Challenges for Engineers in Particle Accelerators

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CERN

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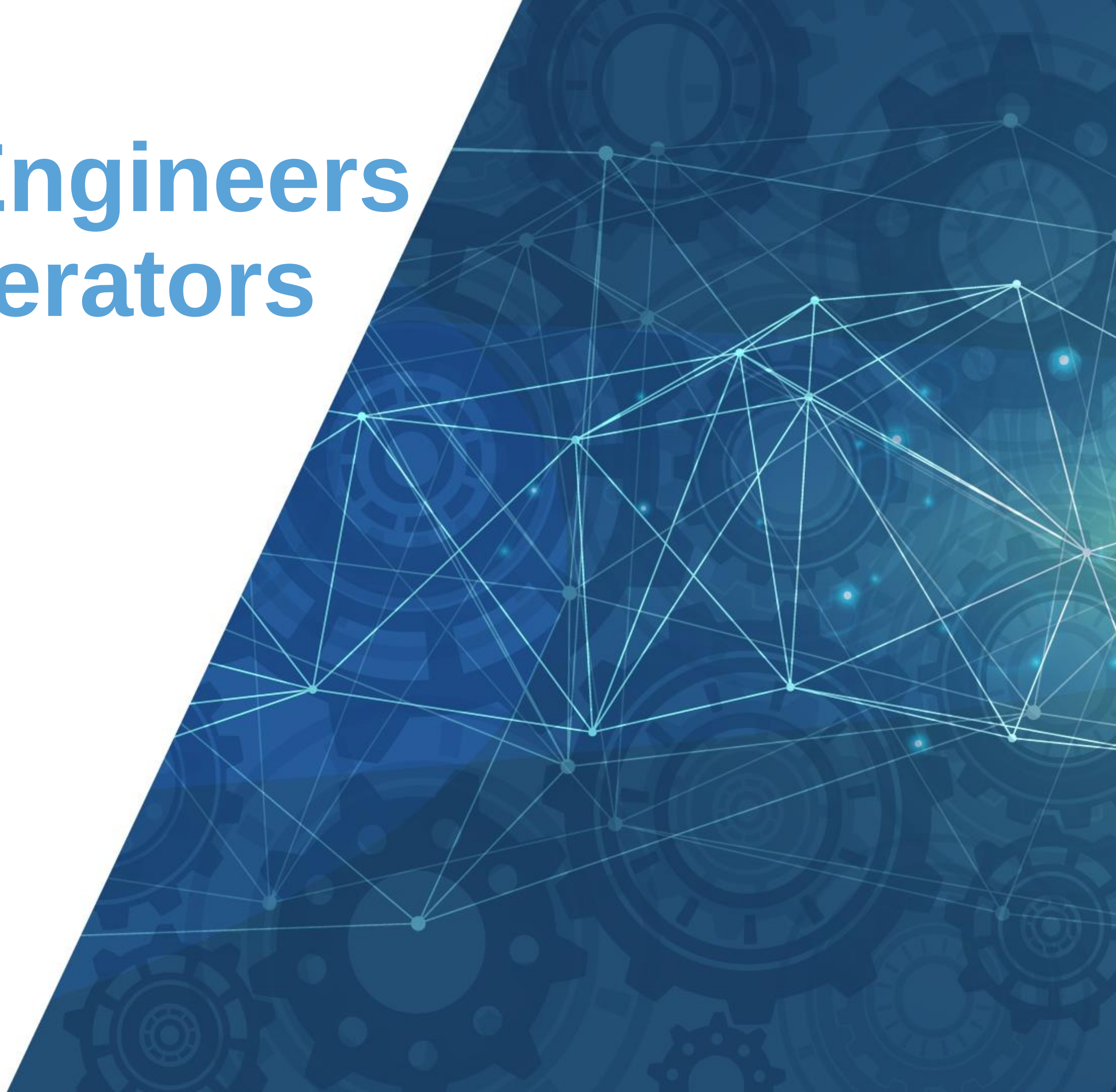


Agenda

- Introduction to CERN
- The LHC and the High Luminosity LHC
- The European Strategy for High Energy Physics
- The Future Circular Collider
- CLIC and the ILC
- Plasma accelerators
- Conclusions

Science for peace

CERN was founded in 1954 with 12 European Member States

CERN's annual budget is 1200 MCHF (equivalent to a medium-sized European university)

As of 31 December 2020
Employees:
2635 staff, **756** fellows

Associates:
11 399 users, **1687** others

23 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Finland – France – Germany – Greece
Hungary – Israel – Italy – Netherlands – Norway
Poland – Portugal – Romania – Serbia – Slovakia
Spain – Sweden – Switzerland – United Kingdom

