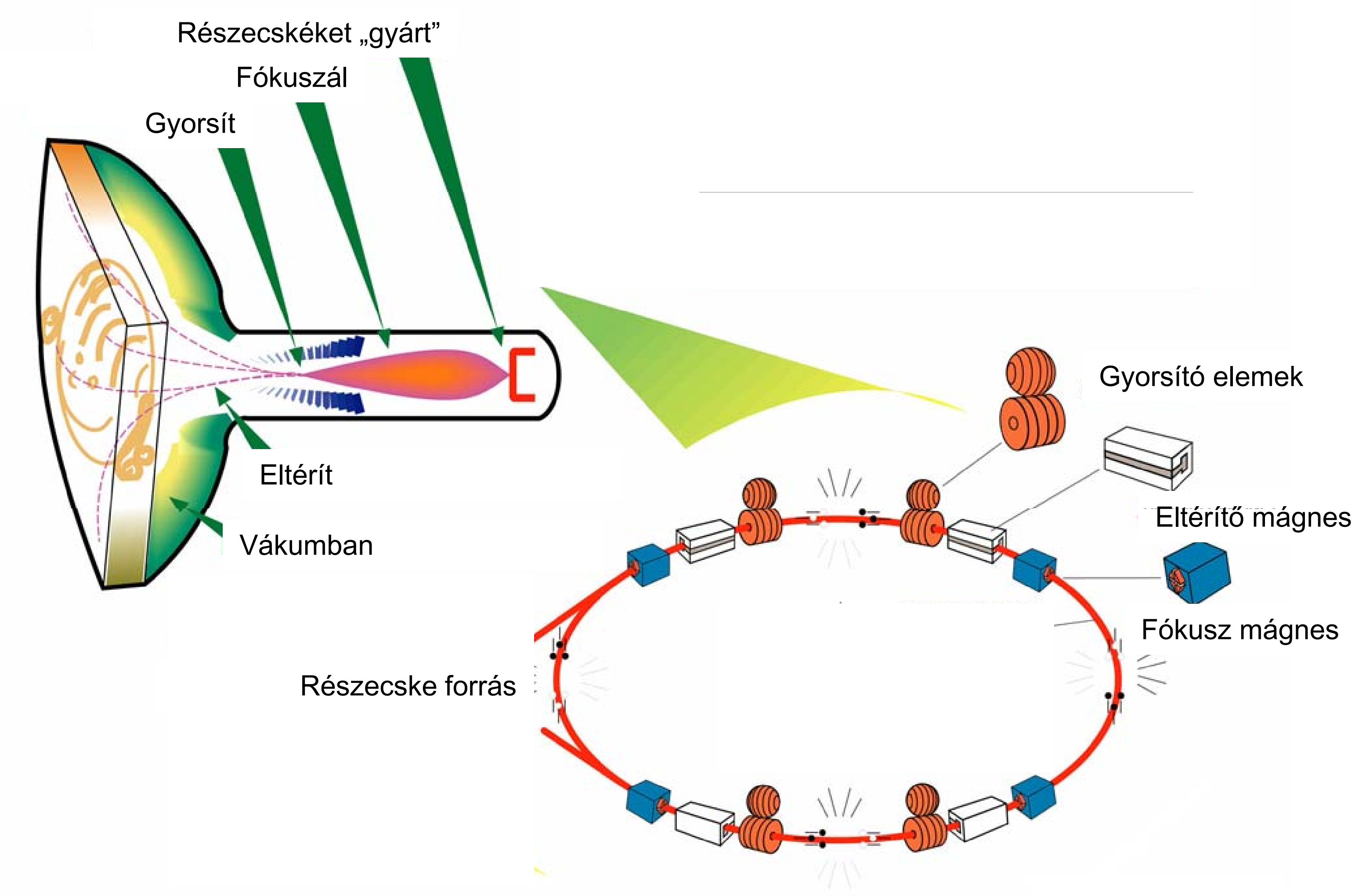
„Egy az Isten (CERN) és LHC az Ő prófétája.”

ACCELERATORS

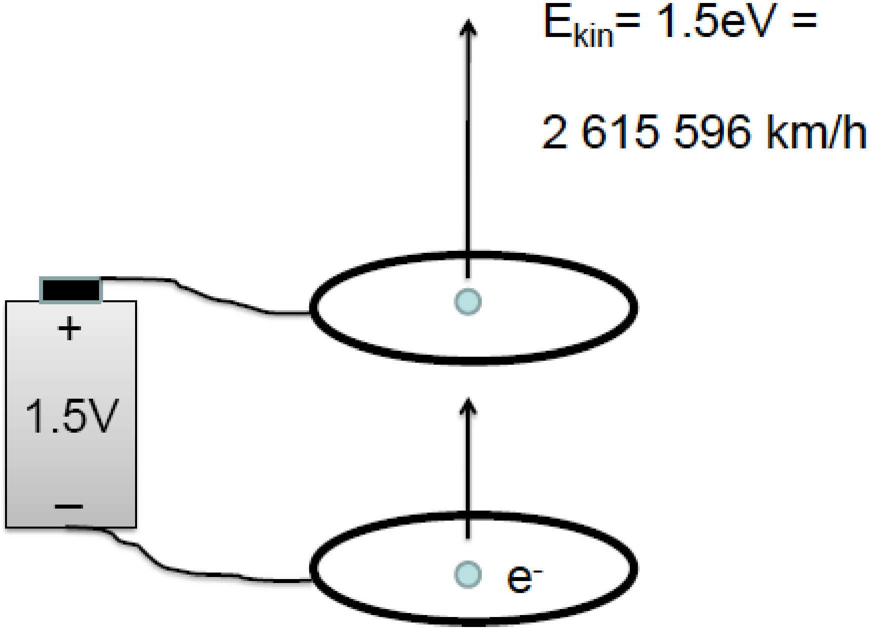
G. Vesztergombi

HTP2007, Geneva

A televízió készülék!



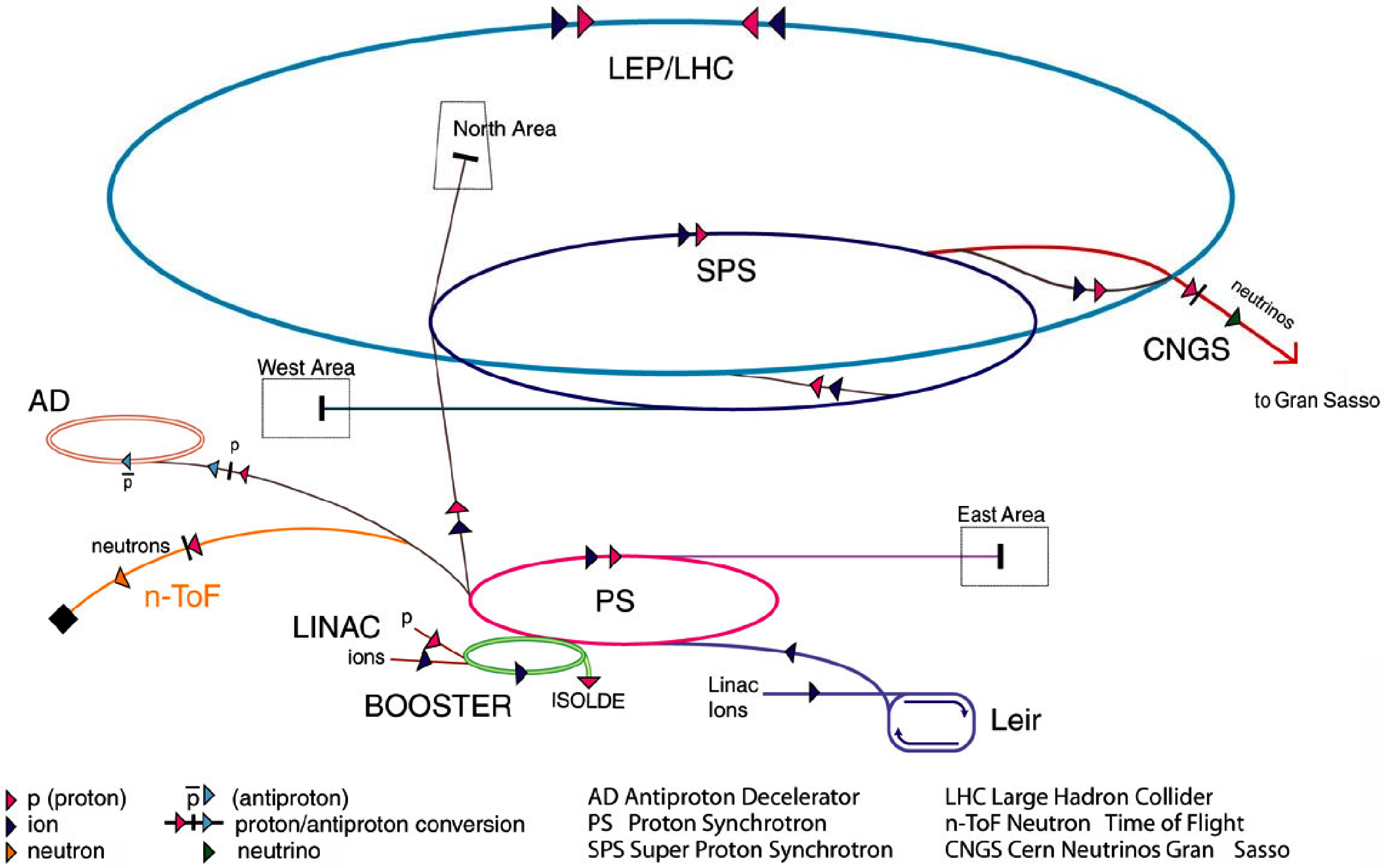
Build your own Accelerator



Even the longest journey is started by the FIRST step (eV)!!!!!!!!!!!!

14 TeV = 10 000 000 * 1 000 000 * 1.4 eV

CERN gyorsító komplexuma



WHY

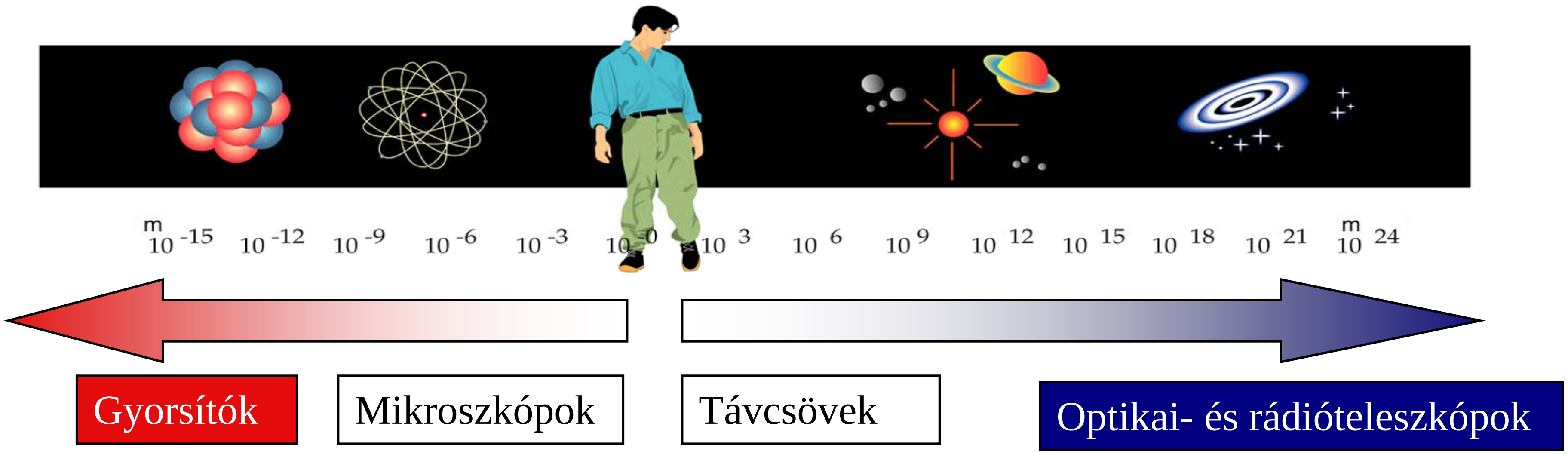
ARE WE BUILDING

BIGGER AND BIGGER

ACCELERATORS

????

A részcskefizika az anyag legparányibb építőköveit vizsgálja módszeres alapossággal



SCIENCE between WAR and PEACE

Már a görögök......... **Archimedes** died in battle of Syracus

- **Galilei**...”On 8 August 16O9, he *invited the Venetian Senate* to examine his spy-glass from the *tower of St. Marco*, with spectacular success: three days later, he made a present of it to the Senate, accompanied by a letter in which he explained that the instrument, which magnified objects **nine** times would prove of utmost importance in war. It made it possible to see *‘sails and shipping that were so far of that it was two hours before they were seen with the naked eye, steering full-sail into the harbour’* thus being invaluable against invasion by sea. ... The grateful Senate of Venice promptly doubled Galilelo’s salary ... and made his professorship at Padua a lifelong one.

- It was not the first and not the last time that pure research, that starved cur, snapped up a bone from the warlord’s banquet.” A. Koestler: The SLEEPWALKERS p.369.

- **L. Szilárd, A. Einstein, Oppenheimer, E. Teller**....

SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

Press Release PR/56
12 February, 1960

It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays from distant stars, so the very character of the laws governing the properties of the many new elementary particles which have been discovered in recent years, and especially their transmutations in violent collisions, can only be studied by using atomic particles accelerated to immense energies. Actually we are here confronted with most challenging problems at the border of physical knowledge, the exploration of which promises to give us a deeper understanding of the laws responsible for the very existence and stability of matter.

All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws.

Small detail... Bohr was not completely right, the "new" elementary particles are not elementary but mesons, namely formed by quarks http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/debrog2.html

A convenient form for the DeBroglie wavelength expression is

$$\lambda = \frac{hc}{pc} \qquad pc \approx \sqrt{2 \cdot KE \cdot m_0 c^2}$$

where hc = 1239.84 eV nm and pc is expressed in electron volts.

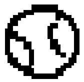
This is particularly appropriate for comparison with photon wavelengths since for the photon, pc=E and a 1 eV photon is seen immediately to have a wavelength of 1240 nm. For massive particles with kinetic energy KE which is much less than their rest mass energies:

For an electron with KE = 1 eV and rest mass energy 0.511 MeV, the associated DeBroglie wavelength is 1.23 nm, about a thousand times smaller than a 1 eV photon. (This is why the limiting resolution of an electron microscope is much higher than that of an optical microscope.)

DeBroglie Wavelength

$$\lambda = \frac{h}{p}$$

Does this relationship apply to all particles? Consider a pitched baseball:



$\longrightarrow$ v = 40 m/s = 90 mi/hr

m=0.15 kg

$$\lambda = \frac{h}{mv} = \frac{6.626 \times 10^{-34}\ \mathrm{J\,s}}{(0.15\ \mathrm{kg})(40\ \mathrm{m/s})} = 1.1 \times 10^{-34}\ \mathrm{m}$$

10^{-10}m Atomic diameter

10^{-14}m Nuclear Diameter

For an electron accelerated through 100 Volts: v= 5.9×10^{6} m/s

$$\lambda = \frac{6.626 \times 10^{-34}\ \mathrm{Js}}{(9.11 \times 10^{-31}\ \mathrm{kg})(5.9 \times 10^{6}\ \mathrm{m/s})} = 1.2 \times 10^{-10} = 0.12\ \mathrm{nm}$$

This is on the order of atomic dimensions and is much shorter than the shortest visible light wavelength of about 390 nm.

The **Compton wavelength** λ of a particle is given by

$$\lambda = \frac{h}{mc} = 2\pi\frac{\hbar}{mc}$$

where h is the Planck constant, m is the particle's mass, c is the speed of light.

The CODATA 2002 value for the Compton wavelength of the electron is $2.4263102175\times10^{-12}$ meter with a standard uncertainty of $0.0000000033\times10^{-12}$ m.[1] Other particles have different Compton wavelengths.

The Compton wavelength can be thought of as a fundamental limitation on measuring the position of a particle, taking quantum mechanics and special relativity into account.

This depends on the mass m of the particle. To see this, note that we can measure the position of a particle by bouncing light off it - but measuring the position accurately requires light of short wavelength. Light with a short wavelength consists of photons of high energy. If the energy of these photons exceeds mc^2, when one hits the particle whose position is being measured the collision may have enough energy to create a new particle of the same type. This renders moot the question of the original particle's location.

This argument also shows that the Compton wavelength is the cutoff below which quantum field theory– which can describe particle creation and annihilation – becomes important.

We can make the above argument a bit more precise as follows. Suppose we wish to measure the position of a particle to within an accuracy Δx

.

Then the uncertainty relation for position and momentum We can make the above says that

$$\Delta x \, \Delta p \geq \hbar/2$$

so the uncertainty in the particle's momentum satisfies

$$\Delta p \geq \frac{\hbar}{2\Delta x}$$

Using the relativistic relation between momentum and energy, when Δp exceeds *mc* then the uncertainty in energy is greater than mc^2 , which is enough energy to create another particle of the same type. So, with a little algebra, we see there is a fundamental limitation

$$\Delta x \geq \frac{\hbar}{2mc}$$

So, at least to within an order of magnitude, the uncertainty in position must be greater than the Compton wavelength h/mc

The Compton wavelength can be contrasted with the de Broglie wavelength, which depends on the momentum of a particle and determines the cutoff between particle and wave behavior in quantum mechanics.

For fermions, the Compton wavelength sets the cross-section of interactions. For example, the cross-section for Thomson scattering of a photon from an electron is equal to

$$(8\pi/3)\alpha^2\lambda_e^2$$

,

where α is the fine-structure constant and λ_e is the Compton wavelength of the electron.

For gauge bosons, the Compton wavelength sets the effective range of the Yukawa interaction: since the photon is massless, electromagnetism has infinite range.

CREATE NEW PARTICLE requires ENERGY

elektron positron pair E> 1 MeV

antiproton E > 4 * proton mass

Z weak-boson E > 90 proton mass

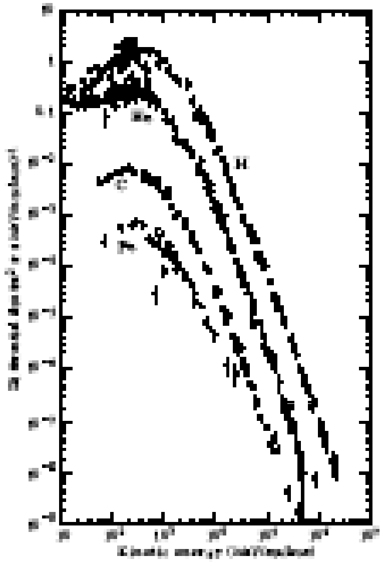
WW weak-boson pair E > 160 proton mass

Higgs-boson (if about 120 GeV/c^2) E > 220 proton mass

Why particle accelerators ?

- Why accelerators: need to produce under controlled conditions HIGH INTENSITY, at a CHOSEN ENERGY particle beams of GIVEN PARTICLE SPECIES to do an EXPERIMENT
- An experiment consist of colliding particles either onto a fixed target or with another particle beam.
- The cosmo is already doing this with different mechanisms: while I am speaking about 66 10^9 particles/cm2/s are traversing you body, with this spectrum before being filtered by the atmosphere.

The universe is able to accelerate particles up to 10^6 MeV protons (See cosmology lectures)



How an accelerator/collider works

- An accelerator is composed by a sequence of elements which form the machine LATTICE. The elements generate either a magnetic or electric field that can be varying in time.

- Everything is governed by the LORENTZ force:

$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

Basic concept 1 – why we need magnets

- Lorentz force

The force F acting on charge q in fields E and B

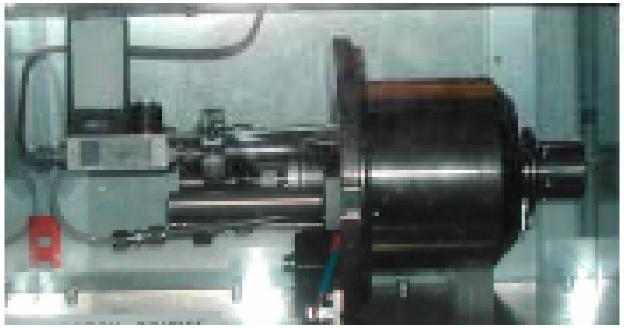
$$F = q(E + v \times B)$$

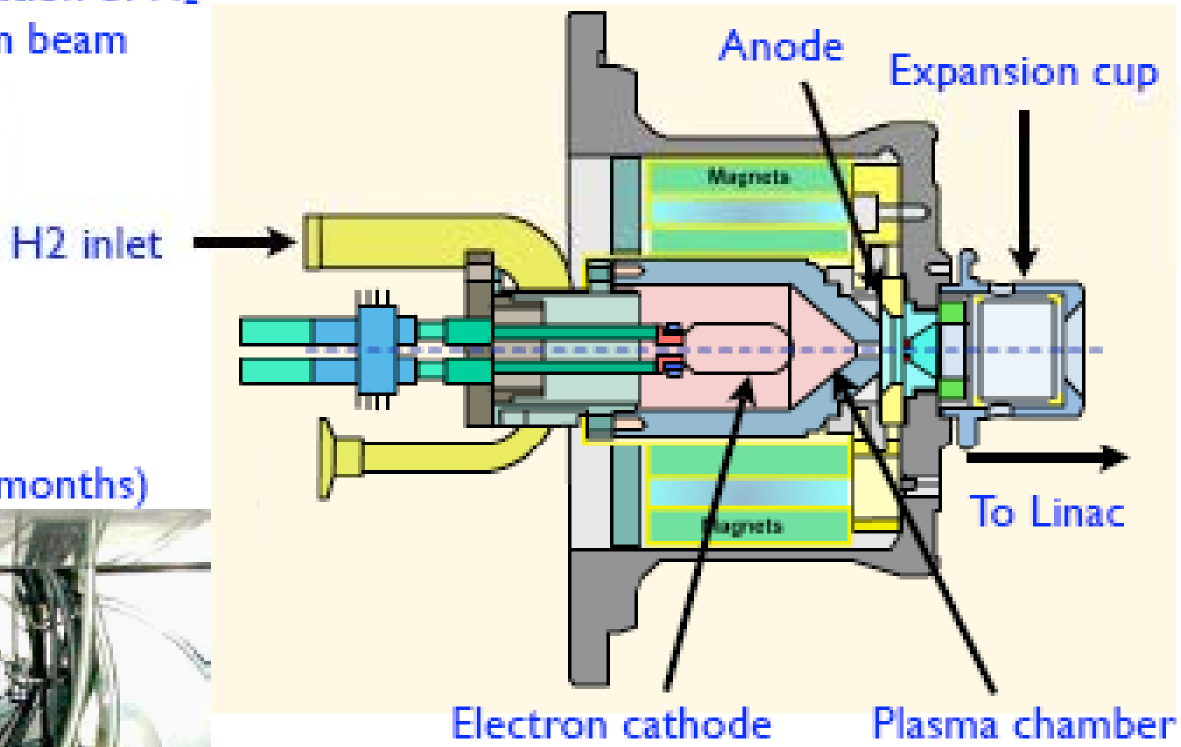
Units			
Units	Force	F	newton
	Electric field	E	V/m
	Magnetic field	B	tesla
	Velocity	v	m/s

Accelerators – control of beams of particles
Detectors – identification of particles by measuring tracks

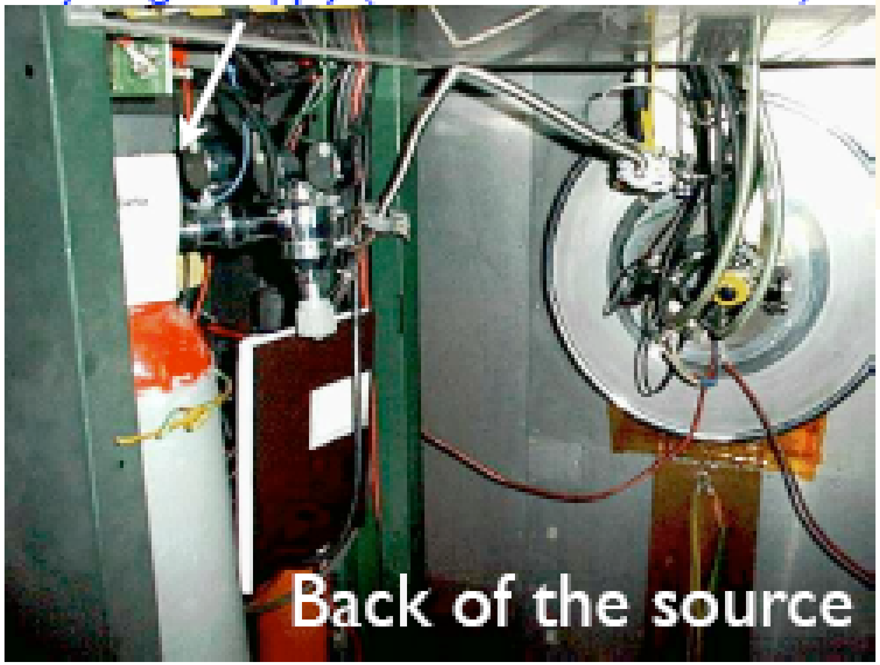
How to get protons: duoplasmatron source

