Very High Energy Hadron Colliders

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Acknowledgments to many colleagues, in particular M. Benedikt, D. Schulte, F. Zimmermann, G. de Rijk, L. Bottura, R. Schmidt, M. Zerlauth

Outline

Introduction

Luminosity

Magnets

High intensity beams

Machine protection

Infrastructure and injectors

High energy colliders

- (Very) high energy hadron colliders (VHEC) are generally considered to be discovery machines, for example the heaviest particles of the standard model like b, t, Z, W and H were discovered by HCs. And the search is still ongoing…

But Where Is Everybody?

N. Arkani-Hamed, FCC kickoff meeting, 2014

- With modern detector technology, (very high energy) hadron colliders can also turn into precision machines for some measurements.

High energy colliders

- In this talk I will consider as ‘very high energy’ everything that is higher than the LHC 7 TeV per beam.
  - There are currently two VHECs – **FCC-hh and SPPC** – that are studied actively.
  - Some past studies also meet my criteria – **SSC and VLHC** – and I will also mentioned them when appropriate.

- The challenges of such machine span a very wide range of topics. The following subset of aspects will be touched today:
  - Magnets,
  - Synchrotron radiation,
  - High intensity beam dynamics,
  - Injector chain,
  - Machine protection,
  - Civil engineering and infrastructure,
  - Availability and operation.

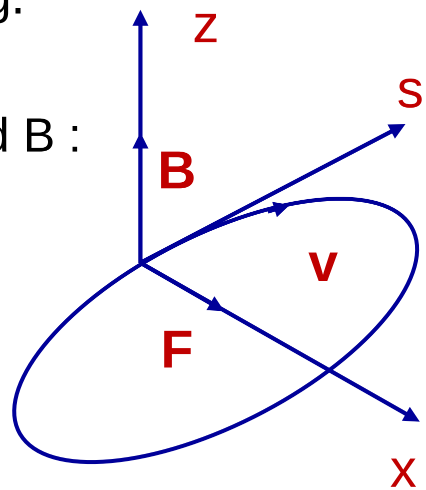
Energy

Colliders take advantage of the Lorentz force to bend the beams, usually with a planar ring and a vertical dipole field for bending.

The momentum of a particle with charge Ze in a magnetic field B :

$$p = B \cdot \rho \cdot Z \cdot e$$

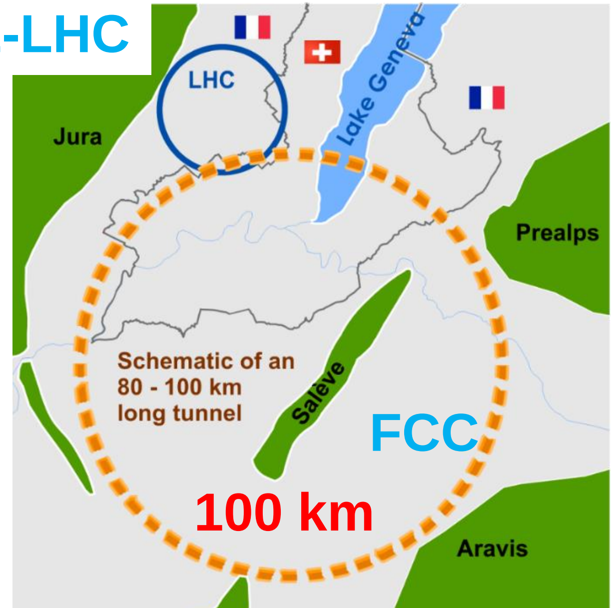
radius of curvature

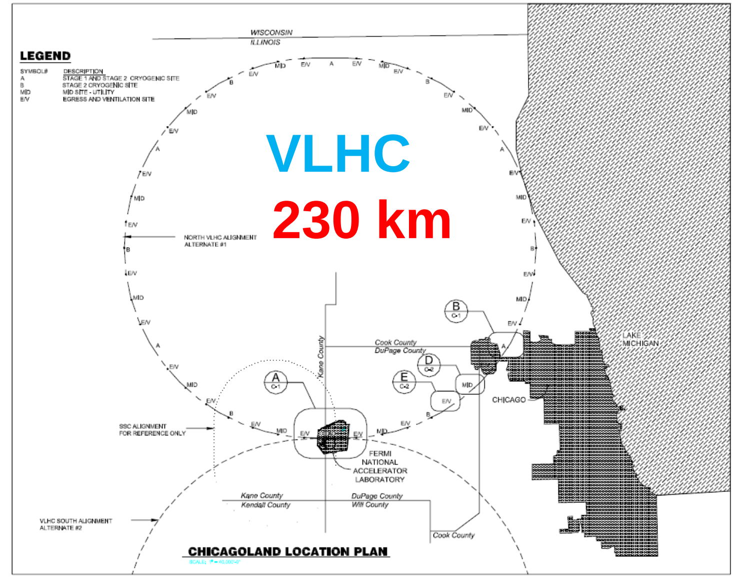


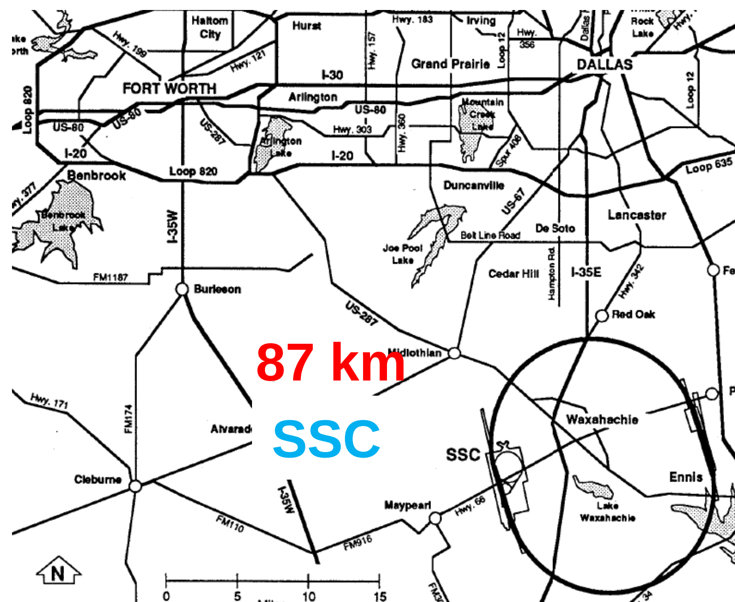
- The LHC holds the record of magnetic field with **7.7 T** (**6.5 TeV**) operational field (**design 8.33 T and 7 TeV**).
- VHECs are usually aiming at a **B-field increase of a factor ~2 wrt LHC**.
- Since a factor 2 in energy (from B) is not generally considered 'insufficient', **the size (ρ) is also increased**.
  - *Notable exception of **HE-LHC**, the energy doubled version of LHC, to be installed in the same tunnel.*

Very large colliders

27 km
HE-LHC





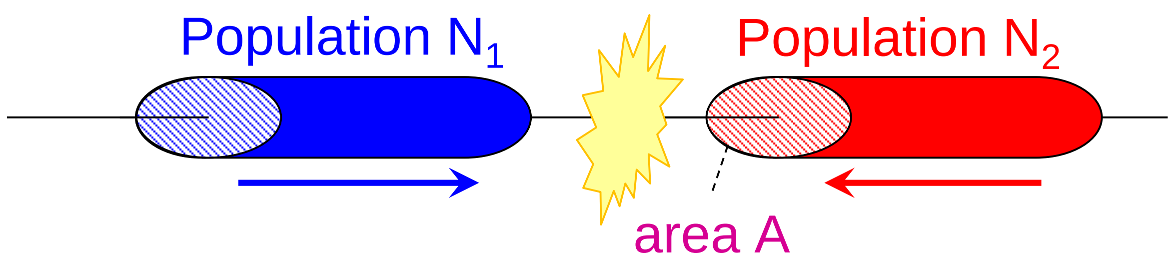


Luminosity

Another key parameter for the experiments is the event rate dN/dt. For a physics process with *cross-section σ* it is proprotional to the collider **Luminosity *L***:

$$dN/dt = L\sigma$$

unit of L :
1/(surface × time)

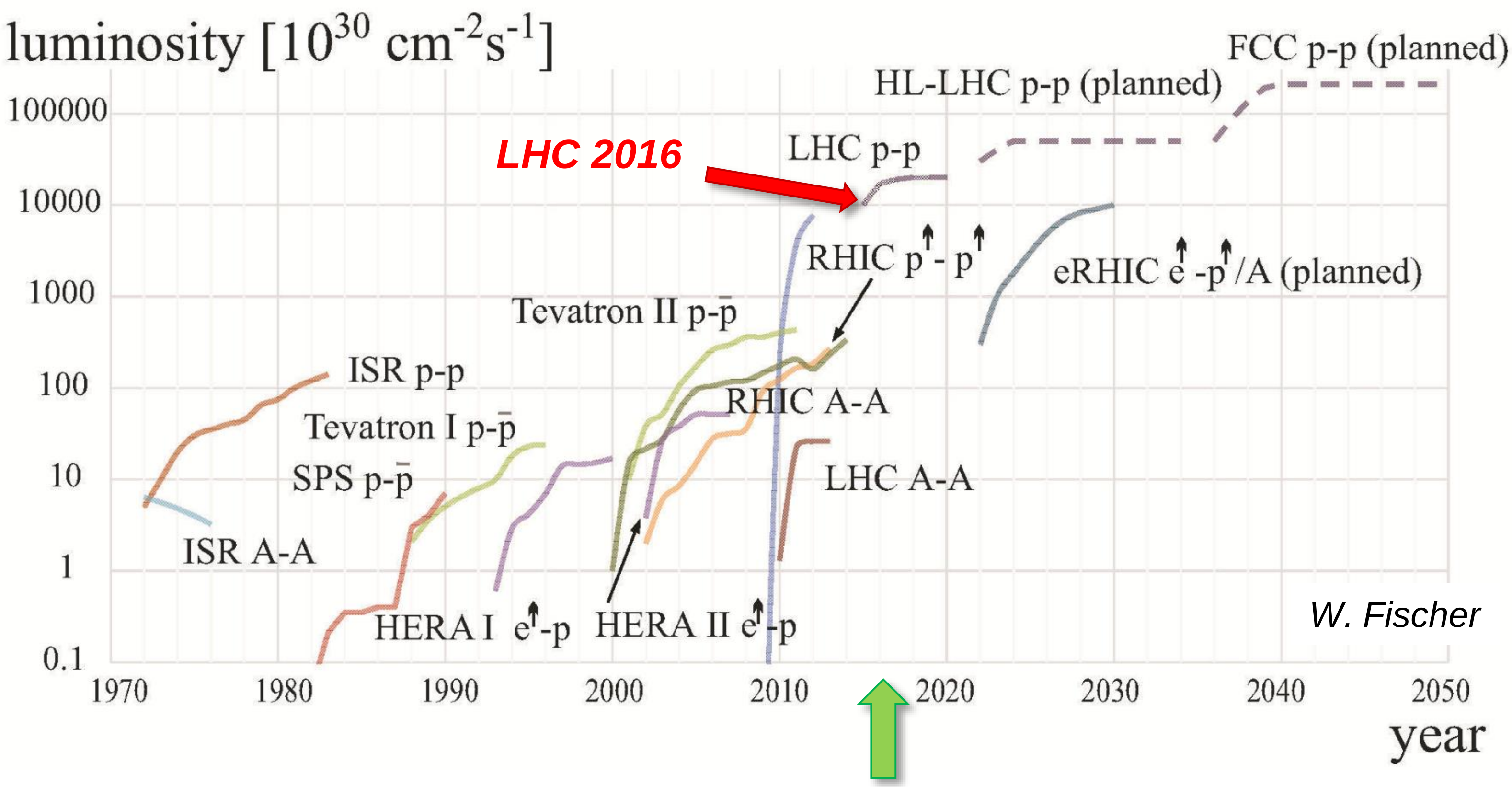


$$\text{Collision rate} \propto \sigma \times \underbrace{\frac{N1 \times N2}{A} \times \text{encounters/second}}_{L}$$

To maximize L we have to squeeze as many particles as possible into the smallest possible volume !

Hadron collider luminosity

- The LHC is the latest in the series of the large hadron colliders after the ISR, SPS, Tevatron, HERA and RHIC.
- The LHC pushes the luminosity frontier by a factor ~25 and the energy frontier by a factor ~7 wrt Tevatron.



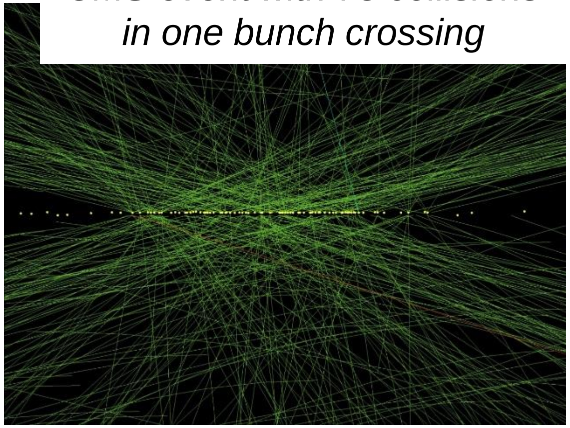
Event pile-up and stored energy

- The LHC design parameters remained rather stable over time since the 1980's, except for the luminosity (and intensity) that was pushed to ~1×10^{34} cm^{-2}s^{-1} to compete with SSC.

  *This implied an **average number of collisions by bunch crossing** of ~20 instead of 1-2 collisions that were the baseline for SSC.*

- VHECs are able to produce such high luminosities that the **pile-up will move into the range of 100-500**: it is a huge detector challenge to be able to analyze such events and extract useful physics from them !

CMS event with 78 collisions in one bunch crossing



- Correlated to the high luminosity and beam energy, **the energy stored in the beams** becomes even more extreme than at LHC.

  'Star wars' regime

VHEC challenges

Magnetic fields:

- Magnet design and protection.
- Cryogenic system.

Luminosity:

- Beam dynamics (stability, vacuum effects and synchrotron radiation).
- Stored energy (accelerator protection and beam loss control).
- Radiation to detectors and accelerator components.
- Event pile-up → for the experiments.

Dimensions:

- Tunnel location.
- Infrastructure.
- Injectors.

Parameter table

- Comparison of key parameters of proposed very high energy hadron colliders.
  - Please note that for some machines, there is more than one parameter set !
  - Within a factor ~2 the bunch parameters are identical for all the designs > SSC.

Parameter	LHC	HE-LHC	SSC	VLHC	FCC-hh	SPPC
Circumference [km]	27.7	27.7	87.1	233	100	54
Beam energy [TeV]	7	14	20	78.5	50	36
Dipole field [T]	8.33	16	6.6	11.2	16	20
Injection energy [TeV]	0.45	0.45	2	9.8	1-3	2.1
Intensity / bunch [10^{11} p]	1.15	2.20	0.08	0.75	1.00	2.00
No bunches	2800	2800	17424	37152	10060	5798
Intensity / beam [10^{14} p]	3.2	6.2	1.3	27.9	10.6	11.5
Luminosity [10^{34} $cm^{-2}s^{-1}$]	1	20	0.1	2	5	12
Stored beam energy [GJ]	0.36	1.38	0.42	35	8.4	6.68
Synchr. rad. power [W/m/beam]	0.18	3.2	1	4.7	30	58

FCC-hh & SPPC are the VHECs that are currently studied in detail

Outline

Introduction

Luminosity

Magnets

High intensity beams

Machine protection

Infrastructure and injectors

Collider luminosity

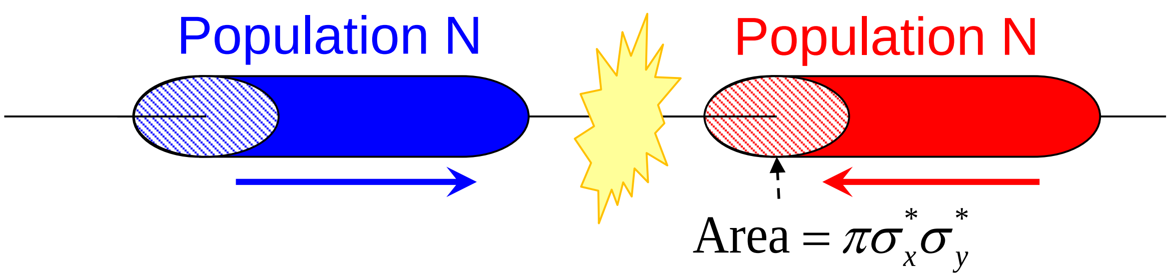
Expression for the luminosity L (for equal particle populations, Gaussian profiles and round beams) :

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

k, N, ε : beam properties

β : property of the beam optics*

F : beam dynamics



- ***σ^*_x, σ^*_y*** *: transverse rms beam sizes - $(\sigma^*)^2 = \beta^*\varepsilon$*
- ***β^** :** *betatron (beam envelope) function ⇔ optics*
- ***ε* :** *beam emittance (phase space volume)*
- ***k*** *: number of particle bunches per beam.*
- ***N*** *: number of particles per bunch.*
- ***f*** *: revolution frequency*
- *$\gamma = E/m$.*
- ***F*** *: geometric correction factor (crossing angles...).*

**** refers to the IP***

Beam parameters

- The intrinsic beam parameters are defined by the injectors:
  - ***Bunch spacing*** *(→ k) : minimum (design) = 5-25 ns (⇔ 1.5-7.5 m),*
  - ***Bunch intensity N****: up to ~ 2×10^{11} p/bunch,*
  - ***Bunch emittance*** ε *: 1-3.5 mm mrad.*

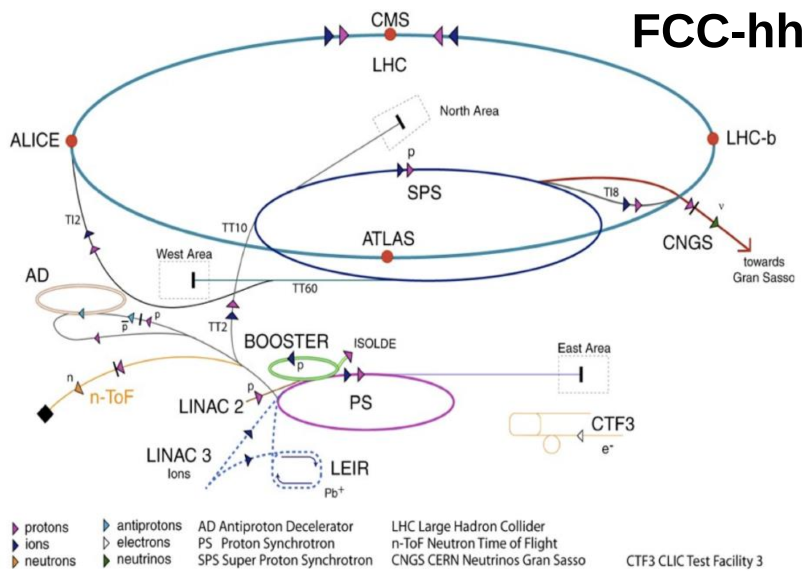
$$L = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}F$$

- The **quality of the beam is defined in the injector chain** – it is an essential component of a VHEC.
- For the LHC startup CERN has refurbished its injector chain to produce the bright LHC beams, a second upgrade wave is now in progress (to be completed in 2020) to more than double N and N/ε (brightness).

