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

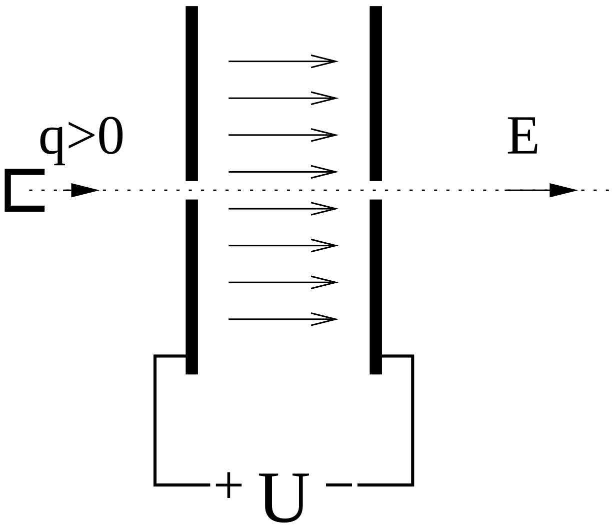
Akceleratory

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

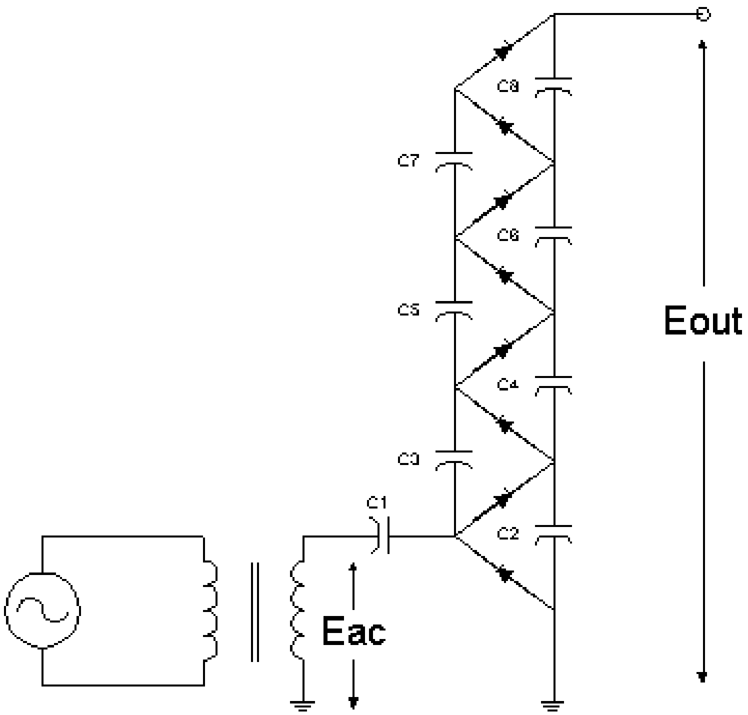
Uzyskiwana energia:

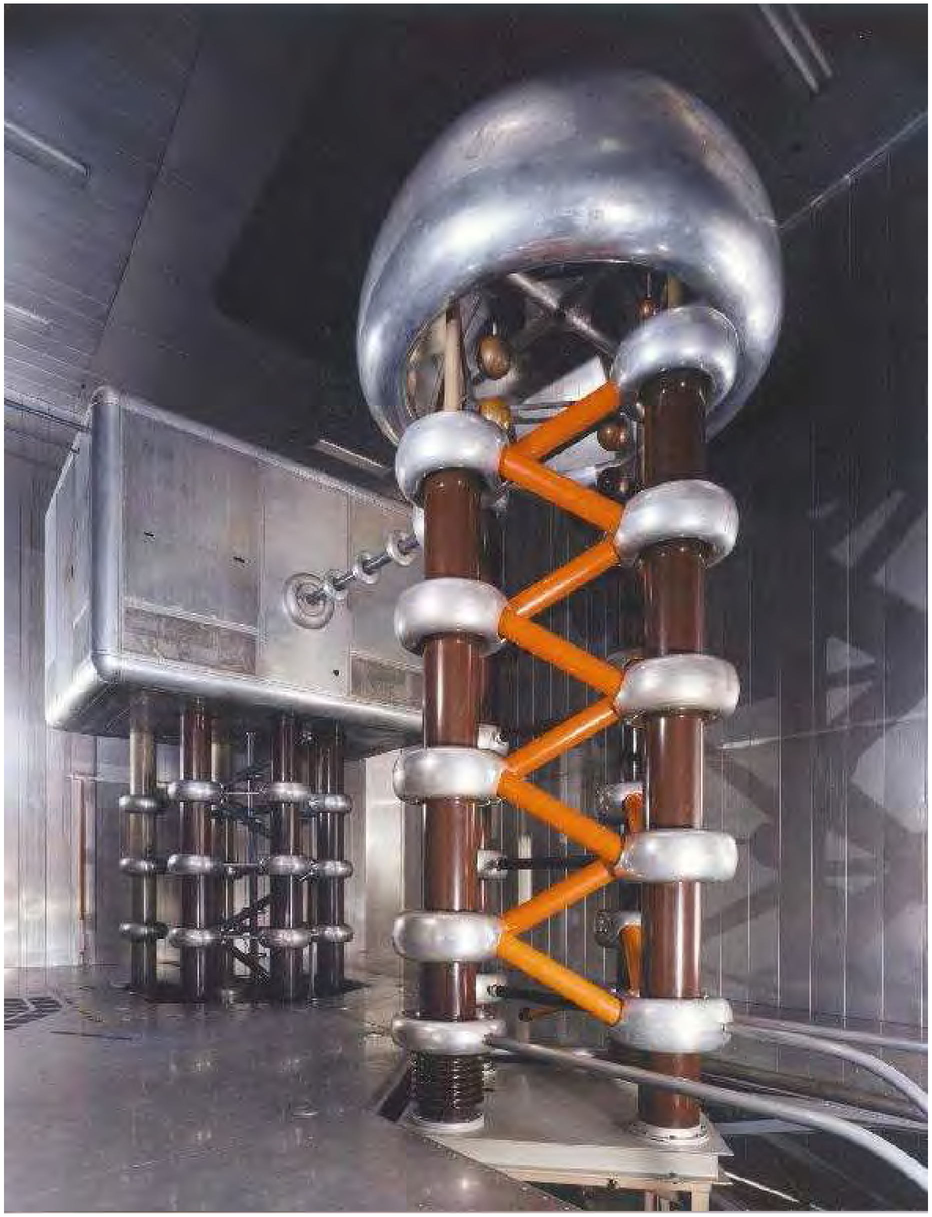
$$E = E_\circ + U \cdot q$$

Akceleratory

Generator Cockrofta-Waltona

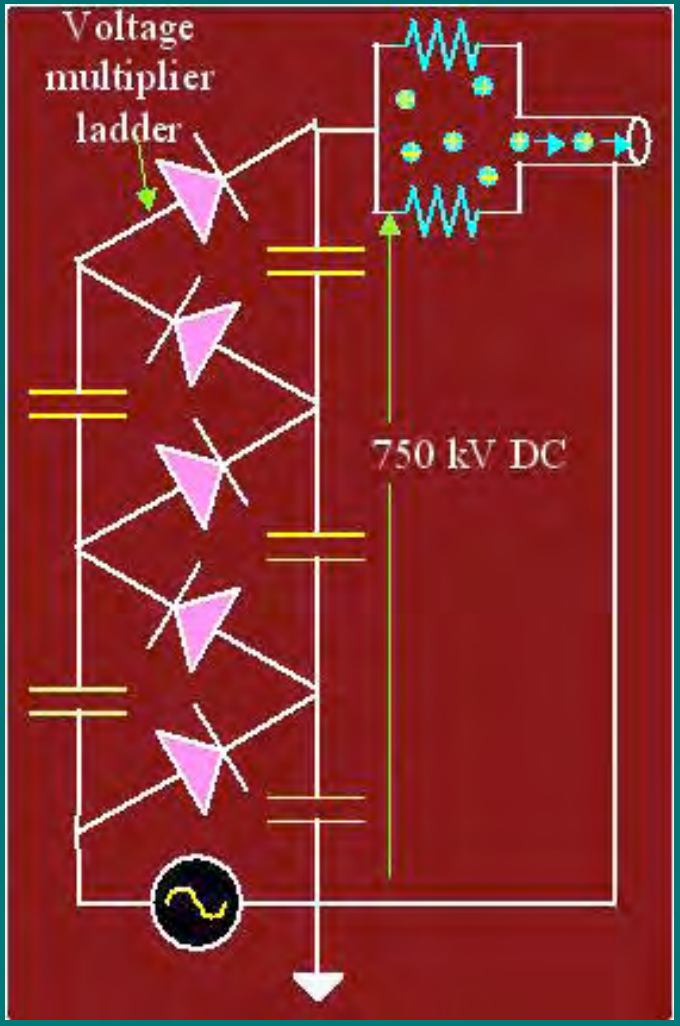
Schemat



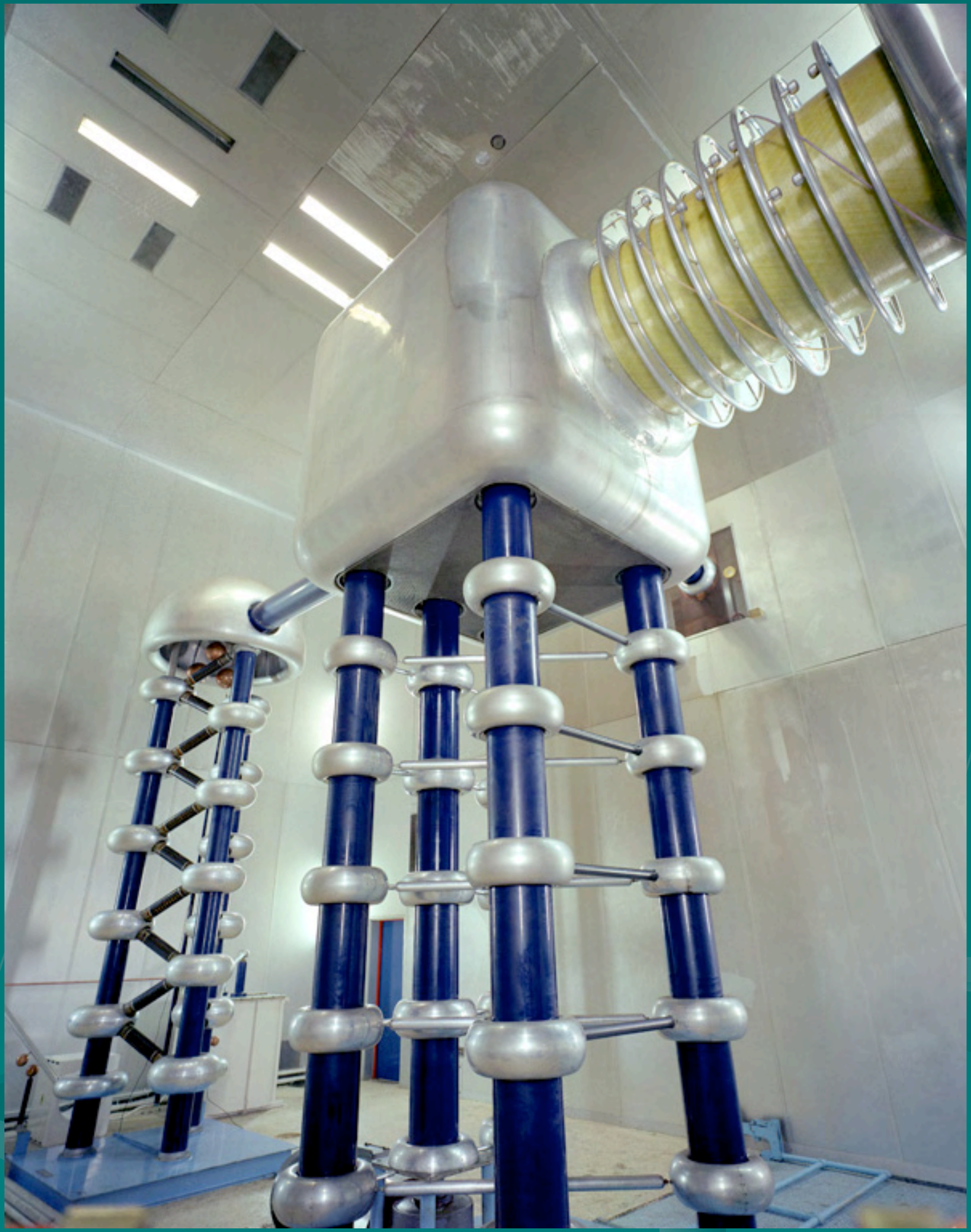


Cockroft Walton @ Tevatron

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



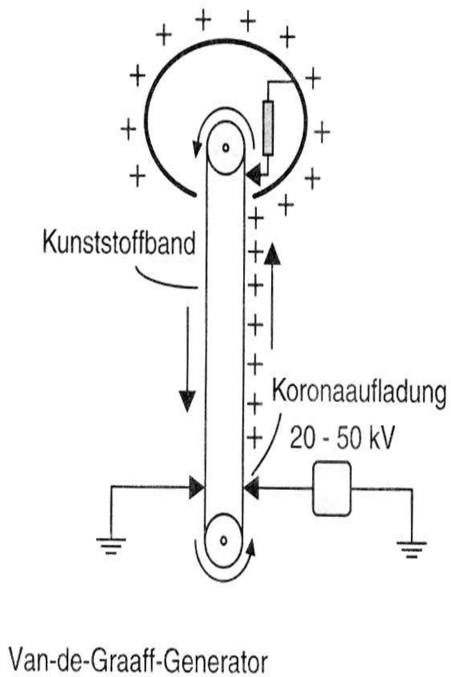
Converts AC voltage V to DC voltage n x V



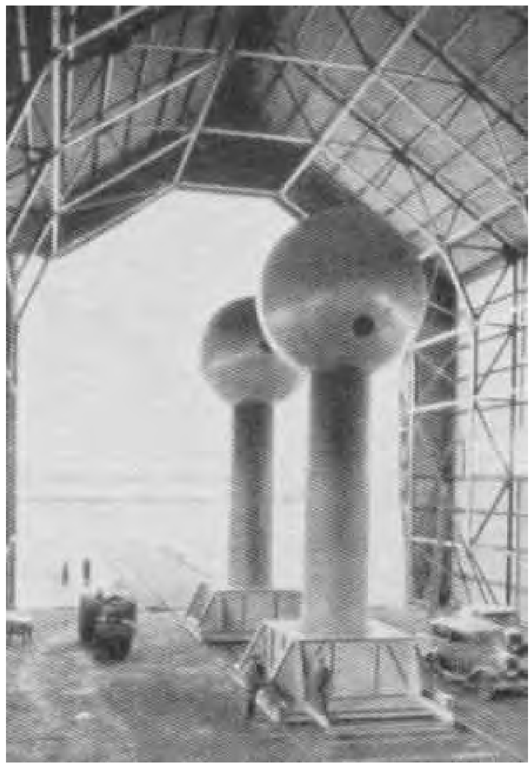
Akceleratory

Generator Van de Graaffa

Schemat



Historia

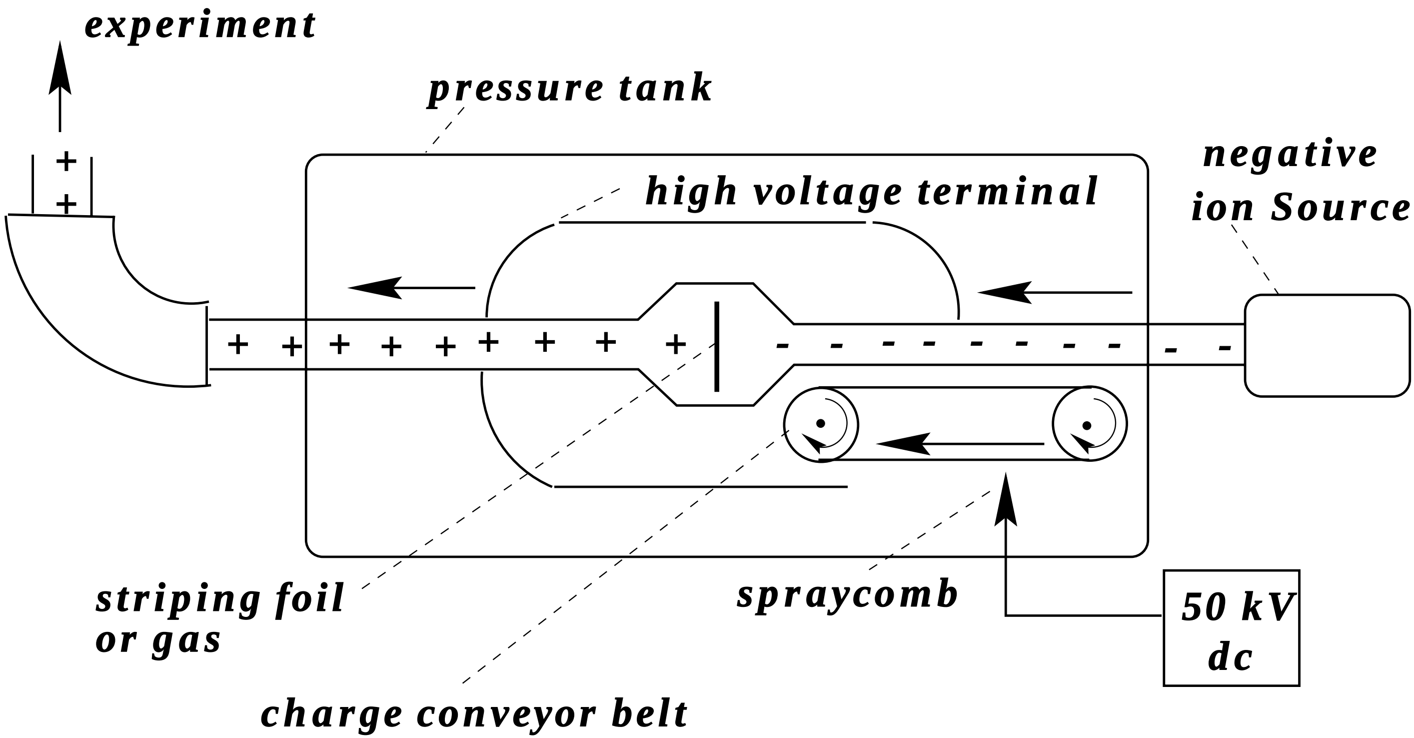


Współczesne urządzenie

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

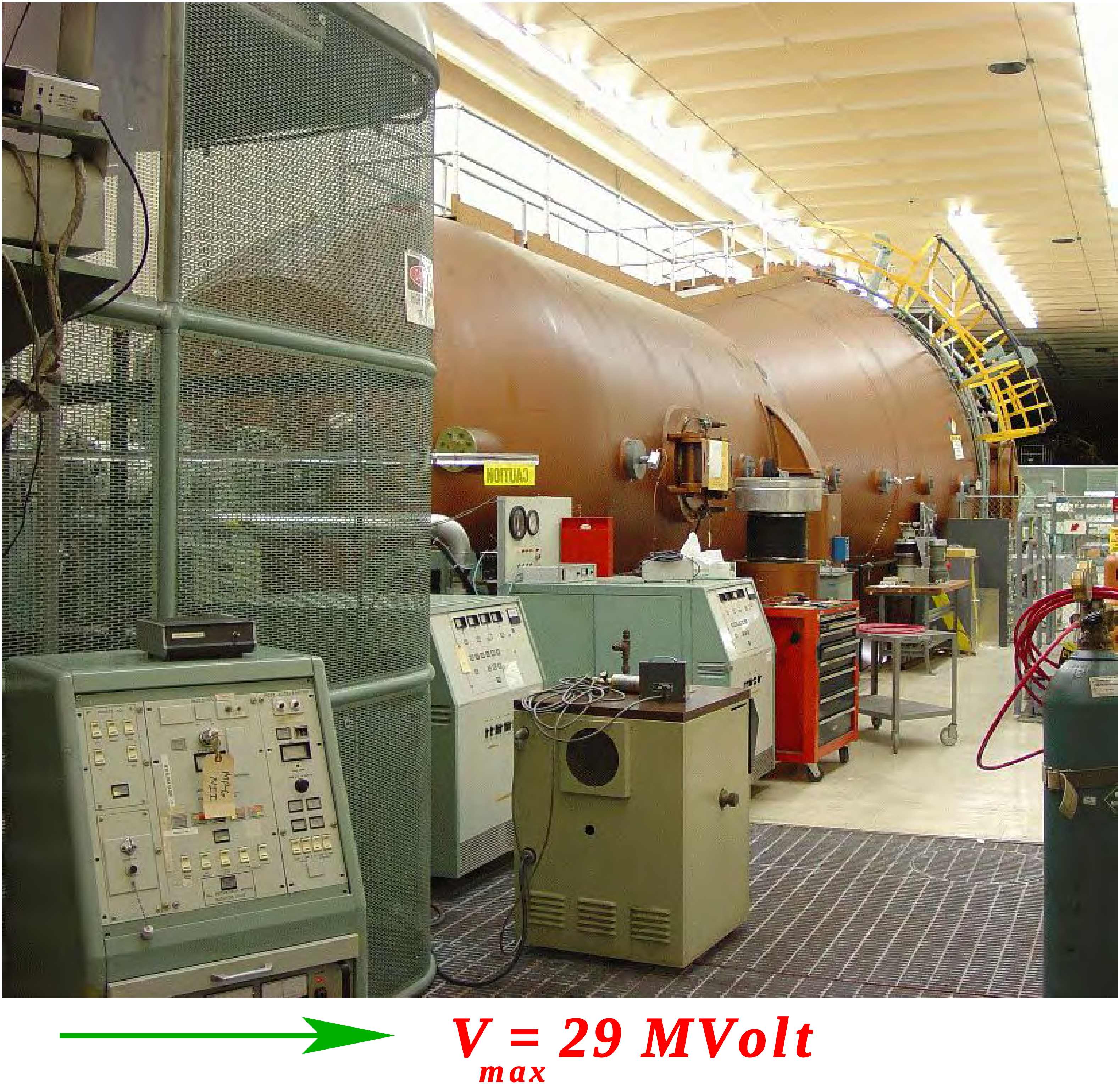
$\Rightarrow E \sim 30\ MeV$ $\Rightarrow$ **zbyt mało dla fizyki cząstek...**

Tandem generator:



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

AGS Complex at BNL



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

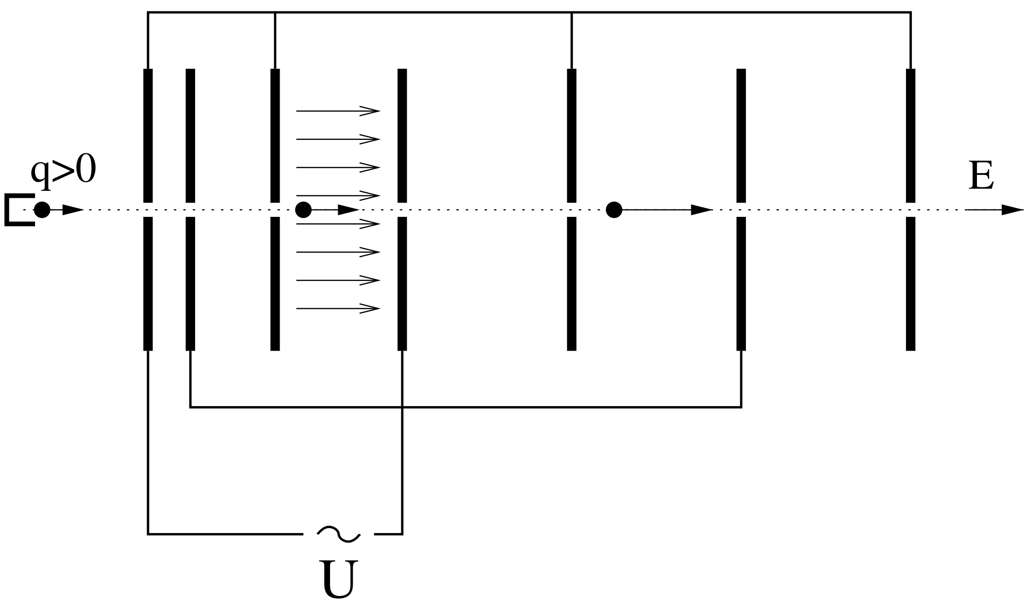
$$E_{max} = 29\ MeV\ (p);\ 385\ MeV\ (U)$$

Akceleratory

Akcelerator liniowy

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

Cząstka przechodzi przez kolejne "kondensatory"



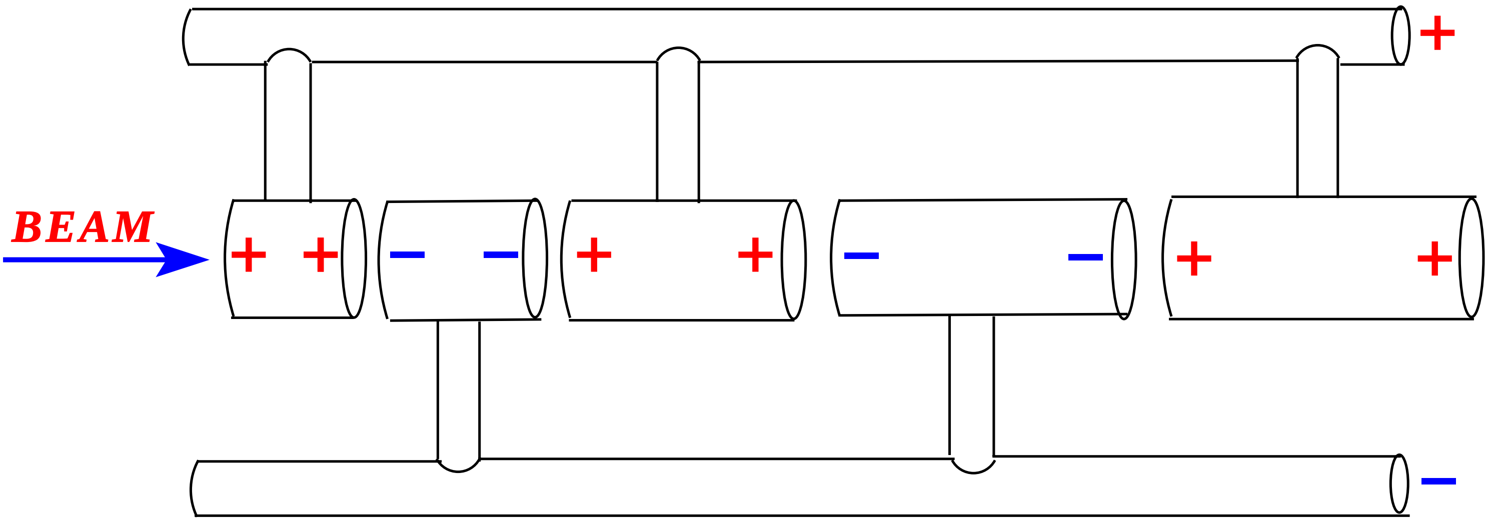
Przy odpowiednim dobraniu długości kolejnych elementów i częstości napięcia zasilającego, cząstka trafia zawsze na pole przyspieszające.

