# Teilchenbeschleuniger

## lecture for German Teachers Programme

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accelerator history

accelerator physics

CERN accelerators

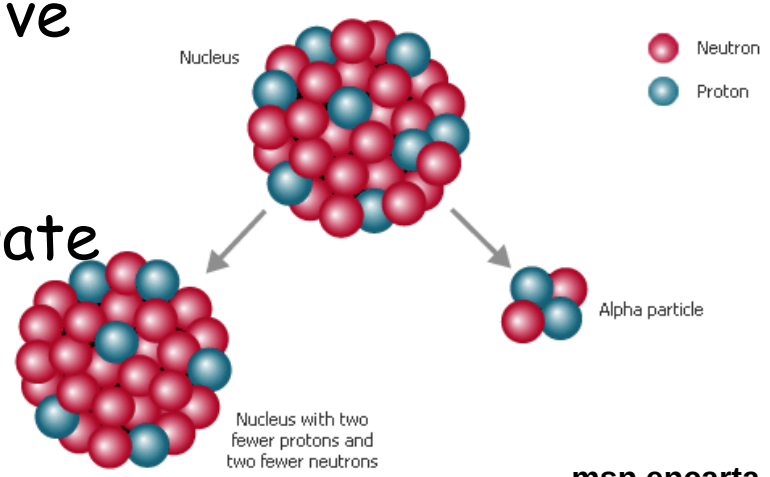
industrial applications

future accelerators

# why accelerators?

early experiments to probe matter used naturally occurring radioactive isotopes ($\alpha$ and $\beta$ particles);

upper energy limit ~10 MeV for $\alpha$ particles is insufficient to penetrate repulsive electrostatic energy barrier of most nuclei




msn encarta

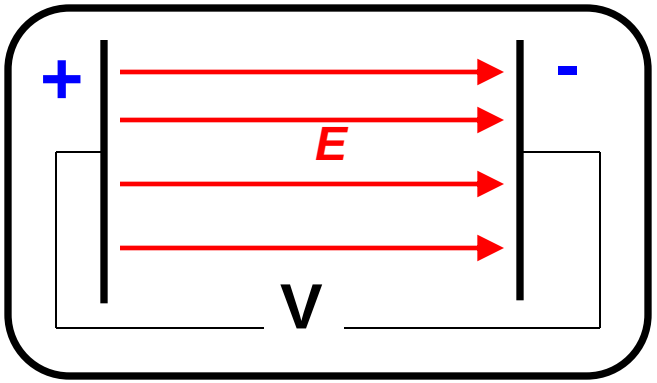
**Lord Rutherford (1927):**

*"What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power.*

*… **I see no reason why such a requirement cannot be made practical."***

# early accelerators – high voltage

simplest way to accelerate a particle is by using a battery




requires:
- source of high voltage
- accelerating tube

1927/28: Kurt Urban, Arno Brasch, and Fritz Lange tried to harness lightning in the Swiss Alps; they achieved 15 MV, but one of the three experimenters was fatally electrocuted

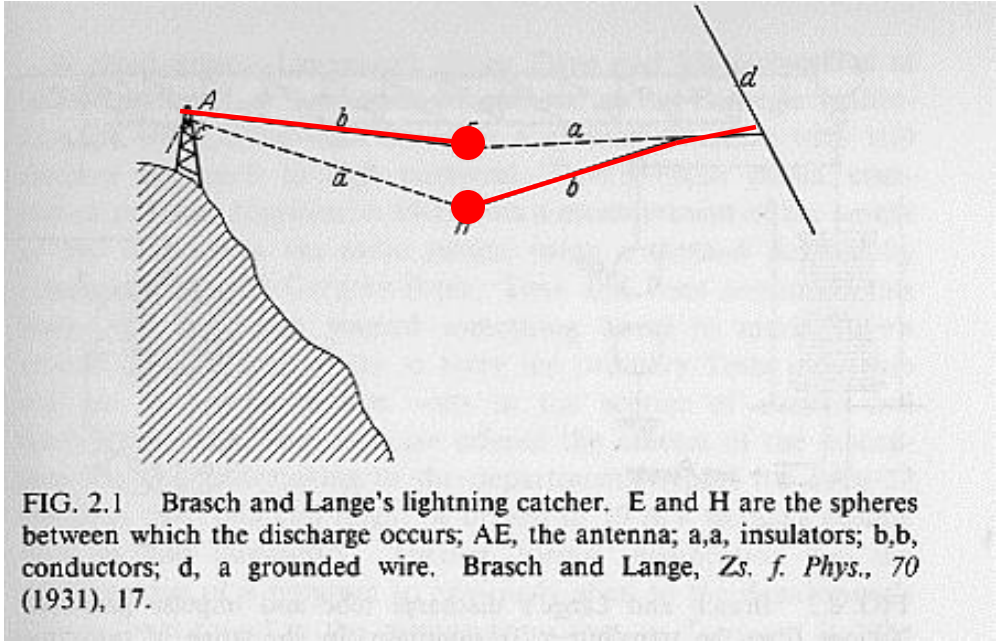
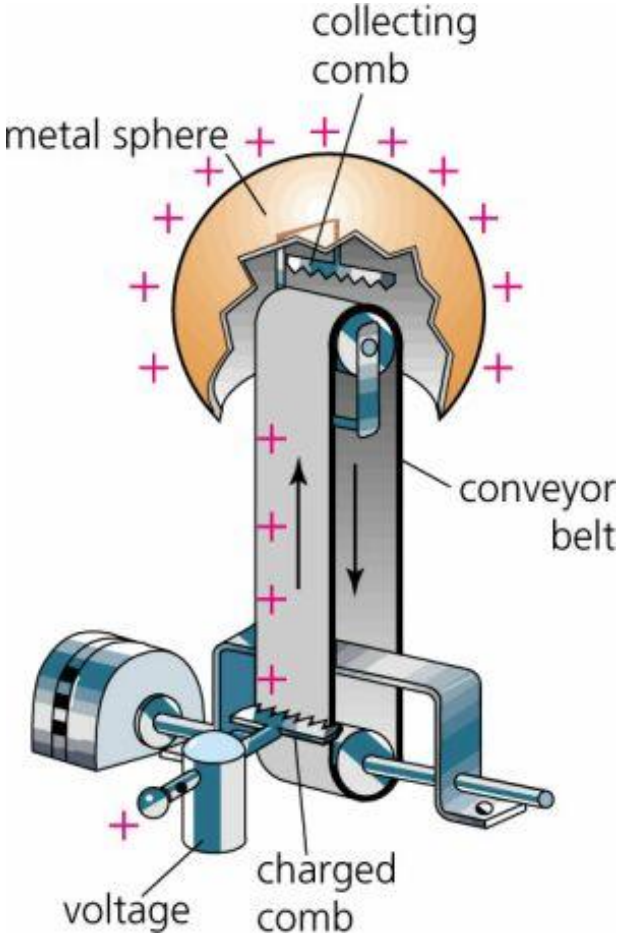



FIG. 2.1 Brasch and Lange's lightning catcher. E and H are the spheres between which the discharge occurs; AE, the antenna; a,a, insulators; b,b, conductors; d, a grounded wire. Brasch and Lange, *Zs. f. Phys., 70* (1931), 17.

# early accelerators – high voltage

electrostatic accelerator – Van de Graaff generator 1931

**Robert Jemison Van De Graaff 1901-1967**



**1933 MIT; 7 MV generator**

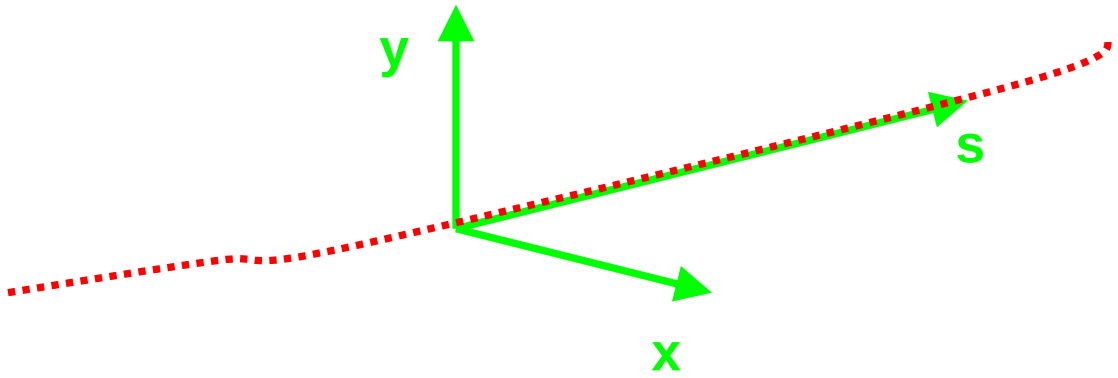
# accelerator: charged particles - beam- moving in electromagnetic field

Lorentz force

$$\vec{F}_{\text{Lorentz}} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Hamiltonian

$$H\left(\vec{x}, \vec{p}, t\right) = e\Phi\left(\vec{x}, \vec{p}, t\right) + c\left[\left(\vec{p} - e\vec{A}\left(\vec{x}, t\right)\right) + m_0^2 c^2\right]^{1/2}$$

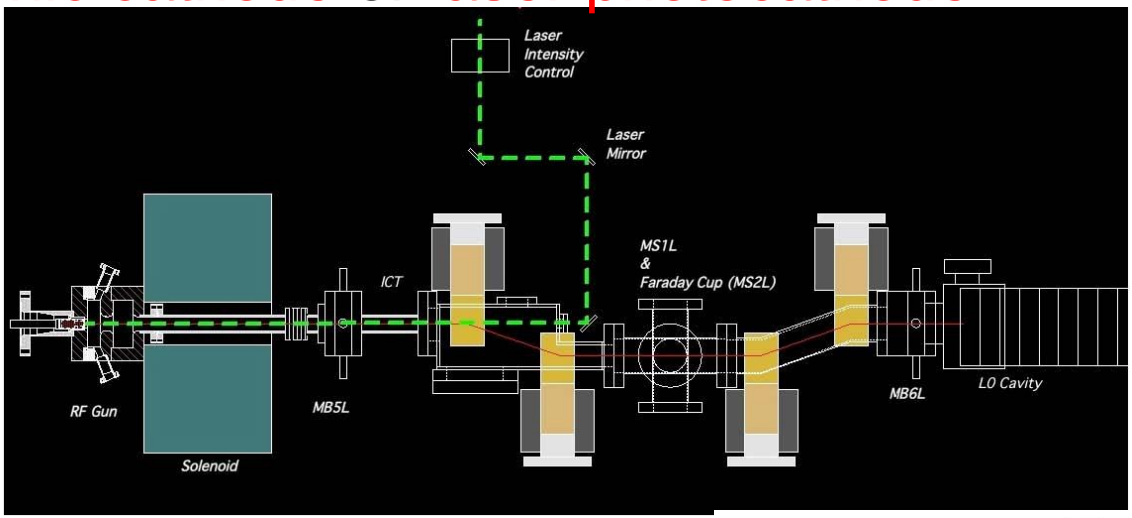


# which particles?

- ***e*⁺, *e*⁻** (former LEP, future CLIC)
- ***p*** (PS, SPS, LHC,…), $\overline{p}$ (former SPS collider)
- **heavy ions** - lead etc. (PS, SPS, LHC)
- **negative ions**, $H^-$ (future CERN linac)
- unstable particles (**μ, π, *K*, unstable isotopes**,…) – requiring rapid acceleration
- even **neutral beams** (e.g. *n*, using the neutron's magnetic dipole moment for steering… at BNL);
- **ν beams** (CERN to Gran Sasso)

# particle sources - examples

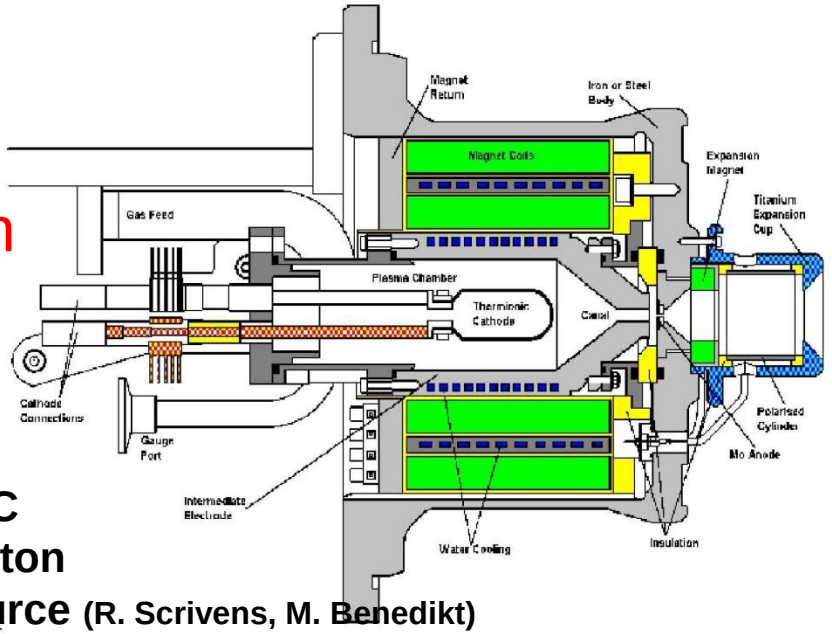
***e*$^-$**: thermionic cathode or laser photocathode




**laser rf e- gun at KEK ATF (N. Terunuma)**

***e*$^+$**: GeV e$^-$ beam on target, laser Compton source (proposed), sources based on synchroton radiation

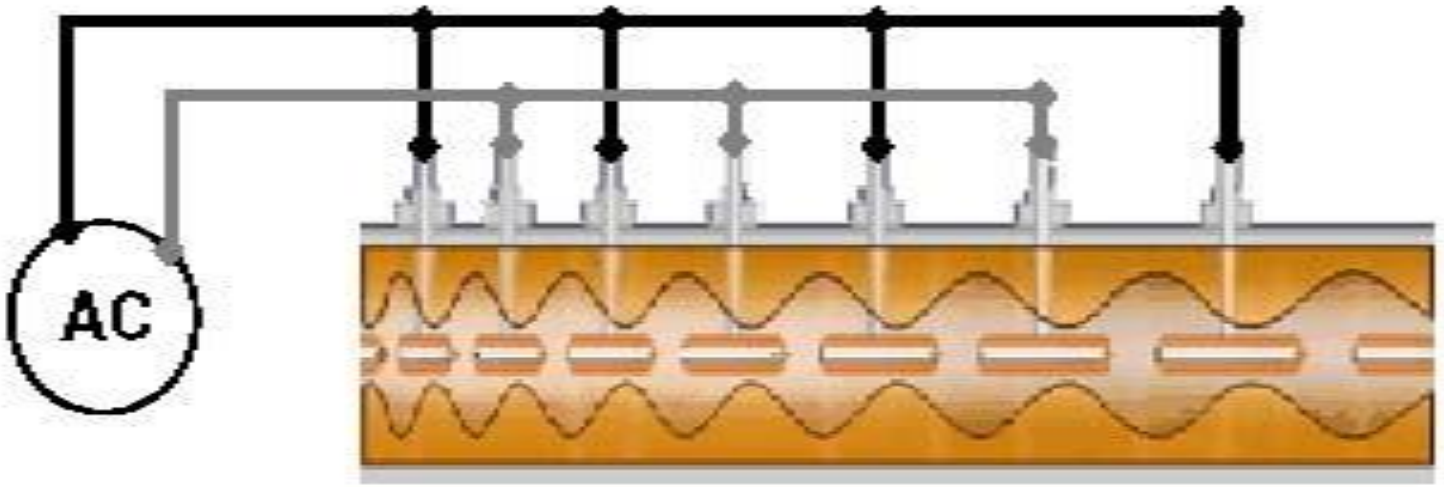
***p*** and ***ions***: plasma sources – static electric+magnetic fields + rf




**LHC proton source (R. Scrivens, M. Benedikt)**

# drift tube linear accelerator

1924 Ising, 1928 Wideroe, 50 keV *Na* & *K* ions (1 drift tube)
1931 Sloan and Lawrence, 2.8 MeV *Hg* ions (2 m, 36 drift tubes)
**acceleration occurs only in gap between electrodes**

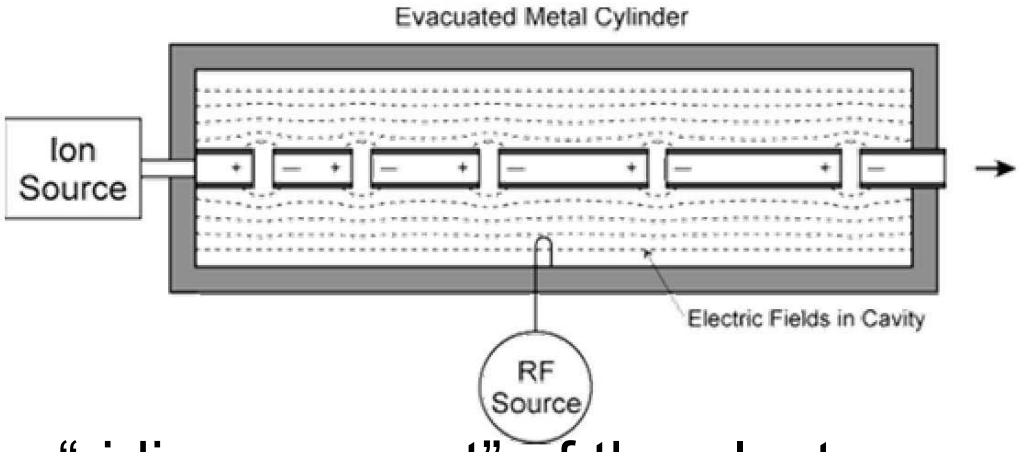



**particles arrive in bunches** timed to enter gap
when field is accelerating

while **particles are inside tube the field is reversed**

# Alvarez linear accelerator (1946)

**resonant behavior of cavity provides longitudinal electric field**




particles are “riding on crest” of the electromagnetic wave

possible due to the development of ultrahigh frequency technology (e.g. klystron) before and during World War II

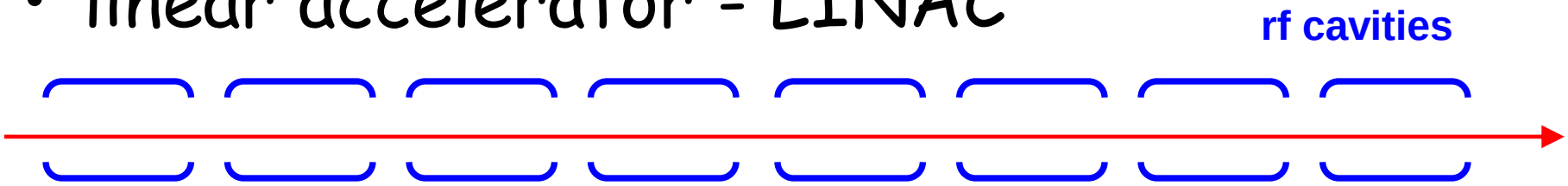
this is an example of **rf cavity accelerator**

used for protons and ions, for *p* energies 50-200 MeV

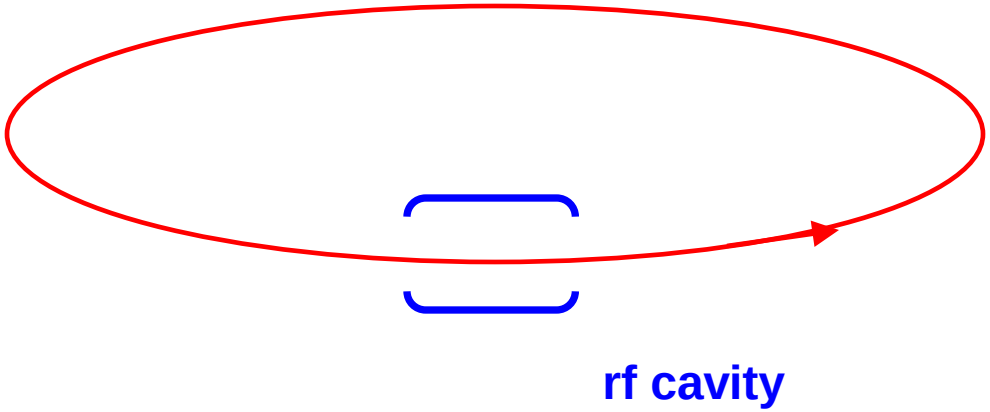
CERN Alvarez linac (50-MeV protons)

# main types of accelerators

- linear accelerator - LINAC




- circular accelerators: synchrotrons, storage rings



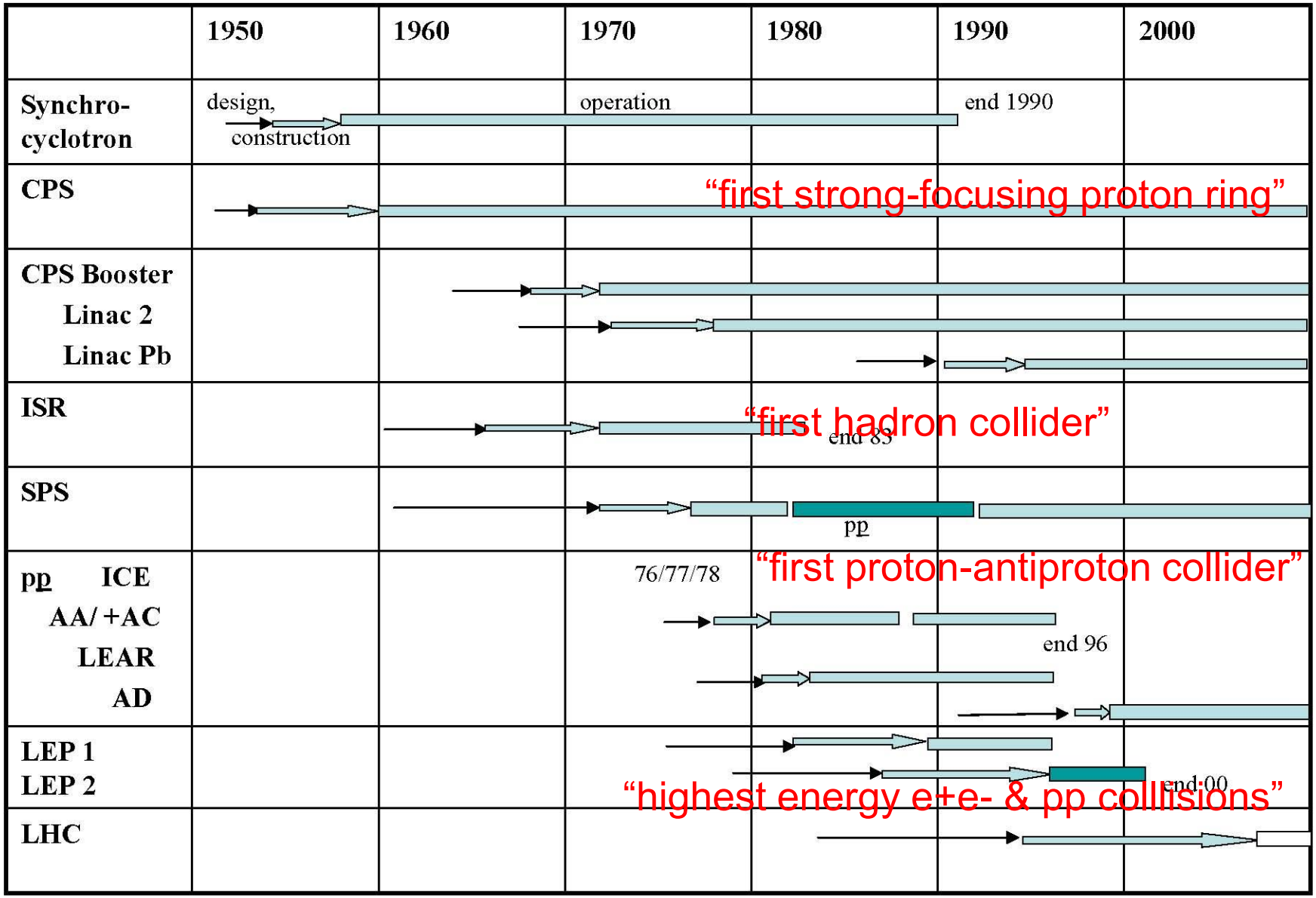

particles are accelerated many times by same rf cavity

# CERN accelerators

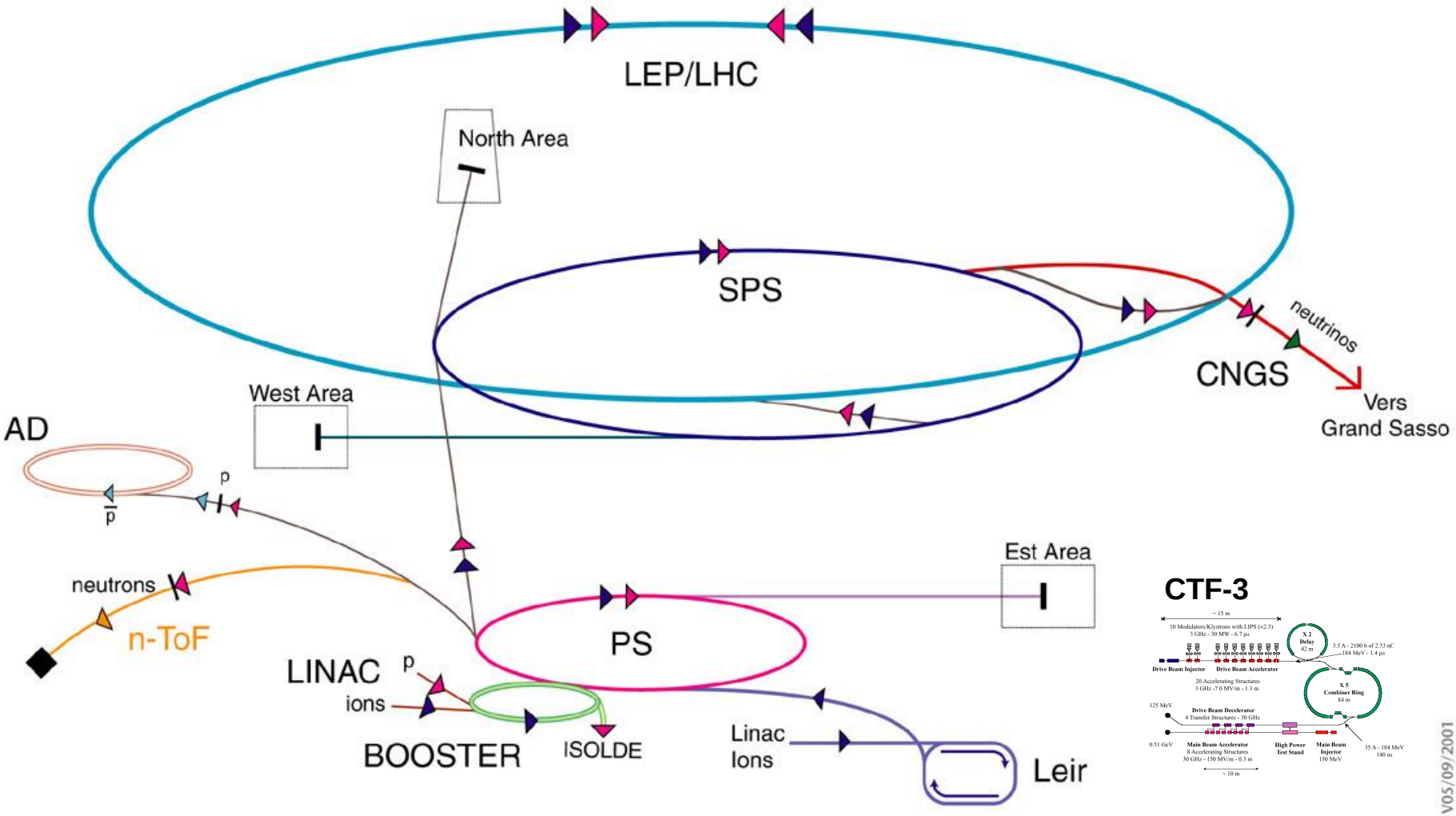
- PS – Proton Synchrotron (1959-)
- ISR - Intersecting Storage Rings (1971-1985)
- SPS – Super Proton Synchrotron (1976-)
- LEP – Large Electron-Positron storage ring (1989-2001)
- LHC – Large Hadron Collider (2008-)
- CLIC – Compact Linear Collider (?-)
- FCC – Future Circular Collider (?-)

K. Hubner

# Evolution of Accelerator Park



# Accelerator chain of CERN (operating or approved projects)




CTF-3

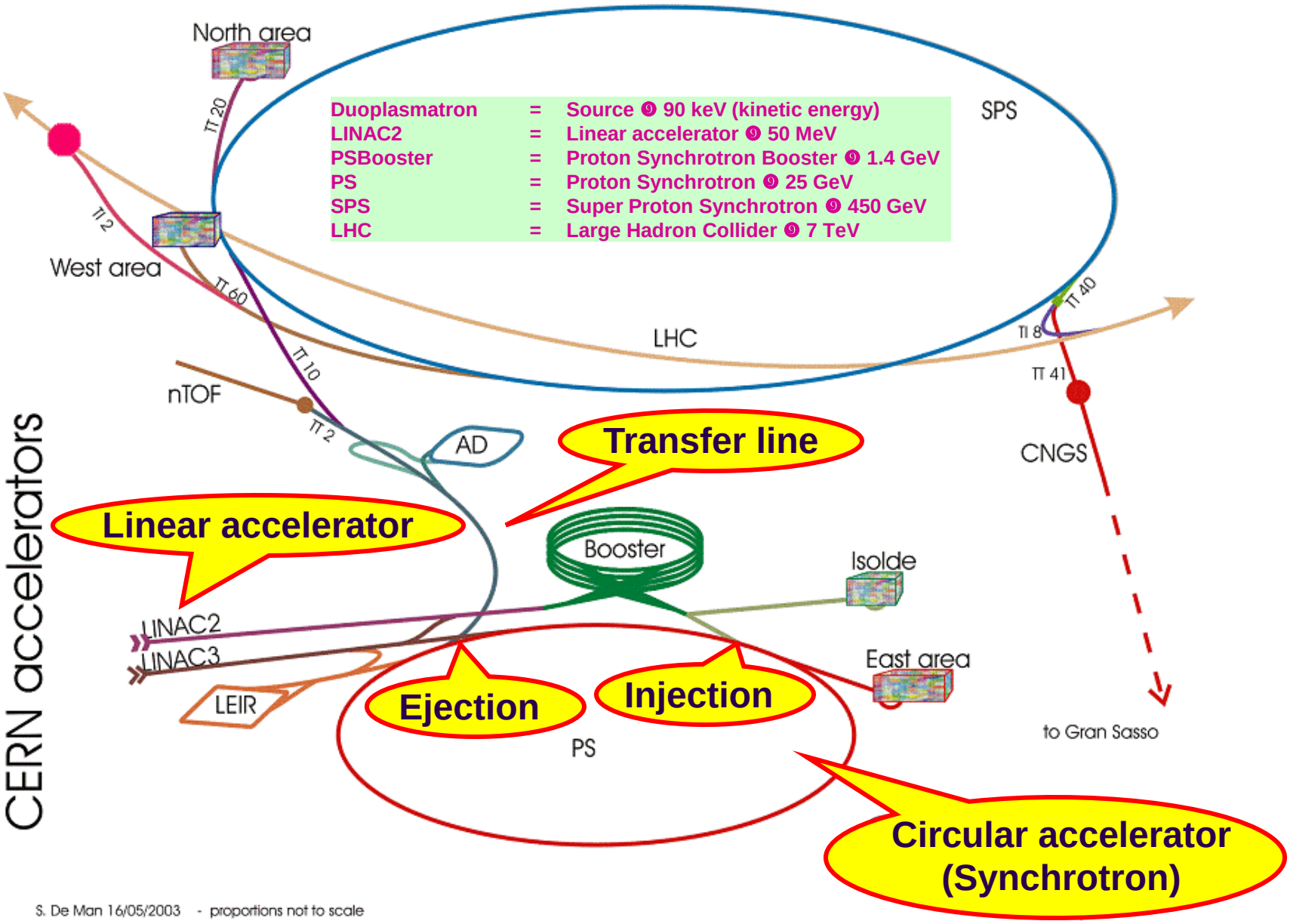


p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso

CERN AC_HF205_V05/09/2001




# LHC and its injector chain

# devices in accelerators

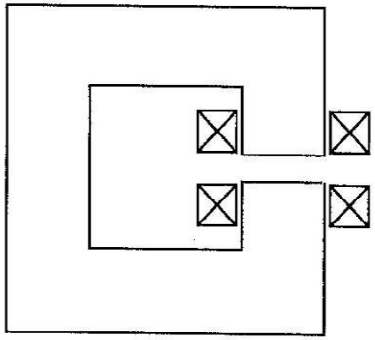
- dipole ***magnets*** → bending
- quadrupole magnets → focusing
- sextupole magnets → chromatic correction
- ***rf cavity*** → acceleration
- pulsed magnets for injection & extraction
- collimators & masks

magnets: normal-conducting coils + iron yokes, or materials with permanent magnetization, or **superconducting** (higher field)

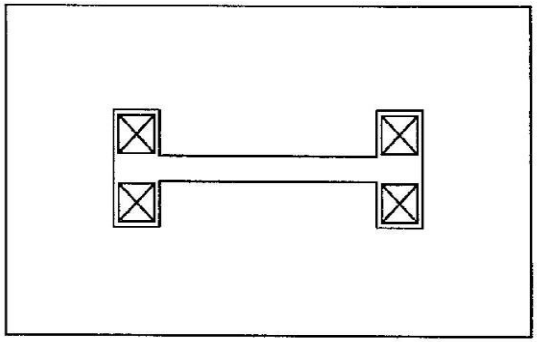
cavities: normal or **superconducting**

# dipole magnets with coils and Fe yokes

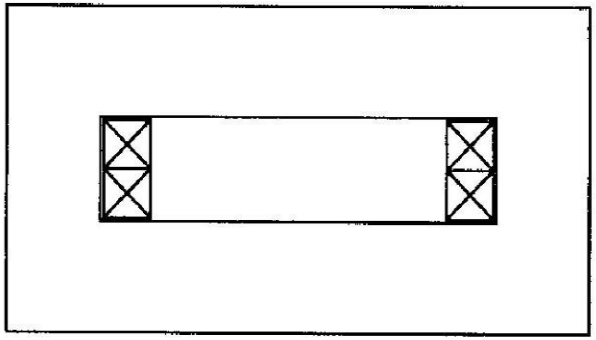
C-shape magnet:

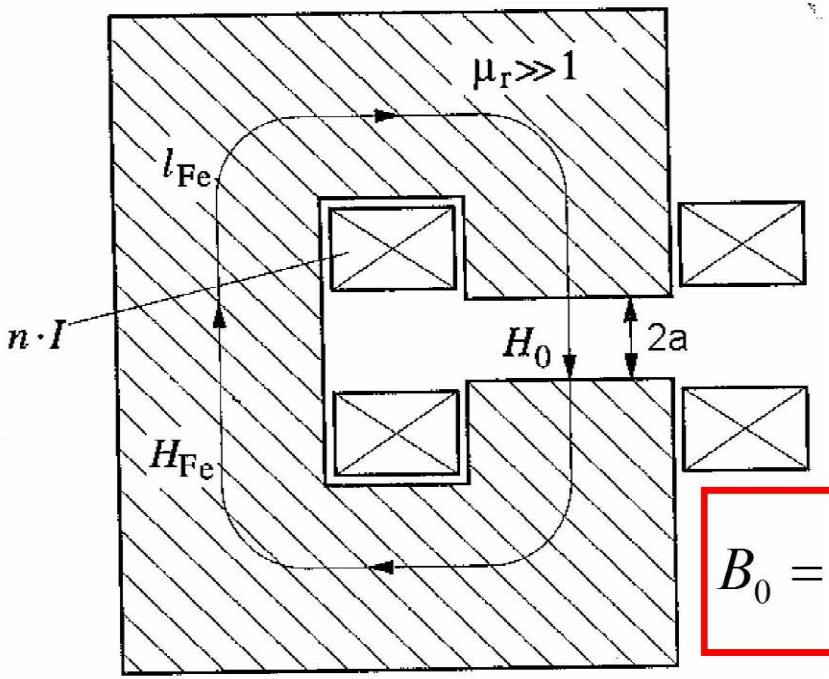


H-shape magnet:



