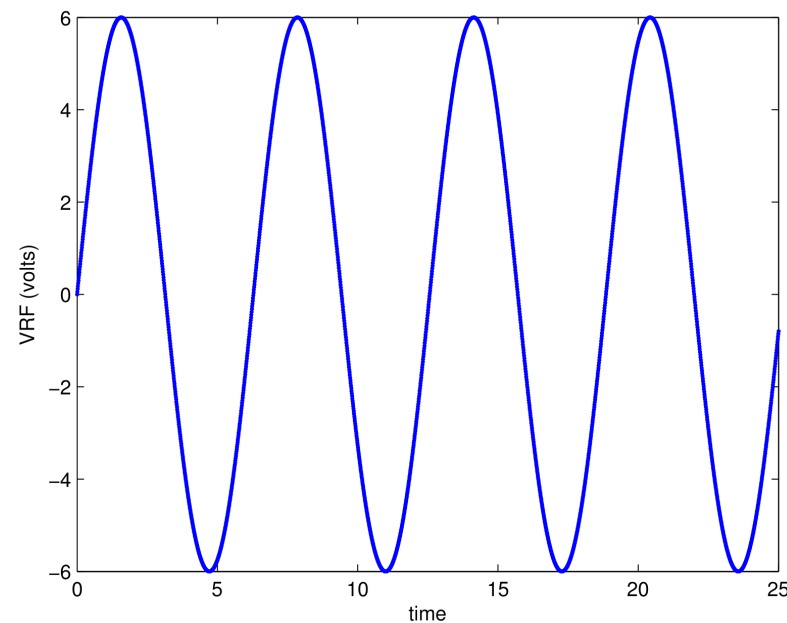
$$E_s = E_0 J_0(k_c r) e^{i(\omega t - ks)}$$

$$E_\theta = 0$$

$$E_r = -i \frac{k}{k_c} E_0 J'_0(k_c r) e^{i(\omega t - ks)}$$

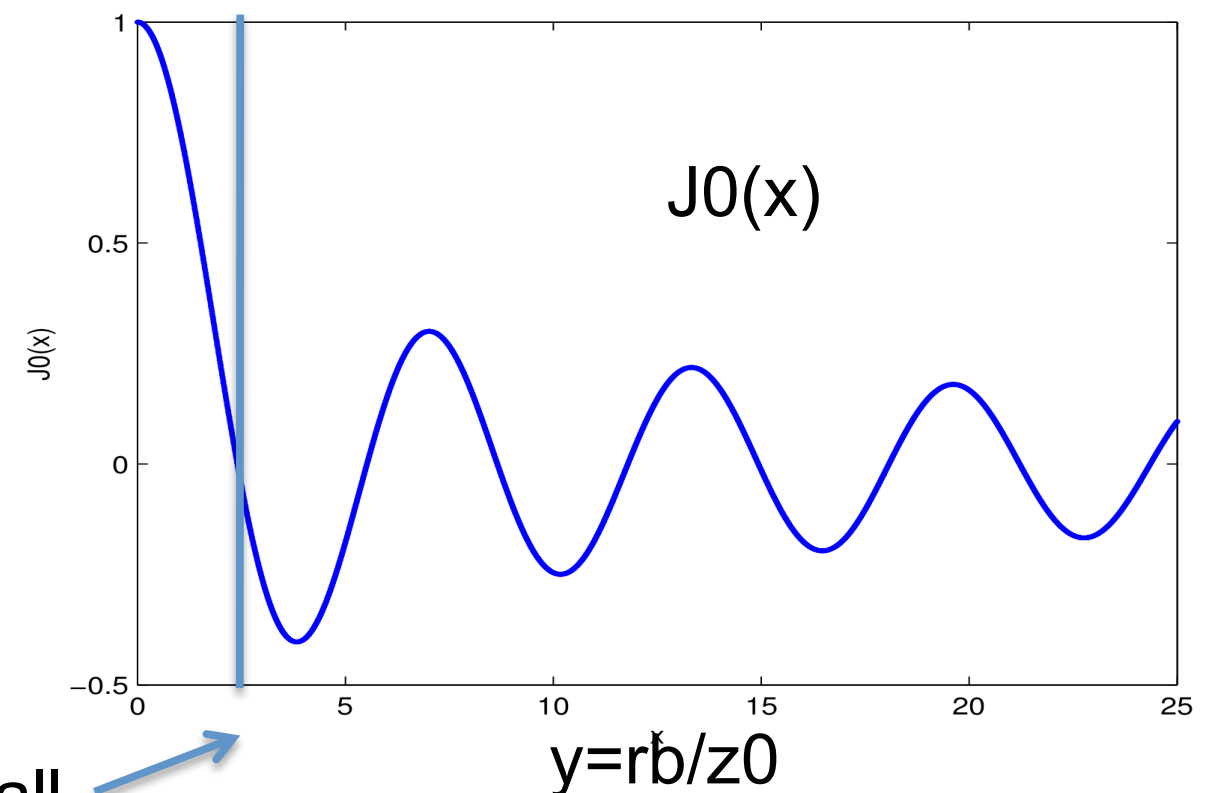
$$k_c^2 = \left(\frac{\omega^2}{c^2} \right) - k^2$$

$$\omega_c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \frac{z_0}{b} \quad z_0 = 2.405$$



voltage across cavity in time

see e.g. Wiedemann, pp34-35

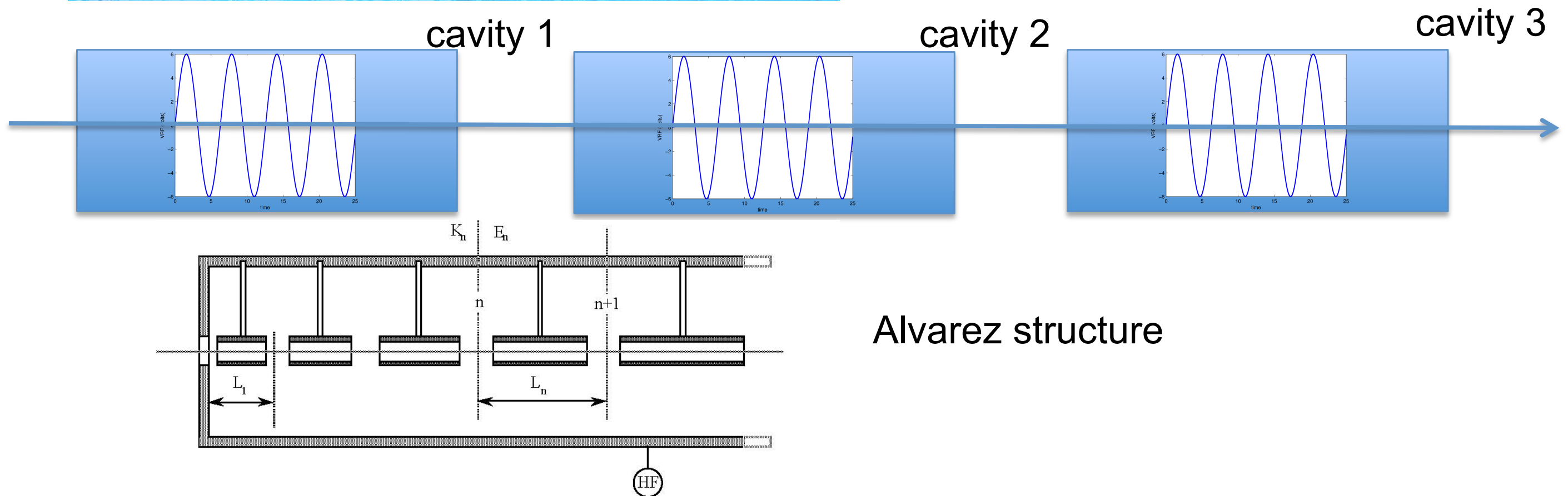


cavity wall

How to use the cavity?



“Spread some Awesome”
wave pool at Club Manila East
Taytay, Philippines



Power for dynamic field acceleration

Now we need to power these cavities.

Important development was **klystron**

first prototype by Varian brothers in 1937
uses velocity modulation of electron beam to amplify
an RF signal.