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





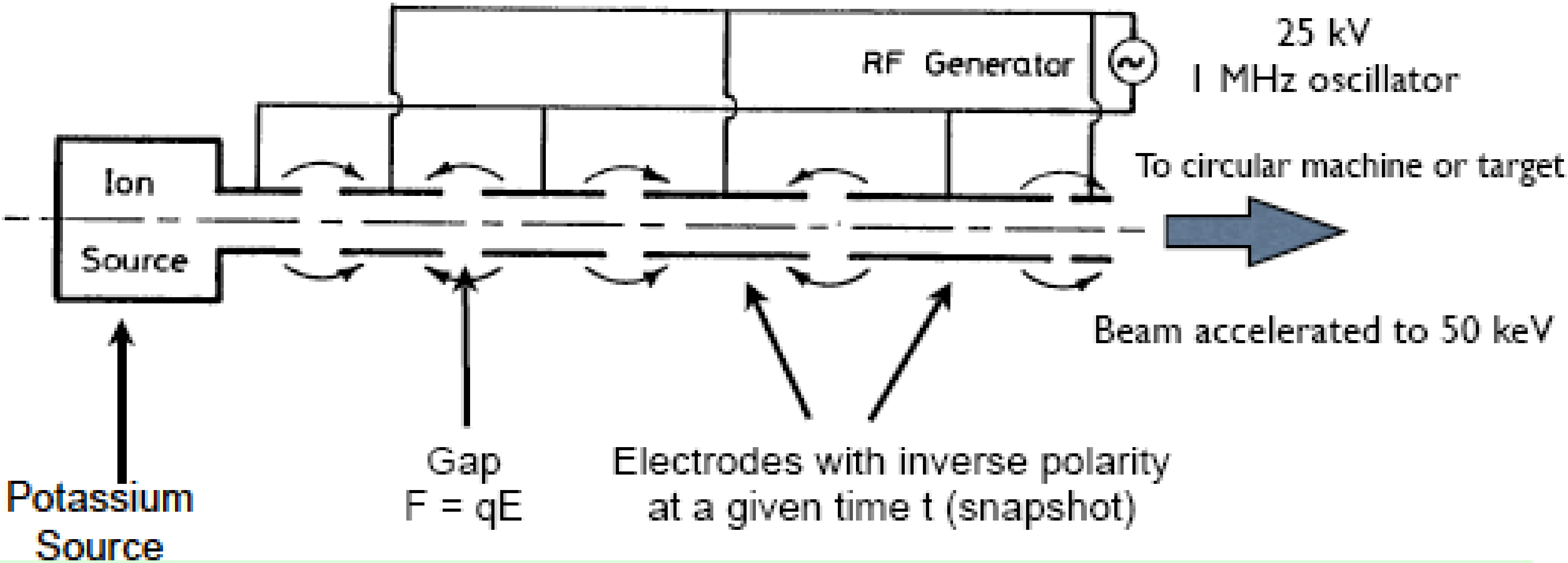
Hydrogen supply (one lasts for 6 months)



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

The SPACE SHUTTLE goes only up to 8 km/s

Wideroe linac: the first linear accelerating structure



First linac composed by drift tubes interleaved by acceleration gaps powered by an RF generator. (1928)

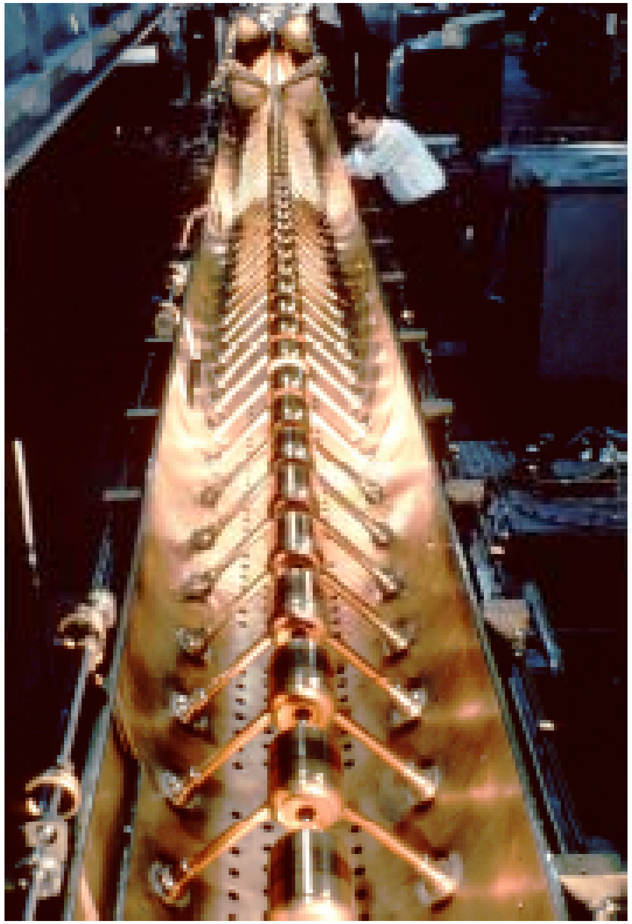
Obs: the drift tube length has to increase because particles are not yet relativistic.
To an energy increase corresponds a speed increase, and the particle has to travel more in the shielded region to be in phase with the accelerating field.

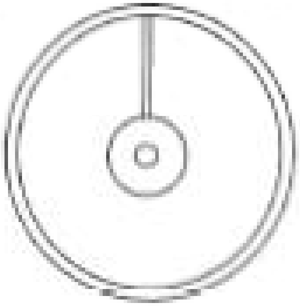
Main limitation: after a certain energy, the length of the drift tube is too long.
The RF frequency has increase to some 10 MHz, need to enclose the structure in a resonator to avoid field losses.

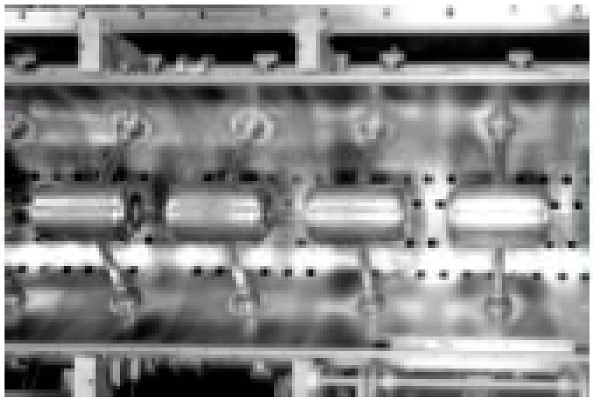
Alvarez drift tube linac

Linac composed by drift tubes interleaved by acceleration gaps as Wideroe linac, but field generated in a resonant cavity. The frequency of the field can go up to 200 MHz.

Currently we have two Linacs at CERN with Alvaretz structure, for protons and ions.



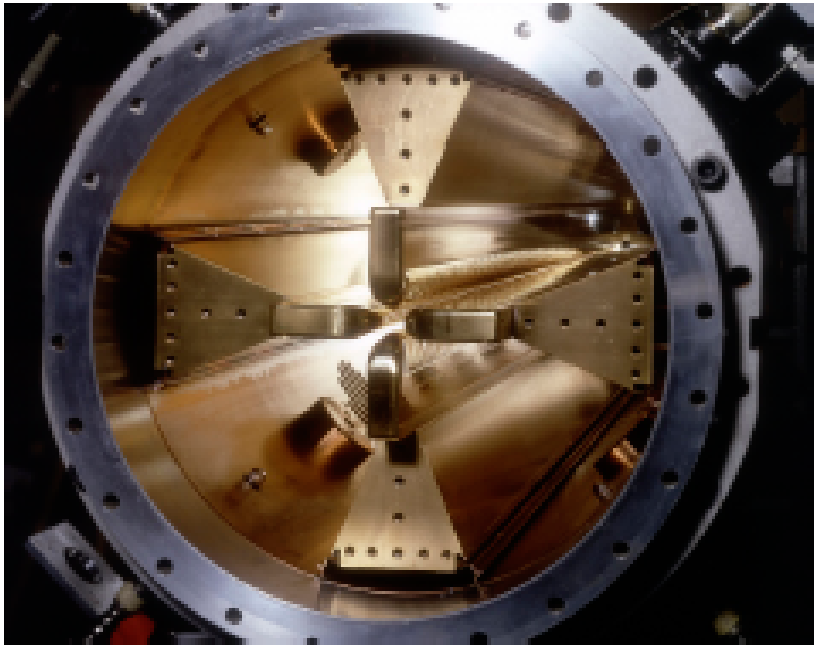




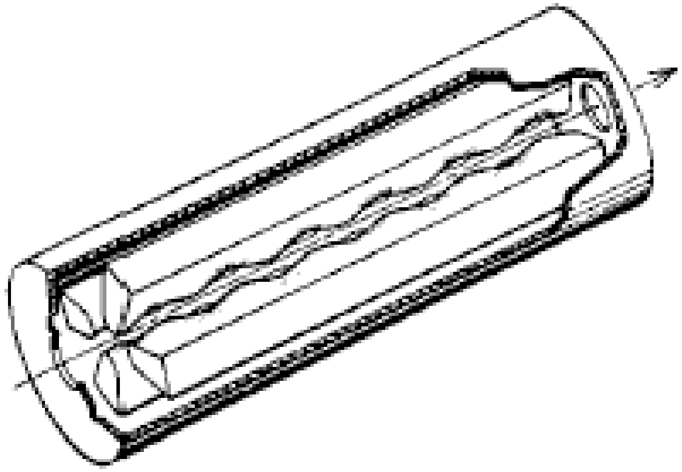
Inner structure of Linac 1 (Alvarez type). The drift tubes are supported on stems, through which the current for the quadrupole magnets (located inside the tubes) and the cooling water are supplied. Linac 1 accelerated protons to 50 MeV.

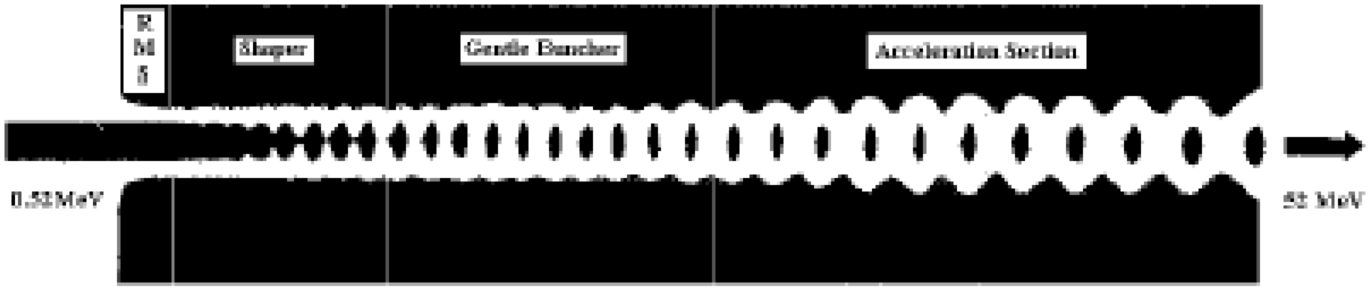
See lecture of Delahaye, J-P (CERN) the 10th August for linear collider

RFQ Bunching and first acceleration

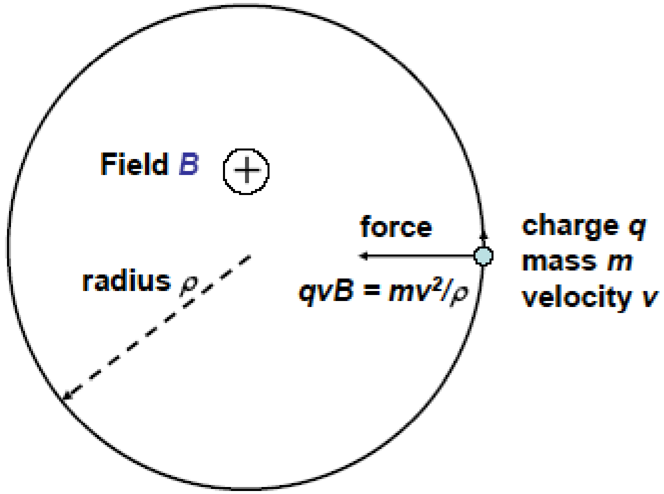


Radio frequency quadrupole:
Electric field varying with time in a resonant cavity focuses and bunches particles at low energy





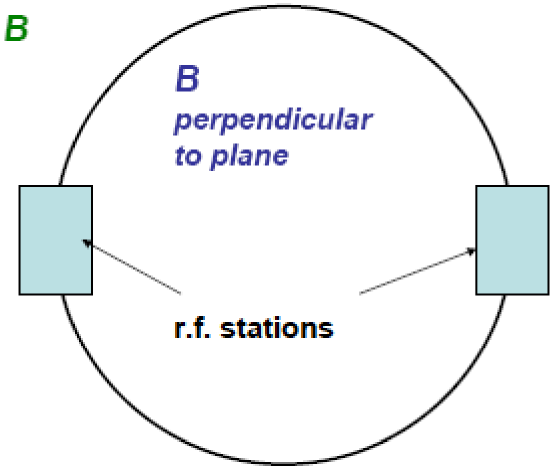
Circular motion of a charged particle in a constant magnetic field

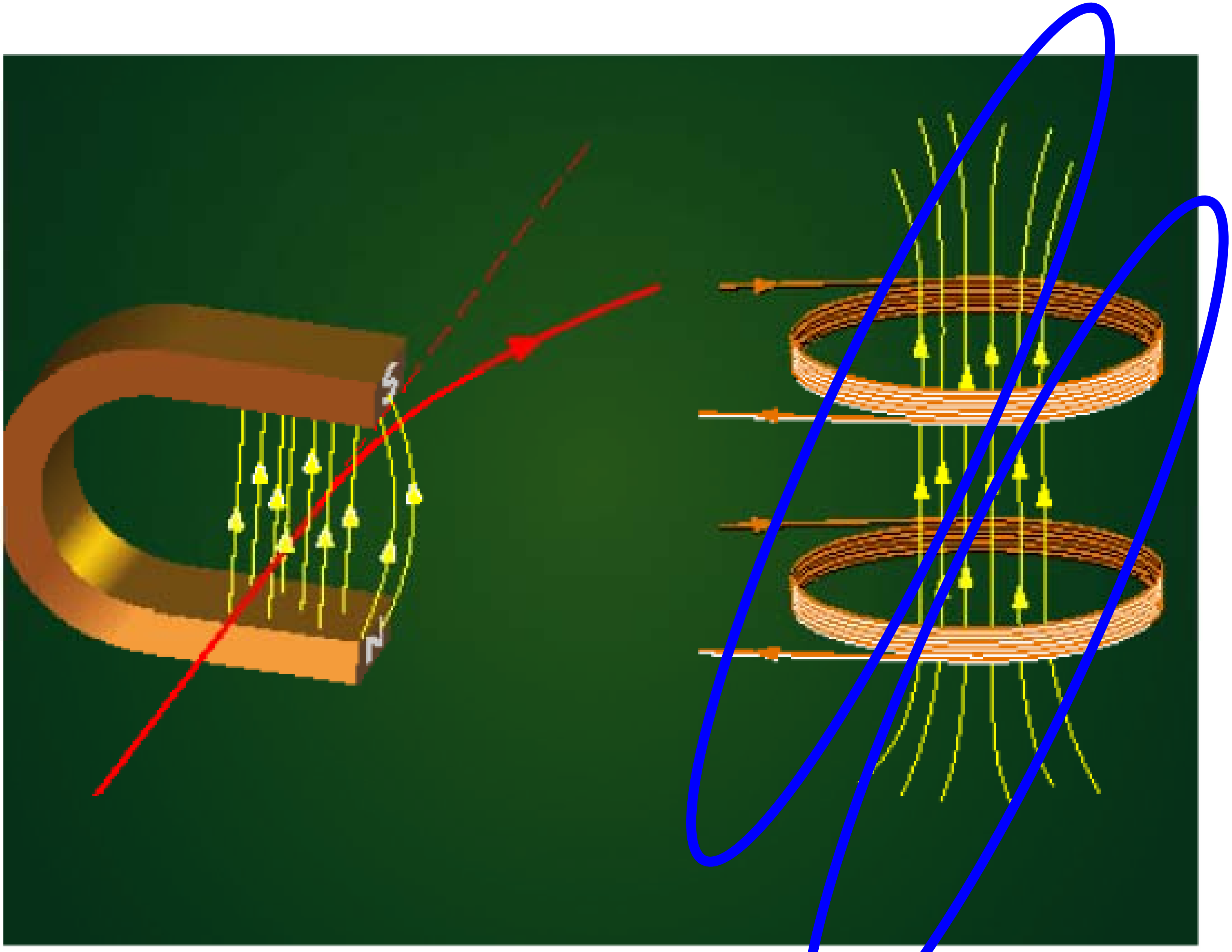


Synchrotron acceleration

Accelerating field generated by r.f. sources

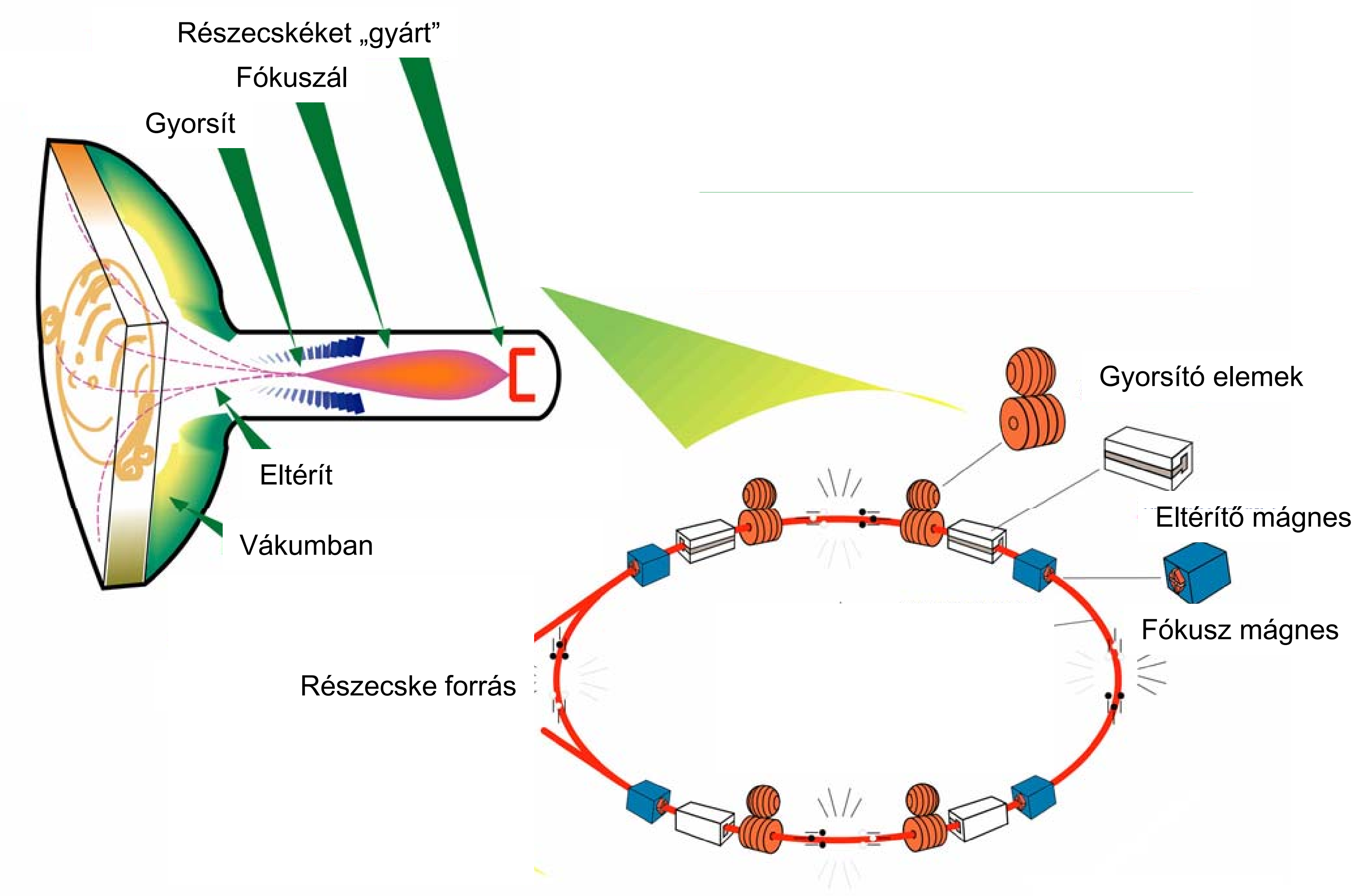
beam contained in narrow channel, by ramping B





High energy dipol magnet= elongated solen

A televízió készülék!



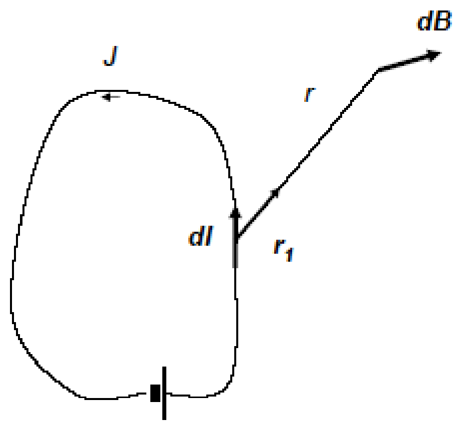
Basic concept 2 – how to get the field

- **Magnetic induction**

  The magnetic induction *dB* produced by current element *Jdl* is

  $$\mathbf{dB = (\mu_0/4\pi) J dl \times r_1/r^2}$$

  where $\mu_0 = 4\pi \times 10^{-7}$



Basic concept 3 – the downside

- Lorentz force (again!)

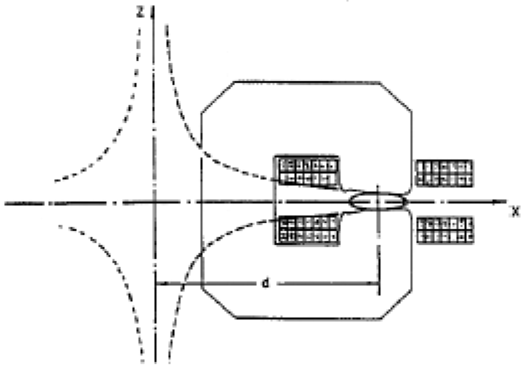
The force d*F* acting on an element of conductor dl carrying current *J* in a magnetic field *B*

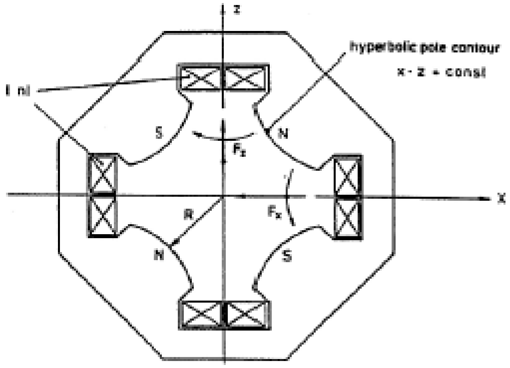
$$dF = Jdl \times B$$

Units	Force	***F***	newton
	Current	***J***	ampere
	Magnetic field	***B***	tesla

In order to produce the field, the current has to be large – the resulting force is important → major problem

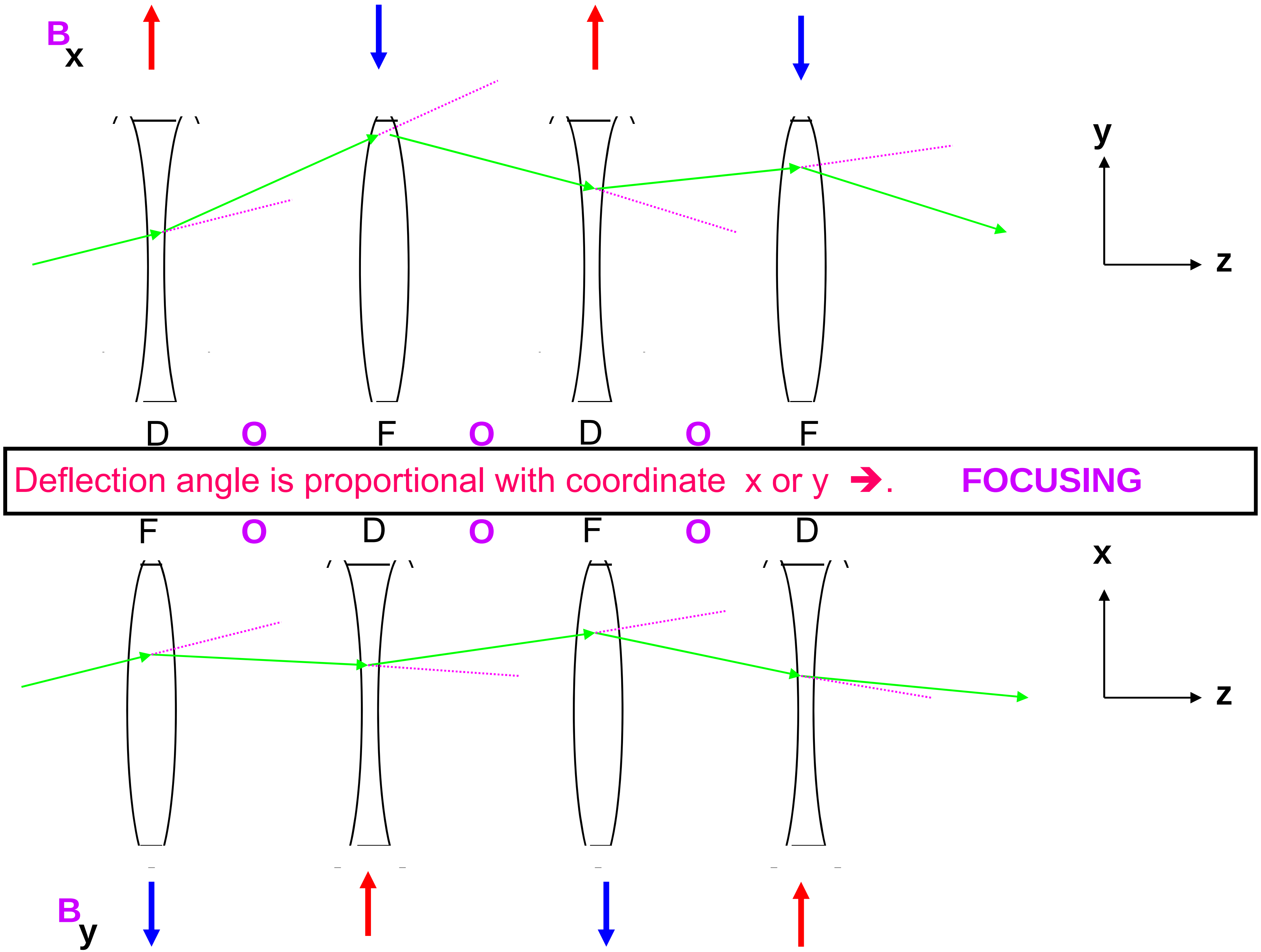
Quadrupole magnet





Dipole + quadrupole =

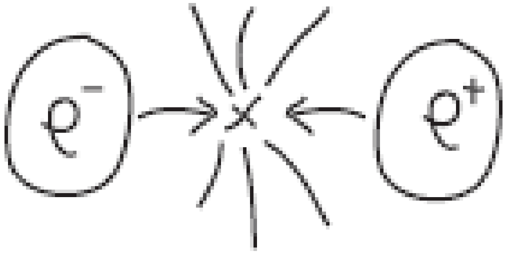
Combined function magnet



Bx
y
z
D O F O D O F
Deflection angle is proportional with coordinate x or y ➔. FOCUSING
F O D O F O D
x
z
By

The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

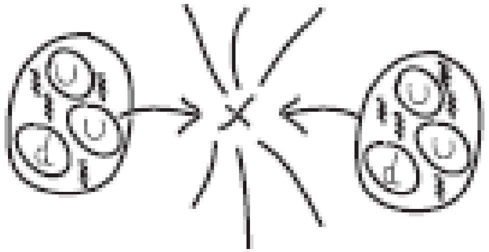
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region.

