Practical Accelerator Physics

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January 7-11, 2008
Lectures at RRCAT, Indore, India

These lectures are available on
http://www-ap.fnal.gov/users/cbhat/

Syllabus

Lecture 1
- Introduction, Basic Definitions and Formulas, Units and Terminology, Basic Relativistic Formalism, Types of Accelerators, An example of a high energy accelerator complex.

Lecture 2
- Accelerator Optics and Transverse Beam Dynamics
  - –Accelerator and beamline magnets
  - –Beam transport and FODO lattice
  - –Weak and strong focusing, circular accelerators
  - –Coordinate system, Hills equation, Aspects of transverse beam dynamics

Lectures 3-5
- Longitudinal Beam Dynamics
  - –RF cavities
  - –Equations of motion and Longitudinal Phase space, RF bucket and area
- Beam Diagnostic Instrumentation
- Practical Issues for commissioning and operation of the accelerator
  - –Closed orbit, closure, tune, tune space
  - –Chromaticity and chromatic corrections
  - –Beam injection and extraction issues
  - –Aperture scan and optimization
  - –Beam Acceleration and beam storage
  - –RF capture and RF gymnastics
- Recent Developments in Beam operation: RF gymnastics

[Bias towards protons]

Terminology in Accelerator Physics

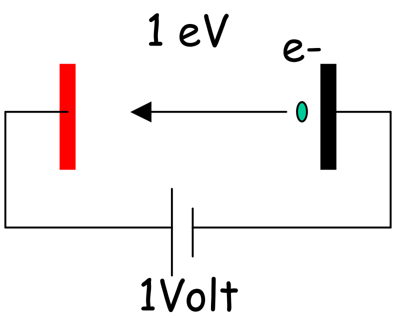
- **Units:** In accelerator literature one comes across both *MKS* and *CGS* systems. In these lectures I will try to stick to the MKS system.
- **Energy:**

  Electron volt: It is the amount of kinetic energy gained by a single unbound electron when it passes through an electrostatic potential difference of one volt

  KE= kinetic energy
  Total Energy

  } At low energies Total energy >> KE
  At high energies KE~ Total energy

  keV, MeV, GeV, TeV etc.



- **Momentum:**

  Measured in units of [MeV/c], [GeV/c], [TeV/c]
- **Beam Current:**

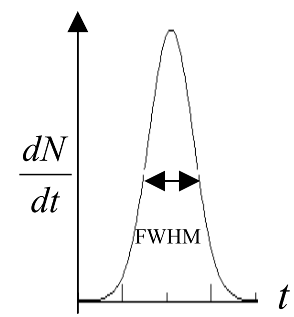
  Unit of current = Amp
  = 1 Coulomb/sec

  $$I = \frac{dq}{dt}$$ Charge passing through/unit time

  - Beam Transport: Beam particles pass only once

    $$I = eZ\Phi; \quad \Phi \text{ is the flux (number of particles)/unit time}$$
  - Linear Accelerator: Beam particles get accelerated every time

    $$I_{\text{Peak Current}} = \frac{\text{Pulse Intensity}}{\text{FWHM}}$$



  - Circular Accelerator: Same particle goes through the same section f_{rev} times/sec

    $$I = eZNf_{\text{rev}}$$

- **Luminosity:** is the total number of interactions/unit area/unit time during collisions of two entities

$$L = f\frac{N_1 N_2}{A_{eff}} \equiv \frac{\text{Number of Events for a Process}}{\text{Cross Section for the Process}}$$

- **Phase Space:**

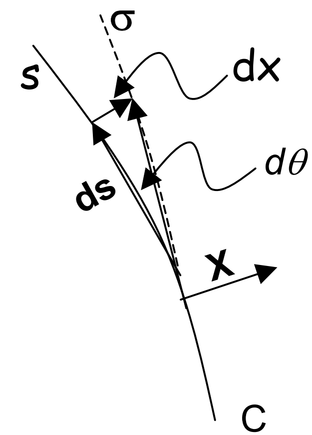
A particle is characterized by its

Position coordinate- x

Momentum coordinate - p

The space in which all possible values for "x" and "p" can be represented is phase space

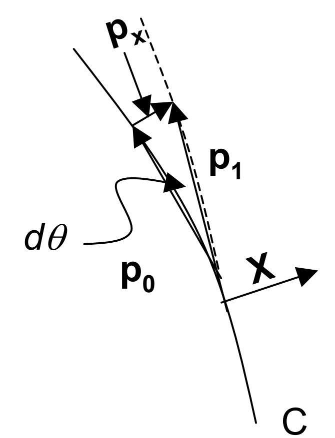
$$d\theta \cong \tan(d\theta) = \frac{d\text{x}}{ds} = \text{x}'$$



Assume that trajectory of a particle, σ, is in the plane of paper (board). Let "C" be the reference trajectory (beam center) and "s" be its curvilinear coordinate along "C"

- Phase space with (x, p_x) as coordinate axes is called "horizontal phase space"
- Similarly "vertical phase space"

$$p_x = p_0 \tan(d\theta) \approx p_0 d\theta = p_0 \text{x}'$$



Liouville's Theorem: ***"In the absence of collision and dissipation, the local density in phase space must remain constant."***

$$\int p\,d\text{x} = \text{constant}$$

If ρ_1 and ρ_2 are phase space densities at instants t_1 and t_2 then, $\rho_1 = \rho_2$ ➔ Phase space volumes or areas are the same

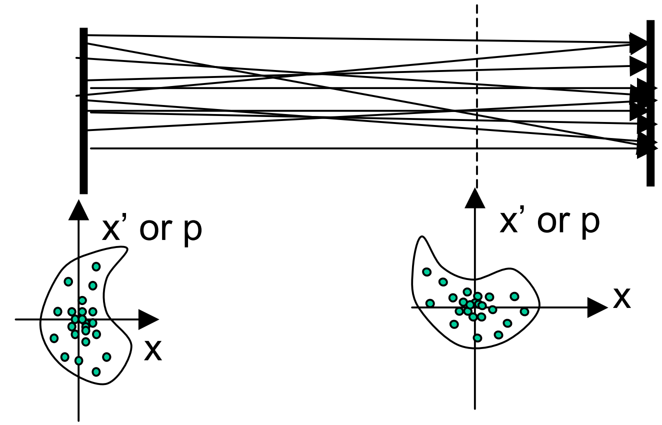
Examples

<u>Beam transport:</u>

	t= t1	t=t2
Part#1	(x1, x1′)	(x1+v∆t, x1′)
Part#2	(x2, x2′)	(x2+v∆t, x2′)

Relative distance do not change. Hence, density remain unchanged, and so on.

No acceleration



<u>Beam Acceleration</u>: Similar visualization is a bit difficult but,is still true.

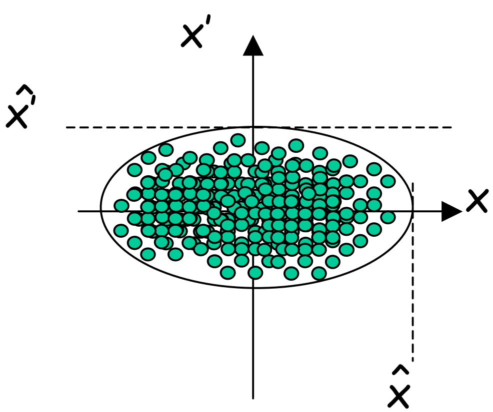
If phase space distribution of all the particles in a beam form an ellipse with $\hat{x}$ and $\hat{x}'$ as their maximum values then the Liouville’s theorem states that

$\pi p_0 \hat{x}\hat{x}' = \text{constant}$ and if accelerated $\Rightarrow$

$$\pi p_0 \hat{x}_0 \hat{x}_0' = \pi p_1 \hat{x}_1 \hat{x}_1'$$

$$= \pi (m_0 c)\underbrace{(\beta\gamma)_0 \hat{x}_0 \hat{x}_0'} = \pi (m_0 c)\underbrace{(\beta\gamma)_1 \hat{x}_1 \hat{x}_1'} = \text{constant}$$

Normalized emittance



Relativistic Expressions

The total energy of an accelerted particle in a high energy accelerator is often >> rest mass energy of the particle. So we have to use relativistic mechanics

$$\Delta s = \gamma \Delta s^* \quad \text{where} \quad \gamma = (1-\beta_s^2)^{-\frac{1}{2}}$$

* $\Rightarrow$ Lab frame of reference

$$\Rightarrow V = \gamma V^*$$; Volume scales linearly with γ

$$\Rightarrow \rho = \frac{\rho^*}{\gamma}$$; charge density scales as **1/**γ

Total Energy:

$$E = \gamma m_0 c^2 = \sqrt{p^2 c^2 + m_0^2 c^4}$$

Kinetic Energy:

$$E_{kin} = E - m_0 c^2 = (\gamma - 1) m_0 c^2$$

$$\Delta E_{kin} = \int_{Laccel} F.ds$$

Momentum of a Particle:

$$cp = \sqrt{E^2 - m_0^2 c^4} = \beta\gamma m_0 c^2$$

Differential Forms:

$$dcp = \frac{m_0 c^2}{\beta} d\gamma = \frac{dE}{\beta} = \frac{dE_{kin}}{\beta} = \gamma^3 m_0 c^2 d\beta$$

$$\frac{dcp}{cp} = \frac{1}{\beta^2}\frac{d\gamma}{\gamma} = \gamma^2 \frac{d\beta}{\beta}$$

Electromagnetic Field:

$$E_x^* = \gamma[E_x - \beta_s B_y]; \qquad B_x^* = \gamma[B_x - \beta_s E_y]$$

$$E_y^* = \gamma[E_y - \beta_s B_x]; \qquad B_y^* = \gamma[E_y + \beta_s E_x]$$

$$E_s^* = E_s; \qquad B_z^* = B_z$$

A pure electric/magnetic field in the lab-frame of reference will be a combination of “E” and “M” fields in particle-frame of reference.

Maxwell's Equations

Gauss law for E $\oint_S \vec{E}.d\vec{A} = \frac{q}{\varepsilon_0}$ — How electric charge gives rise to electric field; field lines begin and end on charges

Gauss law for B $\oint_S \vec{B}.d\vec{A} = 0$ — No magnetic charge; magnetic field lines do not begin or end.

Faraday's law of induction $\oint_L \vec{E}.d\vec{l} = -\frac{d\phi_B}{dt}$ — Changing magnetic field induces electric field.

Ampere's law $\oint_L \vec{B}.d\vec{l} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\phi_E}{dt}$ — A steady electric field gives rise to magnetic field. 2nd Term is displacement current

$\varepsilon_0 =$ permittivity constant = absolute di-electric constant, = 8.859 × 10^{-12} $\text{Columb}^2/\text{Newton.meter}^2$

$\mu_0 =$ Permeability constant, =4π × 10^{-7} Tesla meter/Amp

Lorentz Force: $\vec{F} = q\left(\vec{E} + (\vec{V} \times \vec{B})\right)$

Change in momentum: $\Delta p = \int \vec{F}.dt$

Change in kinetic energy:

$$\Delta E_{kin} = \int \vec{F}.d\vec{s} \; ; \; ds = \beta c dt$$

$$\Delta E_{kin} = \beta c \Delta p$$

$$\Delta E_{kin} = q\int \vec{E}.d\vec{s} + q\int (\vec{v} \times \vec{B})\vec{v}\mathrm{dt}$$

Types of Accelerators

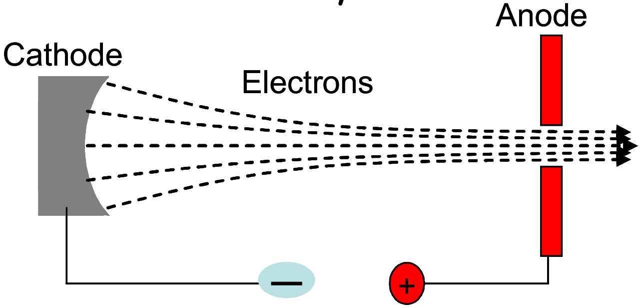
- The charged particle accelerators are broadly classified into two types.
  - Linear Accelerators: Cascade Accelerators, Van De Graff, LINAC, RFQ etc.
  - Circular Accelerators: Cyclotron, Microtron, Synchrotron, Betatron, etc.