name "klystron" is derived from a
Greek meaning to wash or break over



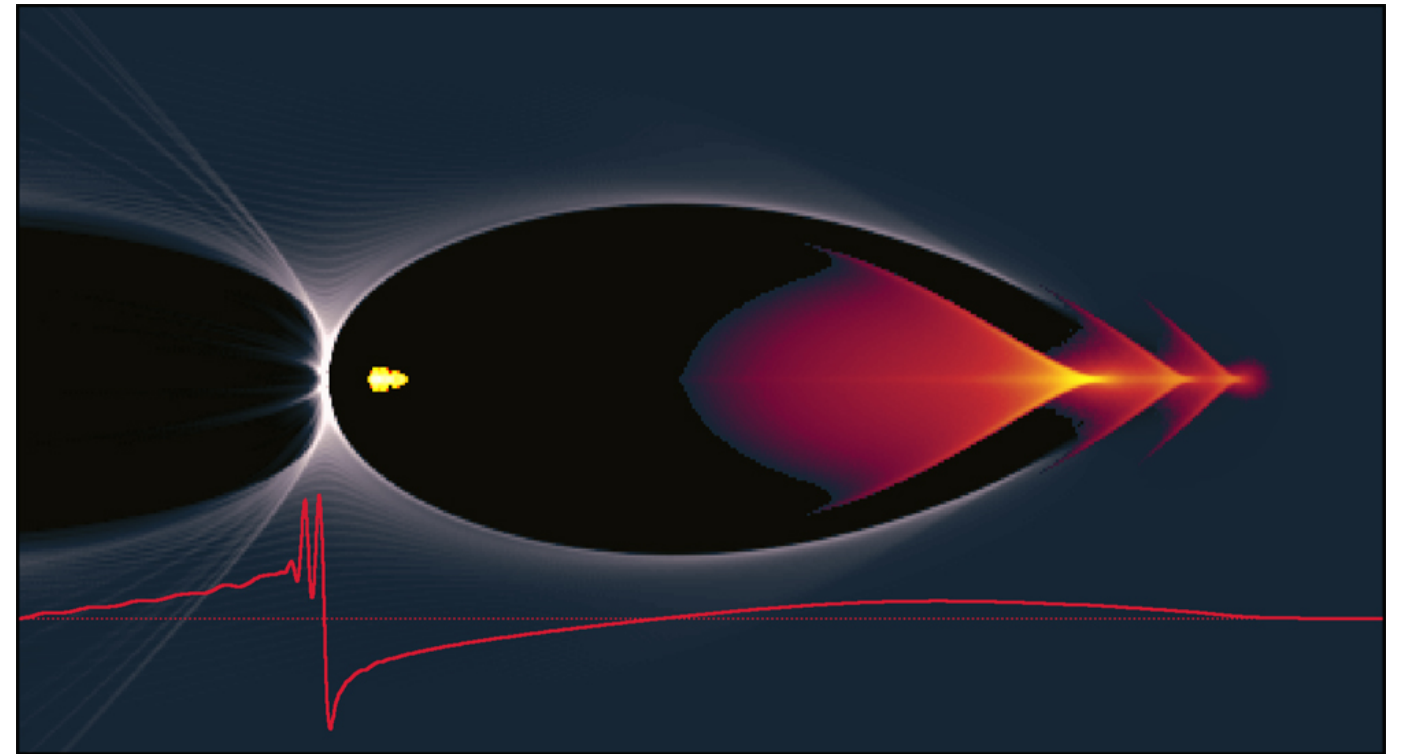
SLAC klystron gallery



klystron from Aust. synch.

Other approaches to acceleration

plasma wakefield acceleration



simulation from code OSIRIS:
Martinez de la Ossa et al., Phys. Rev. Lett. 111, 245003 (2013)
Momose et al., Nat. Med. 2, 473 (1996)

1.5 cm long laser plasma wakefield accelerator, -> 210 MeV, 10 fs pulse
Fuchs, et. al., Nature Physics 5, 826 - 829 (2009)

issue: limited current

Extensions to Electrostatic Acceleration

How high voltage gradient can be achieved?



Cockcroft-Walton (0.1-1 MV)



Van de Graaff 10-100 MV

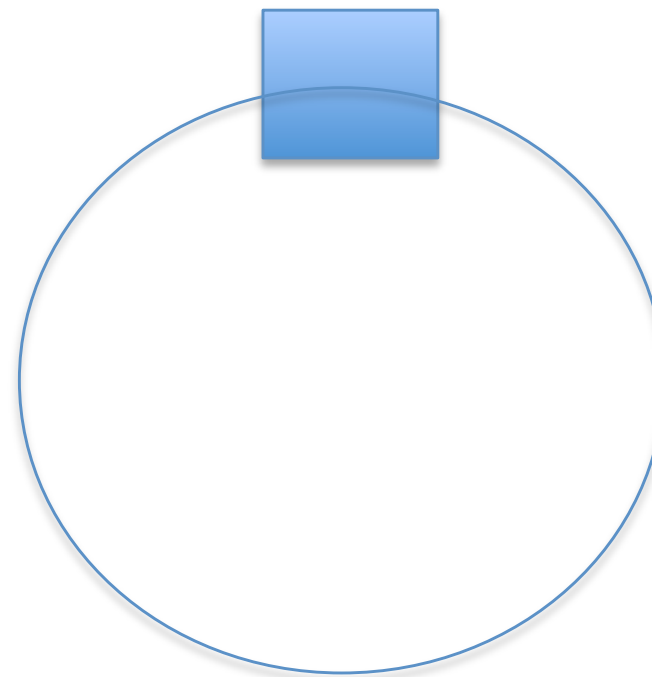
Acceleration Configuration

linear



could use electrostatic or time varying
(cavity structure)

circular



only time varying is possible!

linear

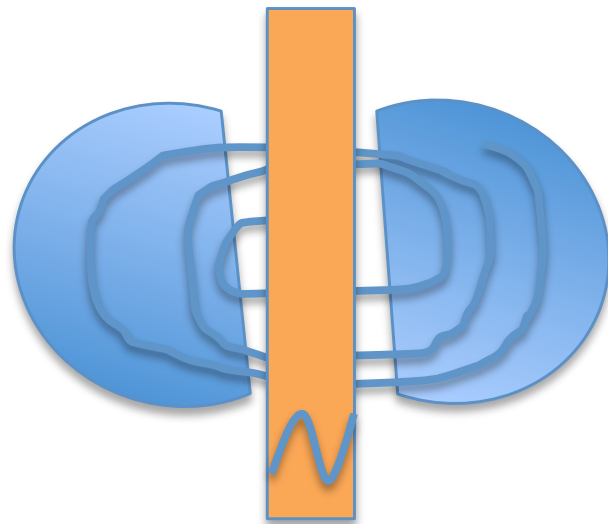


SLAC 2 mile long (3.2 km)
since 1966
reached 50 GeV electrons

Circular Configuration

nice idea is to make a circle, and electron gets some energy each time around!

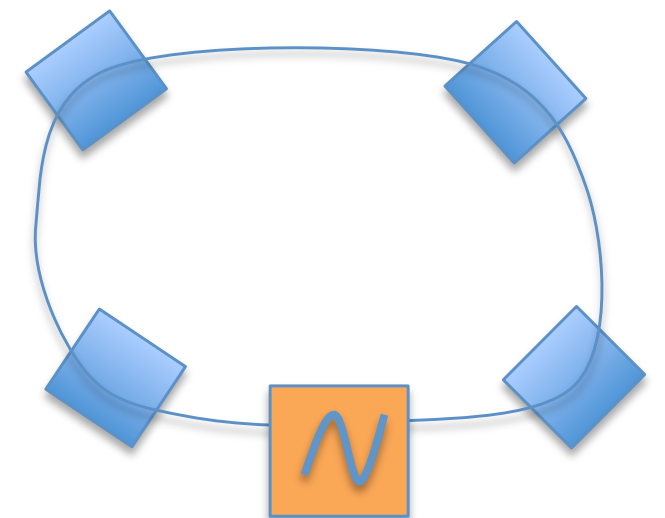
cyclotron



microtron



synchrotron



(must ramp dipoles for acceleration)