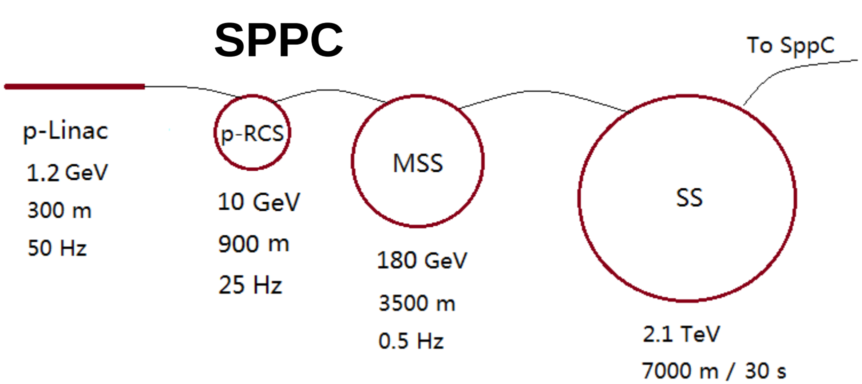
→ Presentation by M. Zerlauth (Monday)

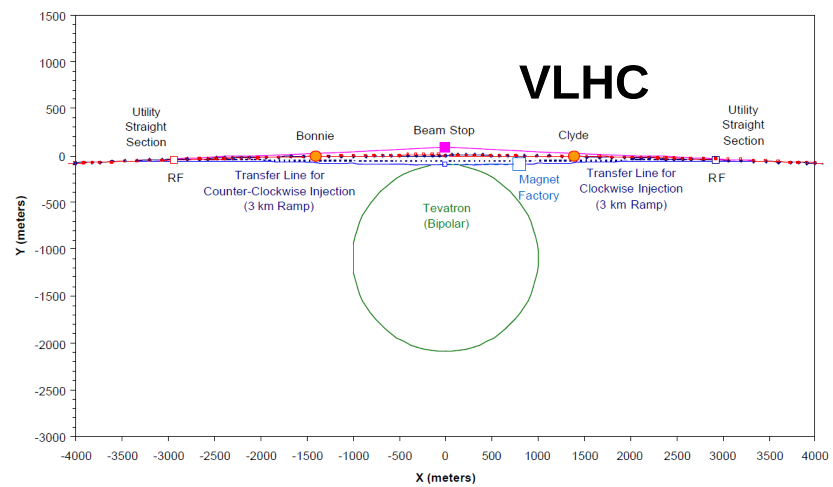
Injectors

- A high energy collider requires a long and complex injector chain.
- Two facilities in the World that can provide TeV beams : FNAL and CERN.
- 'Green field' adds extra cost...



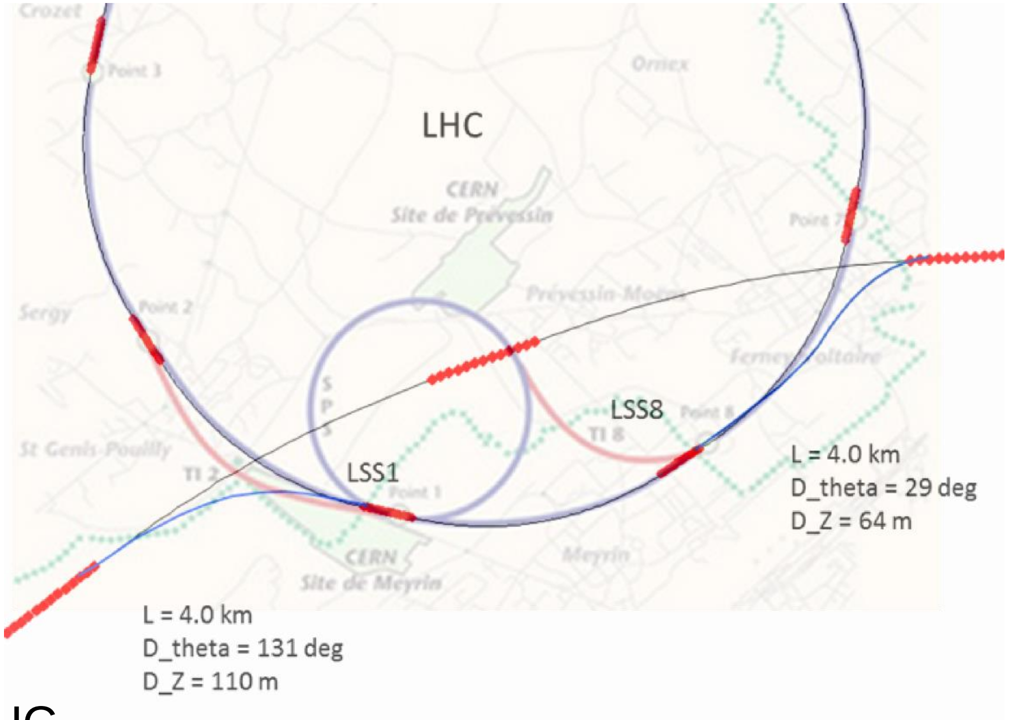
	Max. P (GeV/c)	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	157
PS	26	628
SPS	450	6'911
LHC	3'000	26'657





Main FCC injector options:

- **SPS → LHC → FCC**
- SPS/SPS$_{upgrade}$ → FCC
- SPS → FCC booster → FCC



Current baseline:

- Injection energy **3.3 TeV** with beams provided by a modified LHC.

Alternative options:

- Injection energy around **1.5 TeV.**
- Compatible with: SPS$_{upgrade}$, LHC, FCC booster.
- Worry for this option is the *field range* of > 30 in FCC: control of field errors at injection may be very tricky.

Interaction region

- VHECs operate with 2 beams in separate vacuum chambers. They beams are merged into a single vacuum chamber only around the experiments.
- All interaction region designs are similar.
  - Already the SSC interaction region was conceptually similar to the newer VHECs, except that the rings were stacked vertically as opposed to horizontally for LHC, HE-LHC, FCC-hh.

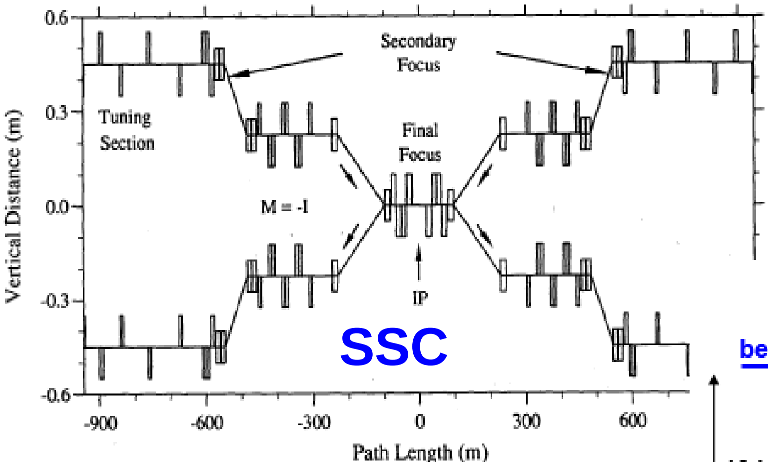
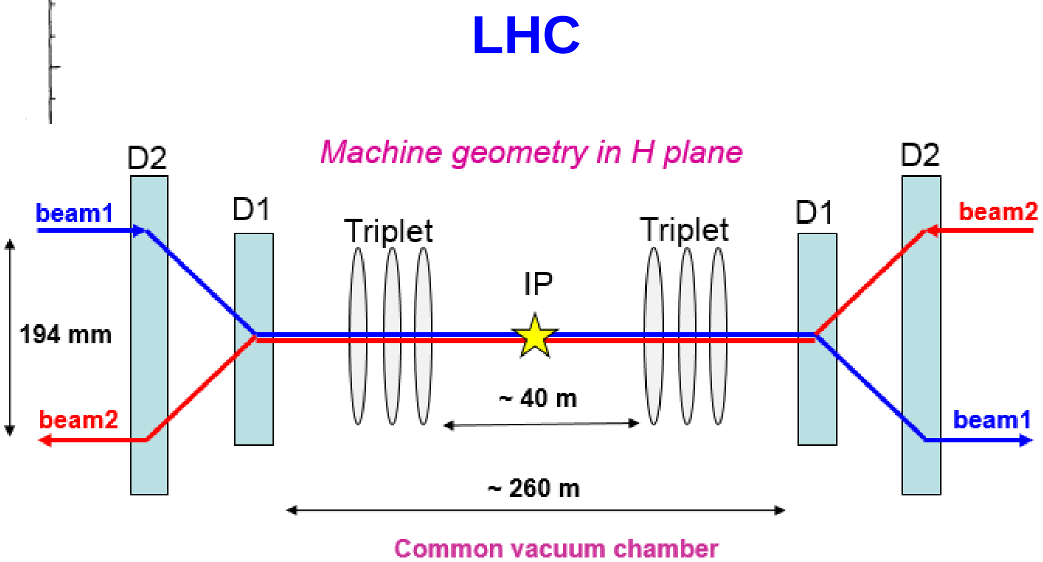


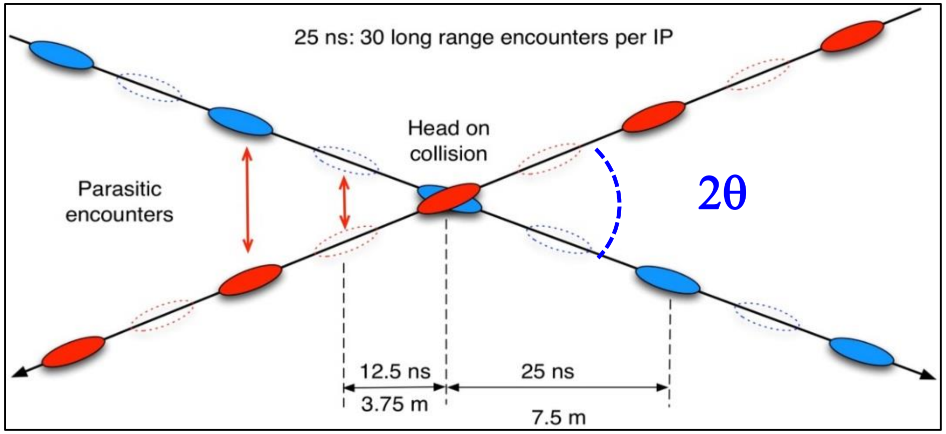
Figure 9-1. General Layout of the Interaction Region.



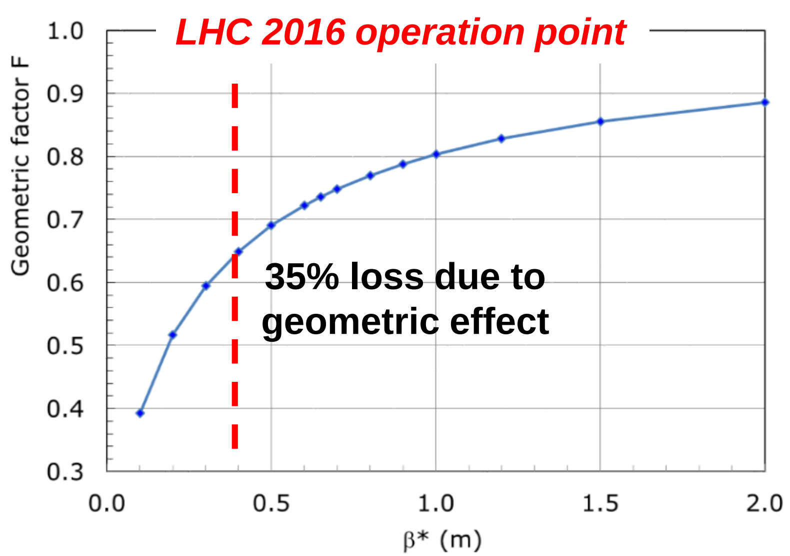
D1,D2 :
Separation / recombination dipoles

Collision point geometry

- A **crossing angle** between the beams is needed to minimize the electromagnetic interactions (***beam-beam*** effects) in the common vacuum chamber (final focus region).
  - Min. separation ~10 beam sizes.
  - 30 encounters per IP at the LHC.



- Consequences of colliding at an angle:
  - Significant geometric luminosity reduction that depends on beam size and bunch length: **steep function of the beam size** ($\beta^* \varepsilon = \sigma^{*2}$).
  - Reduction of the aperture.

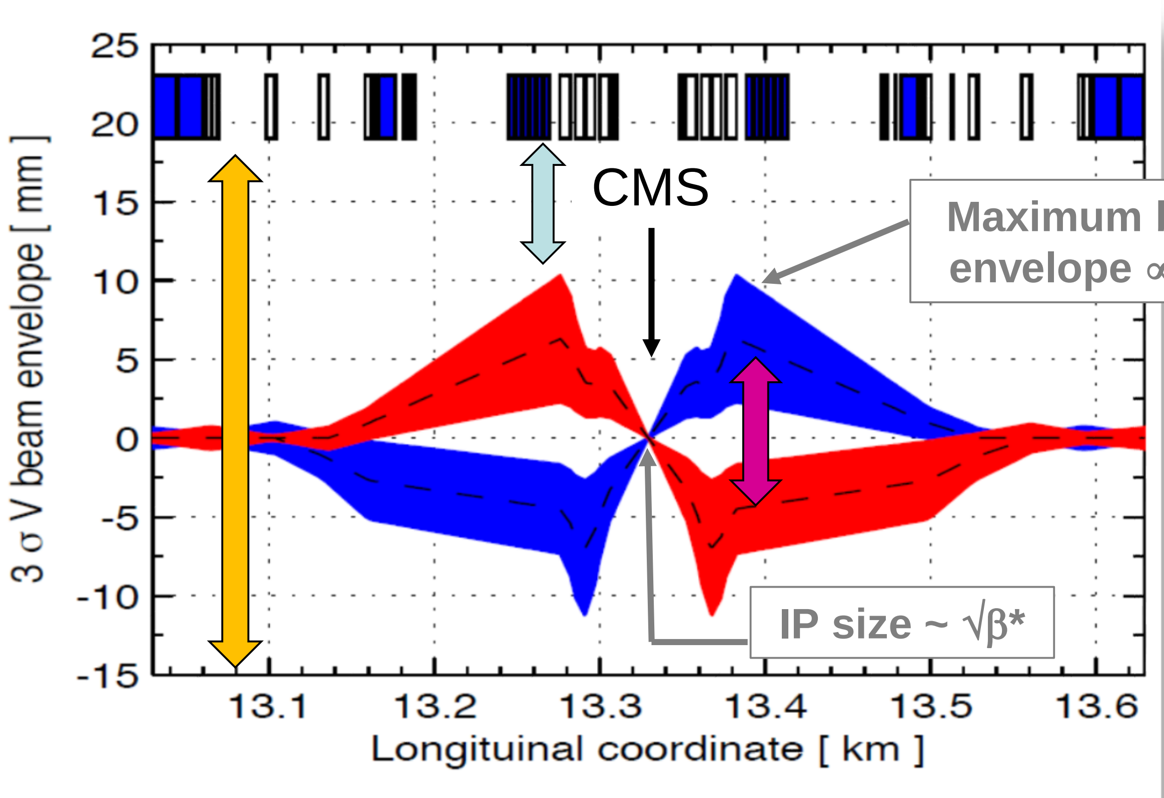


$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} F$$

The minimum beam size (**or beam envelope β***) is determined by:

- *The mechanical aperture around the IP → need LARGE magnets,*
- *The crossing angle ($\theta \propto k$, N, $1/\sqrt{\beta^*}$),*
- *The margin to the aperture.*

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} F$$

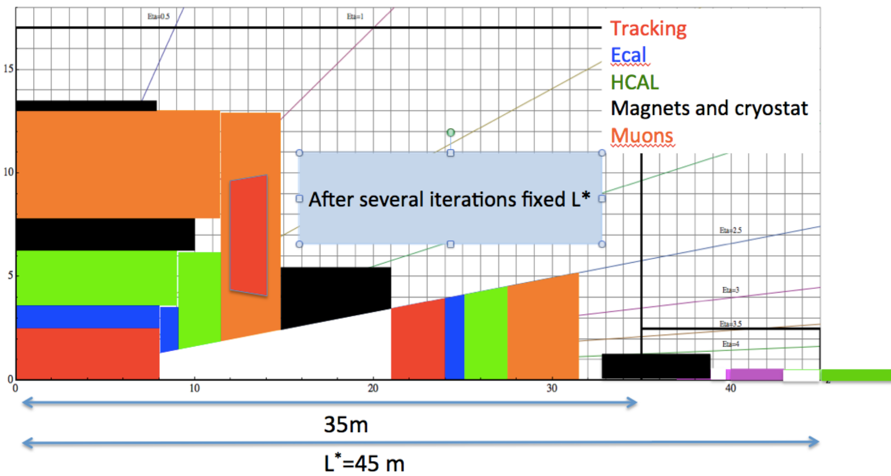


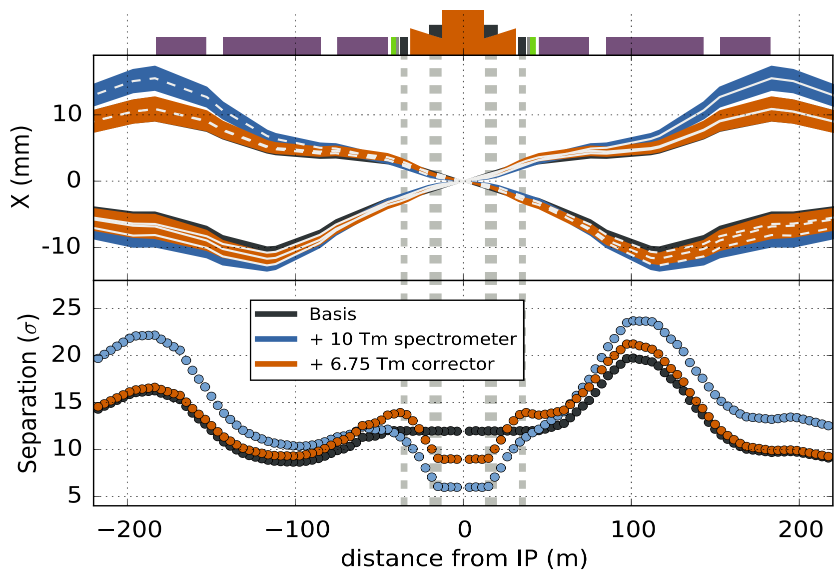
LHC example

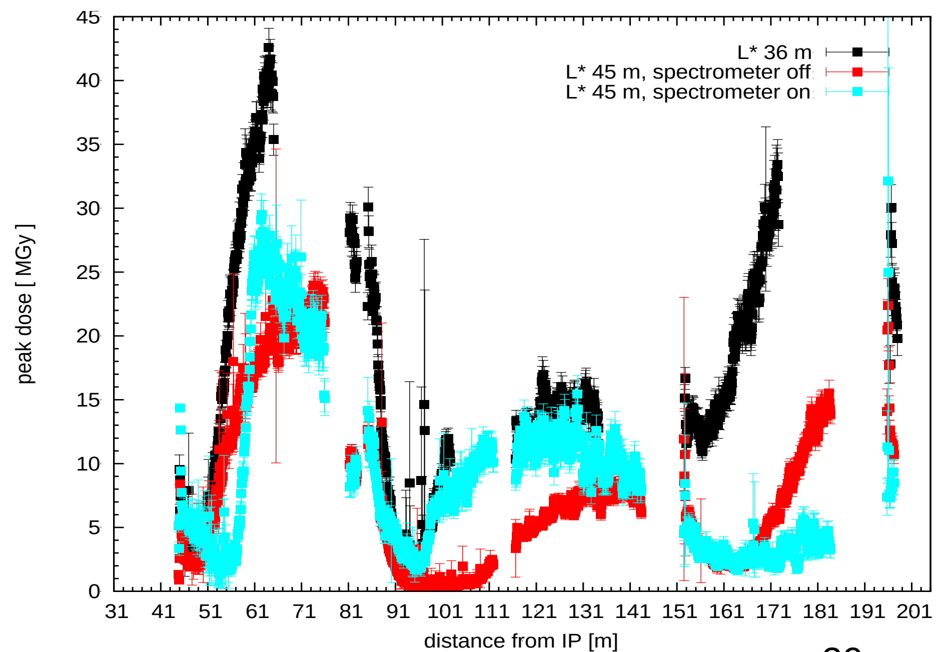
IR design challenges – FCC-hh

Design of interaction region

- Distance from IP to first machine quadrupole L^*=45 m.
- Integrated spectrometers and compensation dipoles.
- Optics and magnet optimization for beam stay clear (aperture) and collision debris.
    - ✓ Magnet lifetime should be ≥ 3 years (from radiation damage).