Precision measurement (LEP)

Cons: above a certain energy is no more convenient to use electron because of too high syncrotron radiation (last lecture)

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll < 2Eb

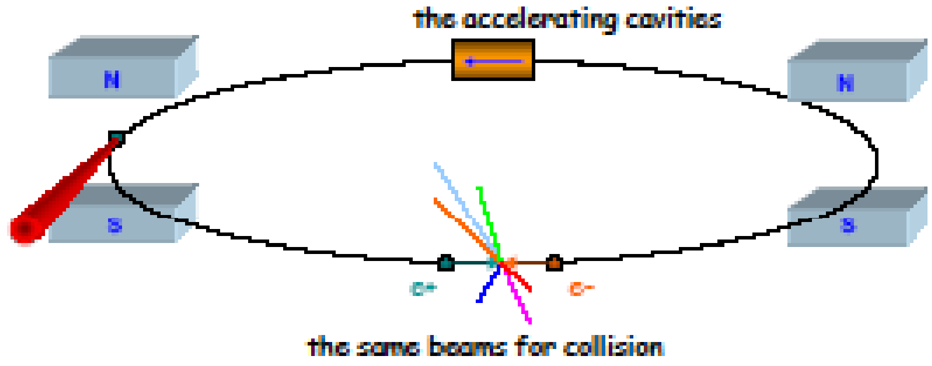
Pros: with a single energy possible to scan different processes at different energies.

Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

Why a linear collider ?

Circular colliders use magnets to bend particle trajectories
Their advantage is that they re-use many times



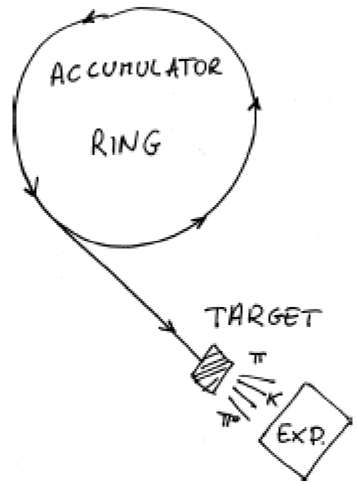
However, charged particles emit synchrotron radiation in a magnetic field

$$P = \frac{2}{3}\frac{r_e}{(m_o c^2)^3}\frac{E^4}{\rho^2} \quad \Rightarrow \quad \Delta E_{turn} = \frac{4}{3}\pi\frac{r_e}{(m_o c^2)^3}\frac{E^4}{\rho}$$

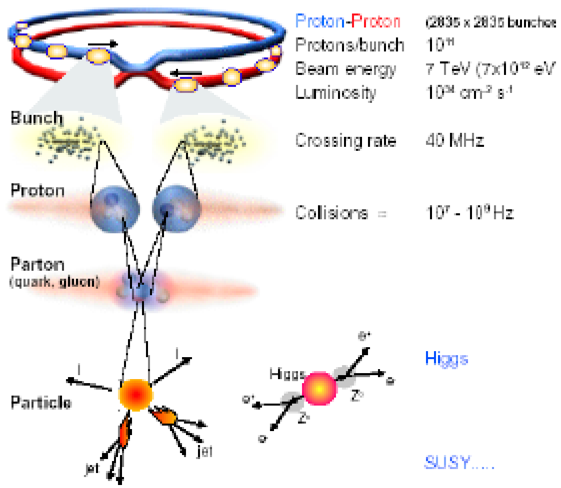
Much less important for heavy particles, like protons

Different approaches: fixed target vs collider

Fixed target



Storage ring/collider



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (3/3)

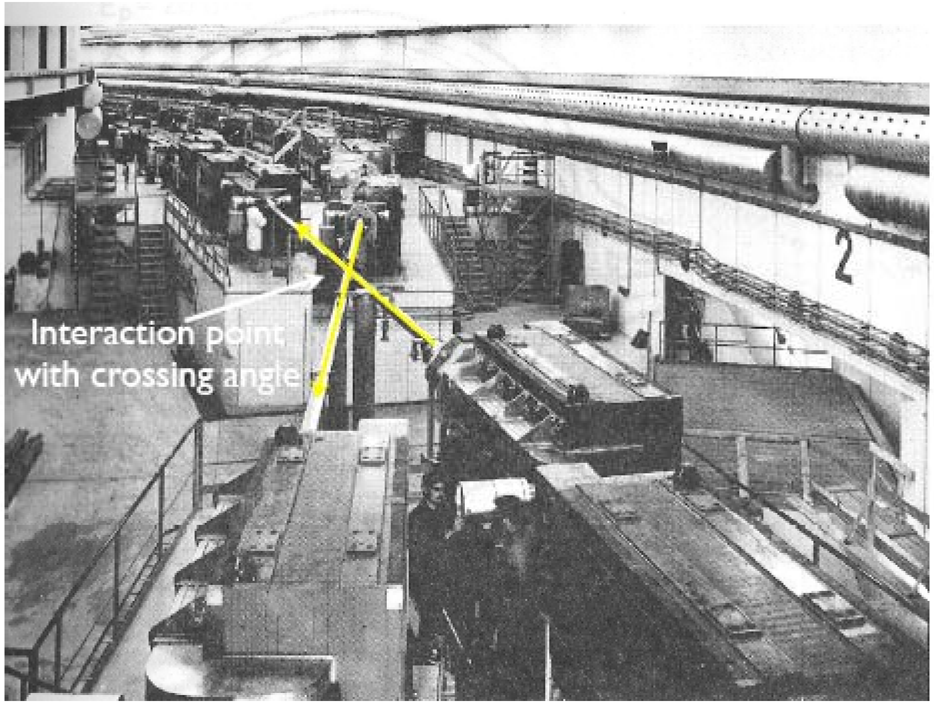
- INTEGRATED LUMINOSITY $L_{\text{int}} = \int_0^T L(t)\, dt$

$\Rightarrow$ The real figure of merit = $L_{\text{int}}\, \sigma_{event} = \text{number of events}$

- LHC integrated Luminosity expected per year: [80-120] fb^{-1}

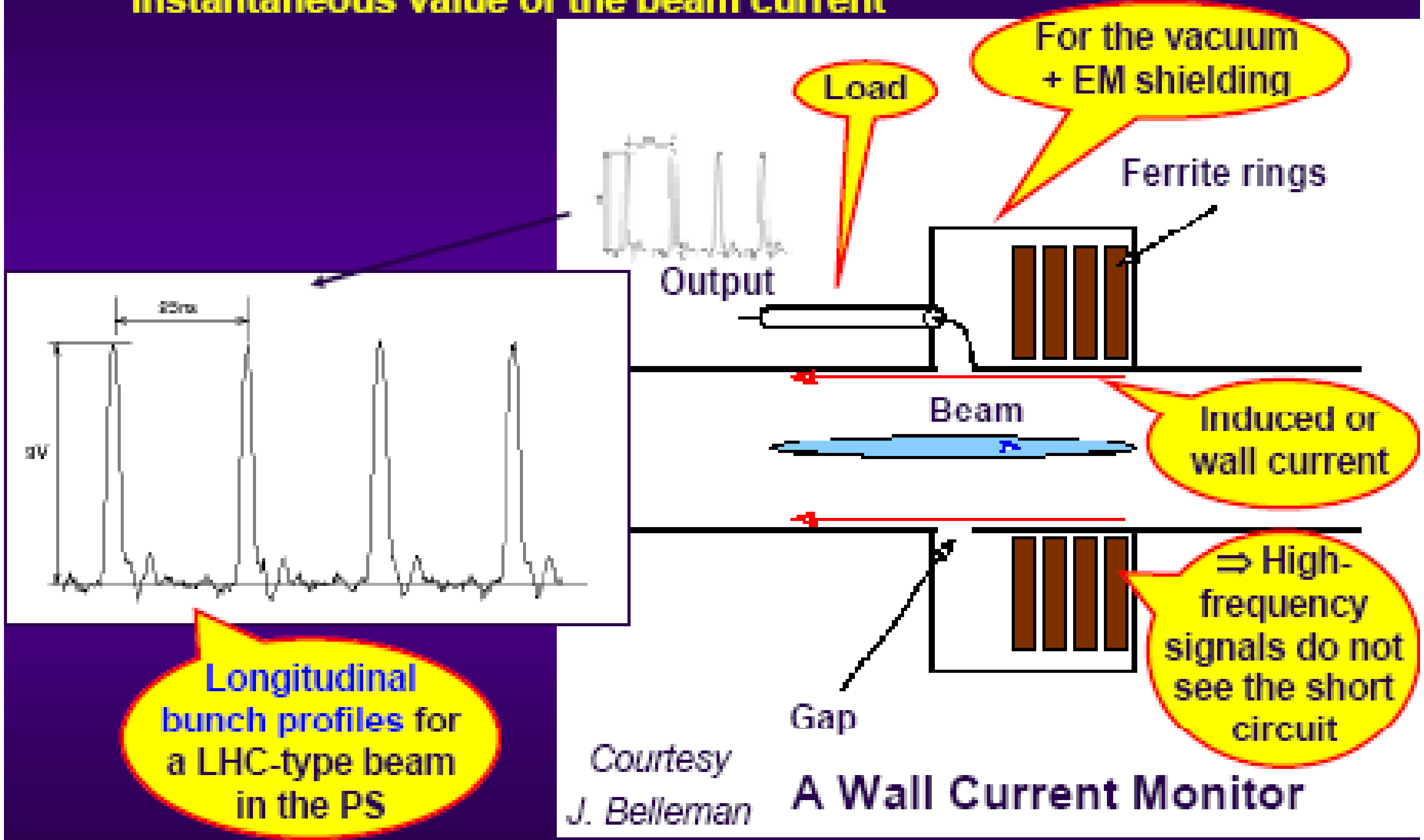
Reminder: 1 barn = 10^{-24} cm^2
and femto = 10^{-15}

ISR

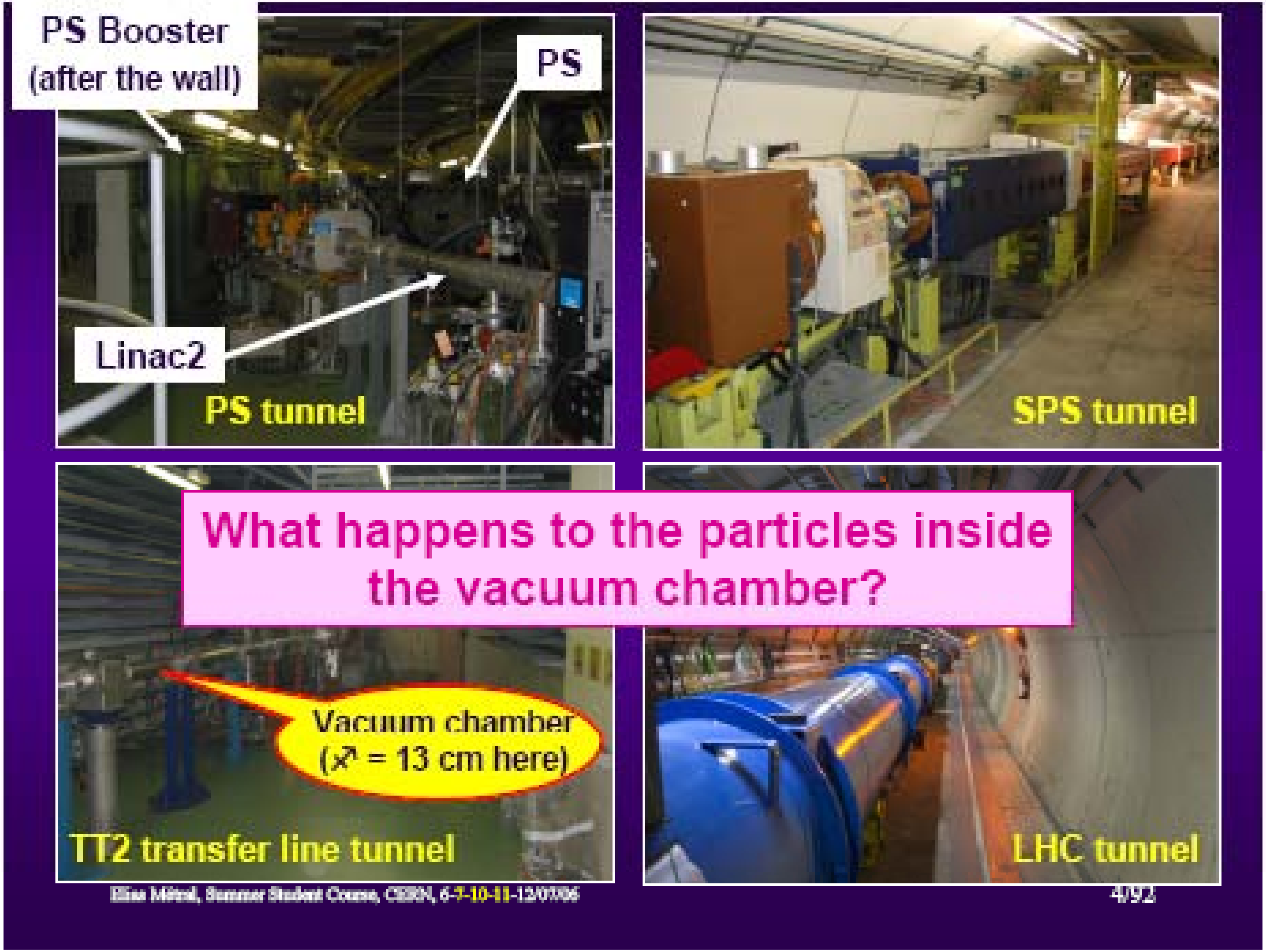


BEAM CONTROL (2/12)

- **WALL CURRENT MONITOR = Device used to measure the instantaneous value of the beam current**

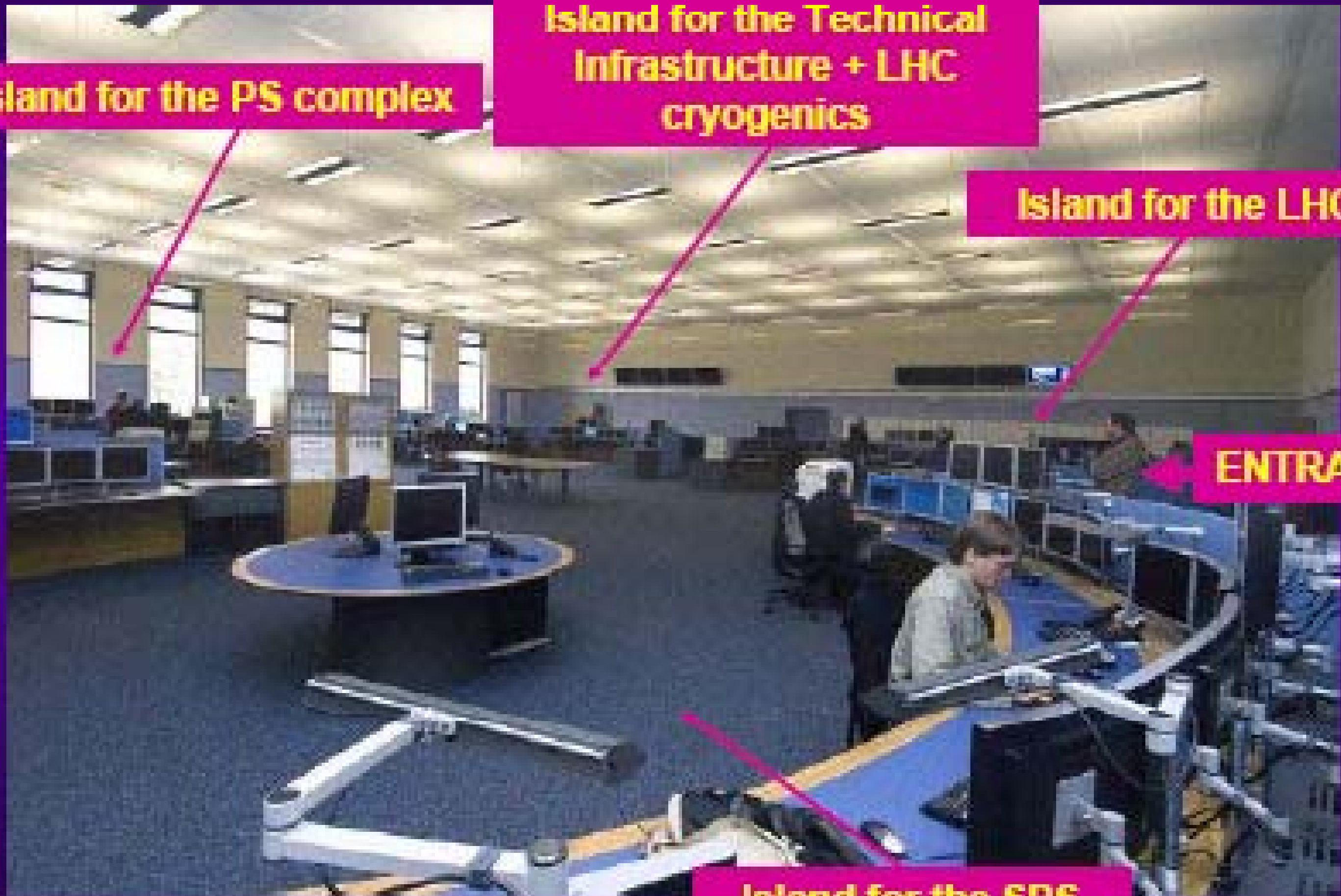


BEAM CONTROL (3/12)


PS Booster
(after the wall)
PS
Linac2
PS tunnel
SPS tunnel
What happens to the particles inside the vacuum chamber?
Vacuum chamber
(⌀ = 13 cm here)
TT2 transfer line tunnel
LHC tunnel
Elias Métral, Summer Student Course, CERN, 6-7-10-11-12/07/06
4/92

BEAM CONTROL (1/12)

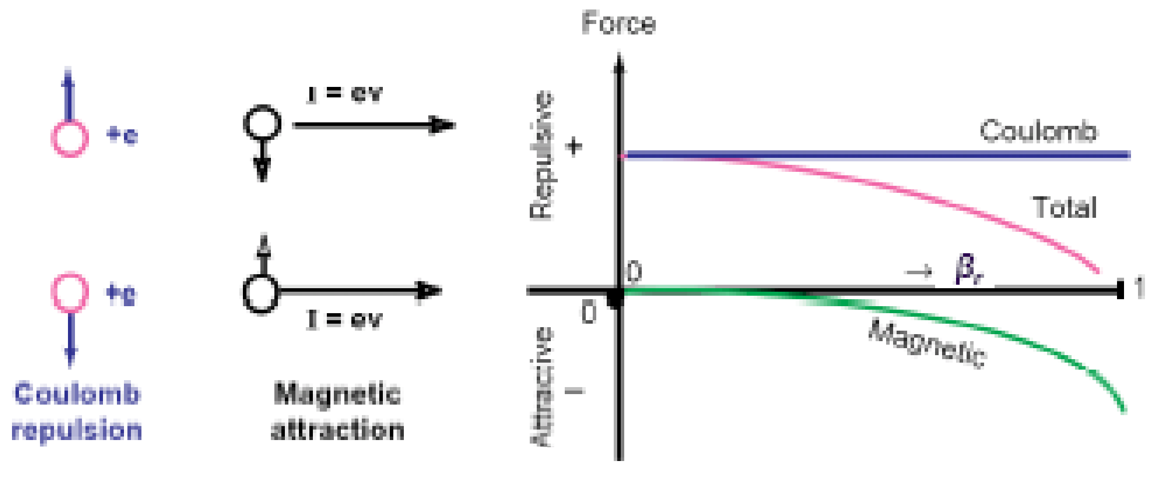
- New CERN Control Centre (CCC) at Prevessin since March 2006



LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (1/35)

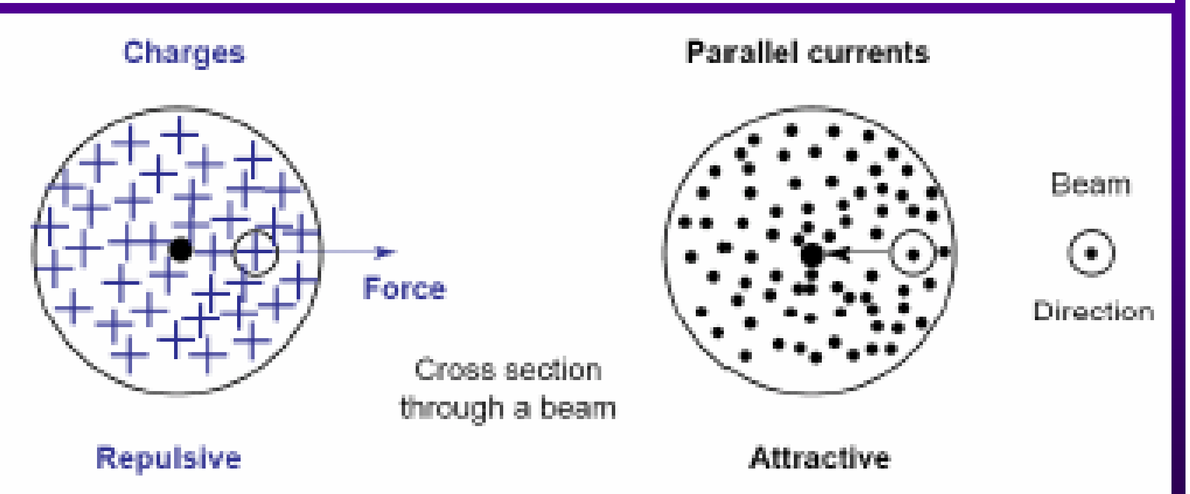
Space charge

2 particles at rest or travelling



Courtesy K. Schindl

Many charged particles travelling in an unbunched beam with circular cross-section



Superconductivity in high energy particle accelerator magnets

- 1981 CERN: ISR, SC low-beta insertion to increase luminosity
- 1985 Fermilab: Tevatron, 2 x 800 GeV *superconducting p-pbar collider*
- 1989 CERN starts LEP - the world's highest energy e^-e^+ collider
- 1991 HERA at DESY - the first major facility for colliding for protons (SC ring) with electrons or positrons
- 1999 RHIC at BNL - the major facility for colliding ions
- 2007 CERN will start the LHC - the world's highest energy proton-proton collider (superconducting, twin-bore magnets)

Superconductivity in high energy physics detector magnets

Not an exhaustive list!

- 1969 CERN – BEBC, Big European Bubble Chamber (solenoid)
- 1972 CERN – Omega magnet (large aperture dipole)
- 1977 CERN/ISR – Solenoid
- 1978 DESY – CELLO (solenoid)
- 1983 SLAC/PEP4 – TPC solenoid
- 1985 KEK/TRISTAN – TOPAZ, VENUS (solenoids)
- 1988 CERN/LEP – ALEPH, DELPHI (solenoids)
- 1990 DESY/HERA – ZEUS (solenoid)
- 1997 SLAC – BABAR (solenoid)
- 2004 KEK – BESS-Polar (ultra-thin solenoid)
- 2007 CERN/LHC – CMS (solenoid), ATLAS (Toroids, solenoid)

Magnet parameters for accelerators

- **Dipole – Magnetic rigidity $B\rho$**

$$F = qvB \Rightarrow B\rho = mv/q = p/q$$

So, for $q = e$ (electronic charge), $B\rho = 3.3356p$ [T.m]

(momentum p in GeV/c)

- **Quadrupole – Gradient k**

Field gradient $K \equiv dB_z/dx$ [T/m]

Focusing quadrupole QF focuses horizontally

Defocusing quadrupole QD focuses vertically

- **FODO Cell**

Alternate focusing and defocusing elements with a non-focusing drift space between them ⇒ Net focusing

But why bother with superconductivity ?