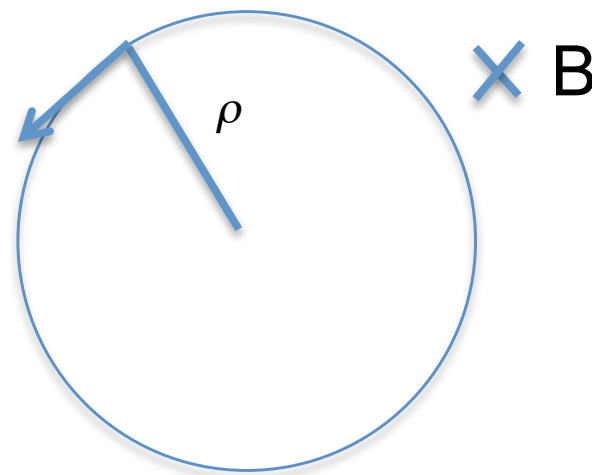
cyclotron

Consider constant magnetic field

$$C = 2\pi\rho$$

$$B\rho = \frac{P}{q}$$

$$f = \frac{Bq}{2\pi\gamma m}$$



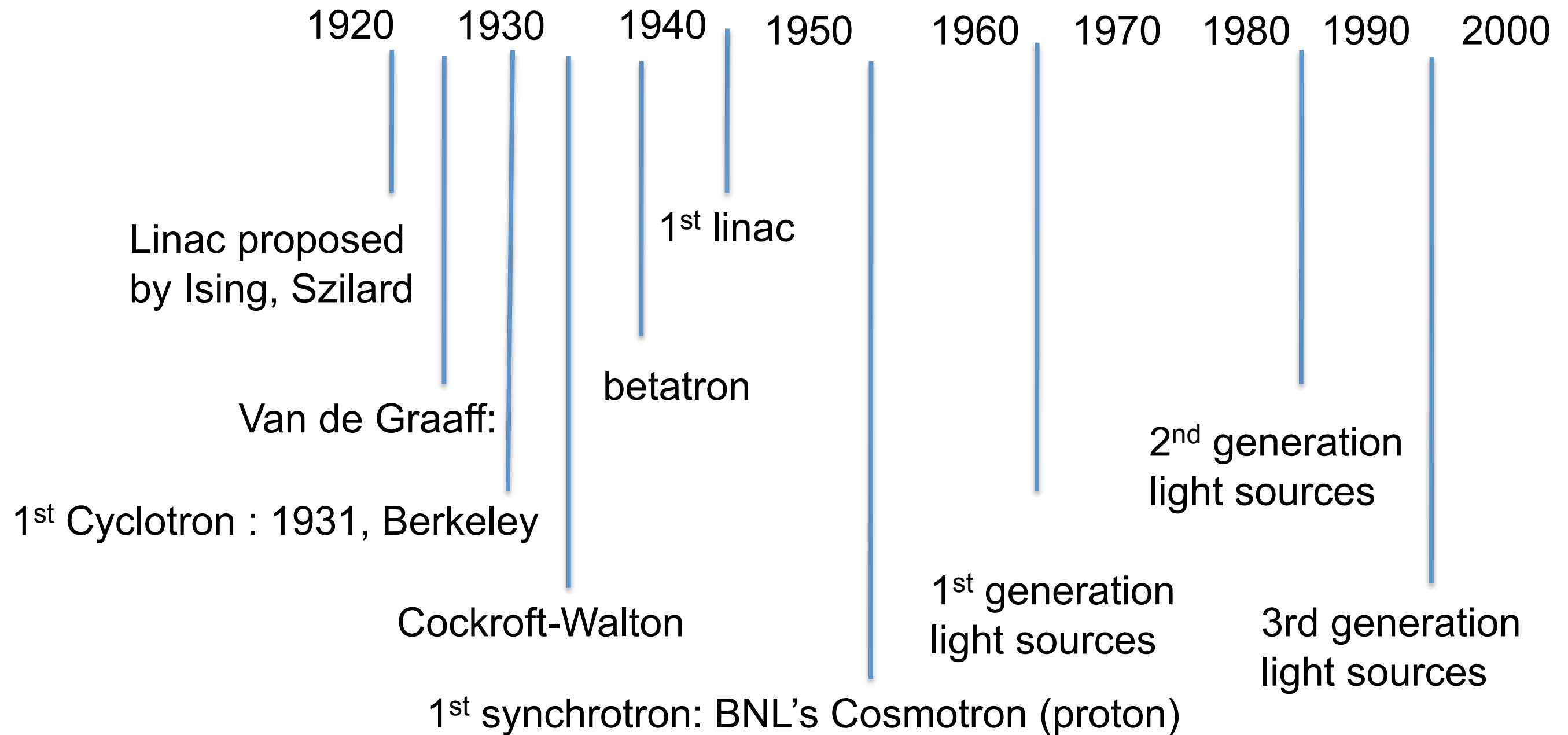
in practical units:

$$B\rho = 3.33 E[GeV]$$

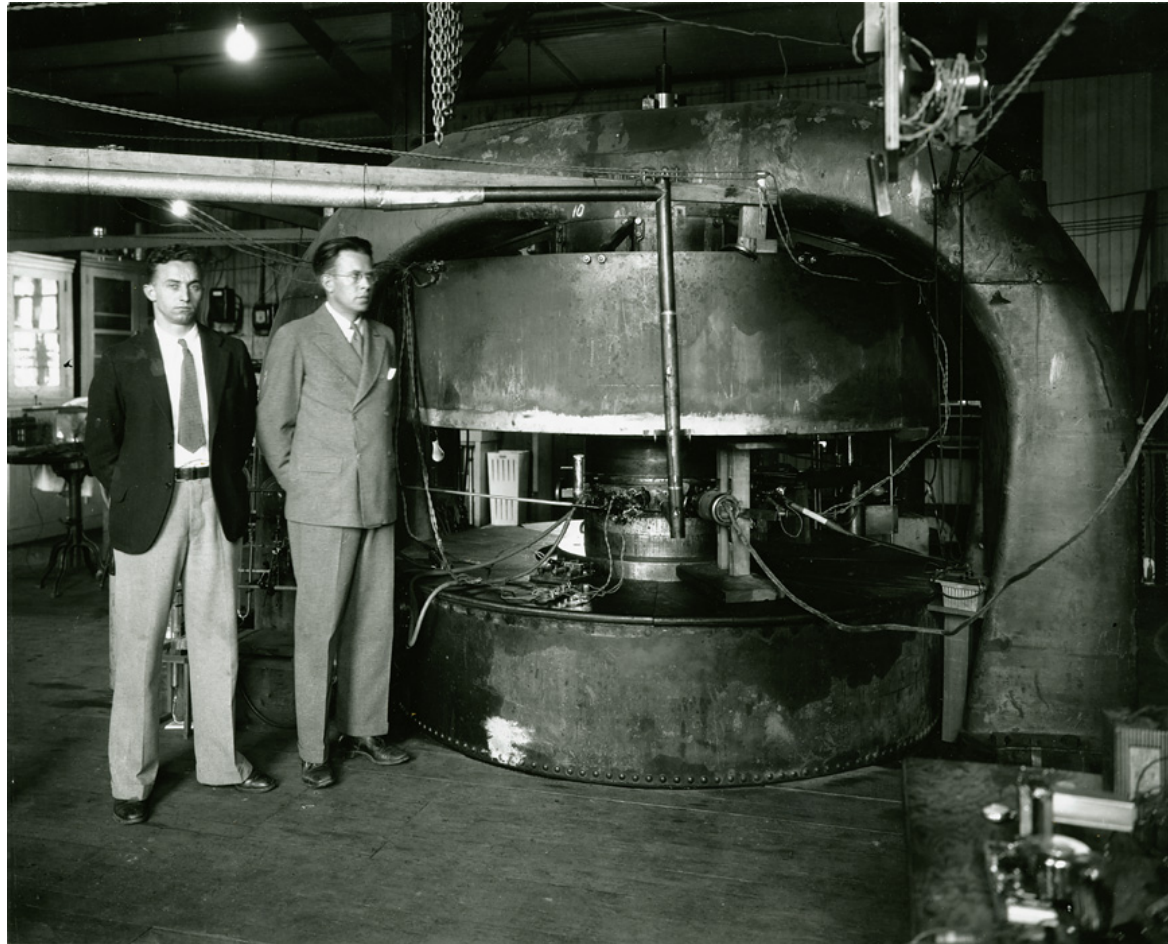
cyclotron frequency
constant for non-relativistic

(for relativistic, need to alter frequency-> synchrocyclotron)

history



Cyclotron, Microtron



27" cyclotron, E.O. Lawrence, Berkeley
13 MeV
1932

<http://bancroft.berkeley.edu/Exhibits/physics/bigscience02.html>

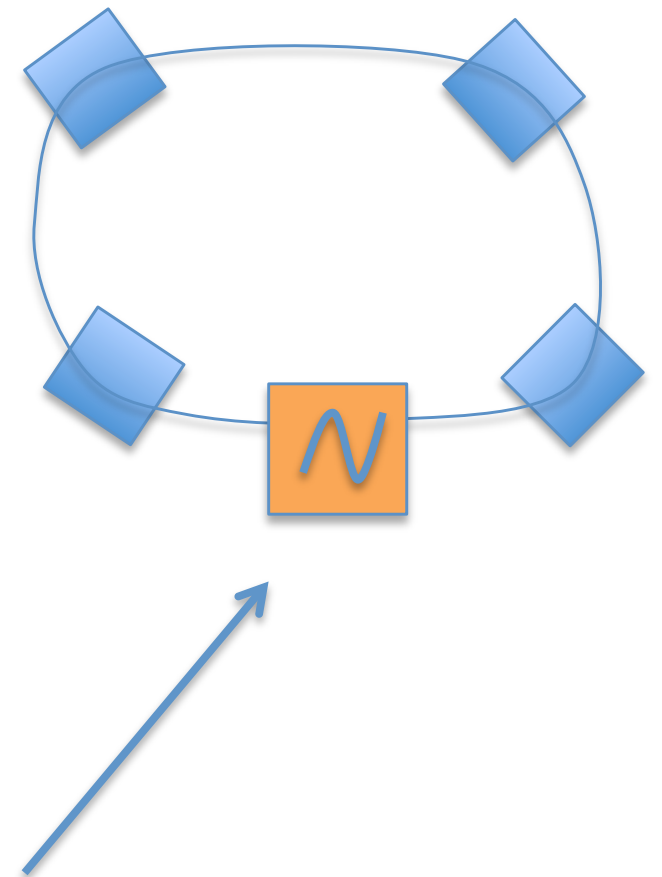


electron microtron, Frascati,
12-20 MeV
~1954

courtesy N. Carmignani

Synchrotrons

Synchrotrons may be accelerators or storage rings.



RF cavity provides energy plus longitudinal focusing.

We cover the beam dynamics in synchrotrons (transverse + longitudinal) in the next lecture.

Synchrotrons for colliders



AdA, Frascati.

