Teilchenbeschleuniger

lecture for German Teachers Programme

26 Oktober 2014

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Beams Department (BE),
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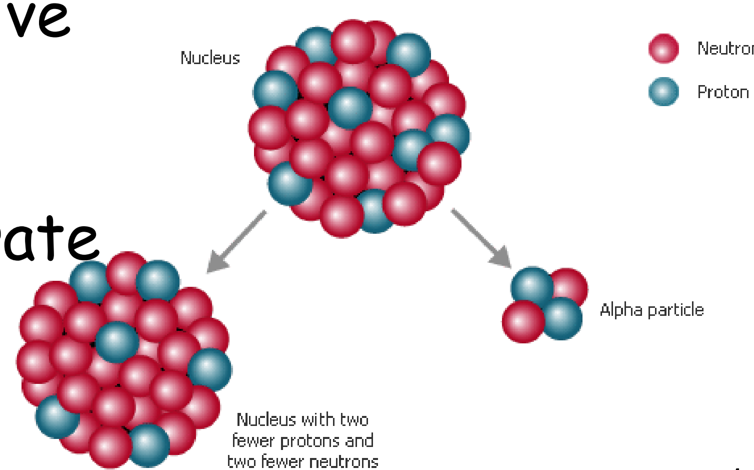
contents

- accelerator history
- accelerator physics
- CERN accelerators
- accelerator applications
- future accelerators

genesis of accelerators

early experiments to probe matter used naturally occurring radioactive isotopes (α and β particles);

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



msn encarta

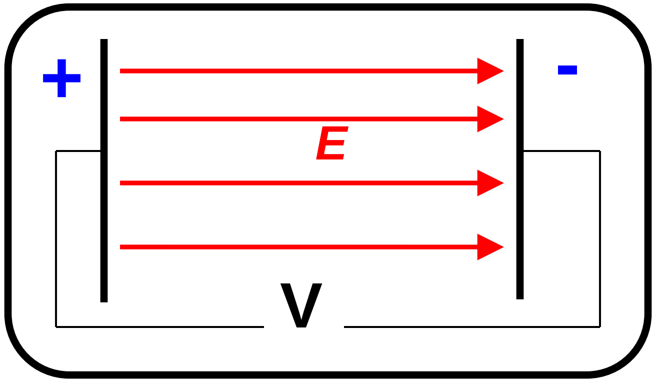
Lord Rutherford (1927):

"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 (TH Charlottenburg) tried to harness lightning in the Swiss Alps; they achieved 15 MV, but one of the three experimenters was fatally electrocuted

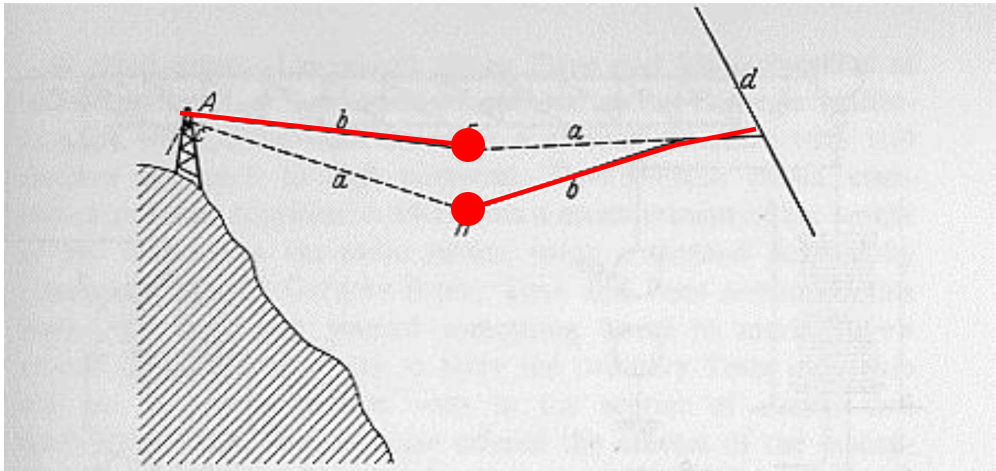
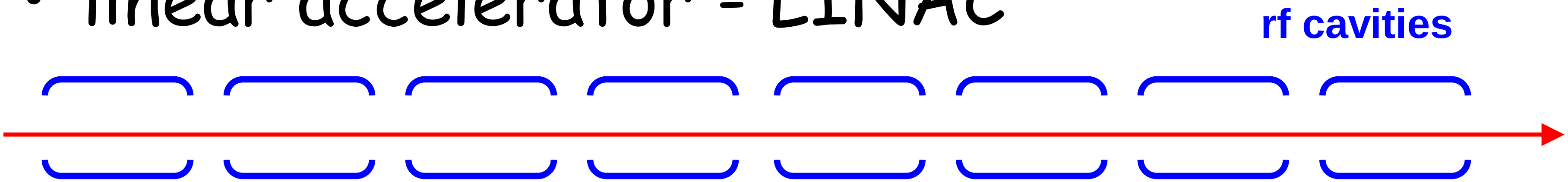


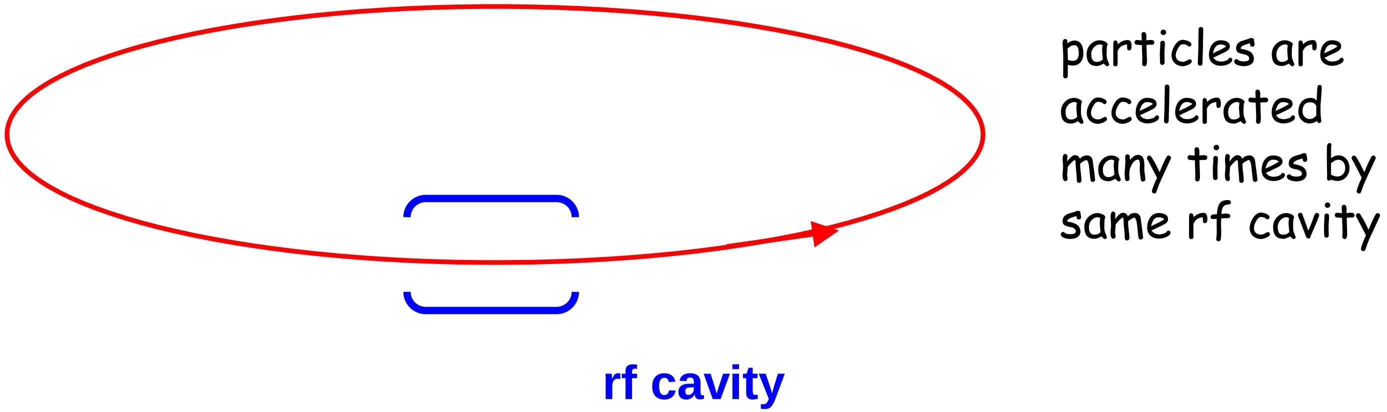
FIG. 2.1 Brasch and Lange's lightning catcher. E and H are the spheres between which the discharge occurs; AE, the antenna; a,a, insulators; b,b, conductors; d, a grounded wire. Brasch and Lange, *Zs. f. Phys.*, *70* (1931), 17.

basic types of modern accelerators

- linear accelerator - LINAC



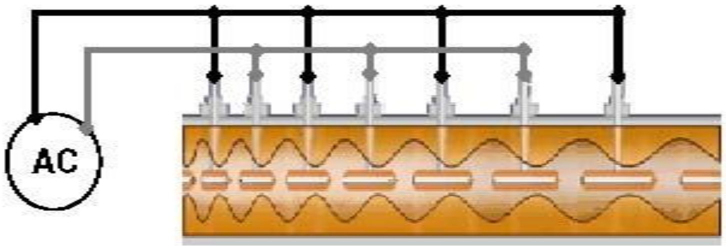
- circular accelerators: synchrotrons, storage rings



- hybrid: recirculating linacs

linear accelerators

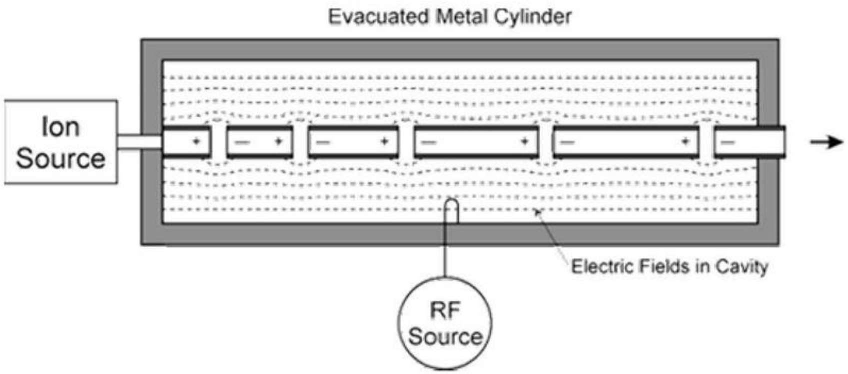
1924 Ising, 1928 Wideroe, 50 keV *Na* & *K* ions (1 drift tube)
1931 Sloan and Lawrence, 2.8 MeV *Hg* ions (2 m, 36 drift tubes)



S. Feher, U Melbourne

acceleration occurs only in gap between electrodes

1946 Alvarez

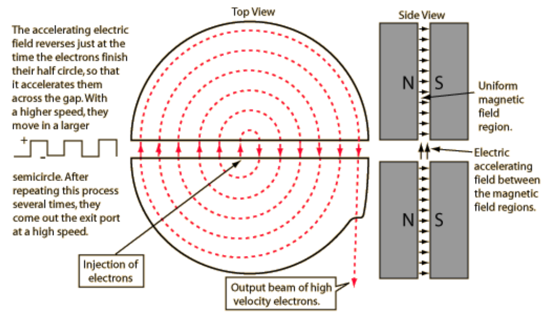


used for protons and ions, for *p* energies 50-200 MeV
resonant behavior of cavity provides longitudinal electric field ;
became possible due to the development of ultrahigh frequency technology (e.g. klystron) before and during World War II

CERN Alvarez linac (50-MeV protons)

circular accelerators

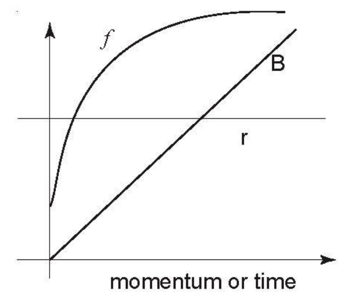
- **cyclotron**
  (1929, 1930)



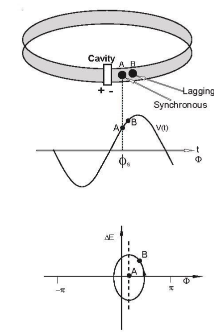
acc. el. field reverses each half circle

- **synchrotron**
  (1934, 1943, 1944, 1945)

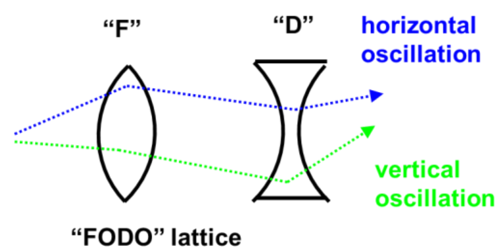
rf frequency changes with magnetic field so as to keep particles on a constant circle



“phase stability”



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



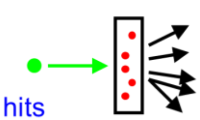
novel idea: combination of two lenses focuses in both planes simultaneously

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

centre-of-mass energy:

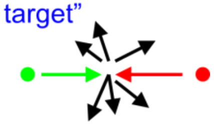
$$E_{\text{c.m}} = \sqrt{2E_{\text{beam}}M_{\text{target}}c^2}$$

beam hits a “fixed target”



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

two beams collide



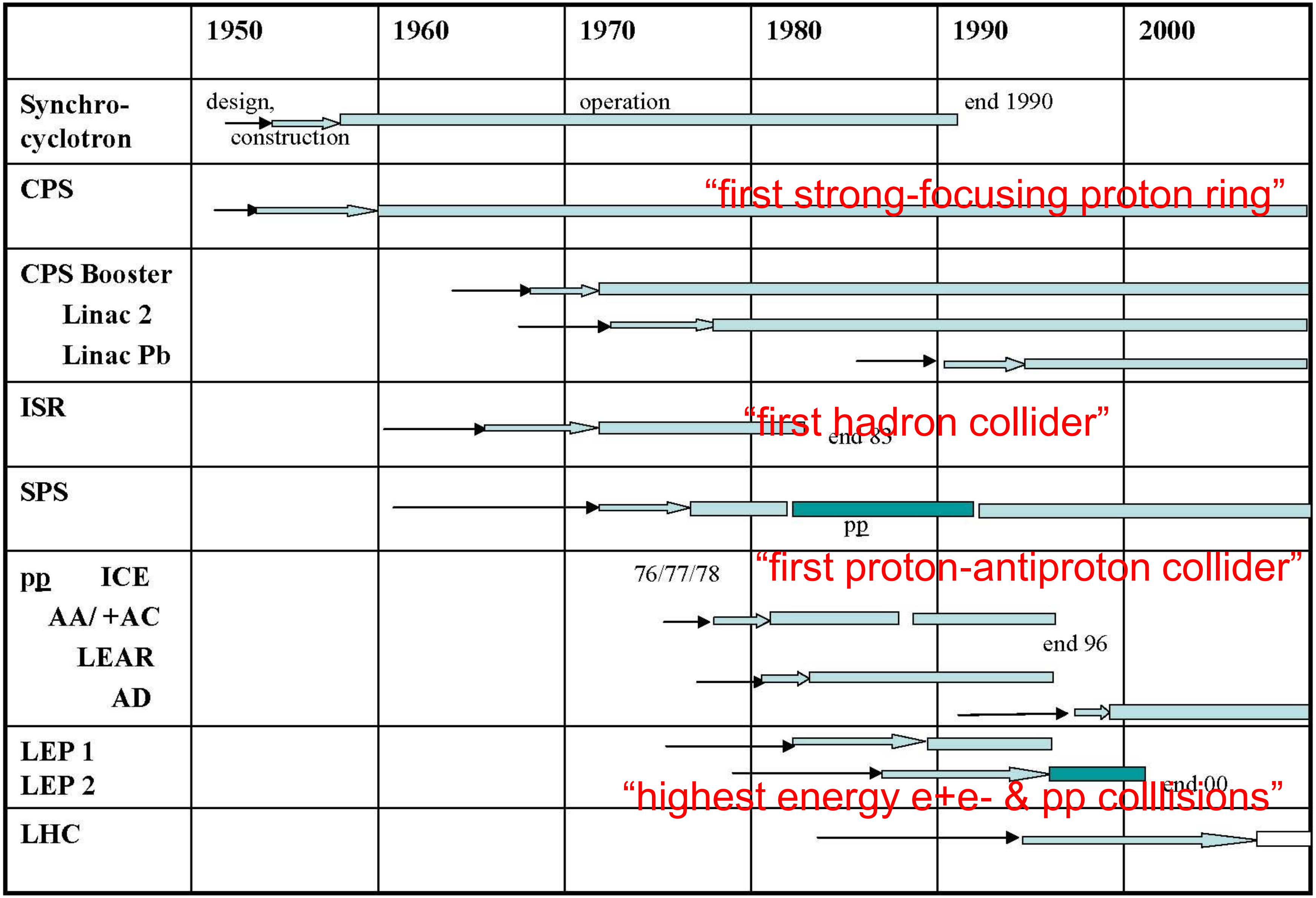
much higher c.m. energies than for fixed target

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

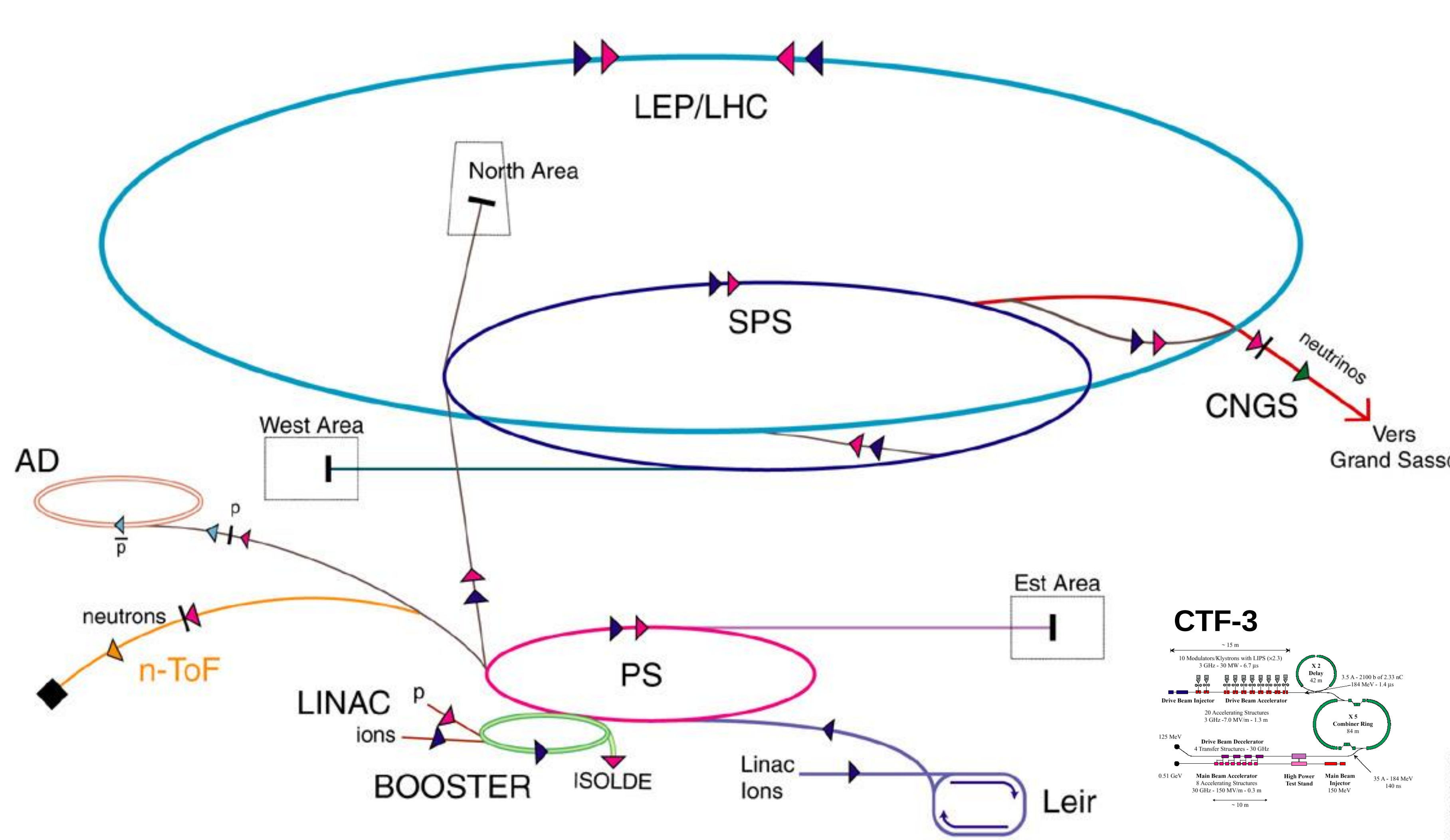
Evolution of Accelerator Park



aerial view of the CERN ISR around 1971


CERN ISR ~1971
the first hadron collider
8

Accelerator chain of CERN (operating or approved projects)

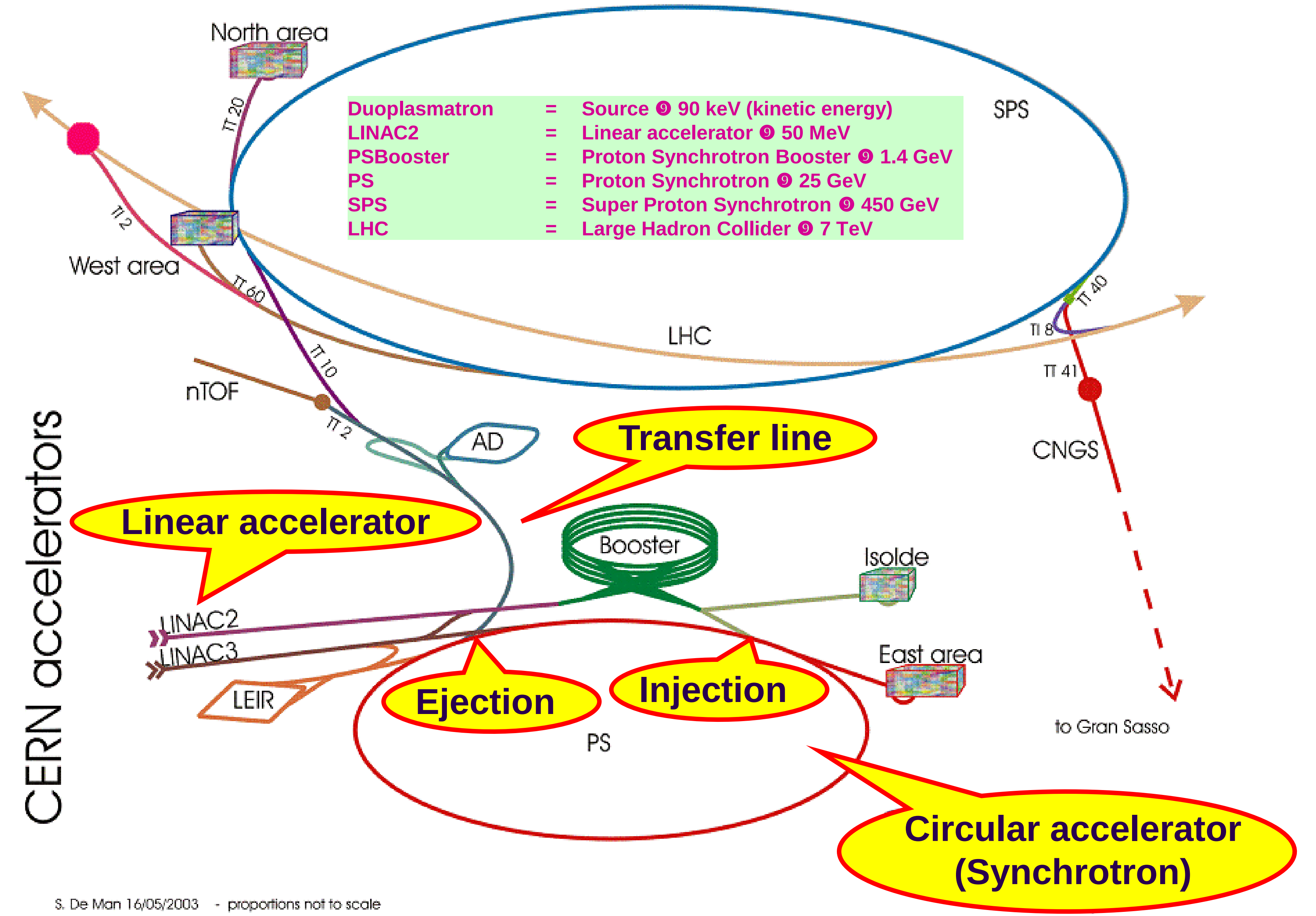


p (proton)
ion
neutrons

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



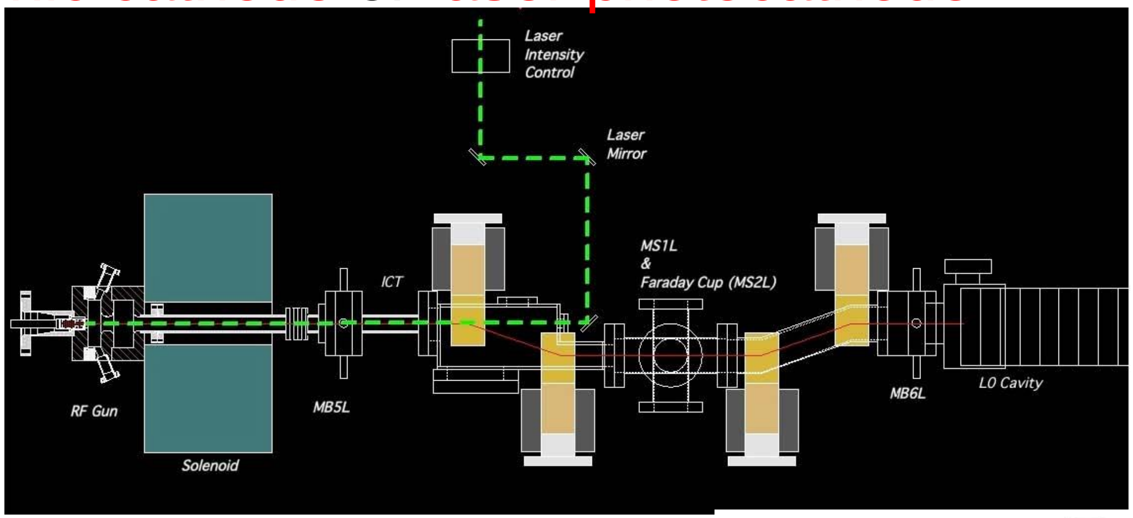
LHC and its injector chain

which particles?

- ***e^+, e^-*** (former LEP, future CLIC)
- ***p*** (PS, SPS, LHC,...), $\bar{p}$ (former SPS collider)
- **heavy ions** - lead etc. (PS, SPS, LHC)
- **negative ions**, H^- (future CERN Linac4)
- 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

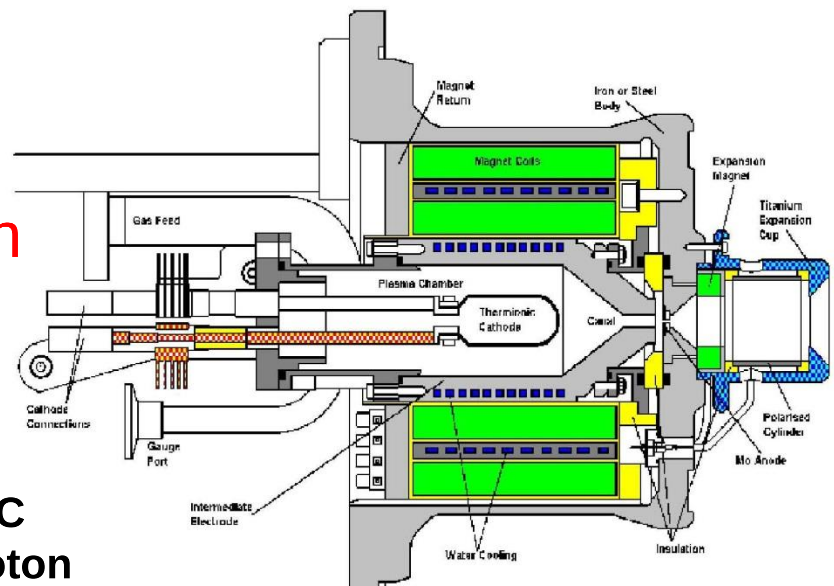
e$^-$: thermionic cathode or laser photocathode



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)

devices in accelerators

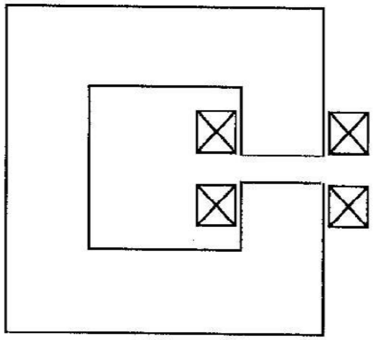
- dipole ***magnets*** → bending
- quadrupole magnets → focusing
- sextupole magnets → chromatic correction
- ***rf cavity*** → acceleration
- pulsed magnets for injection & extraction
- collimators & masks

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

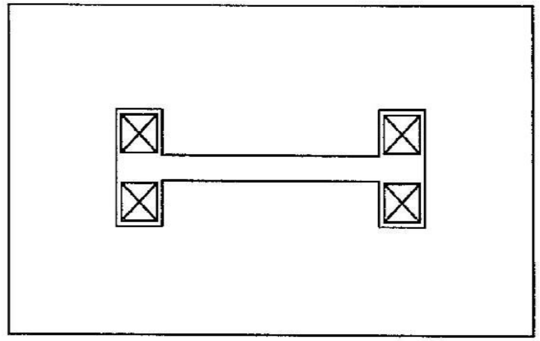
cavities: normal or **superconducting**

dipole magnets with coils and Fe yokes

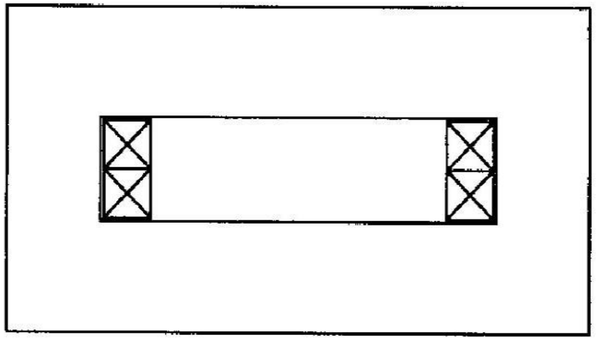
C-shape magnet:

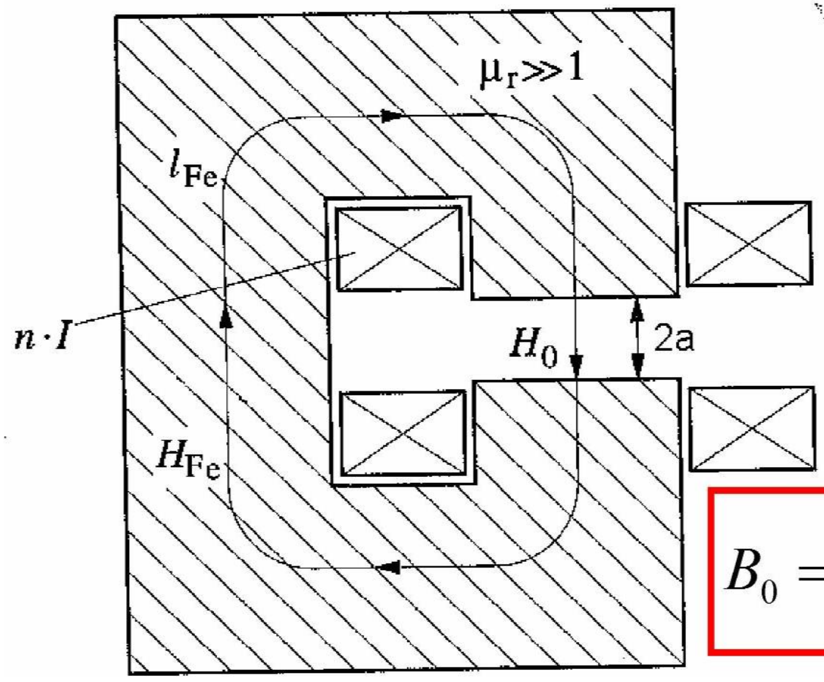


H-shape magnet:



Window frame magnet:





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

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

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

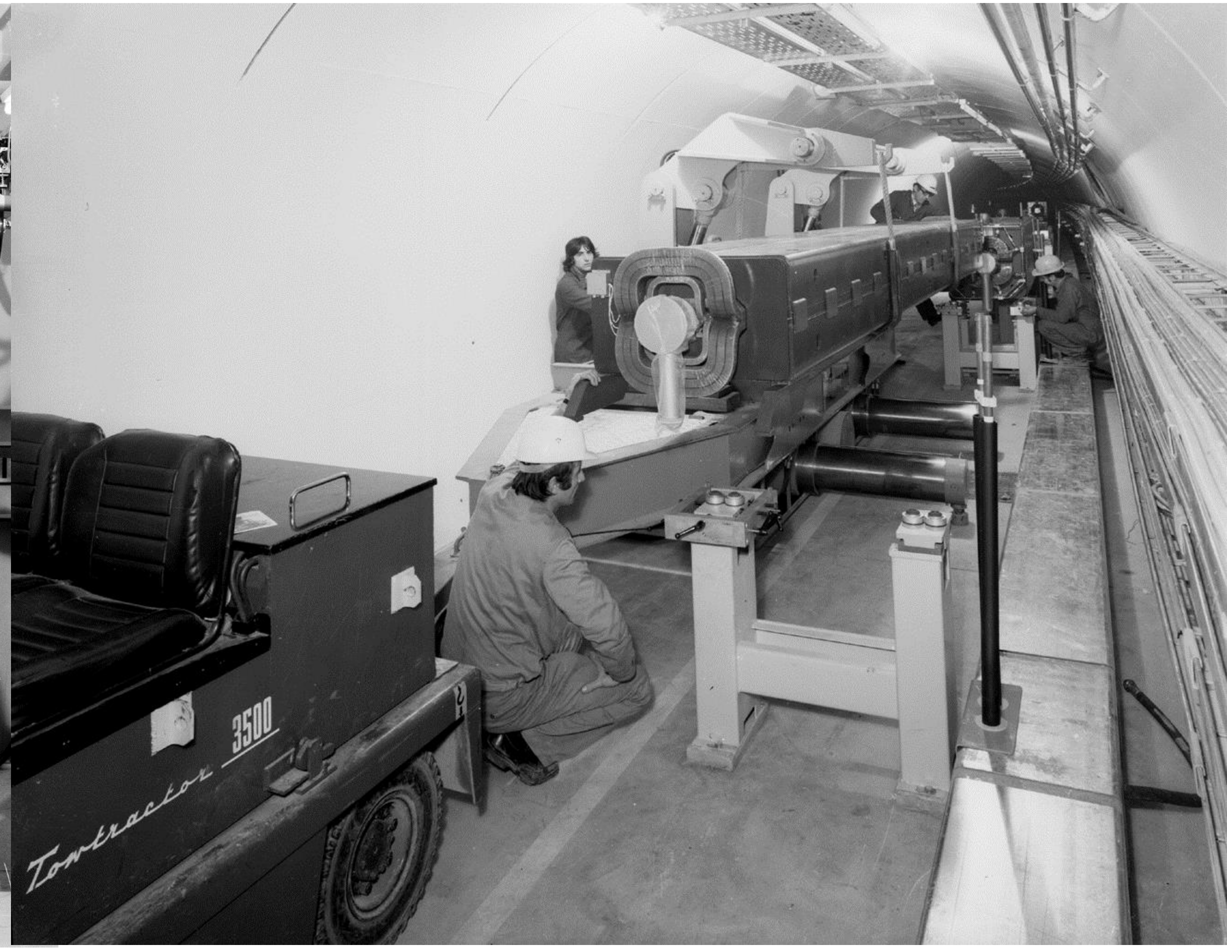
$$= \tfrac{1}{\mu_r} H_0 l_{Fe} + H_0 2a \approx H_0 2a$$

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

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

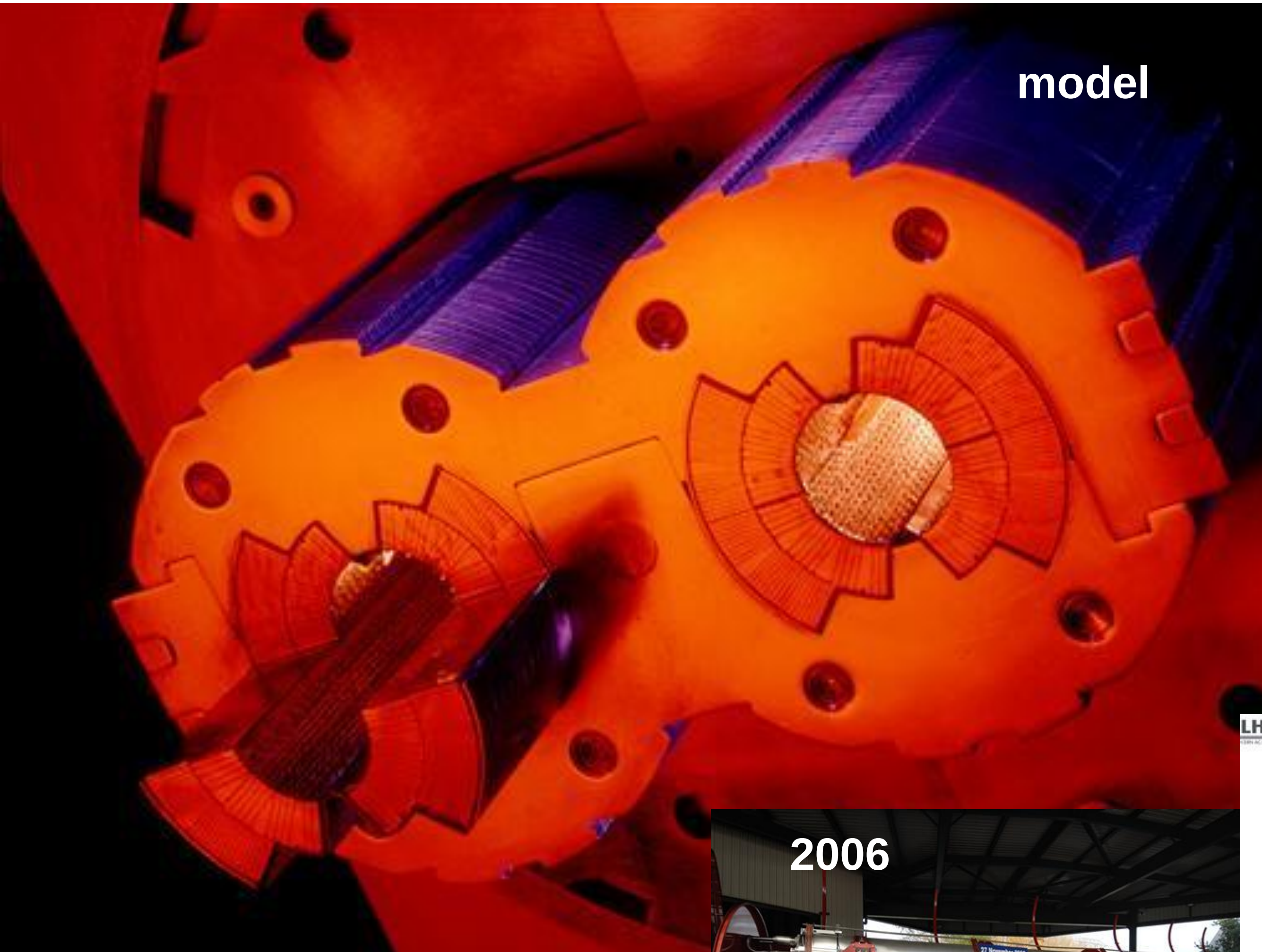
SPS dipole magnet – 2 T

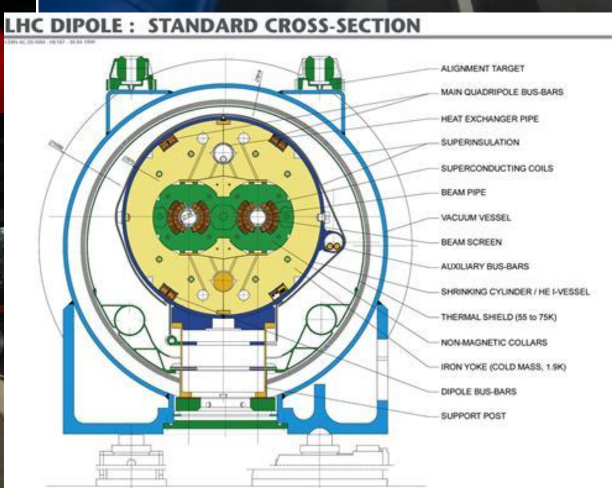
1973



1974

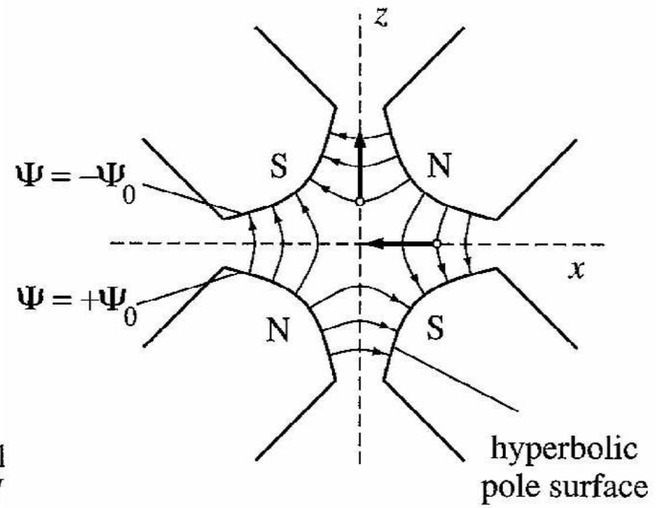
LHC s.c. dipole magnet – 8.33 T

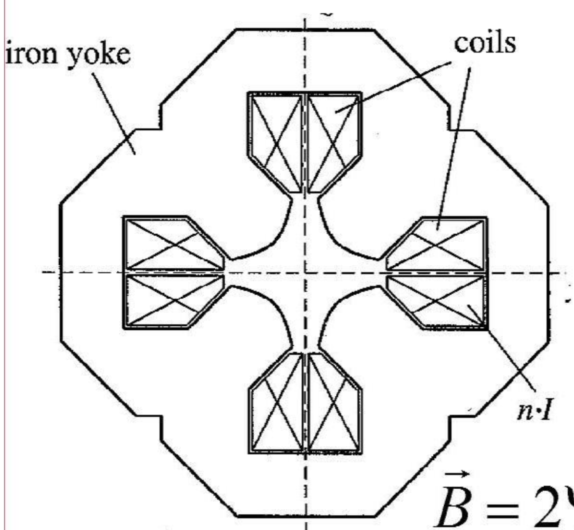


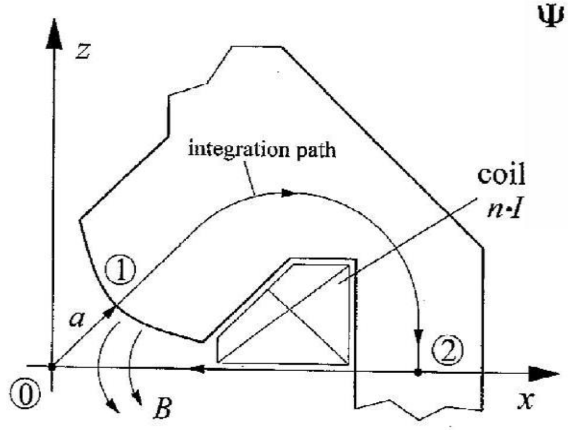


quadrupole magnets with coils & Fe yokes

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







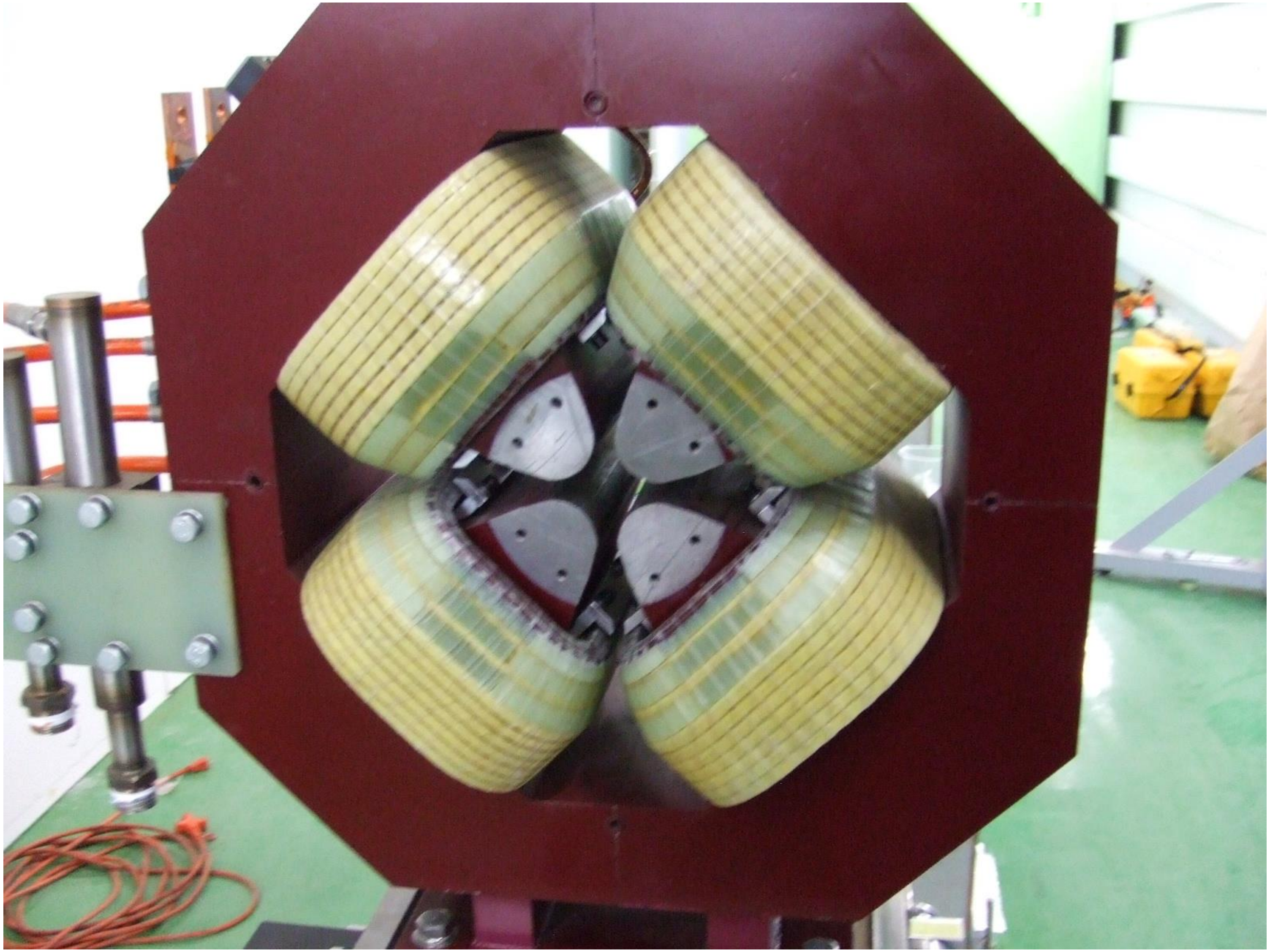
$$\vec{B} = 2\Psi_2 \begin{pmatrix} y \\ x \end{pmatrix} \quad \Rightarrow \quad \vec{B}(0 \mapsto 1) = 2\Psi_2 r\,\vec{e}_r$$