Linear Accelerators:

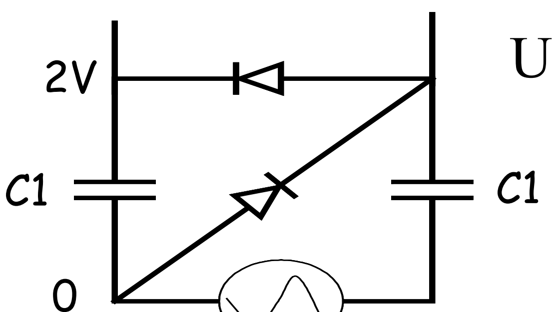
In a linear accelerator charged particles are accelerated either by electrostatic fields or rf (radio-frequency) cavities.

$$\Delta p = \int F dt = q\int E.dt$$

$$\Delta E = q\int \vec{E}.d\vec{s}$$



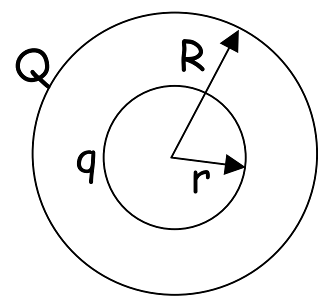
Cockcroft-Walton Accelerators or Cascade Accelerators



Vpeak=V

$$U = 2nV$$

Van de Graff Accelerators



The electro static potential of the large sphere is partly caused by "q" and partly by its own charge

$$V_R = \frac{1}{4\pi\varepsilon_0}\left[\frac{Q}{R} + \frac{q}{R}\right]$$

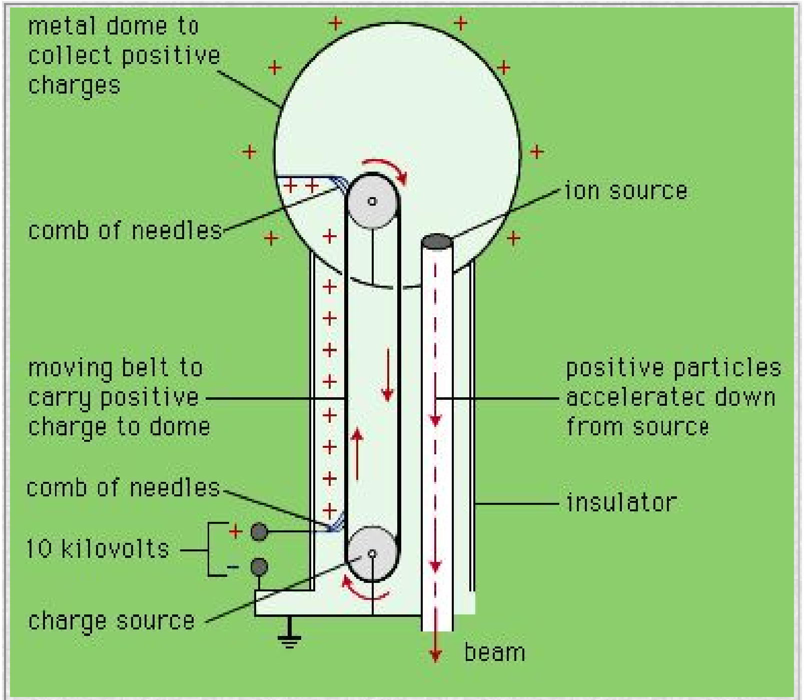
$$V_r = \frac{1}{4\pi\varepsilon_0}\left[\frac{q}{r} + \frac{Q}{R}\right]$$

$$V = V_r - V_R = \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{r} - \frac{1}{R}\right]$$

V is always +ve, This is the principle of Van-de Graff

Van-de Graaff and Pelletrons

Simplified version of Van de Graaff



Simplified version of a Van de Graaff high-voltage electrostatic generator

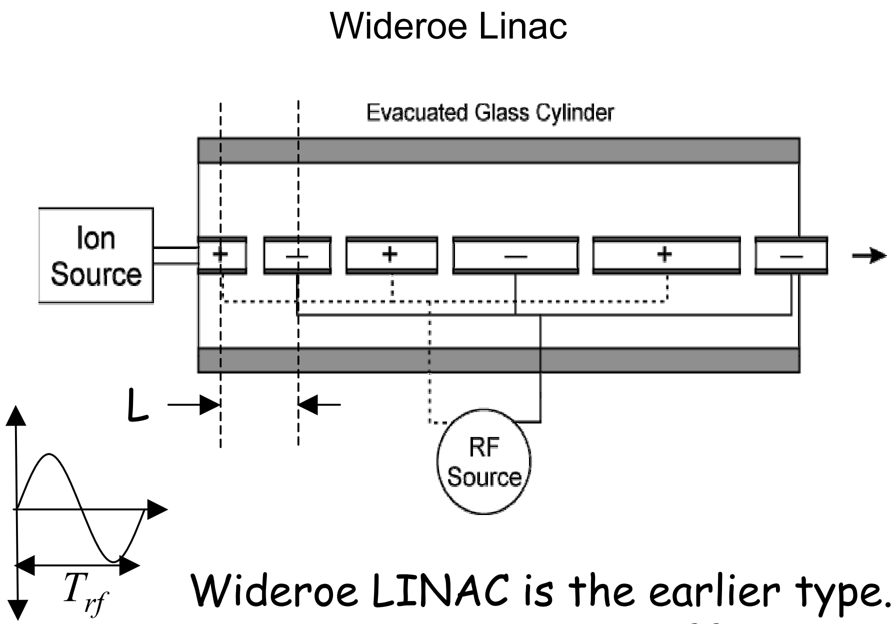
The charges always move from inside sphere to outside Dome

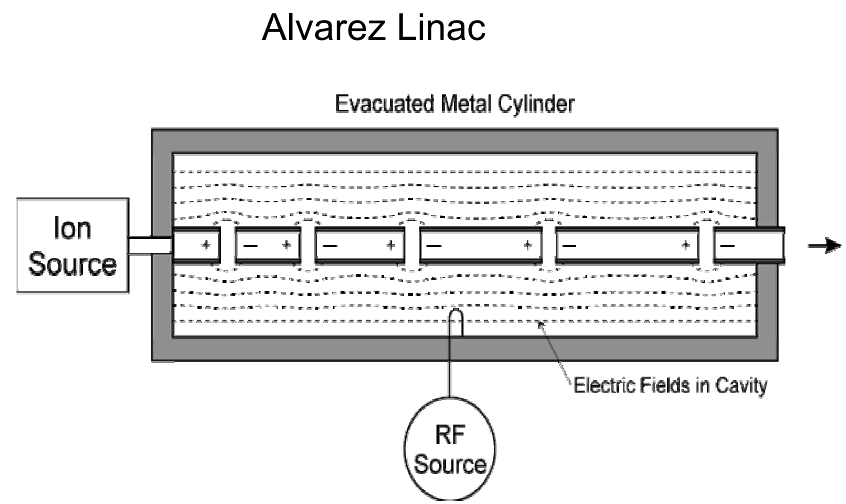
A Pelletron is an electrostatic accelerator with an improved belt design; it has a moving belt made of metal pellets connected with nylon links to carry the charge.

Fermilab 4.3 MeV Pelletron for antiproton cooling in the 8 GeV Recycler

LINAC

In its simplest form, a LINAC is a set of drift tubes that have rf voltage applied so that the particles gets accelerated at the gaps; inside the cylindrical tubes they do not see any E field.





Wideroe LINAC is the earlier type. As v→ velocity of light, the Wideroe LINAC becomes very inefficient. So the Alvarez type became prevalent.

Synchronous condition for LINACs is

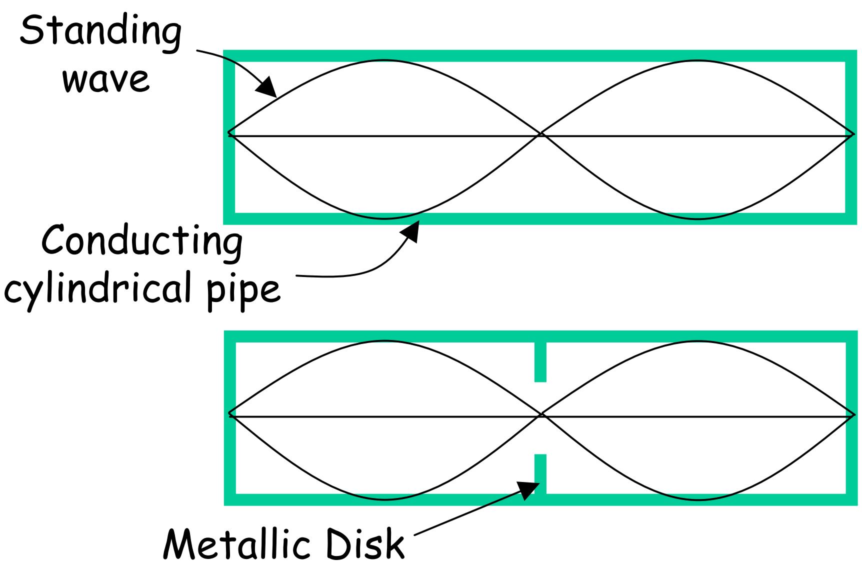
$$L = \frac{1}{2} \mathrm{v} T_{rf}$$

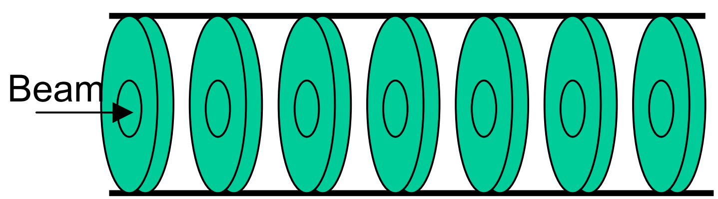
v= velocity of the particle
Trf= rf period

Fermilab: Old LINAC up to 200 MeV and currently up to 116MeV with Alvarez type accelerator

Disk-loaded Wave Guide Accelerators

A **wave guide** is a pipe of conducting material where an oscillating electromagnetic field can be established.





But, we know that

$$v_{particle} v_{Phase} = c^2 \text{ and } v_{particle} < c$$

To accelerate we must have phase velocity to be equal to particle velocity i.e.,

$$V_{particle} \approx V_{Phase}$$

To achieve this condition we add metallic disks so that phase velocity can be reduced.