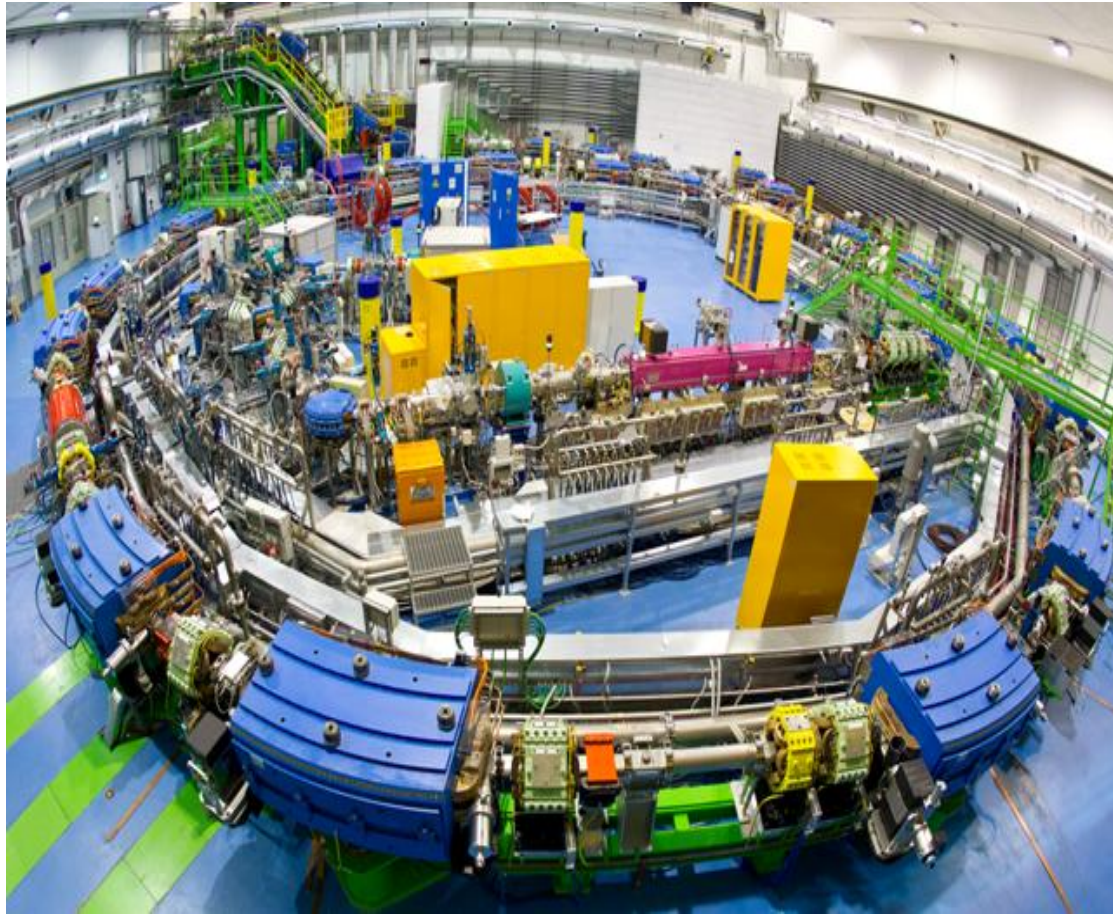
The first colliding ring e-e⁺ synchrotron.
1961, 250 MeV circ = 3 m