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

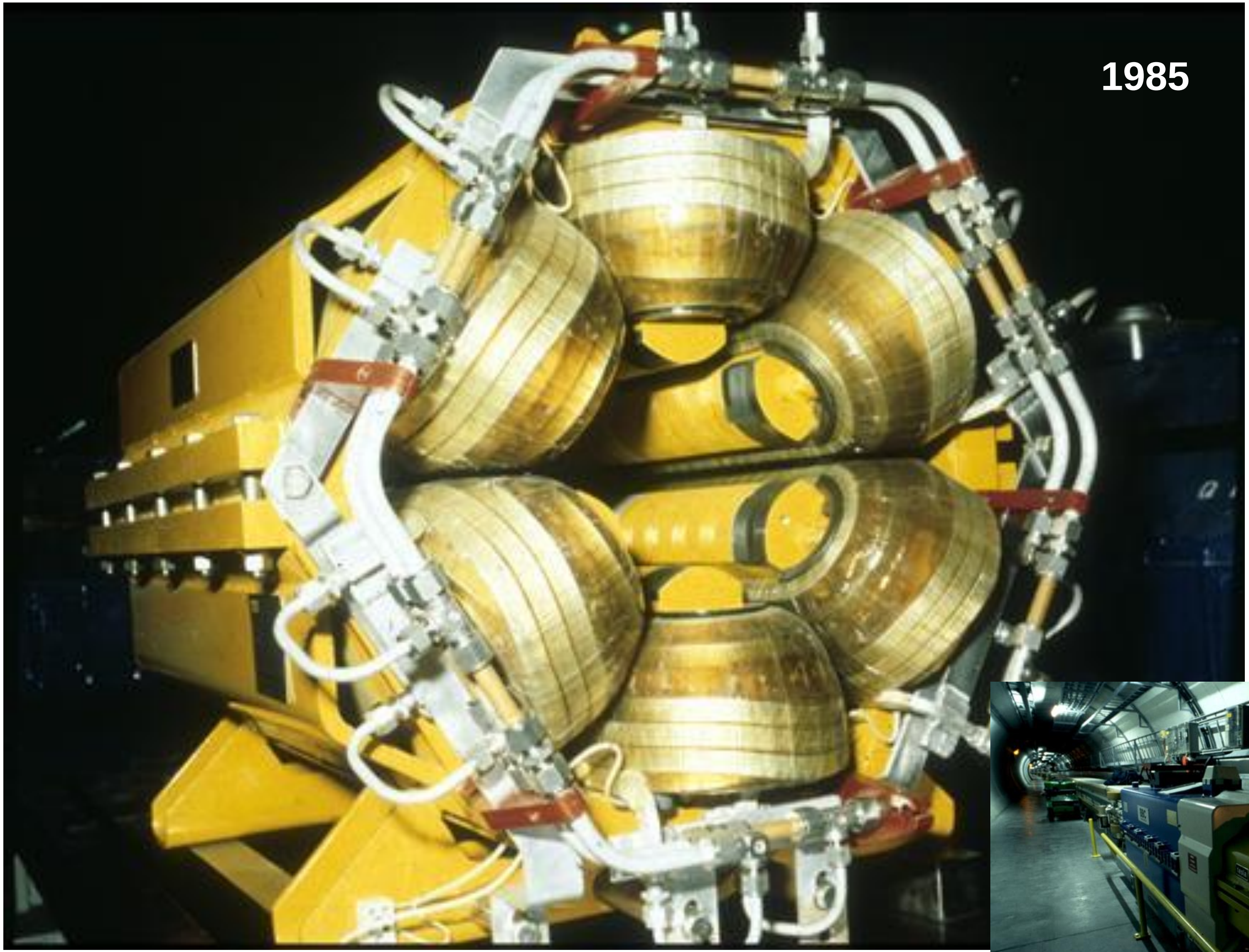
Quadrupole strength:

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

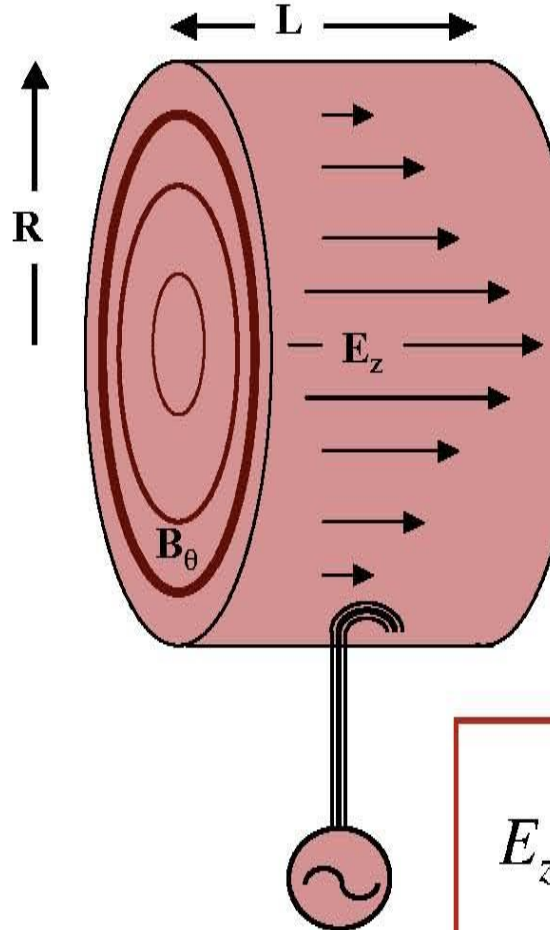
quadrupole magnet in KEK-ATF2

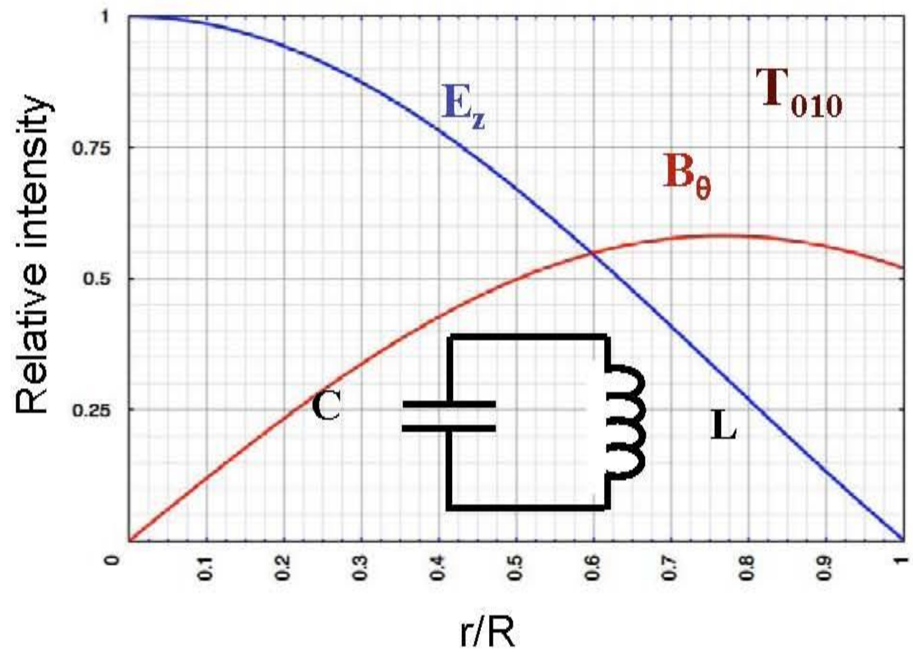


LEP sextupole magnet



“pillbox” model of rf cavity





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

LEP accelerating cavity

… and there are also some German physicists at CERN

29. April 2008

… and sometimes German presidents

2. April 2014

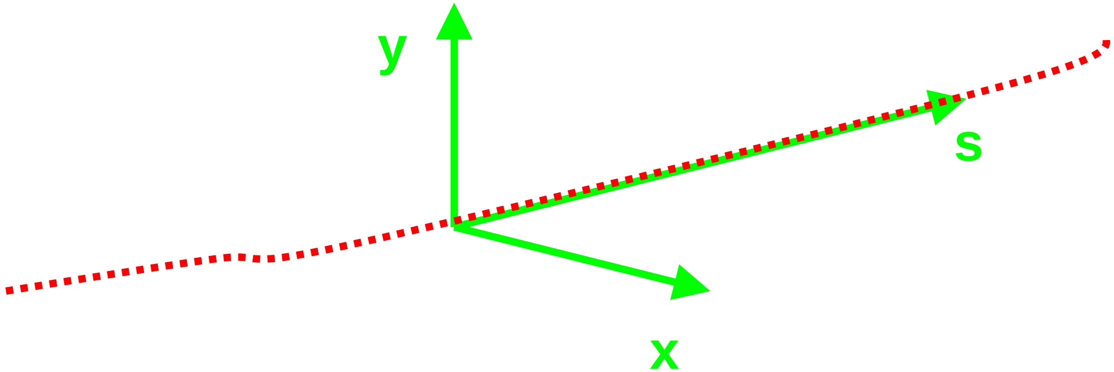
accelerator: charged particles – beam-moving in electromagnetic field

Lorentz force

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

Hamiltonian

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



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

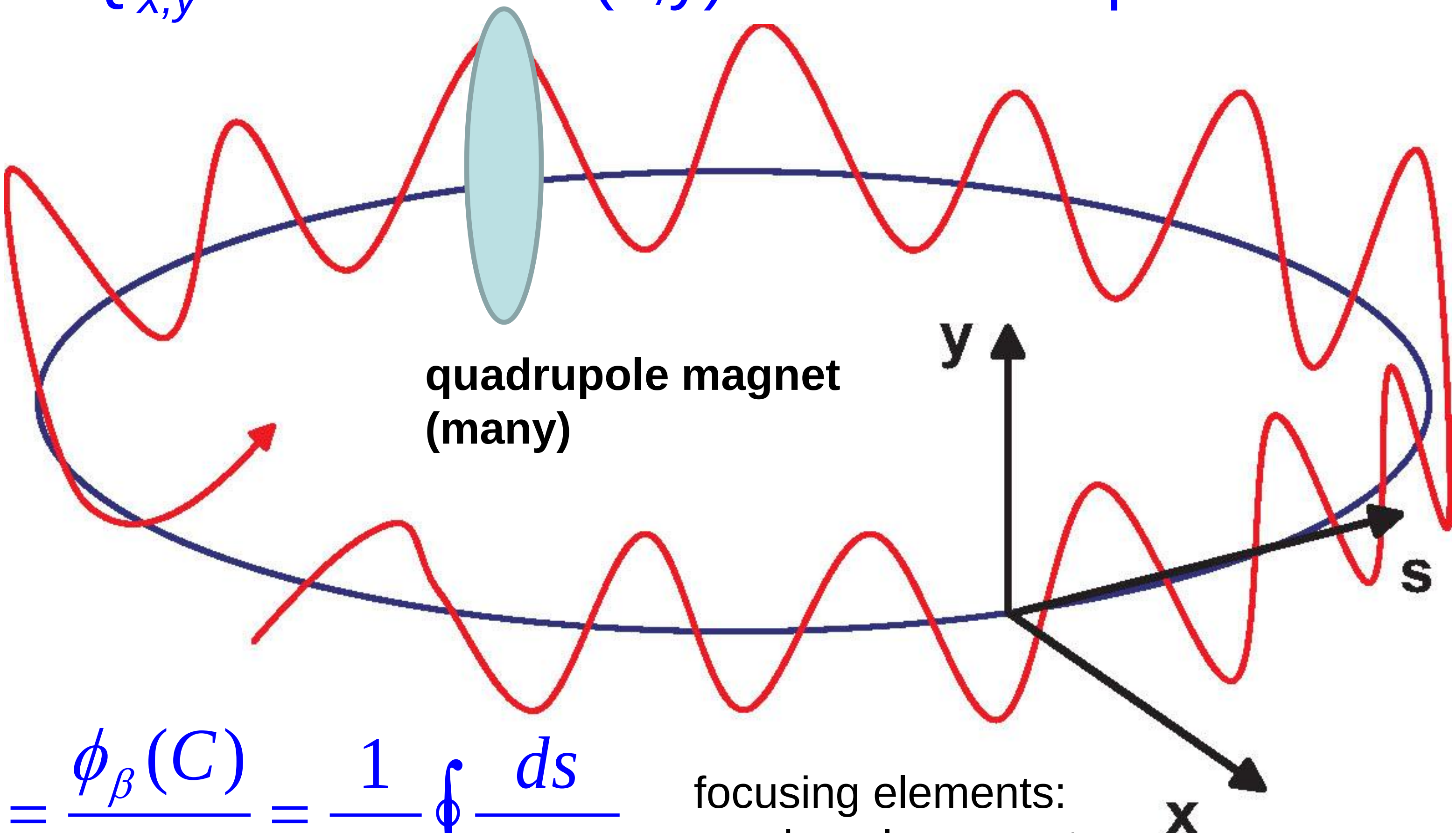
- solutions of Hill's equations very similar to Bloch waves ("periodic function" x "plane wave") in solid-state crystals; accelerator representation as "beta function"

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

A_0 & ϕ_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

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

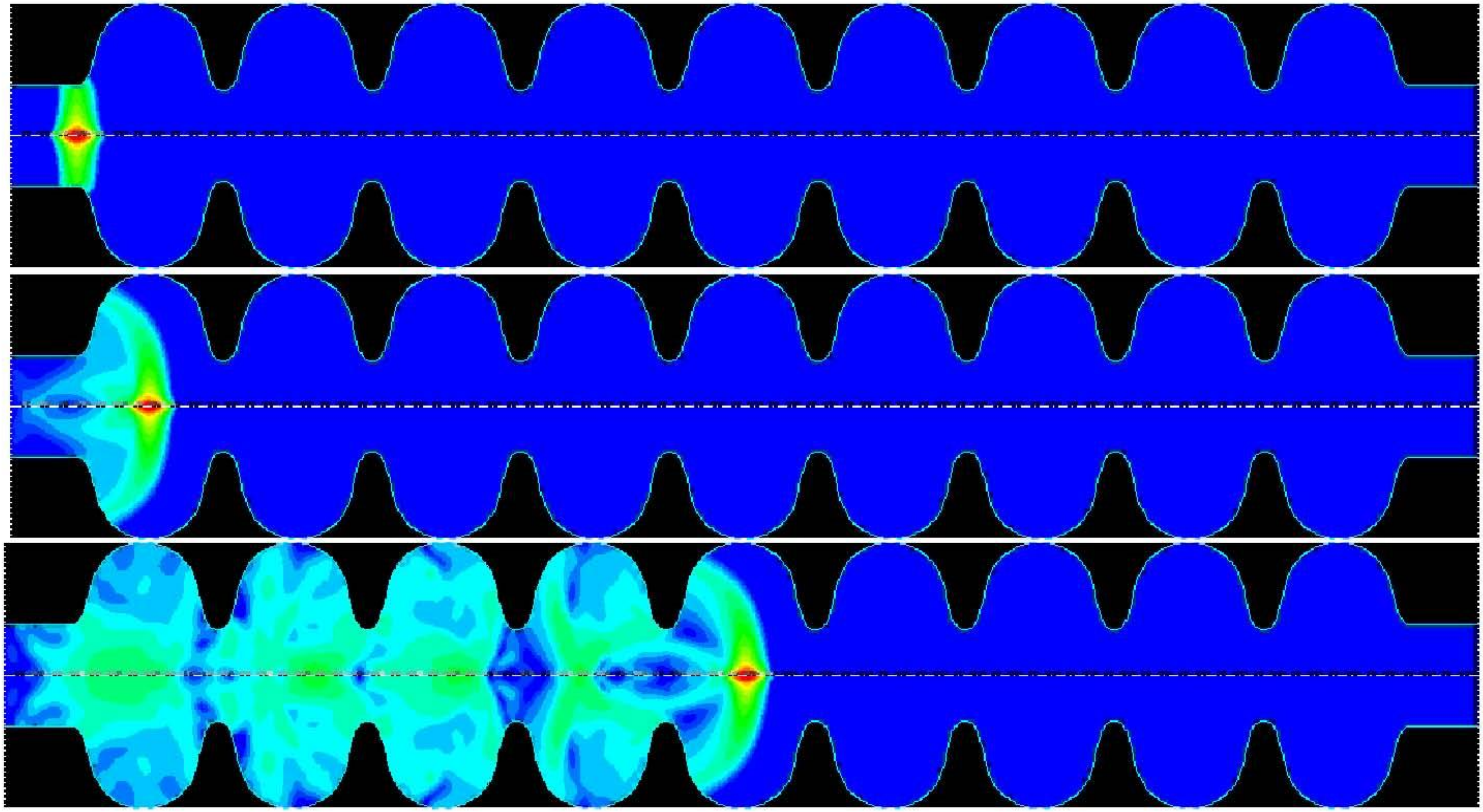
beam particles are like elephants…

- 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***

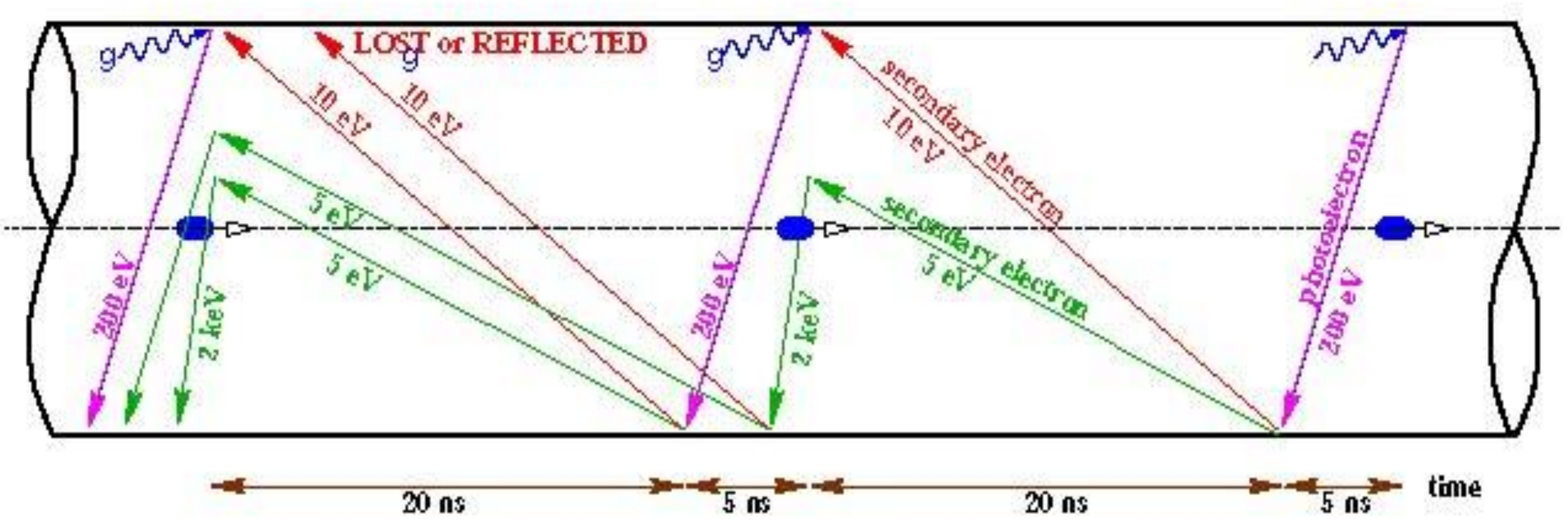
example - "wake fields"



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

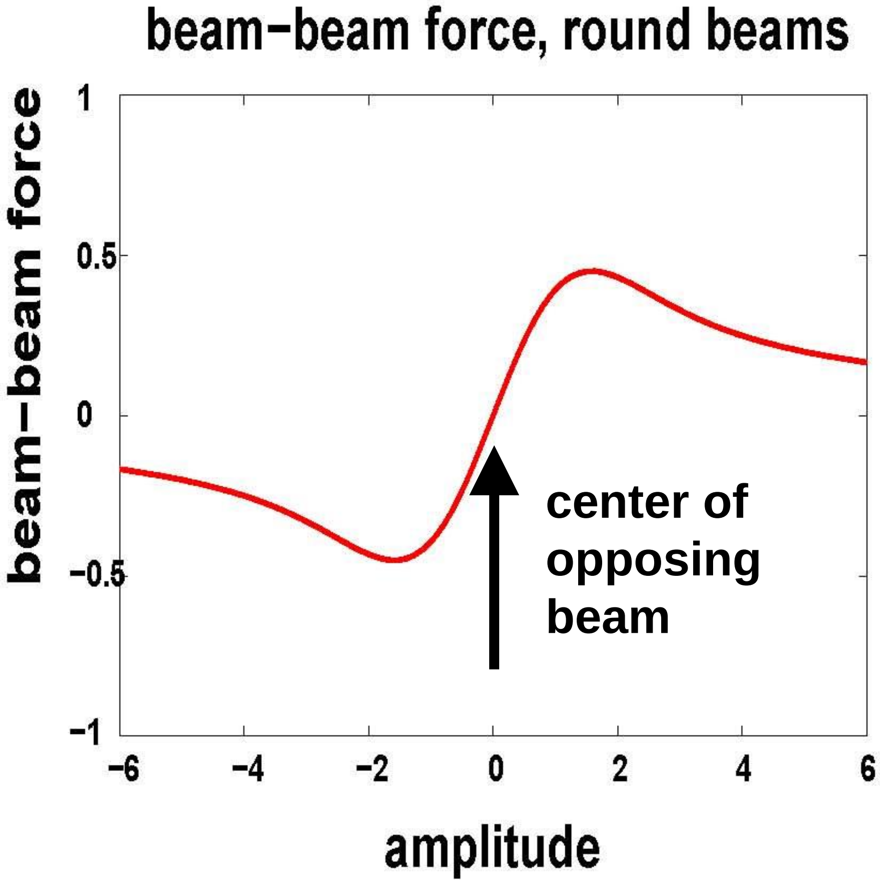


schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

[F. Ruggiero]

→ beam instabilities

(nonlinear) beam-beam force



W. Herr

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

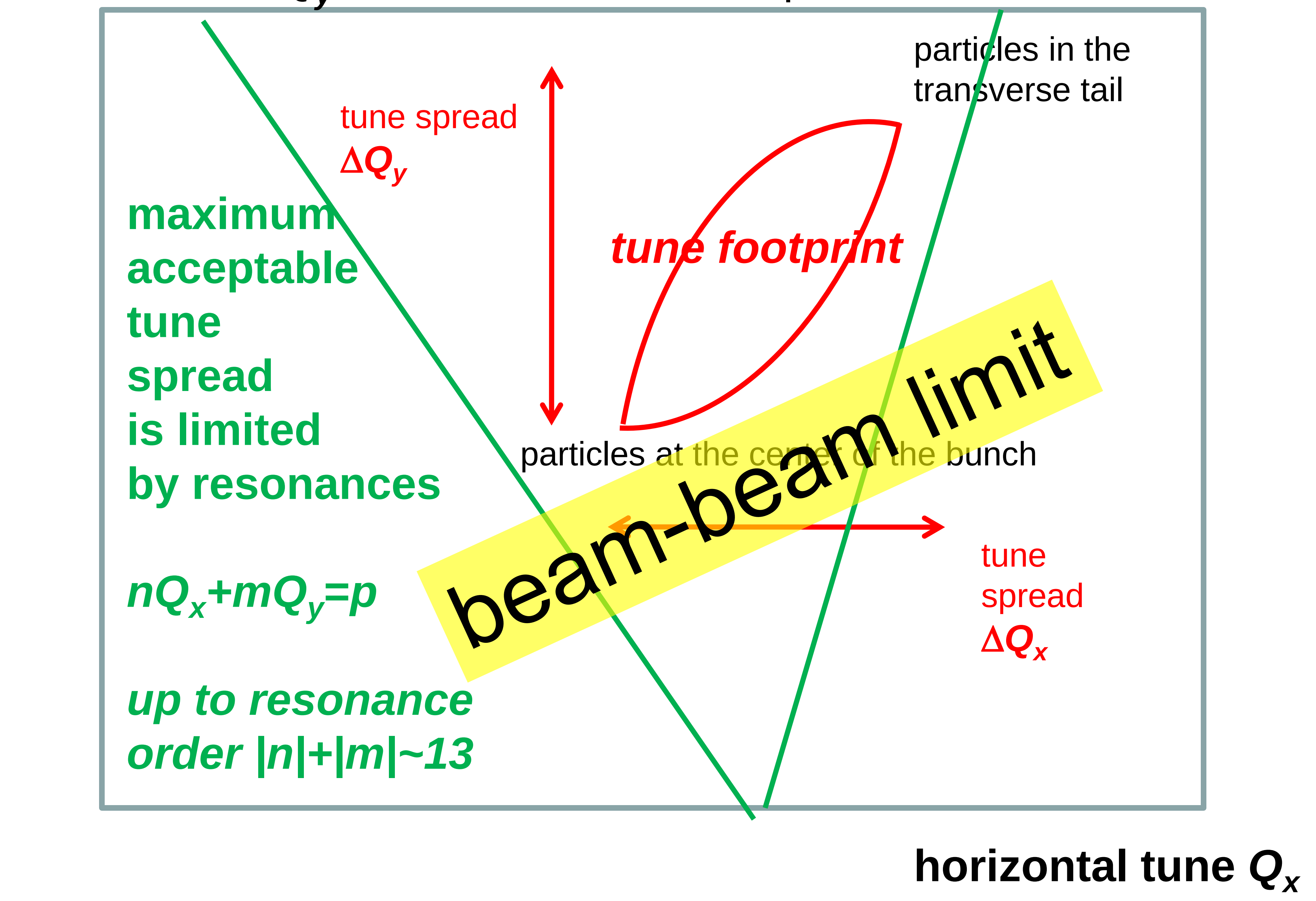
at small amplitude similar to effect of defocusing quadrupole

for pure head-on collision

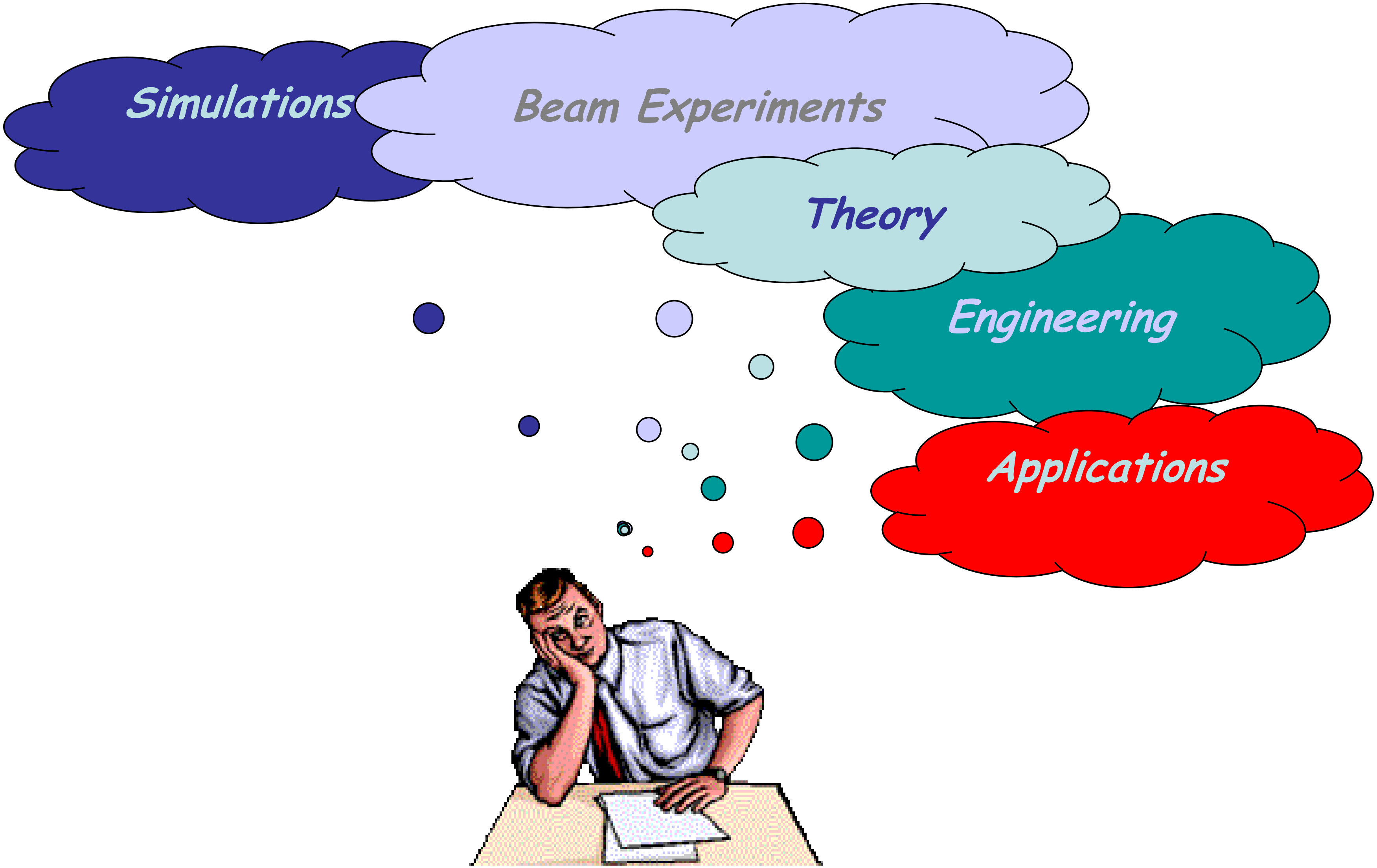
$$\Delta Q_{x.y;\max} = \xi_{x,y} = \frac{2N_b r_0 \beta^*}{4\pi\gamma\left(2\sigma^{*2}\right)} = \frac{N_b}{\varepsilon_N}\frac{r_0}{4\pi}$$

for single collision (nominal LHC ~0.0033

beam-beam tune spread from head-on collisio



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


CERN LIBRARIES, GENEVA

LEP/LIBRARY

SCAN-0008106

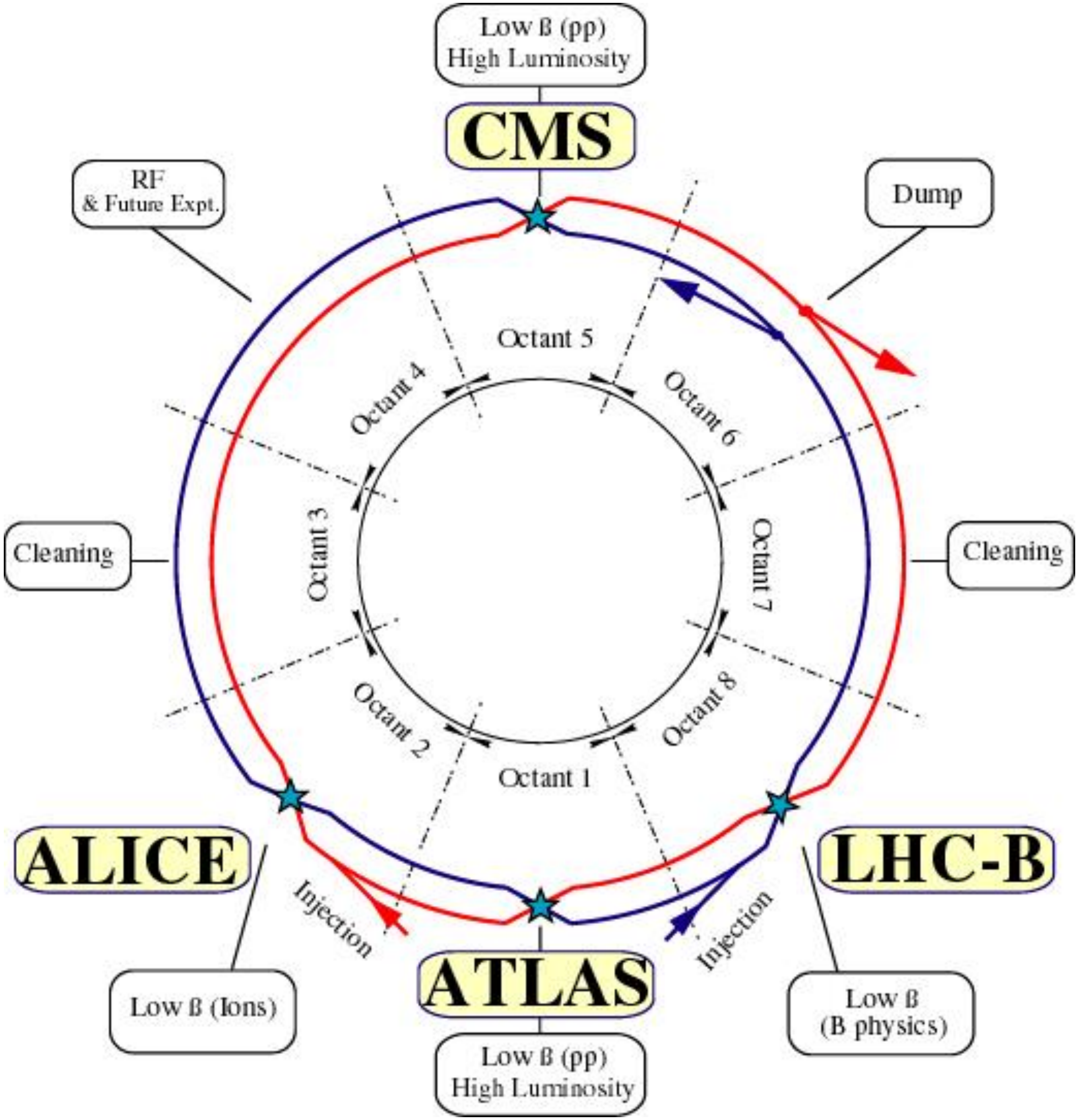
LEP Note 440

11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

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



design parameters

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

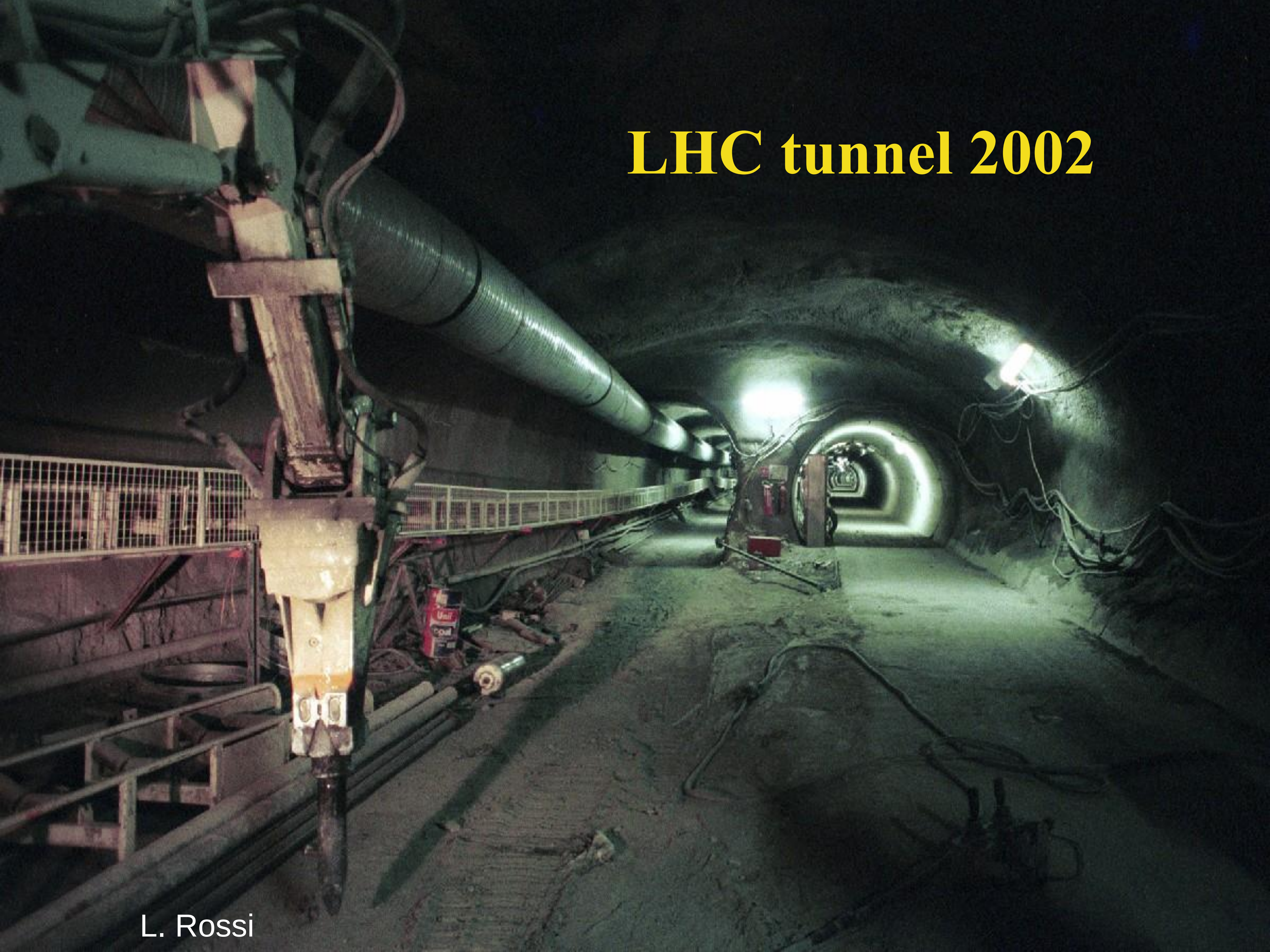
1.15×10^{11} p/bunch
2808 bunches/beam

360 MJ/beam

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

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


LHC magnets stored on parking lots
before installation


LHC tunnel 2002
L. Rossi


LHC tunnel 2006
L. Rossi

luminosity

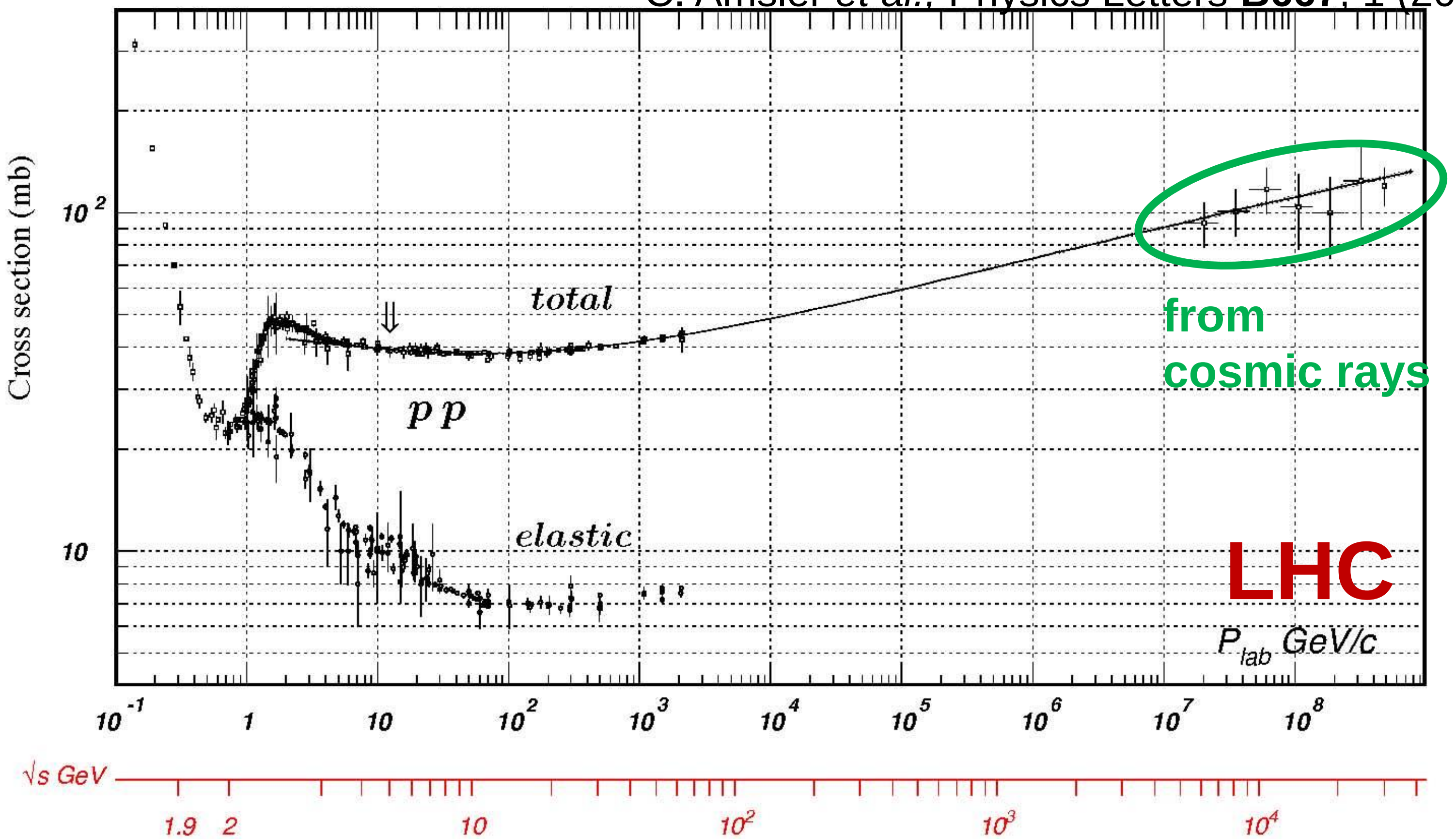
$$R = \sigma L$$

reaction rate

cross section

luminosity

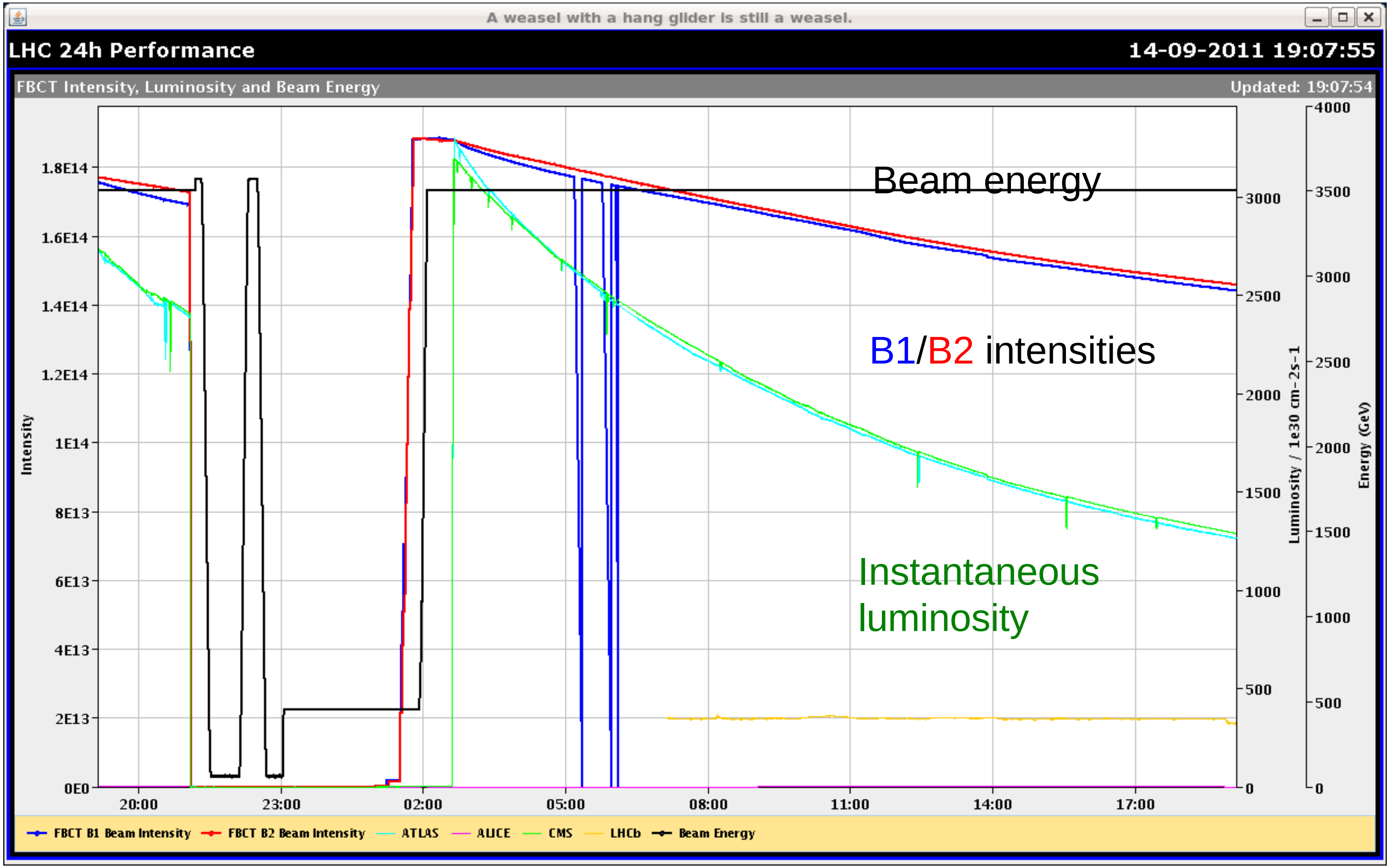
C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)



