Metody eksperymentalne w fizyce wysokich energii

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Wykład VIII

- Akceleratory czastek

Przygotowany w oparciu o materiały m.in. z

CERN Summer school 2008
Introduction to accelerators by Elias Metral and Simone Gilardoni

International School for Linear Colliders 2008
The Fermilab Accelerator Complex by R. Dixon

Lectures on Accelerators by Oliver Brüning

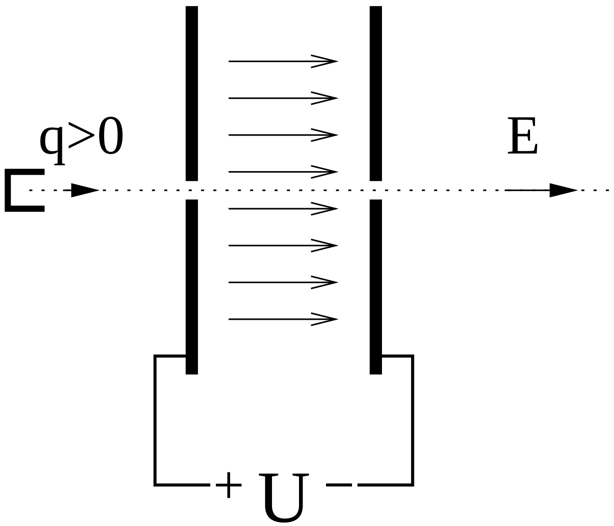
Akceleratory

Akceleratory elektrostatyczne

W 1919 roku Rutherford wskazał na korzyści z przyspieszania cząstek.

Najprostszym akceleratorem cząstek jest pole elektrostatyczne:

np. kondensator



Problemem jest uzyskanie odpowiednio wysokiej różnicy napięć:

⇒ generator Cockrofta-Waltona (1932): 750 kV

⇒ generator Van de Graaffa (1931): 1.5 MV

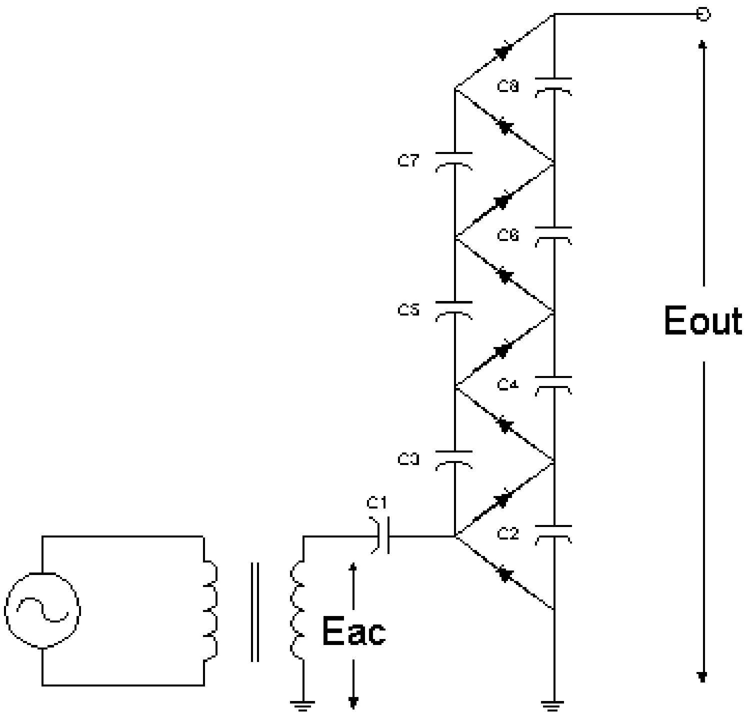
Uzyskiwana energia:

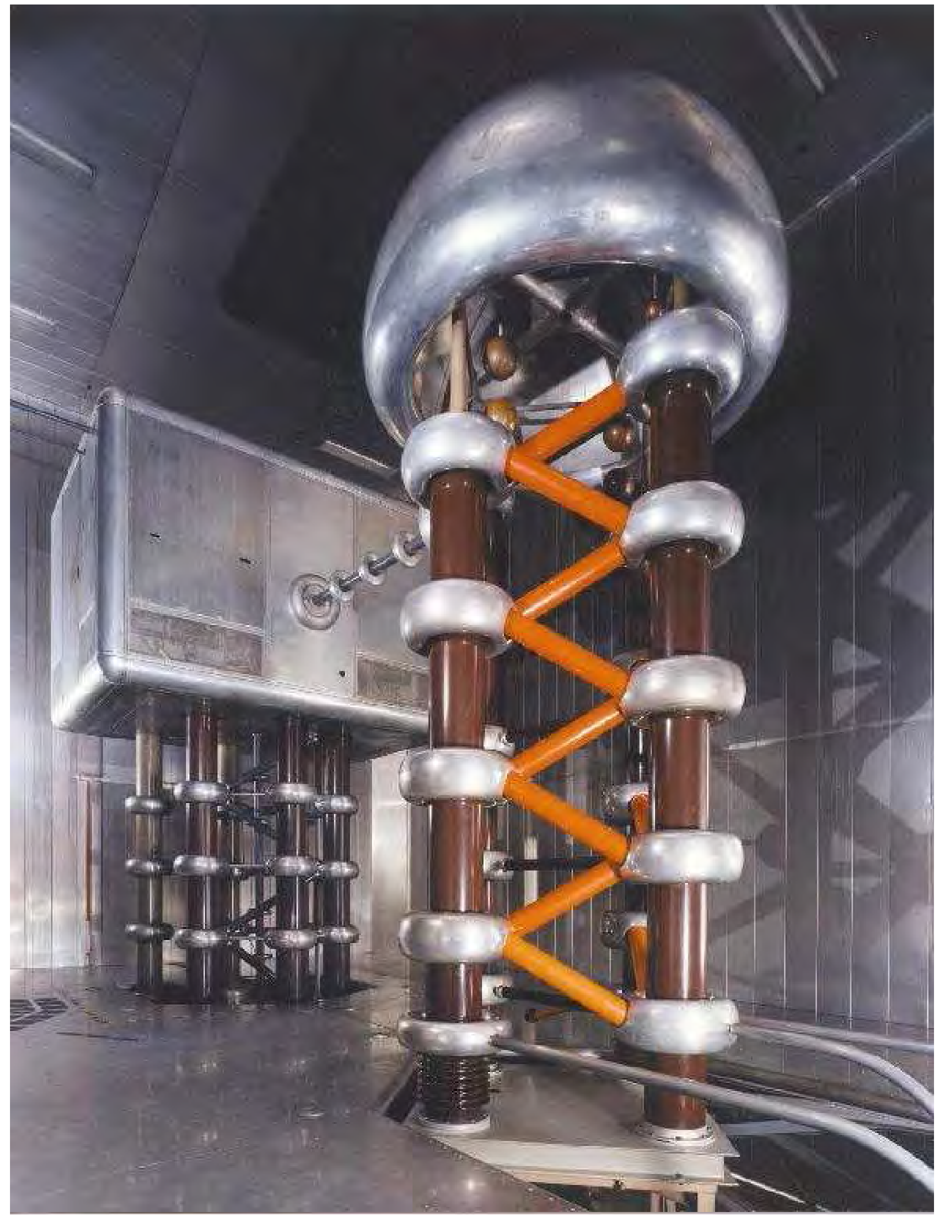
$$E = E_{\circ} + U \cdot q$$

Akceleratory

Generator Cockrofta-Waltona

Schemat

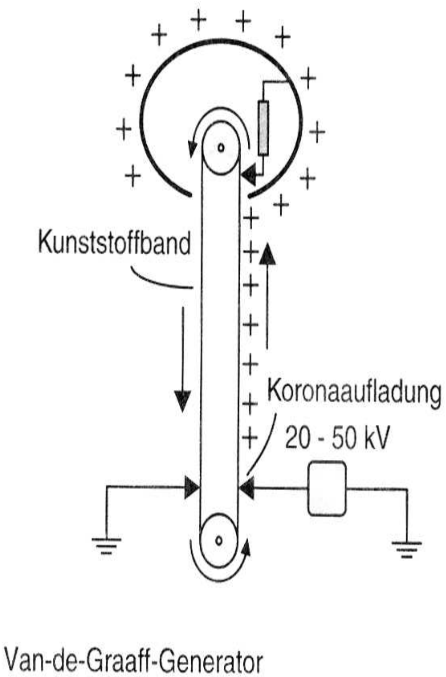




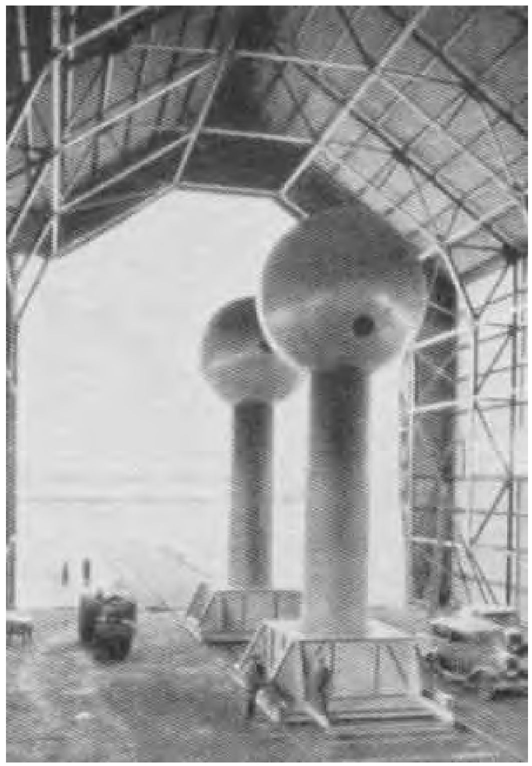
Akceleratory

Generator Van de Graaffa

Schemat



Historia

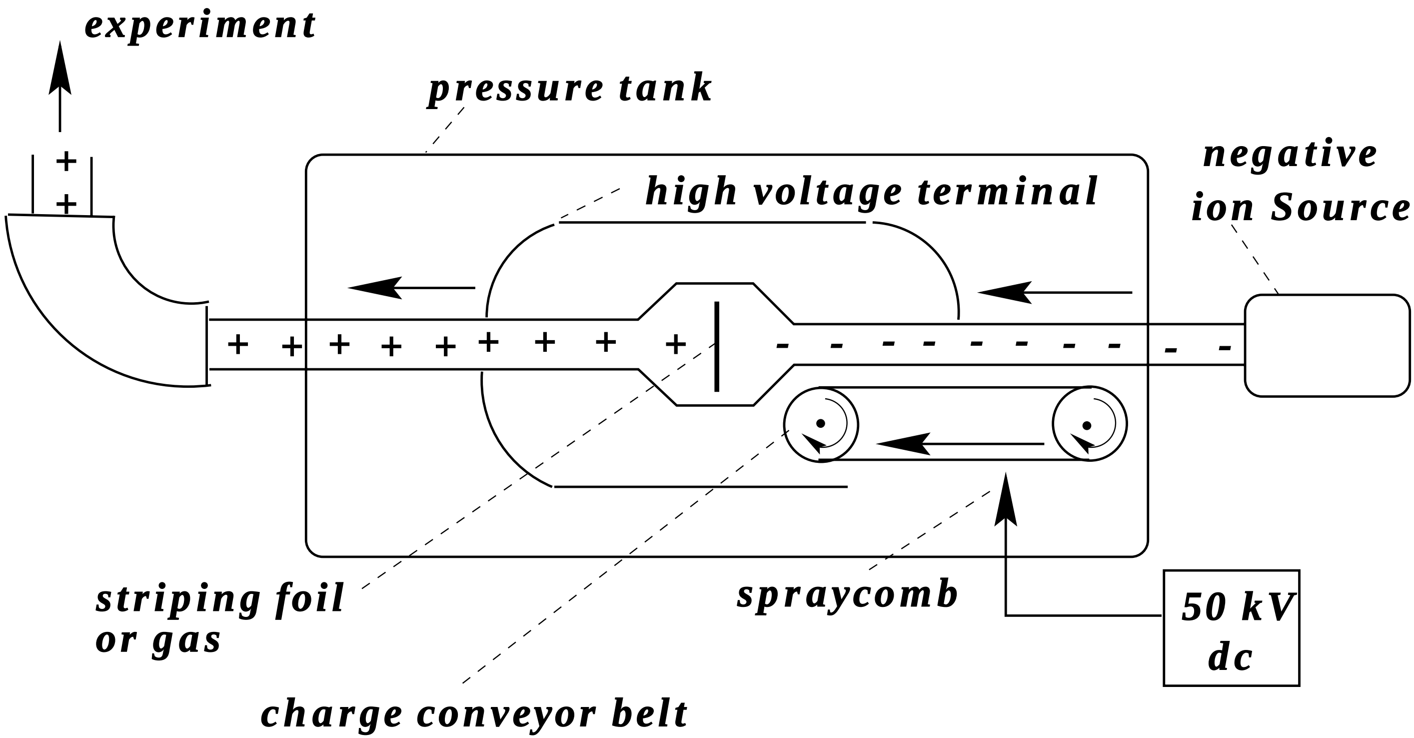


Współczesne urządzenie

Obecnie różnice napięć jakie potrafimy wytwarzać ograniczone są do rzędu 30 MV

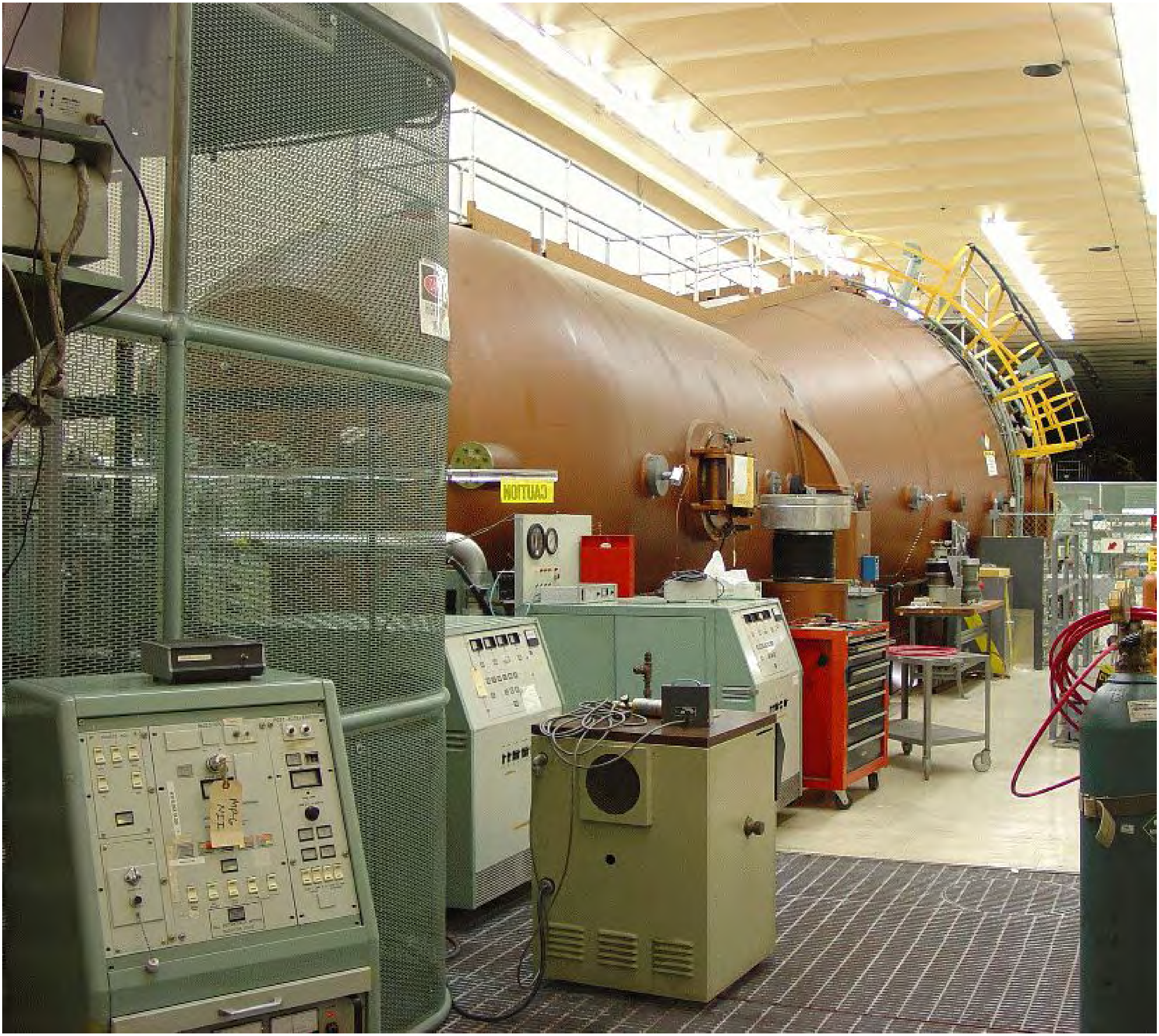
$\Rightarrow E \sim 30\ MeV$ $\Rightarrow$ **zbyt mało dla fizyki cząstek...**

Tandem generator:



$\rightarrow$ $V_{max} = 25$ MVolt

AGS Complex at BNL

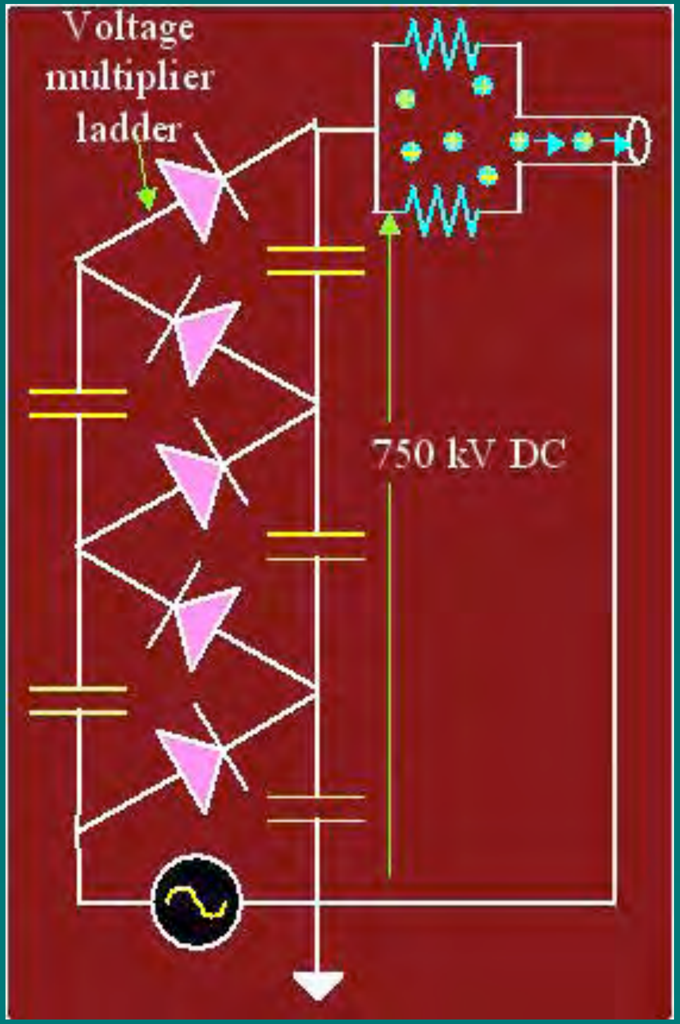


$\rightarrow$ $V_{max} = 29\ MVolt$

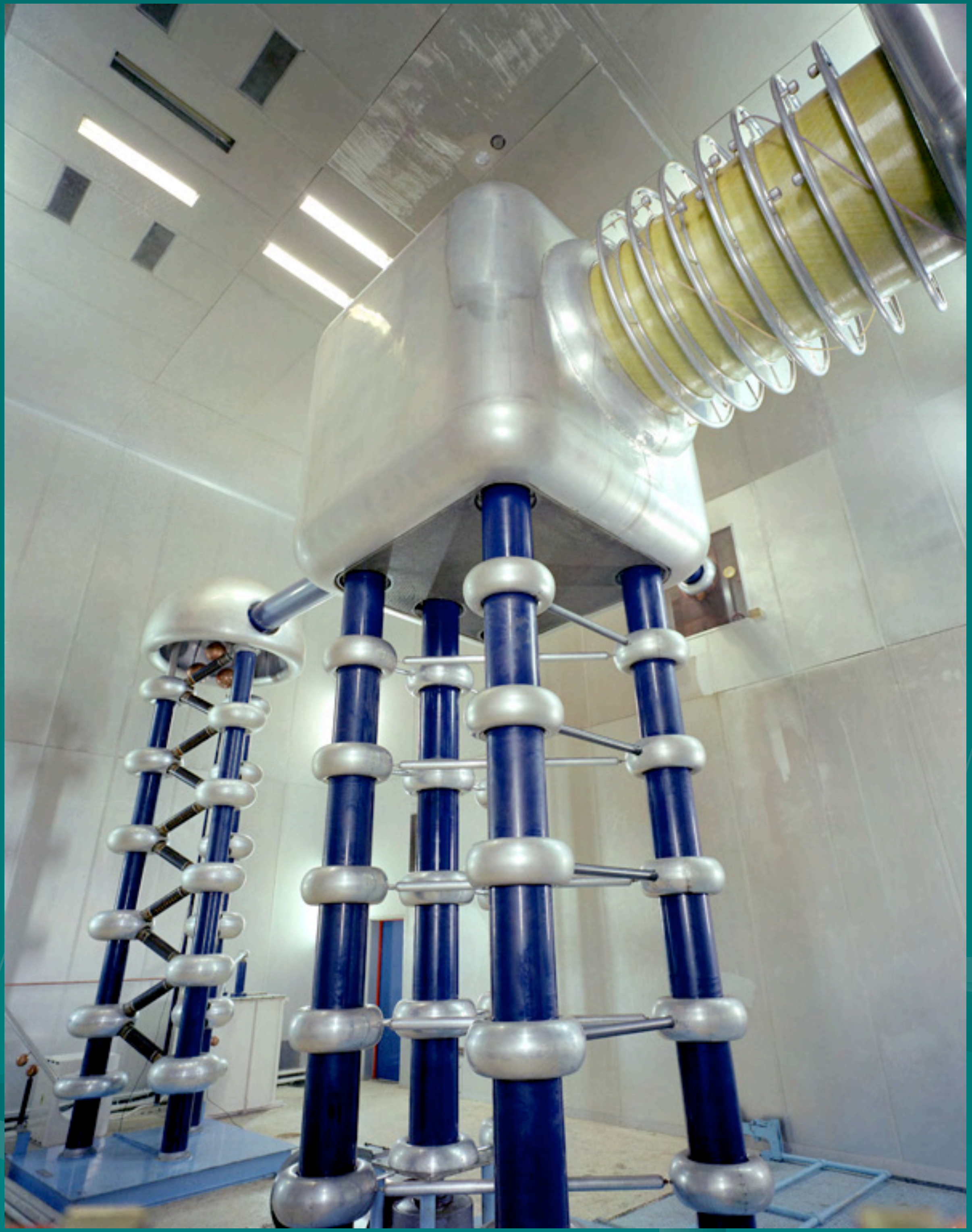
$\rightarrow$ $E_{max} = 29\ MeV\ (p);\ 385\ MeV\ (U)$

Cockroft Walton @ Tevatron

- Two 750 KeV H^- ma sources
- Beam is injected into the Linac from either source



Converts AC voltage V to DC voltage n x V

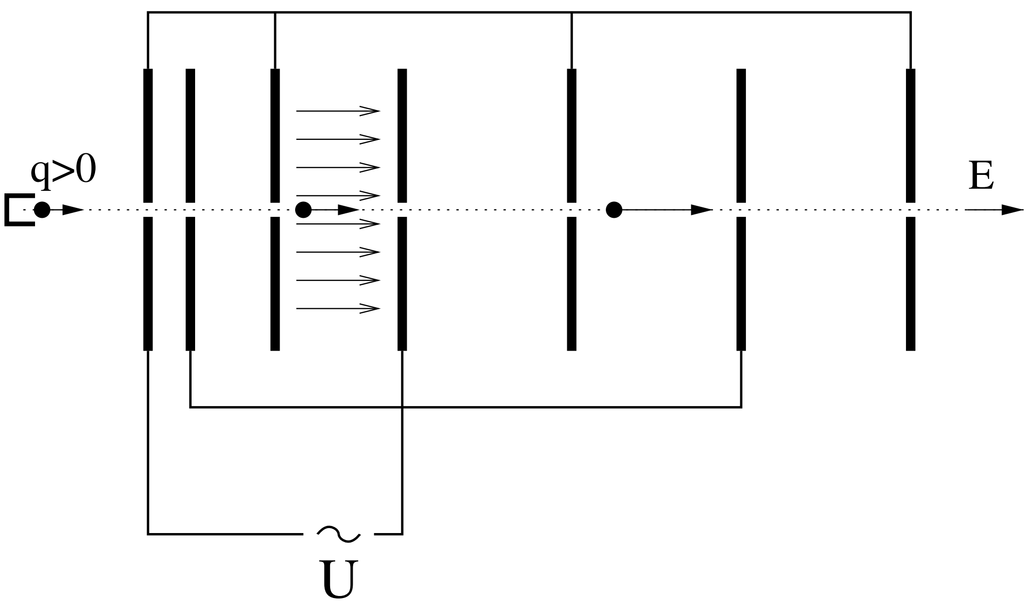


Akceleratory

Akcelerator liniowy

Idea: Gustav Ising 1924. Pierwsze urządzenia: Rolf Wideroe 1927, Lawrence 1931.

Cząstka przechodzi przez kolejne "kondensatory"



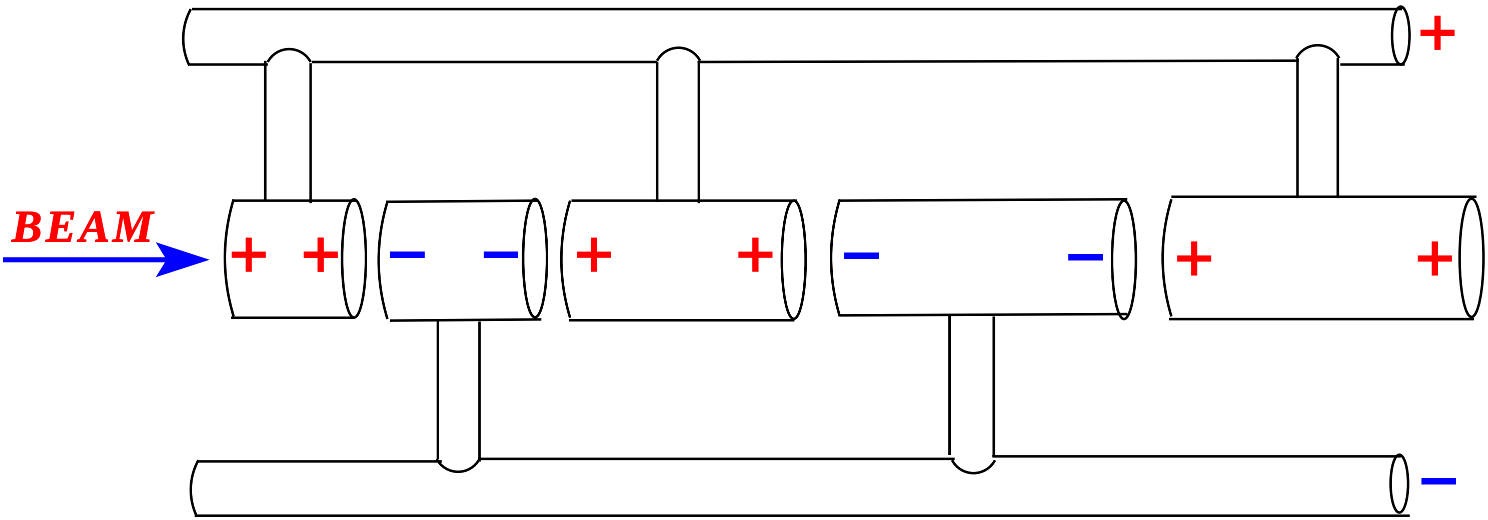
Przy odpowiednim dobraniu długości kolejnych elementów i częstości napięcia zasilającego, cząstka trafia zawsze na pole przyspieszające.

$\Rightarrow$ zwielokrotnienie uzyskiwanych energii

Częstość jest zazwyczaj stała. Długości kolejnych elementów rosną proporcjonalnie do prędkości cząstki.

Dla $E \gg m$, prędkość $\beta \to 1$: L=const.