LHC, Geneva

Largest high energy collider (p-p and other)
2010, 7 TeV circ = 27 km

Hadron therapy Synchrotrons



CNAO synchrotron, Pavia, Italy

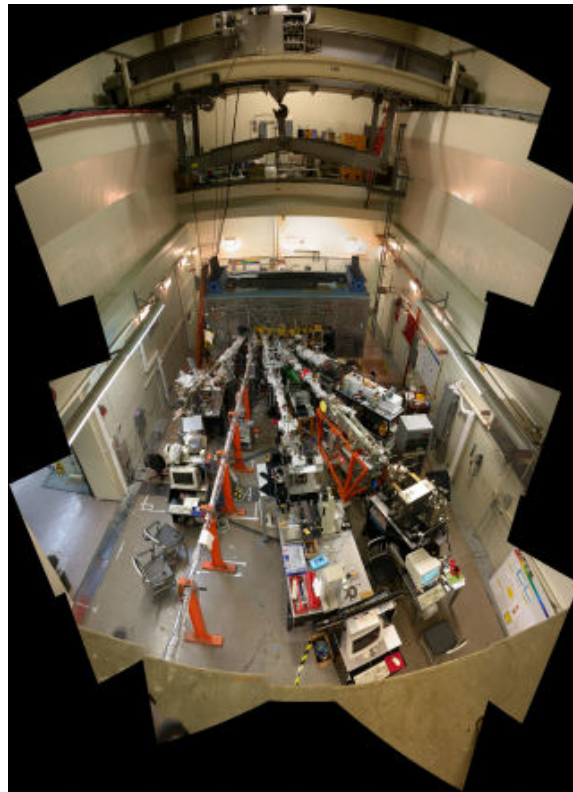
carbon ions or protons



HIMAC synchrotron, Chiba, Japan

He, C, Ne, Si, and Ar ions

synchrotron light sources



1st generation

SURF, NIST, Maryland, US
1961, 0.18GeV



3rd generation

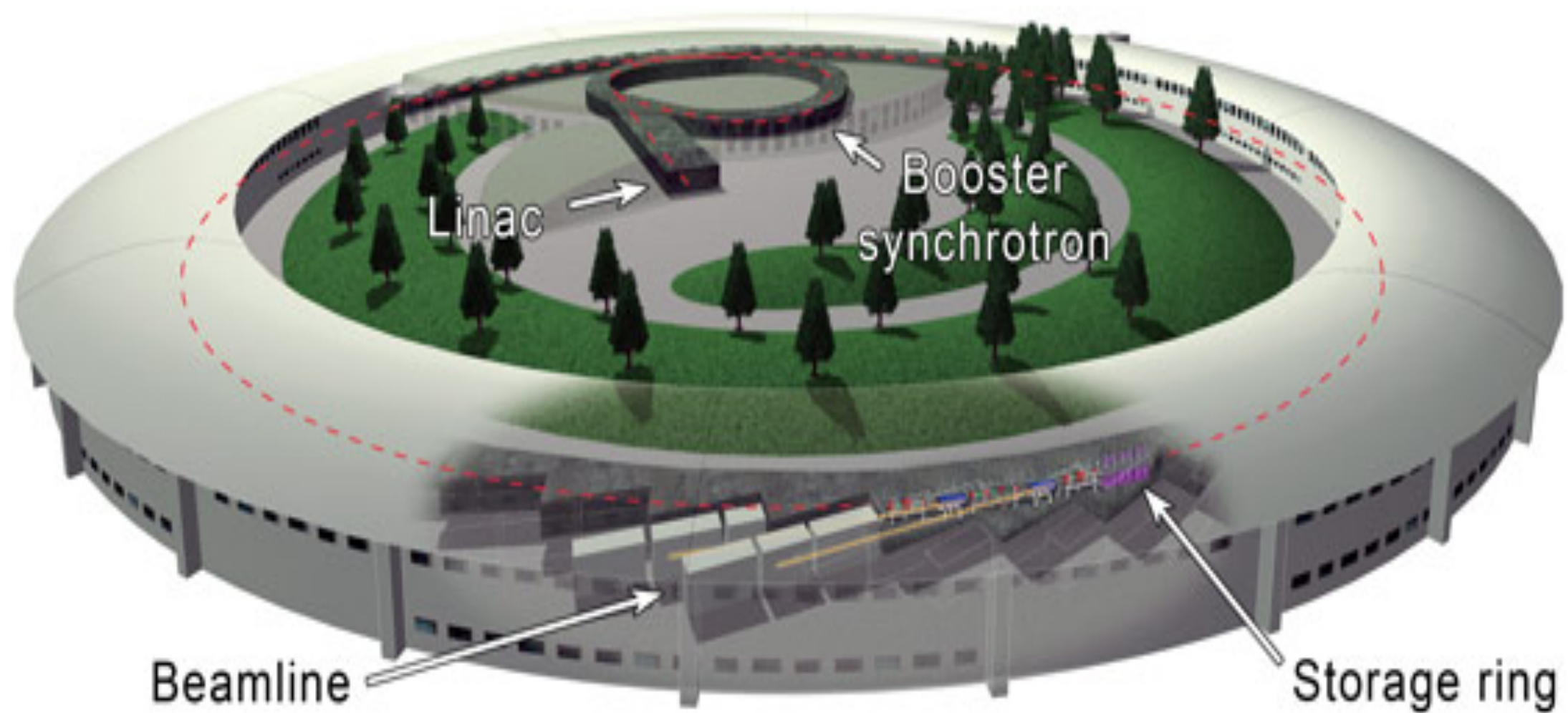
ESRF, Grenoble, France
1994, 6 GeV



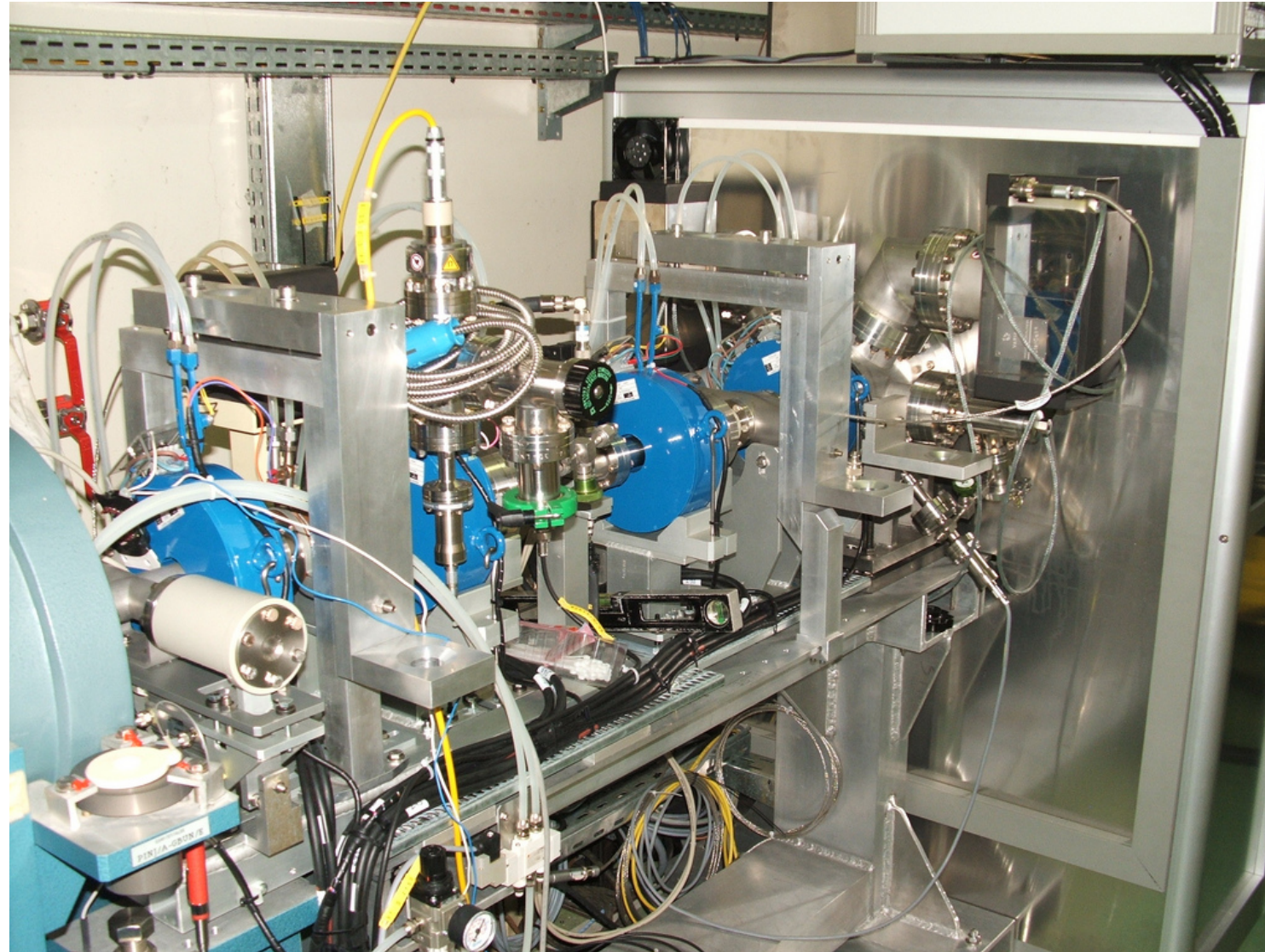
2nd generation

SRS, Daresbury, UK
1981, 2GeV

ESRF acceleration complex



Electron Gun and pre-buncher



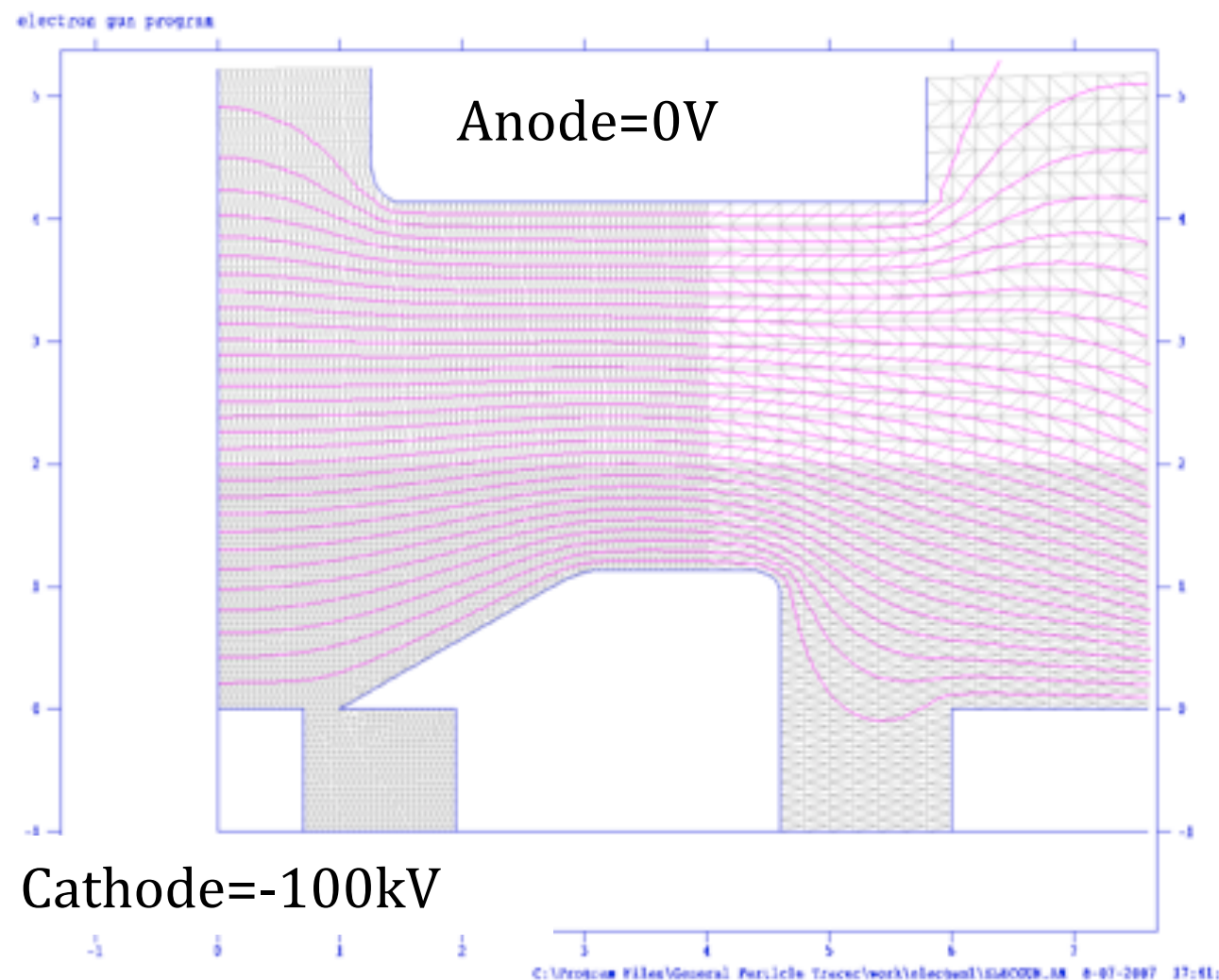
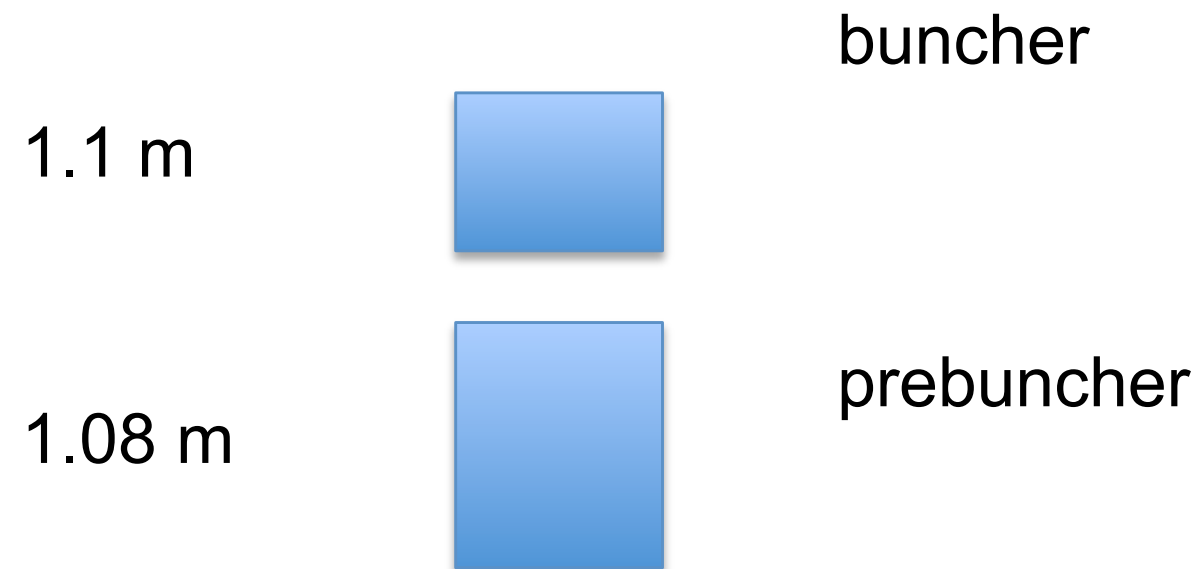
impulse to
gun determines
bunch shape and
length