3 Associates Member States in the pre-stage to membership

Cyprus – Estonia – Slovenia

7 Associate Member States

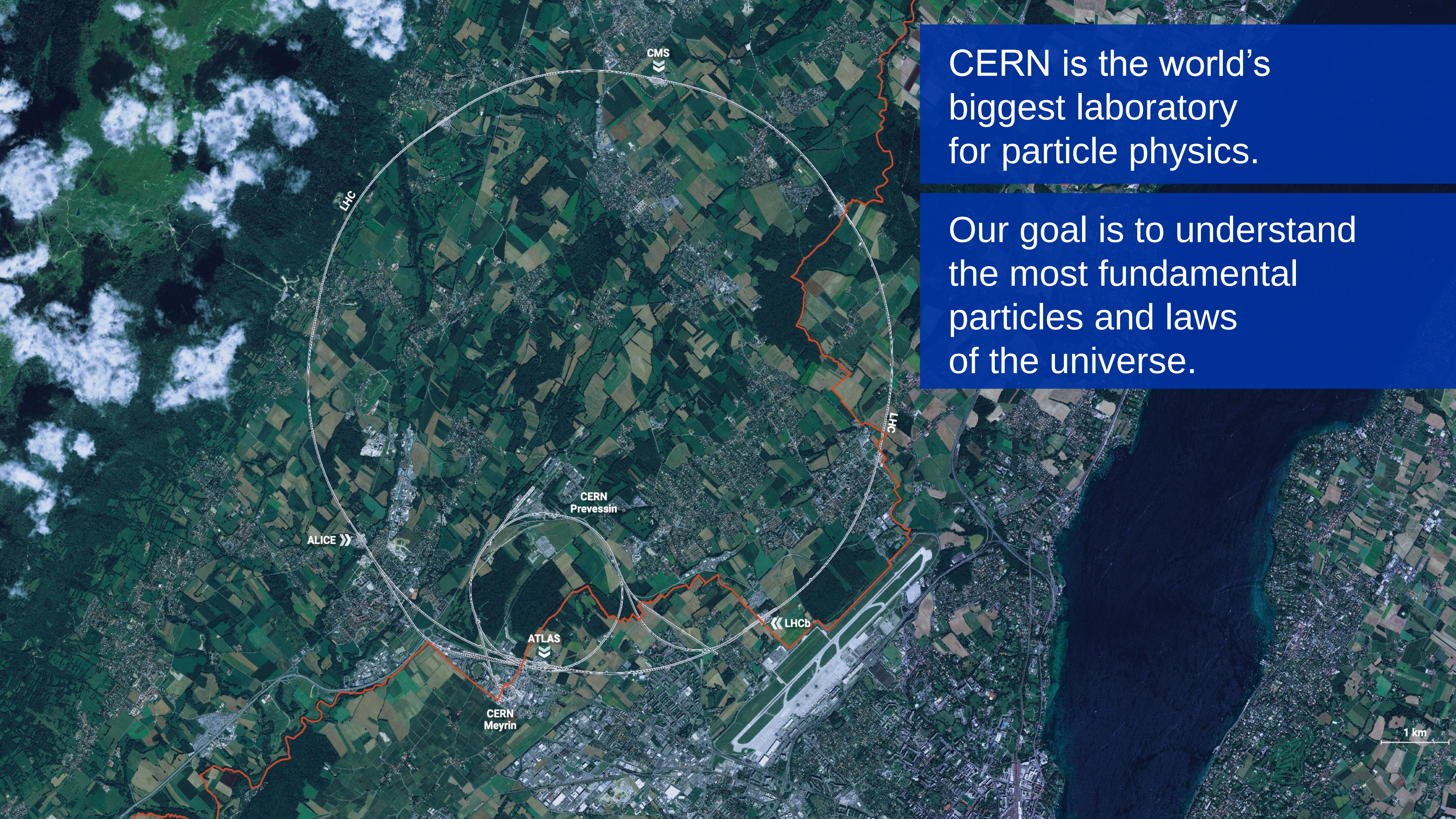
Croatia – India – Latvia – Lithuania – Pakistan – Turkey – Ukraine