Symmetric line:



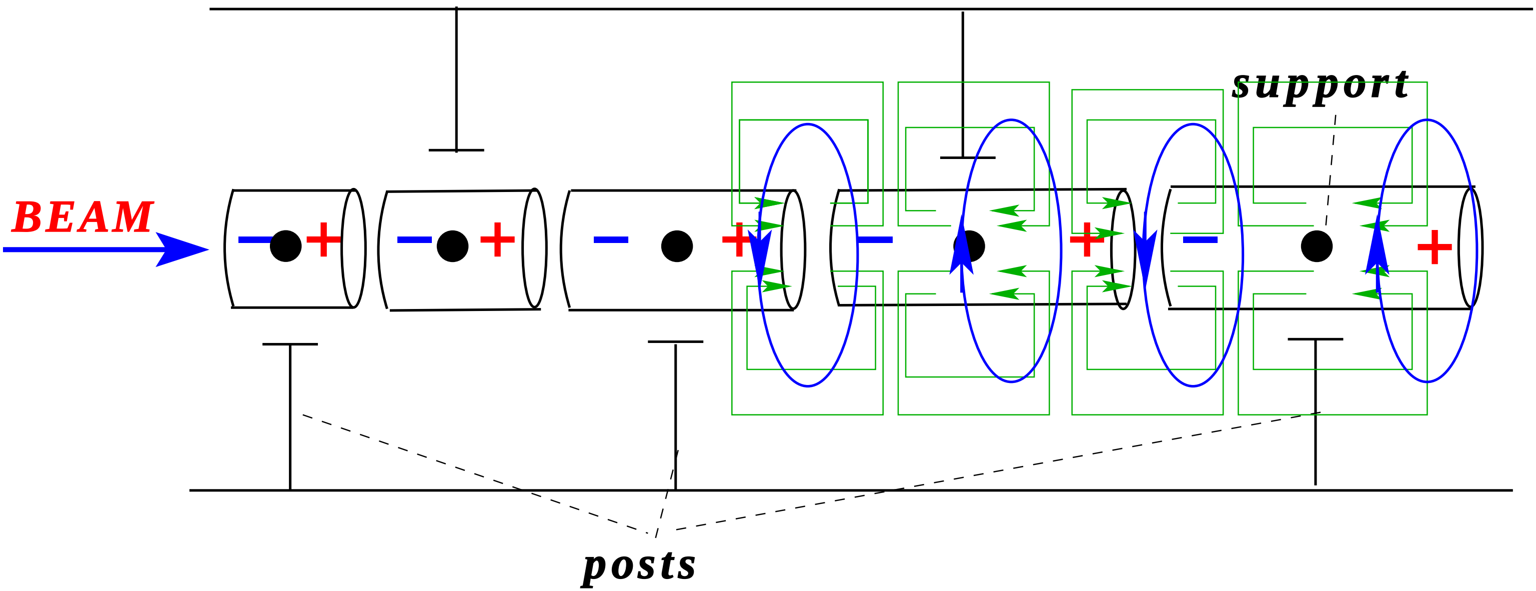
$l = v_{part} \cdot T/2$

- 1928: demonstrated by Wideroe

1MHz, 25kV oscillator → 50kV potassium ions

Alvarez: 1946

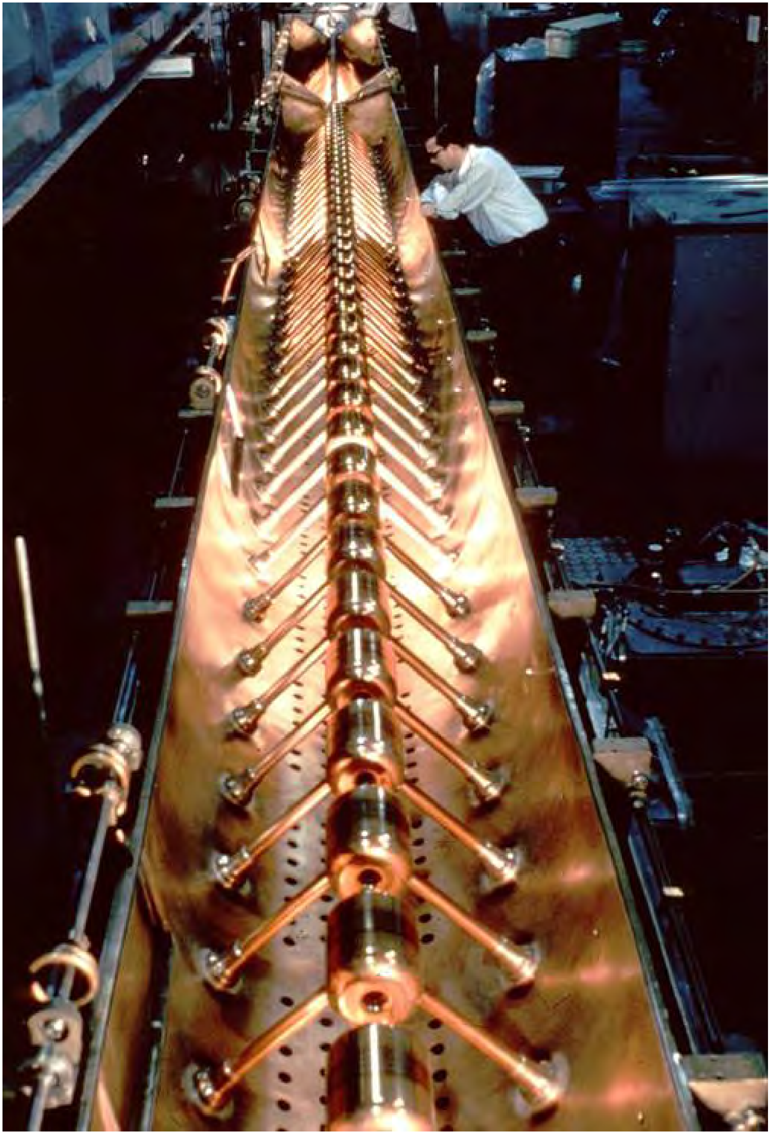
$$l = v_{part} \cdot \lambda / c$$



- ***Tubes are passive***

→ ***we can use high frequencies!***

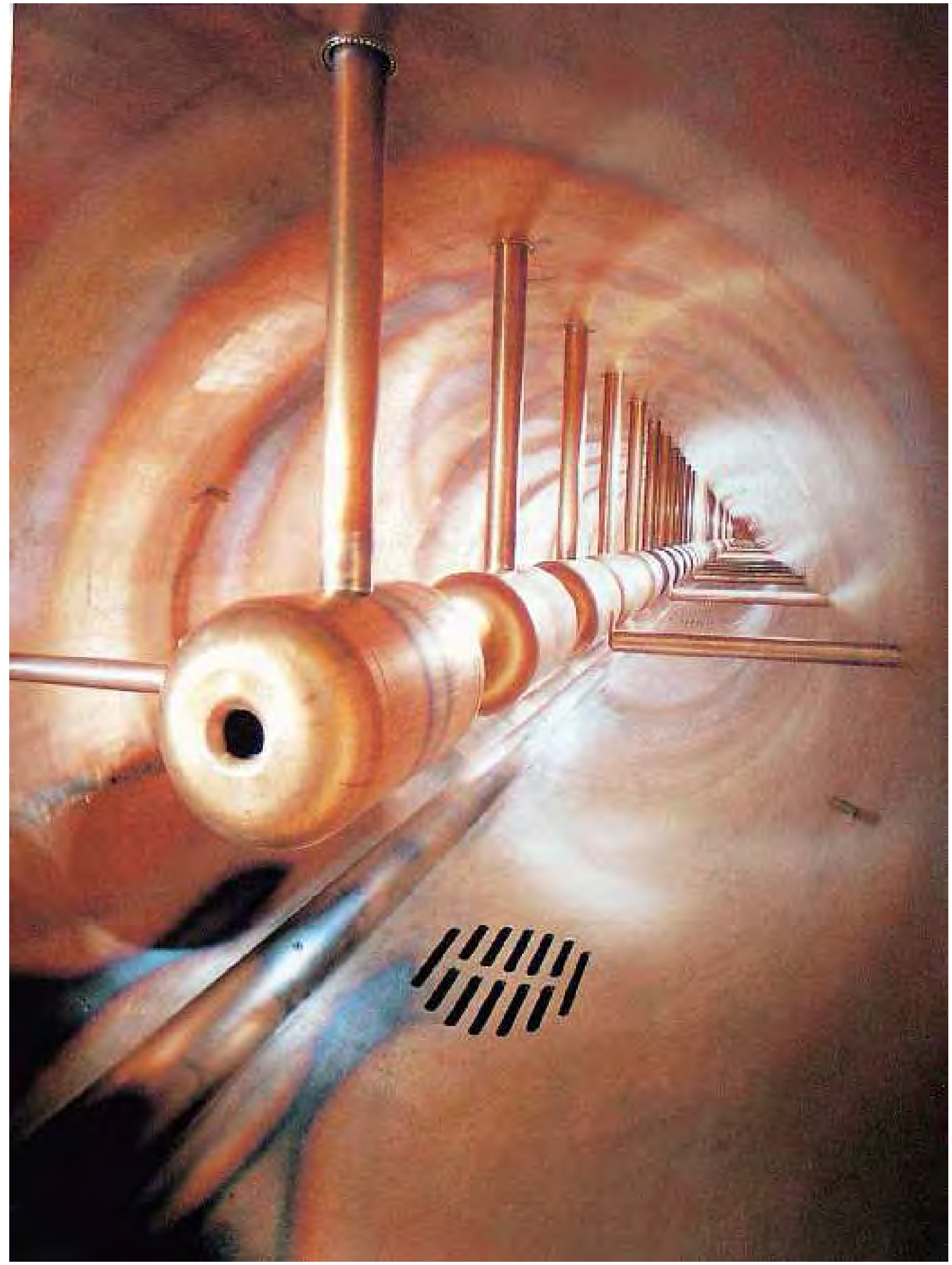
(f = 200 MHz gives good tube size)



Pre–accelerator for most accelerators:

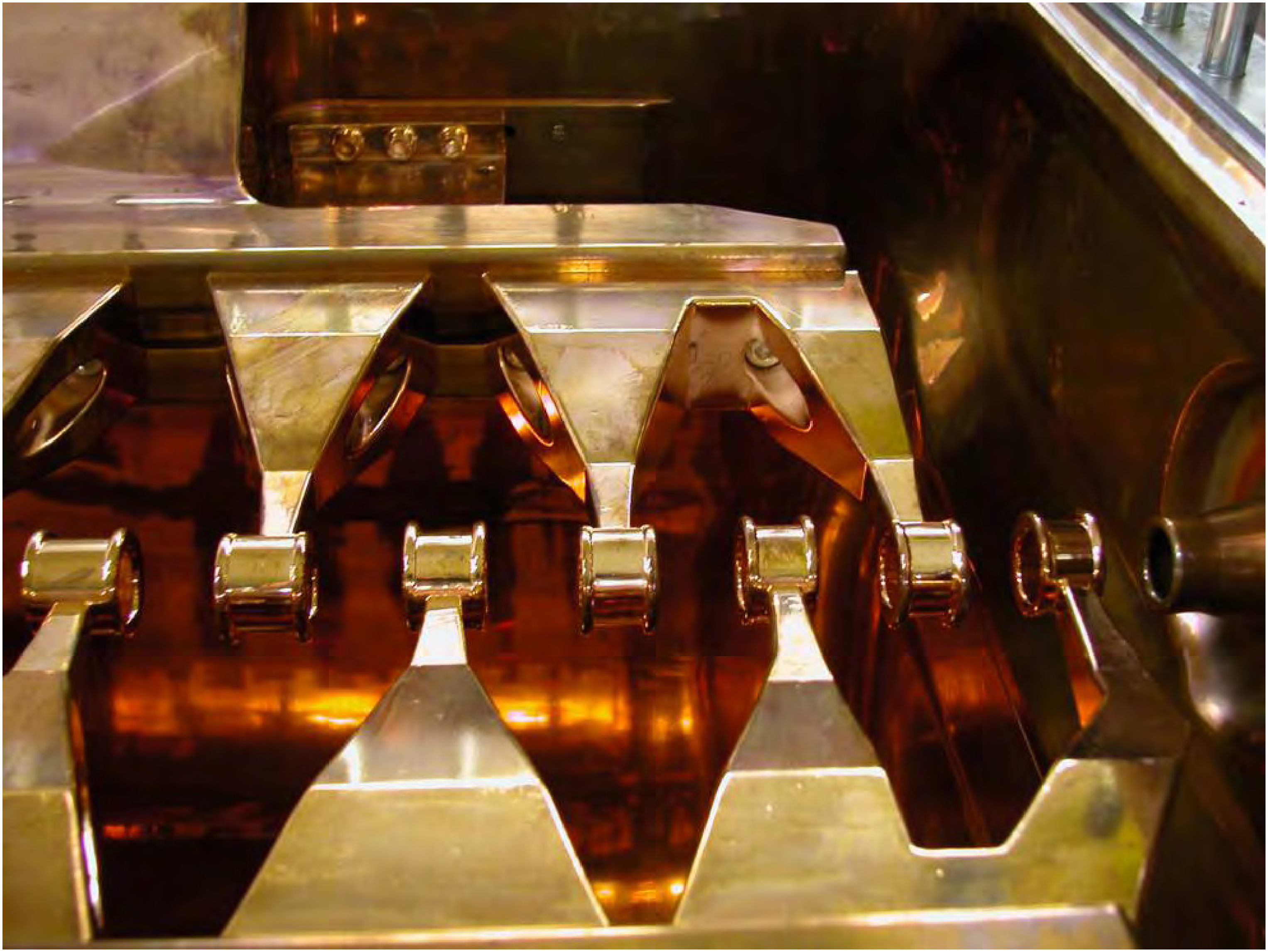
e.g. at CERN

Liniowy akcelerator protonów
w ośrodku Fermilab (USA)



Interdigital H Structure (TE−Modes)

used for the Pb ion acceleration at CERN

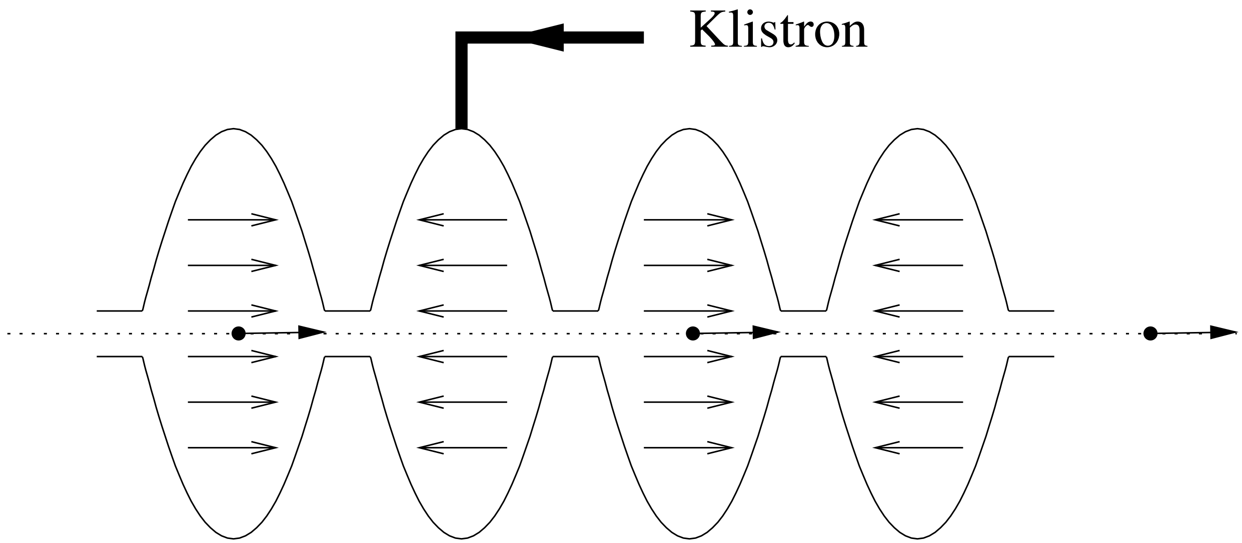


SPS at CERN

Akceleratory

Wnęka rezonansowa

W praktyce do przyspieszania cząstek wykorzystujemy wnęki rezonansowe:

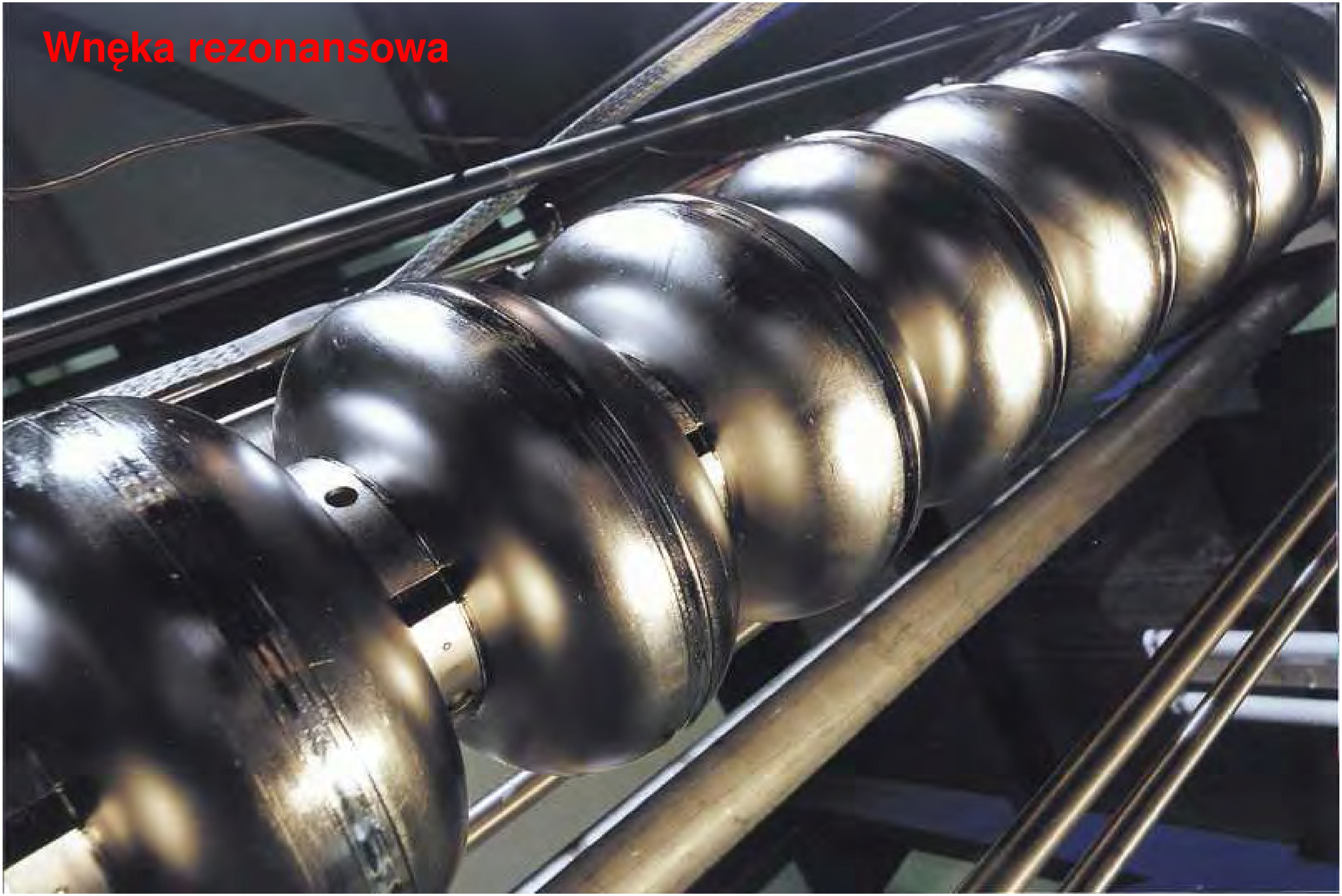


Wewnątrz wnęki wytwarzana jest stojąca fala elektromagnetyczna.

Częstości rzędu 1 GHz - mikrofale.

Wnęki rezonansowe pozwalają uzyskiwać natężenia pola rzędu 10 MV/m

$\Rightarrow$ dla uzyskania energii 1 GeV potrzebny jest akcelerator liniowy o długości $\sim$ 100 m


Wnęka rezonansowa

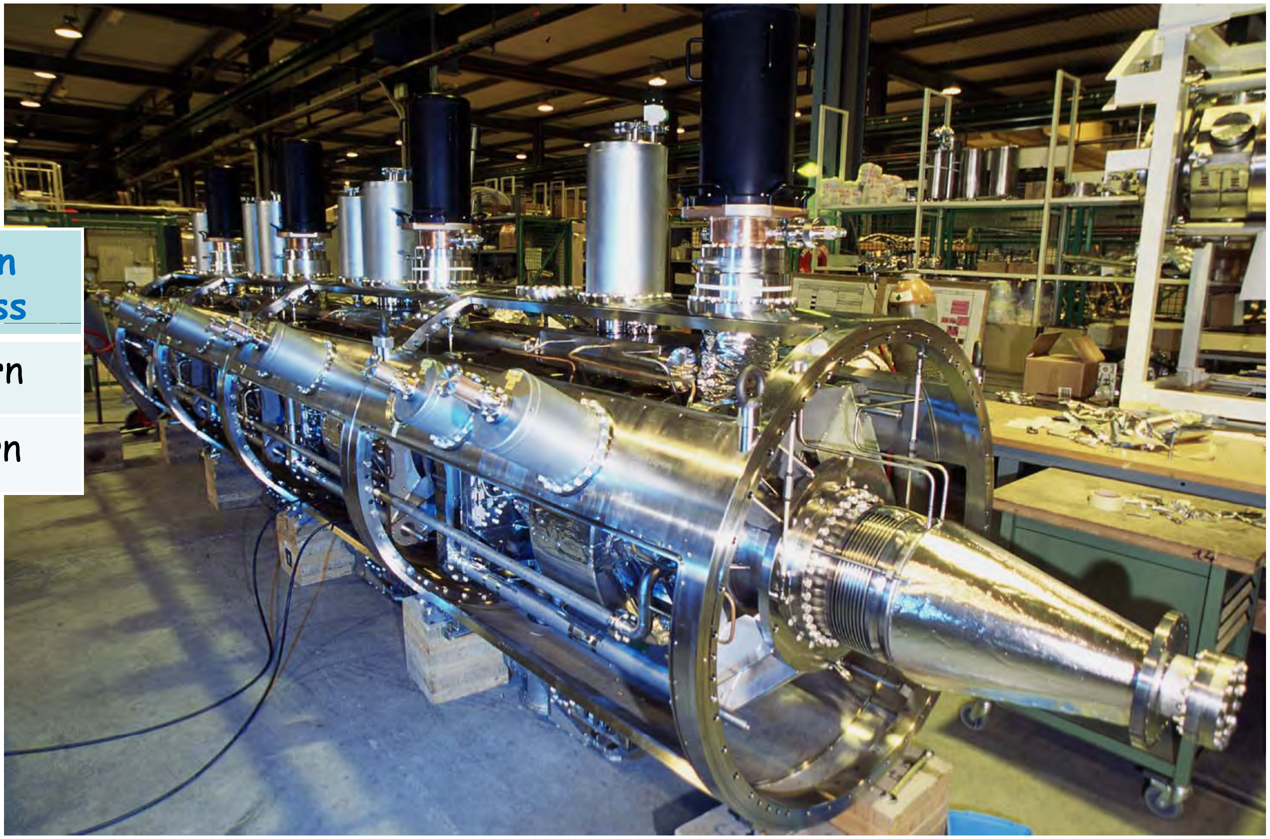
LHC RF system

- The LHC RF system operates at 400 MHz.
- It is composed of 16 superconducting cavities, 8 per beam.
- Peak accelerating voltage of 16 MV/beam.

For LEP at 104 GeV : 3600 MV/beam !

	Synchrotron radiation loss
LHC @ 7 TeV	6.7 keV /turn
LEP @ 104 GeV	~3 GeV /turn

The LHC beam radiates a sufficient amount of visible photons to be actually observable with a camera ! (total power ~ 0.2 W/m)



Akceleratory

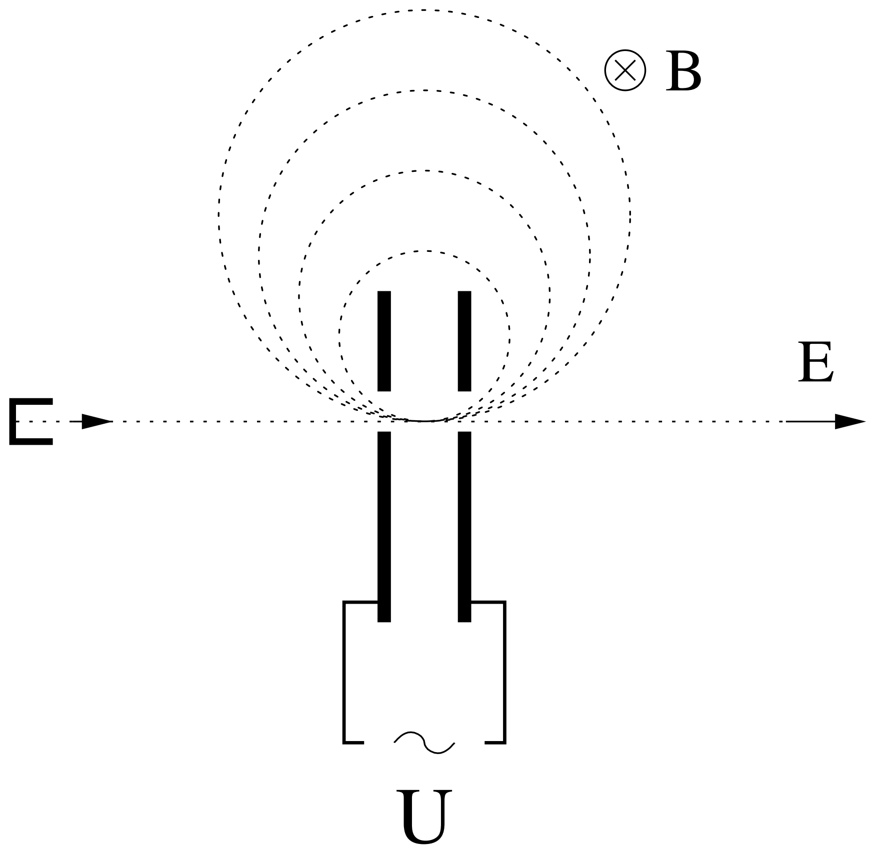
Akcelerator kołowy

Zamiast używać wielu wnęk możemy wykorzystać pole magnetyczne do "zapętlenia" cząstki.

Cząstki mogą przechodzić przez wnękę przyspieszającą wiele razy...