σ_{tot}~ 100 mbarn ~ 10^{-25} cm^2

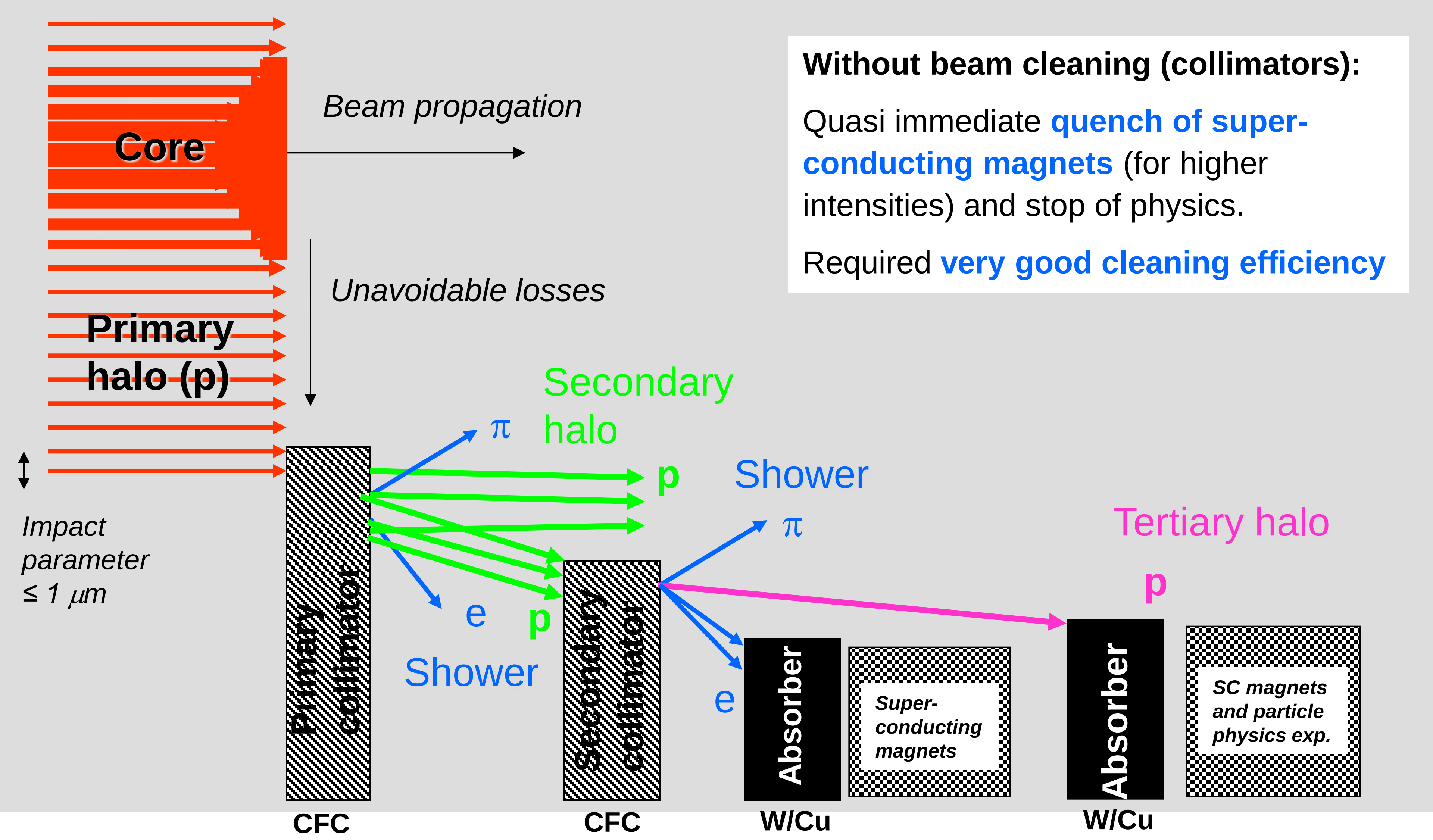
$\sigma_{inelastic}$~ 60 mbarn~ 6×10^{-26} cm^2

intensity and luminosity: good LHC fill...



R. Assmann, 19.09.2011

LHC – multistage cleaning



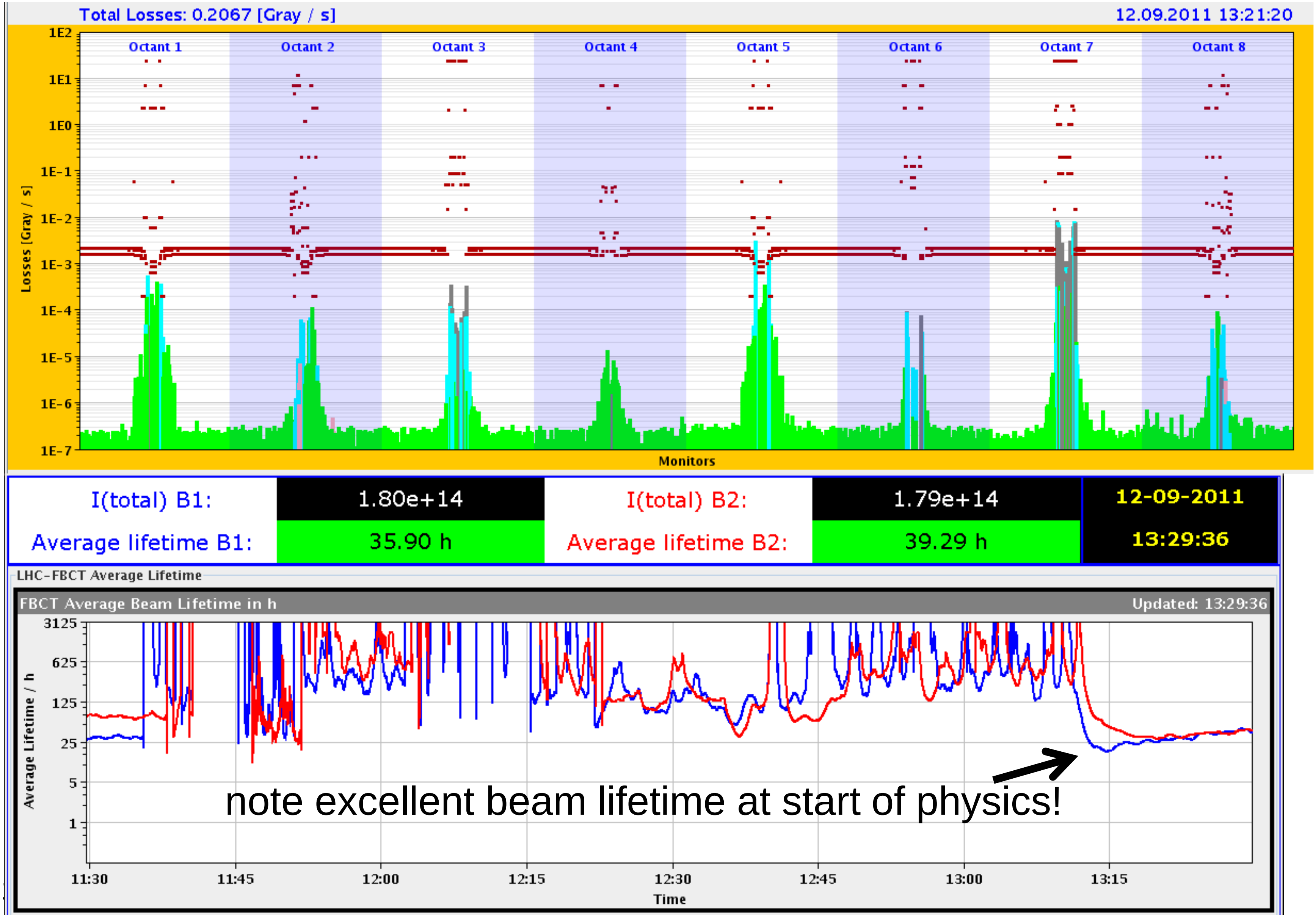
Without beam cleaning (collimators):

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

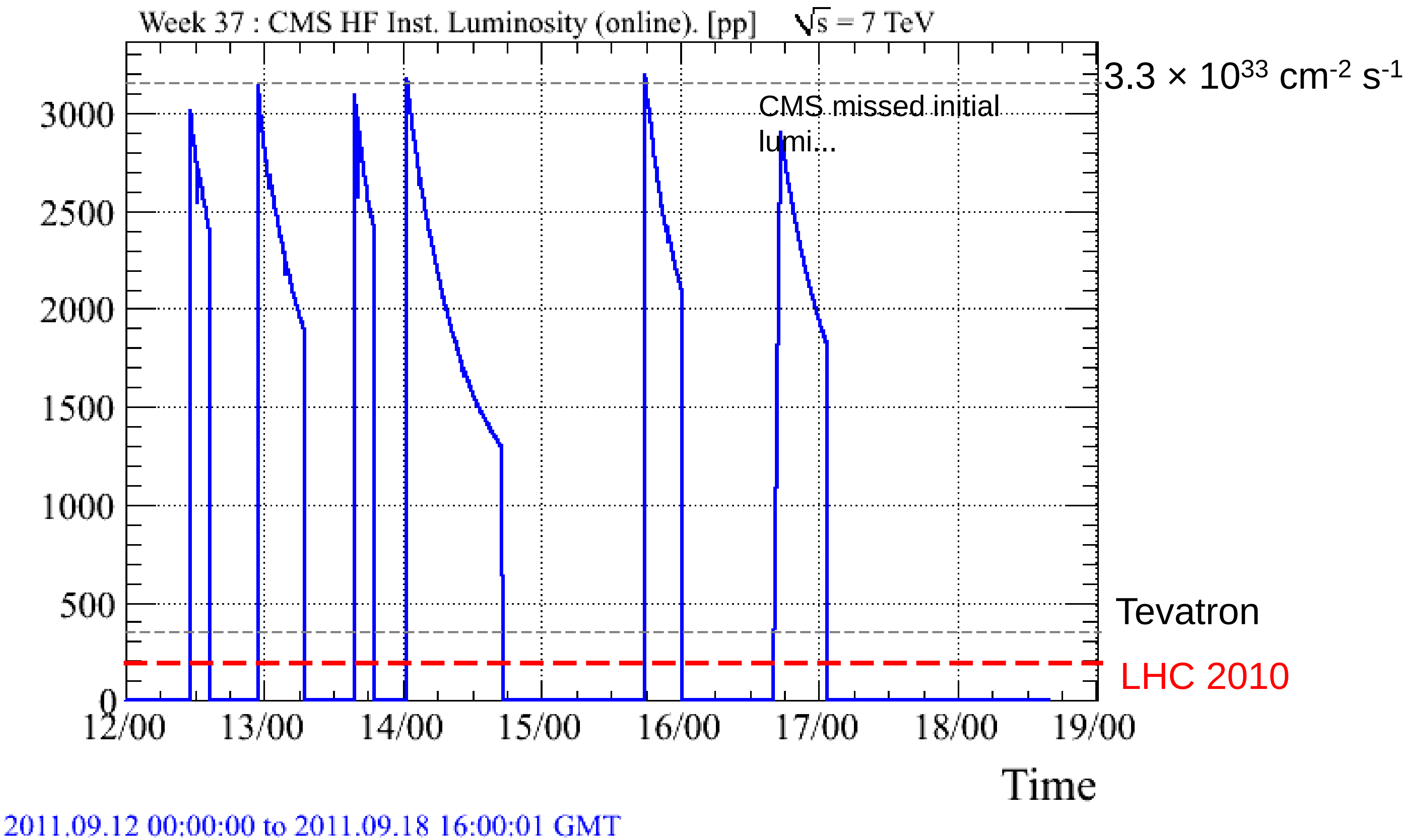
Required **very good cleaning efficiency**

R. Assmann

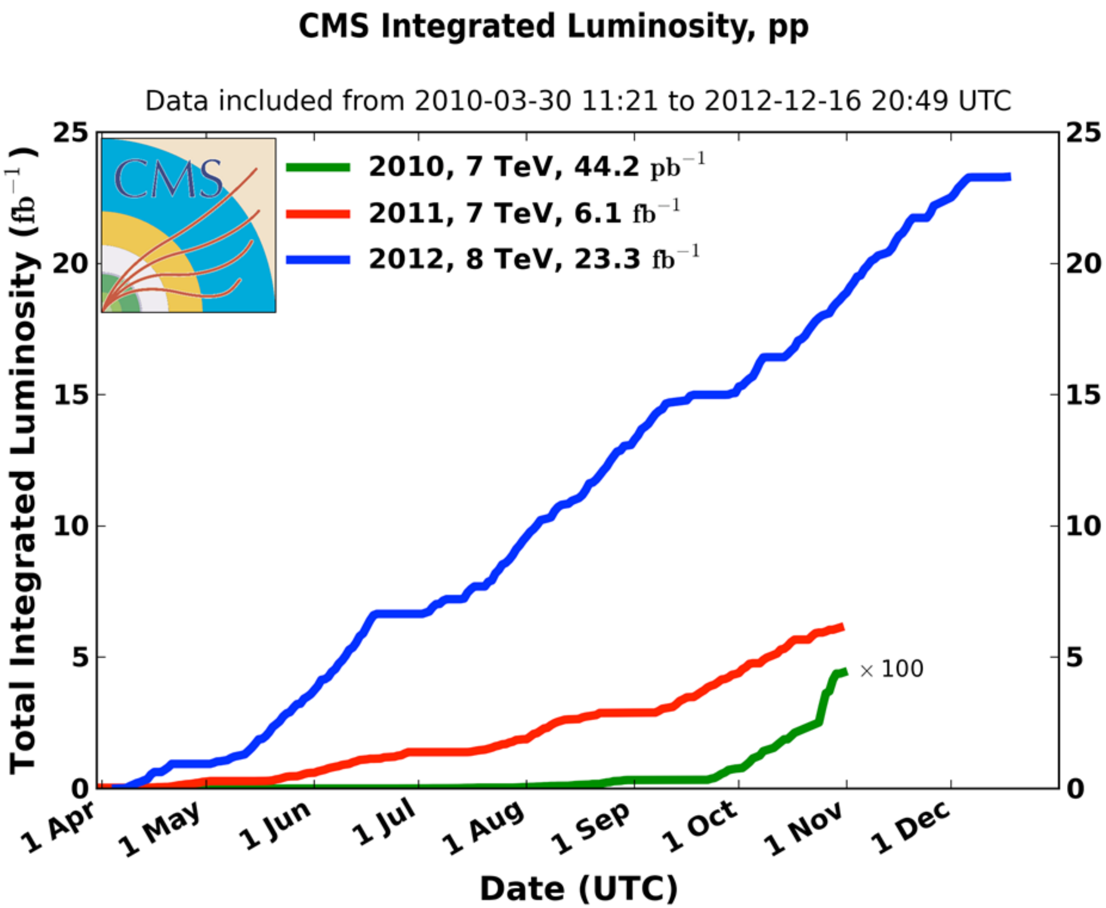
Losses & Lifetime at Start of Physics



Week 37 (2011) seen from CMS...



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]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
normalized **emittance** [mm-mrad]	~2.0	~2.4	~2.5	3.75
peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

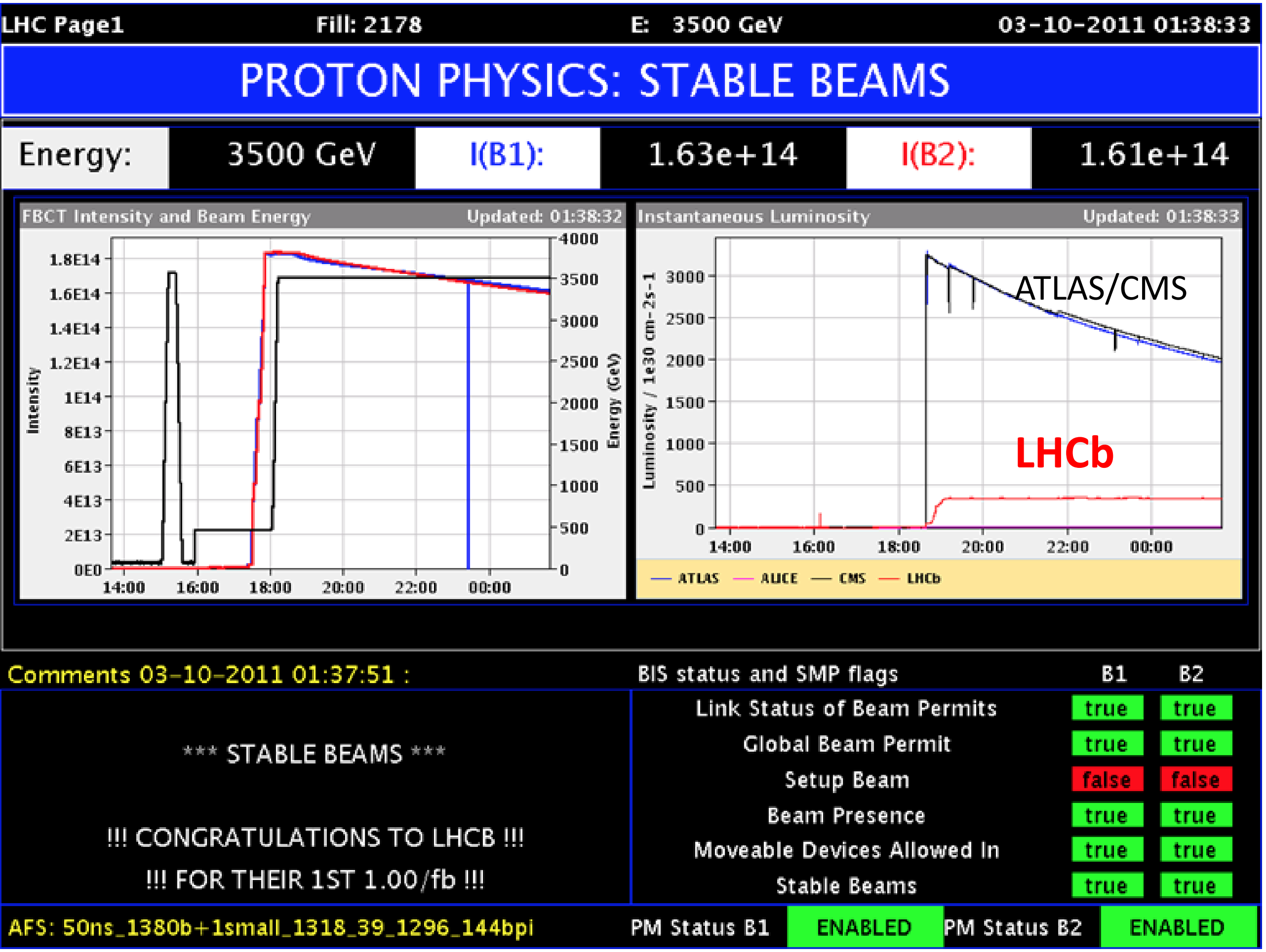
>2x design when scaled to 7 TeV

M. Lamont, IPAC'13

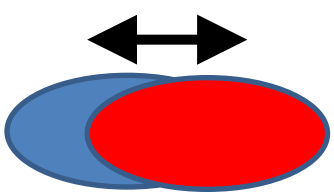
LHCb

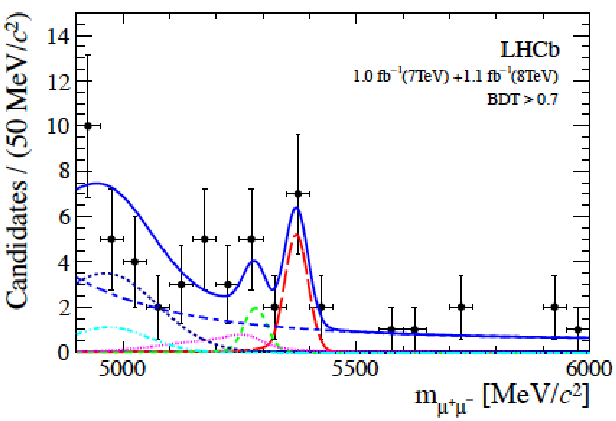
luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation

(with tilted crossing angle)



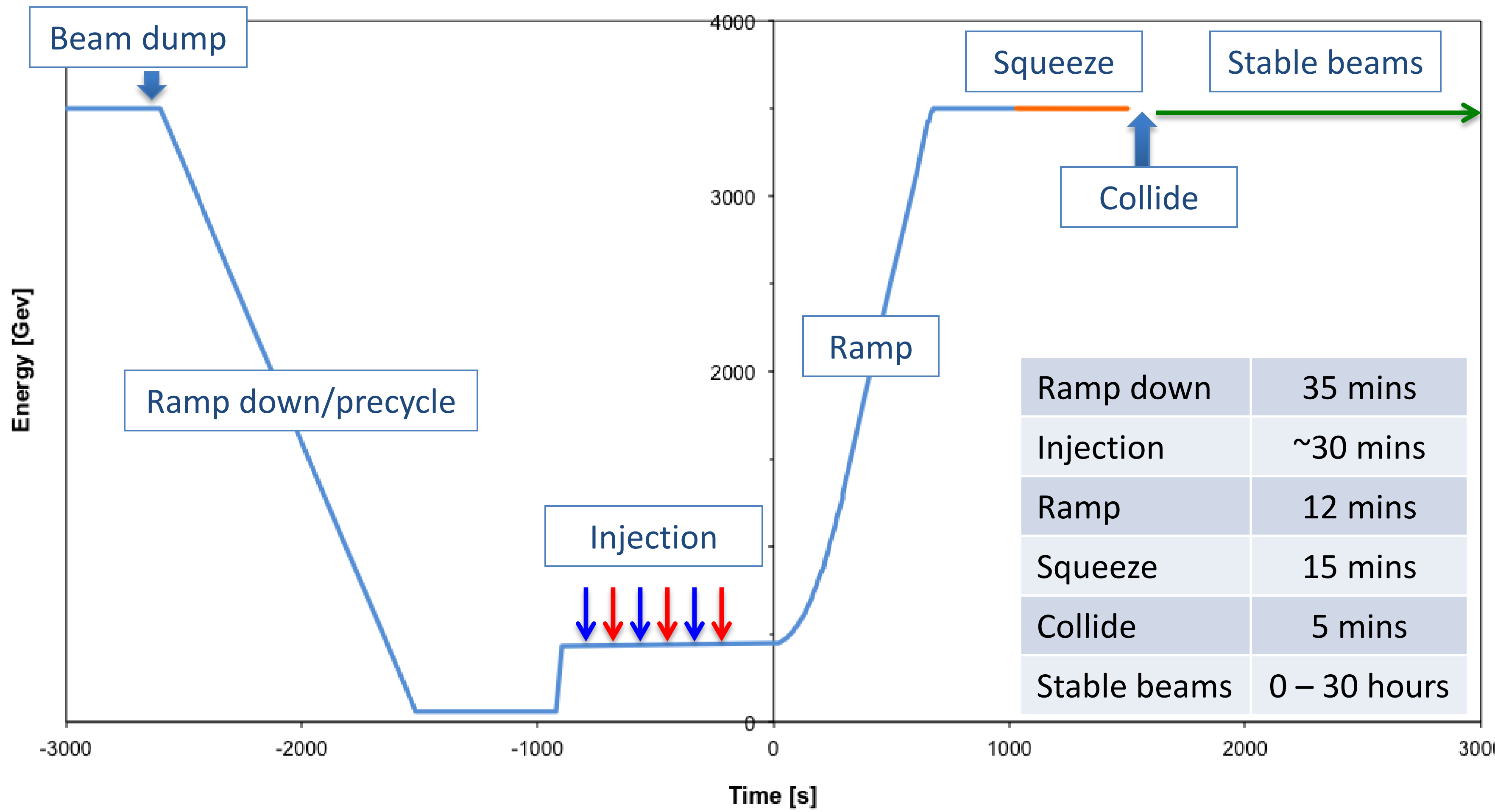
first evidence for the decay $B_s \to \mu^+ \mu^-$





M. Lamont, IPAC'13

operational cycle



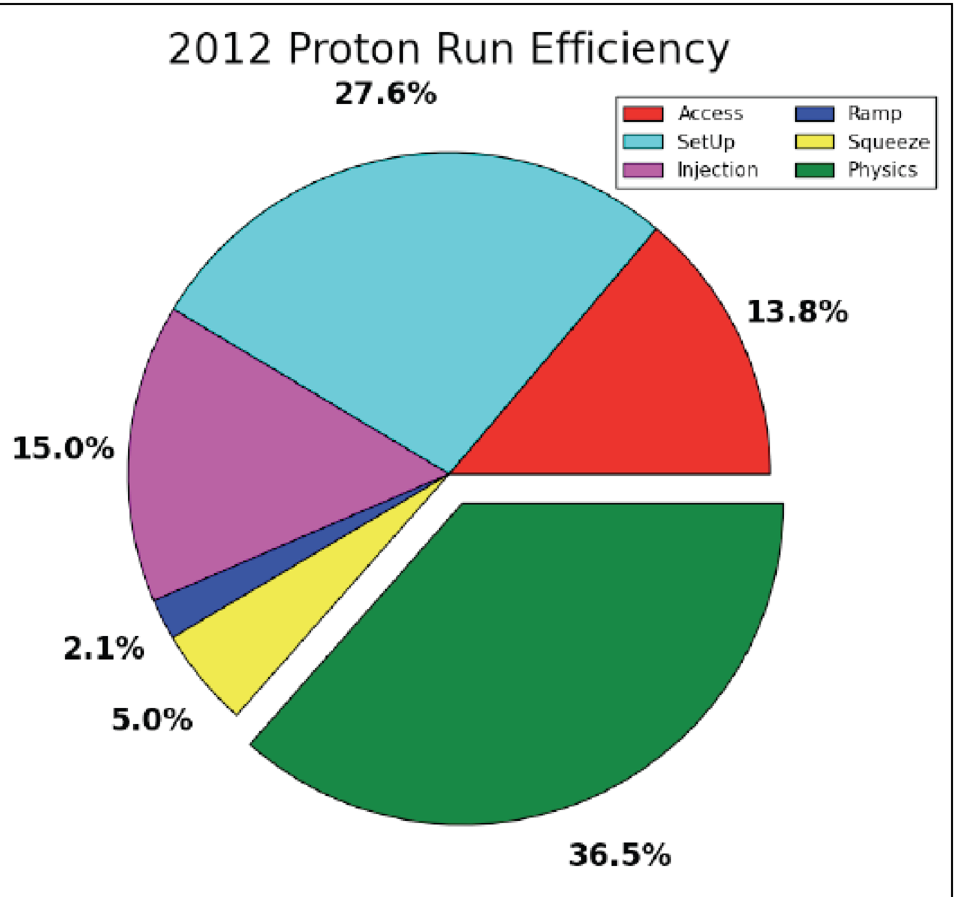
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