6 Observers

Japan – Russia – USA
European Union – JINR – UNESCO

More than 50 Cooperation Agreements with non-Member States and Territories

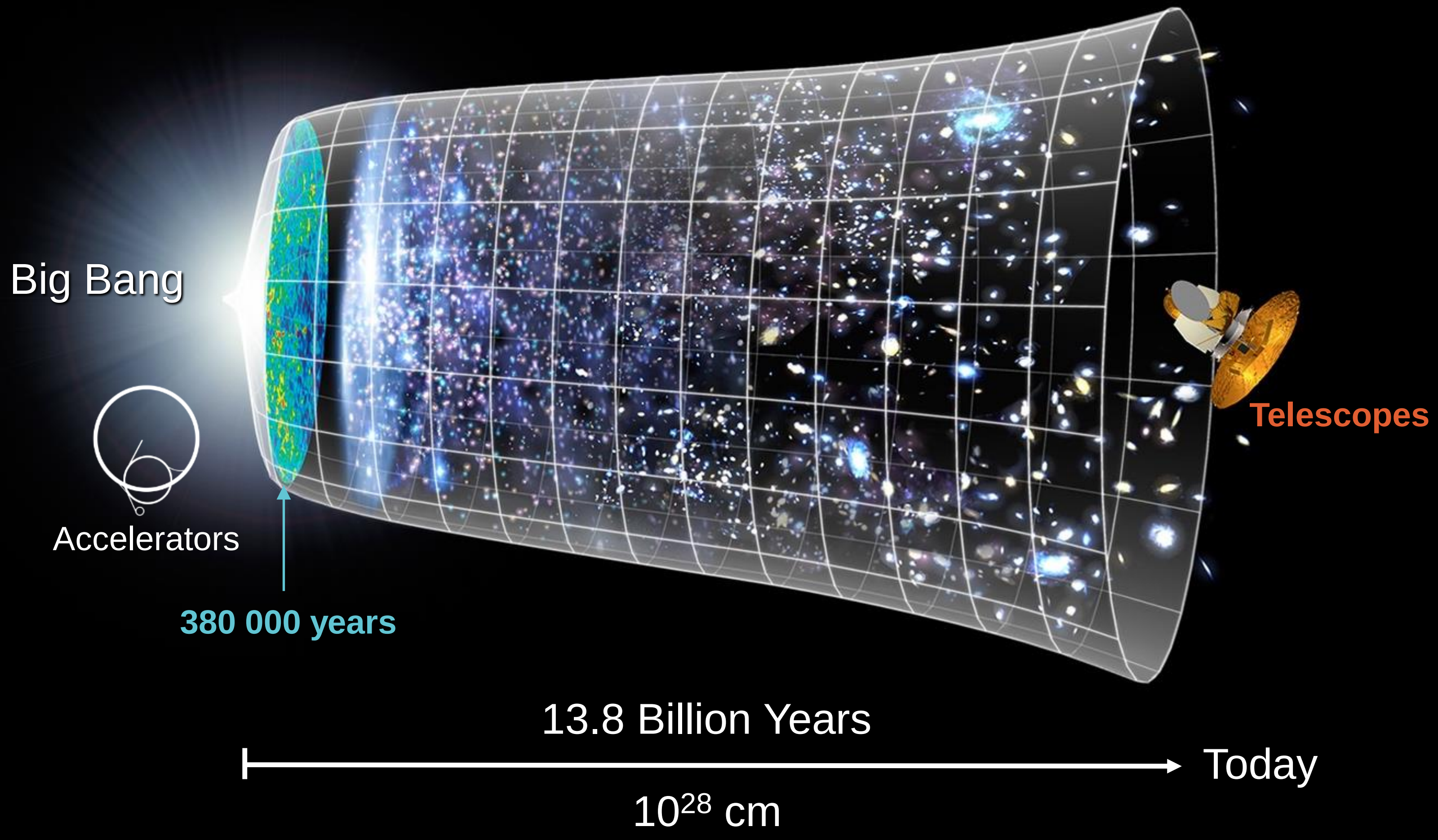
Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Brazil – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Iceland
Iran – Jordan – Kazakhstan – Latvia – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal
New Zealand – North Macedonia – Palestine – Paraguay – People's Republic of China – Peru – Philippines – Qatar
Republic of Korea – Saudi Arabia – Sri Lanka – South Africa – Thailand – Tunisia – United Arab Emirates – Vietnam



CERN is the world’s
biggest laboratory
for particle physics.

Our goal is to understand
the most fundamental
particles and laws
of the universe.

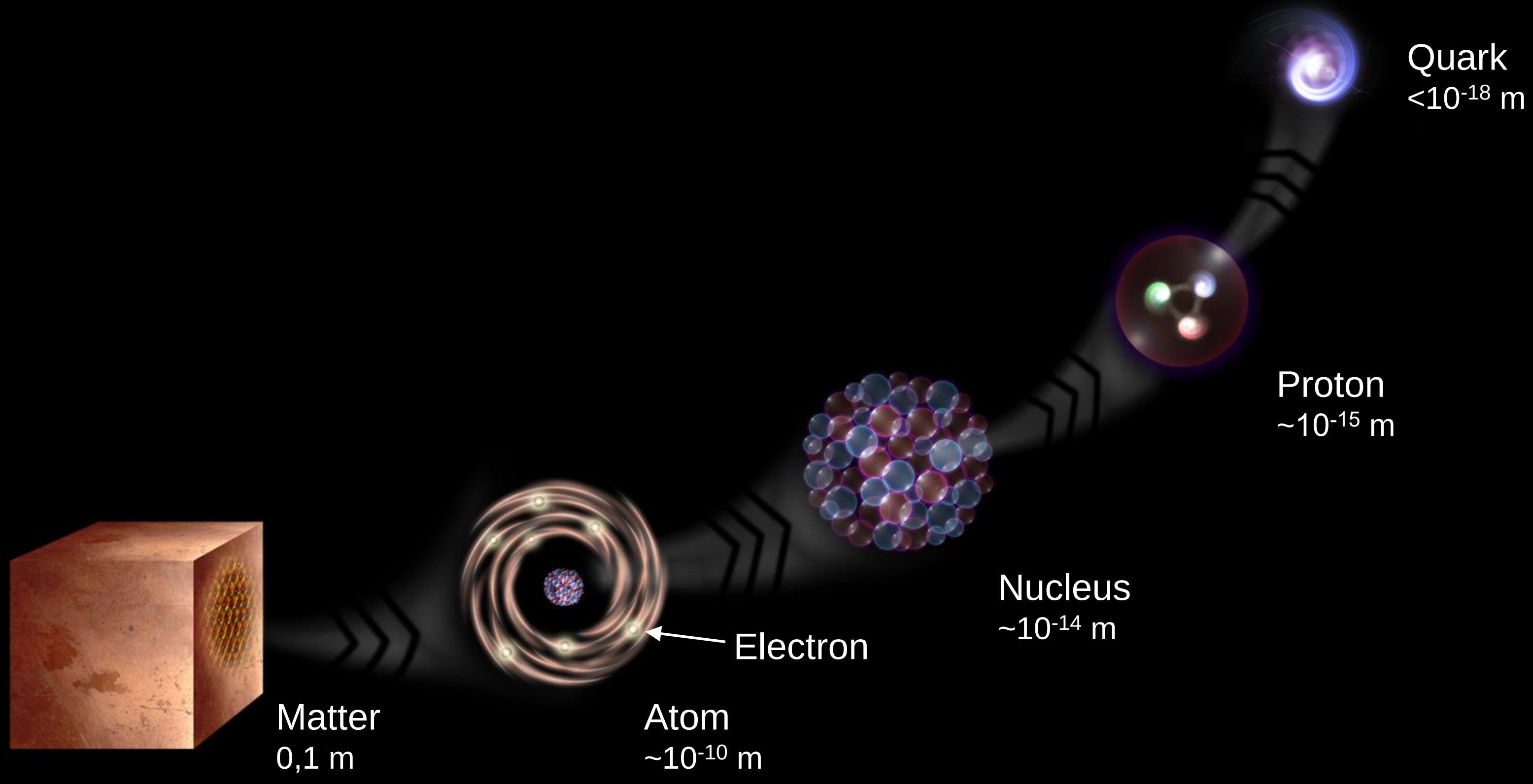
How did the universe begin?