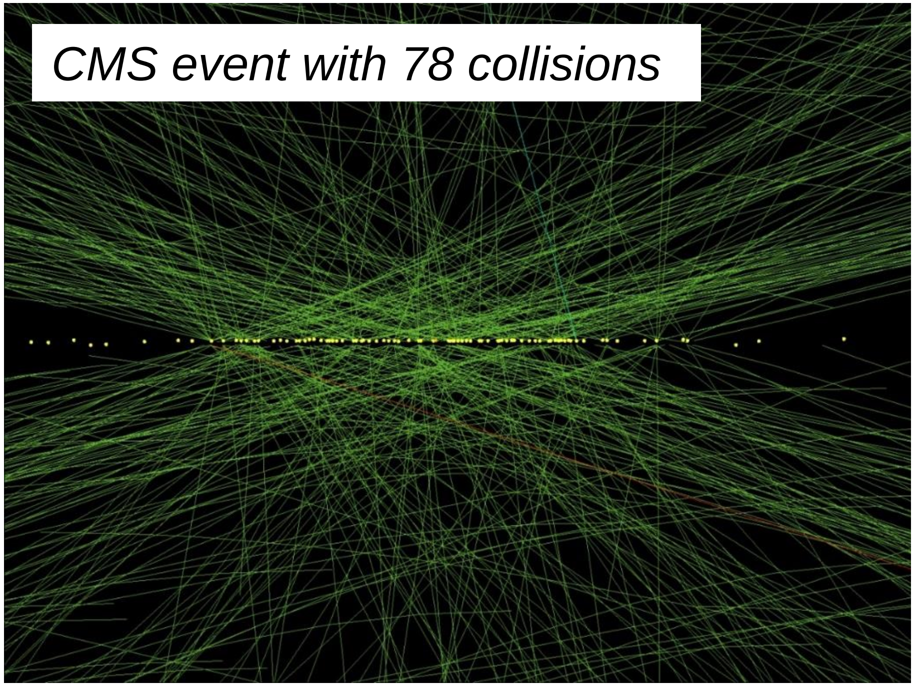






Event pile-up – LHC 'legacy'

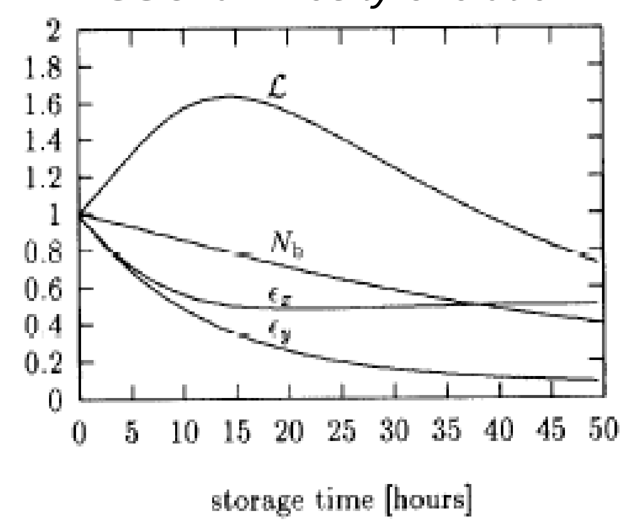
- To compete with SSC, the LHC had to push the event pile-up significantly above 1-2 events per bunch crossing.
- The LHC is currently operating with a *peak average event pile-up* of **~40 events/crossing** (design ~27). But statistical fluctuations generate events that have many more events.
- For the LHC luminosity upgrade HL-LHC, the number of events per crossing will be pushed to **~120** !
- VHECs push the limit to **~500** !!



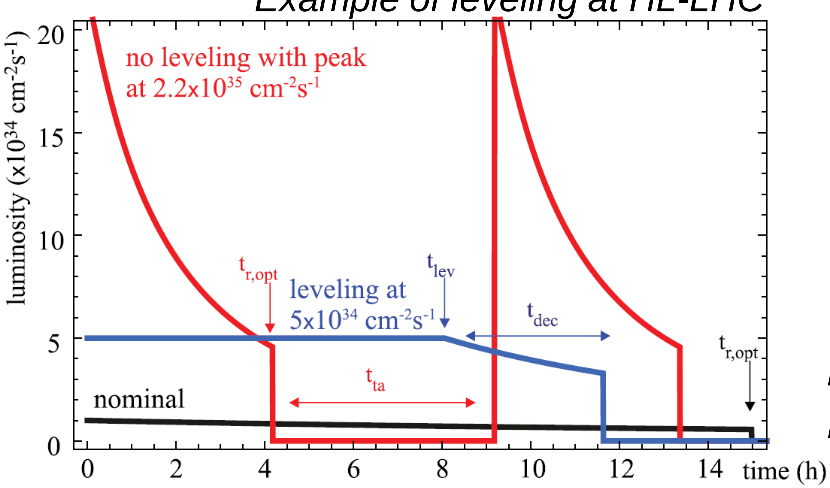
Luminosity levelling

- VHECs (starting with LHC) enter a new regime for proton beams where **synchrotron radiation is damping the beam sizes** (transverse and longitudinal) of the colliding beams !
- This can lead to a luminosity that initially increases as the damping (~1 hour at FCC-hh) is able to overcome the losses, providing 'free' performance gains.
- VHECs (starting with high luminosity LHC upgrade HL-LHC) will be able to provide more luminosity than the experiments can 'swallow': opens the door to **levelling the luminosity** with beam offsets, β* etc at near constant value !

SSC luminosity evolution



Example of leveling at HL-LHC



D. Shulte et al,

PRSTAB 18, 101002 (2015)

Outline

- Introduction
- Luminosity
- **Magnets**
- High intensity beams
- Machine protection
- Infrastructure and injectors

LHC legacy – 2-in-1

<u>LHC design choices</u>:

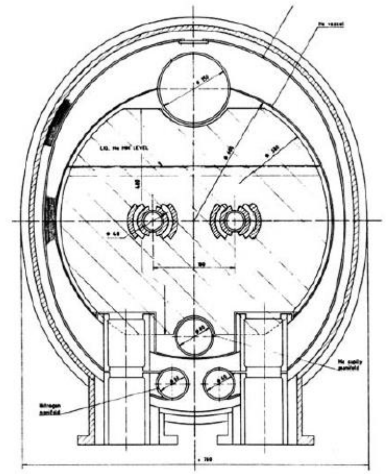
- High magnetic fields – 8T,

  ⇒ super-conducting magnets

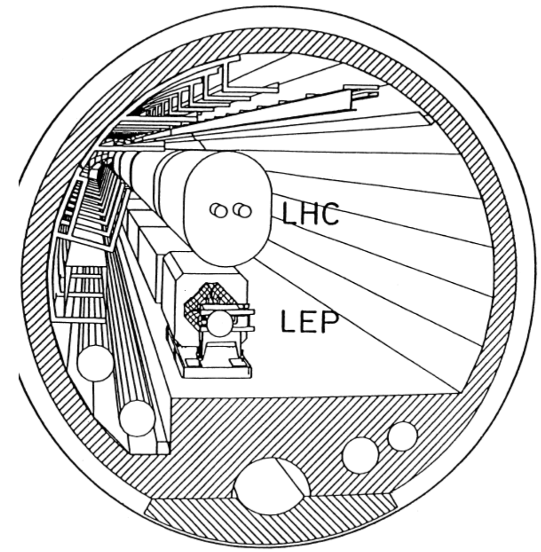
- **2 in 1 magnet design**,

  ⇒ more complex magnet design,
  but only one single cryostat

- Superfluid Helium.



1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

Post-LHC designs are all based on the 2-in-1 concept.

The SSC designers opted for independent rings (2 separate cryostats) to be able to commission / operate one ring without the other.

From concepts to accelerator magnets

- While 8.3 T dipole magnets (LHC) have been produced by industry, there is a long road ahead to build 15-20 T accelerator grade magnets.

From many short prototypes to

- ✓ longer prototypes,
- ✓ ‘hand-made’ magnets (by the Labs),
- ✓ industrial production.

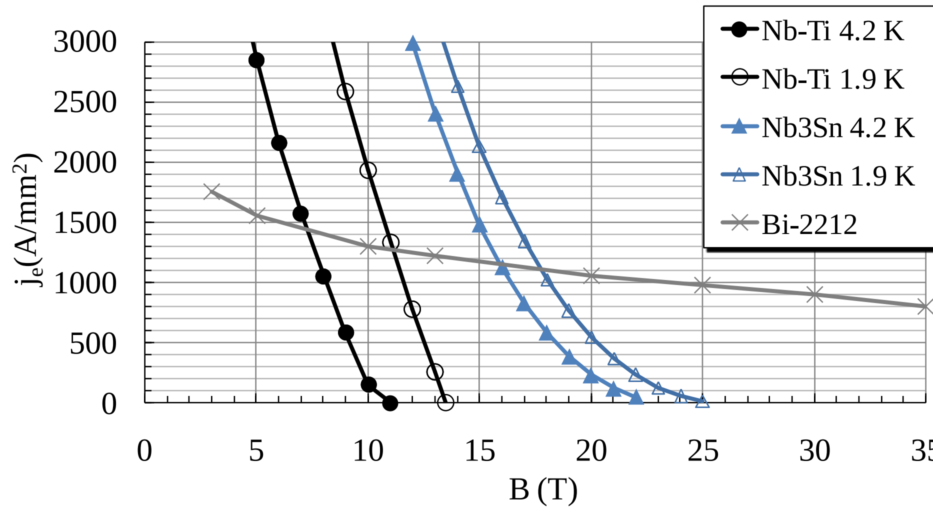
LBNL HD1 Nb_3Sn short prototype

LHC NbTi dipole lowered into the tunnel

Superconductors

Nb-Ti is the workhorse for 4 to 10 T:

- *Reaches J ~2500 A/mm^2 at 6 T and 4.2 K or at 9 T and 1.9 K.*
- *Well known industrial process, good mechanical properties.*
- *Thousands of accelerator magnets have been built.*
- *10 T field in the coil is the practical limit at 1.9 K.*



Courtesy E. Todesco & G. De Rijk

Nb_3Sn is the current road to 16 to 20 T

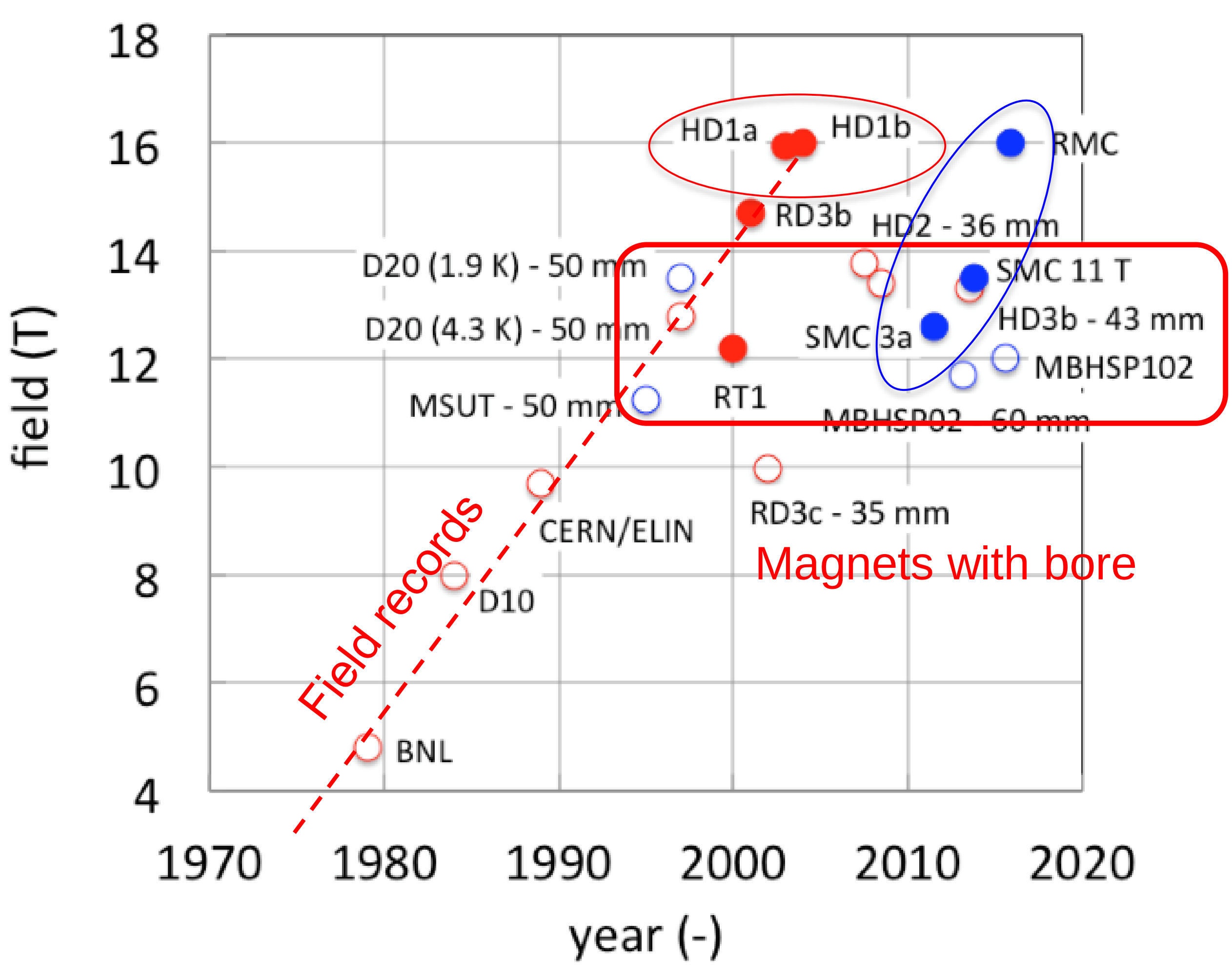
- *Can reach up to J ~3000 A/mm^2 at 12 T and 4.2 K.*
- *Complex industrial process, higher cost, brittle and strain sensitive.*
- *~25 short models for accelerator magnets have been built.*
- *~20 T field in the coil is the practical limit at 1.9 K.*
- *Accelerator grade 11 T dipoles and high field quadrupoles in design phase for HL-LHC.*

HTS materials: dreaming of 40 T (Bi-2212, YBCO)

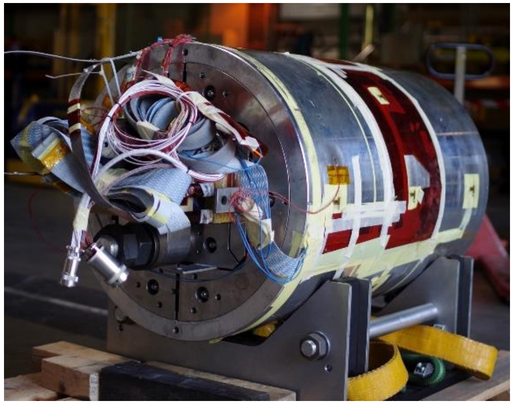
- *Current density is low, but very little dependence on the magnetic field.*
- *Used in solenoids, used in power lines – no accelerator magnets (only 1 model) yet.*

Highest “dipole” fields

G. De Rijk – FCC week Rome



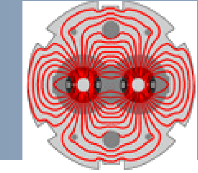
LBNL HD1



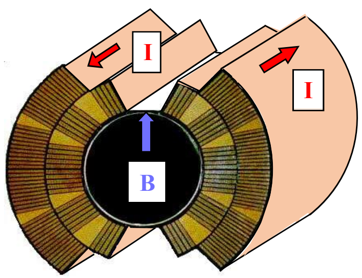
CERN RMC

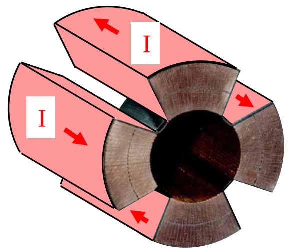
Record fields for SC magnets in “dipole” configuration

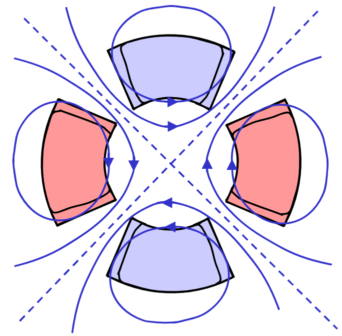
Accelerator magnets are special

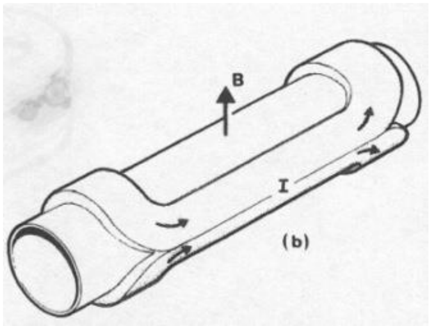


- Cylindrical volume with perpendicular field.
- Dipoles, quadrupoles, etc,





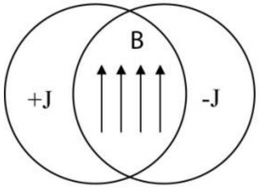




Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

- Field quality: $\frac{\Delta B_z}{|B|} \leq few \cdot 10^{-4}$

CosΘ coil : J = J_0 cosΘ



- Field quality formulated and measured in a multipole expansion,

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \qquad b_n, a_n \leq few \cdot units$$

- Long dipole magnets ranging from 6 m (Tevatron) to 15 m (LHC). Often magnets are bend (9.14 mm sagitta for the LHC dipoles).