Pierwszy tego typu akcelerator (cyklotron) zbudował w 1931 roku Ernest Lawrence

Schemat poglądowy:

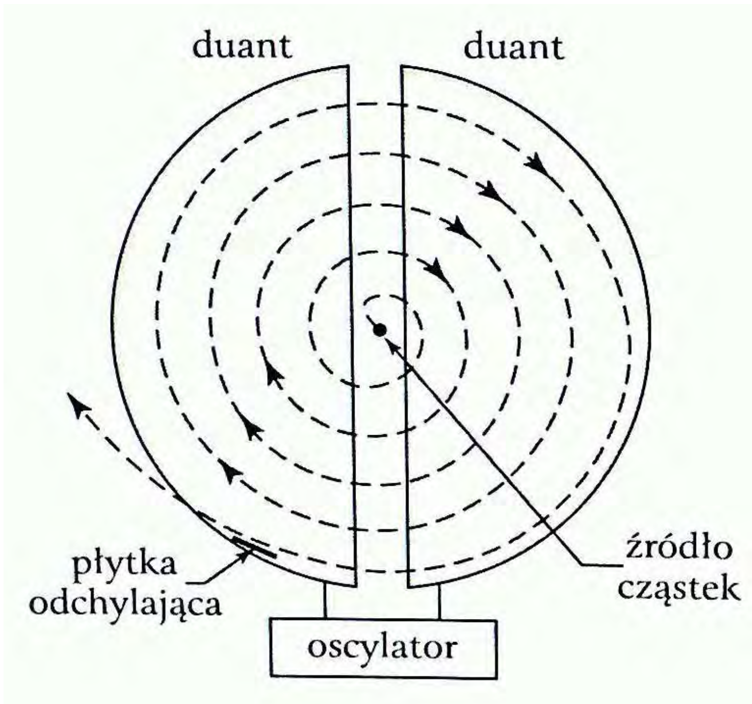


Akceleratory

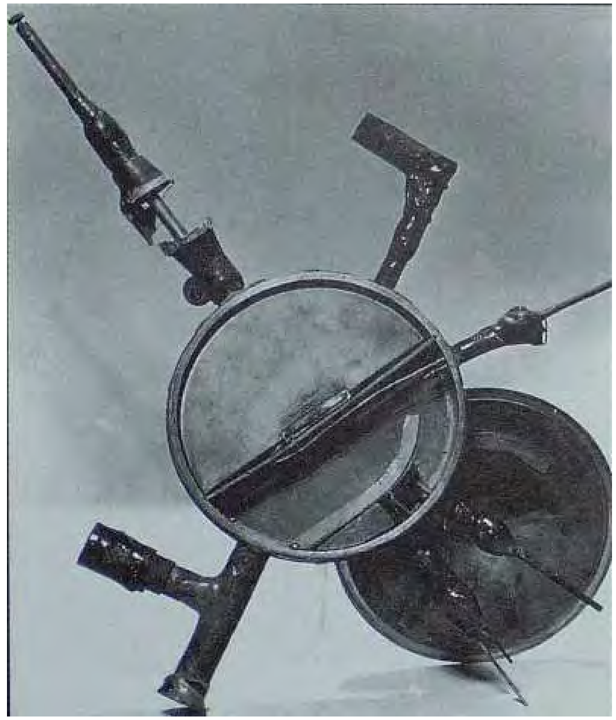
Cyklotron

Ernest Lawrence

Schemat



Pierwszy cyklotron



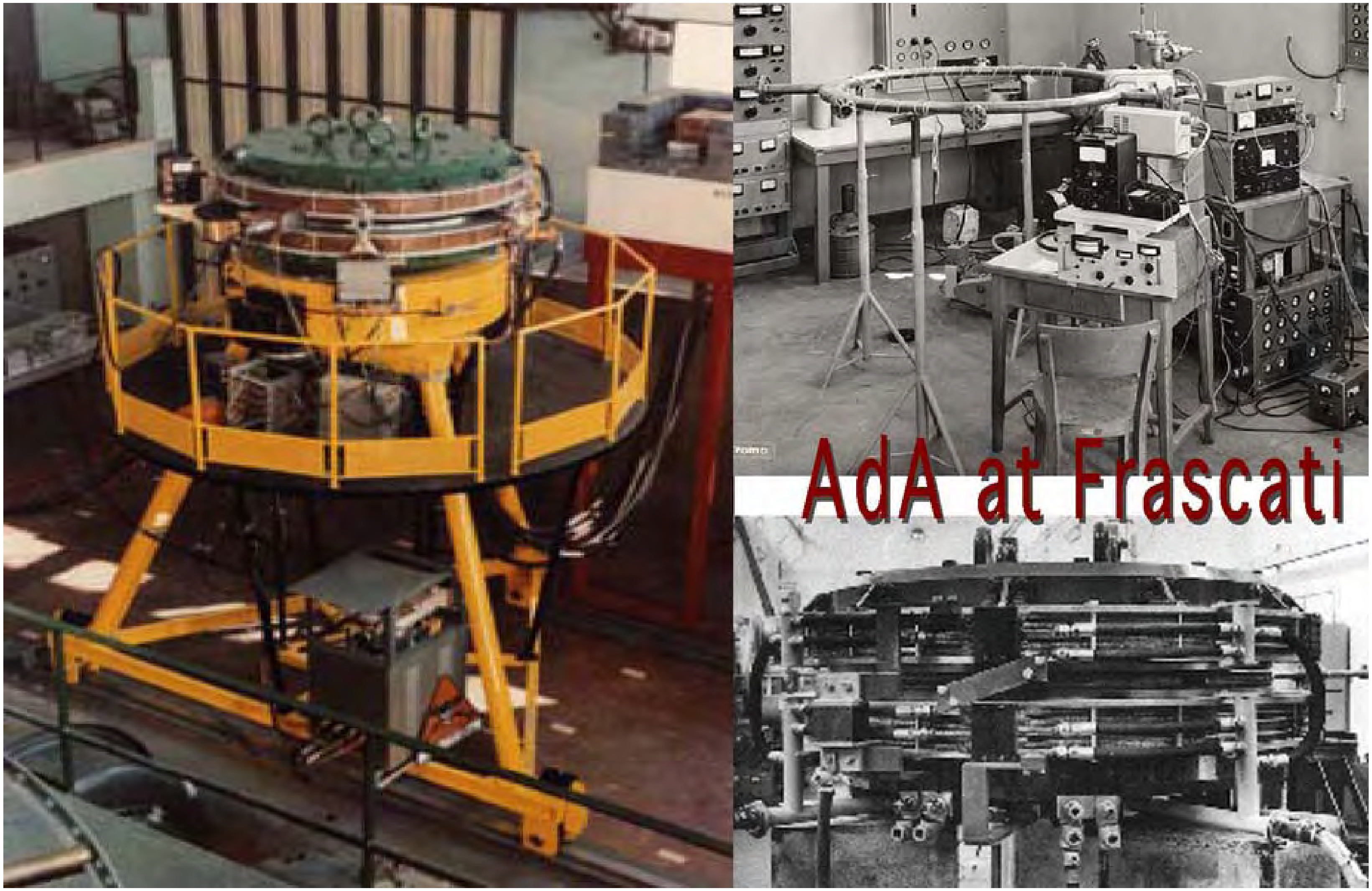
Akceleratory

Synchrotron

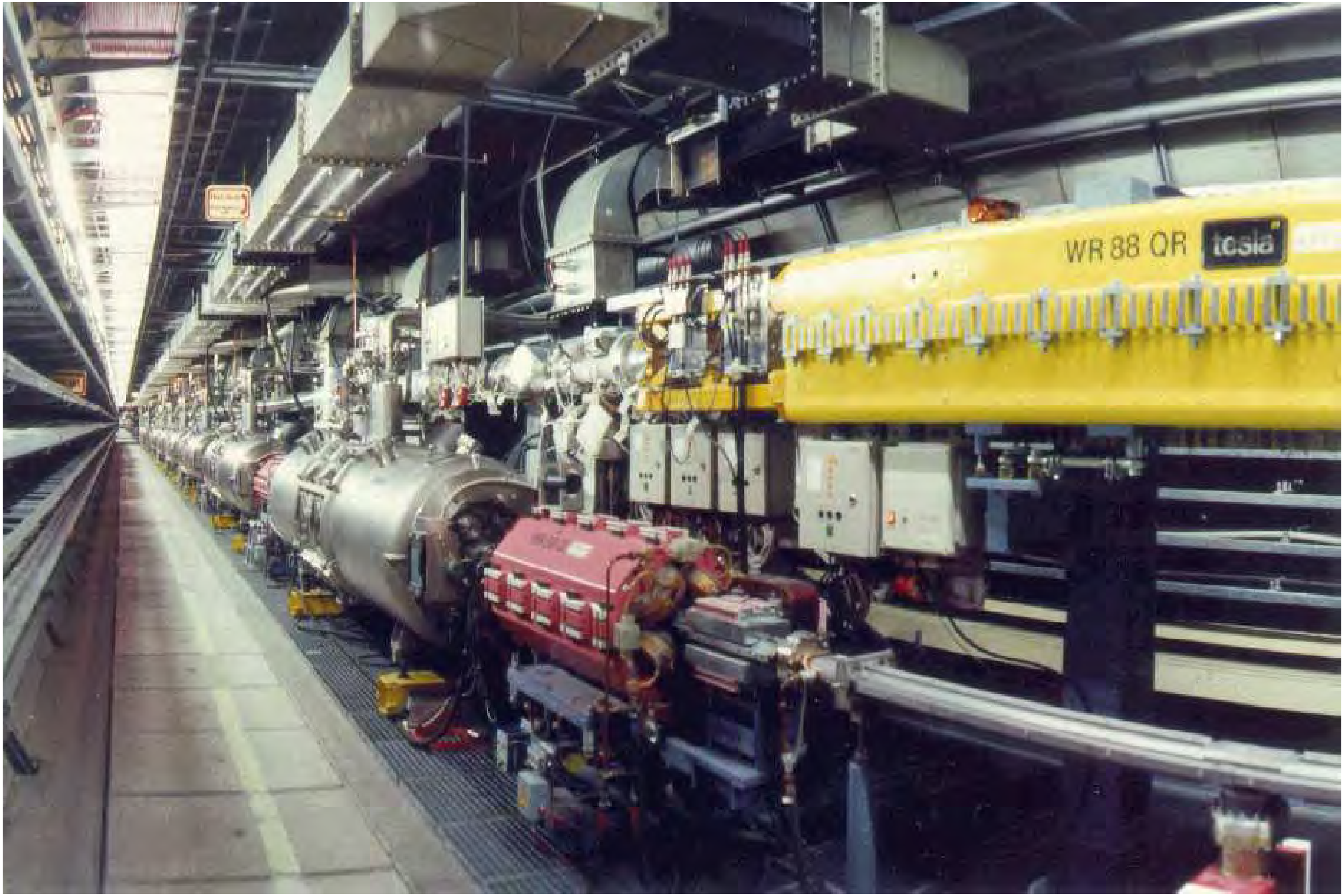
1955

Rosnące pole magnetyczne utrzymuje cząstki na stałej orbicie

The First Collider: AdA @ Frascati (1961)

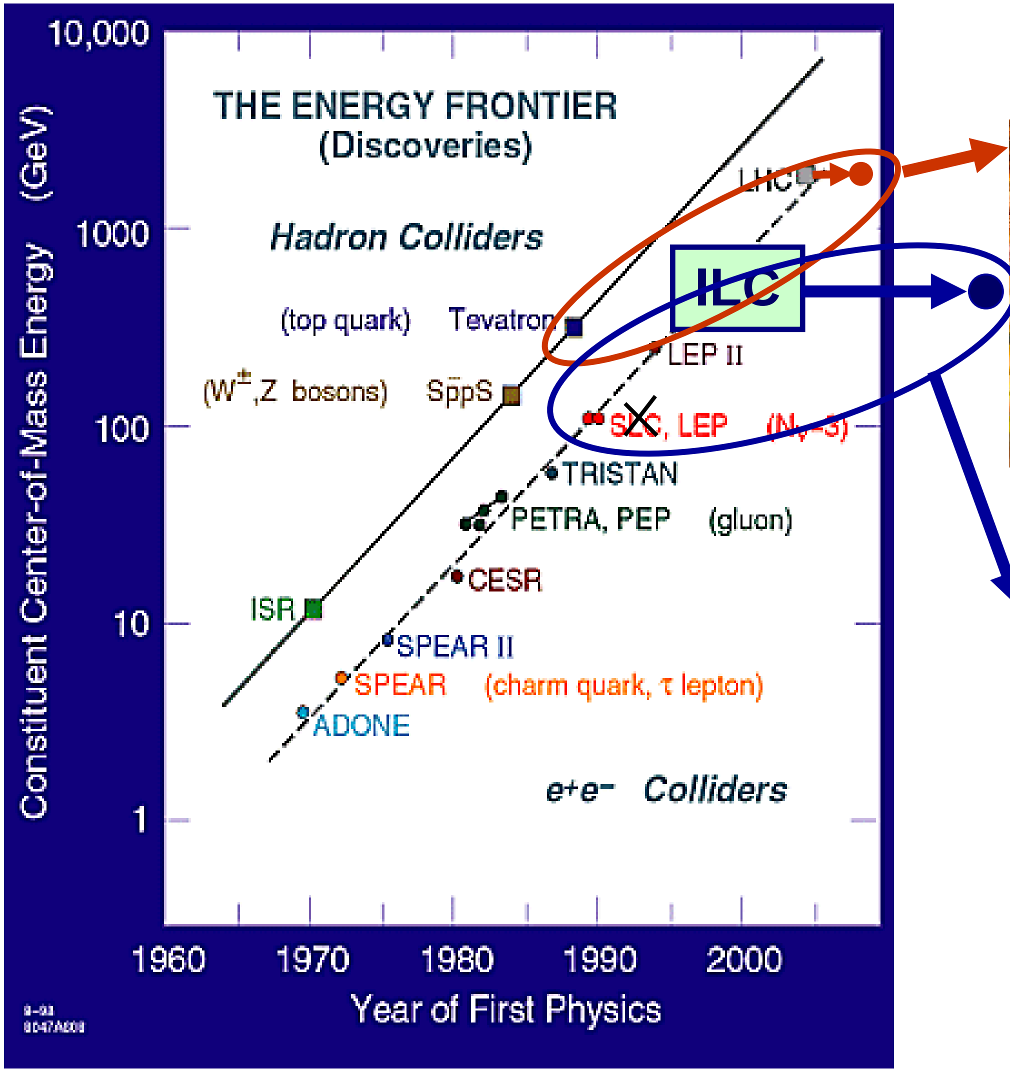


HERA, DESY, Niemcy

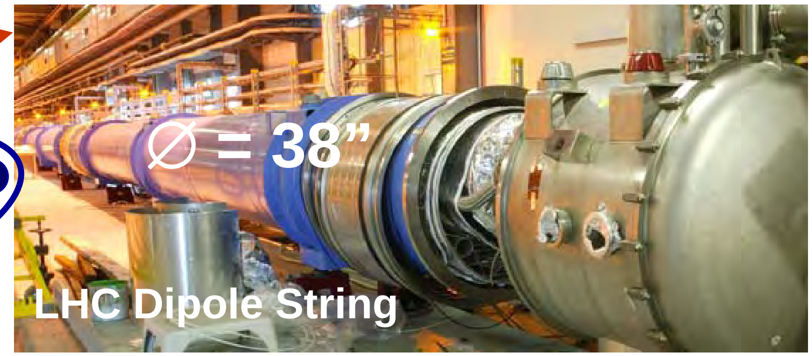


LHC Tunnel view

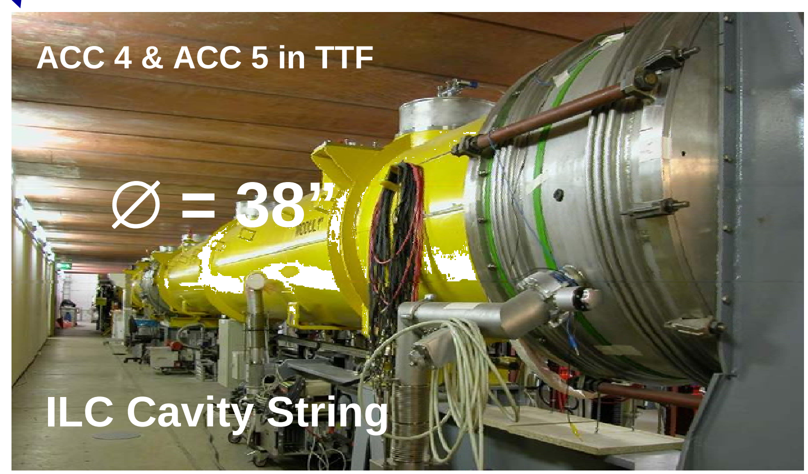
Energy Frontier and Accelerator Tech.



Superconducting Dipoles

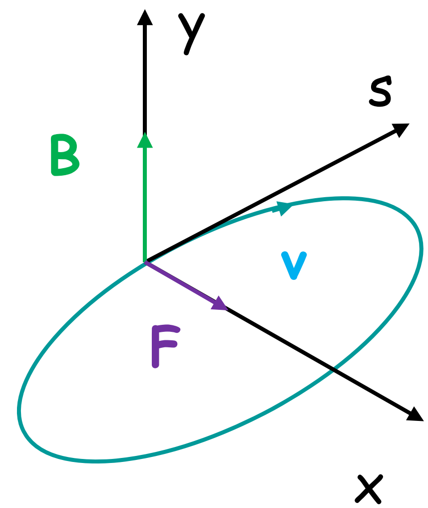


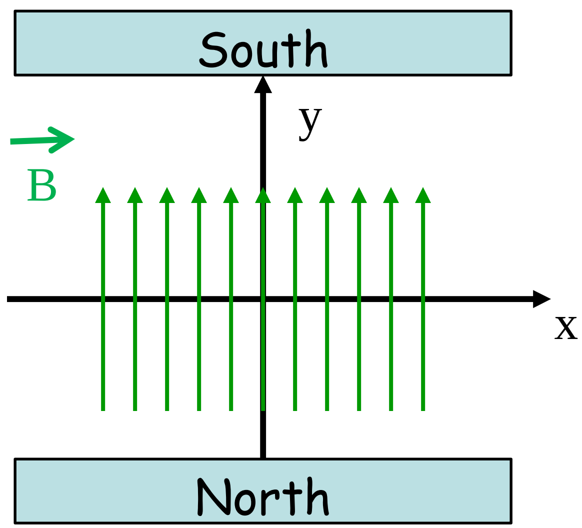
Superconducting RF Cavities



Dipole fields

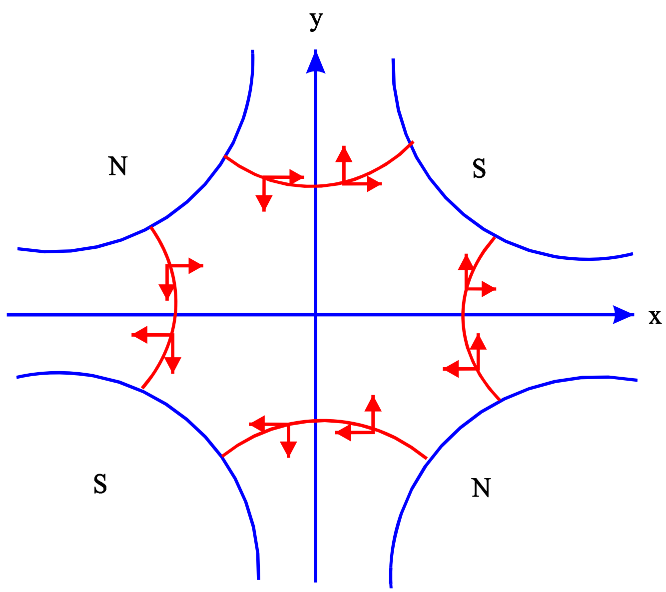
- Dipole magnets are the simplest accelerator magnets and have 'just' 2 poles.
- Their field is constant across the magnet.
- They are used to bend the beam and define the reference path.
- The dipoles define the beam MOMENTUM !



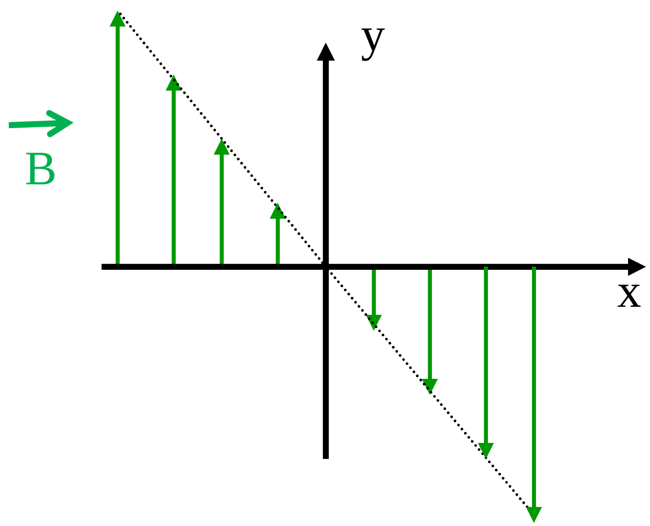


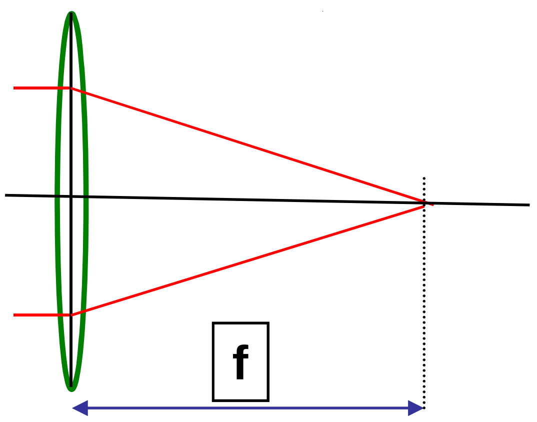
$$B = \frac{p}{e_0 \cdot R}$$

Quadrupolar field - focusing



- A quadrupole magnet has 4 poles, 2 north and 2 south.
- The poles are arranged symmetrically around the axis of the magnet.
- There is no magnetic field along the central axis.
- The field increases linearly with distance to the axis.



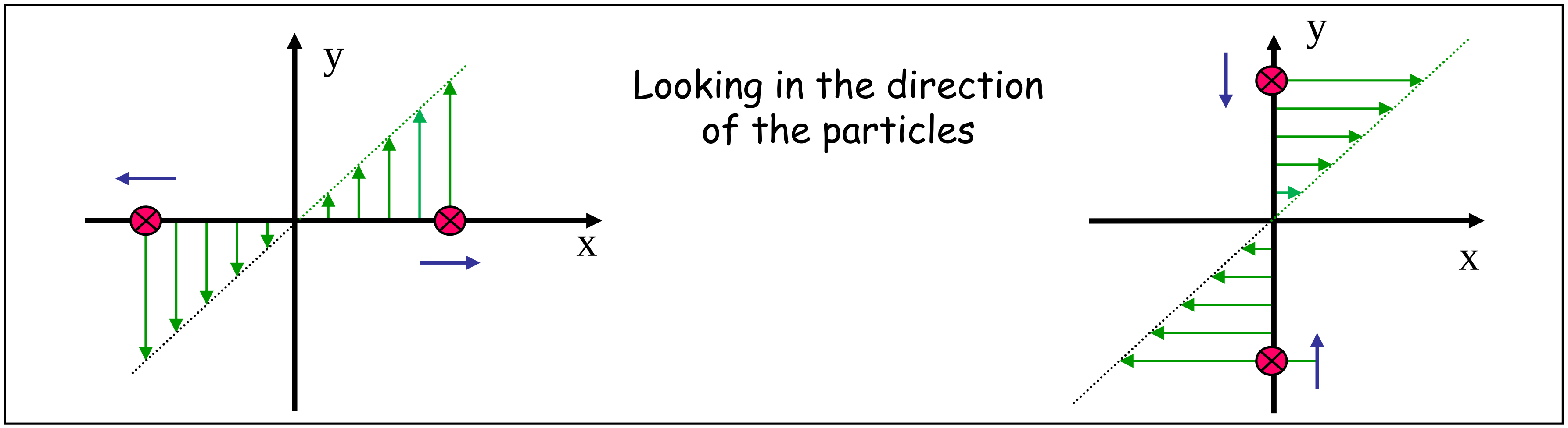


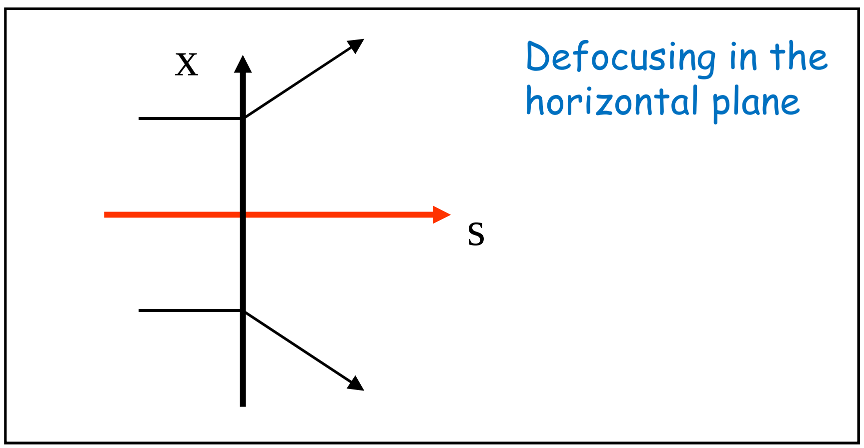
- In a given plane, the quadrupole has the same properties like a classical optical lens.

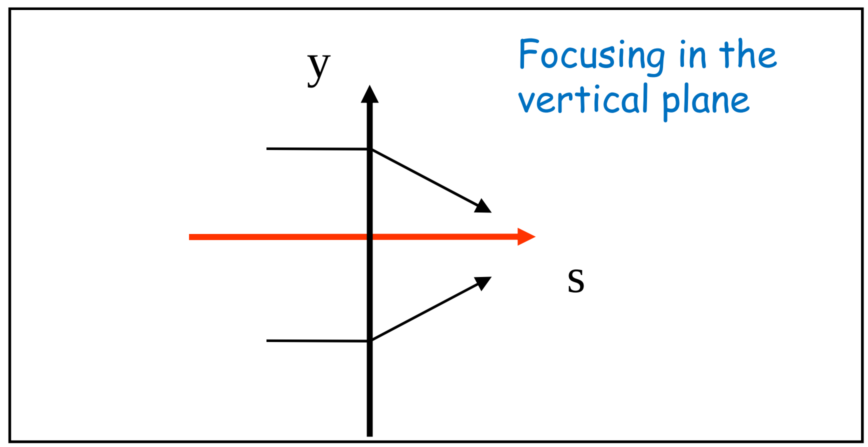
Focusing

But a quadrupole differs from an optical lens :

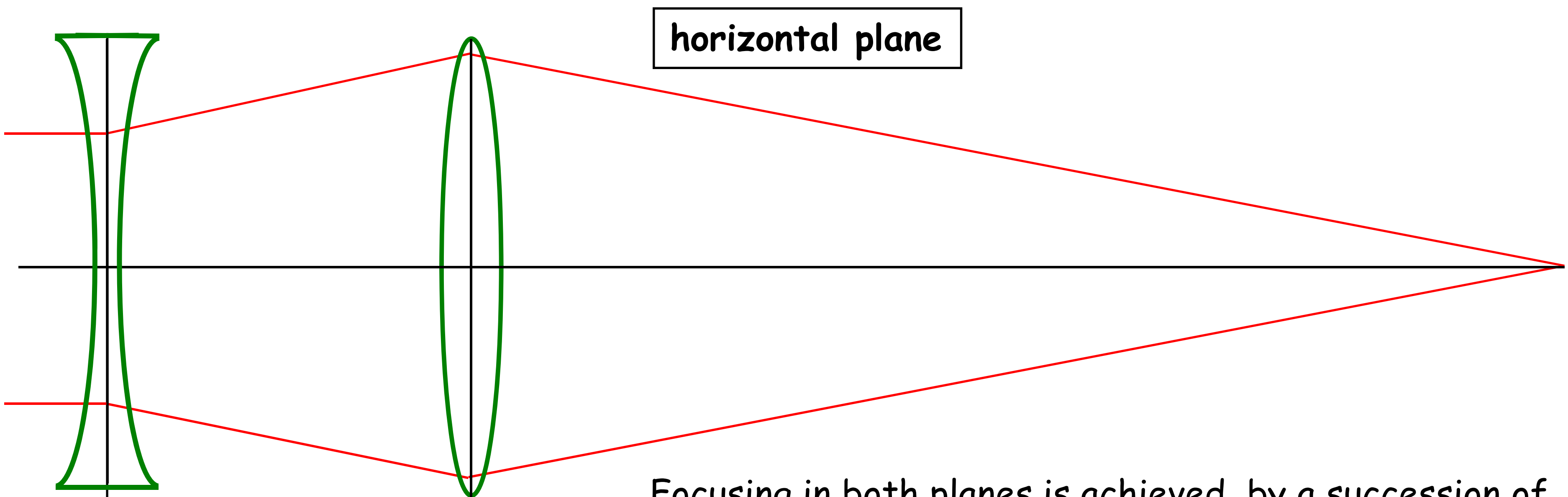
It is focusing in one plane, defocusing in the other !!!