- No Ohm's law

  ⇒ no significant power consumption
  (but requires power for refrigeration…)

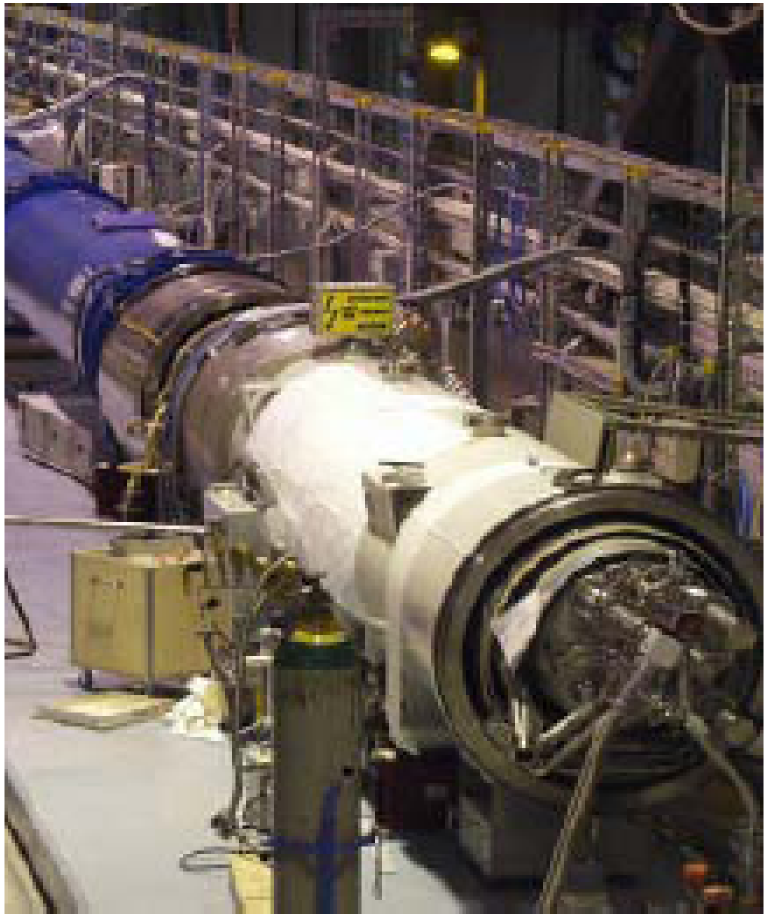
  ⇒ lower power bills

- ampere turns are cheap, need less iron
  ⇒ higher magnetic fields
  ⇒ higher energies and smaller rings
  ⇒ reduced capital cost

- high current density
  ⇒ compact windings
  ⇒ high gradients
  ⇒ higher luminosity

BUT

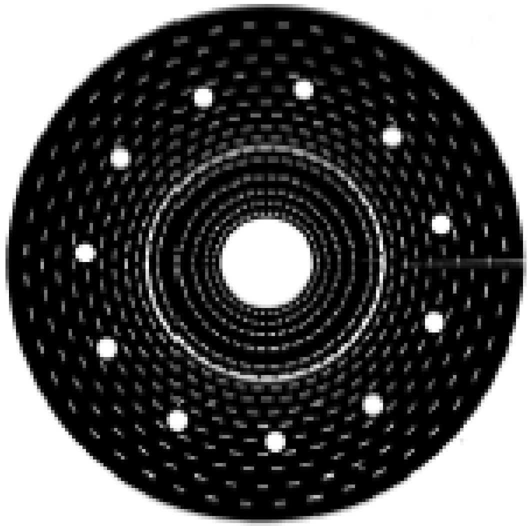
- SC magnets difficult to make and run (there's not much safety margin!)
- They need refrigeration, insulation, protection and cryogenic pipework



The <u>real</u> reason: it lets us do things we can't do without it !

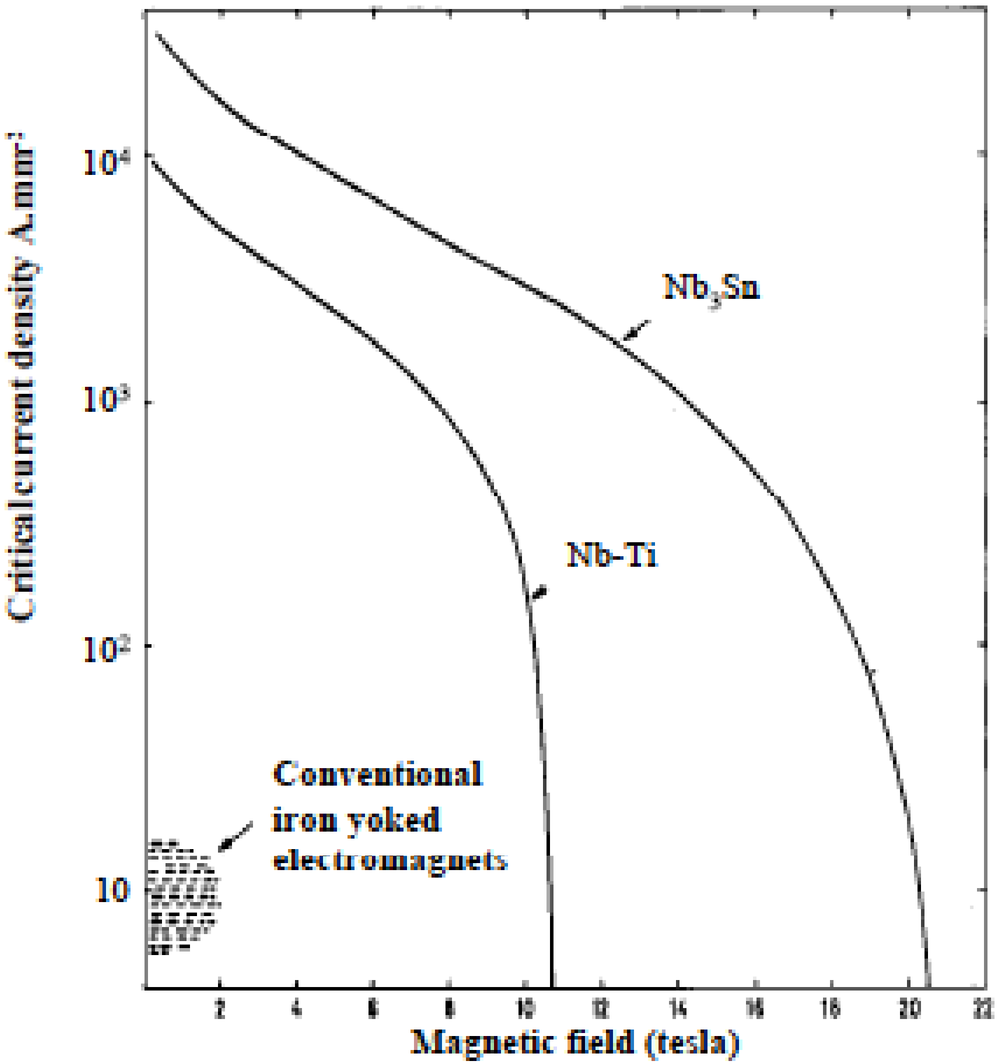
We need high fields, but…

- Iron dominated magnets limited by iron saturation at 2 T !
- Permanent magnets practically limited in the range 1-2 T
- Copper (or Al) dominated magnets 50-100 T but for ms !!!



Disk of Bitter magnet; pulsed cryogenic magnet for 40 T - 5 ms

Superconducting vs. normal magnets

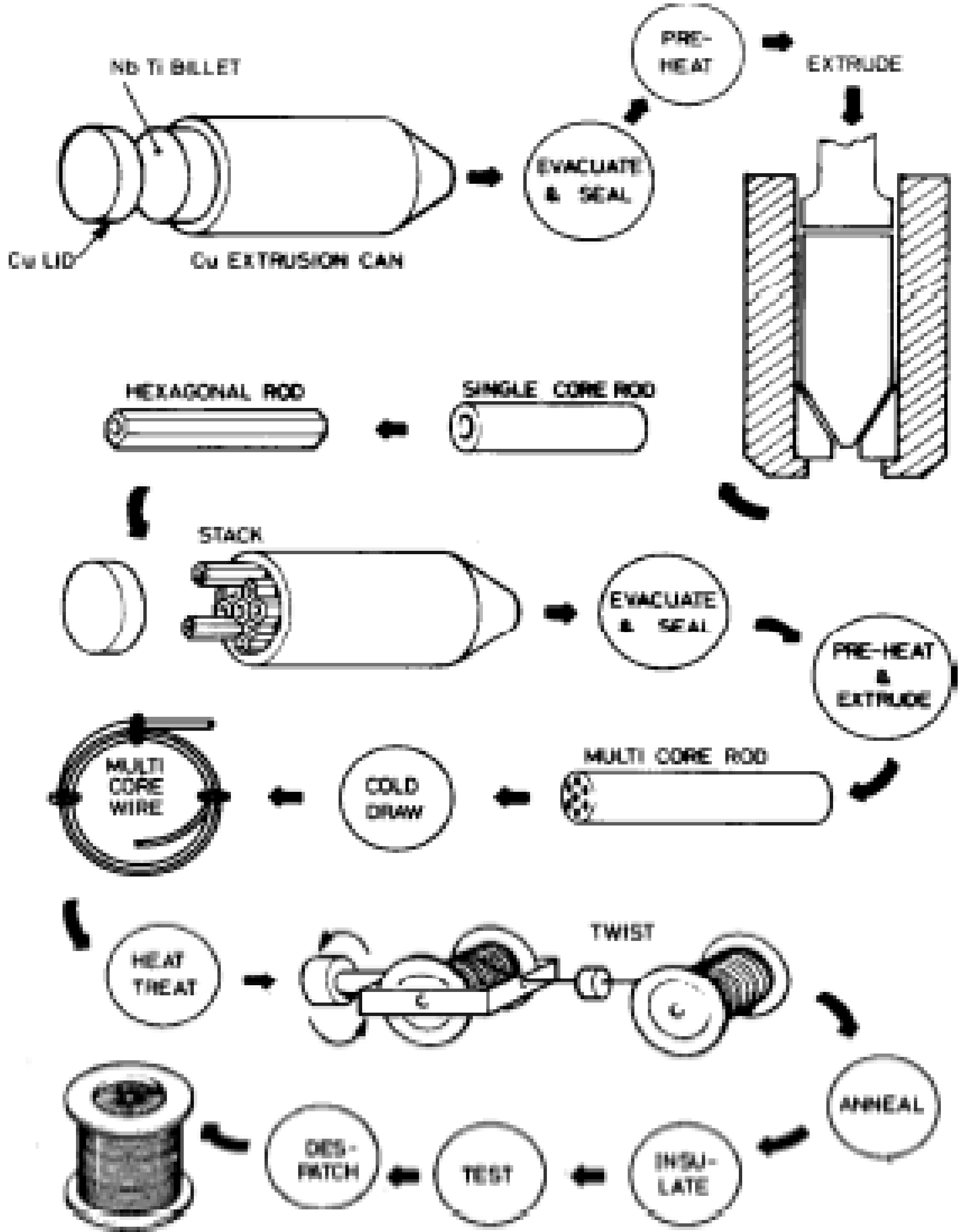


- Magnets usually work in boiling liquid helium, where the critical is represented by a curve of current versus field at 4.2K
- Niobium tin Nb_3Sn has a much higher performance in terms of critical current field and temperature than Nb-Ti

  but it is brittle intermetallic compound with poor mechanical properties

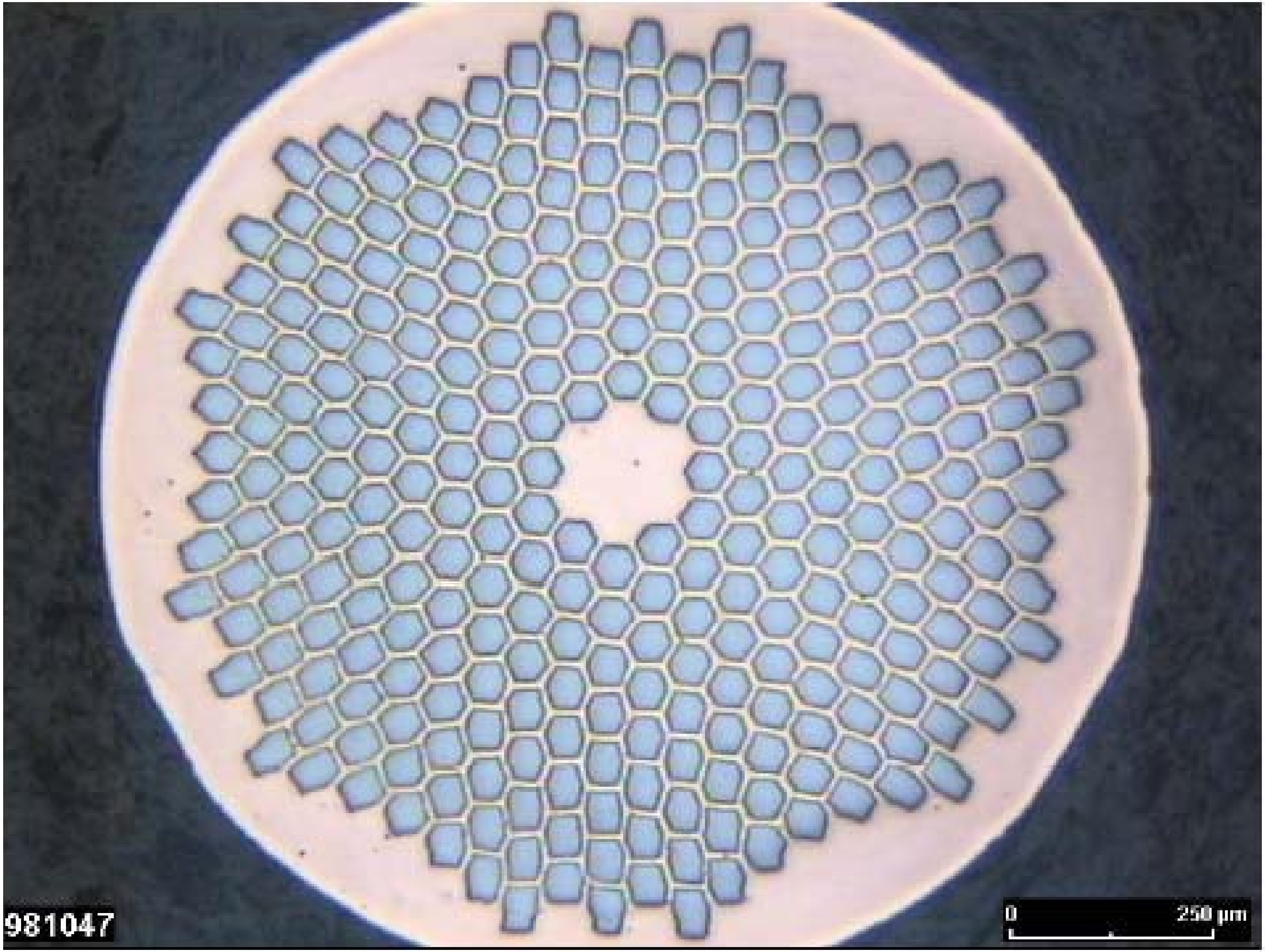
However

- The field and current density of both superconductors are much better than those of conventional electromagnets



Manufacture of Nb-Ti

- vacuum melting of NbTi billets
- hot extrusion of the copper NbTi composite
- sequence of cold drawing and intermediate heat treatments to precipitate flux pinning centres
- for very fine filaments, we must avoid the formation of brittle CuTi intermetallic compounds during heat treatment
  (this is done by enclosing the Nb-Ti in a thin Nb shell)
- twisting (to avoid coupling)


981047
0
250 µm

The need for cables

- A single 5μm filament of NbTi in 6T carries 50mA
- A composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A

- For good tracking we connect synchrotron magnets in series
- For stored energy *E*, rise time *t* and operating current *I*, charging voltage *V*

$$E = \frac{1}{2} L I^2 \qquad\qquad V = \frac{L I}{t} = \frac{2E}{I t}$$

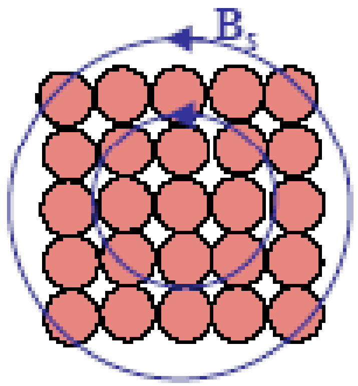
for 5 to 10kA, we need 20 to 40 wires in parallel --- a cable

RHIC at BNL E = 40kJ/m, t = 75s, 30 strand cable
cable I = 5kA, charge voltage per km = 213V
wire I = 167A, charge voltage per km = 6400V

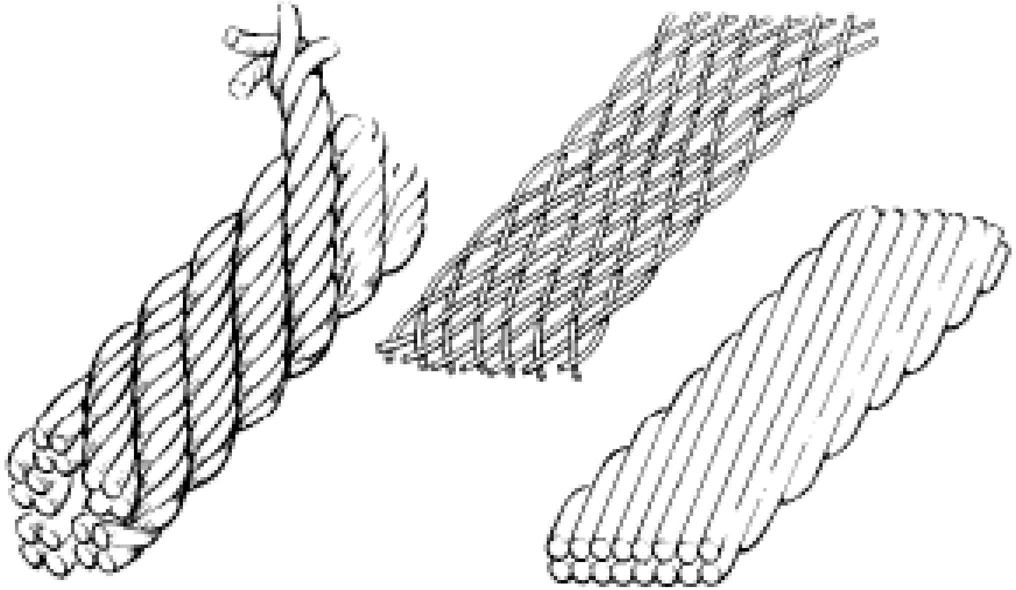
FAIR at GSI E = 74kJ/m, t = 4s, 30 strand cable
cable I = 6.8kA, charge voltage per km = 5.4kV
wire I = 227A, charge voltage per km = 163kV

Types of cable

- Cables carry a large current and this generates a self field
- Wires are twisted to avoid flux linkage between the filaments, for the same reasons we should avoid flux linkage between wires in a cable
- BUT twisting this cable doesn't help if the inner wires are always inside and the outer outside

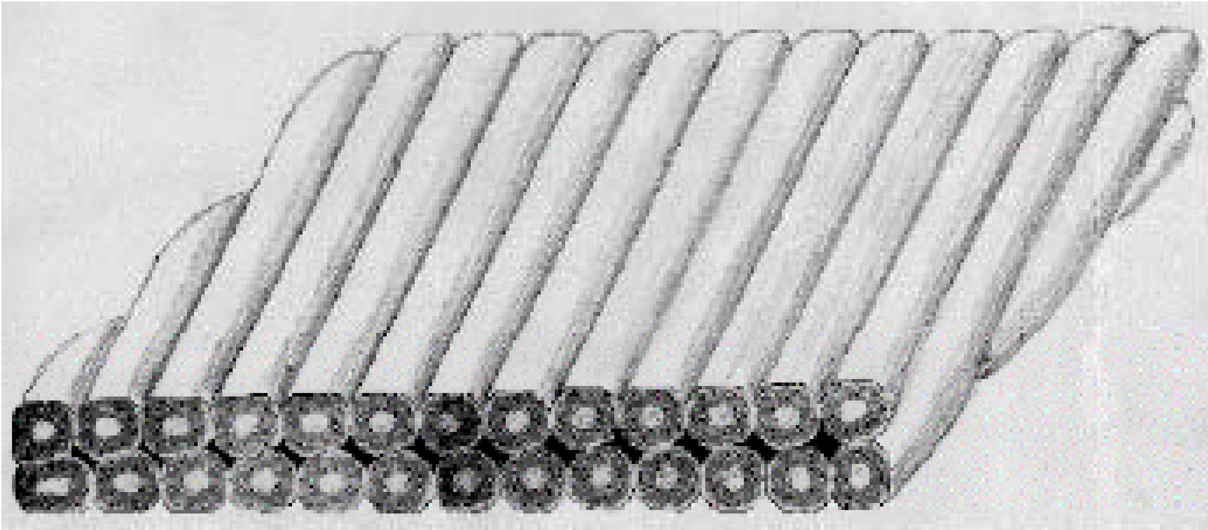


- Wires must be fully transposed, i.e. every wire must change places with every other wire along the length of the cable so that, on the average, no flux is enclosed
- three types of fully transposed cable have been tried in accelerators
  - rope
  - braid
  - Rutherford



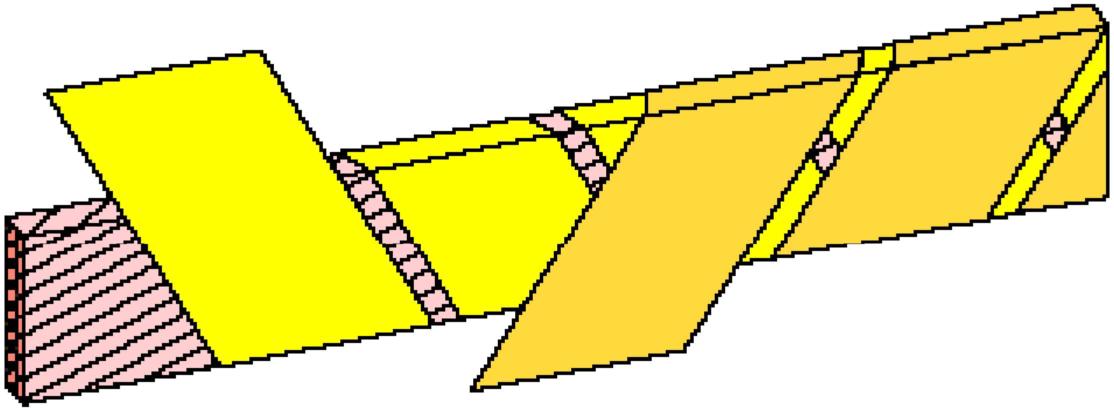
Rutherford cable

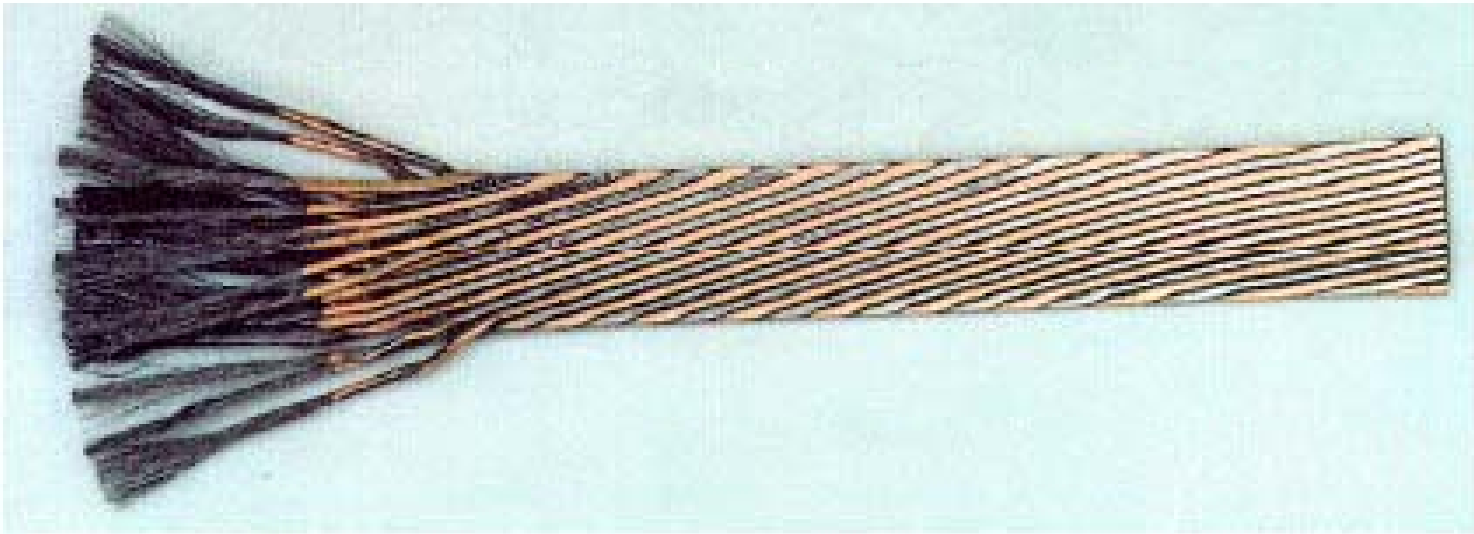
- So-called because it was first proposed by the team at the Rutherford Lab.



- The cable is usually insulated by wrapping 2 or 3 layers of Kapton, with gaps to allow penetration of liquid helium. The outer layer is adhesive layer for bonding adjacent turns.