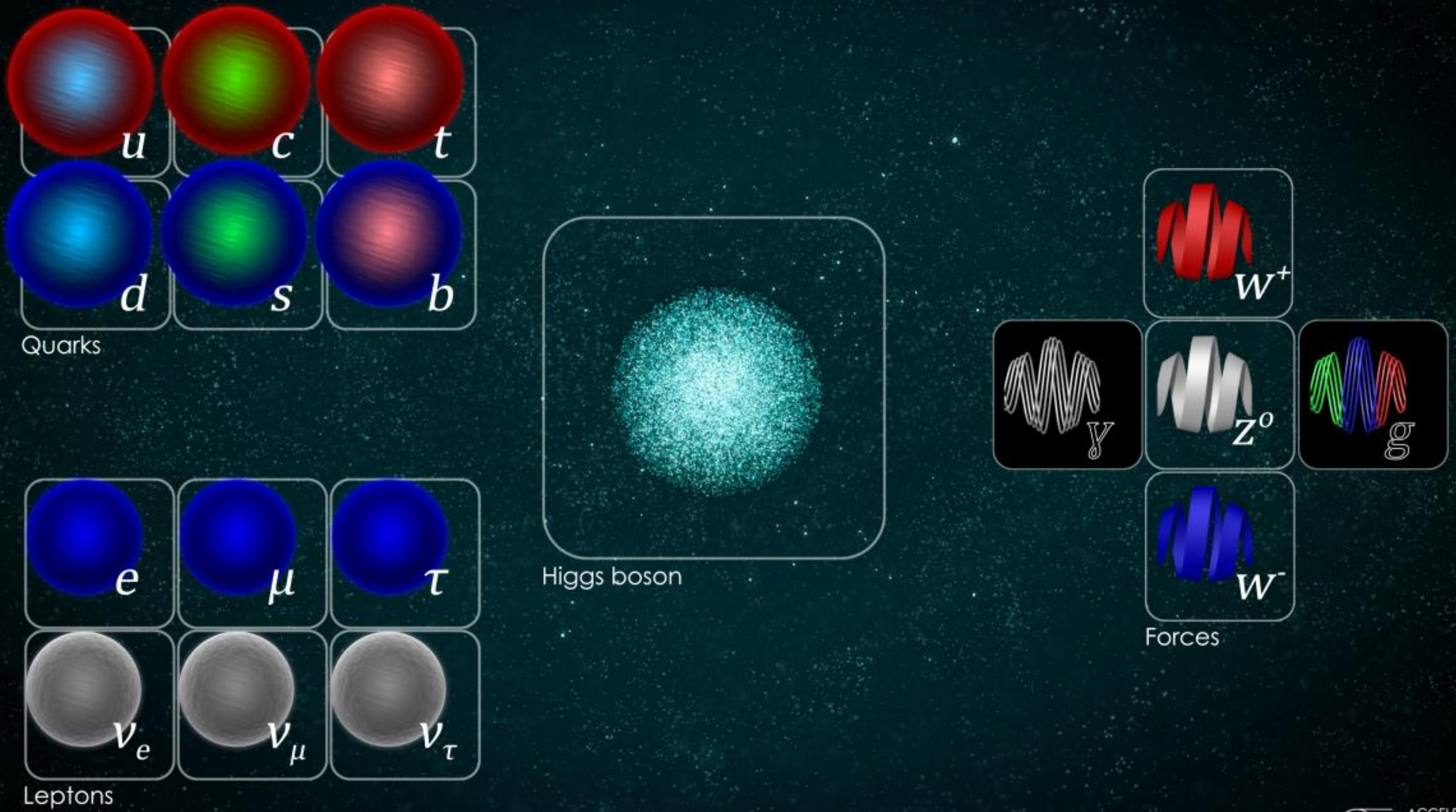


We reproduce the conditions a fraction of a second after the Big Bang, to gain insight into the structure and evolution of the universe.