turn around 2 to 3 hours on a good day

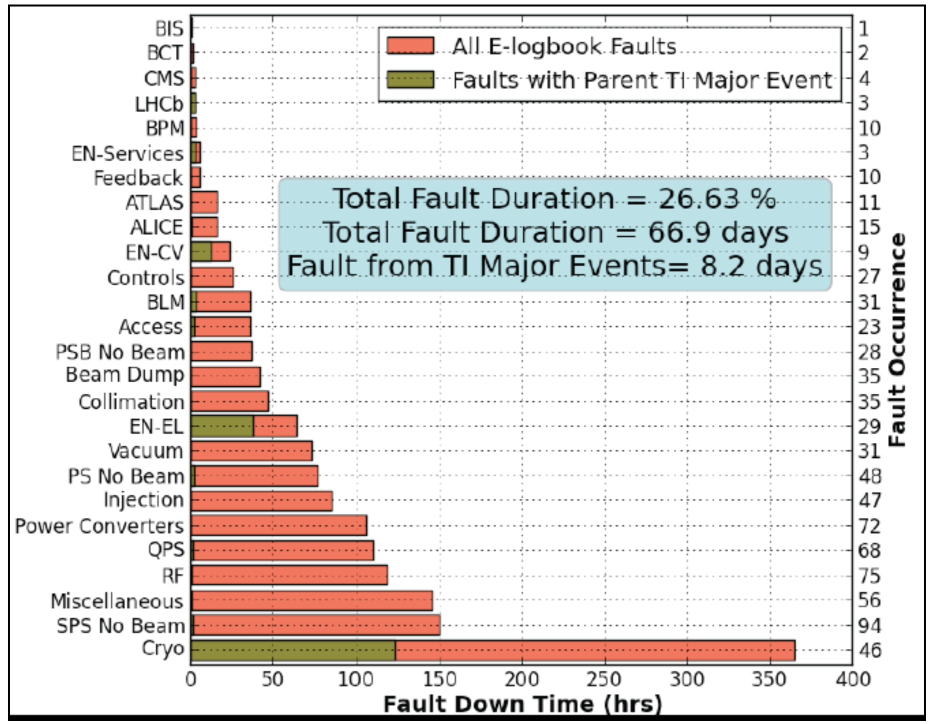
M. Lamont, IPAC'13

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



SB Time: 73.2 days   Total Time: 200.5 days

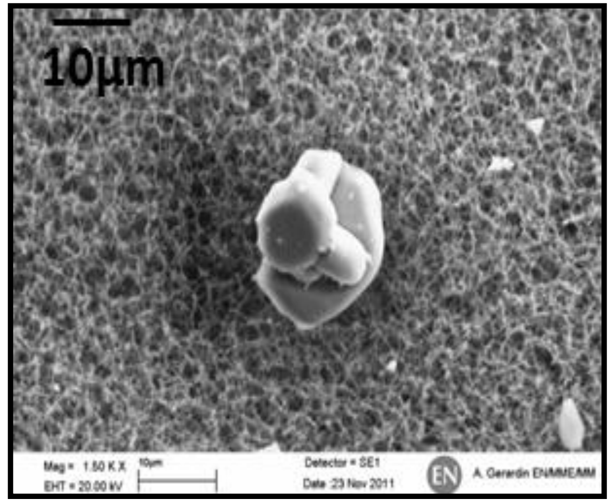


Cryogenics availability in 2012: 93.7%

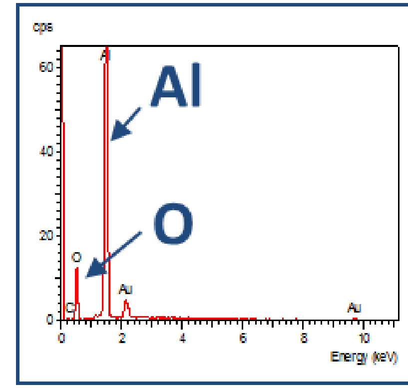
M. Lamont, IPAC’13

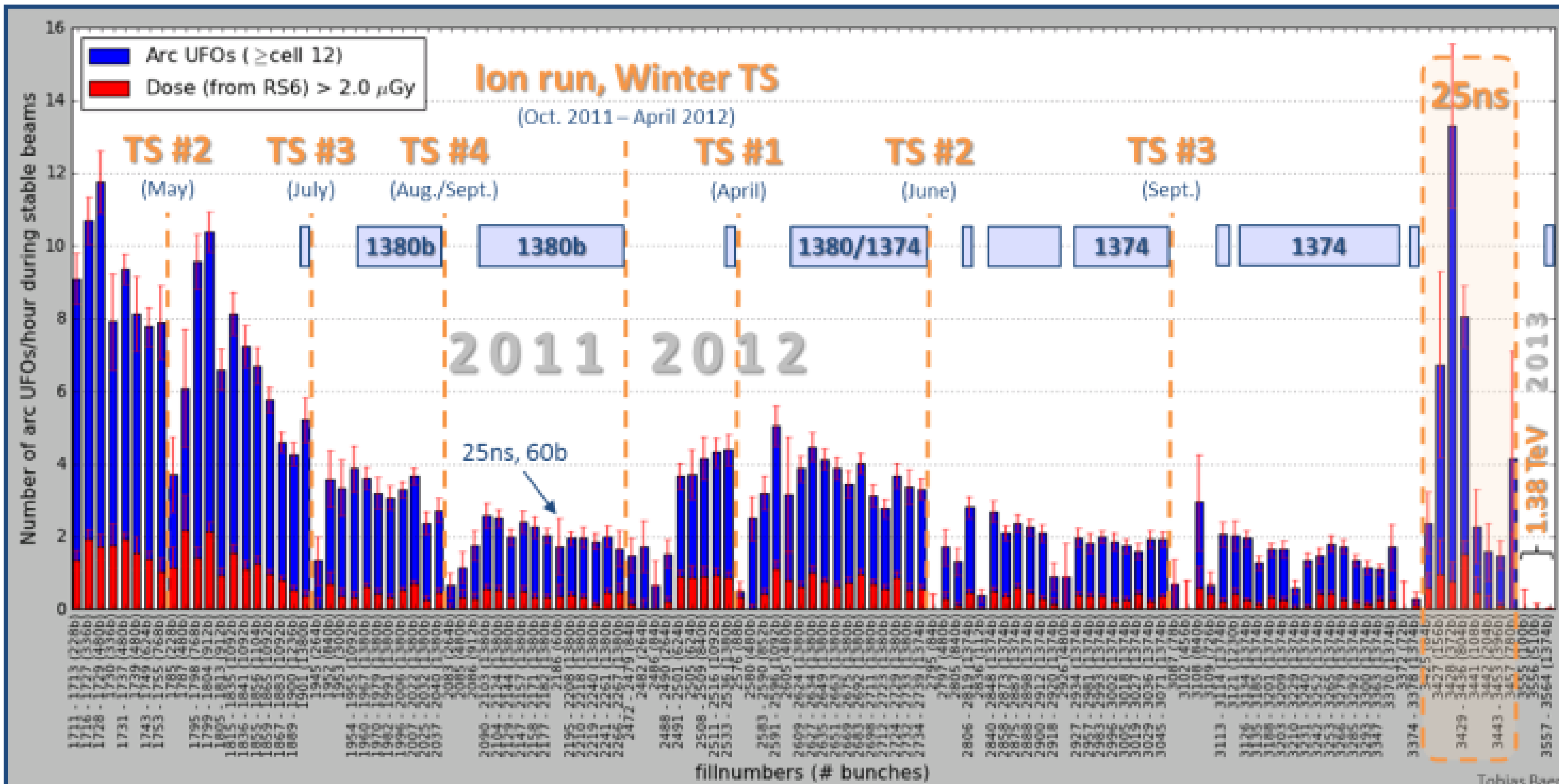
“UFOs” in the LHC

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

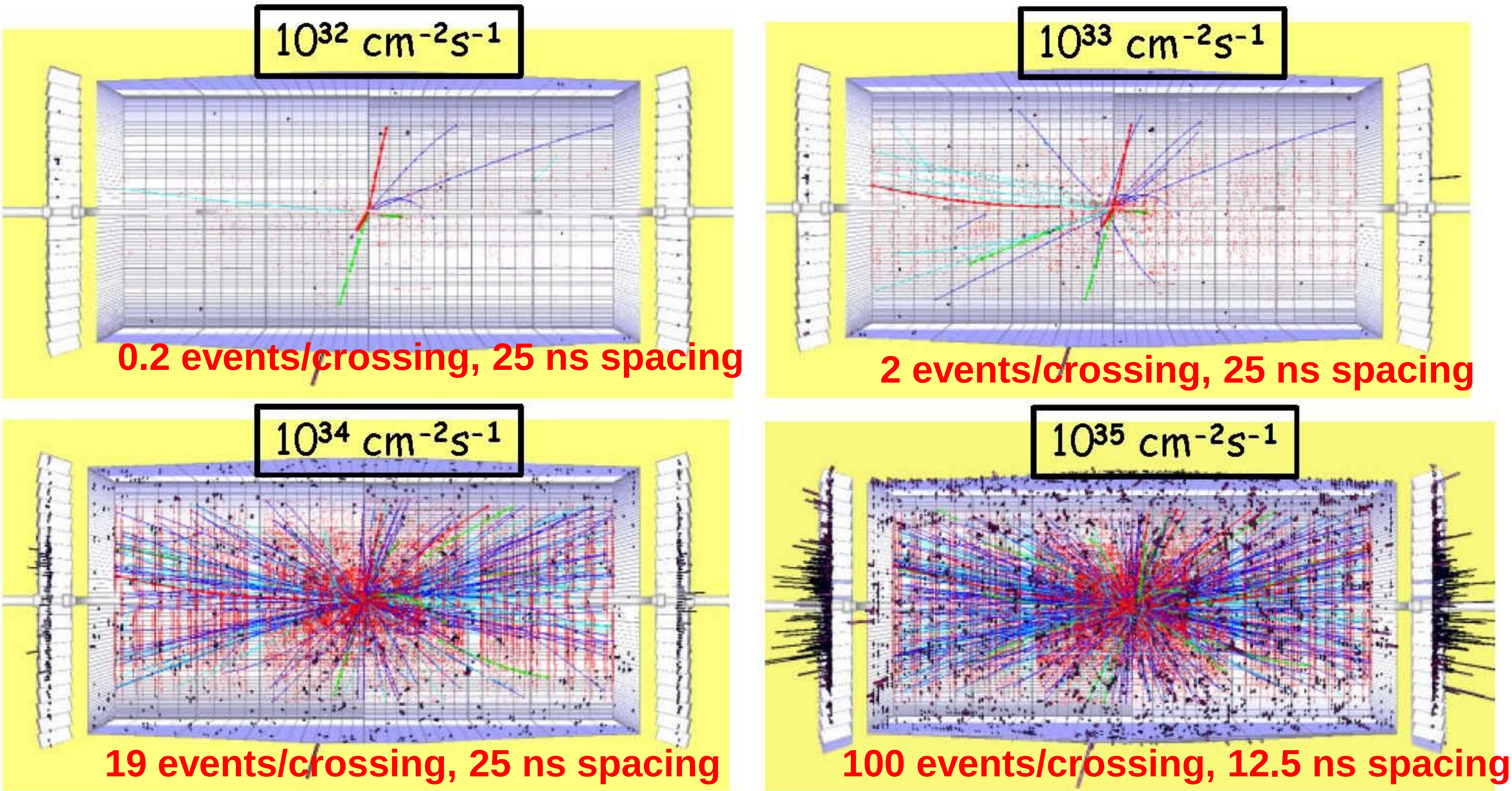


T. Baer



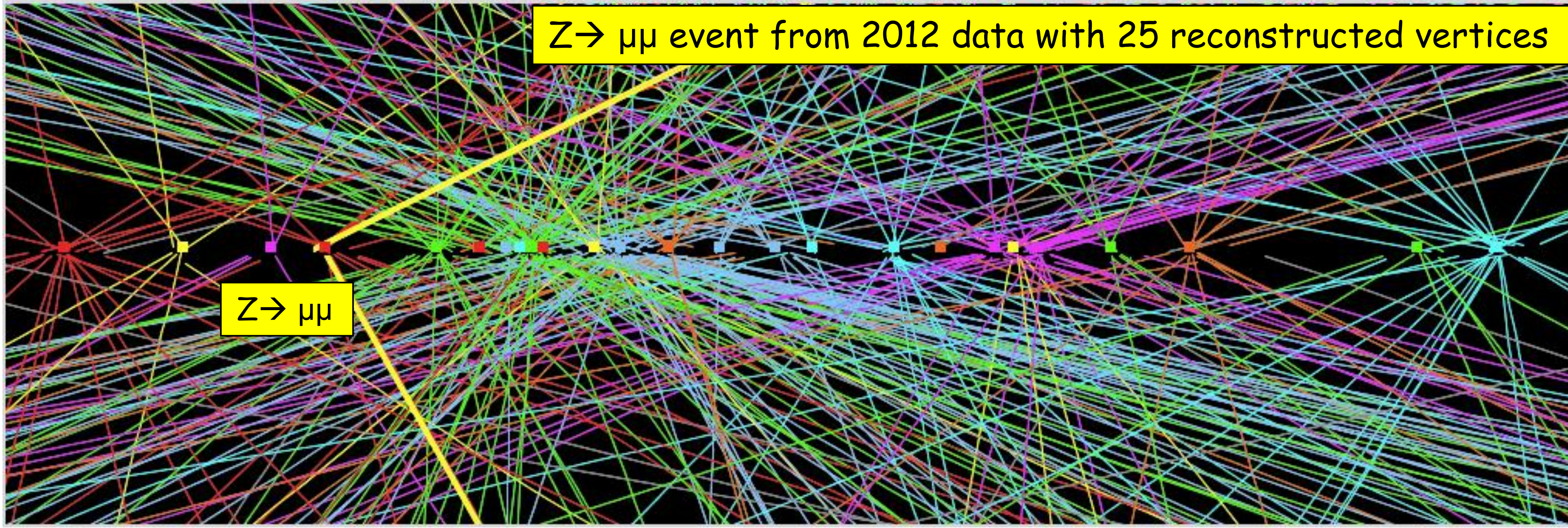


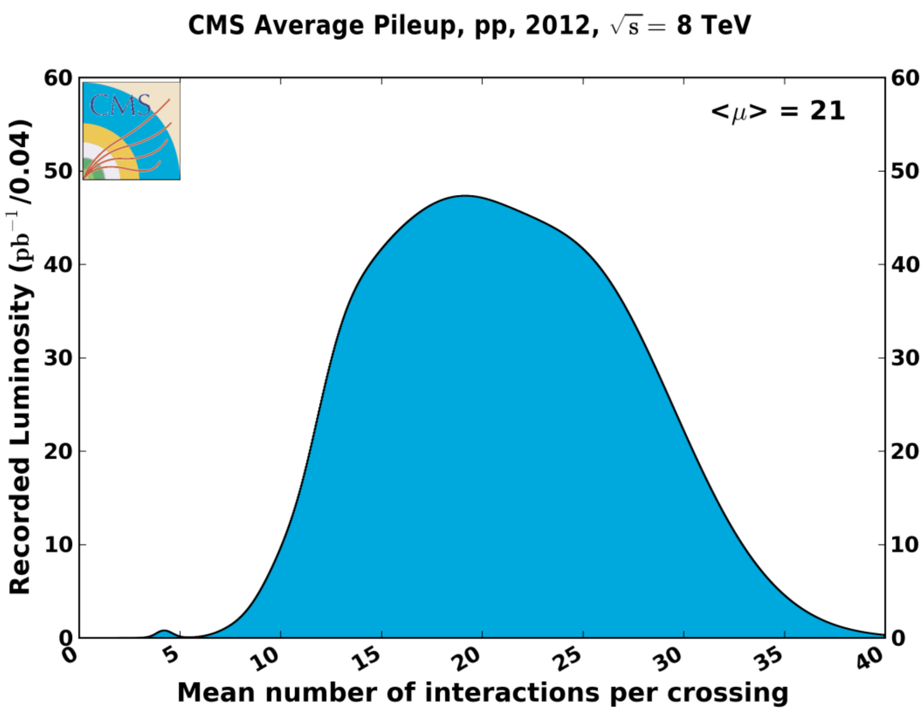
event pile up in detector



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

I. Osborne





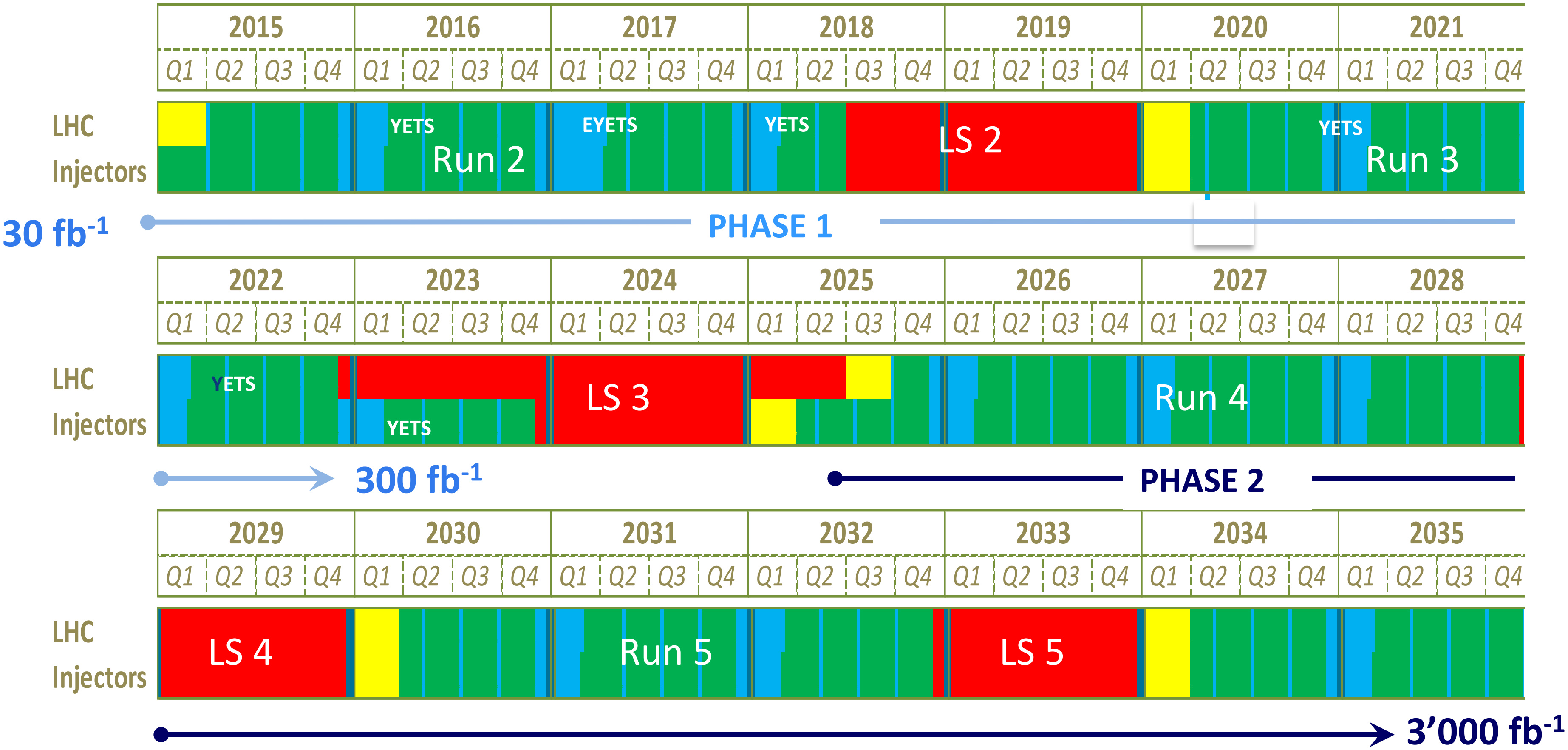
pile up
will increase
at higher energy
→
experiments
request
25 ns
operation
in 2015

LHC roadmap: schedule until 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

(Extended) Year End Technical Stop: (E)YETS

Physics
Shutdown
Beam commissioning
Technical stop



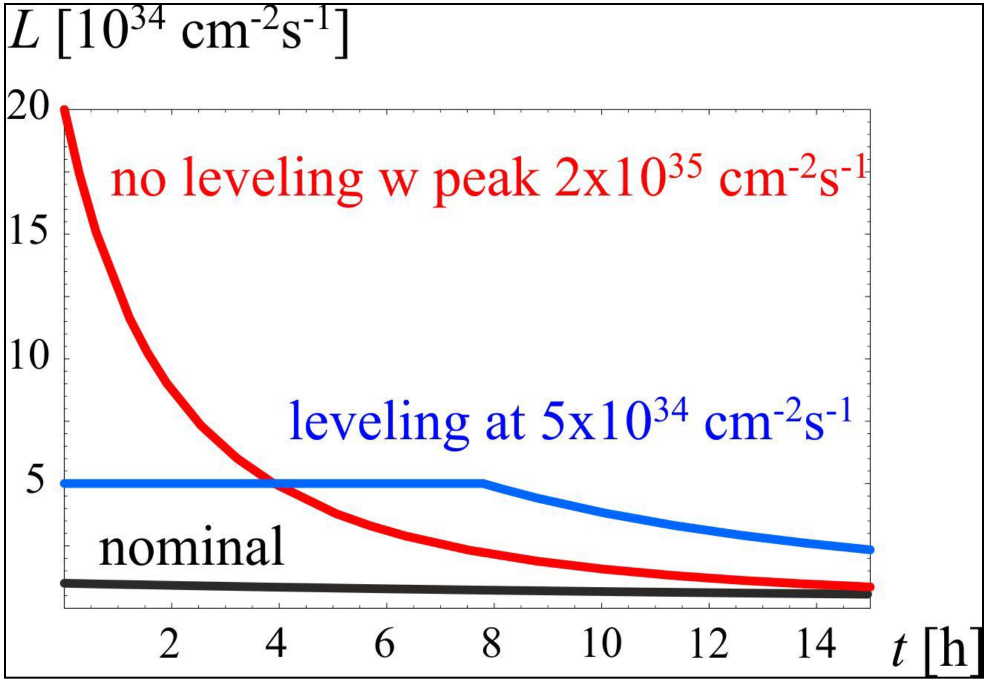
F. Bordry

Phase 2: HL-LHC

HL-LHC

M. Lamont

- 3000 fb^{-1} (10x design) delivered ~10 years
- high “virtual” luminosity with **levelling**



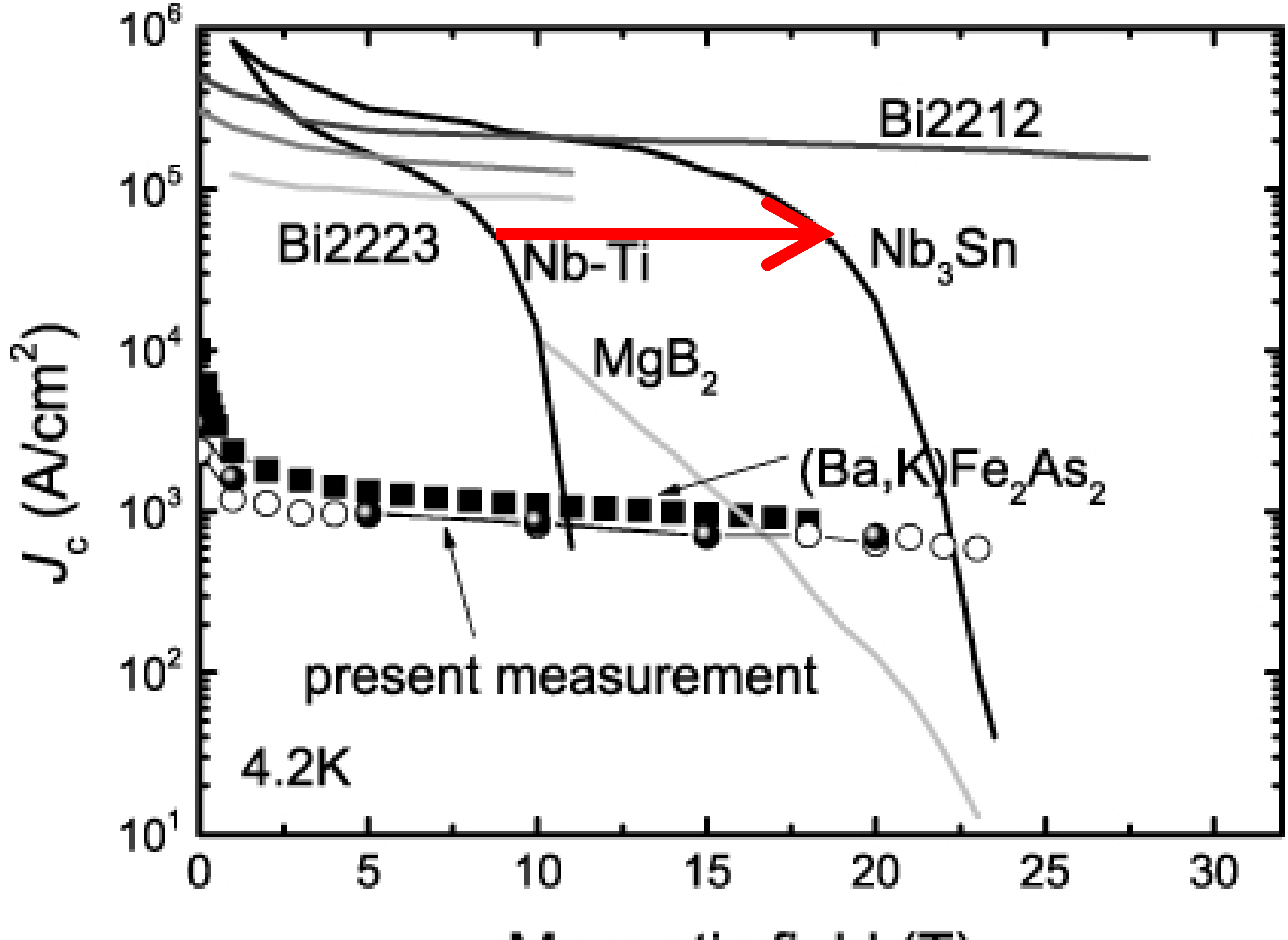
5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity

pile-up ~140 events per bunch crossing

3 fb^{-1} per day

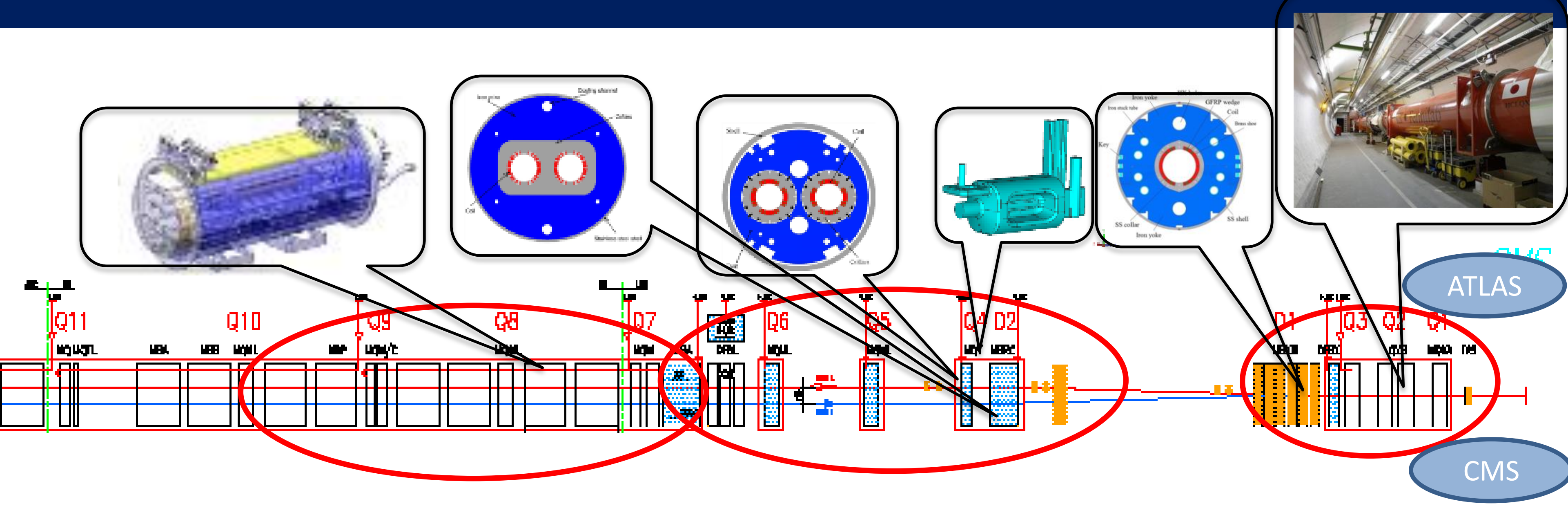
~250 fb^{-1} /year

technology transition: *Nb-Ti* →*Nb_3Sn*



O. Bruning

HL-LHC - critical zones around IP1 & IP5



3. For collimation we also need to change the DS in the continuous cryostat: **11-T Nb_3Sn dipole**

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

1. **New quadrupole triplet based on Nb_3Sn (12 T at coil)** required due to:

-Radiation damage

-Need for more aperture

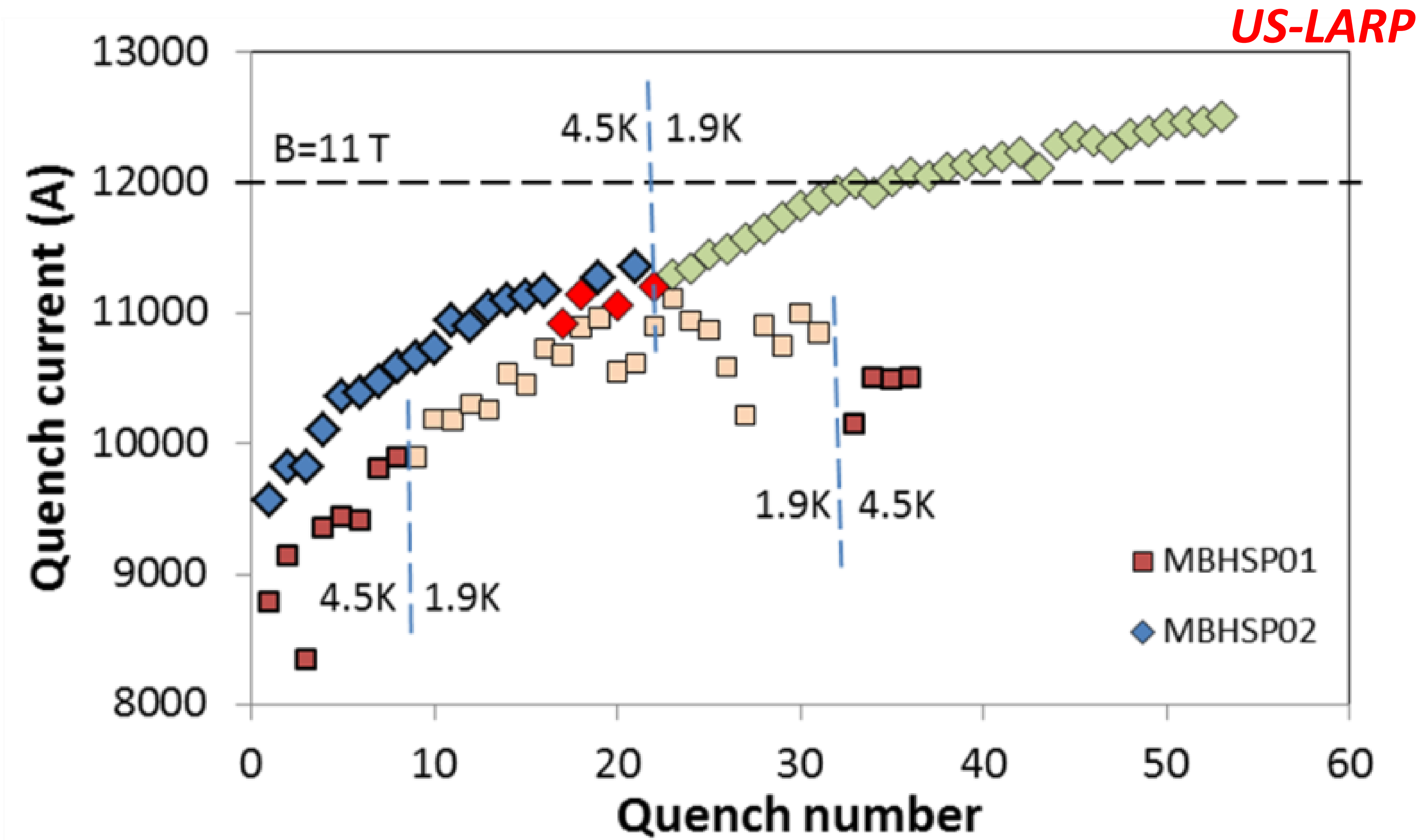
Changing the triplet region is not enough for reaching the HL-LHC goal!

→ more than 1.2 km of LHC plus technical infrastructure (e.g. Cryo and Powering)

→ *Nb_3Sn* dipoles & quadrupoles

O. Brüning, L. Rossi

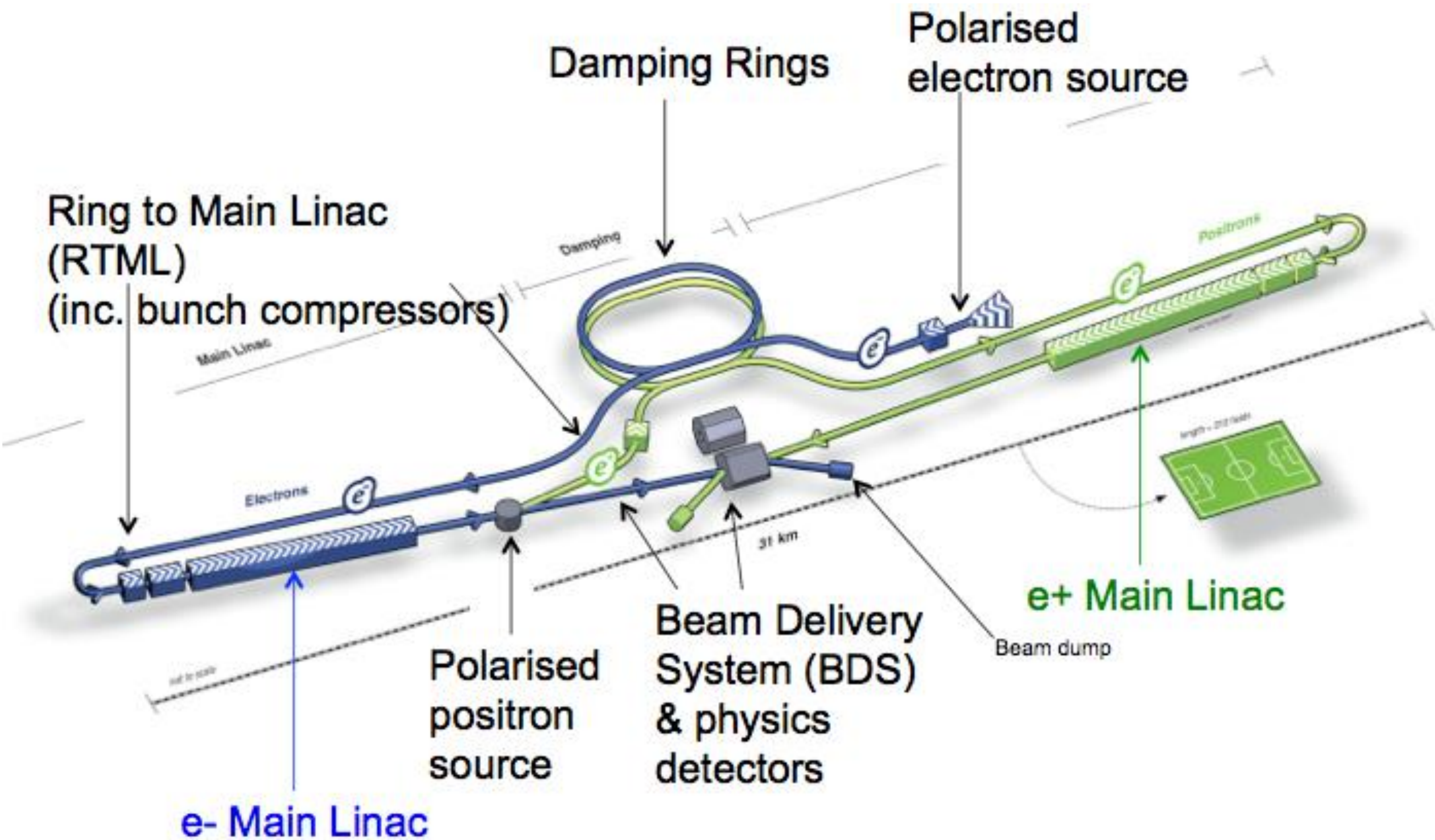
FNAL: *Nb_3Sn* dipole demonstrators



MBHSP02 (1 m) passed 11 T field during training at 1.9 K with *I* = 12080 A on 5 March 2013

International Linear Collider (ILC)

total length ~30 (500 GeV) - 50 km (1 TeV)

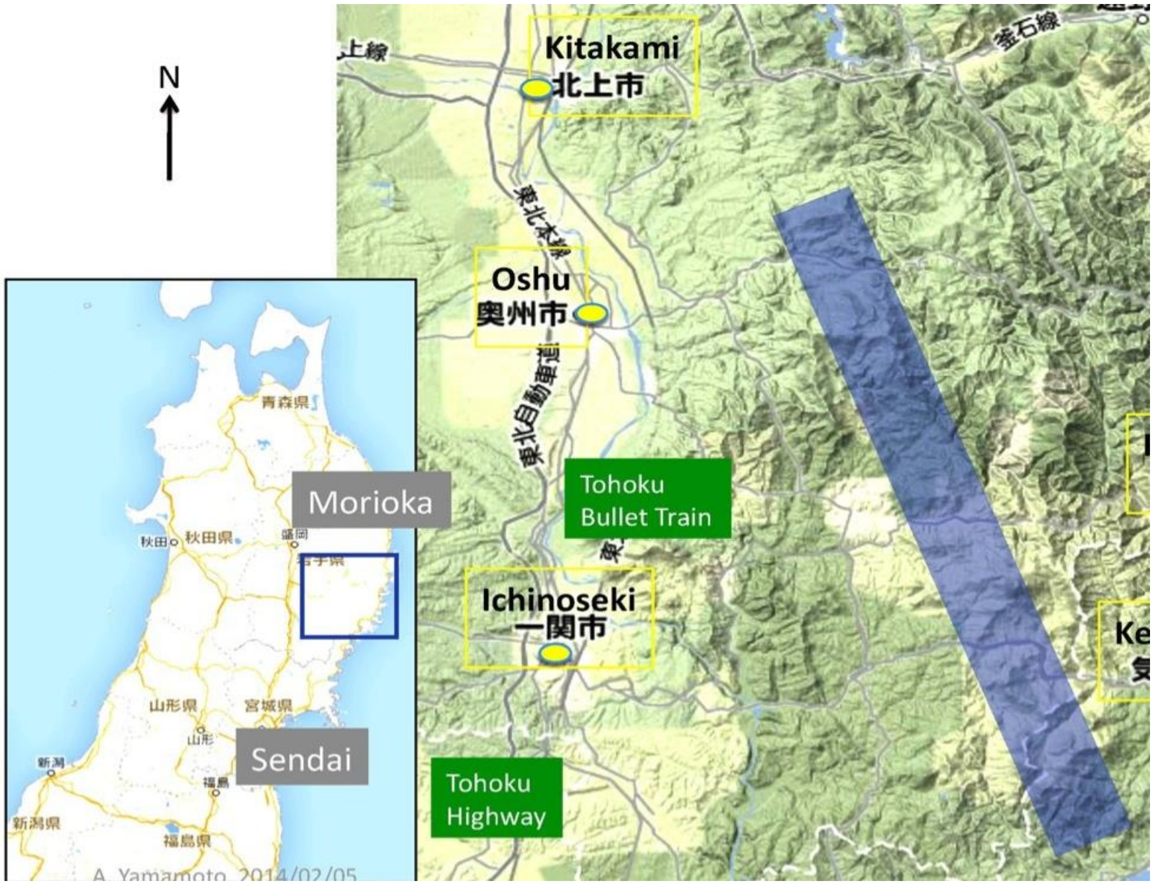


SC acceleration structures ~ 30 MV/m; **TDR completed in 2012**, ILC technology used for XFEL at DESY; present optimistic time line: construction start in 2018 & 1st physics in 2027?

International Linear Collider (ILC) - 2

Japanese HEP community expressed interest in hosting the ILC. Site chosen: 北上市 (Kitakami) in Northern Japan. Under review by Japanese ministry MEXT.

Courtesy F. Simon



accelerator applications

Source: Accelerators and Beams (APS-DPP), ORNL

Accelerator Applications

- >30000 accelerators already in use around the World
- Annual sales: >$3.5B
- Annual product, etc, sales: >$0.5T
- Fit into a few broad categories:
  - Energy
  - Environment
  - Healthcare
  - Industry
  - Security and defence
  - Research

(Healthcare and Industry: Most of the World's accelerators)

Rob Edgecock,
RAL & U. Huddersfield

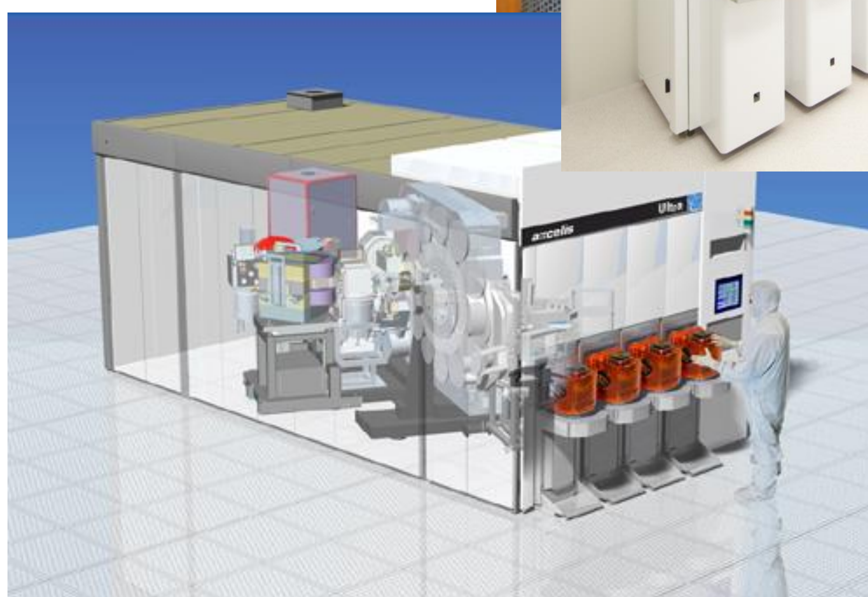
Accelerator Applications

>30000 accelerators in use world-wide:

- **44% for radiotherapy**
- **41% for ion implantation**
- **9% for industrial applications**
- **4% low energy research**
- **1% medical isotope production**
- **<1% research**

Treating cancer

Making better semi-conductors



Rob Edgecock,
RAL & U. Huddersfield

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"Curing" materials; sterilisation; carbon dating; treating flue gases; treating water; etc

Rob Edgecock,
RAL & U. Huddersfield

Accelerator Applications

>30000 accelerators in use world-wide:

- **44% for radiotherapy**
- **41% for ion implantation**
- **9% for industrial applications**
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- **1% medical isotope production**
- **<1% research**

Microanalysis of materials, mass spectroscopy, PIXE, etc

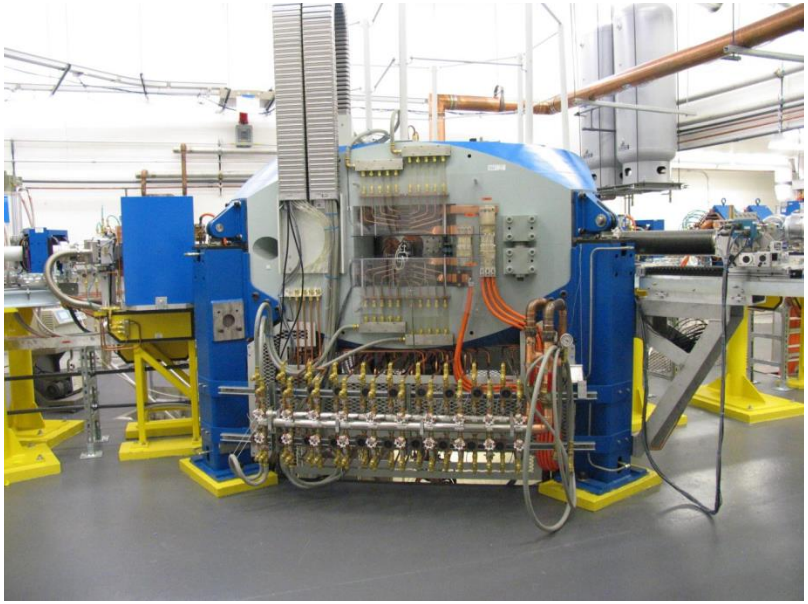
Rob Edgecock,
RAL & U. Huddersfield

Accelerator Applications

>30000 accelerators in use world-wide:

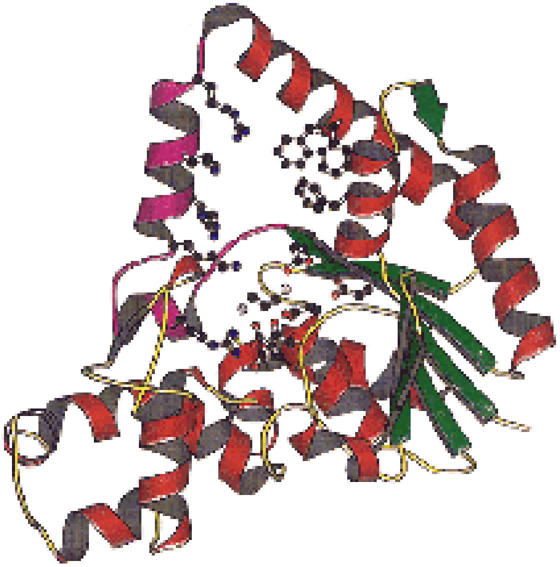
- **44% for radiotherapy**
- **41% for ion implantation**
- **9% for industrial applications**
- **4% low energy research**
- **1% medical isotope production**

For PET and SPECT medical imaging, etc

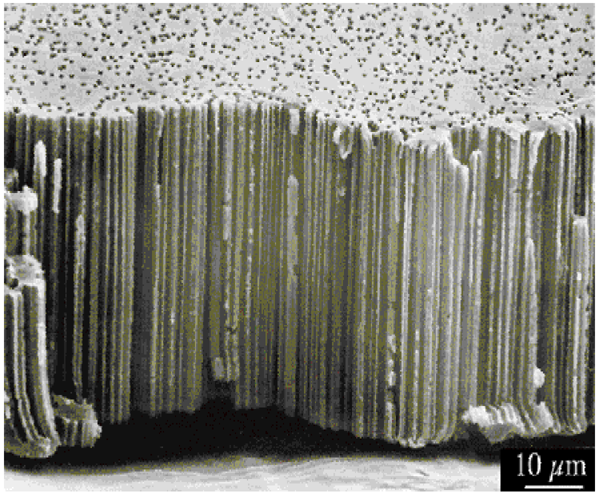


Rob Edgecock,
RAL & U. Huddersfield

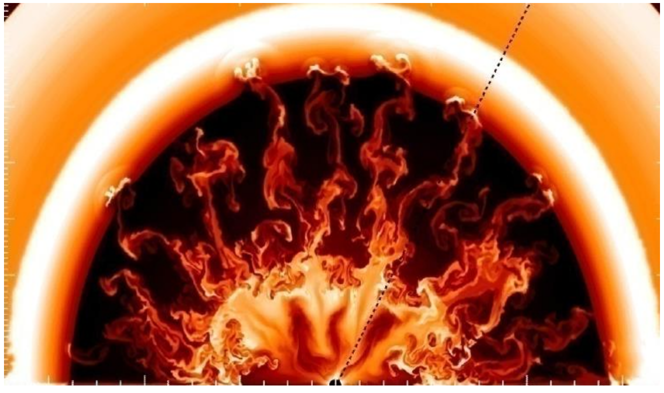
further examples of accelerator applications



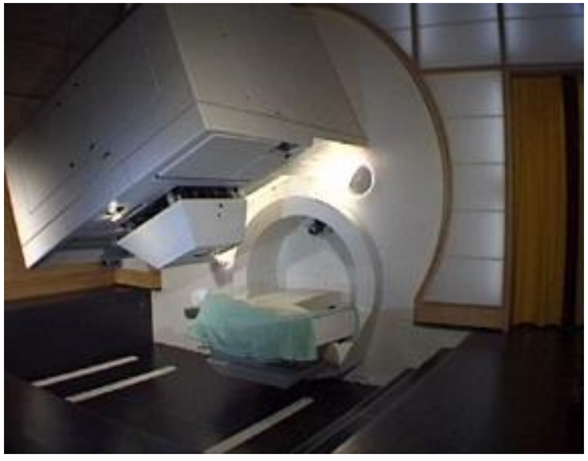
Synchrotron Light (ESRF)
5'-exonuclease from bacteriophage T5
(diffraction pattern →enzyme structure)