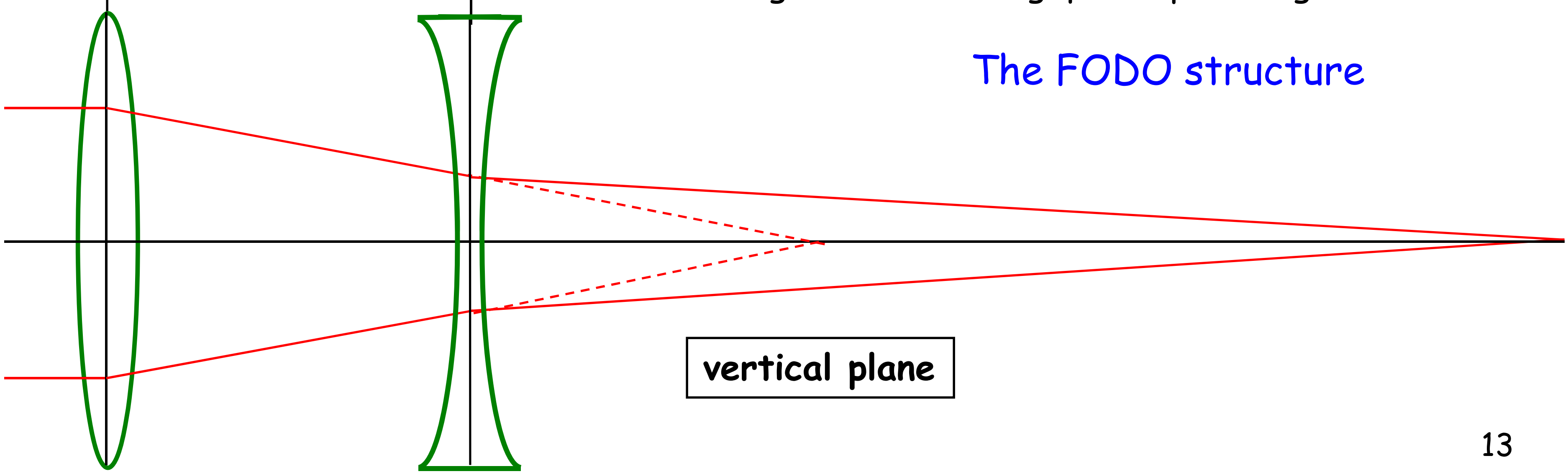


Accelerator lattice

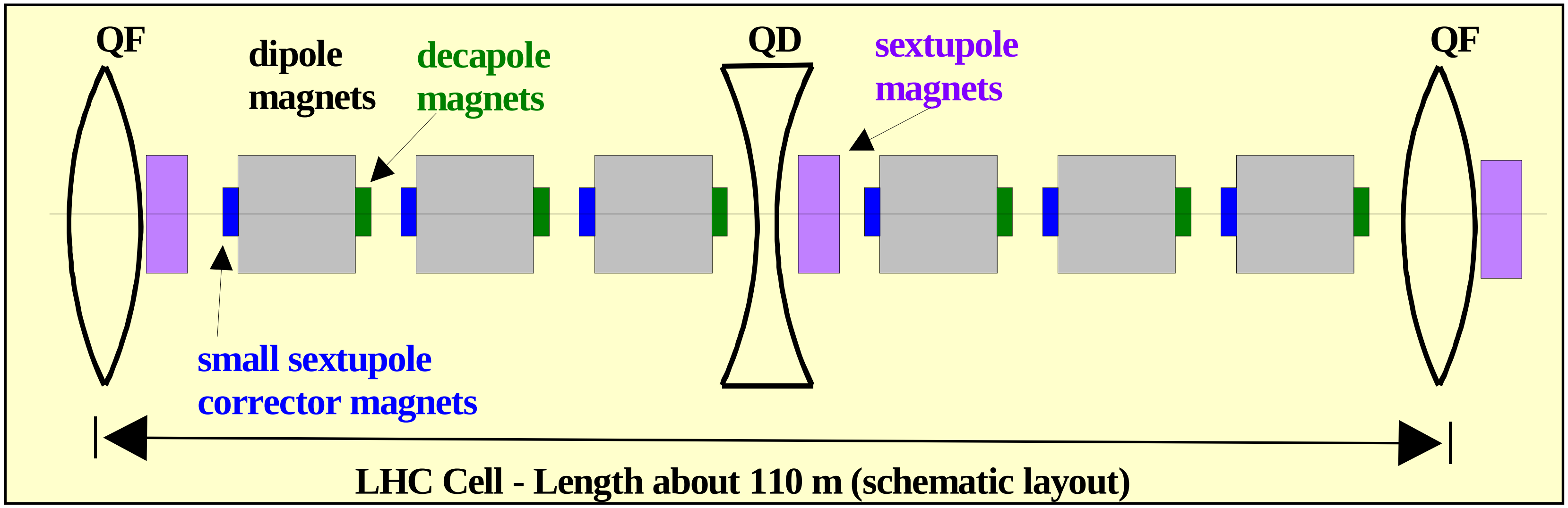


Focusing in both planes is achieved by a succession of focusing and defocusing quadrupole magnets :

The FODO structure

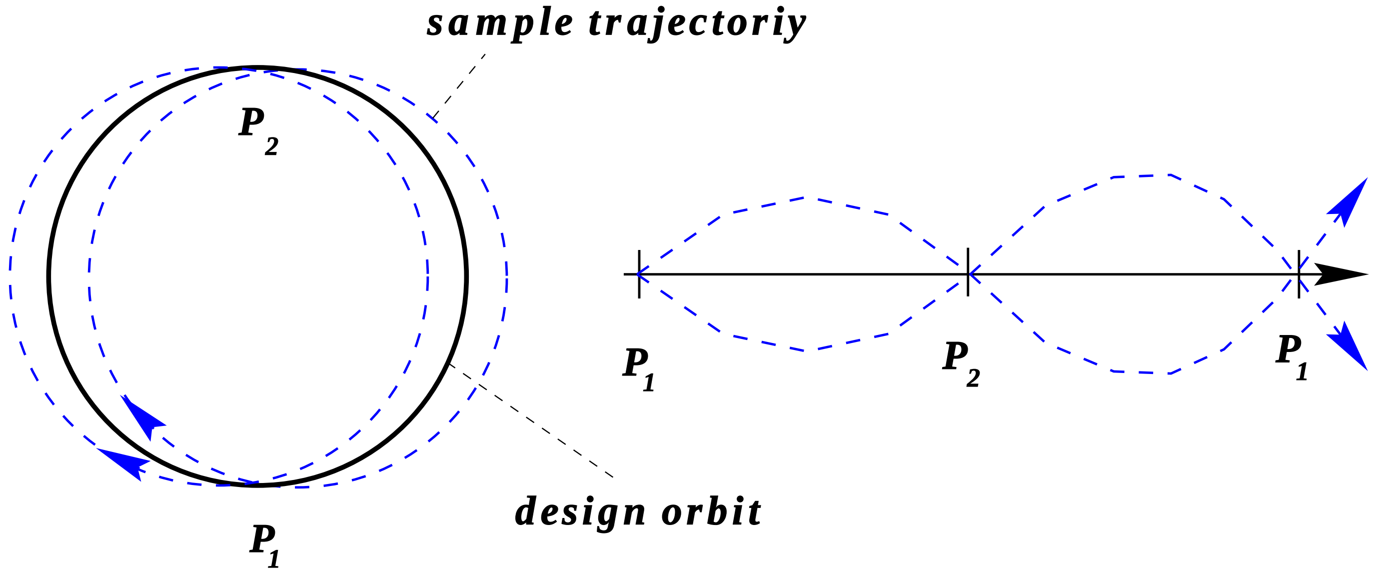


LHC arc lattice



- Dipole- und Quadrupol magnets
  - Provide a stable trajectory for particles with nominal momentum.
- Sextupole magnets
  - Correct the trajectories for off momentum particles (‚chromatic' errors).
- Multipole-corrector magnets
  - Sextupole - and decapole corrector magnets at end of dipoles
  - Used to compensate field imperfections if the dipole magnets. To stabilize trajectories for particles at larger amplitudes – beam lifetime !

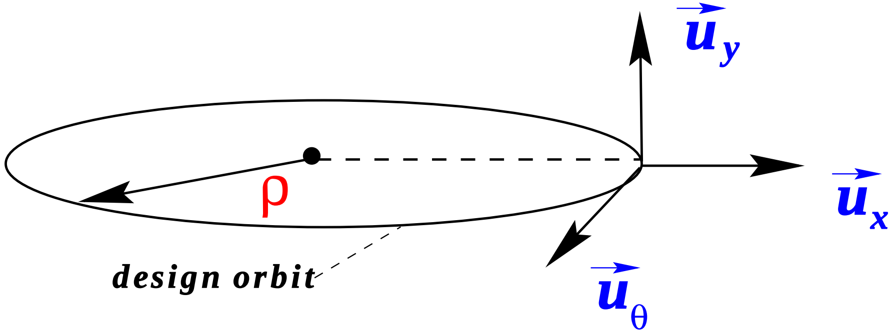
Geometrical Focusing:



Equation of Motion

Rotating Coordinate System:

$$x(t) = a \cdot \sin(\omega \cdot t + \phi_0)$$



$$\omega = \omega_{rev}$$

$$\omega_{rev} = 2 \cdot \pi \cdot \frac{v}{L}$$

$$\omega_{rev} = \frac{v}{\rho}$$

$$\frac{d^2x}{dt^2} = -v^2 \cdot \frac{1}{\rho^2} \cdot x$$

Optic Functions

Hills Equation:

$$\frac{d^2x}{ds^2} + K(s)\cdot x = 0; \qquad K(s) = \begin{cases} 0 & \text{drift} \\ 1/\rho^2 & \text{dipole} \\ \frac{q\cdot g}{p} & \text{quadrupole} \end{cases}$$

$$K(s) = K(s + L)$$

[general: $K(s)\cdot x = F/(p\cdot v)$]

$$K(s) = \text{const.} \longrightarrow x = A\cdot \sin(\sqrt{K}\cdot s + \phi_0)$$

Transfer matrices

Let $\mathbf{x}(s) = \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix}$ be the “position vector”

$$\mathbf{x}(s) = M(s|s_0)\, \mathbf{x}(s_0)$$

where $M(s|s_0)$ is the betatron transfer matrix

The passage through a magnetic element can be described by a 2x2 matrix, which transforms the "position vector" of a particle before the element to the position vector after it

Solutions with constant K

$y'' + K(s)\,y = 0$; $y = x$ or z

$Y(s) = a\cos(\sqrt{K}s + b)$ — $K > 0$ focusing quad

$Y(s) = as + b$ — $K = 0$ drift space

$Y(s) = a\cosh(\sqrt{-K}s + b)$ — $K < 0$ defocusing quad

$$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

$K = 0$ drift space of length L

$$M_x = \begin{pmatrix} \cos\phi & \sin\phi/\sqrt{|K|} \\ -\sqrt{|K|}\,\sin\phi & \cos\phi \end{pmatrix}$$

$K > 0$ focusing quad

$\phi = s\sqrt{|K|}$

$$M_z = \begin{pmatrix} \cosh\phi & \sinh\phi/\sqrt{|K|} \\ -\sqrt{|K|}\,\sinh\phi & \cosh\phi \end{pmatrix}$$

$K < 0$ defocusing quad

Floquet Theorem:

$$x = \sqrt{A \cdot \beta(s)} \cdot \sin(\phi(s) + \phi_0)$$

$$\beta(s) = \beta(s + L); \qquad \phi(s) = \int \frac{1}{\beta}\, ds$$

→ ***differential equation for β !***

Envelope Function:

$$y(s) = \sqrt{A \cdot \beta} \cdot \sin\left(\frac{2\pi}{L} \cdot Q \cdot s + \phi_0\right)$$

amplitude term due to injector

amplitude term due to focusing

sorage ring circumference

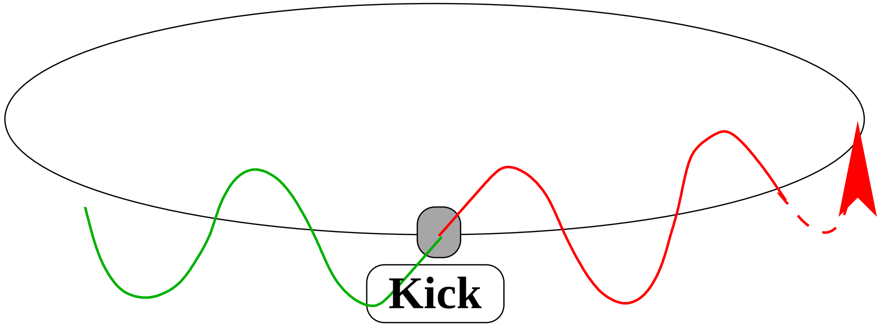
- $$\beta(s + L) = \beta(s)$$

- Number of oscillations per turn

$$Q = \frac{1}{2\pi} \cdot \oint \frac{1}{\beta(s)} \, ds$$

Orbit Stability

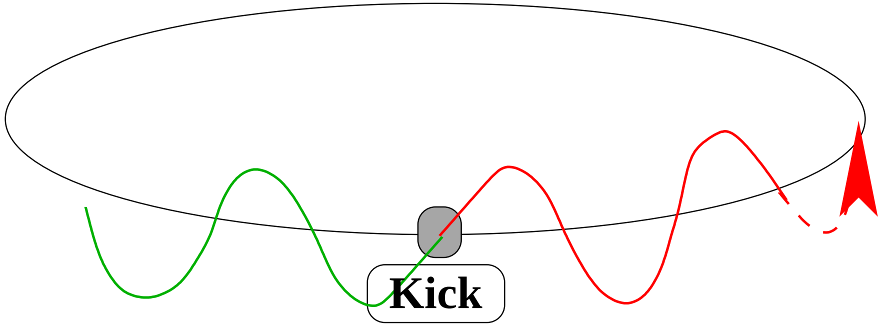
dipole error and Q = N:



→ *the perturbation adds up*

watch out for integer tunes!

Orbit Stability



field errors:

the perturbations add up for Q = 1/n

watch out for fractional tunes!

minimise field errors

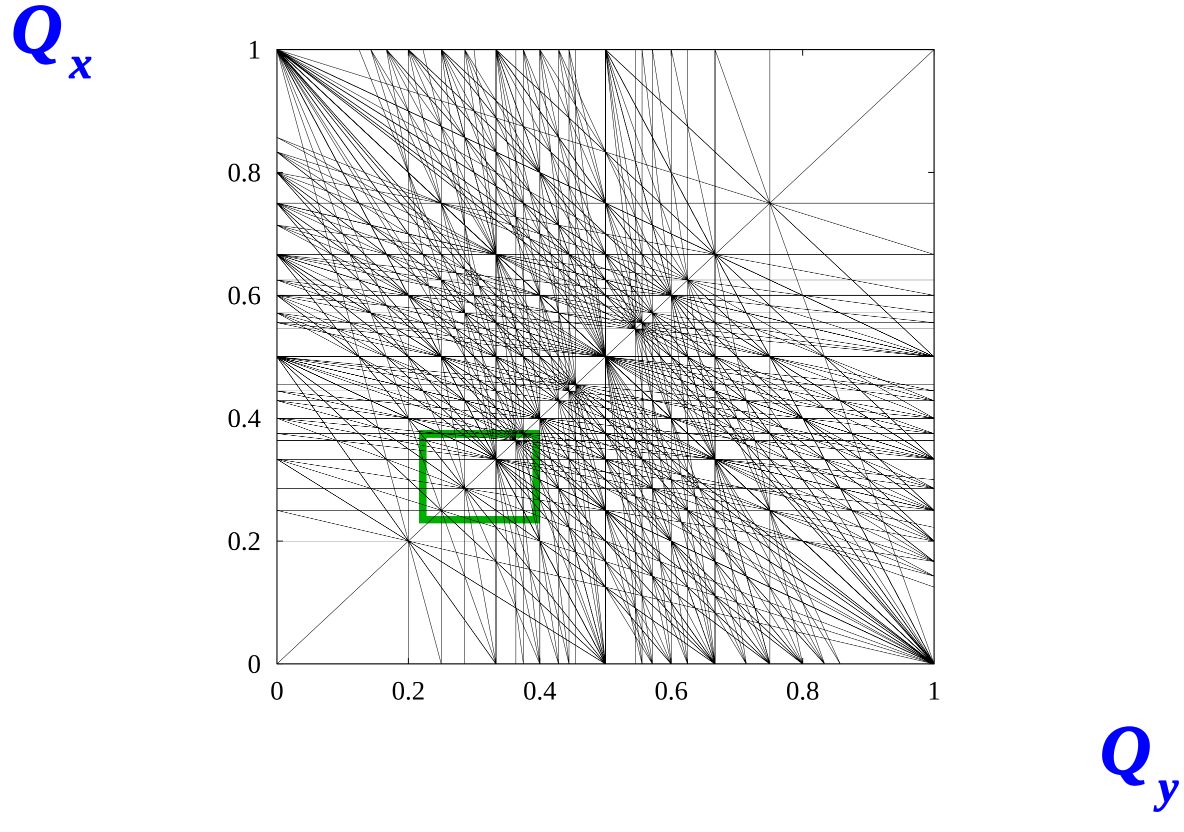
and avoid strong resonances!

Tune Diagram

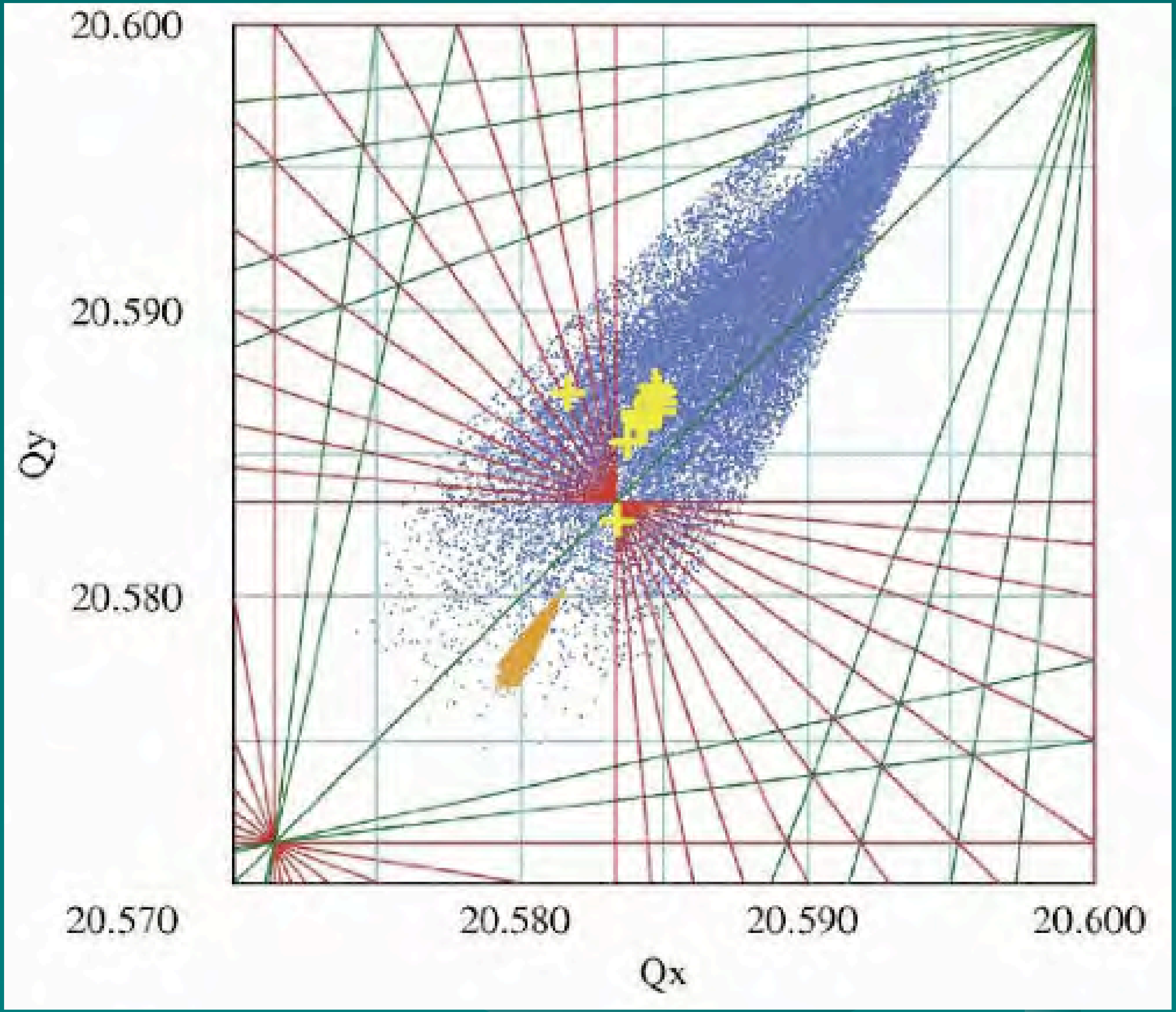
resonances: $n \cdot Q_x + m \cdot Q_y + r \cdot Q_s = p$

strength: $h \propto A^{n+m+s}$

→ ***avoid low order resonances!***



Tune Plane of the Tevatron



Phase Space

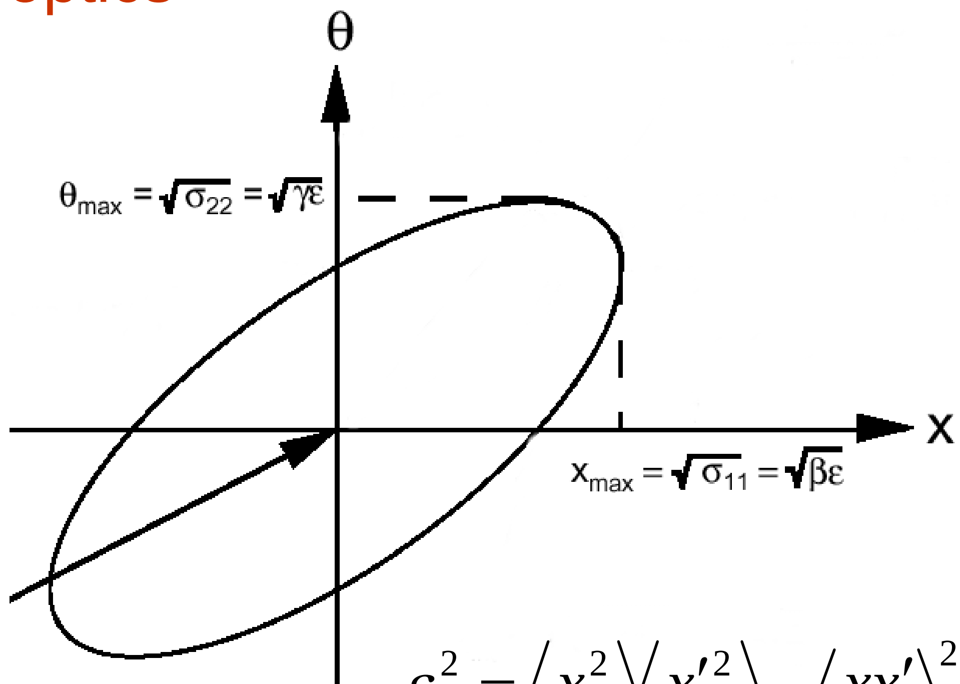
Beta function β characterize optics

Emittance ε is phase space volume of the beam – optics analogy is the wavelength

Tilt is parameterized with α

Beam size: $(\varepsilon\ \beta)^{1/2}$

Divergence: $(\varepsilon\ /\beta)^{1/2}$

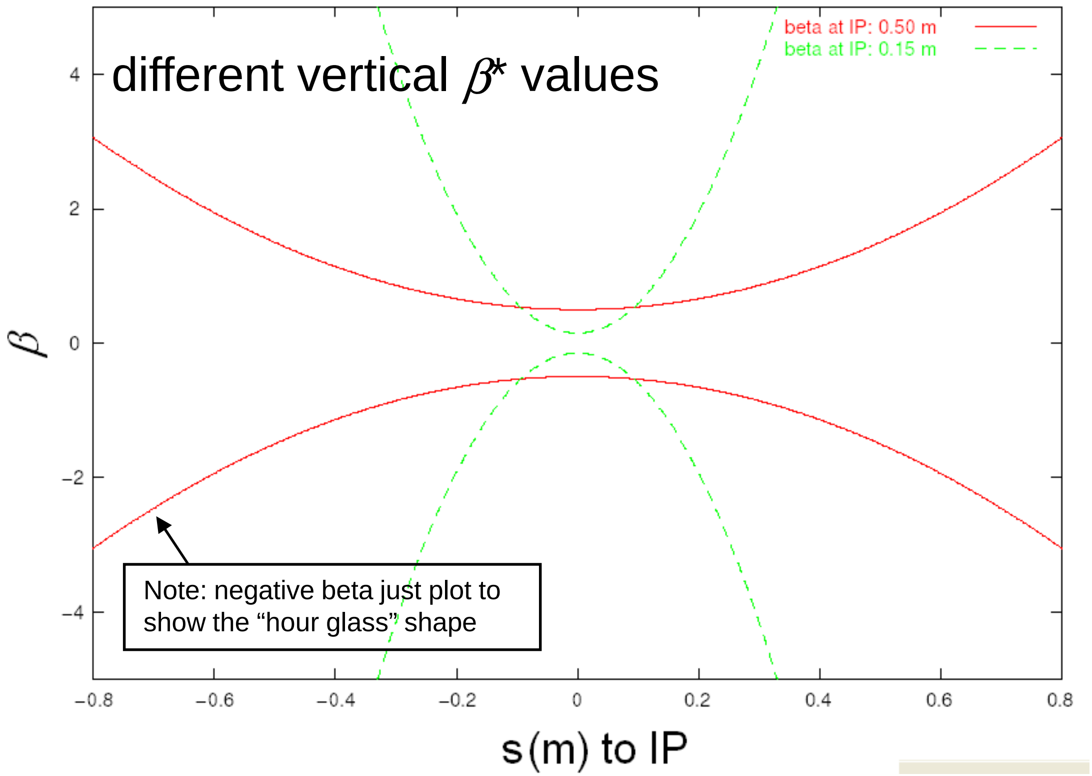


$$\varepsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2$$

Squeeze on beam size → increase angular divergence

Beam emittance is not conserved during acceleration → normalized emittance should be $\gamma\varepsilon$

Final Focus : Fundamental Limits (hour glass effect)



Transverse beam sizes cannot be considered constant but vary with β near IP. Beta has quadratic dependence with distance s

$$\beta(s) = \beta^* \left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$$

Beam sizes vary linearly with s at IP

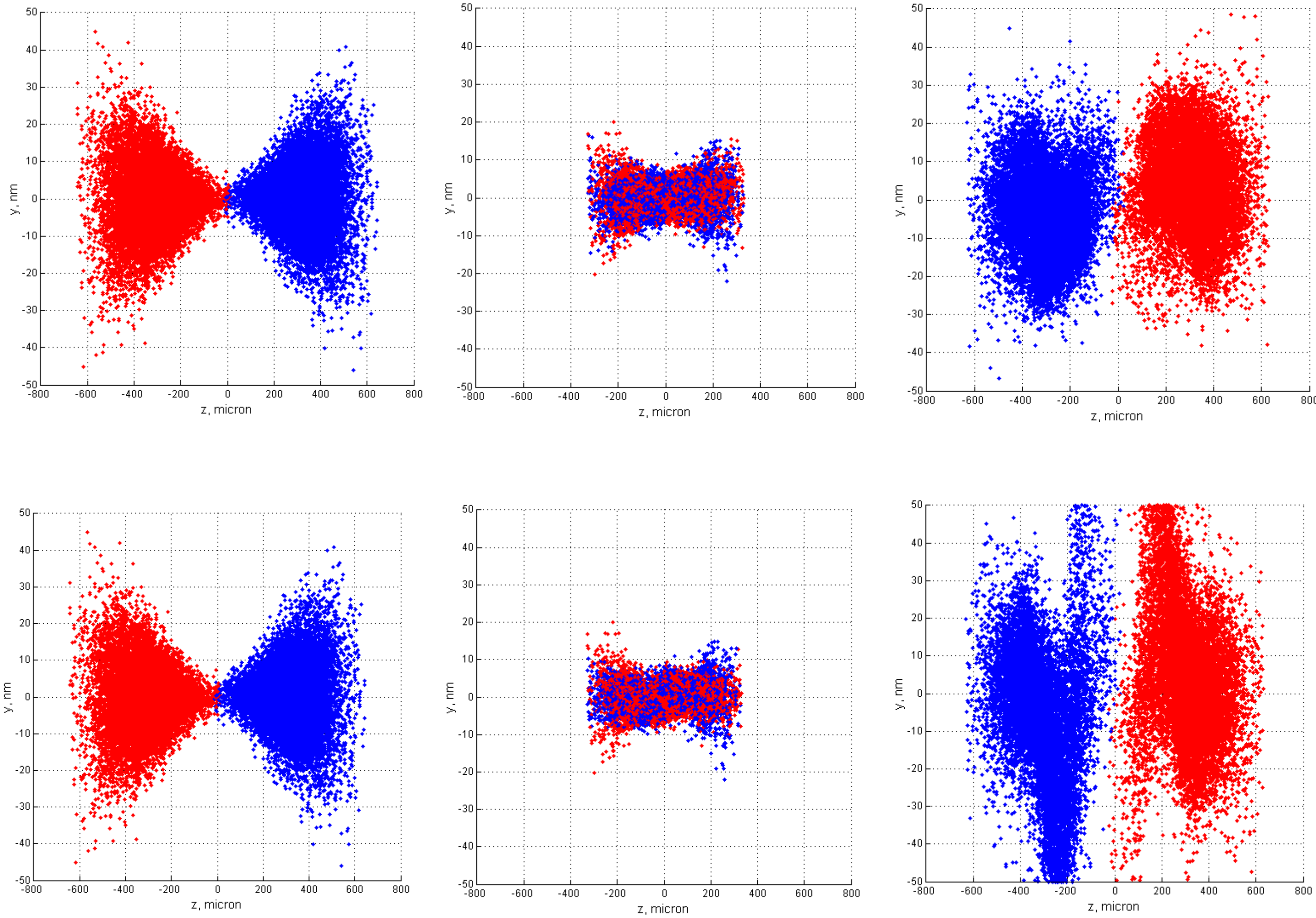
$$\sigma_y(s) = \sqrt{\beta_y(s)\varepsilon_y}$$

Important when $\beta_y \approx \sigma_z$ since not all particles collide at minimum of transverse beam size → reducing luminosity.

"hour glass" effect from shape of β

Single Bunch Kink (2)

Single bunch kink due to 1% initial offset between beams



$D_y = 12$

$D_y = 24$

LHC - yet another collider?