  - NB: the adhesive faces outwards, not bonding to the cable (to avoid energy release by bond failure, which could quench the magnet)





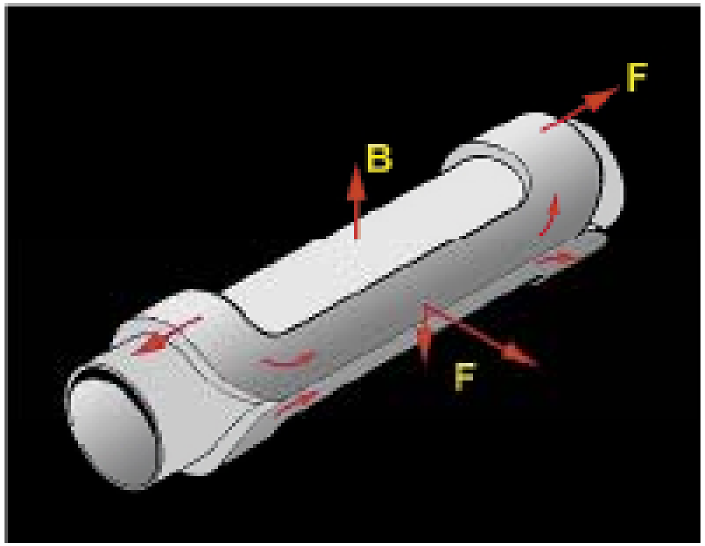
LHC dipole cable

ATLAS conductor:
Rutherford cable
embedded in pure
aluminium stabilizer

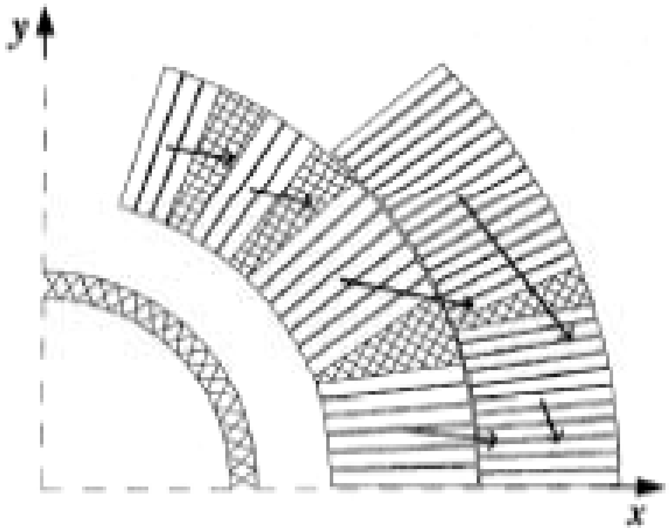
Accelerator magnet design - III

$J_{overall} \approx 500\ A/mm^2$ e.m. forces are not held by conductors – they tend to tear apart the winding

Concept

➤ 

Reality

➤ 

Electro-magnetic forces are

NOT SELF-SUPPORTING

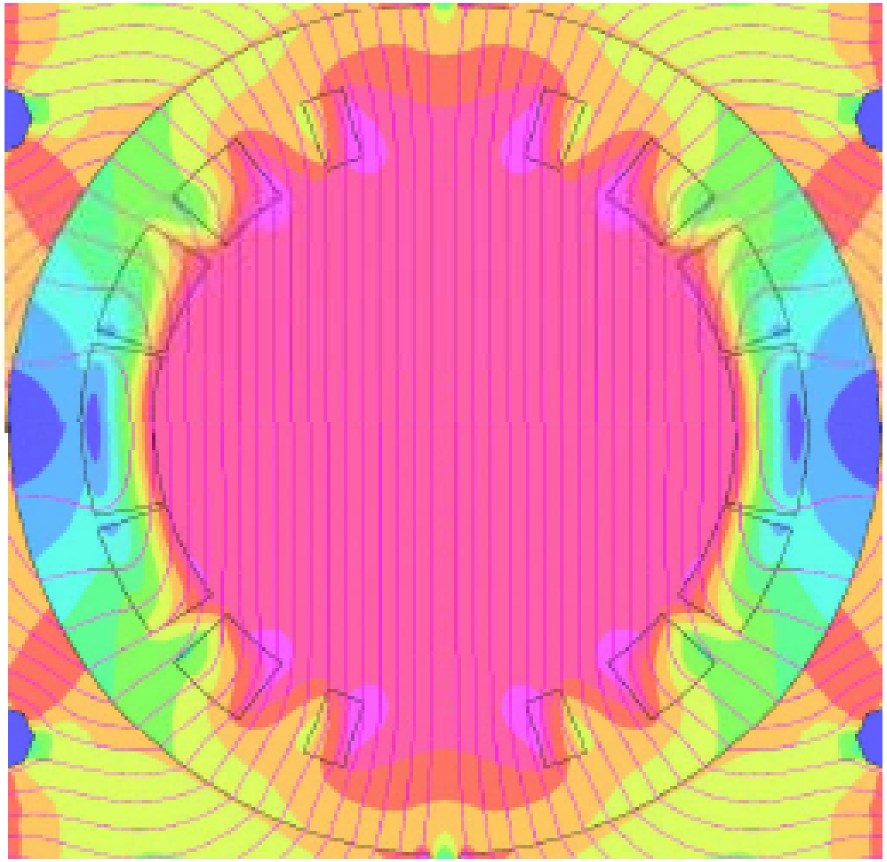
Accelerator magnet design

So real magnets use blocks of conductors to approximate the ideal cosine theta distribution of current density.

There are sophisticated programs available to do this, e.g. ROXIE, Opera, etc.

ROXIE also generates the data for machining the end spacers

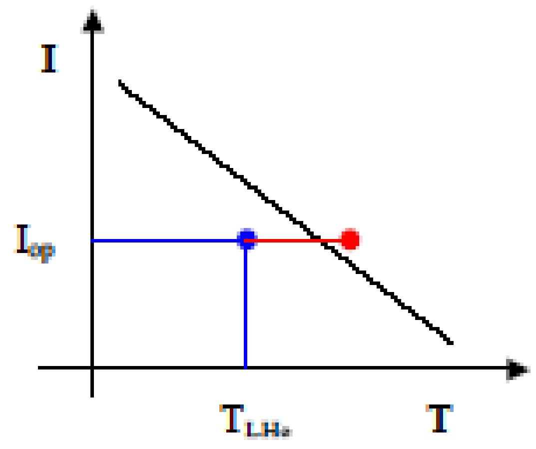
For calculating the effect of the forces ANSYS is used.

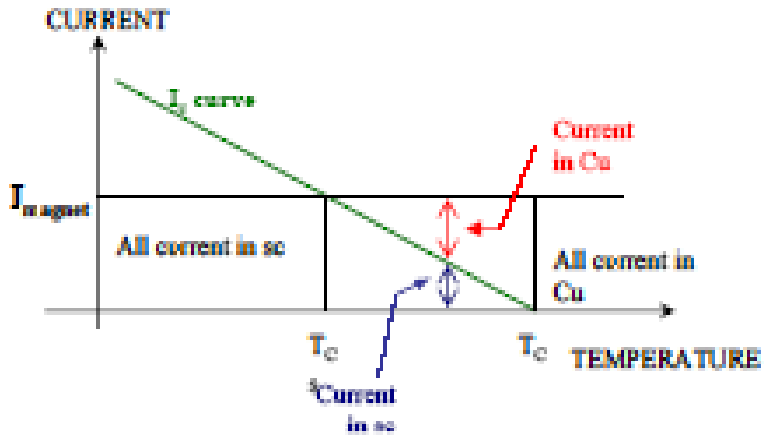


Superconductors are not stable

Superconductors are NOT stable against perturbation.
ΔE of μJ are enough to drive superconductor normal!

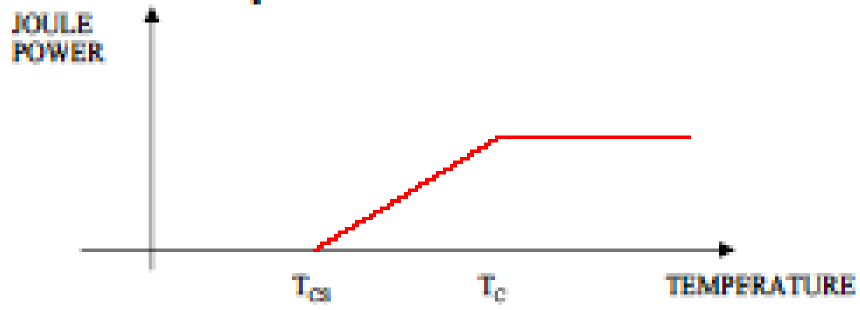
Heat capacity drops at low temperature ($T << T_{Debey}$) :
$C \propto T^3 \Rightarrow \Delta T = \Delta E/\gamma C$. So small ΔE generates big ΔT
$\Rightarrow$ operating point beyond critical surface $\Rightarrow$ QUENCH





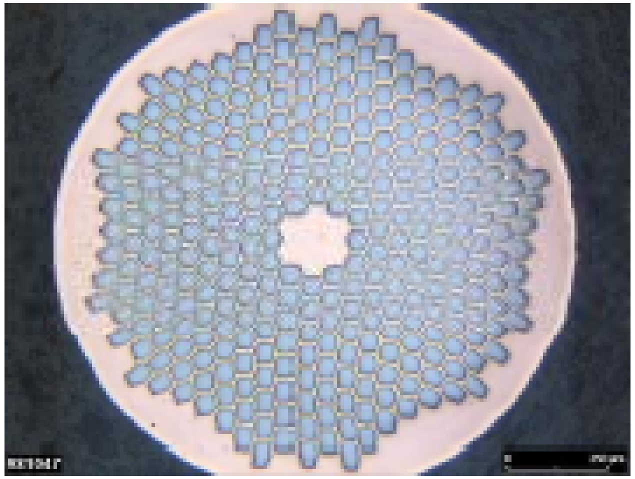
Electrodynamic stability: intimate contact between the superconductor and a highly conductive material.

Direct cooling : LHe, and more HEII, are good coolants, capable of removing heat in milliseconds! Latent heat 10-1000 times that of the specific heat of metals.



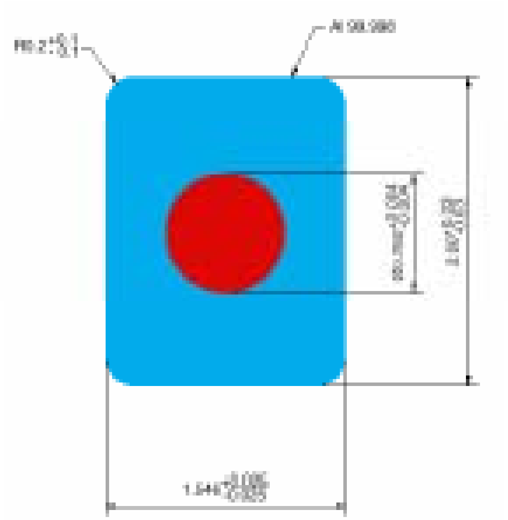
Wires, cables and stabilized conductors

Recap. – superconductors are multifilamentary wires, where hundreds or thousands of fine filaments are embedded in a stabilising matrix. The wire is strongly twisted (5-50 mm pitch length) for stability.



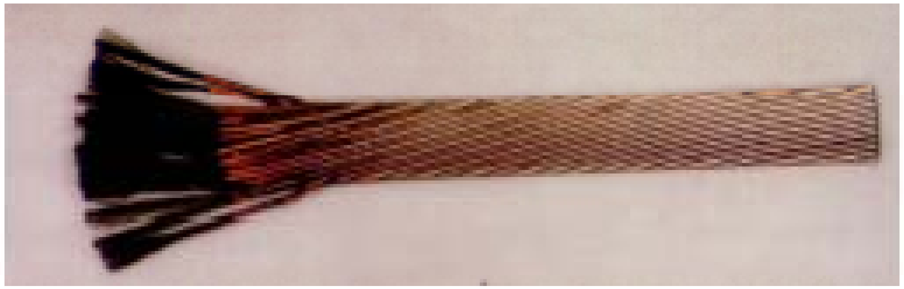
← Atlas Cu/NbTi wire

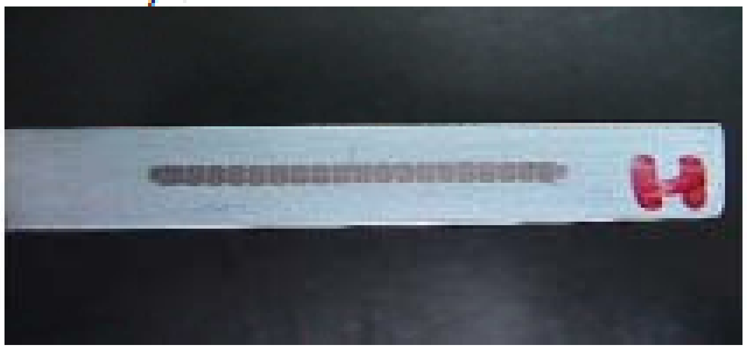
AMS-02 Cu/NbTi/Al →



Rutherford cable for
↓ LHC dipole

Atlas conductor
(Rutherford cable
coextruded with pure Al) ↓

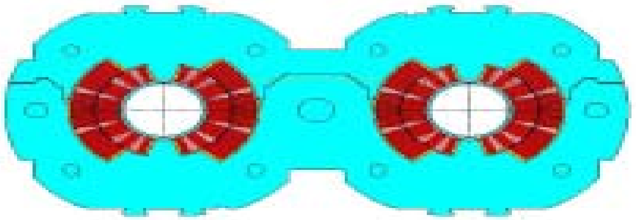


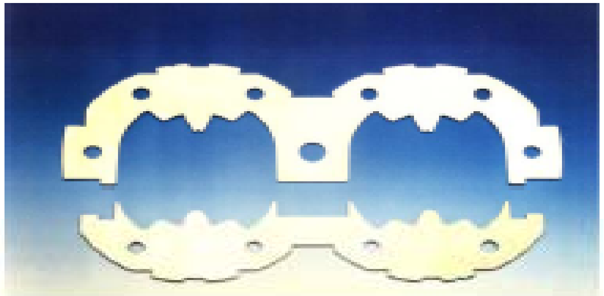


Optimization of magnet cross-section:
5) Collars

Collars are a key element of a magnet

They control prestress (mechanics) and Field Quality





Collars and collaring define precisely the final coil shape

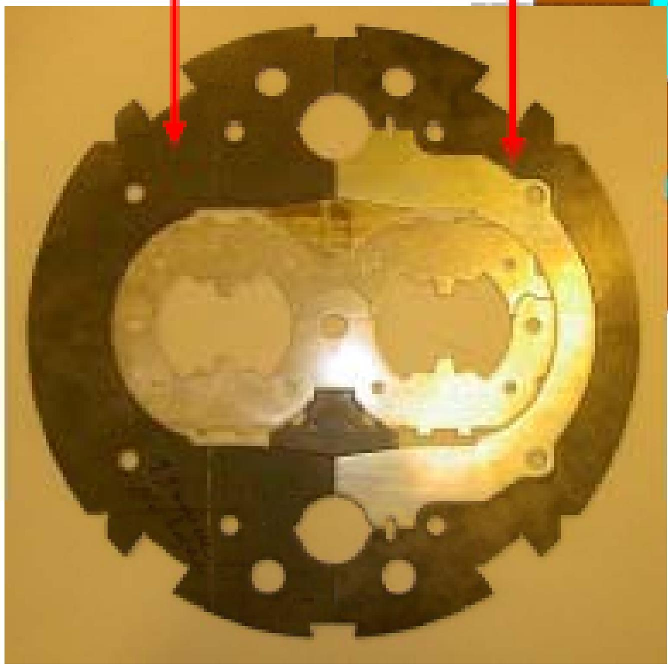
The collars are made of stainless steel

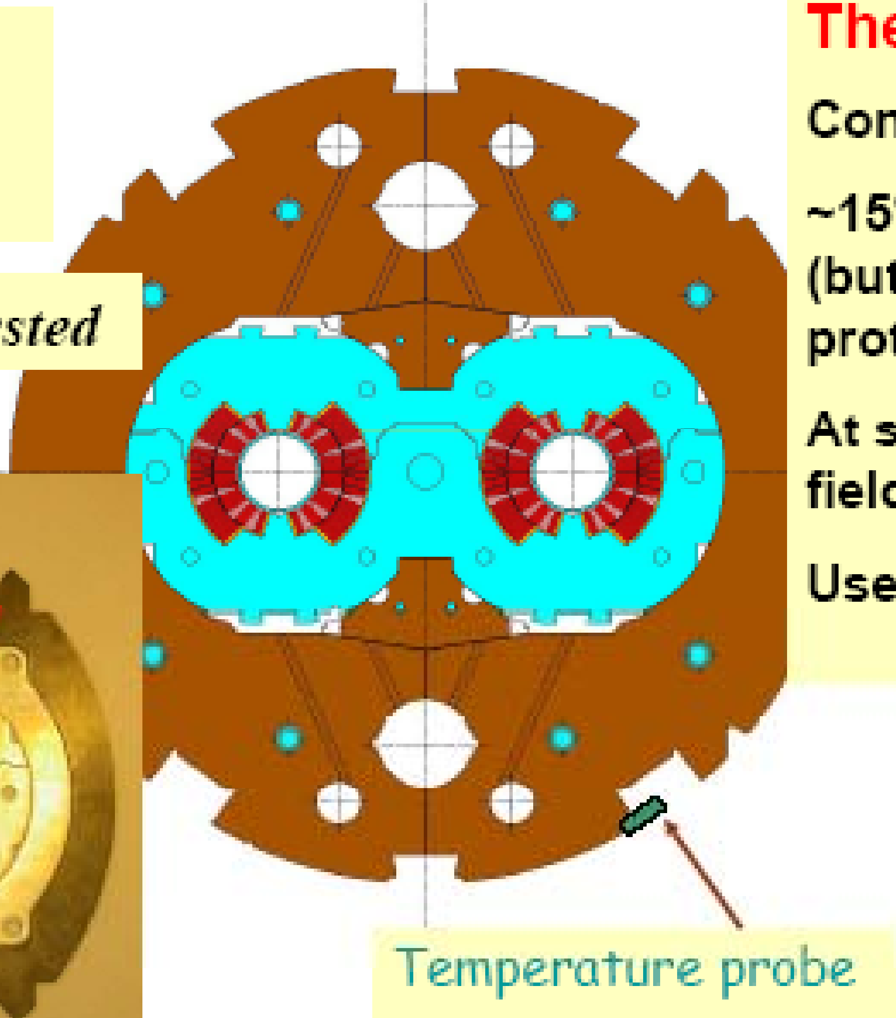
Optimization of magnet cross-section: 5) yoke laminations

One supplier for the steel 45,000 tons

Precise vertical gap

Regular *Nested*





The iron yoke:

Controls stray field

~15% field increase (but bigger gain for protection)

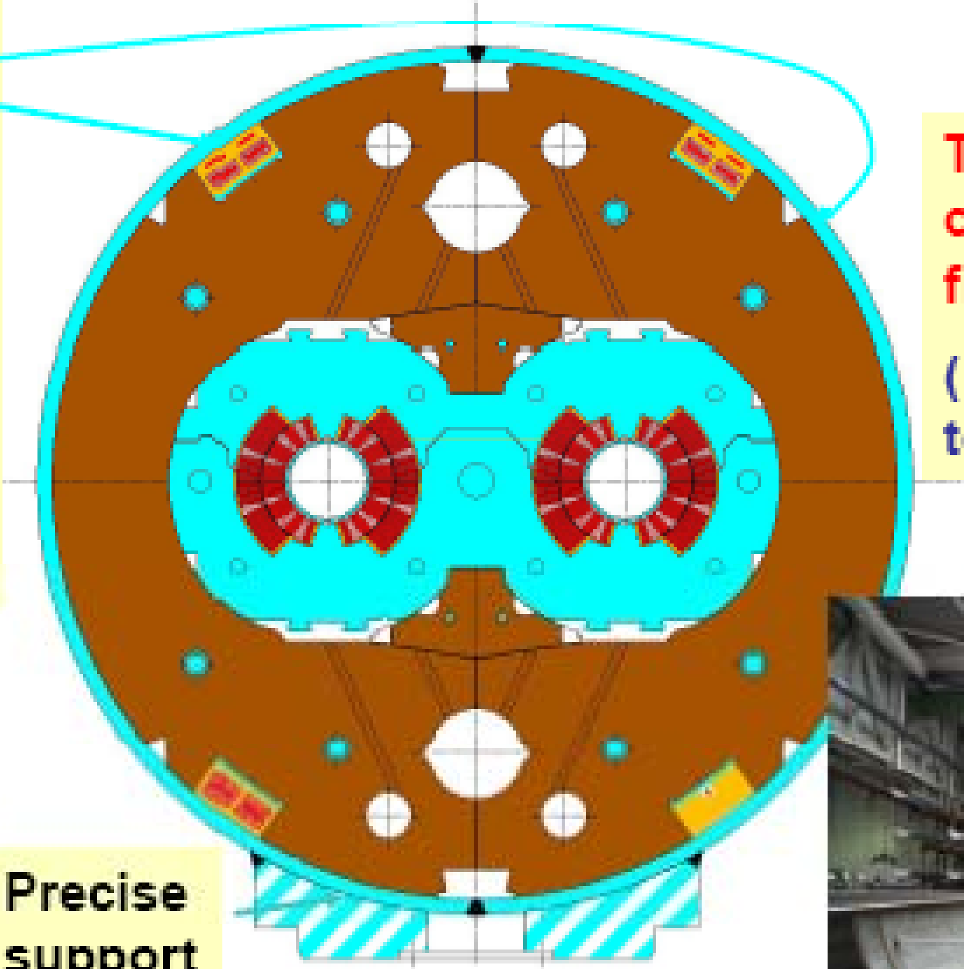
At saturation affects field quality (6-pole)

Used to trim length (magnetic)

Optimization of magnet cross-section: 6) Shrinking cylinder and support

Two half shells, welded on the magnet

(Many difficulties)

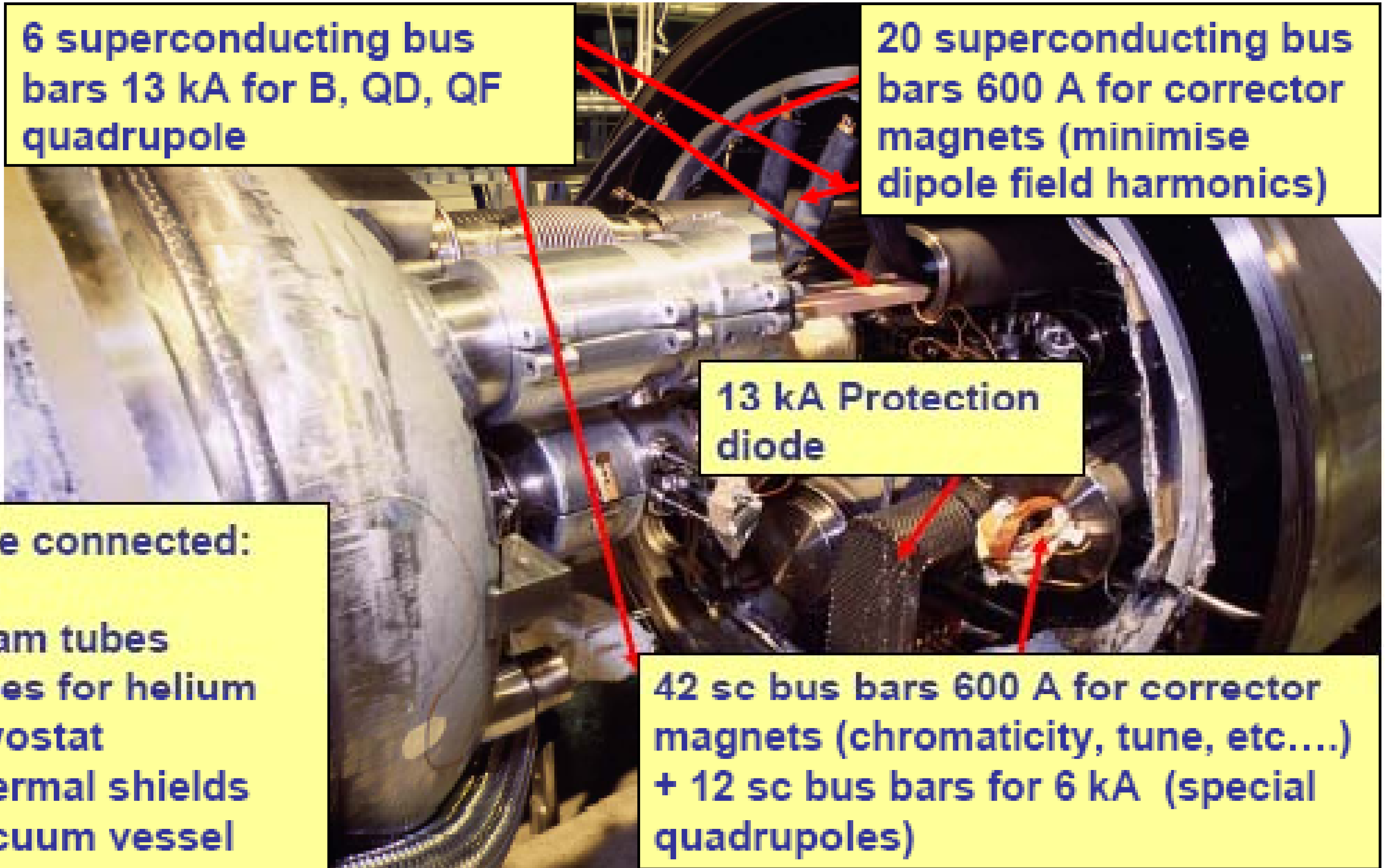


Precise support

Tolerance on curvature released from ± 1 to ± 2.5 mm.