For the structure shown here, we can show that the gain in kinetic energy for

$$V(t) = V_0 \cos(\omega t) \quad \text{is}$$

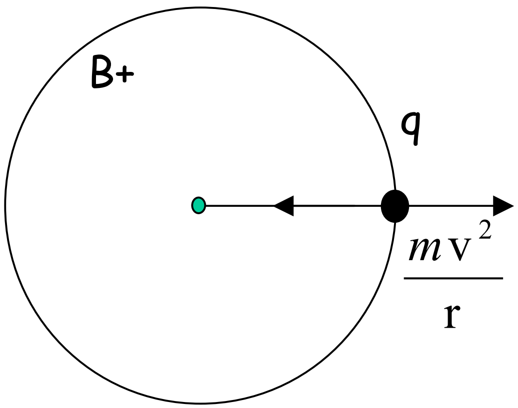
$$\Delta E = eV_0 T_t$$

T_t is called "transit time factor".
The disk-loaded structure is not quite efficient for $v_{particle} \ll c$, but works well for $v_{particle} \approx c$.

Fermilab: 400 MeV side-coupled rf cavities

Circular Accelerators

Cyclotron: E. O. Lawrence and M.S. Livingston in 1931 (conventional cyclotrons)
In the absence of an accelerating field, a charged particle follows a circular orbit in a constant magnetic field

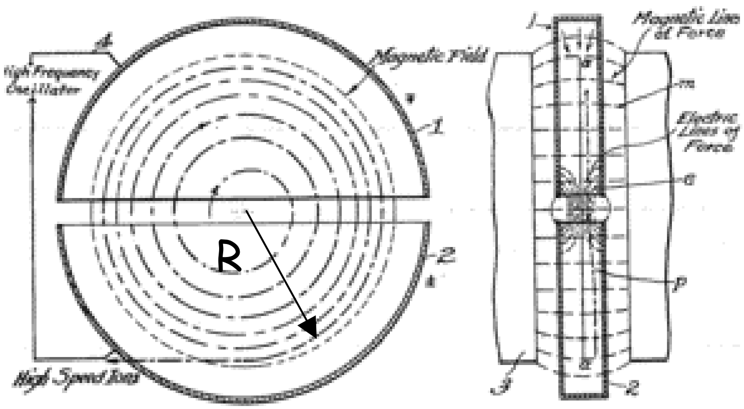


$$F = q\,\vec{v} \times \vec{B} = \frac{mv^2}{r}$$

$$\therefore\ \frac{v}{r} = \omega = \frac{qB}{m}$$

since v and B are perpendicular to one another vxB=vB

At non-relativistic speeds ω is independent of particle velocity. Now, if a "D" shaped rf cavity is introduced and make the cavity voltage oscillate with an AC voltage, then, one can accelerate the particle by rf voltage and confine it in the magnetic field till it hits the extraction orbit R.



The gain in KE is $KE = \frac{p^2}{2m} = \frac{mv^2}{2} = \frac{1}{2} m \left[\frac{q^2}{m}\right] B^2 R^2$

In practice, the maximum energy attained by this type of circular accelerator is about 22 MeV for deuterons

Synchro-cyclotron: McMillan (USA) and Veksler (USSR) in 1945

At relativistic speeds, ω is not independent of velocity of the particle, i.e.,

$$\omega = \frac{v}{r} = \frac{qB}{m_0\gamma} \text{ where } \gamma = \left[1-\frac{v^2}{c^2}\right]^{-\frac{1}{2}} \Rightarrow f_{rf} \sim \frac{1}{\gamma(t)}$$

Therefore, one can keep synchronicity in a cyclotron by changing ω so that **$\omega m_0\gamma$=constant**. This is the principle of synchro-cyclotron.

The particle energy at any time is obtained by

$$1/r = qB/pc \text{ with } pc = \sqrt{E_{kin}(E_{kin}+2m_0c^2)} = qBr$$

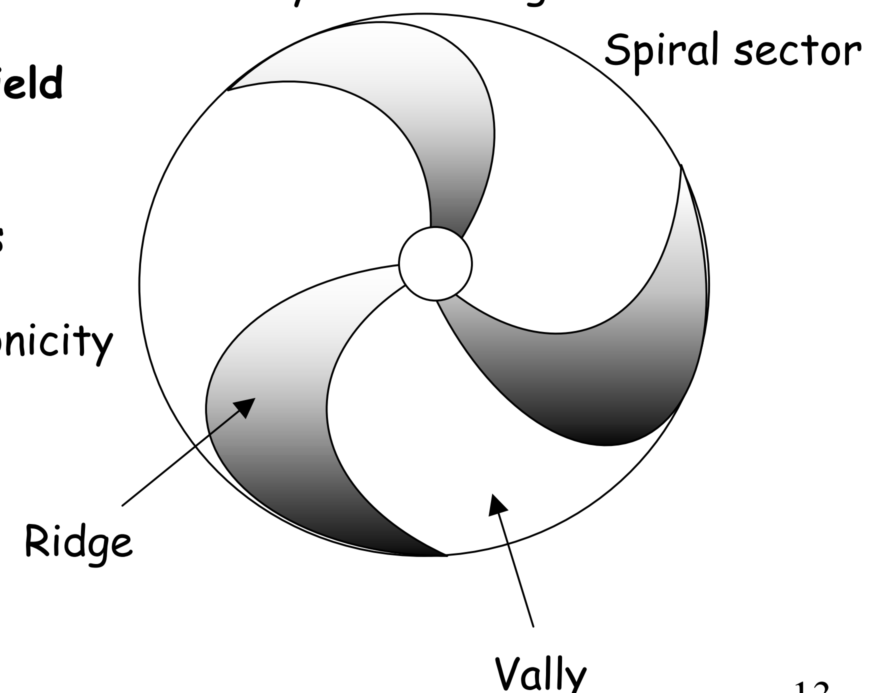
Proof of principle Synchro-cyclotron: 37 in. cyclotron at Berkeley!
Emax achieved = 350MeV. Rmax=184 in, Magnet Weighed about 4300 tons !!!

Isochronous-Cyclotron (azimuthally-varying-field cyclotrons- AVF cyclotrons):
Thomas from Ohio State Univ, 1938,
In the above equation the angular velocity ω has radial dependence. So by introducing the radial dependence in the magnetic field B, the synchronicity can be maintained, i.e,

$$\omega = \frac{qB(r(t))}{m_0\gamma(t)}$$

Examples: TRIUMF, IUCF, MSU, VEC etc.
500MeV

Pole piece of cyclotron Magnet

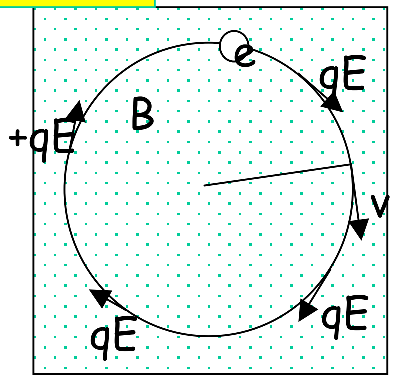


Betatron: Kerst, University of Illinois, Urbana , 1941

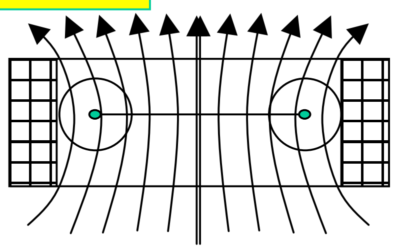
Time-varying magnetic field induces electric field around a closed loop (Faraday's law of induction). This is the principle behind the "Betatron"

$$\frac{d\phi}{dt} = -\int_L \vec{E} \bullet d\vec{l}$$

Top View



Side View



The magnetic field keeps the charged particles in a circular orbit and the varying magnetic field induces particle acceleration.

If <B> is the average magnetic field then the total flux is given by,

$$\phi_B = \pi r^2 < B >$$

$$\therefore \int_L \vec{E} \bullet d\vec{l} = 2\pi r E = \pi r^2 \frac{d < B >}{dt} \quad \text{or} \quad E = \frac{r}{2}\frac{d < B >}{dt}$$

This changing magnetic field imparts force on the charge q=e

$$F = \frac{dp}{dt} = qE = \frac{qr}{2}\frac{d < B >}{dt}. \text{ Integrating with t}: \Delta p = \frac{qr}{2}\Delta < B >$$

Further at radius r

$$p = qB_{\text{Orbit}} r \Rightarrow \Delta p = qr\Delta B_{\text{Orbit}}$$

Comparing the above two identities we get

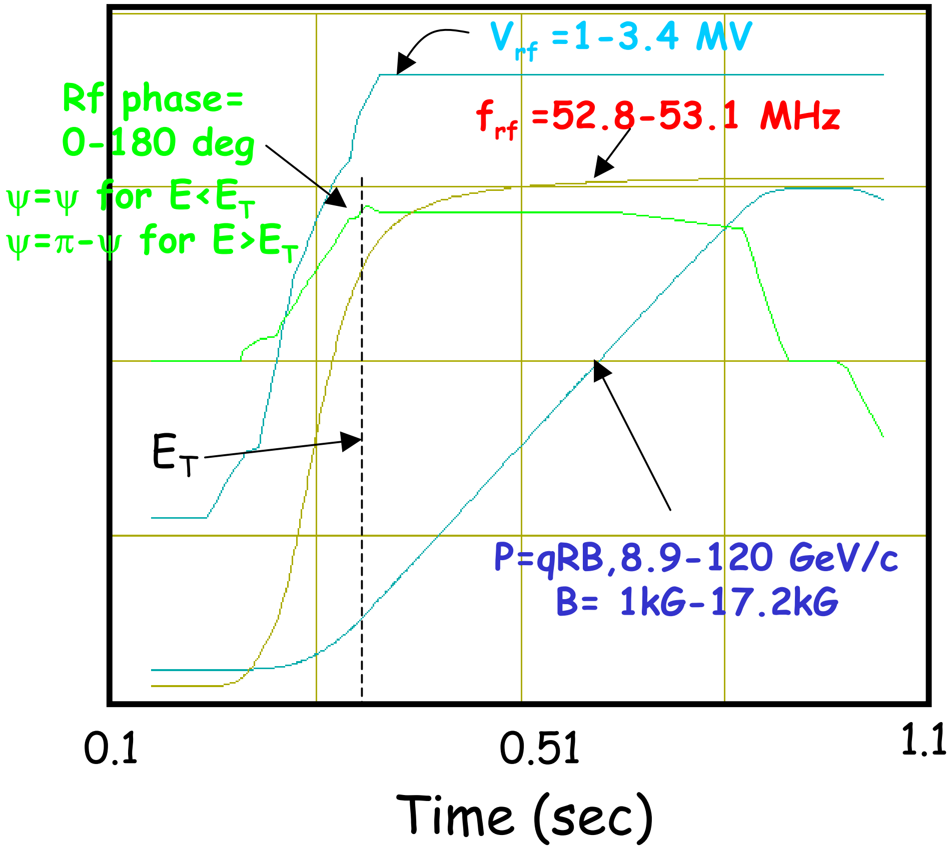
$$\Delta < B > = 2\Delta B_{\text{Orbit}}$$ This is called "Wideroe ½ condition"

There are >200 betatrons commercially used around the world.