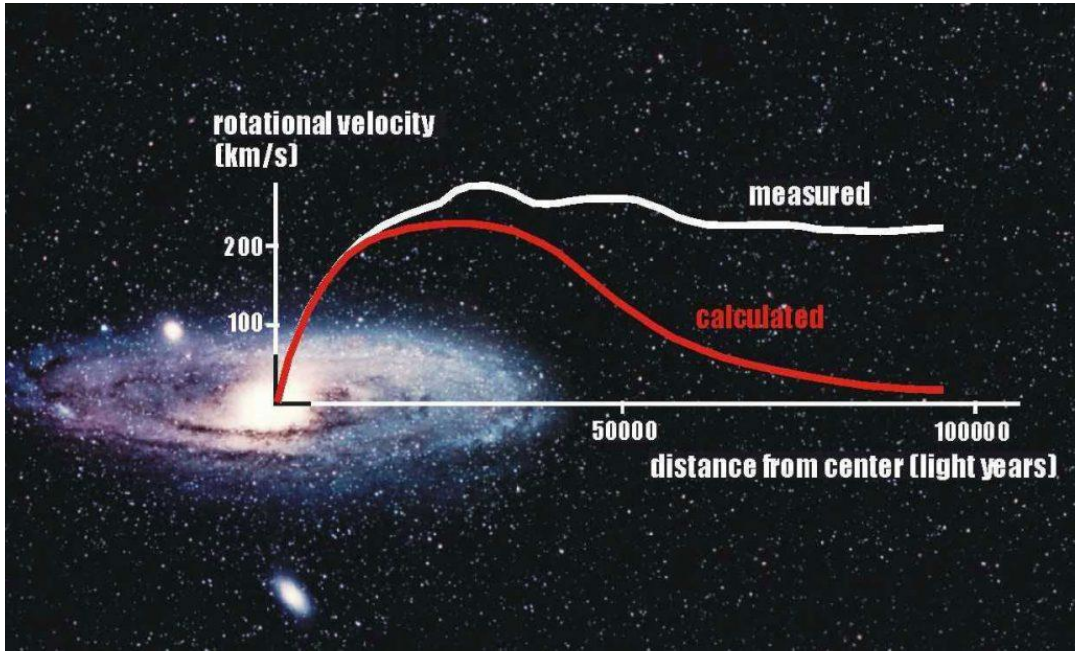
What is the universe made of?

We study the elementary building blocks of matter and the forces that control their behaviour



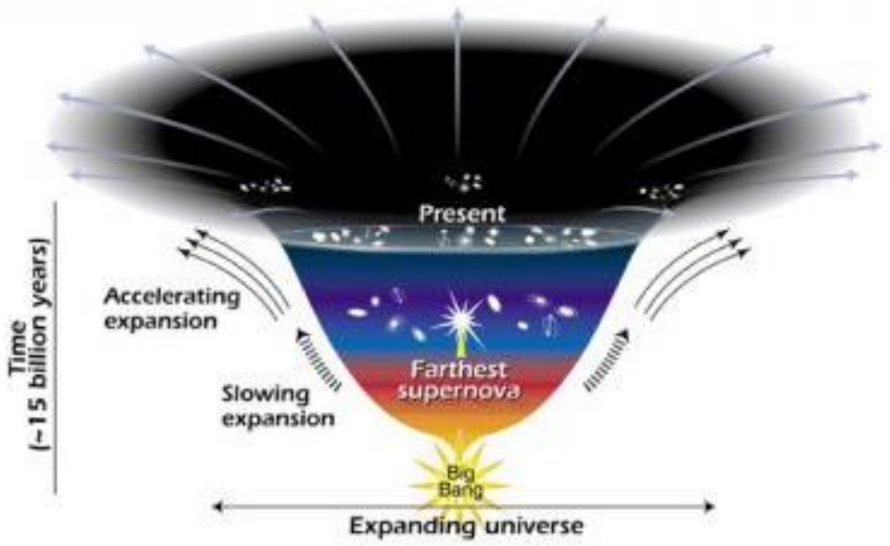

u
c
t
d
s
b
Quarks
e
μ
τ
ν_e
ν_μ
ν_τ
Leptons
Higgs boson
W^+
γ
Z^0
g
W^-
Forces

Dark Matter



- Introduced to explain some cosmological phenomena that cannot be explained taking into account only ordinary matter, e.g. increased rotational velocity of the periphery of certain galaxies