Window frame magnet:






$$\vec{B}_\perp(\text{out}) = \vec{B}_\perp(\text{in})$$

$$\vec{H}_\perp(\text{out}) = \mu_r \vec{H}_\perp(\text{in})$$

$$2nI = \oint \vec{H} \cdot d\vec{s} = H_{Fe} l_{Fe} + H_0 2a$$

$$= \frac{1}{\mu_r} H_0 l_{Fe} + H_0 2a \approx H_0 2a$$

$$B_0 = \mu_0 \frac{nI}{a}$$

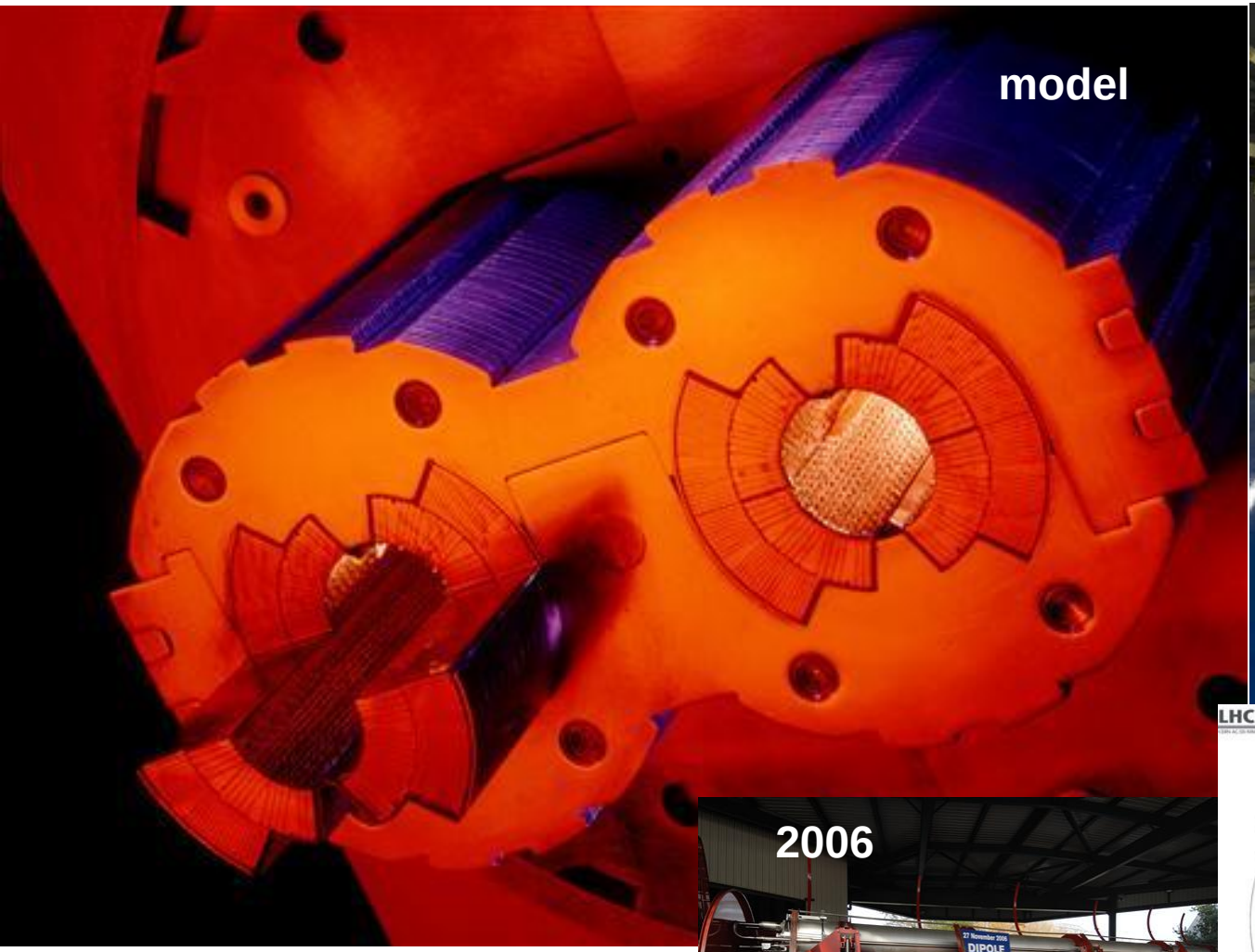
Dipole strength: $\frac{1}{\rho} = \frac{q\mu_0}{p} \frac{nI}{a}$

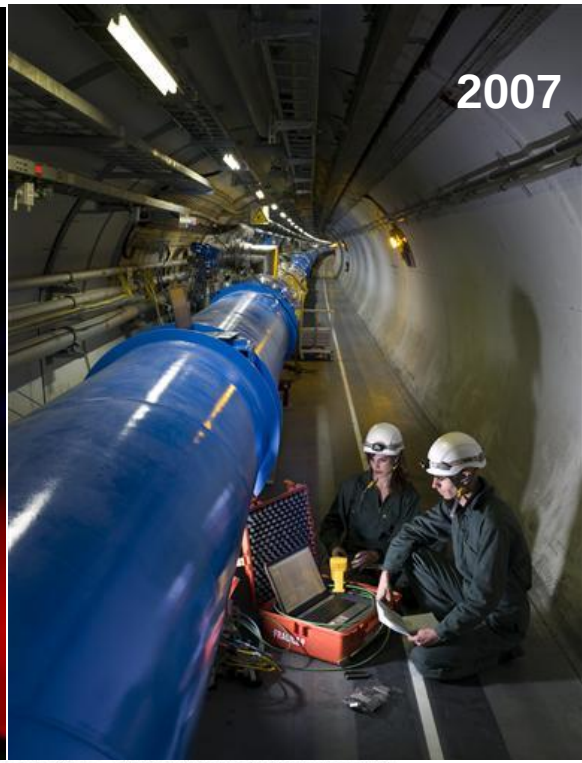
# SPS dipole magnet – 2 T

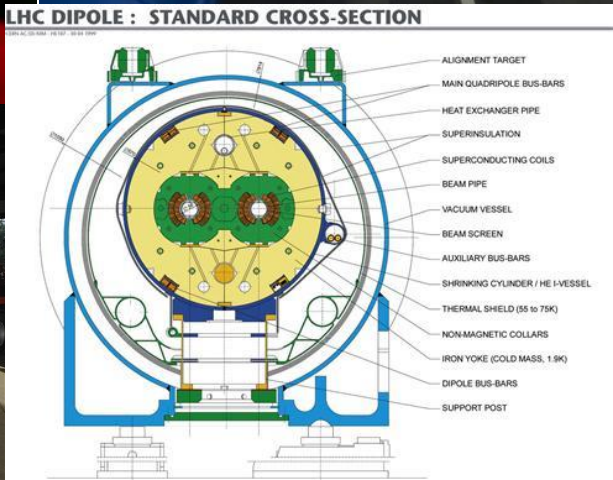
1973

1974

# LHC s.c. dipole magnet – 8.33 T

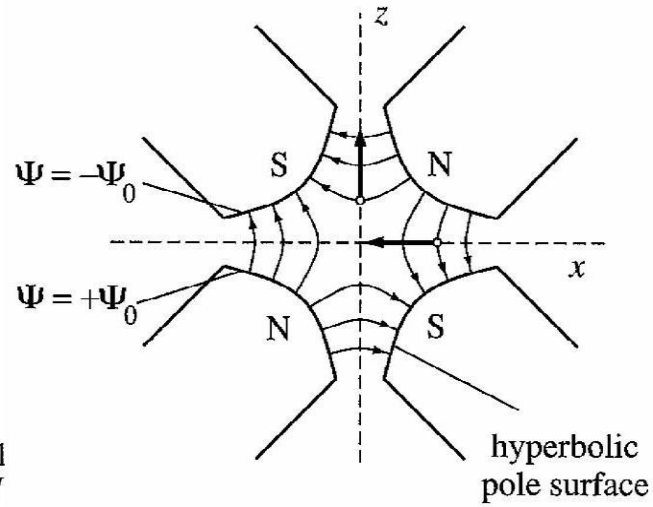


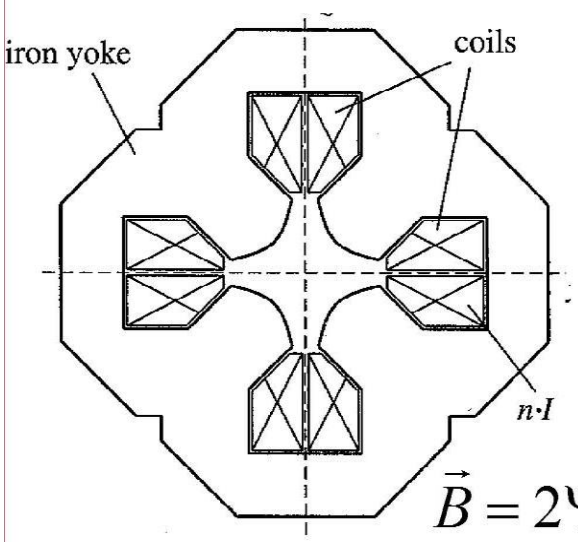



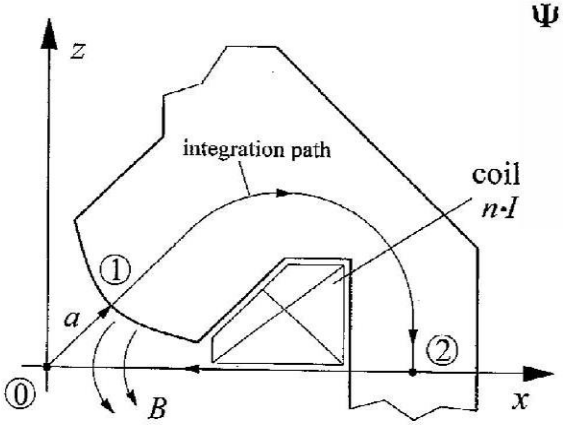


# quadrupole magnets with coils & Fe yokes

$$\psi = -\Psi_2 \cdot 2xy \quad \Rightarrow \quad \text{Equipotential: } x = \frac{\text{const.}}{y}$$



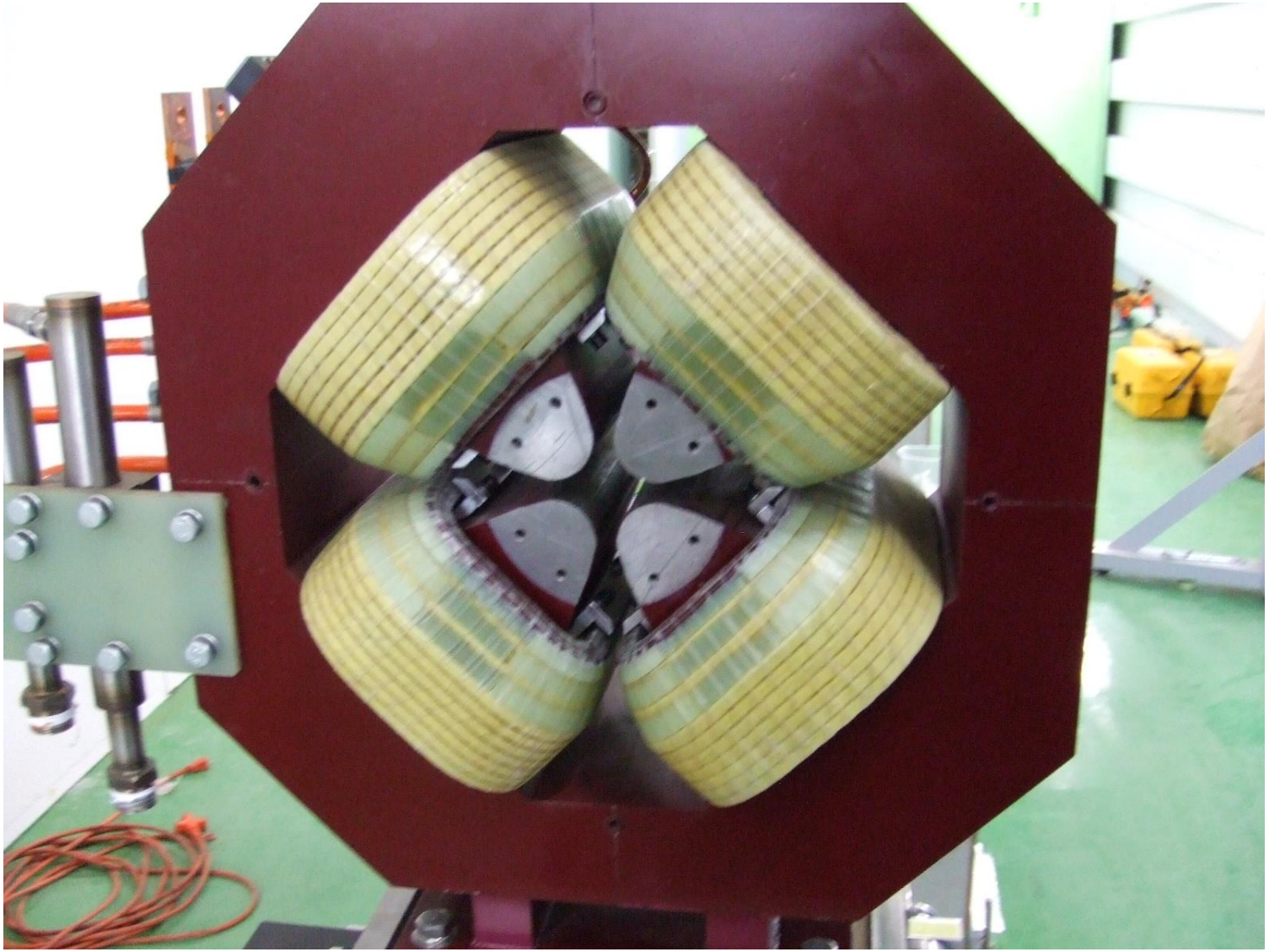

$$\vec{B} = 2\Psi_2 \begin{pmatrix} y \\ x \end{pmatrix} \quad \Rightarrow \quad \vec{B}(0 \mapsto 1) = 2\Psi_2 r\, \vec{e}_r$$

Quadrupole strength:

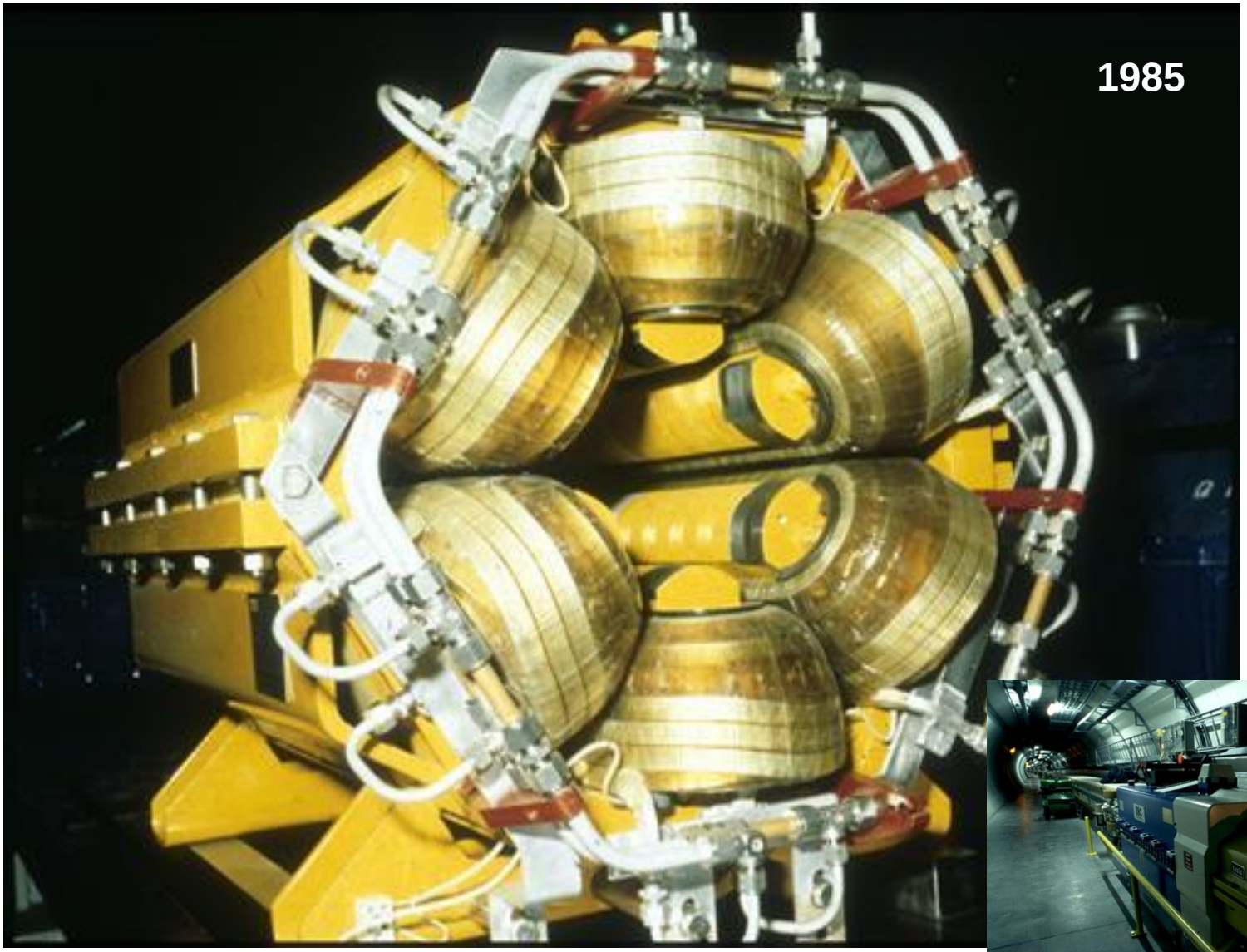
$$nI = \oint \vec{H} \cdot d\vec{s} \approx \int_0^a H_r dr = \Psi_2 \frac{a^2}{\mu_0}$$

$$k_1 = \frac{q}{p} \partial_x B_y \Big|_0 = \frac{q\mu_0}{p} \frac{2nI}{a^2}$$

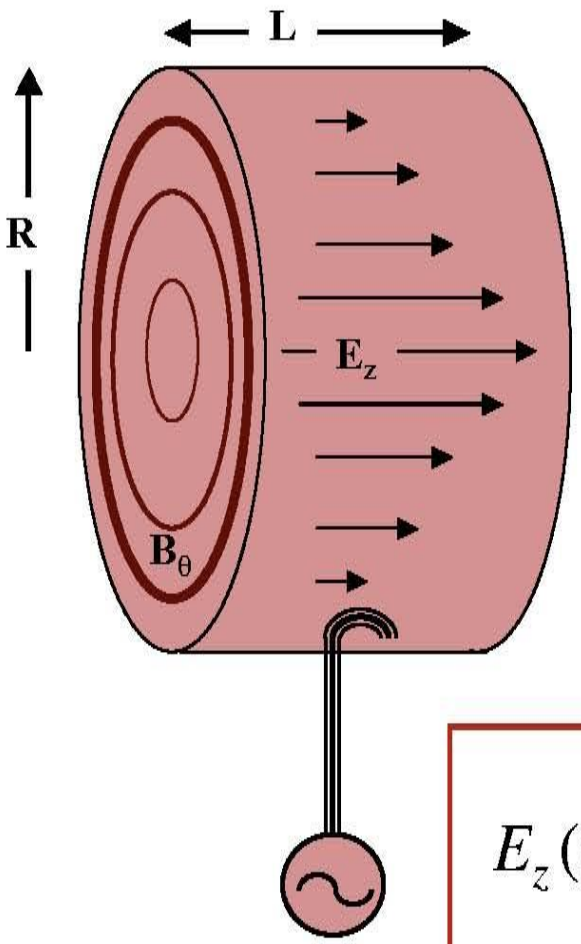
# quadrupole magnet in KEK-ATF2

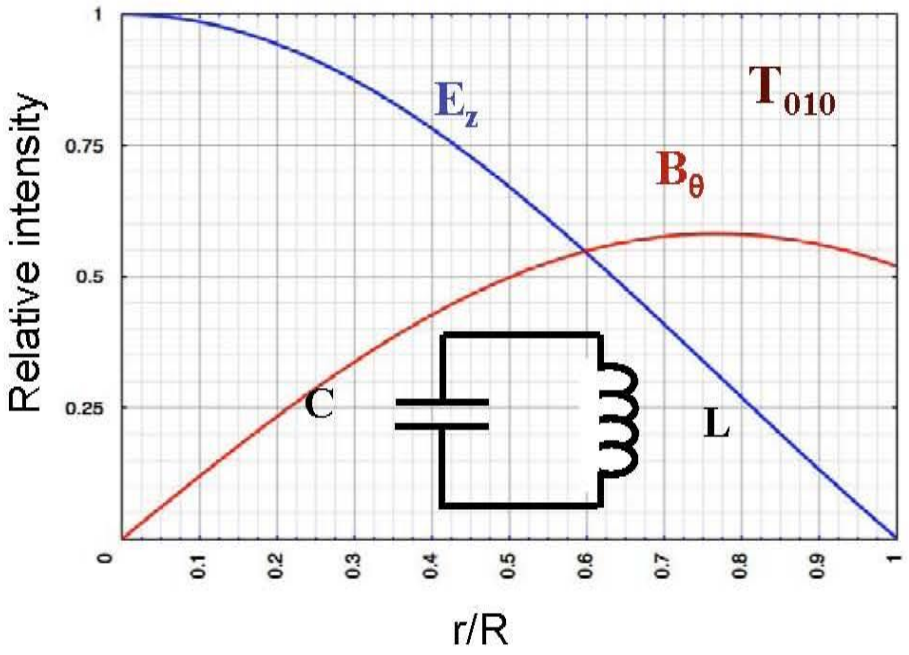


# LEP sextupole magnet



# “pillbox” model of rf cavity




$$E_z(r) = E_o\, J_o\left(\frac{\omega}{c} r\right) \quad \Longrightarrow \quad \omega = 2.405\,\frac{c}{R}$$

# LEP accelerating cavity

# … and there are also some German physicists at CERN

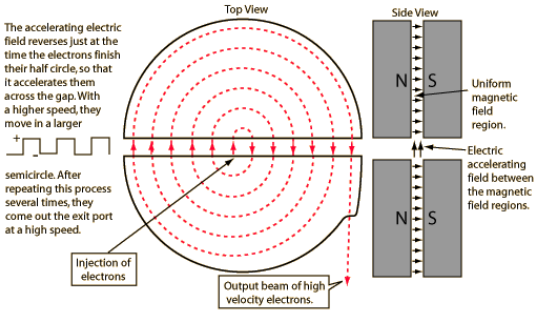
29. April 2008

# … and sometimes German presidents

2. April 2014

# 4 milestones in accelerator physics

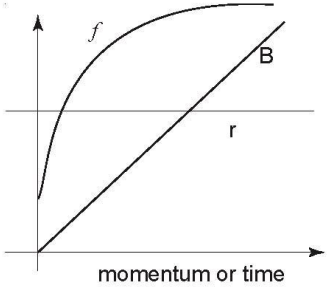
- cyclotron
  (1929, 1930)



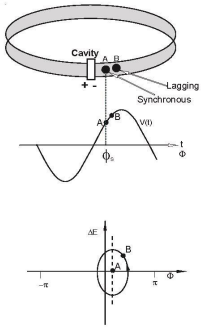

acc. el. field reverses each half circle

- synchrotron
  (1934, 1943, 1944, 1945)

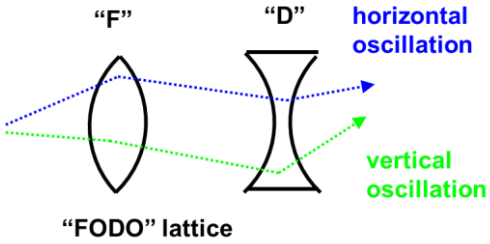
rf frequency changes with magnetic field so as to keep particles on a constant circle




"phase stability"




- strong focusing
  (1950, 1952, 1959: **PS**)



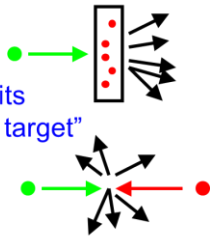

novel idea: combination of two lenses focuses in both planes simultaneously

- colliding beams
  (1943, 1956, 1961, 1971: **ISR**)

centre-of-mass energy:

$$E_{\mathrm{c.m.}} = \sqrt{2E_{\mathrm{beam}}M_{\mathrm{target}}c^2}$$ beam hits a "fixed target"

$$E_{\mathrm{c.m.}} = 2E_{\mathrm{beam}}$$ two beams collide



much higher c.m. energies than for fixed target

aerial view of the CERN ISR around 1971

CERN ISR ~1971
8

# beam optics in circular machines

- linear optics described by periodic **Hill's equation**

$$x'' + K(s)x = 0$$

where $x' \equiv \frac{p_x}{p_s}$ and $K(s) = K(s + C)$

**s: longitudinal coordinate**
**C: circumference**

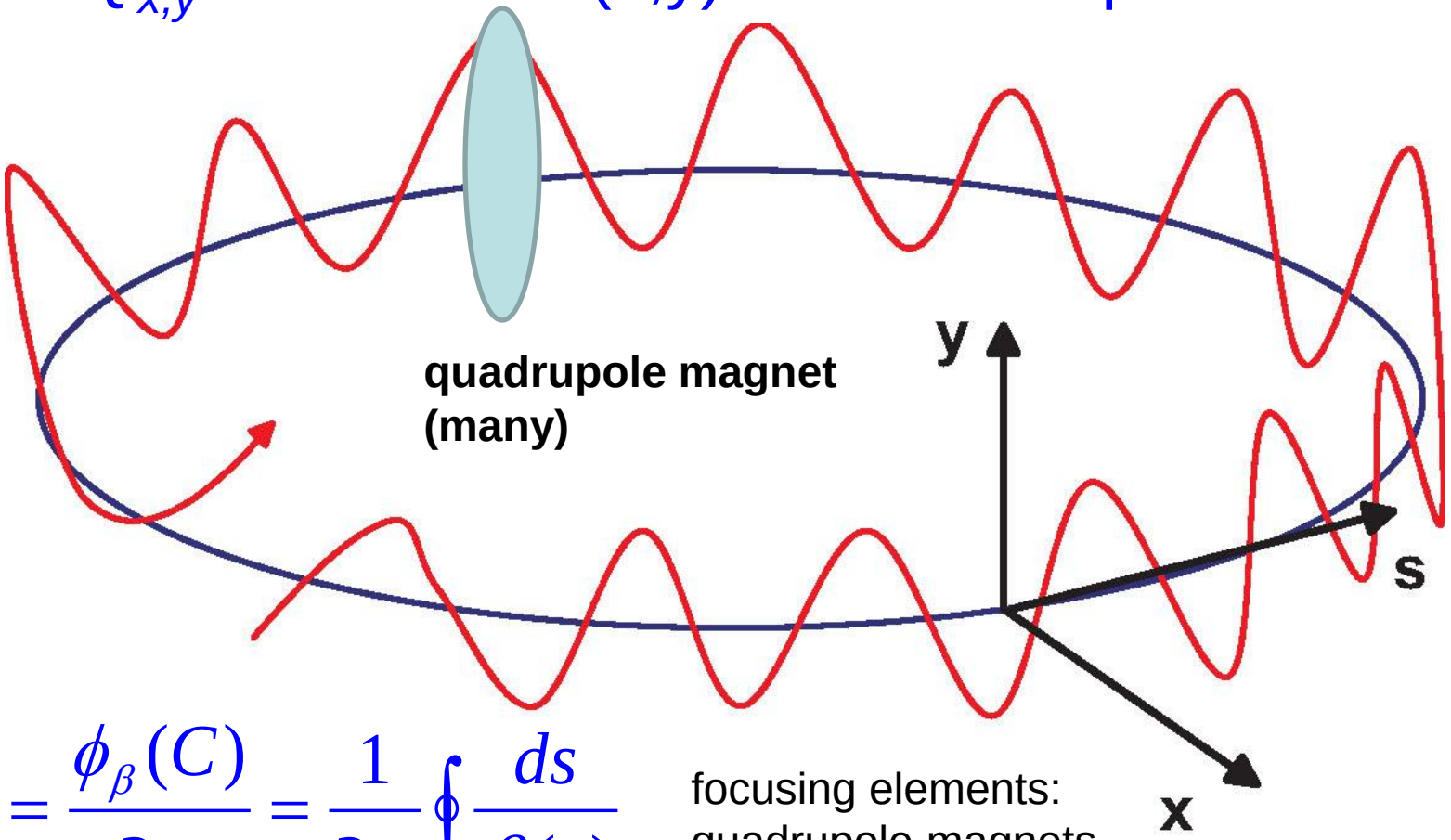
- solutions of Hill's equations very similar to Bloch waves ("periodic function" x "plane wave") in solid-state crystals; accelerator representation as "beta function"

$$x(s) = A_0 \sqrt{\beta(s)} \cos\left( \int_0^s \frac{ds'}{\beta(s')} + \phi_0 \right)$$

**$A_0$ & $\phi_0$: constants determined by initial conditions**

schematic of **betatron oscillation** around storage ring

**tune** $Q_{x,y}$= number of (x,y) oscillations per turn




$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

focusing elements:
quadrupole magnets

$$\sigma(s) = \sqrt{\frac{\beta(s)\varepsilon_N}{\gamma}}$$

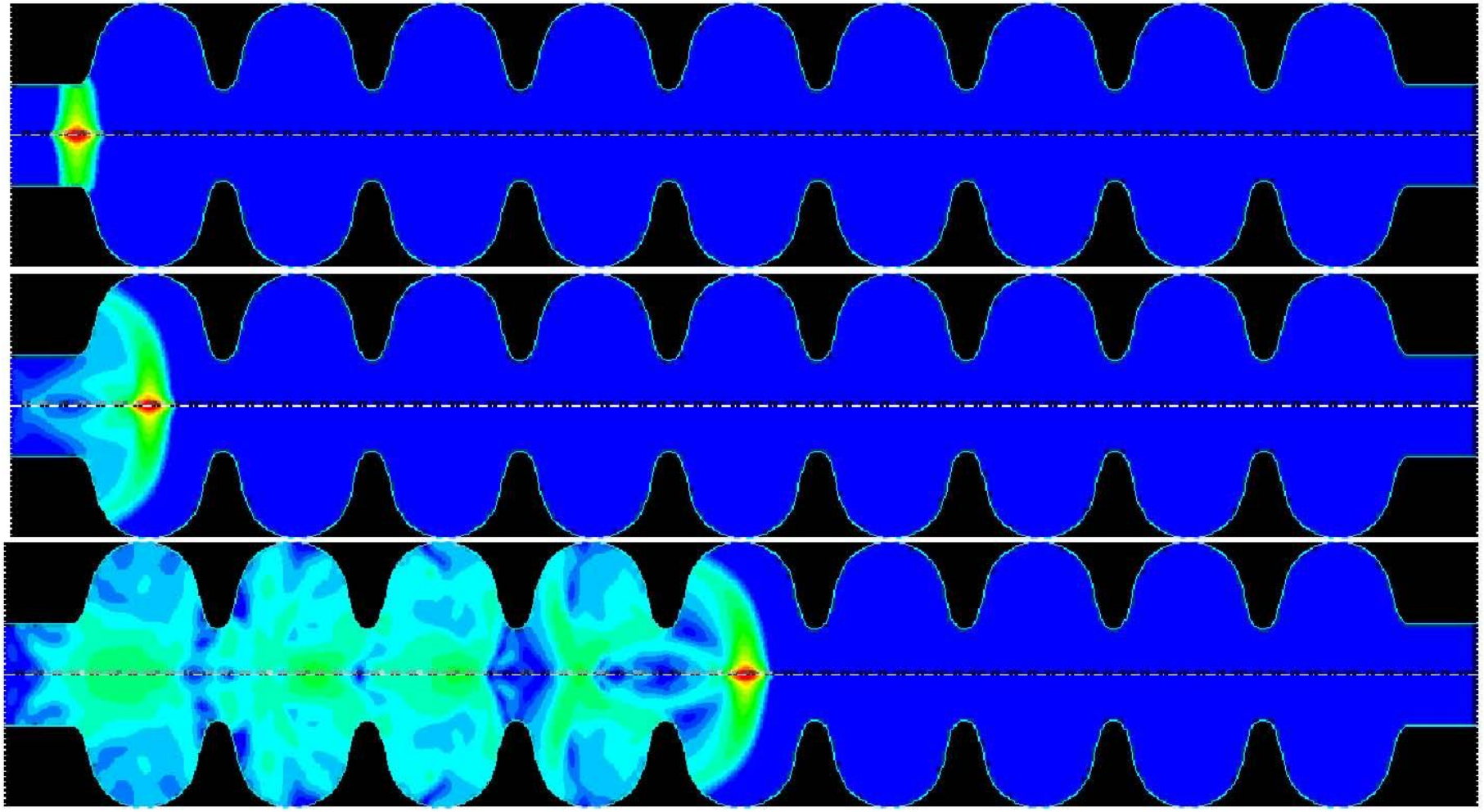
# *beam particles are like elephants…*

- they have good memory
- they won’t forgive you
- they are easily perturbed and mistakes add up

# *… and they are not alone!*

particles do not move independently;
many of the limits of accelerator performance arise from interactions between beam particles = ***collective effects***

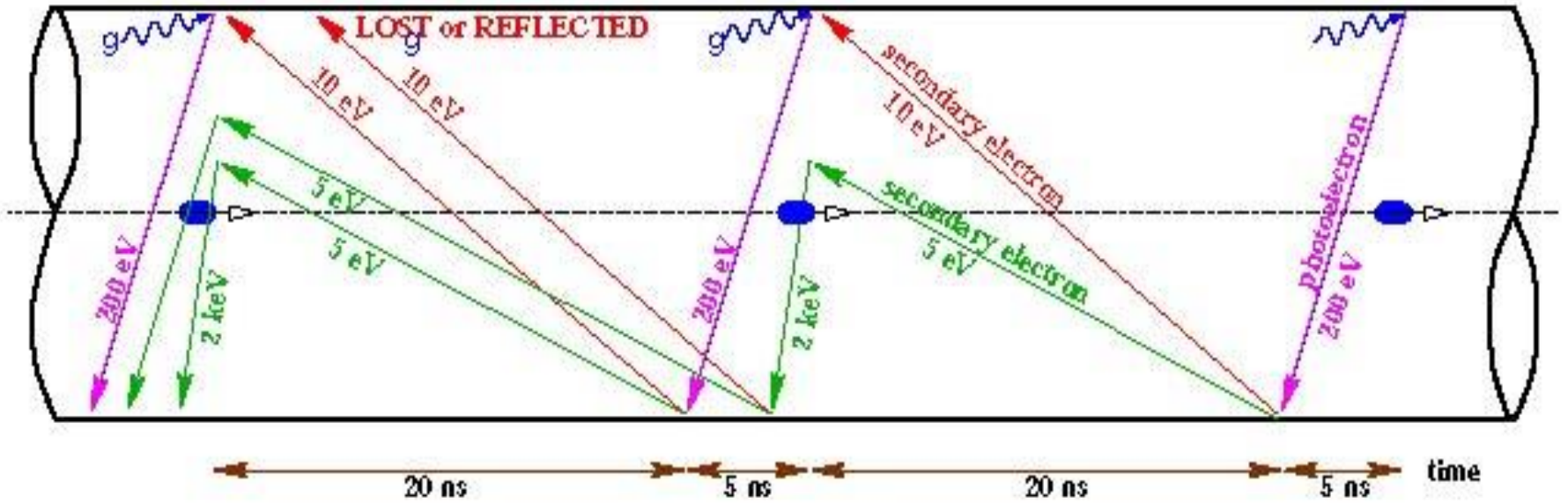
# example - “wake fields”