Synchrotrons

The circular accelerators which make use of both synchronously varying rf field (amplitude and frequency) and magnetic field are called synchrotrons.

$$\frac{1}{R} = \text{Constant} = \frac{qB}{p} \; ; \qquad f_{\text{rev}} = \frac{ZeB}{2\pi\, p}$$



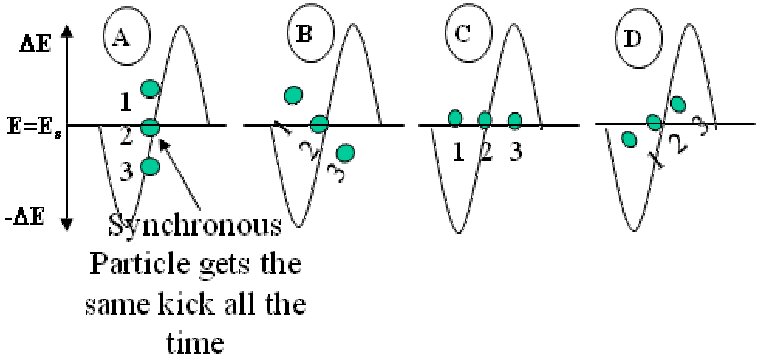
Example of a synchronously varying magnetic field and rf frequency.

All modern high energy circular accelerators operate on similar principle.

One of the important features of synchrotrons is **phase focusing.** Without the discovery of phase focusing these accelerators would not have existed. This credit goes to McMillan and Veksler.

Phase Focusing

The particle that gains exactly the "designed" or "nominal" energy during acceleration process is called "***synchronous particle***".

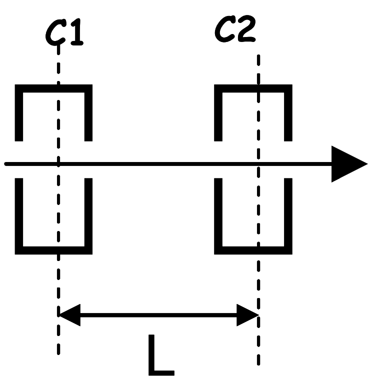


Let us assume a sinusoidal accelerating voltage on the rf cavity in a circular accelerator. Let the three particles arrive at the accelerating gap as shown in Fig.A. Then all particles get same acceleration kick as shown (which is zero). Consequently, next time particle "1" arrives at the rf gap earlier than the rest and gets negative kick relative to "2"; "3" gets positive kick relative to "2". After this passage, the (ΔE,ϕ) picture looks like as in Fig.B . And, so on.

On the whole, all particles below certain ±ΔE get the same kick and hence form a bunch. ⇒ "phase focusing"

This feature is vital to beam acceleration in an accelerator ⇒ "phase stability"

Synchronicity condition and Harmonic Number:



Let $qE = qE_0\, e^{-i\psi_s} = qE_0\, e^{-i(\omega t - ks)}$

Synchronicity condition demands that synchronous angle=constant

$$\Rightarrow \dot{\psi}_s = \frac{d}{dt}(\omega t - ks) = \omega - k\frac{ds}{dt} = \omega - k\beta c = 0 \quad \therefore \text{Synchronicity condition is } k = \frac{2\pi}{L}$$

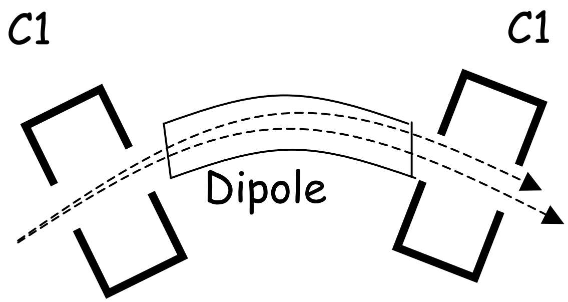
or $\omega = k\beta c = \frac{2\pi}{L}\beta c = \frac{2\pi}{L}h\beta c = \frac{2\pi}{\Delta T}h$

h= harmonic number
ΔT is time of traversal between C1 and C2

Momentum Compaction Factor:

In reality we have to consider following two important factors

1. k changes as energy increases (synchronicity condition demands k to change)
2. Need to apply corrections to path length for off-momentum particles. This is quite obvious if there is a dipole between C1 and C2



To incorporate these aspects in our formalism we look at a small variation of $\dot{\psi}$

$$\Delta\dot{\psi} = \underbrace{\Delta\omega}_{\approx 0} - \Delta(k\beta c) = -\Delta(k\beta c)$$

$$= -kc\Delta\beta - \beta c\Delta k$$

$$= -kc\Delta\beta - \beta c\frac{\partial k}{\partial p}\Delta p \qquad \frac{\partial k}{\partial p} = \frac{\partial k}{\partial L}\frac{\partial L}{\partial p} \quad \& \quad k_s = \frac{2\pi}{L_s}$$

$$\frac{\partial k}{\partial L} = -\frac{2\pi}{L^2} = -\frac{2\pi}{L}\frac{1}{L} \approx -\frac{k_s}{L_s} \quad \& \quad \frac{\partial L}{\partial p} \approx \left[\frac{dL}{L}\Big/\frac{dp}{p}\right]\frac{L_s}{p_s} = \alpha_c\frac{L_s}{p_s} \qquad \therefore \frac{\partial k}{\partial p} \approx -\alpha_c\frac{k_s}{p_s}$$

From relativity $\Delta\beta = \frac{\beta}{\gamma^2}\frac{\Delta p}{p} \approx \frac{\beta_s}{\gamma_s^2}\frac{\Delta p}{p_s}$

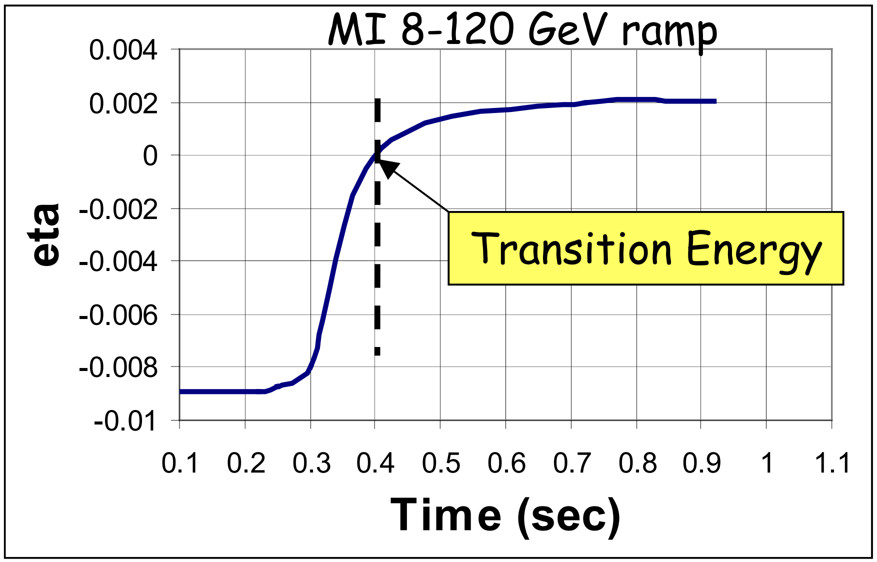
$$\Delta\dot{\psi} = -\beta_s k_s c\left[\frac{1}{\gamma_s^2} - \alpha_c\right]\frac{\Delta p}{p_s}$$

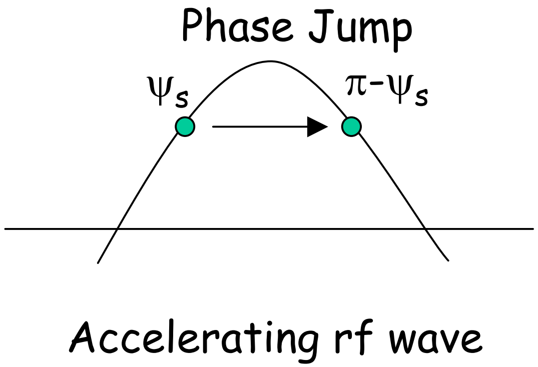
$\alpha_c \Rightarrow$ **Momentum Factor**

$\eta = \left[\alpha_c - \frac{1}{\gamma_s^2}\right] \Rightarrow$ **Slip Factor**

Transition Energy:

$$\eta = \left[\alpha_c - \frac{1}{\gamma_0^{\ 2}}\right] \Rightarrow \left[\frac{1}{\gamma_T^{\ 2}} - \frac{1}{\gamma_0^{\ 2}}\right]$$





The momentum compaction factor is an important aspect of rf acceleration. Further, this is an inherent feature of transverse and longitudinal beam dynamics in accelerator physics

Vacuum

The particle have to be transported or accelerator in very high vacuum. The typical vacuum is,

a. For transfer lines vacuum ~ 10^{-7} torr (**torr** = 1/760 atm *exactly)*
b. For a low intensity rapid cycling accelerators a vacuum of 10^{-7} to 10^{-8} torr may be good.
c. For high intensity we need better than 10^{-8} torr
d. For beam storage rings vacuum > 10^{-9} torr

An Example of A High Energy Accelerator Complex

Fermilab has six synchrotrons & four types of LINAC

Linear Accelerators

2- Cockcroft-Walton:
0-750KeV

Alvarez LINAC :
750keV – 116 MeV
200MHz

Disk-loaded side coupled cavity LINAC:
116 MeV- 400MeV
802MHz

Pelletron:
4.3 MeV
electron accelerator for beam cooling

Circular Machines

Booster (accelerator):
Energy: 400 MeV - 8 GeV, rf frequency: 37.7-52.82MHz, Dipole magnetic field: 0.67 kG-6.3kG

Debuncher (electromagnet storage ring):
Energy: 8 GeV, rf frequency: 52.82MHz,
Dipole magnetic field: 17kG

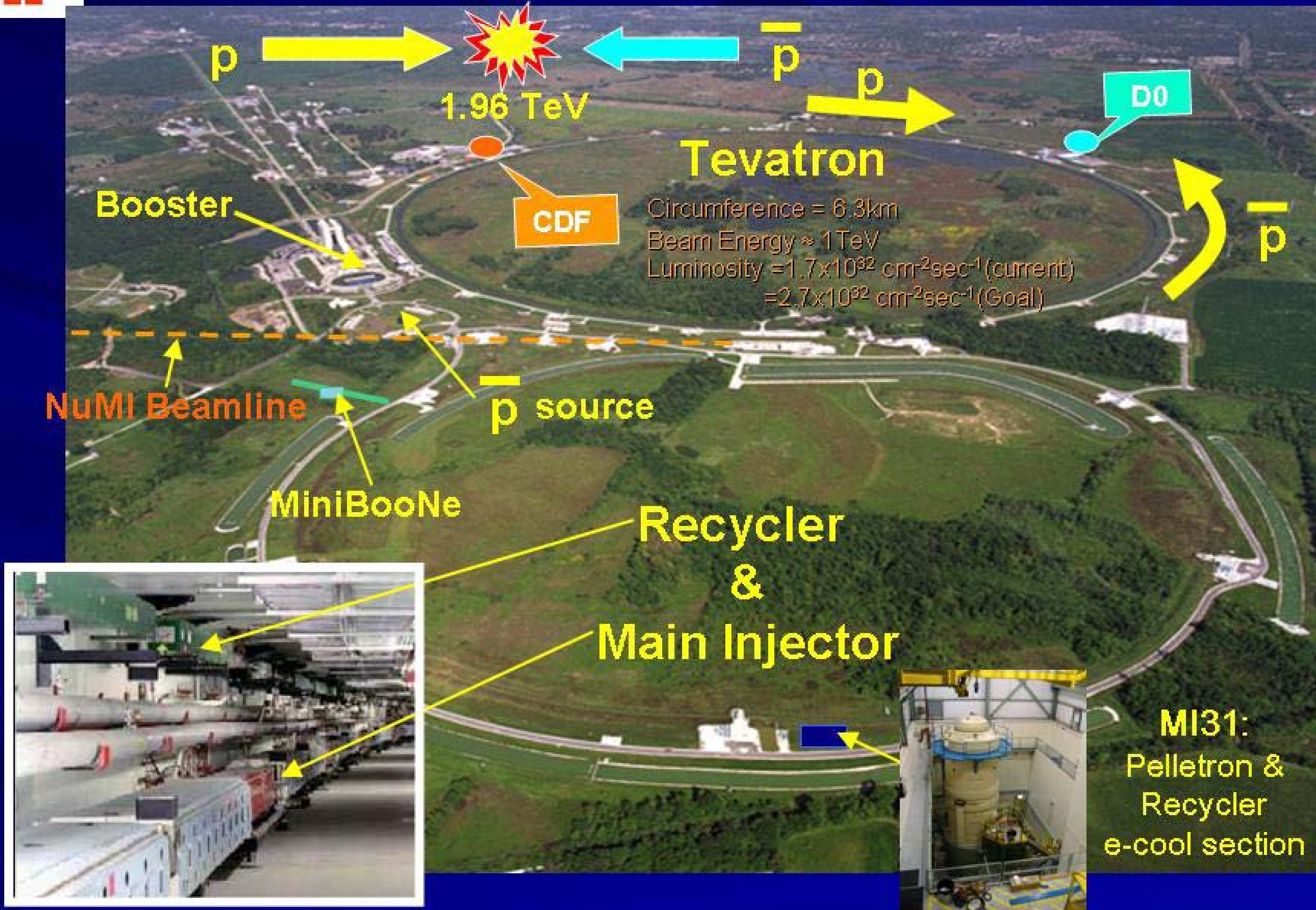
Accumulator (electromagnet storage ring):
Energy: 8 GeV, rf frequency: 52.82MHz,
Dipole magnetic field: 16.98kG (1.689 Tesla)