$\Rightarrow$ zwielokrotnienie uzyskiwanych energii

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

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

Symmetric line:



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

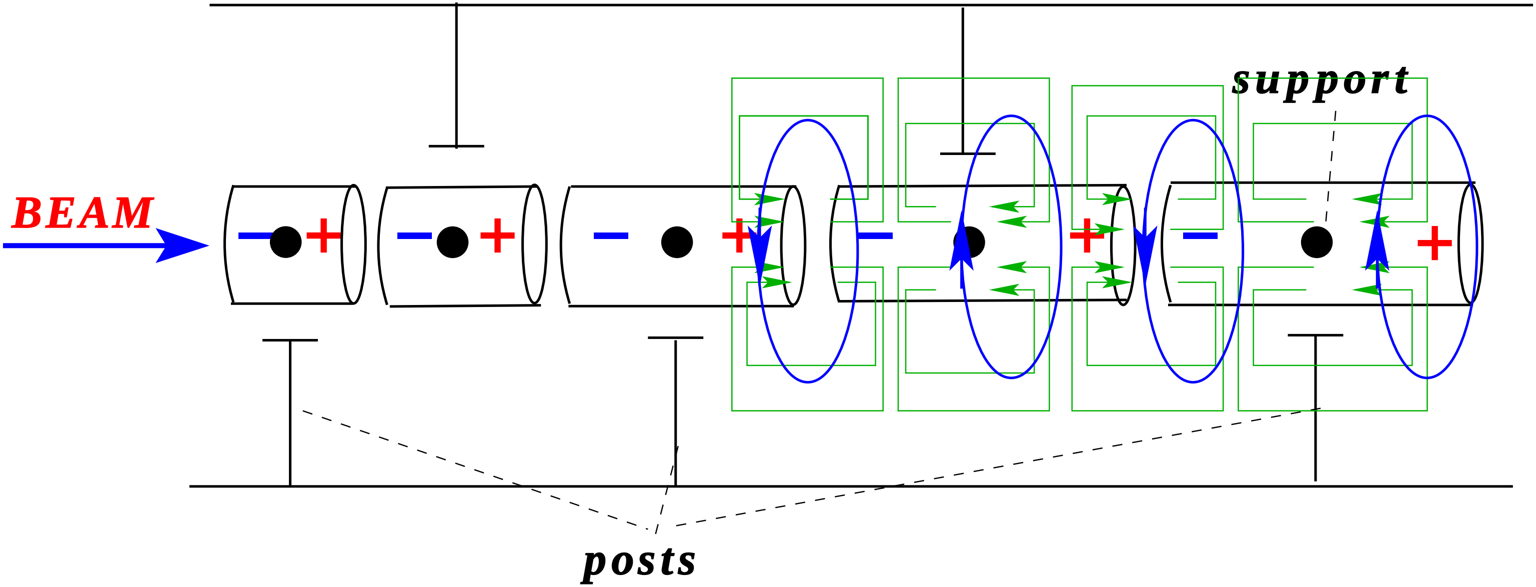
- **1928:** ***demonstrated by Wideroe***

1MHz, 25kV oscillator

→ ***50kV potassium ions***

Alvarez: 1946

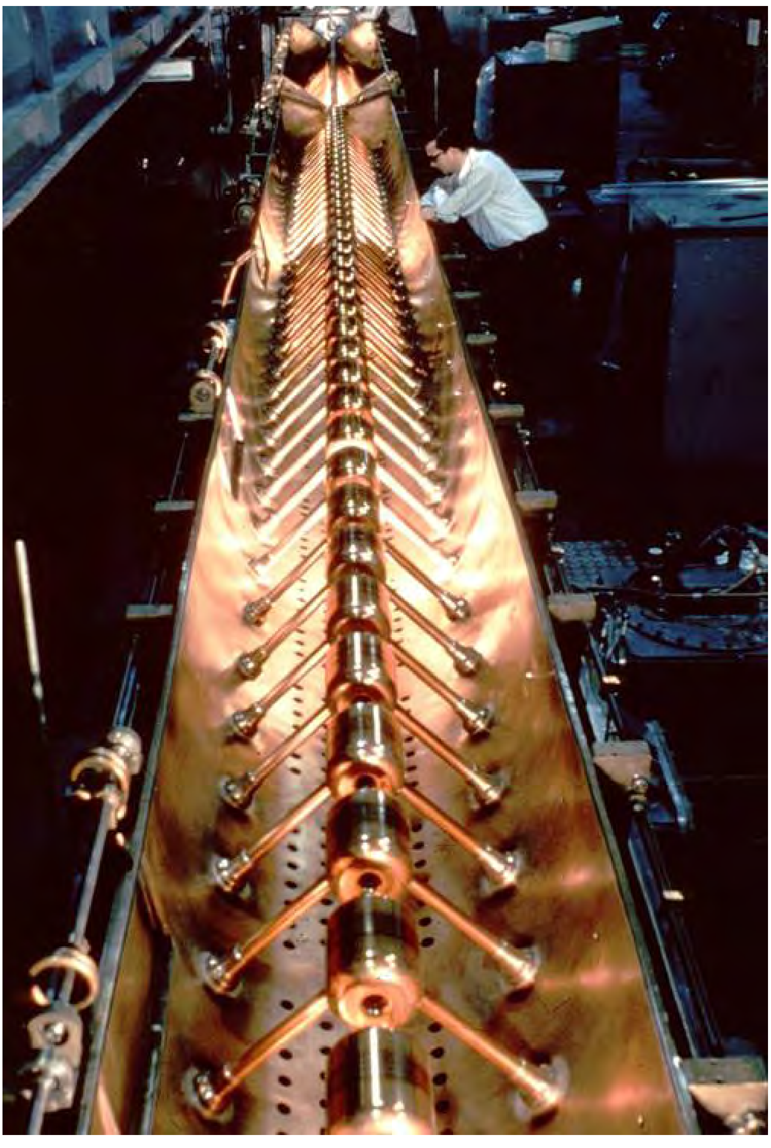
$$l = v_{part} \cdot \lambda / c$$



- *Tubes are passive*

→ *we can use high frequencies!*

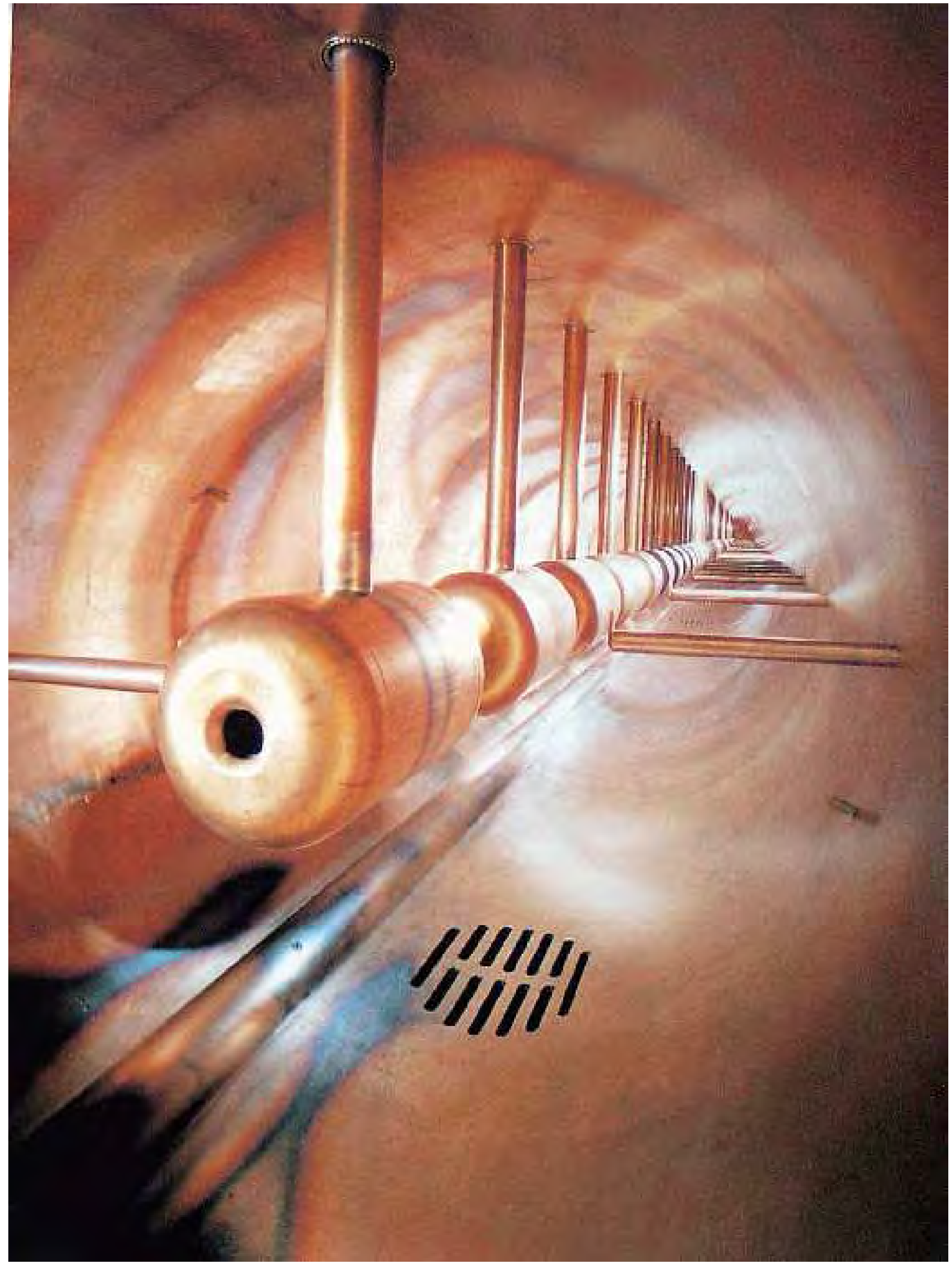
(f = 200 MHz gives good tube size)



Pre–accelerator for most accelerators:

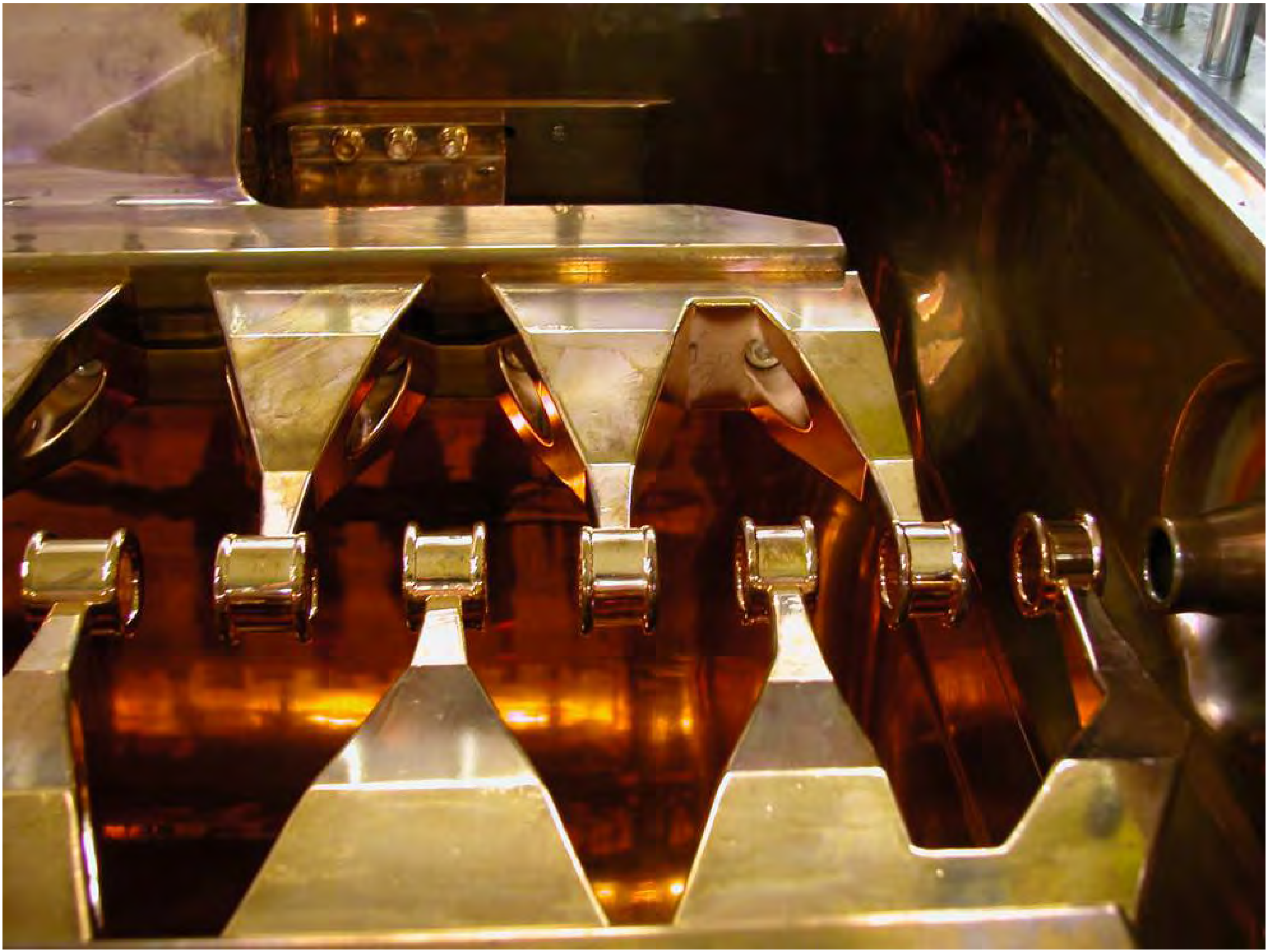
e.g. at CERN

Liniowy akcelerator protonów
w ośrodku Fermilab (USA)



Interdigital H Structure (TE−Modes)

used for the Pb ion acceleration at CERN

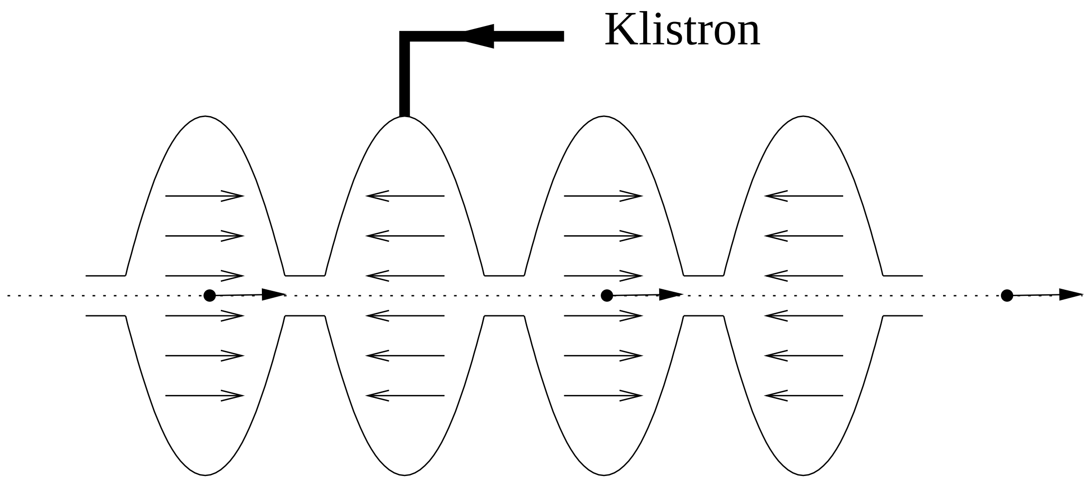


SPS at CERN

Akceleratory

Wnęka rezonansowa

Do dalszego przyspieszania cząstek wykorzystujemy tzw. wnęki rezonansowe:



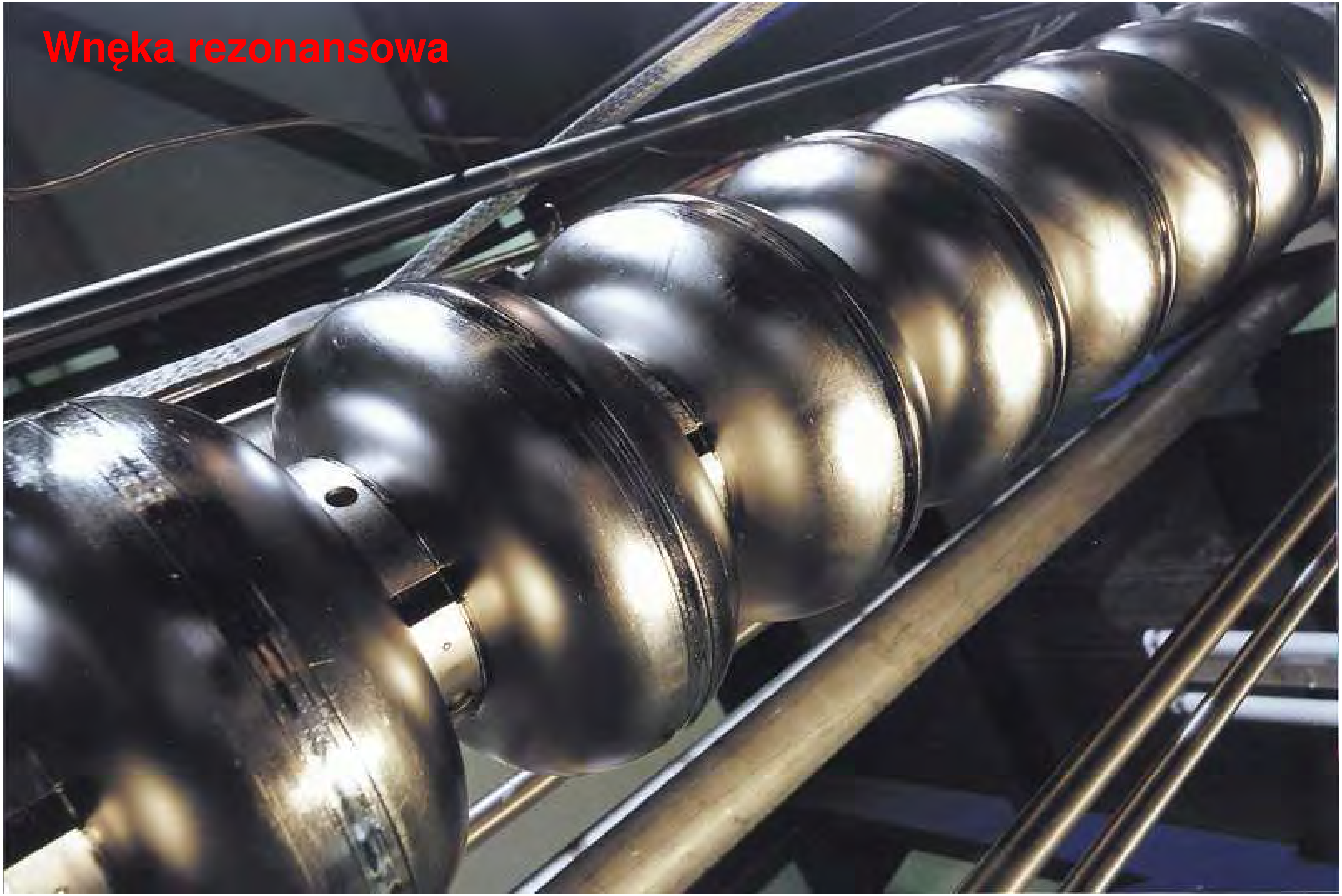
Wewnątrz wnęki wytwarzana jest stojąca fala elektromagnetyczna.

Długość fali/wnęki jest tak dobrana, że cząstka zawsze trafia na pole przyspieszające.

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

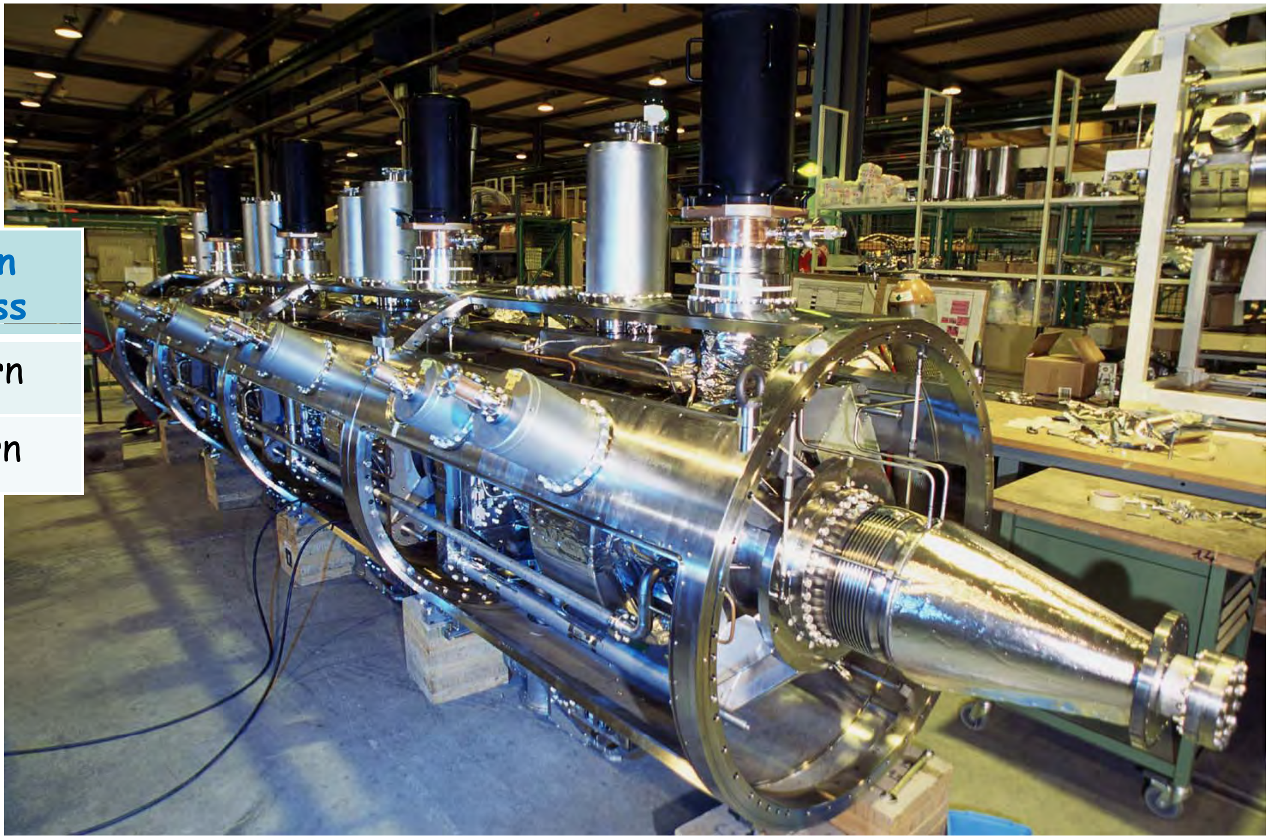
LHC RF system

- 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

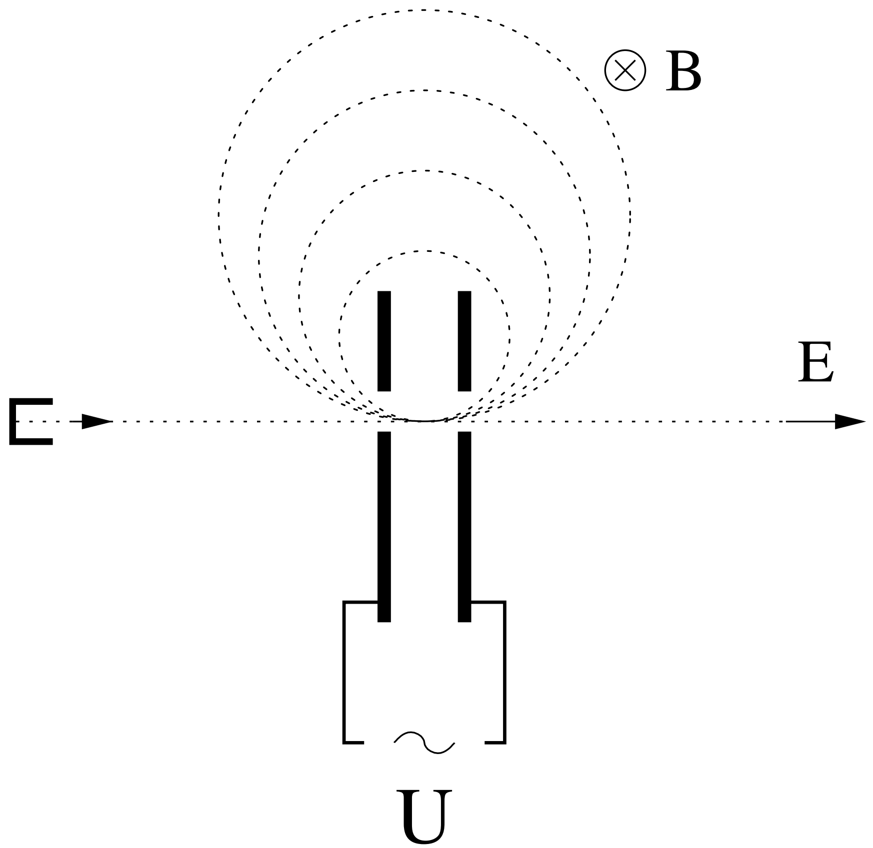
Akcelerator kołowy

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:

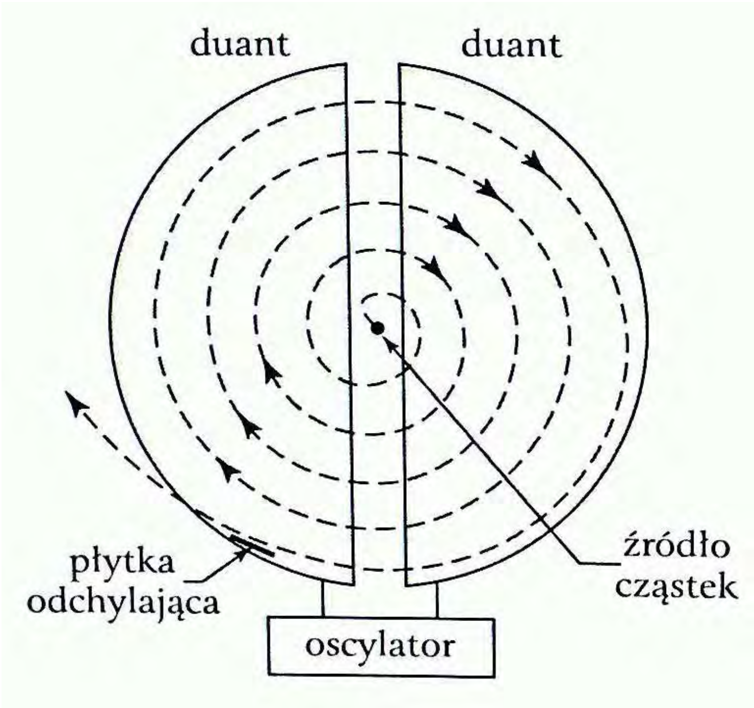


Akceleratory

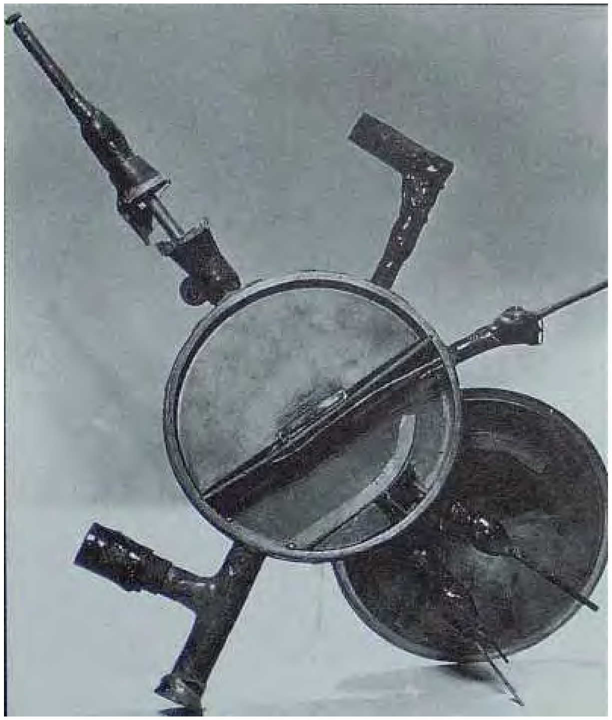
Cyklotron

Ernest Lawrence

Schemat



Pierwszy cyklotron



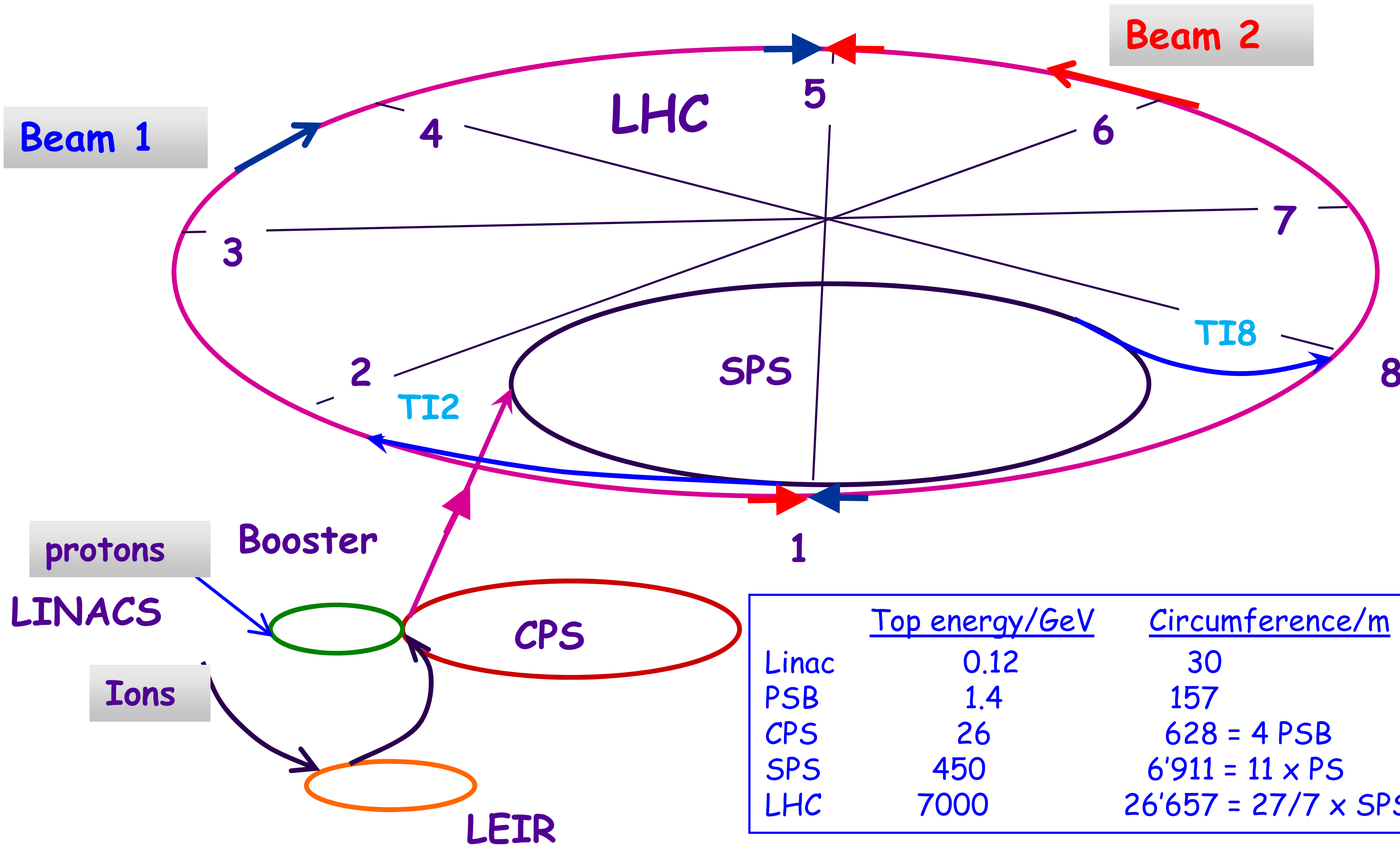
Akceleratory

Synchrotron

1955

Rosnące pole magnetyczne utrzymuje cząstki na stałej orbicie

LHC Tunnel view



	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

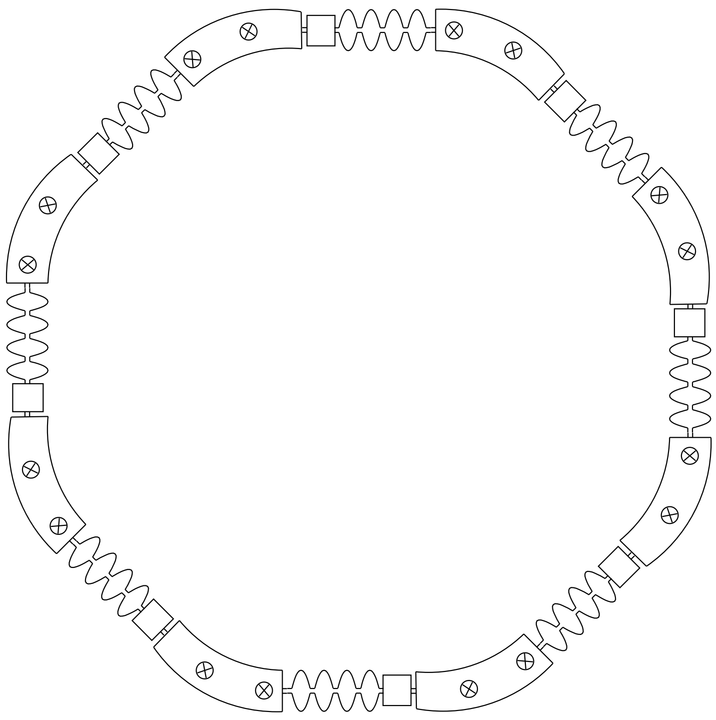
Note the energy gain/machine of 10 to 20 – and not more !
The gain is typical for the useful range of magnets !!!

Akceleratory

Akcelerator kołowy

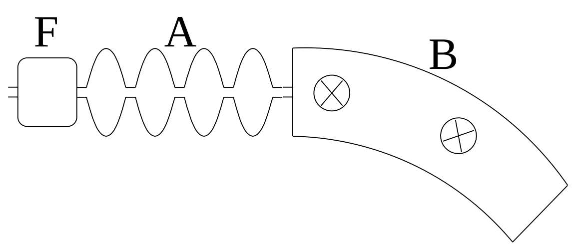
W praktyce akceleratory kołowe zbudowane są z wielu powtarzających się segmentów:

Schemat akceleratora:

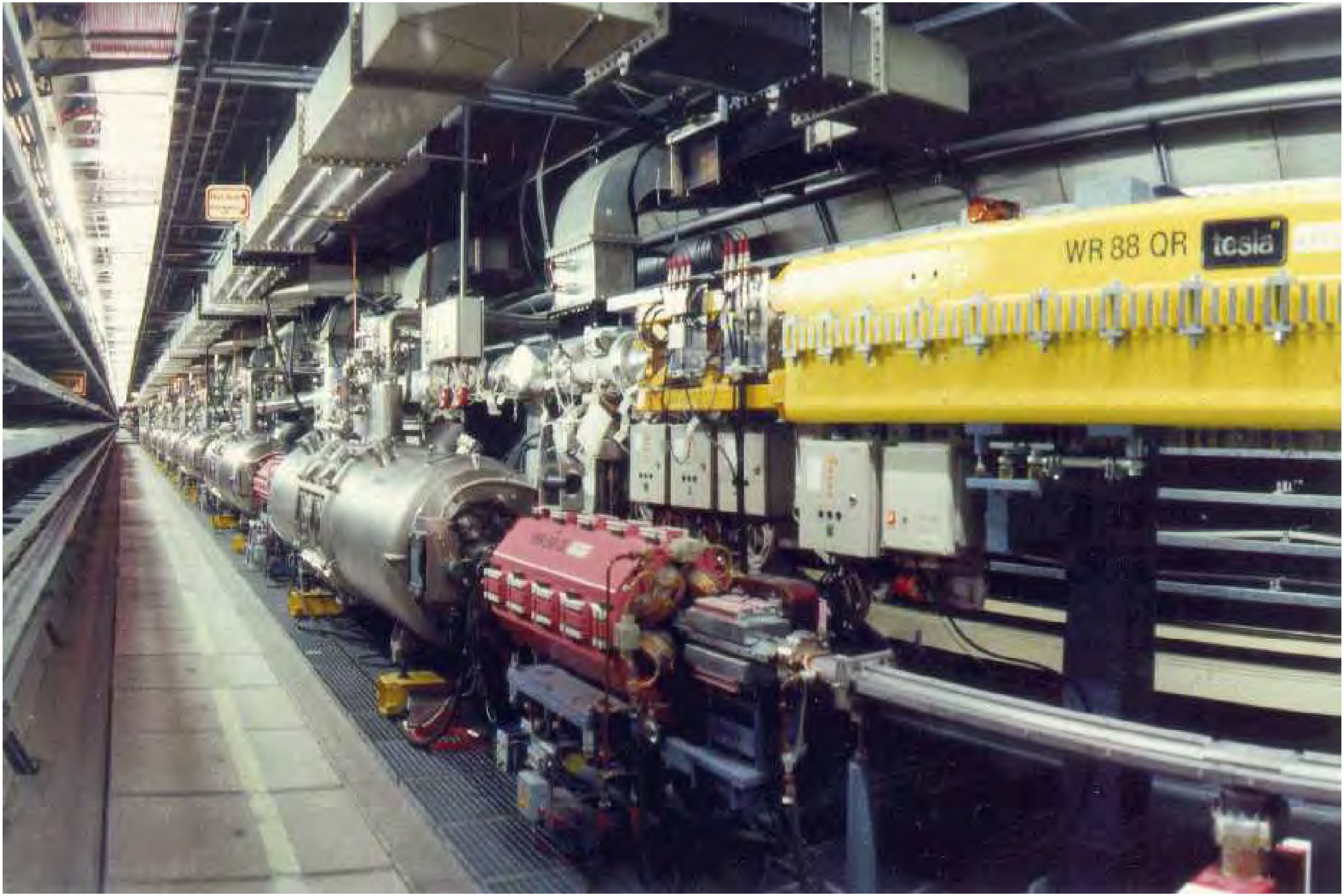


Każdy segment składa się z

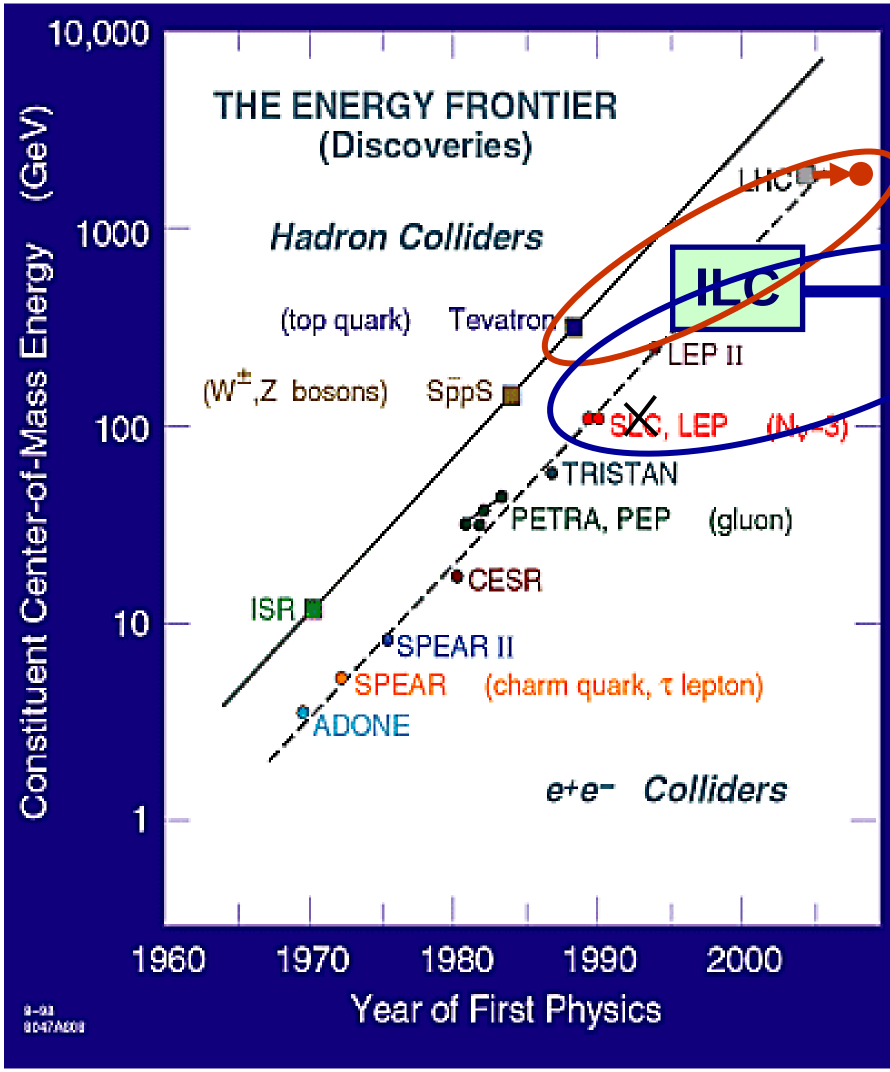
- wnęk przyspieszających (A)
- magnesów zakrzywiających (B)
- układów ogniskujących (F)



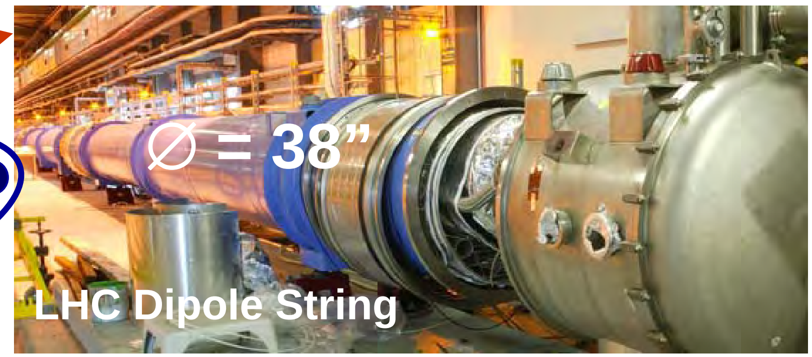
HERA, DESY, Niemcy



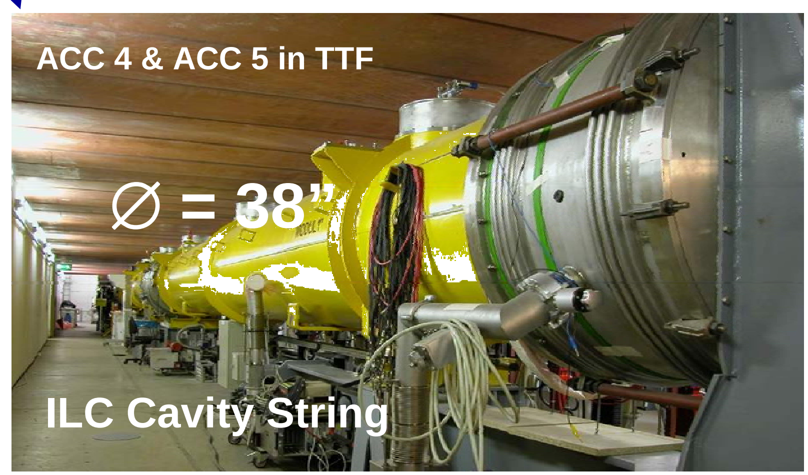
Energy Frontier and Accelerator Tech.



Superconducting Dipoles



Superconducting RF Cavities



Ogniskowanie

Magnesy dipolowe pozwalają utrzymać przyspieszane cząstki na orbicie kołowej. Pole w magnesach definiuje energię wiązki - rośnie w trakcie przyspieszania.

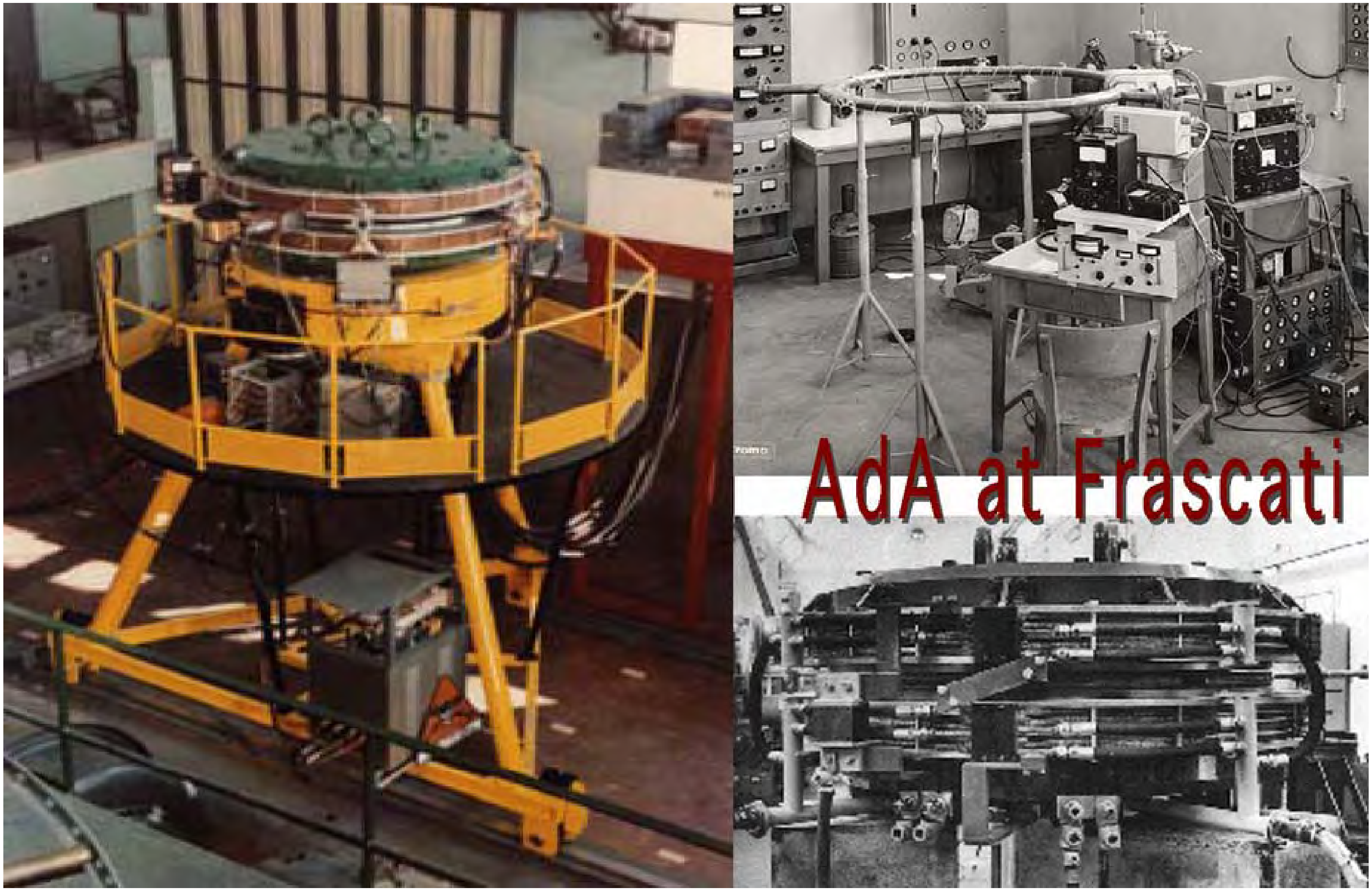
Same wnęki przyspieszające i magnesy dipolowe nie wystarczają. Wiązka ma naturalne (w chwili wstrzyknięcia) rozmycie przestrzenne i pędowe, rośnie ono też na skutek niedoskonałości pól i oddziaływania wiązki.

Wiązka "puchnie" w trakcie przyspieszania i gdybyśmy temu nie przeciwdziałali utrzymanie wiązki wewnątrz rury akceleratora przez parę godzin byłoby niemożliwe.

"Silne ogniskowanie" (strong focusing):

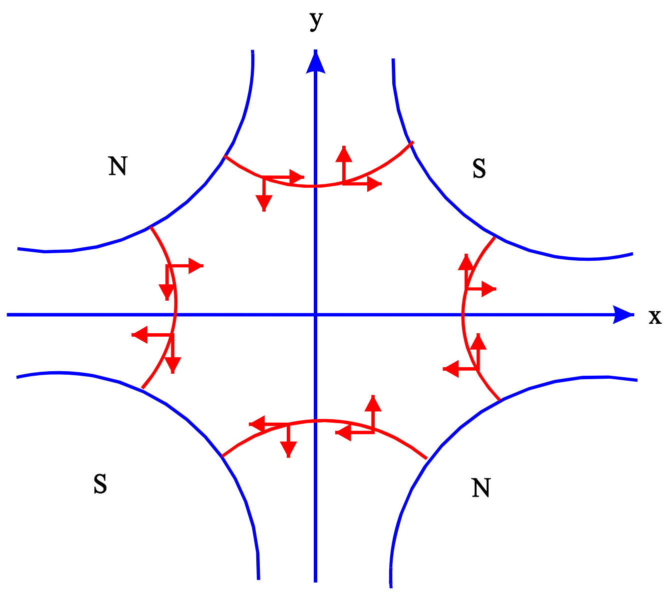
1959 PS @ CERN (25 GeV)   1960 AGS @ BNL (33 GeV)

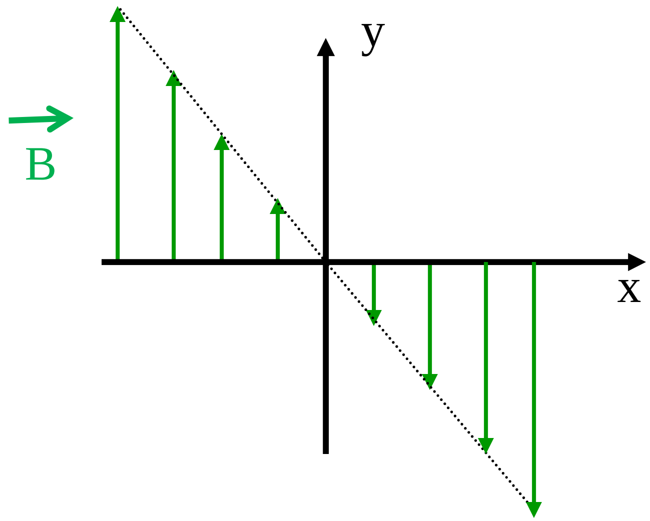
The First Collider: AdA @ Frascati (1961)



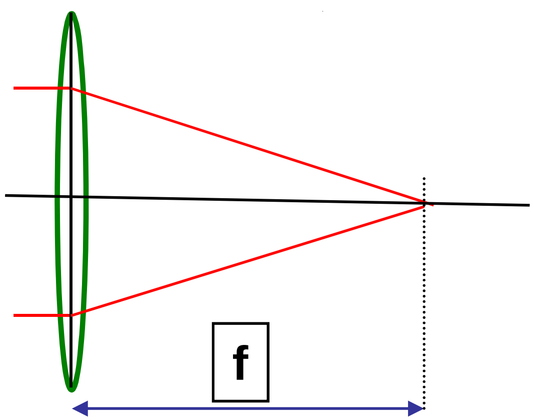
Quadrupolar field - focusing

- 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.





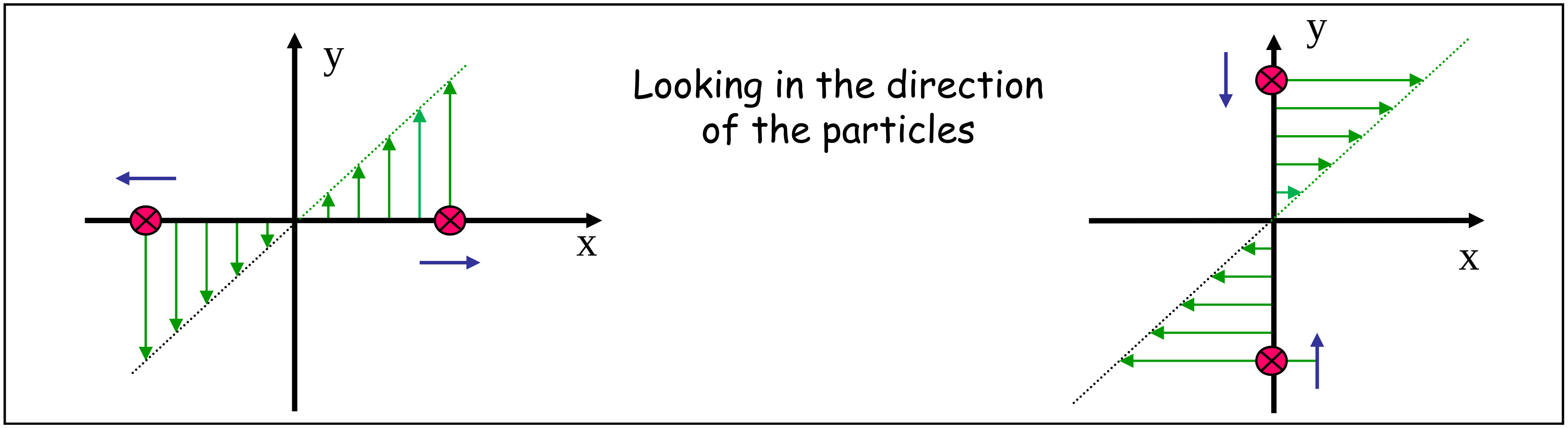
- In a given plane, the quadrupole has the same properties like a classical optical lens.