pre-buncher does not
accelerate

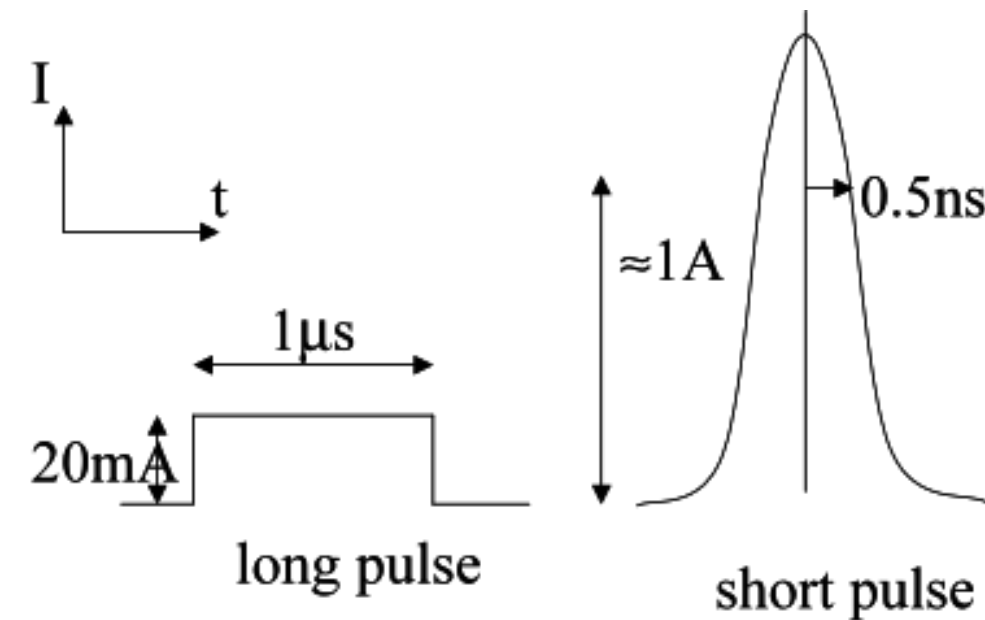
100 keV triode gun
 $\gamma = 1.2$

gun is triggered either at 10 Hz or at 1 Hz

electron gun



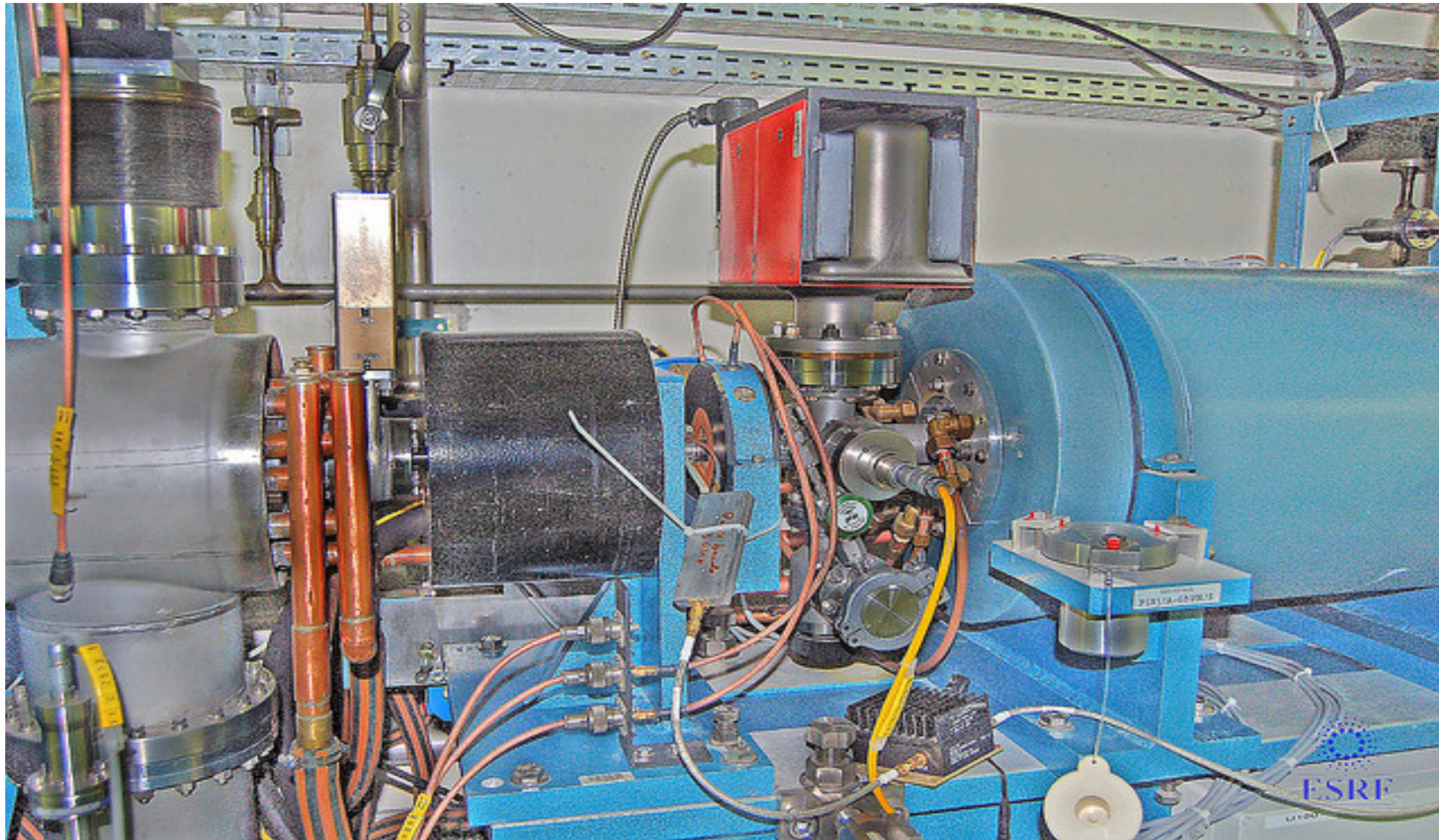
long and short pulse modes



EIMAC Y-845 cathode

T. Perron et. al.
Theoretical Studies on the new Preinjector
08-01/Theory note

ESRF buncher



$$\gamma = 22.5$$

$$\gamma = 1.2$$

ESRF Linac



Two 6 meter sections, each with 2/3 phase advance

Two RF modulators, each equipped with a
35MW Thomson TH2100 klystron

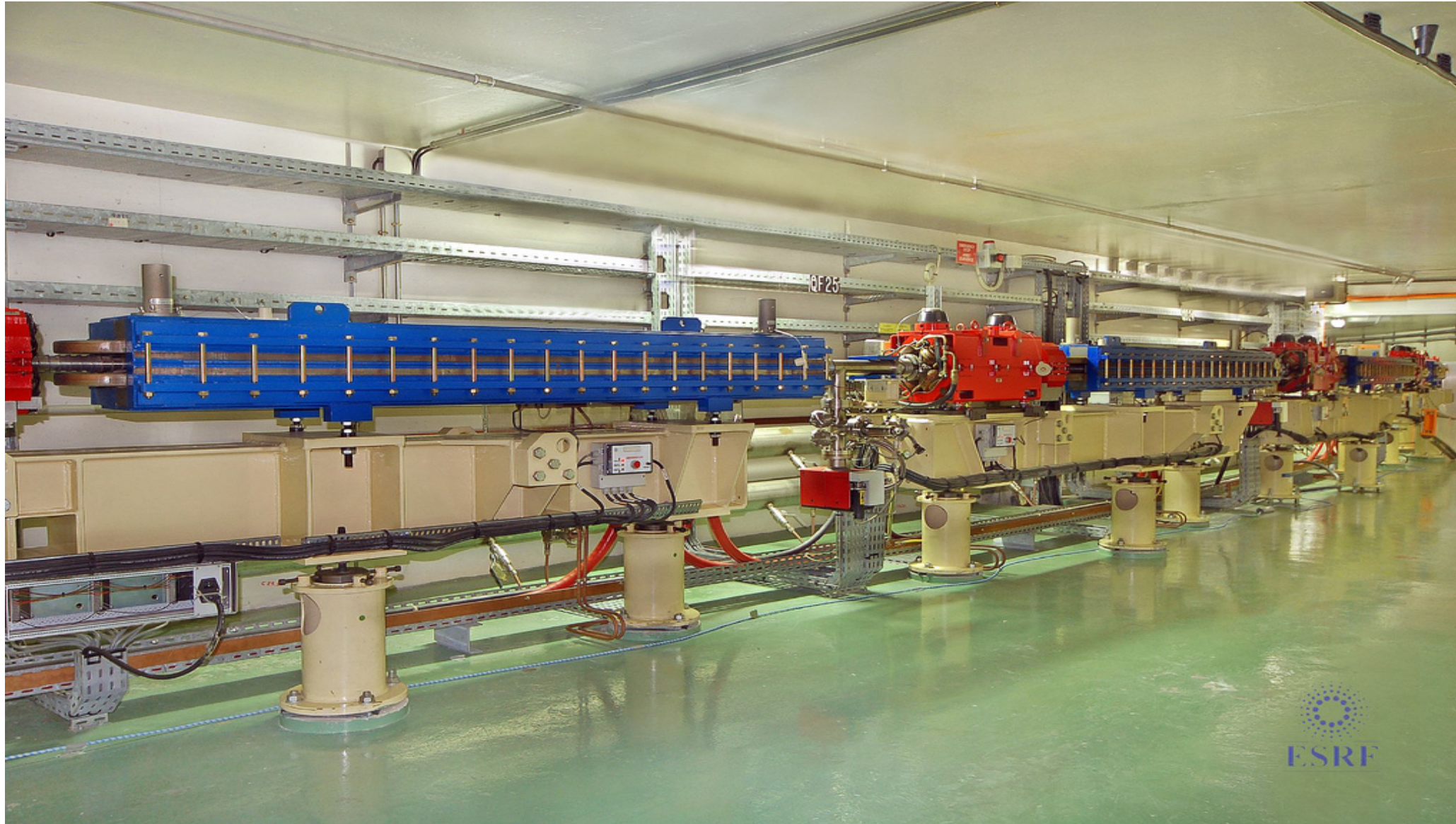
$$\gamma = 22.5 \rightarrow 391 \quad (200 \text{ MeV})$$

Transfer Line 1



Electrons go from end of linac to booster.

