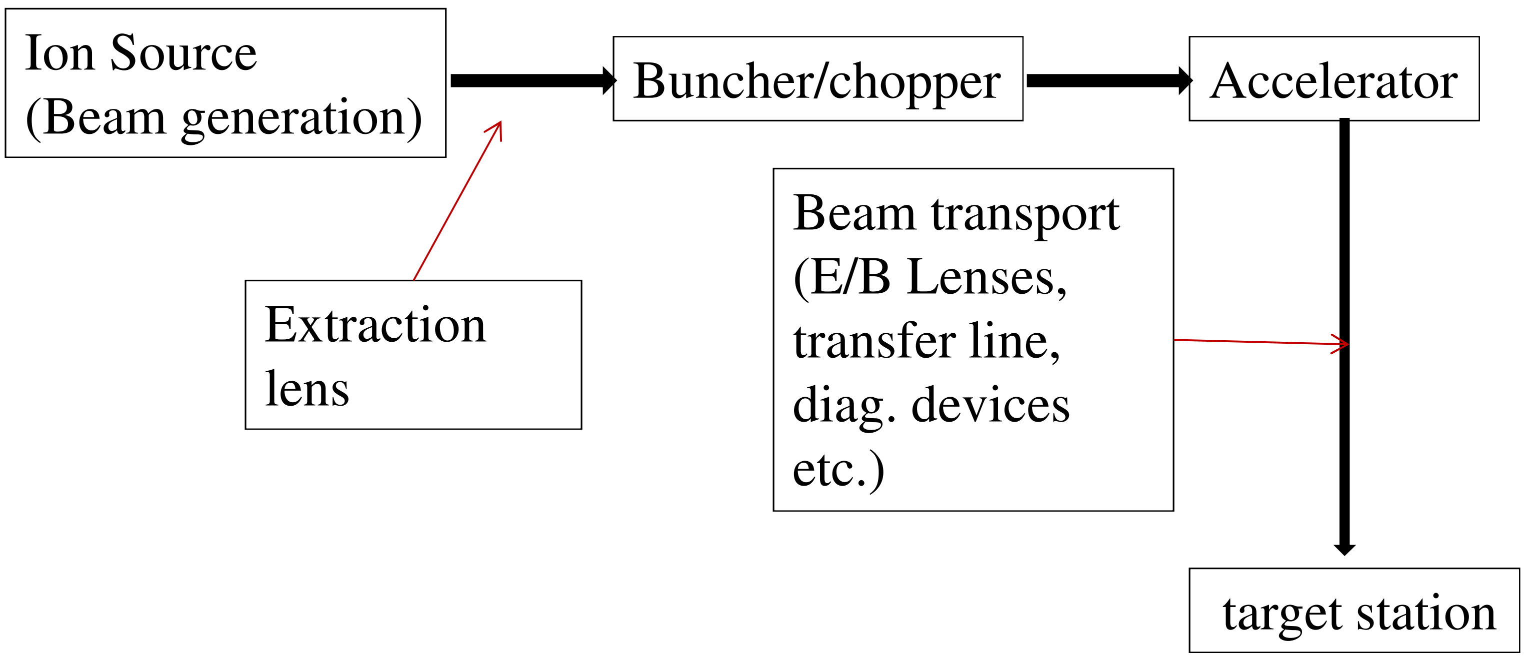
ACCELERATOR

Interaction of "q" with static/dynamic E/B & Technical realization

Controlled Manipulation of an ensamble of charged particles



Brief history of accelerators

1919 Rutherford gets the first nuclear reactions using natural alpha rays (radio activity) of some MeV).

« He notes already that he will need many MeV to study the atomic nucleus »

1932 Cockcroft & Walton build a 700 KV electrostatic generator and break Lithium nucleus with 400 KeV protons.

(Nobel Price in 1951)

1924 Ising proposes the acceleration using a variable electric field between drift tubes (the father of the Linac).

1928 Wideroe uses **Ising** principle with an RF generator, 1MHz, 25 kV and accelerate potassium ions up to 50 keV.

1929 Lawrence driven by **Wideroe** & **Ising** ideas invents the cyclotron.

1931 Livingston demonstrates the cyclotron principle by accelerating hydrogen ions up to 80 KeV.

Brief history of accelerators

1932 The cyclotron of Lawrence produces protons at 1.25 MeV and « breaks atoms » a few weeks after Cockcroft & Walton
(Nobel Prize in 1939)

1923 Wideroe invents the concept of betatron

1927 Wideroe builds a model of betatron but fails

1940 Kerst re-invents the betatron which produces 2.2 MeV electrons

1950 Kerst builds a 300 MeV betatron

Electrons , Protons, Heavy Ions: non-relativistic, realtivistic

Antiparticles : p/e on heavy Z target $\rightarrow \bar{p}$, e^+

$\rightarrow$ cooling/damping ring, accumulator ring

Beam +Fixed target

Collider

Non-relativistic : E increases $\rightarrow$ v increases

Relativistic : v ~ constant, differences in beam dynamics vanish

Beam intensity /luminosity = $e\, Z\, \dot{N}$

Pulsed beam : instantaneous current, average current

Types of accelerators

	Kinetic energy W	
	Electrons	Protons/ions
Electrostatic Van de Graaf &Tandems		20-35 MeV (Vivitron)
Betraton	10-300 MeV	
Microtron	25-150 MeV	
Cyclotron		10-100 MeV
Synchro-cyclotron		100-750 MeV
Synchrotron	1-10 GeV	1-1000 GeV
Storage ring	1-7 GeV (ESRF)	
Collider ring	10-100 GeV (LEP)	1-7 TeV (LHC)
Linacs	20 MeV-50 GeV (SLC)	50-800 MeV(LAMPF)
Linear collider	50-1000 GeV (TESLA)	

Total energy = Rest energy + Kinetic energy

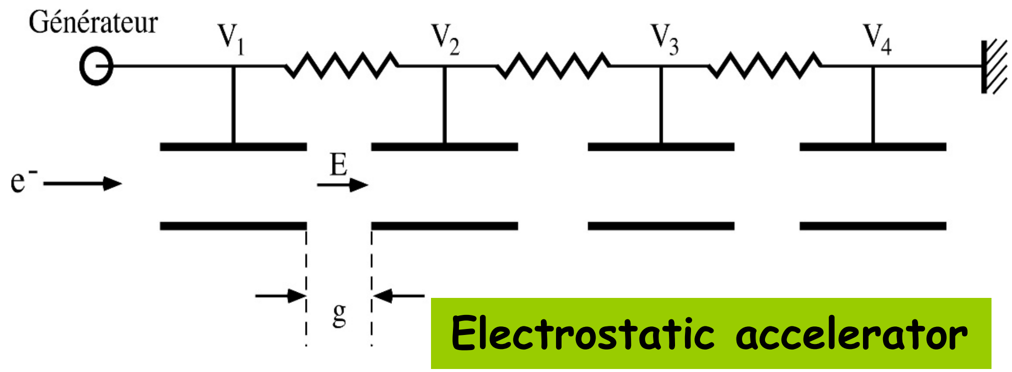
$= E_0 + W$ $E_0 = m_0c^2$ ⇒ electron E_0=0,511 MeV
protons E_0=938 MeV

Methods of Acceleration

1_ Electrostatic Field

Energy gain : $W=n.e(V_2-V_1)$

limitation : $V_{generator} = \Sigma V_i$

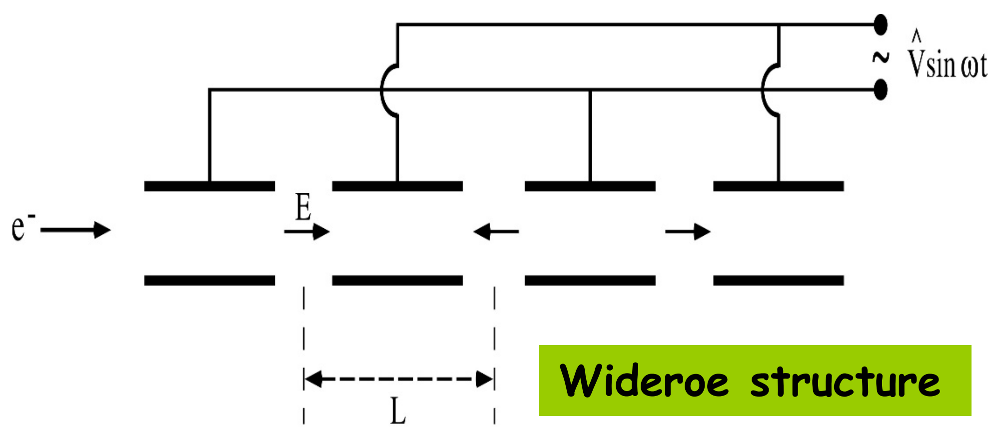


2_ Radio-frequency Field

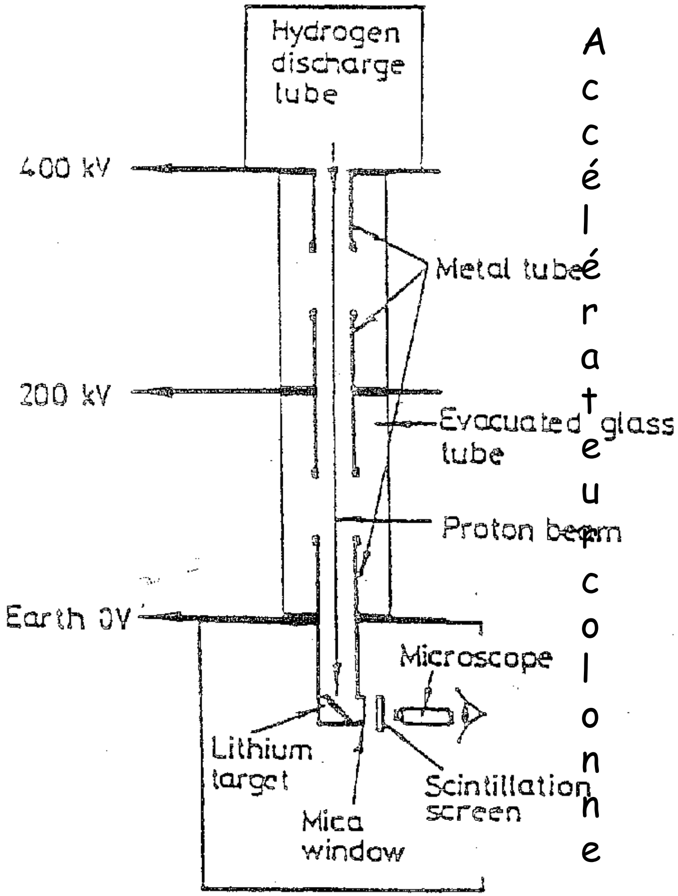
Synchronism : → $L=vT/2$

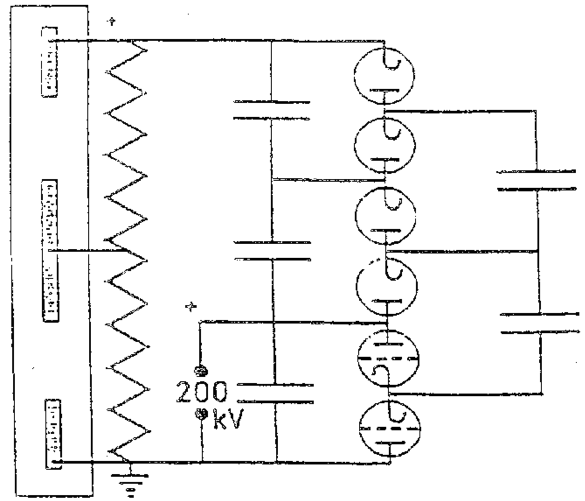
v=particle velocity **T= RF period**

also : $$L = v\frac{T}{2} = \beta\frac{\lambda_0}{2}$$



Electrostatic accelerator

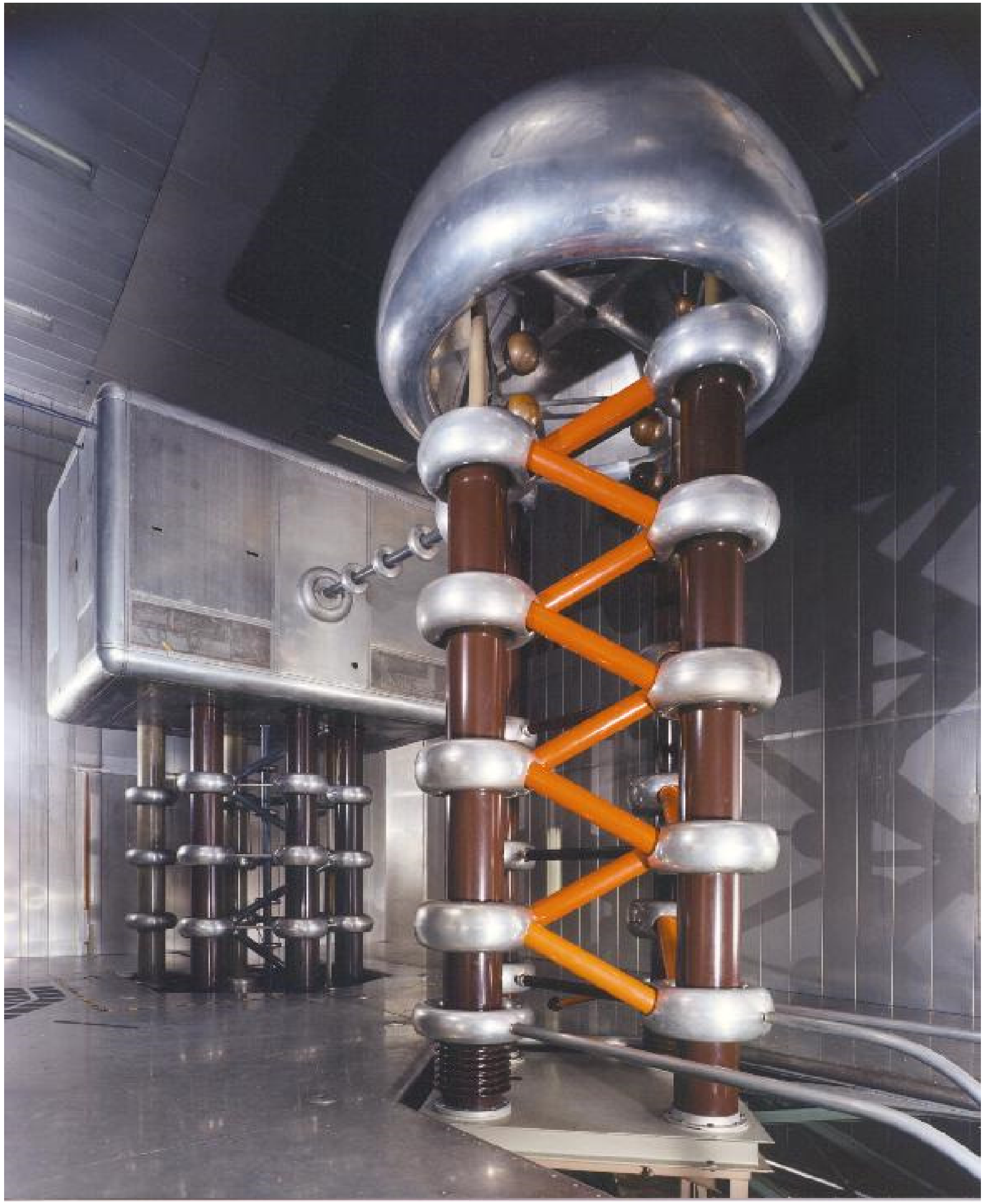




d.c. high voltage generator

Accelerating column

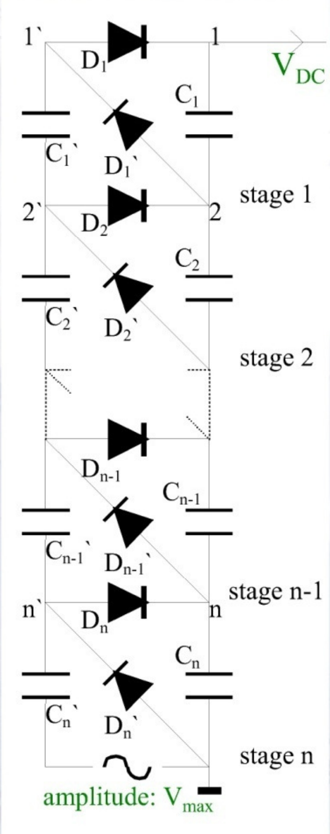
HV system used by Cockcroft & Walton to break the lithium nucleus

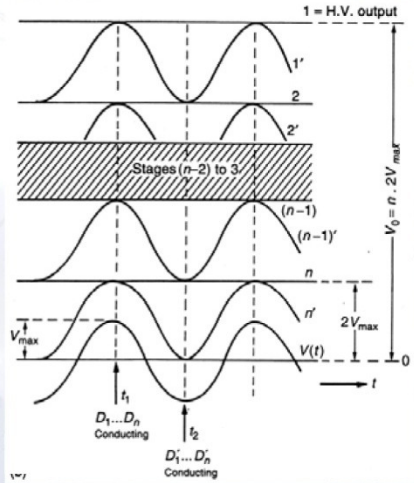


Because of its simplicity of design, the Cockcroft and Walton accelerator is in use today to provide sources of neutrons (^{2}H + $^{2}H \rightarrow n + {}^{3}He$ can be done successfully at a few hundred keV) and also as an injector of particles, especially protons, for high energy accelerators.