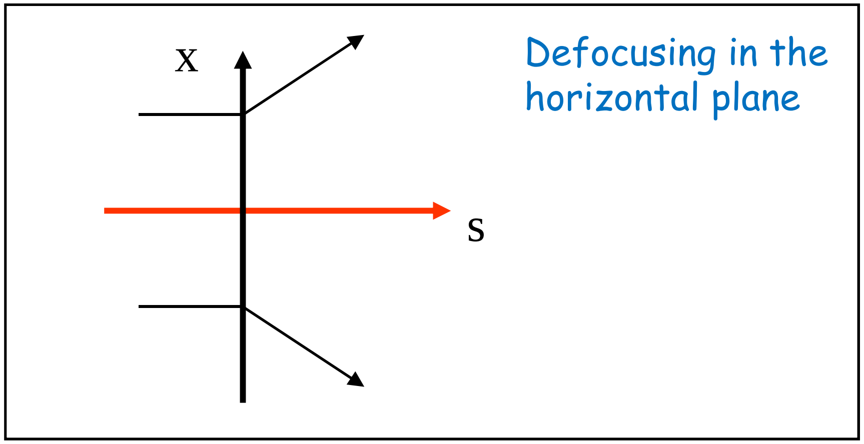


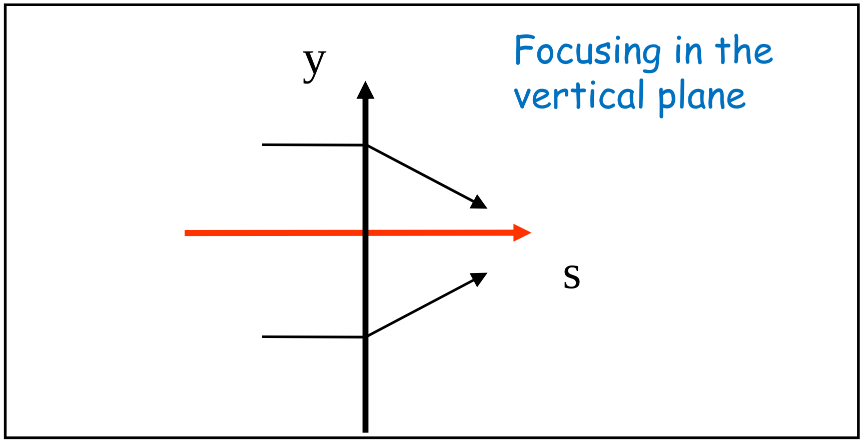
Focusing

But a quadrupole differs from an optical lens :

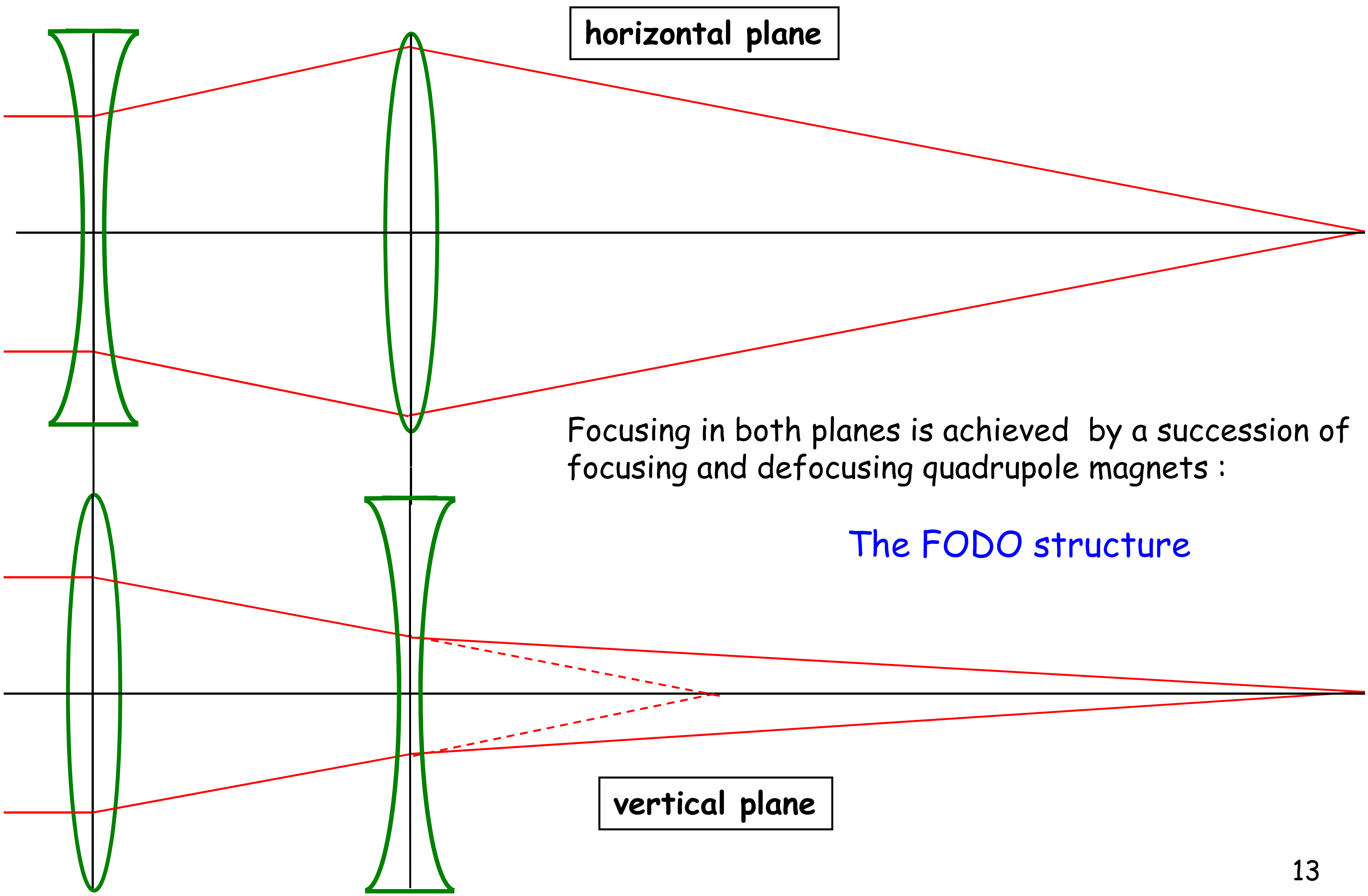
It is focusing in one plane, defocusing in the other !!!







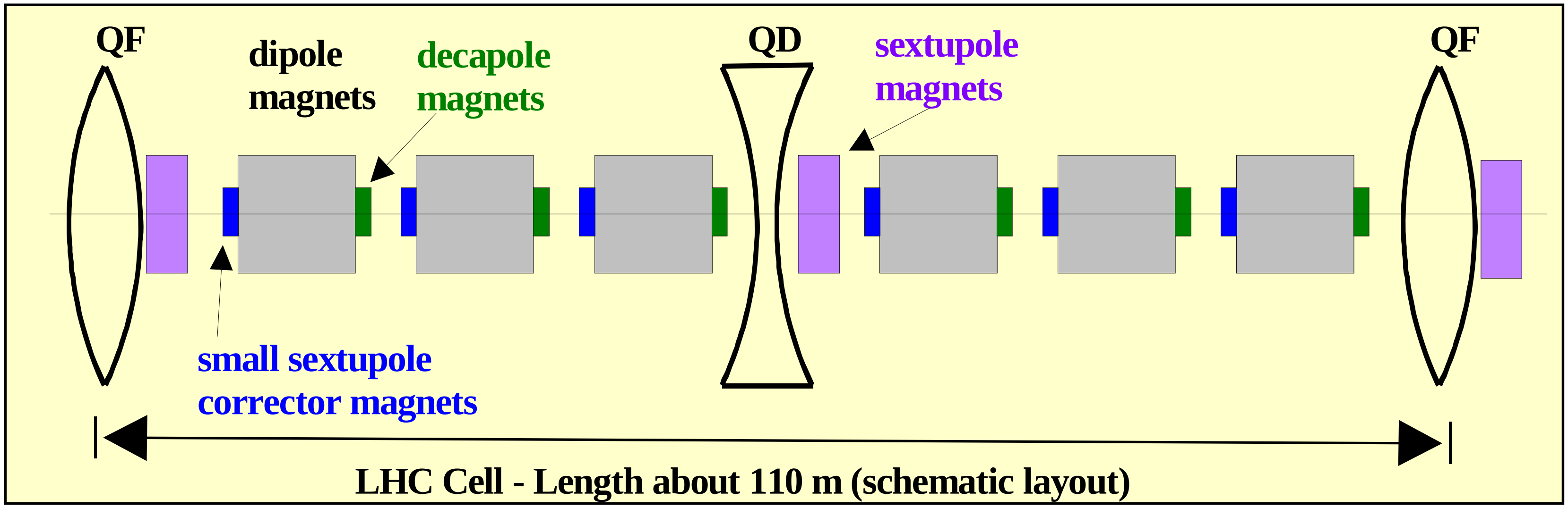
Accelerator lattice



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

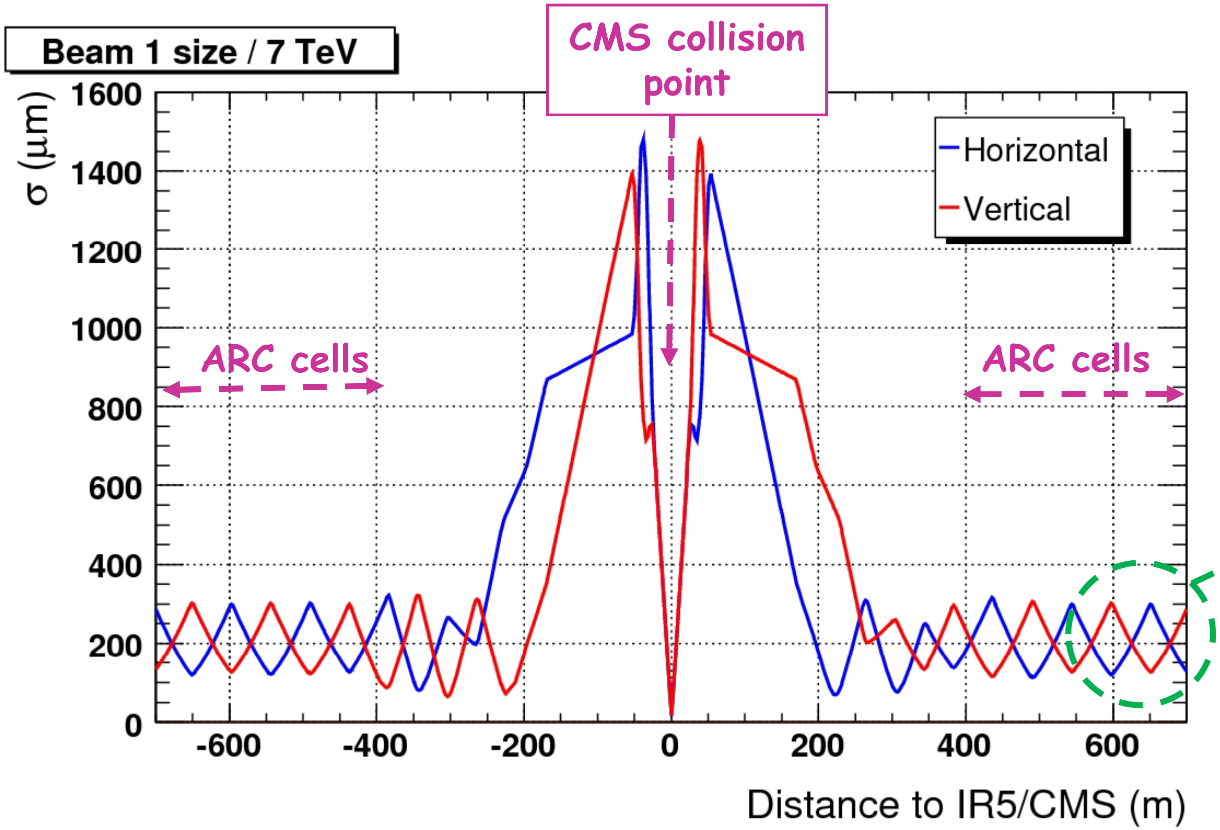
The FODO structure

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 !

Beam envelope



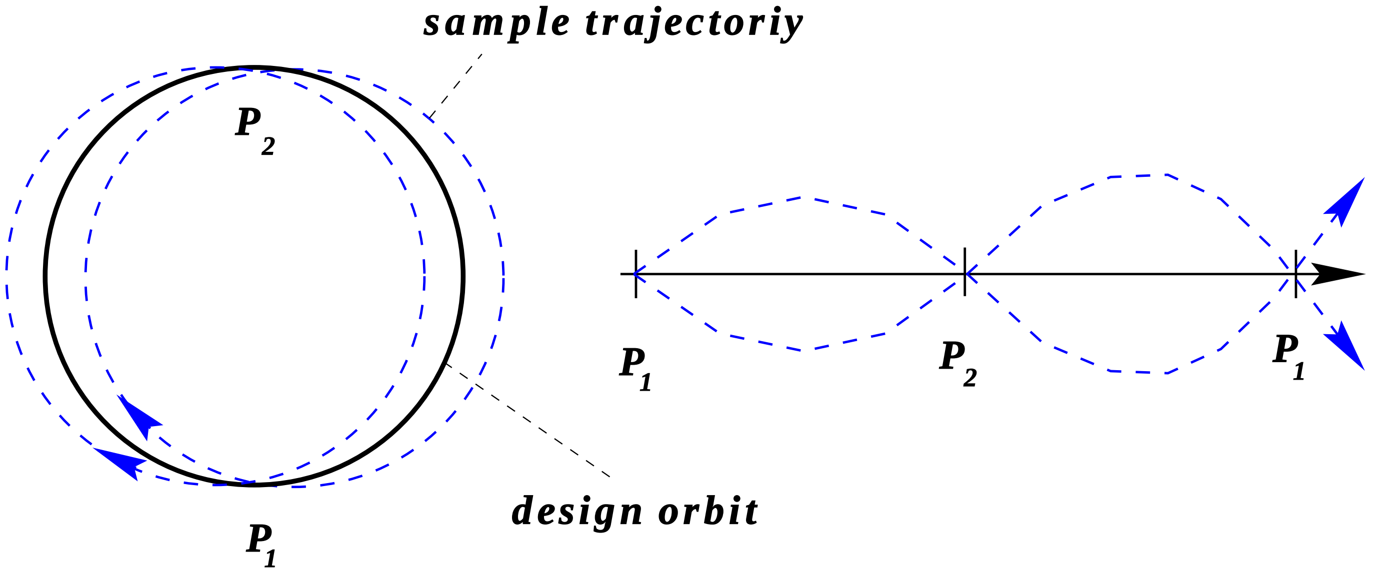
Fits through the hole of a needle!

- ❑ 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)

W jednorodnym polu magnetycznym cząstka naładowana zawsze wróci do punktu wyjścia (w płaszczyźnie prostopadłej do pola)

Geometrical Focusing:

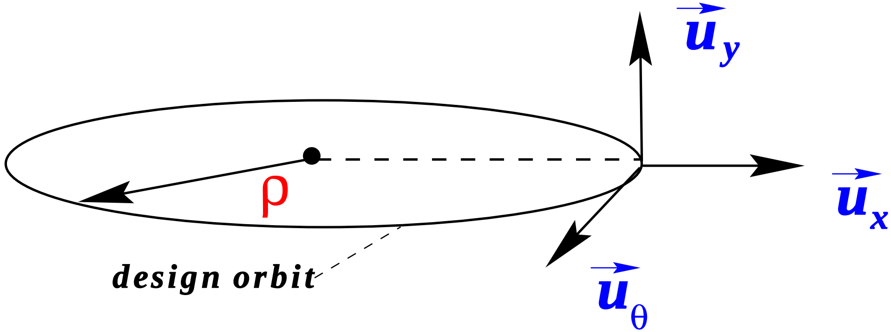


Opis ruchu cząstki upraszcza się jeśli zamiast rozważać pełen jej ruch opisujemy odchylenie od nominalnej (idelanej) trajektorii

Equation of Motion

Rotating Coordinate System:

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



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

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

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

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

Opisując trajektorię cząstki możemy wyeliminować z równań czas - t
zamieniając na drogę wzdłuż nominalnego toru ruchu - s

Optic Functions

Hills Equation:

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

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

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

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

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

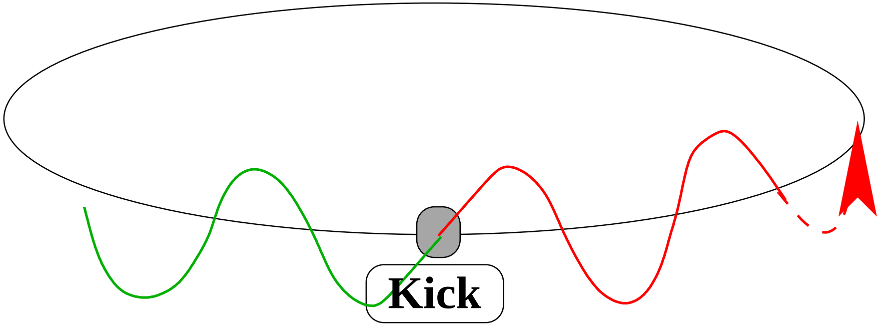
- $$\beta(s + L) = \beta(s)$$

- Number of oscillations per turn

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

Orbit Stability

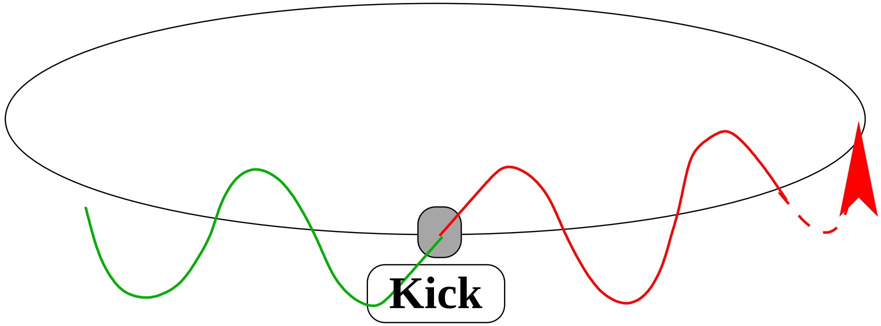
dipole error and Q = N:



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

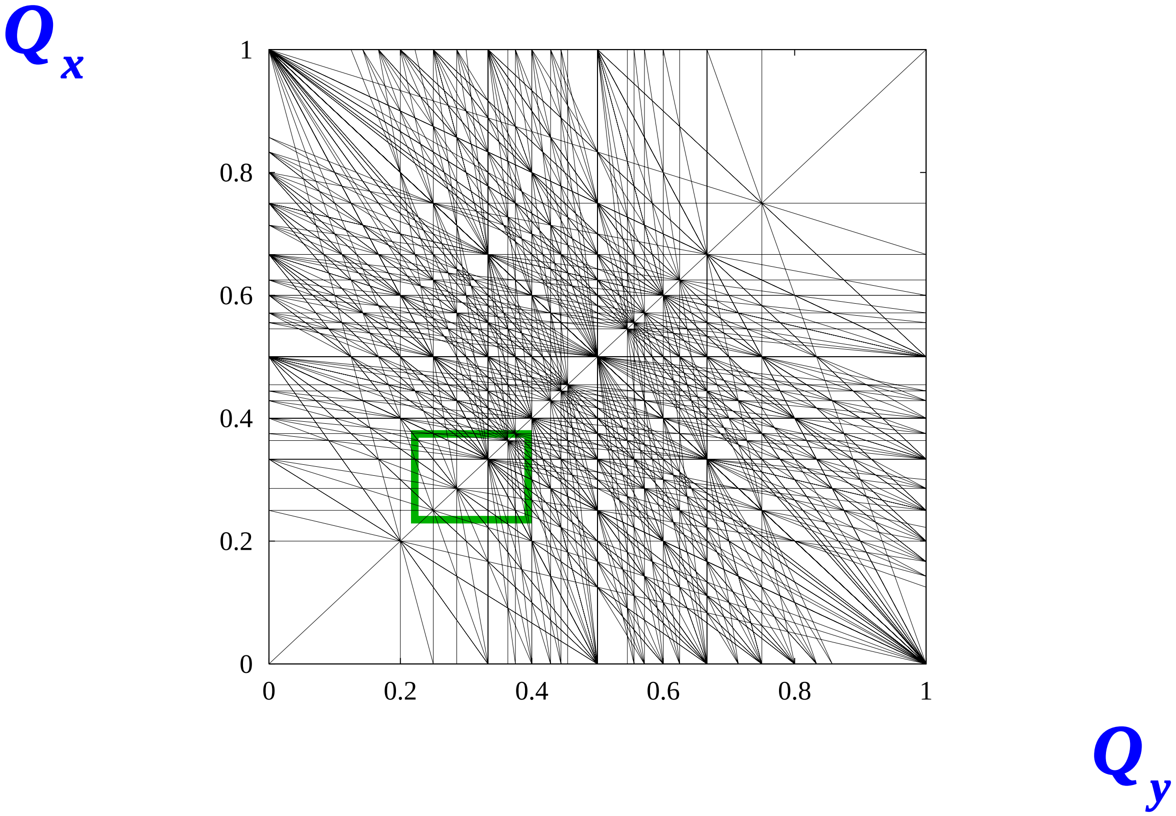
and avoid strong resonances!

Tune Diagram

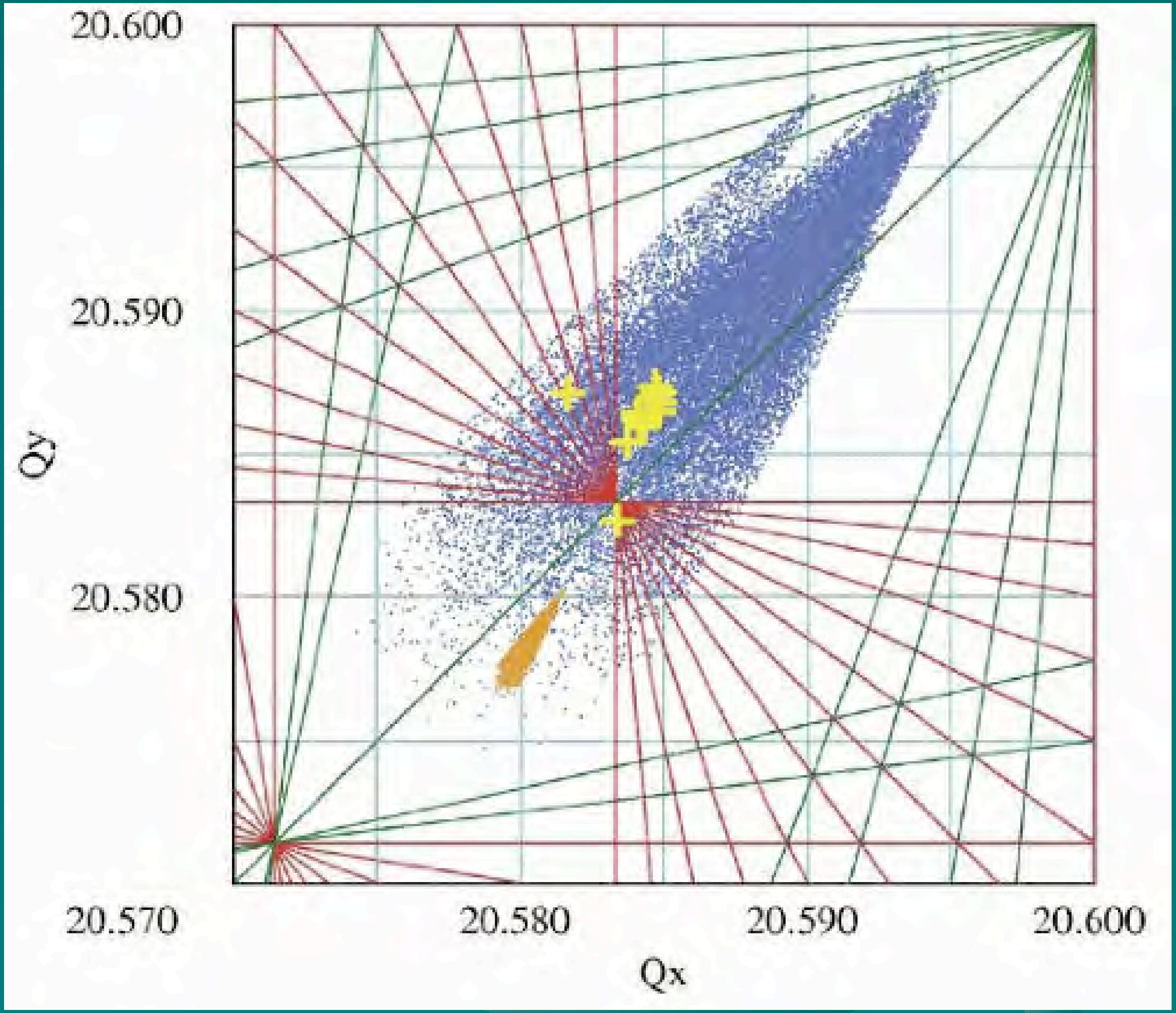
resonances: $n \cdot Q_x + m \cdot Q_y + r \cdot Q_s = p$