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



Heavy ion fusion
shock simulation



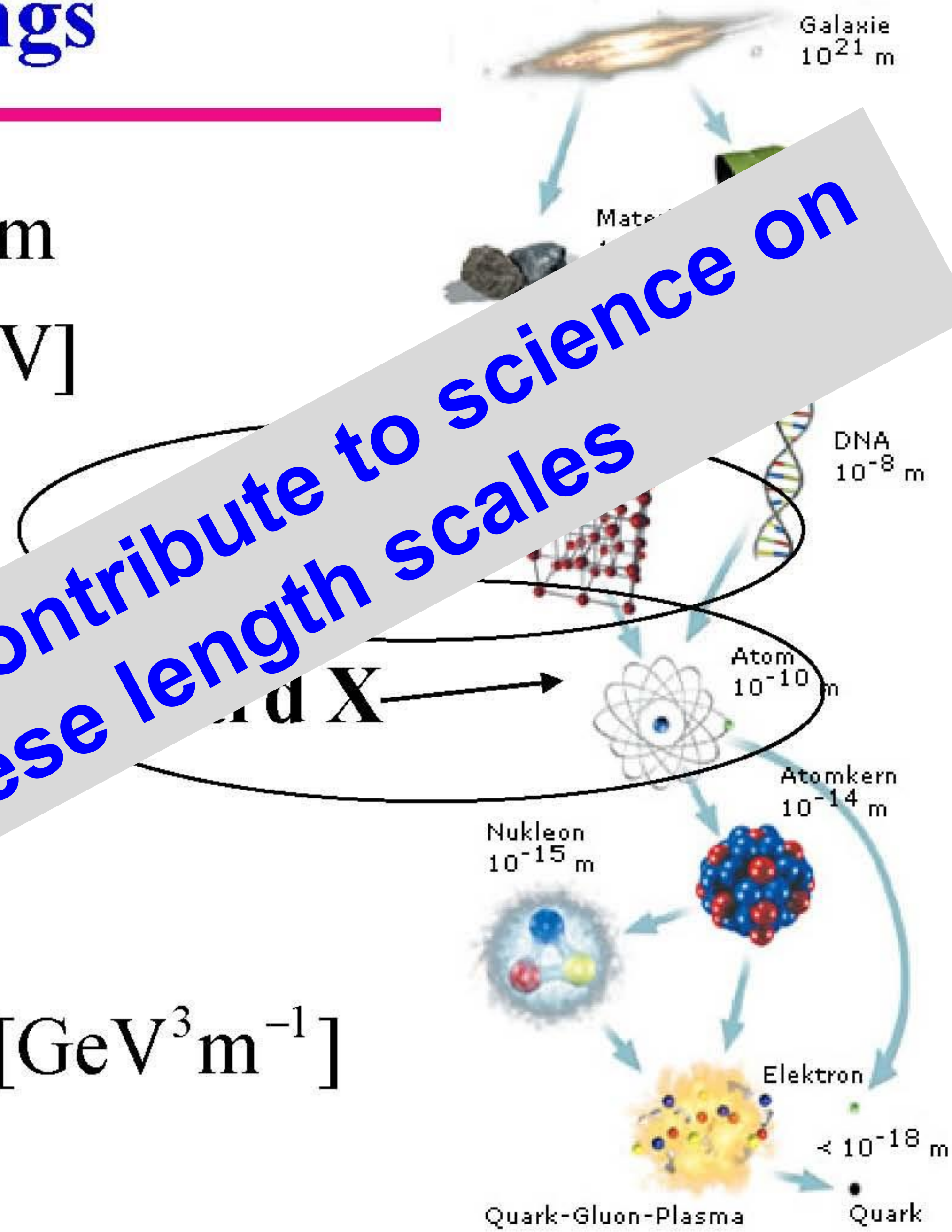
Proton therapy (PSI)
gantry

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

The scale of things

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

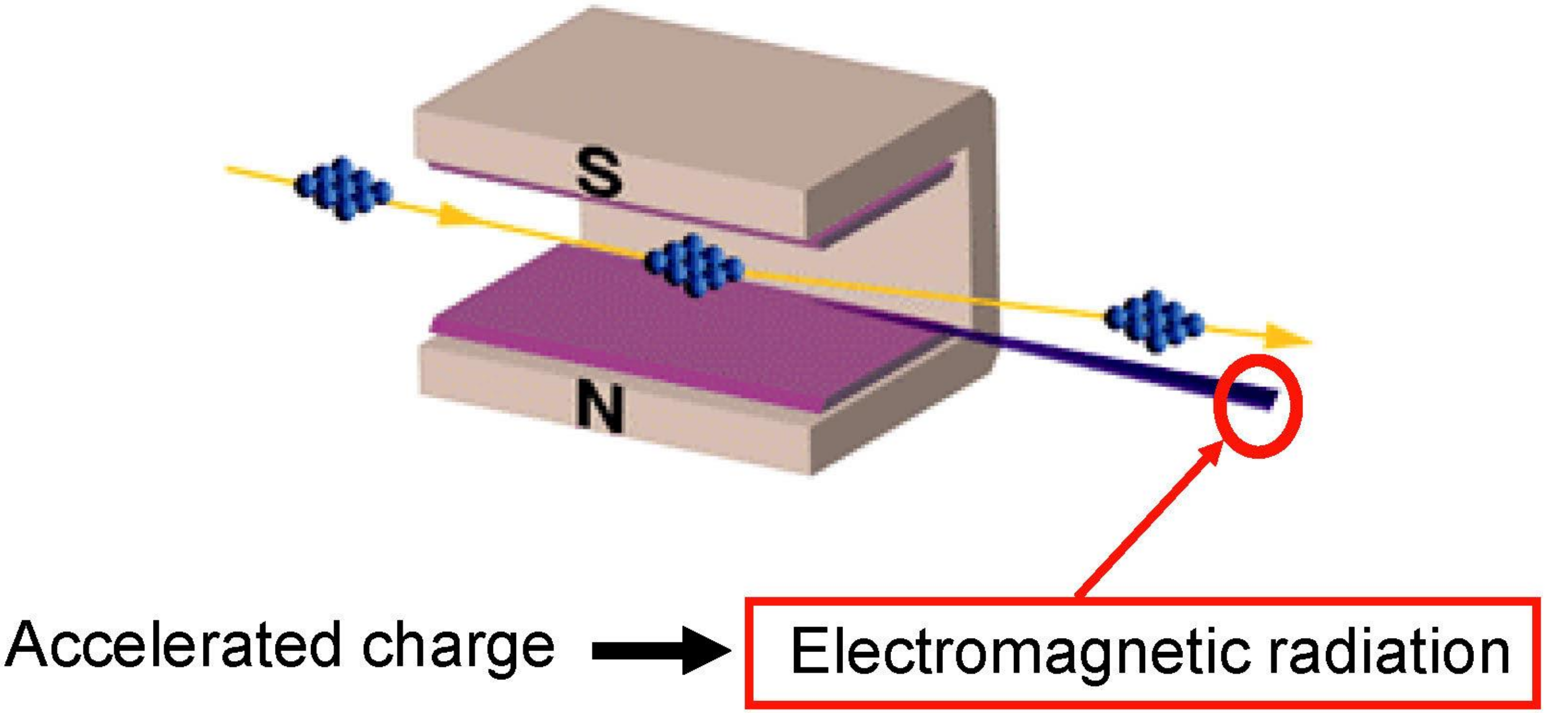
$$= 12.4/E_{photon}\ \ [\text{MeV}]$$



accelerators contribute to science on all these length scales

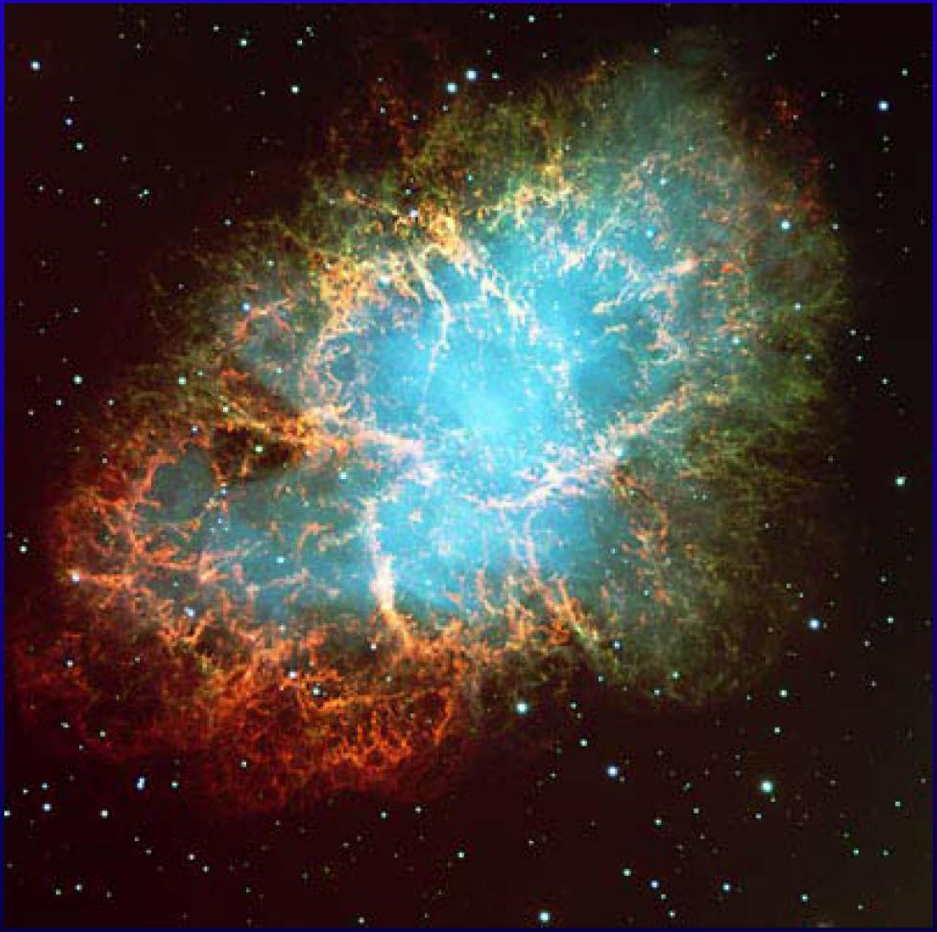
$$E_{photon} = 2218\,\frac{E^3_{beam}}{r}\,[\text{GeV}^3\text{m}^{-1}]$$

curved orbit of e^- in magnetic field



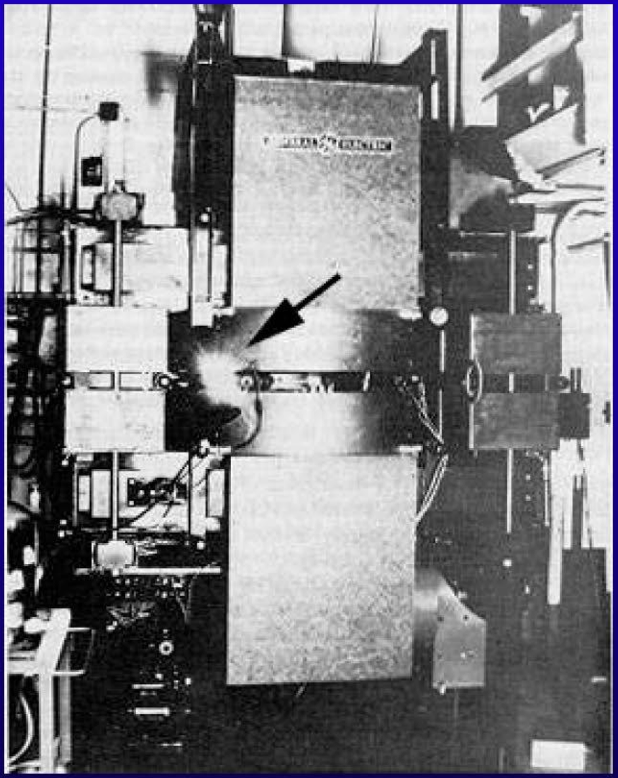
L. Rivkin

Crab Nebula
6000 light years away



First light observed
1054 AD

GE Synchrotron
New York State



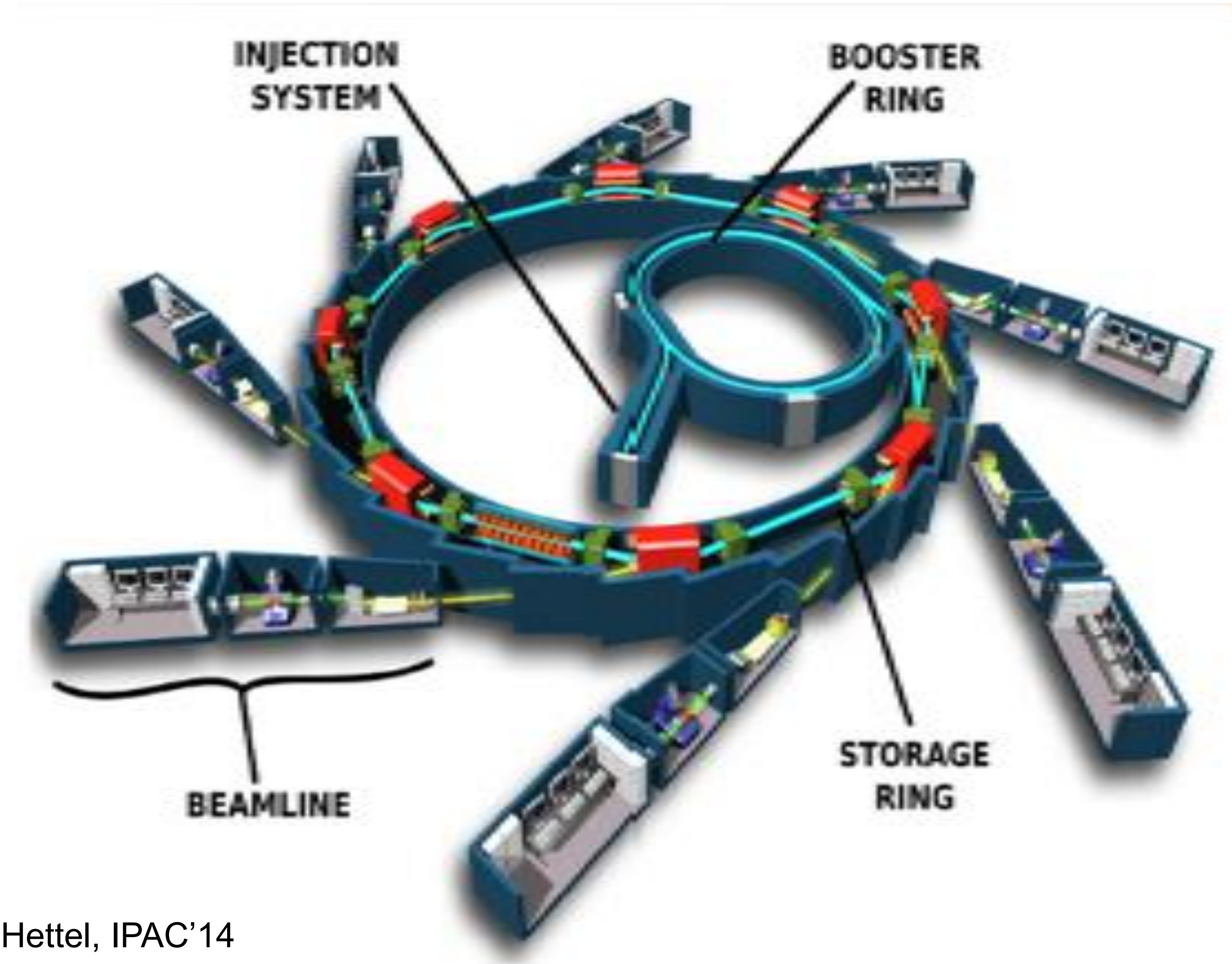
First light observed
1947

L. Rivkin

synchrotron light sources in the world

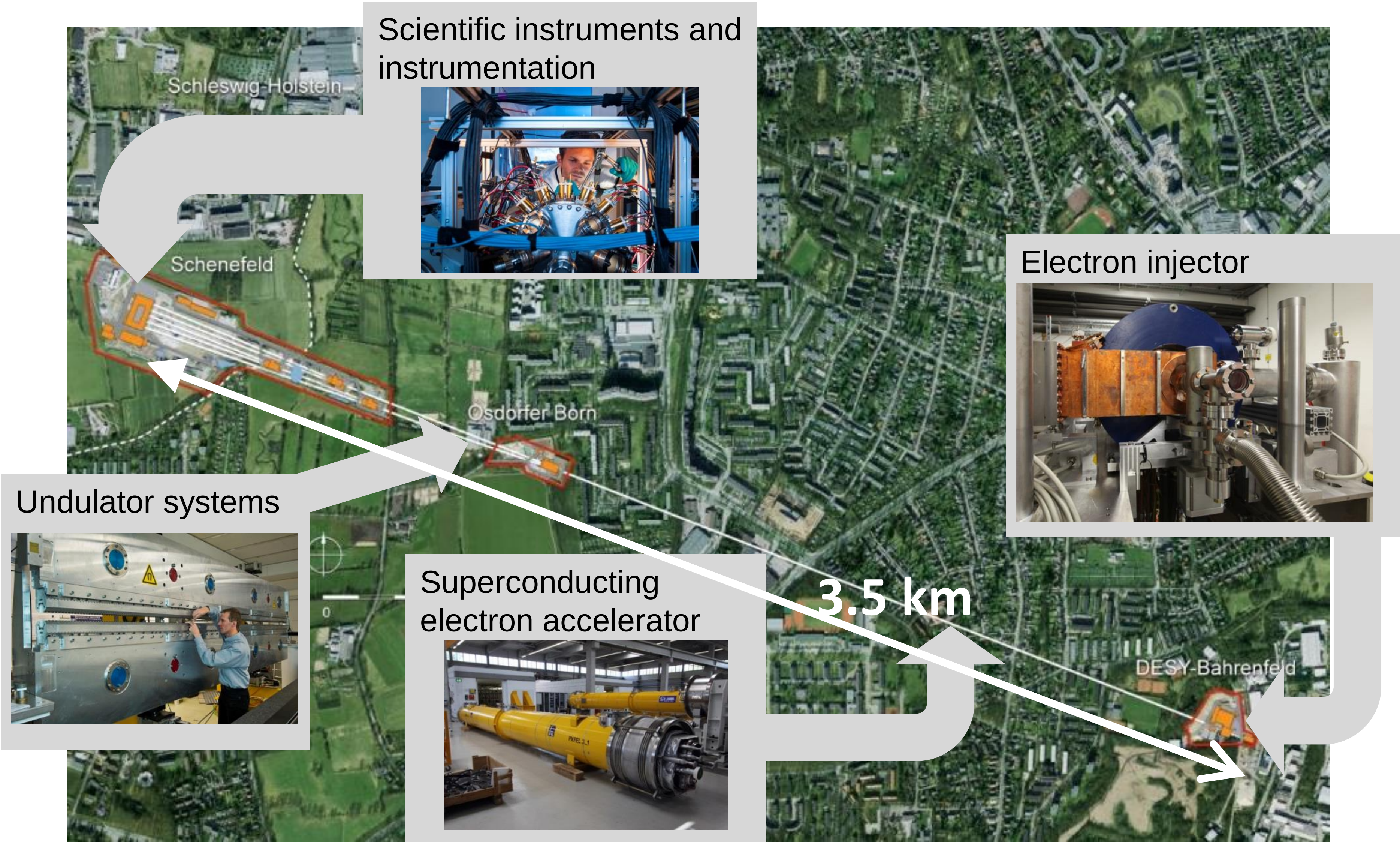
→ basic and applied research, including material science, archeology , earth science, space science, life science, medicine

storage ring light source



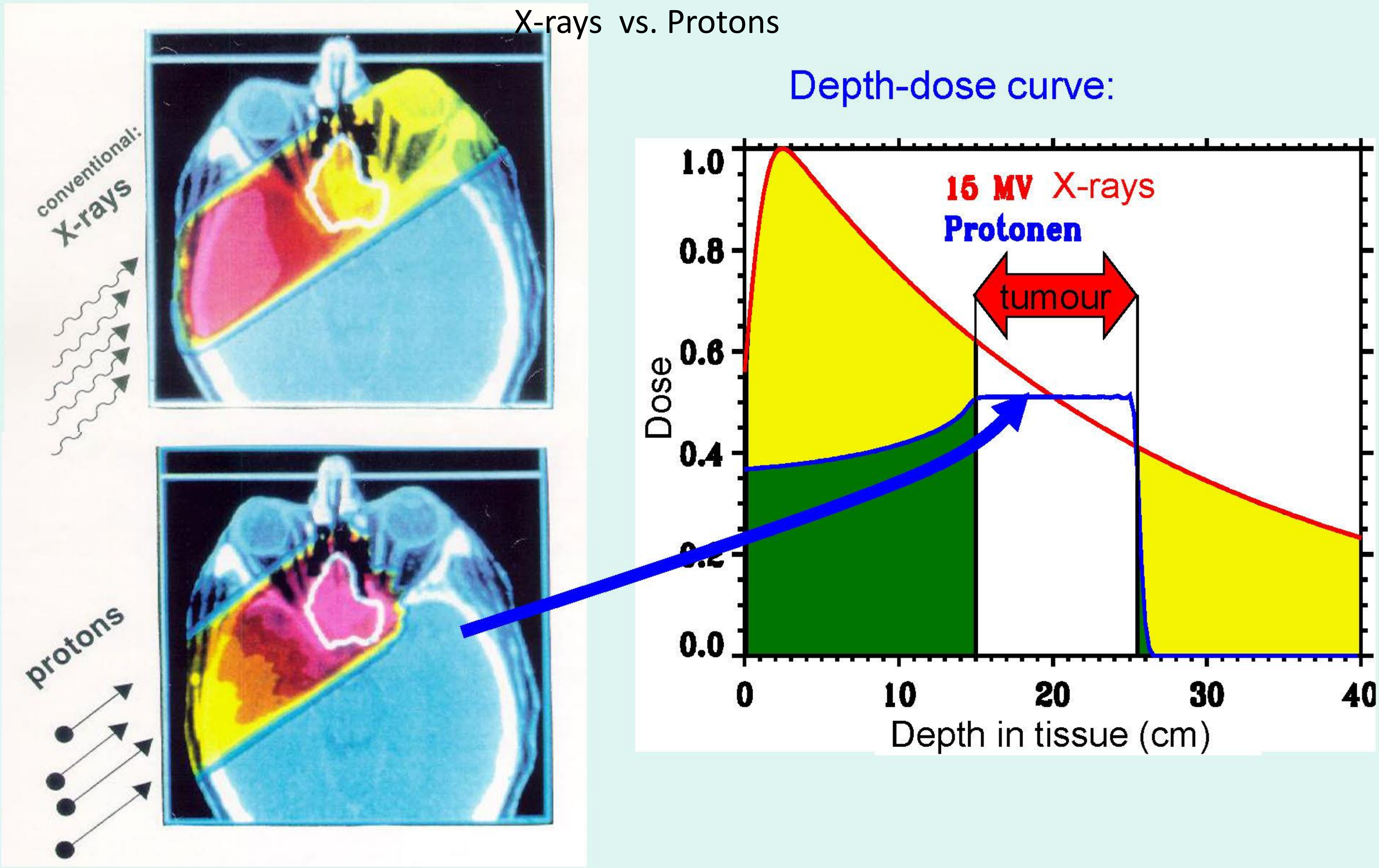
R. Hettel, IPAC'14

European XFEL in Hamburg



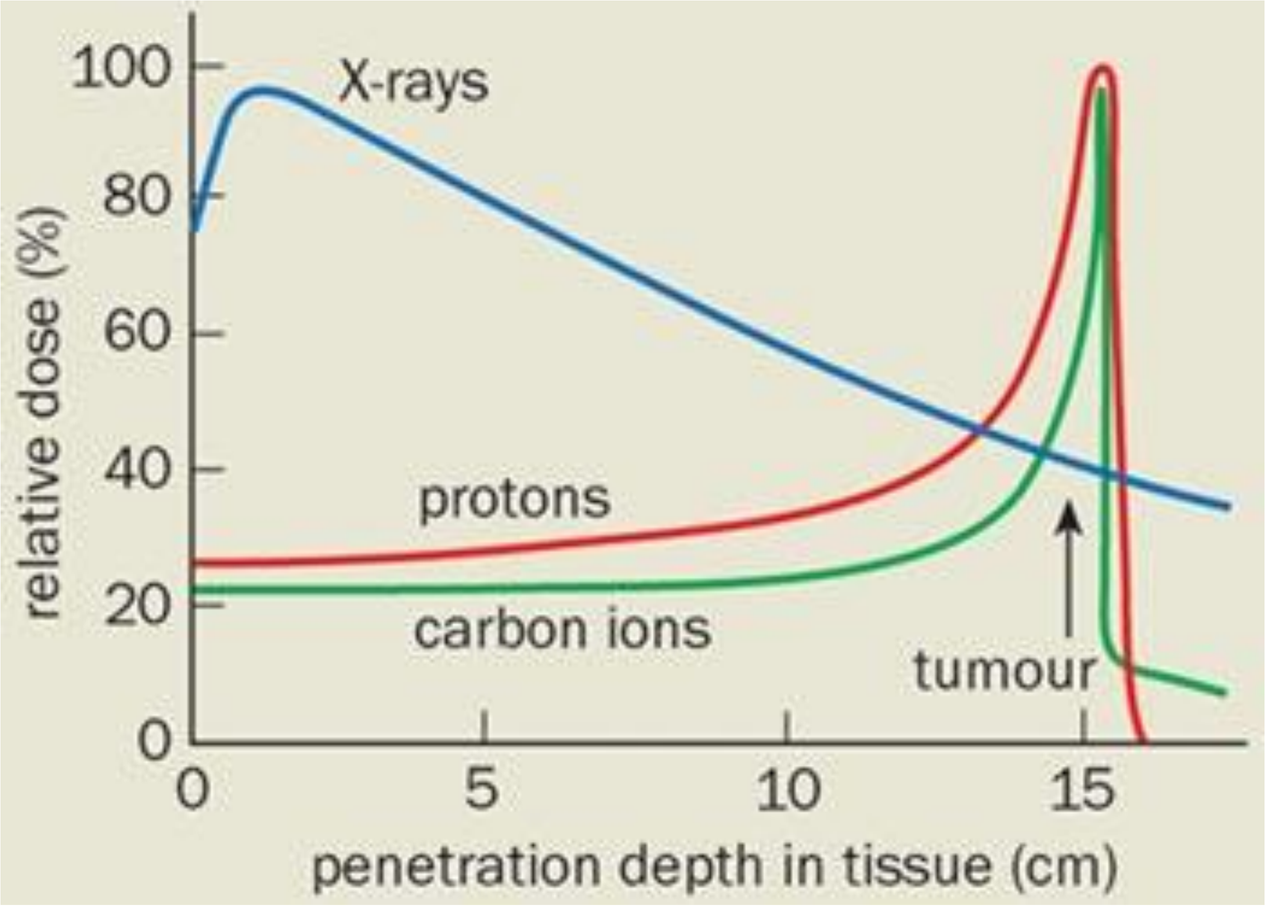
cancer treatment - X rays vs protons

X-rays vs. Protons



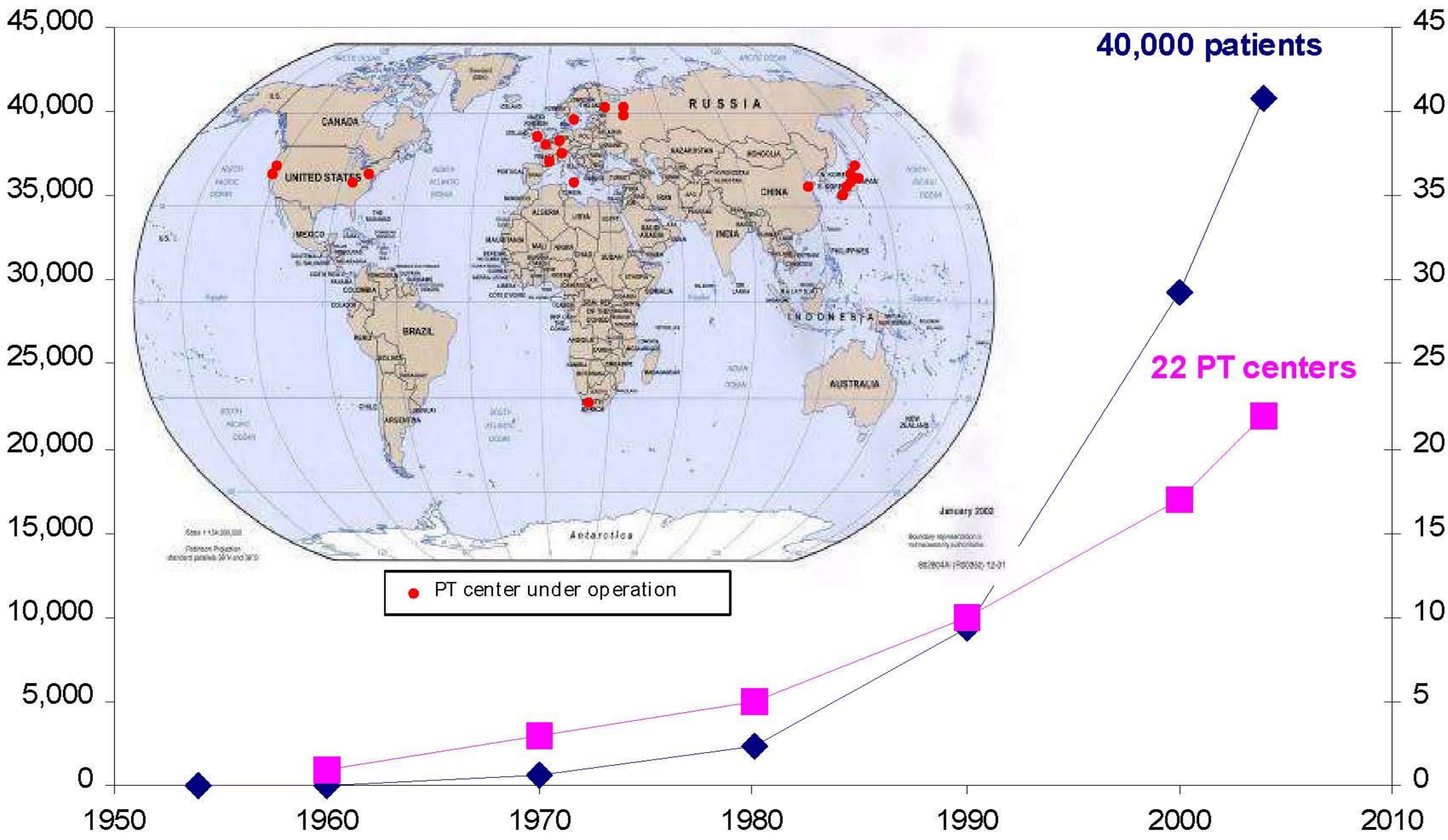
M. Schippers, M. Seidel
IPAC'14

how (accelerated) particles can be therapeutic



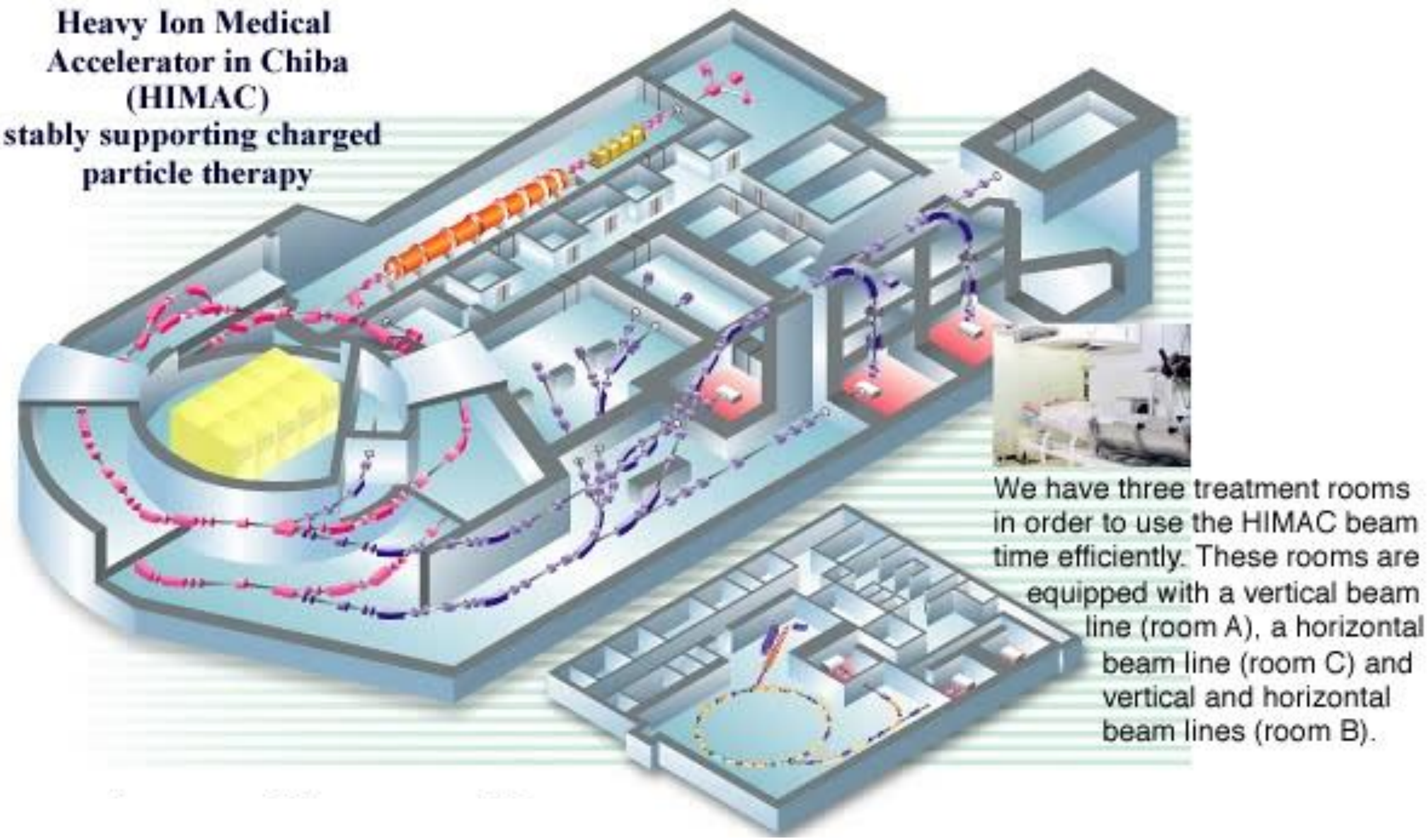
X-rays (photons) lose energy rapidly by ionization as they travel through the body.
On the other hand, charged particles such as protons and carbon ions deposit most of their energy at a specific depth that depends on their energy (called the Bragg peak). This means that they can deliver a high radiation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

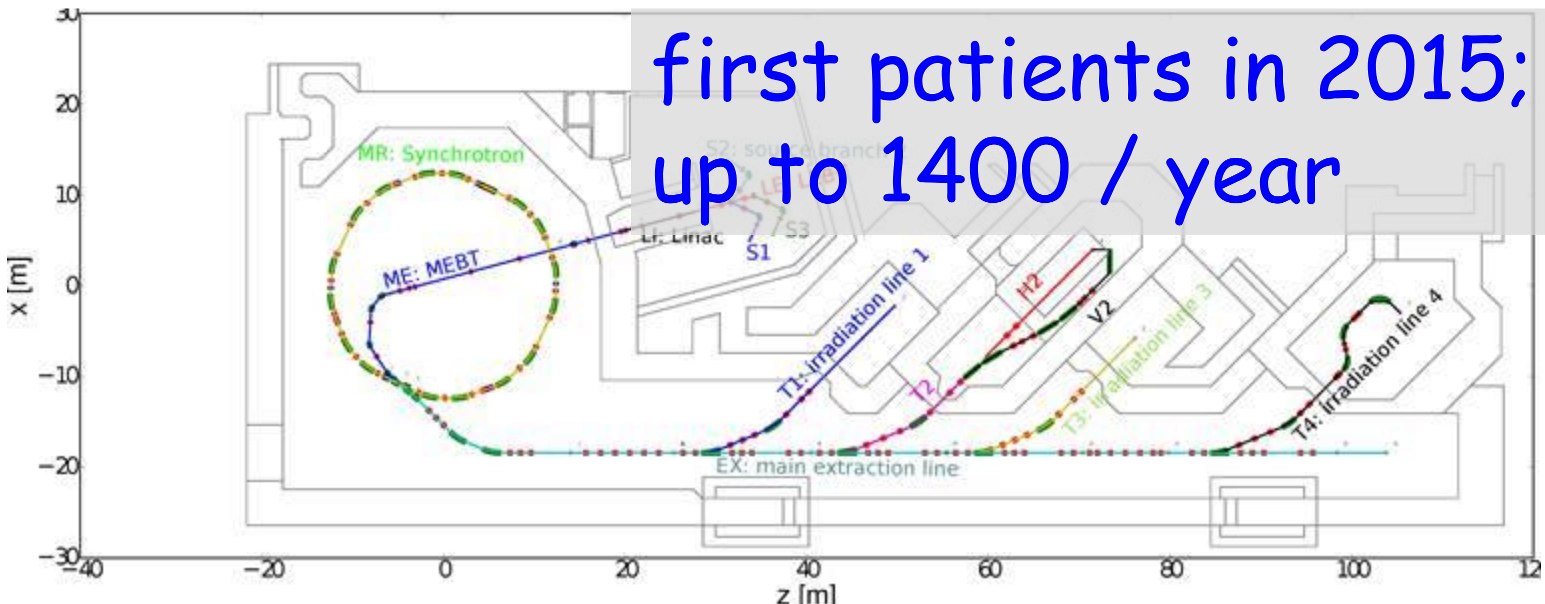


in operation with patients since 1994

NIRS

MedAustron in Wiener Neustadt

built in close collaboration with CERN



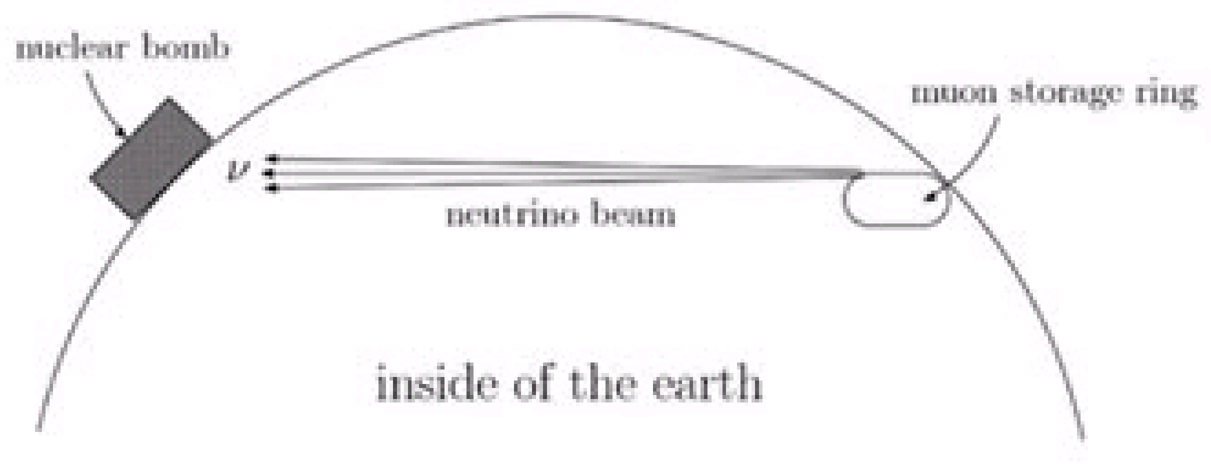
first patients in 2015;
up to 1400 / year

ν beam neutralising nuclear bombs?

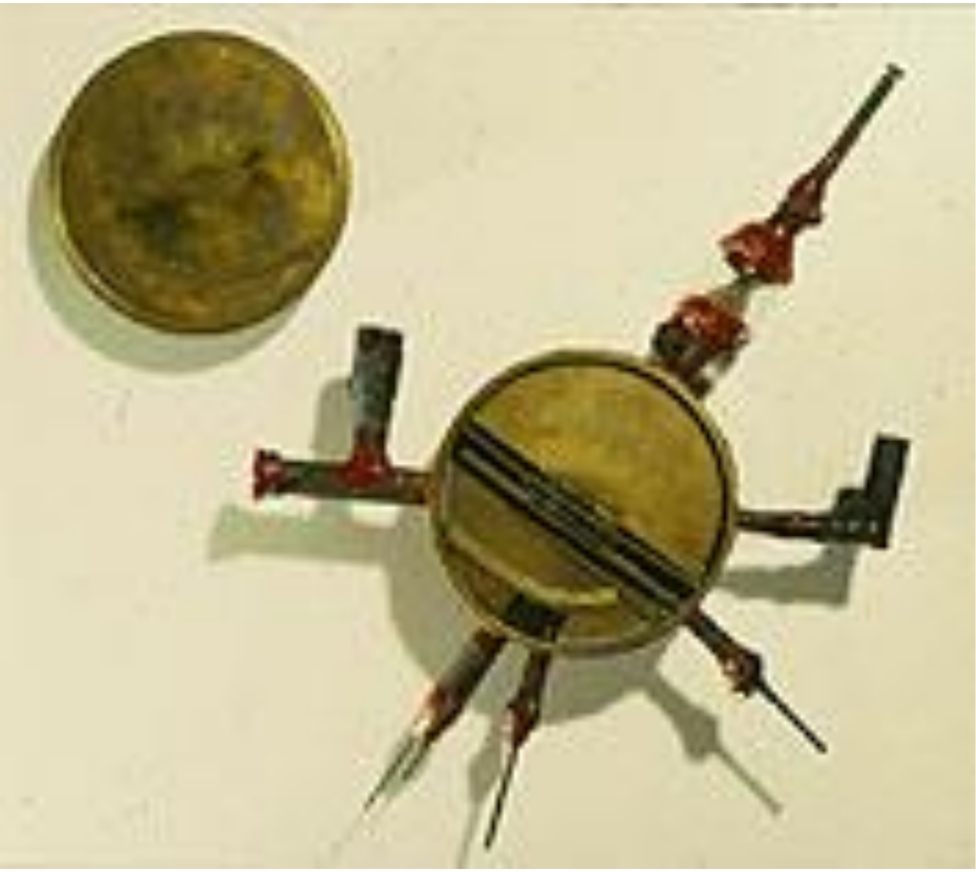
"A super-powered neutrino generator could in theory be used to instantly destroy nuclear weapons anywhere on the planet, according to a team of Japanese scientists.

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?

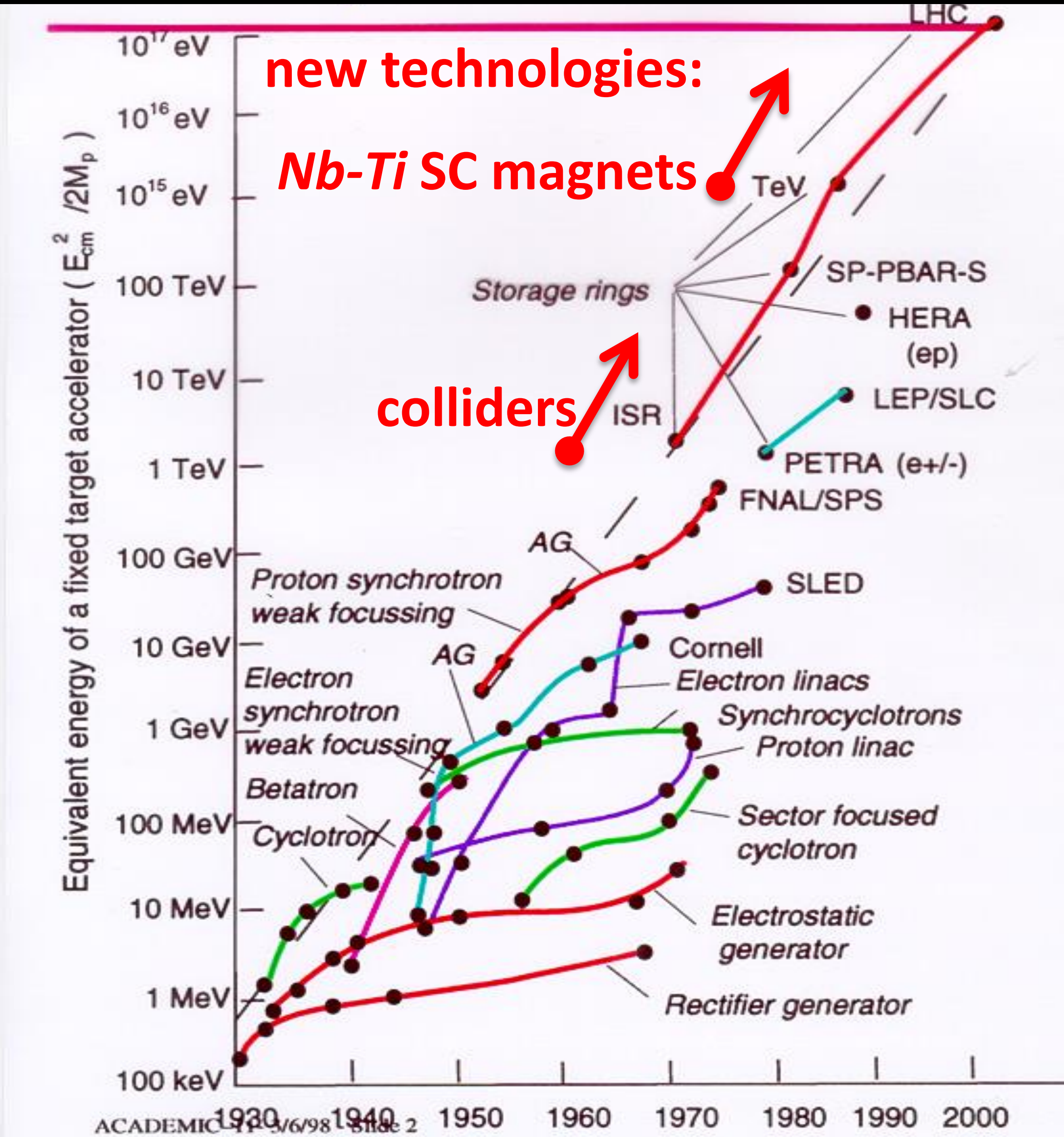
- quantum mechanics: de Broglie wavelength $\lambda = h/p$

  → examining matter at smaller distance requires higher momentum particles

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

  → high-energy collisions are needed to create these particles

evolution of beam energy over 70 years



repeated jumps from saturating to emerging technologies

storage rings have been the frontrunner technology for the last ~50 years

P. Lebrun

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

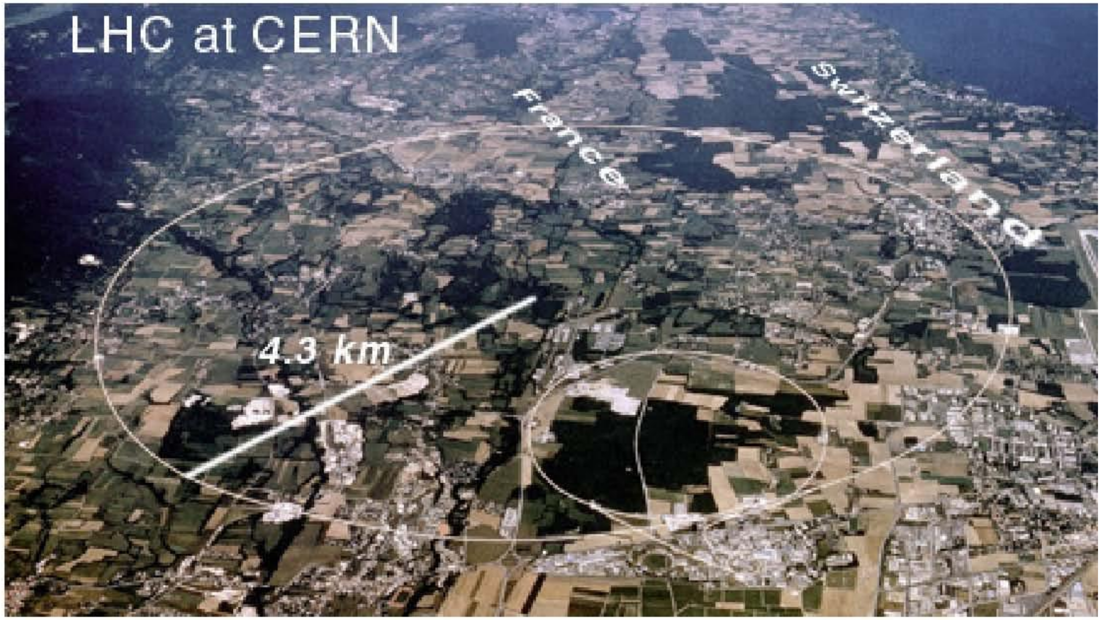
energy limits

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

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.