Cascaded Rectifier

(Greinacher; Cockcroft - Walton)



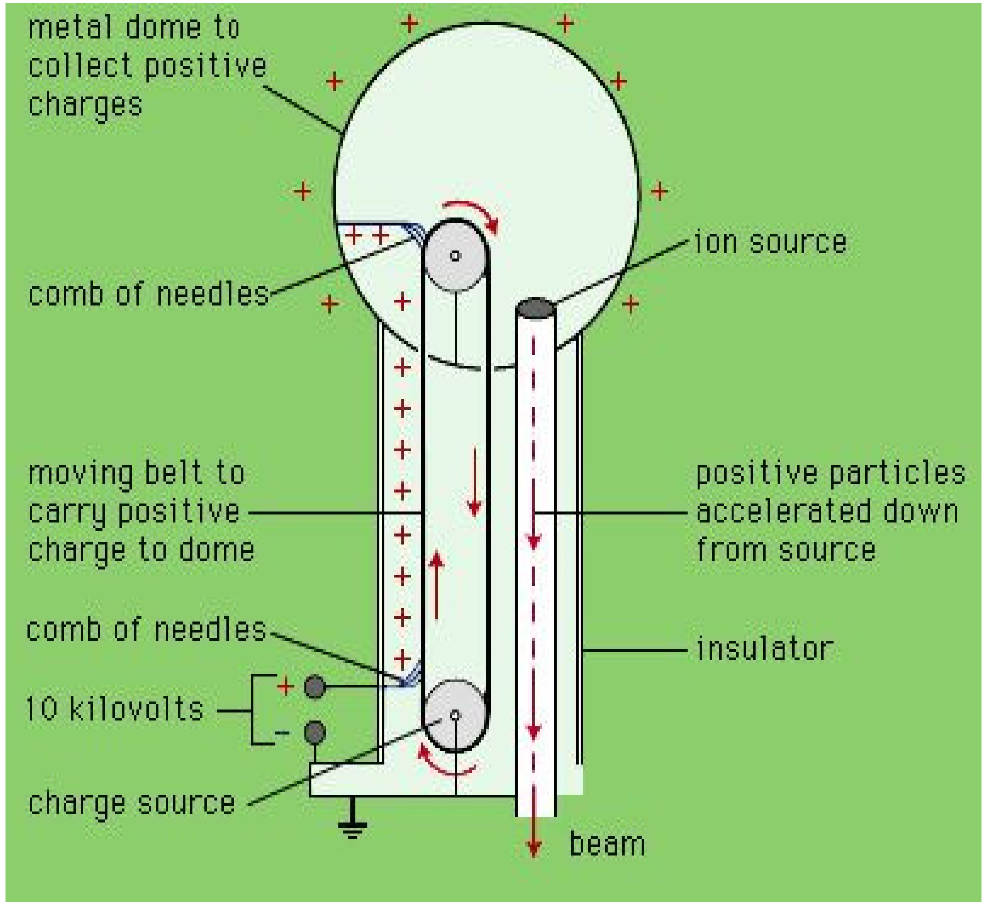


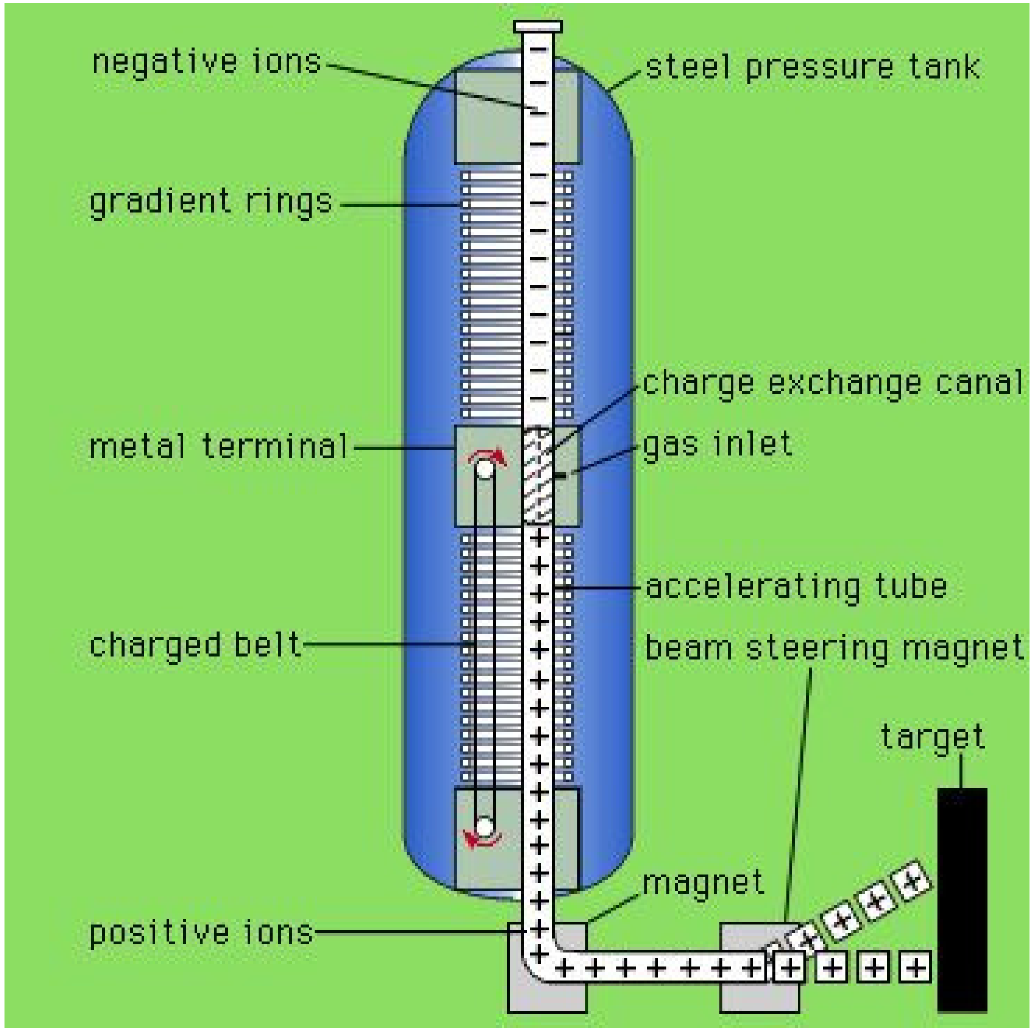
$$V_{DC} = 2nV_{\max}$$

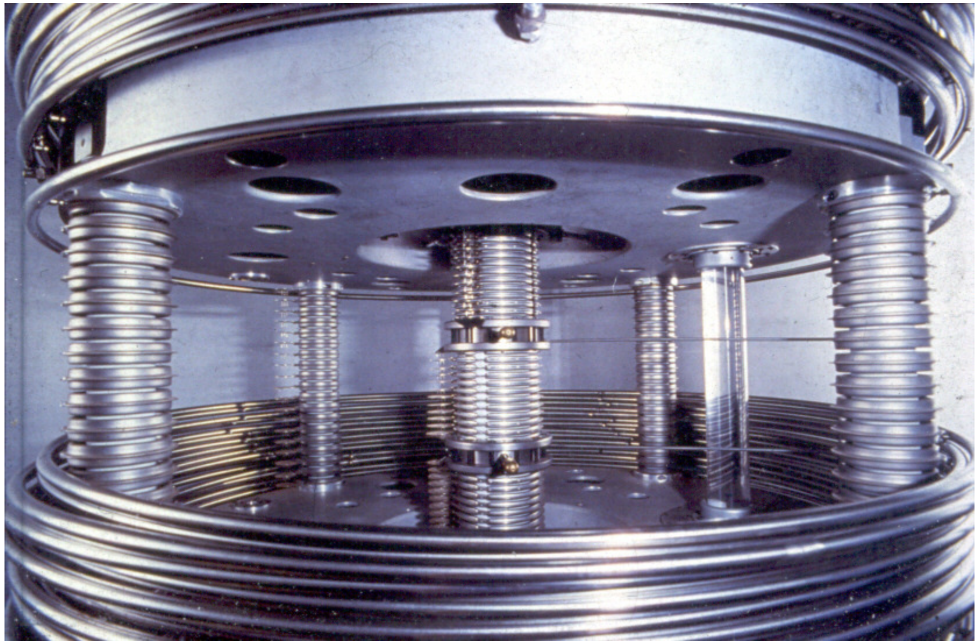
Voltage: 2 MV

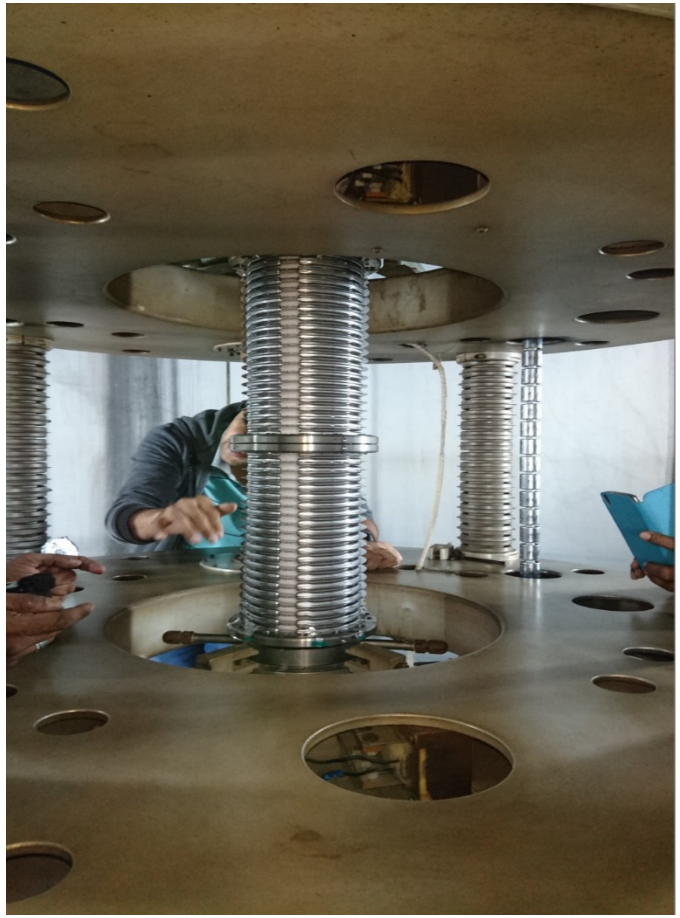
Reduce δV (~n²) and ΔV (~n³) by:

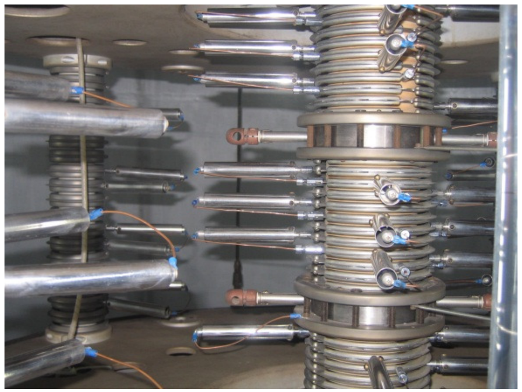
- larger C's (more energy in cascade)
- higher f (up to tens of kilohertz)

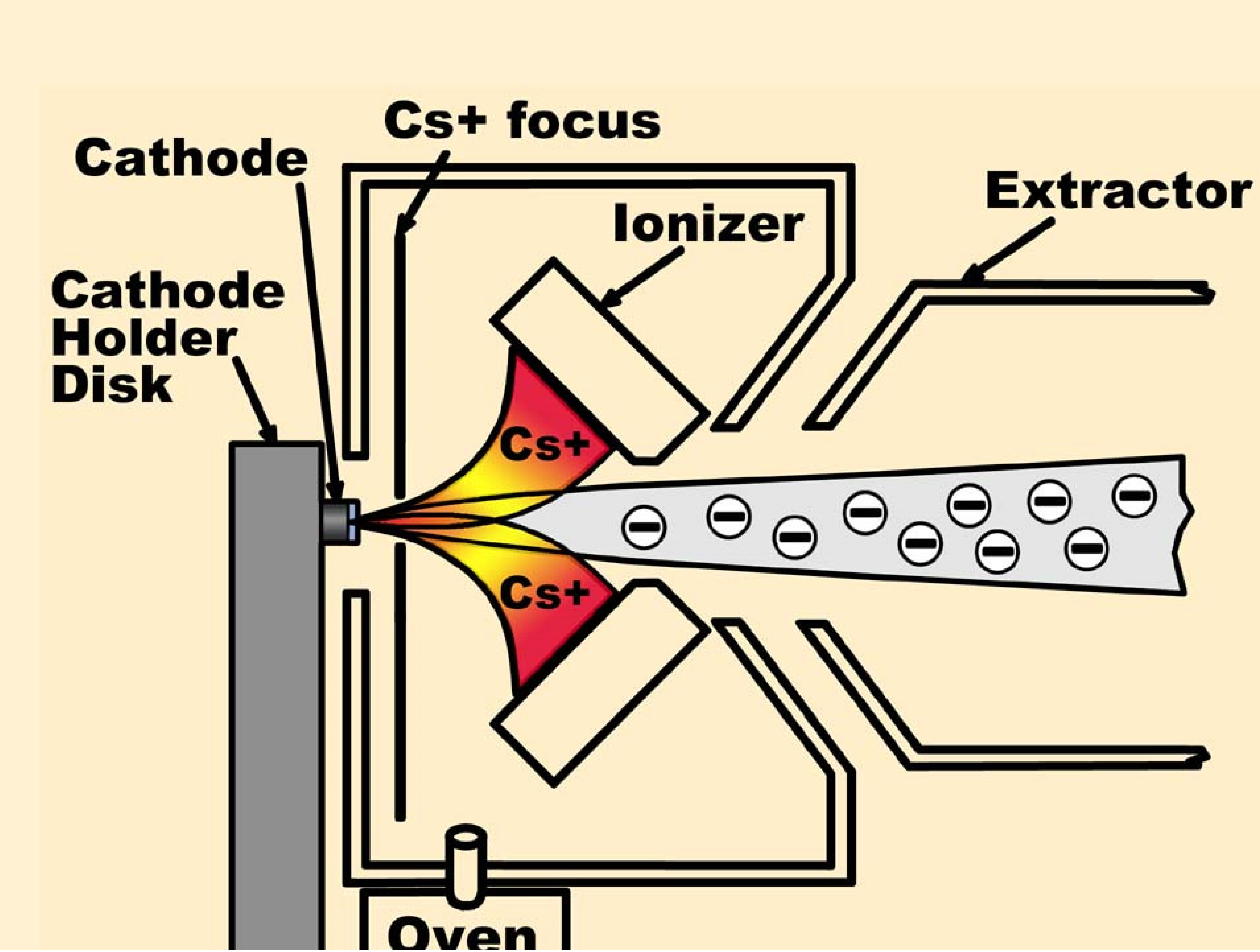

metal dome to
collect positive
charges
ion source
comb of needles
moving belt to
carry positive
charge to dome
positive particles
accelerated down
from source
comb of needles
insulator
10 kilovolts
charge source
beam


negative ions
steel pressure tank
gradient rings
charge exchange canal
metal terminal
gas inlet
accelerating tube
charged belt
beam steering magnet
target
magnet
positive ions