The LHC surpasses existing accelerators/colliders in 2 aspects :

- The energy of the beam of 7 TeV that is achieved within the size constraints of the existing 26.7 km LEP tunnel.

LHC dipole field	8.3 T
HERA/Tevatron	~ 4 T

A factor <u>2</u> in field

A factor <u>4</u> in size

- The luminosity of the collider that will reach unprecedented values for a hadron machine:

LHC	pp	~ 10^{34} cm^{-2} s^{-1}
Tevatron	$p\bar{p}$	2×10^{32} cm^{-2} s^{-1}
SppbarS	$p\bar{p}$	6×10^{30} cm^{-2} s^{-1}

A factor <u>100</u> in luminosity

The combination of very high field magnets and very high beam intensities required to reach the luminosity targets makes operation of the LHC a great challenge !

Luminosity challenges

The event rate N for a physics process with cross-section σ is proprotional to the collider Luminosity L:

$$N = L\sigma$$

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

k = number of bunches = 2808
N = no. protons per bunch = 1.15×10^11
f = revolution frequency = 11.25 kHz
σ^*_x, σ^*_y *= beam sizes at collision point (hor./vert.) = 16 μm*

To maximize L:

- **Many bunches (k)**
- **Many protons per bunch (N)**
- **A small beam size $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$**

β^* : characterizes the beam envelope (optics), varies along the ring, mim. at the collision points.

ε : is the phase space volume occupied by the beam (constant along the ring).

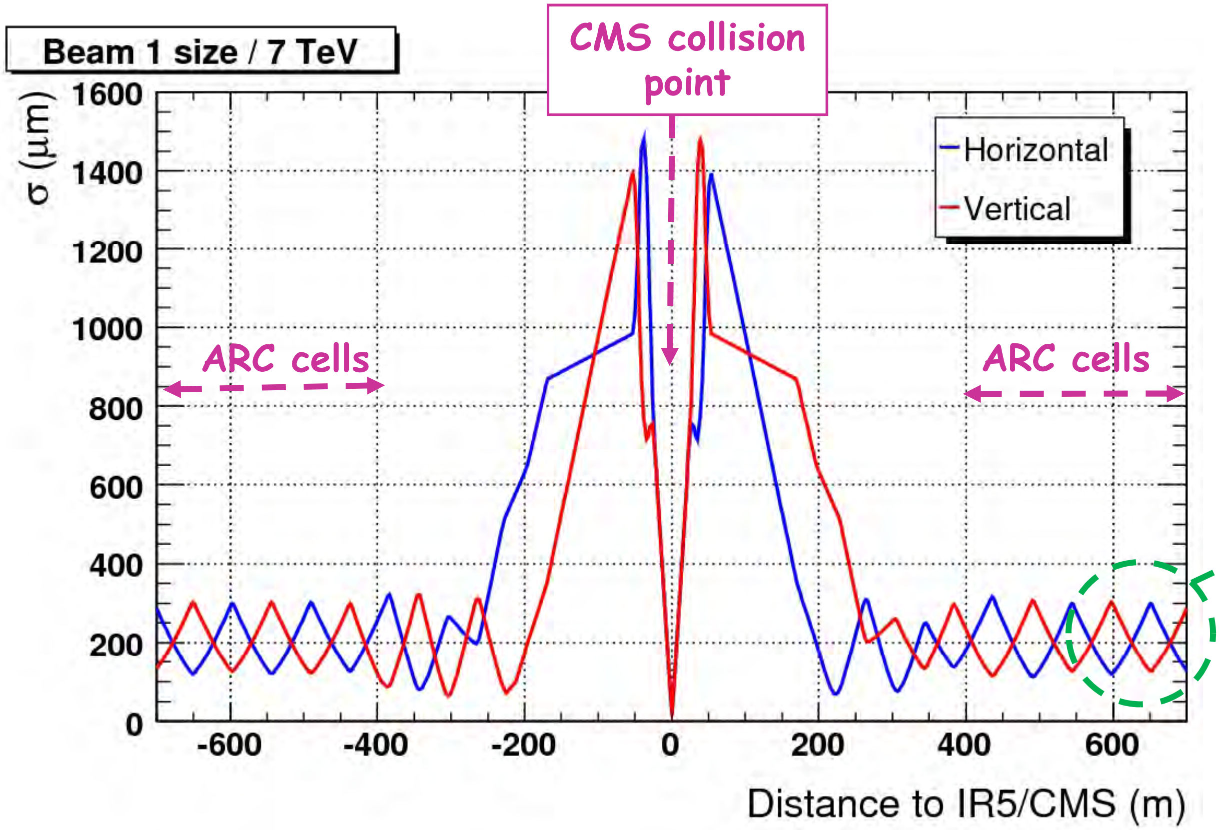
High beam "brillance" N/ε (particles per phase space volume)

→ Injector chain performance !

Small envelope

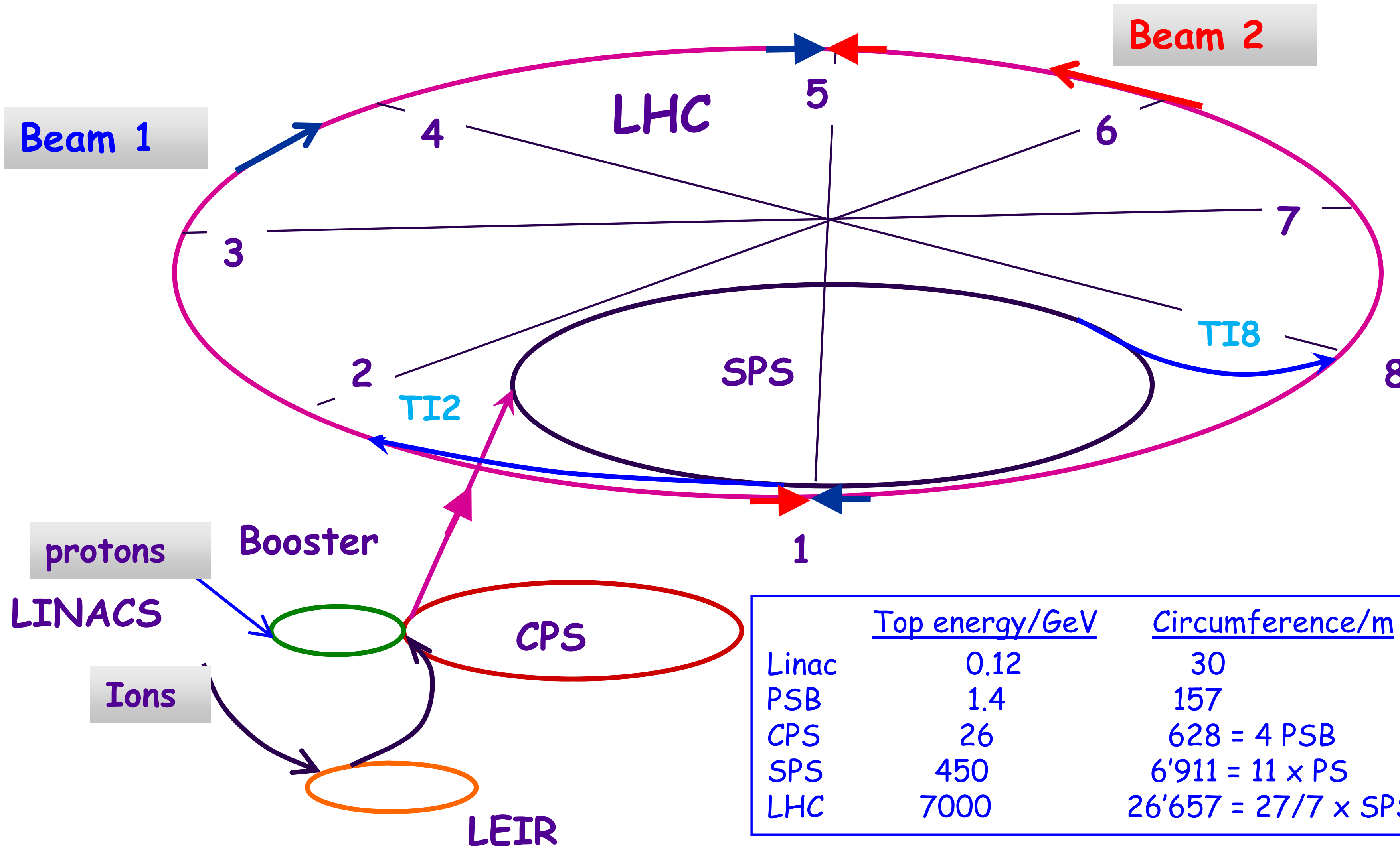
→ Strong focusing !

Beam envelope



- The envelope of the size beam is given by the so-called <u>'β'-function</u> (⇔ optics):
  - In the arcs the optics follows a regular pattern.
  - In the long straight sections, the optics is matched to the 'telescope' that provides very strong focusing at the collision point.
- Collision point size (rms, defined by 'β*'):

  CMS & ATLAS : 16 μm   LHCb : 22 – 160 μm   ALICE : 16 μm (ions) / >160 μm (p)



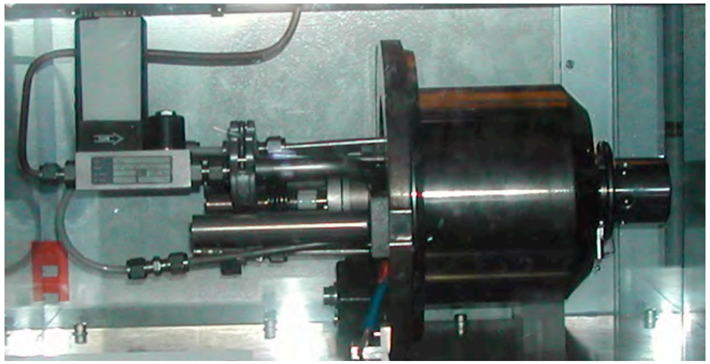
	Top energy/GeV	Circumference/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

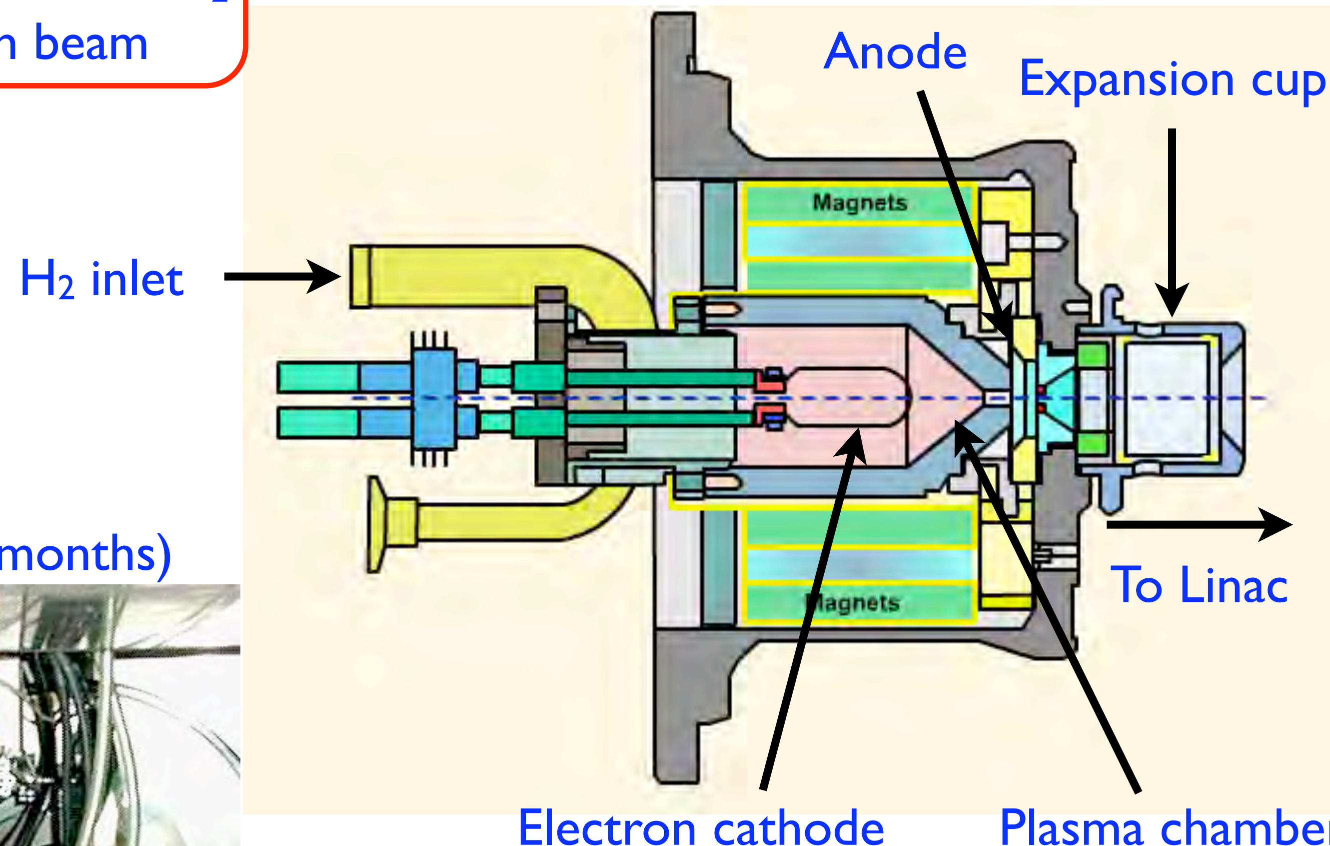
Note the energy gain/machine of 10 to 20 – and not more !

The gain is typical for the useful range of magnets !!!

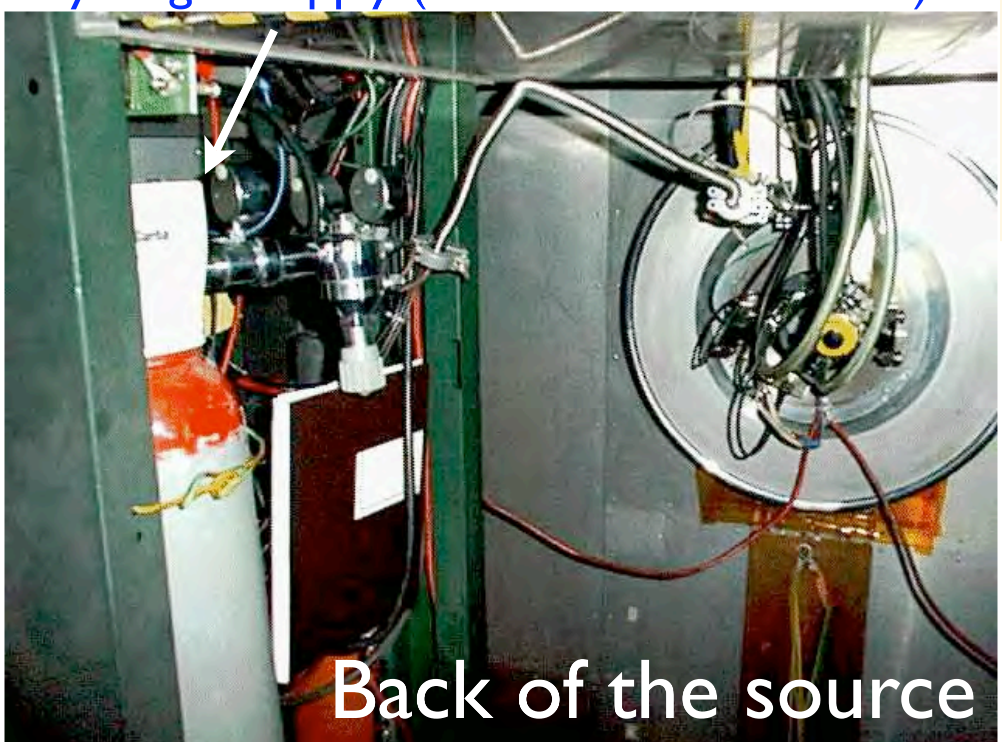
How to get protons: duoplasmatron source

Protons are produced by the ionization of H_2 plasma enhanced by an electron beam





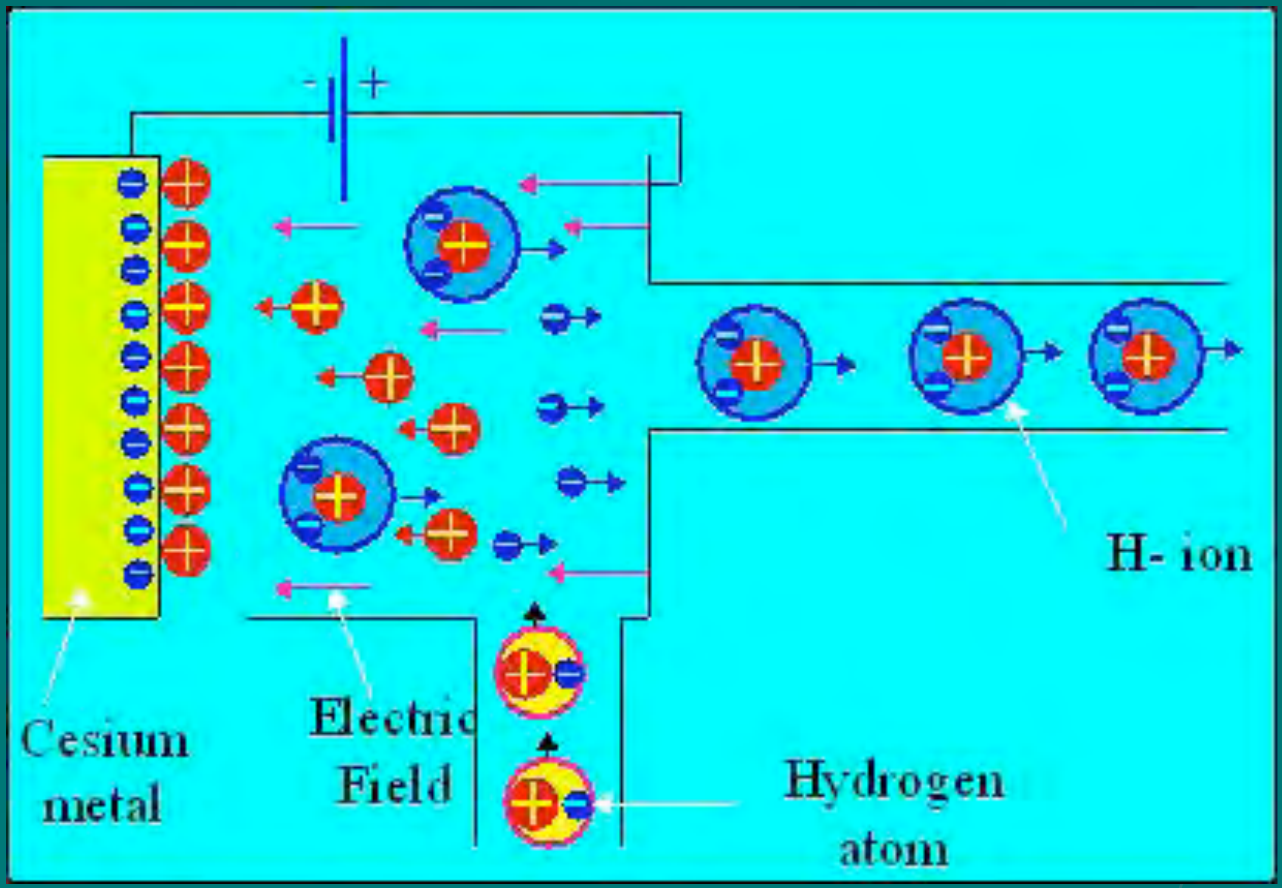
Hydrogen supply (one lasts for 6 months)



Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, $v \approx 4000$ km/s

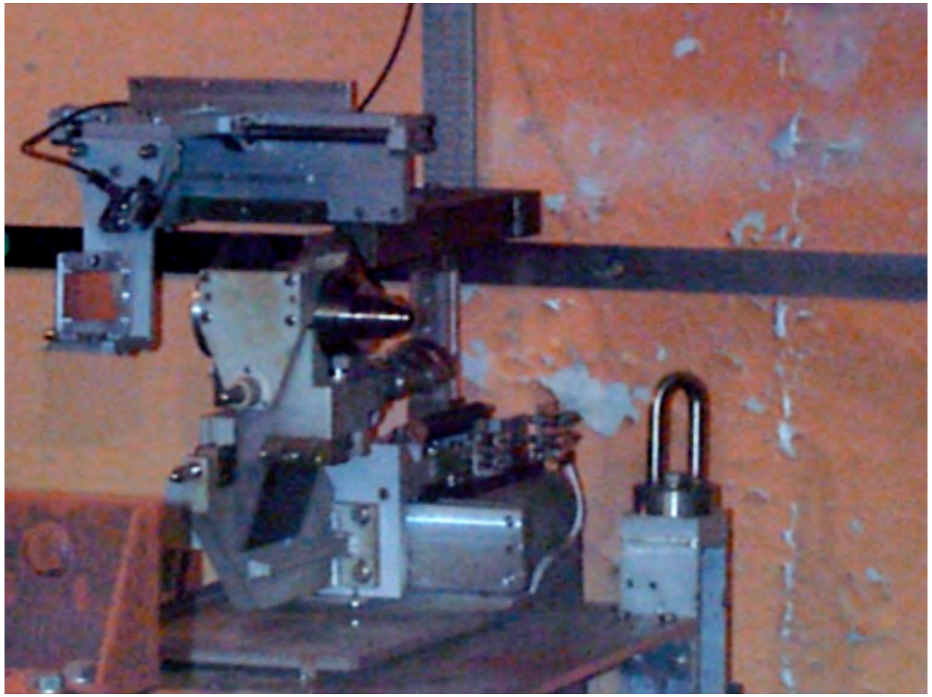
The SPACE SHUTTLE goes only up to 8 km/s

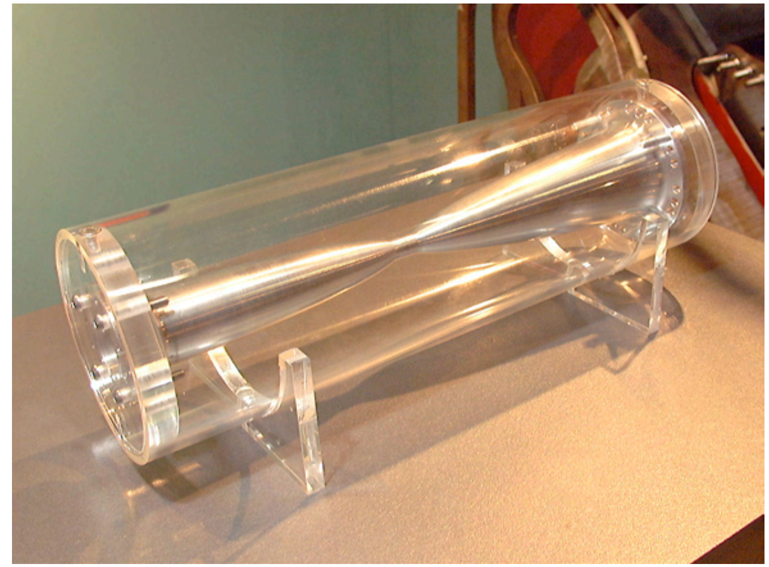
H^- Source

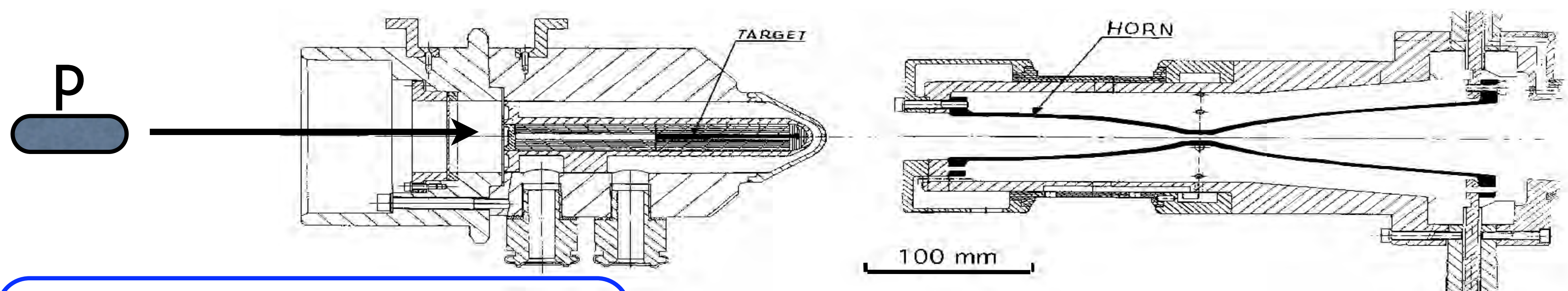


- Hydrogen is drawn to the cesium surface
- Cesium gives up an electron easily
- Some hydrogen atoms with 2 electrons are knocked off the cesium by incoming Hydrogen ions

How to get antiprotons







Starting from high energy p and with a very low efficiency

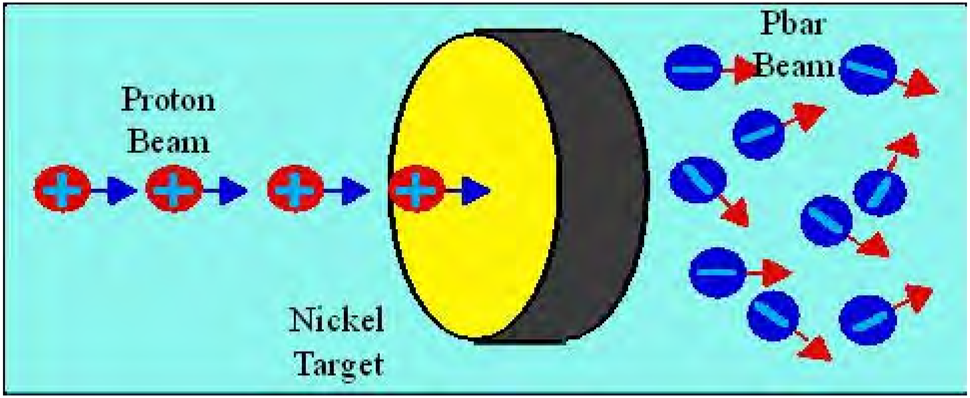
$$p + p \rightarrow p + p + p + \bar{p}$$

See lecture on Antimatter

Stochastic Cooling

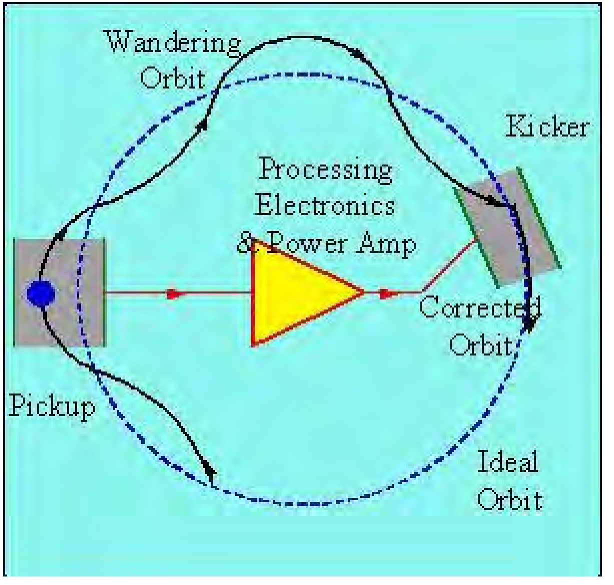
The antiprotons leave the target at a wide range of energies, positions and angles. This randomness is equivalent to temperature so we say that the beam coming off the target is "hot." This "hot" beam will have a difficult time fitting into a beam pipe of reasonable dimensions. Also, this hot beam is very diffuse and not very "bright". Bright beams are needed in the collider in order to increase the probability that a rare particle might be created.

Stochastic cooling is a technique that is used to remove the randomness of the "hot" beam on a particle by particle basis. Simone van der Meer won the Nobel prize for its invention.



Stochastic Cooling systems are used in both the Debuncher and the Accumulator.