(But still very difficult to achieve)

Interconnection between two SC magnets



To be connected:

- Beam tubes
- Pipes for helium
- Cryostat
- Thermal shields
- Vacuum vessel
- Superconducting cables

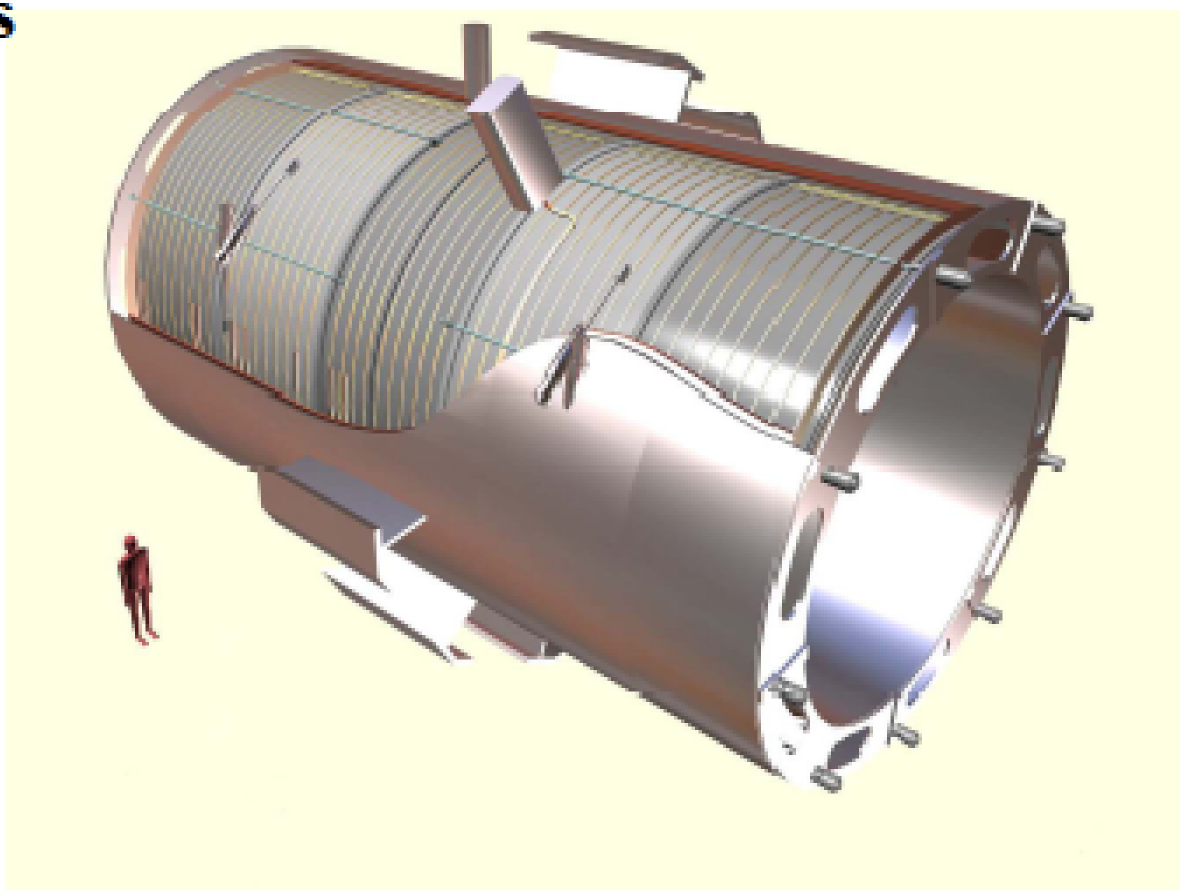
The Solenoid for the CMS experiment

The 4 T solenoid for the CMS (Compact(!) Muon Solenoid) experiment will be the most powerful coil ever built!
∅7 m, L = 13 m, E = 2.5 GJ

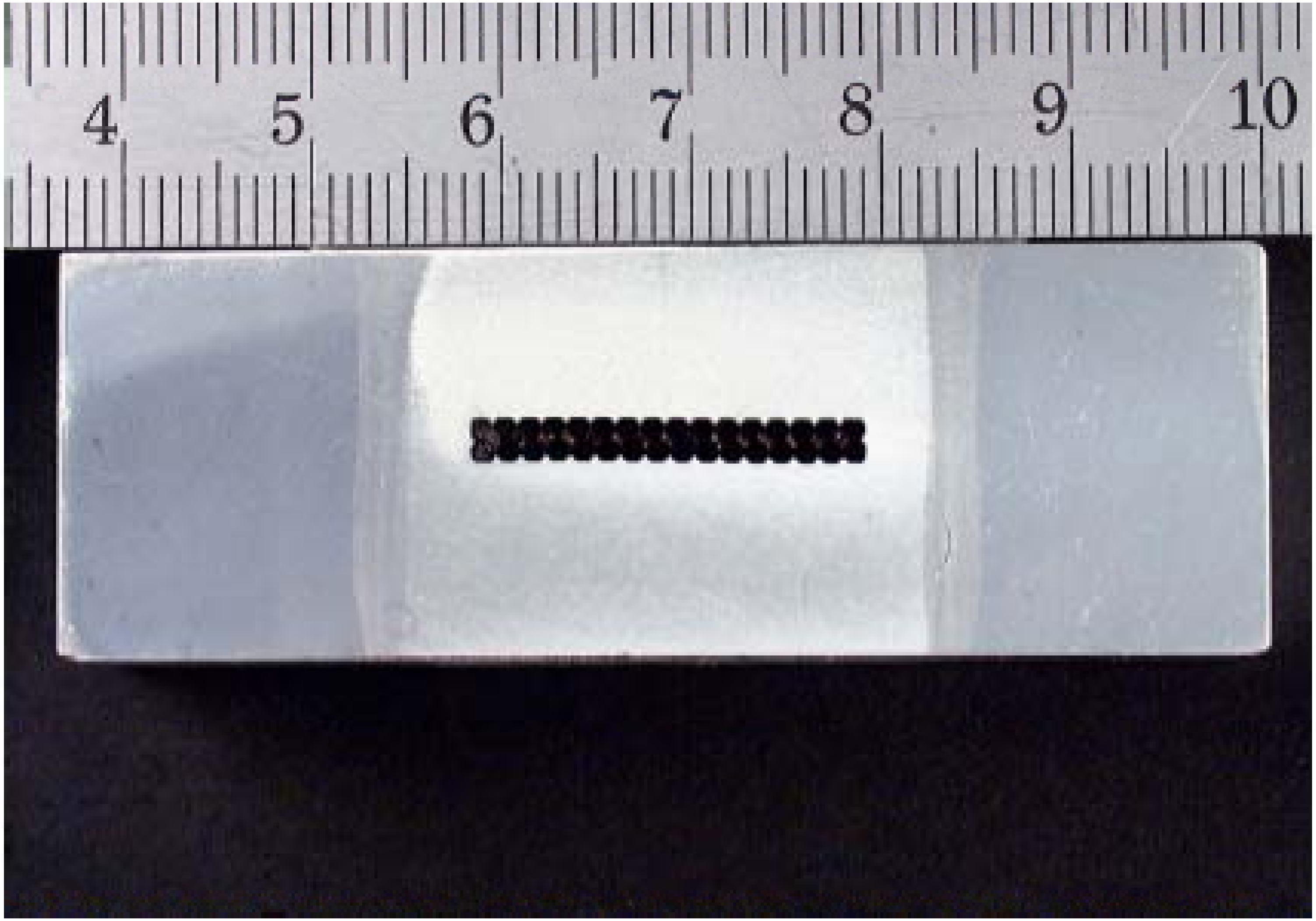
It features a 4-layer coil, wound from a specially developed conductor that has been reinforced to take the large hoop stresses.

The five coil modules are each as large as can be transported by road.

The magnet has been assembled at CERN and tests will start next week.



The CMS conductor

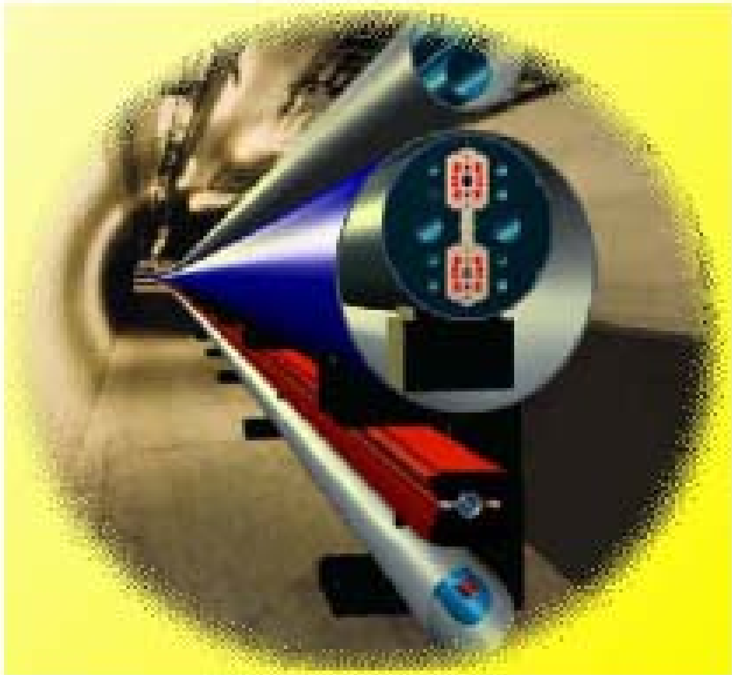


CMS magnet assembled vertically prior to swivelling

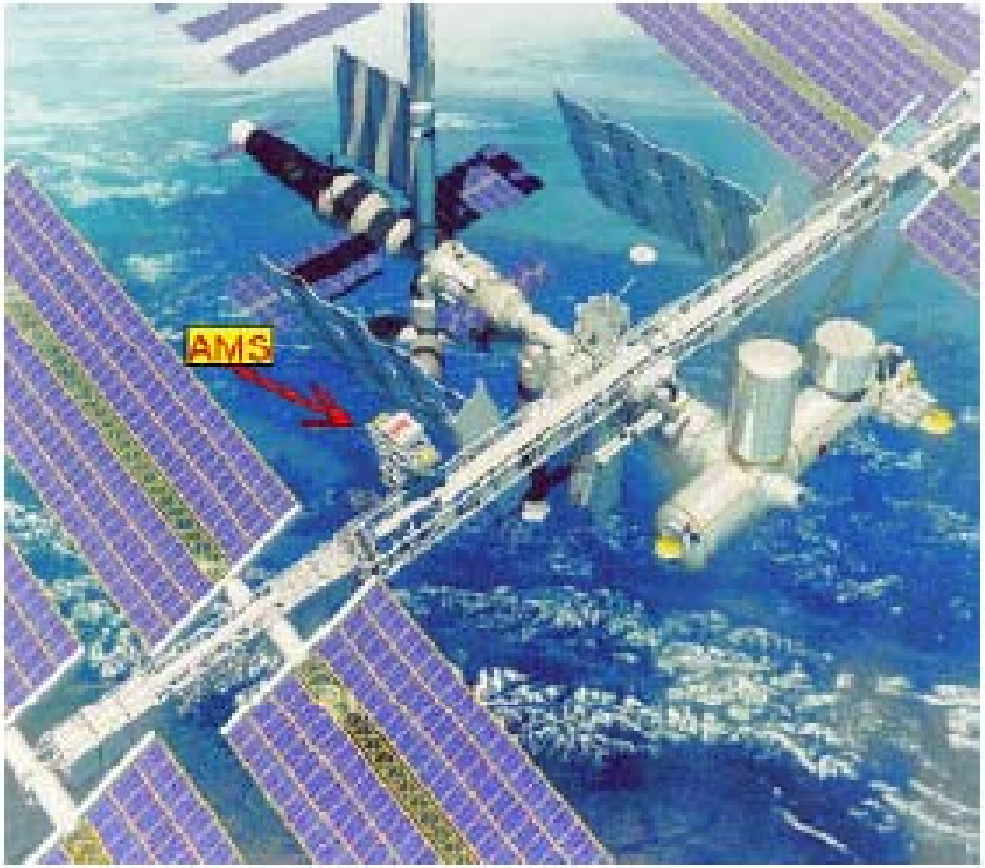
And then ? After 2015 ?
Why not an energy upgrade for LHC !

With a new type of magnet

?



Or a future in outer space?



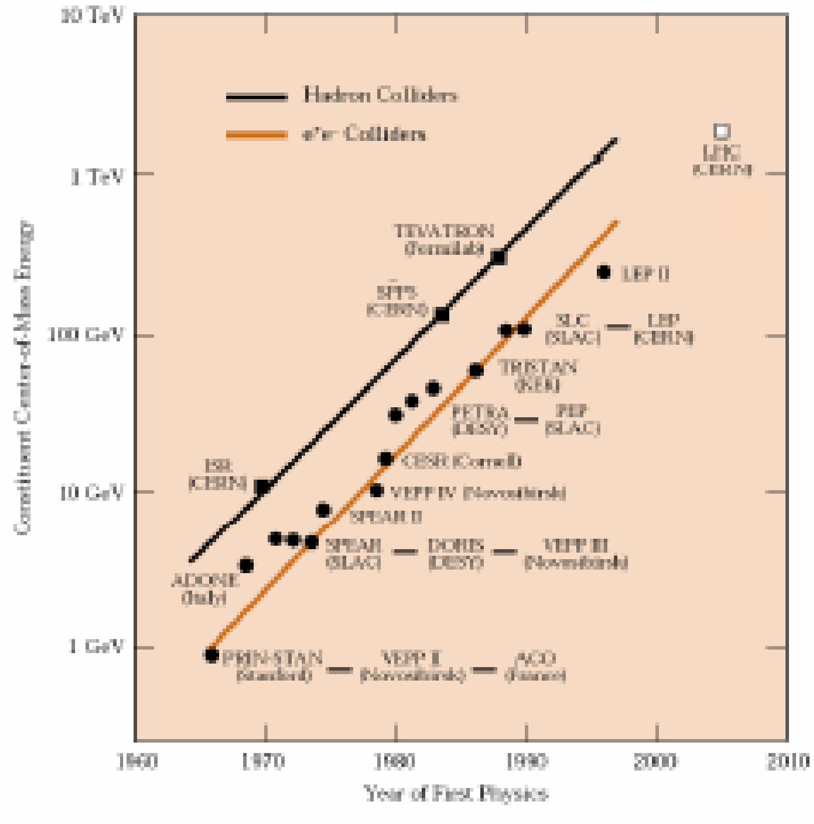
Outline

- Motivation for Linear Colliders
- The world landscape
- The International Linear Collider (ILC) with SC RF technology in the TeV range
- The Compact Linear Collider (CLIC) with Two-Beam technology in the Multi-TeV range
- Main challenges
- What has been achieved so far
- What remains to be demonstrated
- The facilities to address the key issues
- Plans and schedule
- Conclusion

(courtesy of B.Barish and R.Corsini for some slides)

Lepton and Hadron facilities complementary
CLIC for discovery and physics of new particles

- Particle accelerators have a long, successful history as indispensable tools in the quest to understand Nature at smaller and smaller scales
- Since the 70s, most new revelations in particle physics have come from colliders - machines using two accelerated beams in collision



Energy (exponentially !) increasing with time

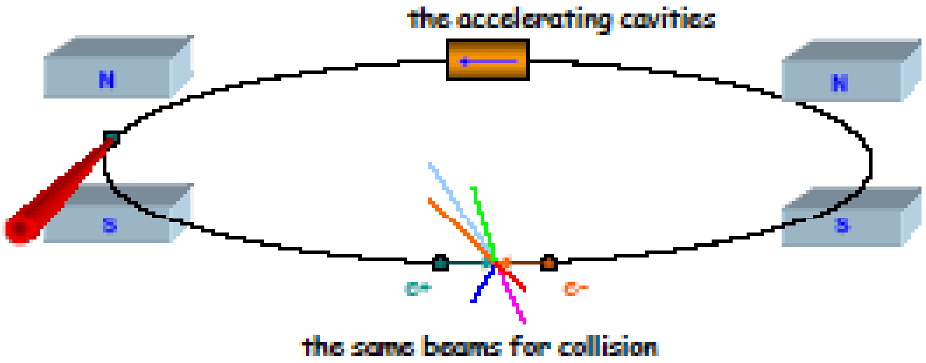
⇒ a factor 10 increase every 8 years!

- Hadron Colliders at the energy frontier as discovery facilities
- Lepton Colliders for precision physics
- LHC coming online from 2007
- **Consensus for a future lepton linear collider to complement LHC physics with**

Ecm > 400 GeV

Why a linear collider ?

Circular colliders use magnets to bend particle trajectories
Their advantage is that they re-use many times



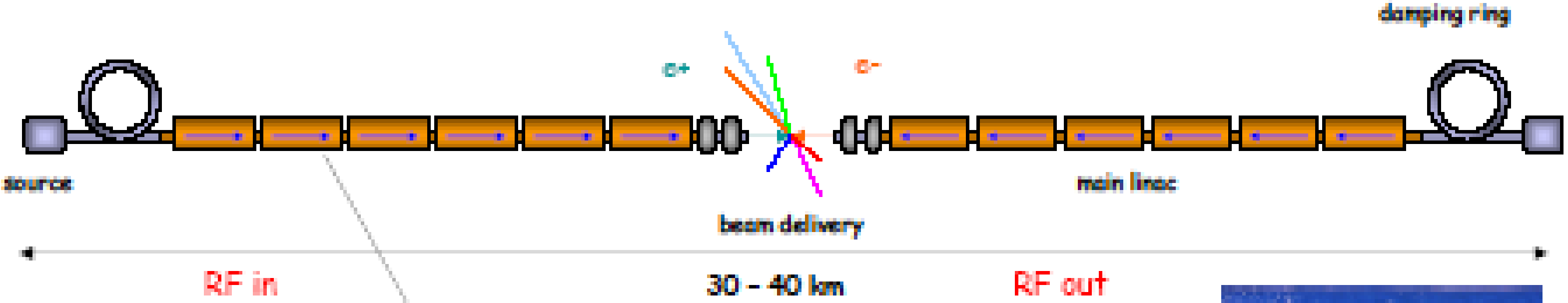
However, charged particles emit synchrotron radiation in a magnetic field

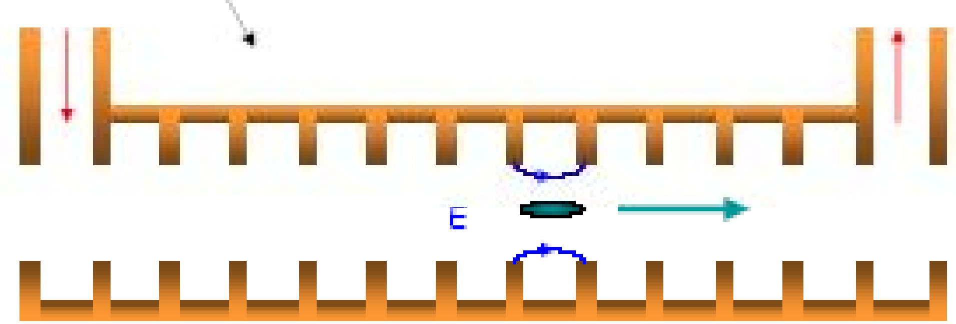
$$P = \frac{2}{3}\frac{r_e}{(m_o c^2)^3}\frac{E^4}{\rho^2} \quad \Rightarrow \quad \Delta E_{turn} = \frac{4}{3}\pi\frac{r_e}{(m_o c^2)^3}\frac{E^4}{\rho}$$

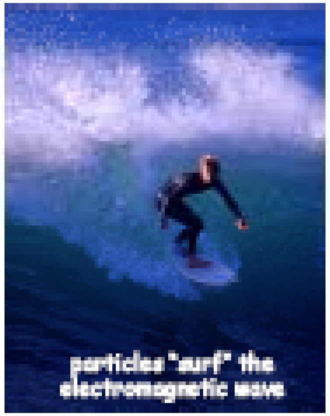
Much less important for heavy particles, like protons

A linear collider uses the accelerating cavities only once

- Lots of them !
- Need a high accelerating gradient to reach the wanted energy in a "reasonable" length (total cost, cultural limit)



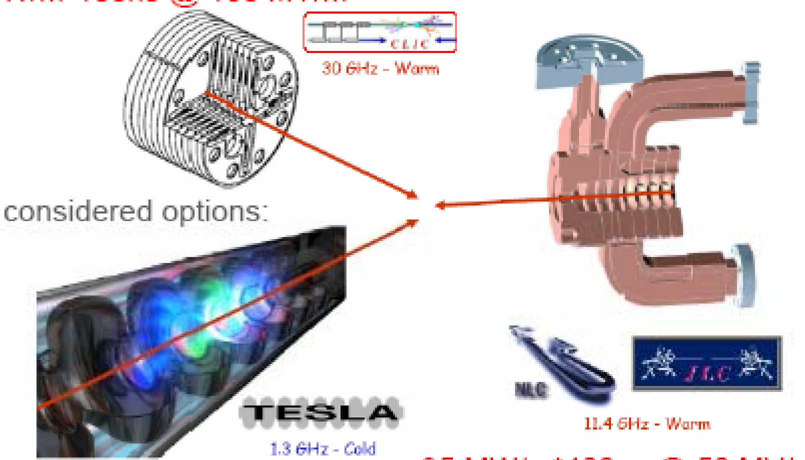




Intern[al] Technology Review Panel (2001-2003)

350 MW/m*100ns @ 150 MV/m

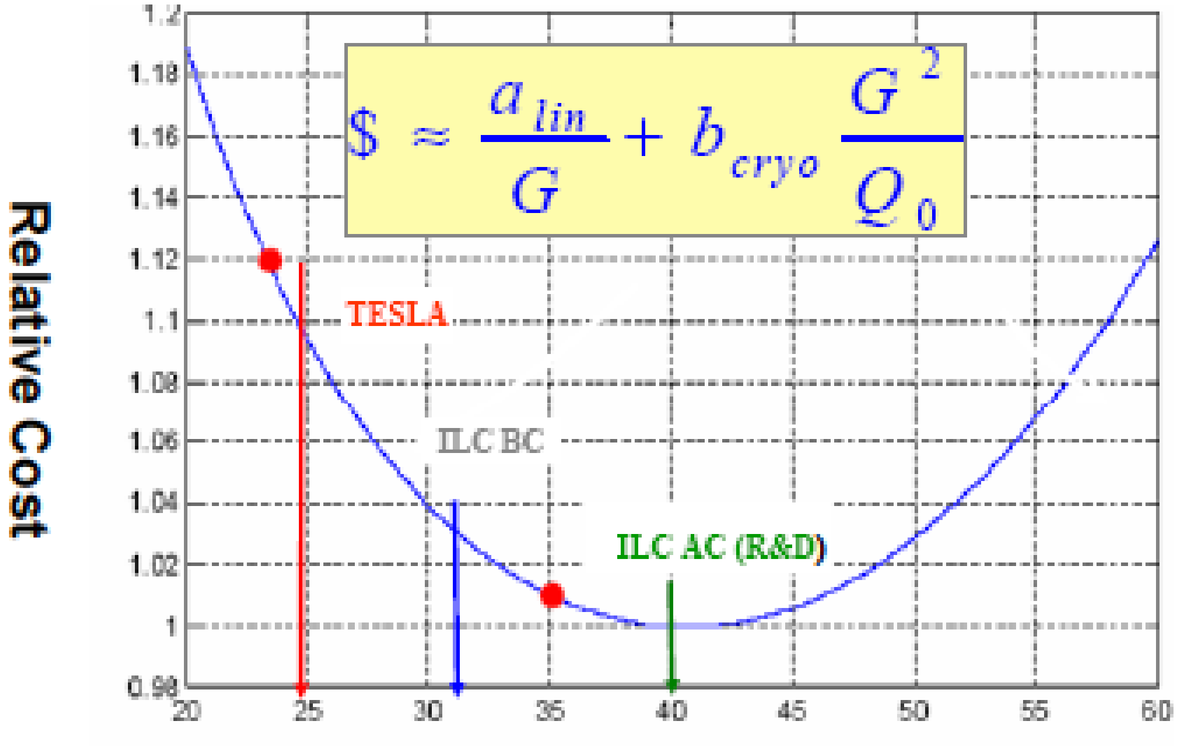
The 3 considered options:



350 kW/m*1.3ms @ 35 MV/m

95 MW/m*400ns @ 50 MV/m

How Costs Scale with Gradient?



C. Adolphsen (SLAC) **Gradient MV/m**

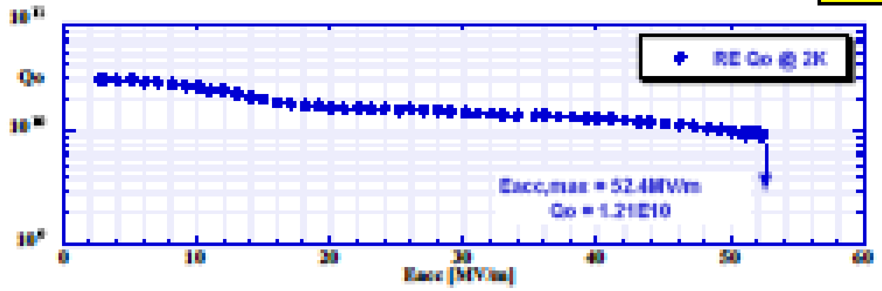
25 MV/m demonstrated by TESLA collaboration

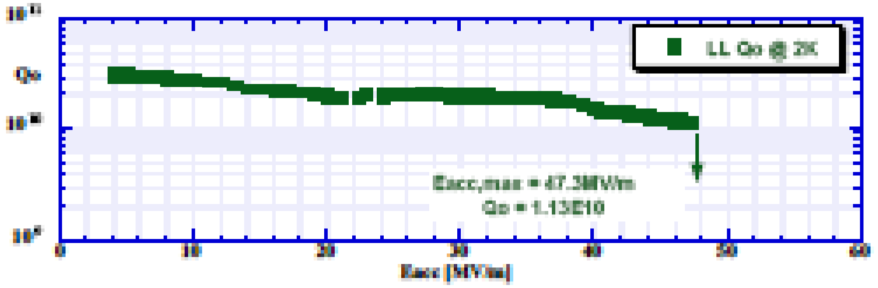
31.5 MV/m adopted for ILC Baseline Configuration

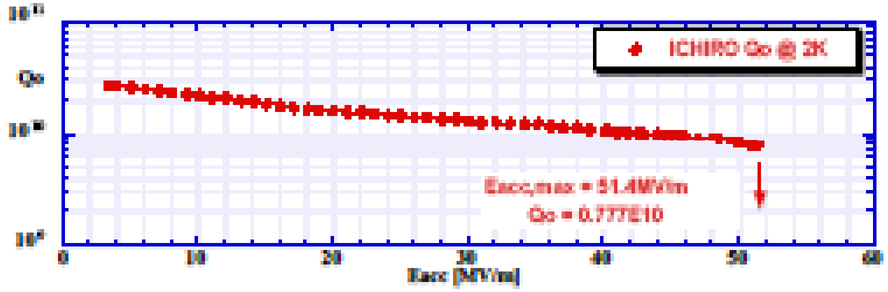
R&D towards 40 MV/m

Principle proof of the 50MV/m in 2005

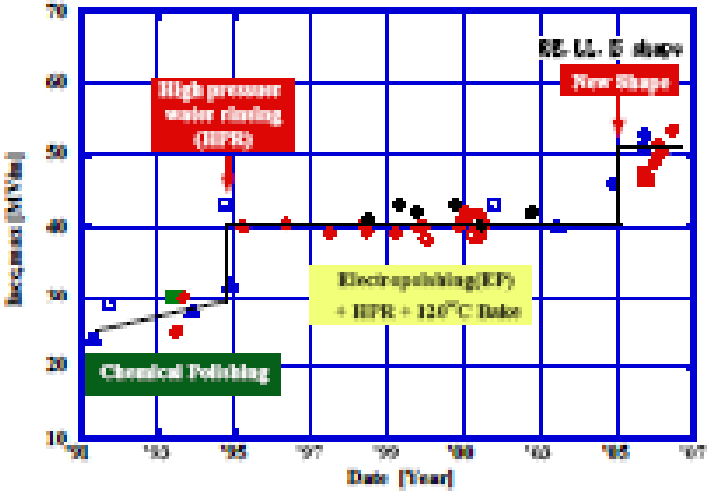
KEK



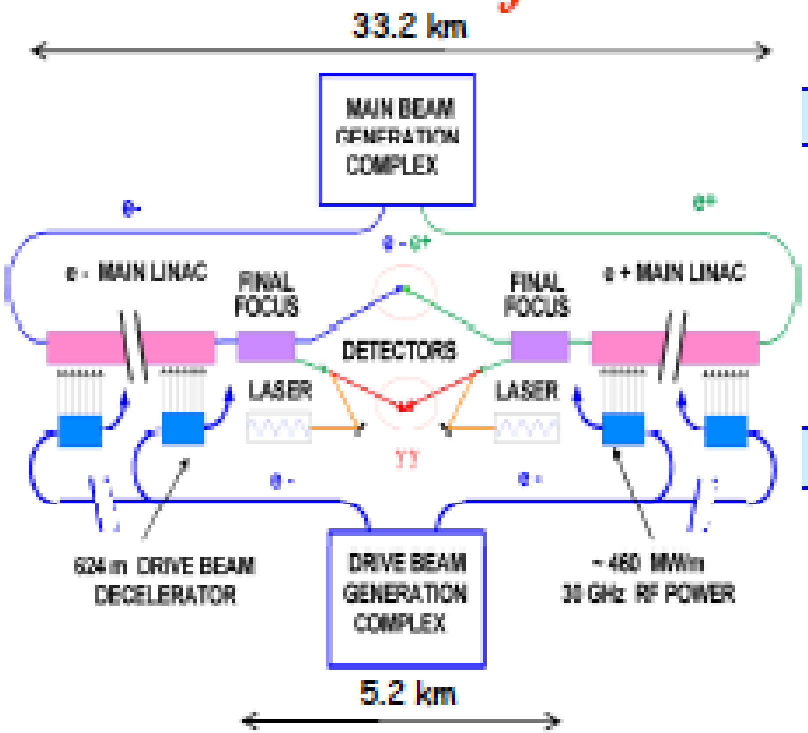




Re-entrant Low-Loss



CLIC technology for Multi-TeV Linear Colliders



Overall layout for a center of mass energy of 3 TeV/c

- High acceleration gradient (150 MV/m)