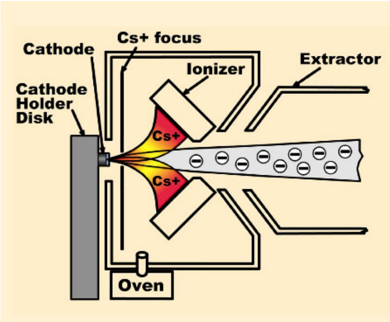








Cs+ focus
Cathode
Extractor
Ionizer
Cathode
Holder
Disk
Cs+
Cs+
Oven



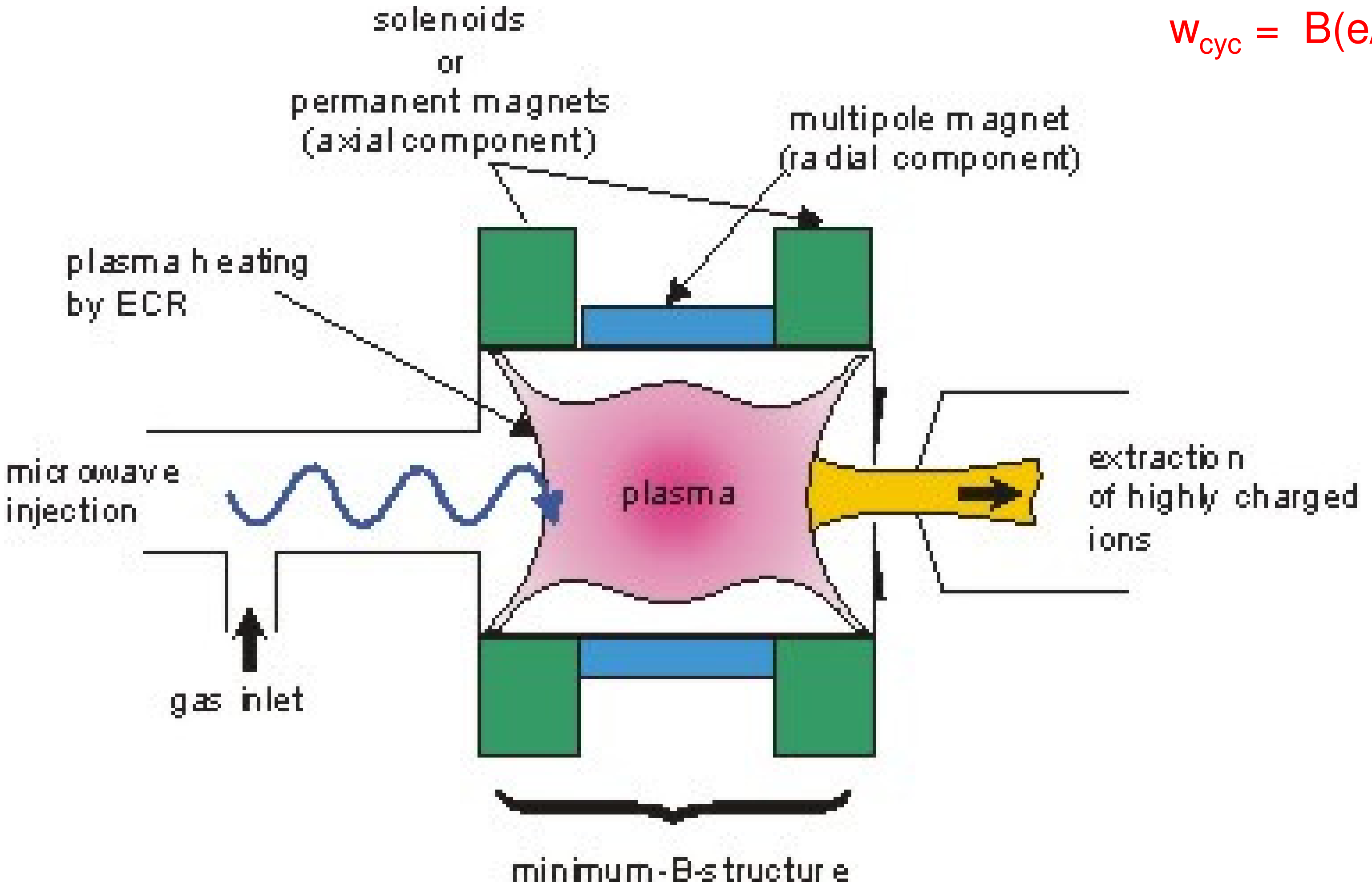
•Cesium vapour comes from the cesium oven into area between the cooled cathode and the heated ionizing surface.

•Some of the cesium condenses on the front of the cathode and some of the cesium is ionized by the hot surface.

•The ionized cesium accelerates towards the cathode, sputtering particles from the cathode through the condensed cesium layer.

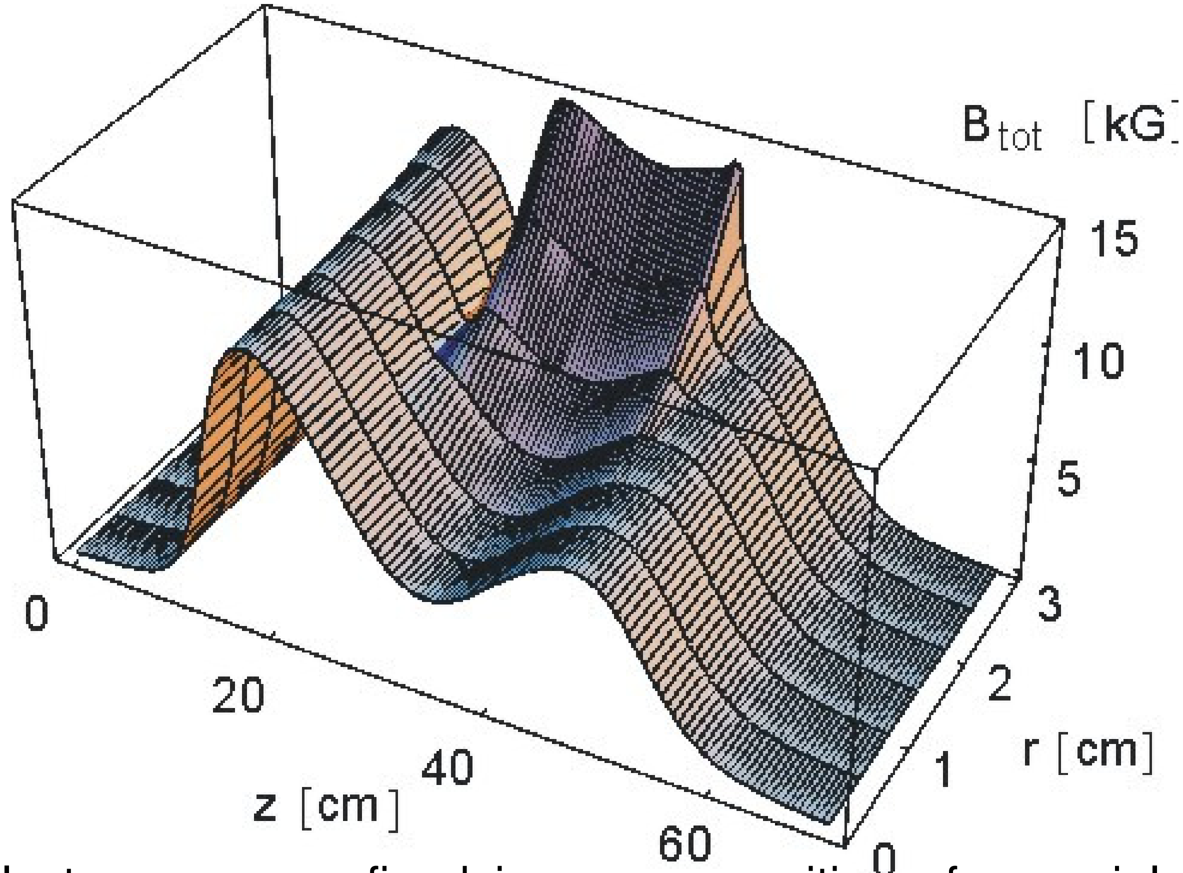
•Some materials will preferentially sputter negative ions. Other materials will preferentially sputter neutral or positive particles which pick up electrons as they pass through the condensed cesium layer, producing negative ions

$w_{cyc} = B(e/m)$



only electron beam ion sources (EBIS) and electron cyclotron resonance (ECR) ion sources are capable of producing highly charged ions of all natural elements with *Q* (charge state)/Z (atomic number) > 0.5.

$w_{cyc} = B(e/m)$



•The plasma electrons are confined in a superposition of an axial magnetic field component (produced by solenoids /permanent magnets) and the radial magnetic field of a multipole magnet. This results in a so-called *minimum-B-structure-* minimum in the middle of the structure and increases in all directions.

•A closed surface is created where the electron cyclotron resonance condition is fulfilled. Electrons passing through that surface can be accelerated resonantly.

•Furthermore, a high mirror ratio of the magnetic field leads to long confinement times for the plasma electrons.

• mulitple passes, gain high energies and yield high charge states via successive single ionization.

High Voltage measurement

Secondary electrons

Corona discharges

SF6 for high dielectric constant

Stable operation

Excellent beam emittance

Precise energy

Ease of energy variation

Nuclear Physics, Material science, Industry,

AMS

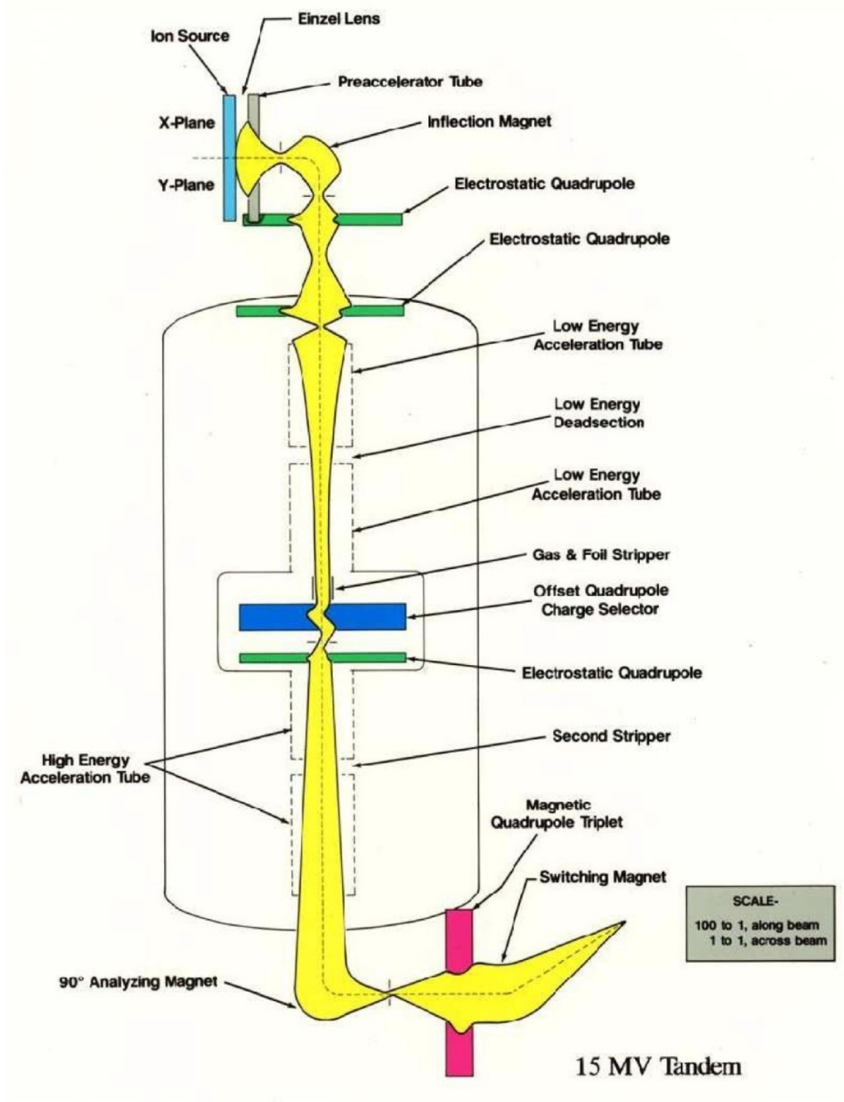


Fig. 8: Beam envelopes in a 15 MV Tandem accelerator from NEC (courtesy of G. A. Norton, NEC)

LINAC

Advantages

- Can handle high beam currents
- High duty cycle
- Low radiation losses

Draw backs

- space and cavity consuming
- The synchrotron radiation damping of e-/e+ used to reduce native beam emittance

Main Usage

- Low energy injectors (high duty cycle, dominated by space-charge force)
- High intensity/power beams
- ILC at very high energy (no radiation losses)

Methods of Acceleration

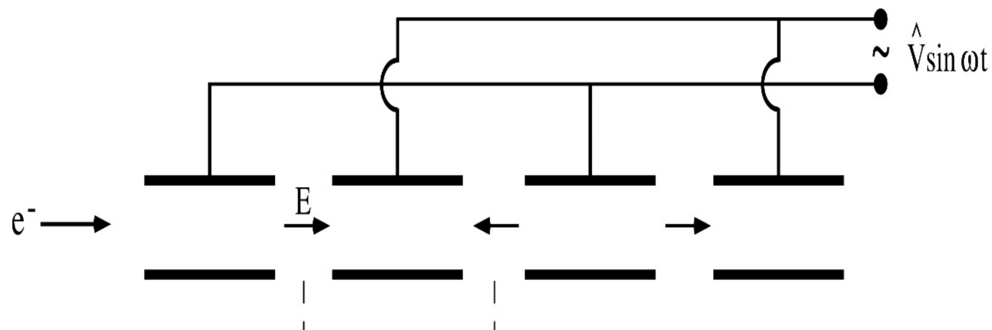
Radio-frequency Field

Synchronism : → $L = vT/2$

v=particle velocity **T= RF period**

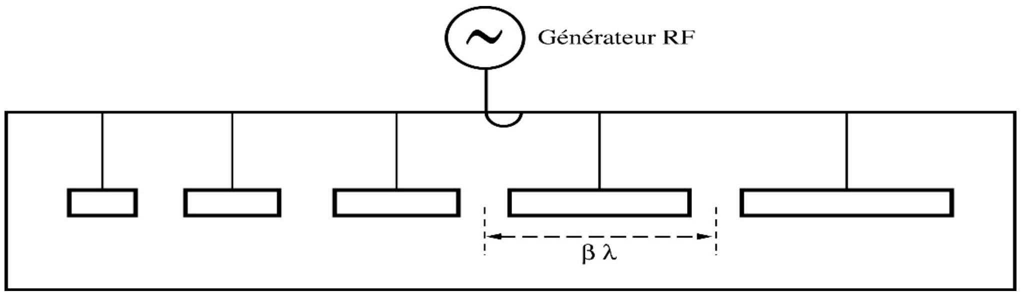
also :

$$L = v\frac{T}{2} = \beta\frac{\lambda_0}{2}$$



Wideroe structure

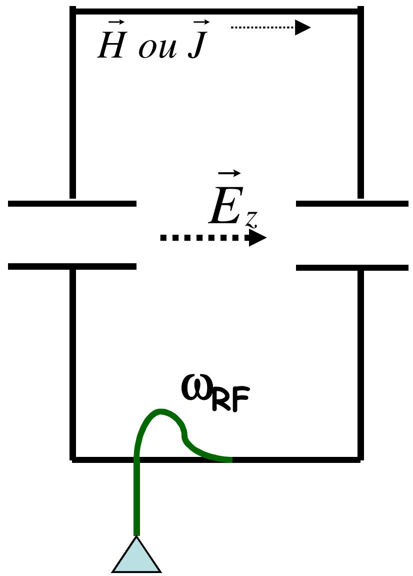
radiated power ∝ ωCV



ALVAREZ structure

In order to reduce the radiated power, the gap is enclosed in a resonant volume at the operating frequency.

The advantage of Resonant Cavities



-Each such cavity can be independently powered from the RF generator.

- The electromagnetic power is now constrained in the resonant volume.

- Note however that joule losses will occur in the cavity walls (unless made of superconducting materials)

- Considering RF acceleration, it is obvious that when particles get high velocities the drift spaces get longer and one loses on the efficiency. The solution consists of using a higher operating frequency.