G. Hoffstaetter, USPAS2006

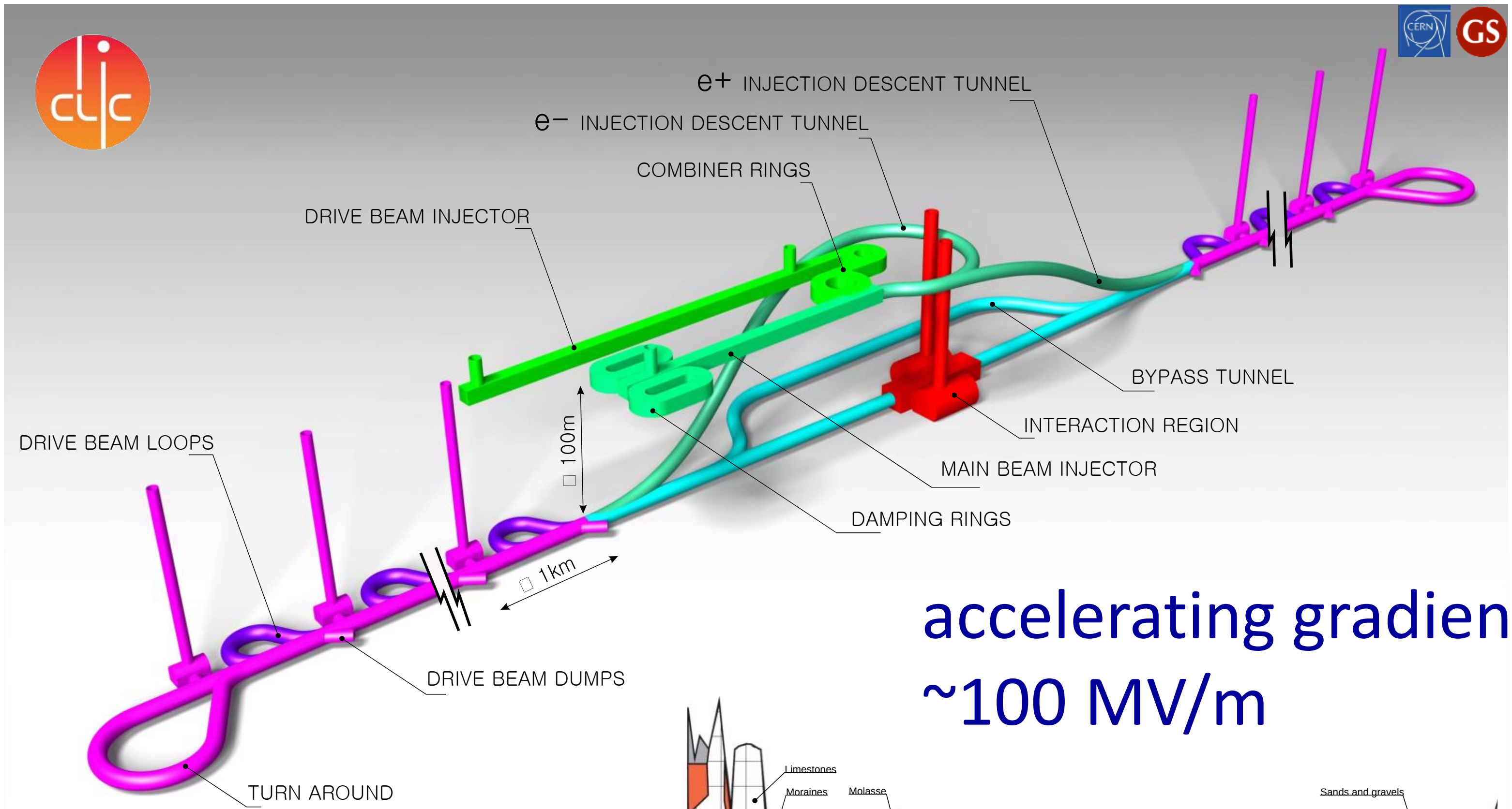
European Strategy Update 2013

*"CERN should undertake **design studies** for accelerator projects in a **global context**, with emphasis on proton-proton and electron-positron **high-energy frontier** machines."*

strategy adopted by CERN Council in 2013

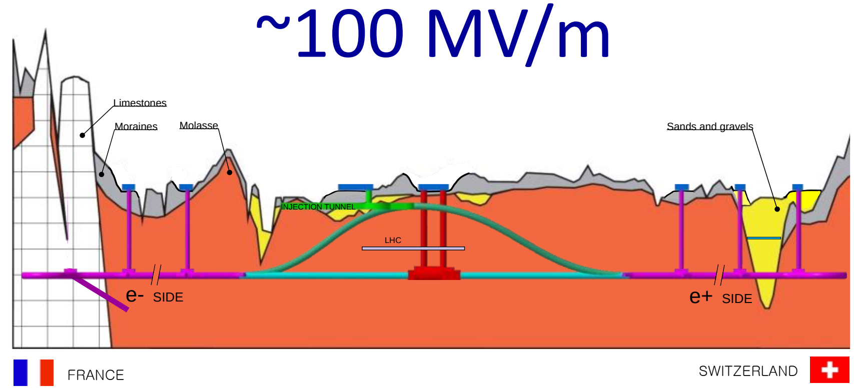
Compact Linear Collider (CLIC)

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



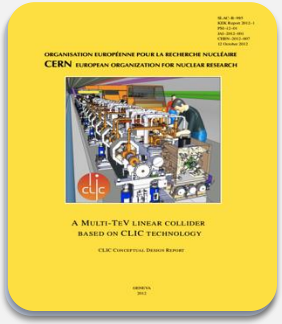
accelerating gradient

~100 MV/m



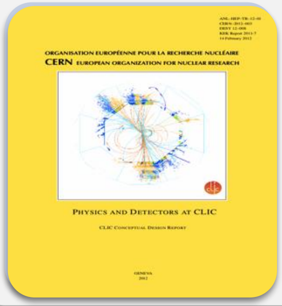
key technologies: 2-beam accel., drive-beam , X-band RF

CLIC Conceptual Design Report 2012



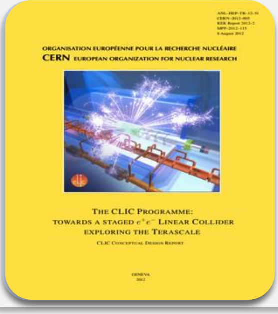
Vol 1: The CLIC accelerator and site facilities (H.Schmickler)

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- Complete, presented in SPC in March 2011, in print: https://edms.cern.ch/document/1234244/



Vol 2: Physics and detectors at CLIC (L.Linssen)

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- Completed and printed, presented in SPC in December 2011 http://arxiv.org/pdf/1202.5940v1



Vol 3: “CLIC study summary” (S.Stapnes)

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- Completed and printed, submitted for the European Strategy Open Meeting in September http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

~1400 authors, ~1200 pages

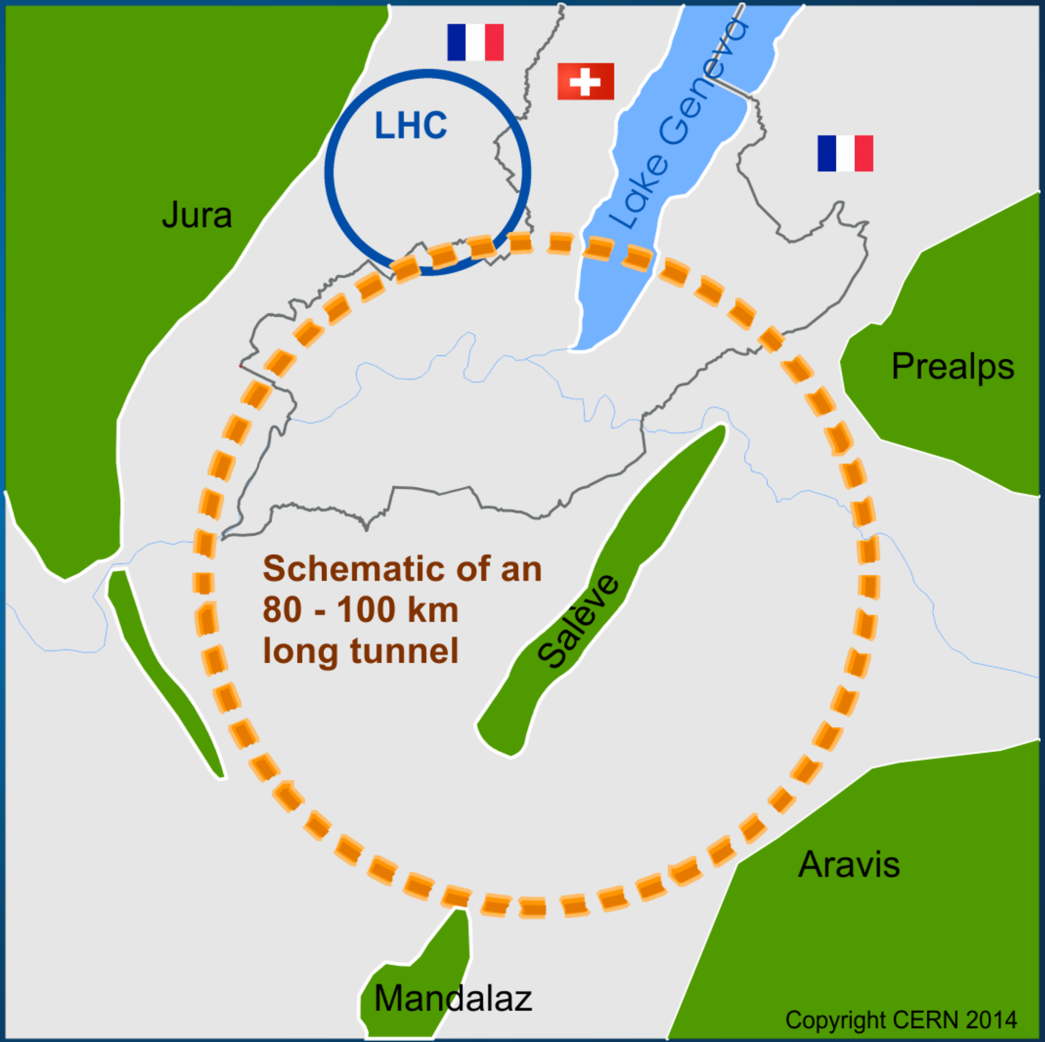
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

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

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

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



CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042

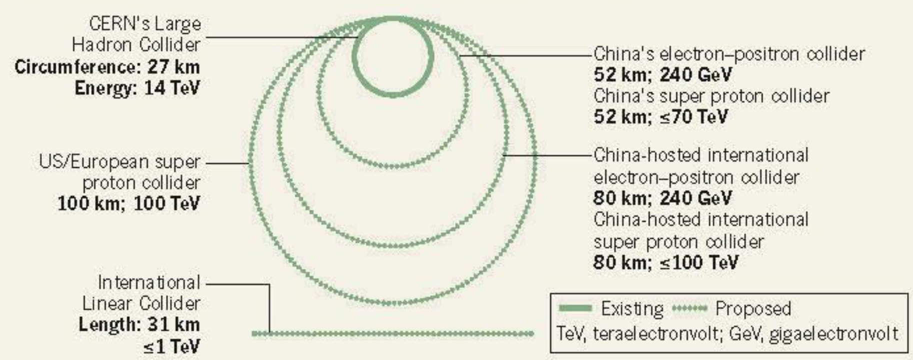
CepC/SppC project – recent news in *Nature*

24 J U LY 2014 | VO L 511 | NAT U R E | 3

IN FOCUS NEWS

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



PARTICLE PHYSICS

China plans super collider

Proposals for two accelerators could see country become collider capital of the world.

BY ELIZABETH GIBNEY

For decades, Europe and the United States have led the way when it comes to high-energy particle colliders. But a proposal by China that is quietly gathering momentum has raised the possibility that the country could soon position itself at the forefront of particle physics.

Scientists at the Institute of High Energy Physics (IHEP) in Beijing, working with international collaborators, are planning to build a 'Higgs factory' by 2028 — a 52-kilometre underground ring that would smash together electrons and positrons. Collisions of these fundamental particles would allow the Higgs China hopes that it would also be a stepping stone to a next-generation collider — a super proton–proton collider — in the same tunnel.

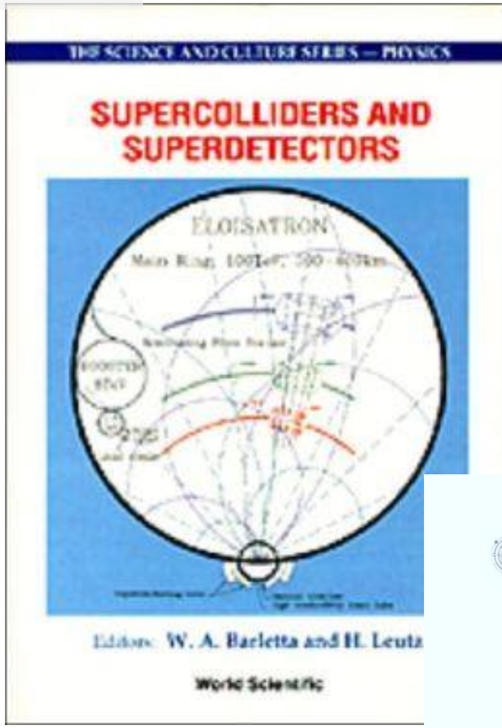
European and US teams have both shown interest in building their own super collider (see *Nature* **503**, 177; 2013), but the huge amount of research needed before such a machine could be built means that the earliest date either can aim for is 2035. China would like to build its electron–positron collider in the meantime, unaided by international funding if needs be, and follow it up as fast as technologically possible with the super proton collider. Because only one super collider is likely to be built, China's momentum puts it firmly in the driving seat.

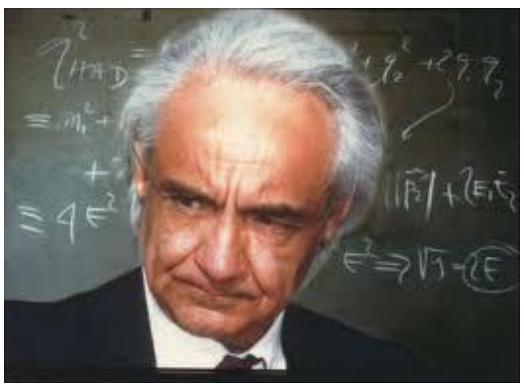
Electron–positron colliders and hadron colliders such as the LHC complement each other. Hadron colliders are sledgehammers, smashing together protons (a kind of hadron that comprises three fundamental particles called quarks) at high energies to see what emerges. Lower-energy electron–positron machines produce cleaner collisions that are easier to analyse, because they are already smashing together fundamental particles. By examining in detail the interactions of the Higgs boson with other particles, the proposed Chinese collider should, for example, be able to detect whether the Higgs is a simple particle or something more exotic. This would help physicists to work out whether the particle fits with

previous studies in Italy (ELOISATRON 300 km), US (SSC 87 km, VLHC/VLLC 233 km) & Japan (94 km)

ex. ELOISATRON

Supercolliders Superdetectors: Proceedings of the 19th and 25th Workshops of the INFN Eloisatron Project





ex. SSC


C.T. Murphy
SSC-SR-2020

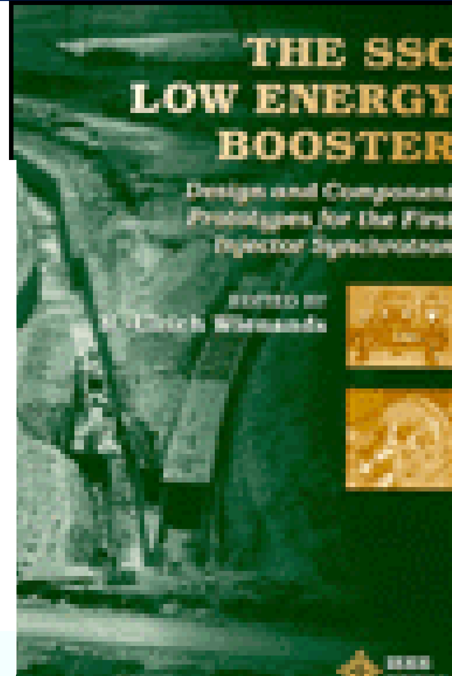
Conceptual Design of the Superconducting Super Collider

SSC Central Design Group*

March 1986

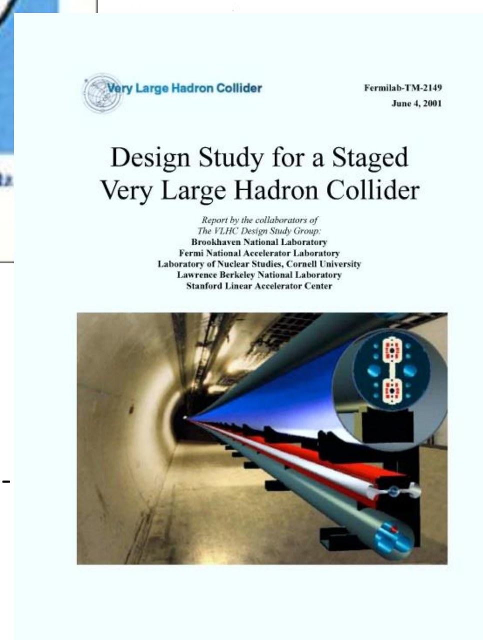
*Operated by Universities Research Association under contract with the U.S. Department of Energy

SSC CDR 1986



H. Ulrich Wienands, The SSC Low Energy Booster: Design and Component Prototypes for the First Injector Synchrotron, IEEE Press 1997

ex. VLHC


Very Large Hadron Collider

Fermilab-TM-2149
June 4, 2001

Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center

VLHC Design Study Group Collaboration **June 2001**. 271 pp. SLAC-R-591, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149

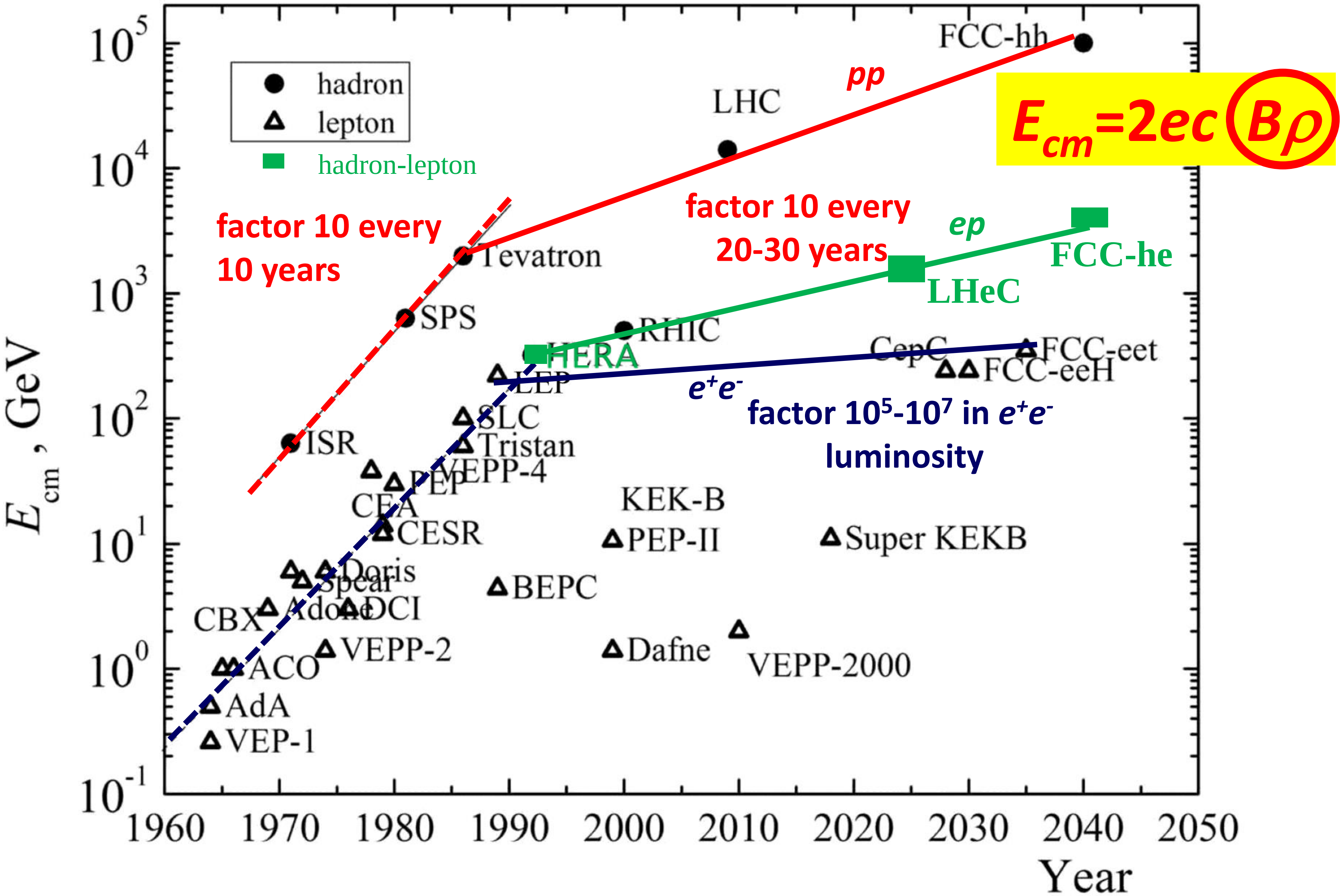
http://www.vlhc.org/

ex. TRISTAN-II

study 1983

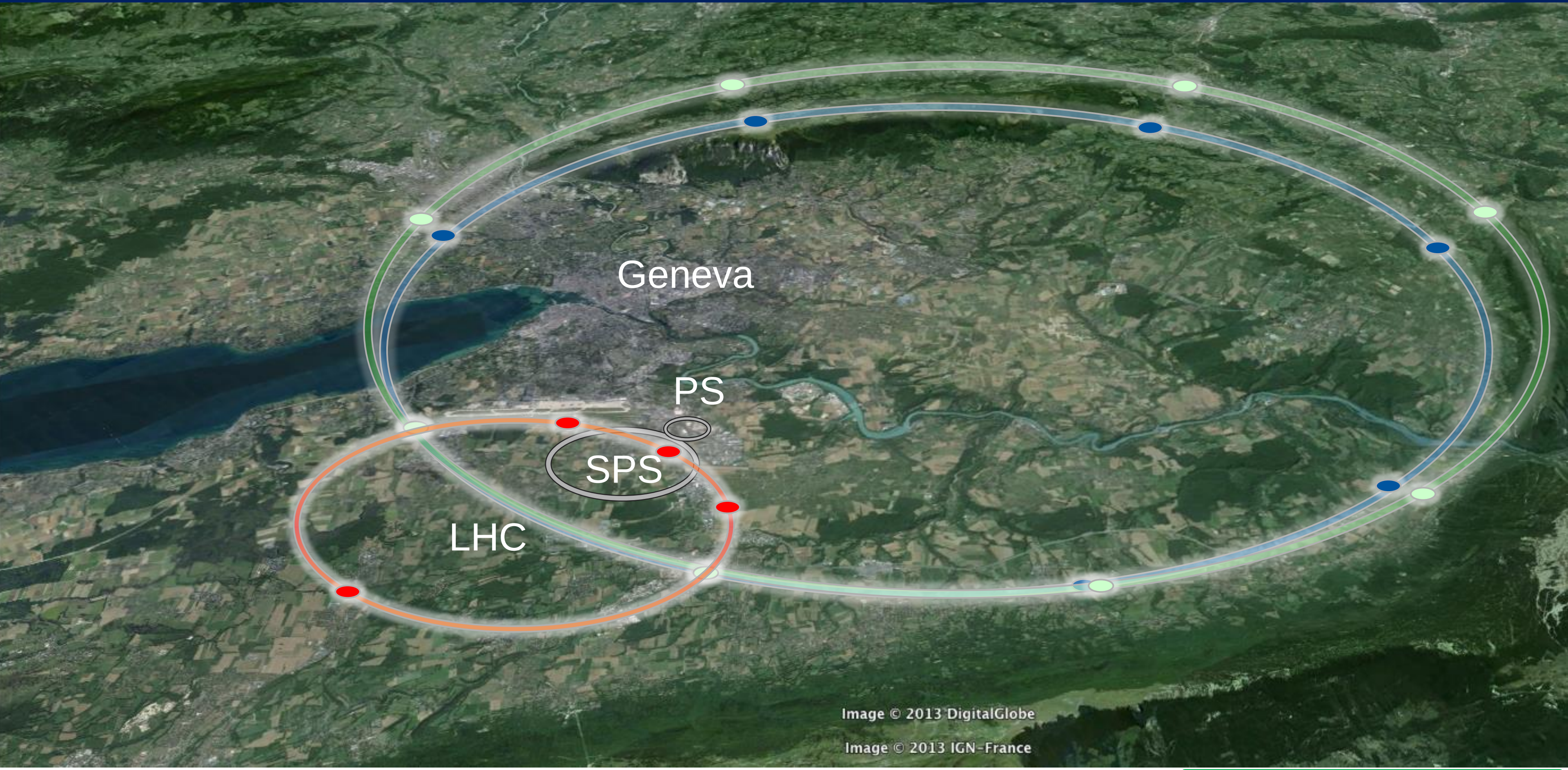
30 km diameter
94 km circumference
20 access shafts

collider c.m. energy vs. year



Courtesy V. Shiltsev

FCC-hh: 100 TeV *pp* collider



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

L. Bottura
B. Strauss

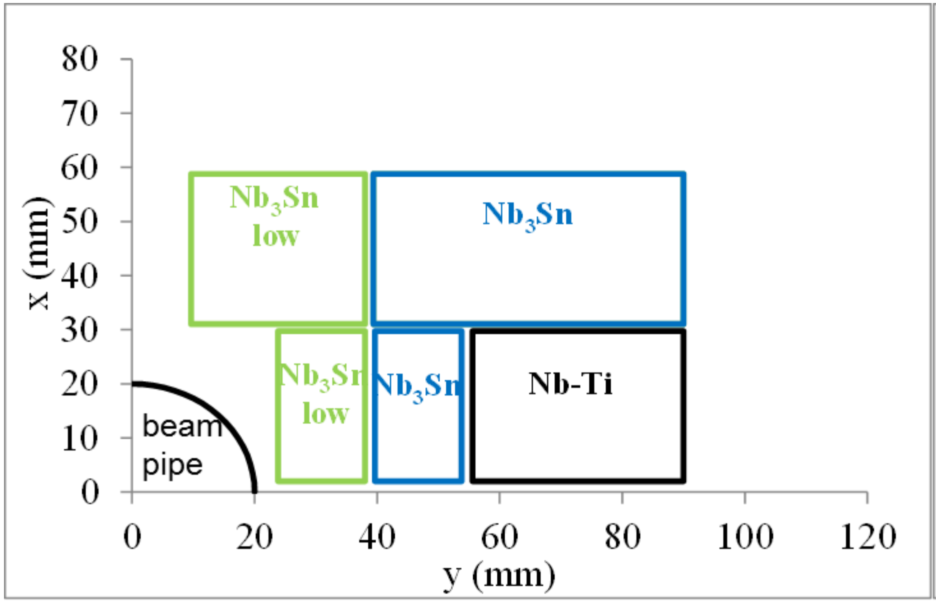
FCC kick-off meeting U. Geneva, Feb. 2014

≈350 participants

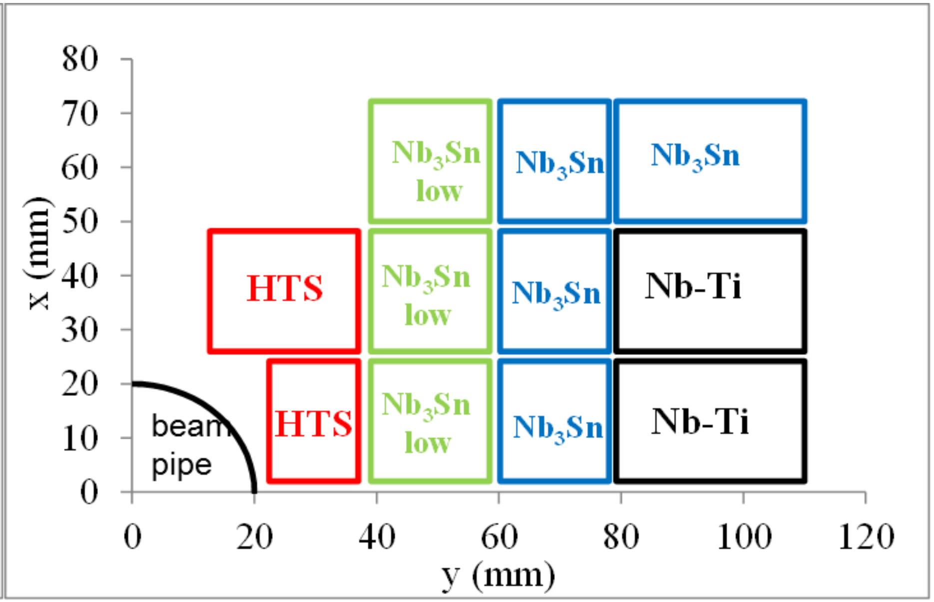

SPIEGEL ONLINE
YAHOO! JAPAN ニュース
INDIA Science
BBC NEWS
SCIENCE & ENVIRONMENT
18 February 2014 Last updated at 21:24 GMT
Cern considers building huge physics machine
By Roland Pease
Science writer
The possibility of building an underground "atom-smasher" four times the size of the Large Hadron Collider is to be explored by experts.
The decision follows a high level meeting of scientists this week in Geneva, near the European particle physics centre, Cern.
【AFP＝時事】欧州合同原子核研究所（European Organisation for Nuclear Research、CERN）は6日、「神の粒子」とも呼ばれる有名なヒッグス粒子（Higgs Boson）を発見した加速器の7倍の出力を持つ粒子衝突型円形加速器の建設を視野に入れていると発表した。
■衝突エネルギーは100兆電子ボルト前後に
FCCはおそらくLHCと同じ区域内に設置される
込まれるかもしれない、とCERNは声明で述べ
Sport
Property
Edward Snowden
H7N9 avi
powerful collider
Freitag, 14. Februar 2014
Frankfurter Allgemeine
Wissen
THEMEN BLOGS ARCHIV MEIN FAZ.NET
Lebensstil Technik & Motor
Sciences
SCIENCES Vidéos Archéologie Biologie Cosmos Géologie Mathématiques Médecine
ÉDITION ABONNÉS
Discussions sur un nouvel accélérateur de particules géant
great interest & fascination around the world!

cost-optimized high-field dipole magnets

15-16 T: *Nb-Ti* & *Nb_3Sn*



20 T: *Nb-Ti* & *Nb_3Sn* & *HTS*



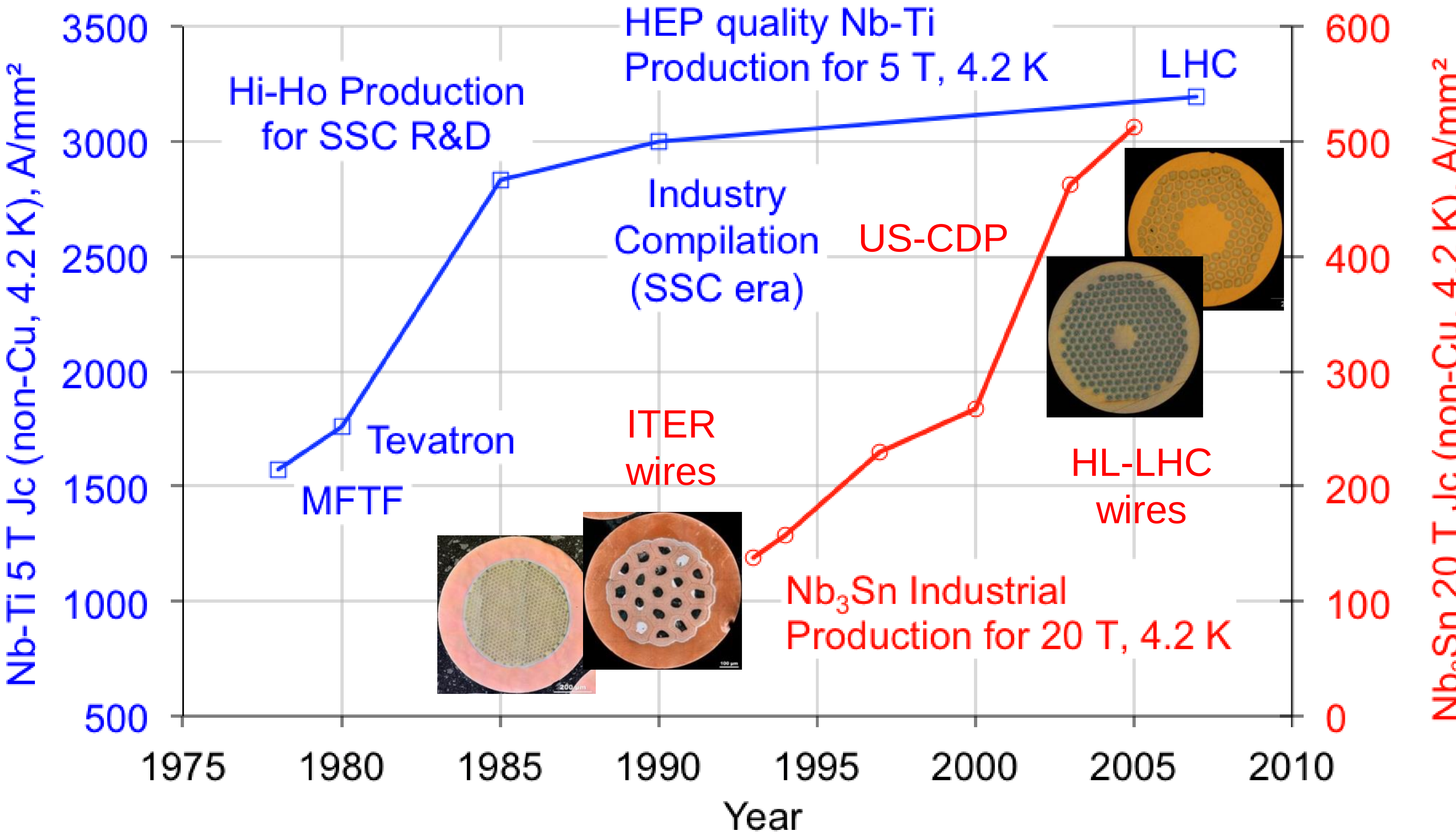
only a quarter is shown

"hybrid magnets"

example block-coil layout

L. Rossi, E. Todesco, P. McIntyre

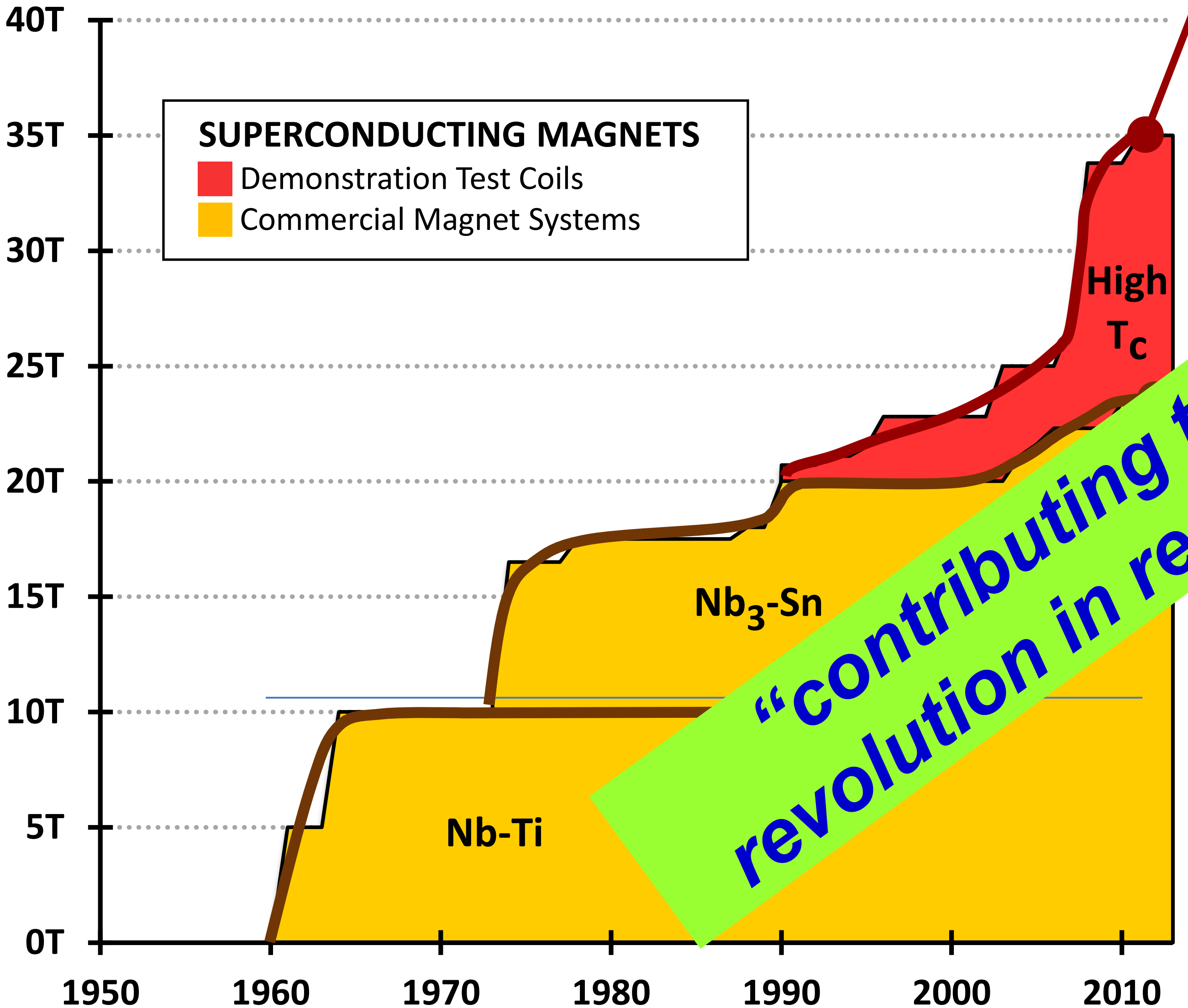
Nb_3Sn vs *Nb-Ti* SC wire production



B. Strauss, data by courtesy of J. Parrell (US DOE OST)

superconducting magnet technology

SC solenoid magnets (dipoles to follow)



35 T Proof-of-Principle Demo

(4T HTS Test Coil in a 31T Background Magnetic Field)

ϕ 39 mm

23.5 T (1GHz NMR) Nb_3-Sn Superconducting Magnets

(Manufactured Commercially)

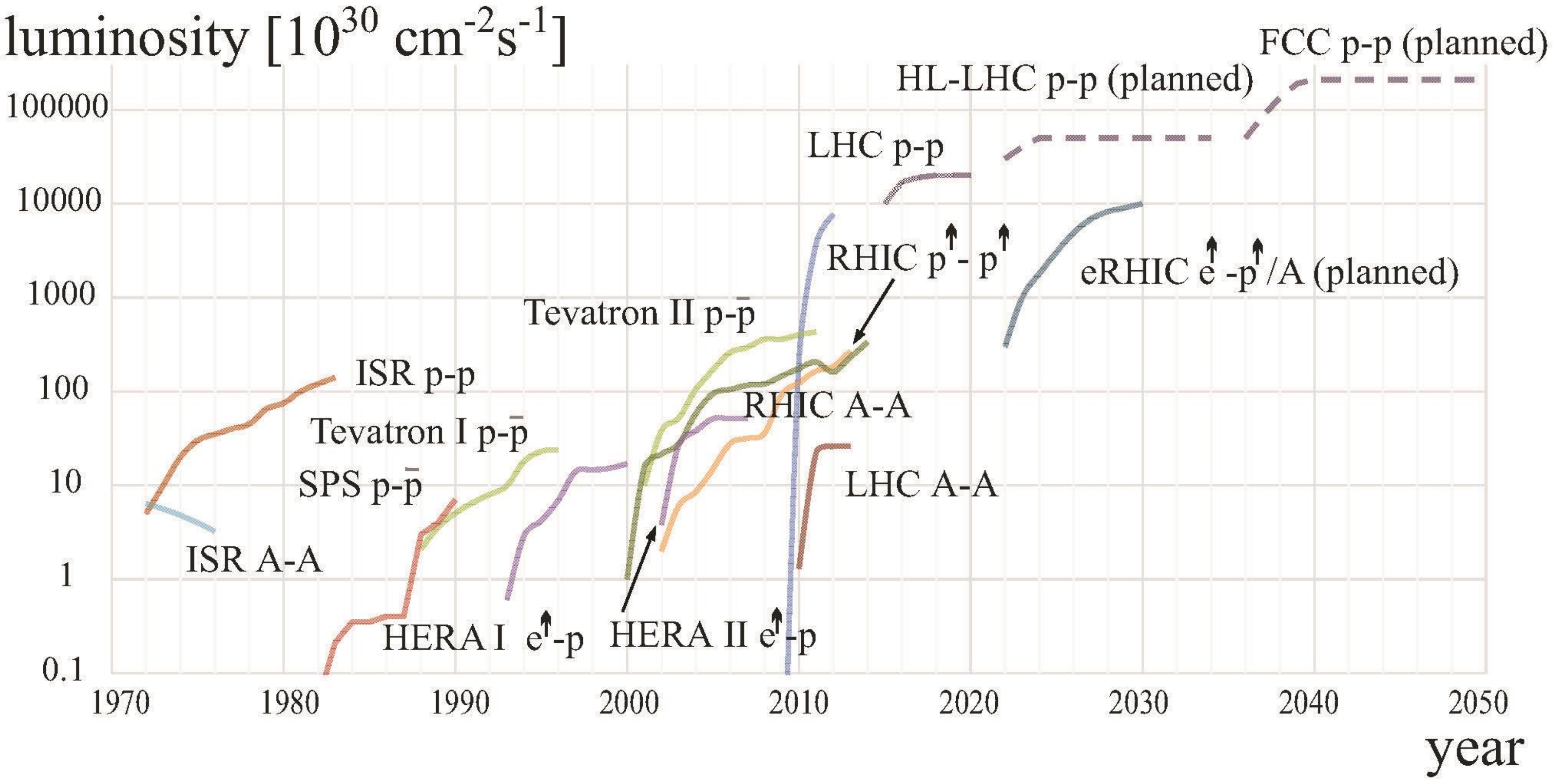
G. Boebinger, NHMFL

magnet R&D - possible spin offs & synergies

example : electric power transmission using HTS cables

„Pilotstrecke AmpaCity: zum ersten Mal wird mitten in einer Großstadt (Essen) ein Supraleiter (HTS: BSSCO) für den Stromtransport in ein existierendes Stromnetz eingebunden.“

hadron-collider peak luminosity vs. year



Courtesy W. Fischer

LHC run 1 (2012-13) accumulated more integrated luminosity than all previous hadron colliders together!

machine protection

energy per proton beam

LHC: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)