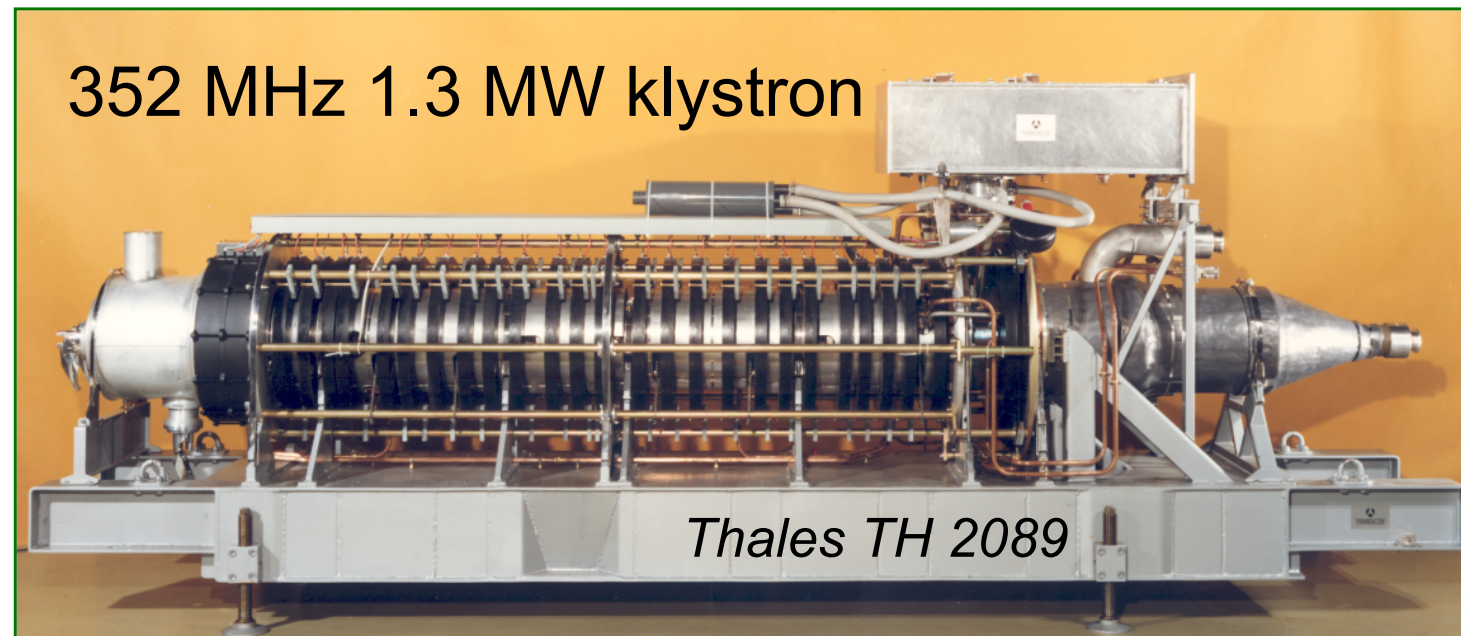
booster synchrotron



300 m circumference (~ 1 microsecond)
emittance is 120 nm at 6 GeV
 $E=200\text{MeV} - 6\text{GeV}$

(labeled SY)

Power Supply

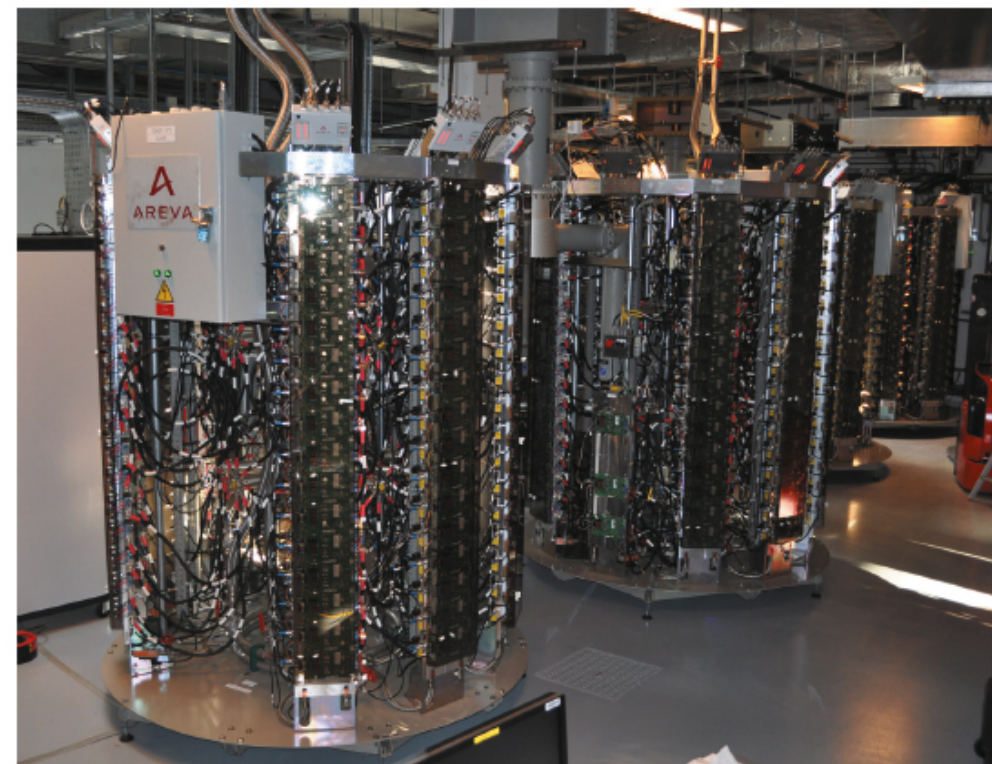


connected to RF cavity
via rectangular waveguide

(J. Jacob)

solid state amplifiers

352.2 MHz – 150 kW



Booster

ramping period: 10 Hz
cavity frequency: 352.2 MHz
harmonic number: 252



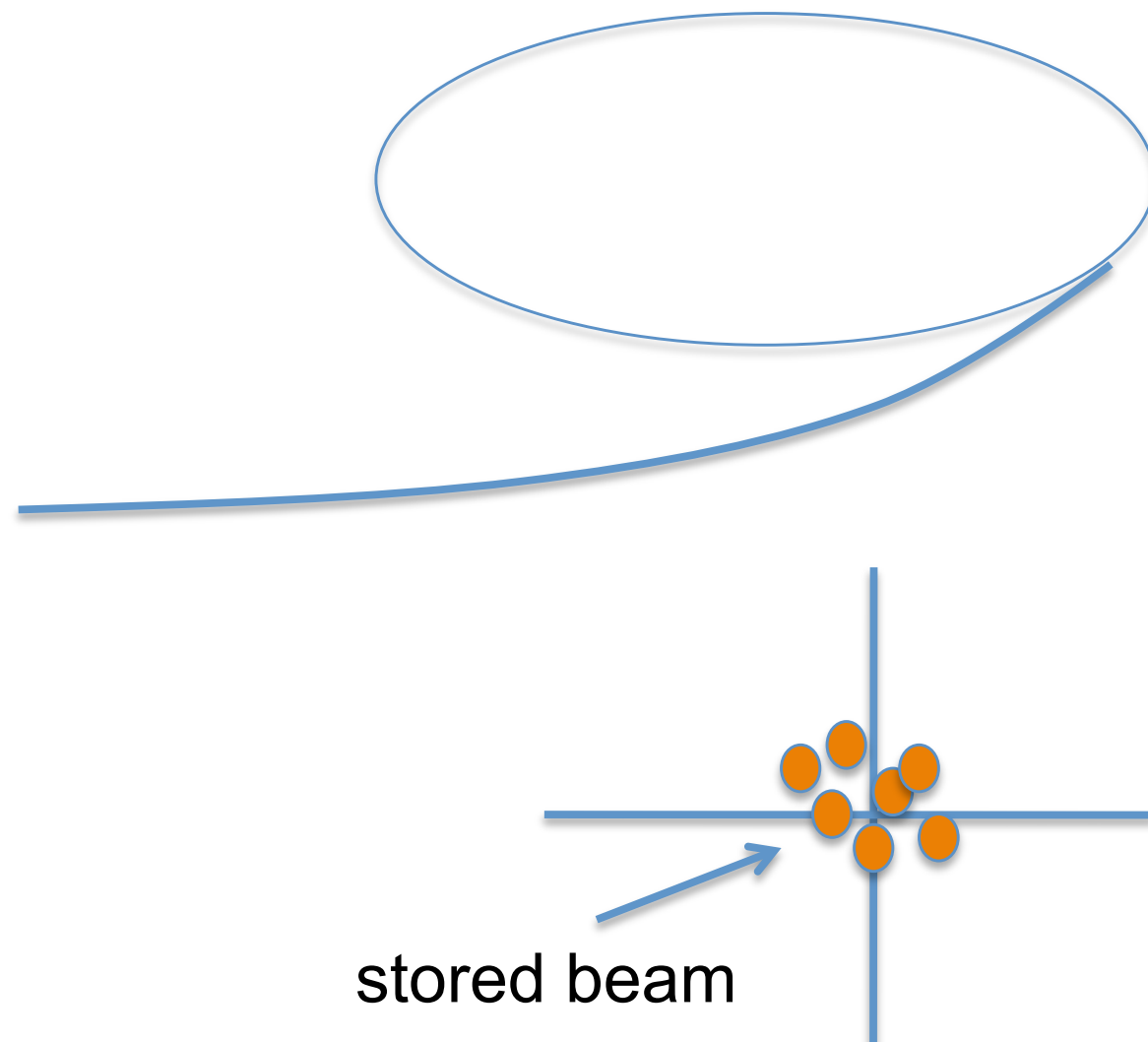
<u>Magnet</u>	<u>number</u>	<u>max strength</u>	<u>length</u>	<u>gap</u>
Dipole	66	0.91 T	2.09 m	h=32 mm
Quadrup.	78	15.0 T/m	0.60 m	r=30 mm
Sextup.	54	143 T/m ²	0.14 m	r=30 mm
Orbit cor.	78	1.5 mrad	0.12 m	h=70 mm