- The power lost by radiation, due to circulating currents on the electrodes, is proportional to the RF frequency. The solution consists of enclosing the system in a cavity which resonant frequency matches the RF generator frequency.

- The RF resonator with suitably designed drift tubes constitutes the basic accelerating structure in LINACs
- Particles in synchronisation with the phase of the RF voltage.
- A finite electrical resistance of the internal surfaces of the cavity results in loss of RF power and the quality factor Q of the cavity is a measure of this loss.
- The power dissipation can be reduced drastically by using superconducting surfaces, whereby Q values in the range 10^8-10^9 can be obtained.
- Accelerating fields for heavy ions ~3 MV/m can be easily achieved for RF power dissipation of ~5–10 watts.

Why superconducting?

$Q = f/\Delta f = \omega U/P$; Quality factor

QWR: f=150MHz, $\omega \sim 10^9$

E~3 MV/m

U (stored energy) ~0.5 Joules

Q(Cu, 300K)~10^4; P~50 kWatts

Q(Pb, 4.2K) ~10^8; P~5 Watts

ε(4.2K:300K)~1:750

Superconducting LINAC smaller & efficient

Use of superconducting technology leads to

considerable saving of electrical power

a compact accelerator design

simplifies the RF control electronics since the power levels are low.

Remember: even in the superconducting state, the AC surface resistance R_S is not zero but has a finite though small value; R_S is a function of f, T_C and temperature

At higher power levels, the surface magnetic and electric fields in the resonator become very large and the power dissipation is dominated by losses at high magnetic fields due to flux penetration and at high electric fields due to field emission.

In addition, thermal breakdown of superconductivity can occur due to the presence of small defect regions on the superconducting surface. ***careful design and fabrication of resonators is essential to maintain high Q values at very high accelerating field values.***

Purity of the material RRR

Transit Time factor T(β) < 1 → velocity acceptance of linac

Average electric field $E = \frac{V}{l}$

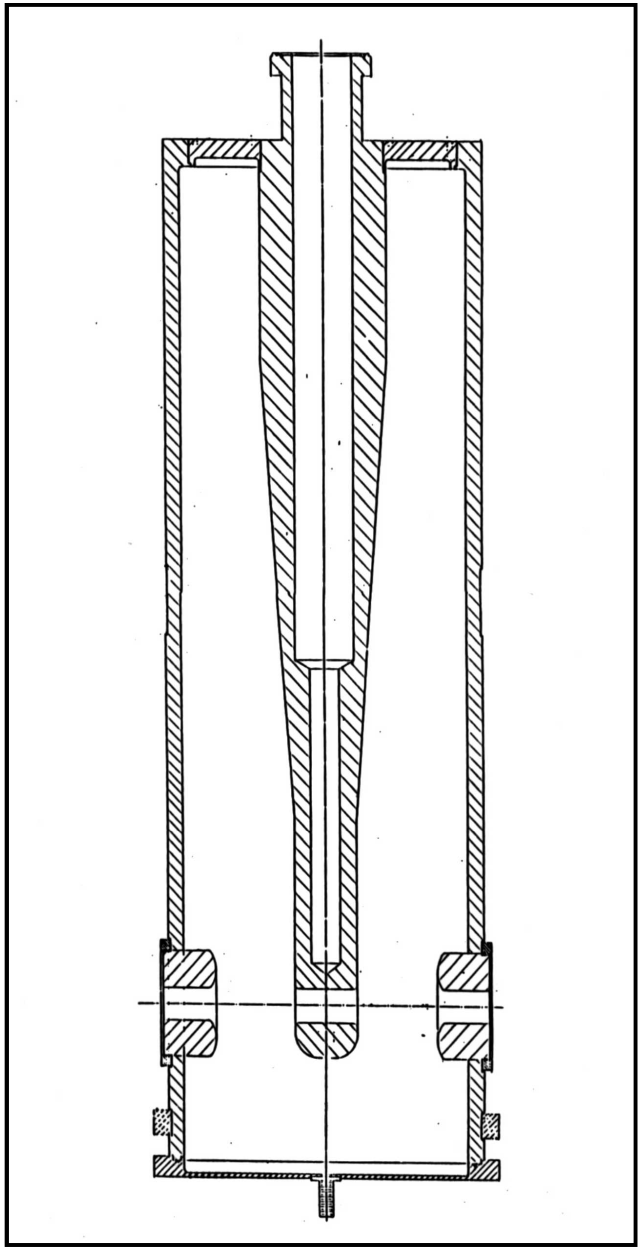
Effective shunt Impedance of the cavity – geometry dependence

$$ZT^2 = \frac{(\Delta U'_{max})^2}{2P'_d}$$

$\Delta U'_{max}$: *max energy gain per unit length*

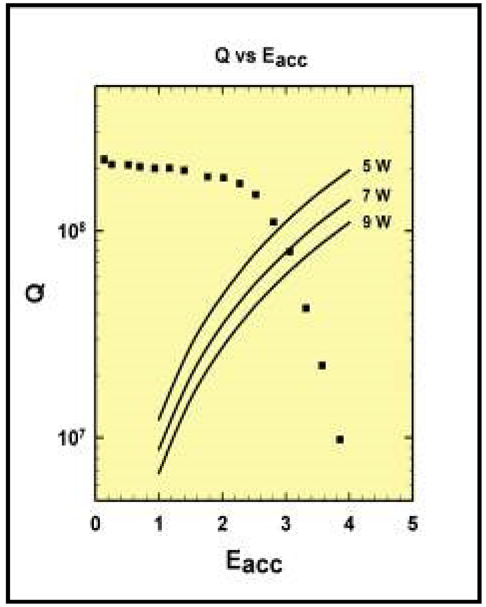
P'_d : *power lost per unit time*

higher aperture, smaller shunt impedence



Quarter Wave Resonators

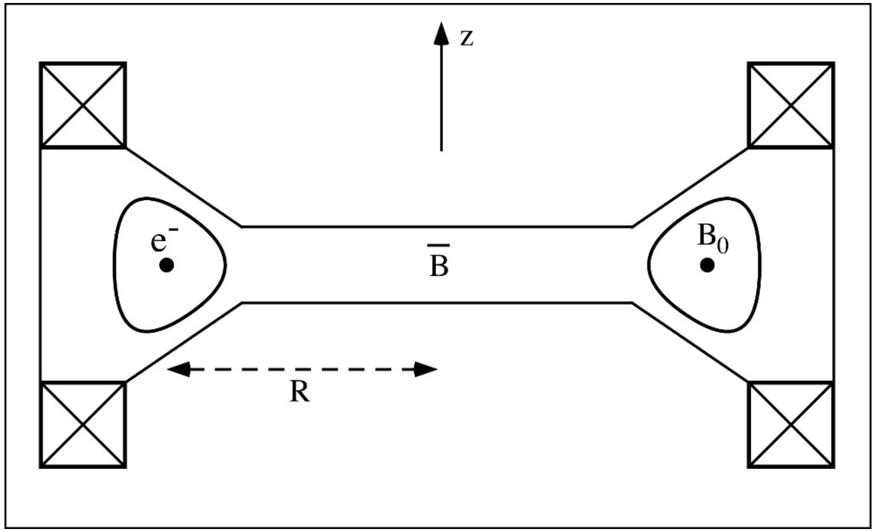
Material	OFHC Cu
Superconducting surface	2 µm thick. Pb
Frequency	150 MHz
Cavity Length	64 cm
Cavity Diameter	20 cm
Optimum velocity	β=0.1
Design goal	2.5 to 3 MV/m
	@ 6 to 9 Watts



$$\vec{E} = -\vec{\nabla}\phi - \frac{\partial \vec{A}}{\partial t}$$

$$\vec{B} = \mu \vec{H} = \vec{\nabla} \times \vec{A}$$

Betatron



Induction law

$$2\pi R E_\theta = -\frac{d\Phi}{dt} = -\pi R^2 \frac{d\overline{B_z}}{dt}$$

Newton-Lorentz force

$$\frac{dp}{dt} = eE_\vartheta = -\frac{1}{2} e R \frac{d\overline{B_z}}{dt}$$

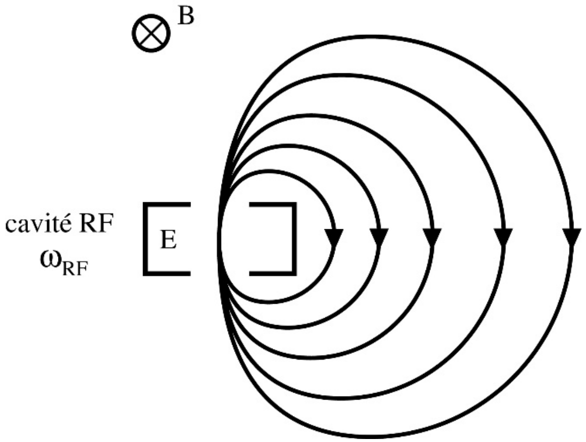
A constant trajectory also requires :

$$p = -e R B_0$$

$$\frac{dp}{dt} = -e R \frac{dB_0}{dt} \quad \Rightarrow \quad B_o = \frac{1}{2}\overline{B_z}$$

The betatron uses a variable magnetic field with time. The pole shaping gives a magnetic field Bo at the location of the trajectory, smaller than the average magnetic field.

Microtron



If the first turn is synchronous :

$$\frac{\Delta T_r}{T_{RF}} = integer \Rightarrow \Delta\gamma_{turn} = integer\,(\gamma_0 = 1)$$

Energy gain per turn
- electrons → 0.511 MeV
- protons → 0.938 GeV !!!

Since required energy gains are large the concept is essentially valid for electrons.

Synchrotrons

Synchrotrons are the present standard accelerators for particle physics research.

Both the magnitude of the magnetic field and *rf* frequency are varied to maintain a synchronous particle at a constant orbit radius.

The constant-radius feature is very important; bending and focusing fields need extend over only a small volume.

This minimizes the cost of the magnets, allowing construction of large-diameter machines.

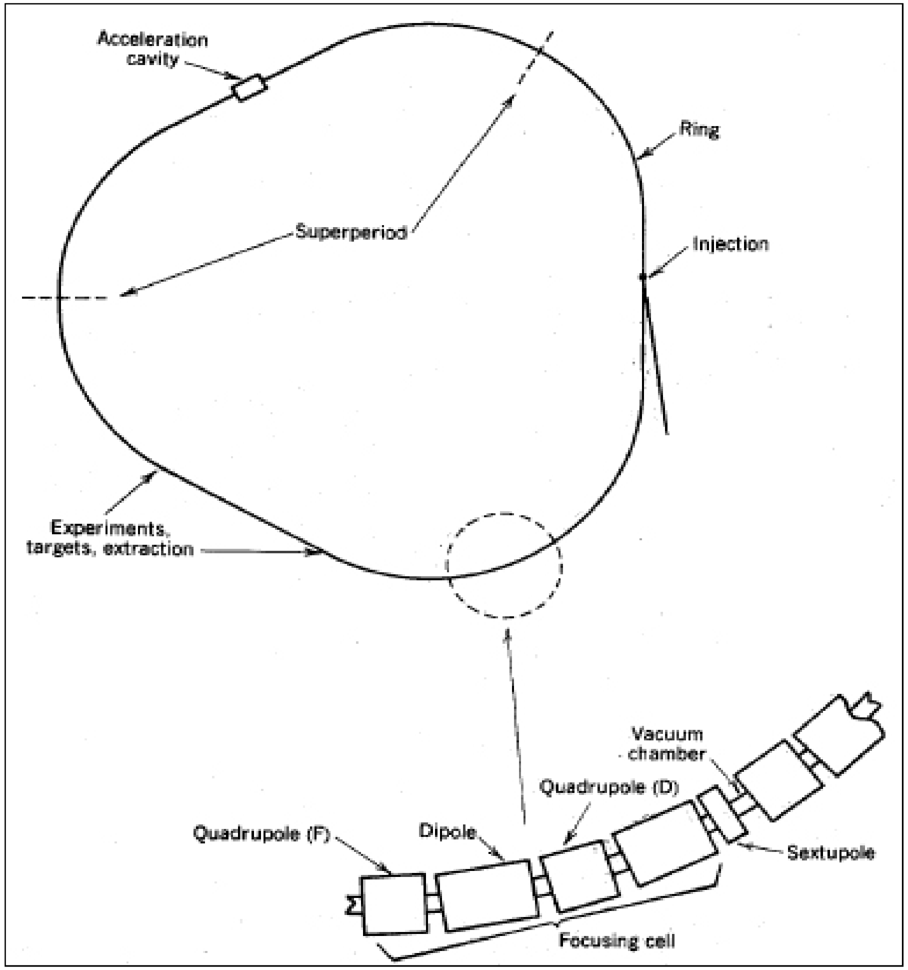


Table 3.1. Parameter disposition for different acceleration principles

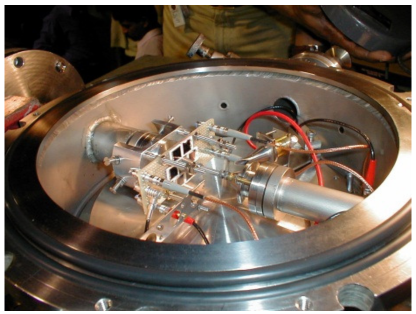
principle	energy γ	velocity v	orbit r	field B	frequency f_{rf}	flux
Cyclotron:	1	var.	$\sim v$	const.	const.	cont.[a]
Synchro cyclotron:	var.	var.	$\sim p$	$B(r)$	$\sim \frac{B(r)}{\gamma(t)}$	pulsed
Isochron cyclotron:	var.	var.	$r = f(p)$	$B(r, \varphi)$	const.	cont.[a]
Proton/Ion-synchrotron:	var.	var.	R	$\sim p(t)$	$\sim v(t)$	pulsed
Electron-synchrotron:	var.	const.	R	$\sim p(t)$	const.	pulsed

[a] continuous beam, but rf modulated

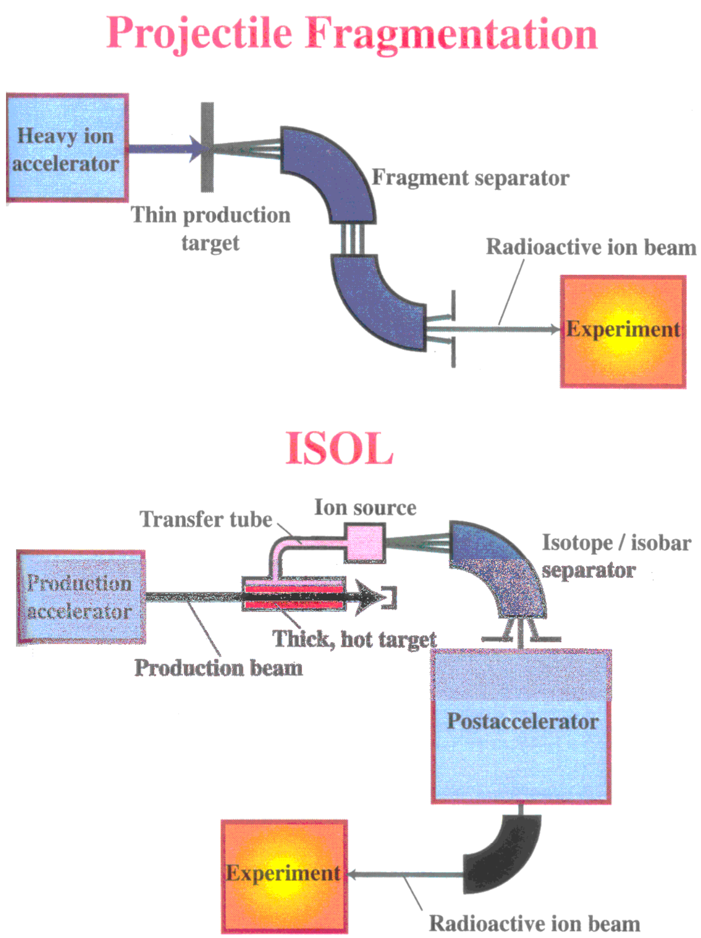
Stable vs. Unstable ?