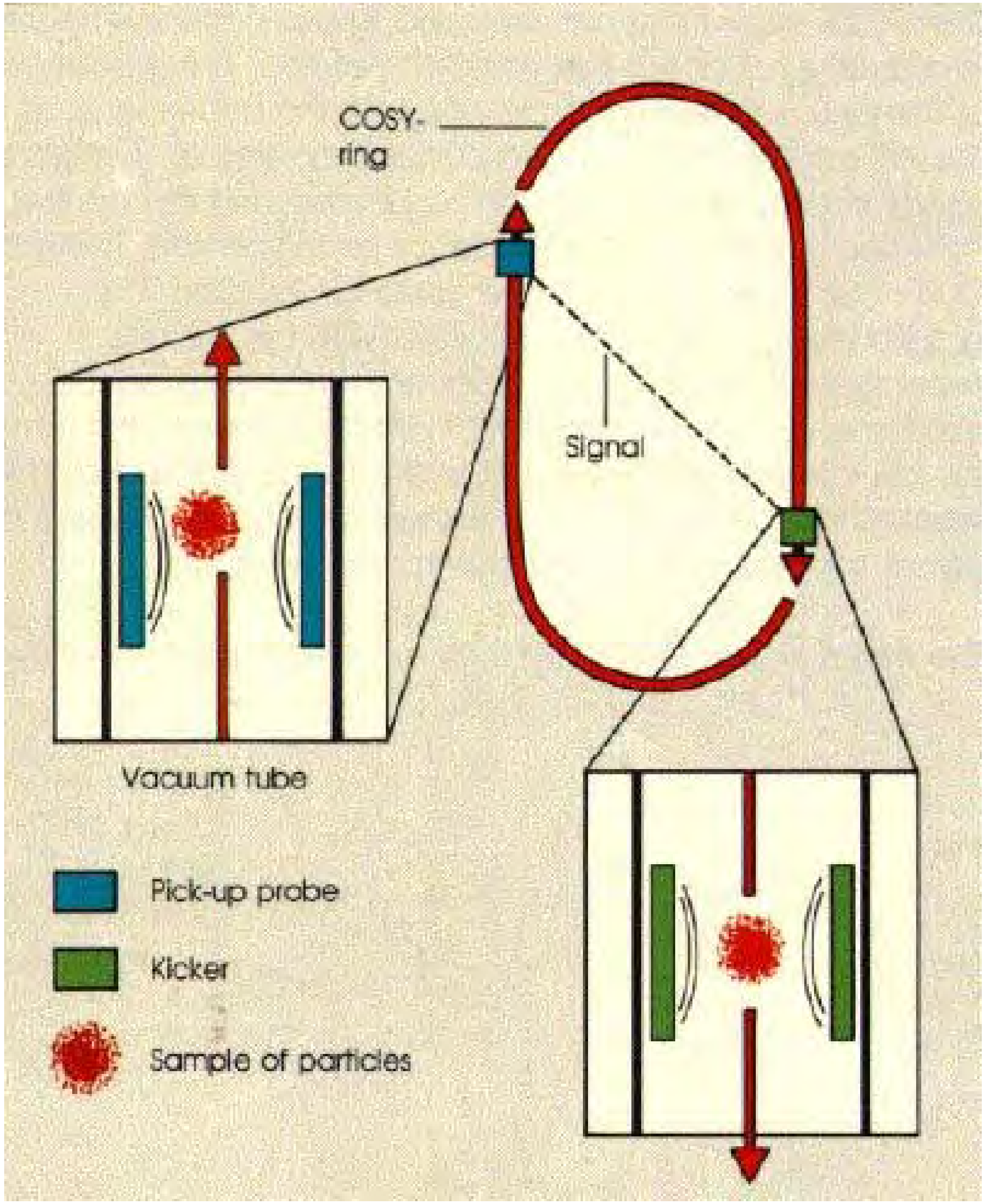
Stochastic cooling uses feedback. A pickup electrode measures an "error" signal for a given particle. This "error" signal could be that particle's position or energy. The pickup signal can be extremely small, on the order of 2 trillionths of a Watt.



Many of the pickups are cooled to liquid Nitrogen tempertures (-320°F) to reduce the effect of thermal noise. In the future, the temperature of some of the pickups will be reduced to liquid Helium temperatures (-452°F).

This signal is processed and amplified. The gain of some systems is about 150 dB (a factor of 10^{15})

The opposite of the “error” signal is applied to the antiproton at the kicker. The kicker signal can be as large as 1500 Watts.



chłodzenie stochastyczne

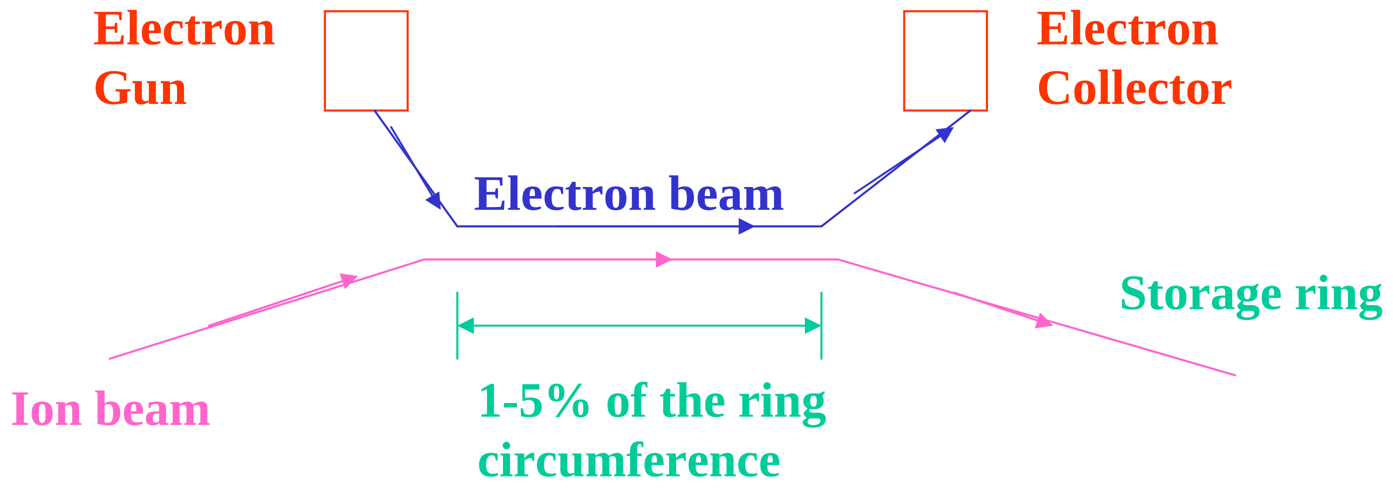
Simon van der Meer
Nagroda Nobla 1984

Electron Cooling

How does electron cooling work?

The velocity of the electrons is made equal to the average velocity of the ions.

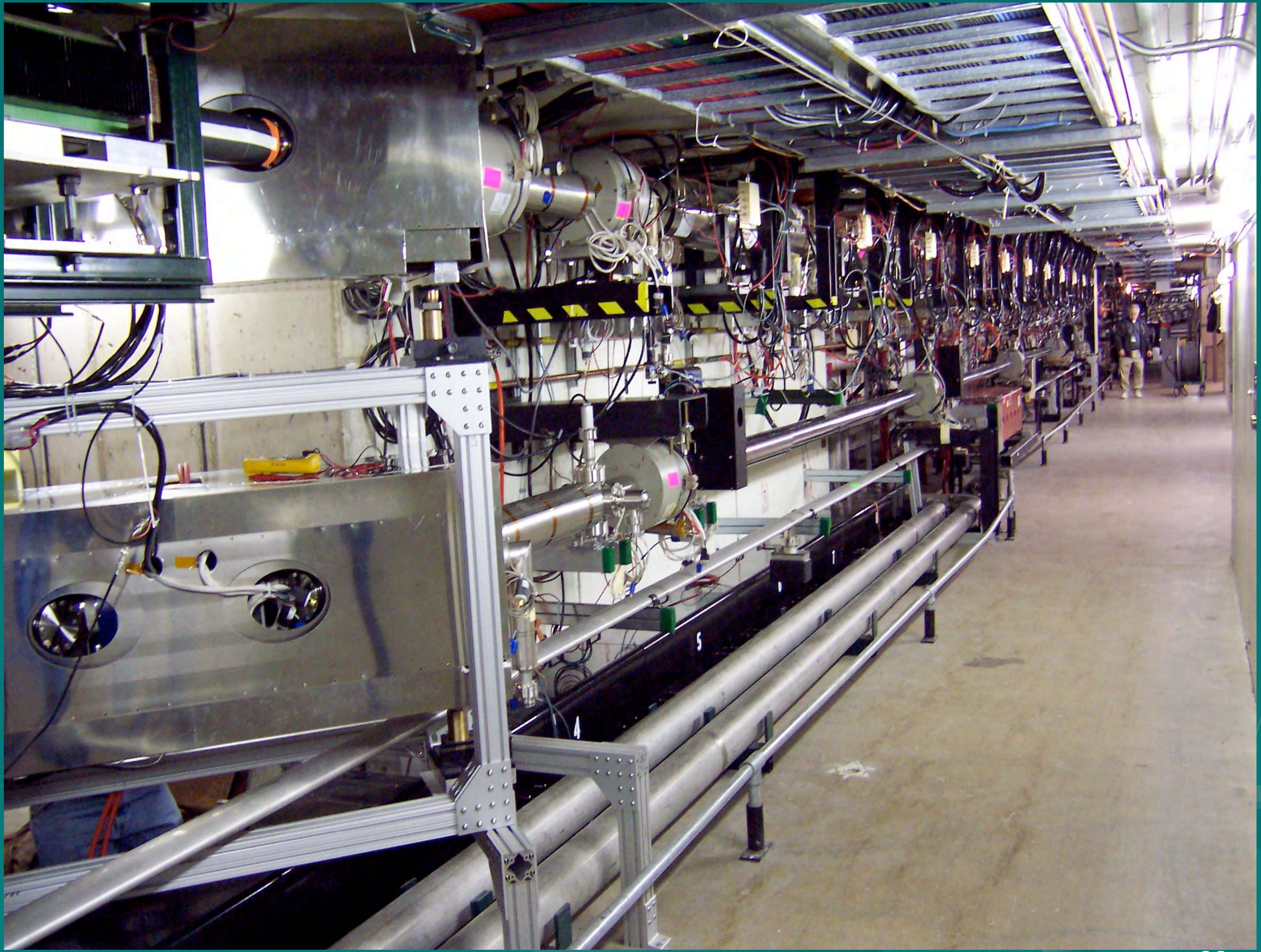
The ions undergo Coulomb scattering in the electron "gas" and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



Sergei Nagaitsev (Fermilab/AD)

2

Electron Cooling Beamline



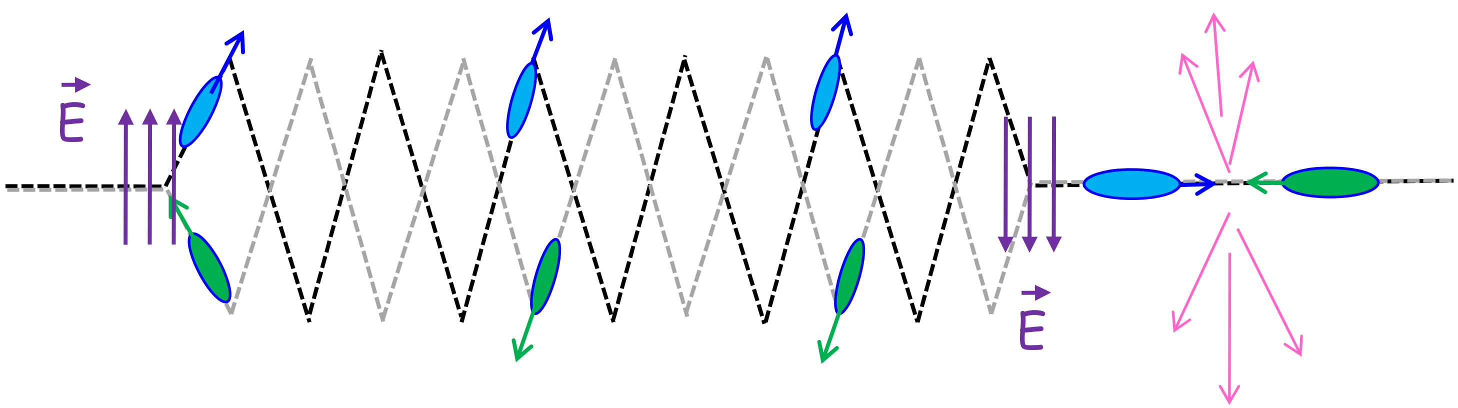
COoler SYnchrotron COSY

Tevatron

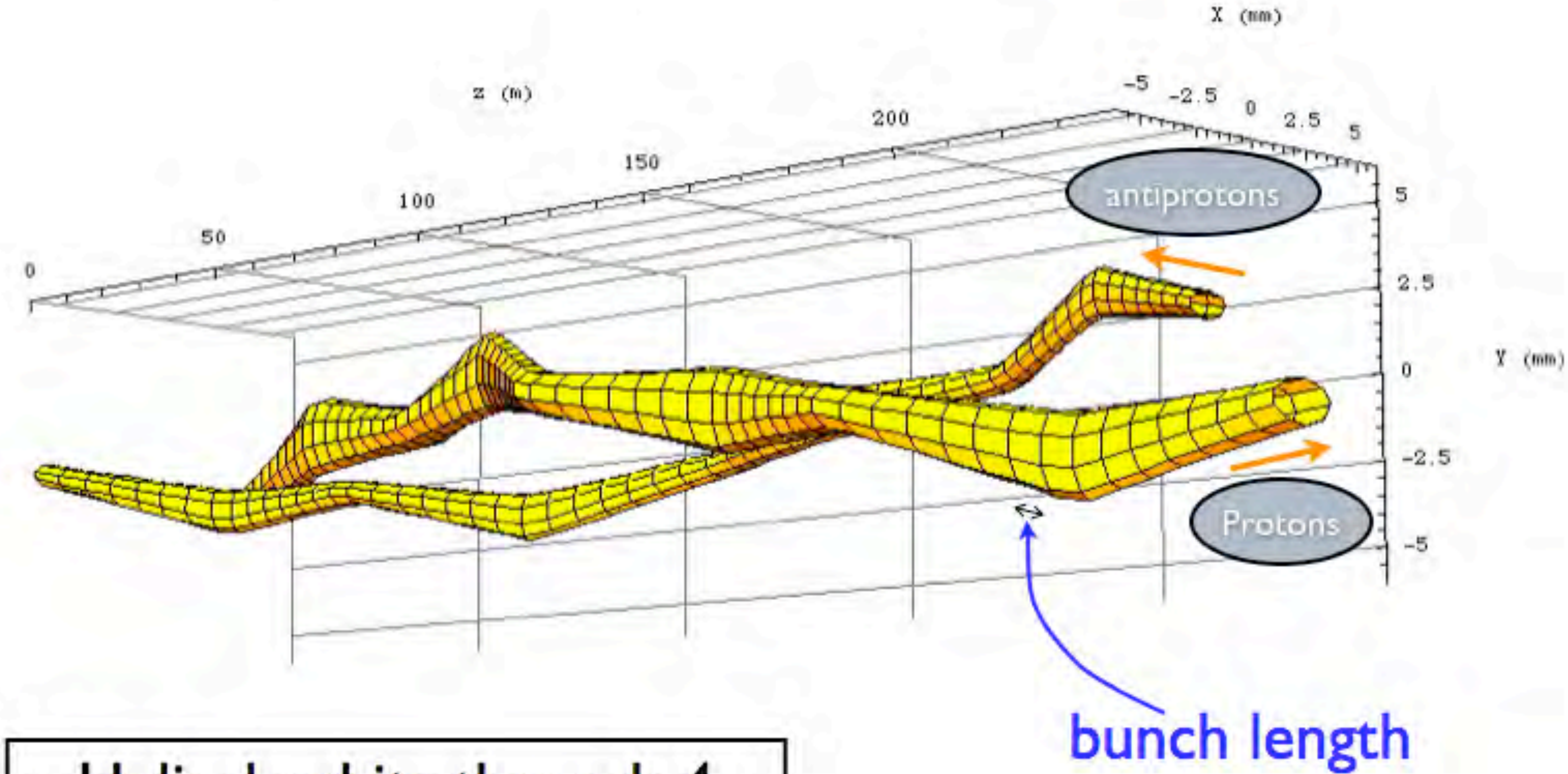
- The TEVATRON is presently the 'energy frontier' collider in operation at FNAL, with a beam energy of 980 GeV and a size of ~ ¼ LHC.
- It is the first super-conducting collider ever build.
- It collides proton and anti-proton bunches that circulate in opposite directions in the SAME vacuum chamber.
- The TEVATRON has undergone a number of remarkable upgrades and it presently collides 36 proton with 36 anti-proton bunches (k=36), with bunch populations (N) similar to the ones of the LHC (but there are always fewer anti-protons !).
- One of the problems at the TEVATRON are the long-distance encounters of the bunches in the arc sections. A complicated separation scheme with electrostatic elements has to be used:

Luminosity gain of LHC comes basically from k !!

Tricky to operate !!

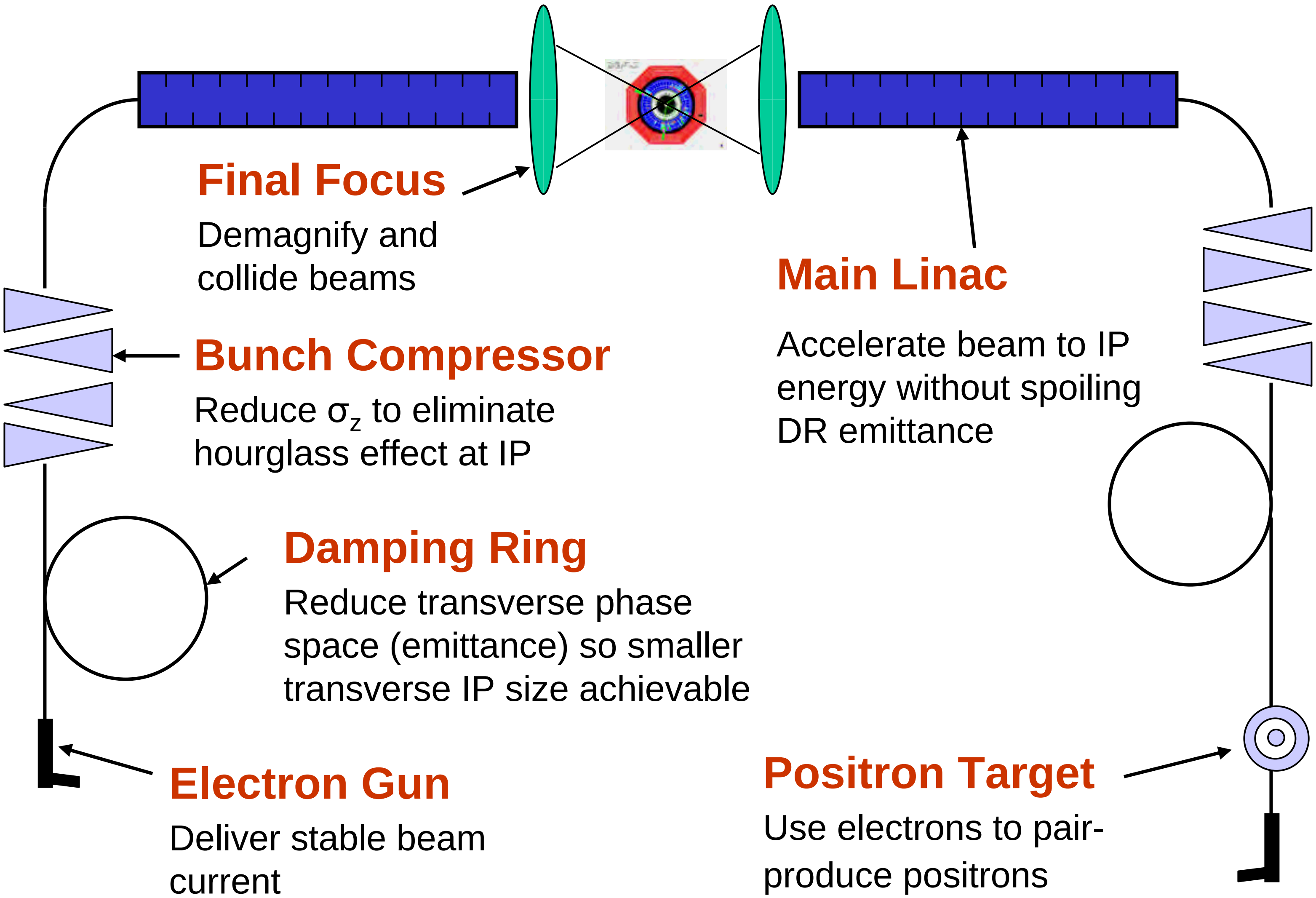


Tevatron Beam Envelopes



Helical orbits through 4 standard arc cells

Linear Collider Conceptual Scheme



Luminosity: Beam Size & Beam Power

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D$$

$f_{rep} \cdot n_b$ tends to be low in a linear collider

	L [cm^{-2} s^{-1}]	f_{rep} [s^{-1}]	n_b	N [10^{10}]	σ_x [μm]	σ_y [μm]
ILC	**$2 \cdot 10^{34}$**	**5**	**3000**	**2**	**0.5**	**0.005**
SLC	$2 \cdot 10^{30}$	120	1	4	1.5	0.5
LEP II	$5 \cdot 10^{31}$	10,000	8	30	240	4
PEP II	$1 \cdot 10^{34}$	140,000	1700	6	155	4

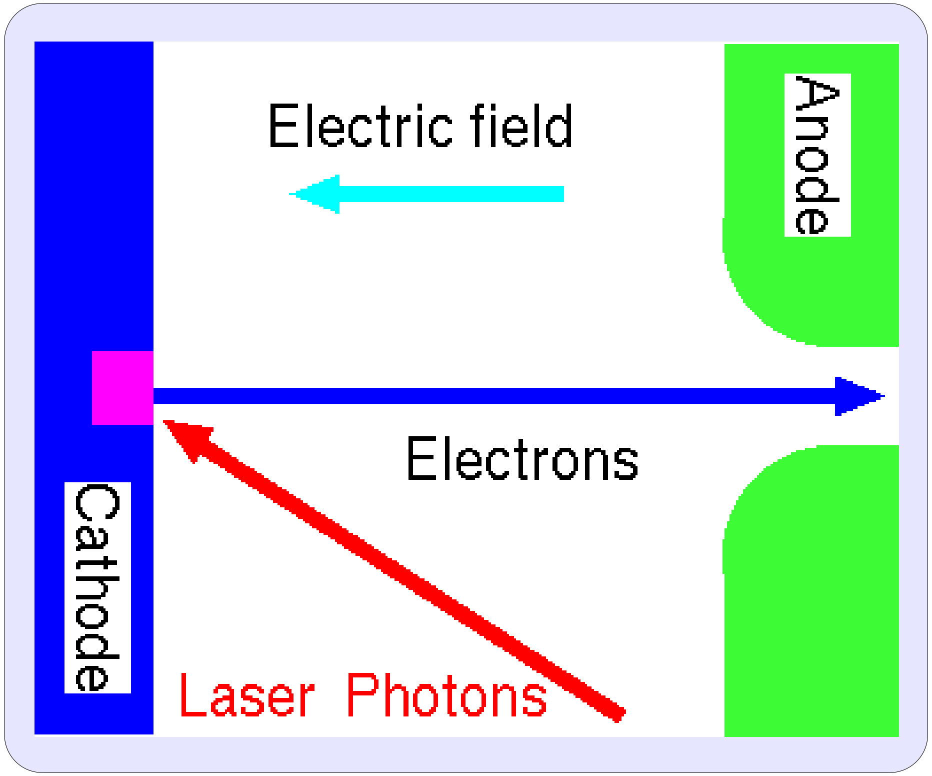
The beam-beam tune shift limit is much looser in a linear collider than a storage rings → achieve luminosity with spot size and bunch charge

- Small spots mean small emittances, $\varepsilon_{x,y}$ and small β-functions, $\beta_{x,y}$

$$\sigma_{x,y} = \sqrt{\beta_{x,y} \cdot \varepsilon_{x,y}}$$

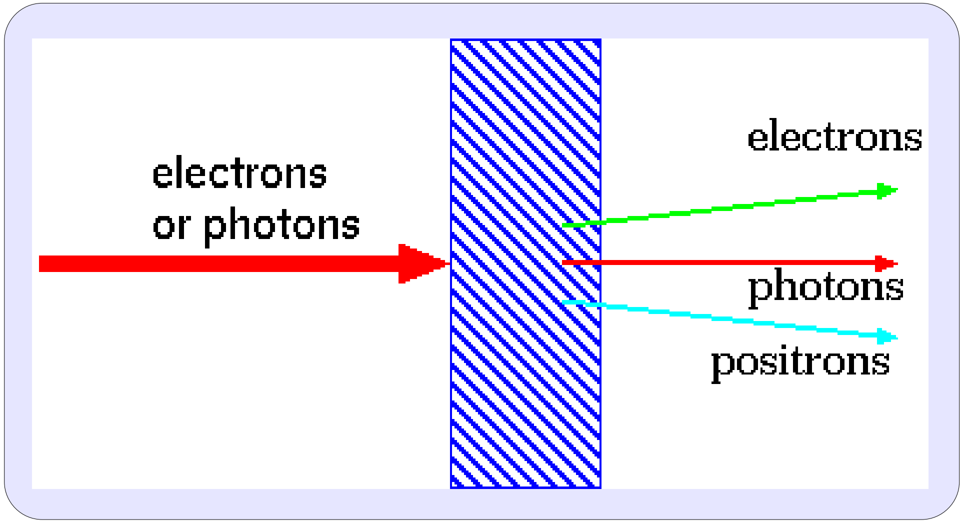
Photo-Cathode DC Gun

- Electron beam is generated by Photo-emission with laser.
- Beam extraction by a static electric field (100 - 300 kV).
- GaAs for polarized electron beam, can be used. It is for ILC.



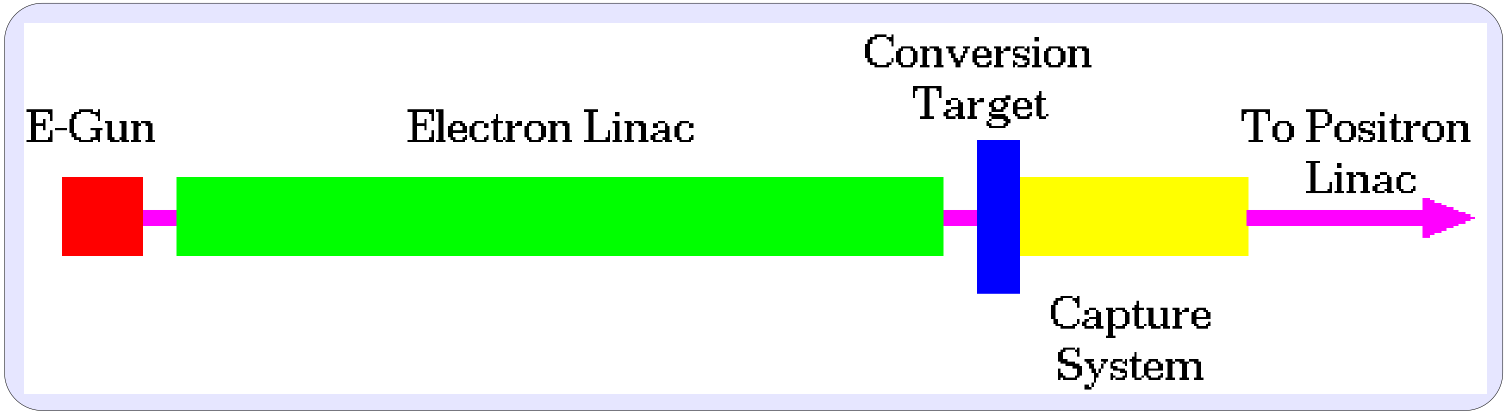
Summary for Positron Generation

- Positron is generated through pair-creation process.
- Driver beam (electron >100s MeV or photon > 10 MeV) is injected onto the converter and positron is obtained as a mixed flux of e+, e-, and photon.
- Regime is different : EM shower for electron and non-shower for photon.



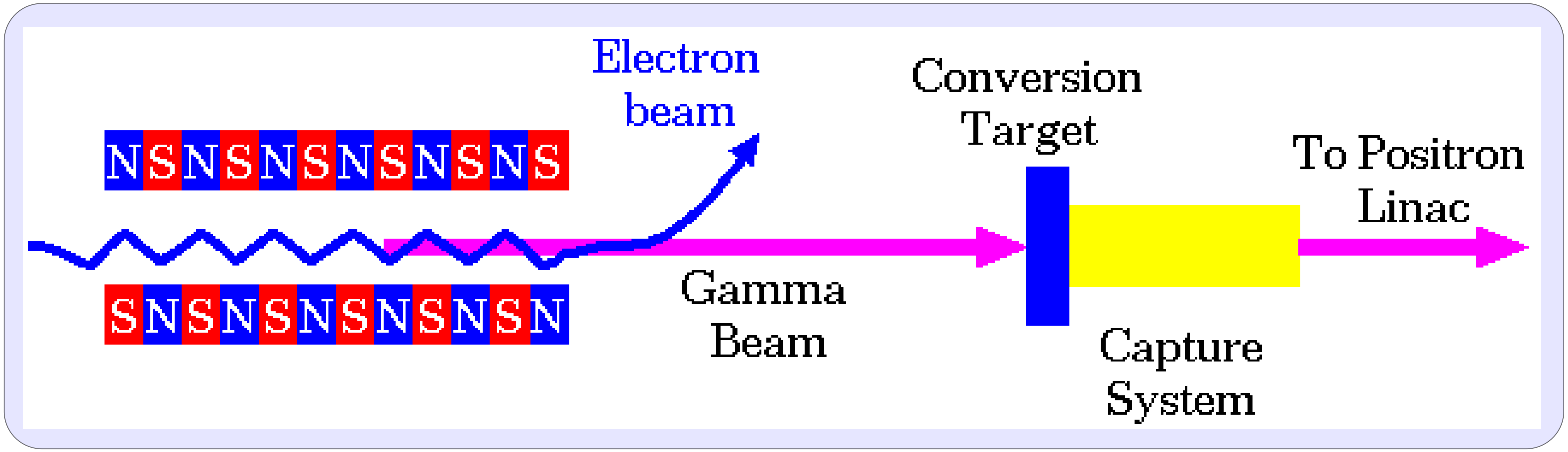
Electron Driven Scheme

- Several GeVs driver electron beam.
- High Density Material for EM shower evolution.
- Positron capture by QWT or AMD + NC accelerator tube with solenoid focusing.