D. Trines, Bodrum 2007

electromagnetic field induced by the beam
can act back on later particles or on later turns
→ instability (similar wakes driven by ions & e-)

# electron cloud in the LHC

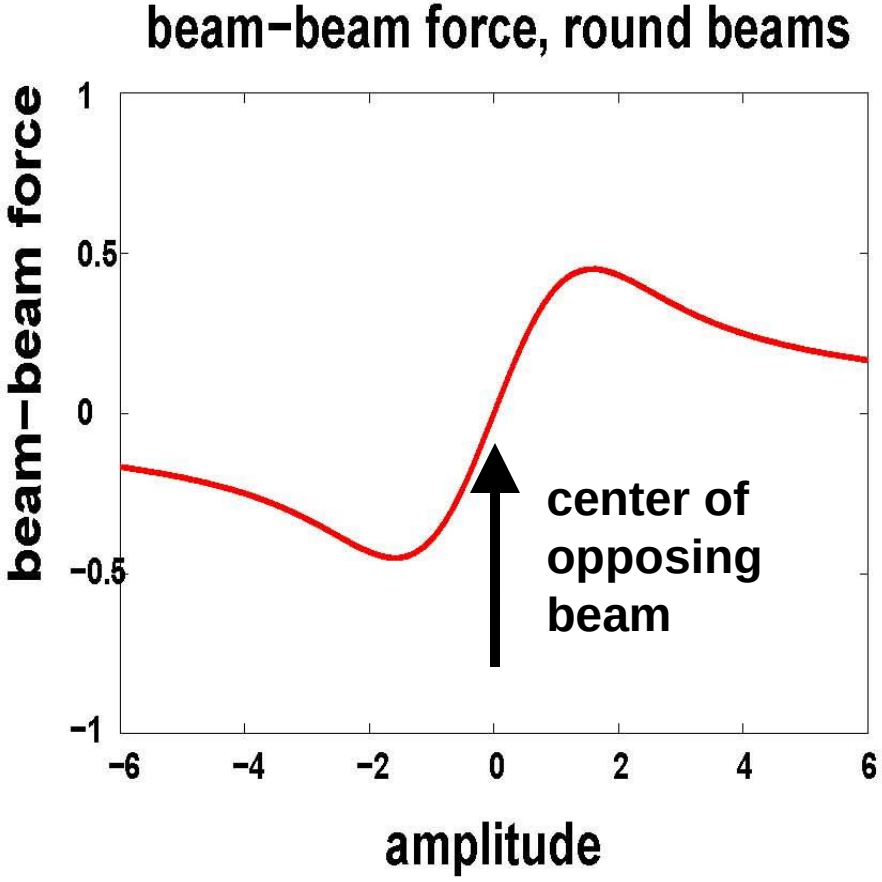



schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

[F. Ruggiero]

→ beam instabilities

# (nonlinear) beam-beam force




W. Herr

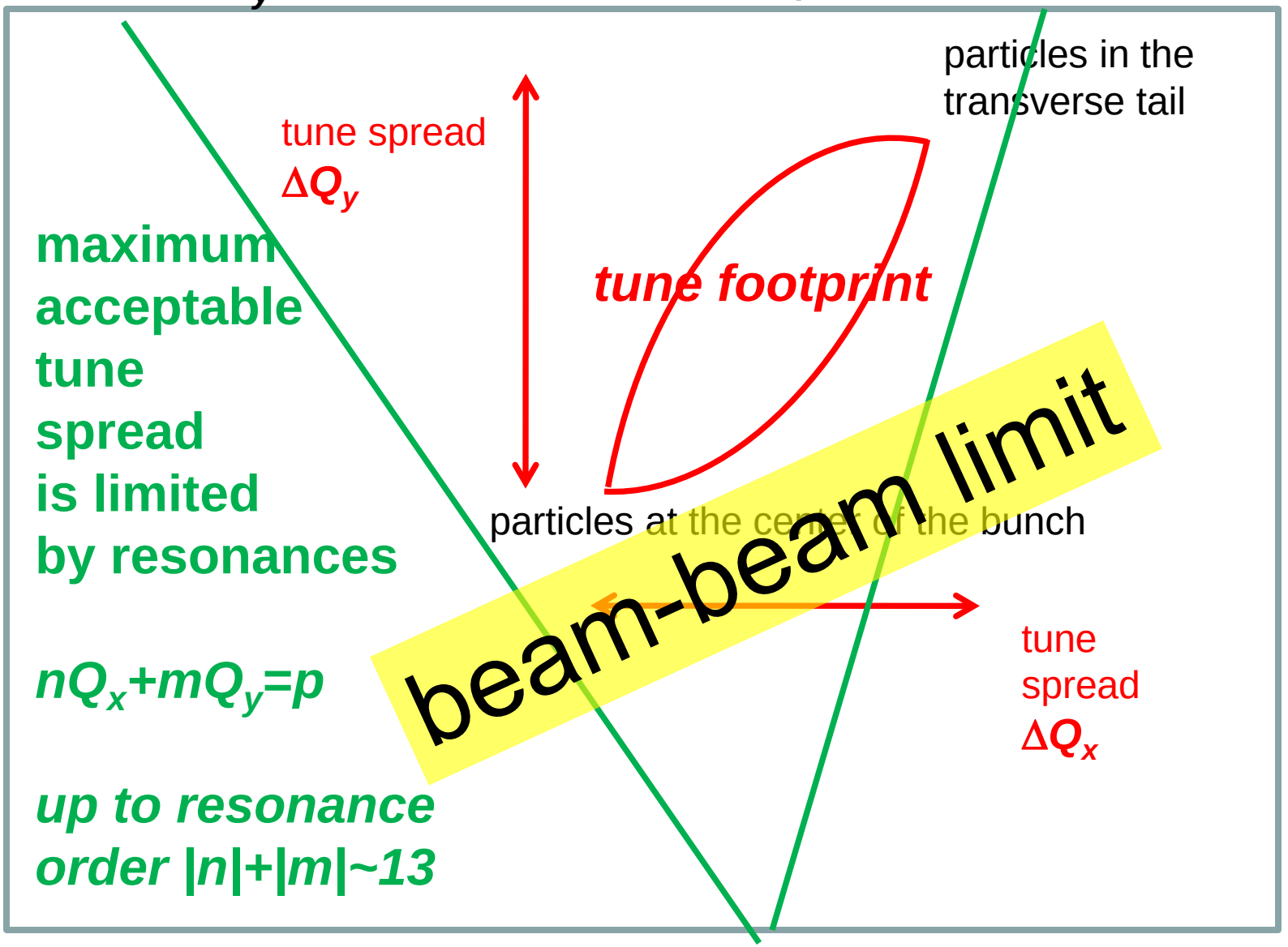
- Force varies strongly with amplitude
- Exponential function:
- Contains many high order multipoles

at small amplitude similar to effect of defocusing quadrupole

for pure head-on collision

$$\Delta Q_{x.y;\max} = \xi_{x,y} = \frac{2N_b r_0 \beta^*}{4\pi\gamma\left(2\sigma^{*2}\right)} = \frac{N_b}{\varepsilon_N}\frac{r_0}{4\pi}$$

for single collision (nominal LHC ~0.0033


vertical tune $Q_y$
beam-beam tune spread from head-on collisio
particles in the transverse tail
tune spread $\Delta Q_y$
maximum acceptable tune spread is limited by resonances
$nQ_x+mQ_y=p$
up to resonance order $|n|+|m|\sim13$
tune footprint
particles at the center of the bunch
beam-beam limit
tune spread $\Delta Q_x$
horizontal tune $Q_x$

# accelerator physics

# the LHC

# *short LHC history*

**1983 *LEP Note 440*** - S. Myers and W. Schnell propose twin-ring *pp* collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle

1992 EoI, LoI of experiments

1993 SSC termination

**1994 CERN Council: LHC approval**

1995-98 cooperation w.Japan,India,Russia,Canada,&US

2000 LEP completion

2006 last s.c. dipole delivered

**2008 first beam**

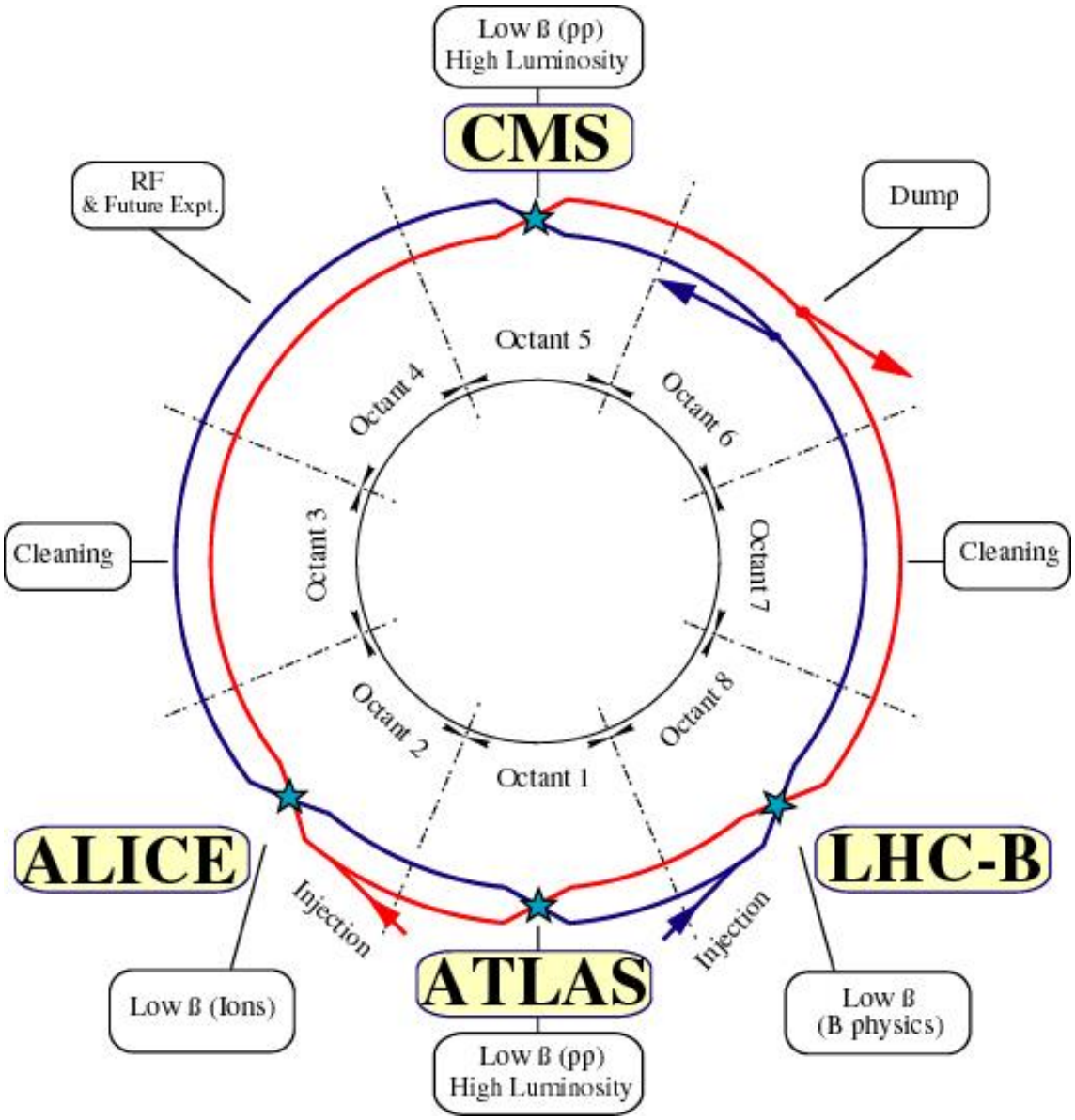
**2010 first collisions at 3.5 TeV beam energy**

**2015 collisions at ~design energy (plan)**

***>30 years!***

**now is the time to plan for ~2040**

# LHC: highest energy *pp*, *AA*, and *pA* collider




**design parameters**

c.m. energy = 14 TeV (*p*)
luminosity =$10^{34}$ cm$^{-2}$s$^{-1}$

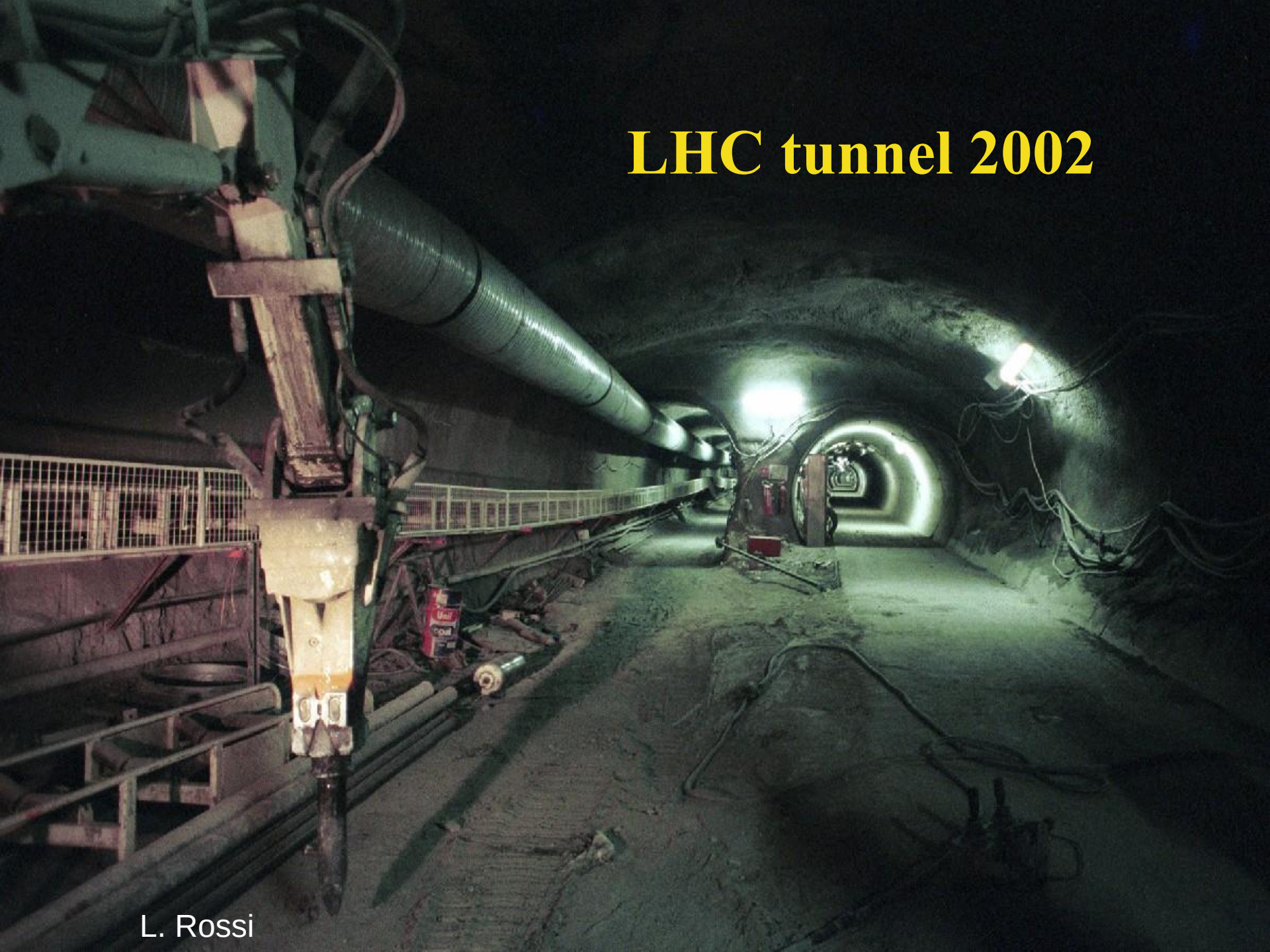
1.15x$10^{11}$ p/bunch
2808 bunches/beam

360 MJ/beam

$\gamma\varepsilon$=3.75 $\mu$m
$\beta^*$=0.55 m
$\theta_c$=285 $\mu$rad
$\sigma_z$=7.55 cm
$\sigma^*$=16.6$\mu$m

# all s.c. magnets were tested in “SM18”

# LHC magnets stored on parking lots before installation


LHC tunnel 2002

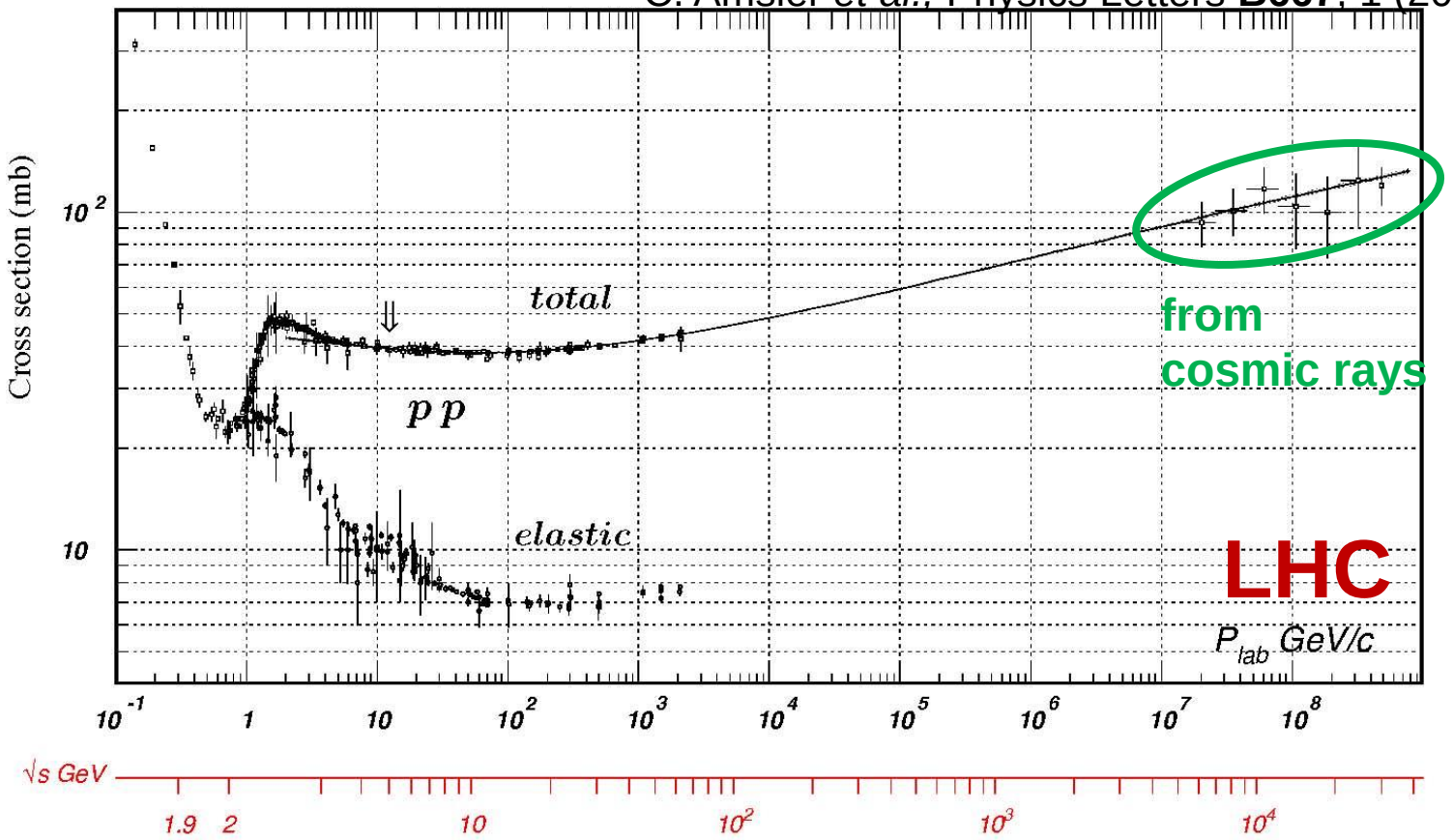
LHC tunnel 2006

# *luminosity*

$$R = \sigma L$$

**reaction rate** — **cross section** — **luminosity**

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)

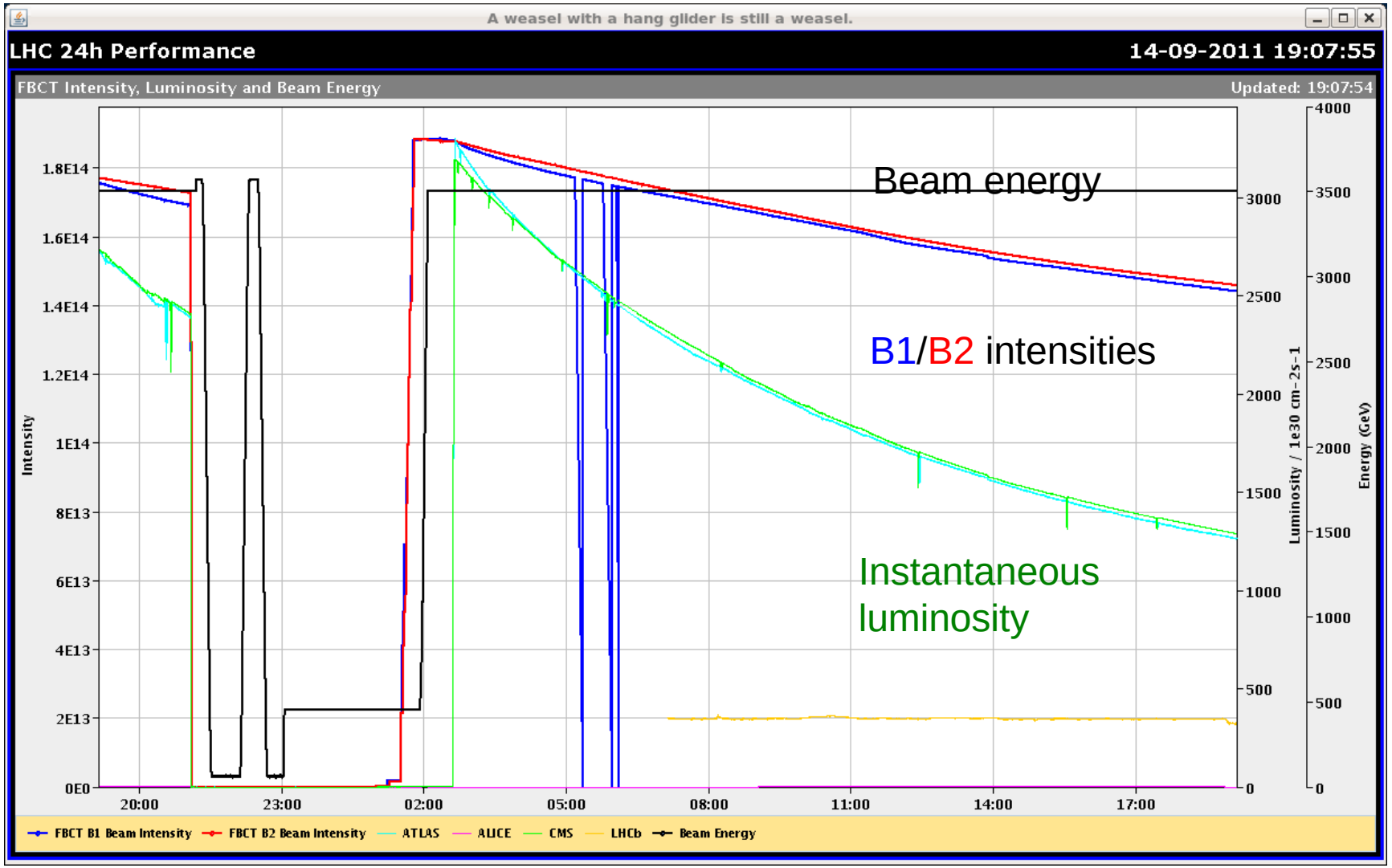



$\sigma_{tot}$~
**100 mbarn**
**~ $10^{-25}$ cm$^2$**

**from cosmic rays**

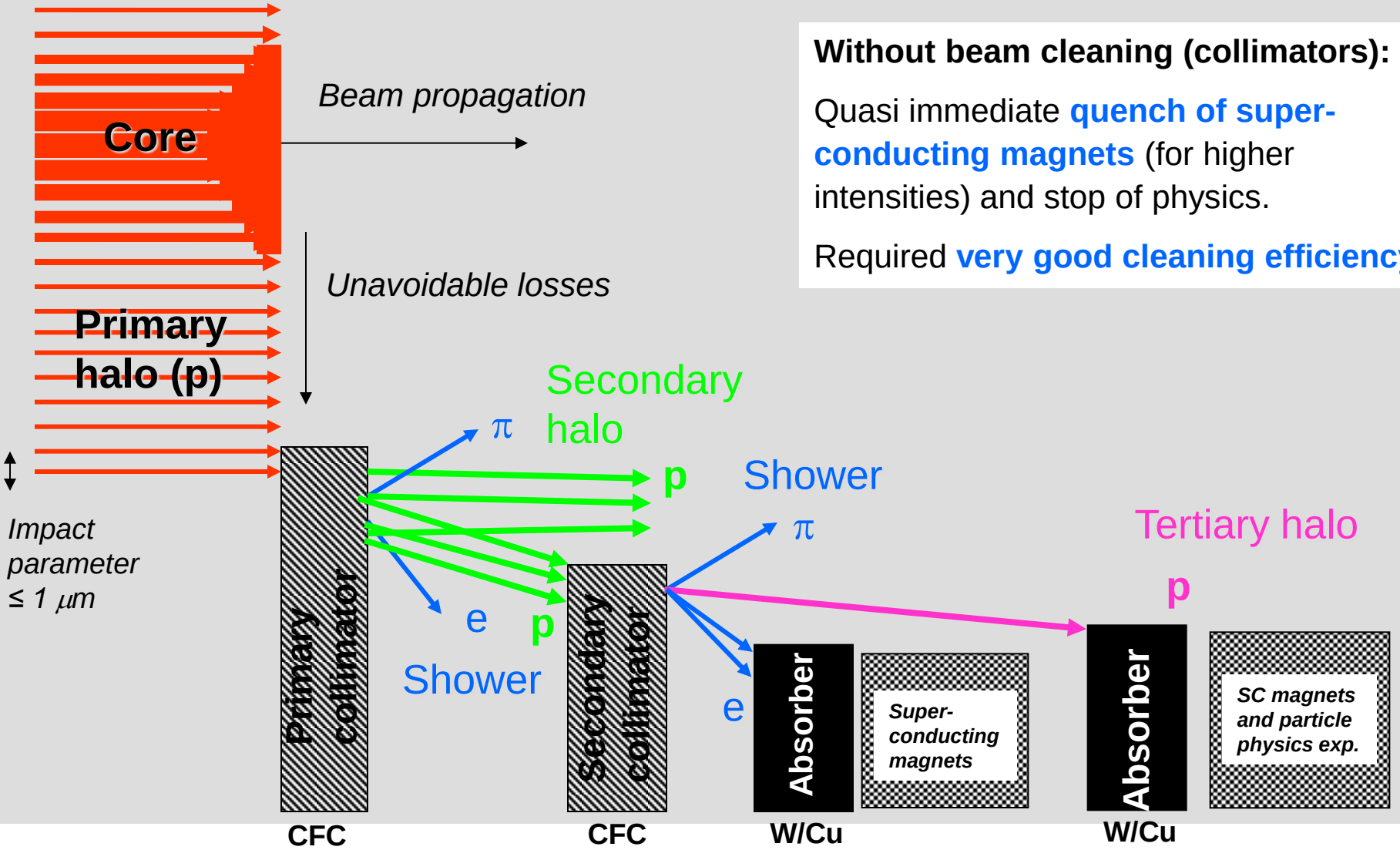
$\sigma_{inelastic}$~
**60 mbarn~**
**6x$10^{-26}$ cm$^2$**

# intensity and luminosity: good LHC fill...




R. Assmann, 19.09.2011

# LHC – multistage cleaning



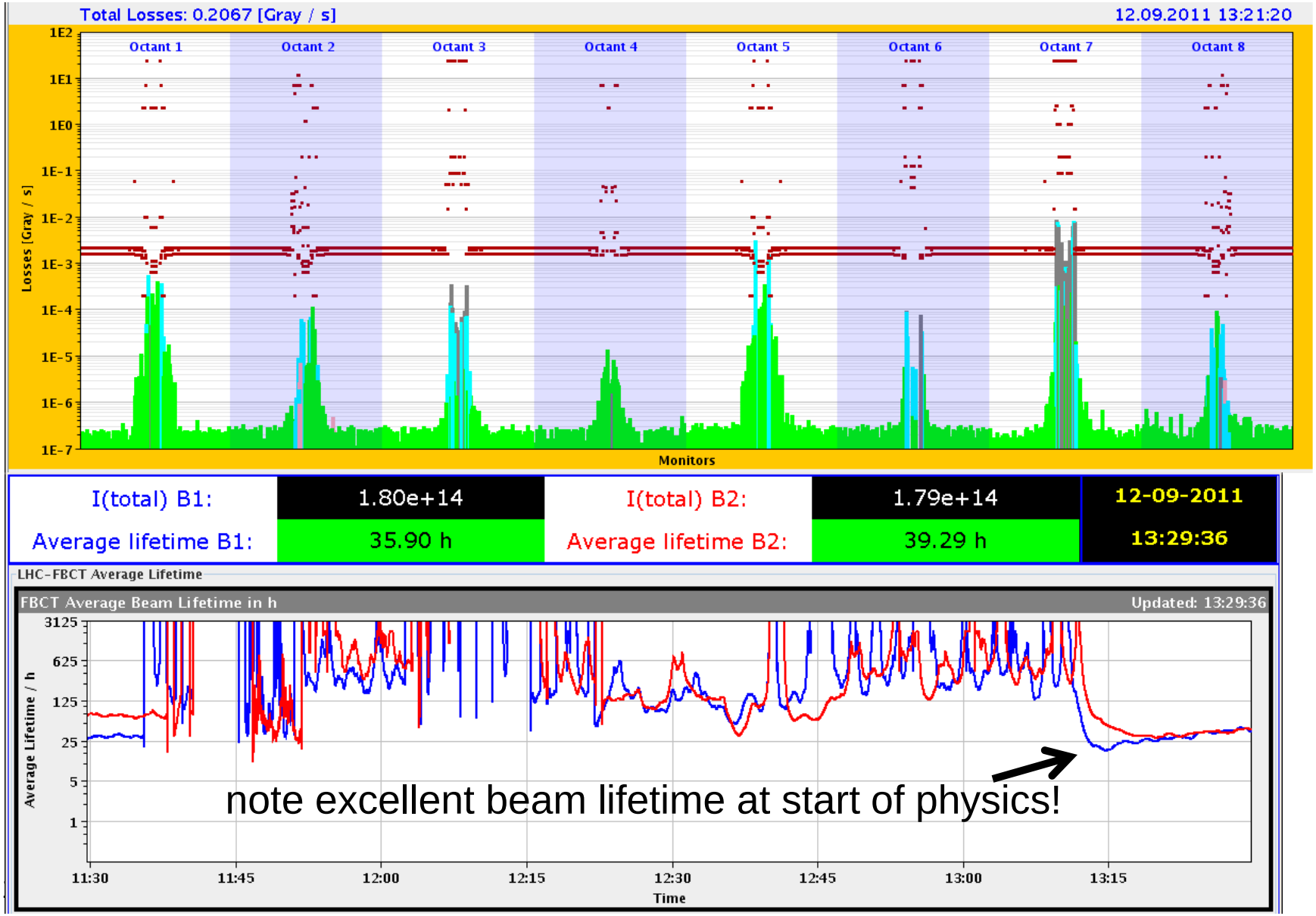

**Without beam cleaning (collimators):**

Quasi immediate **quench of super-conducting magnets** (for higher intensities) and stop of physics.