Stable beams – controlled experiments

- unique beam selection (specific N,Z)
- well defined energy
- well collimated beam (small spatial and angular spread)
  defines interaction point on target, angles of scattered particles etc.
- large intensities (>10^{10} pps)
  Easier tracking and measurement of beam particles
- no decay products from the beam itself
  Cleaner environments for experiment,
  lesser background issues



Why experiments with RIB pose more challenges?



Study of very short lived nuclei

RIKEN (JAPAN), MSU, GSI

reaction products

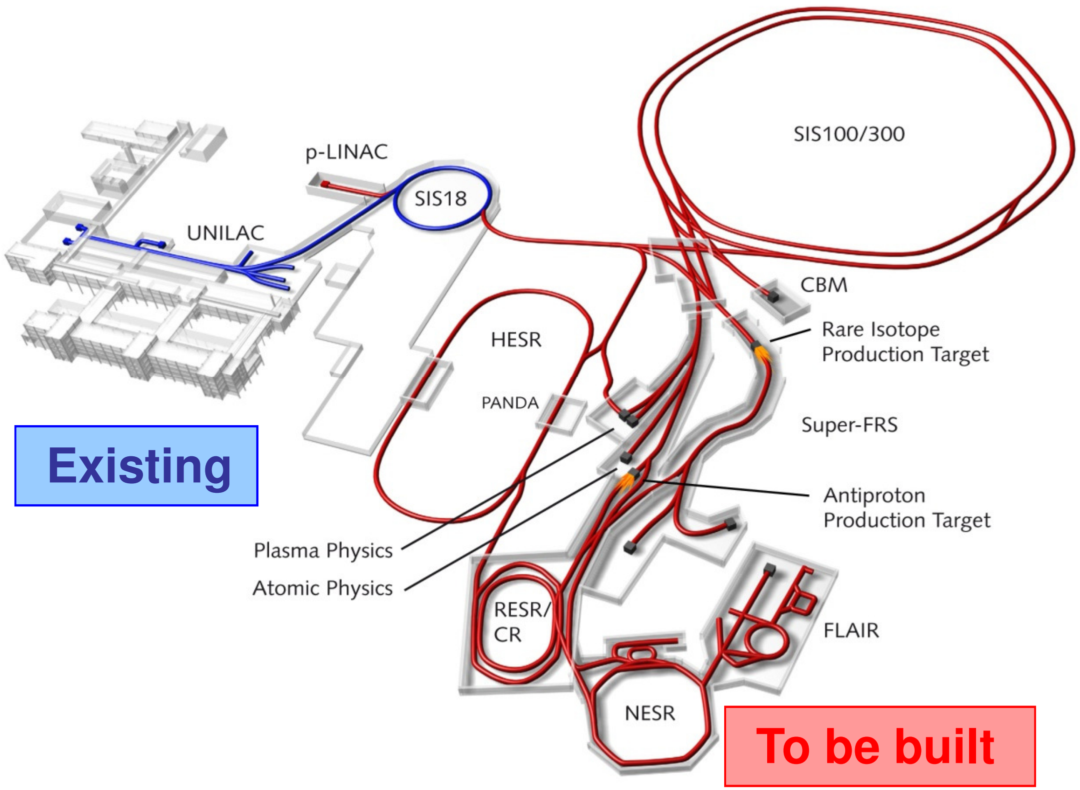
- angular spread, energy (momentum spread)
- isotopic/isobaric mixture
- background
  - scattered primary beam, in flight decays

Specific beams−controlled experiments

Univ. of Louvain, GANIL, ORNL, TRIUMF

- good energy definition
- large spot size
- background
  - in flight decays

FAIR – The Facility



Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- $2(4)\times10^{13}$/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

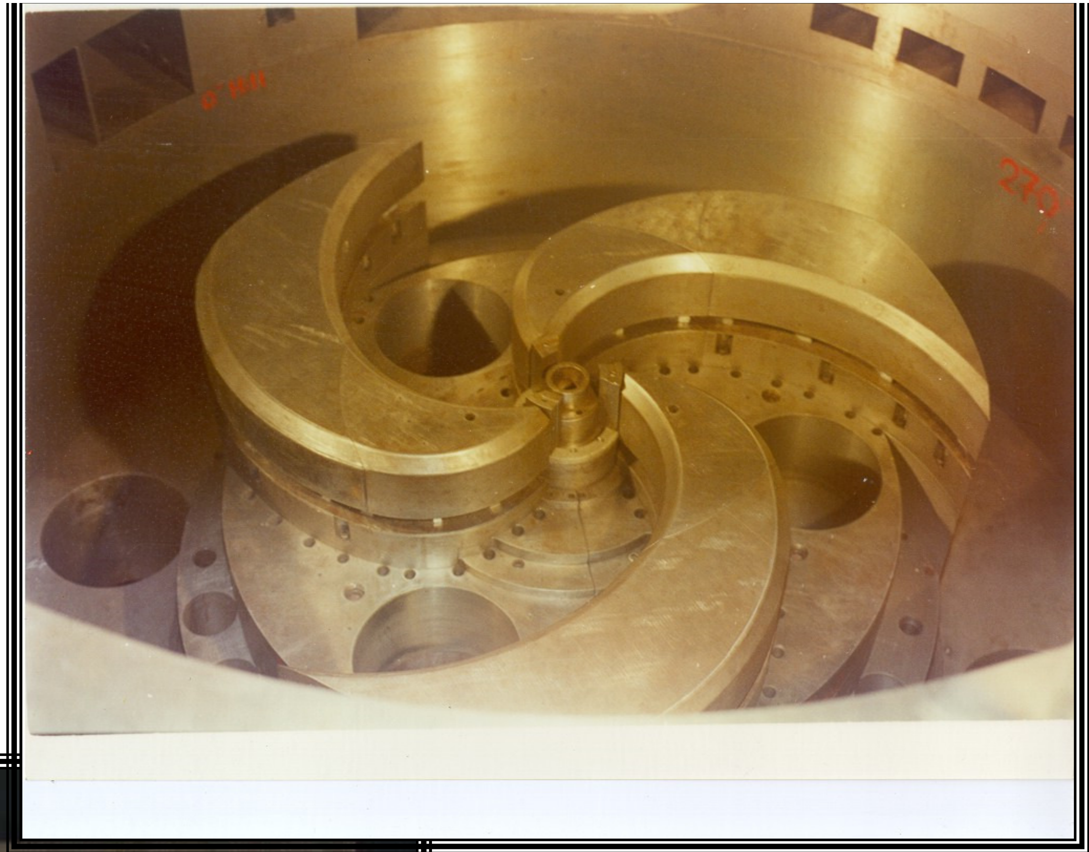
- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

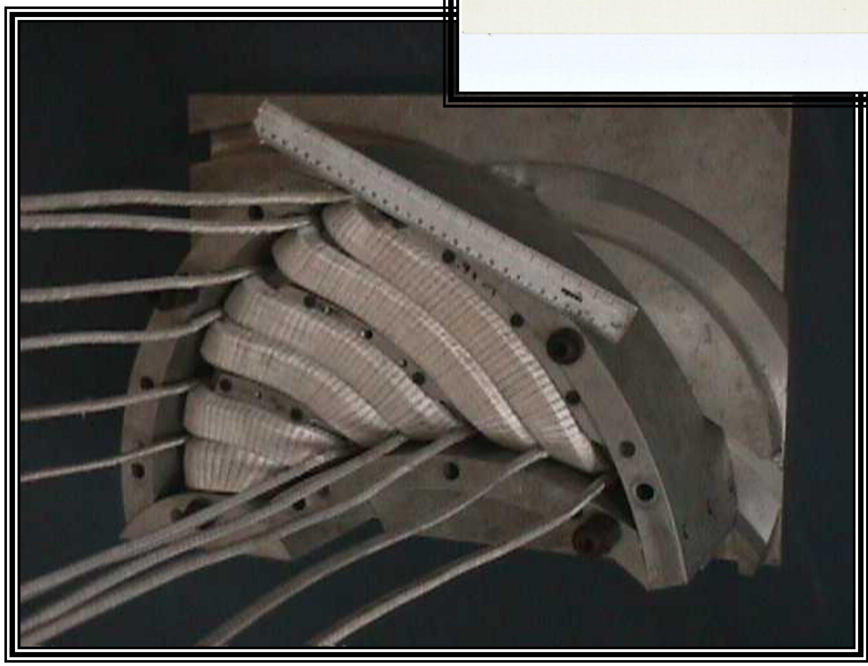
Storage and Cooler Rings

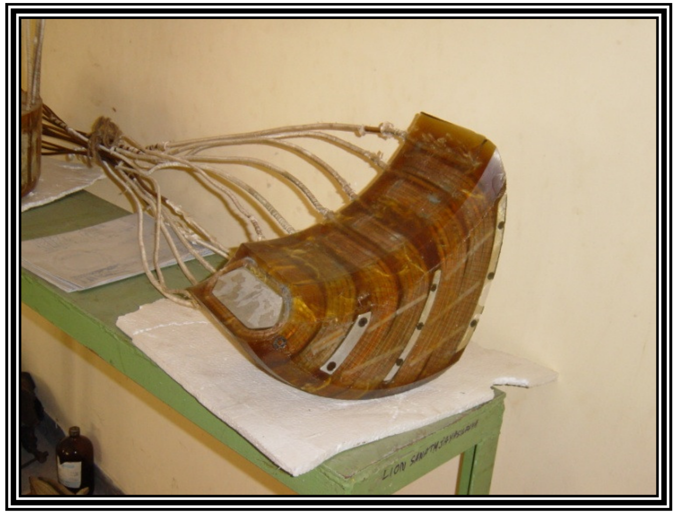
- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets


270





Buncher.

RF cavity TM010.

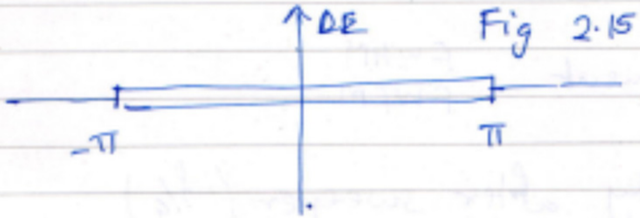
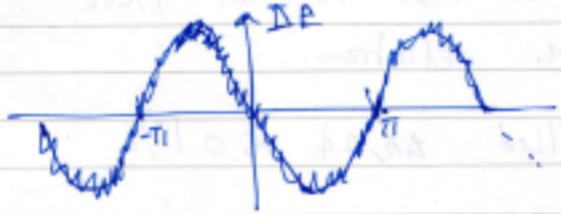


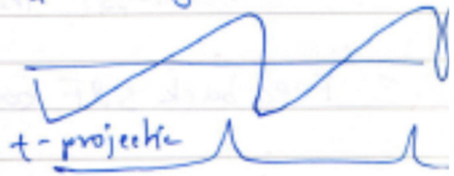
Fig 2.15

$\Delta E \sim 0.$
$\Delta T \{-\pi, \pi\}$

some are accelerated /decelerated.



after length L



prebuncher $V = V_0 \sin\phi$

$\Delta E = eV_0 \sin\phi.$
$= mc^2 \beta \gamma^3 \Delta\beta$

$\Delta v \Delta t = \frac{\phi}{2\pi} \lambda_{rf}.$

$\Delta t = \frac{\lambda_{rf}}{2\pi} \cdot \frac{mv}{eV_0}.$

$L = v\Delta t = \frac{2E_{kin}}{k_{rf} e V_0}.$

$k_{rf} = 2\pi/\lambda_{rf}$

$\delta L = \frac{\delta E_{kin}}{k_{rf} e V_0}.$
bunch length

Double Harmonic buncher $f/16$, $f/8$

$\epsilon \approx 66\%$.

- sweeper $f/32$ $\tau \simeq 106.7$ ns.
- chopper ($>1\mu s$)

- Time measurement FWHM FWTM.

phase pickup cavity after sweeper ($f/4$)

↓

- feedback to correct ~~for~~ transit time variations. through pelletron.