Recycler Ring (permanent magnet storage ring):
Energy: 8 GeV, Wide band rf system,
Dipole magnetic field: 1.33kG and 1.375kG

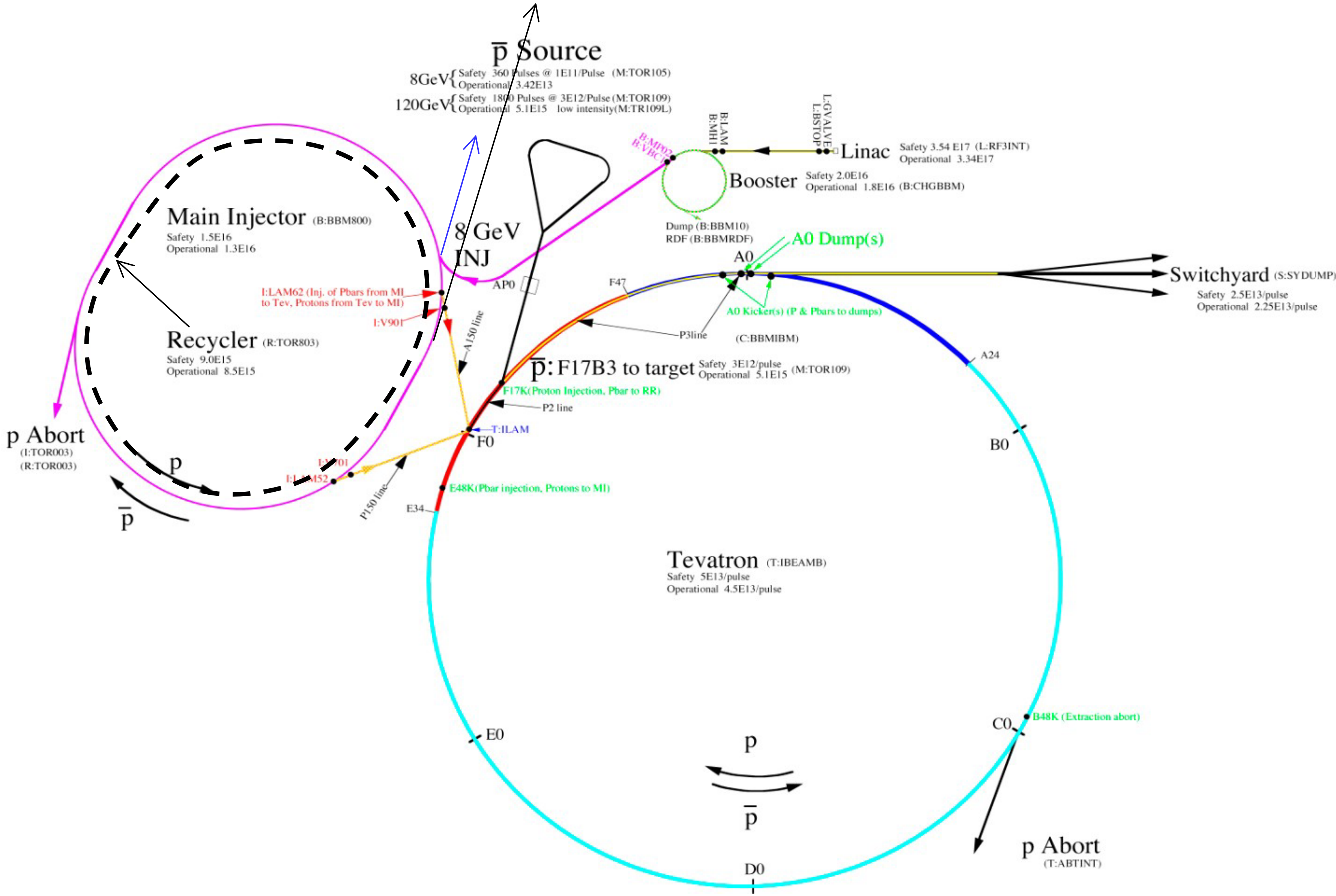
Main Injector (accelerator as well as decelerator):
Energy: 8 -150 GeV,
rf frequency: 52.82-53.3 MHz,
Dipole magnetic field: 1kG-17.2kG

Tevatron (accelerator as well as decelerator):
Energy: 150 GeV-1 TeV, rf frequency: 53.3 MHz,
Dipole magnetic field: 0.66 Tesla-4.4 Tesla