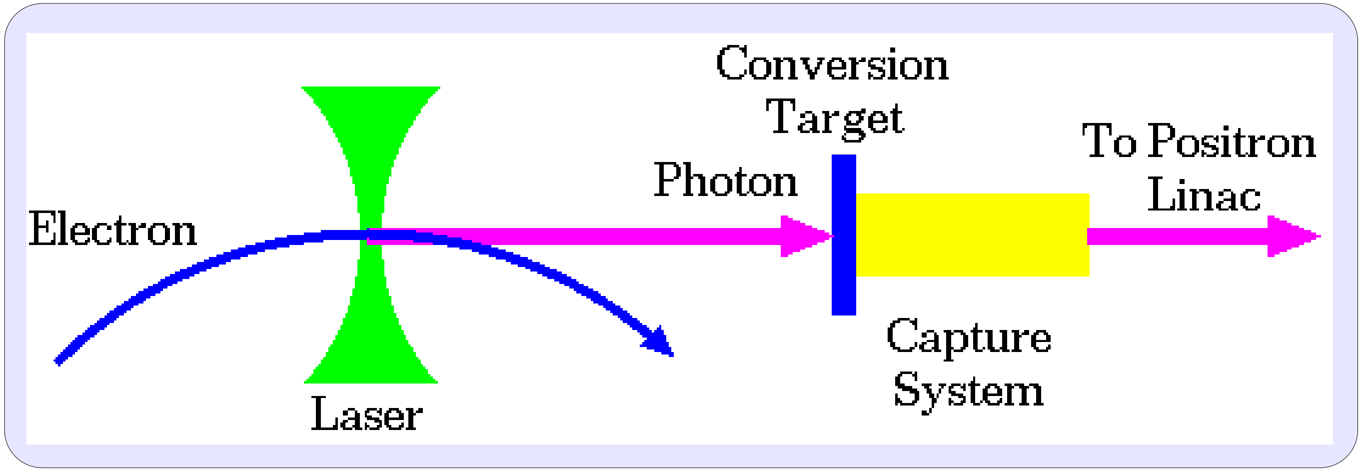
Undulator Scheme

- By passing more than 100 GeV energy electrons through a short period undulator, more than ~10MeV energy gamma rays are generated.
- This gamma ray is converted to positrons in a heavy material.
- Same capture system.



Compton Scheme

- Compton back scattering between several GeVs electron and laser photons generates ~ 30 MeV gamma rays.
- These gamma rays are converted to positrons.
- If the laser is circularly polarized, positron can be polarized.

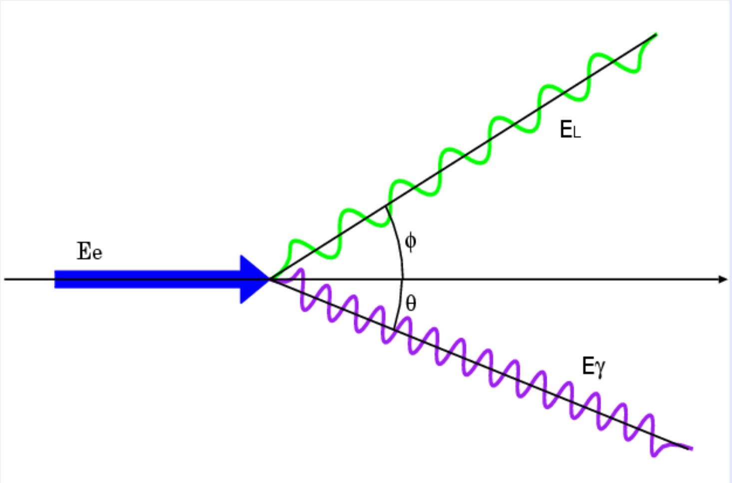


Compton Back-scattering

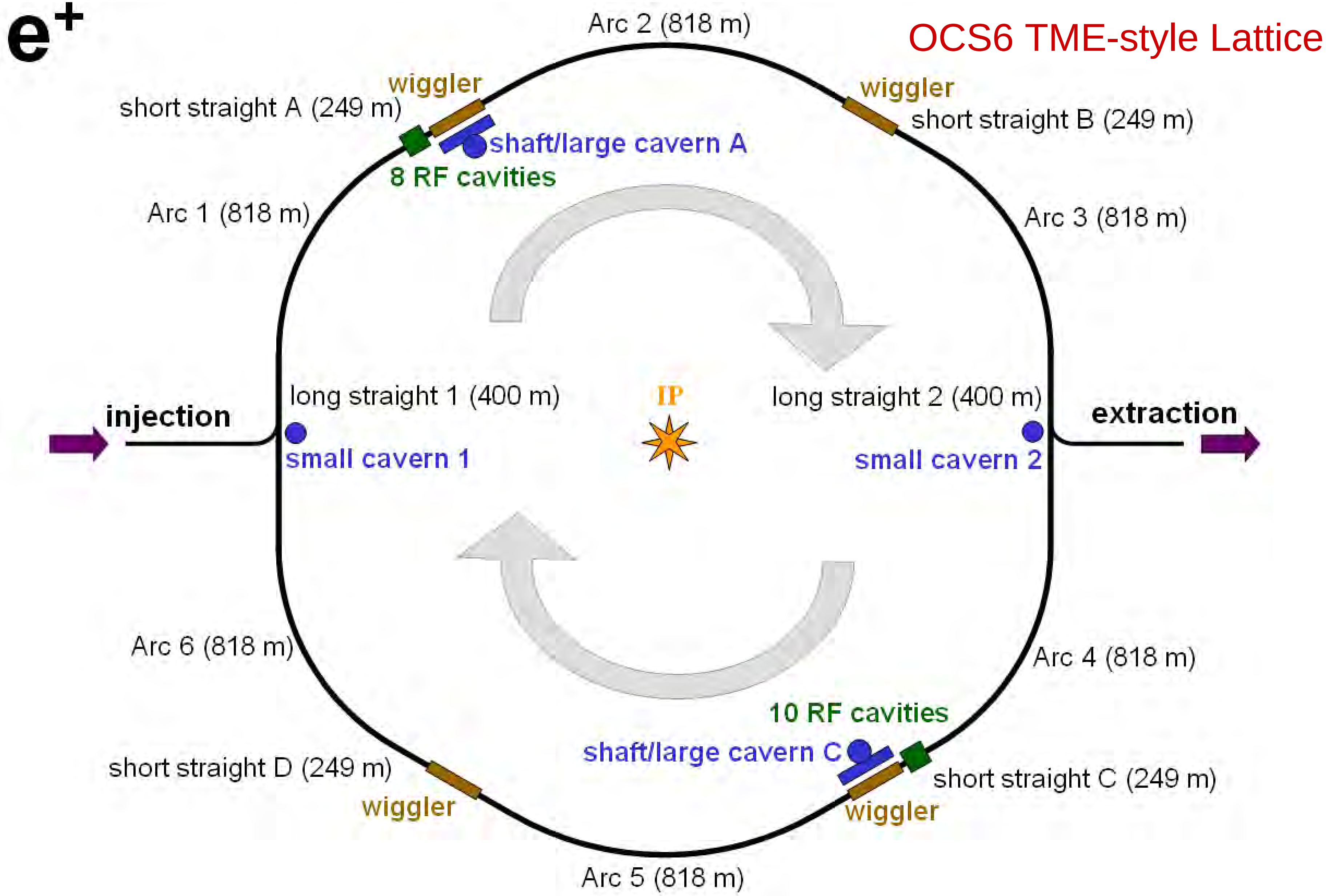
- Inverse Compton scattering between laser photon and electron beam.
- Laser acts as a quite short period undulator; high energy gamma (several 10s MeV) is obtained with few GeV electron beam.

$$E_\gamma \sim \frac{4\gamma^2 mc^2 E_L}{mc^2 + 4\gamma E_L}$$

- E_L : Laser energy 1eV @ 1um.
- Electron beam 1GeV, $\gamma = 2000$.
- E_γ ~ 16MeV



The RDR Damping Ring Layout



Synchrotron Radiation

We will only concern ourselves with electron/positron rings. The instantaneous power radiated by a relativistic electron with energy E in a magnetic field resulting in bending radius ρ is:

$$P_\gamma = \frac{cC_\gamma E^4}{2\pi\rho^2} = \frac{e^2c^3}{2\pi}C_\gamma E^2 B^2$$ where $C_\gamma = 8.85\times10^{-5}\, m/\left(GeV\right)^3$

We can integrate this expression over one revolution to obtain the energy loss per turn:

$$U_0 = \frac{C_\gamma E^4}{2\pi}\oint\frac{ds}{\rho^2} = \frac{C_\gamma E^4}{2\pi} I_2$$ where I_2 is the 2nd radiation integral

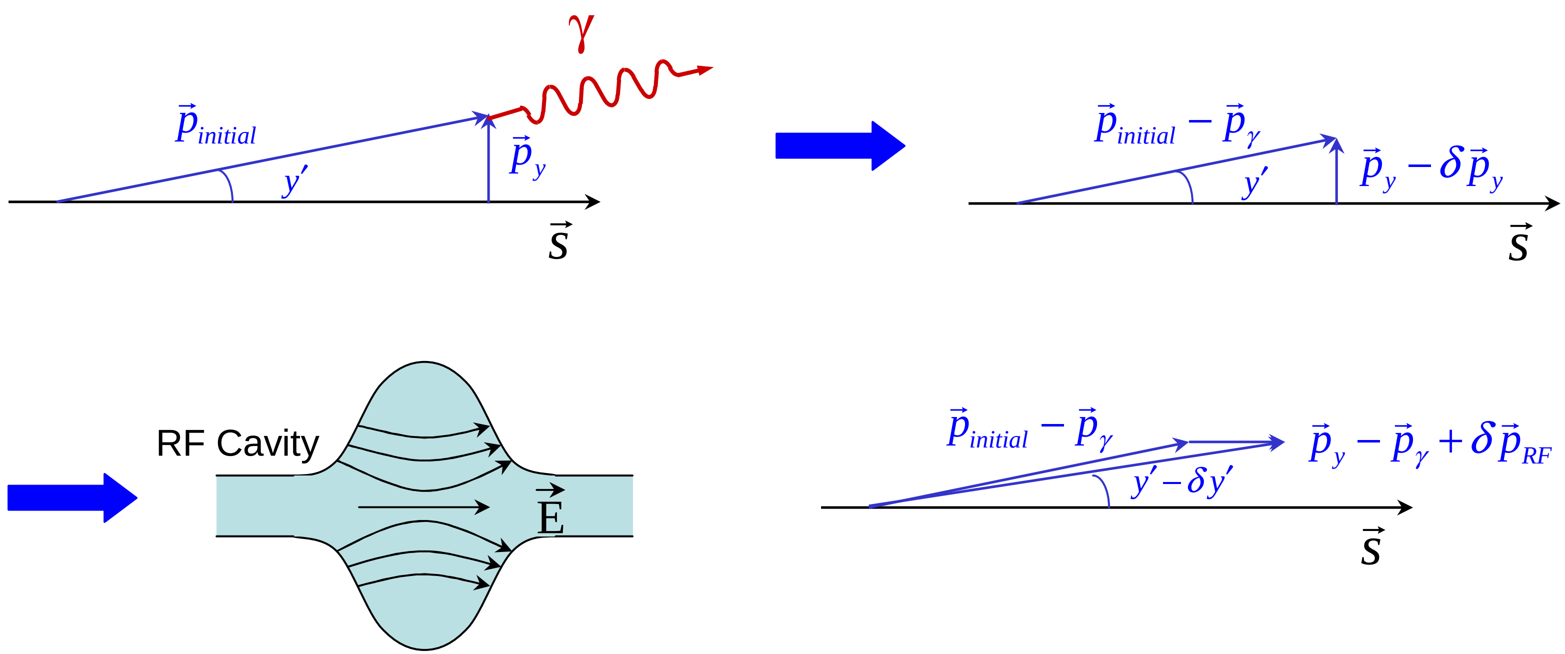
For a lattice with uniform bending radius (iso-magnetic) this yields:

$$U_0\left[eV\right] = 8.85\times10^4\,\frac{E^4\left[GeV\right]}{\rho\left[m\right]}$$

If this energy were not replaced, the particles would lose energy and gradually spiral inward until they would be lost by striking the vacuum chamber wall. The RF cavities replace this lost energy by providing momentum kicks to the beam in the longitudinal direction.

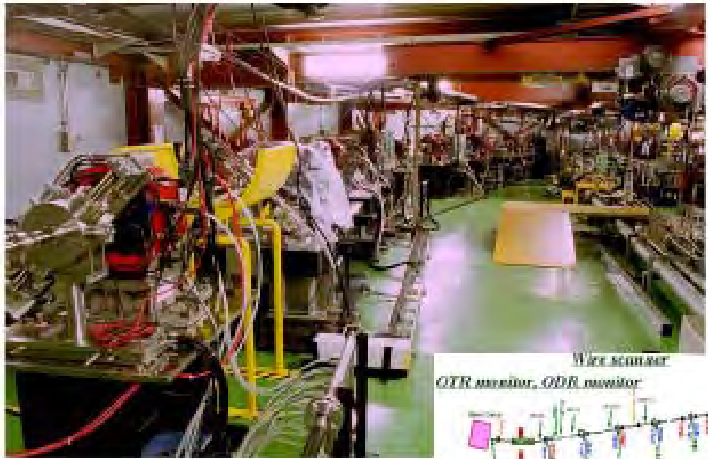
Radiation Damping of Vertical Betatron Motion

We look first at the vertical dimension where, for an ideal machine, we do not need to consider effects of vertical dispersion.



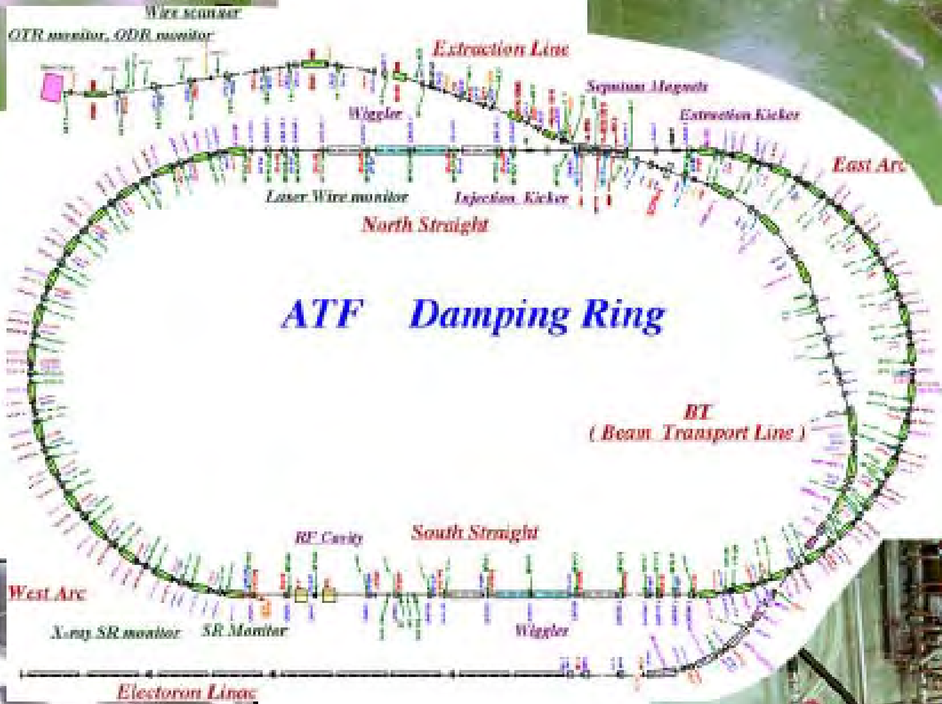
The change in y' after the RF cavity can be written as:

$$\delta y' = -y' \frac{\delta p_{RF}}{p} = -y' \frac{\delta E}{E}$$



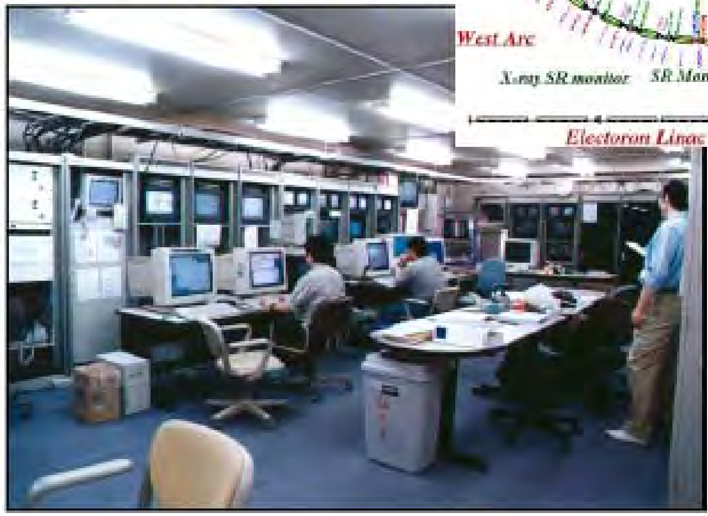
Extraction Line

ATF



Damping Ring

Control Room

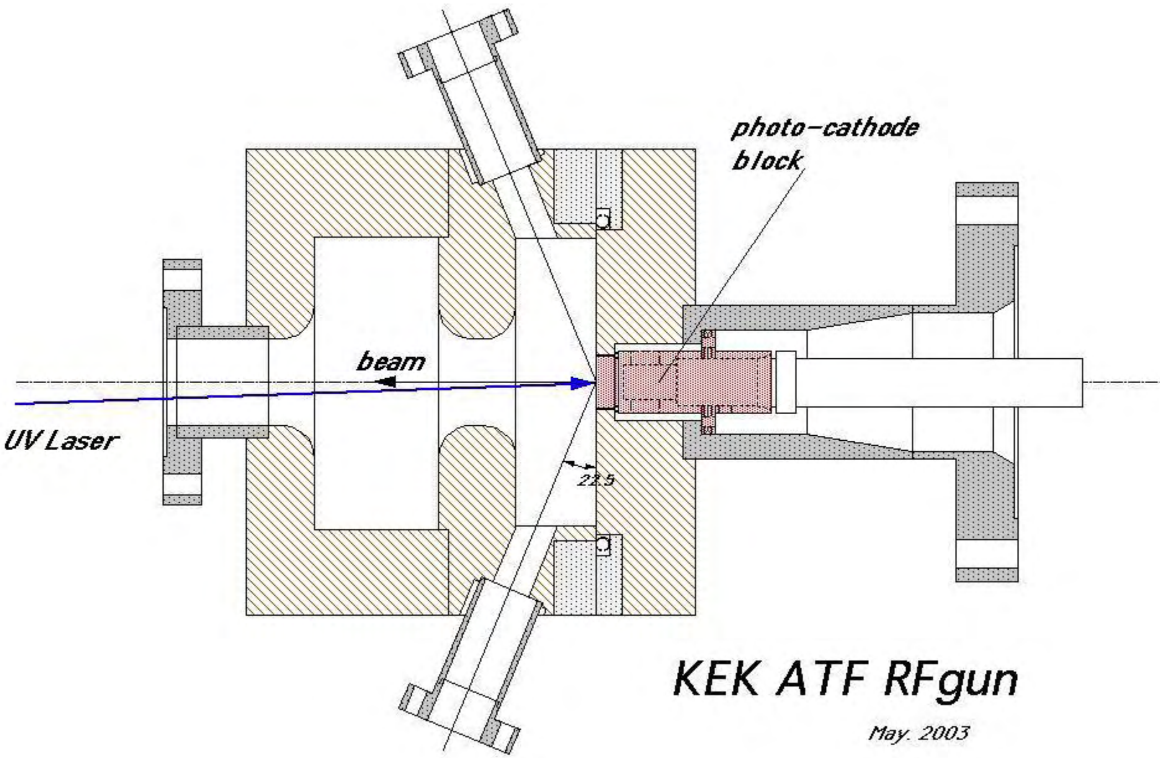


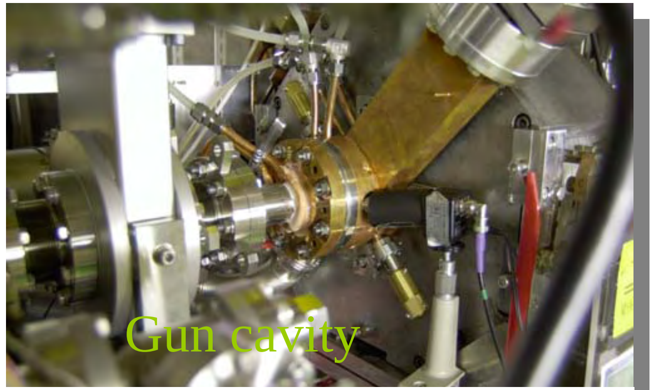
Linac

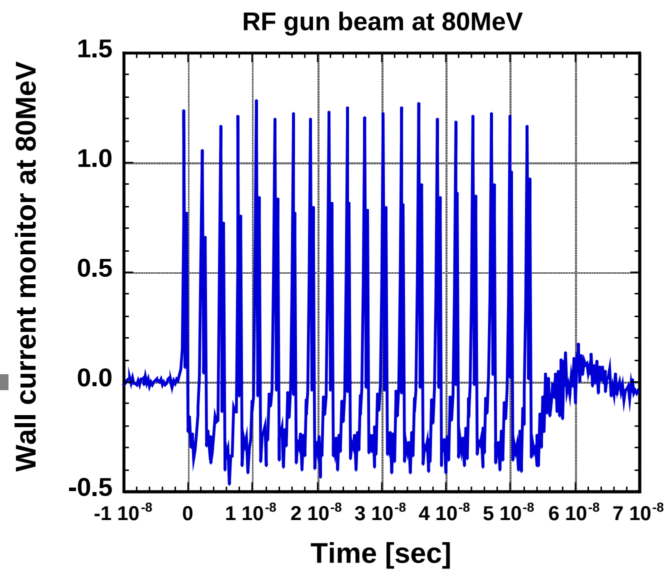
Machine performance

Look at experimental measurement results.

Multi-bunch electron beam generation







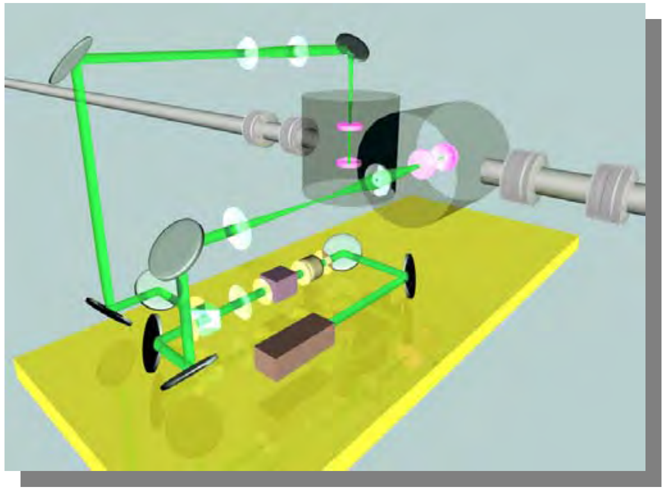
High quality Multi-bunch beam is generated.

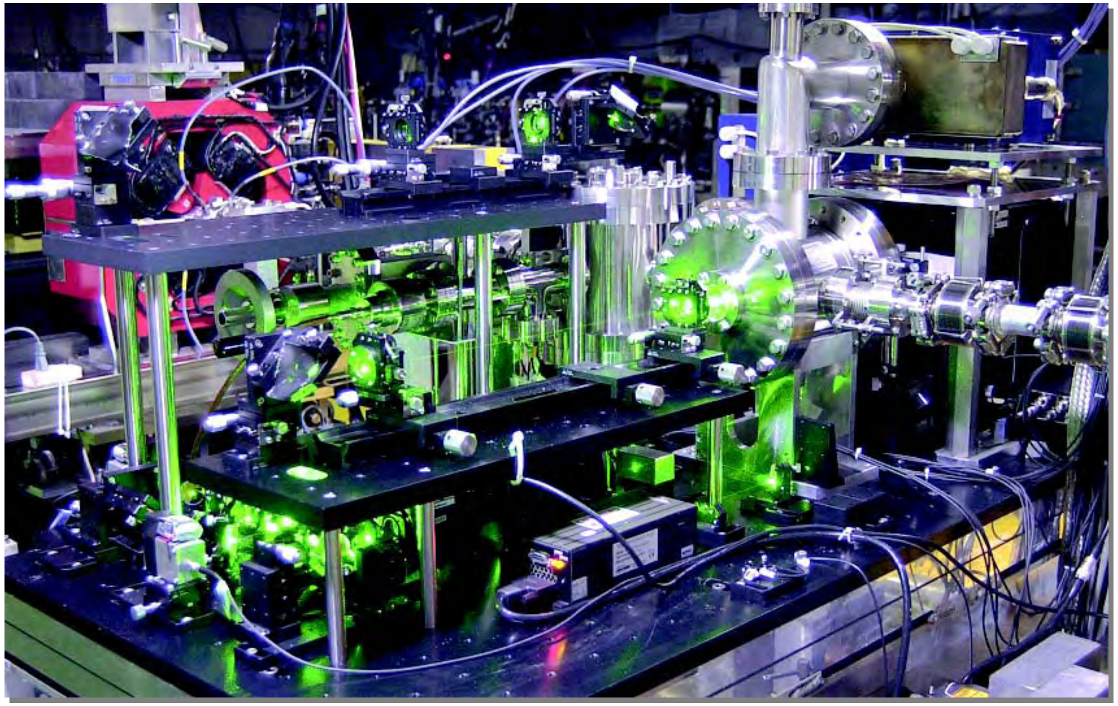
1 ~ 20 bunches / pulse, 2.8ns spacing

~ 2 x 10^{10} electrons / bunch

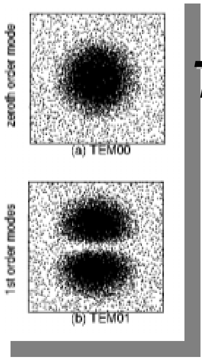
Laser wire scanner in DR

for X & Y scan, for single/multi-bunch



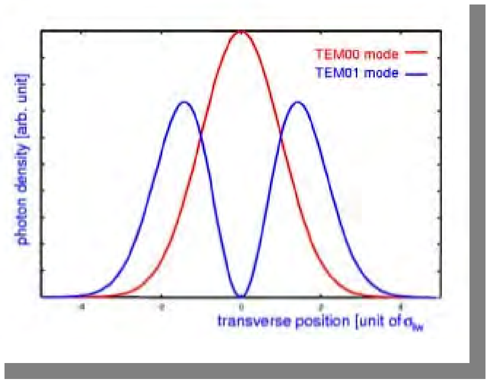


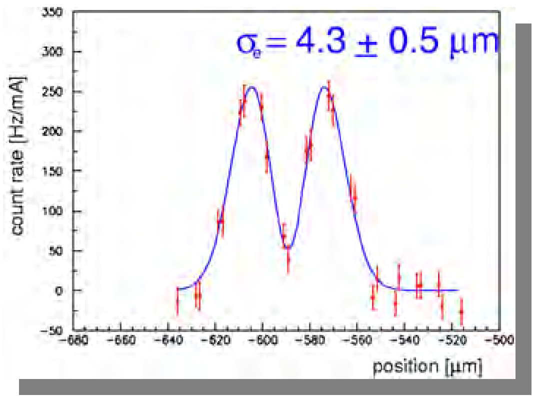
Two optical cavity chamber
For X-wire and Y-wire



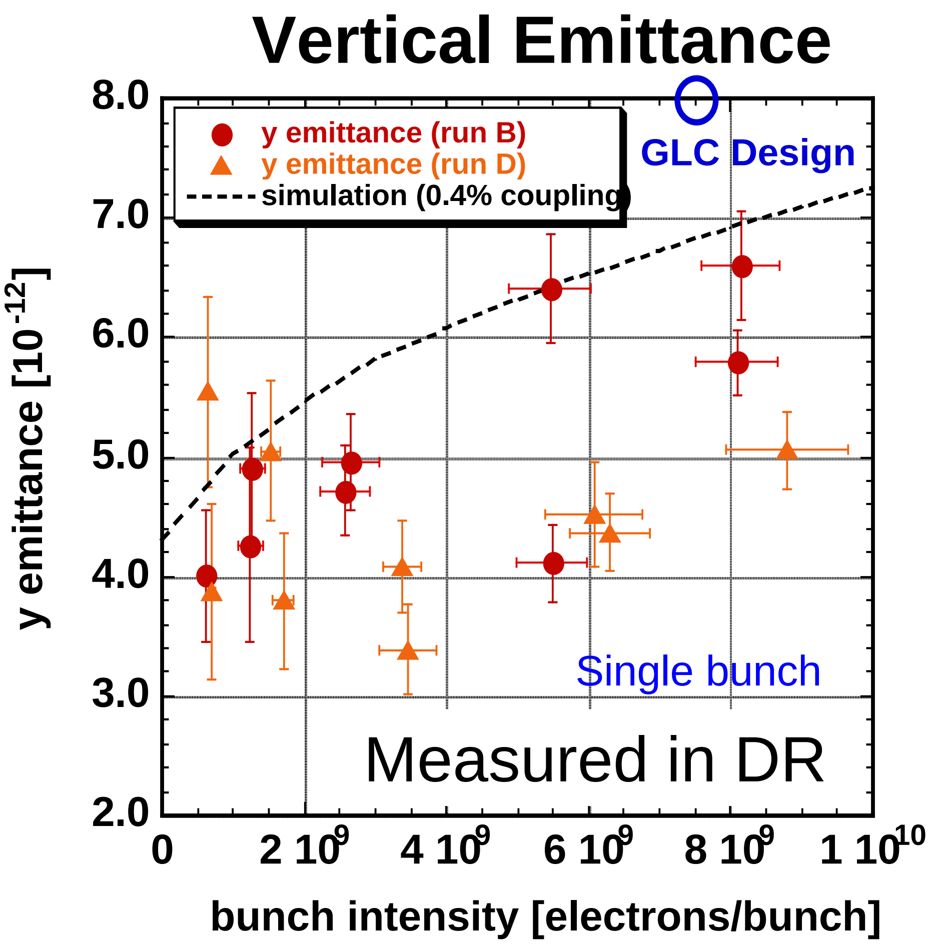
TEM00 wire

TEM01 wire





Possibility of 1pm-rad ε_y



Kubo's simulation:

BPM offset error should be < 0.1 mm. ("BBA")

Then, ε_y ~ 2 pm will be achieved.