Required **very good cleaning efficiency**

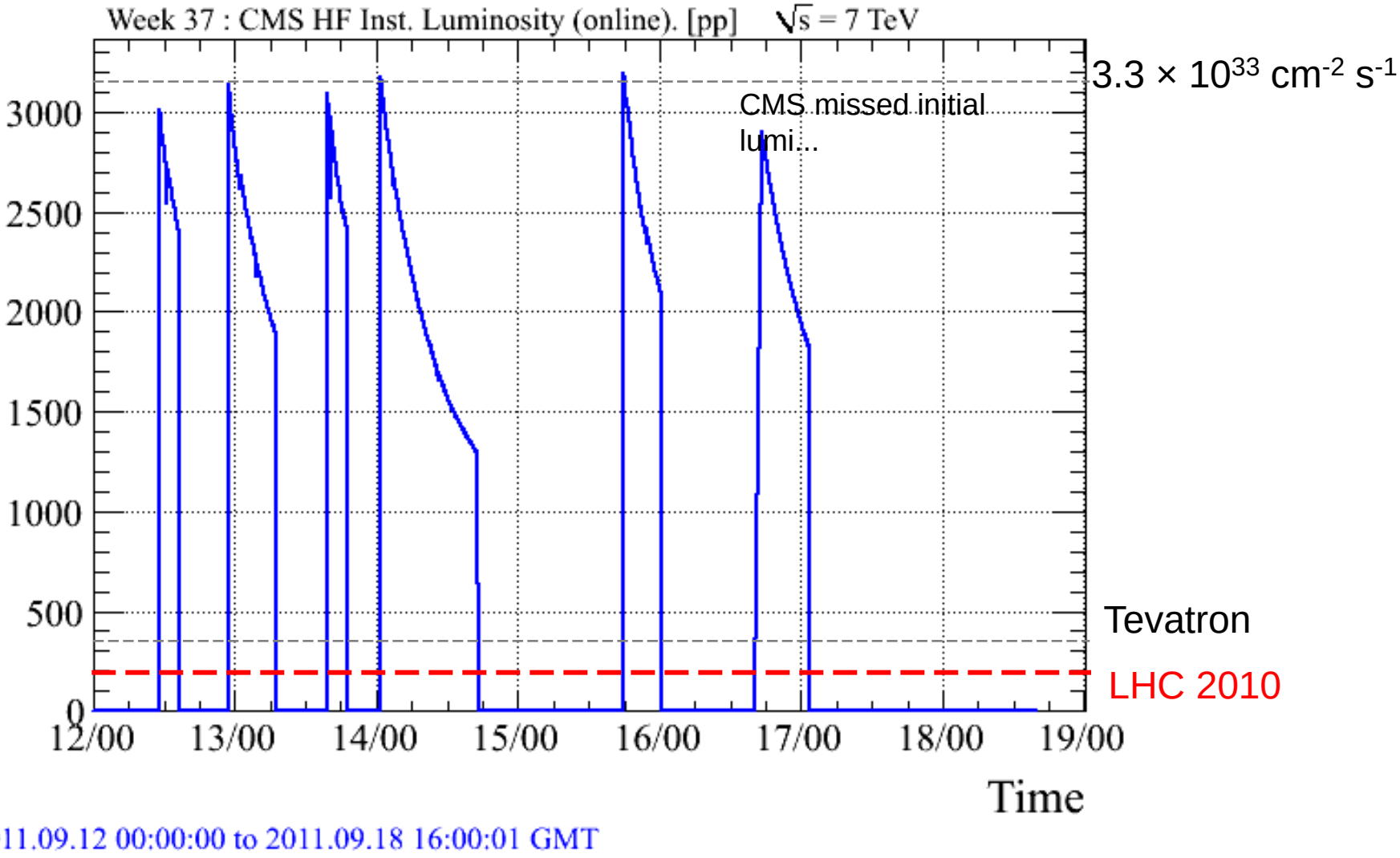
R. Assmann

# Losses & Lifetime at Start of Physics



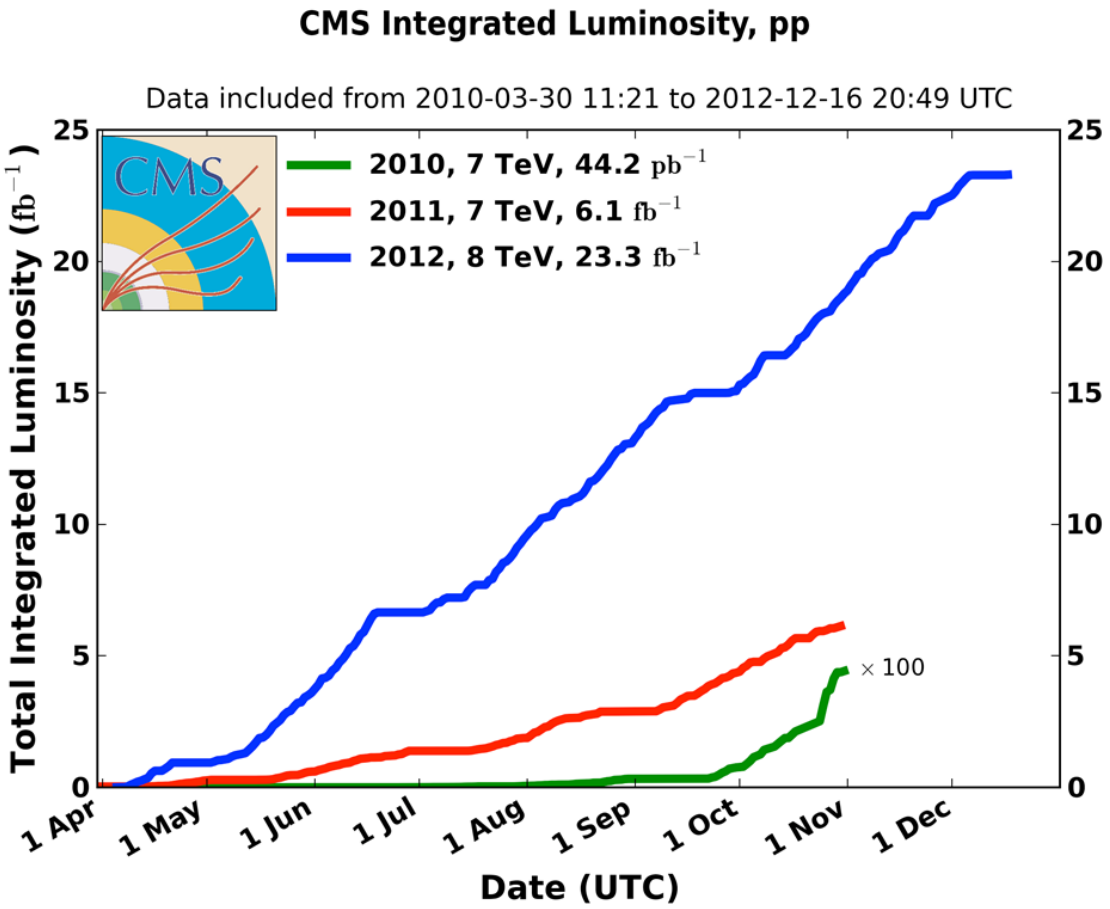

R. Assmann, 19.09.2011

# Week 37 (2011) seen from CMS...




R. Assmann, 19.09.2011

# integrated *pp* luminosity 2010-12




- 2010: **0.04 fb$^{-1}$**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb$^{-1}$**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb$^{-1}$**
  - 8 TeV CoM
  - Production

M. Lamont, IPAC'13

# peak performance through the years

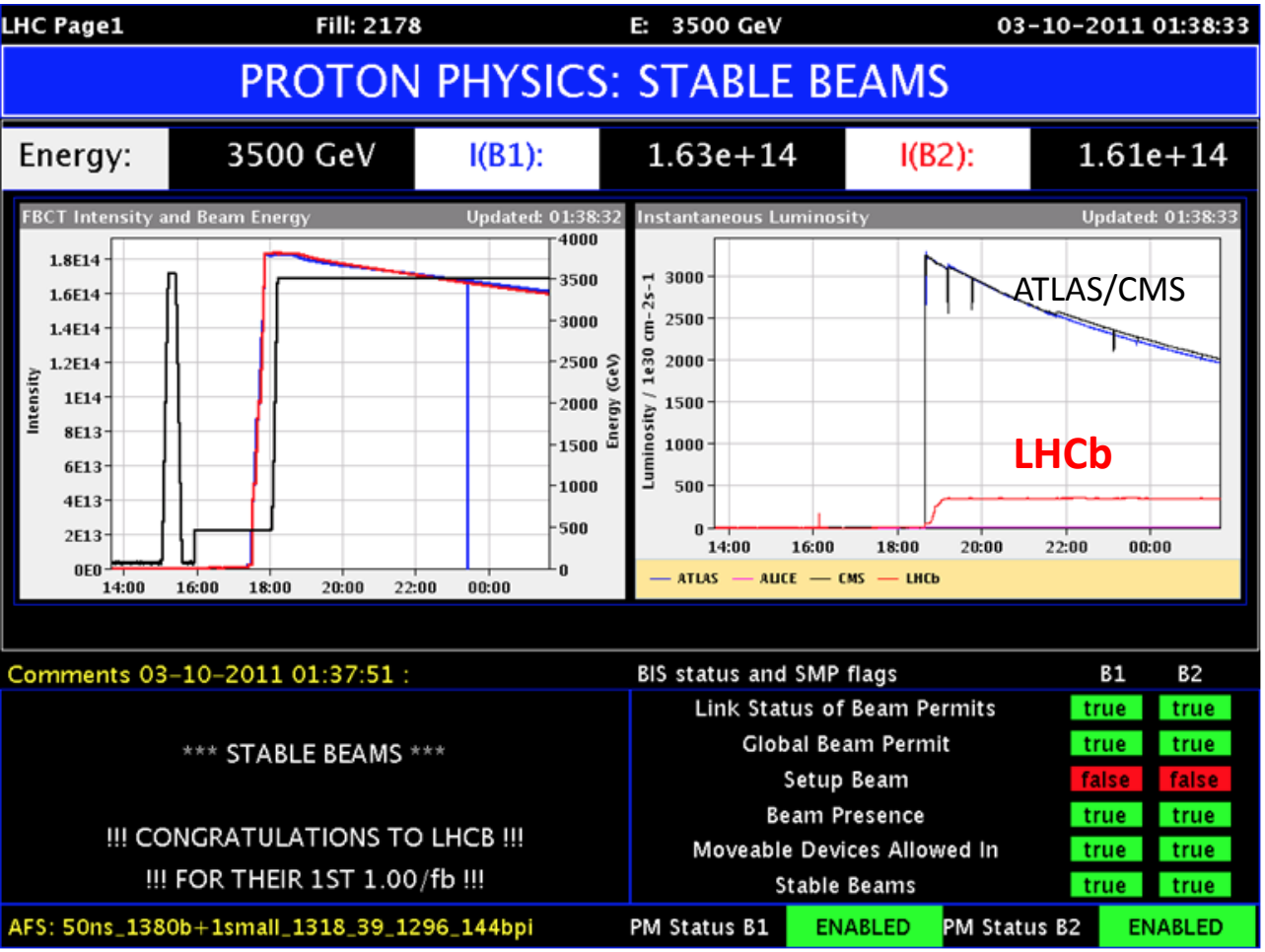
| | 2010 | 2011 | 2012 | Nominal |
|---|---|---|---|---|
| bunch spacing [ns] | 150 | 50 | 50 | 25 |
| **no. of bunches** | 368 | 1380 | 1380 | 2808 |
| **beta*** [m] ATLAS and CMS | 3.5 | 1.0 | 0.6 | 0.55 |
| max. **bunch intensity** [protons/bunch] | $1.2 \times 10^{11}$ | $1.45 \times 10^{11}$ | $1.7 \times 10^{11}$ | $1.15 \times 10^{11}$ |
| normalized **emittance** [mm-mrad] | ~2.0 | ~2.4 | ~2.5 | 3.75 |
| peak luminosity [$cm^{-2}s^{-1}$] | $2.1 \times 10^{32}$ | $3.7 \times 10^{33}$ | $7.7 \times 10^{33}$ | $1.0 \times 10^{34}$ |

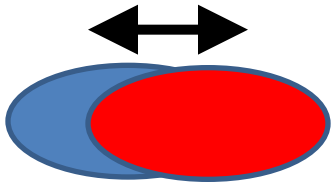
**>2x design when scaled to 7 TeV**

M. Lamont, IPAC'13

# LHCb

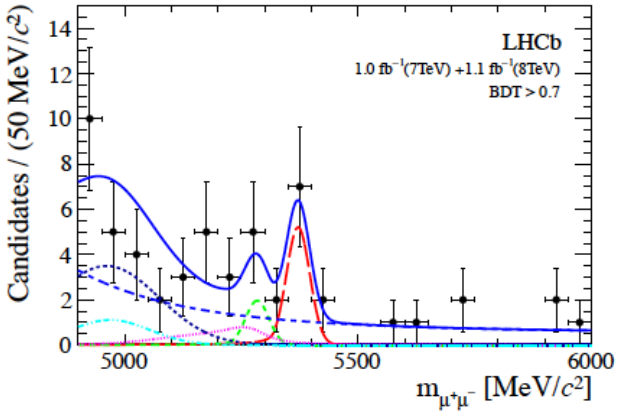
**luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation**
(with tilted crossing angle)



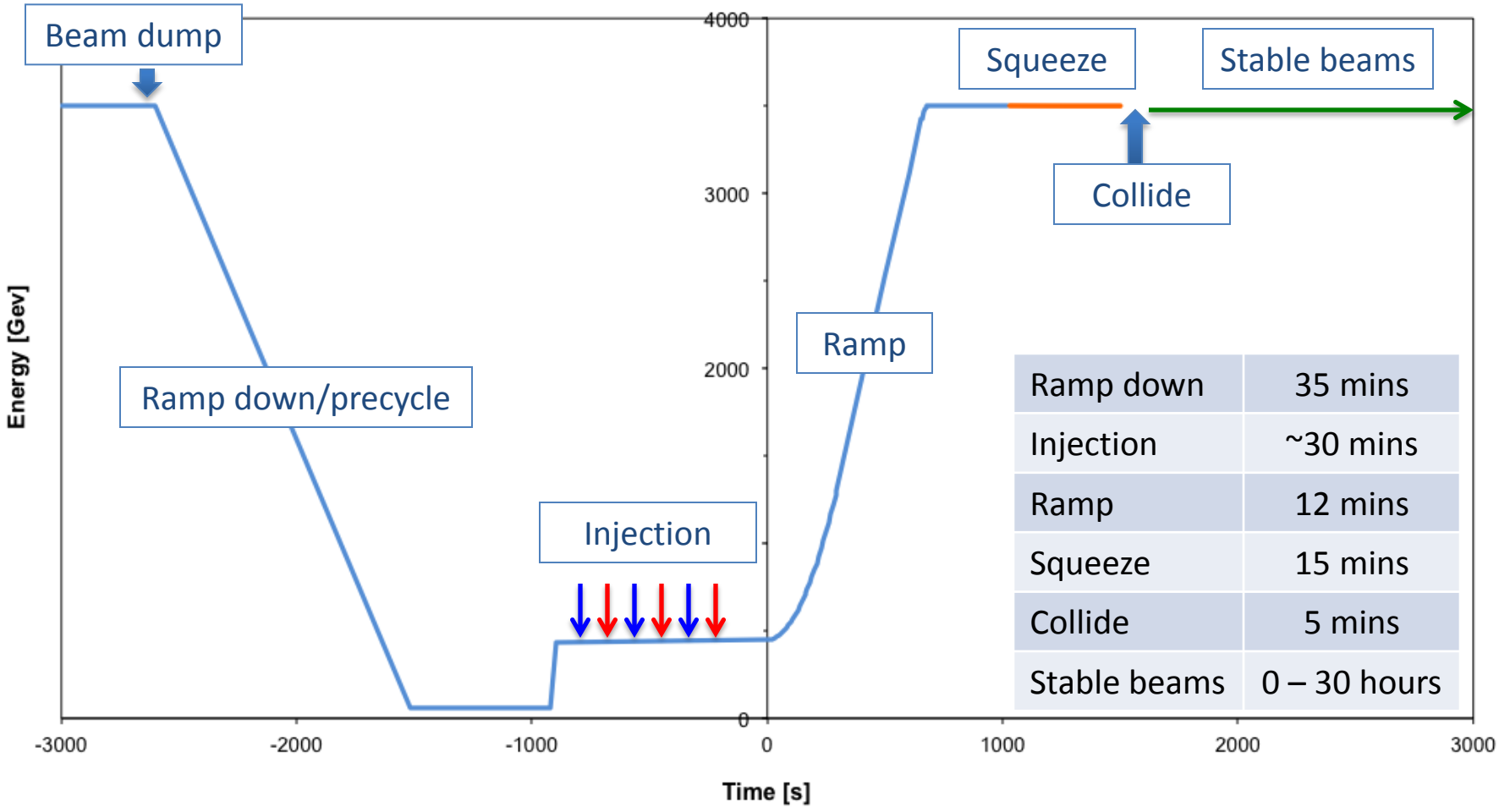



M. Lamont, IPAC'13

**first evidence for the decay $B_s$ -> $\mu^+ \mu^-$**



# operational cycle

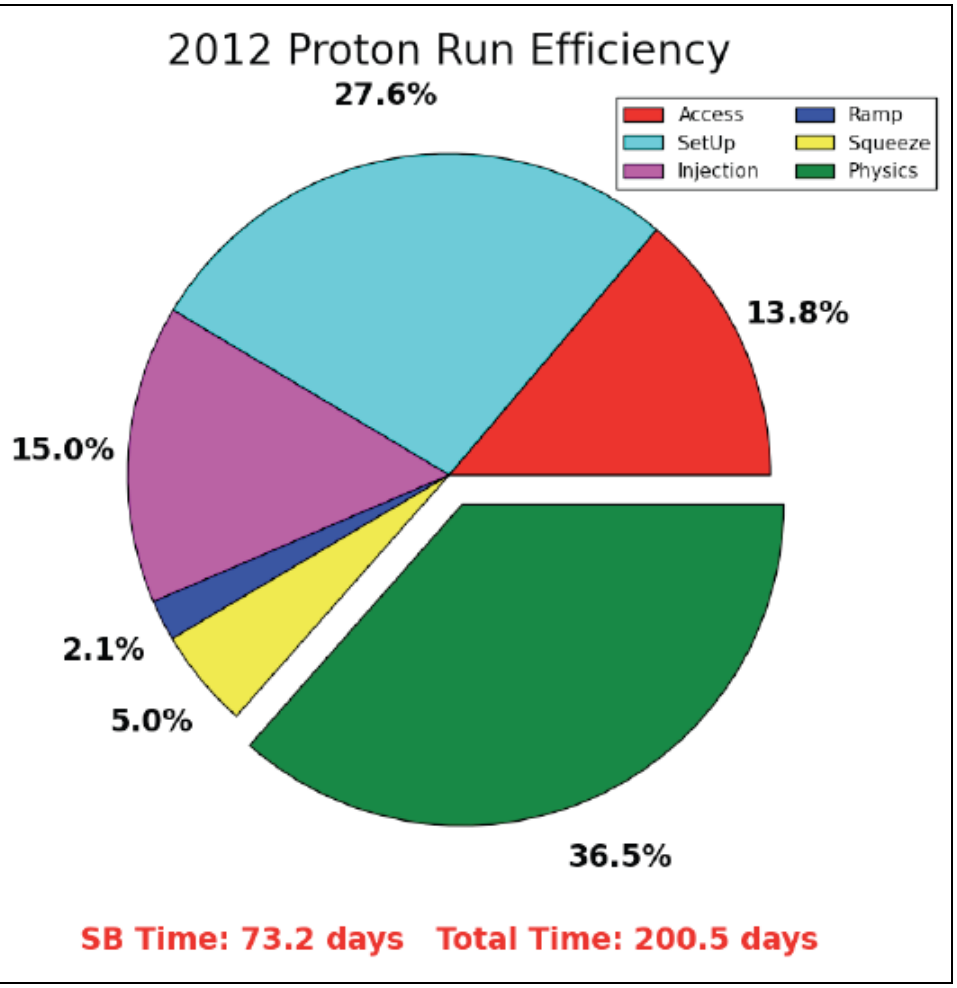


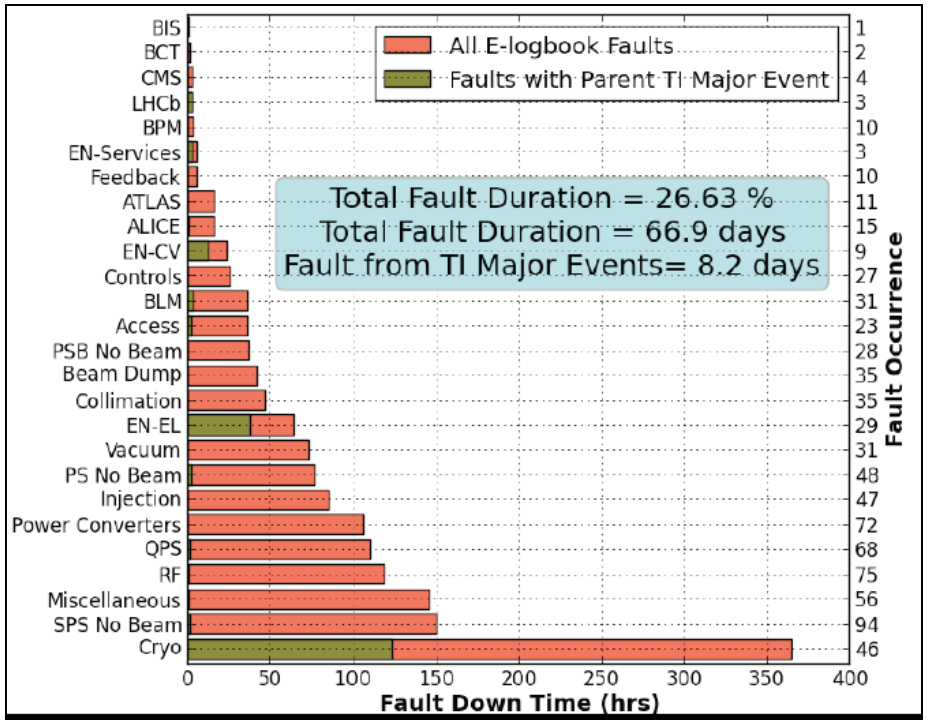

| | |
|---|---|
| Ramp down | 35 mins |
| Injection | ~30 mins |
| Ramp | 12 mins |
| Squeeze | 15 mins |
| Collide | 5 mins |
| Stable beams | 0 – 30 hours |

turn around 2 to 3 hours on a good day

# availability

- "There are a lot of things that can go wrong – it's always a battle"
- Pretty good availability considering the complexity and principles of operation



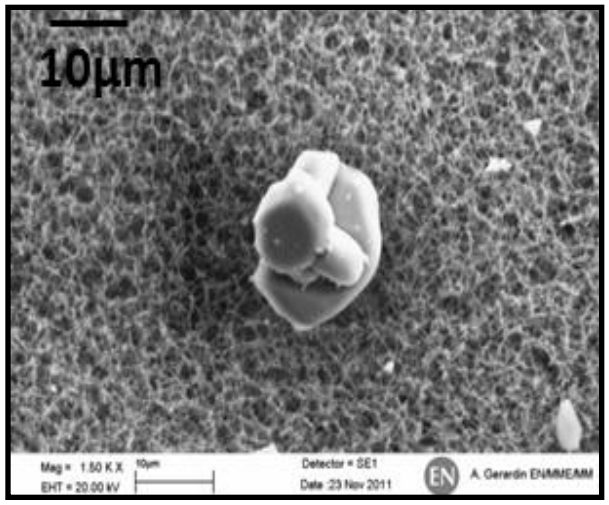

**Cryogenics availability in 2012: 93.7%**



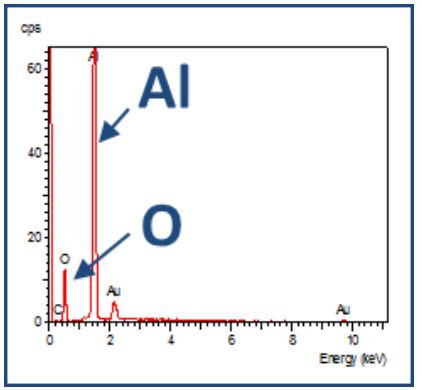
M. Lamont, IPAC'13

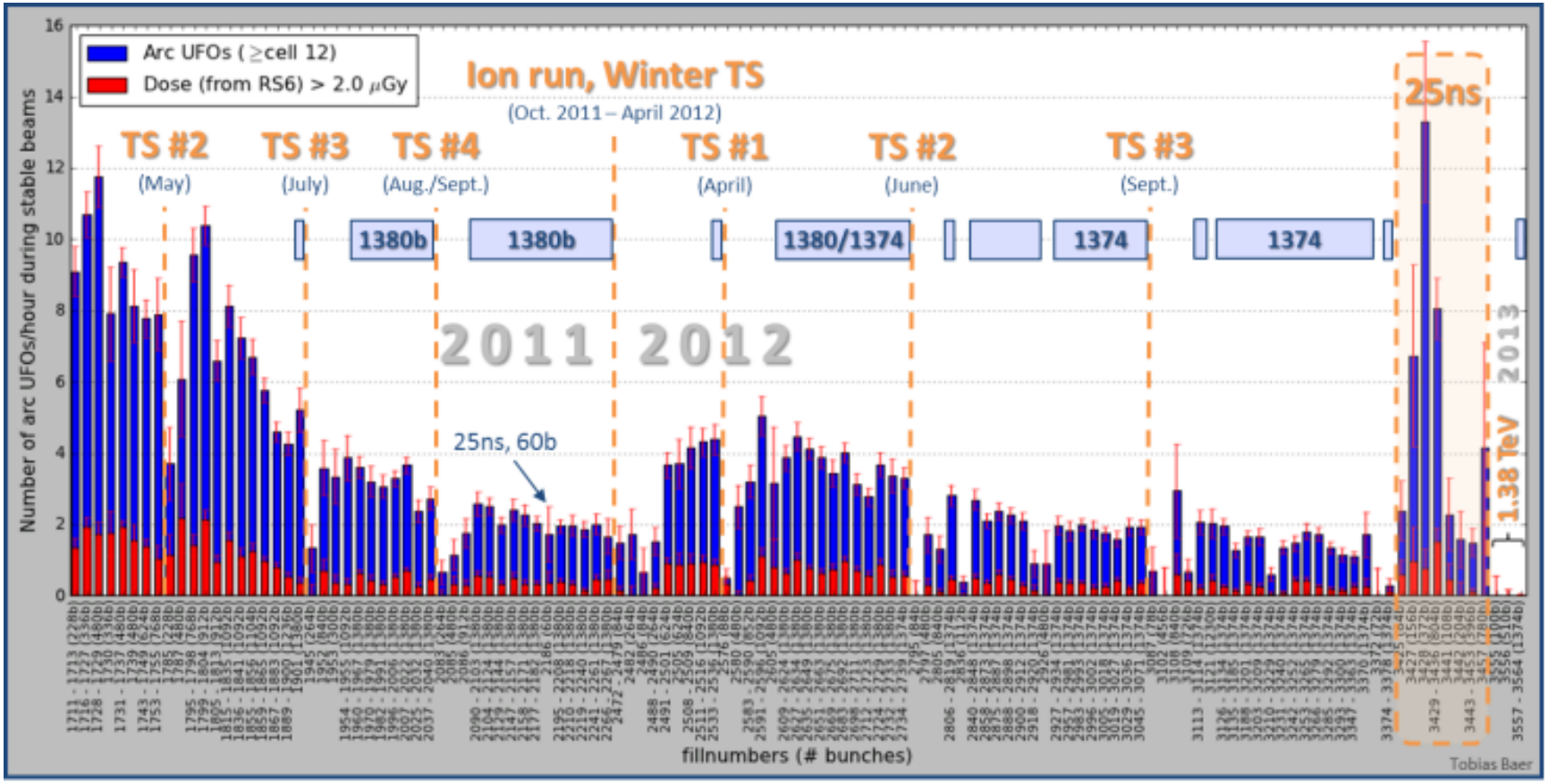
# “UFOs” in the LHC

- 20 dumps in 2012
- time scale 50-200 µs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

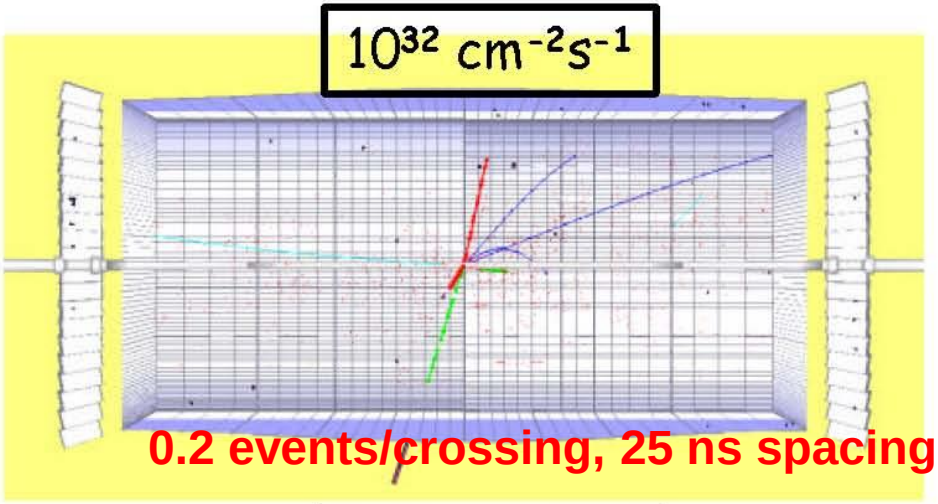



T. Baer

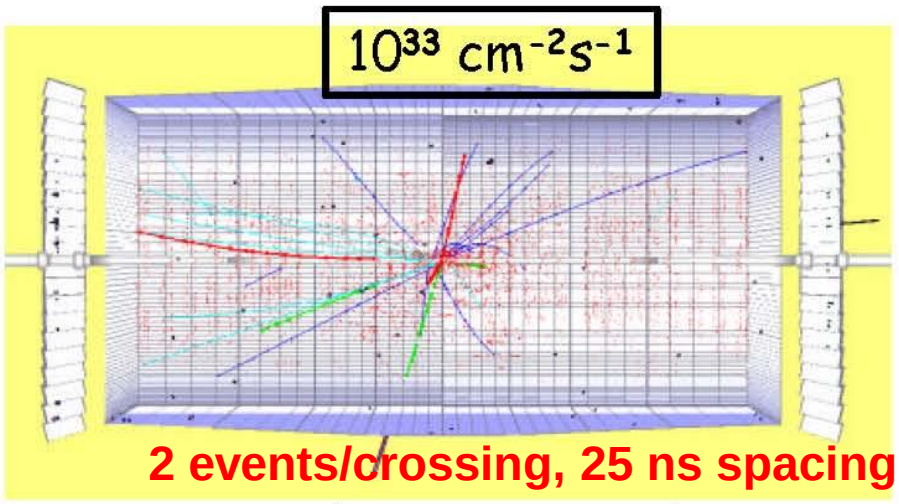


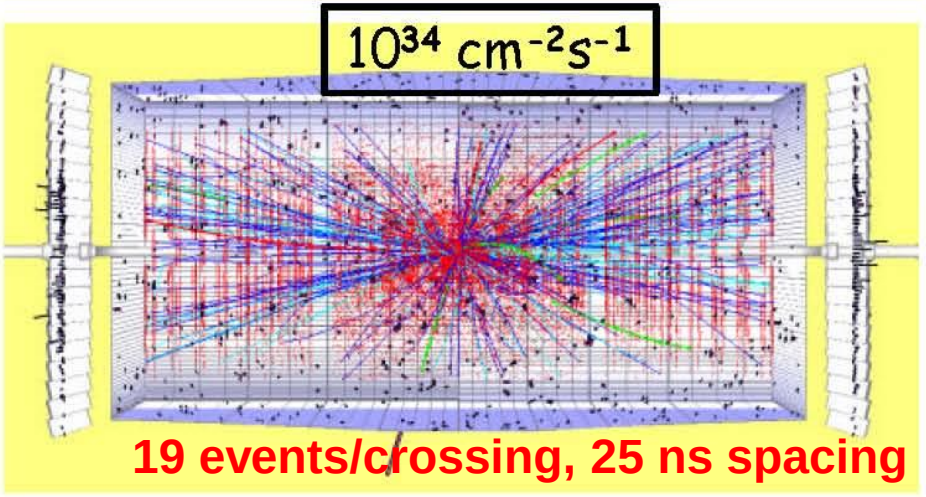
# *event pile up in detector*



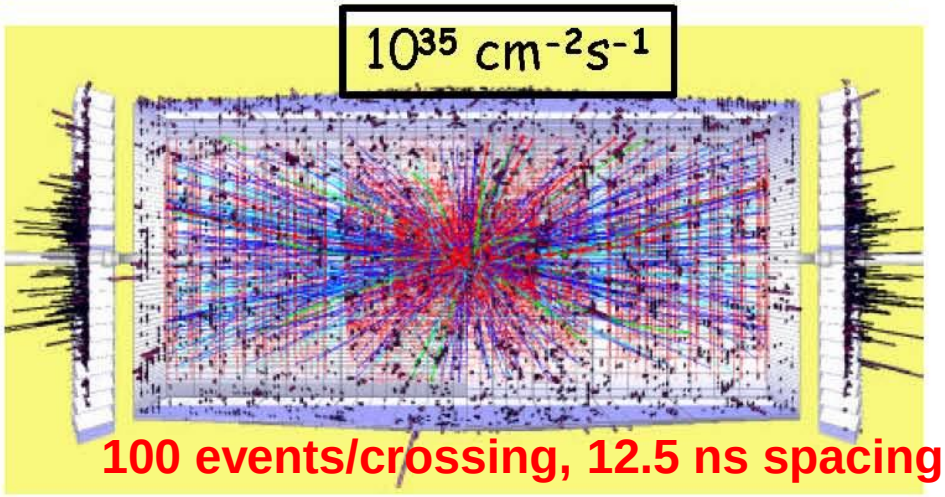

**0.2 events/crossing, 25 ns spacing**




**2 events/crossing, 25 ns spacing**



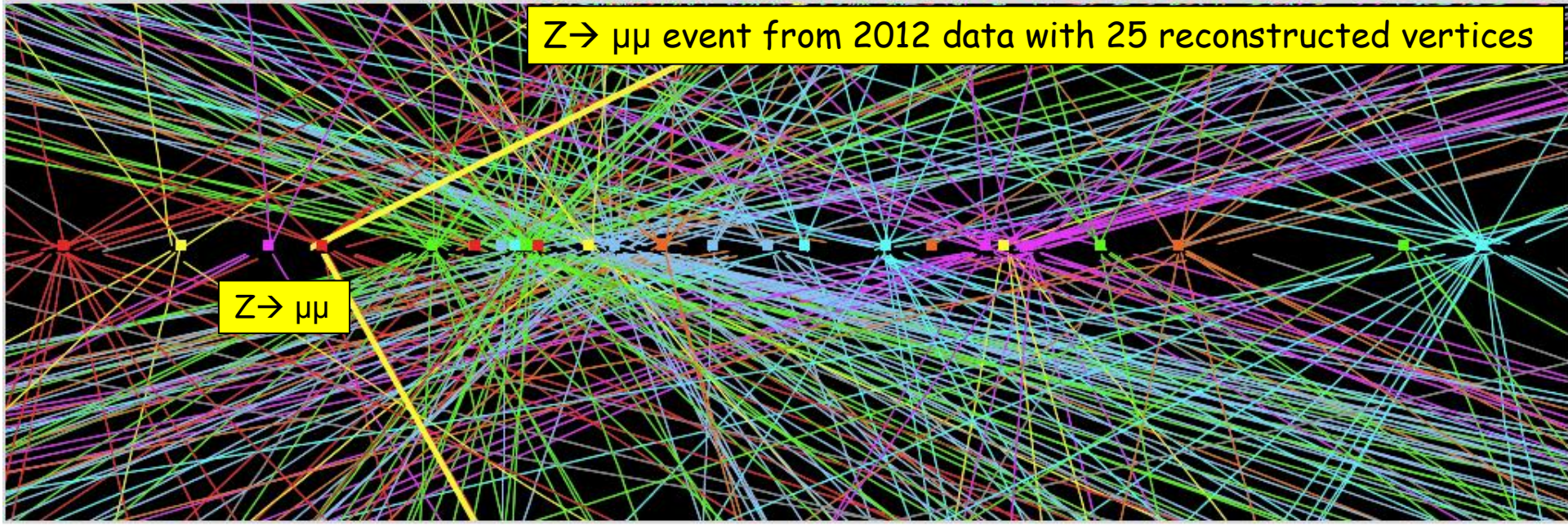

**19 events/crossing, 25 ns spacing**

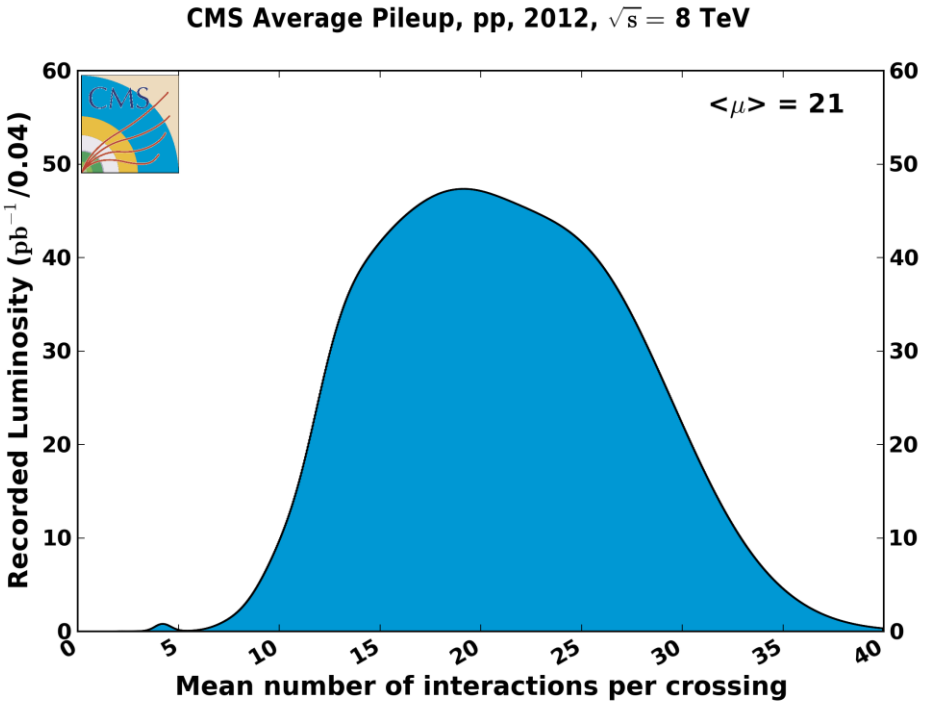



**100 events/crossing, 12.5 ns spacing**

$p_t$ > 1 GeV/c cut, i.e. all soft tracks removed

I. Osborne

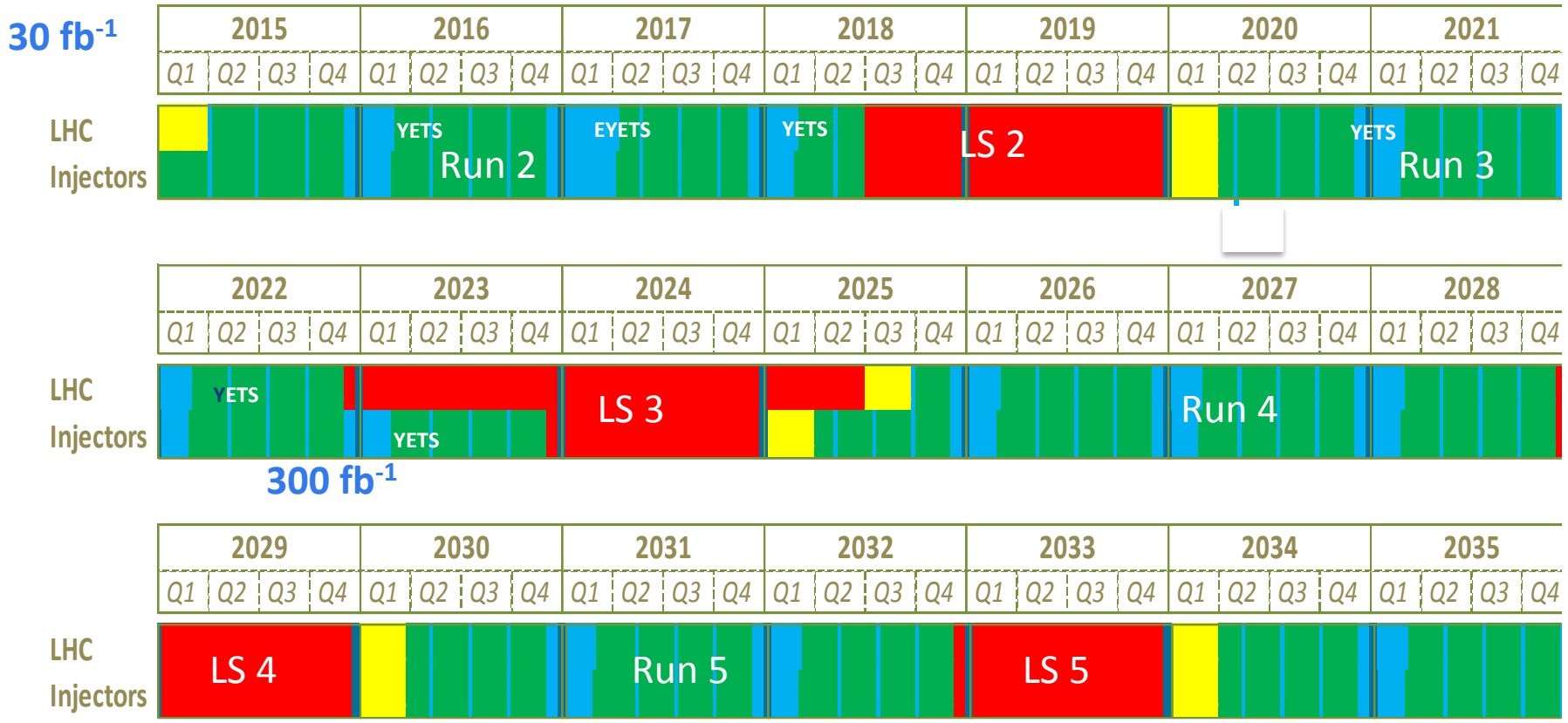



**pile up will increase at higher energy → experiments request 25 ns operation in 2015**

# LHC schedule 2015-2035

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC




F. Bordry

*LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)*

# *accelerator applications*

# Accelerators running in the world

| CATEGORY OF ACCELERATORS | NUMBER IN USE (*) | |
|---|---|---|
| High Energy acc. (E >1GeV) | ~120 | |
| Synchrotron radiation sources | >100 | |
| Medical radioisotope production | ~200 | 9000 |
| Radiotherapy accelerators | > 7500 | |
| Research acc. included biomedical research | ~1000 | |
| Acc. for industrial processing and research | ~1500 | |
| Ion implanters, surface modification | >7000 | |
| TOTAL | > 17500 | |