FCC-hh magnet challenges and roadmap

FCC-hh baseline: 16 T Nb_3Sn technology for 100 TeV in 100 km

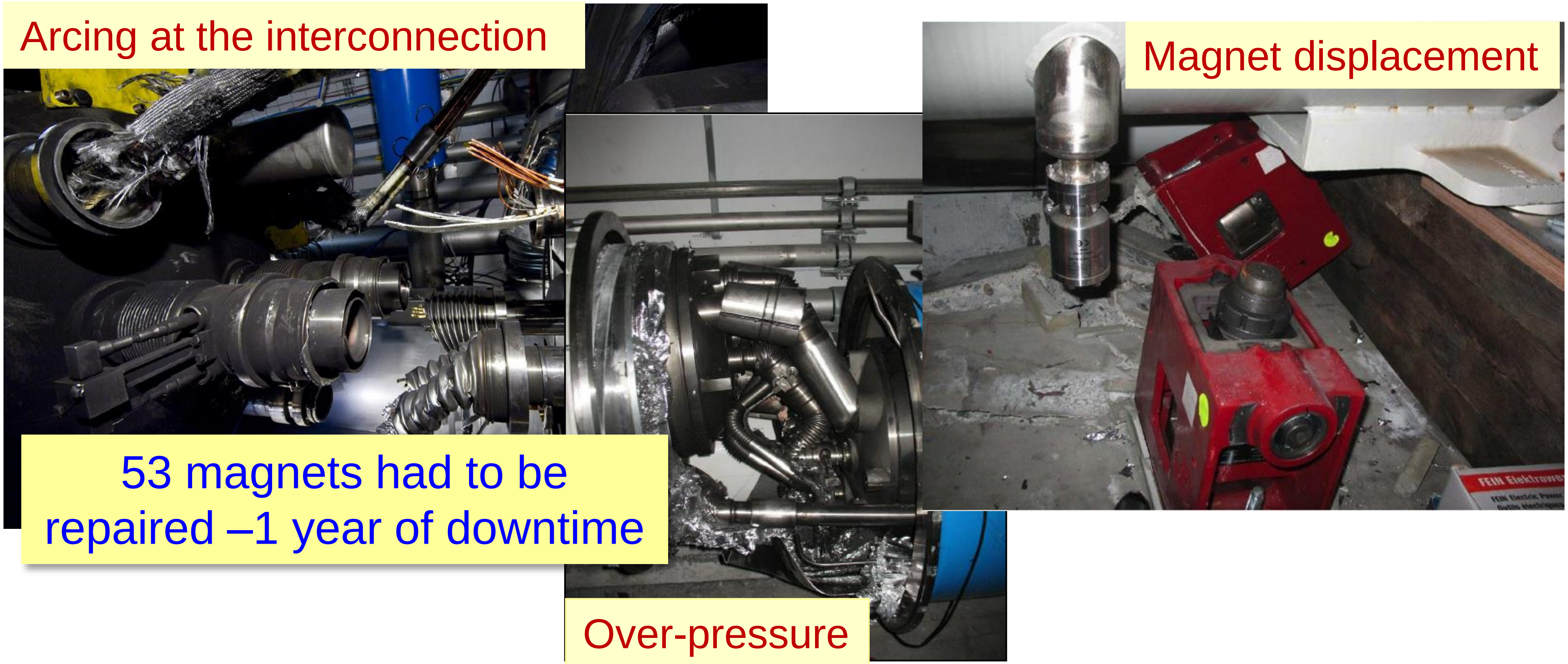
- **Develop Nb_3Sn-based 16 T dipole technology**
  - With sufficient aperture of ~40 mm (LHC = 56 mm) and accelerator features (field quality, ability to protect, cycling operation).
  - Learn from Nb_3Sn magnets in the LHC (HL-LHC 11 T dipoles).
  - Technology push to achieve duplication of critical current density of Nb_3Sn.
  - Possible goal: 16 T short dipole models by 2018 (World-wide collaboration).

- **In parallel HTS development targeting 20 T**
  - HTS insert, generating 5 T additional field, ~40mm aperture and accelerator features.
  - R&D goal: demonstrate HTS/LTS technology for building magnets with a field of 20 T.

LHC incident – magnet protection

In 2008 a severe accident happened at the LHC without beam.

A magnet interconnect was defect and the electrical circuit opened. An electrical arc provoked a Helium pressure wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km. Around **400 MJ** were released in the incident (600 MJ stored).



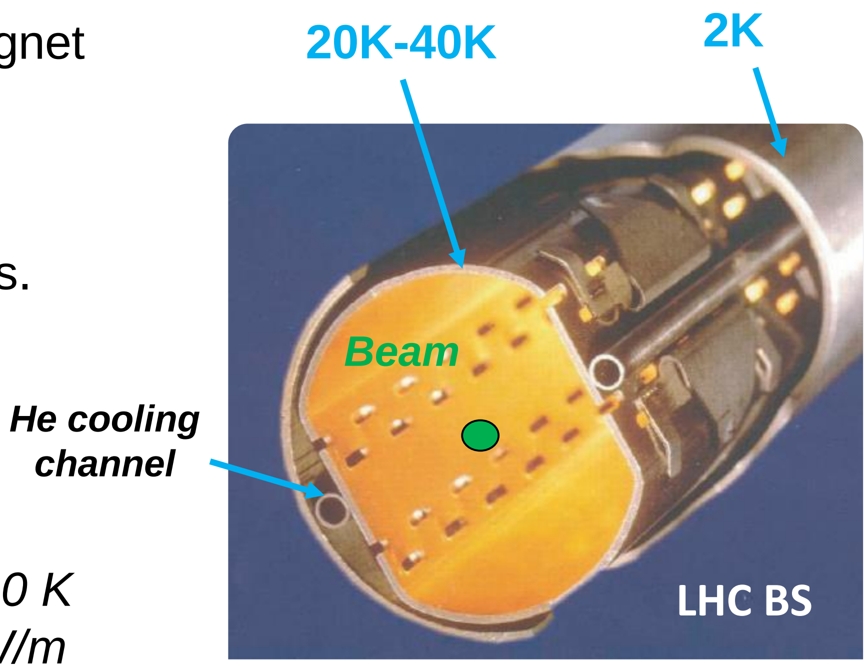
53 magnets had to be repaired –1 year of downtime

The stored magnetic energy increases even further with VHECs – magnet protection and quality control will become even more critical !

Synchrotron radiation

- Synchrotron radiation (SR) from the proton beams is beneficial for luminosity (cooling) and diagnostics (profile measurements).
- But SR also deposits heat inside a magnet that is operated at cryogenic temperature → very expensive to remove the heat at low temperature !

- To protect the inner aperture of the magnet (at 1.9-4 K) a **beam screen (BS)** is inserted into the vacuum chamber as shielding against synchrotron radiation, image currents and also electron clouds.



At the LHC the BS is operated at 20-40 K for a total energy deposition of ~1.5 W/m

(0.2 W/m from SR)

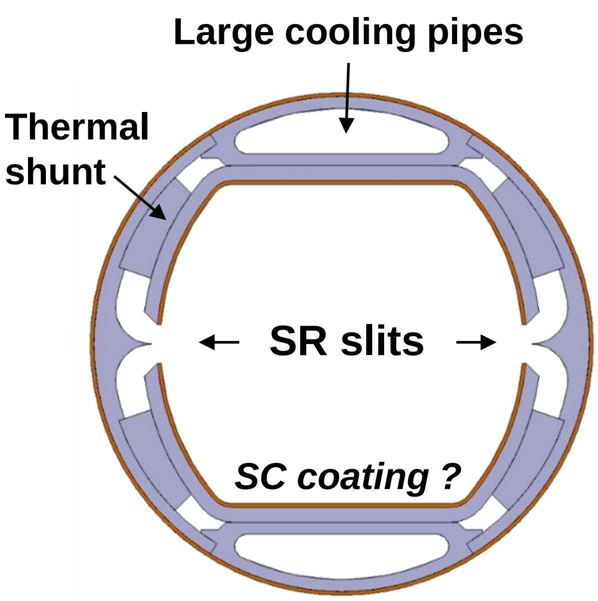
Beam-screens for FCC-hh

High synchrotron radiation load of protons @ 50 TeV:

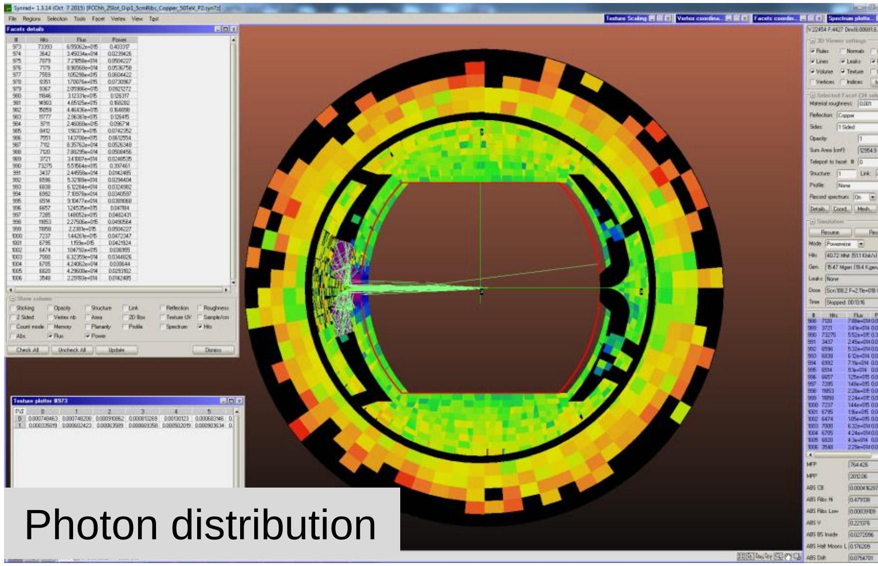
- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs**

Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- avoids photo-electrons, helps vacuum

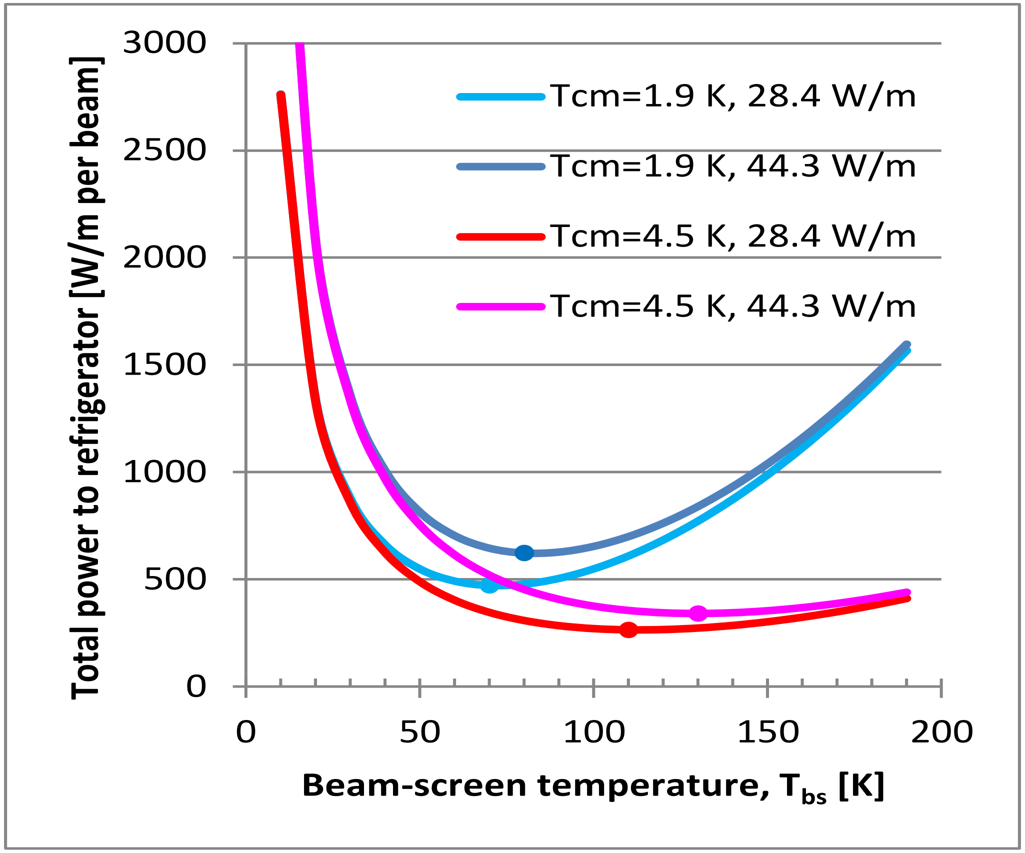


FCC-hh beam screen prototype



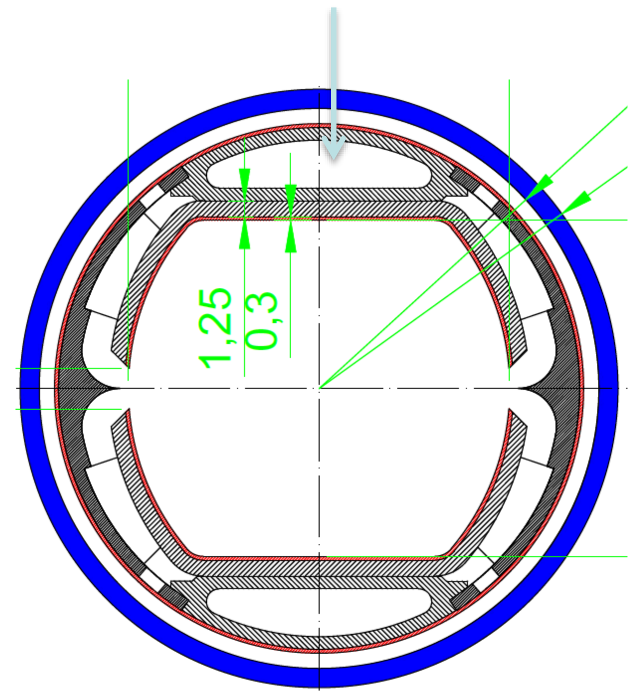
Photon distribution

Beam screen cooling at FCC-hh



L. Tavian, C. König, Ph. Lebrun

Cross section determines length that can be cooled



16K beam-screen would require 300 MW for cooling

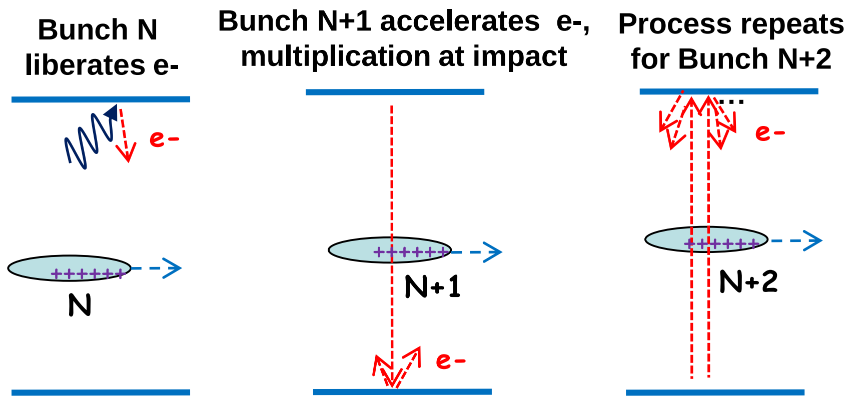
50K requires 100 MW → current baseline

For 4K magnets would prefer T > 100K

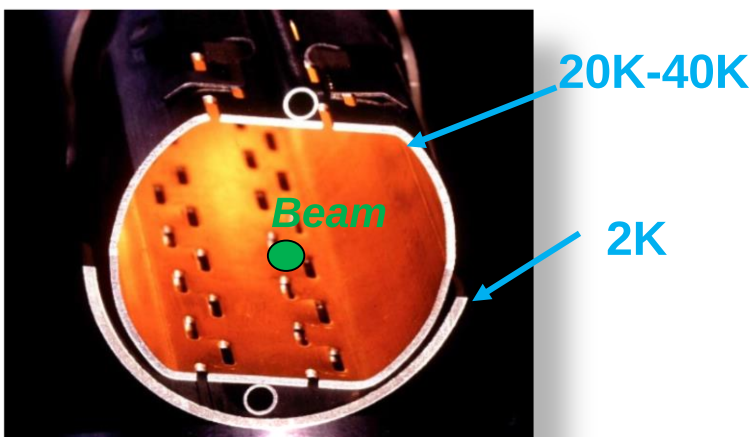
- But more impedance to the beam (higher resistivity)

Electron clouds

- ❑ **Electron cloud** effects:
  - – Vacuum pressure rise.
  - – Impact on beam quality (emittance growth, instabilities, particle losses).
  - – Excessive energy deposition on the vacuum chamber (~20K at LHC) → heat load on the cryogenic system.
- ❑ Electron clouds affect all high intensity machines with **<u>positive</u>** bunch charge (e^+ ⇔ B-factories).



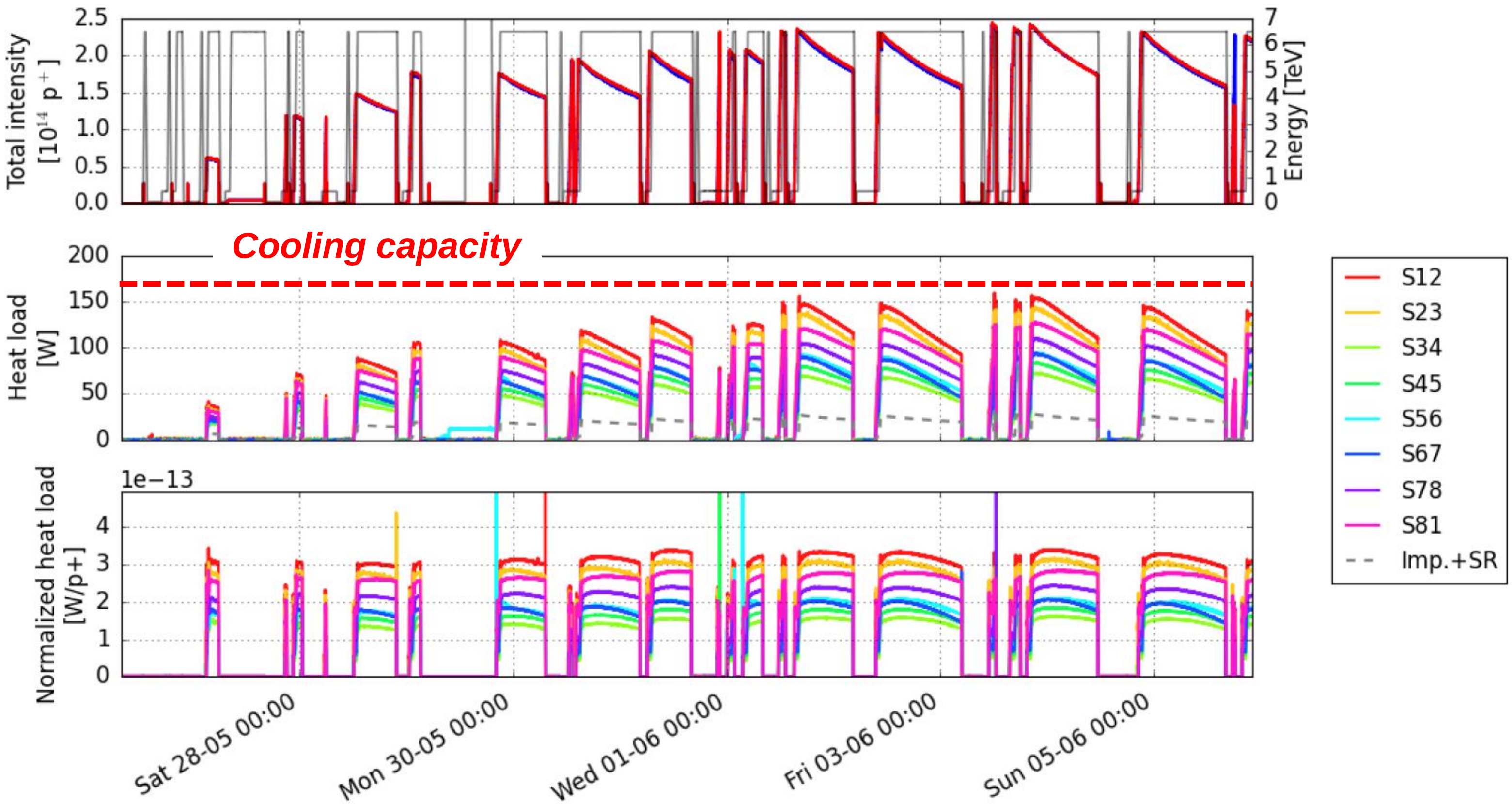
If the probably of emitting a secondary electron (Secondary emission yield [SEY]) above threshold $SEY>SEY_{th}$ ➔ avalanche effect (multipacting)
SEY_{th} depends on bunch spacing and population



<u>Remedies</u>:

- ❑ Conditioning by **beam-induced electron bombardment** (“**scrubbing**”) leading to a progressive reduction of SEY – LHC case.
- ❑ Vacuum chamber coating or shaping.