- Feed back SRF controlled $\Delta A, \Delta\phi \lesssim 0.1\%$

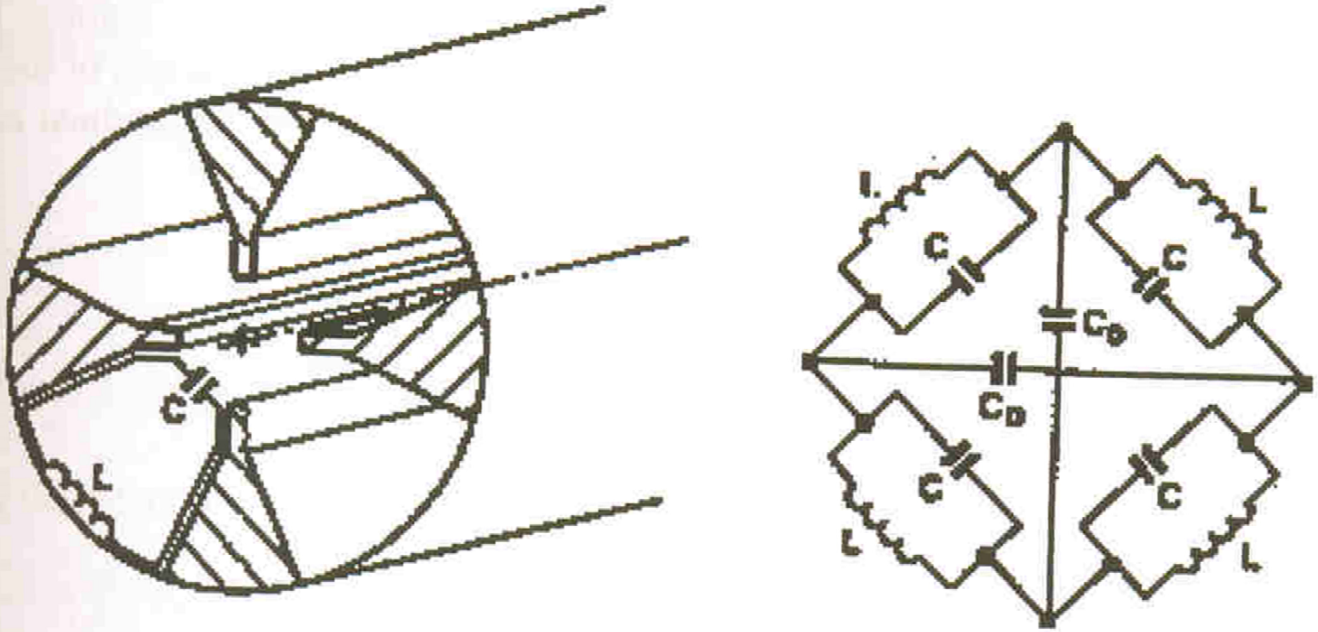


Fig. 4: Electrical

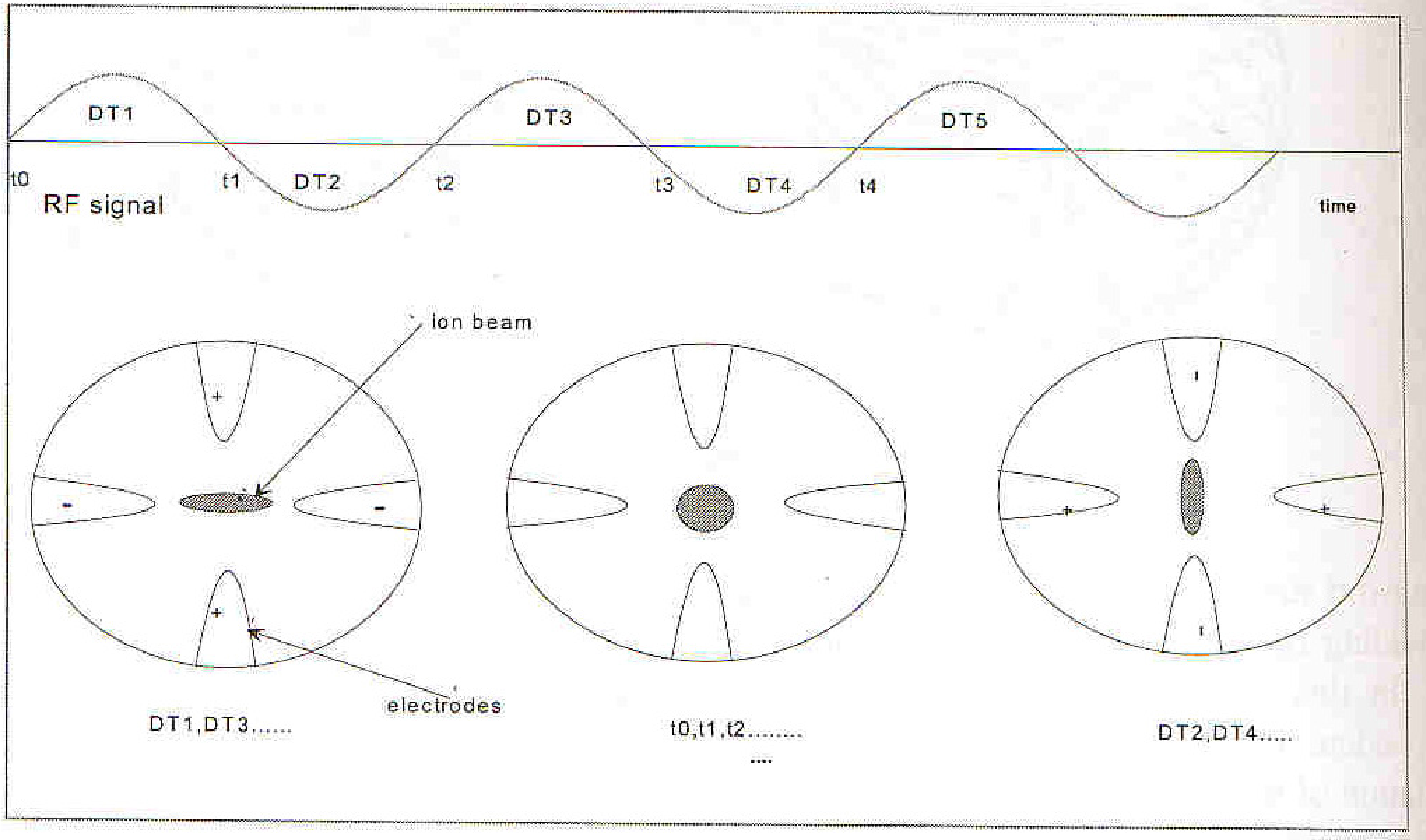
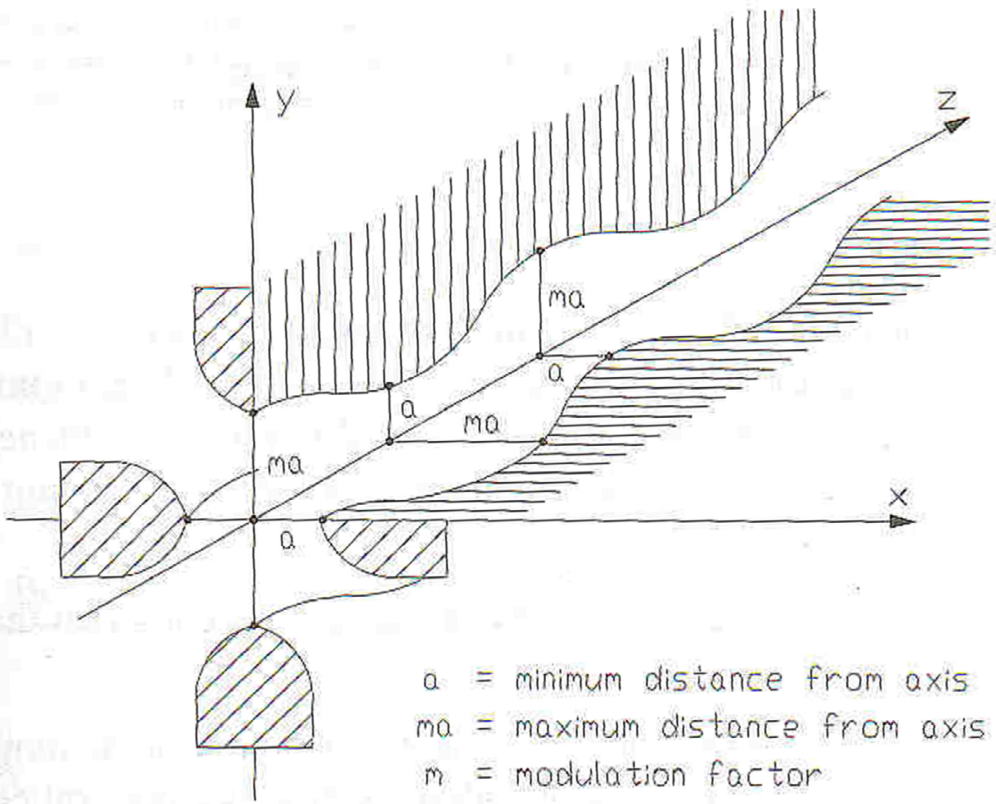
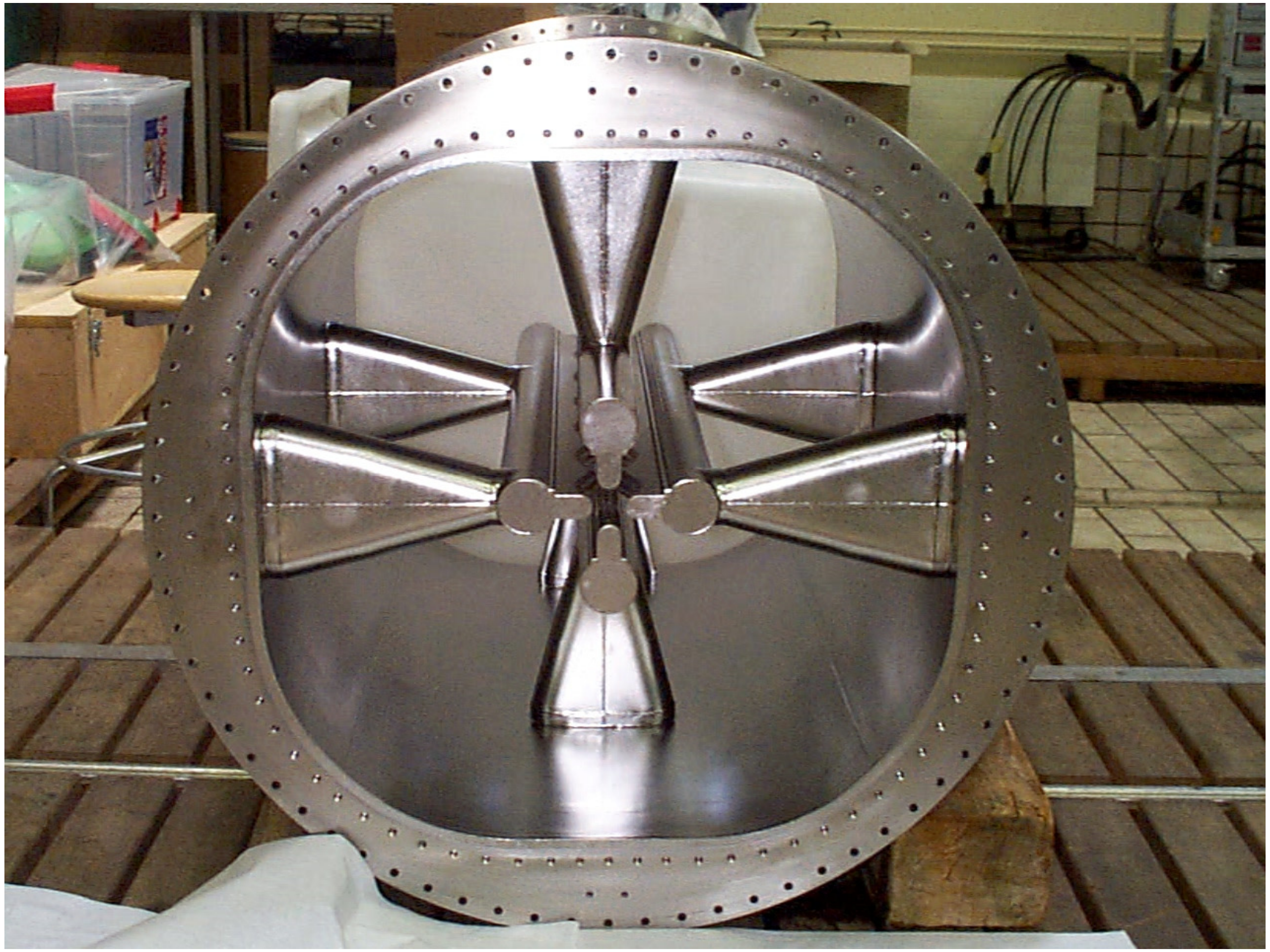


Fig. 6: Time-varying transverse focusing field in a RFQ

TE210
mode


y
z
x
ma
a
ma
a
ma
a
a = minimum distance from axis
ma = maximum distance from axis
m = modulation factor



6D phase space : motion of particles

$$\bar{x} = (x, p_x, y, p_y, z, p_z)$$

$$x_p = \tan^{-1} \beta\gamma \frac{p_z}{p_x} \simeq \beta\gamma \frac{p_x}{p_z}$$ paraxial approximati..

$$x' = \frac{v_x}{v_z} \qquad y' = \frac{v_y}{v_z}$$

Longitudinal phase space $z, p_z \equiv z, \frac{\Delta p}{p} \equiv E, t$

Transverse phase space (x, x', y, y').

Phase space matching important.

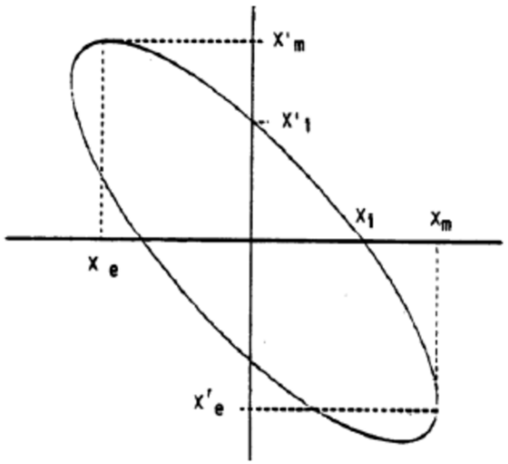
Electrostatic lenses
Magnetic lenses (QD, solenoids)
Steerers

Courant Snyder definition

Under the influence of linear forces, trajectory of particles in phase space (x,x′) follows an elliptical path

$$\gamma \cdot x^2 + 2 \cdot \alpha \cdot x \cdot x_p + \beta \cdot x_p{}^2 = \frac{E}{\pi} = \varepsilon$$

$$\beta\gamma - \alpha^2 = 1$$



ε : Beam Emittance

α, β, γ : Twiss parameters

α > 0 converging beam
α < 0 diverging beam

Louiville's theorem : under the influence of conservative forces, density of phase space stays constant

phase space current must satisfy the continuity equation

Evolution of boundary of ellipse (beam envelope), without having to calculate individual particles

Geometrical beam emittance

rms definition $E_{rms} = \pi \sqrt{\langle x^2 \rangle \cdot \langle x_p^2 \rangle - \langle x \cdot x_p \rangle^2}$ metres

brilliance (~63%)

Admittance : maximum single particle emittance that can be transmitted

Growth of emittance (mm-mrad)

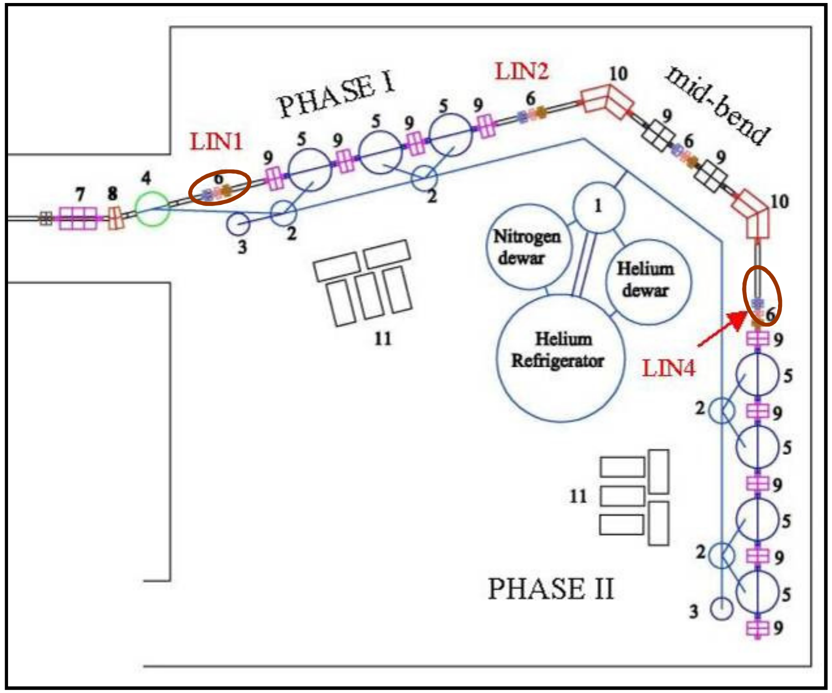
- Steering effects
- Momentum spread
- Focussing errors
- Non-linear effects
- Space-charge effects
- Scattering form foil, gas
- Bends and tune fluctuations
- Power supply ripples
- Intra beam scattering

BEAM : size and divergence

Beam waist : point of minimum beam size

Evolution of longitudinal phase space

Final configuration corresponding to an optimal phase space at target determined by measurement of the transmission and the time structure.



Timing Detector (1" BaF_2)