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

→ ***avoid low order resonances!***

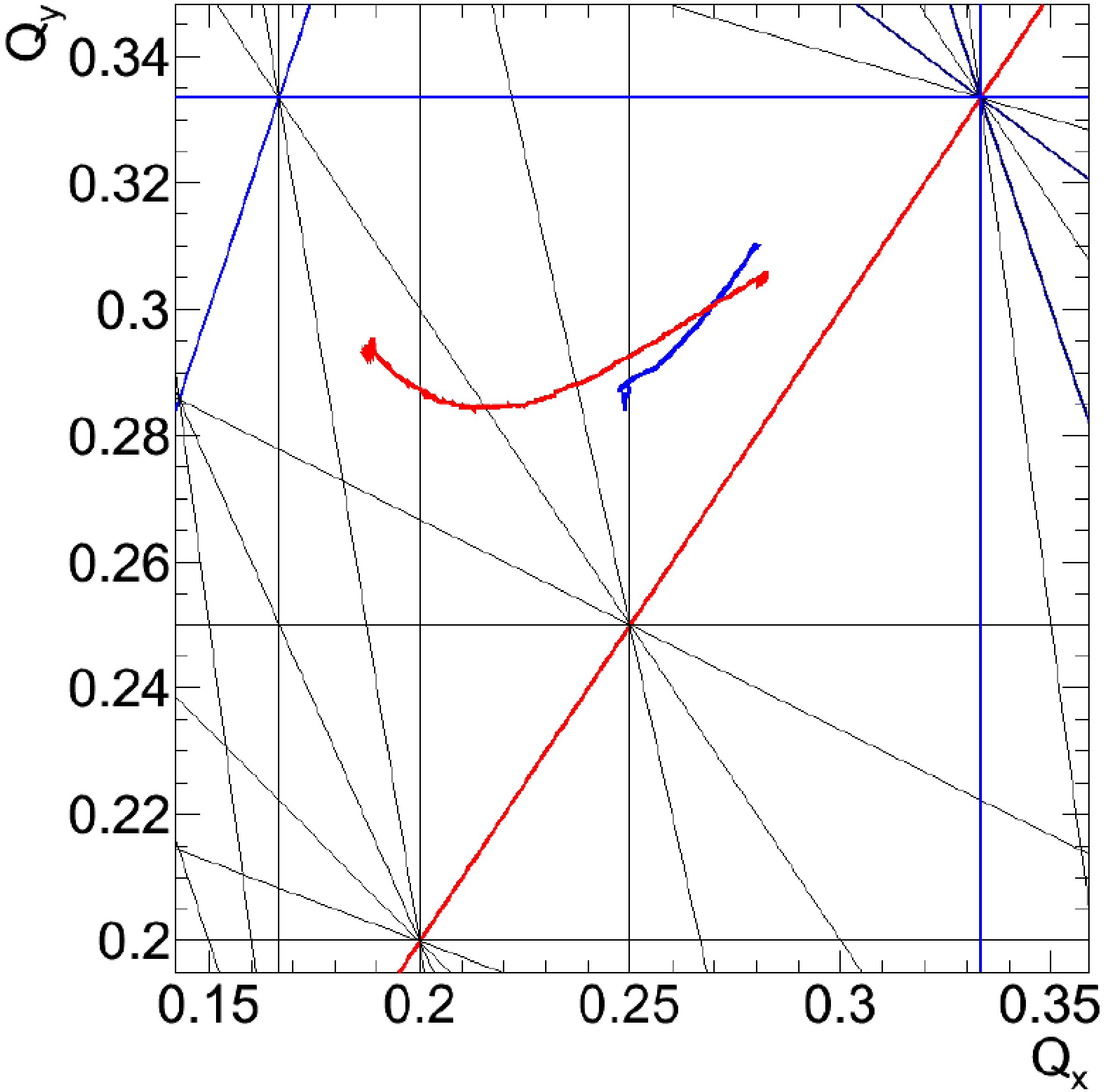


Tune Plane of the Tevatron



LHC: Third Ramp to 1.18 TeV

Tune variations during ramp
Beam 1
Beam 2



Transfer matrices

Let $x(s) = \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix}$ 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

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

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

Phase Space *(for x motion)*

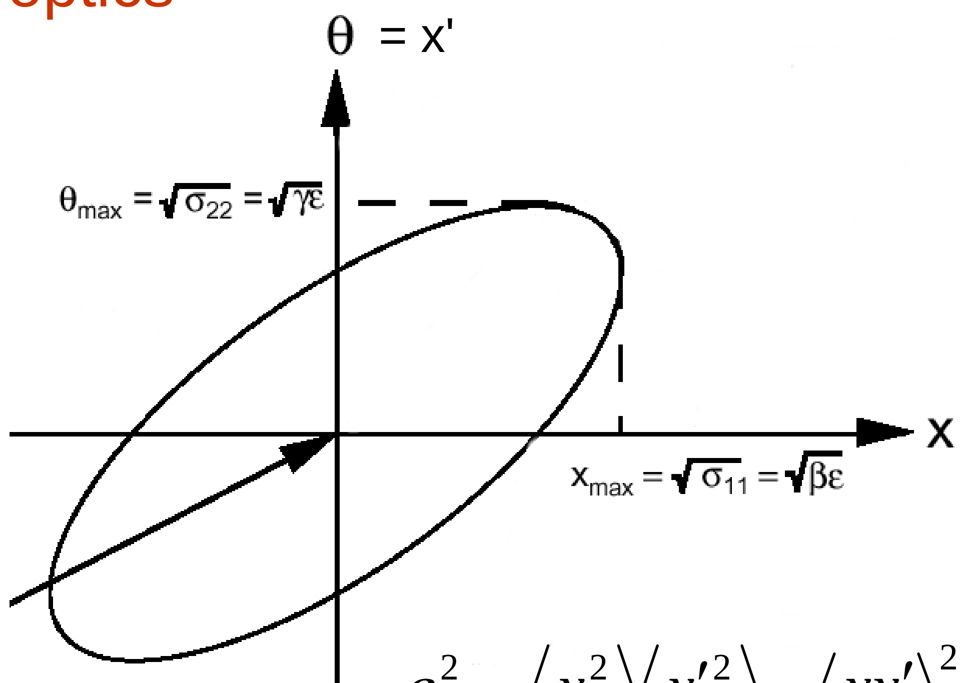
Beta function β characterize optics

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



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

Squeeze on beam size → increase angular divergence

Beam emittance is not conserved during acceleration → normalized emittance should be γε

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).

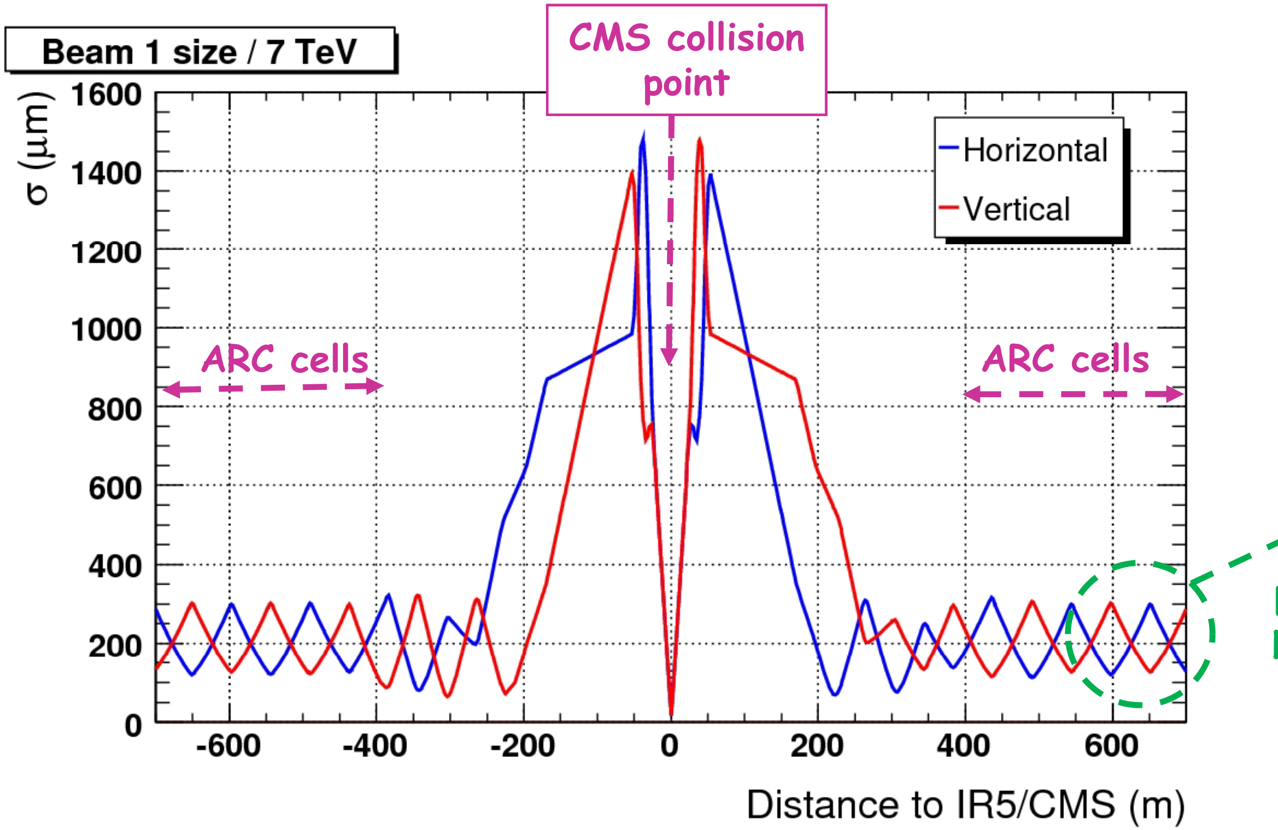
High beam "brillance" N/ε (particles per phase space volume)
→ Injector chain performance !

Small envelope
→ Strong focusing !

Emitancja wiązki nie może być zmniejszona - musimy zadbać, żeby była jak najmniejsza od samego początku !!!
(odpowiednie źródło, dobre prowadzenie na wszystkich etapach przyspieszania; ew. chłodzenie wiązki - później)

Rozmiary wiązki w punkcie oddziaływania - możemy zmniejszać, ale też nie bez ograniczeń...

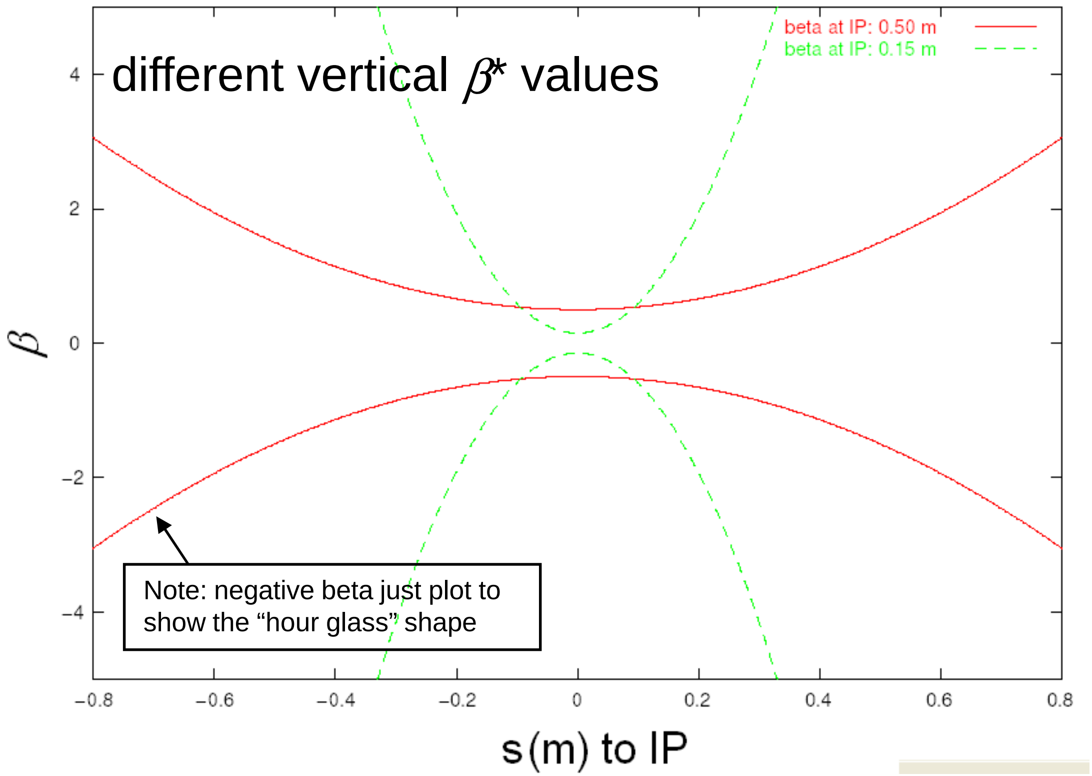
Beam envelope



- 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)

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

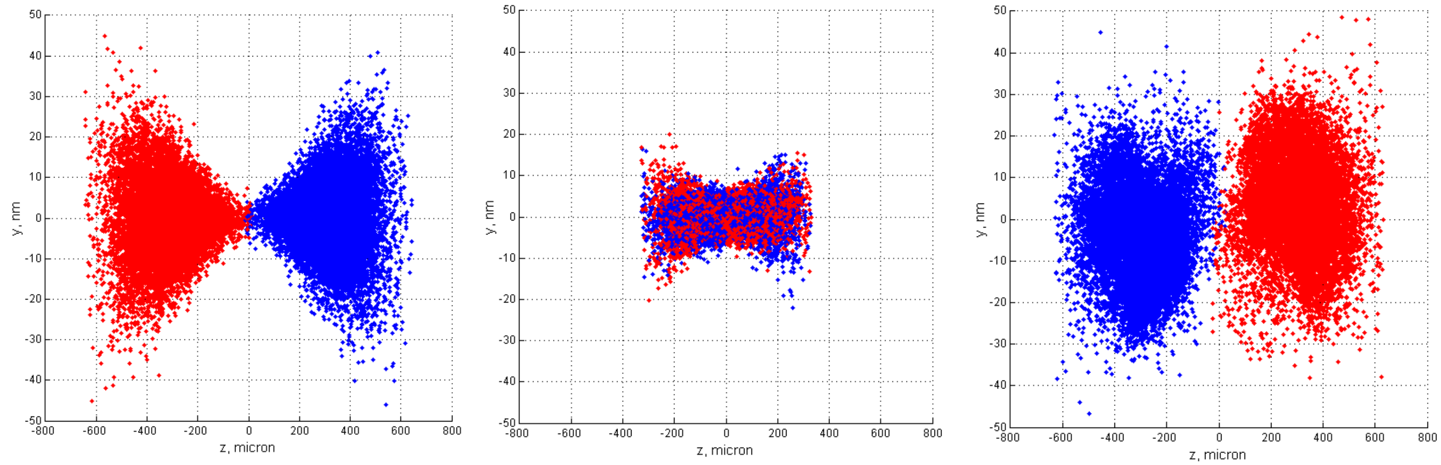
$$\sigma_y(s) = \sqrt{\beta_y(s)\varepsilon_y}$$

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

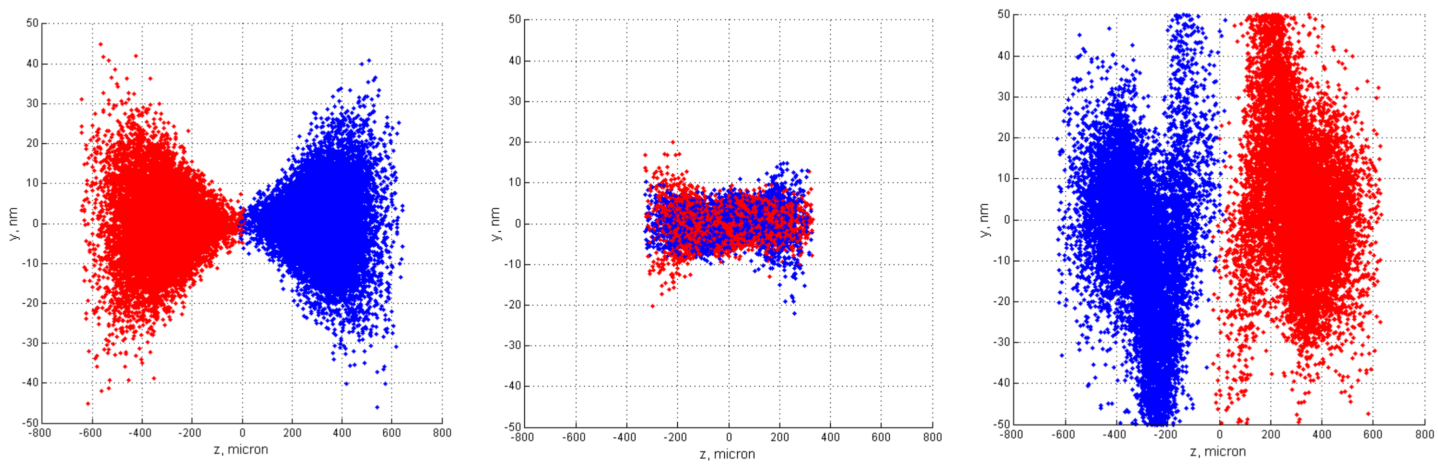
"hour glass" effect from shape of β

Single Bunch Kink (2)

Single bunch kink due to 1% initial offset between beams

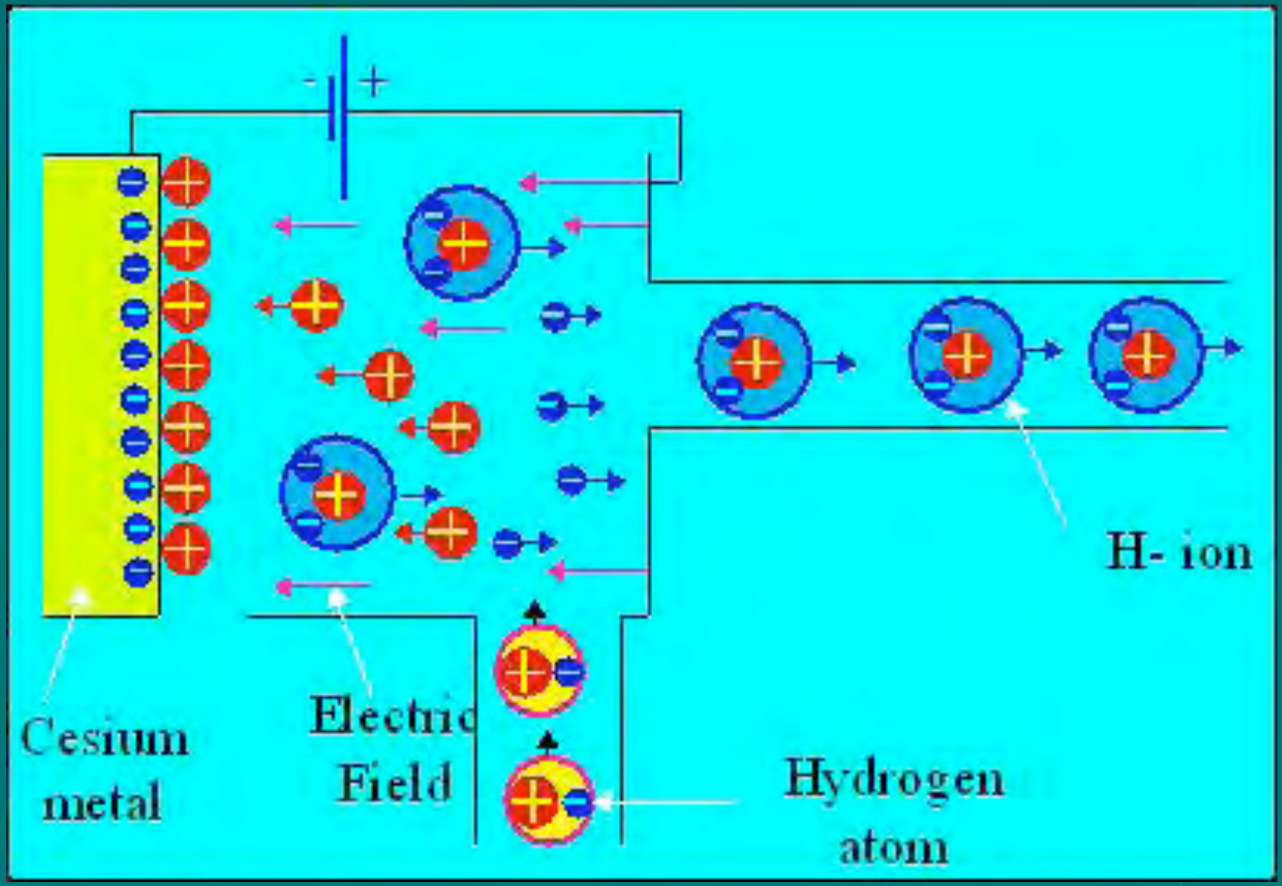


$D_y = 12$



$D_y = 24$

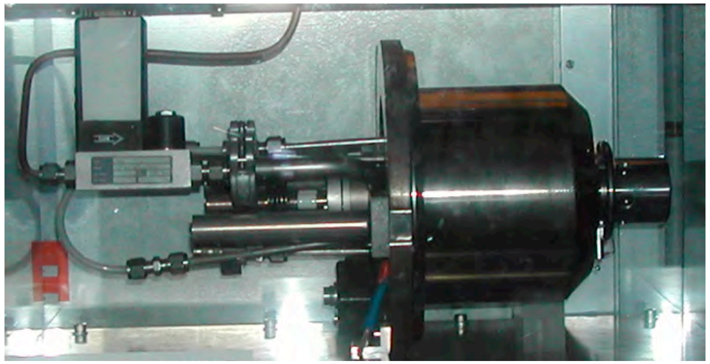
Tevatron H^- Source

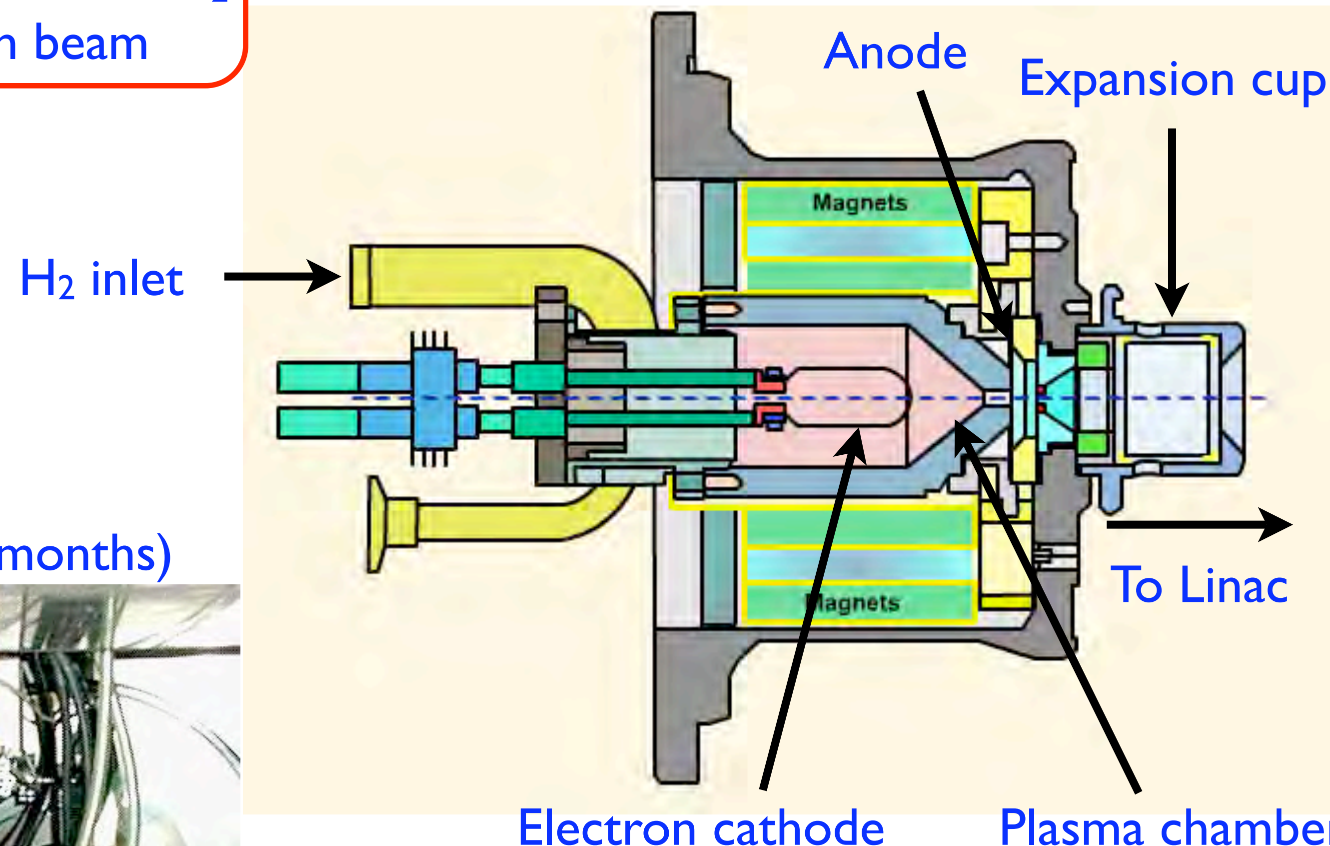


- ✦Hydrogen is drawn to the cesium surface
- ✦Cesium gives up an electron easily
- ✦Some hydrogen atoms with 2 electrons are knocked off the cesium by incoming Hydrogen ions

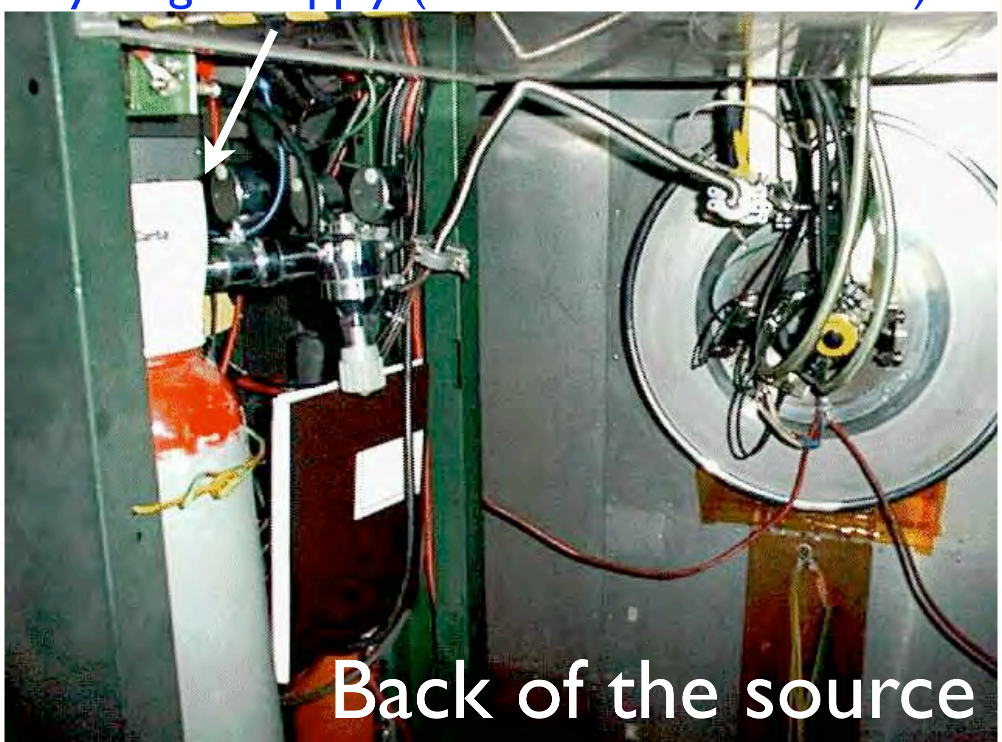
CERN source of protons: duoplasmatron source