- Example of heat load to the LHC cryogenic system (per ~100 m of accelerator) due to electron cloud in regular operation.
- LHC is operated ~ at the limit of the cryogenic cooling capacity of the BS !



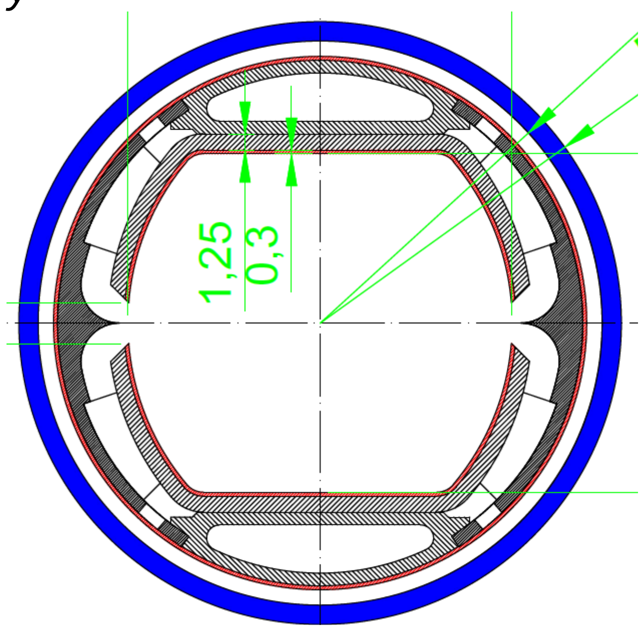
Electron cloud mitigation

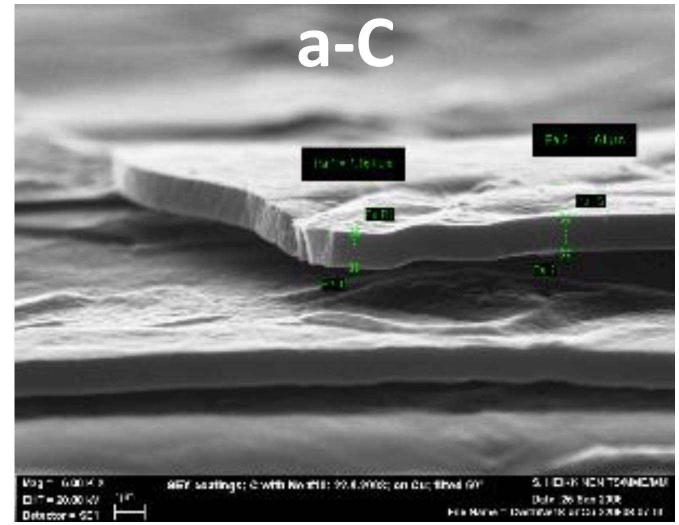
P. Costa Pinto et al.

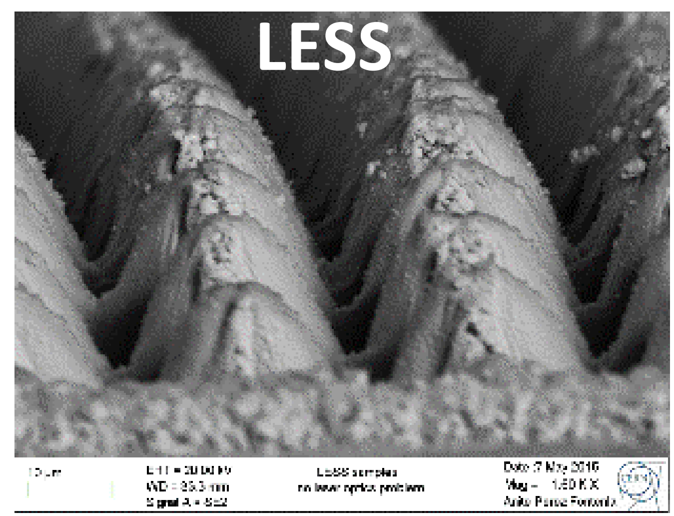
Developments are ongoing to improve the vacuum chamber properties in terms of electron cloud for the LHC luminosity upgrade:

- *Carbon coating of surface*
- *Laser treatment of surface (LESS)*

Geometry is very important !







Outline

Introduction

Luminosity

Magnets

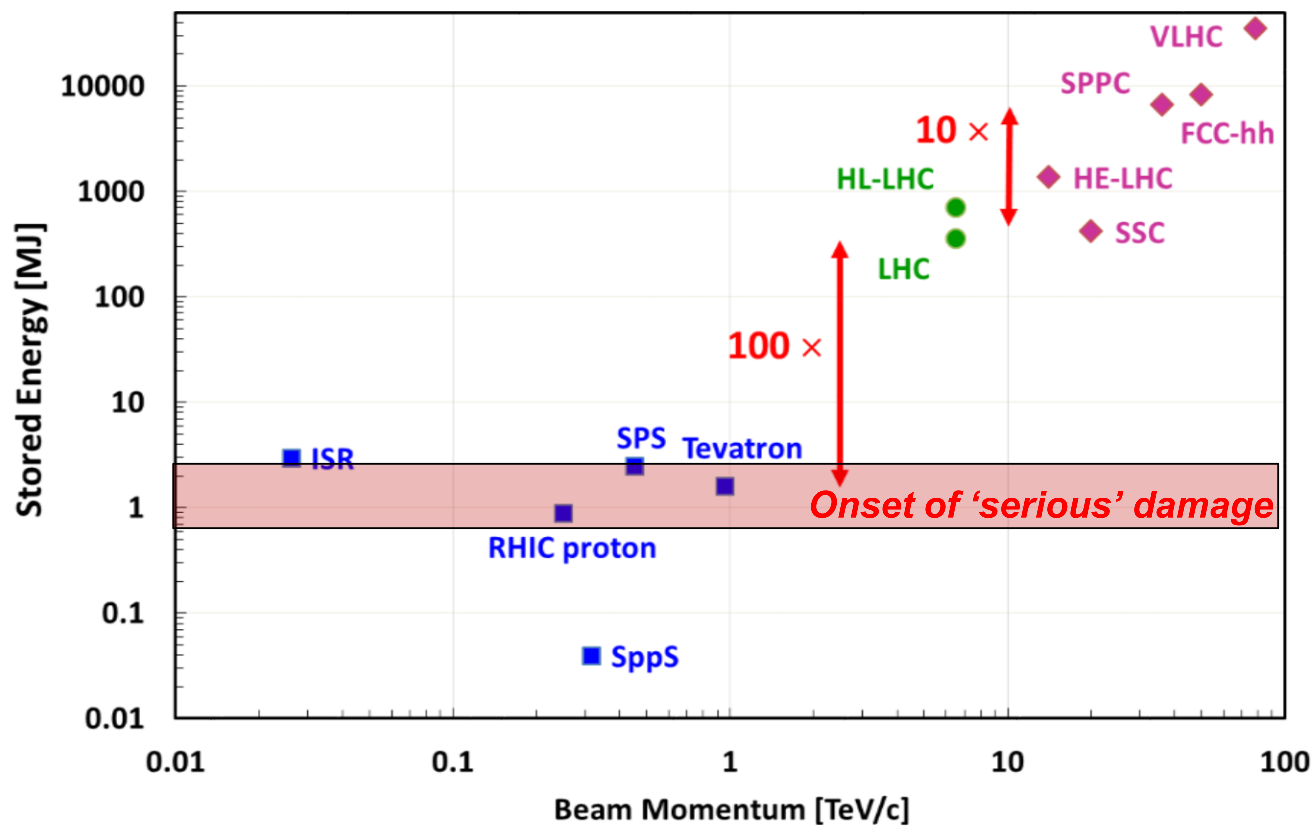
High intensity beams

Machine protection

Infrastructure and injectors

LHC pushed the stored energy from few MJs to > 100 MJs

The large hadron collider will make another step towards GJs



Stored energy ~10 GJ per beam

– At least one order of magnitude higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h).

– Collimation, control of beam losses and radiation effects (shielding) important.

– Injection, beam transfer and beam dump very critical.

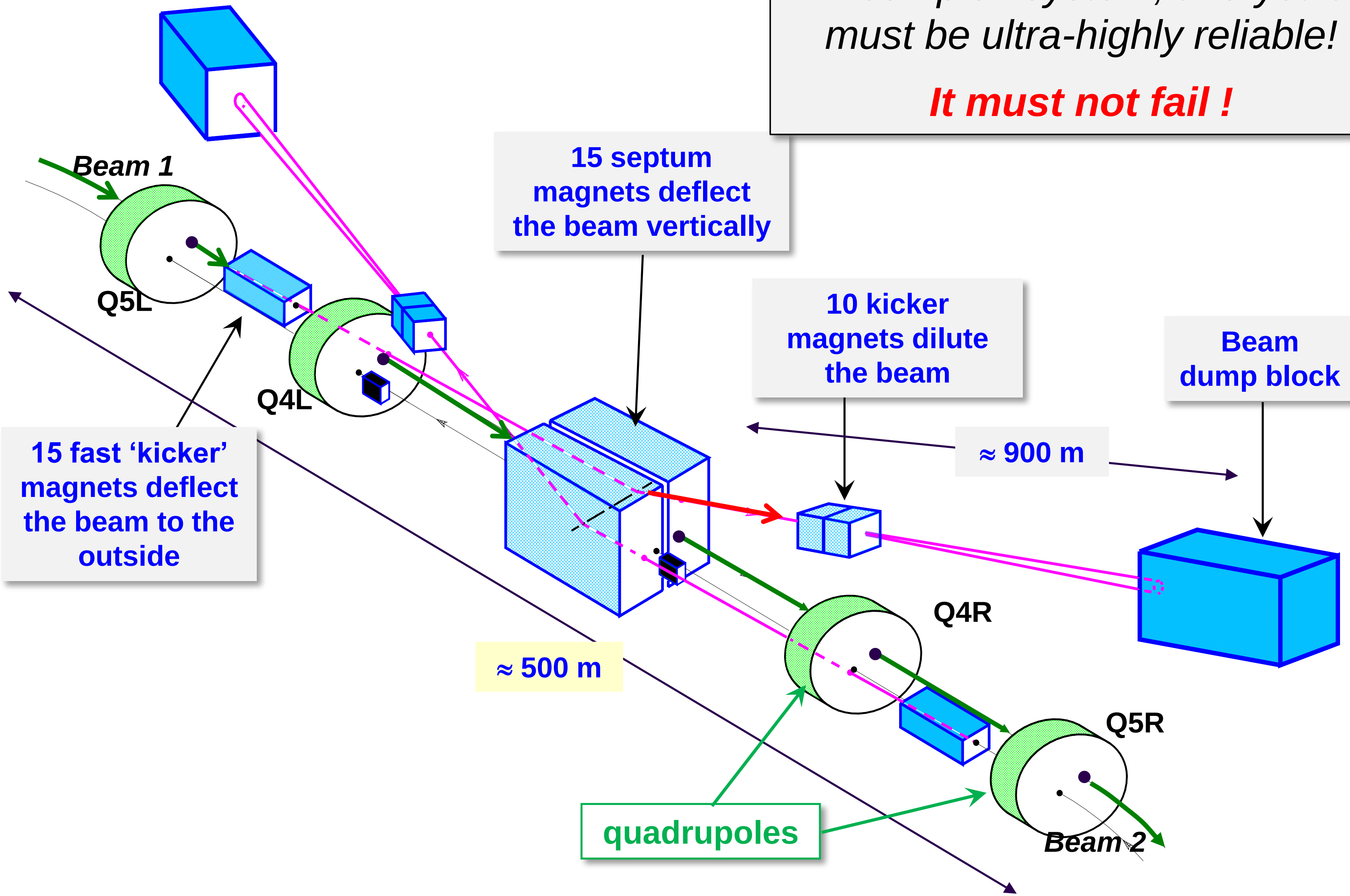
Damage of a beam with an energy of 2 MJ

Machine protection issues to be addressed early on!

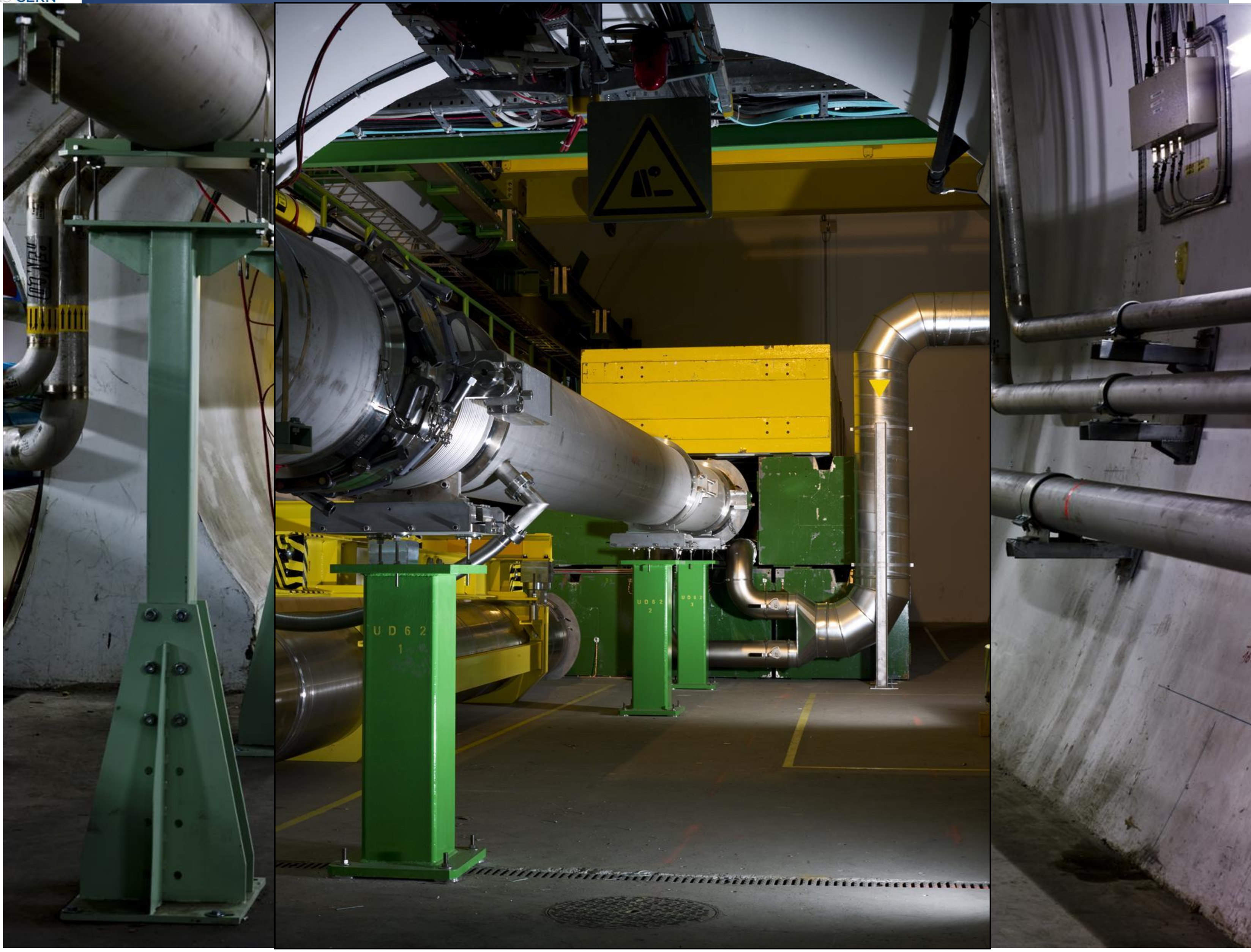
LHC beam dumping system

A complex system, and yet it must be ultra-highly reliable!

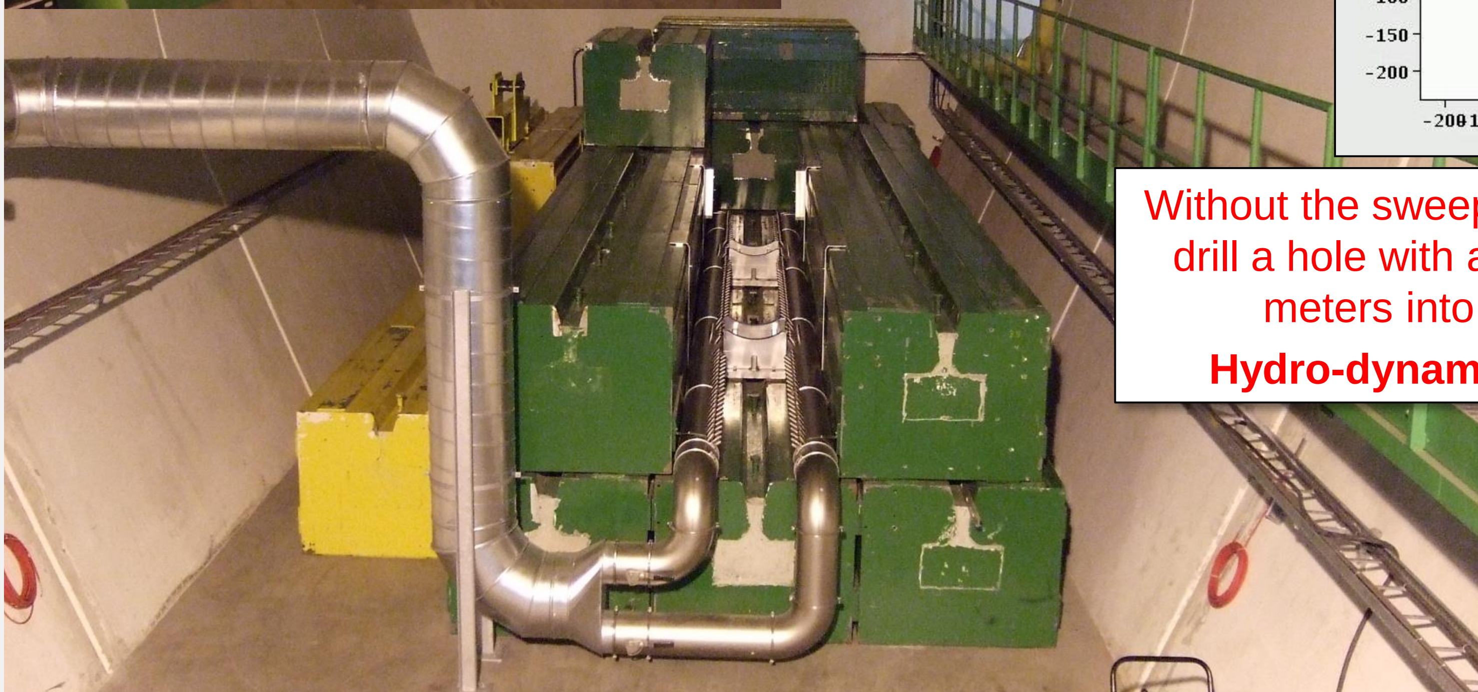
It must not fail !