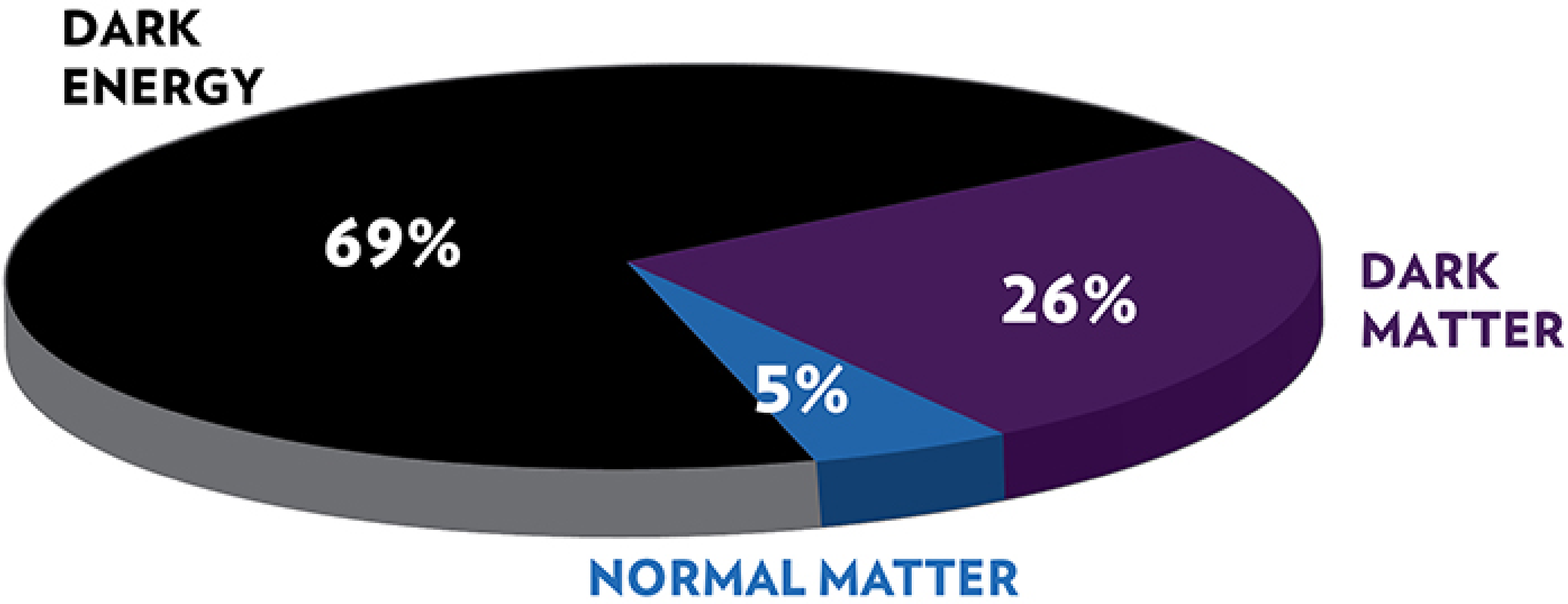
Dark Energy



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

- Introduced to explain the acceleration of the expansion of the universe
- Far (old…) Supernova have been found to be less brilliant than they should…

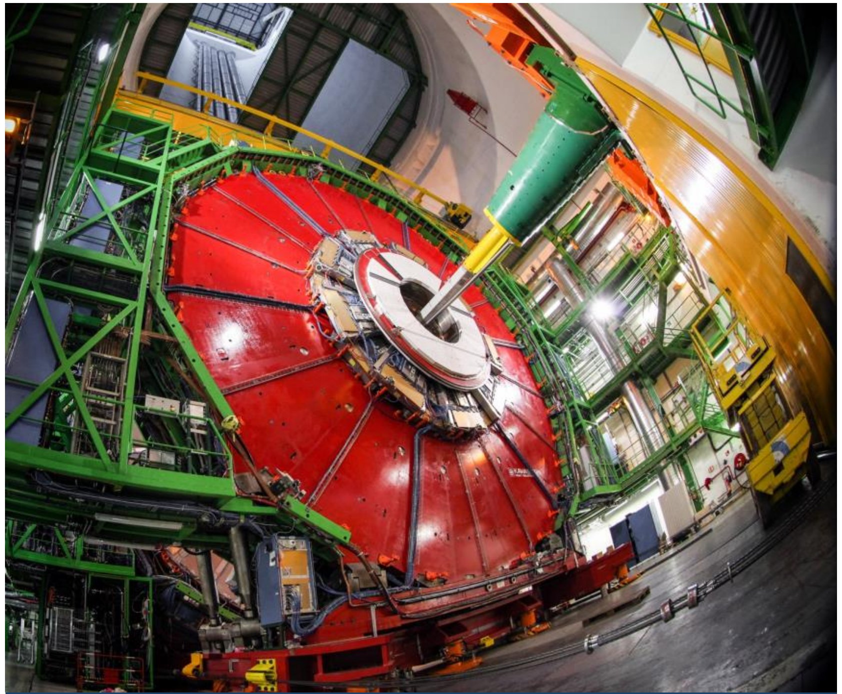
ENERGY DISTRIBUTION OF THE UNIVERSE



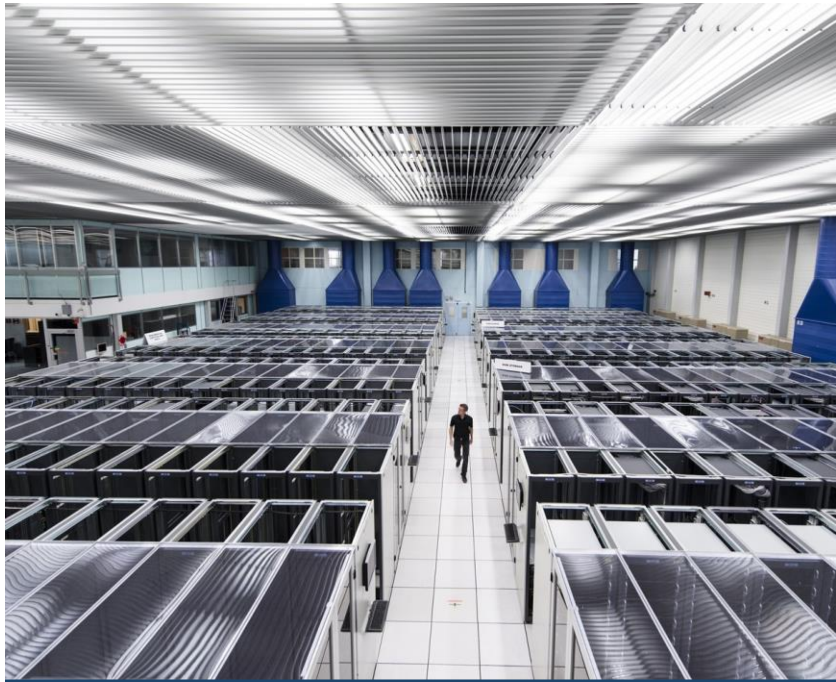
What tools do we use ?