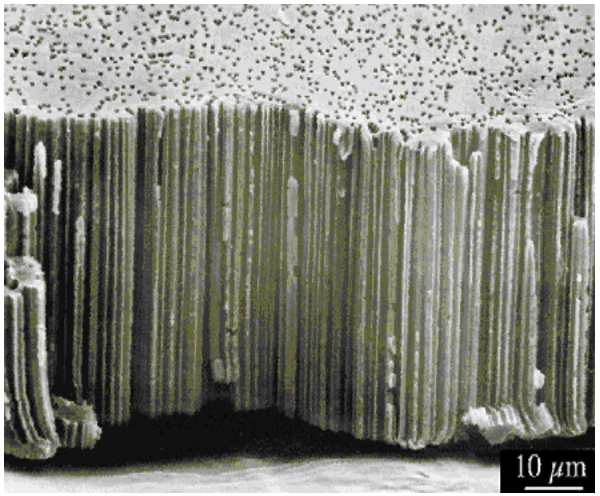
(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004

- About half are used for bio-medical applications

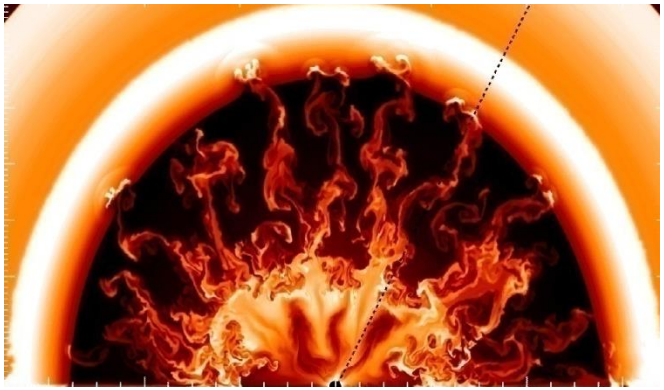
S. Bracchini, TERA

# examples of accelerator applications

**Synchrotron Light (ESRF)**
**5'-exonuclease from bacteriophage T5**
**(diffraction pattern →enzyme structure)**

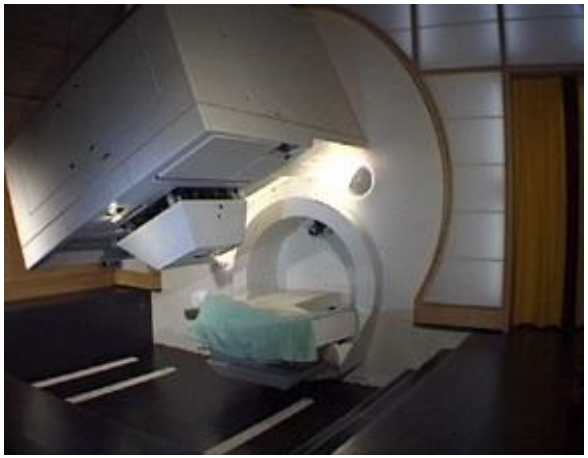



**Ion beams (GSI) etched ion tracks in polymer foil → membrane production.**



**Heavy ion fusion**
shock simulation

B. Logan,
K. Kifonidis
E. Wilson
R. Schmidt

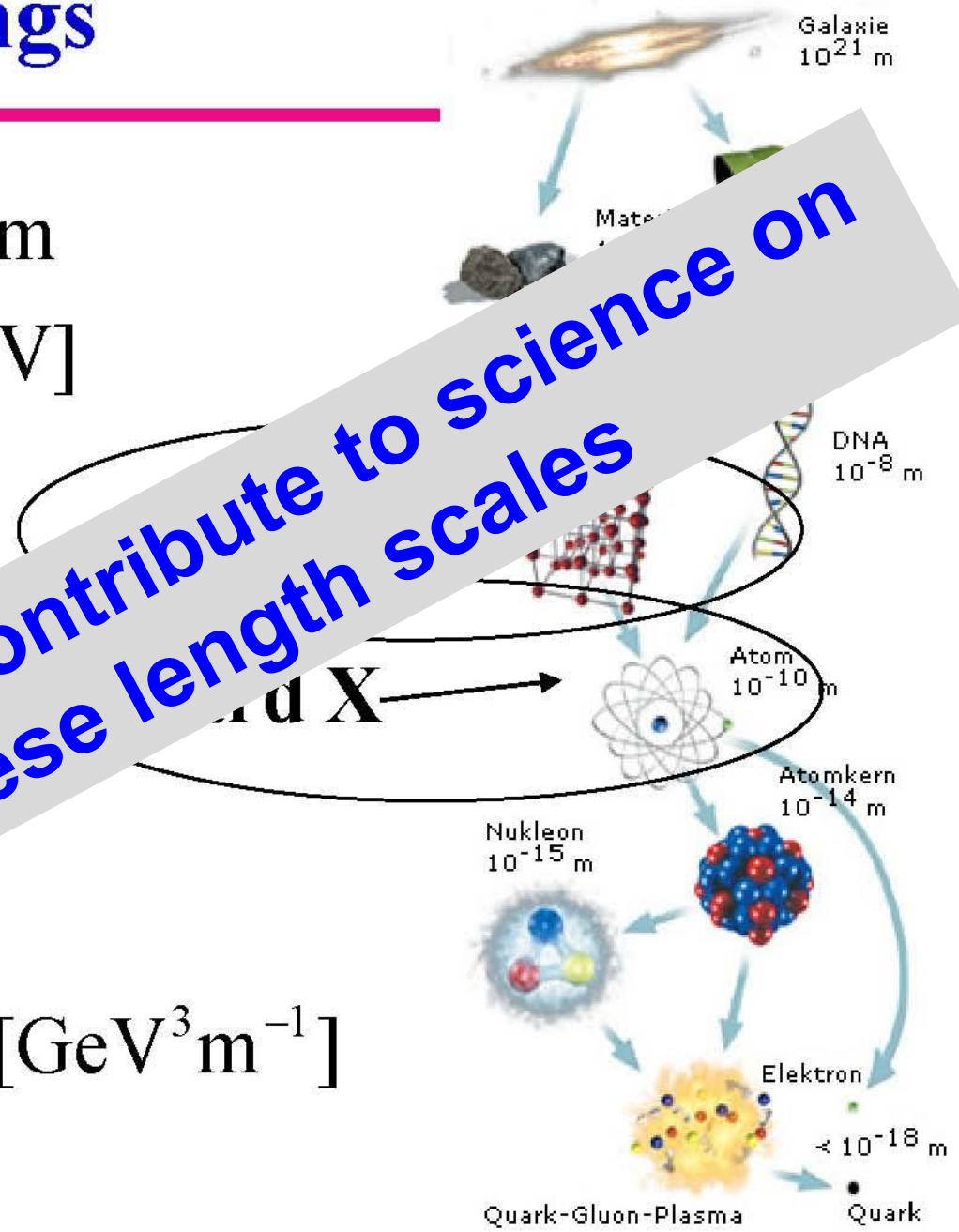


**Proton therapy (PSI)**
**gantry**

# The scale of things

$$1\,\text{angstrom} = 10^{-10}\ \text{m}$$

$$= 12.4/E_{\text{photon}}\ \ [\text{MeV}]$$




accelerators contribute to science on all these length scales

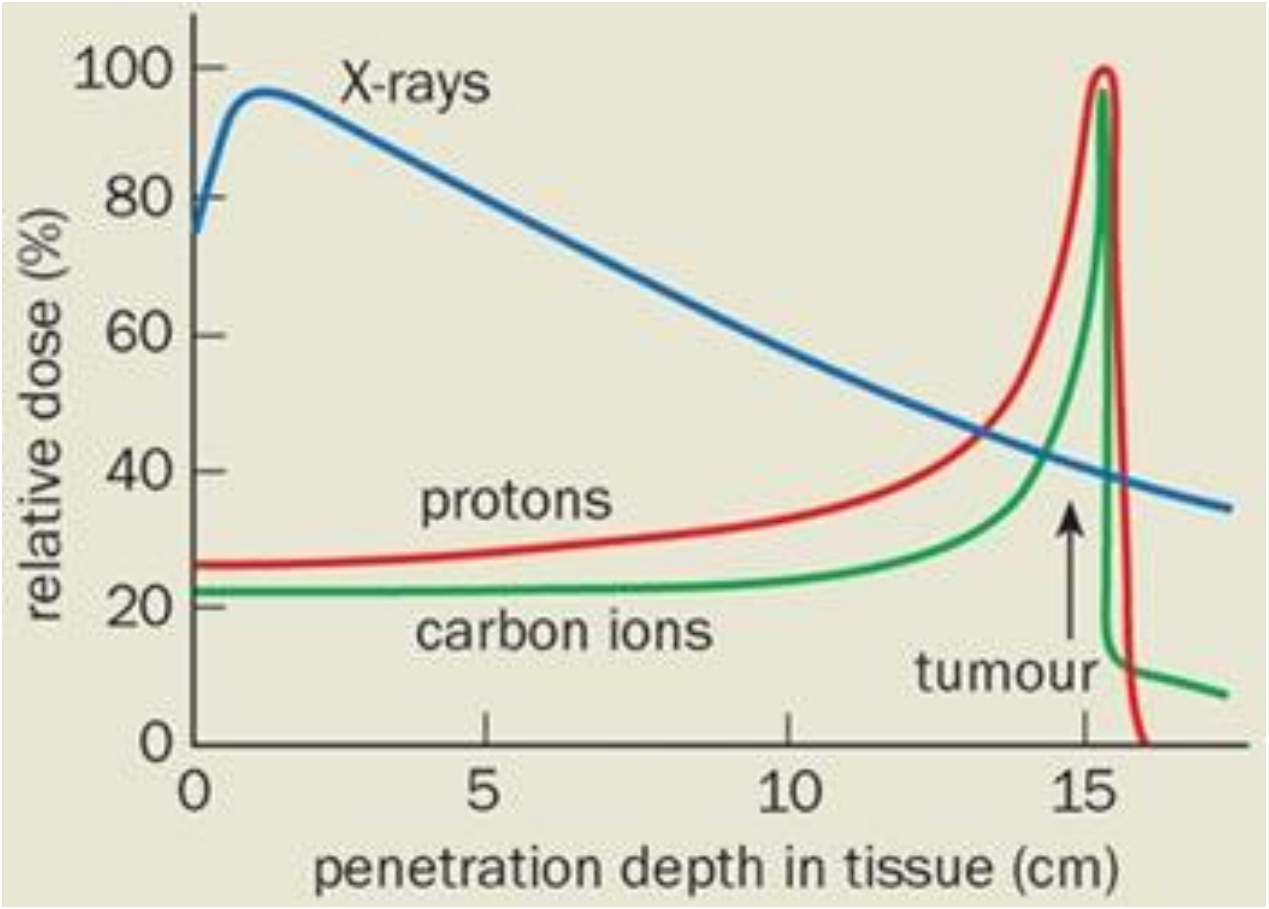
$$E_{\text{photon}} = 2218\,\frac{E_{\text{beam}}^{3}}{r}\,[\text{GeV}^{3}\text{m}^{-1}]$$

# synchrotron light sources in the world

Daresbury laboratory

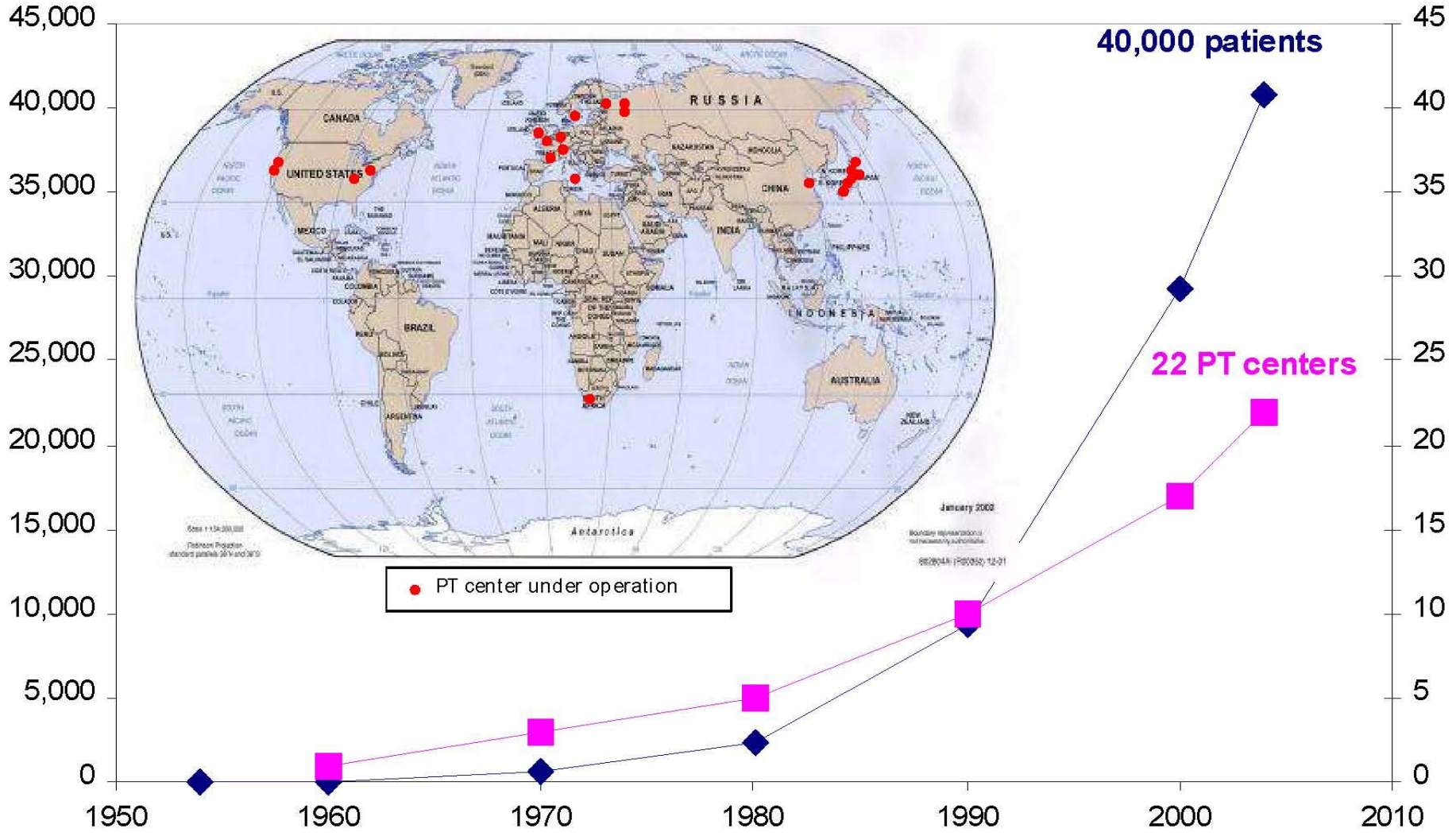
→ basic and applied research, including material science, archeology , earth science, space science, life science, medicine

# how (accelerated) particles can be therapeutic



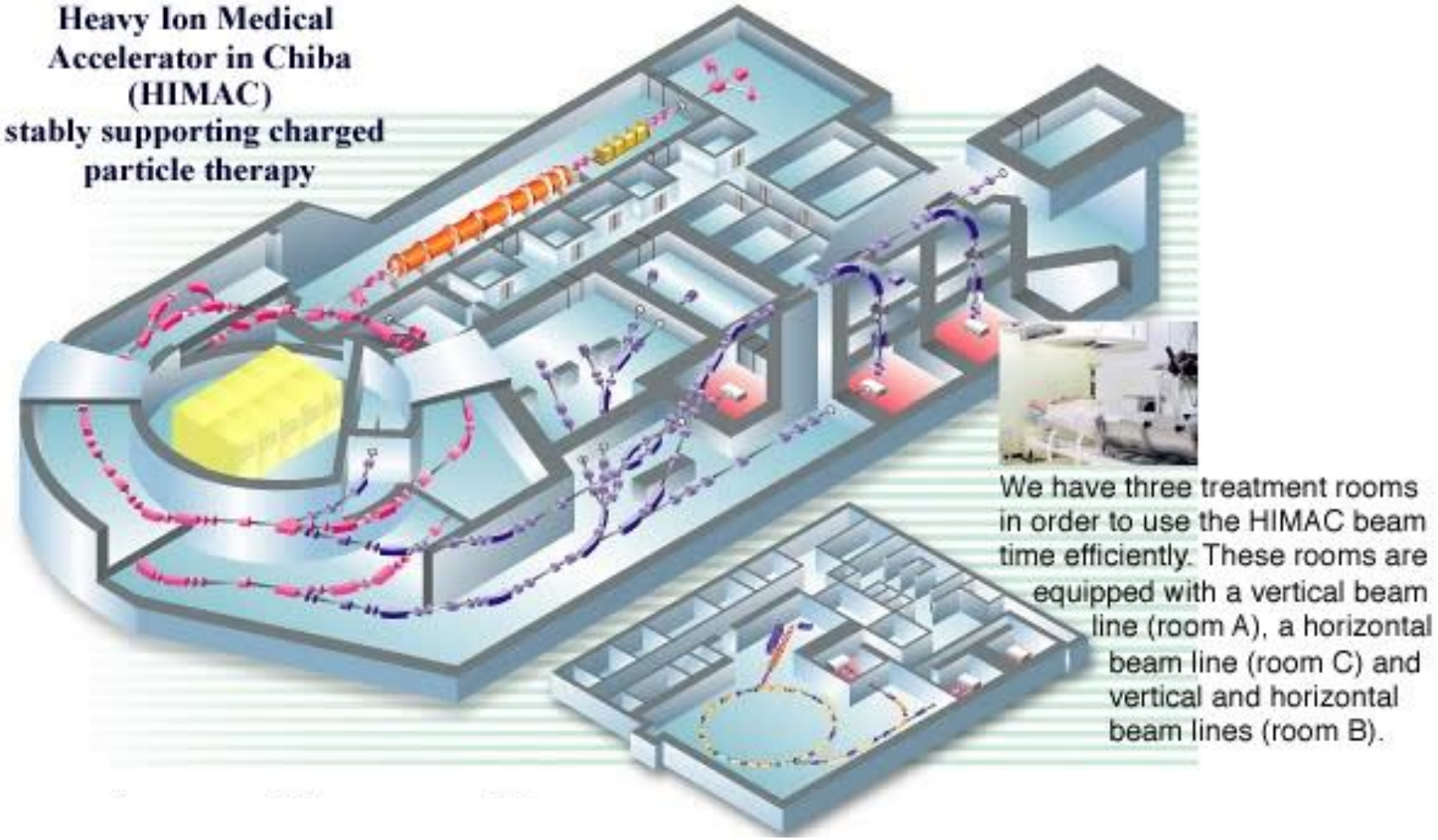

X-rays (photons) lose energy rapidly by ionization as they travel through the body. On the other hand, charged particles such as protons and carbon ions deposit most of their energy at a specific depth that depends on their energy (called the Bragg peak). This means that they can deliver a high radiation dose at a tumor site, while sparing the surrounding healthy tissue. (Physics World, 2003)

# rapid growth in proton cancer-therapy centers




**J. Sisterson, Massachusetts General Hospital**
**S. Peggs et al, PAC'07**

# HIMAC C-ion therapy facility in Japan

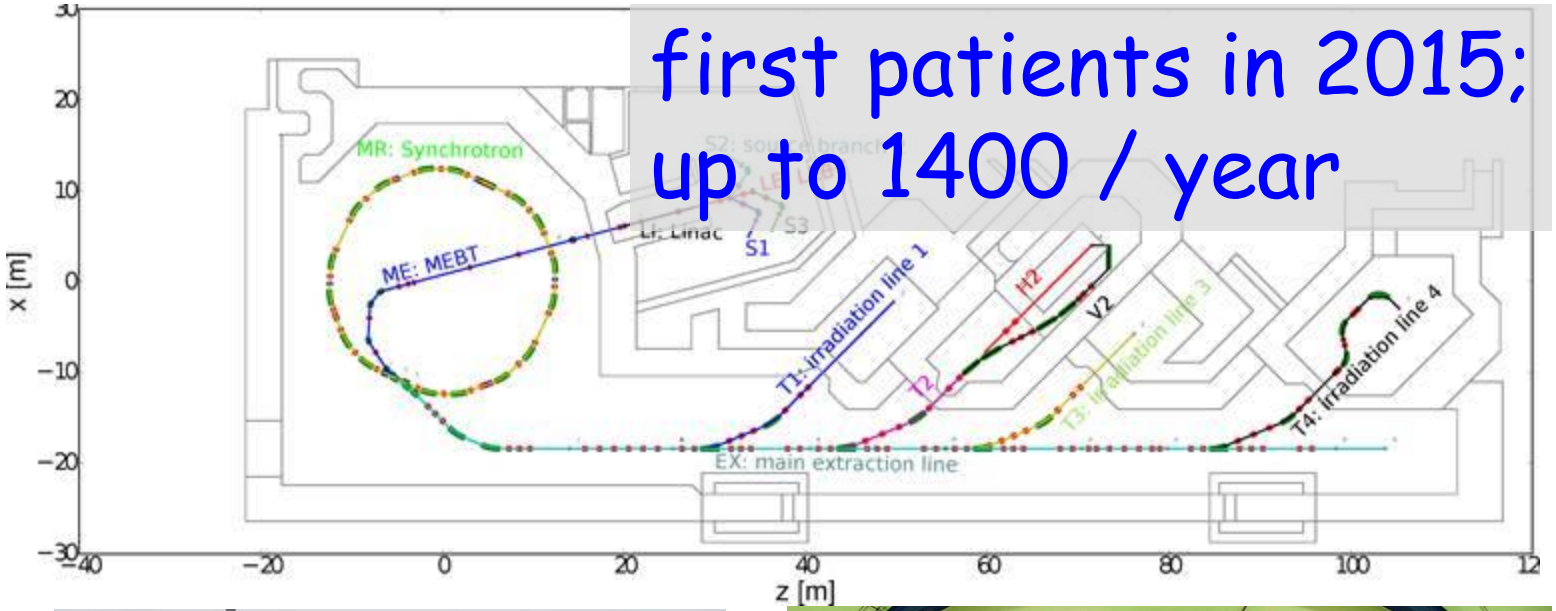



in operation with patients since 1994

NIRS

# MedAustron in Wiener Neustadt

## built in close collaboration with CERN



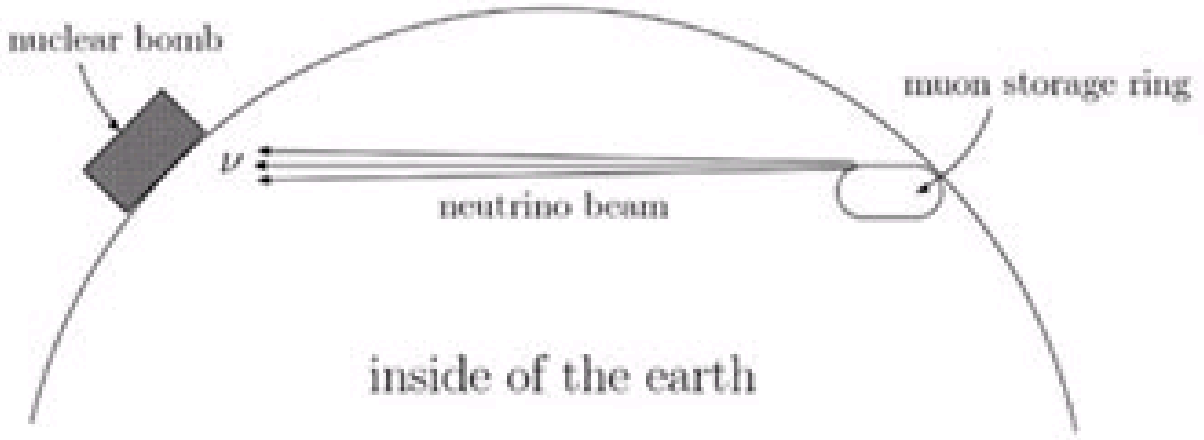

first patients in 2015;
up to 1400 / year

# $\nu$ beam neutralising nuclear bombs?

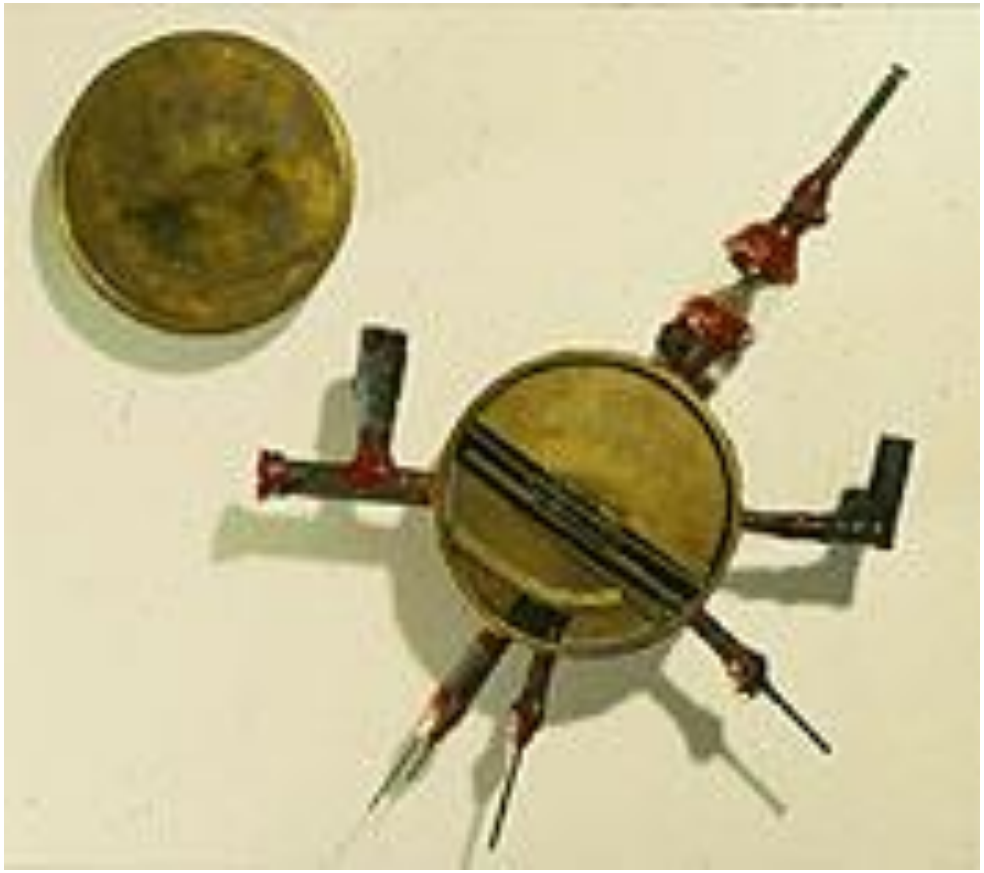
*"A super-powered neutrino generator could in theory be used to instantly destroy nuclear weapons anywhere on the planet, according to a team of Japanese scientists.*

*If it was ever built, a state could use the device to obliterate the nuclear arsenal of its enemy by firing a beam of neutrinos straight through the Earth. But the generator would need to be more than a hundred times more powerful than any existing particle accelerator and over 1000 kilometres wide."*

*New Scientist,*
*14 May 2003*



# the quest for higher energy



1st cyclotron by Ernest O. Lawrence & Stanley Livingston ~1930

diameter 4.5 inches (~11 cm)

final proton energy 1.1 MeV

**“Dr Livingston has asked me to advise you that he has obtained 1,100,000 volt protons. He also suggested that I add ‘Whoopee’!”**
**—Telegram to Lawrence, 3 August 1931**

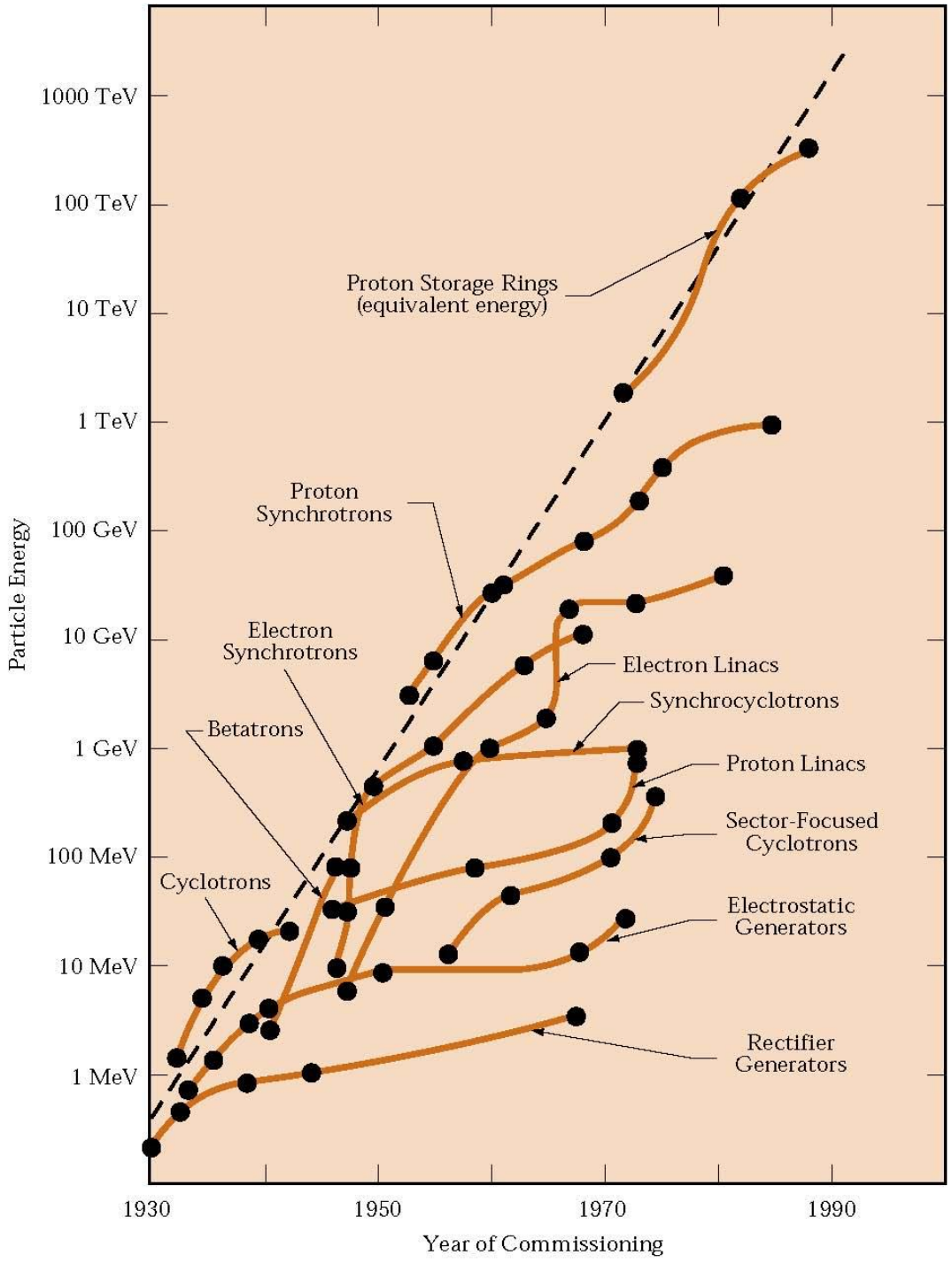
# why higher energy?