LHC dump line

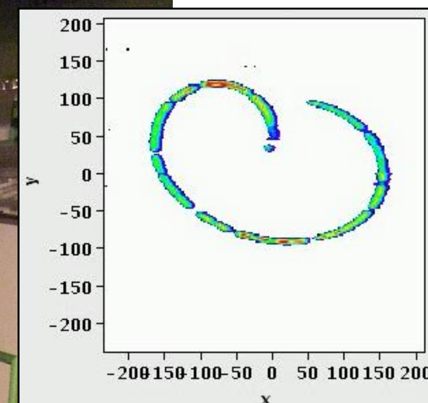


The LHC dump block



The dump block is the only LHC element capable of absorbing the nominal beam.

The beam is swept over dump surface to lower the power density.



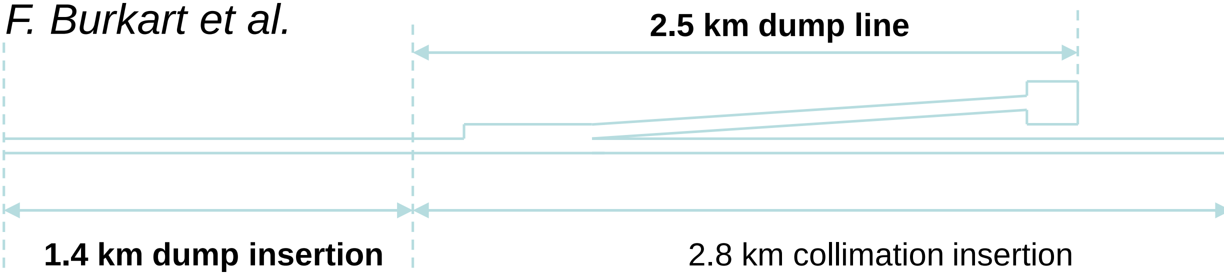
Without the sweep the beam could drill a hole with a depth of a few meters into the block !

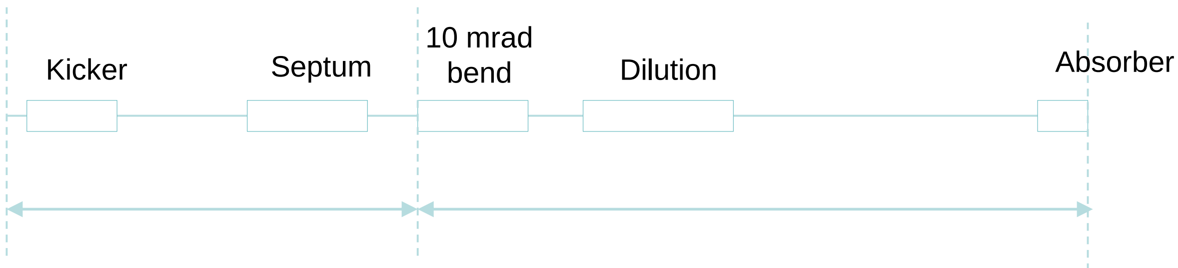
Hydro-dynamic tunnelling

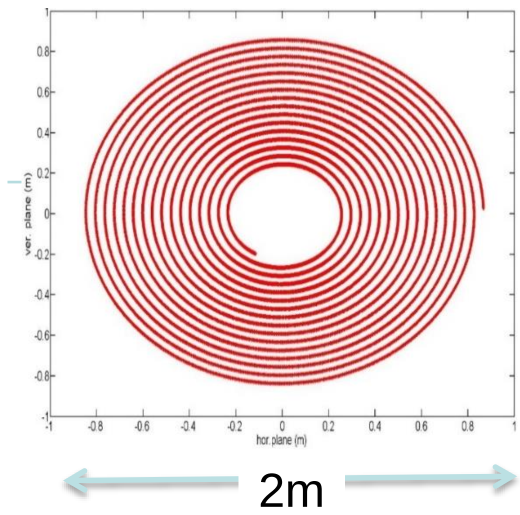
43

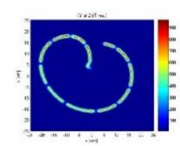
Dump and dilution - FCC-hh

F. Burkart et al.









LHC pattern (same scale)

Horizontal and vertical kicker system as in the LHC

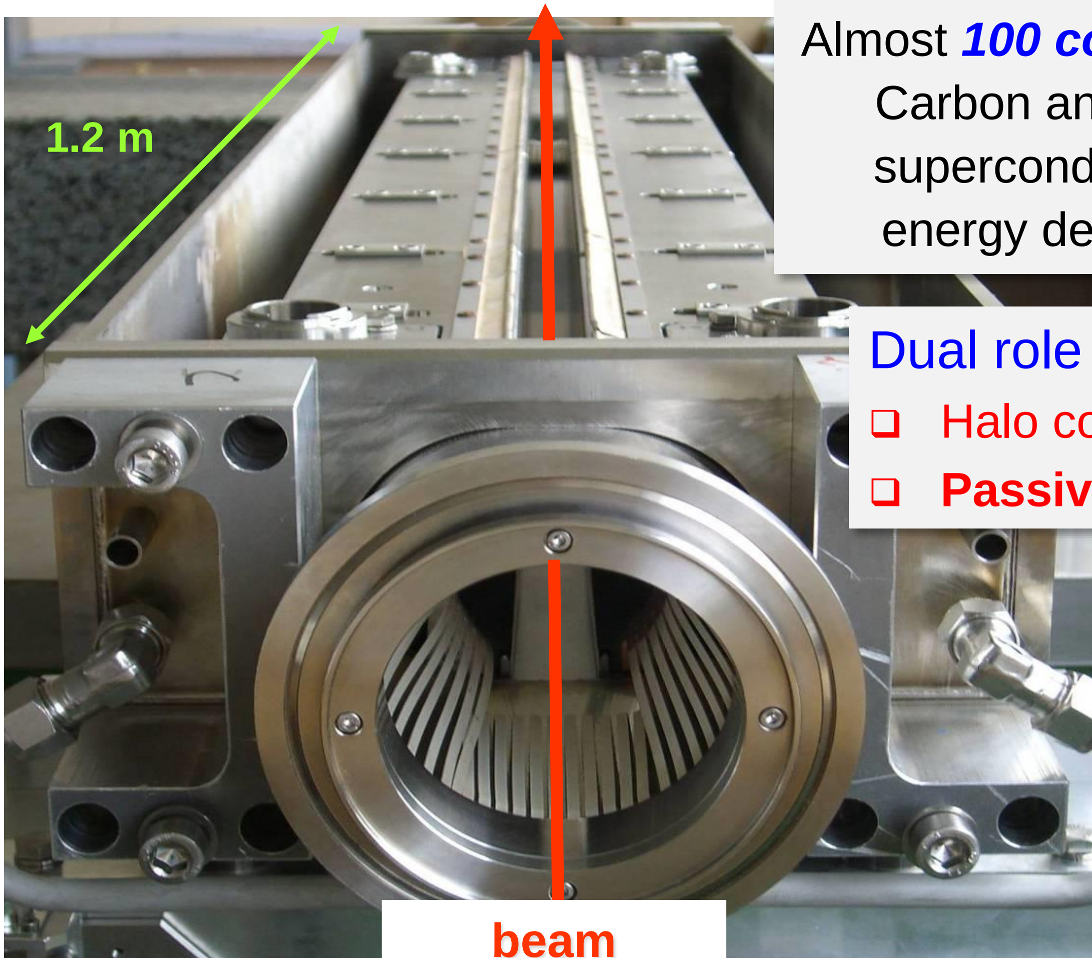
- **~ 300 m long, ~150 kickers (→ advantage for failures).**
- Large magnet apertures required towards dump

Dilution is very critical, different solutions studied

- Require up to 80cm radius for the diluted beam.

Beam collimation (cleaning)

- The LHC is the first hadron collider to require a complex multi-stage collimation system to operate at high intensity.
  - *Previous hadron machines used collimators only for experimental background conditions.*

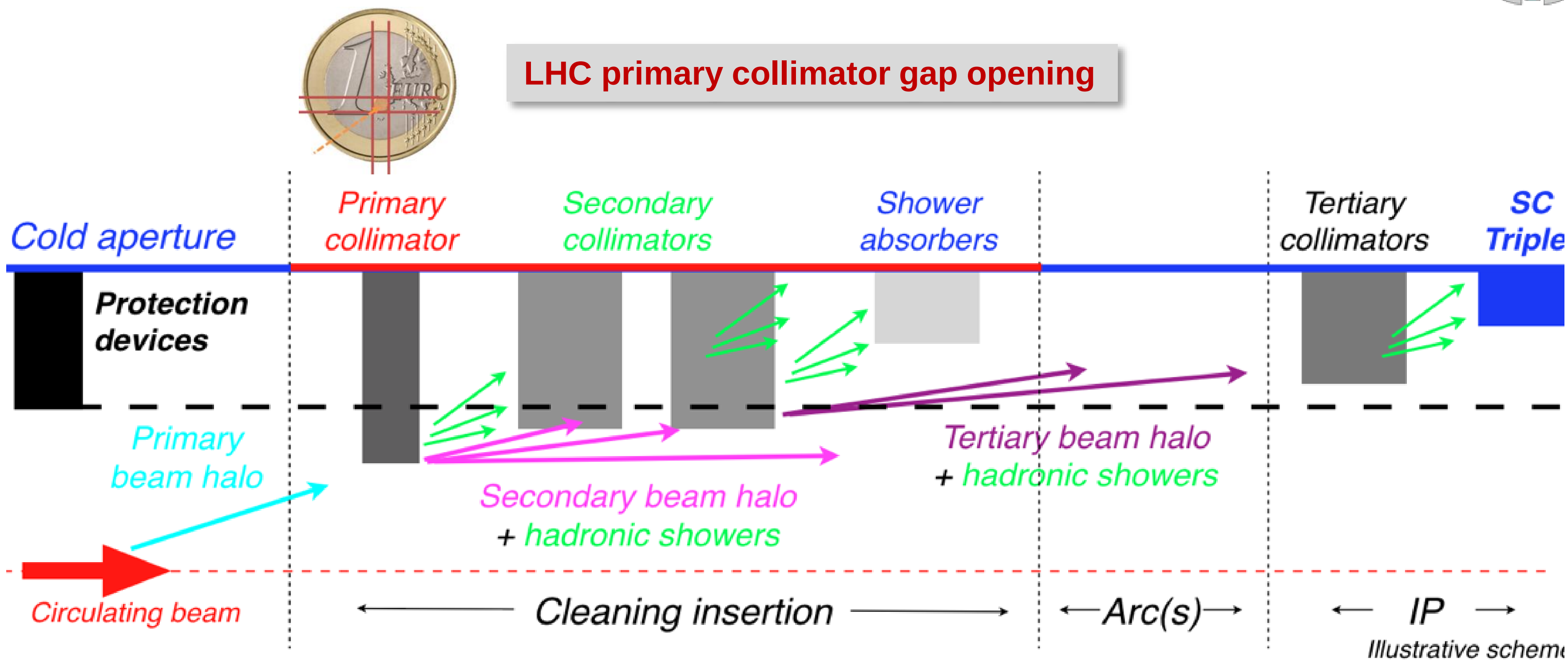


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

Dual role of collimators:

- Halo collimation (cleaning)
- **Passive protection** of the machine

Multi-stage collimation systems



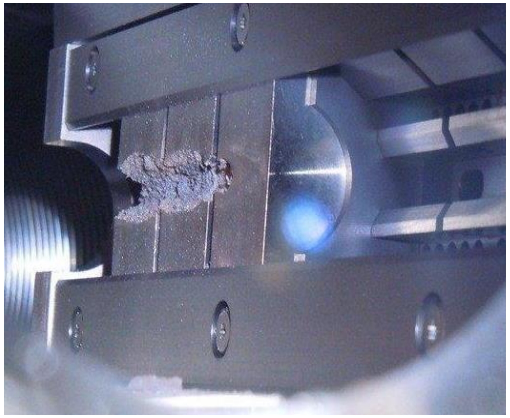
- To be able to absorb the energy of the high energy hadrons, a multi-stage collimation system is required – primary, secondary, tertiary.
  - Demonstrated to work at the LHC – with excellent performance.
- While for LHC the efficient is at the level of **99.95% or better**, VHECs may require one order of magnitude better cleaning.
  - Efficiency = fraction of protons lost from the beam that are intercepted.

New collimator materials

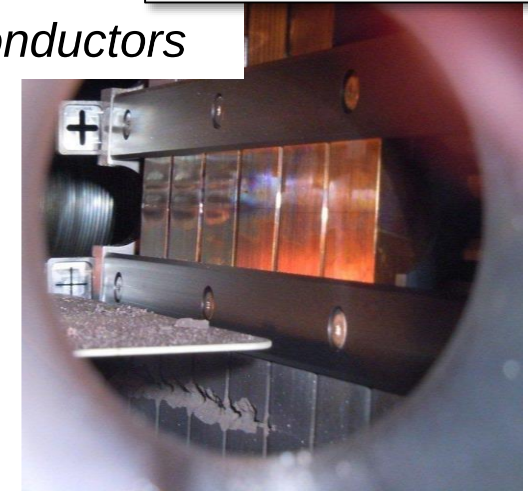
Beam tests for new collimator materials:

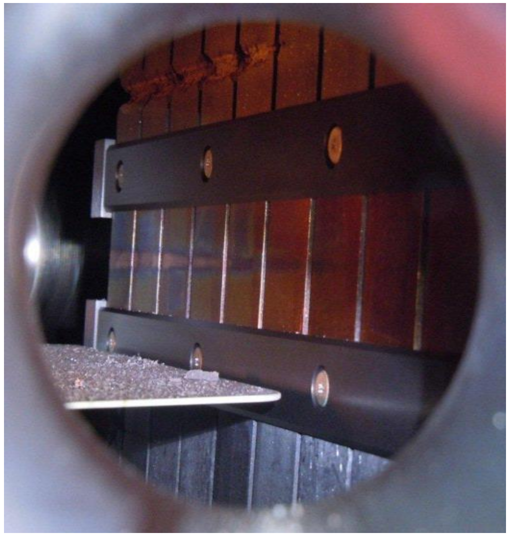
Courtesy A. Bertarelli (EN)

- They should be robust (shock impacts) and good conductors


Inermet 180, 72 bunches


Molybdenum, 72 & 144 bunches


Glidcop, 72 bunches (2 x)


Copper-Diamond 144 bunches


Molybdenum-Copper-Diamond 144 bunches

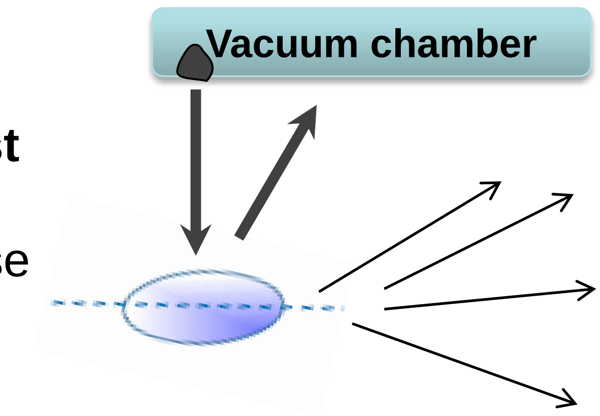

***Molybdenum-Graphite** (3 grades) 144 bunches*

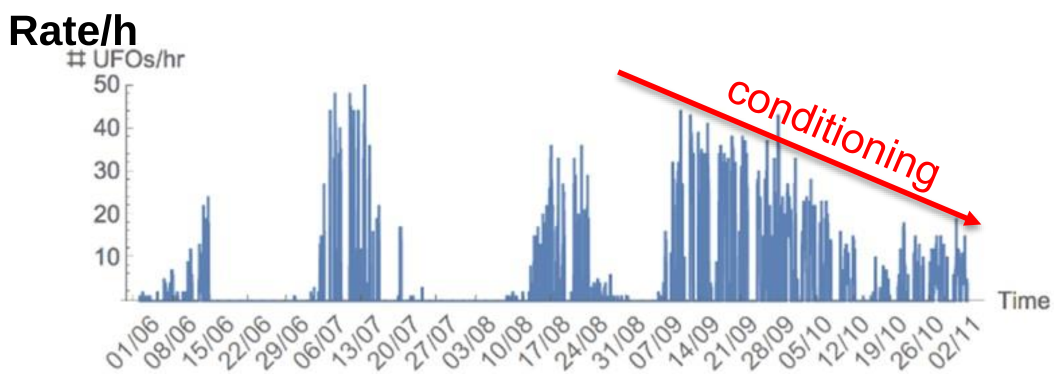
A new regime

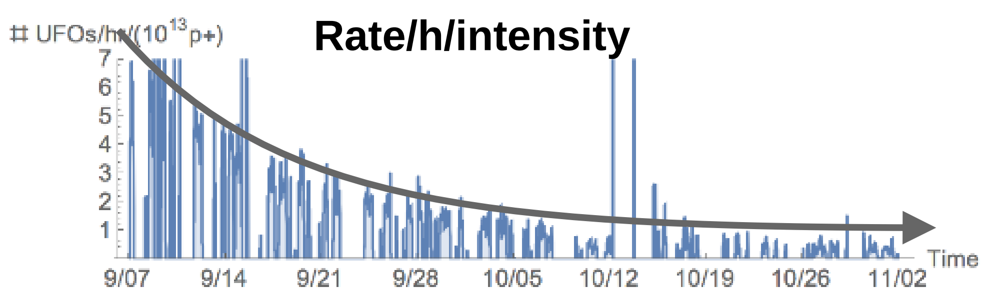
- At the LHC the energy stored in the injected and circulating present a damage to any accelerator component around the beam line, but **passive protection is available to mitigate all failure cases**.
- At the LHC such passive protection will survive the beam impacts in case of failure provided the machine is correctly setup and operate safely.
- For the next generation VHECs, this may no longer the case due to the higher particle energy (more material to absorb the beams) and the higher stored energy: failures could lead to damage of the protection components.