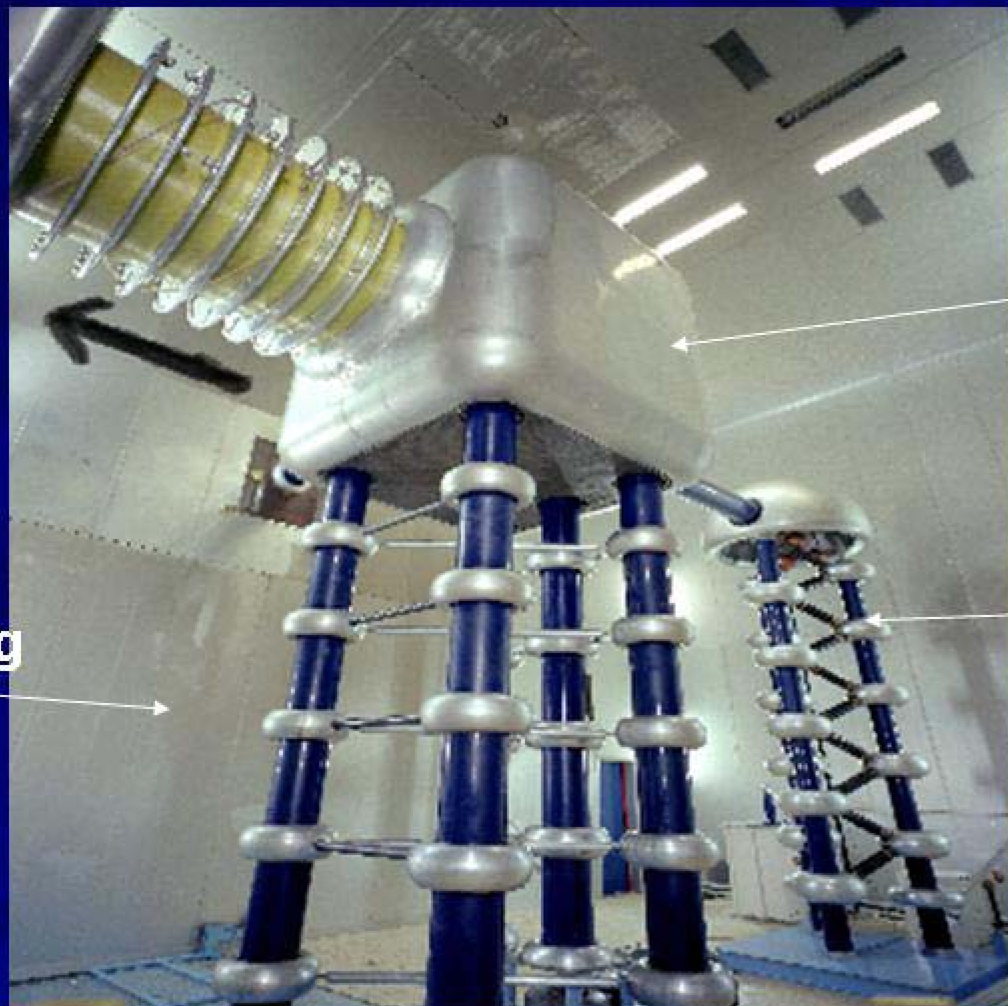
World's Pre-eminent HEP Laboratory



Accelerator Overview



Cockcroft-Walton Accelerator



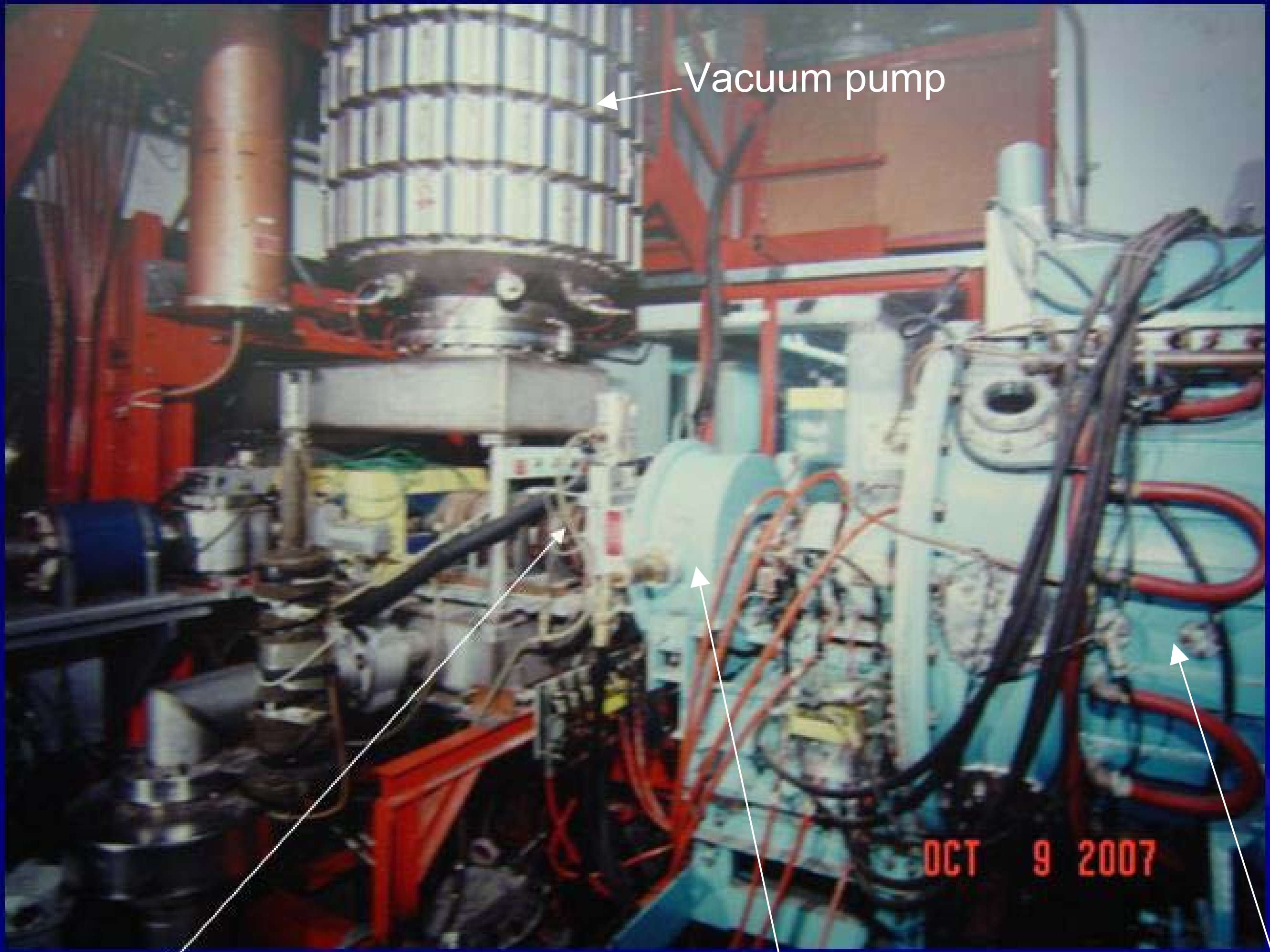
1928

Inside the Dome

H gas cylinder

A magnetron creates the H- ions and sends them on to their first major acceleration

Beam injection point to LINAC



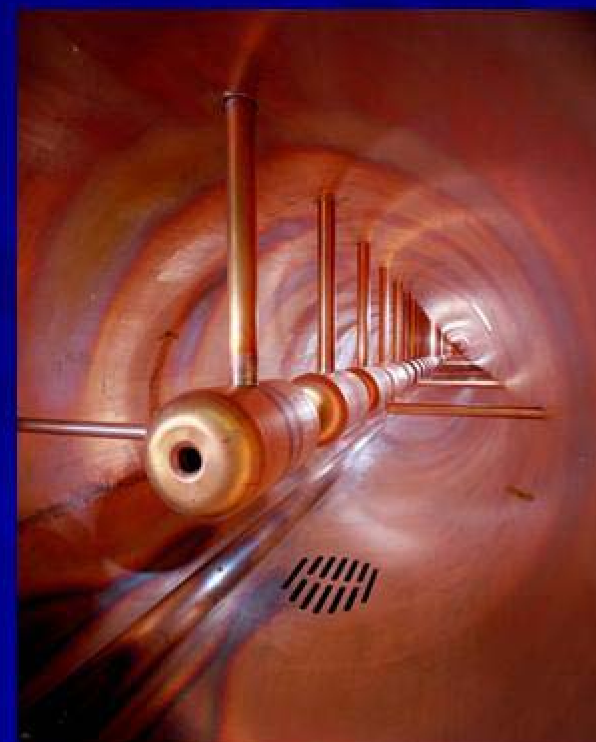
Injection point to Linac

Pre-bunching cavity

First Alvarez
LINAC tank

Alvarez Linac (201MHz) (Vrf ??)

Accelerating Modules



Accelerating Structure inside

Disk-Loaded Side-Coupled Linac

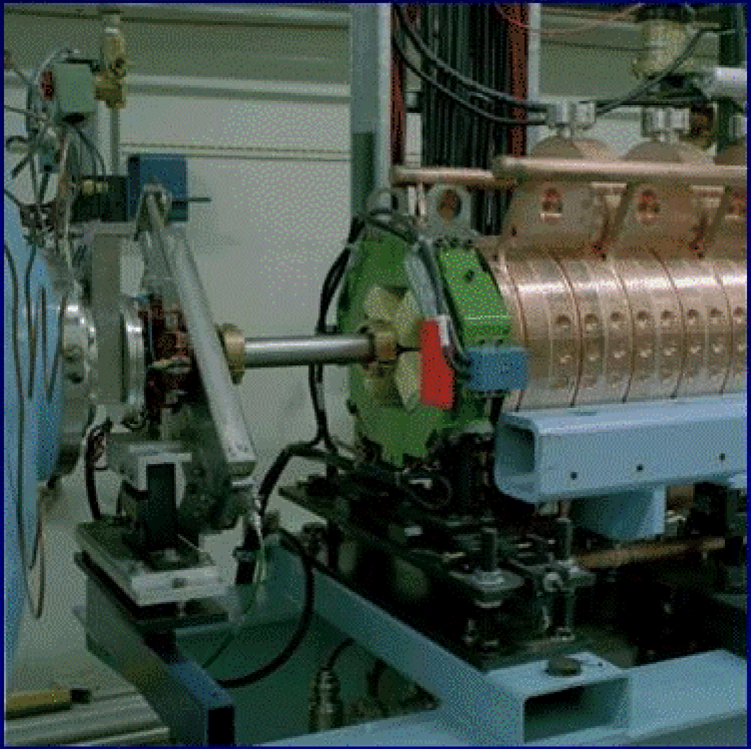


Figure 6.1

Aerial View showing Fermilab Booster

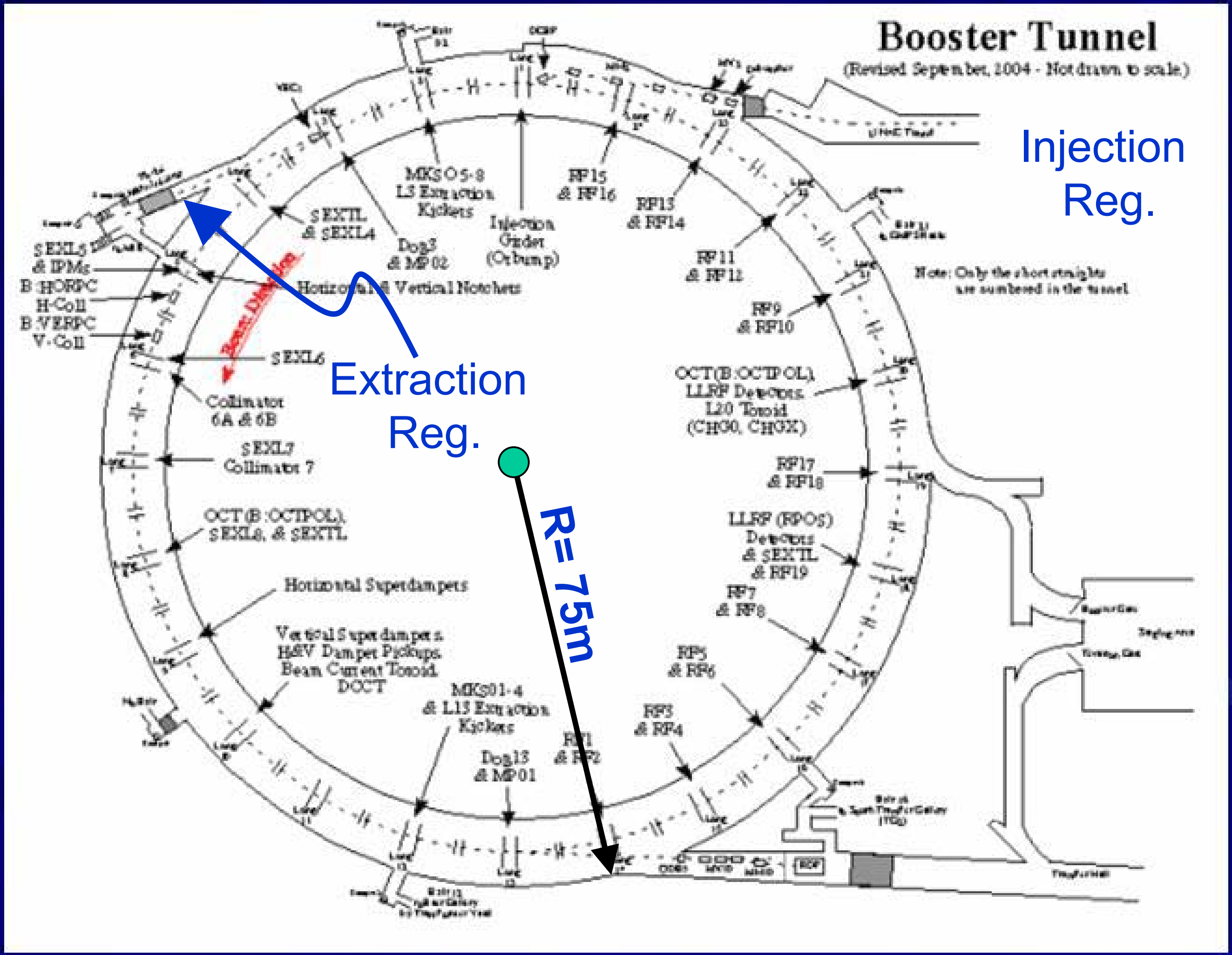
Booster Machine Parameters

Circumference...............................2π x 74.47 meters
Injection energy.............................400 Mev (kinetic)
Extraction energy...........................8 Gev (kinetic)
Cycle time...................................1/15 sec
Harmonic number, h.......................84
Transition gamma...........................5.45
Injection Frequency........................37.77 Mhz
Extraction Frequency......................52.81 Mhz
Maximaum RF voltage.....................0.86 MV
Longitudinal emittance....................0.25 eV sec
Horizontal β max...........................33.7 meters
Vertical β max...............................20.5 meters
Maximum dispersion......................3.2 meters
Tune $\upsilon x = \upsilon y$................................6.7
Transverse emittance(normailized).....12π mm rad
Bend magnet length........................2.9 meters
Standard cell length........................19.76 meters
Bend magnets per cell 4
Bend magnets total.........................96
Typical bunch intensity...................3 x 10e10
Phase advance per cell....................96 degs
Cell type.......................FOFDOOD (DOODFOF)