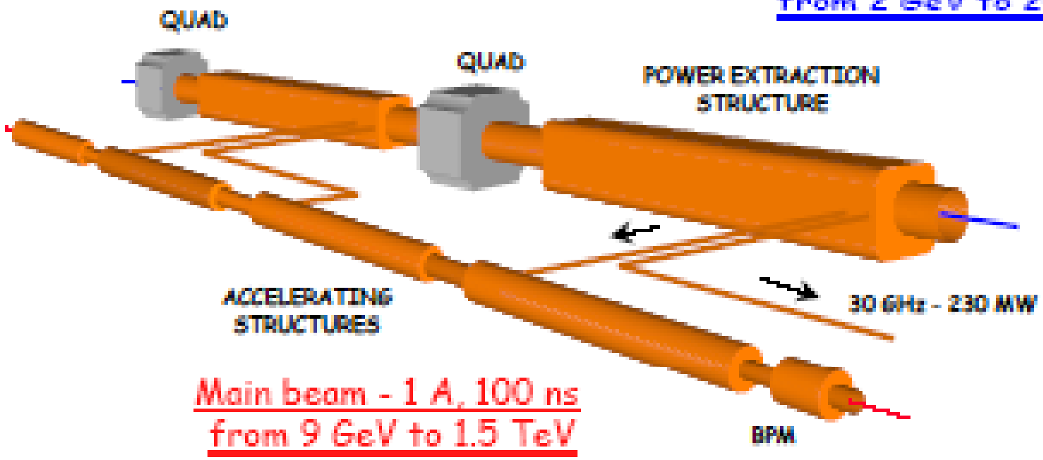
- "Compact" collider - overall length≈33 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)

- Two-Beam Acceleration Scheme

  - RF power generation at high frequency
  - Cost-effective & efficient (~ 10% overall)
  - Simple tunnel, no active elements
  - "modular" design, can be built in stages
  - Easily expendable in energy

CLIC Two-Beam scheme

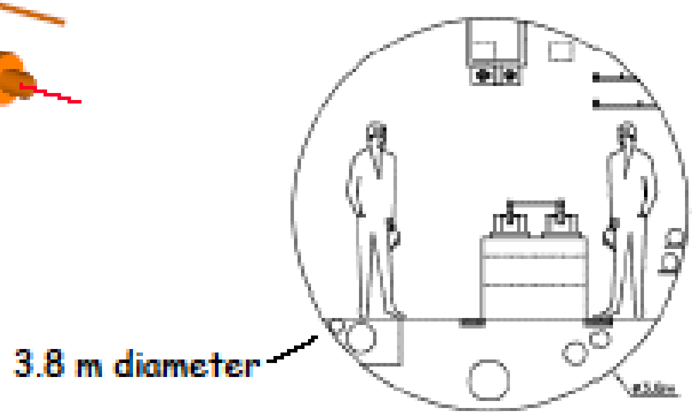
Drive beam - 150 A, 130 ns
from 2 GeV to 200 MeV



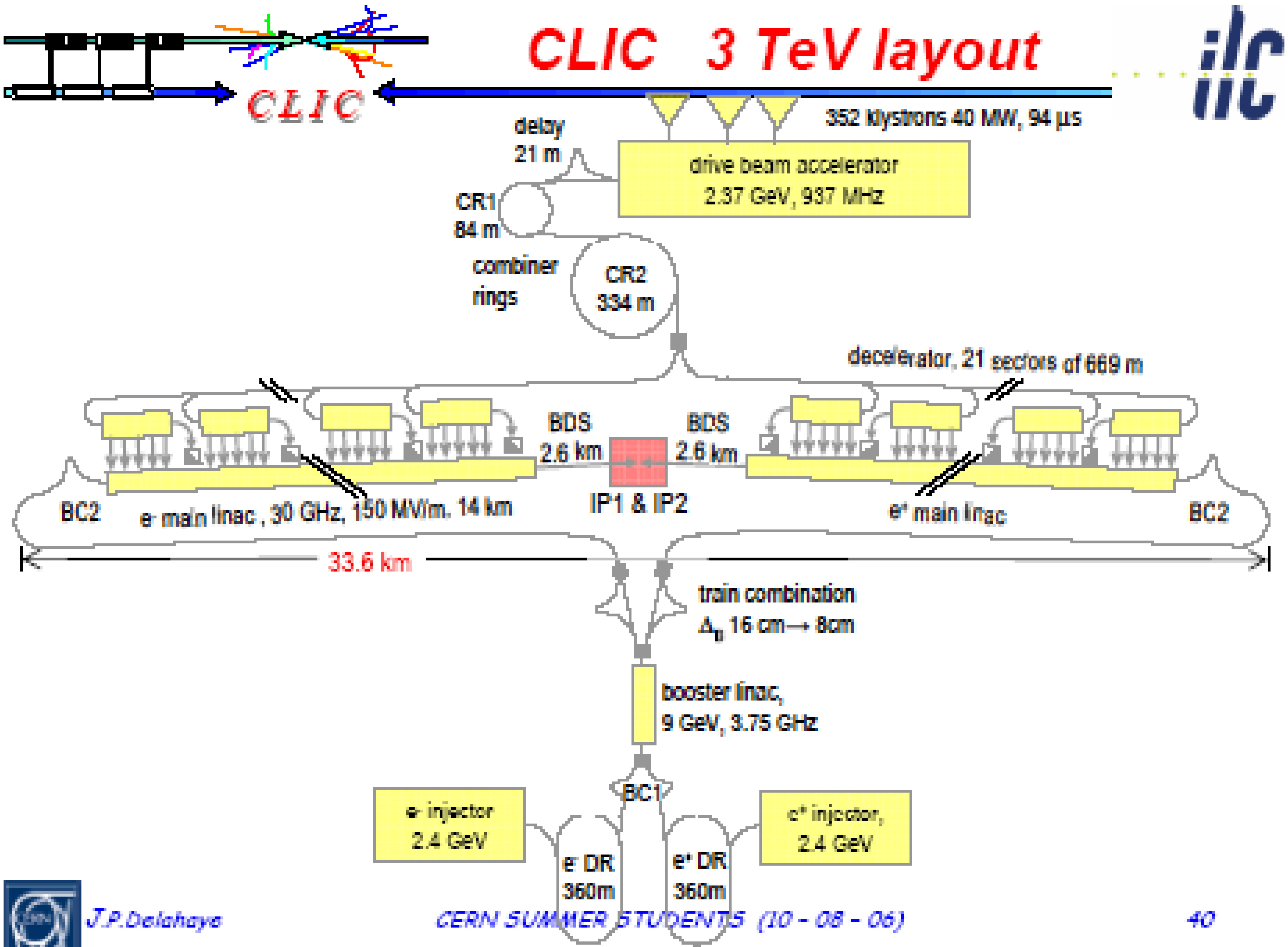
CLIC MODULE

(6000 modules/linac at 3 TeV)

CLIC TUNNEL CROSS-SECTION



CLIC 3 TeV layout



The CLIC main parameters

Center of mass Energy (TeV)	0.5 TeV	3 TeV
Luminosity (10^{34} $cm^{-1}s^{-1}$)	2.1	8.0
Mean energy loss (%)	4.4	21
Photons / electron	0.75	1.5
Coherent pairs per X	700	6.8 10^{8}
Rep. Rate (Hz)	200	100
10^{9} $e^{\pm}$ / bunch	4	4
Bunches / pulse	154	154
Bunch spacing (cm)	20	20
H/V ε_n (10^{-8} rad.m)	200/1	68/1
Beam size (H/V) (nm)	202/1.2	60/0.7
Bunch length (µm)	35	35
Accelerating gradient (MV/m)	150	150
Overall length (km)	7.7	33.2
Power / section (MW)	230	230
RF to beam efficciency (%)	23.1	23.1
AC to beam efficiency (%)	9.3	9.3
Total AC power for RF (MW)	105	319
Total site AC power (MW)	175	410

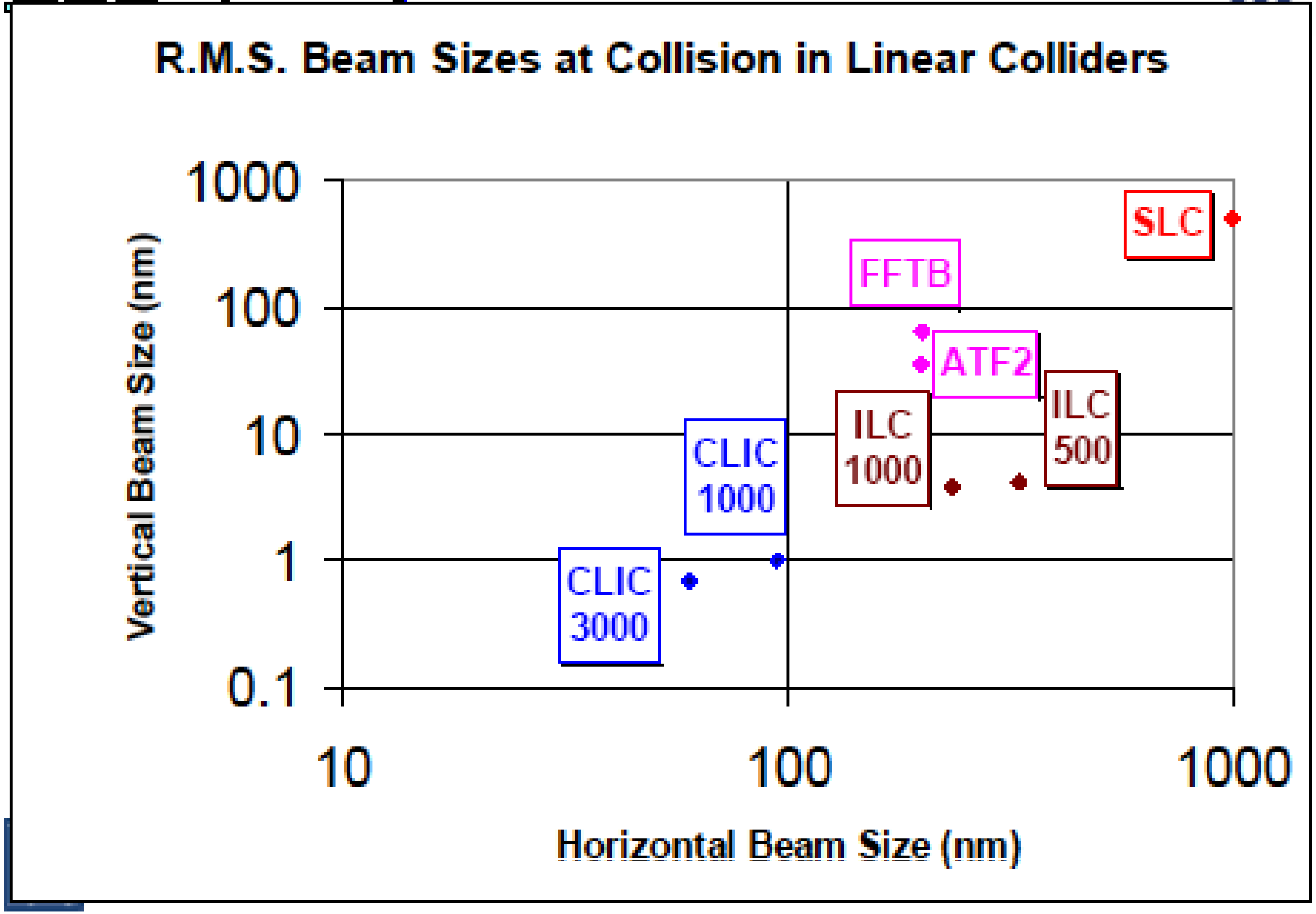
Nanometer stabilisation

Latest stabilization technology applied to the accelerator field

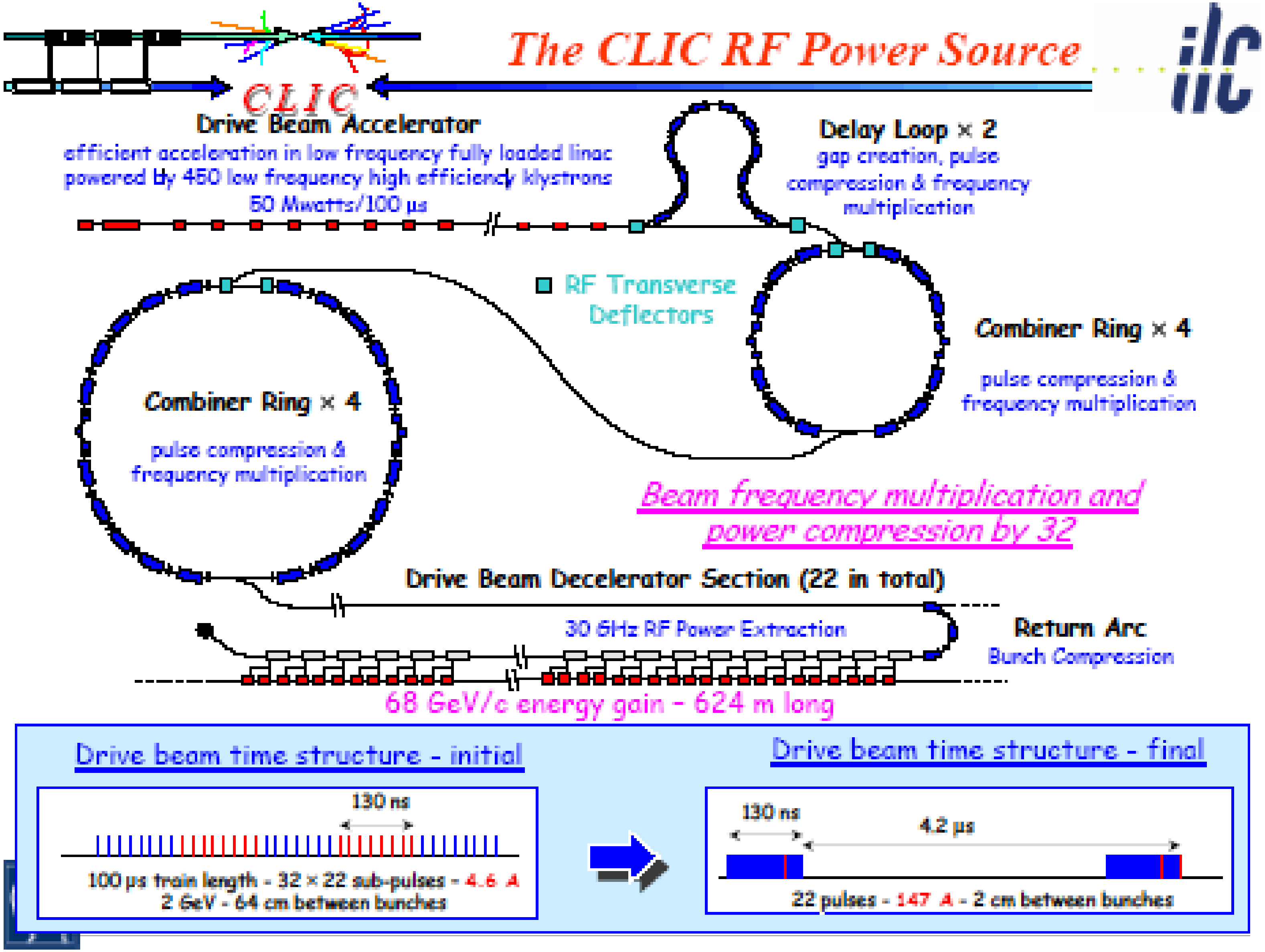
The most stable place on earth!!!

Stabilizing quadrupoles to the **0.5 nm** level!

(up to 10 times better than supporting ground, above 4 Hz)


R.M.S. Beam Sizes at Collision in Linear Colliders
Vertical Beam Size (nm)
1000
100
10
1
0.1
Horizontal Beam Size (nm)
10
100
1000
SLC
FFTB
ATF2
ILC 500
ILC 1000
CLIC 1000
CLIC 3000

The CLIC RF Power Source



What does the RF power Source do?

CLIC

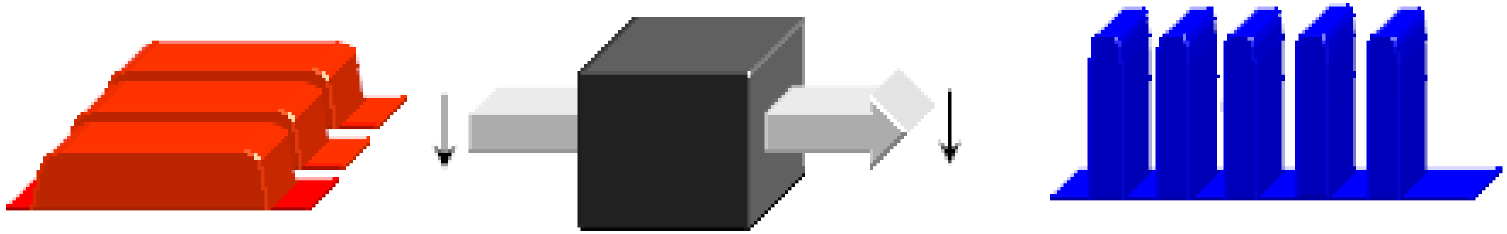
The CLIC RF power source can be described as a "black box", combining *very long RF pulses*, and transforming them in *many short pulses*, with *higher power* and with *higher frequency*

450 MBK Klystrons
Low frequency
High efficiency

Power stored in electron beam

Power extracted from beam in resonant structures

43000
Accelerating Structures
High Frequency - High field



Long RF Pulses
$P_0 \cdot \nu_0 \cdot \tau_0$

Electron beam manipulation
Power compression
Frequency multiplication

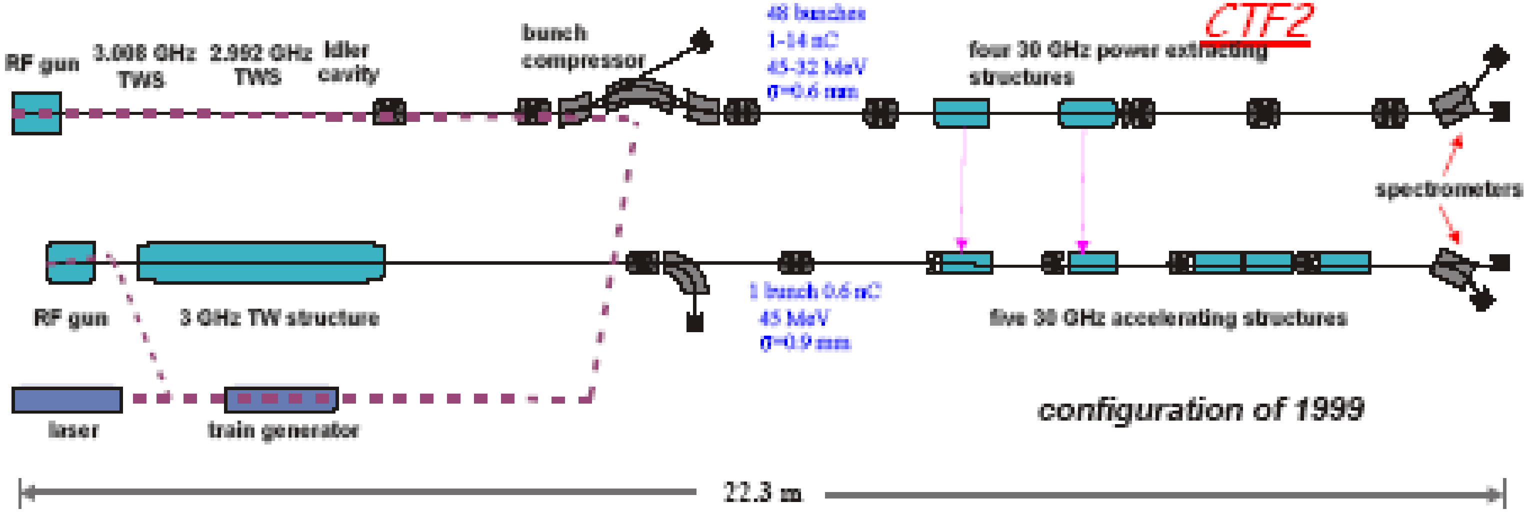
Short RF Pulses
$P_A = P_0 \times N_1$
$\tau_A = \tau_0 / N_2$
$\nu_A = \nu_0 \times N_3$

CLIC Test Facility (CTF2) 1996-2002

CTF2 goals :

- to demonstrate feasibility of CLIC two-beam acceleration scheme
- to study generation of short, intense e-bunches using laser-illuminated PCs in RF guns
- to demonstrate operability of μ-precision active-alignment system in accelerator environment
- to provide a test bed to develop and test accelerator diagnostic equipment
- to provide high power 30 GHz RF power source for high gradient testing ~90 MW 16 ns pulses

All-but-one of 30 GHz two-beam modules removed in 2000 to create a high-gradient test stand.



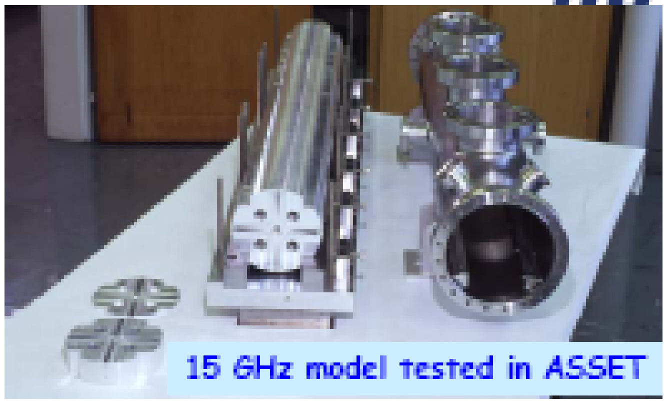
Accelerating structure developments

CLIC

CONTROL OF TRANSVERSE WAKEFIELDS

- short-range wakes ⇐ BNS damping
- long-range wakes ⇐ damping and detuning

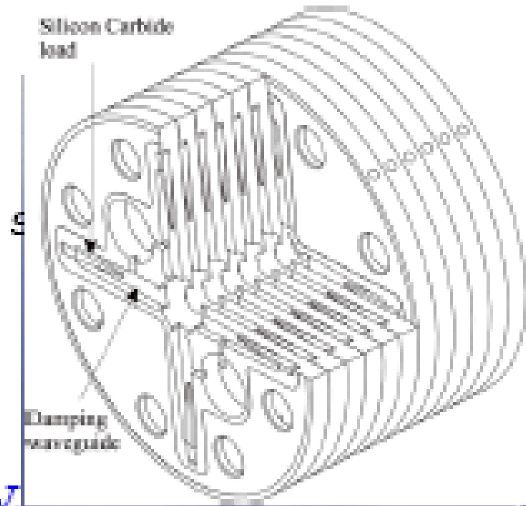
\+ beam-based trajectory correction, ε bump

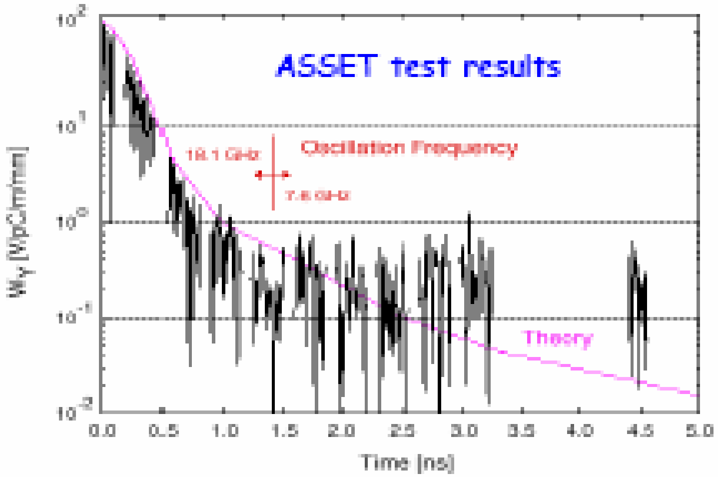


15 GHz model tested in ASSET

For wake suppression - work still focused on here. Each cell is damped by 4 radial WGs terminated by waveguide-damped structures of type shown discrete SiC RF loads.