Magnet re-alignment, < 30 μm.

Then, ε_y ~ 1 pm will be achieved.

Optics model should be good.

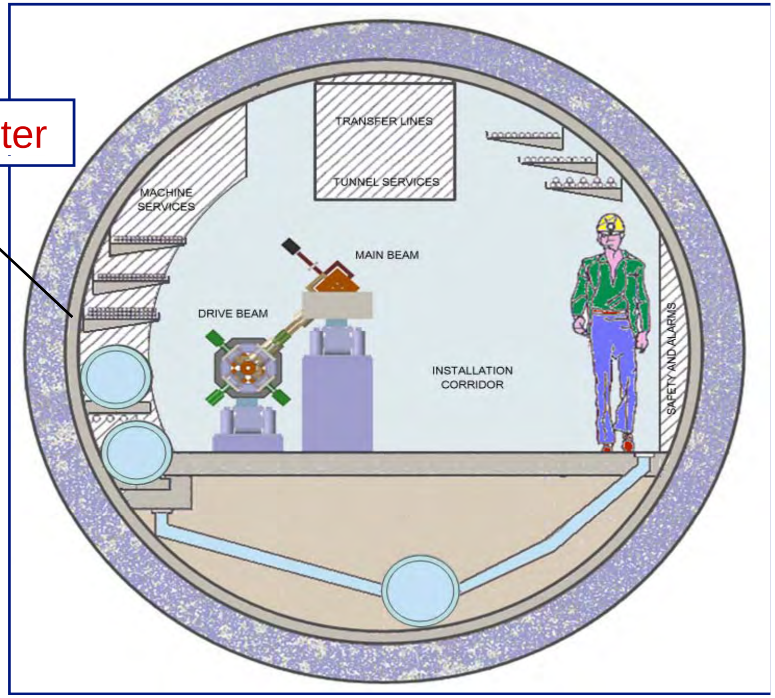
Quad strength error should be < 0.5(?) %

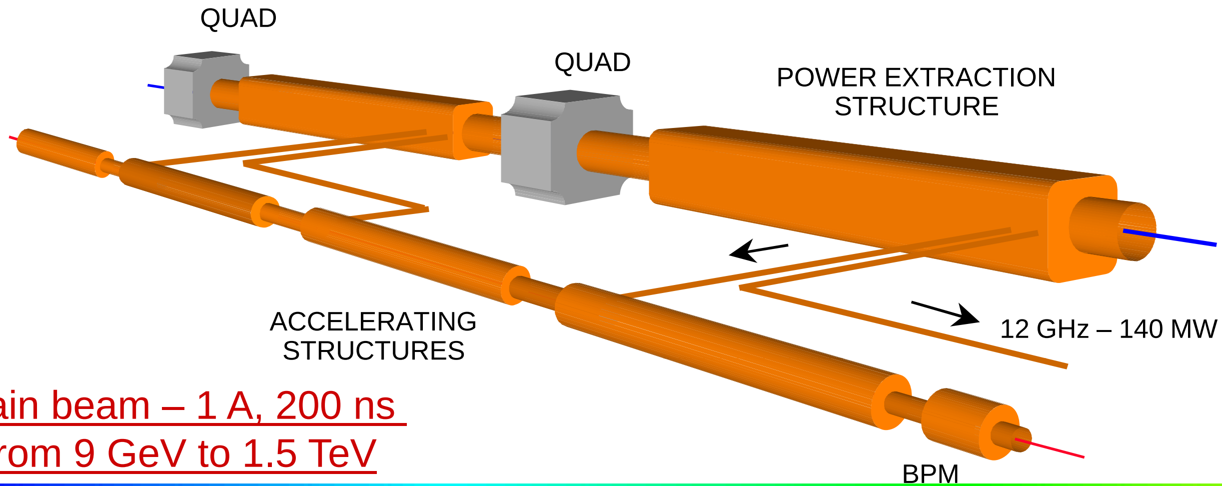
CLIC – basic features

- High acceleration gradient
  - “Compact” collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency (12 GHz)
- Two-Beam Acceleration Scheme
  - High charge Drive Beam (low energy)
  - Low charge Main Beam (high collision energy)
  - ⇒ Simple tunnel, no active elements
  - ⇒ Modular, easy energy upgrade in stages

CLIC TUNNEL CROSS-SECTION

4.5 m diameter





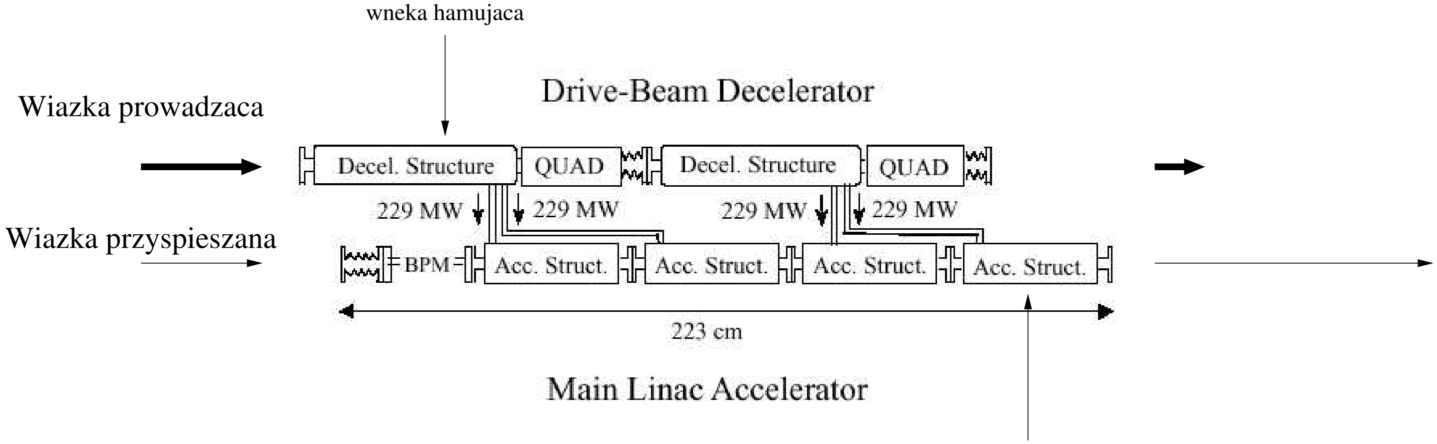
Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

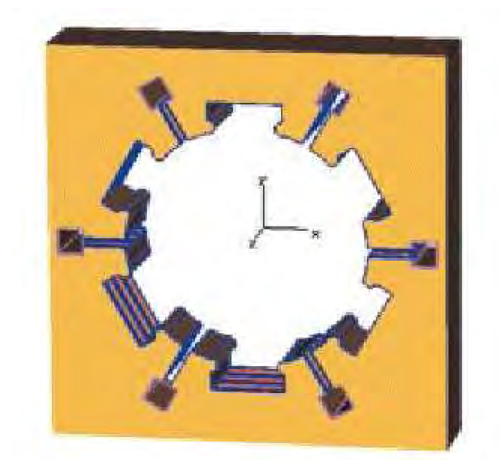
CLIC

Zasada działania

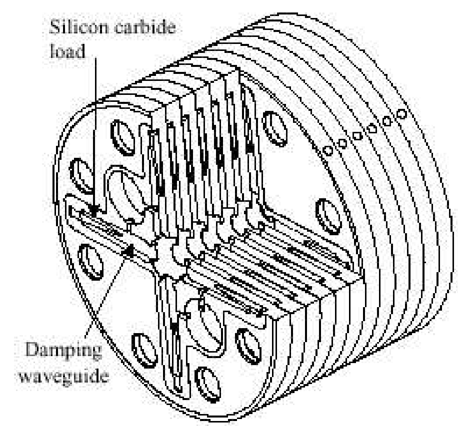
Wiązka prowadząca wytwarza pole elektryczne (falę EM), które przyspiesza drugą wiązkę:



Wnęka hamująca



Wnęka przyspieszająca



"Transformator", sprawność $\sim$ 18%

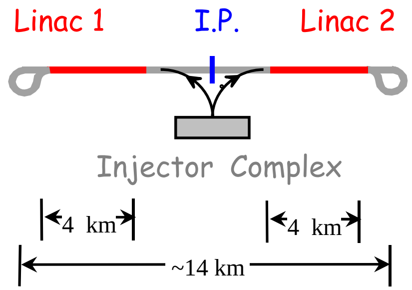
- wiązka prowadząca - duży prąd, mała energia
- wiązka przyspieszana - mały prąd $\Rightarrow$ duża energia

Obecnie przygotowywane są testy kolejnego (3) prototypu

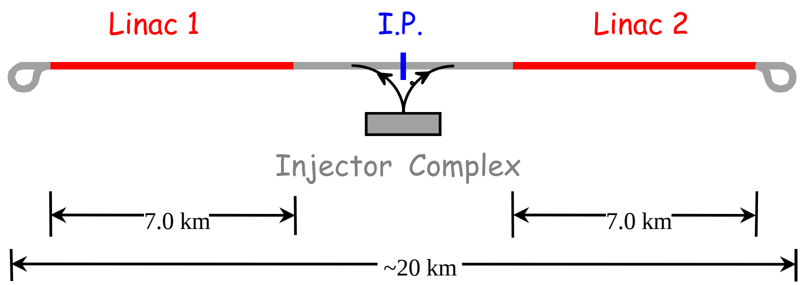
Weryfikacja koncepcji $\sim$ 2010 (?), projekt $\sim$ 2015 (??), uruchomienie $>$ 2020 (???)

CLIC Layout at various energies

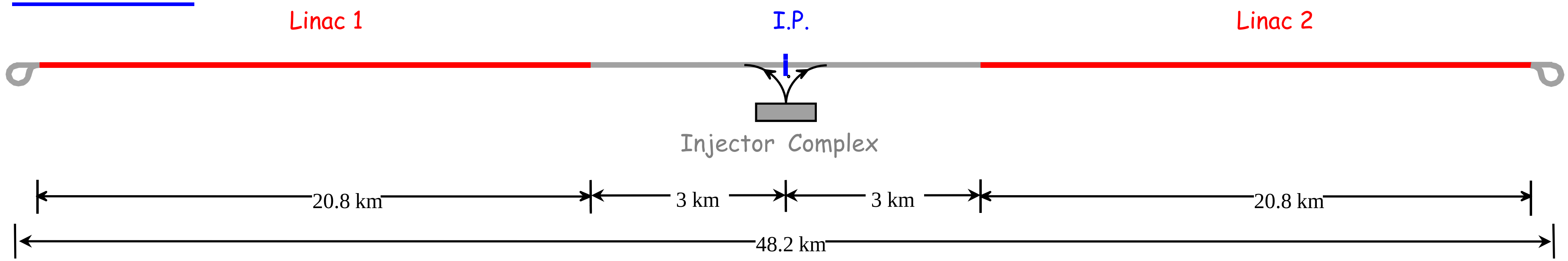
0.5 TeV Stage



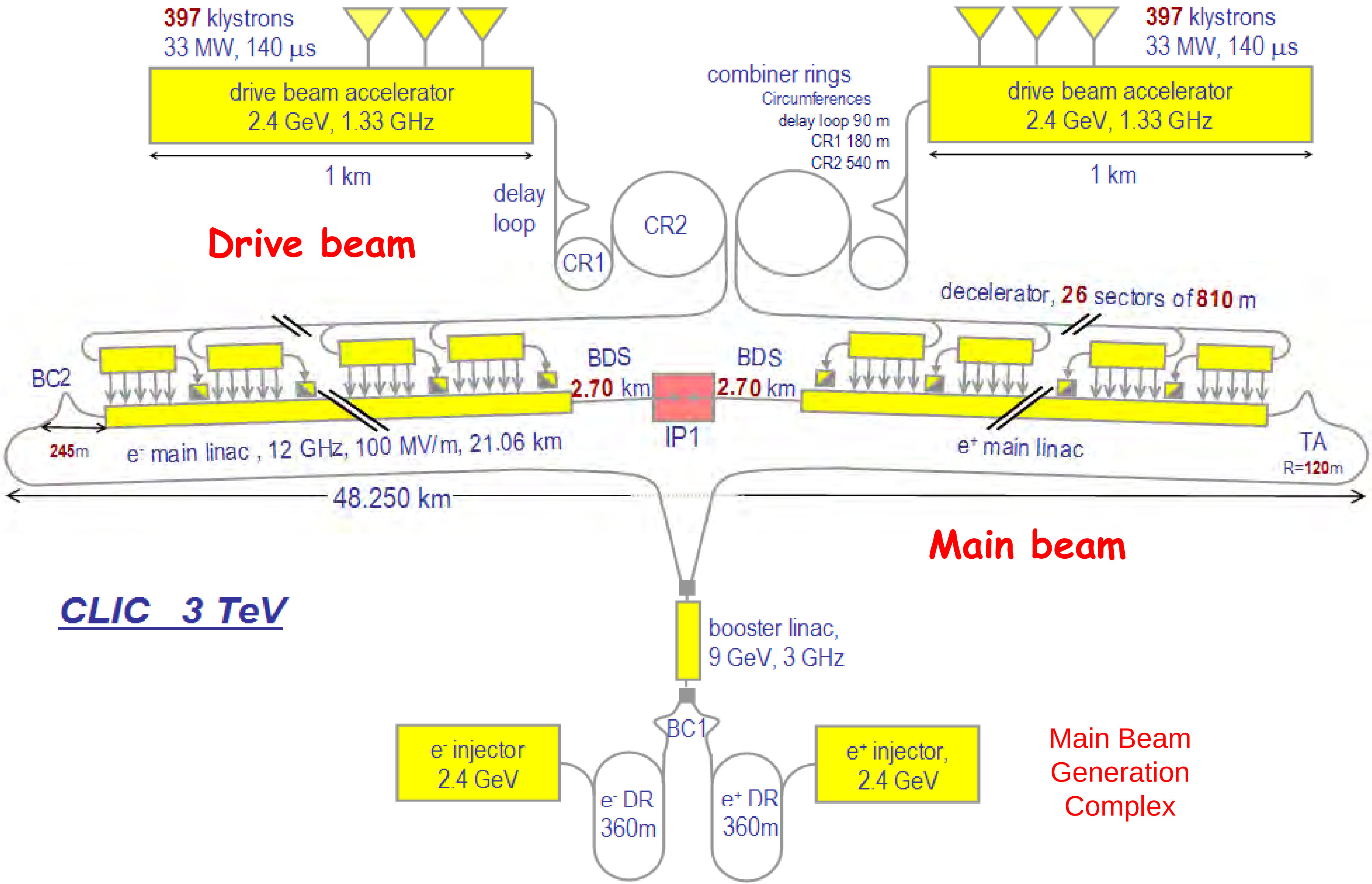
1 TeV Stage



3 TeV Stage



CLIC – overall layout



Zderzenia $\mu^+\mu^-$

Pierwsze pomysły: $\sim$1960

Zalety

$m_\mu/m_e \approx 207$

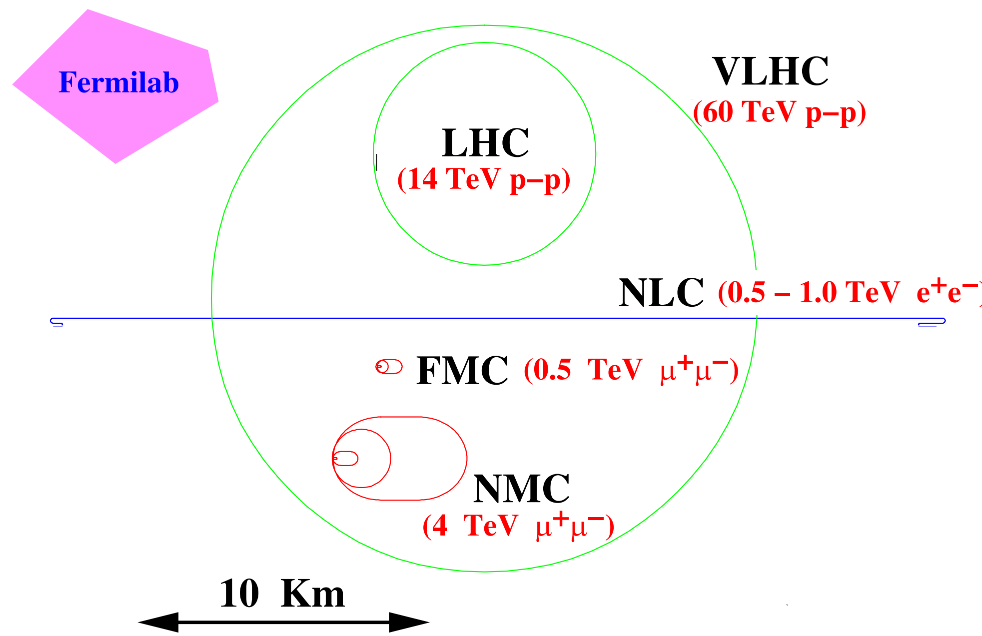
- mniejsze promieniowanie hamowania

$\Rightarrow$ dużo mniejszy pierścień (koszt !!!)

$\Rightarrow$ wyższe energie (!)

$\Rightarrow$ mniejsze rozmycie energii wiązki

- rezonansowa produkcja Higgsa
- fabryka neutrin

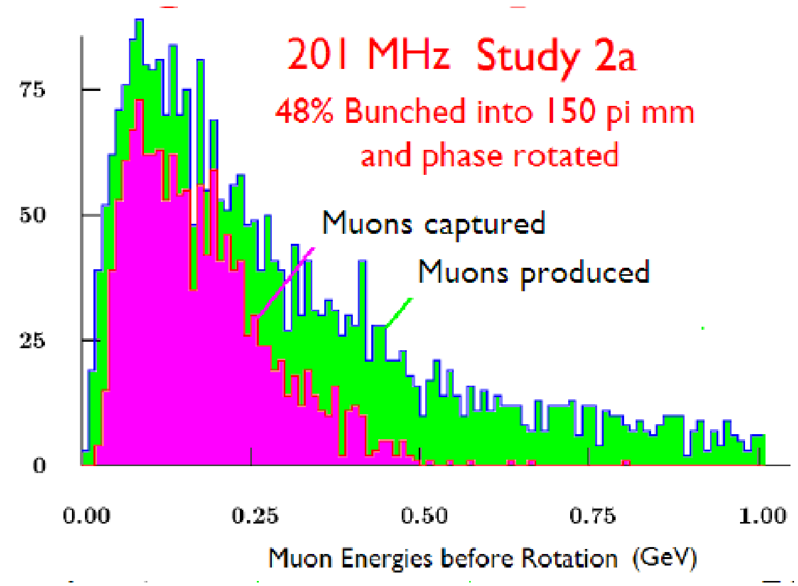


Czy to możliwe ?

Czy potrafimy zbudować akcelerator przeciwbieżnych wiązek $\mu^+\mu^-$?

Why NOT a $\mu^+\mu^-$ collider

- Make muons from the decay of pions
- With pions made from protons on a target
- To avoid excessive proton power, we must capture a large fraction of pions made
  - Use a high field solenoid
    Captures most transverse momenta
  - Use Phase rotation
    Captures most longitudinal moments



- The phase space of the pions is now very large:
  - a transverse emittance of 20 pi mm and
  - a longitudinal emittance of 2 pi m
- These emittances must be somehow be cooled by
  - $\approx$ 1000 in each transverse direction and
  - 40 in longitudinal direction
- A factor of over 10^7 !

Cooling Methods

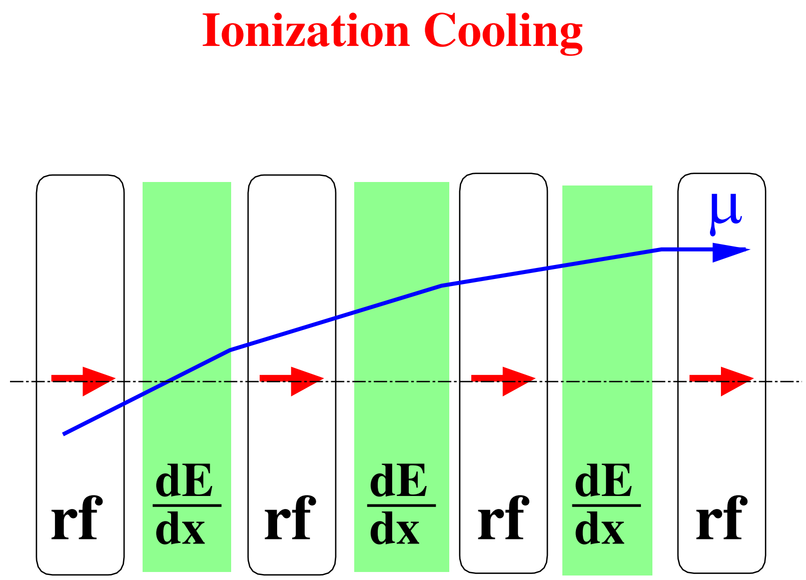
- Electrons are typically cooled (damped) by synchrotron radiation
  but muons radiate too little ($\Delta E \ \propto \ 1/m^3$)
- Protons are typically cooled by a comoving cold electron beam
  too slow
- Or by stochastic methods
  too slow and only works for low intensities ($\tau \ \propto \ 1/\sqrt{N}$)
- Ionization cooling is probably the only hope
- Although optical stochastic cooling after ionization cooling might be useful for very high energies

Zderzenia $\mu^+\mu^-$

Chłodzenie jonizacyjne

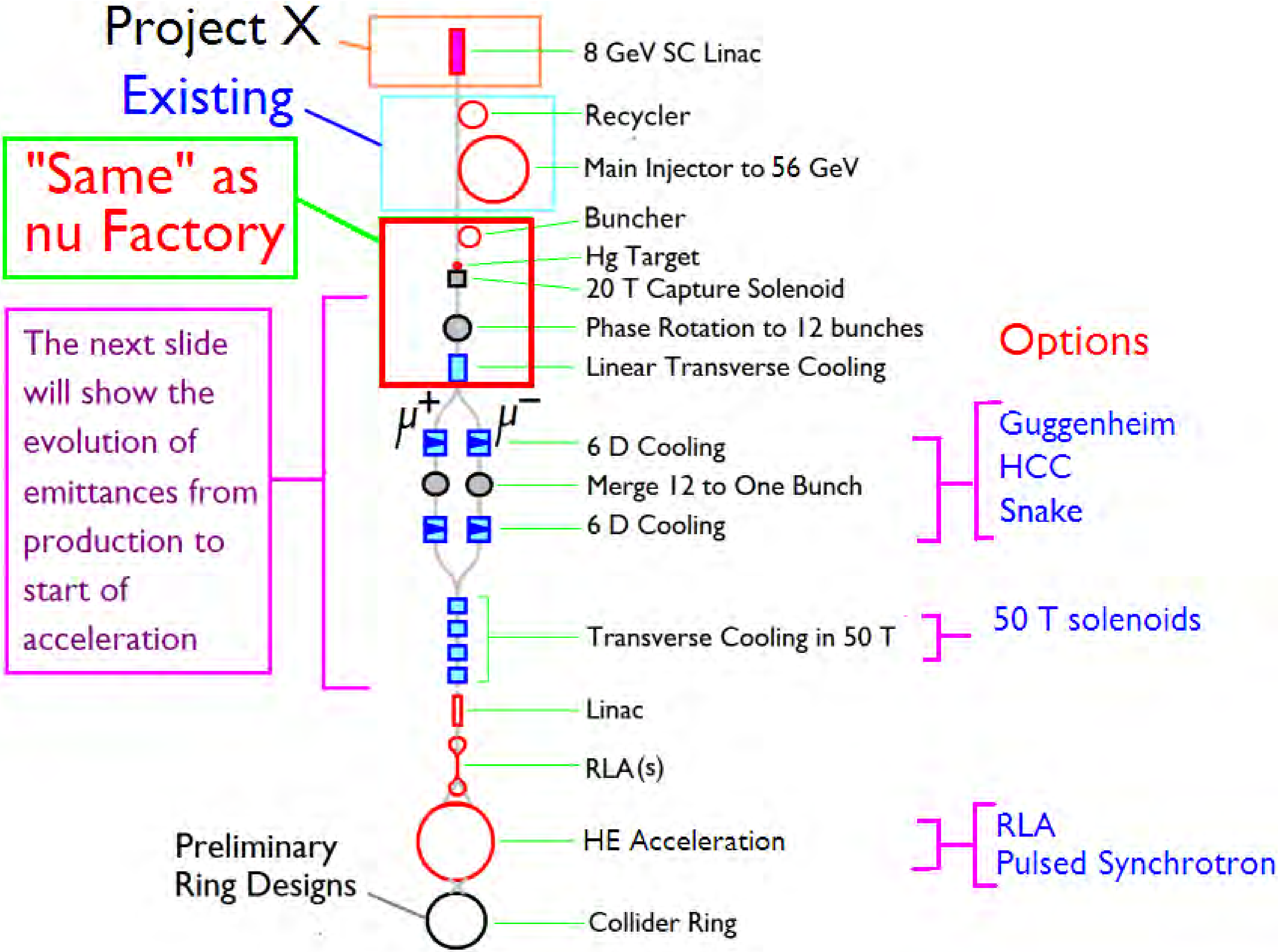
Pomysł: Skrinsky i Parkhomchuk, 1981.

- przechodząc przez warstwy absorbera mion traci energię na jonizację
  $\Rightarrow$ zmniejszenie wszystkich składowych pędu
- we wnękach przyspieszających mion odzyskuje straconą energię
  $\Rightarrow$ tylko podłużną składową pędu



Efekt sumaryczny: zmniejszenie pędów poprzecznych wiązki
$\Rightarrow$ lepsze ogniskowanie $\Rightarrow$ wyższa świetlność

Nie musimy spowalniać mionów do $p \sim 0$
$\Rightarrow$ mniej rozpadów


Project X
Existing
"Same" as nu Factory
The next slide will show the evolution of emittances from production to start of acceleration
Preliminary Ring Designs
8 GeV SC Linac
Recycler
Main Injector to 56 GeV
Buncher
Hg Target
20 T Capture Solenoid
Phase Rotation to 12 bunches
Linear Transverse Cooling
μ+
μ−
6 D Cooling
Merge 12 to One Bunch
6 D Cooling
Transverse Cooling in 50 T
Linac
RLA(s)
HE Acceleration
Collider Ring
Options
Guggenheim
HCC
Snake
50 T solenoids
RLA
Pulsed Synchrotron