RF cavity in booster

Filhol et. al. EPAC '92

Injection

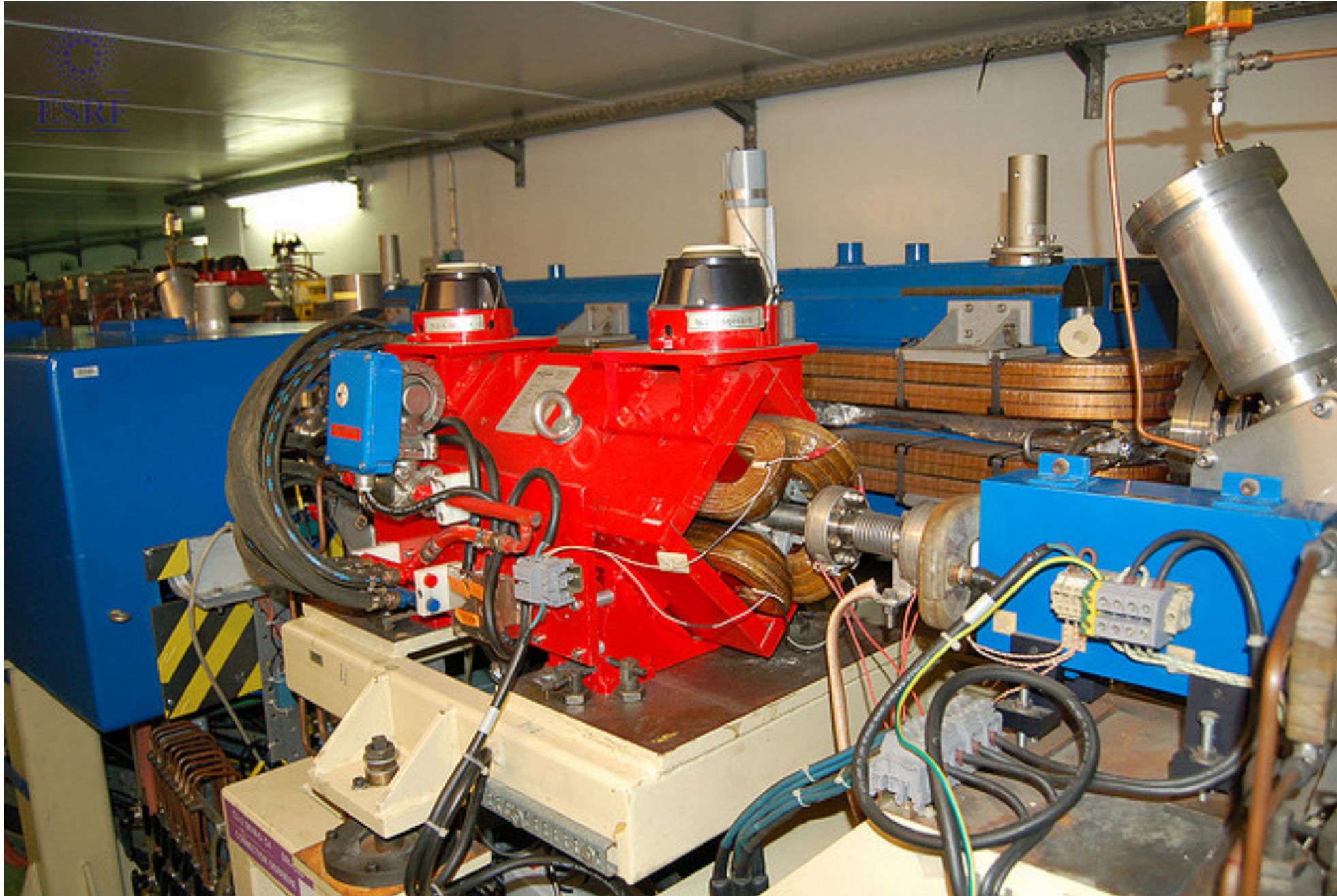
Need to give beam from transfer line to circular synchrotron



We will discuss this in future lectures.

This is one of the very challenging operational aspects of synchrotrons!

Transfer Line 2



Connects booster to storage ring

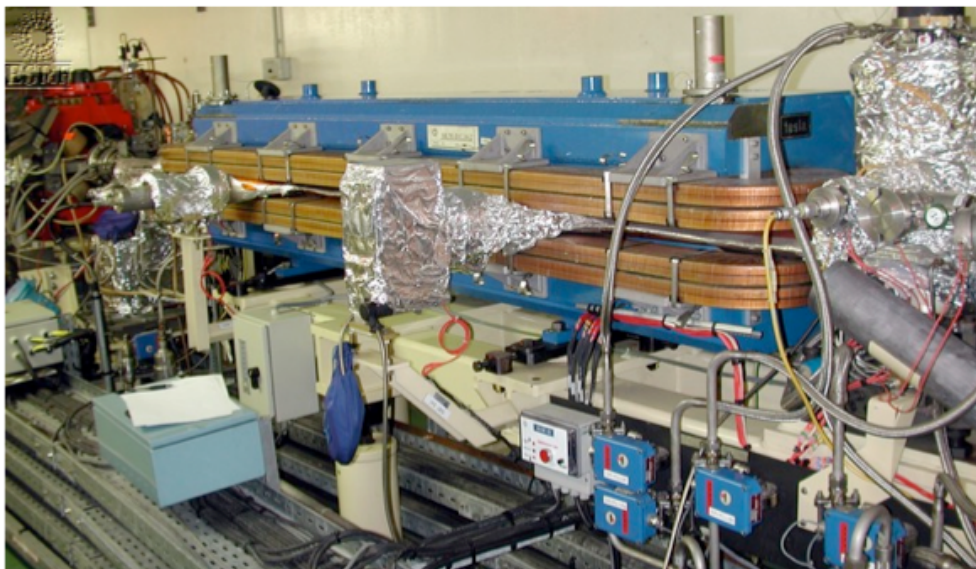
Storage Ring



844 m circumference (2.8 microsecond)
emittance is 4 nm
 $E = 6.04 \text{ GeV}$

More hardware for acceleration and electron beam transport

we will revisit these in future lectures:



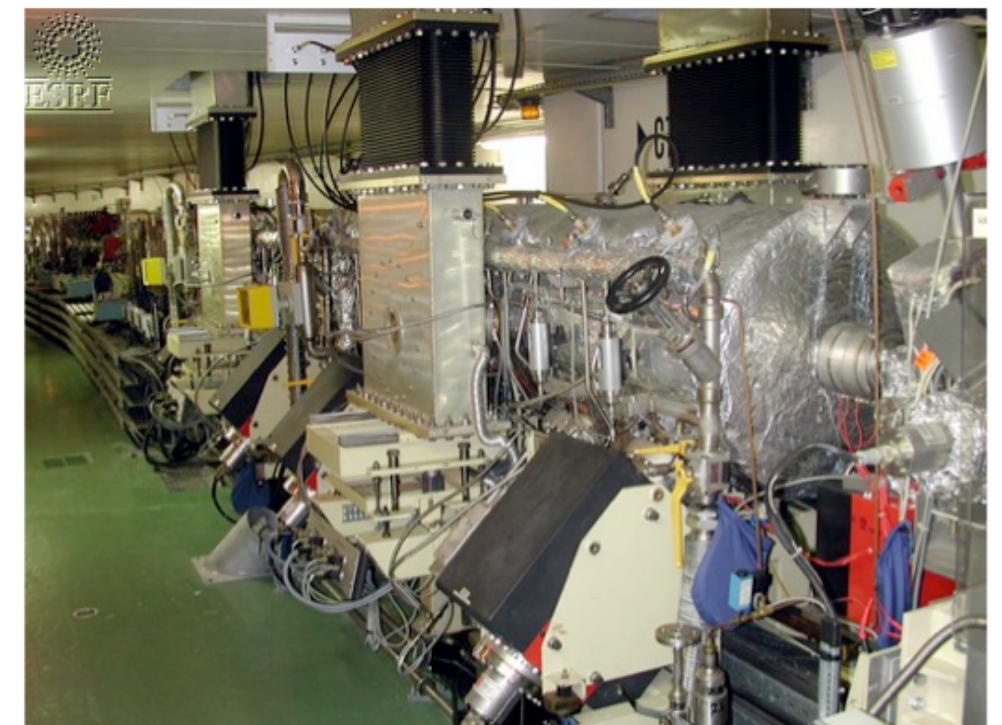
dipole



quadrupole



sextupole



RF cavity

Undulator/Wiggler



X-rays produced for beamlines!!

Thank you for your attention!!