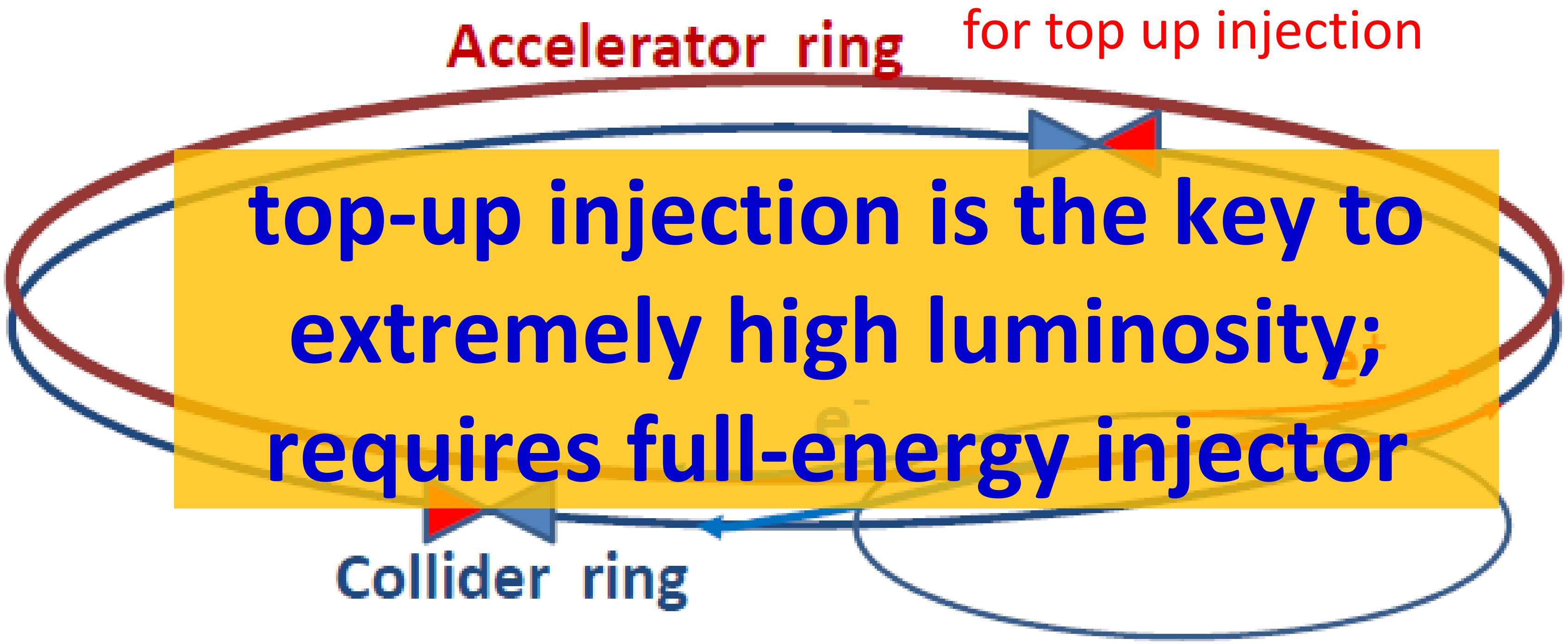
– kinetic energy of Airbus A380 at 720 km/h

– can melt 12 tons of copper, or drill a 300-m long hole

FCC-ee: e^+e^- collider up to 350 (500) GeV

circumference ≈100 km

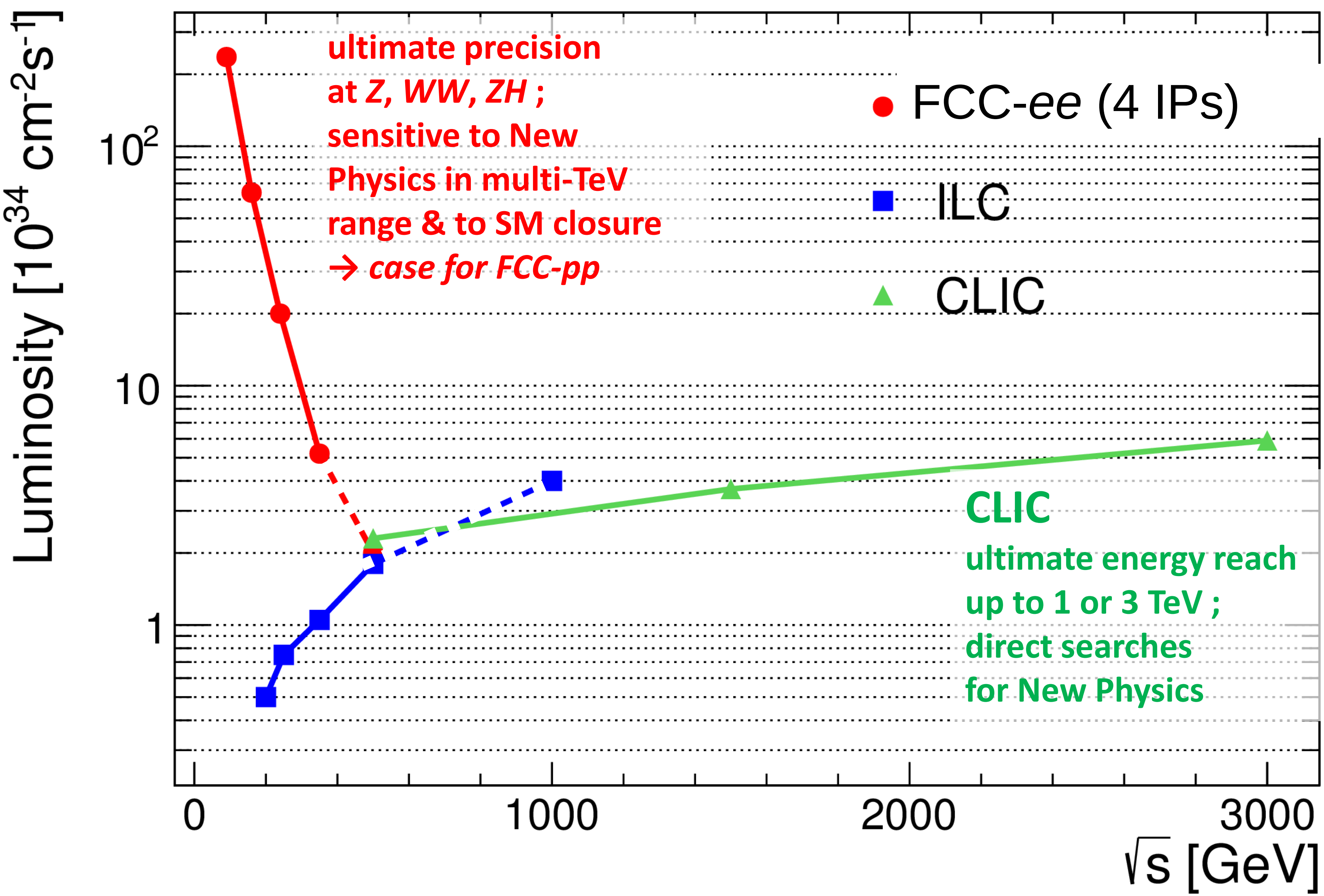
A. Blondel



top-up injection is the key to extremely high luminosity; requires full-energy injector

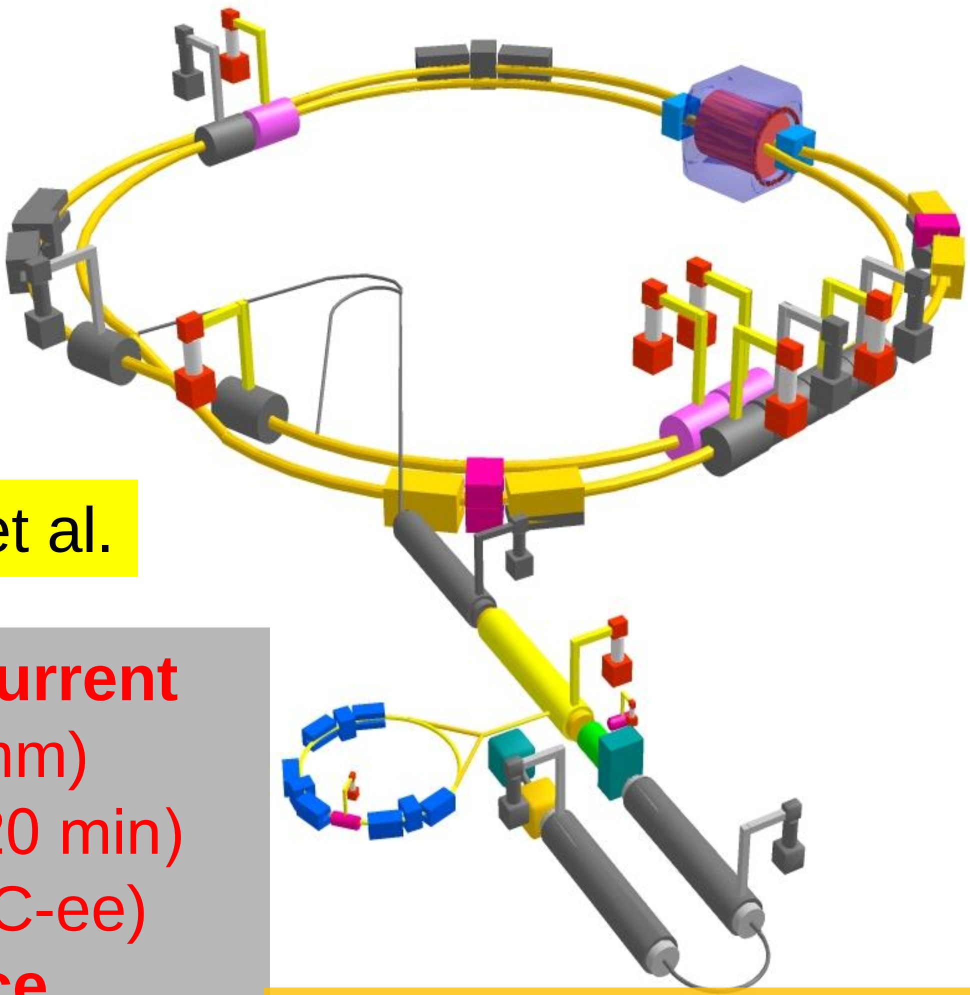
short beam lifetime (~τ_{LEP2}/40) due to high luminosity **supported by top-up injection** (used at KEKB, PEP-II, SLS,…); top-up **also avoids ramping & thermal transients, + eases tuning**

e^+e^- luminosity vs energy



SuperKEKB = *FCC-ee* demonstrator

beam commissioning will start in 2015



K. Oide et al.

top up injection at high current
β_y* =300 μm (FCC-ee: 1 mm)
lifetime 5 min (FCC-ee: ≥20 min)
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)
off momentum acceptance (±1.5%, similar to FCC-ee)
e^+ production rate (2.5x10^{12}/s, FCC-ee: <1.5x10^{12}/s (*Z*

SuperKEKB goes beyond *FCC-ee*, testing all concepts

vertical rms IP spot size

collider / test facility	$\sigma_y{}^*$ [nm]
LEP2	3500
KEKB	940
SLC	700
ATF2, FFTB	45 (*37*), 77
SuperKEKB	***50***
FCC-ee-H	***44***
ILC	*5 – 8*
CLIC	*1 – 2*

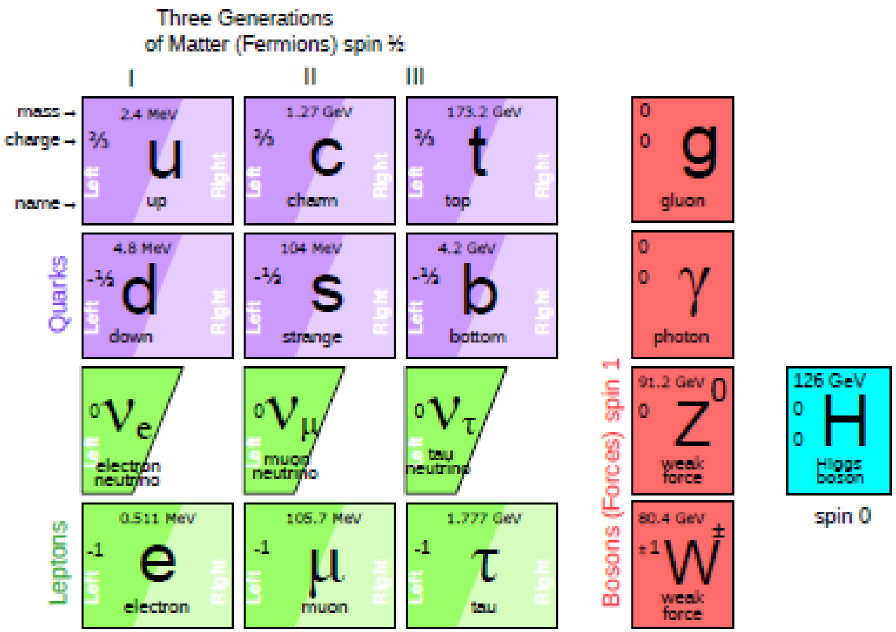
in regular font: achieved

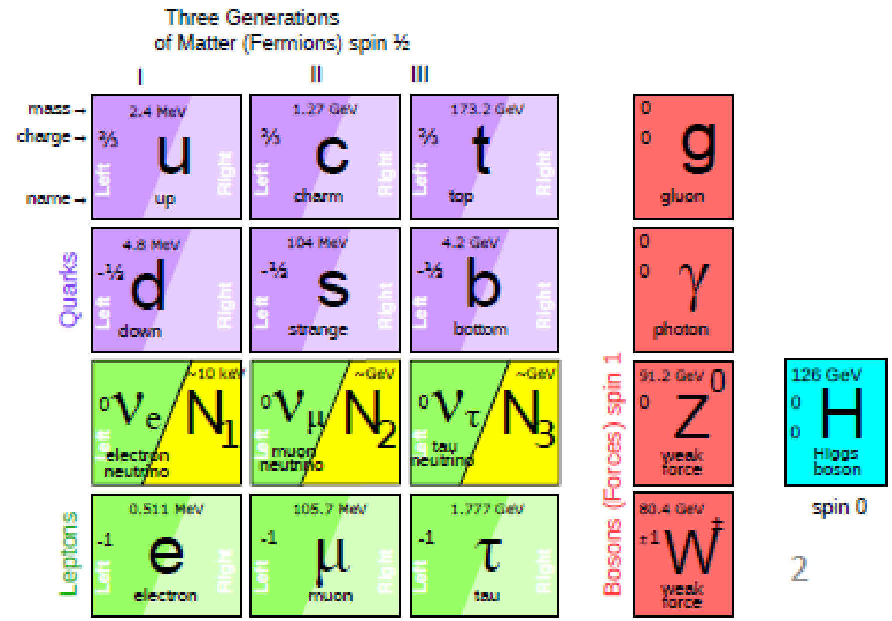
in italics: design values

$\beta_y{}^*$:
5 cm→
1 mm
ε_y:
250 pm→
2 pm

“at least 3 pieces are still missing”

A. Blondel, *The Hunt for Heavy Neutrinos at the Z & H factory*, ICHEP’14





neutrinos have mass...

and this very probably implies new degrees of freedom

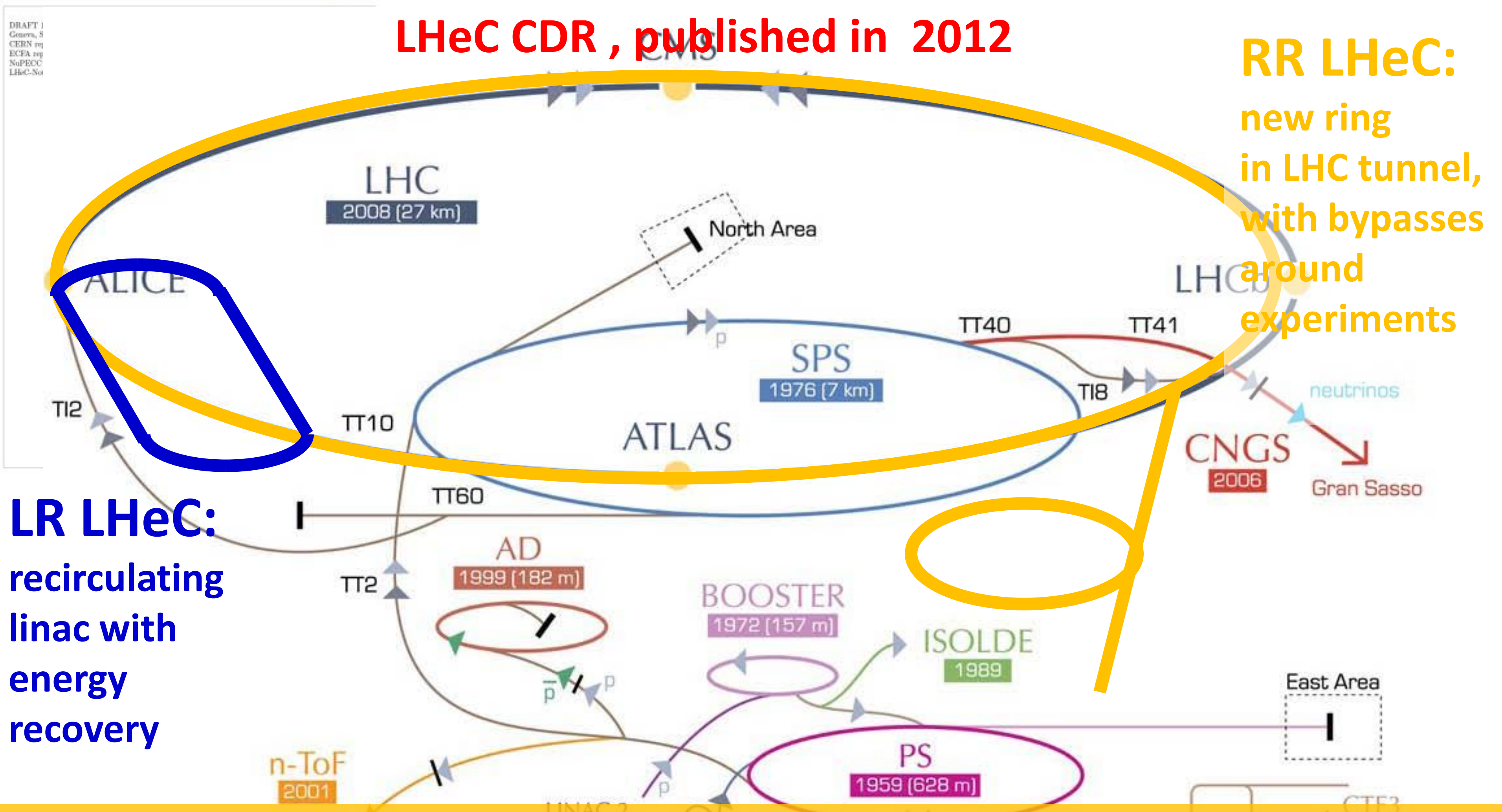
➔ **Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos**

completely unknown masses (meV to ZeV), nearly impossible to find.

.... but could perhaps explain all: DM, BAU, ν-masses

These would lead to spectacular ‘detached vertex’ signatures in Z-> neutrino decays at a Tera-Z factory like FCC-ee

FCC-he: high-energy lepton-hadron collider

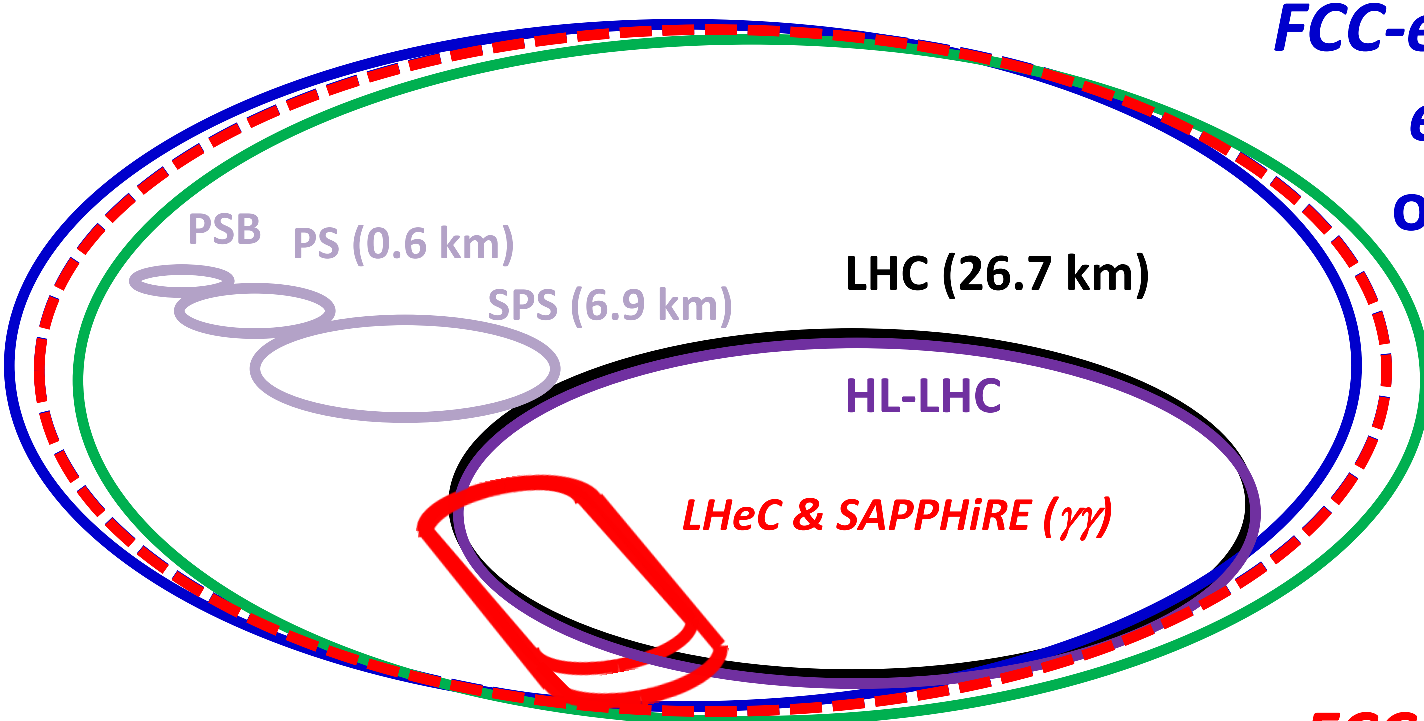


similar two options for *FCC*:
(1) *FCC-ee* ring, (2) ERL – from *LHeC* or new

possible evolution of FCC complex

FCC-ee **(80-100 km, e^+e^-, up to 350 or 500 GeV c.m.)**

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



LHeC as FCC-ee injector?

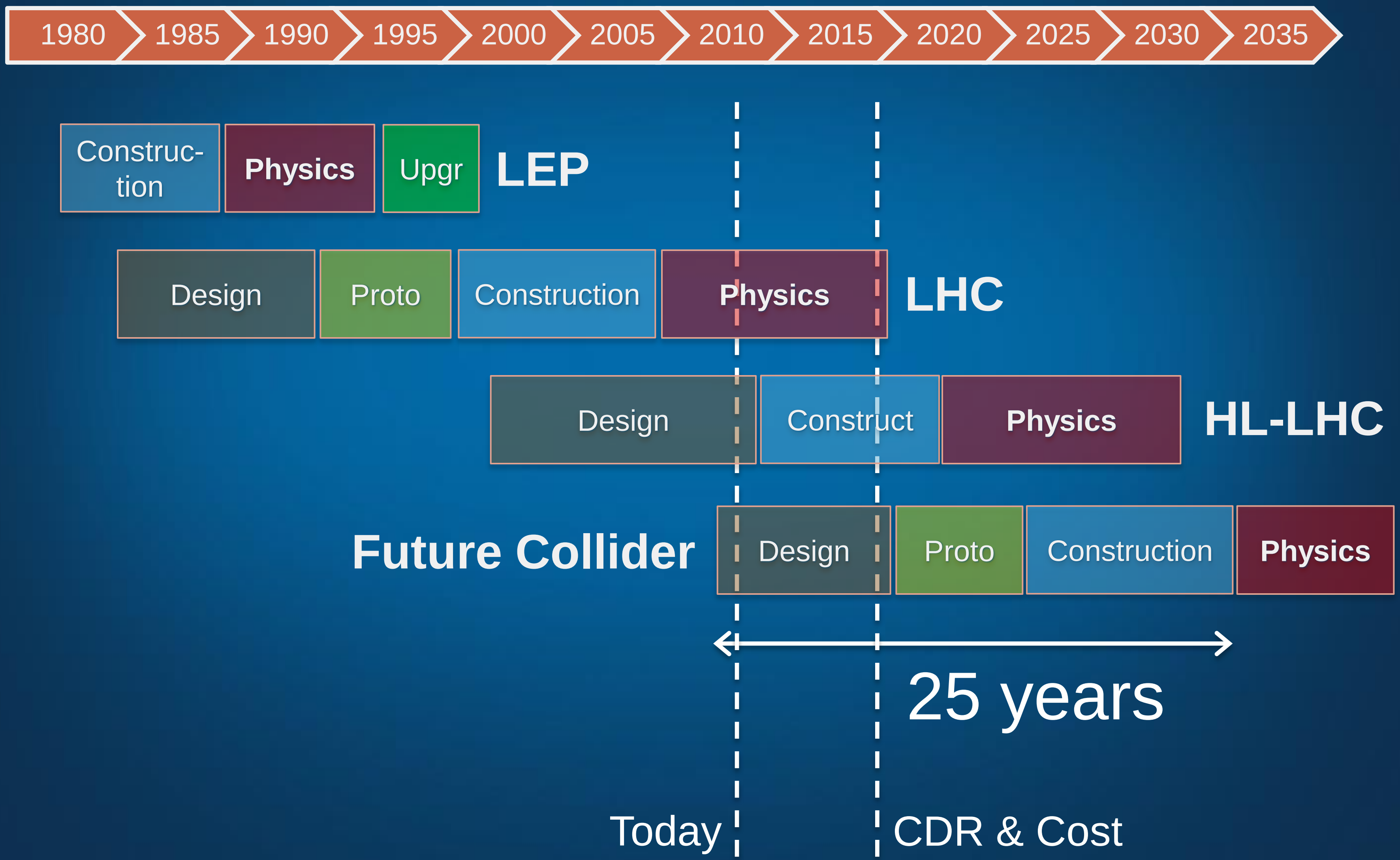
FCC-he **as ring-ring collider ?!**

LHeC-based FCC-he collider?!

FCC-he: $e^{\pm}$ (60-250 GeV) – *p*(50 TeV)/A collisions

≥50 years e^+e^-, *pp*, $e^{\pm}p/A$ physics at highest energies

HEP Timescale



is history repeating itself…?

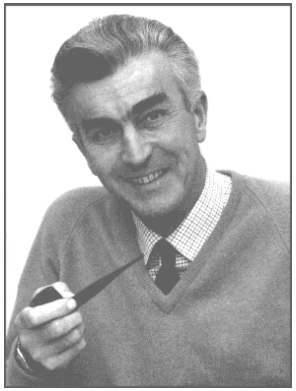
When **Lady Margaret Thatcher** visited CERN in 1982, she also asked the then CERN Director-General **Herwig Schopper** ***how big the next tunnel after LEP would be.***

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.

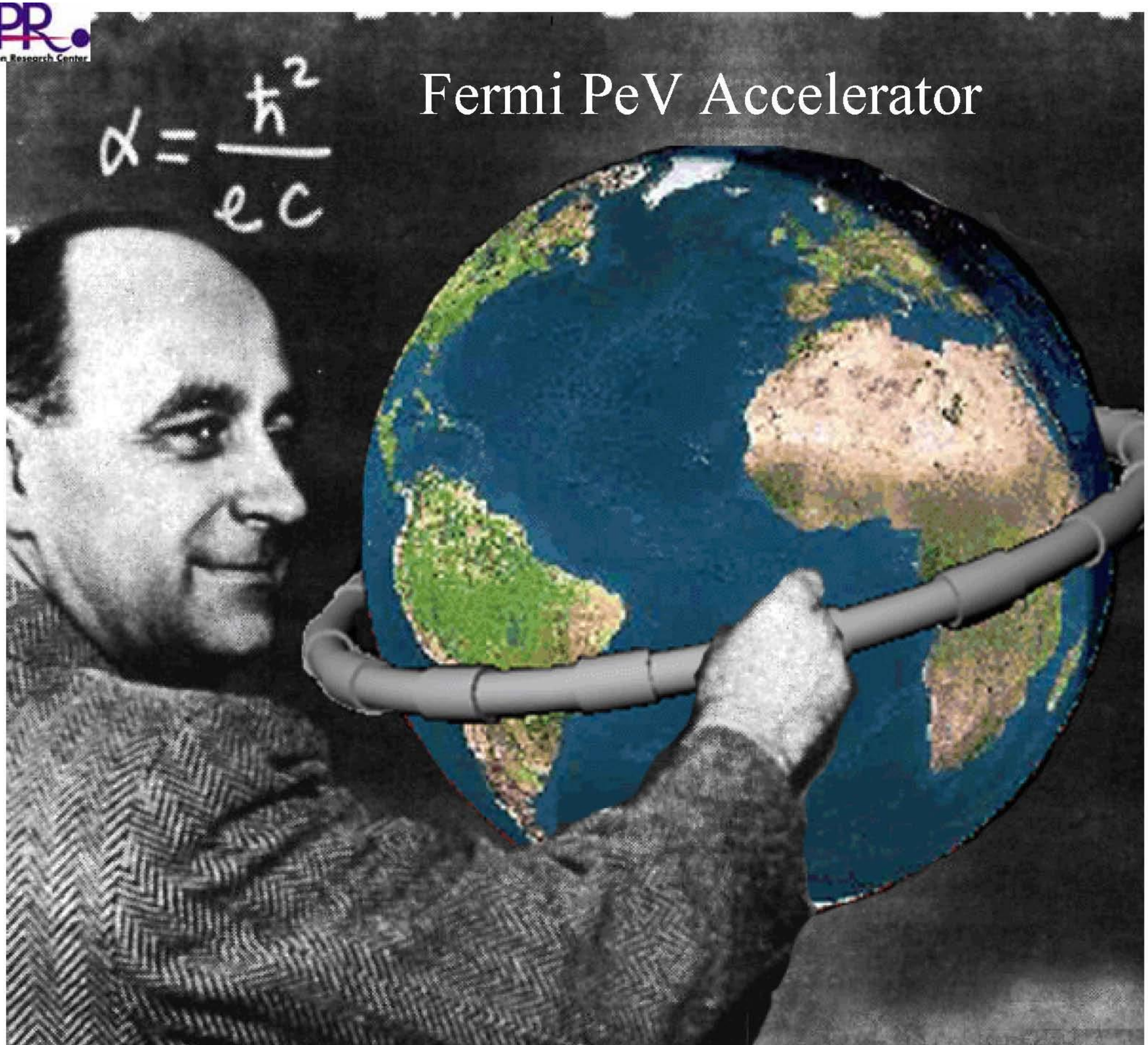


John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

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

The Economist

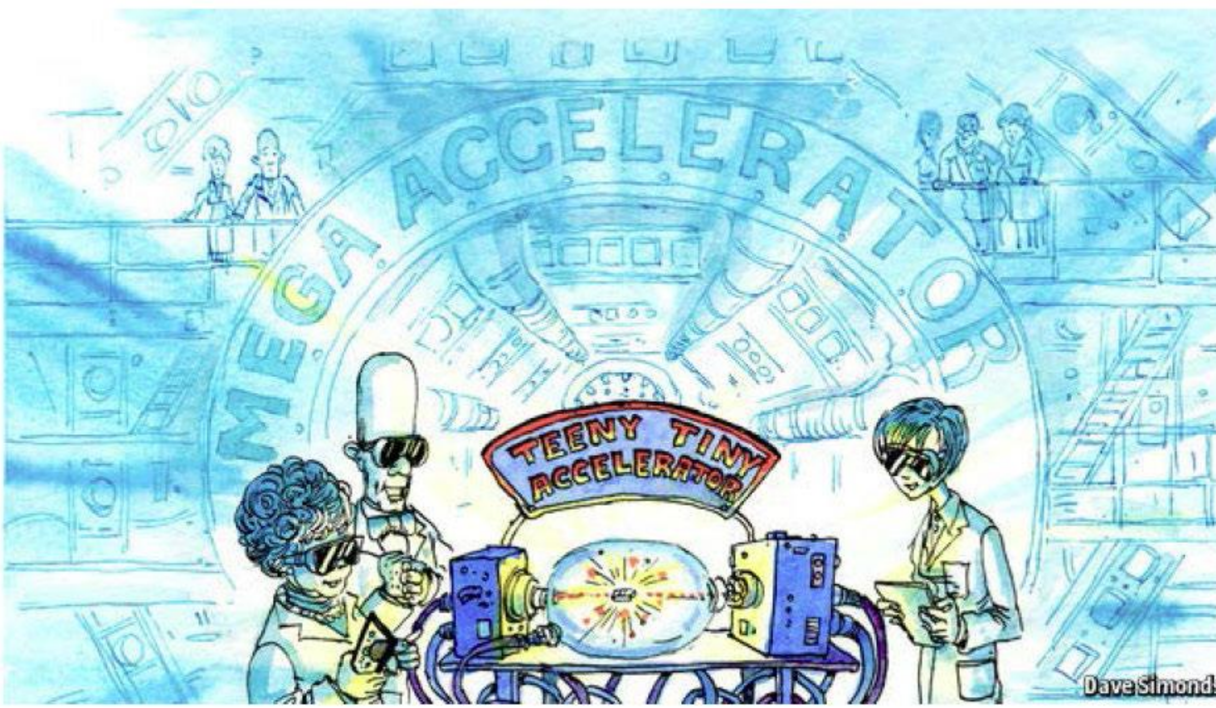
Particle accelerators

Small really is beautiful

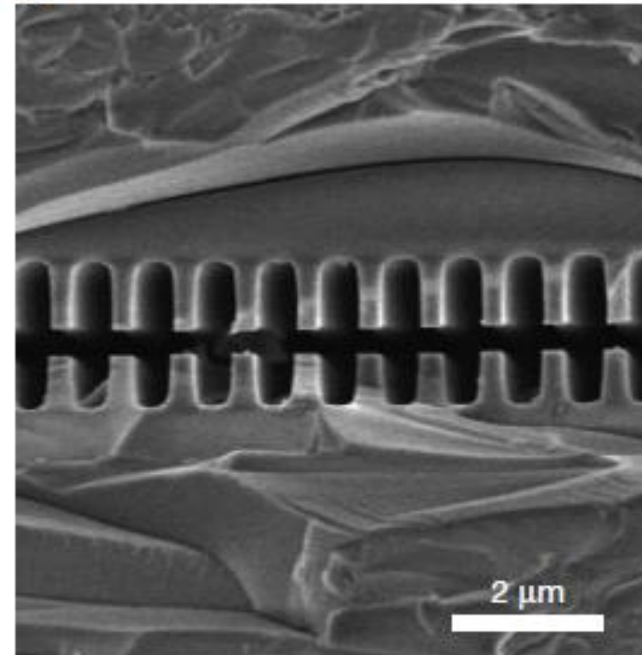
Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically

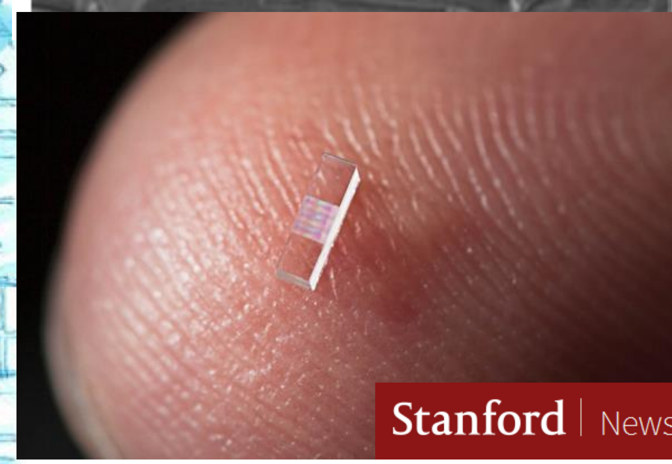
Oct 19th 2013 | From the print edition

Timekeeper Tweet 56



a

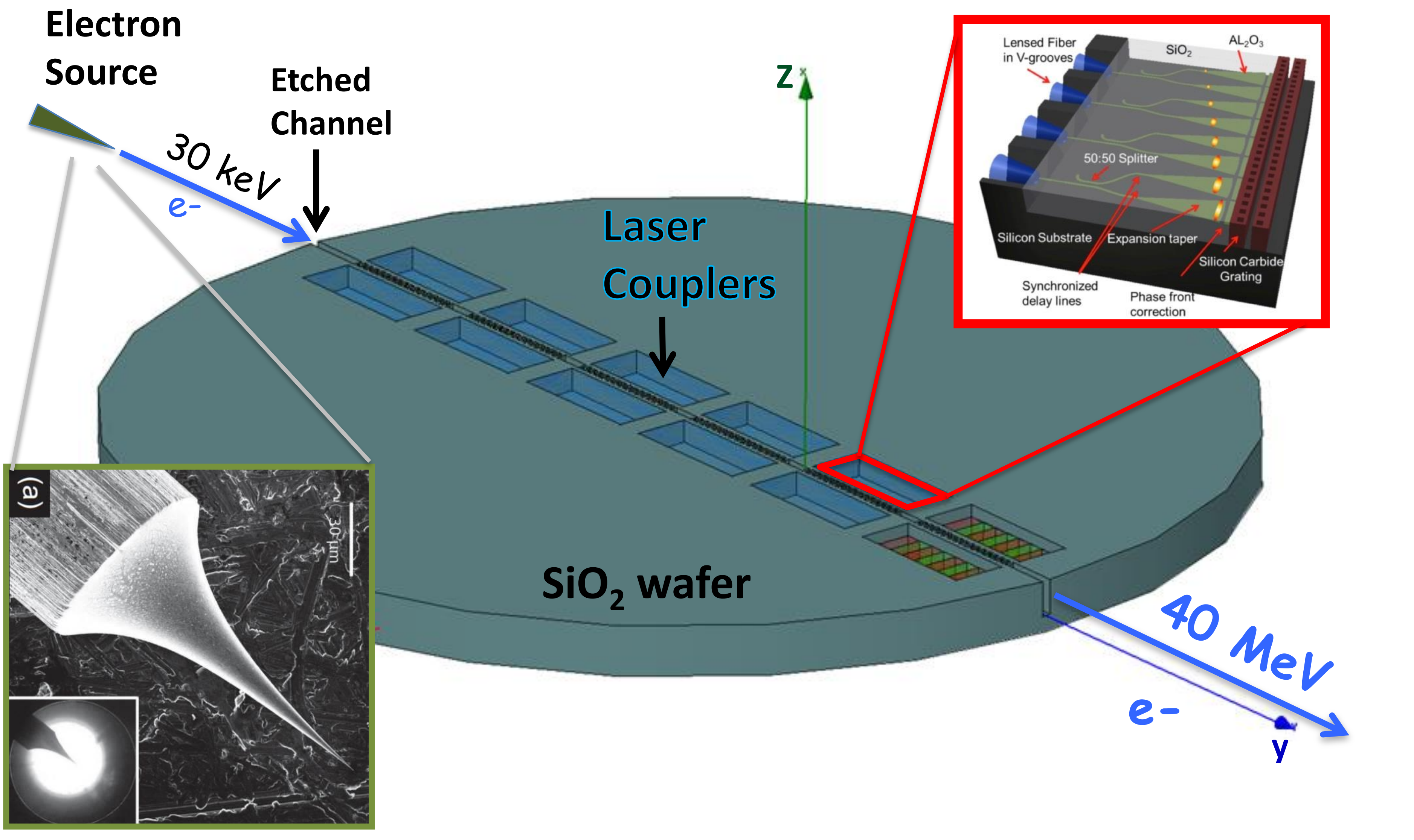




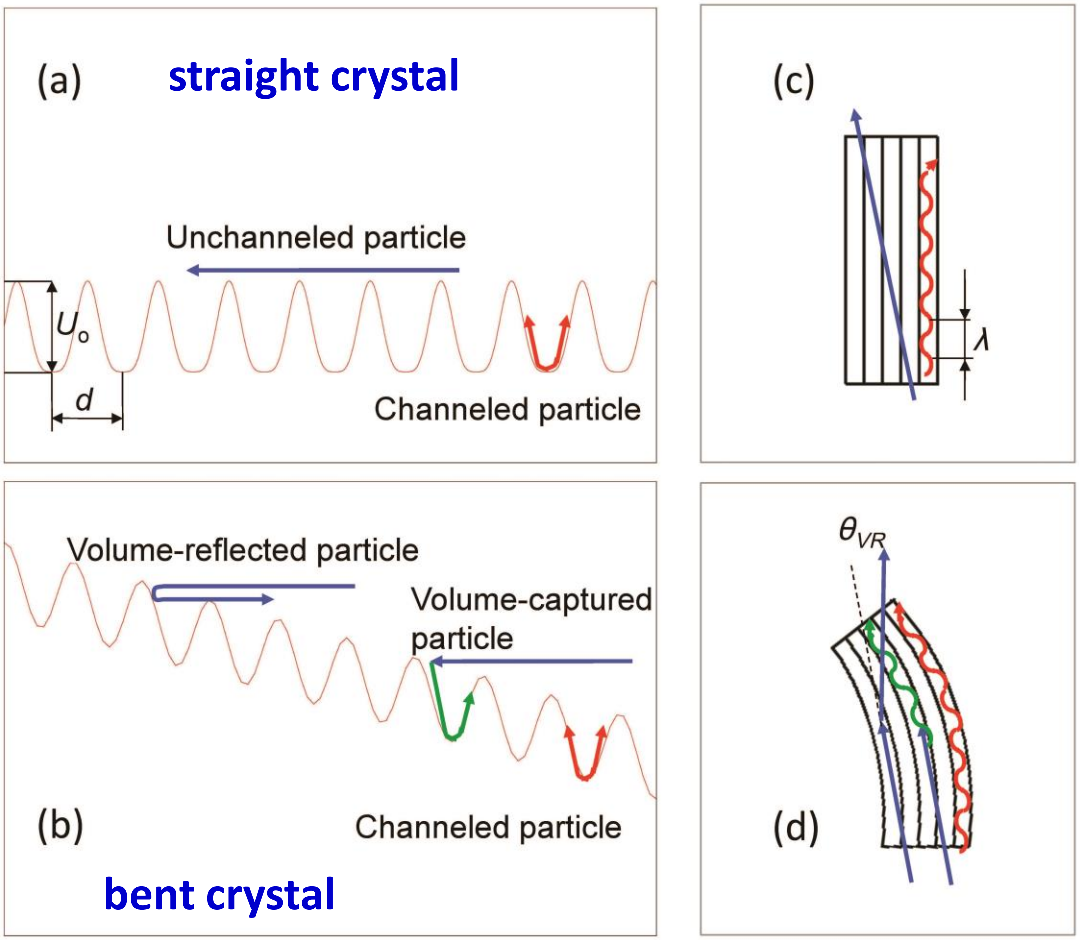
Nature **503**, 91–94 (07 November 2013)

V. Shiltsev

multi-MeV (XFEL) device on wafer in 5-10 years



another possibility – crystals: world's strongest magnets



crystal focusing strength

ϕ~20-60 eV/Å^2

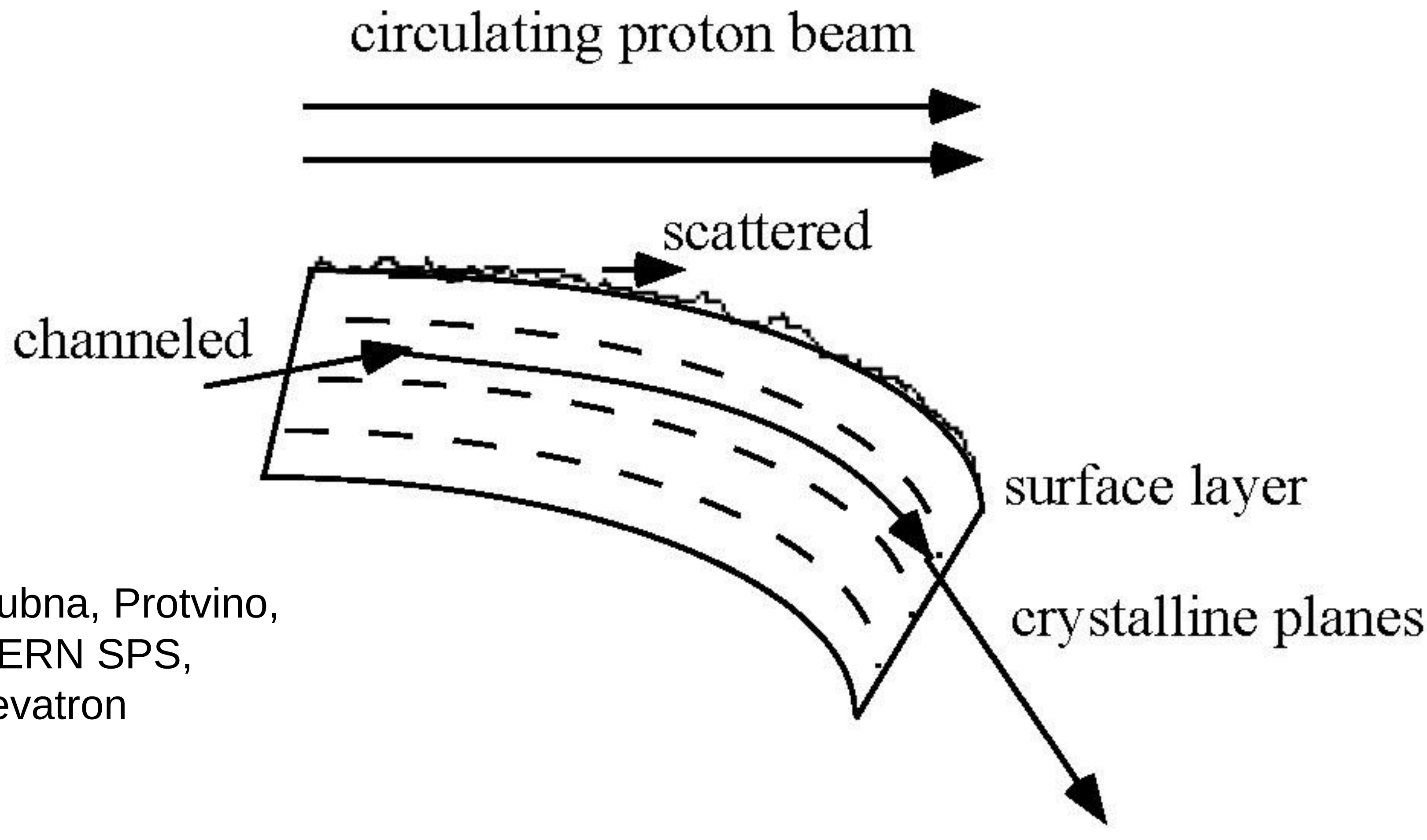
B_{max}≈2000 T !