- quantum mechanics: de Broglie wavelength $\lambda = h/p$

  $\rightarrow$ examining matter at smaller distance requires higher momentum particles

- many of the particles of interest to particle physics are heavy

  $\rightarrow$ high-energy collisions are needed to create these particles




"Livingston plot" of accelerator energy vs. time

about a factor 10 increase every 6-8 years

whenever one technology ran "out of steam" a new technology took over!

can this trend continue?
→ accelerator R&D

*From W.K.H. Panofsky, "Evolution of Particle Accelerators and Colliders," 1997*

1st cyclotron, ~1930
E.O. Lawrence
11-cm diameter
1.1 MeV protons

LHC, 2008
9-km diameter
7 TeV protons

*after ~80 years*
*~$10^7$ x more energy*
*~$10^5$ x larger*

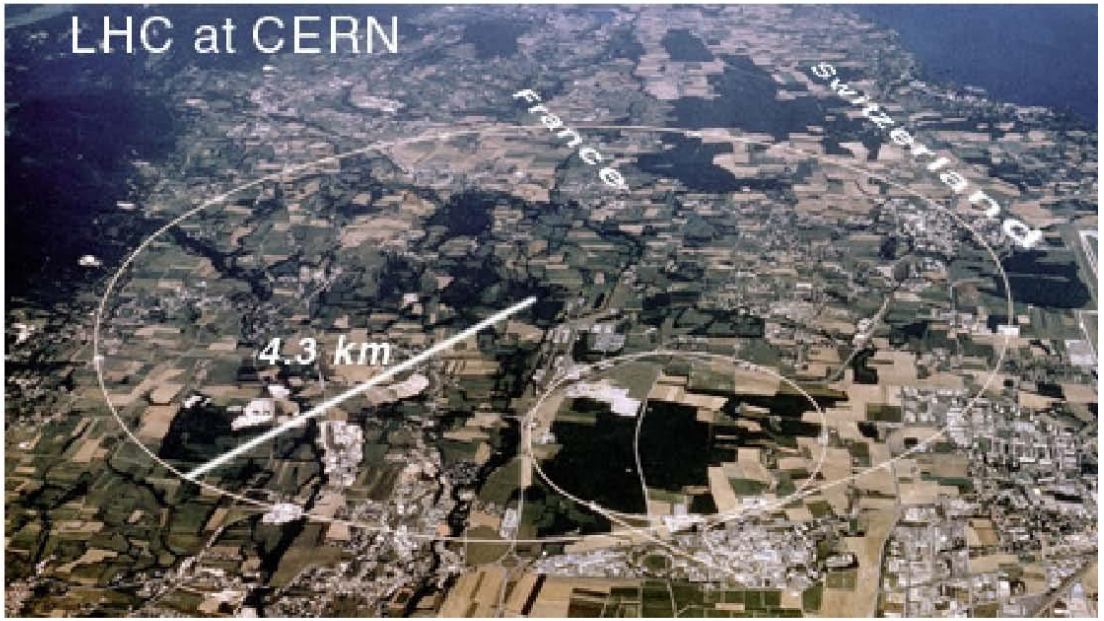
# energy limits

$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \text{The rings become too long}$$

Protons with p = 20 TeV/c , B = 6.8 T would require a 87 km SSC tunnel
Protons with p = 7 TeV/c , B = 8.4 T require CERN's 27 km LHC tunnel

$$P_{\text{radiation}} = \frac{c}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

Energy needed to compensate
Radiation becomes too large

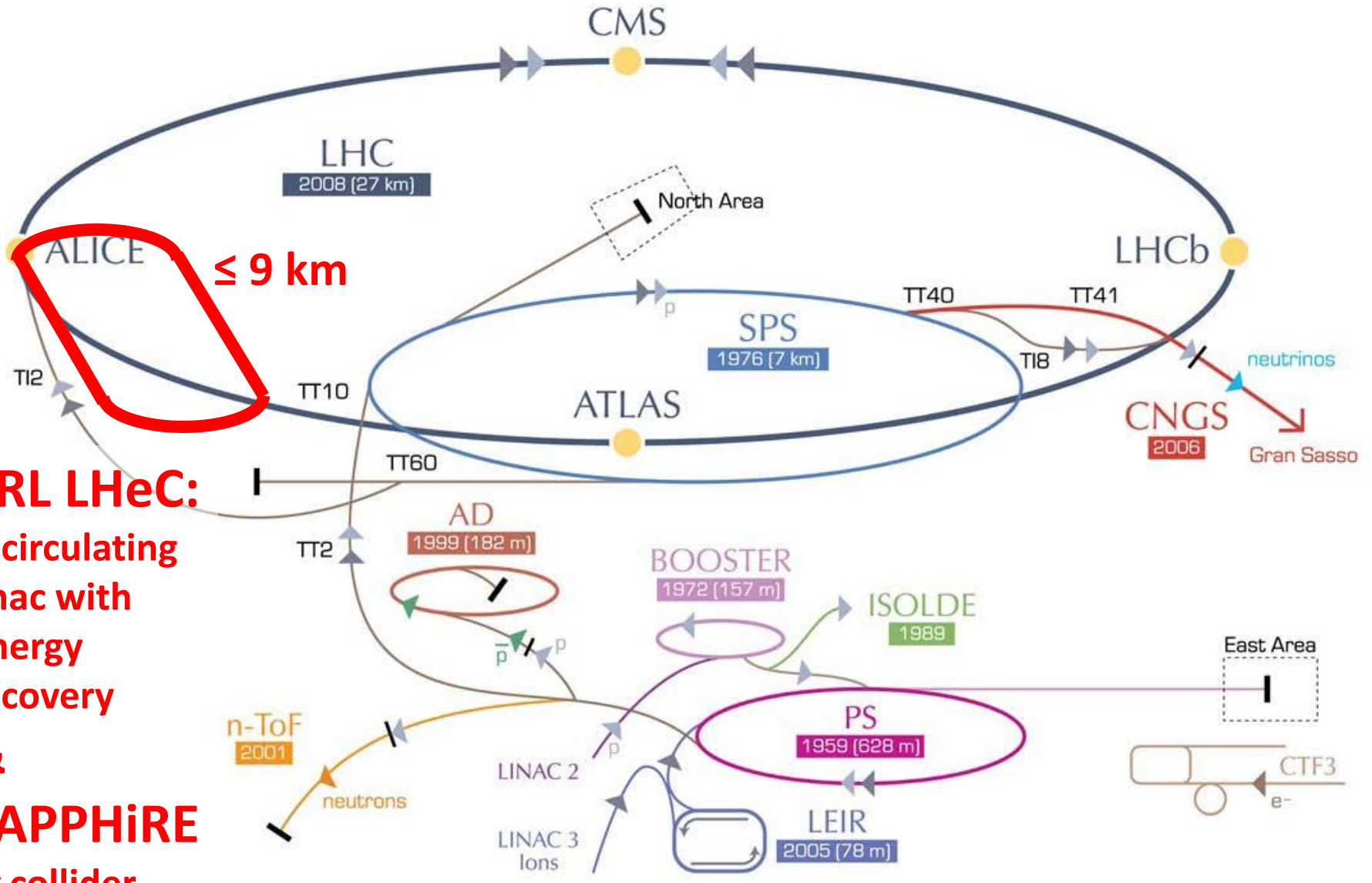



Electron beam with p = 0.1 TeV/c in CERN's 27 km LEP tunnel radiated 20 MW
Each electron lost about 4GeV per turn, requiring many RF accelerating sections.

# future accelerators - towards higher energy

- pe collider – "LHeC" (based on LHC)
- e+e- linear colliders (much less synchrotron radiation) - CLIC
- $\mu$ collider (less synchrotron radiation)
- or e+e- circular collider "Higgs factory" (FCC-ee)
- pp collider with stronger magnets & larger circumference (FCC)
- novel acceleration schemes

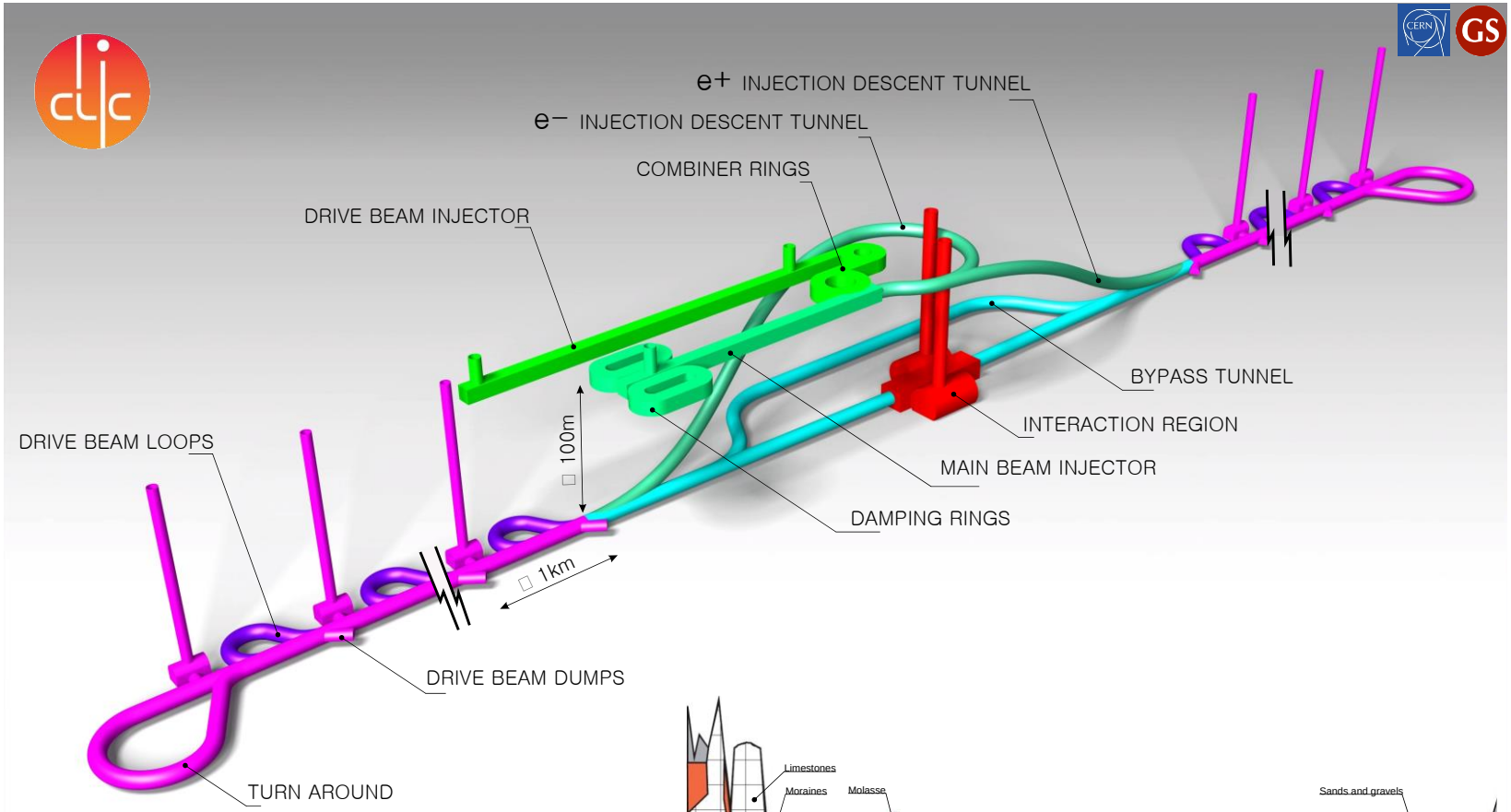
# Large Hadron electron Collider (LHeC)



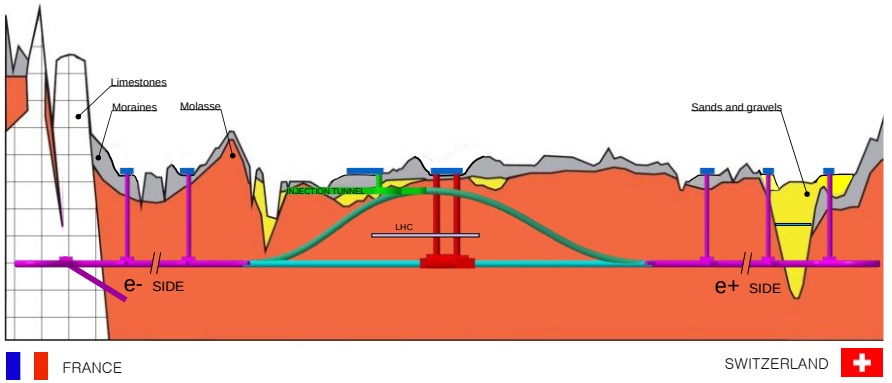

**ERL LHeC:**
**recirculating linac with energy recovery**
**&**
**SAPPHiRE**
**$\gamma\gamma$ collider**

# CLIC linear $e^+e^-$ collider

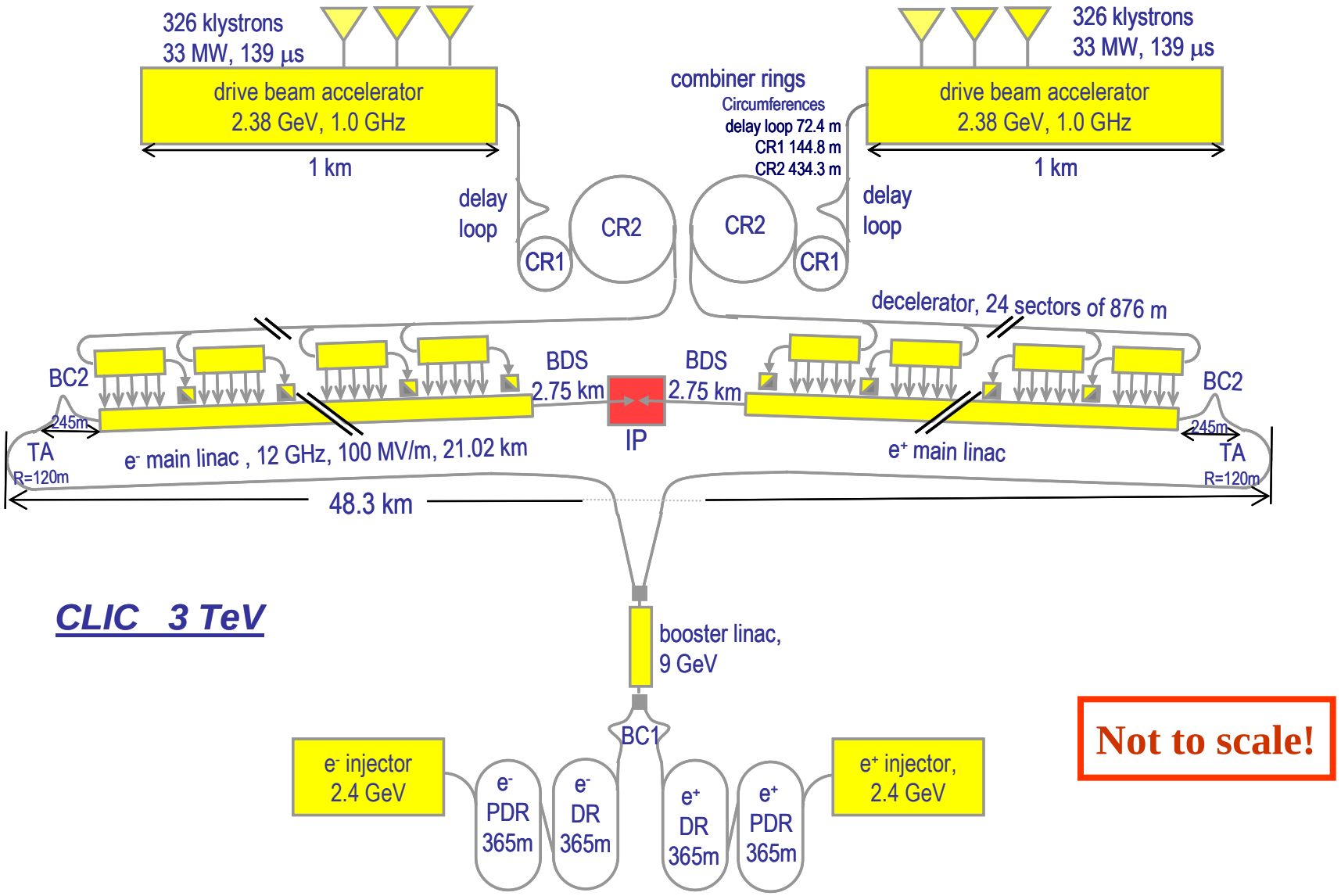
## total length (main linac) ~11 (500 GeV) - 48 km (3 TeV)



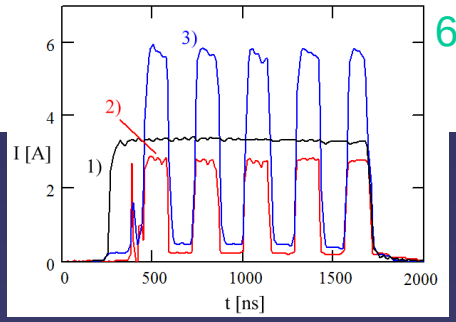

CLIC SCHEMATIC
(not to scale)



# CLIC e+e- collider



# CTF3 Test Facility at CERN & Achievements

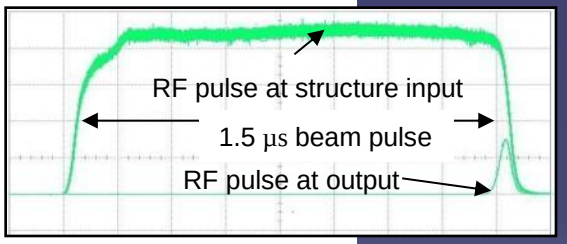


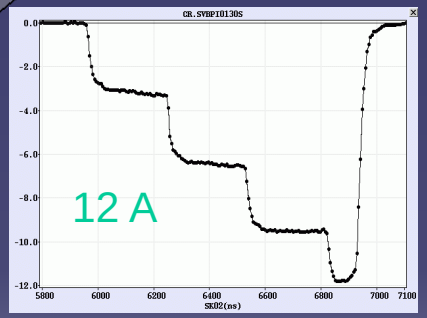

DELAY LOOP

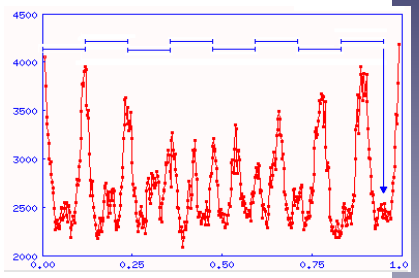
4 A – 1.2 μs
120 Mev

COMBINER RING

DRIVE BEAM LINAC



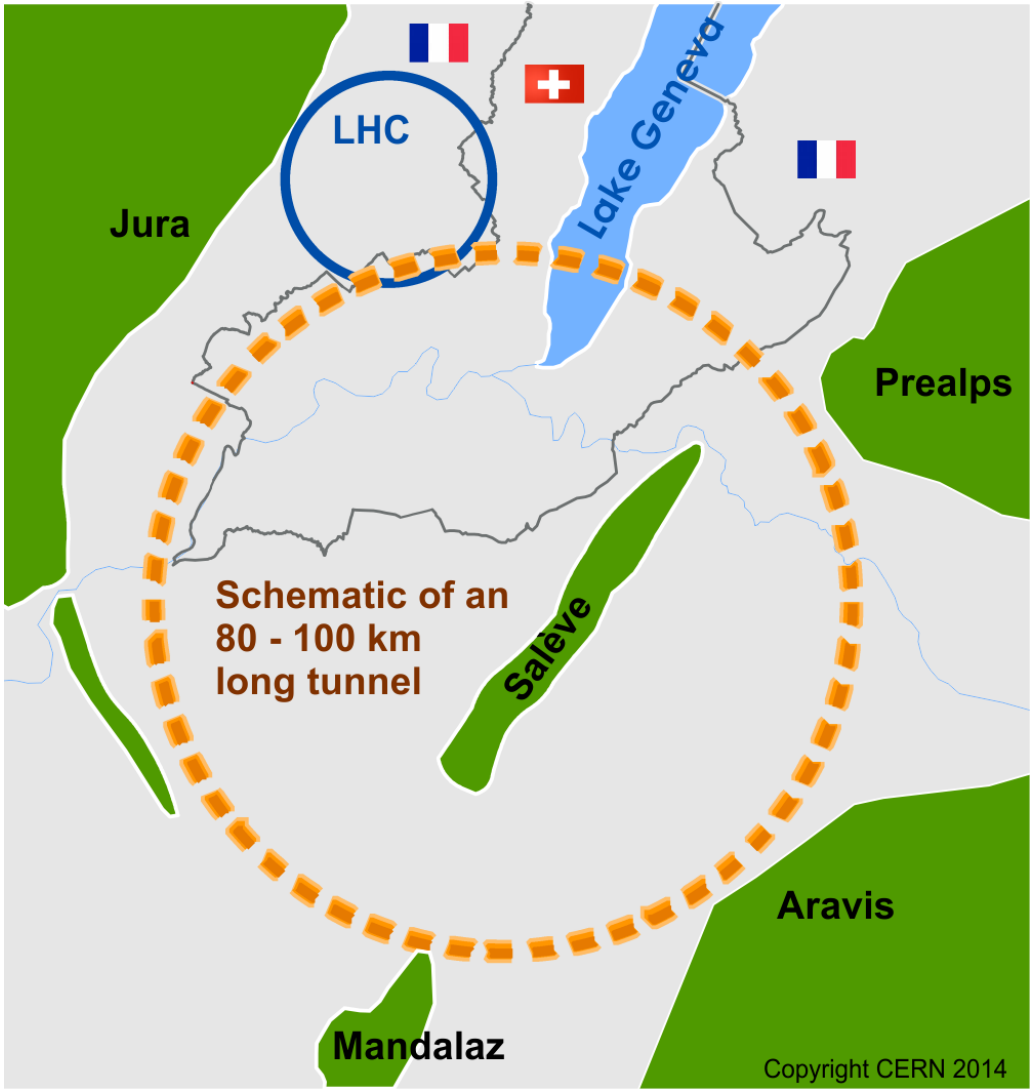
CLEX
CLIC Experimental Area

# Future Circular Collider Study - SCOPE
## CDR and cost review for 2018

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

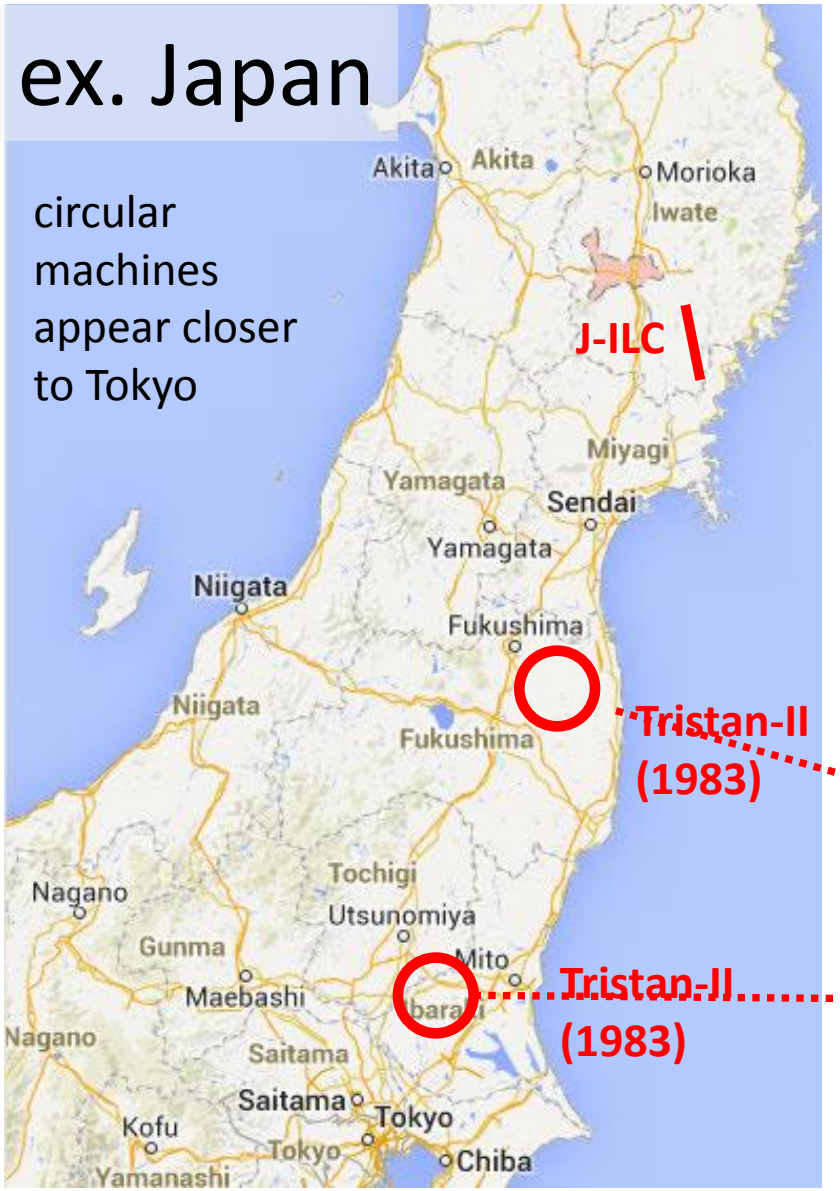
**~16 T ⇒ 100 TeV *pp* in 100 km**
**~20 T ⇒ 100 TeV *pp* in 80 km**

- **$e^+e^-$ collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area

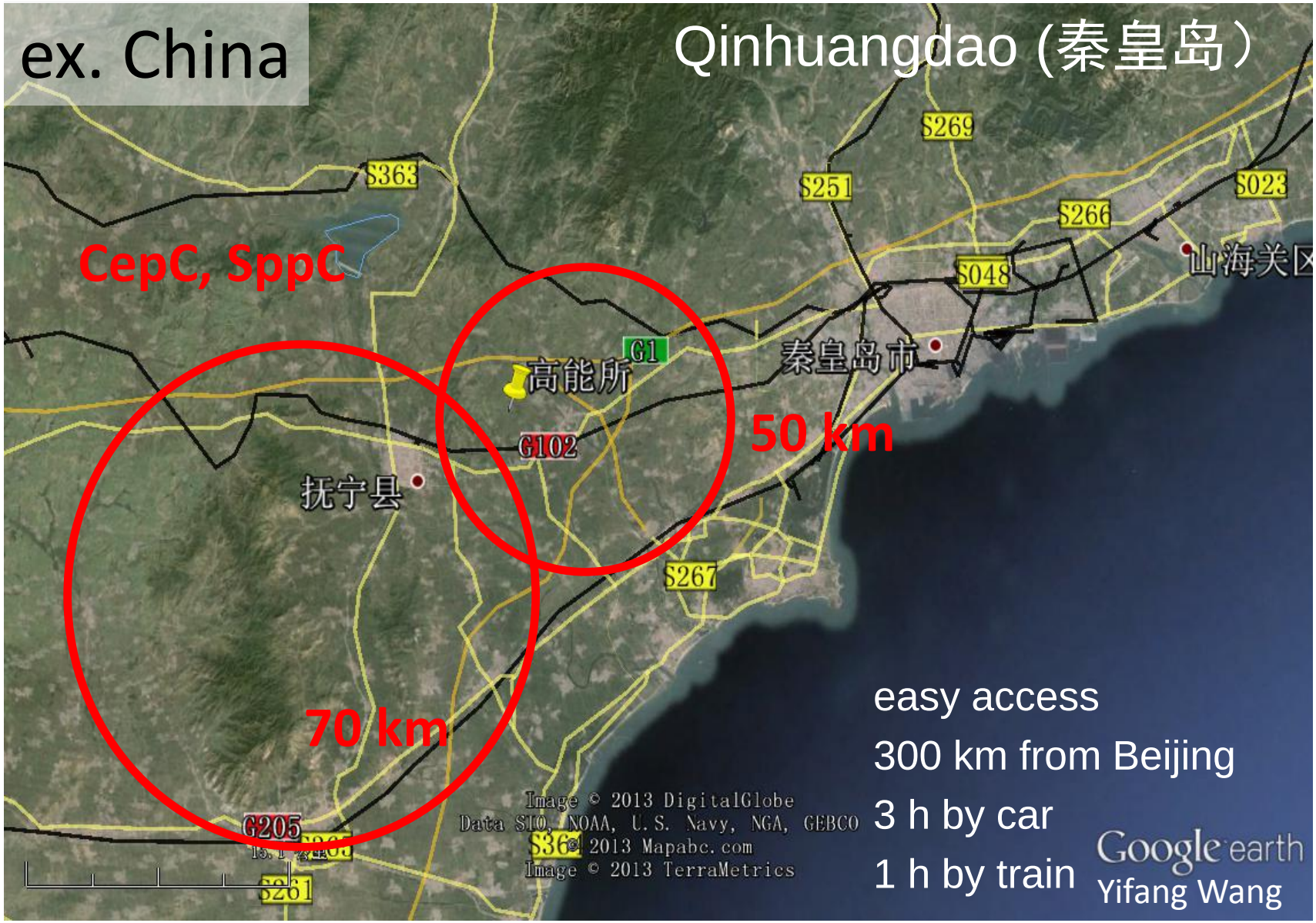



M. Benedikt

# proposed linear & circular colliders



# other proposed circular colliders



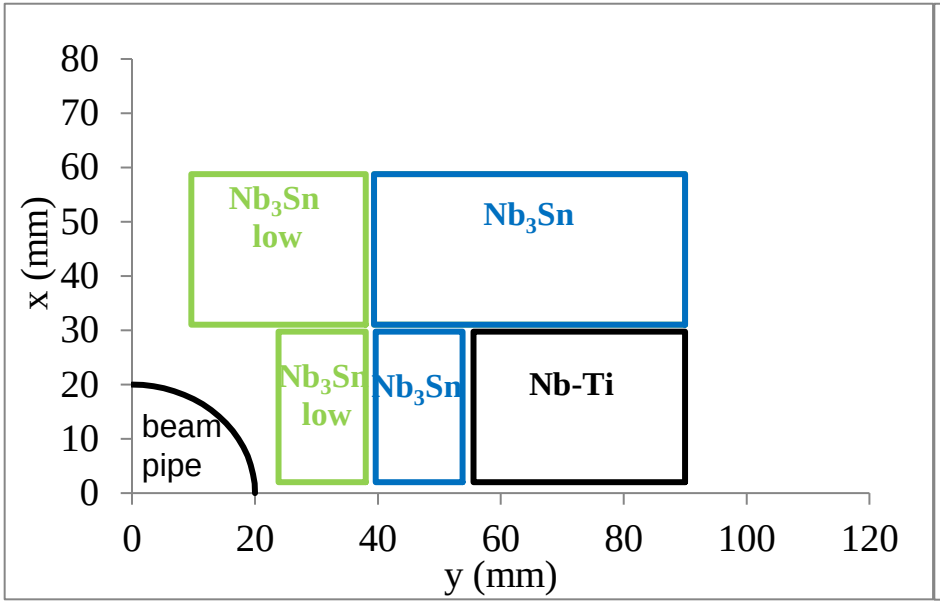
# FCC kick-off meeting U. Geneva, Feb. 2014

≈350 participants

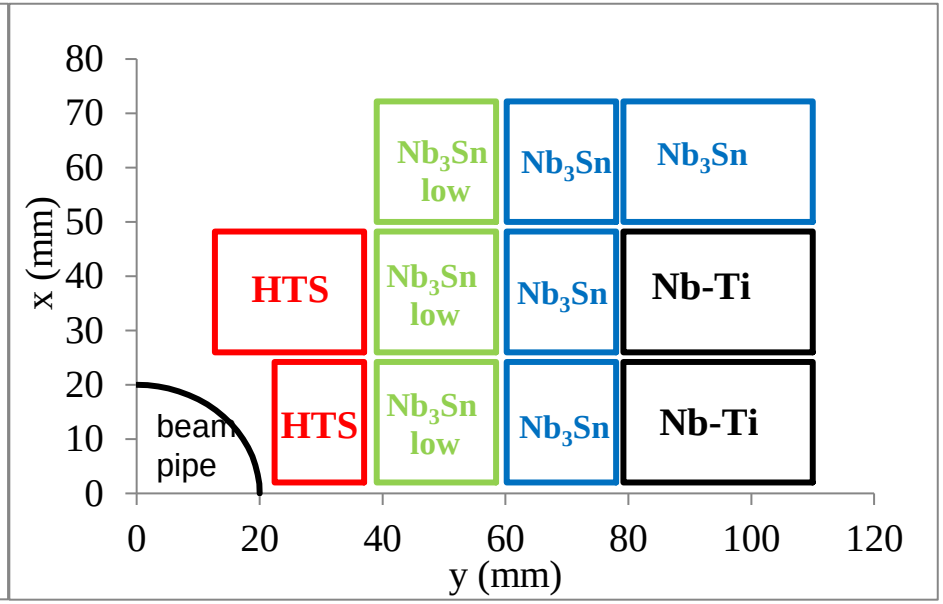
Erfolg des LHC ab

# Cost-Optimized Magnets for FCC

## 15-T dipole




## 20-T dipole

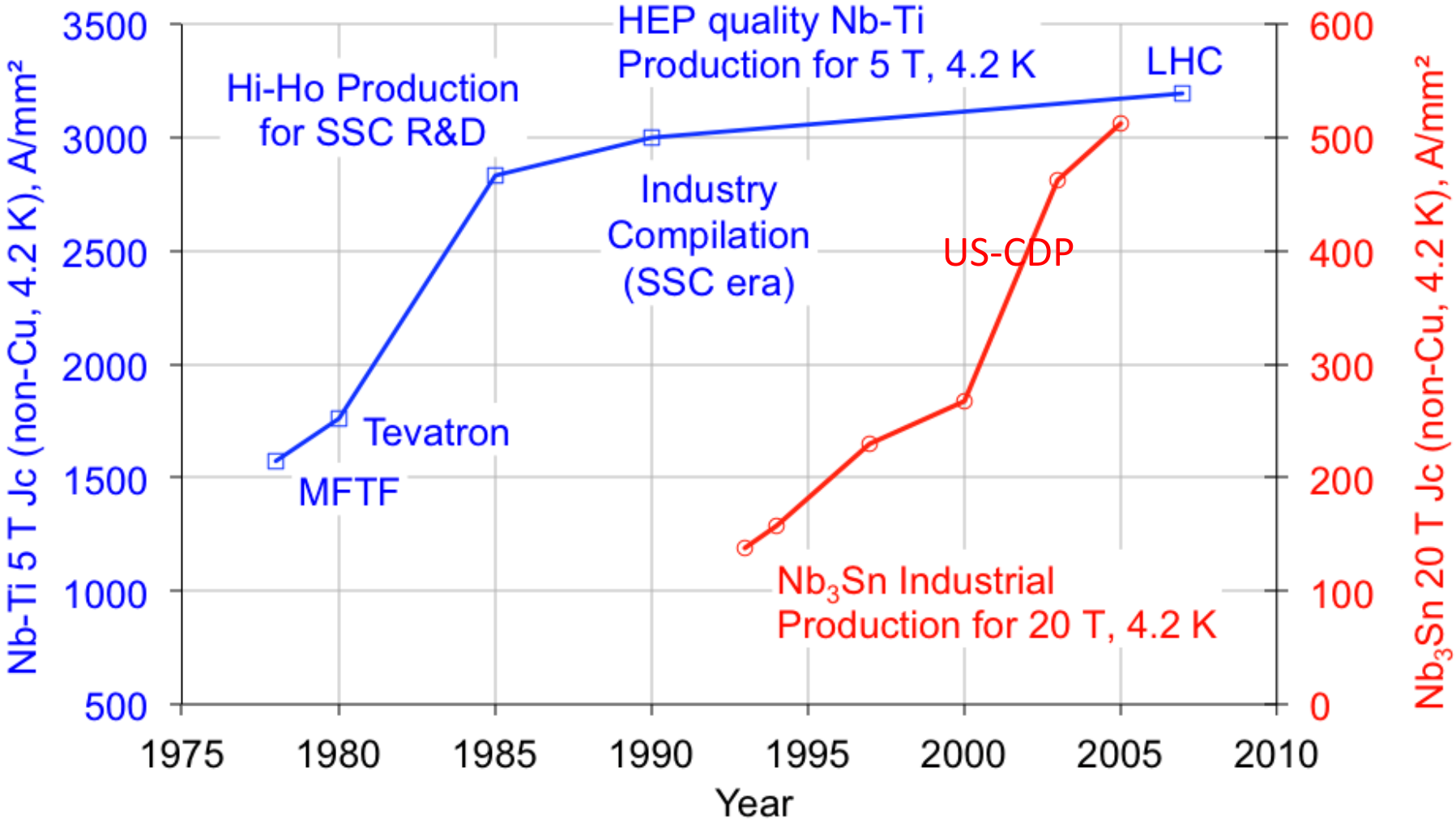



15 T dipoles + 100 km circumference

→ 100 TeV *pp*

E. Todesco, L. Rossi, P. McIntyre

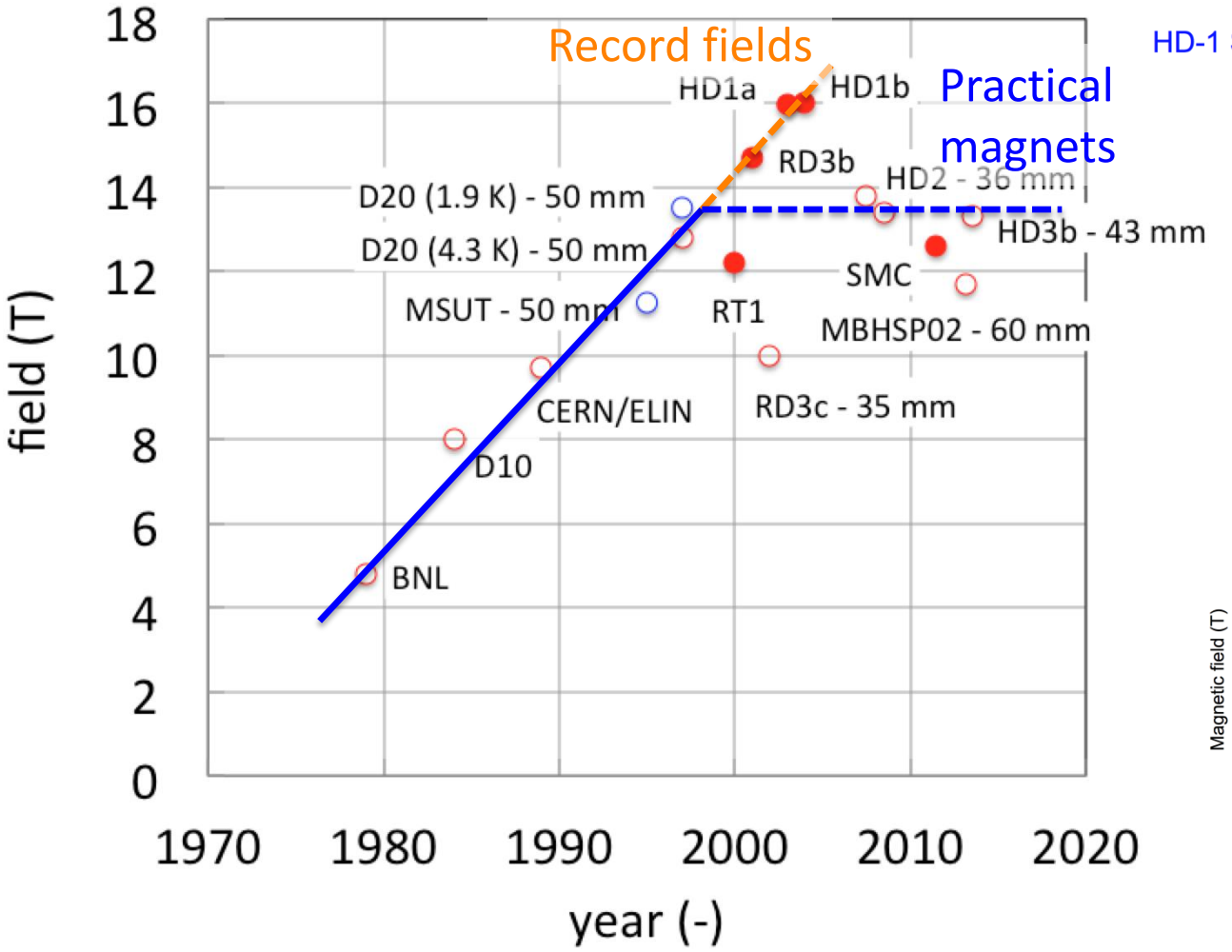
# Evolution of *Nb-Ti* & $Nb_3Sn$ SC Cable