- Three main components are contributing to the success of a project like LHC

ACCELERATORS



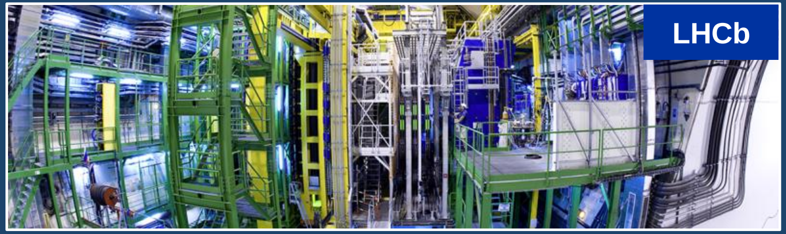
DETECTORS



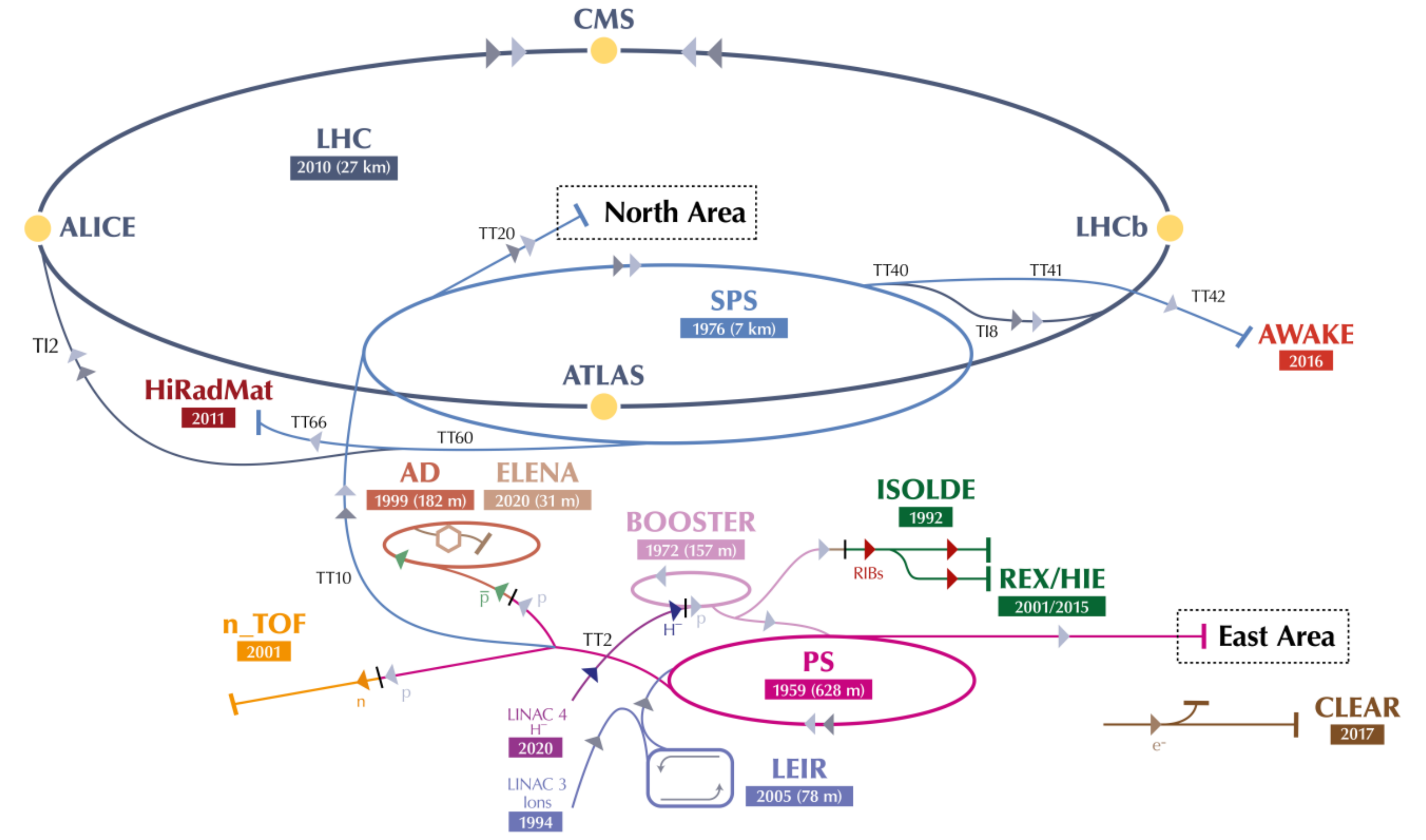
COMPUTING

The most important ingredient

Detectors record the particles formed at the four collision points

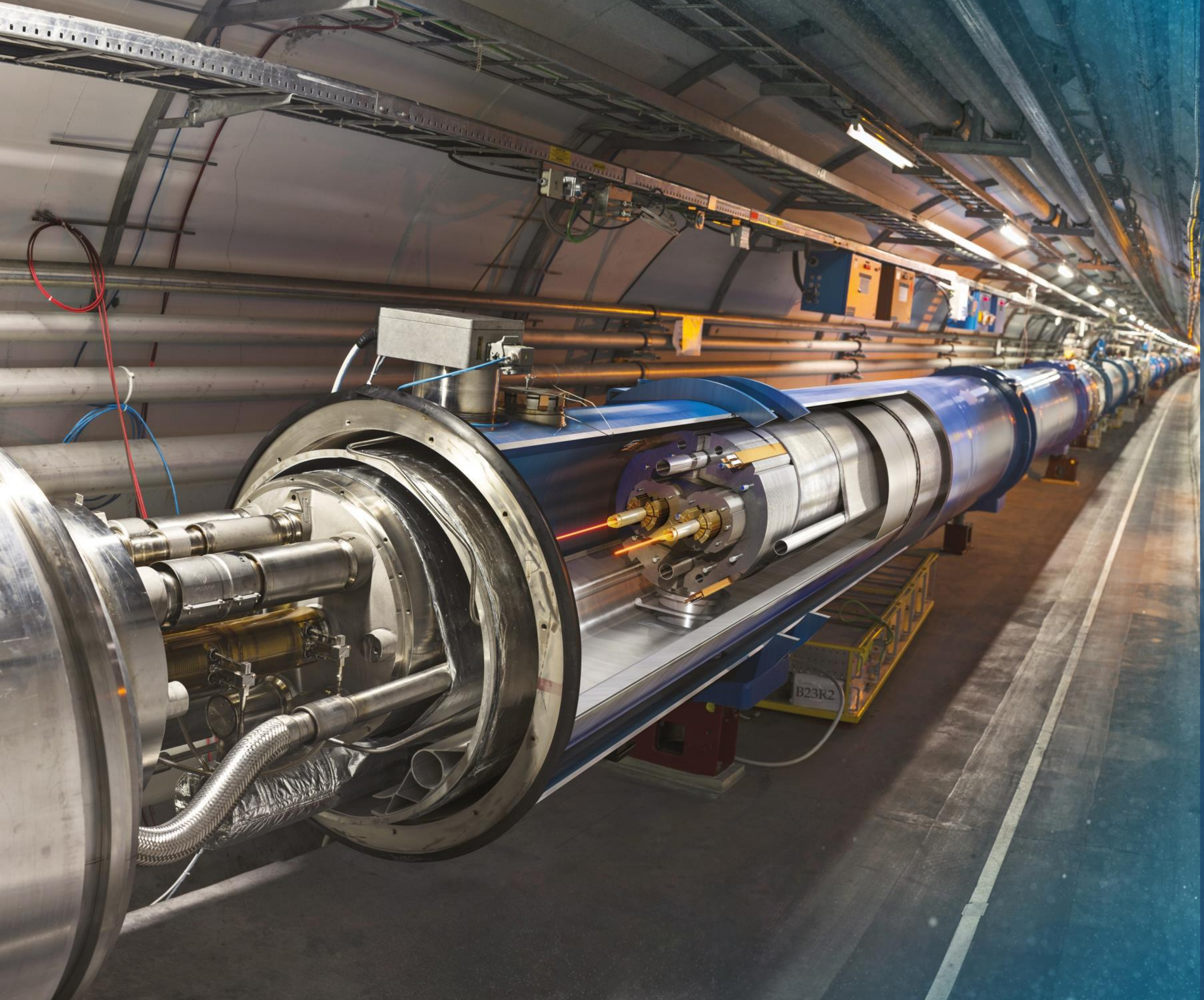


The CERN accelerator complex
Complexe des accélérateurs du CERN