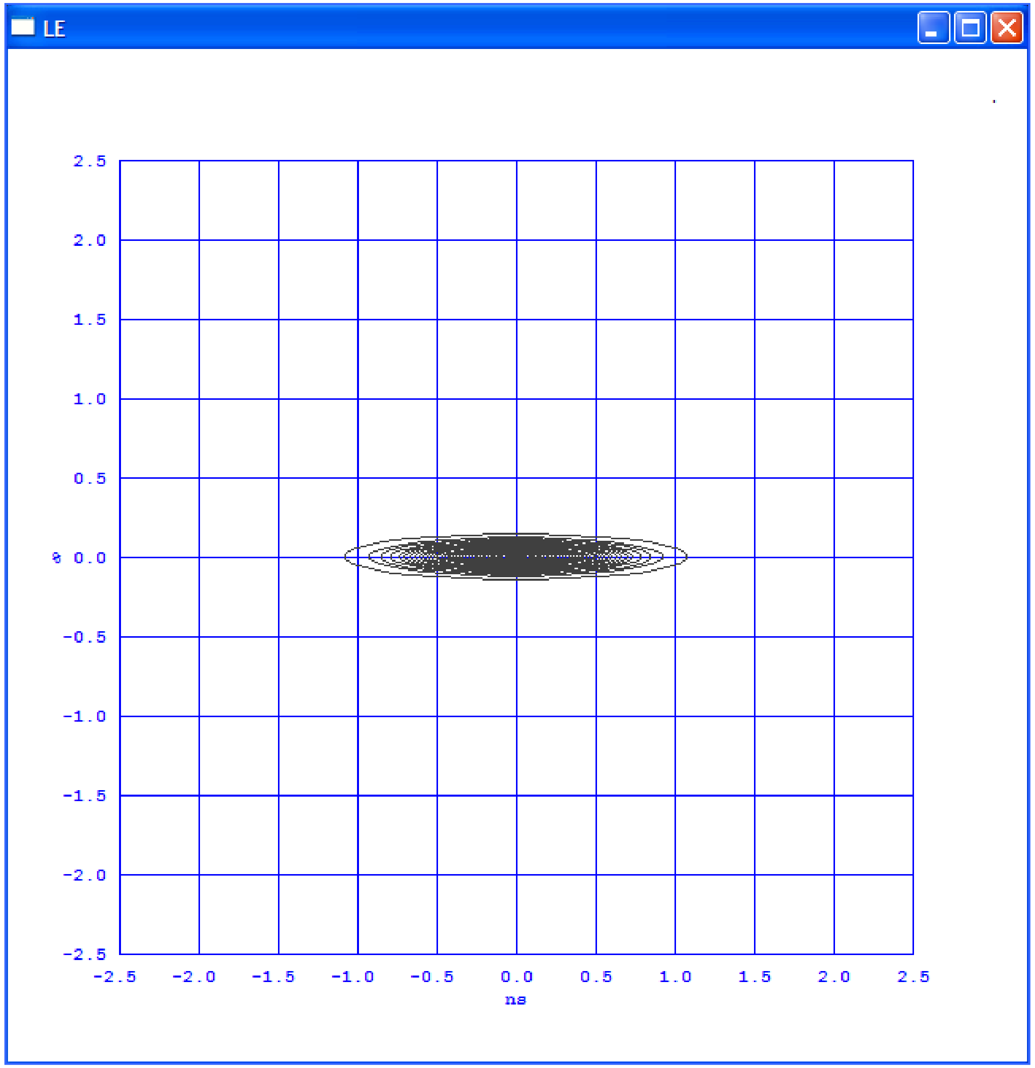
@LIN1 : entrance of Phase I

@LIN4 : entrance of Phase II

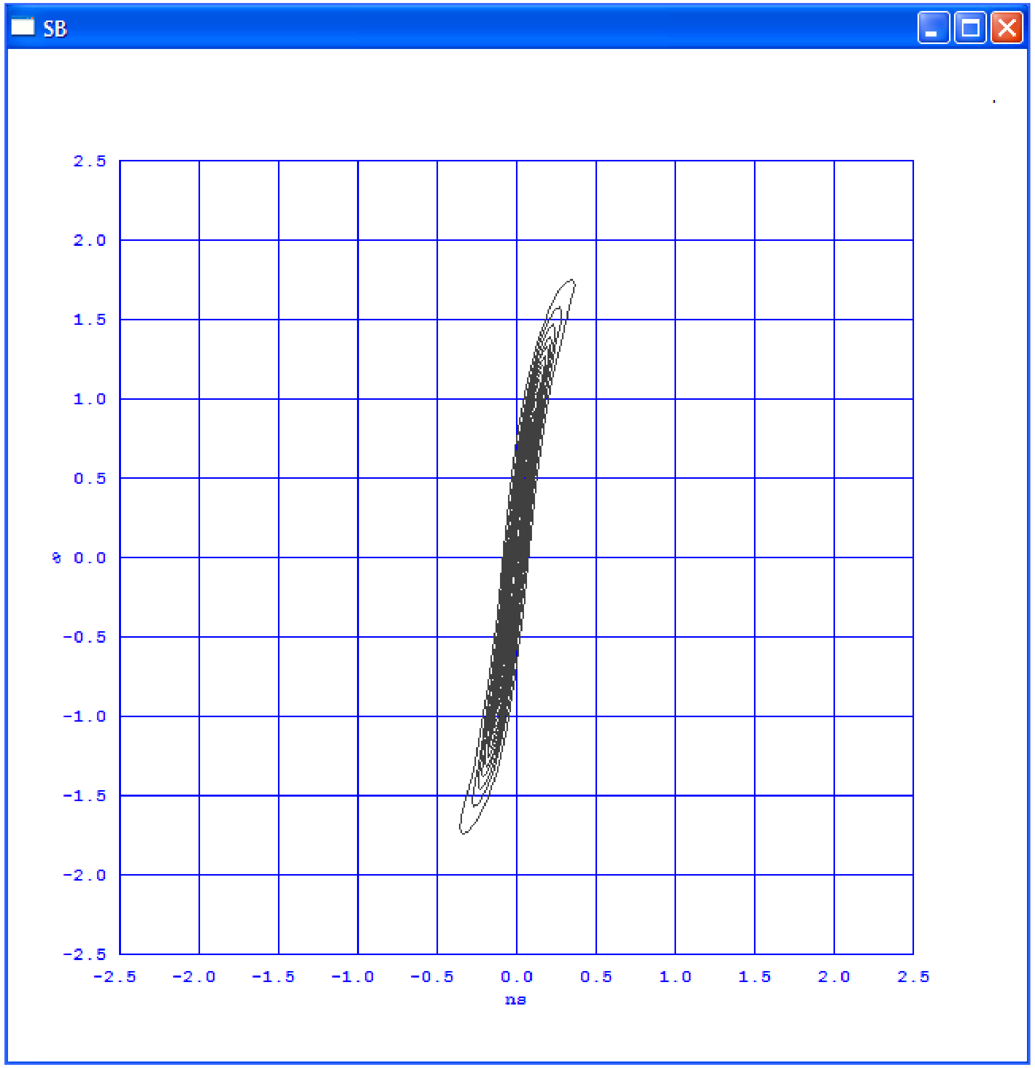
@LIN7 : after switching magnet

@target position

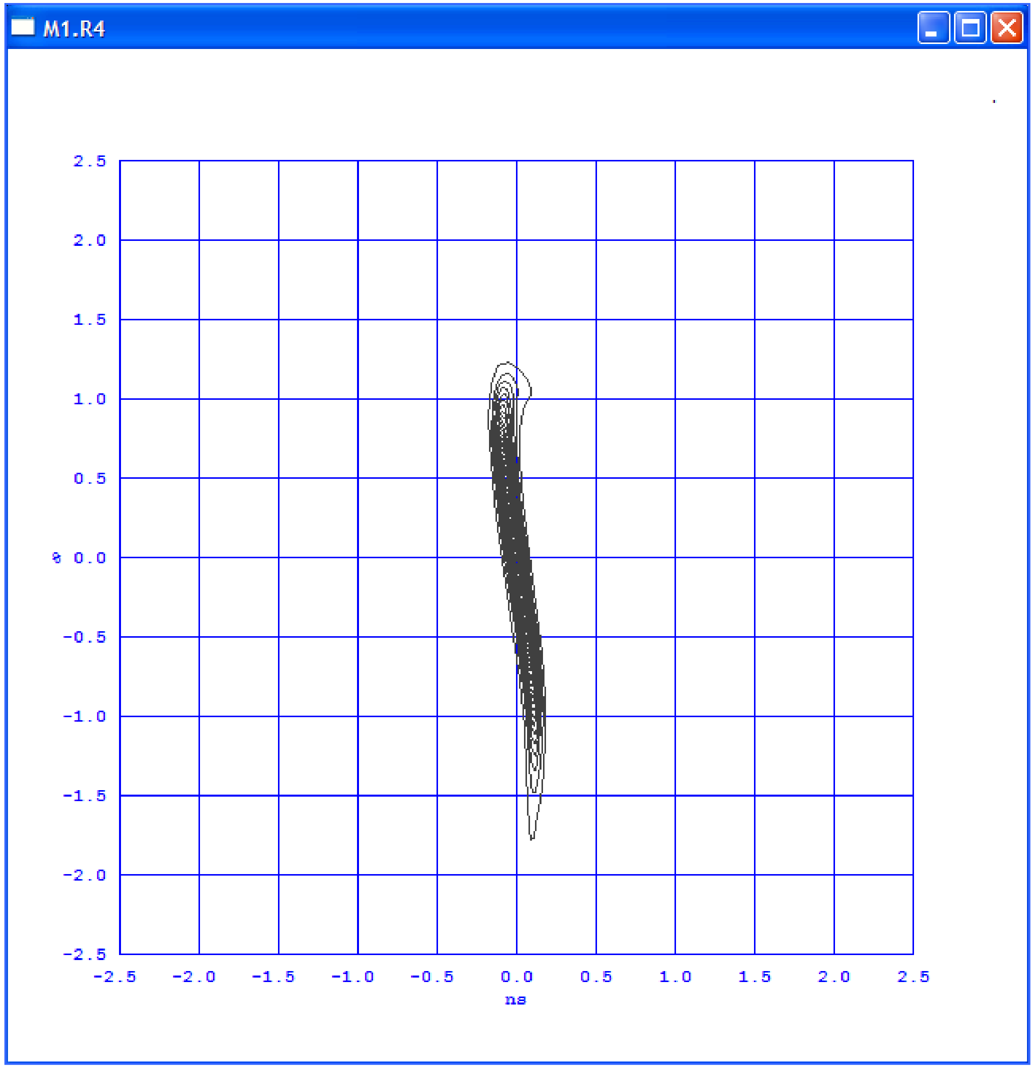
Longitudinal phase space



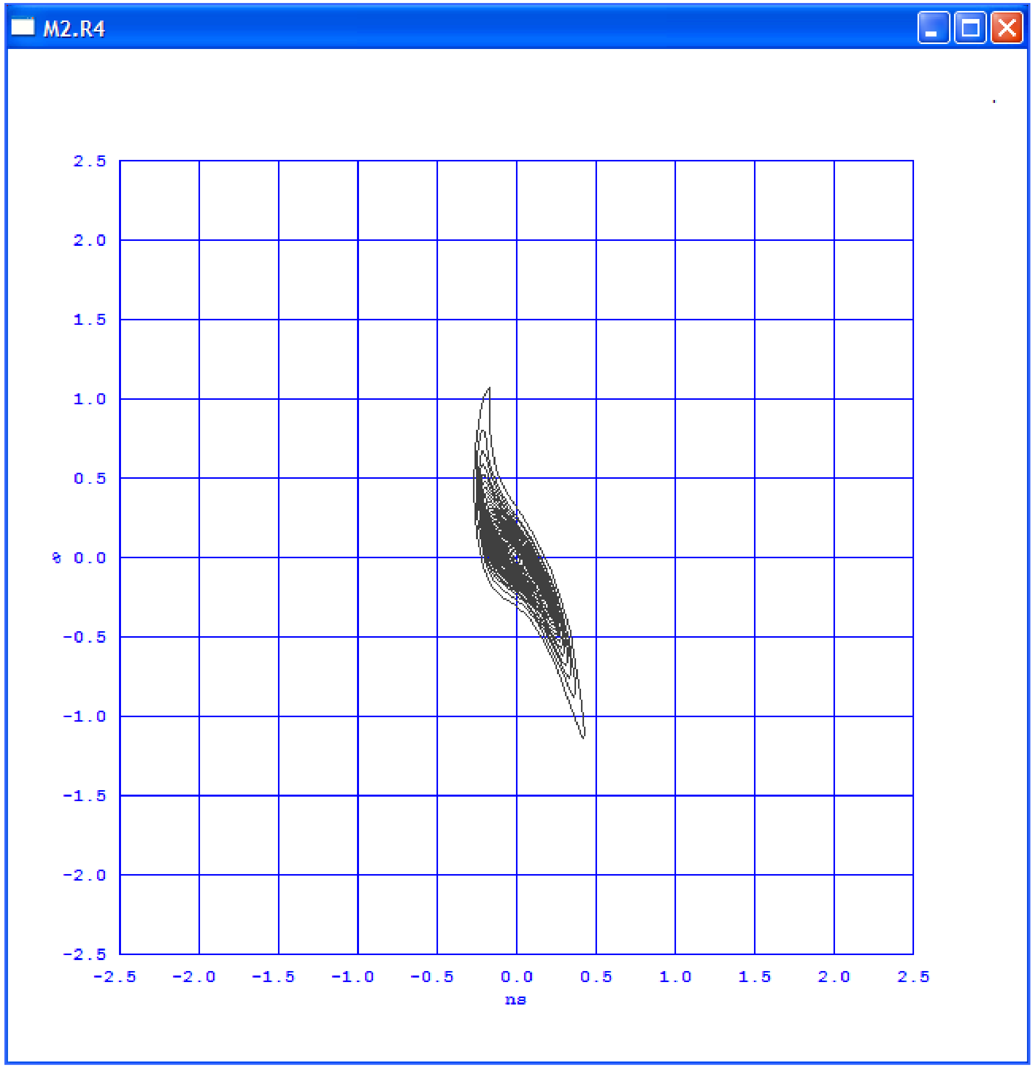
At LINAC Injection



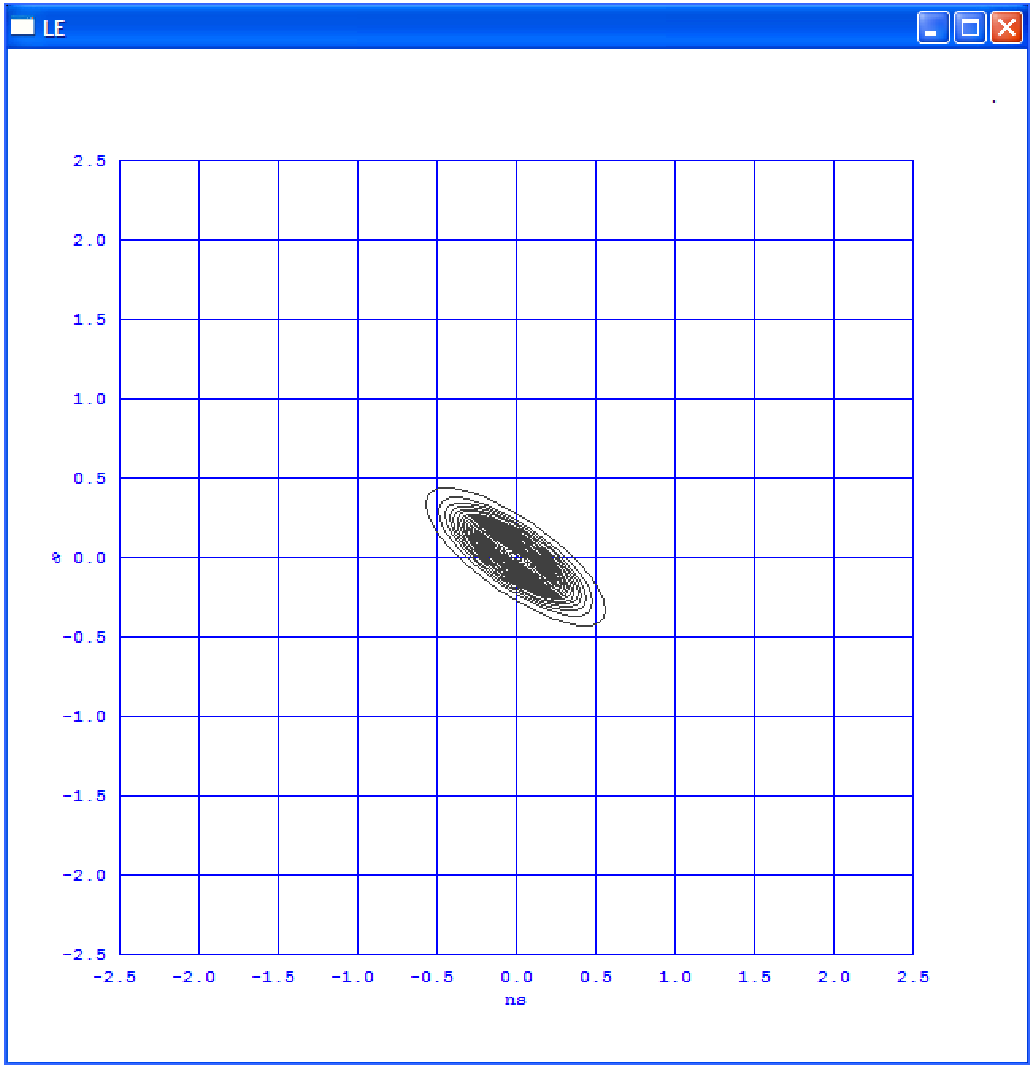
After Superbuncher at the entry of M1



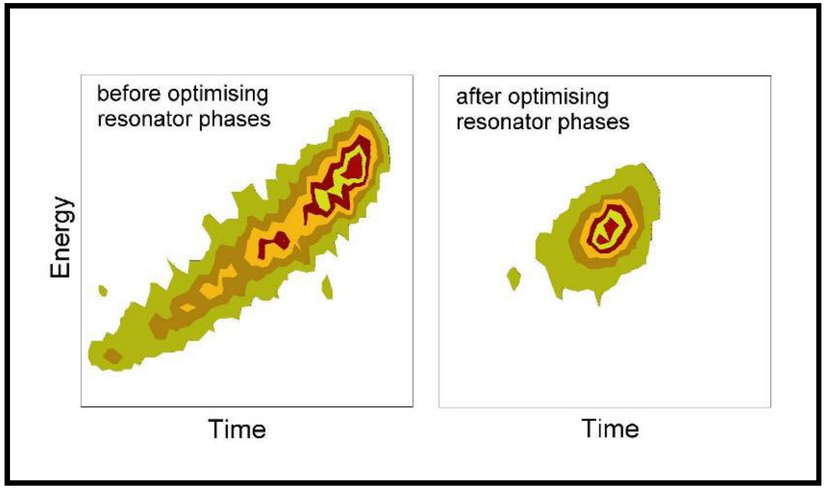
After M1, at the entry of M2



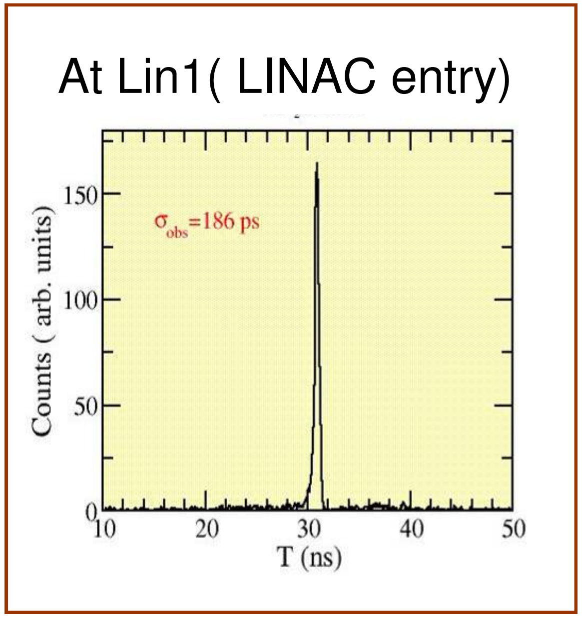
After M2, at the entry of M3

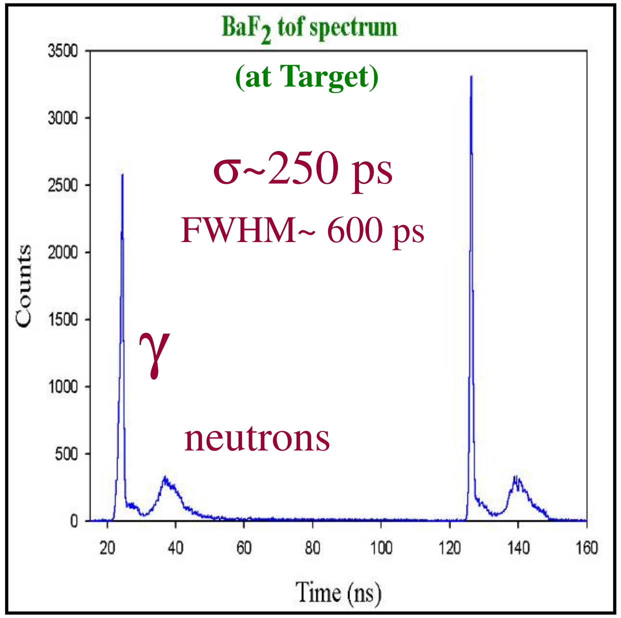


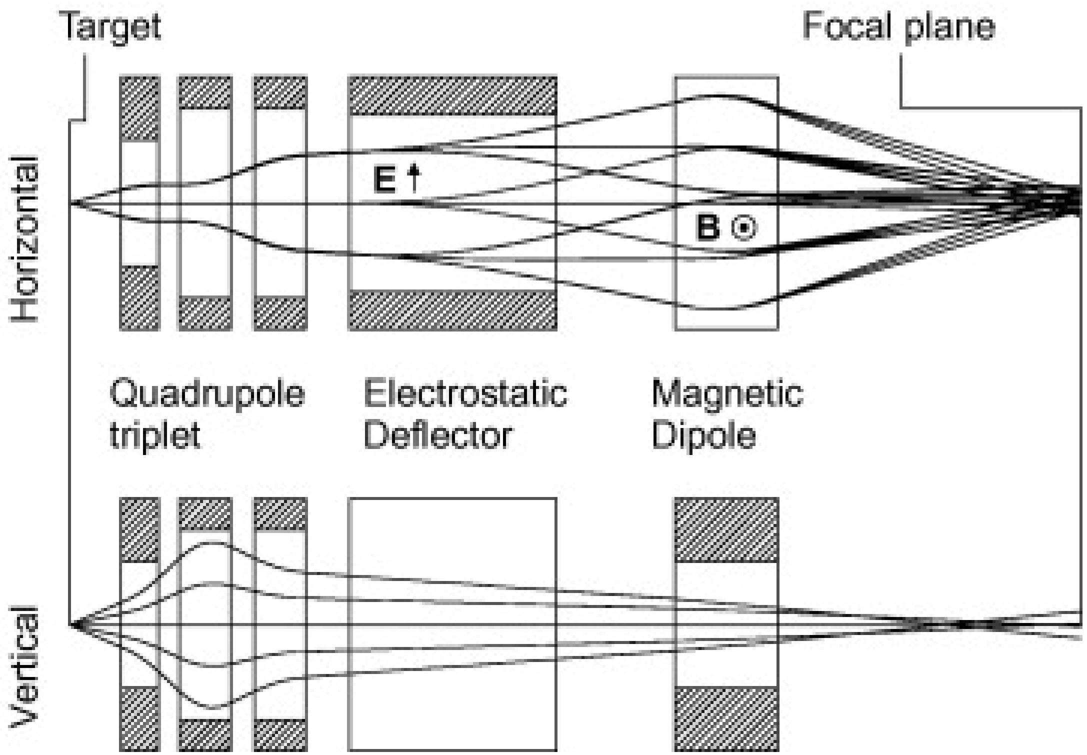
Equivalent distribution for the Phase II

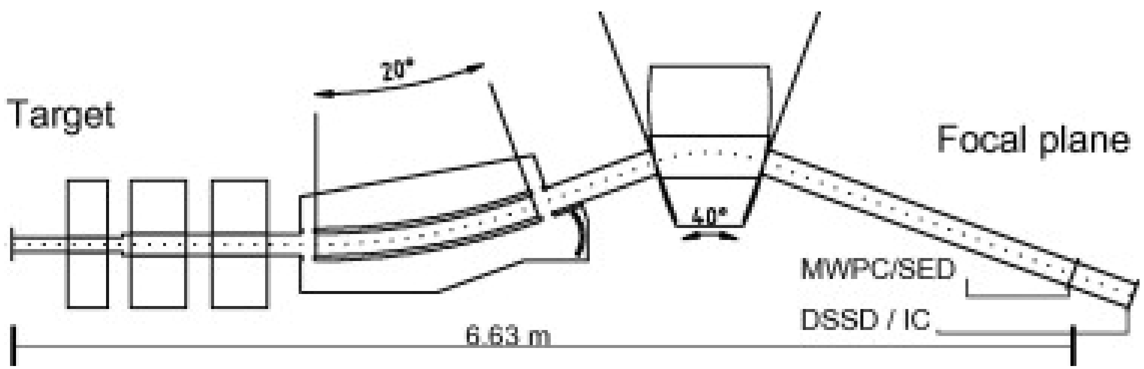


Longitudinal phase space after mid-bend (E-T measurement)






Target
Focal plane
Horizontal
E
B
Quadrupole triplet
Electrostatic Deflector
Magnetic Dipole
Vertical


20°
Target
Focal plane
40°
MWPC/SED
DSSD / IC
6.63 m

Magnets

- *Sector*
- *Wedge*
- *Edge focusing*
- *Higher order component measurement*
- *Wiggler magnet*
- *Fast kicker*
- *Measurement of harmonincs*
- *Measurement of magnetic field- hall probe & NMR*

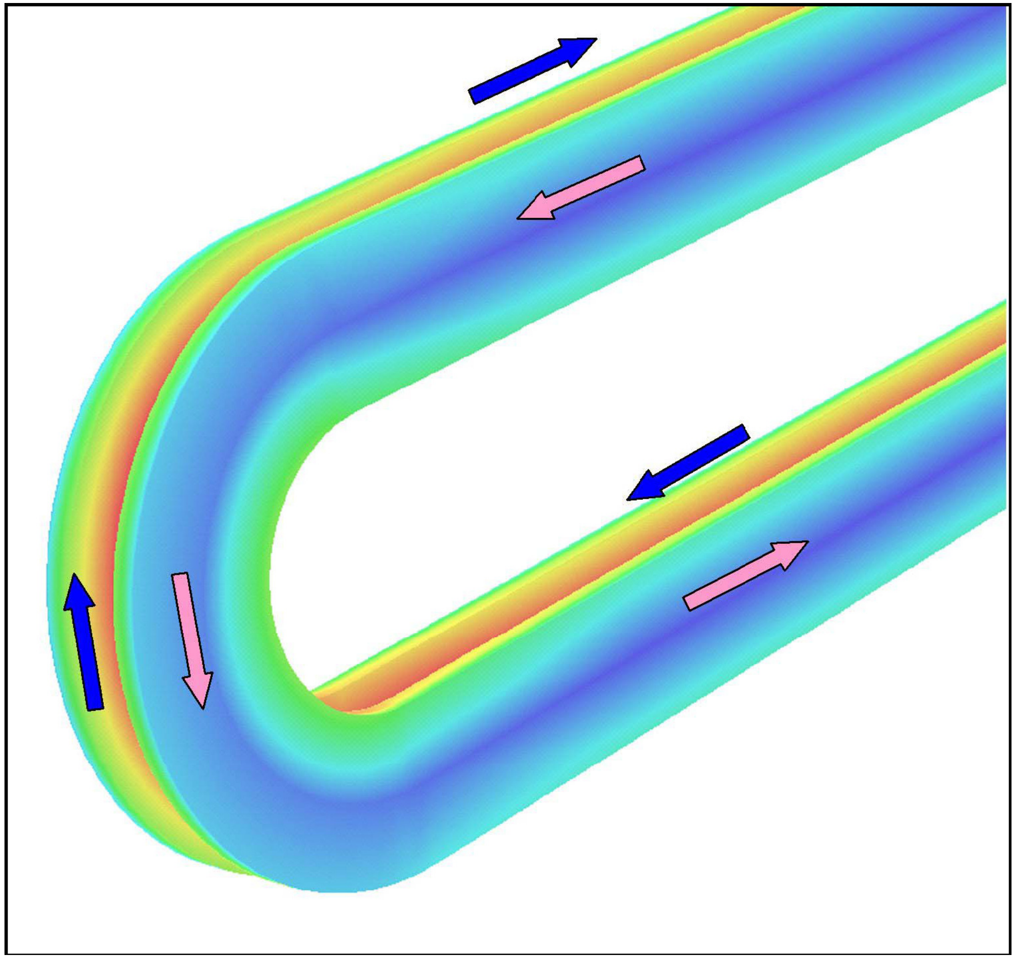


Table 1: Instruments, measured quantities and physical effects used

Instrument	Physical effect	Measured quantity	Effect on the beam
Faraday cup	Charge collection	Intensity	Destructive
Current transformer	Magnetic field	Intensity	Non-destructive
Wall current monitor	Image current	Intensity, longitudinal density distribution	Non-destructive
Pick-up, beam-position monitor (BPM)	Electric/magnetic field	Position, trajectory, orbit	Non-destructive
Secondary emission monitor	Secondary electron emission	Transverse profile, intensity, emittance	Disturbing, at low energy: destructive
Wire scanner	Secondary emission, creation of secondary particles	Transverse profile, emittance	Slightly disturbing