L. Bottura (CERN), J. Parrell (OST)

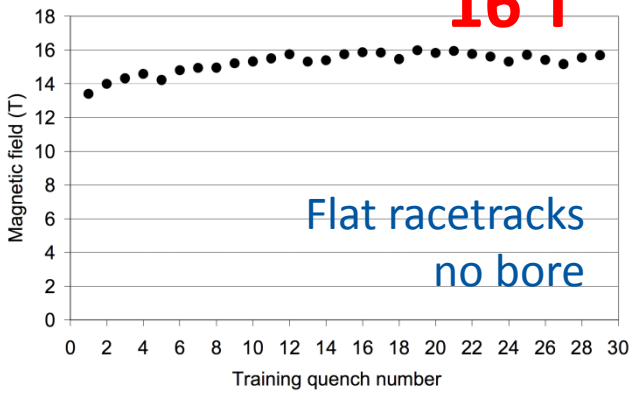
# High-Field Dipoles

Accelerator and Fusion Research Division
LBNL Superconducting Magnet Program
Newsletter
October 2003
Issue No. 2



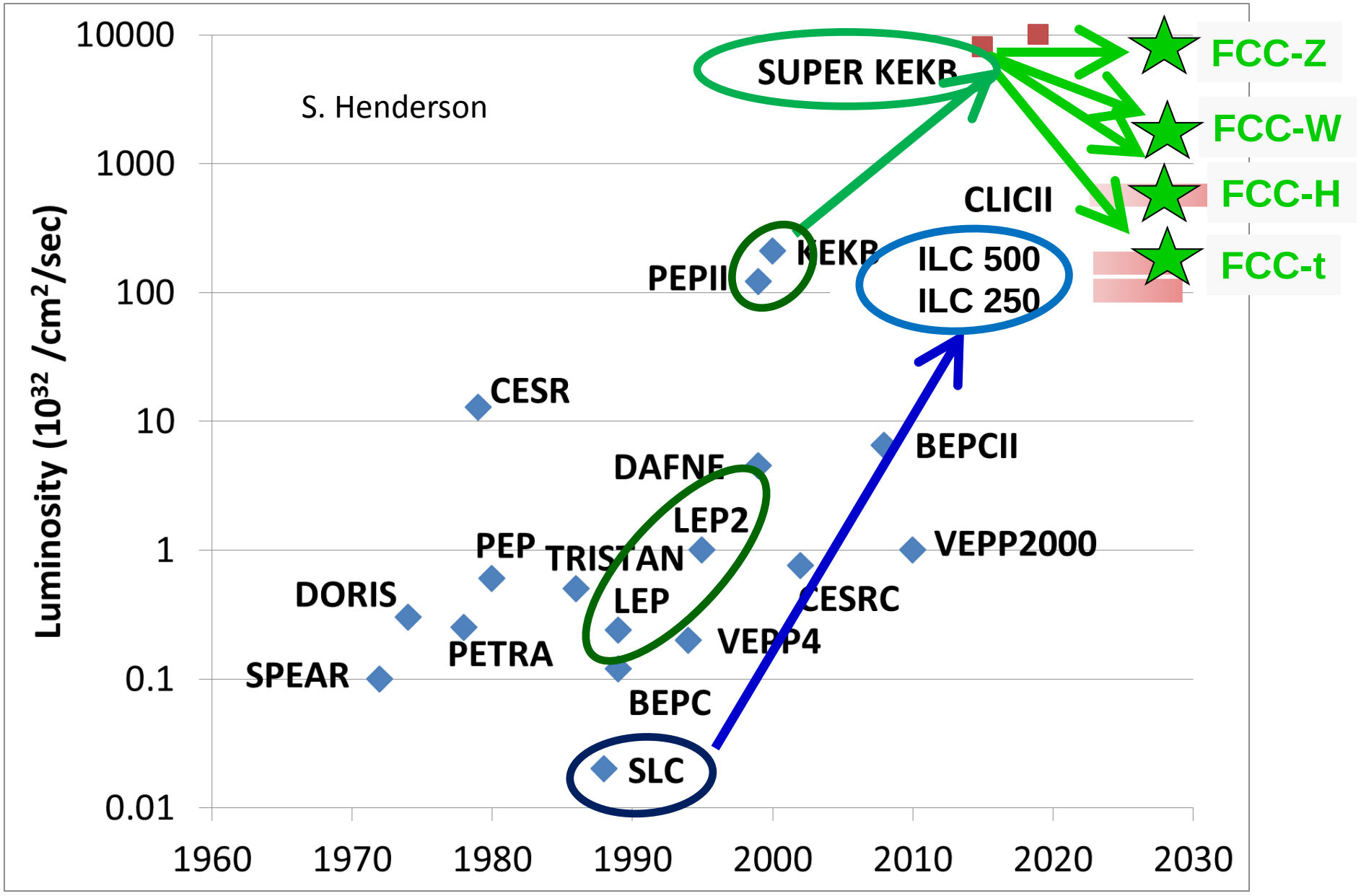

HD-1 Sets New Dipole Field Record

16 T

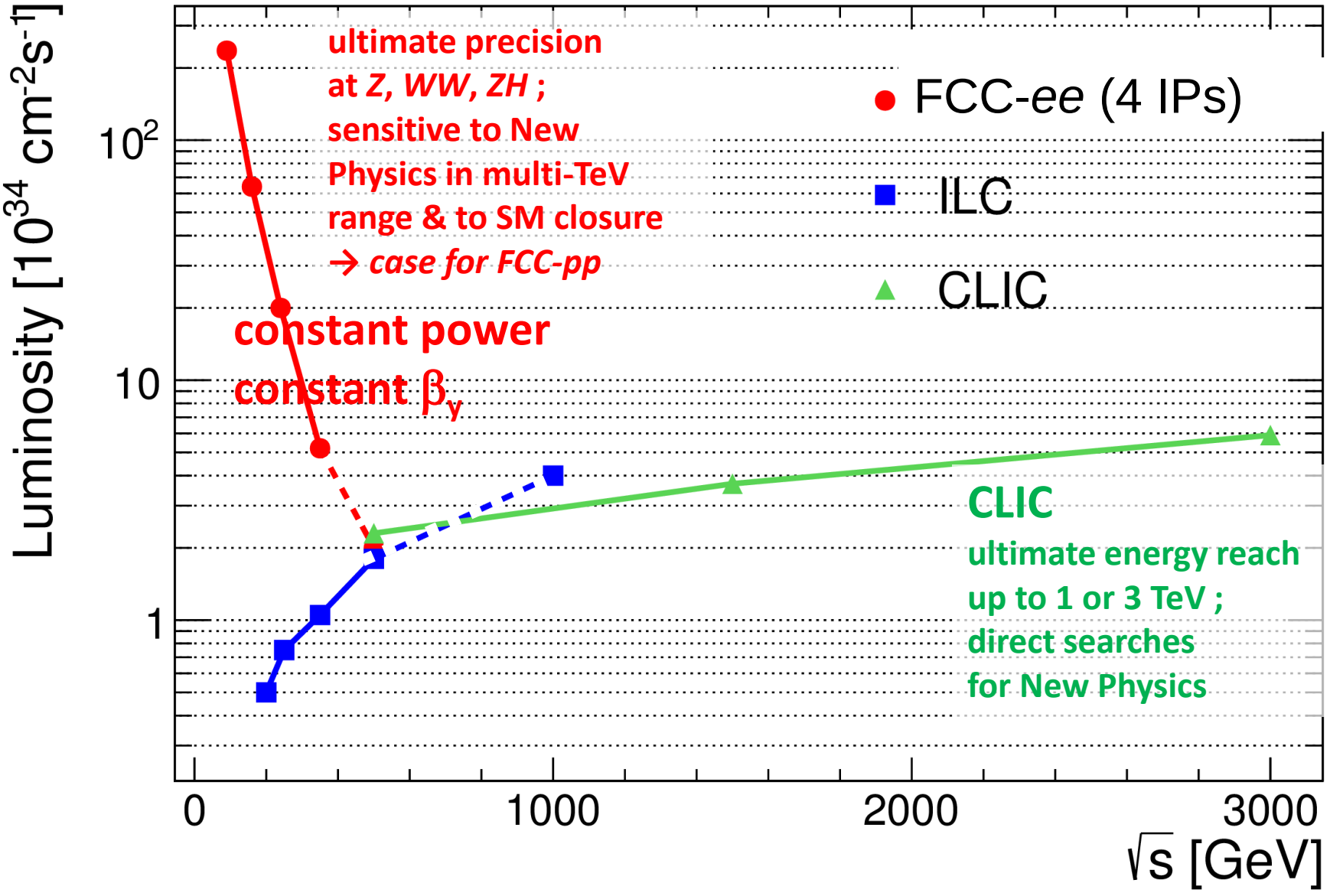



Data by courtesy of L. Rossi (CERN) and S. Caspi (LBNL)

# past, future & proposed $e^+e^-$ colliders

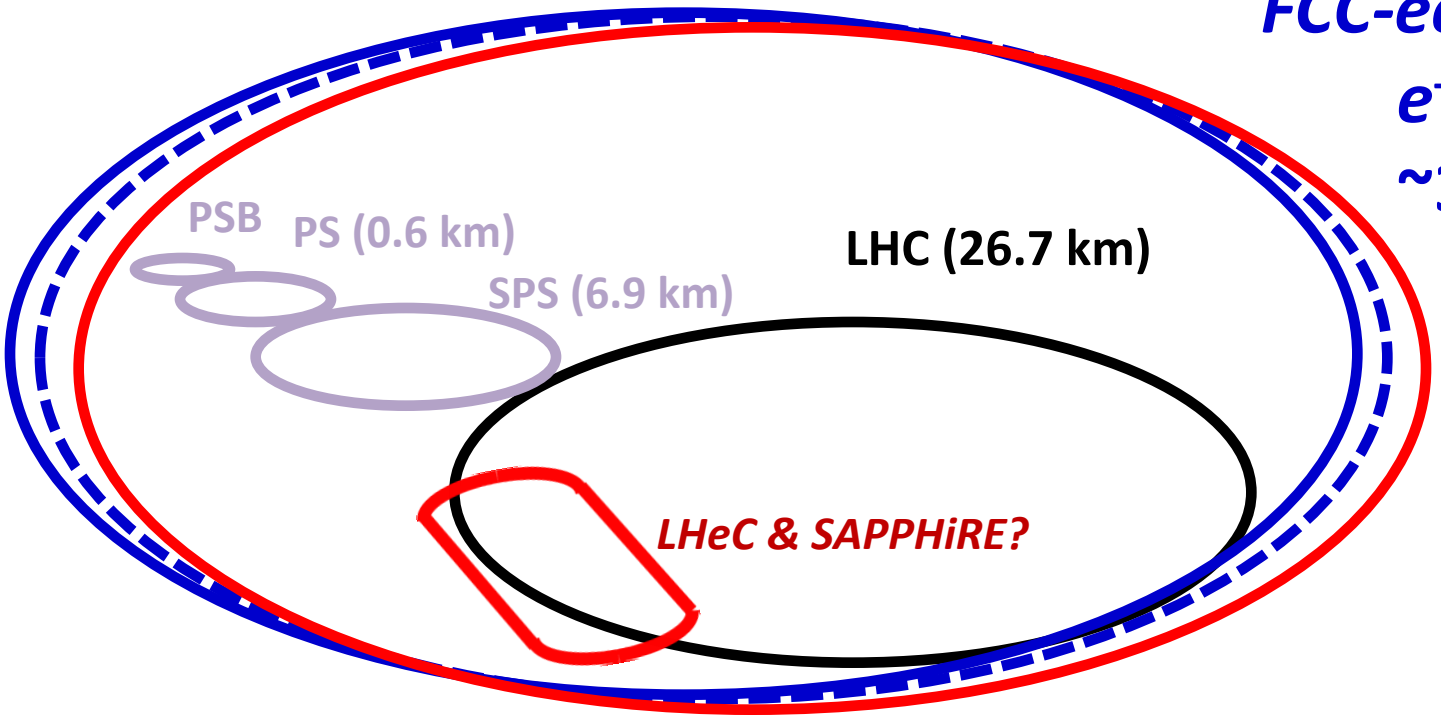


# $e^+e^-$ luminosity vs. energy



# circular roadmap

(CERN implementation)




***FCC-ee*** **(80-100 km, $e^+e^-$, up to ~350 GeV c.m.)**

***FCC-hh*** **(*pp*, up to 100 TeV c.m.)**

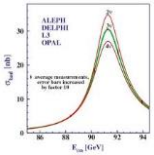
& $e^{\pm}$ **(50-175 GeV) –** ***p*** **(50 TeV)** collisions (*FCC-he*)

**≥50 years of $e^+e^-$, *pp*, *ep/A* physics at highest energies**

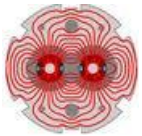
# possible time line at CERN

1980 | 1990 | 2000 | 2010 | 2020 | 2030 | 2040

**LEP** Constr. | Physics | Upgr.




**LHC** Design, R&D | Proto. | Constr. | Physics



**HL-LHC** Design, R&D | Constr. | Physics

High Luminosity LHC

**FCC**

*ee* Design, R&D | Constr. | Physics

*pp* Design, R&D | Constr. | Physics

# *is history repeating itself…?*

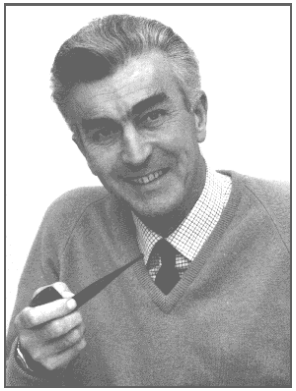
When **Lady Margaret Thatcher** visited CERN in 1982, she also asked the then CERN Director-General **Herwig Schopper** ***how big the next tunnel after LEP would be.***

Margaret Thatcher,
British PM 1979-90

Herwig Schopper
CERN DG 1981-88
built LEP

Dr. Schopper‘s answer was ***there would be no bigger tunnel at CERN***.

Lady Thatcher replied that she had „obtained ***exactly the same answer from*** **Sir John Adams** ***when the SPS was built“ 10 years earlier***, and therefore she didn‘t believe him.

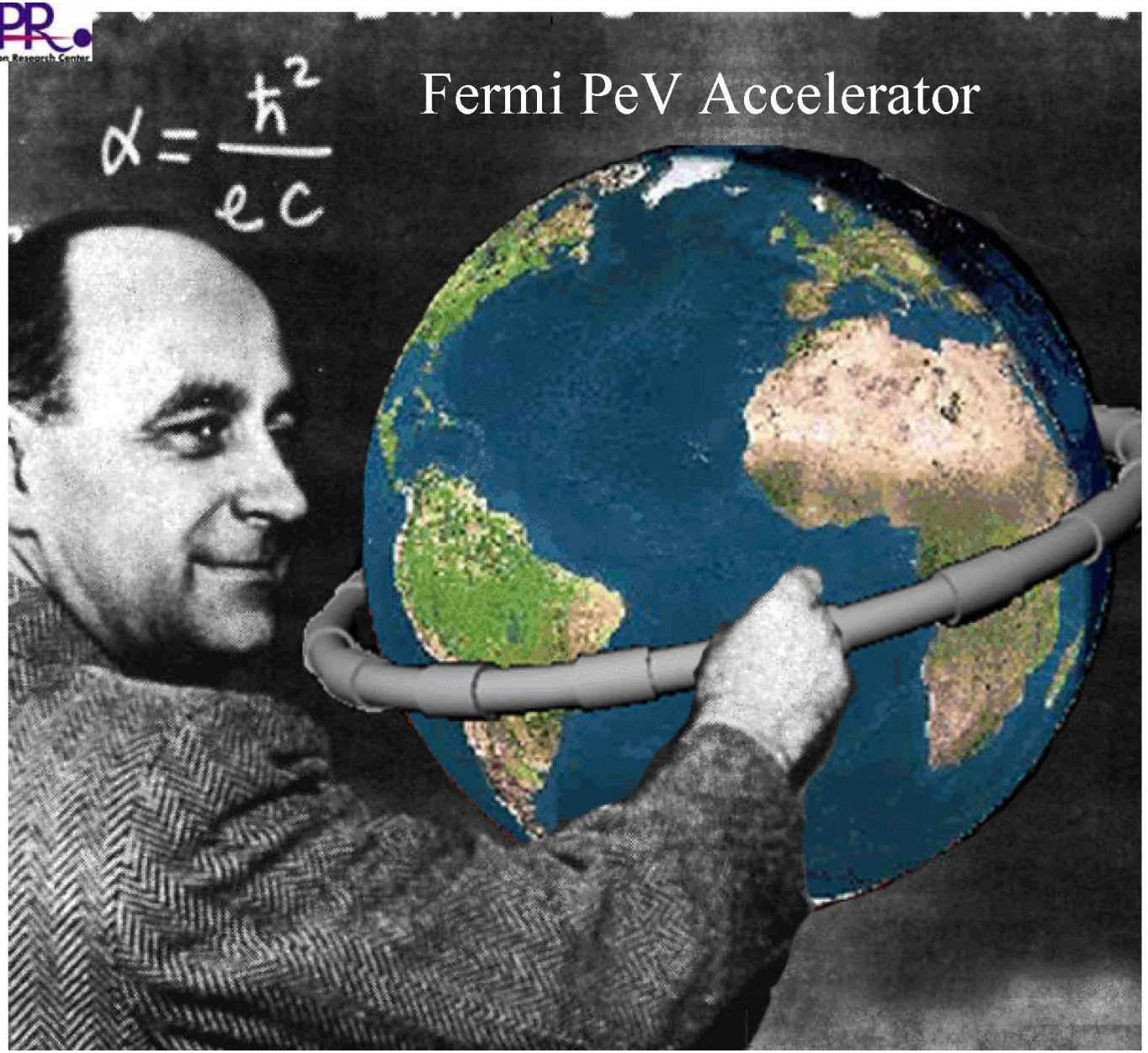


John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

***maybe the Prime Minister was right!?***

Herwig Schopper, private communication, 2013

# *how to go beyond 100 TeV?*




**the definition of the fine-structure constant is wrong**

# laser-driven dielectric microstructure?

October 2013

Particle accelerators

## Small really is beautiful

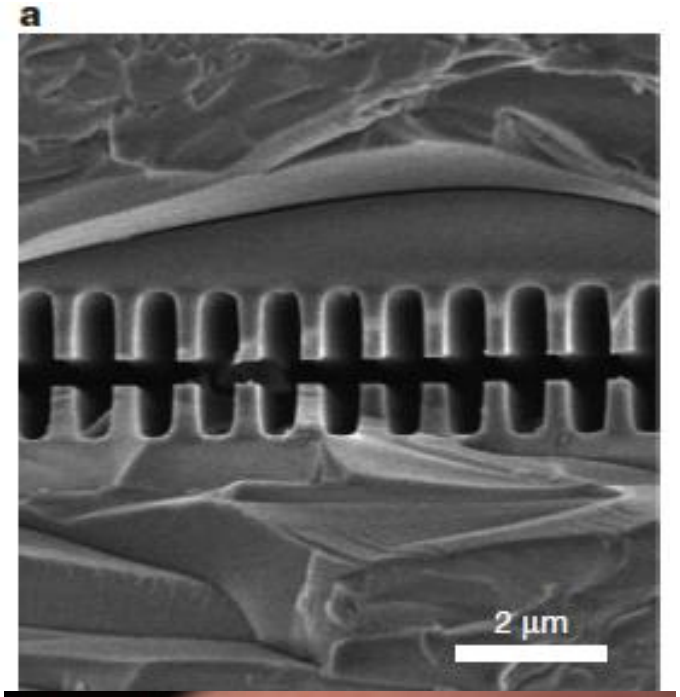
The Economist

**Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically**

Oct 19th 2013 | From the print edition

Timekeeper

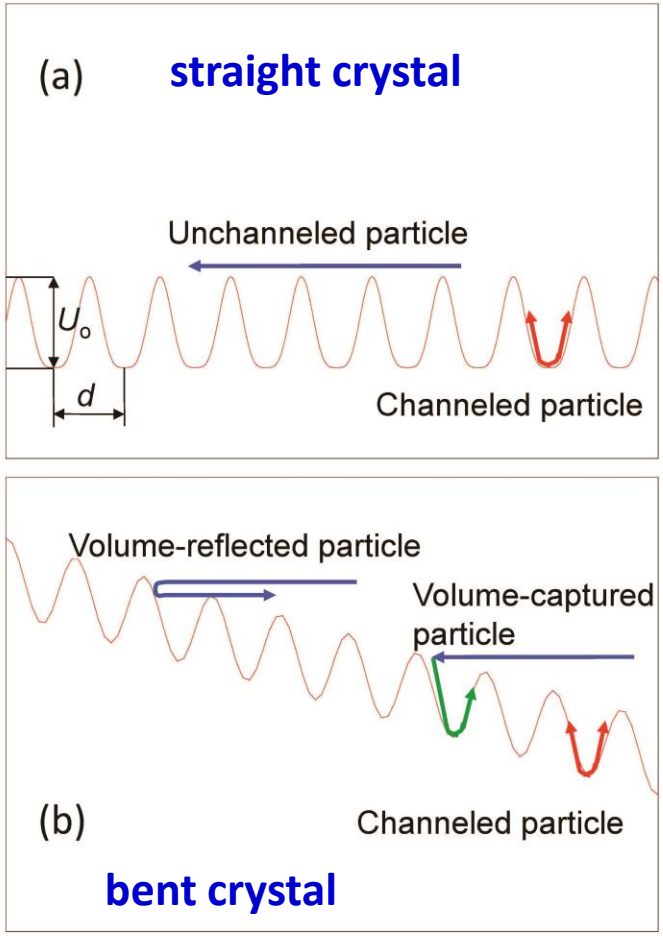
Tweet 56



*Nature* **503**, 91–94 (07 November 2013)

V. Shiltsev

# another possibility – crystals: world's strongest magnets




crystal focusing strength

$\phi$~20-60 eV/Å$^2$

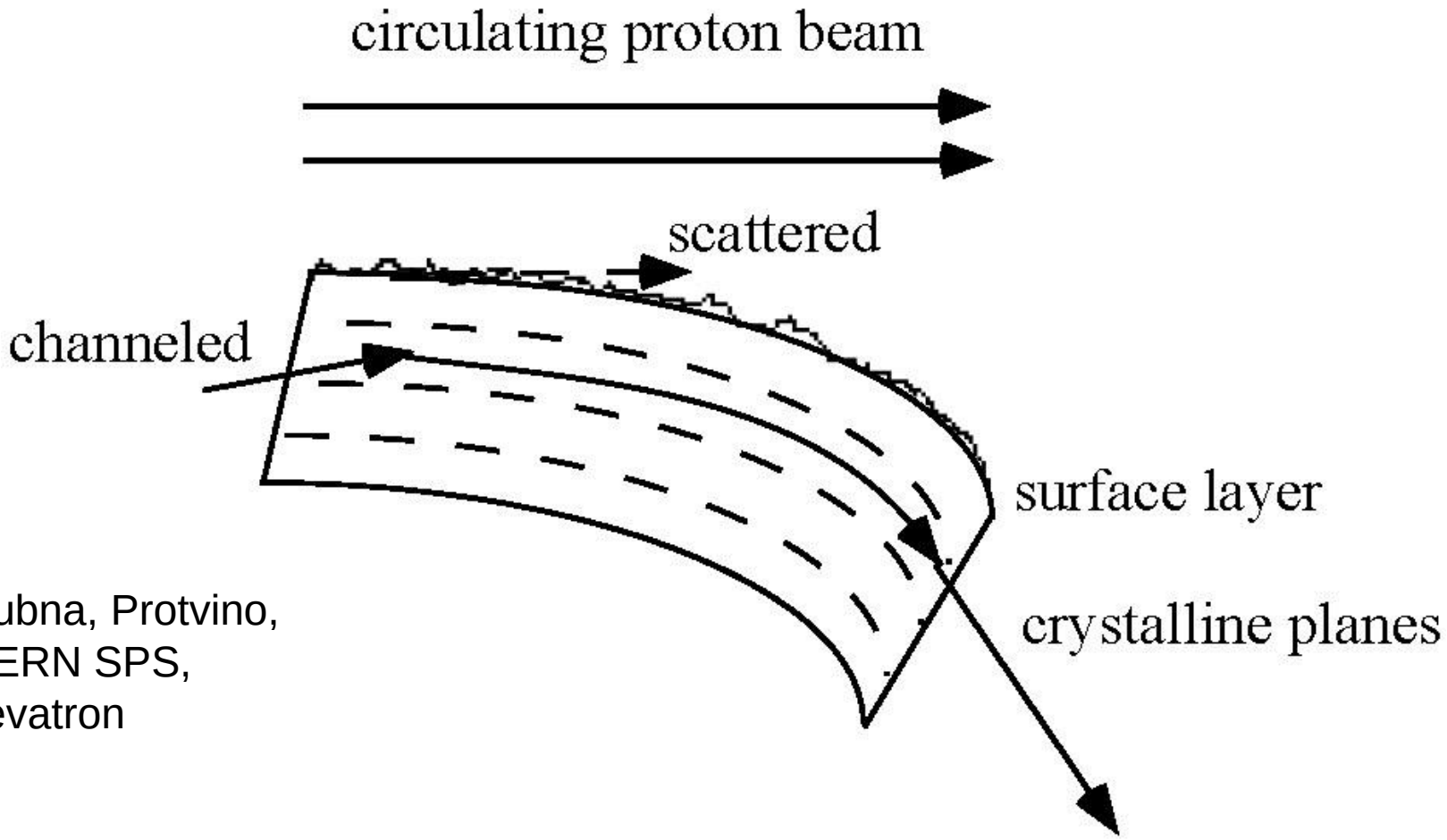
$B_{max}$≈2000 T !

$\lambda=2\pi\beta=2\pi\,(E/\phi)^{1/2}$

W. Scandale, MPL A (2012)

S.A. Bogacz, D. Cline, 1997

# crystal extraction from stored proton/ion beam

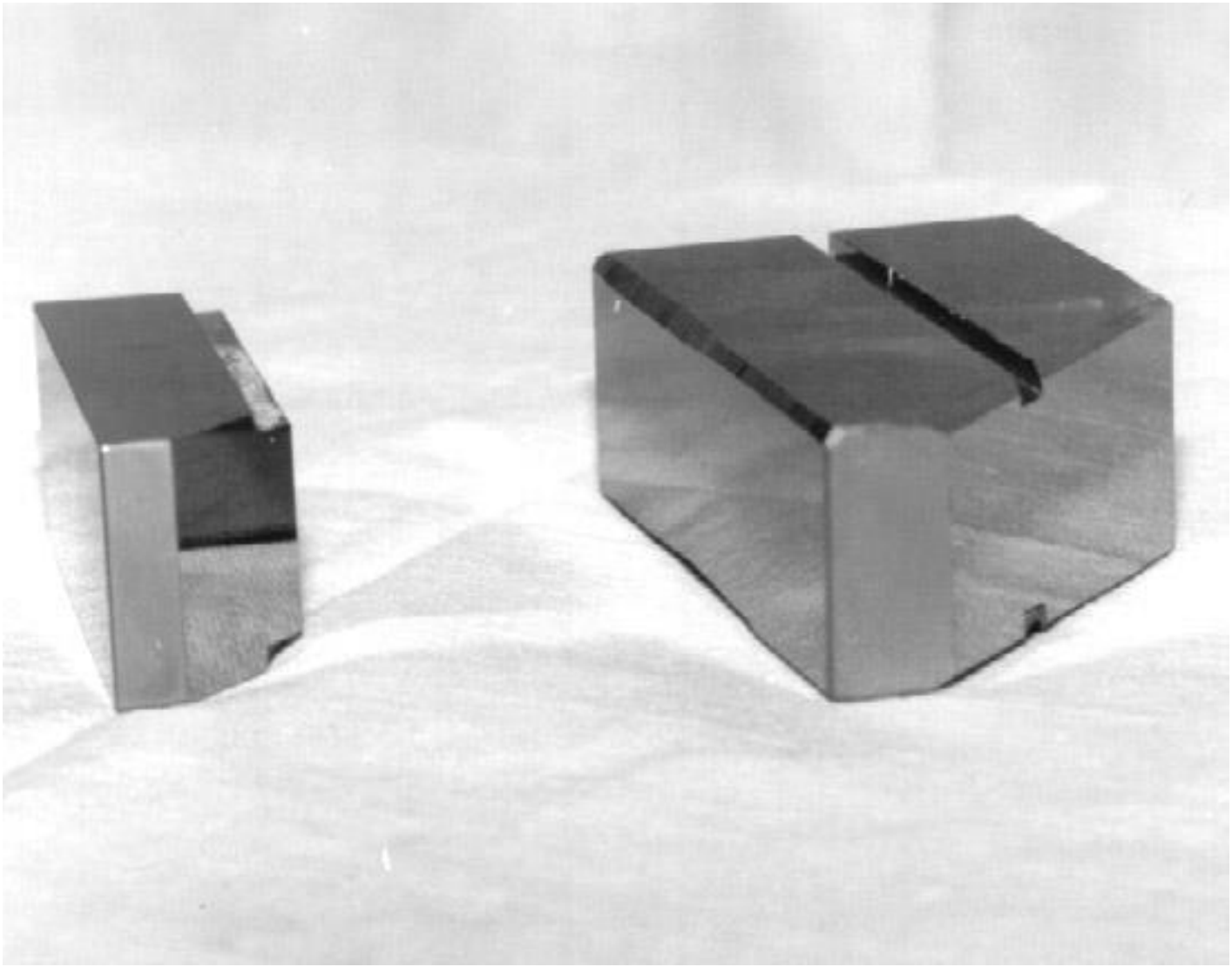



Dubna, Protvino,
CERN SPS,
Tevatron

**since 1978 crystals are used for extracting high-energy protons or ions from storage rings;**

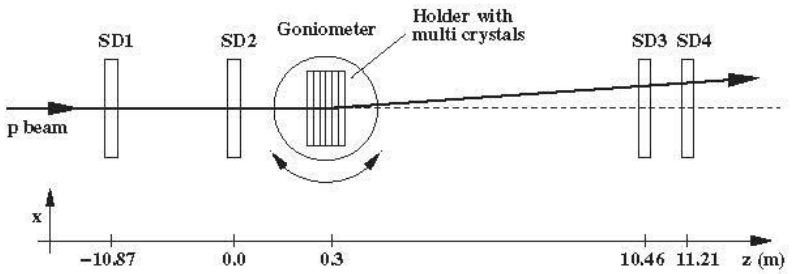
**can they also be used for a circular collider?!**

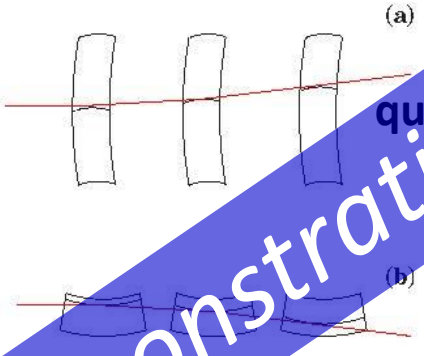
# samples of focusing crystals



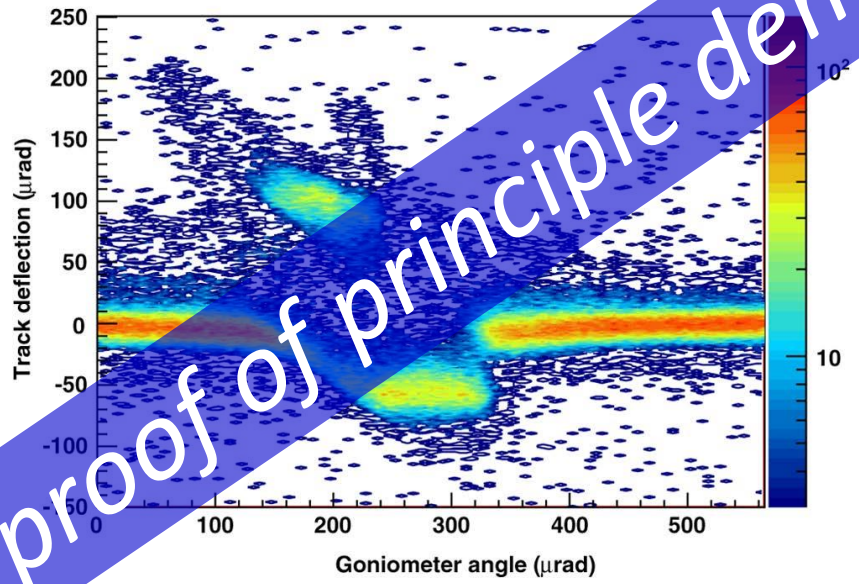
Yuri M.Ivanov, Petersburg Nuclear Physics Institute, 2005

# staging of crystal deflectors




schematic layout of the experimental setup used to study multiple volume reflection at the H8 beam line of the CERN SPS



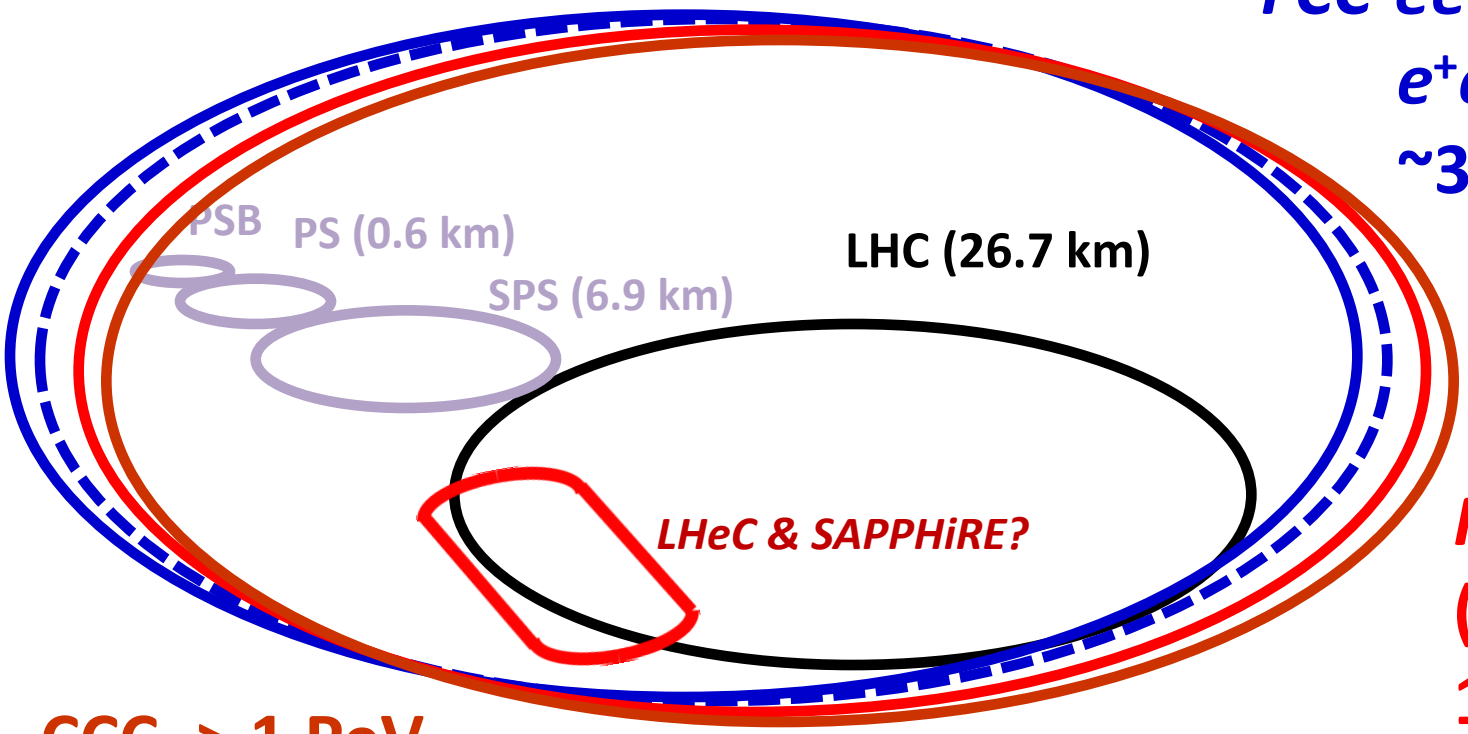

proof of principle demonstration!