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

W. Scandale, MPL A (2012)

S.A. Bogacz, D. Cline, 1997

crystal extraction from stored proton/ion beam

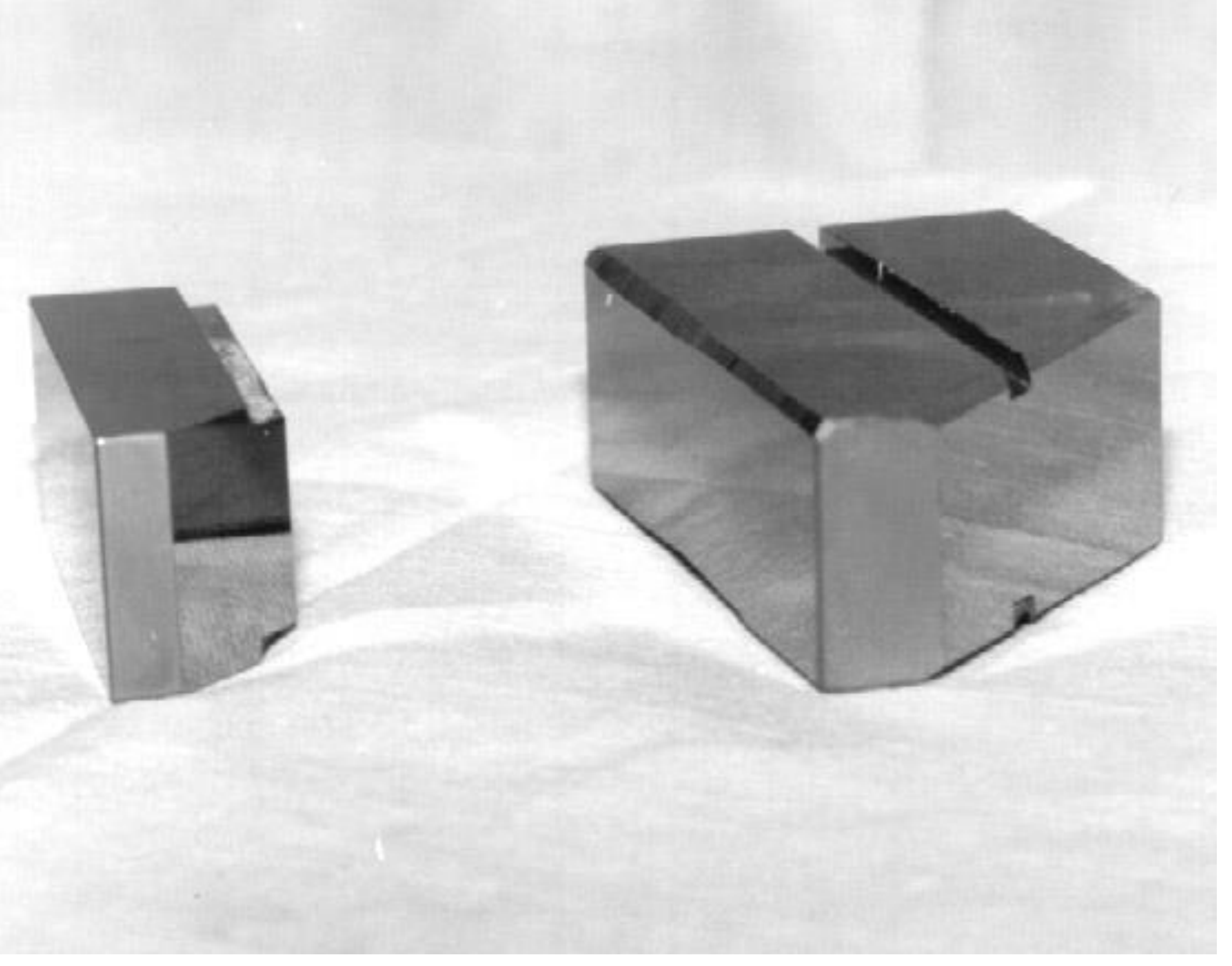


Dubna, Protvino,
CERN SPS,
Tevatron

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

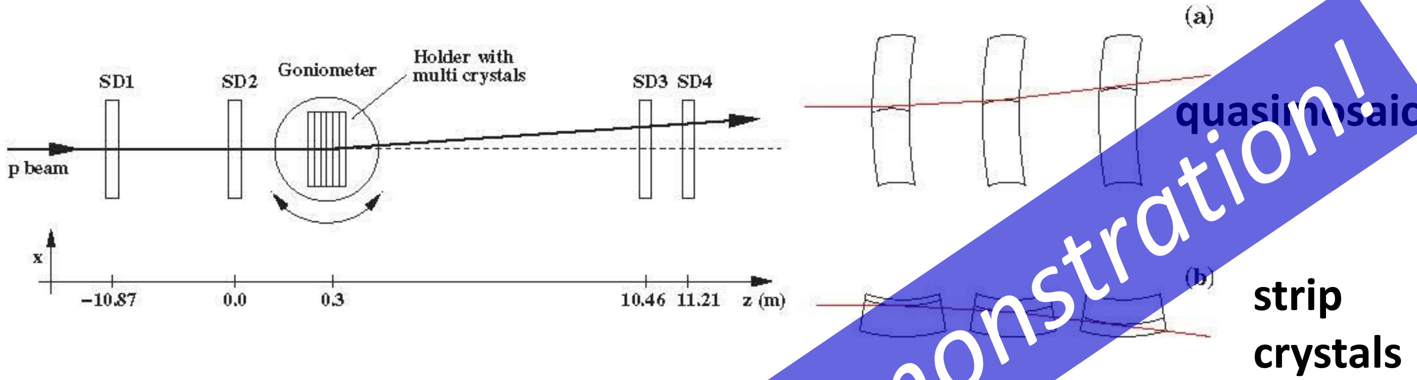
can they also be used for a circular collider?!

samples of focusing crystals

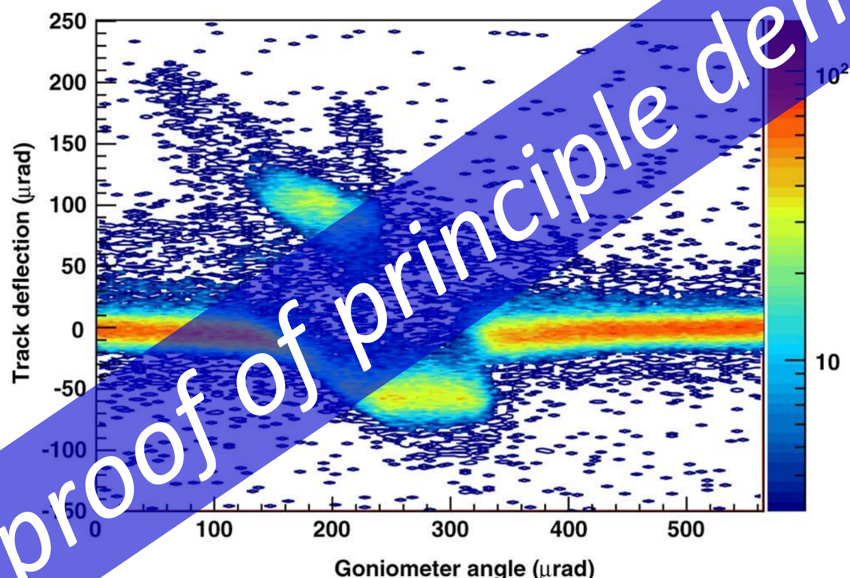


Yuri M.Ivanov, Petersburg Nuclear Physics Institute, 2005

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

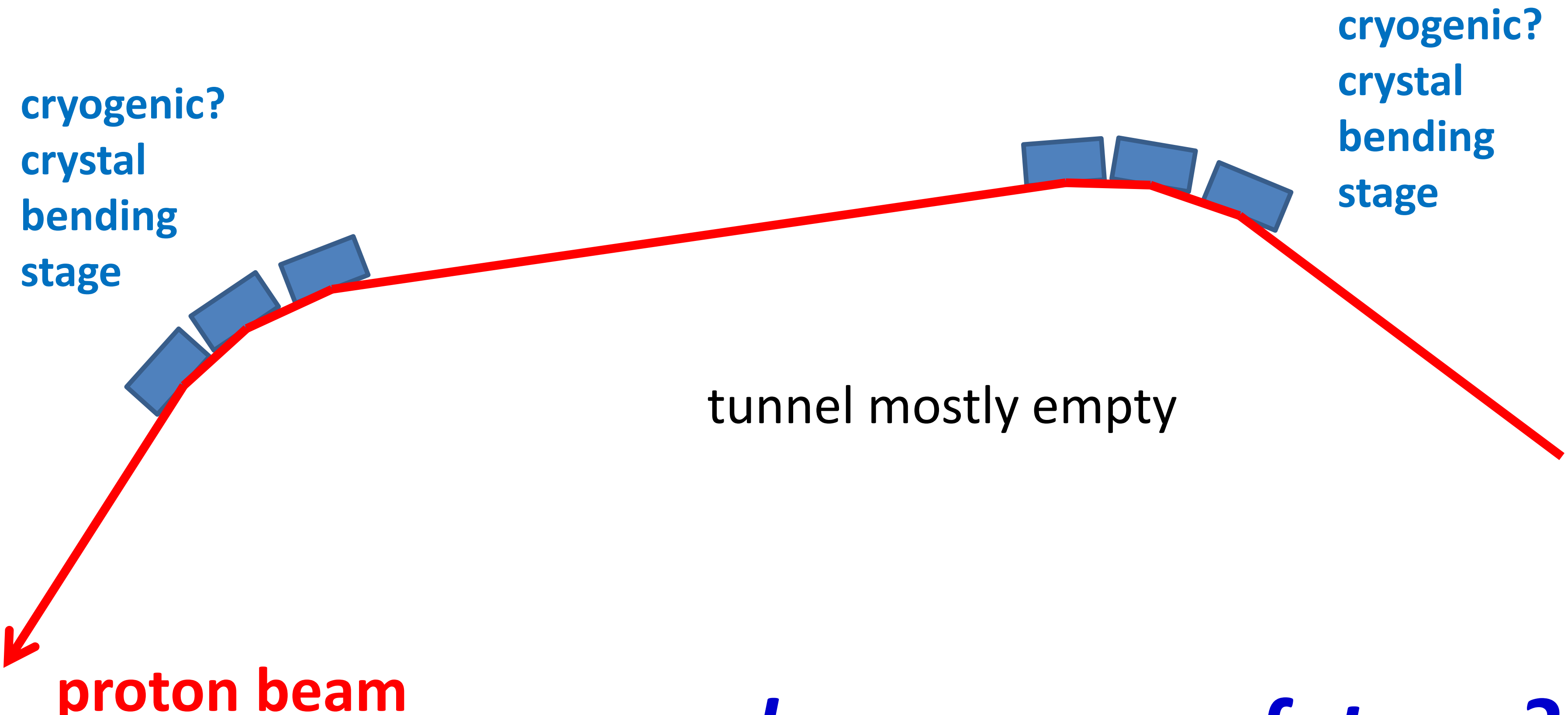


proof of principle demonstration!

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

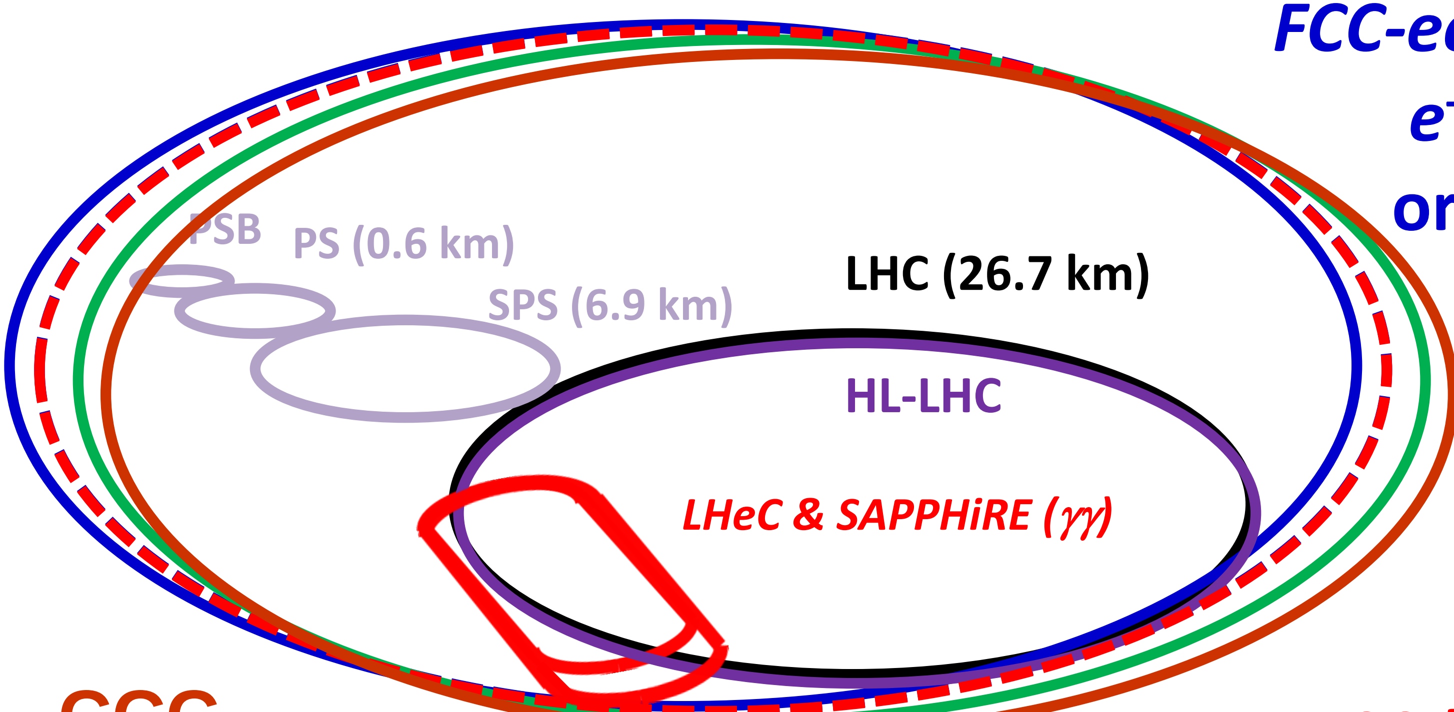
circular crystal collider?



a dream or our future ?

energy ramp using induction acceleration?

possible evolution of FCC complex



FCC-ee **(80-100 km, e^+e^-, up to 350 or 500 GeV c.m.)**

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

CCC, > 1 PeV

LHeC as FCC-ee injector?

LHeC-based FCC-he collider?!

FCC-he **as ring-ring collider ?!**

FCC-he: $e^{\pm}$ (60-250 GeV) – *p*(50 TeV)/A collisions

≥50 years e^+e^-, *pp*, $e^{\pm}p/A$ 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 1.25×10^{11} eV, neither matter nor force!

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

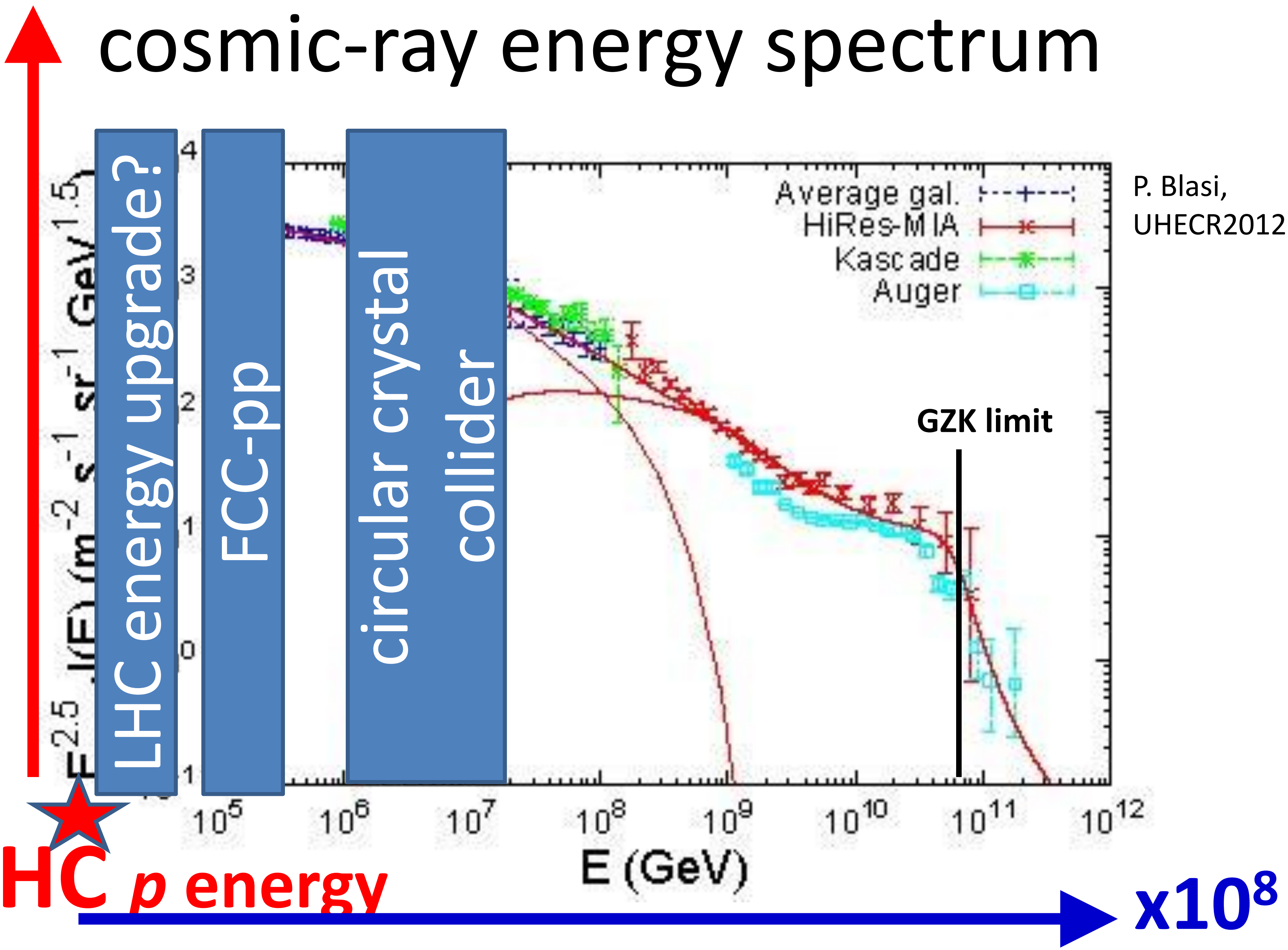
"Oh-my-God-particle"!

(kinetic) energy 3×10^{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

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.
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- S.Y. Lee, "*Accelerator Physics*" - 2nd ed. / Lee, World Scientific, Singapore, 2004.
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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

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appendix:

long shutdown 1

some accelerator history

LHC beam dump

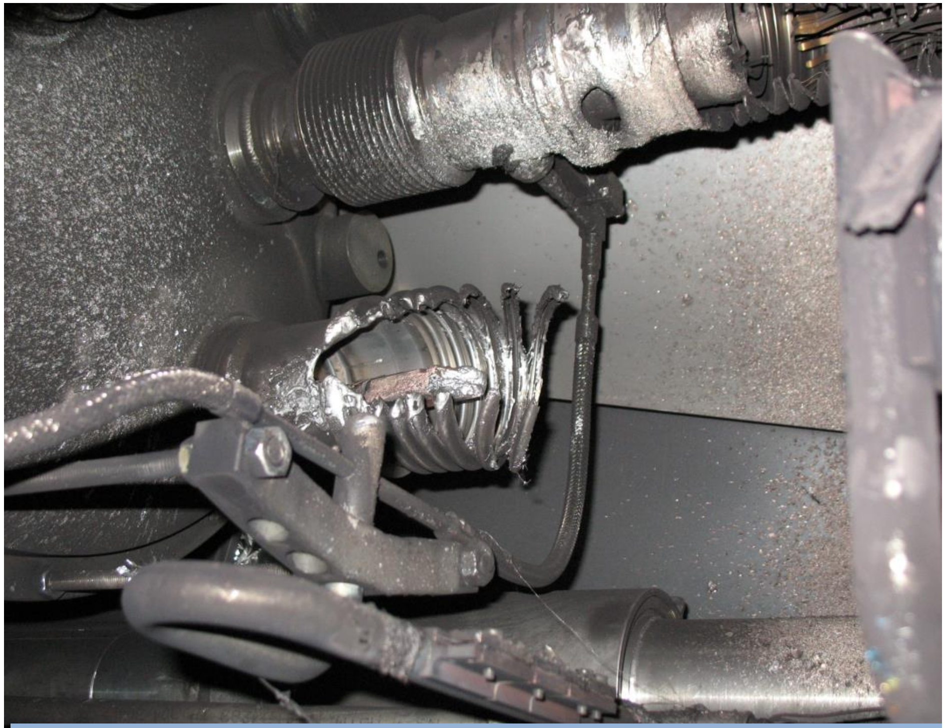
Long Shutdown 1: 2013-14

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

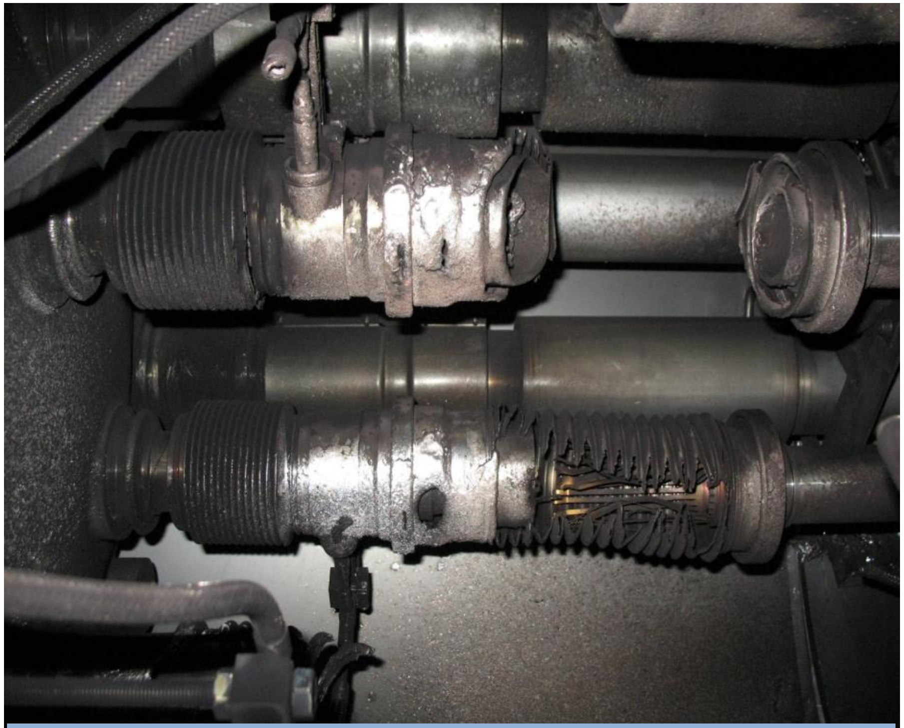
in 2010-12 LHC operated at 7 & 8 TeV c.m. beam energy to avoid any risk

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

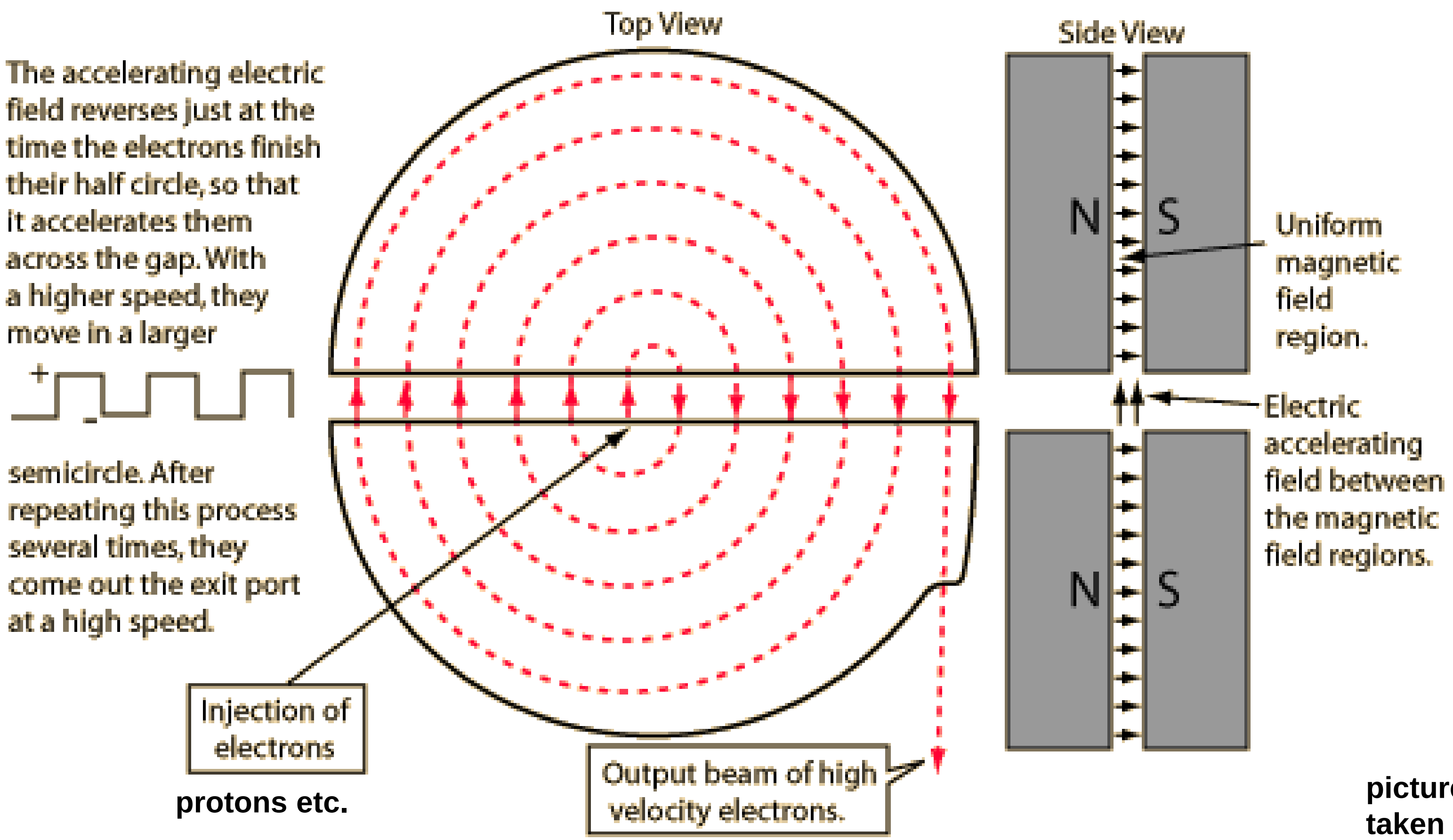


This burnt through beam vacuum and cryogenic lines, rapidly releasing ~2 tons of liquid helium into the vacuum enclosure

R. Veness


VELAN
QV

cyclotron



protons etc.

protons etc.

picture taken from “hyperphysics” web site

history of the cyclotron:

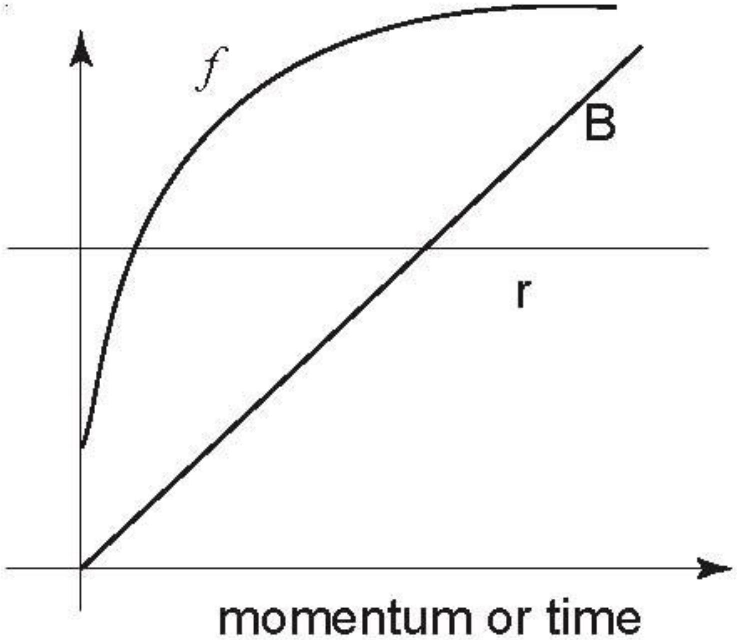
1929 Ernest Lawrence (Berkeley) invented the **cyclotron**

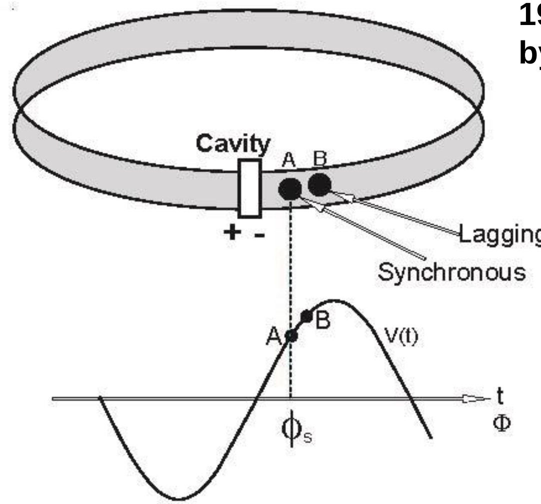
1929 Hungarian physicists Sándor Gaál and **Leo Szilard** both proposed cyclotron concept independently

1930 Lawrence built **first operating cyclotron**

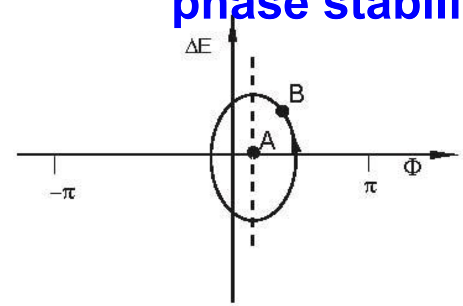
synchrotron

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**"

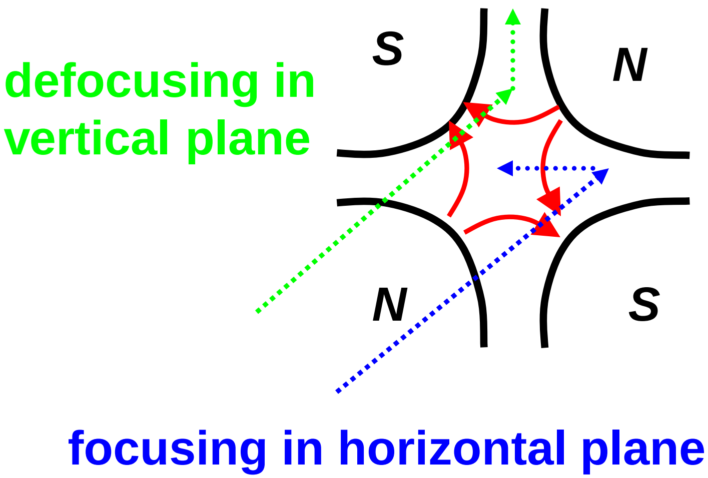
1945 Edwin McMillan in Berkeley independently rediscovered the "phase stability"

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

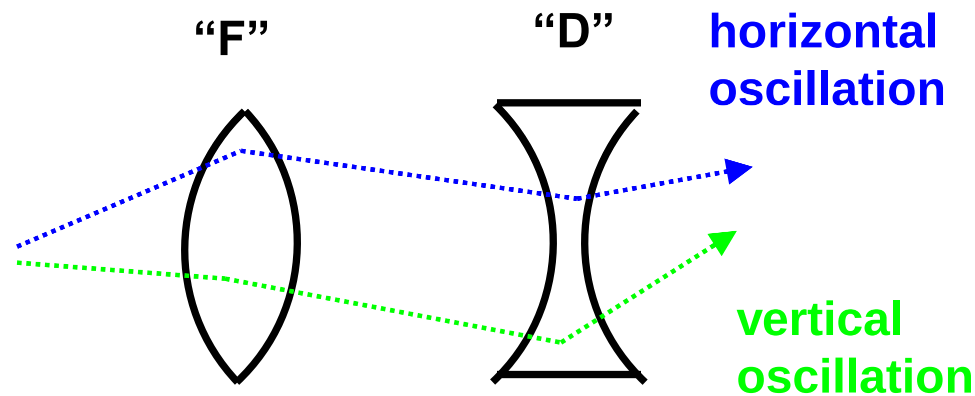
strong focusing

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

example: quadrupole magnet



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



“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

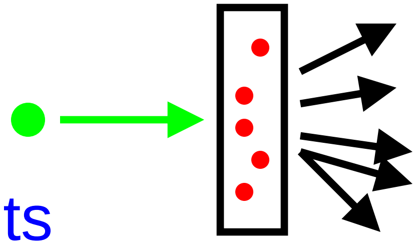
1959 25-GeV Proton Synchrotron (**PS**), the first strong focusing proton ring, starts operation at CERN (1 year before the Brookhaven AGS)

colliding beams

centre-of-mass energy:

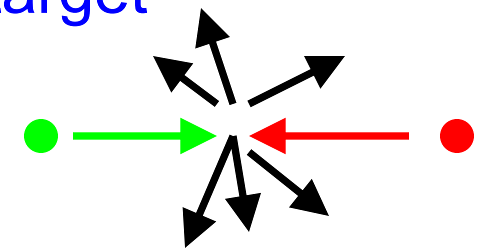
$$E_{\text{c.m.}} = \sqrt{2E_{\text{beam}}M_{\text{target}}c^2}$$

beam hits
a “fixed target”



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

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

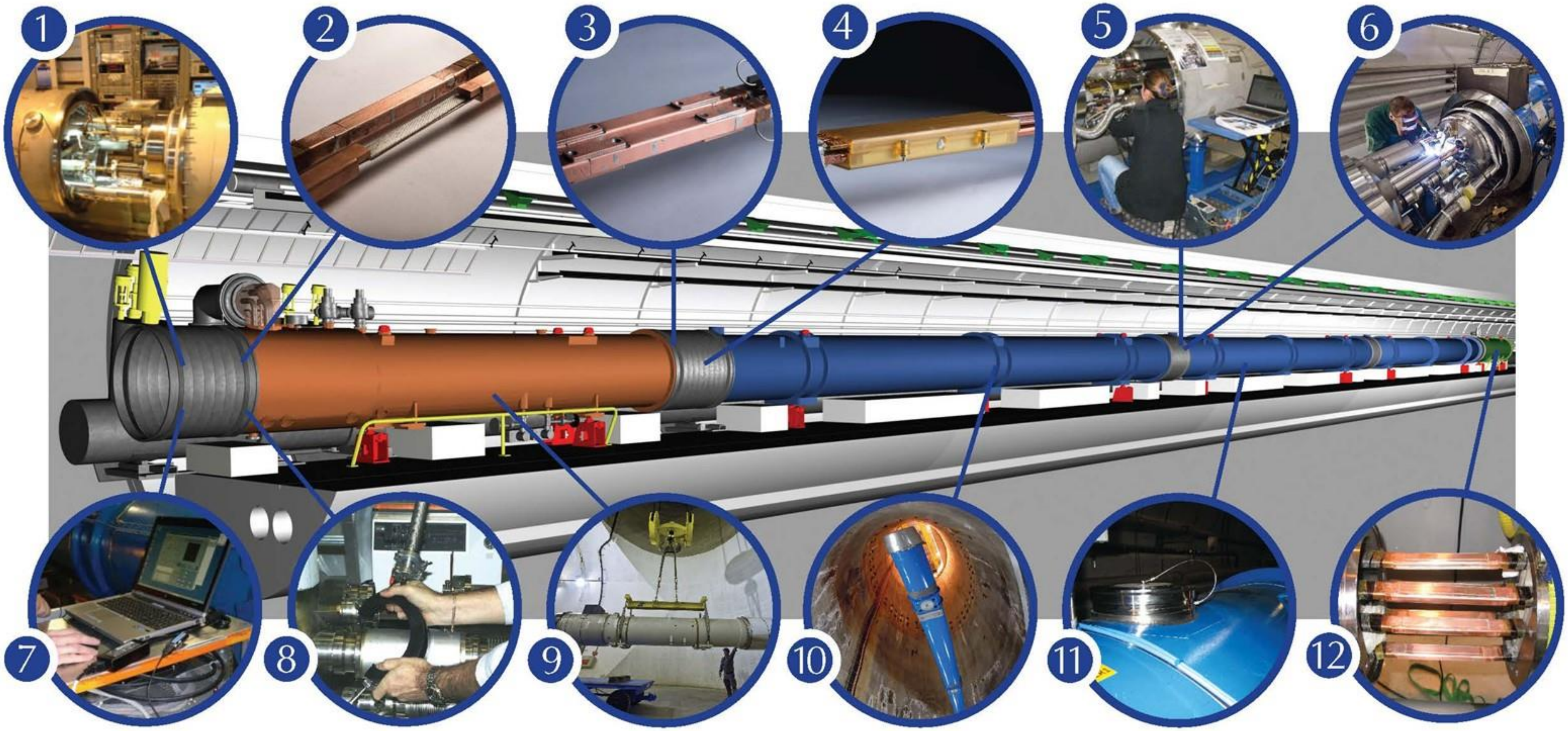
Complete reconstruction of 1500 of these splices

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

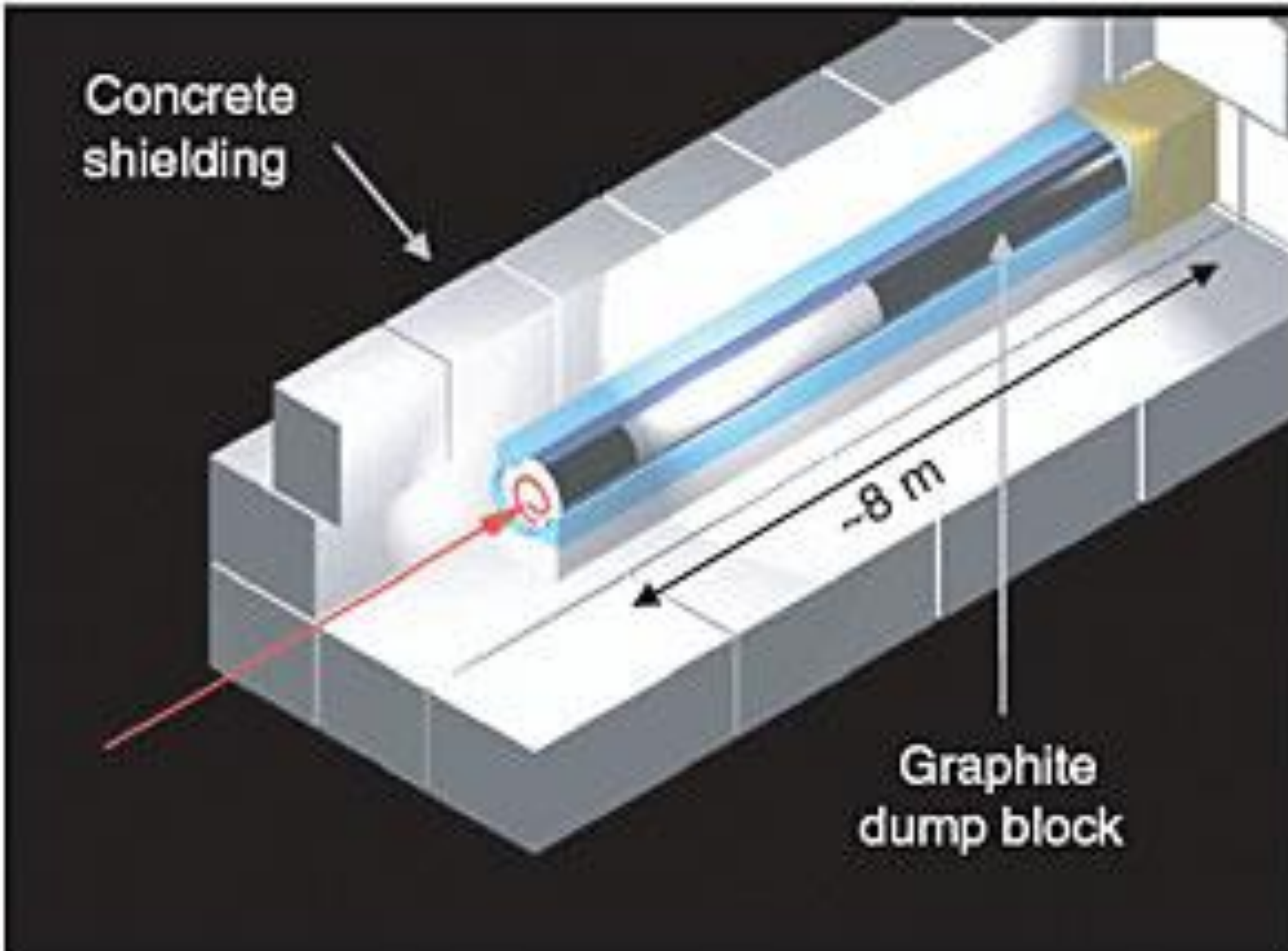
10170 leak tightness tests

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