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





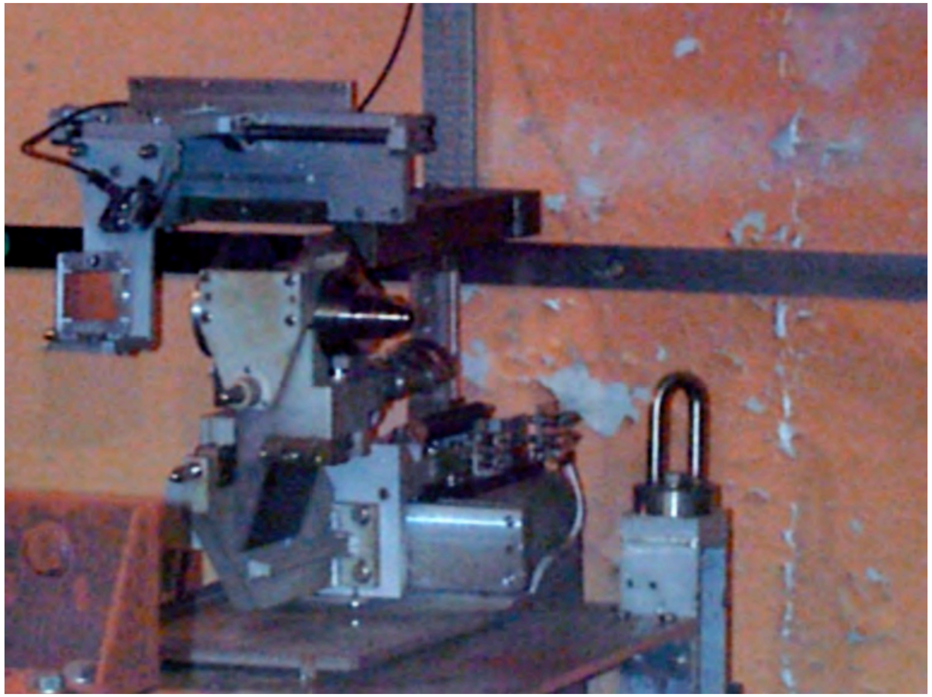
Hydrogen supply (one lasts for 6 months)

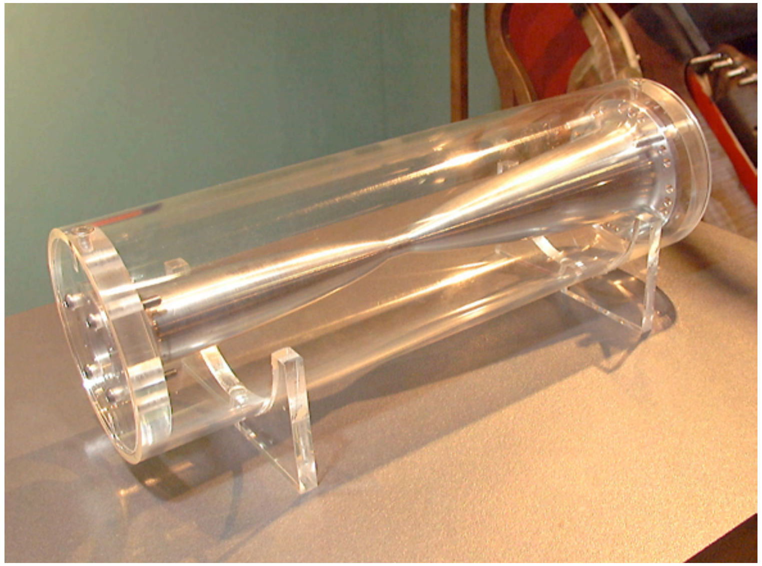


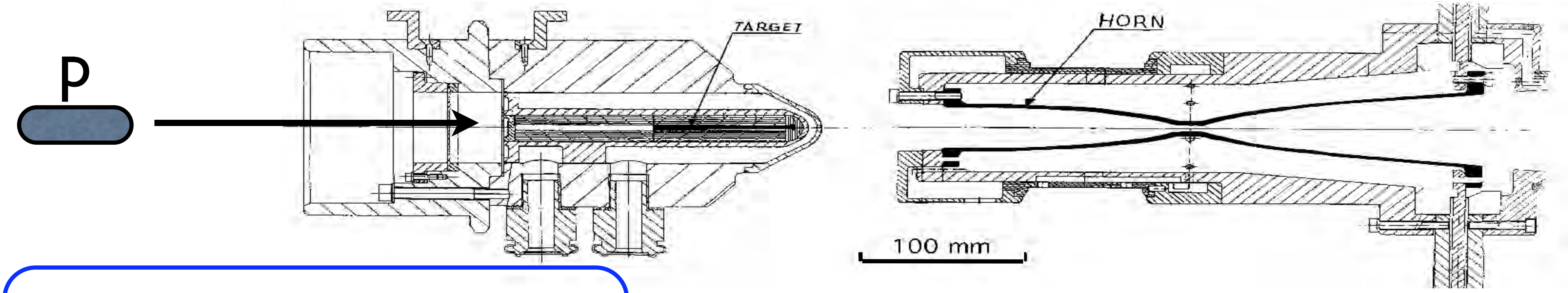
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, $v \approx 4000$ km/s

The SPACE SHUTTLE goes only up to 8 km/s

How to get antiprotons







Starting from high energy p and with a very low efficiency

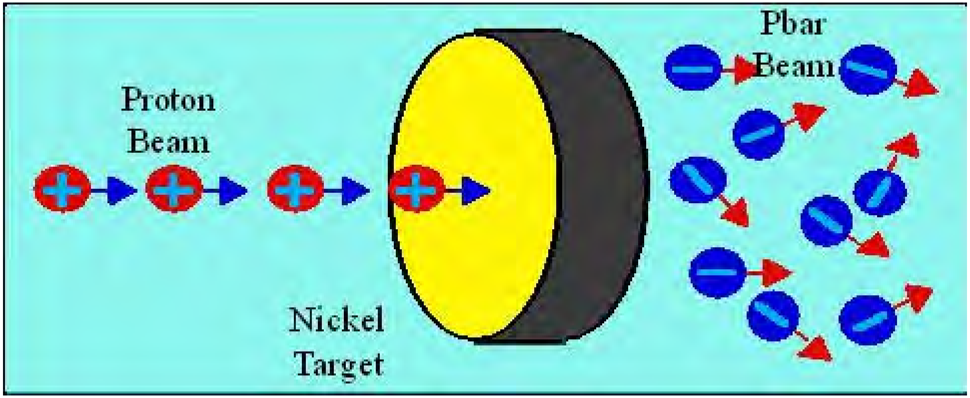
$$p + p \rightarrow p + p + p + \bar{p}$$

See lecture on Antimatter

Stochastic Cooling

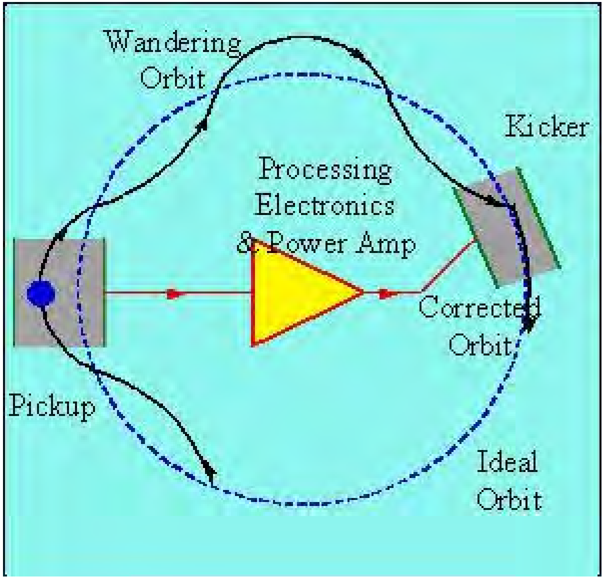
The antiprotons leave the target at a wide range of energies, positions and angles. This randomness is equivalent to temperature so we say that the beam coming off the target is "hot." This "hot" beam will have a difficult time fitting into a beam pipe of reasonable dimensions. Also, this hot beam is 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.

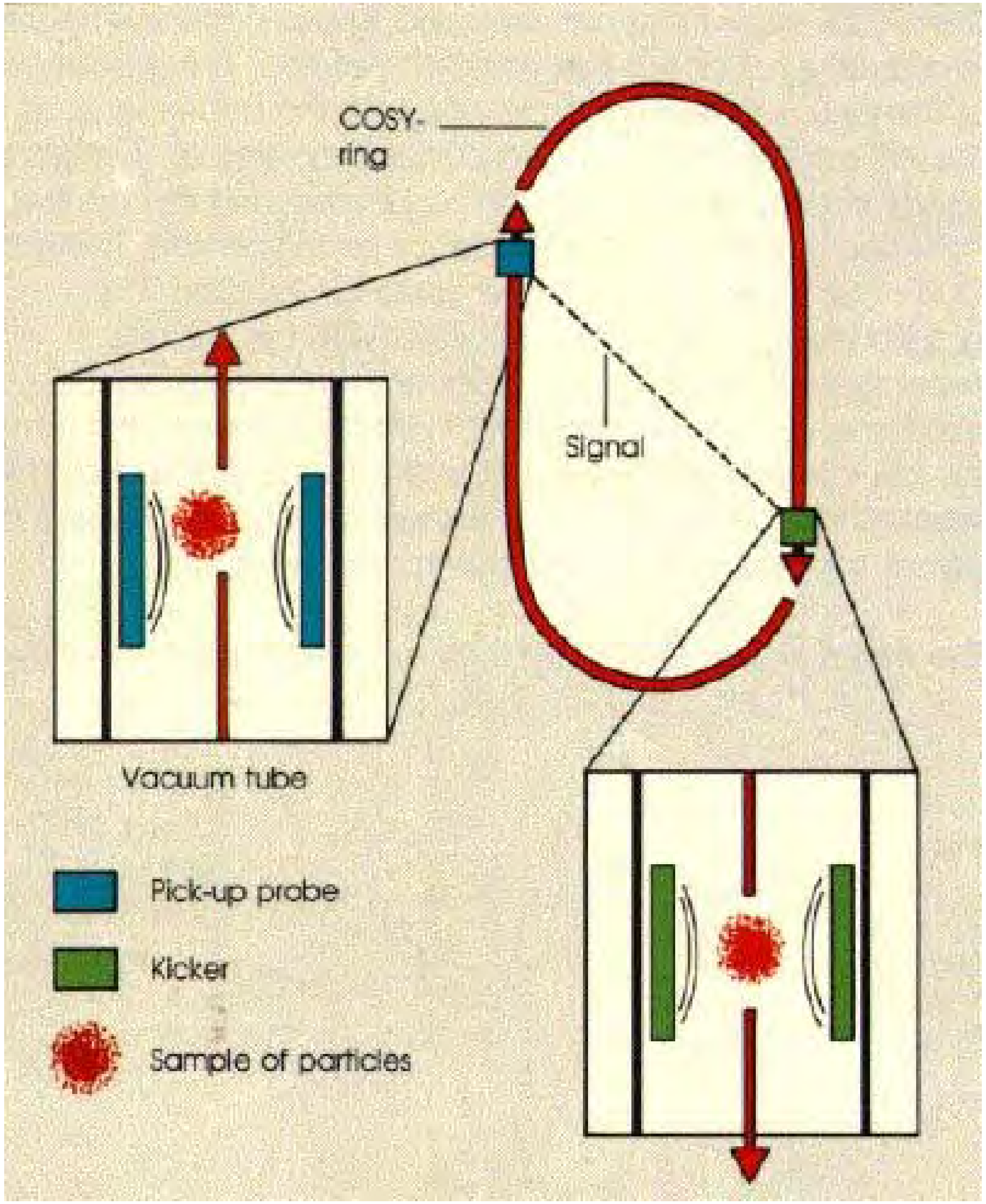
Stochastic cooling uses feedback. A pickup electrode measures an "error" signal for a given particle. This "error" signal could be that particle's position or energy. The pickup signal can be extremely small, on the order of 2 trillionths of a Watt.



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

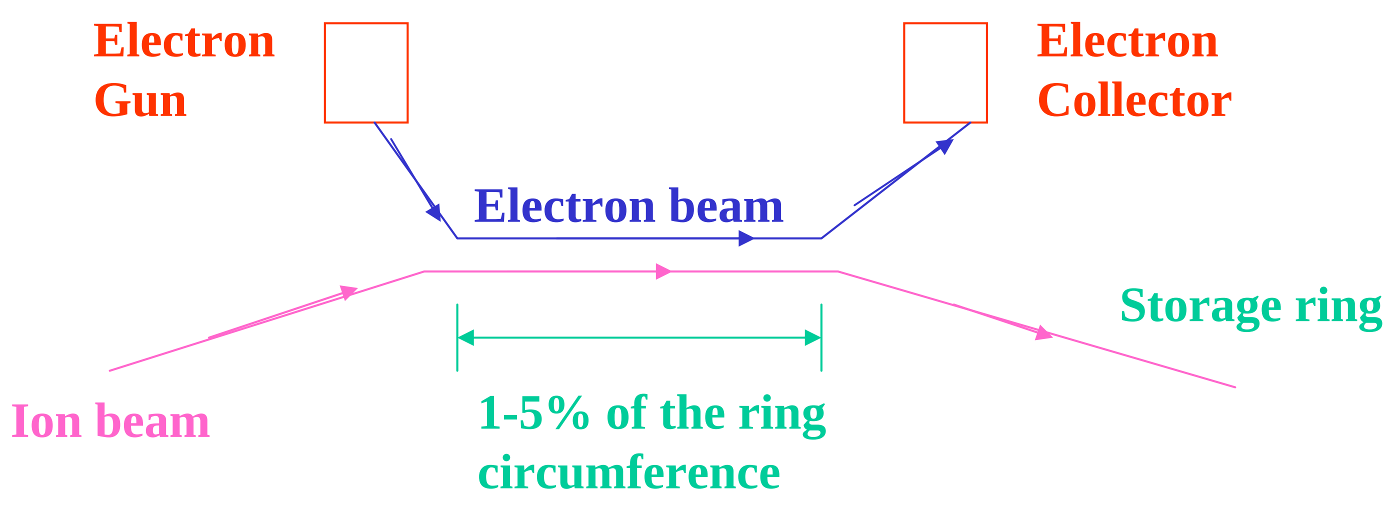
Simon van der Meer
Nagroda Nobla 1984

Electron Cooling

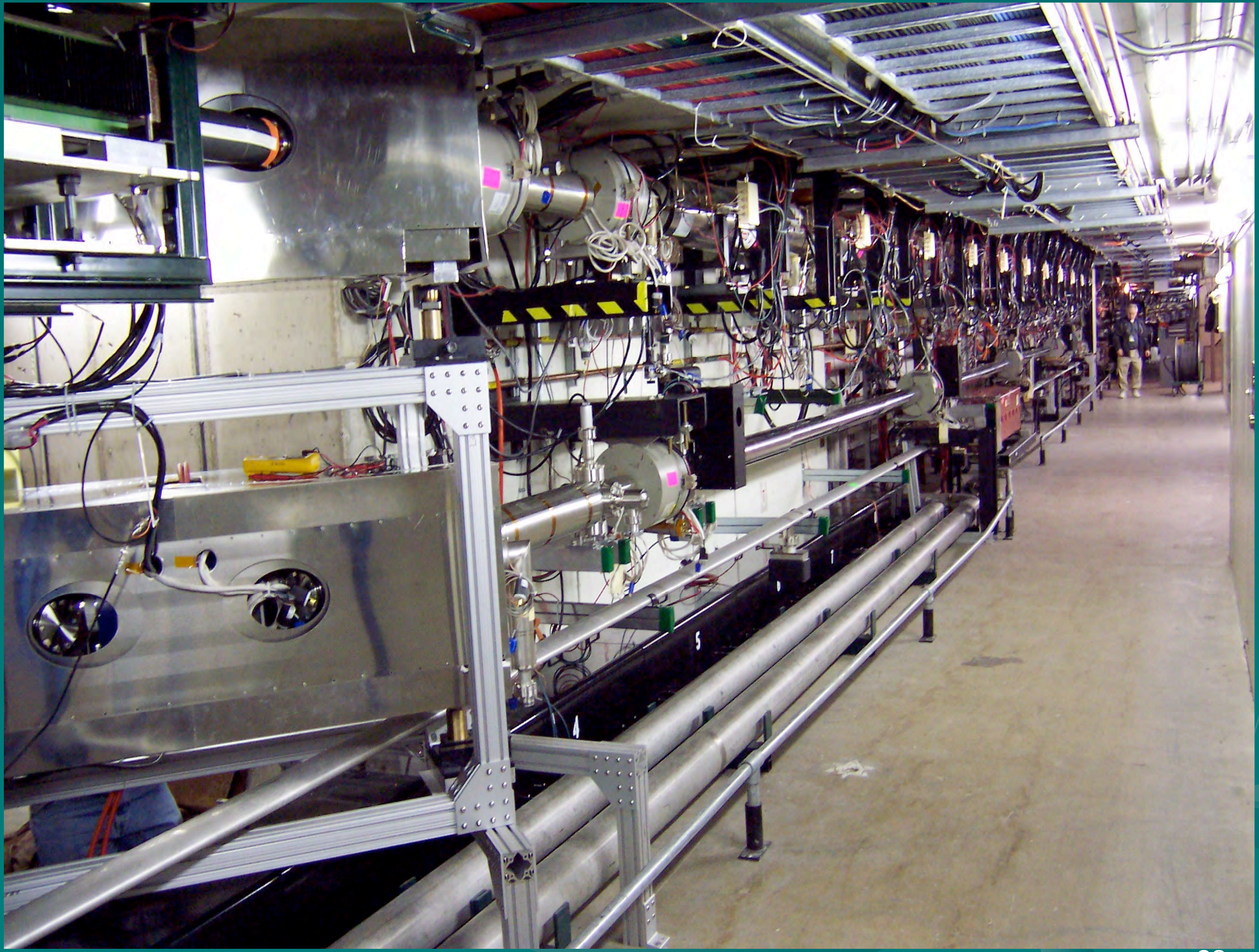
How does electron cooling work?

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.



Electron Cooling Beamline



COoler SYnchrotron COSY

The price of high fields & high luminosity...

When the LHC is operated at 7 TeV with its design luminosity & intensity,

- the LHC magnets store a huge amount of energy in their magnetic fields:
  - per dipole magnet E_{stored} = 7 MJ
  - all magnets E_{stored} = 10.4 GJ

- the 2808 LHC bunches store a large amount of kinetic energy:
  - $E_{bunch} = N \times E = 1.15 \times 10^{11} \times 7$ TeV = 129 kJ
  - $E_{beam} = k \times E_{bunch} = 2808 \times E_{bunch}$ = 362 MJ

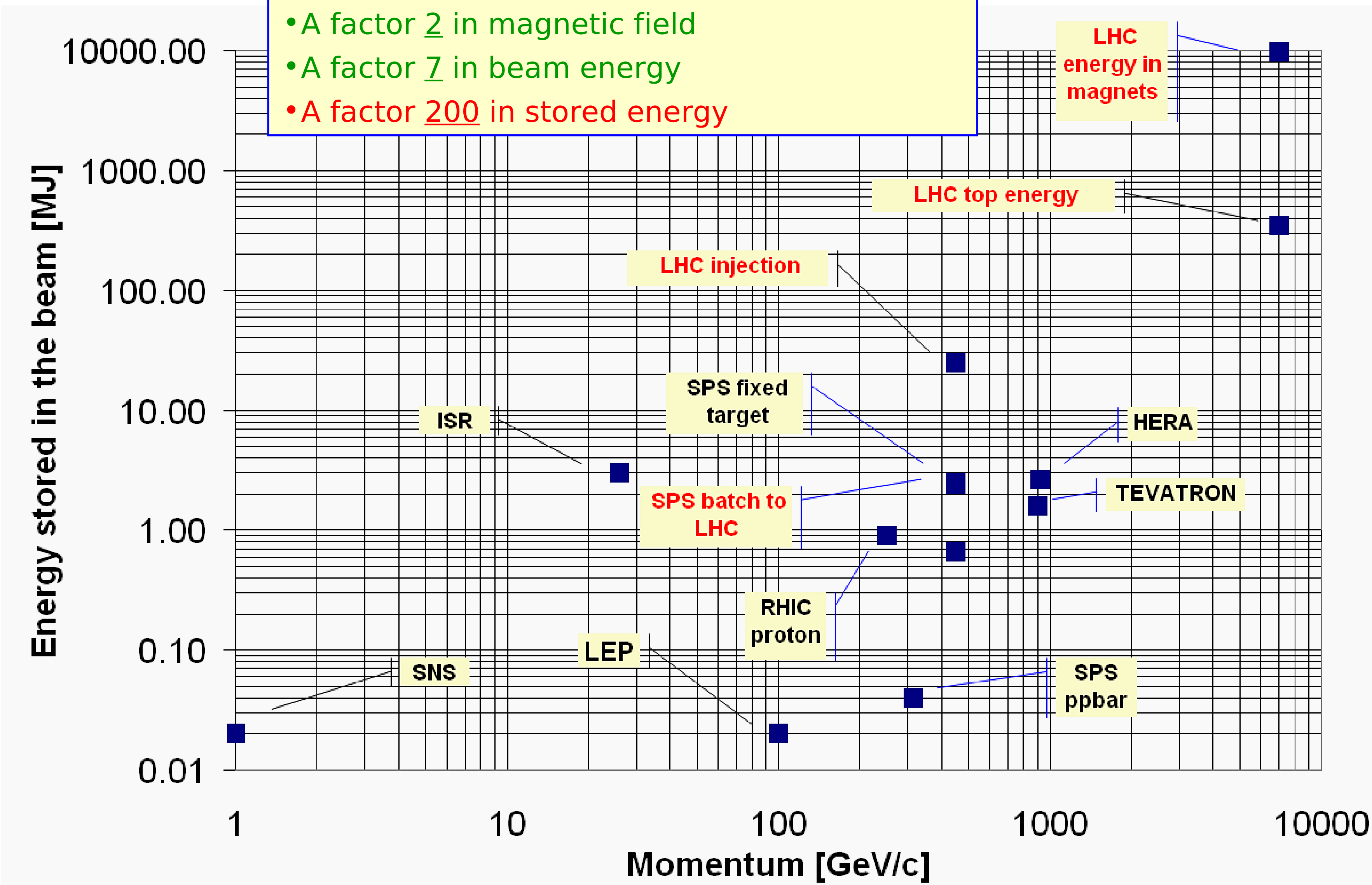
To ensure safe operation (i.e. without damage) we must be able to dispose of all that energy safely !

This is the role of Machine Protection !

Stored Energy

Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy



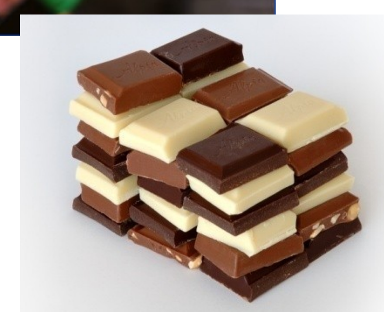
Comparison…

The energy of an A380 at 700 km/hour corresponds to the energy stored in the LHC magnet system :

Sufficient to heat up and melt 15 tons of Copper!!

The energy stored in one LHC beam corresponds approximately to…

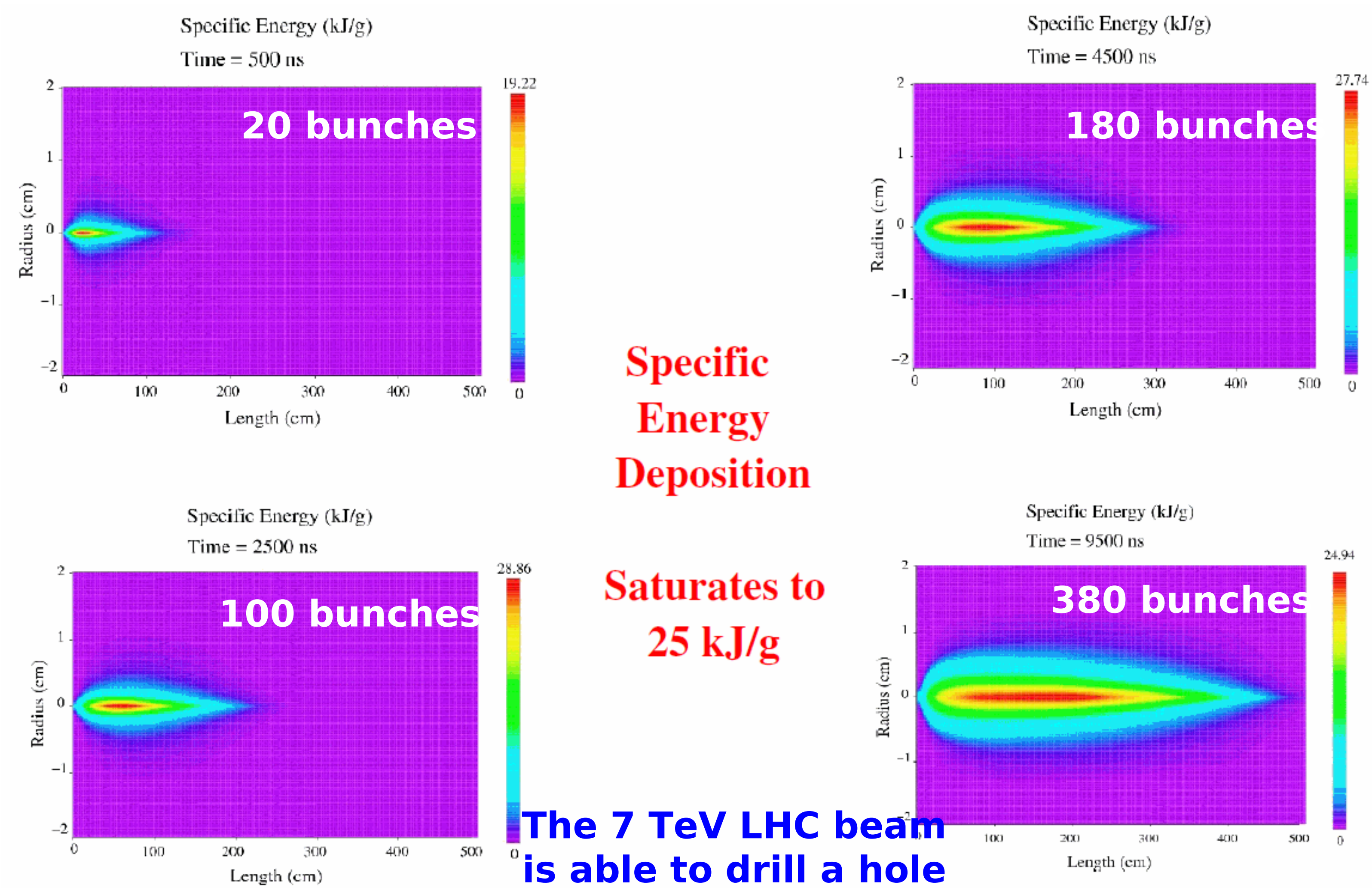
- 90 kg of TNT
- 10-12 litres of gasoline
- 15 kg of chocolate



It's how easily the energy is released that matters most !!