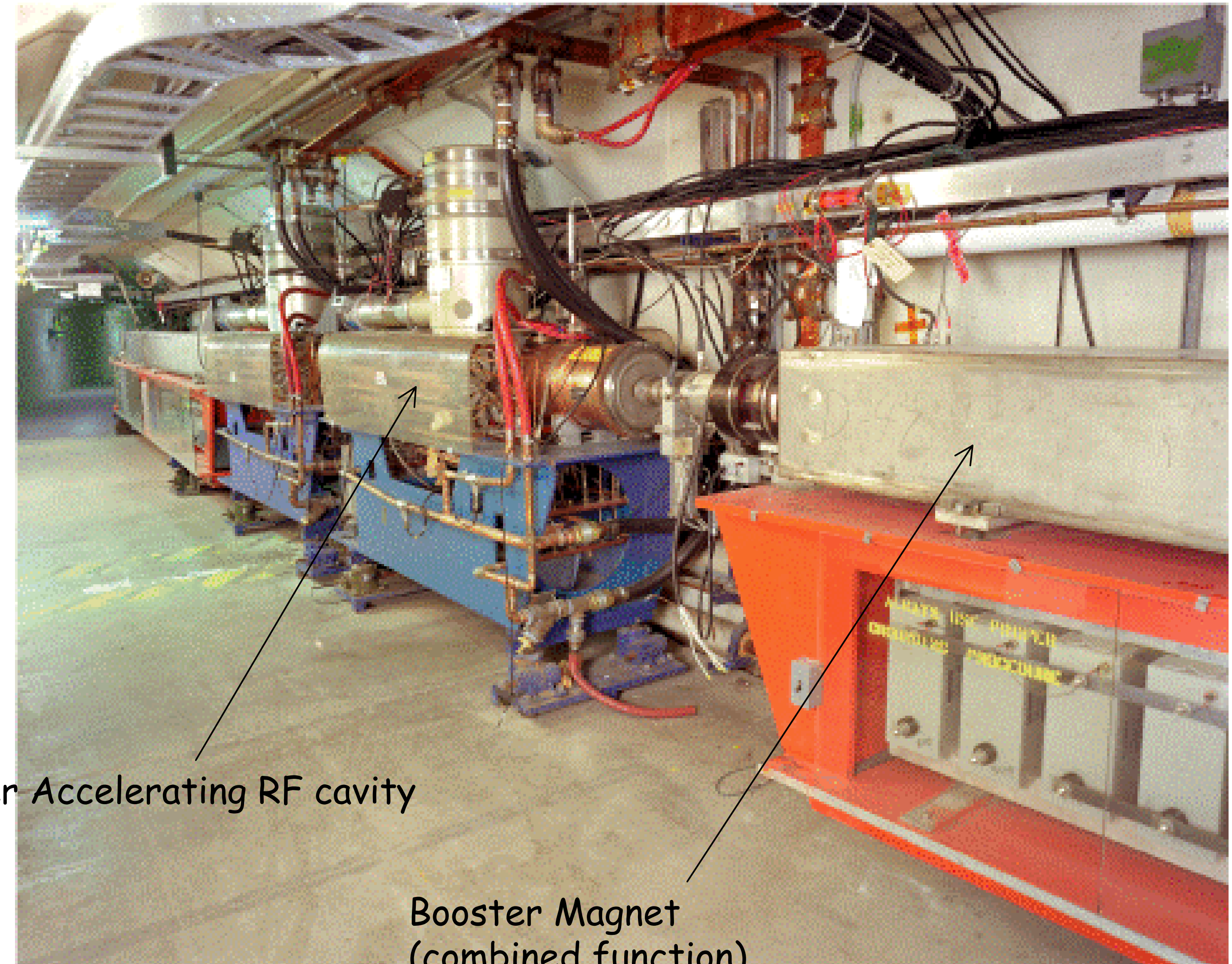
RF frequency Change during beam acceleration

Combined function Magnets

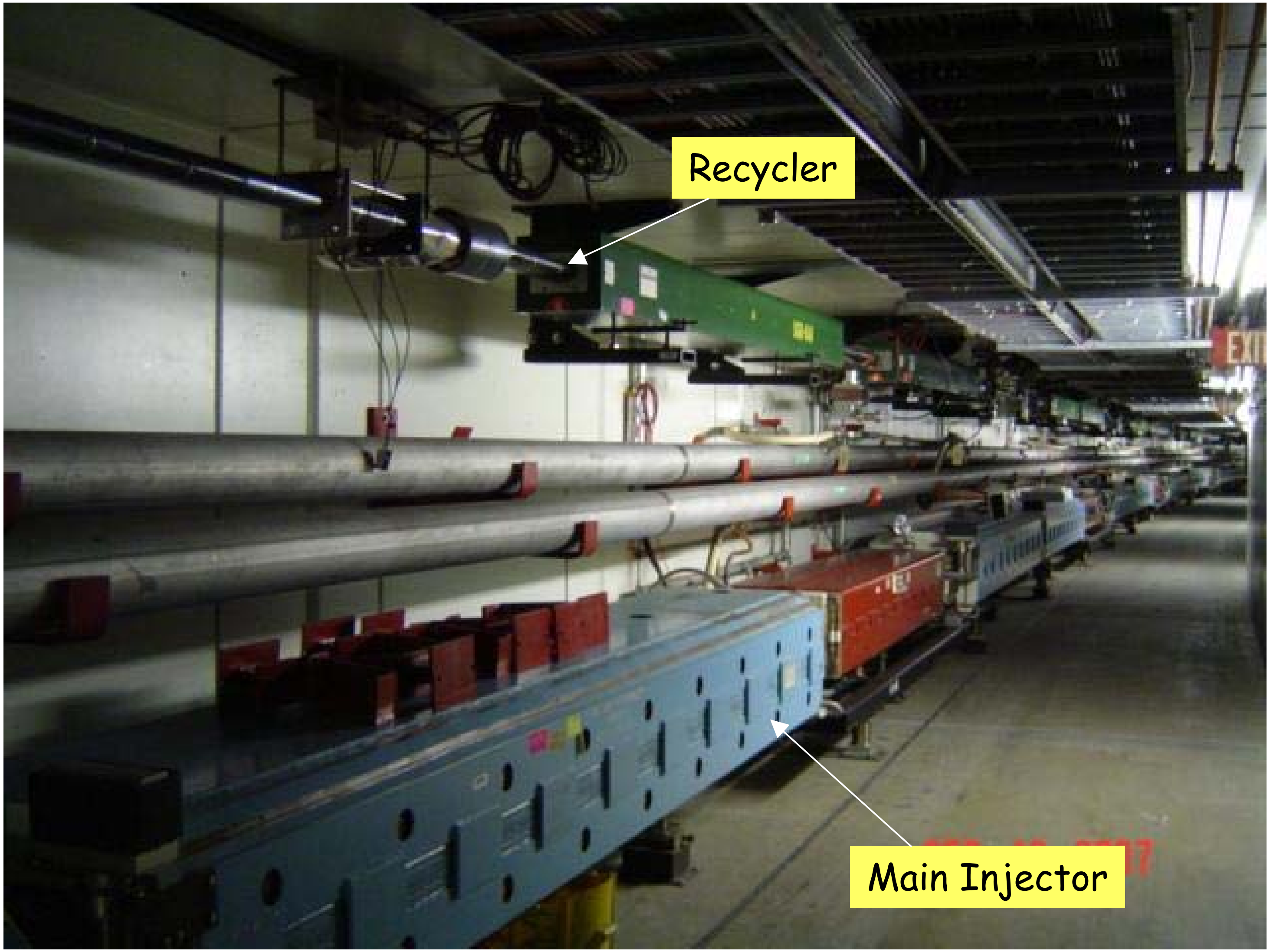
Booster Lay out



8 GeV Booster



Main Injector and Recycler



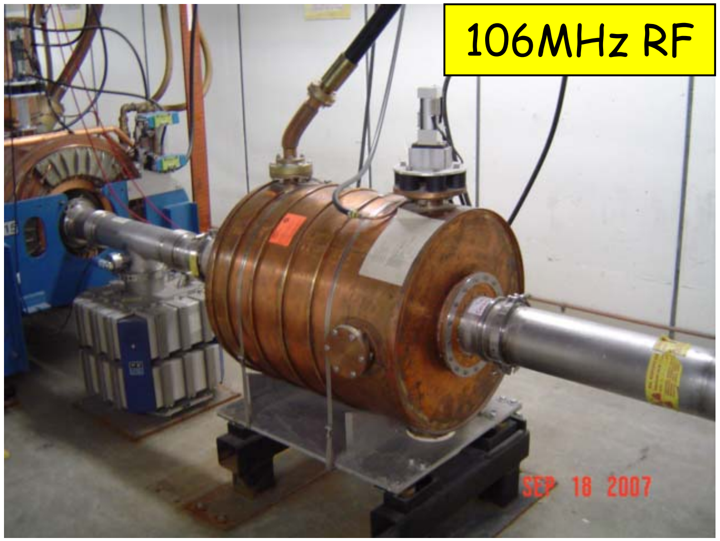
Main Injector Parameters

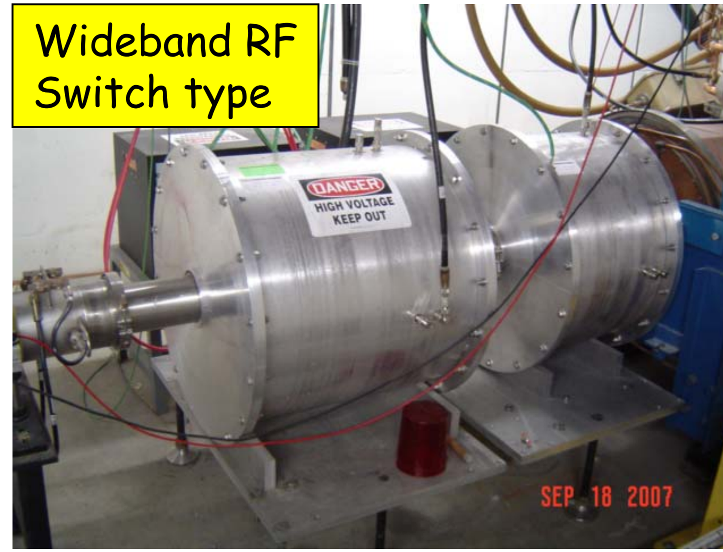
Circumference	3319.419	m
Injection Momentum	8.9	GeV/c
Peak Momentum	150	GeV/c
Minimum Cycle Time (@120 GeV)	< 1.5	s
Minimum Cycle Time (@150 GeV)	2.4	s
Number of Protons	3×10^{13}	
Number of Bunches	498	
Protons/Bunch	6×10^{10}	
Max. Courant-Snyder Amplitude Function (β_{max})	57	m
Maximum Dispersion Function	1.9	m
Phase Advance per Cell	90	degrees
Nominal Horizontal Tune	26.425	
Nominal Vertical Tune	25.415	
Natural Chromaticity (H)	-33.6	
Natural Chromaticity (V)	-33.9	
Transverse Admittance (@ 8.9 GeV)	> 40p	mm-mr
Longitudinal Admittance	> 0.5	eVs
Transverse Emittance (Normalized)	12p	mm-mr
Longitudinal Emittance	0.2	eVs

Harmonic Number (@53 MHz)	588	
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.1	MHz
RF Voltage	4	MV
Transition Gamma	21.8	
Superperiodicity	2	
Number of Straight Sections	8	
Length of Standard Cell	34.5772	m
Length of Dispersion-Suppresser Cell	25.9330	m
Number of Dipoles	216/128	
Dipole Lengths	6.1/4.1	m
Dipole Field (@150 GeV)	17.2	kG
Dipole Field (@8.9 GeV)	1.0	kG
Number of Quadrupoles	128/32/48	
Quadrupole Lengths	2.13/2.54/2.95	m
Quadrupole Gradient at 150 GeV	200	kG/m
Number of Quadrupole Busses	2	