**6 strip crystals in series** (each 2 mm long):
**400 GeV/*c* protons reflected by 40±2 μrad**
[effective field **16 T**]
with **efficiency 0.93±0.04**

W. Scandale et al, Observation of Multiple Volume Reflection of Ultrarelativistic Protons by a Sequence of Several Bent Silicon Crystals, Phys.Rev.Lett. 102 (2009) 084801

# *possible longer-term strategy*

(CERN implementation)




***FCC-ee* (80-100 km, $e^+e^-$, up to ~350 GeV c.m.)**

***FCC-hh* (*pp*, up to 100 TeV c.m.)**

**CCC, > 1 PeV**

& $e^{\pm}$ **(50-175 GeV) –** ***p*** **(50 TeV)** collisions (*FCC-he*)

**≥50 years of $e^+e^-$, *pp*, *ep/A* physics at highest energies**

**followed by >1 PeV circular crystal collider (CCC)?!?**

# highest-energy particles

4 July 2012 CERN, Geneva, Switzerland

Higgs boson – "God particle"? – mass $1.25 \times 10^{11}$ eV, neither matter nor force!

15 October 1991 Dugway Proving Ground, Utah, U.S.A.

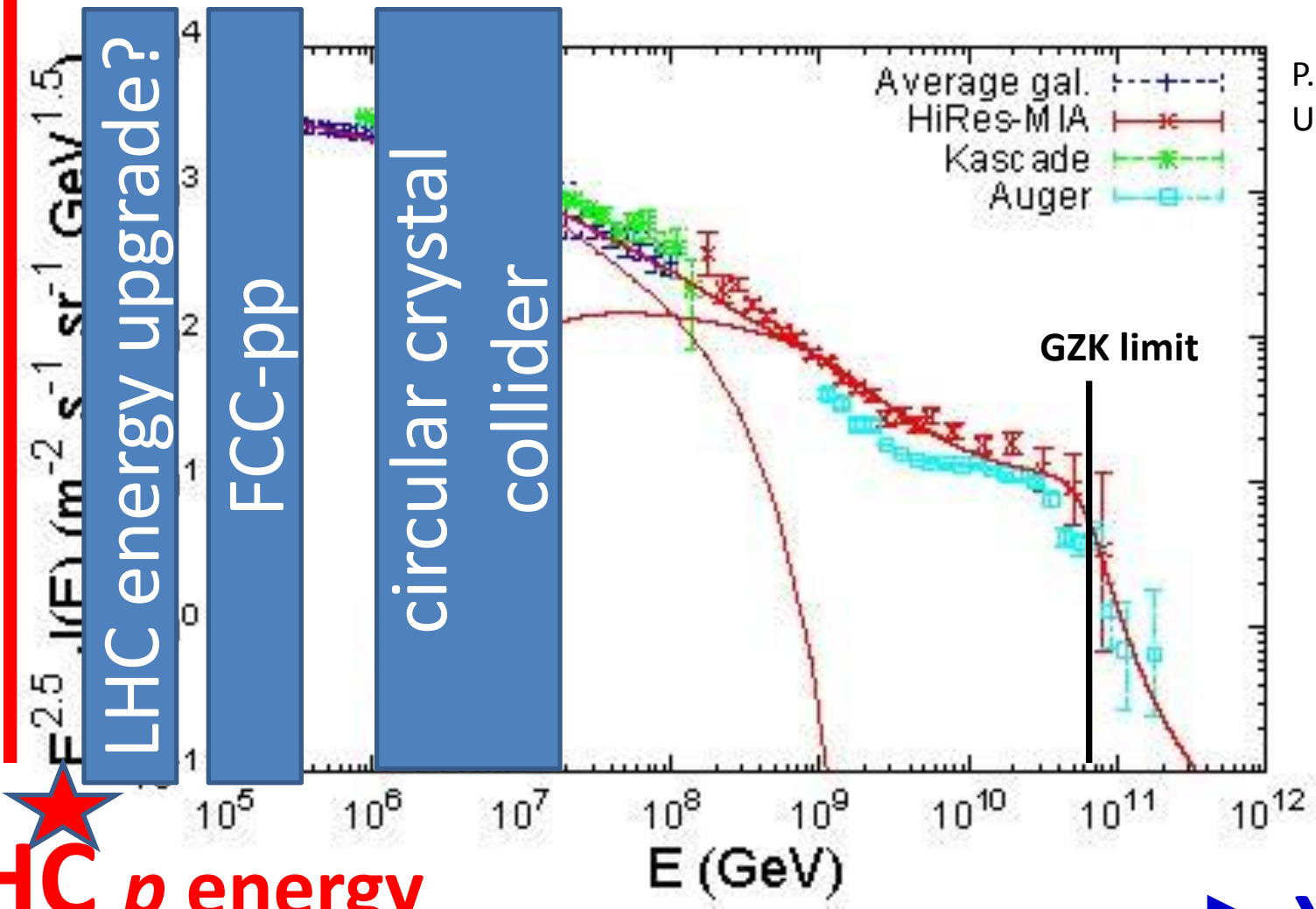
"Oh-my-God-particle"!

(kinetic) energy $3 \times 10^{20}$ eV

($=3 \times 10^{11}$ GeV = 300 EeV)!

# $10^{45}$ m$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{1.5}$!

cosmic-ray energy spectrum




P. Blasi, UHECR2012

LHC *p* energy

x10$^{8}$

# ultimate limit of electromagnetic acceleration

$E_{cr} \approx 10^{18}$ V/m critical field for $e^+e^-$ pair creation - $\hbar/(m_e c)\, e\, E_{cr} \sim m_e c^2$

reaching Planck scale of $10^{28}$ eV

would need $10^{10}$ m long accelerator

[$10^{10}$ m= 1/10th of distance earth-sun]

"*not an inconceivable task for an advanced technological society*"

P. Chen, R, Noble, SLAC-PUB-7402, April 1998

# to know more about accelerator physics … a few references


- M. Conte & W. MacKay, "*An introduction to the physics of particle accelerators*", World Scientific, Singapore, 1991.
- H. Wiedemann, "*Particle accelerator physics, 1 : basic principles and linear beam dynamics*"- 2nd ed. , Springer, Berlin 1999.
- A. Sessler & E. Wilson, "*Engines of Discovery : A Century of Particle Accelerators*," World Scientific, Singapore, 2007.
- S.Y. Lee, "*Accelerator Physics*" - 2nd ed. / Lee, World Scientific, Singapore, 2004.
- J.B. Rosenzweig, "*Fundamentals of Beam Physics*," Oxford Univ. Press, 2003.
- A.W. Chao, M. Tigner, "*Handbook of accelerator physics and engineering*", World Scientific, Singapore,1999

CERN
danke!

# Frank Zimmermann

- 1991 Physik-Diplom U. Hamburg
- 1993 Dr.rer.nat. U. Hamburg
  - Arbeiten zum HERA Beschleuniger am DESY
- 1993-1998 Stanford Linear Accelerator Center
  - Arbeiten am SLAC Linear Collider, B-factory, Future Linear Colliders, usw.
- seit 1999 am CERN
  - LHC Design und Inbetriebnahme, usw.
  - europäische Beschleunigernetzwerke (CARE, EuCARD, EuCARD-2)
  - Entwicklung zukünftiger Beschleuniger

frank.zimmermann@cern.ch

appendix:

long shutdown 1

some accelerator history

LHC beam dump

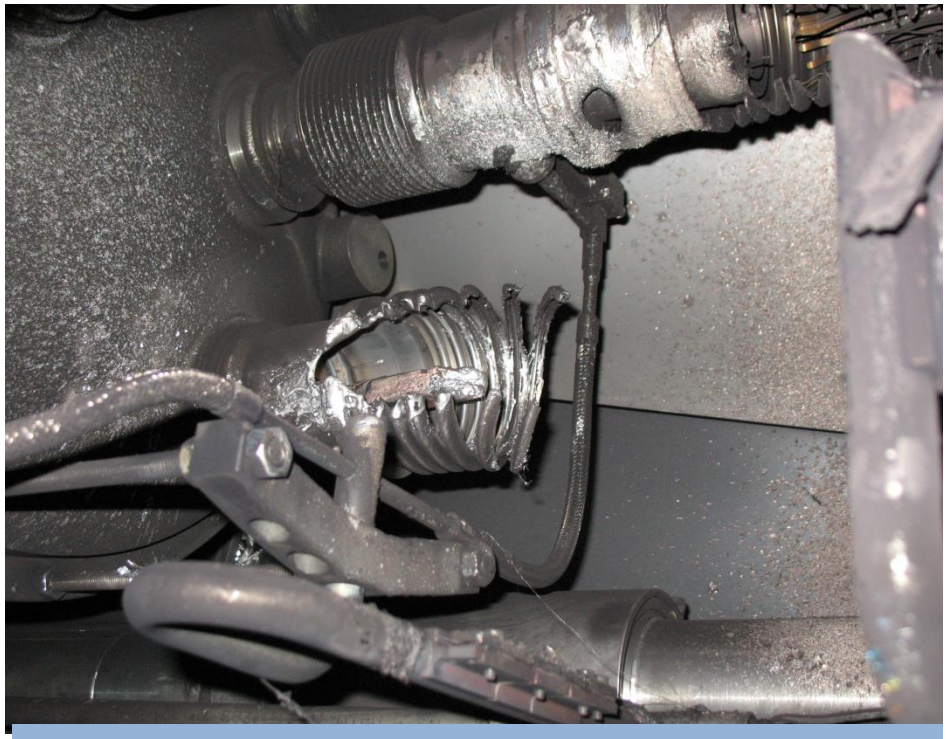
# Long Shutdown 1: 2013-14

after 2008 incident partial consolidation & related problem of imperfect *Cu* stabilizer continuity discovered

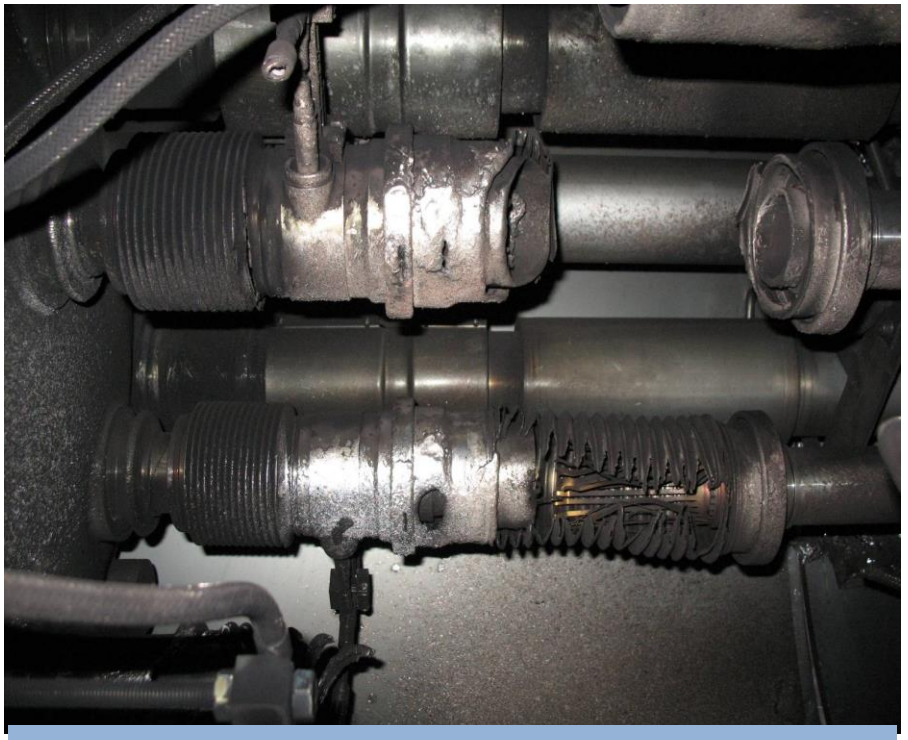
in 2010-12 LHC operated at 7 & 8 TeV c.m. beam energy to avoid any risk

presently: Long Shutdown 1 (LS1) ~2 yr to prepare LHC for 13-14 TeV c.m., detector upgrades in parallel

# 2008 “incident”



A faulty bus-bar (SC splice) in a magnet interconnect failed, leading to an electric arc which dissipated some 275 MJ

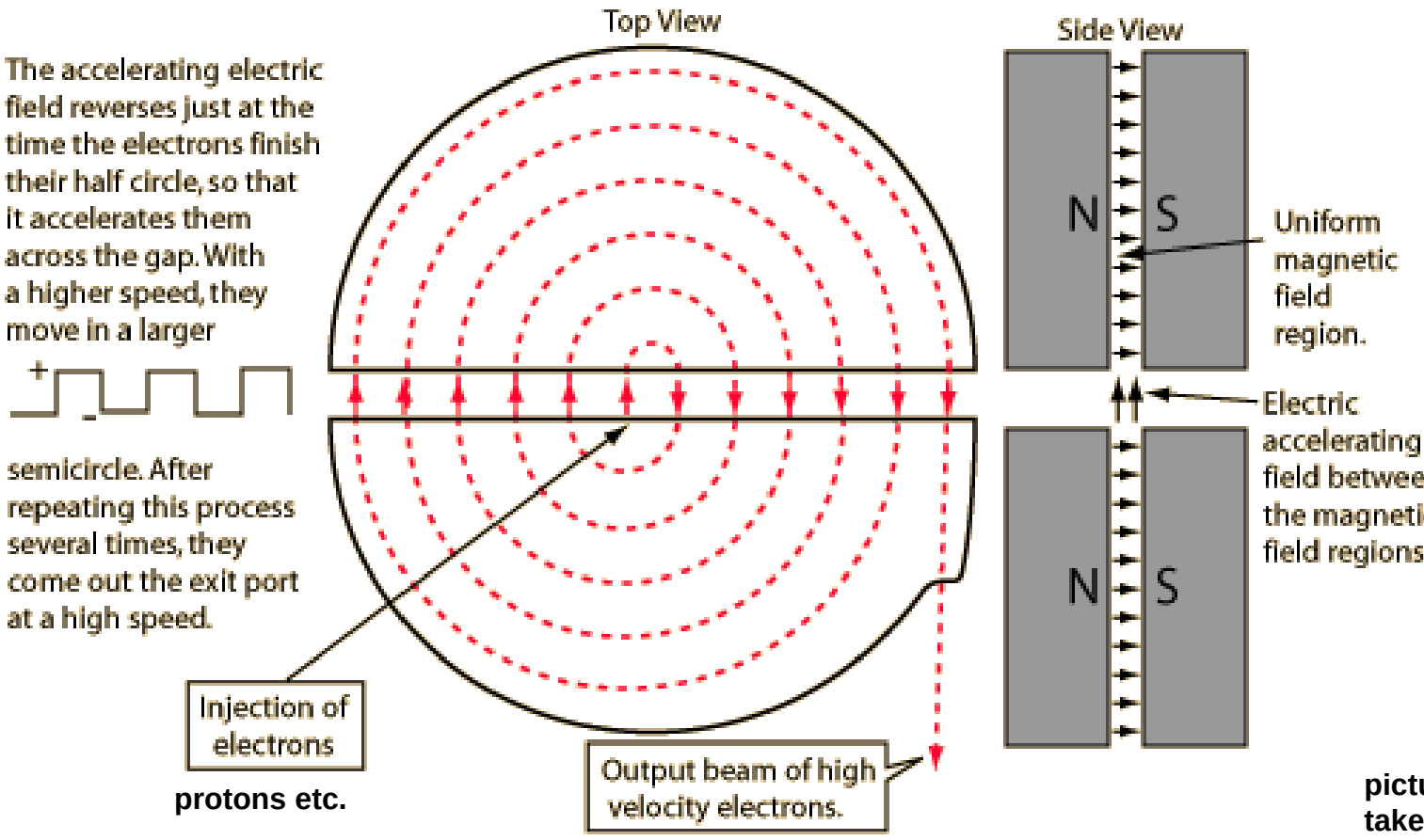


This burnt through beam vacuum and cryogenic lines, rapidly releasing ~2 tons of liquid helium into the vacuum enclosure

R. Veness

VELAN

# *cyclotron*




**picture taken from "hyperphysics" web site**

**history of the cyclotron:**

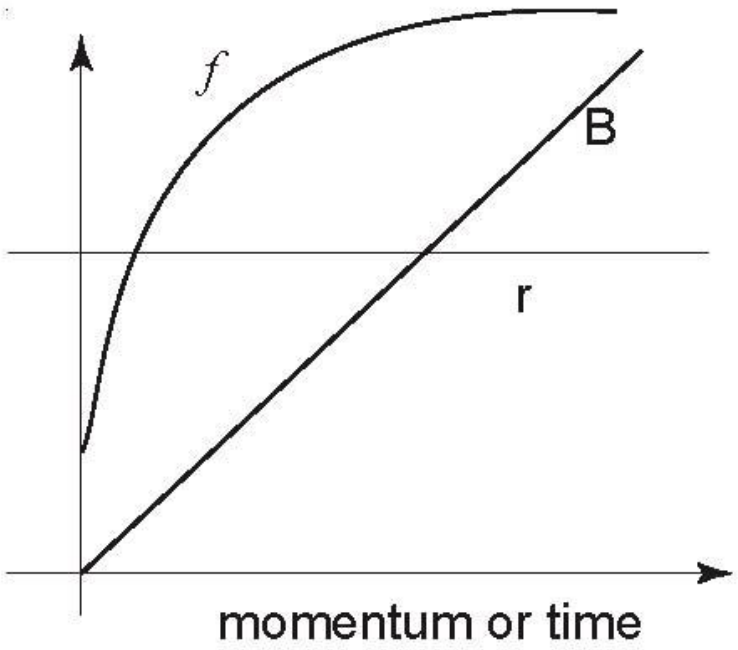
**1929 Ernest Lawrence** (Berkeley) invented the **cyclotron**

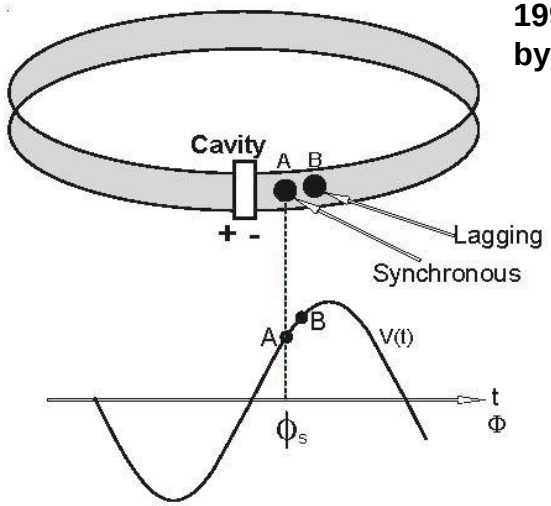
**1929 Hungarian physicists Sándor Gaál** and **Leo Szilard** both proposed cyclotron concept independently

**1930 Lawrence** built **first operating cyclotron**

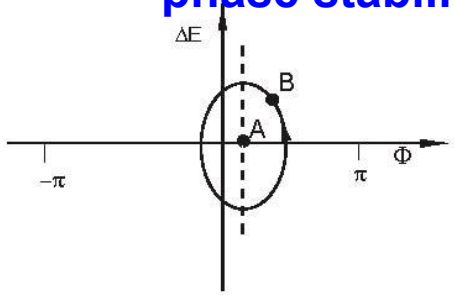
# *synchrotron*

pictures taken from 1998 lecture by E. Wilson




**"phase stability"**




**rf frequency changes with magnetic field**
**so as to keep particles on a constant circle**

**history of the synchrotron:**

**1934 Leo Szilard** files a British patent involving **"phase stability"**

**1943** Australian physicist **Mark Oliphant** invents the **synchrotron**, where accelerating particles are constrained to move in a circle of constant radius

**1944 V.I. Veksler** "re-discovered" the key principle of "**phase stability**"

**1945 Edwin McMillan** in Berkeley independently rediscovered the "phase stability"

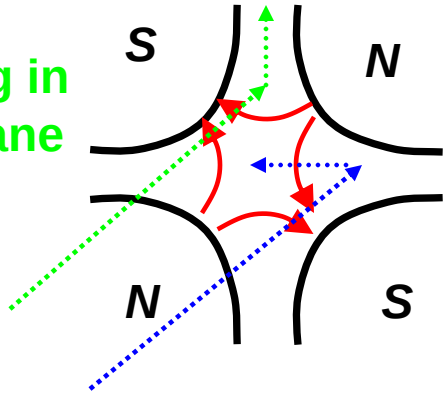
**1945** Norwegian **Rolf Wideroe** developed many formulae and ideas for "synchrotron"

# *strong focusing*

conventional wisdom in 1950: magnetic lens to focus particles both horizontally and vertically cannot be constructed — in contrast to optical lenses, which can
→ “weak focusing” machines, huge magnets, very expensive

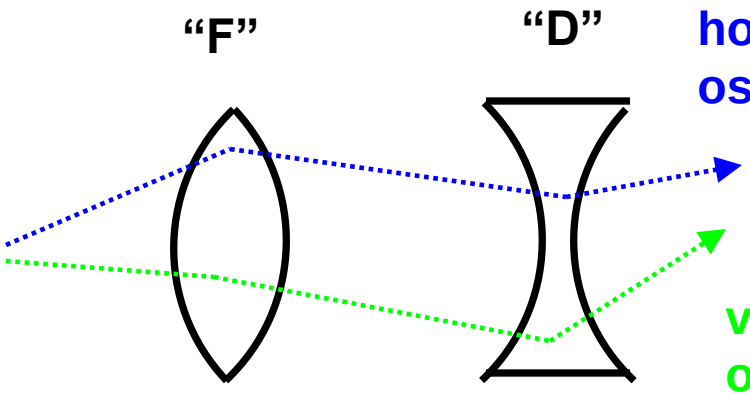
☼ **novel idea: combination of two lenses focuses in both planes simultaneously (“strong focusing”)**

example: quadrupole magnet




**defocusing in vertical plane**

**focusing in horizontal plane**




**“FODO” lattice**

**history of strong focusing:**

**1950** Greek elevator engineer **Nicholas Christofilos** patented this idea in March 1950; Berkeley physicists and others dismissed the idea as nonsense!

**1952** BNL physicists **Ernest Courant** and **Hartland Snyder** reinvent the concept

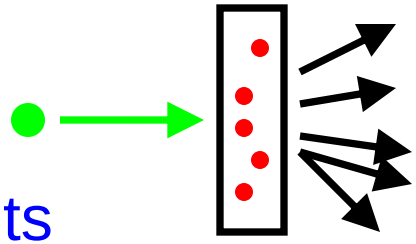
**1959** 25-GeV Proton Synchrotron (**PS**), the first strong focusing proton ring, starts operation at CERN (1 year before the Brookhaven AGS)

# *colliding beams*

**centre-of-mass energy:**

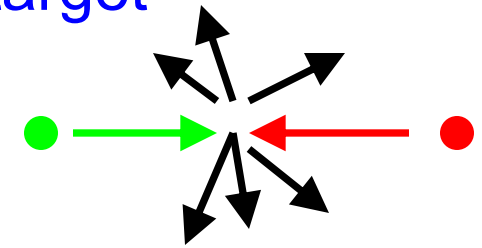
$$E_{\text{c.m.}} = \sqrt{2 E_{\text{beam}} M_{\text{target}} c^2}$$

beam hits
a “fixed target”



$$E_{\text{c.m.}} = 2 E_{\text{beam}}$$

two beams collide



colliding two beams against each other can provide
much higher centre-of-mass energies than fixed target!

**history of colliding beams:**

**1943 Norwegian physicist R. Wideroe invented “storage rings”** whereby particles running in opposite directions were to be made to collide

**1956** idea reinvented by Midwestern Universities Research Association (**MURA**), D. Kerst, G.O.’Neill

**1961** Frascati **AdA** - the first e+e- storage ring

**1971** CERN Intersecting Storage Rings (**ISR**) – the world’s 1st hadron collider!

# The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

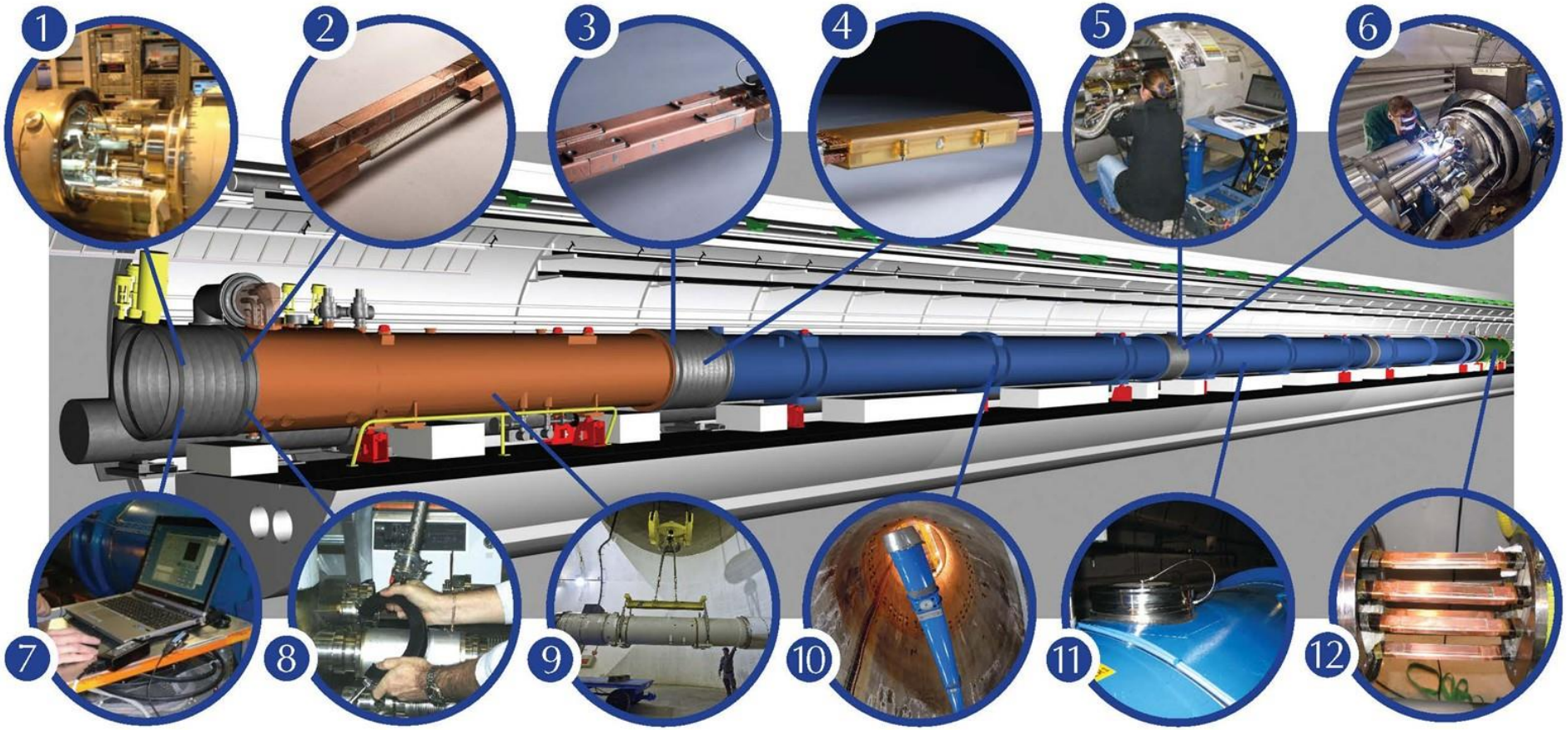
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines




18 000 electrical Quality Assurance tests

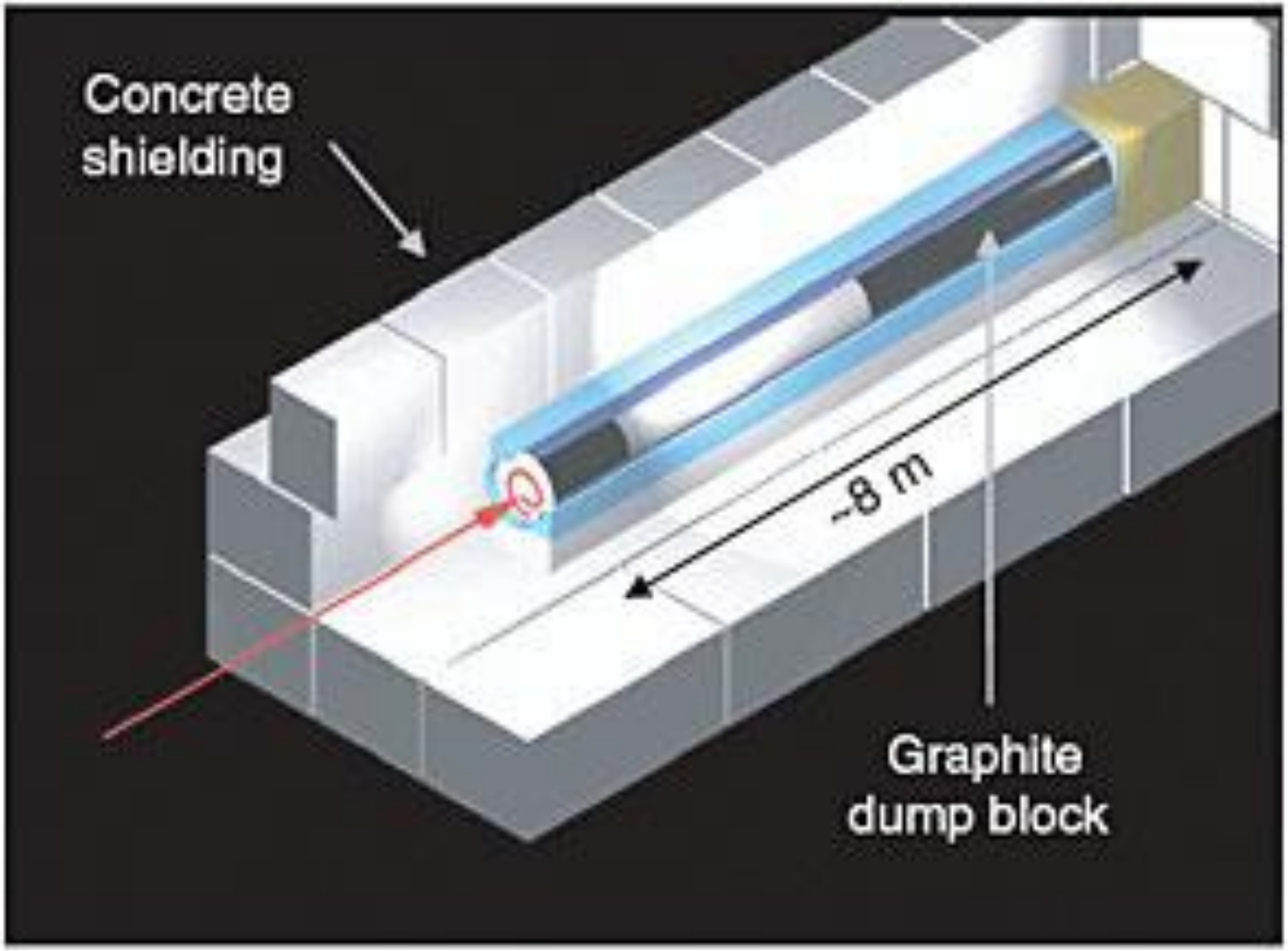
10170 leak tightness tests

4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feedboxes


Concrete
shielding
~8 m
Graphite
dump block