LHC beam impact : energy deposition

7 TeV LHC beam into a 5 m long Copper target



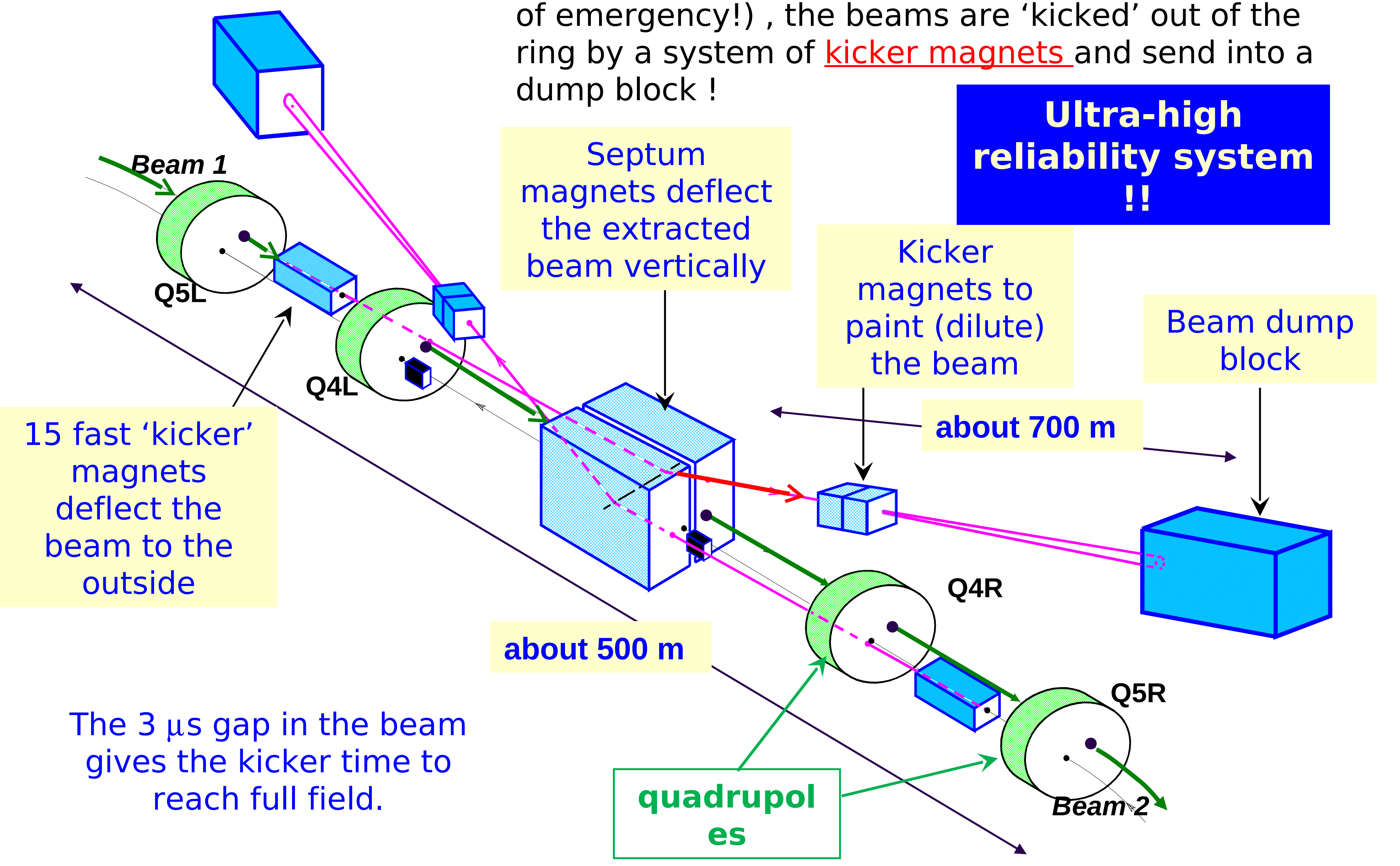
Specific Energy Deposition

Saturates to 25 kJ/g

The 7 TeV LHC beam is able to drill a hole through ~35 m of Copper

Schematic layout of beam dump system in IR6

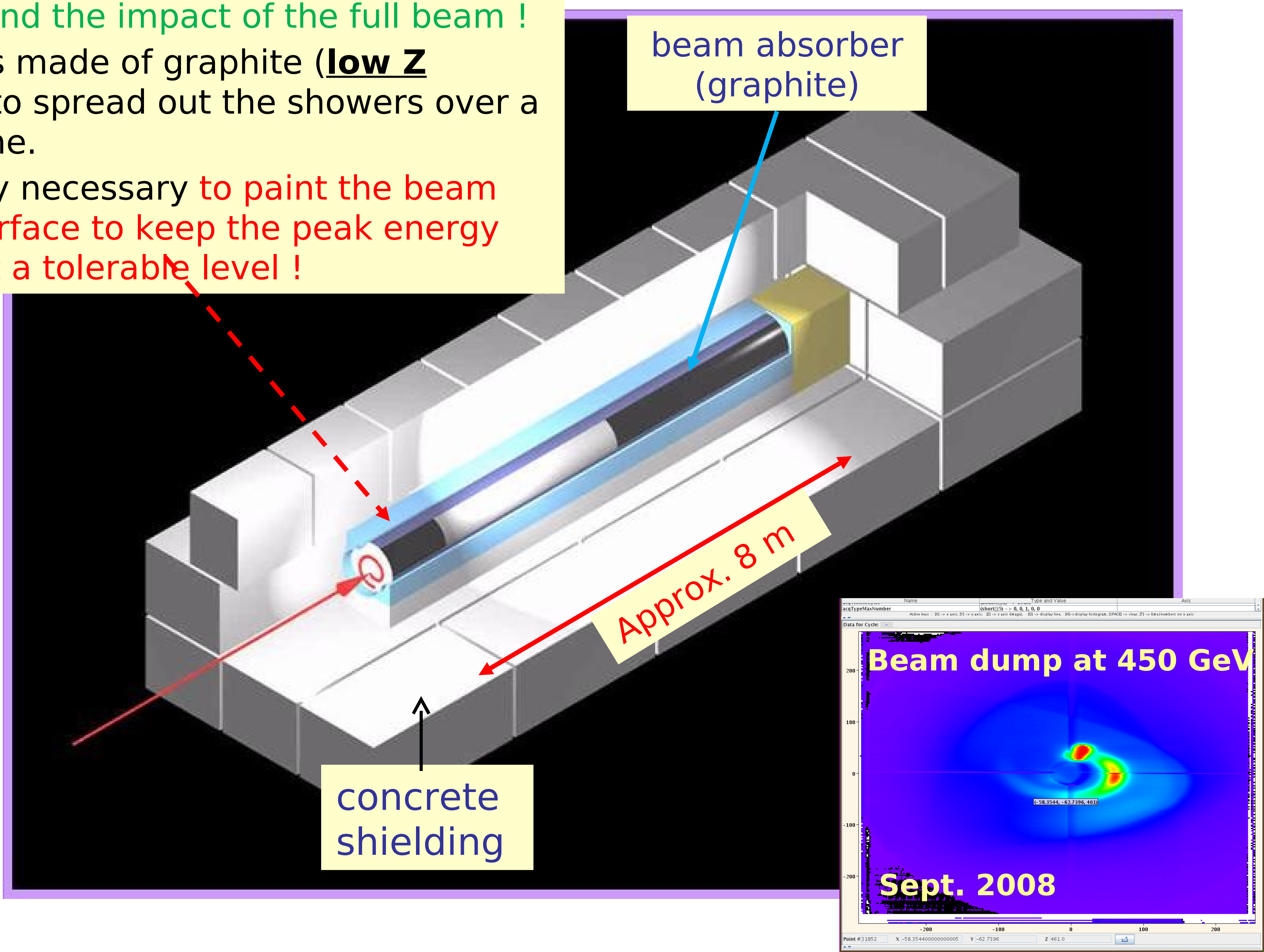
When it is time to get rid of the beams (also in case of emergency!) , the beams are 'kicked' out of the ring by a system of kicker magnets and send into a dump block !



The 3 μs gap in the beam gives the kicker time to reach full field.

The dump block

- This is the **ONLY** element in the LHC that can withstand the impact of the full beam !
- The block is made of graphite (**low Z material**) to spread out the showers over a large volume.
- It is actually necessary to paint the beam over the surface to keep the peak energy densities at a tolerable level !

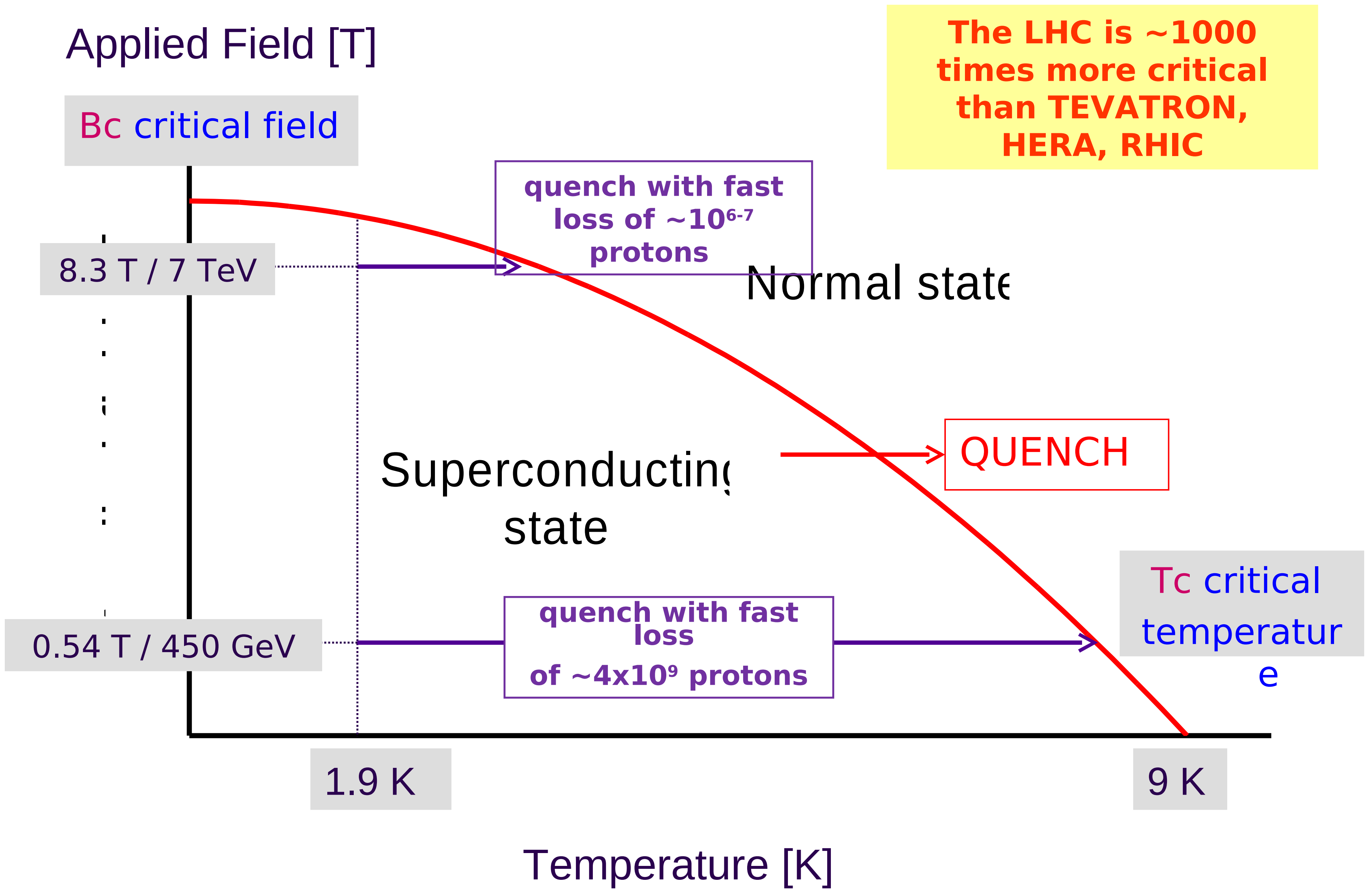


Dump installation

Failure detection example : beam loss monitors

- Ionization chambers to detect beam losses:
  - N_2 gas filling at 100 mbar over-pressure, voltage 1.5 kV
  - Sensitive volume 1.5 l
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are ~**3600** chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !

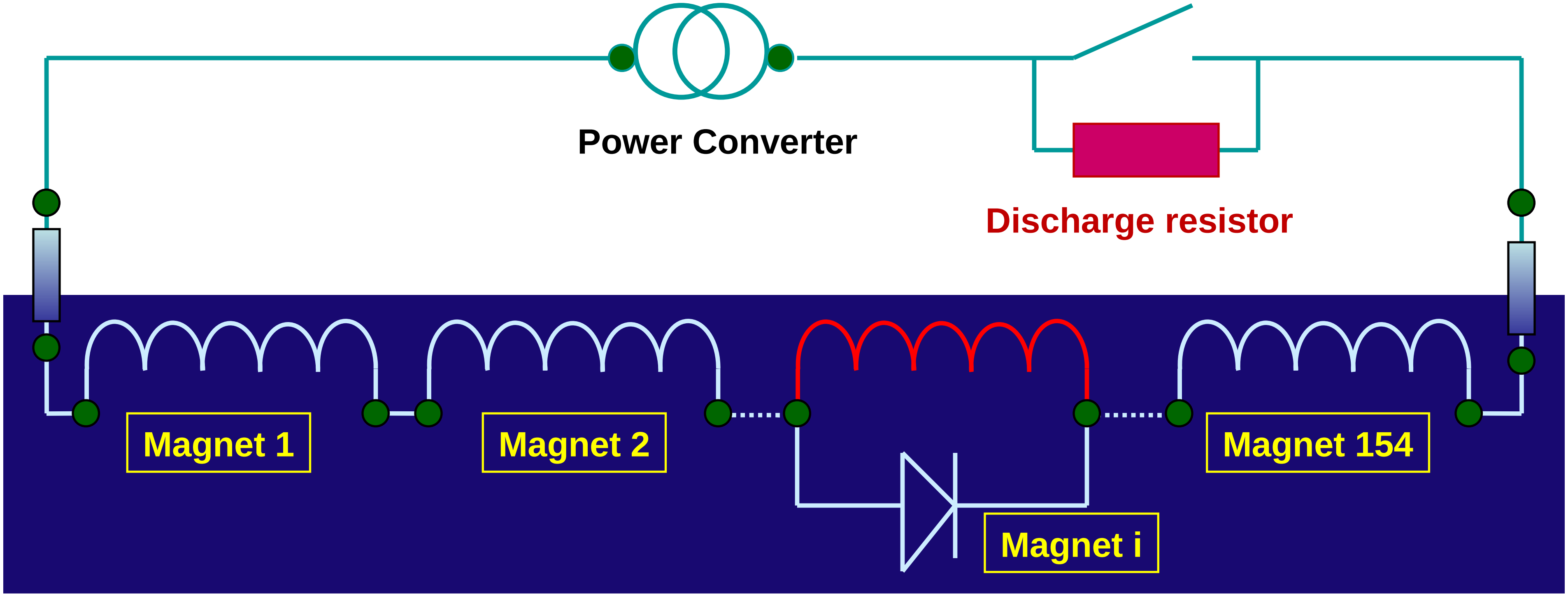
Operational margin of SC magnet



Quench

- A quench is the phase transition from the super-conducting to a normal conducting state.
- Quenches are initiated by an energy in the order of few **milliJoules**
  - Movement of the superconductor by several μm (friction and heat dissipation).
  - Beam losses.
  - Cooling failures.
  - ...
- When part of a magnet quenches, the conductor becomes resistive, which can lead to excessive local energy deposition (temperature rise !!) due to the appearance of Ohmic losses. To protect the magnet:
  - The quench must be detected: a voltage appears over the coil ($R > 0$).
  - The energy release is distributed over the entire magnet by force-quenching the coils using quench heaters (such that the entire magnet quenches !).
  - The magnet current has to be switched off within << 1 second.

Quench - discharge of the energy

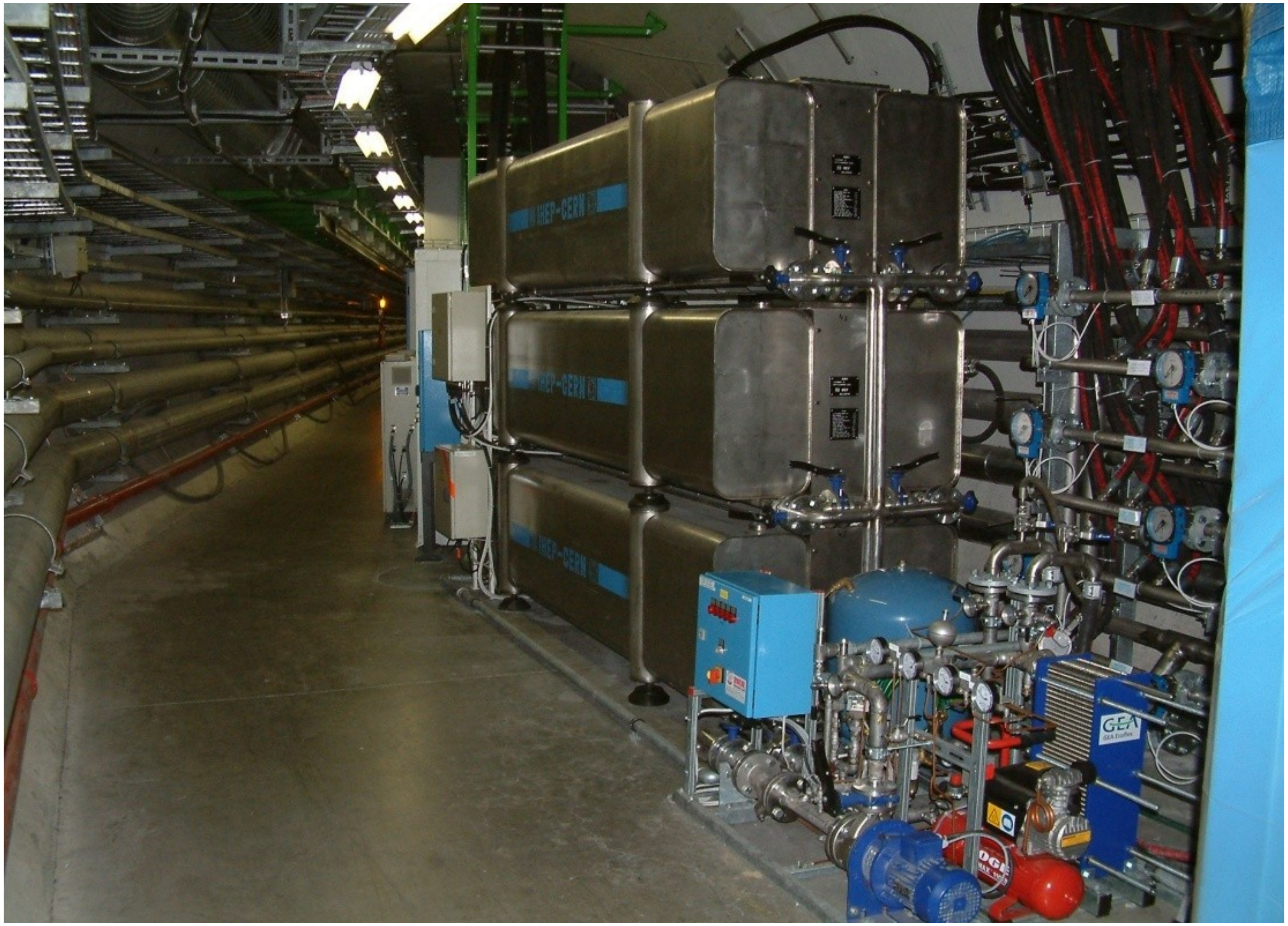


Protection of the magnet after a quench:

- The quench is detected by measuring the **voltage increase** over coil.
- The energy is distributed in the magnet by force-quenching using quench heaters.
- The current in the quenched magnet decays in < 200 ms.
- The current flows through the bypass diode (triggered by the voltage increase over the magnet).
- The current of all other magnets is dischared into the dump resistors.

Dump resistors

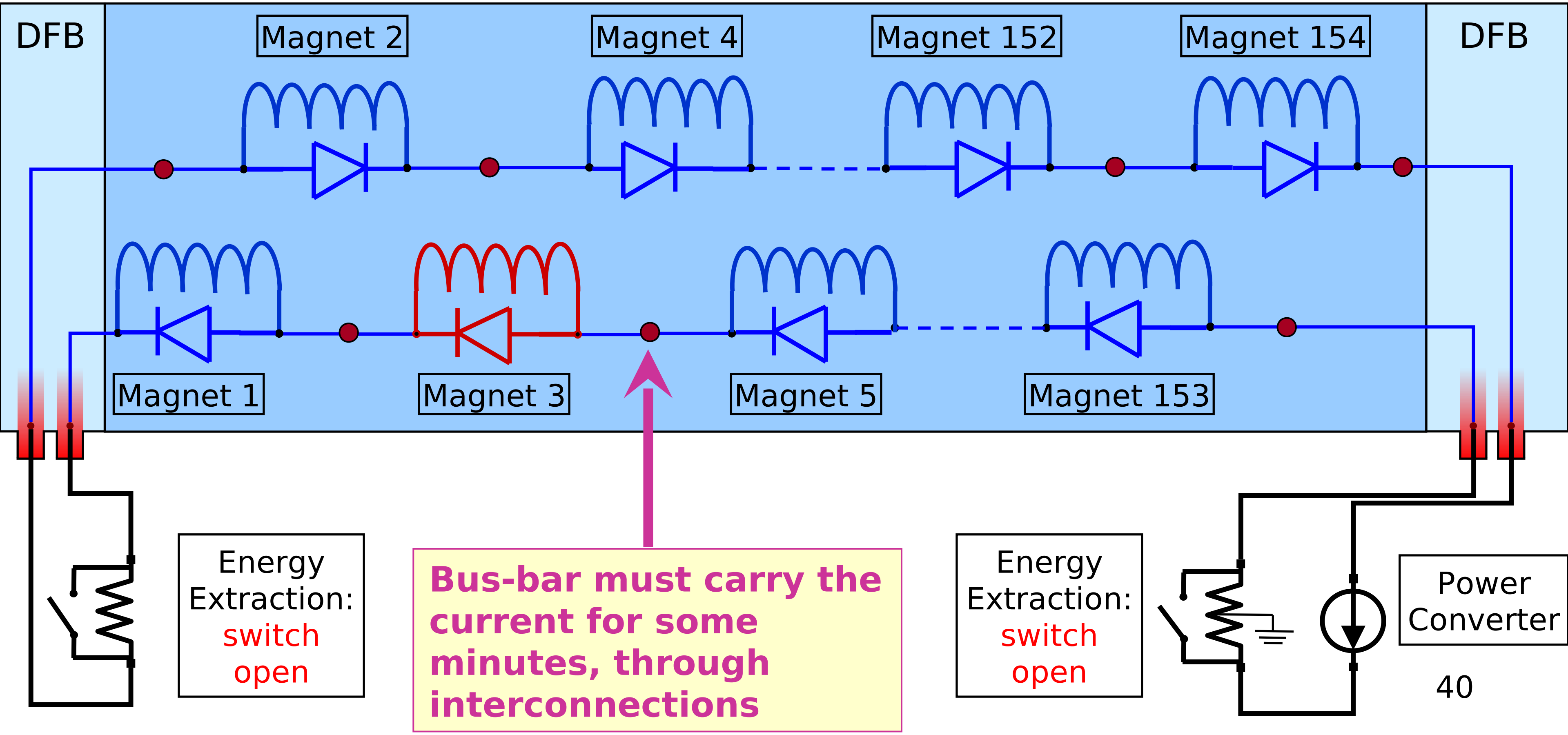
Those large air-cooled resistors can absorb the 1 GJ stored in the dipole magnets (they heat up to few hundred degrees Celsius).