Scintillator screen	Atomic excitation with light emission	Transverse profile, position	Destructive
Residual gas monitor	Ionization	Transverse profile	Non-destructive

magnetization curve will be perfectly symmetric, only odd harmonics of the modulation frequency will be present in the modulation spectrum. It is clear that the pair of coils must be carefully matched such that the induced signal after subtraction is minimized.

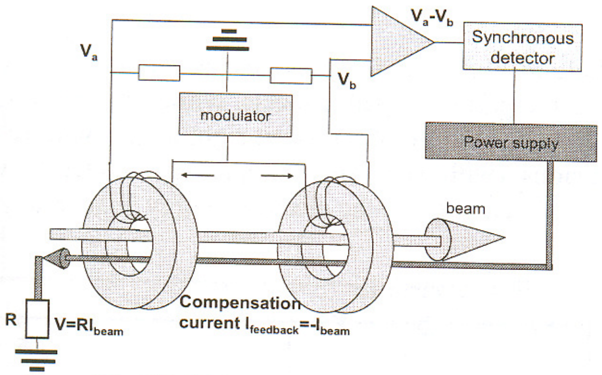


Fig. 13: The zero flux magnetometer

A DC current passing through the coils introduces a bias in the excitation, the sum signal becomes non-zero and even harmonics, in particular the second harmonic, will appear in the spectrum.

A synchronous detector extracts the information about the signal amplitude and phase of the component at the second harmonic of the modulation frequency. This signal is used to create a feedback current cancelling the flux induced by the beam. This feedback current is finally measured.

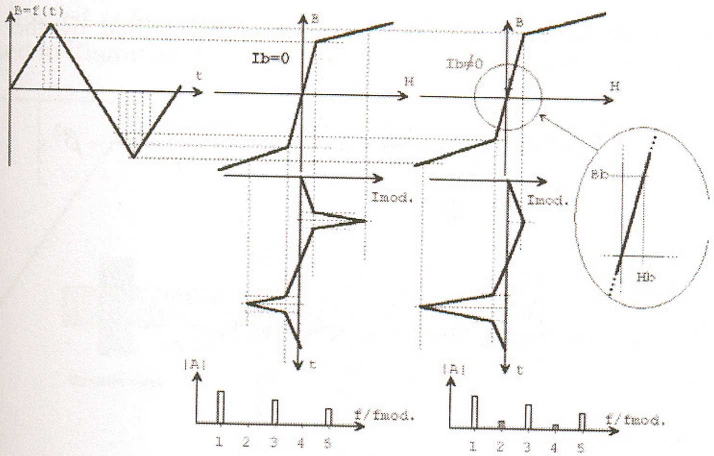
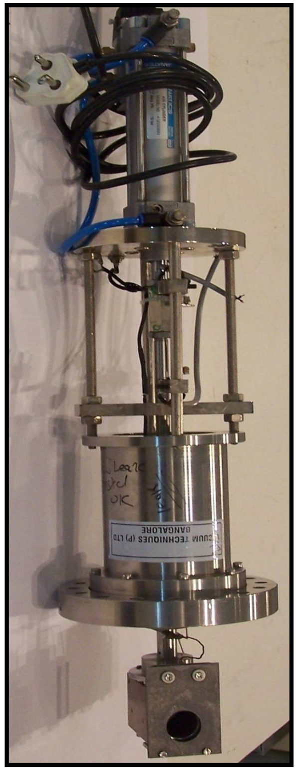


Fig. 14: Modulation of a DCCT left: without beam, right: with beam

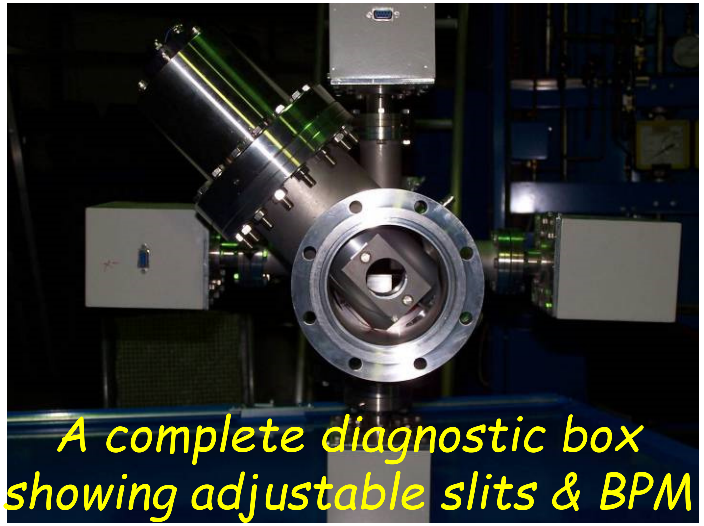
Beam profile monitor

Beam Diagnostic devices

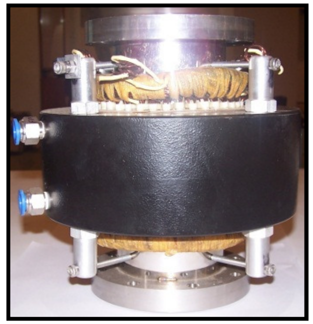
BPM developed at TIFR



Faraday cup



A complete diagnostic box showing adjustable slits & BPM



Magnetic Steerer

Other accelerators

- *Storage rings*
- *Free Electron lasers*
- *Synchrotron radiation sources*
- *Laser based accelerators*

Cryogenics & vacuum

- *Cryogenics production and transport*
- *Thermal anchoring*
- *Minimization of heat load*
- *Quench protections*

Applications

- *Nuclear physics*
- *Particle physics*
- *Atomic physics*
- *Material science*
- *AMS*
- *Medical treatment, isotope production*
- *Industry*
- *Agriculture – foodgrain irradiation*
- *Waste treatment*
- *Energy production*