Vicious little falling objects

- LHC observed strange beam losses that where nicknamed UFOs (**Unidentified Falling Objects**).
- According to the most credible theory, UFOs are **dust particles** that fall into the beam and generate beam losses due to inelastic collisions with the beam. These losses can quench a superconducting magnet.
  - *If the losses are too high, the beams are dumped to avoid a magnet quench (up to 20 times / year)*







- Conditioning is observed over time, and rates come down.
- At the LHC we are **'lucky'** that the dump rates are acceptable, and the beam loss generally below dump threshold. This may NOT be the case for the more sensitive VHECs !

A potential VHEC killer !

Outline

Introduction

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Tevatron

Installed in a 6.3 km tunnel

Depth: ~10 m

LHC

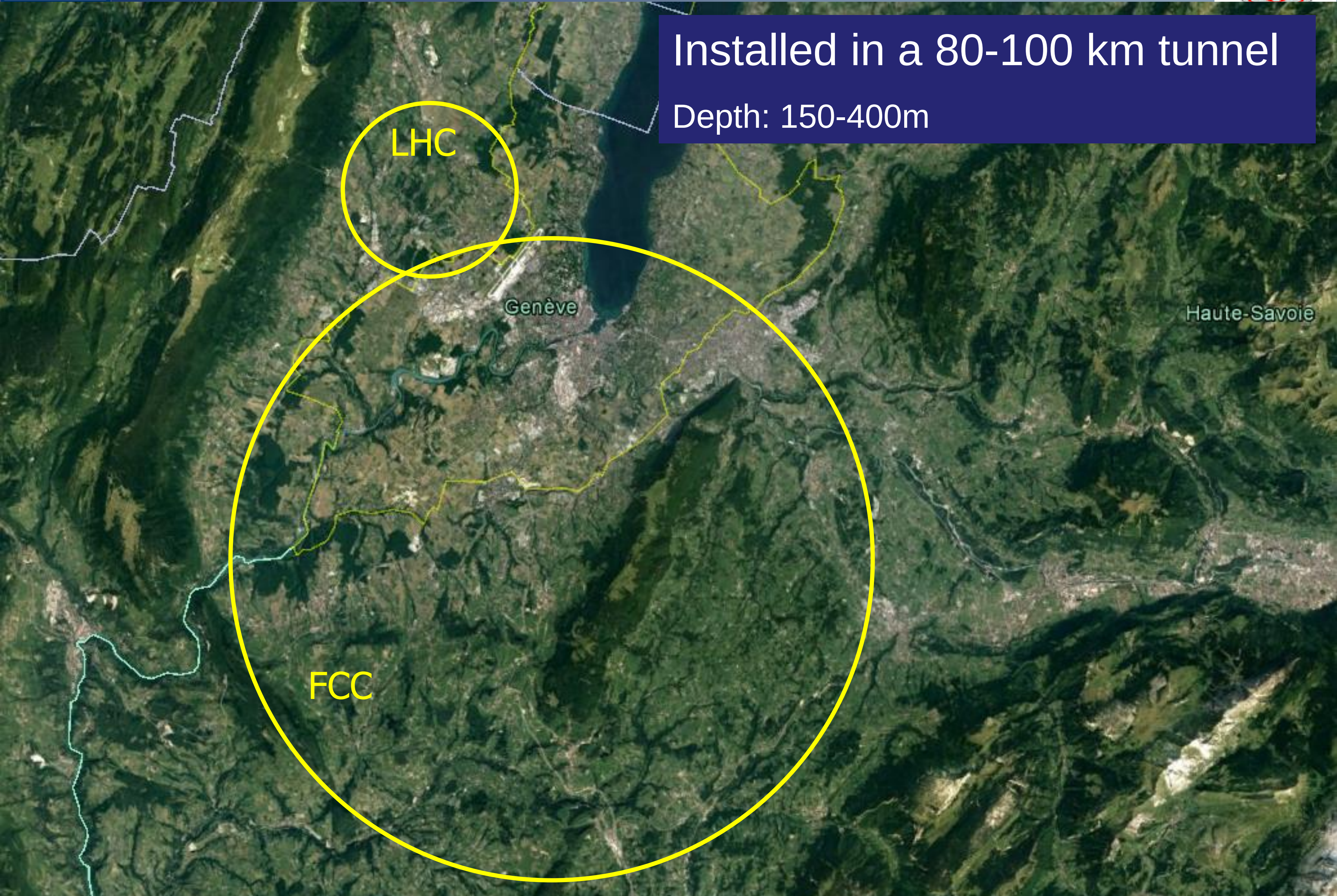
Installed in the 26.7 km LEP tunnel

Depth: 70-140 m

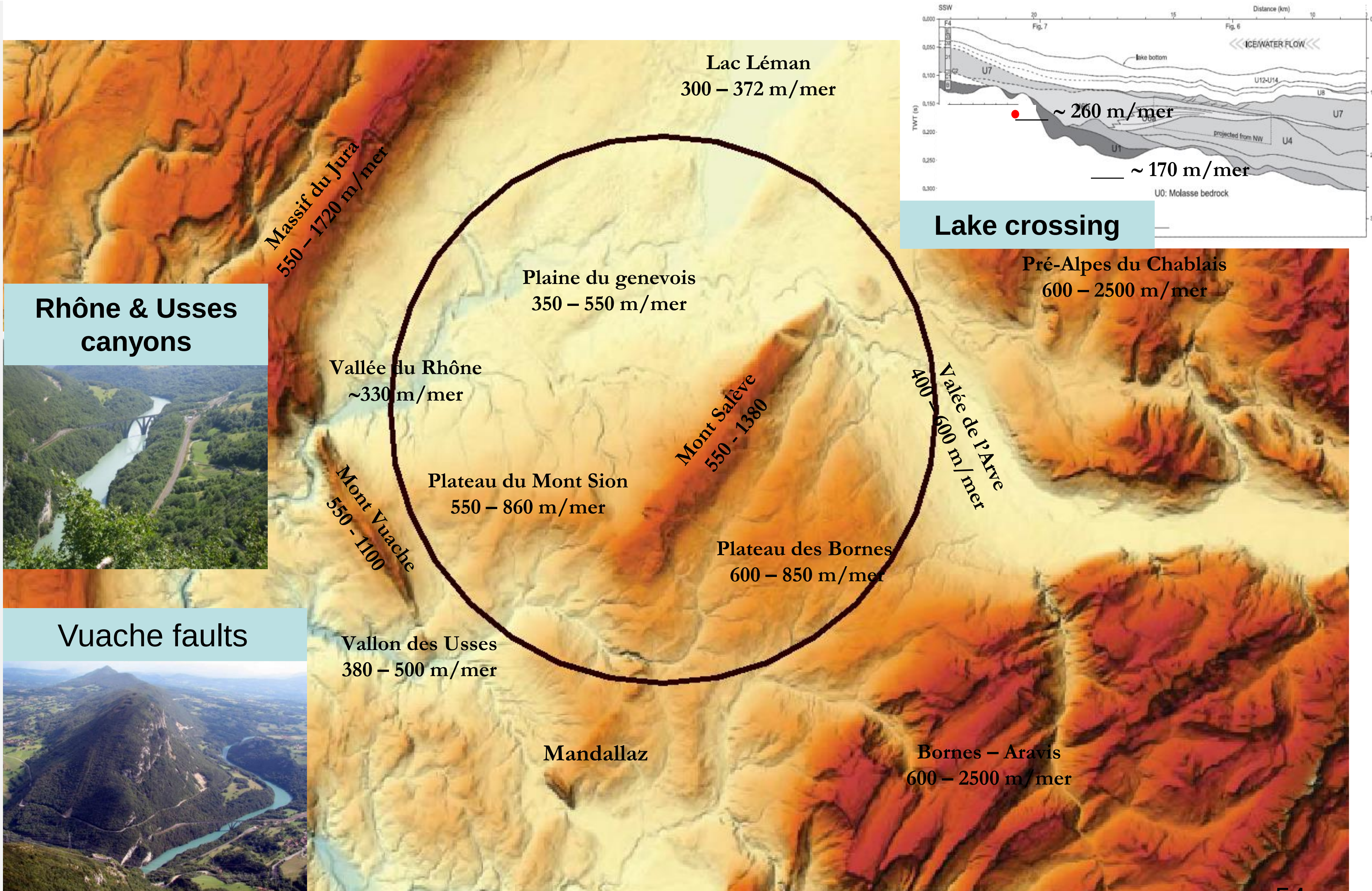
FCC

Installed in a 80-100 km tunnel

Depth: 150-400m



Topographical constraints, critical areas



Lake crossing

Rhône & Usses canyons

Vuache faults

FCC 100 km possible siting

Alignment | Shafts | Query

Choose alignment option: 100km quasi-circular

Tunnel elevation at centre:261mASL

Grad. Params

Azimuth (°): -20

Slope Angle x-x(%): 0.65

Slope Angle y-y(%): 0

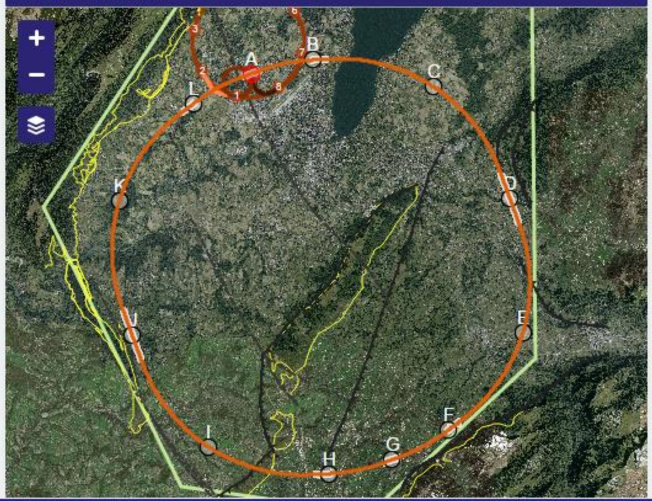
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499731 Y: 1108403

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

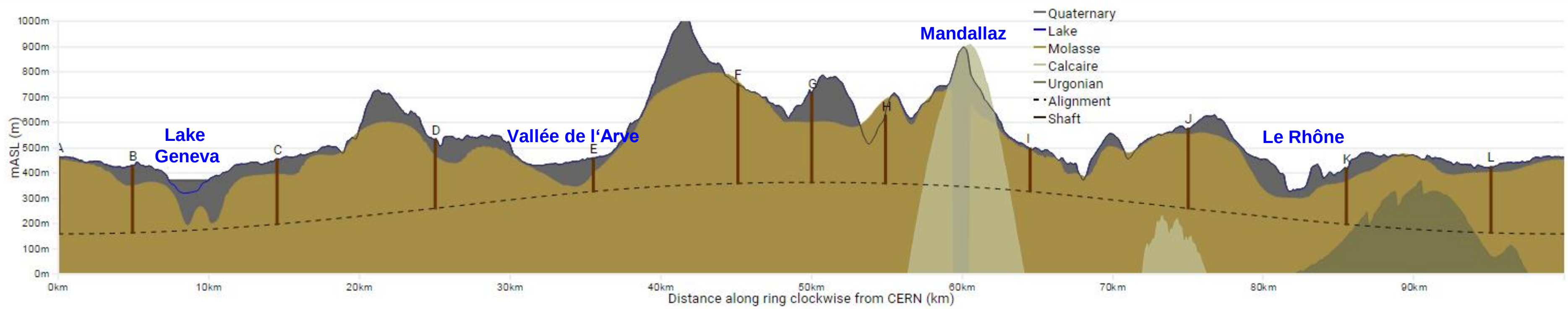
Alignment Location



Geology Intersected by Shafts | Shaft Depths

Shaft Depth (m)		Geology (m)			
Point	Actual	Quaternary	Molasse	Urgonian	Calcaire
A	304	12	292	0	0
B	266	80	186	0	0
C	257	58	199	0	0
D	272	64	208	0	0
E	132	64	68	0	0
F	392	0	392	0	0
G	354	116	237	0	0
H	268	0	268	0	0
I	170	12	158	0	0
J	315	22	293	0	0
K	221	52	169	0	0
L	260	21	239	0	0
Total	3211	501	2710	0	0

Alignment Profile

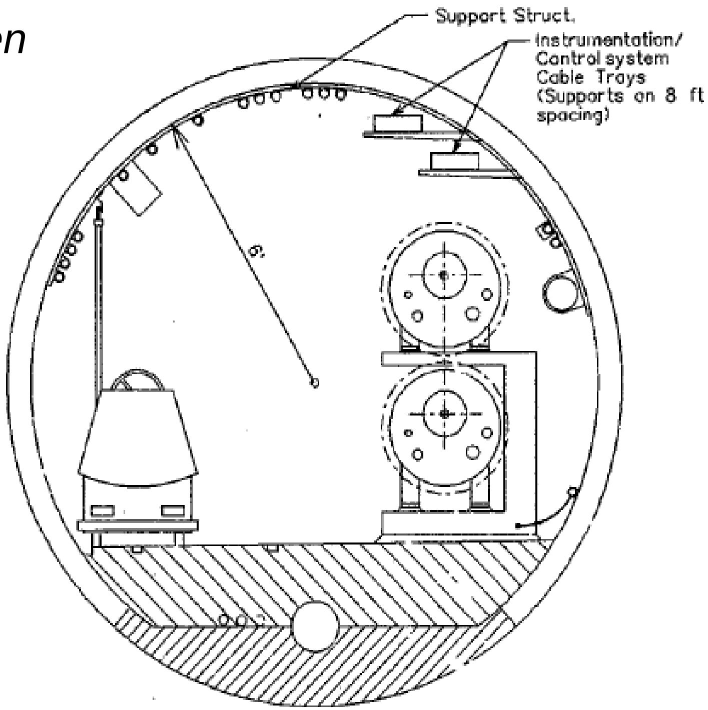


Geology Intersected by Tunnel | Geology Intersected by Section

A tool developed by a consultant firm including all information on the geology is able to model the ring at varying depth, angle etc → layout optimization.

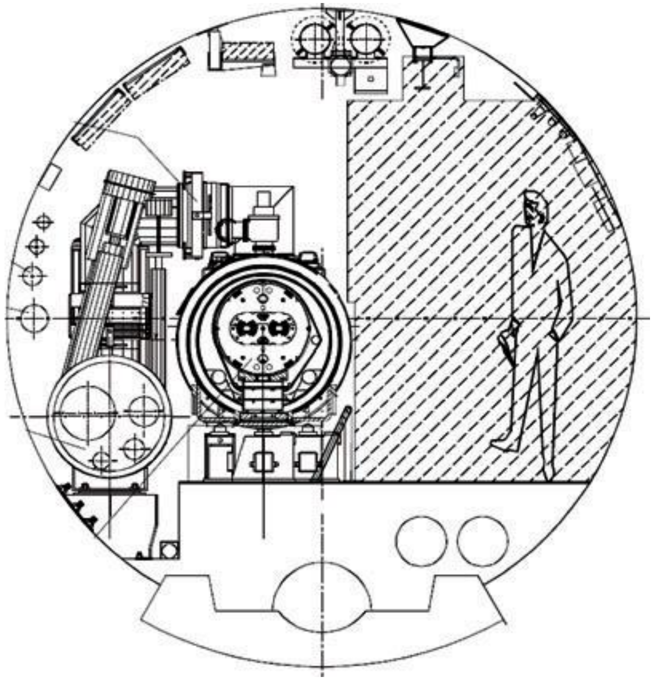
SSC and LHC tunnels

T. Sen



3.7 m

SSC tunnel

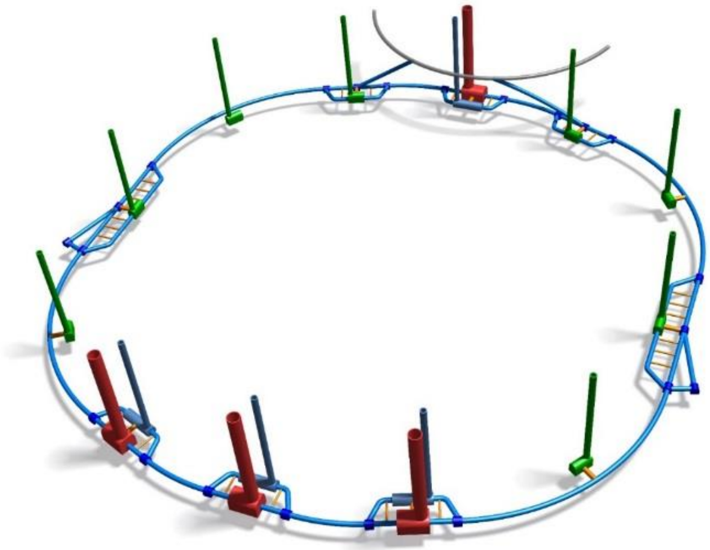


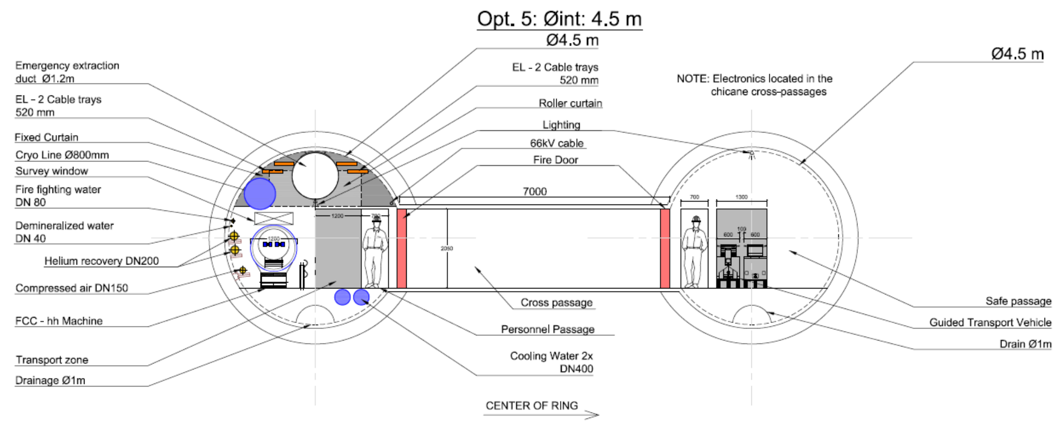
3.8 m

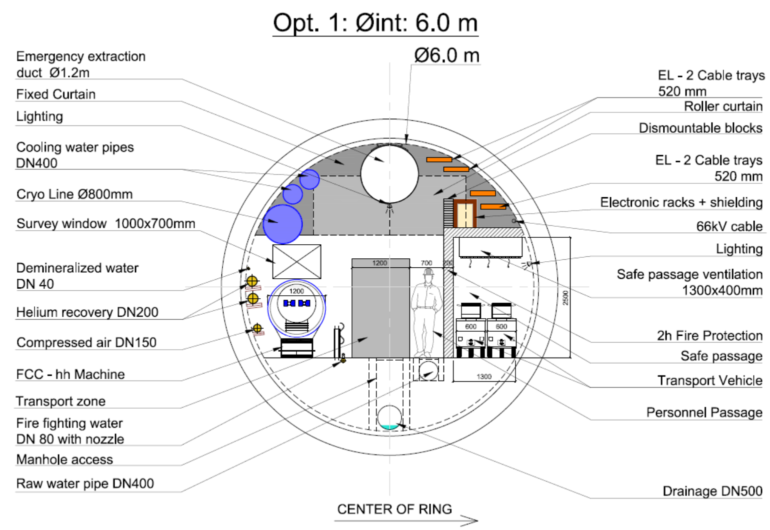
LHC tunnel

- LHC & SSC tunnels quite similar in size.
- **Single tunnels represent a risk to personnel** in case of fire or Helium release due to the long distance to an escape point → LHC experience…