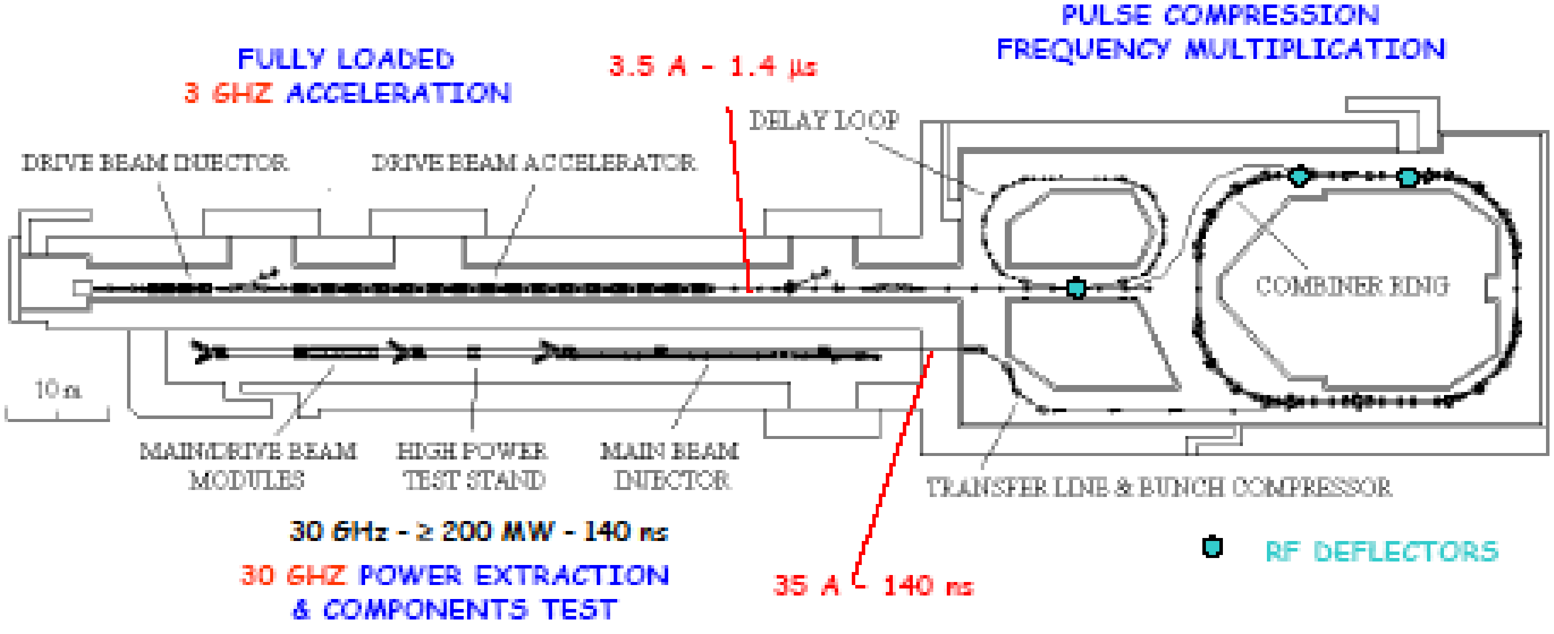
Excellent agreement obtained between theory and experiment - believe we can solve damping problem





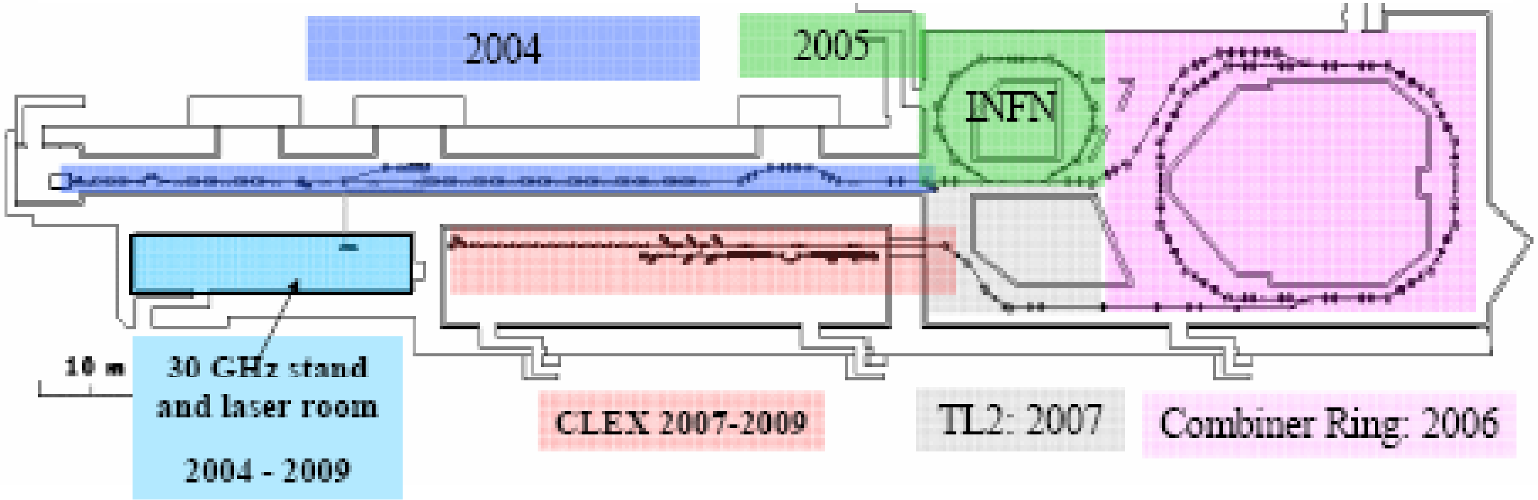
CLIC technology key issues addressed in CLIC Test Facility (CTF3)

Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10
Two Beam RF power generation & component tests with nominal fields & pulse length



CLIC Test Facility (CTF3)

Collaboration: Ankara- INP- CERN –CIEMAT-DAPNIA- Helsinki – LAP-INFN –JINR-INDIA-LAL-LAPP –NWU –RAL –SLAC -Uppsala



Key issues

From 2005: Accelerating structures (bi-metallic) Development& Tests (R2.1)

2007- 2008: Drive beam generation scheme (R1.2)

2008- 2009: Damped accelerating structure with nominal parameters (R1.1)
ON/OFF Power Extraction Structure (R1.3)
Drive beam stability bench marking (R2.2)
CLIC sub-unit (R2.3)

CONCLUSION

- World-wide Consensus for a Lepton Linear Collider as the next HEP facility to complement LHC at the energy frontier
- International Linear Collider based on Super-Conducting RF technology possibly being improved with extensive R&D in world-wide collaboration:
  - Reference Design Report including cost end of 2006
  - Ready to build from 2010 (7 year construction)
  - First phase at 500 GeV beam collision energy
  - Possible upgrade to 1 TeV beam collision energy
- CLIC technology only possible scheme to extend collider beam energy into Multi-TeV energy range
- Very promising results but technology not mature yet, requires challenging R&D
- CLIC-related key issues addressed in CTF3 by 2010

Aim to provide the High Energy Physics community with the feasibility of CLIC technology for Linear Collider in due time, when physics needs will be fully determined following LHC results

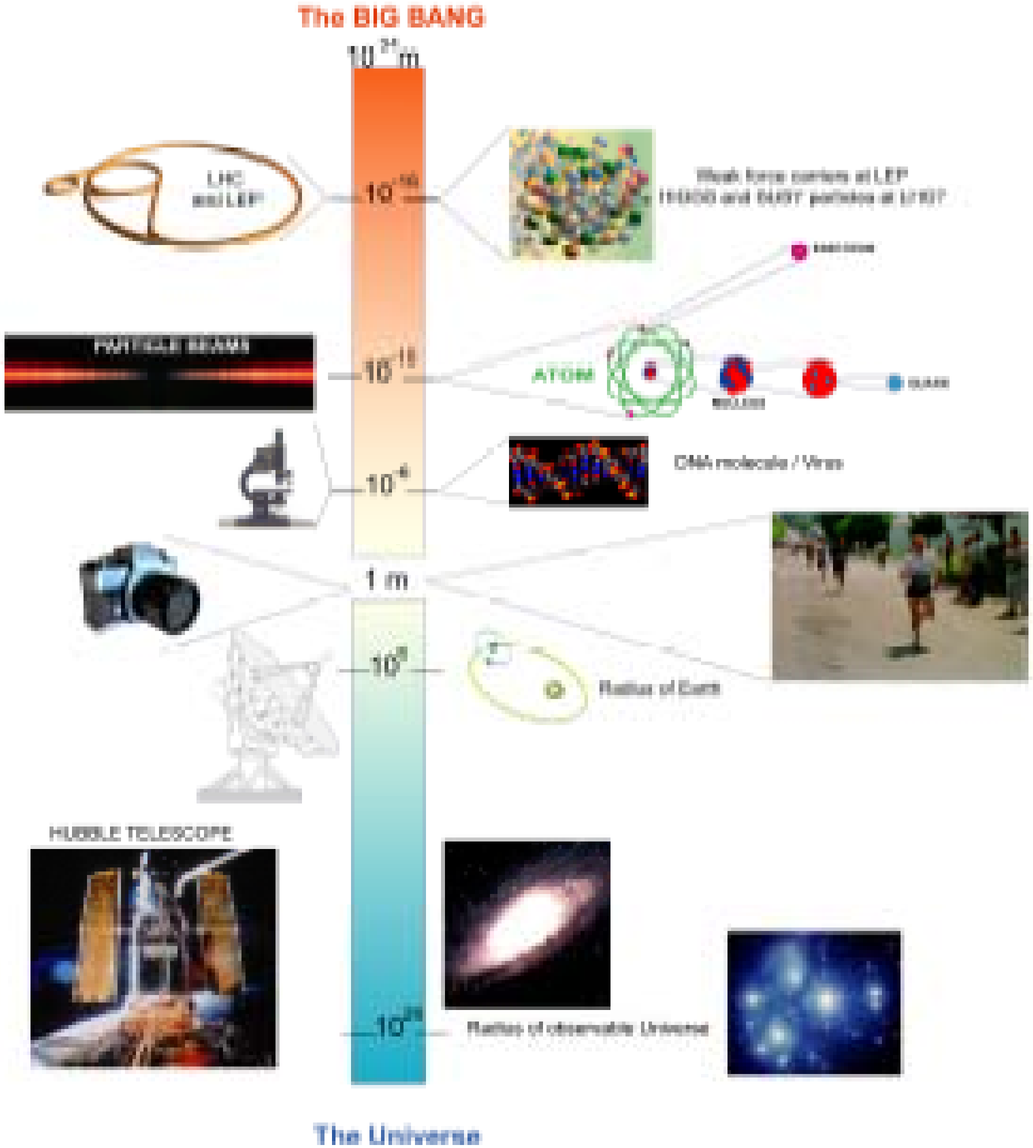
Safety net to the SC technology in case sub-TeV energy range is not considered attractive enough for physics

The Compton wavelength of the electron is one of a trio of related units of length, the other two being the Bohr radius a_0 and the classical electron radius r_e. The Compton wavelength is built from the electron mass m_e, Planck's constant h and the speed of light c. The Bohr radius is built from m_e, h and the electron charge e. The classical electron radius is built from m_e, c and e. Any one of these three lengths can be written in terms of any other using the fine structure constant α:

$$r_e = \frac{\alpha \lambda_e}{2\pi} = \alpha^2 a_0$$

The Planck mass is special because ignoring factors of 2π and the like, the Compton wavelength for this mass is equal to its Schwarzschild radius. This special distance is called the Planck length. This is a simple case of dimensional analysis: the Schwarzschild radius is proportional to the mass, whereas the Compton wavelength is proportional to the inverse of the mass.

The right instrument for a given dimension



Wavelength of probe radiation should be smaller than the object to be resolved

$$\lambda << \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy of Radiation
Atom	10[illegible] m	0.00001 GeV (electrons)
Nucleus	10[illegible] m	0.01 GeV (alphas)
Nucleon	10[illegible] m	0.1 GeV (electrons)
Quarks	?	> 1 GeV (electrons)

Radioactive sources give energies in the range of MeV

Need accelerators for higher energies.

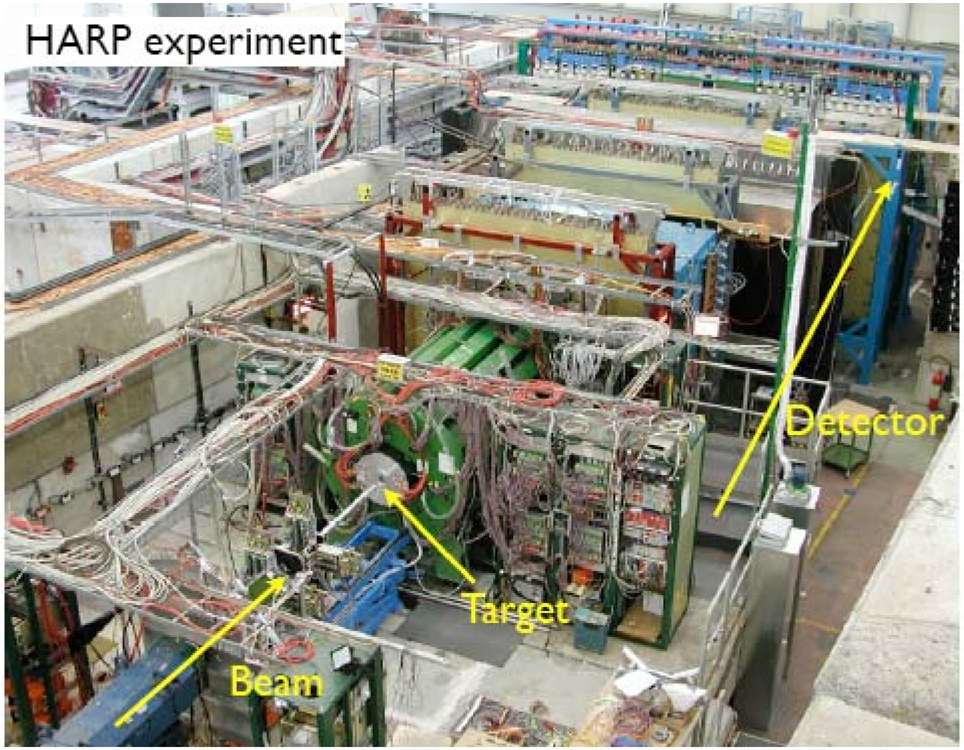
"electronic eyes"

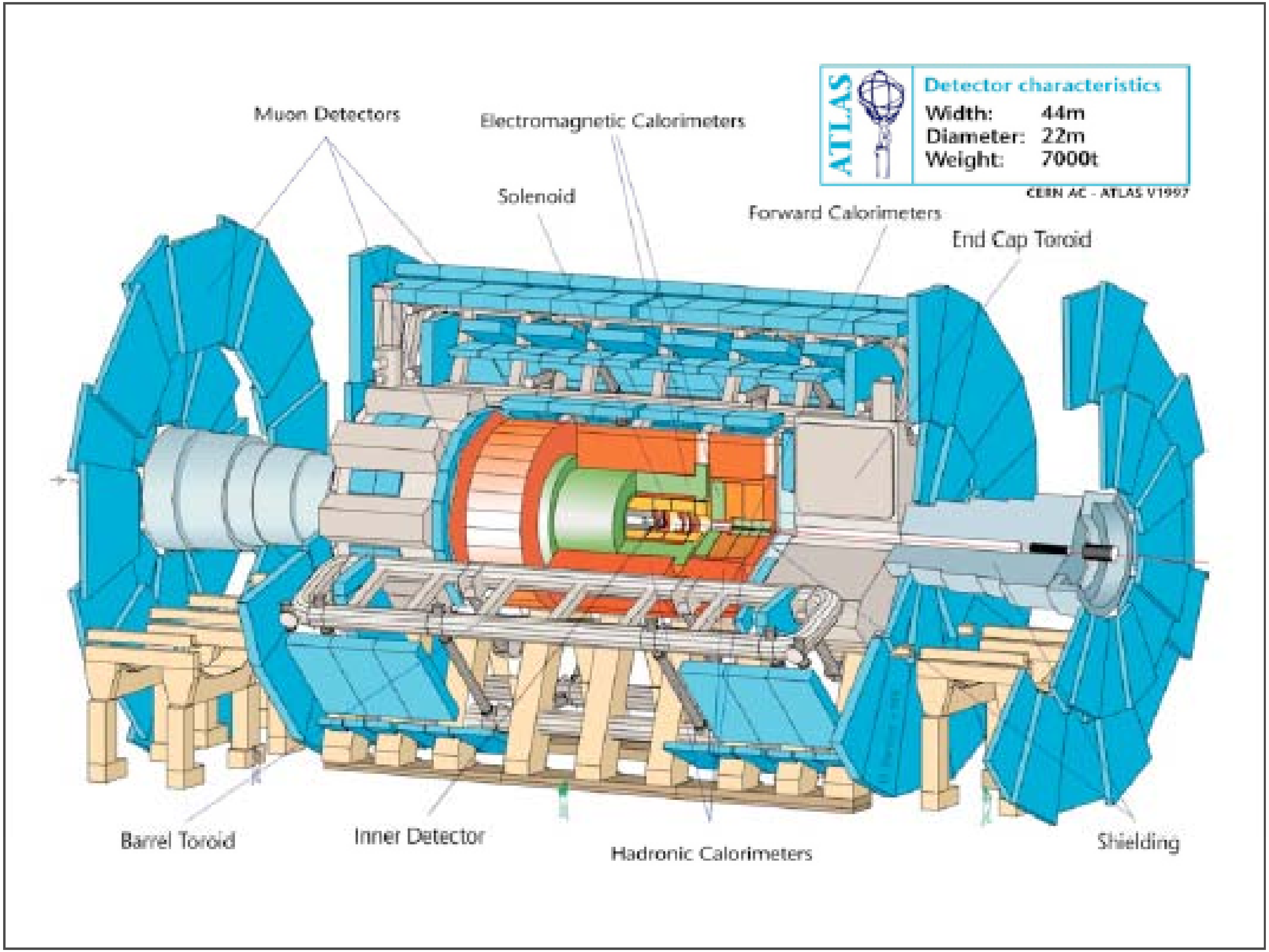
Ps: the typical energy of our life is keV, the energy of chemical reactions

Interlude: a brief recall of energy scales and kinematic relationships

$$m = \sqrt{E^2 + p^2} \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

- WARNING: for purists or non-experts: Energy, Masses and Momentum have different units, which turn to be the same since c (speed of light) is considered equal to one.
  - Energy[GeV], Momentum [GeV/c], Masses [GeV/c^2] (Remember golden rule, $E=mc^2$ has to be true also for units...)
- Just an as a rule of thumb: 0.511 MeV/c^2 (electron mass) corresponds to about 9.109 10^{-31} kg

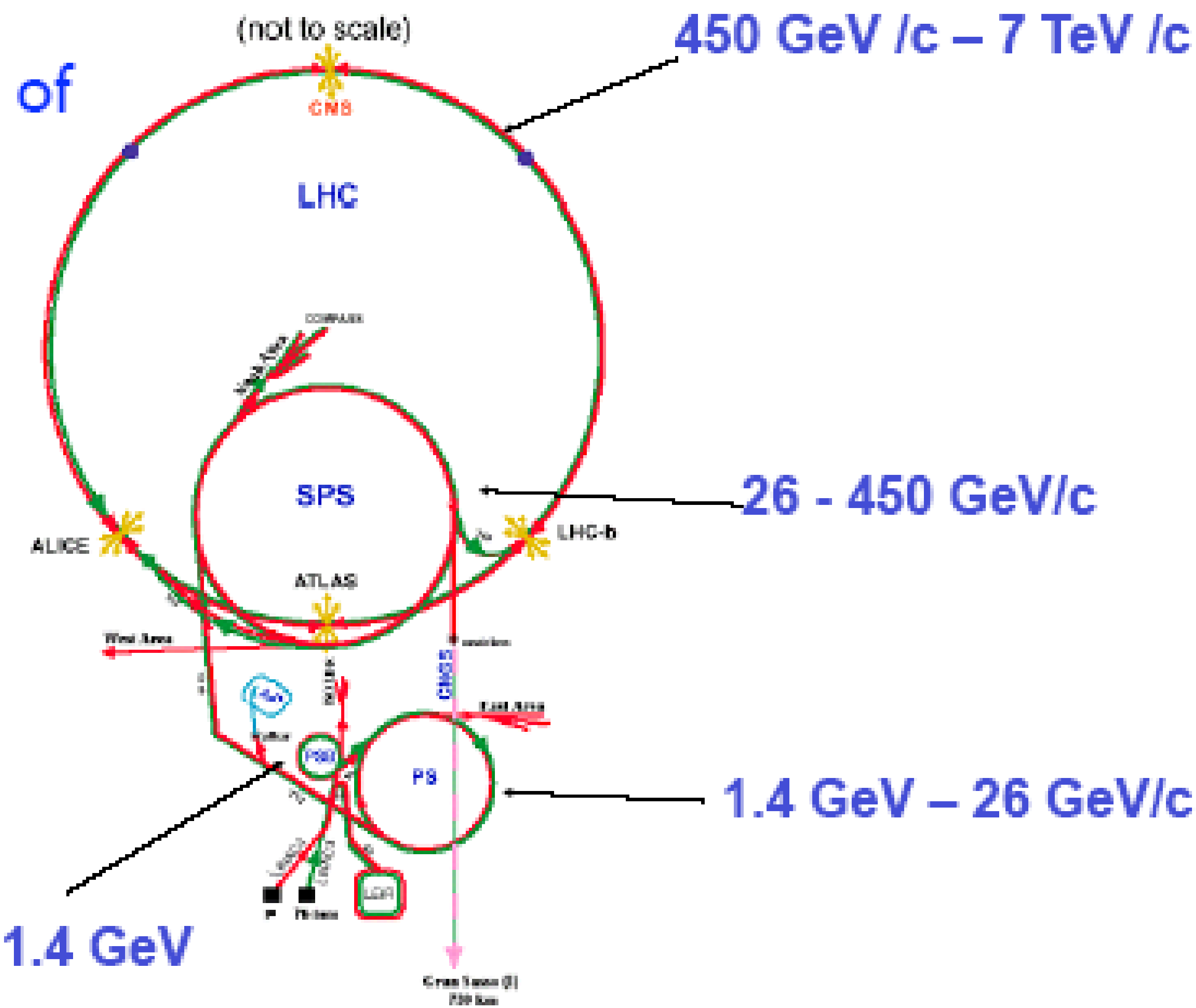

HARP experiment
Detector
Target
Beam

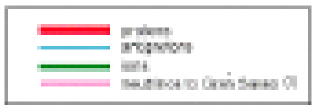


Muon Detectors
Electromagnetic Calorimeters
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

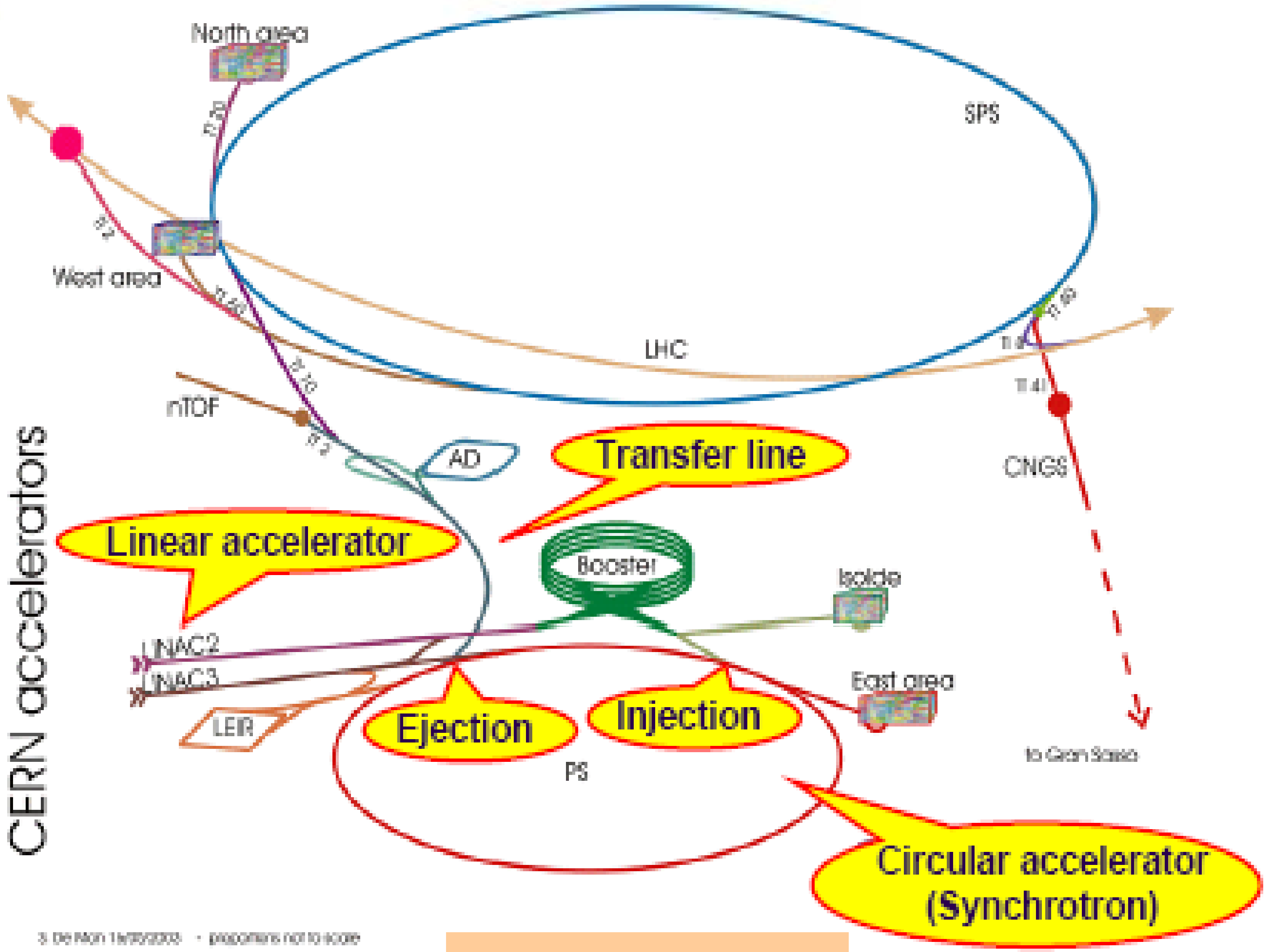
CERN accelerator complex overview

Chain/sequence of accelerators





LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso


CERN accelerators
North area
SPS
West area
LHC
nTOF
AD
Transfer line
CNGS
Linear accelerator
Booster
Isolde
LINAC2
LINAC3
East area
LEIR
Ejection
Injection
PS
to Gran Sasso
Circular accelerator
(Synchrotron)

LHC beam