Dipole magnet protection - again

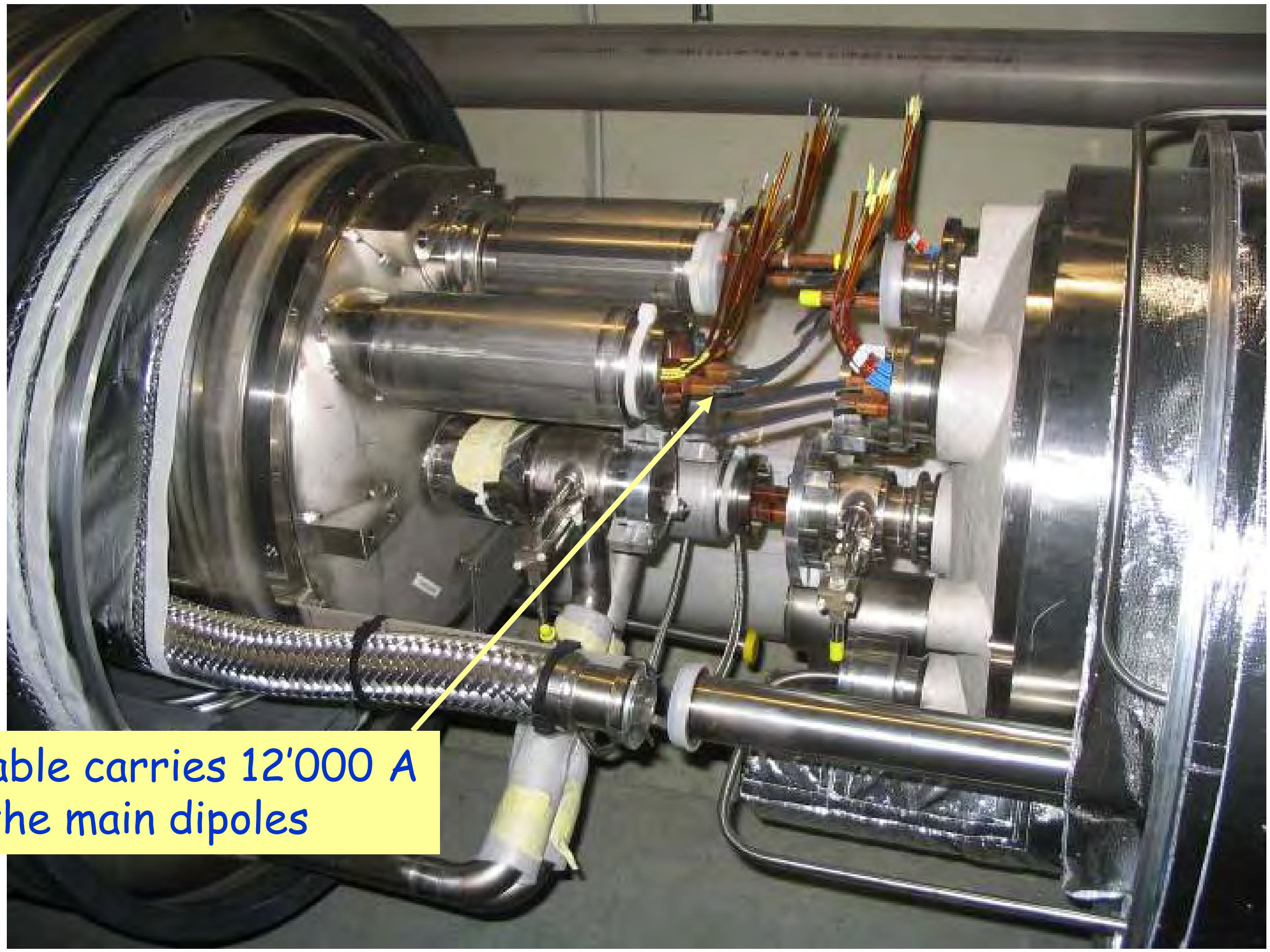
- In case of a quench, the individual magnet is protected (quench protection and diode).
- Resistances are switched into the circuit: the energy is dissipated in the resistances (**current decay time constant of 100 s**).

>> the bus-bar must carry the current until the energy is extracted !



Complex interconnects

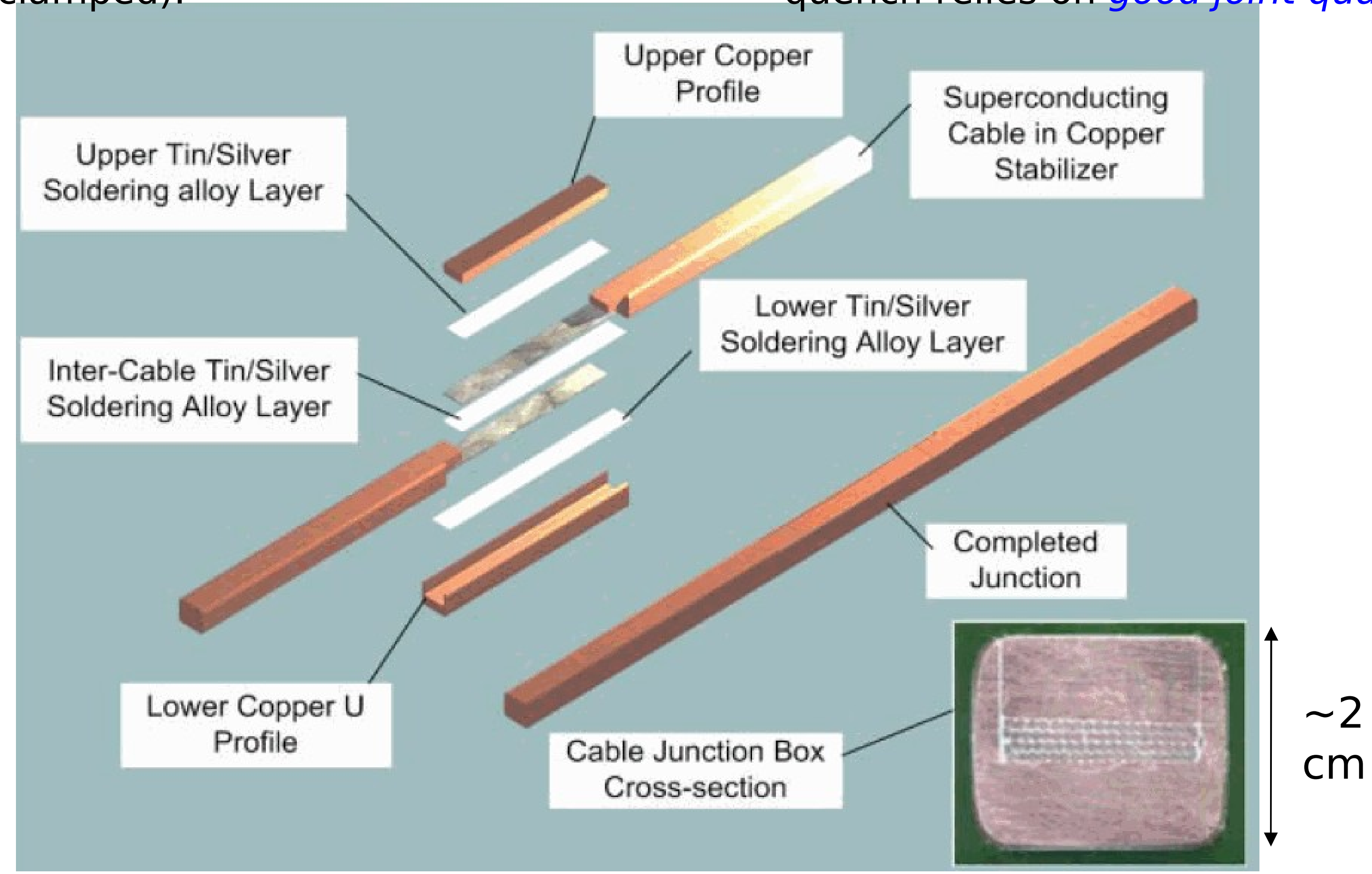
Many complex connections of super-conducting cable that will be buried in a cryostat once the work is finished.



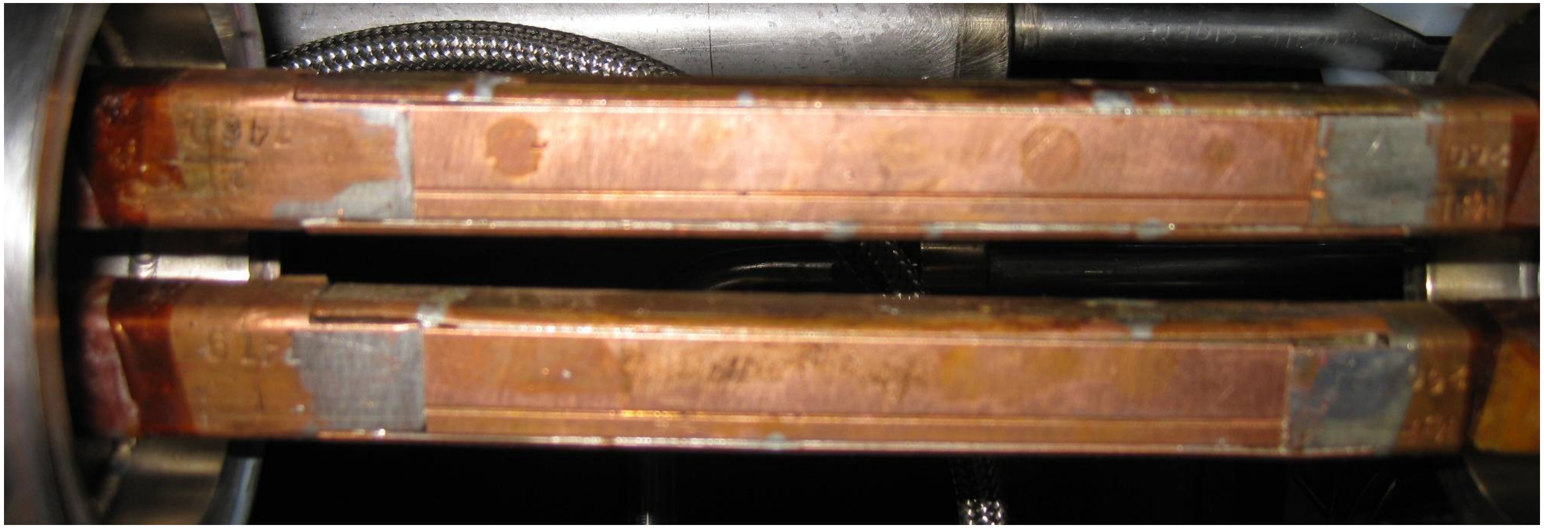
This SC cable carries 12'000 A for the main dipoles

Bus-bar joint (1)

- Superconducting cable embedded in Copper stabilizer.
- Bus bar joint is soldered (not clamped).
- Joint resistance **~0.35 nΩ** (@ 1.9 K).
- Protection of the joint during quench relies on *good joint quality.*



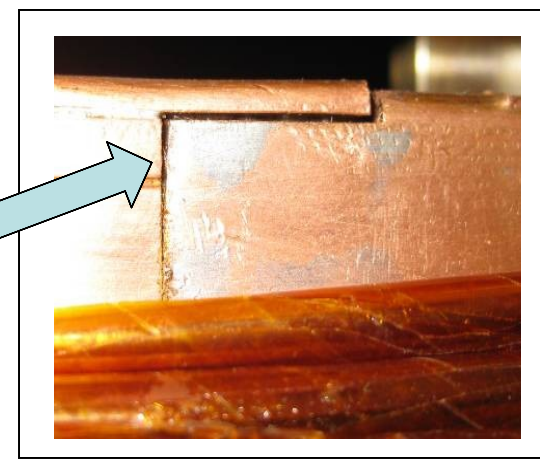
Bus-bar joint (2)



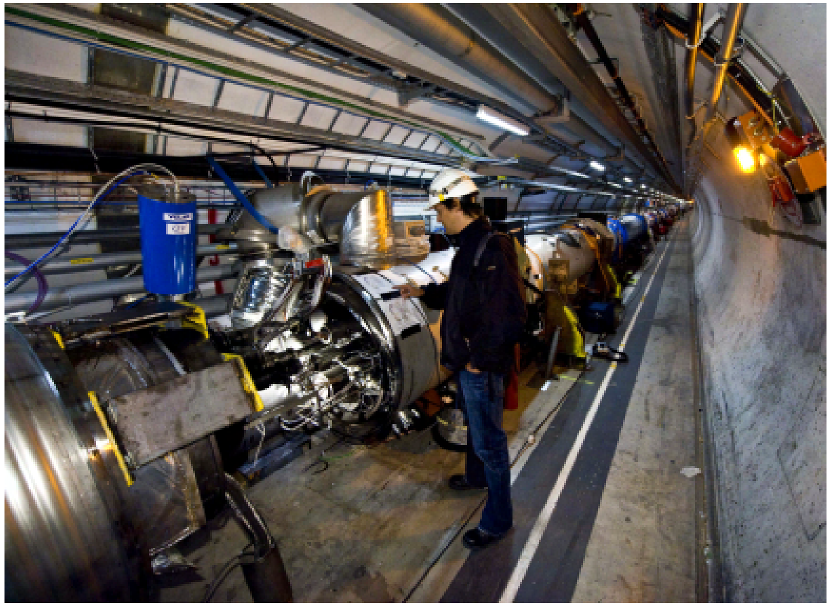
- A post-mortem analysis of the data from the sector with the incident revealed the presence of a 200 nΩ anomalous resistance in the cell of the primary electrical arc. This acted as a heat source that quenched the superconducting cable.

  >> Unfortunately the evidence is destroyed…

- An inspection of accessible joints revealed non-conformities like poor soldering and/or reduced electrical contact as in the example to the right.



Awaria LHC



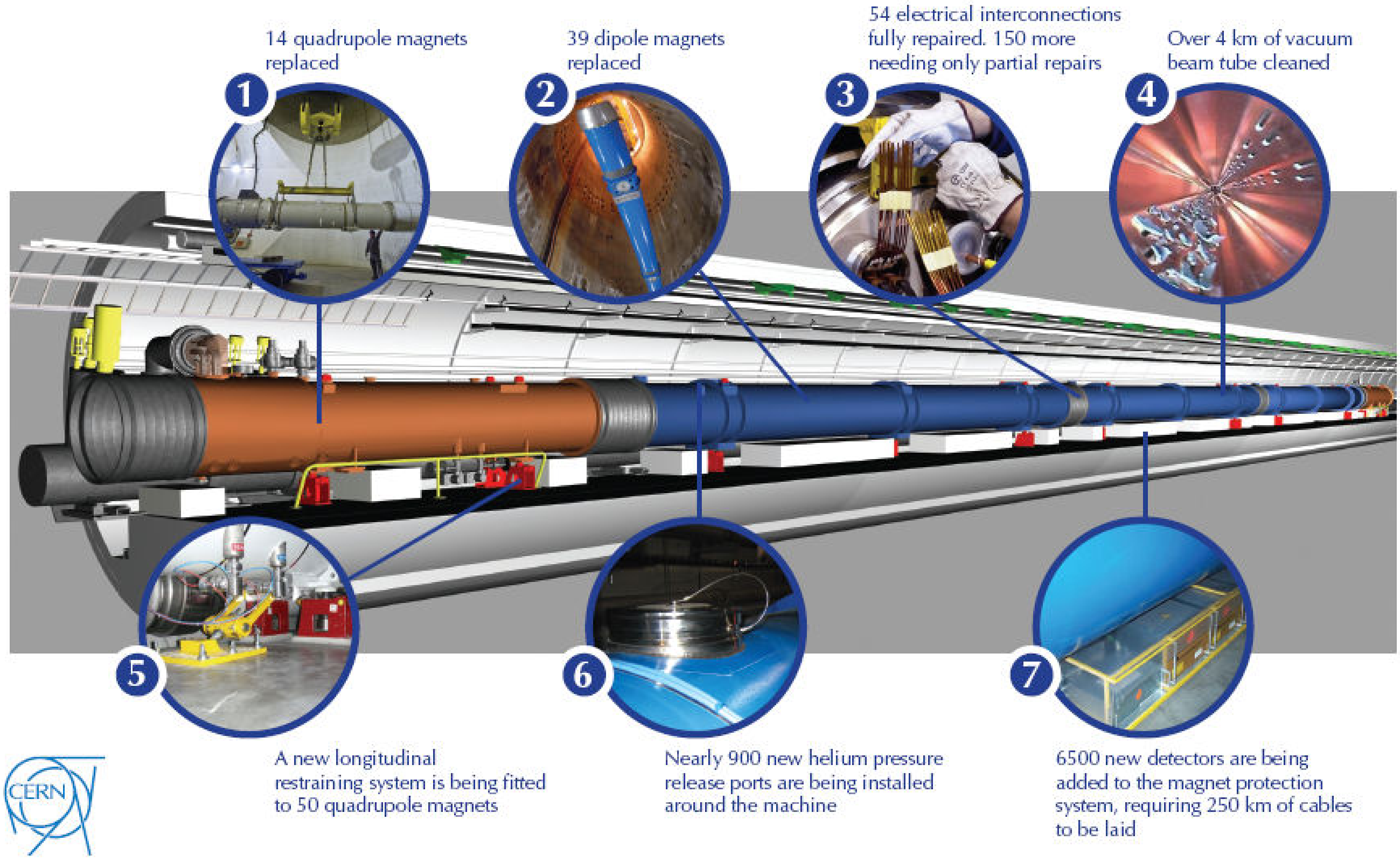
Wadliwy kontakt między dwoma magnesami doprowadził do utraty nadprzewodnictwa na złączu, przepalenia kabla i łuku el.

=> wydzielenie dużej ilości ciepła

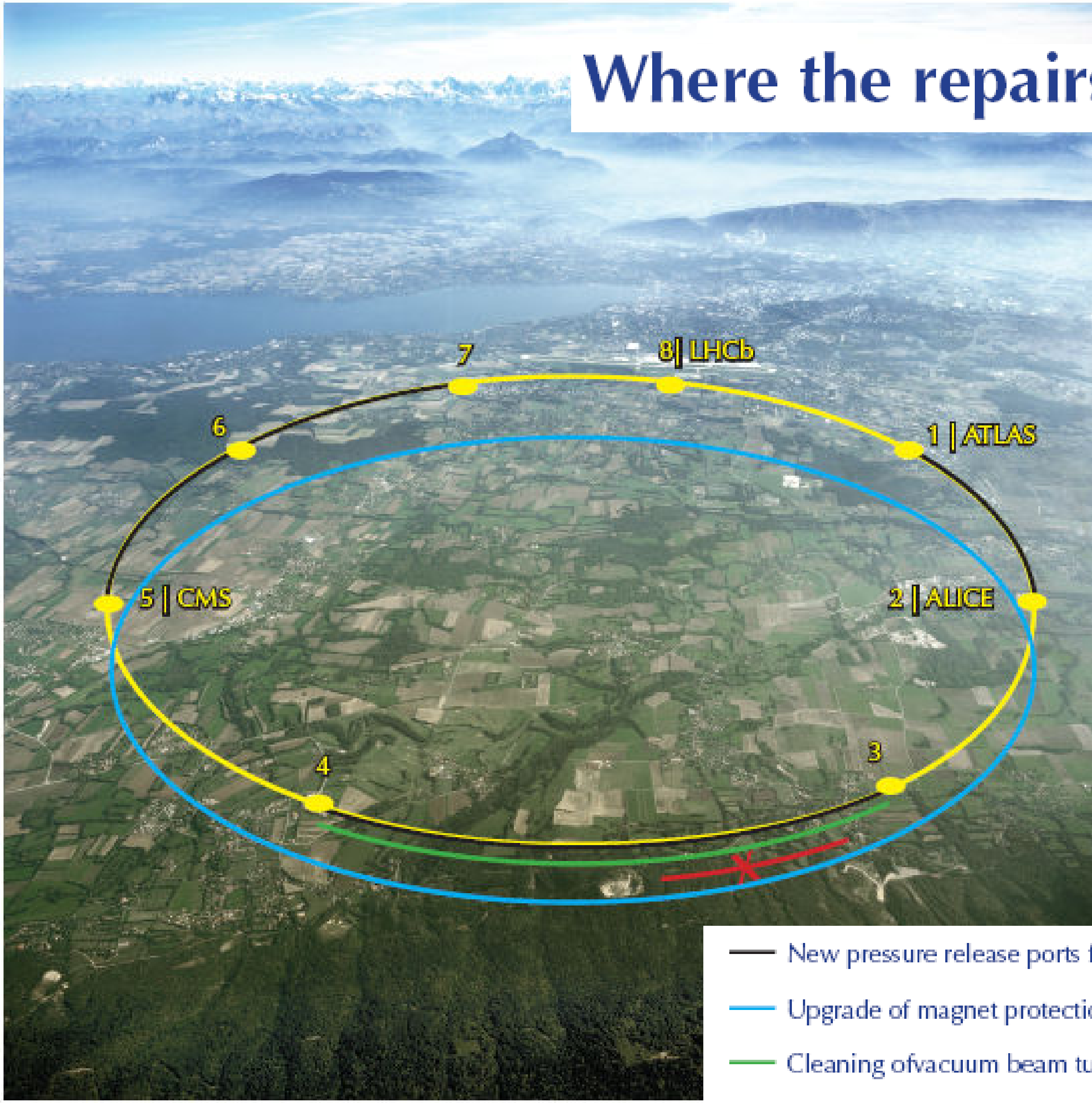
=> wyparowanie dużej objętości helu

=> eksplozję kriostatu (zbyt małe zawory bezpieczeństwa)

The LHC repairs in detail

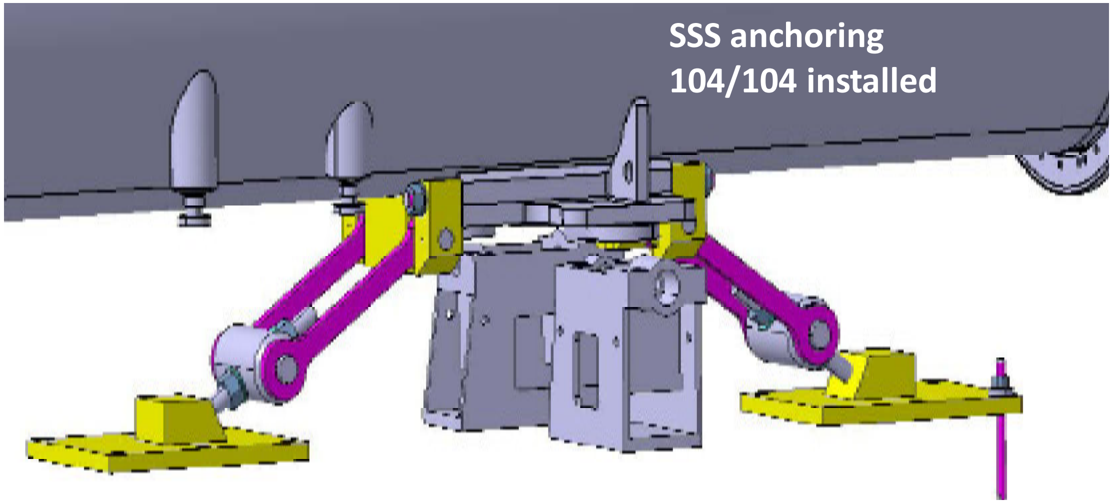


Where the repairs are happening



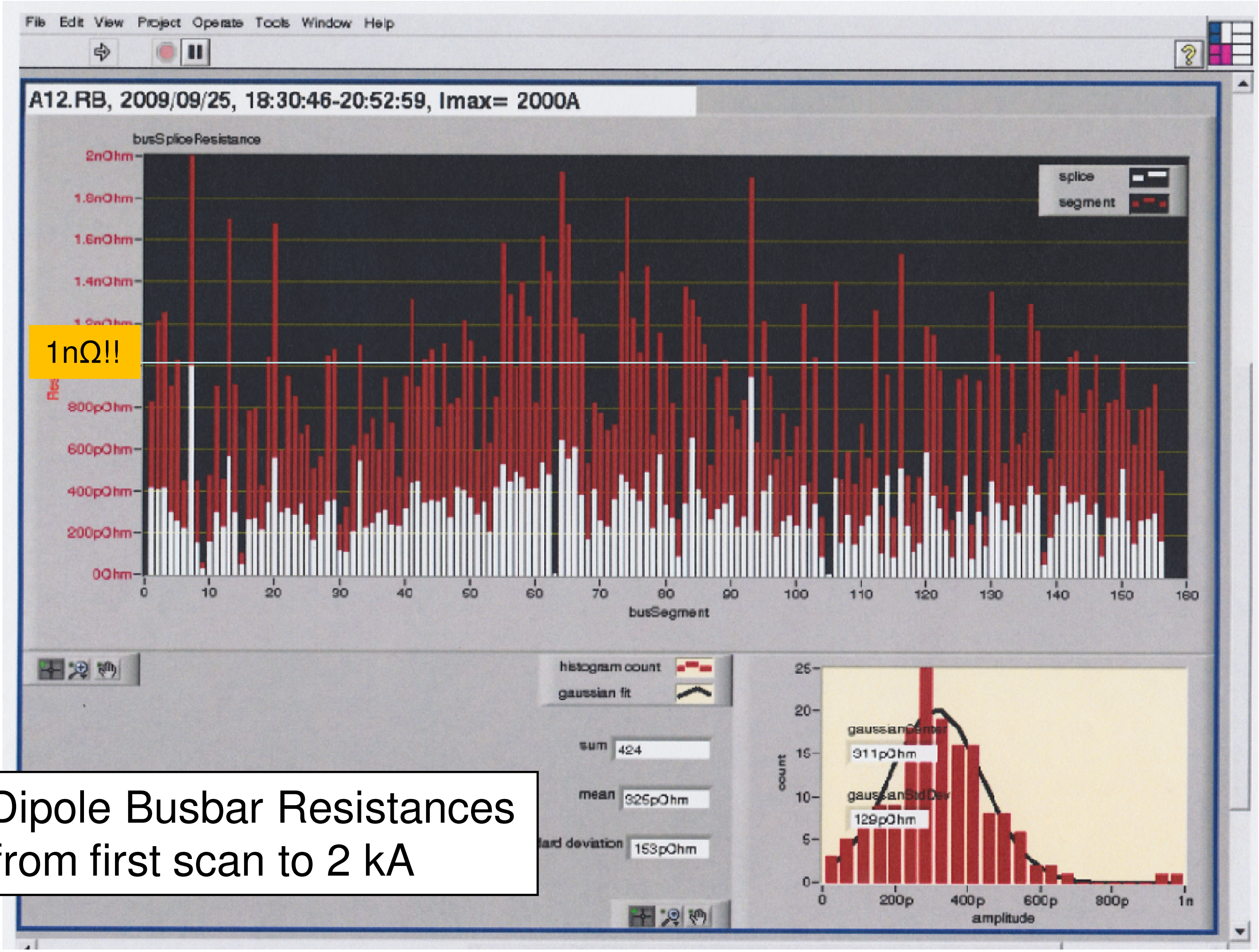
- New pressure release ports fitted
- Upgrade of magnet protection system
- Cleaning ofvacuum beam tube
- Dipole and quadrupole magnets replaced and electrical interconnections
- LHC ring
- X Incident

Magnet protection and anchoring



Splice Mapping of Dipoles

QPS team



First Dipole Busbar Resistances
from first scan to 2 kA

Decision on Initial Beam Operating Energy

(August 2009)

- Highest measured value of excess resistance (R_{long}) in 5 sectors measured at 300K was 53μΩ.
- Operating at 7 TeV cm with energy extraction times of 50s, 10s (dipoles and quadrupoles)
  - Simulations show that resistances of ≤120μΩ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR) and no cooling to the copper stabilizer from the gaseous helium.
- Operating at 10 TeV cm with a dipole energy extraction time of 68 s
  - Simulations show that resistances of ≤67μΩ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR), and with estimated cooling to the stabilizer from the gaseous helium.
- Decision: Operation initially at 7 TeV cm (energy extraction time of 50s, 10s) with a safety factor or more than 2 for the worst stabilizers. During this time
  - monitor carefully all quenches to gain additional information.
  - Continue simulations and validation of simulations by experimentation (FRESCA)
- Then operate at around 10 TeV cm.

Pierwszy przypadek z detektora CMS @ 7 TeV