FCC tunnel layouts



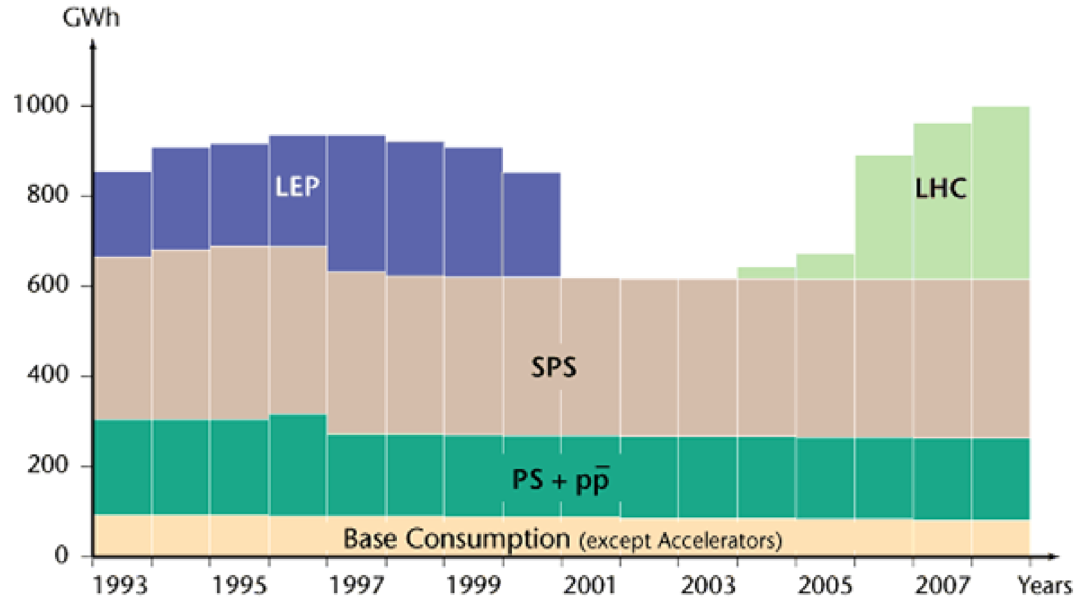




First studies launched on

- *Single vs. double tunnel*
- *Ventilation (fire, Helium !)*
- *Caverns, shafts, underground layout*
- *Technical infrastructures*
- *Safety, access*
- *Transport, integration, installation*
- *Operation aspects*

Electricity consumption - CERN



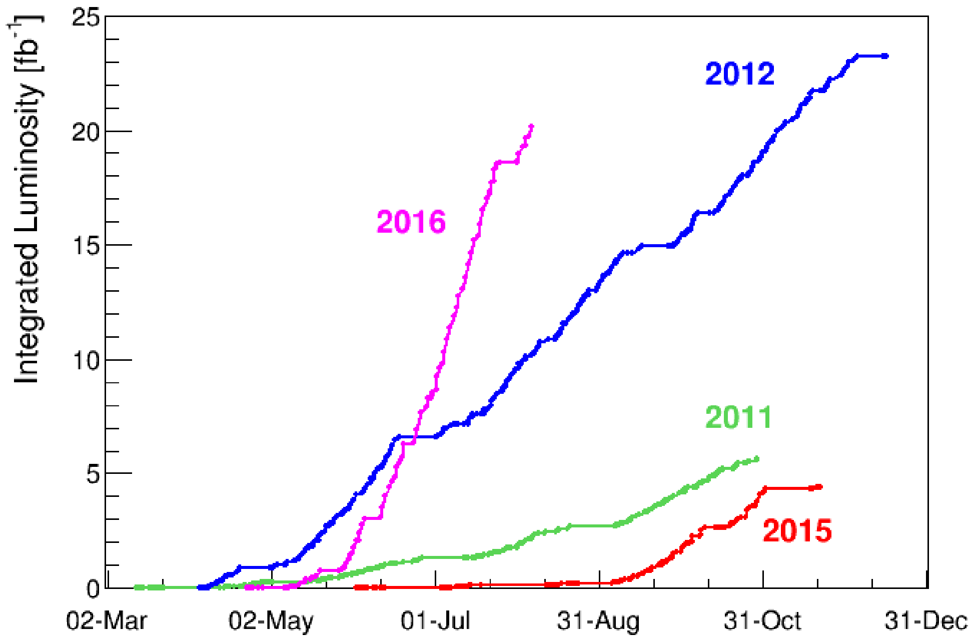
- The current CERN electricity consumption is around ~180 MW.
- The LHC (with experiments) uses ~120 MW (~35 MW for cryogenics).
- A VHEC would require an additional **~250-400 MW** of power.

Operation and availability

- Operating ever larger colliders *increases the number of components* (that can fail !) and the complexity of commissioning and of operation.
- The LHC has demonstrated that **huge cryogenics systems can operate with availability of 95% and higher**.
- The LHC also highlighted the importance of availability, good maintenance and design policies (redundancy): work on availability managed to gain an important factor in the operation efficiency and ultimately integrated luminosity.

Key factor for VHECs !

The main factor to increase the slope in 2016 is much better availability (almost a factor 2 !)



Summary

- VHECs are the potential next generation discovery machines, there are currently 3 projects that are studied: **HE-LHC**, **SPPC** and **FCC-hh**.
- VHECs present us with a number of challenges, the first one being to build ~16 T magnets to be able to run them.
- Beam dynamics challenges are important but potential solutions are in sight.
- Once technical aspects have been solved, the society impact will have to be considered: cost, energy consumption, impact on the environment, effect on property value etc.

Very Large Hadron Collider

Public Acceptance

- Must work on public acceptance from the beginning.
- The old way of "decide, announce, defend" will not work.

P. Limon, VLHC seminar at Fermilab

A few selected references

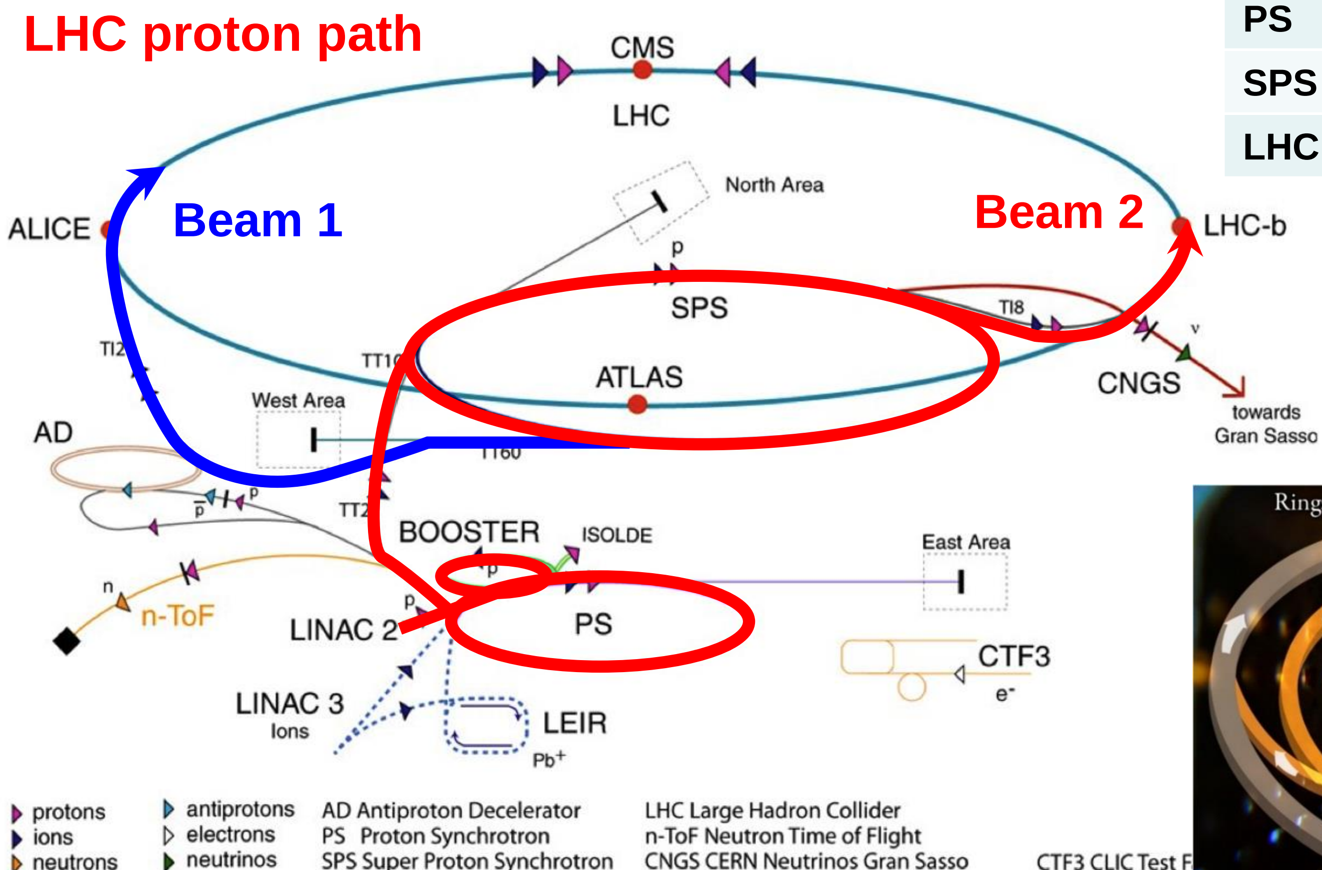
- T. Sen, SSC Parameter Review, Joint Snowmass-EuCARD / AccNet-HiLumi LHC workshop, February 21-22, 2013
- The LHC Design Report, CERN-2004-003
- The VLHC design study group, Design Study for a Staged Very Large Hadron Collider, Fermilab-TM-2149
- P. Limon, Design Study for a Staged Very Large Hadron Collider, Fermilab-TM-2149, 2001
- J. Tang et al, Concept for a Future Super Proton-Proton Collider, arXiv: 1507.03224v1 [hep-ex]
- The Future Circular Collider Study, http://cern.ch/fcc
- FCC week 2016, https://indico.cern.ch/event/438866/

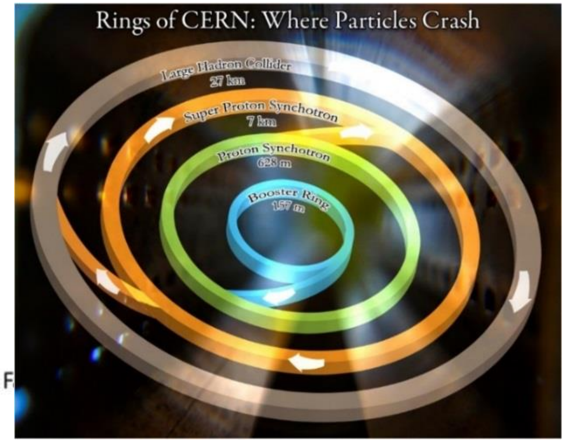
LHC accelerator complex

The proton journey from the source to injection into the LHC lasts ~7-24 seconds

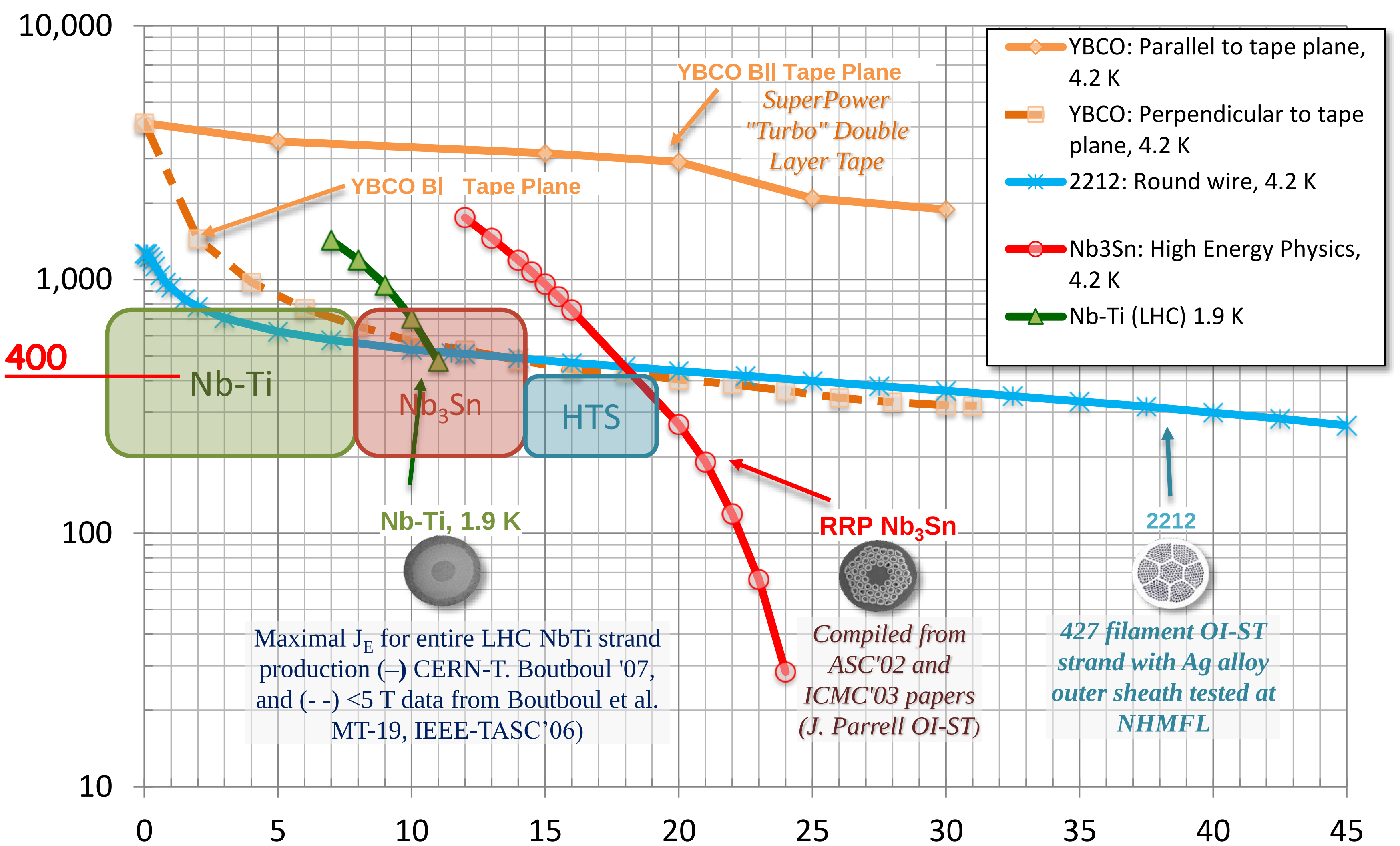
	Max. P (GeV/c)	Length / Circ. (m)
LINAC2*	0.050	30
Booster*	1.4	157
PS	26	628
SPS	450	6'911
LHC	6'500	26'657

***: kinetic energy**





Advanced super-conductors



Ph. Lebrun

Beam Dump Considerations

8GJ kinetic energy per beam

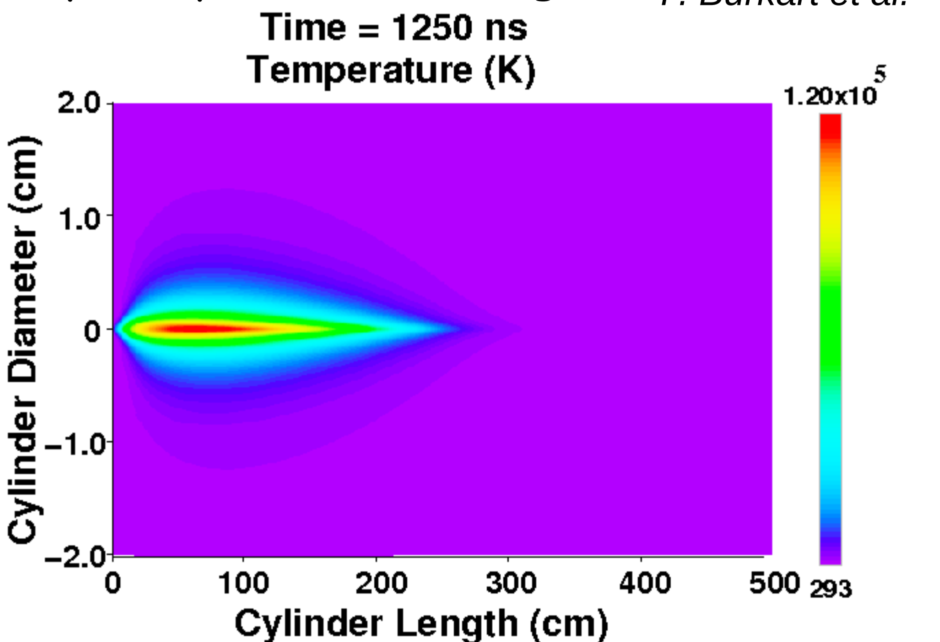
- Airbus A380 at 720km/h
- 2000kg TNT
- 400kg of chocolate
  - Run 25,000km to spent calories
- O(20) times LHC

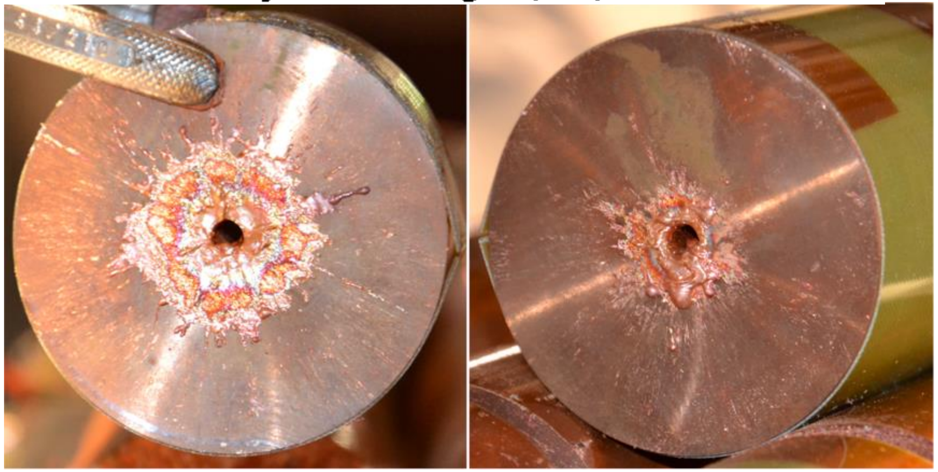
Simulation show beam will penetrate ~ **300 m** in Copper, assuming no dilution.

→ **Dilution required!**

Hydrodynamic tunneling

F. Burkart et al.





Collimation for FCC-hh

- To protect machine and experiments,
- At injection the machine aperture is tightest in the arcs, at collision energy in the magnets next to the experiments