Main Injector RF section

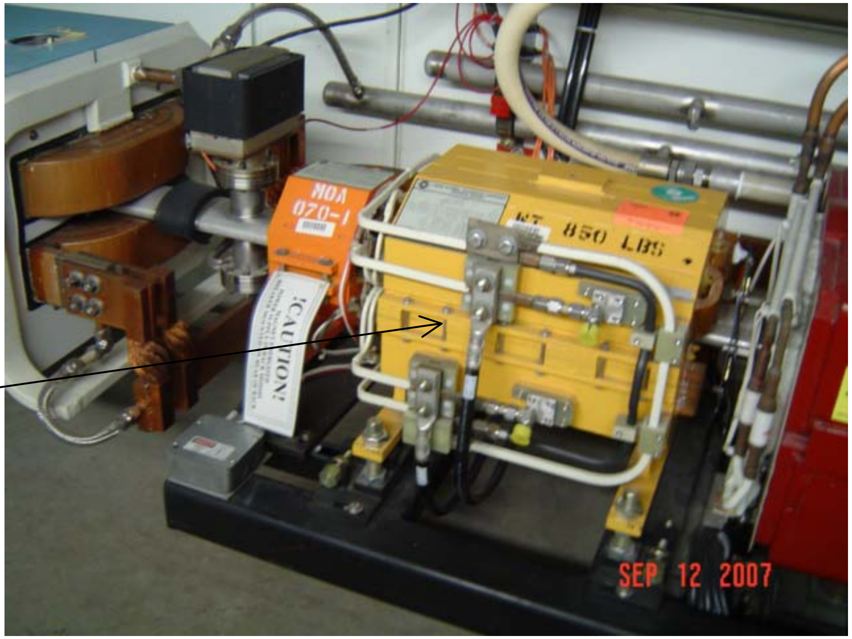
Main Injector RF section





Example of Main Injector Magnets

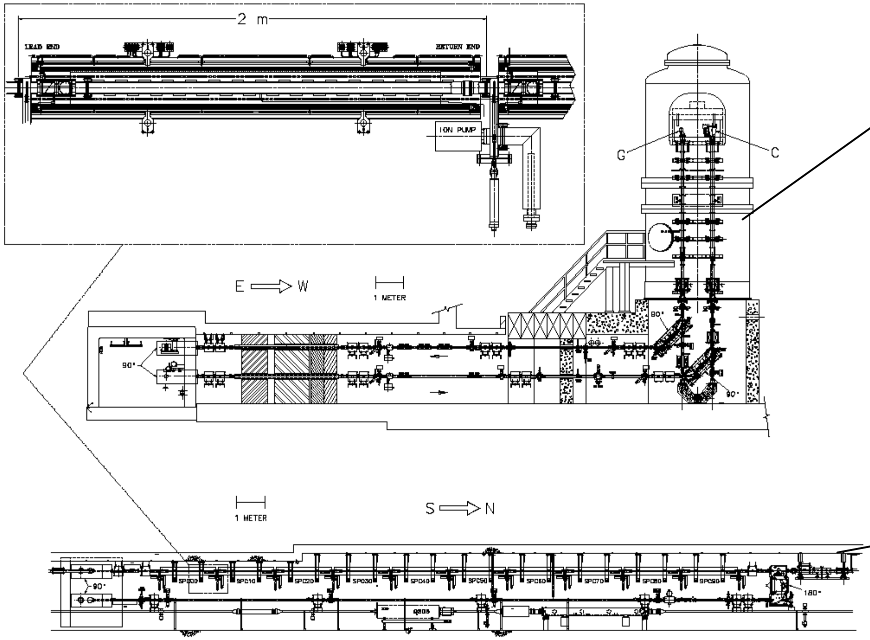
Large aperture Quad

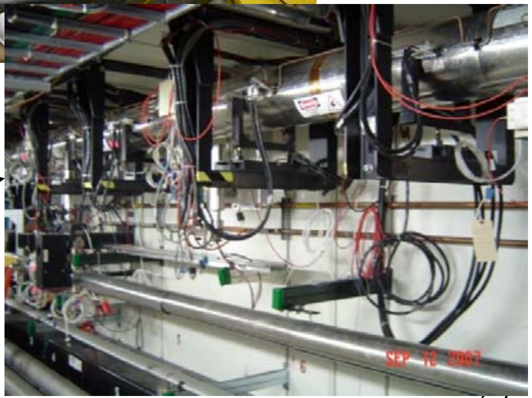


Sextupole magnet

Pelletron for antiproton cooling using e beam

- Electron kinetic energy 4.34 MeV
- Absolute precision of energy ≤ 0.3 %
- Energy ripple ≤ 10^{-4}
- Beam current 0.5 A DC
- Duty factor (averaged over 8 h) 95 %
- Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms ≤ 0.2 mrad





Recycler Parameters
(permanent magnet storage ring)

Circumference	3319.400	m	Superperiodicity	2	
Momentum	8.889	GeV/c	Number of Straight Sections	8	
Number of Antiprotons	2.5×10^{12}	~5E12	No. of Standard Cells in Straight Sections	18	
			Number of Standard Cells in Arcs	54	
Maximum Beta Function	55	m	Number of Dispersion Suppression Cells	32	
Maximum Dispersion Function	2.0	m	Length of Standard Cells	34.576	m
Horizontal Phase Advance per Cell	86.8	degrees	Length of Dispersion Suppression Cells	25.933	m
Vertical Phase Advance per Cell	79.3	degrees			
Nominal Horizontal Tune	25.425		Number of Gradient Magnets	108/108/128	
Nominal Vertical Tune	24.415		Magnetic Length of Gradient Magnets	4.267/4.267/2.845	m
Nominal Horizontal Chromaticity	-2		Bend Field of Gradient Magnets	1.45/1.45/1.45	kG
Nominal Vertical Chromaticity	-2		Quadrupole Field of Gradient Magnets	3.6/-3.6/7.1	kG/m
Transition Gamma	20.7		Sextupole Field of Gradient Magnets	3.3/-5.9/0	kG/m^2
			Number of Lattice Quadrupoles	72	
Transverse Admittance	40	π mmmr	Magnetic Length of Quadrupoles	0.5	m
Fractional Momentum Aperture	1%		Strength of Quadrupoles	30	kG/m

Uses Combined function Magnets
Barrier RF system
Electron cooling and Stochastic cooling

Antiproton Source

Accumulator and Debuncher rings

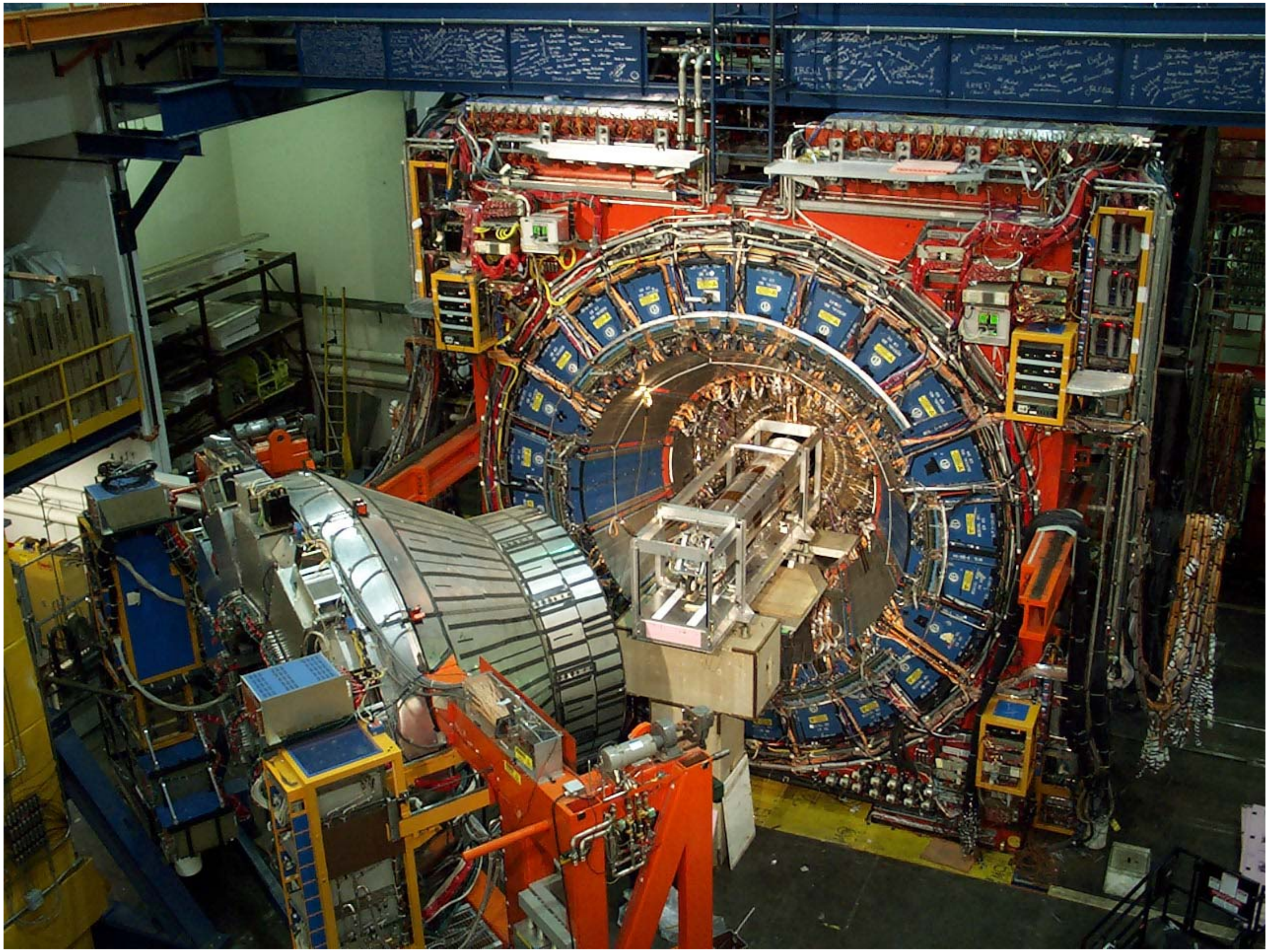
Tevatron Tunnel

Tevatron Parameters

	TEVATRON (Fermilab)
Physics start date	1987
Physics end date	—
Particles collided	$p\bar{p}$
Maximum beam energy (TeV)	0.980
Luminosity (10^{30} cm^{-2}s^{-1})	171
Time between collisions (ns)	396
Crossing angle (μ rad)	0
Energy spread (units 10^{-3})	0.14
Bunch length (cm)	p: 50 $\bar{p}$: 45
Beam radius (10^{-6} m)	p: 29 $\bar{p}$: 21
Free space at interaction point (m)	± 6.5
Luminosity lifetime (hr)	7 (average, start of store)
Filling time (min)	30
Acceleration period (s)	86
Injection energy (TeV)	0.15
Transverse emittance ($10^{-9}\pi$ rad-m)	p: 3 $\bar{p}$: 1.5
β^*, ampl. function at interaction point (m)	0.28

Beam-beam tune shift per crossing (units 10^{-4})	p: 50 $\bar{p}$: 100
RF frequency (MHz)	53
Particles per bunch (units 10^{10})	p: 24 $\bar{p}$: 6
Bunches per ring per species	36
Average beam current per species (mA)	p: 66 $\bar{p}$: 16
Circumference (km)	6.28
Interaction regions	2 high $\mathscr{L}$
Utility insertions	4
Magnetic length of dipole (m)	6.12
Length of standard cell (m)	59.5
Phase advance per cell (deg)	67.8
Dipoles in ring	774
Quadrupoles in ring	216
Magnet type	s.c. $\cos\theta$ warm iron
Peak magnetic field (T)	4.4
$\bar{p}$ source accum. rate (hr^{-1})	16×10^{10}
Max. no. $\bar{p}$ in accum. ring	2.4×10^{12}

CDF Collider Detector



The DØ Detector