▶ H⁻ (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ p̄ (antiprotons) ▶ e⁻ (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials



Large Hadron Collider (LHC)

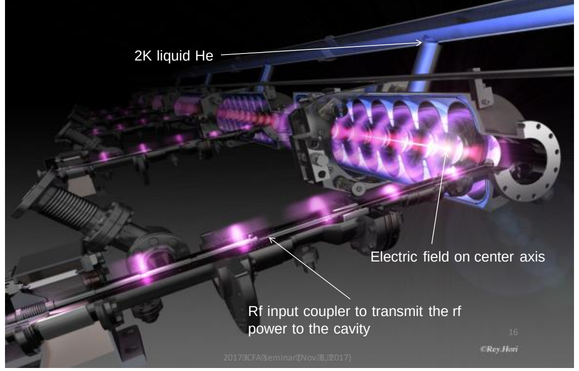
- 27 km in circumference
- About 100 m underground
- Superconducting magnets operated at <2K
- Radiofrequency, beam diagnostics, machine protection aspects pushed to the limtis.
- Used to collide protons or heavy ions (e.g. 208Pb)

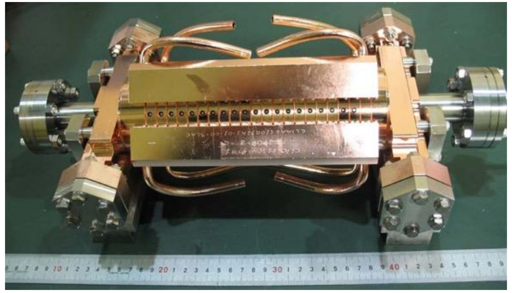
Lorentz equation

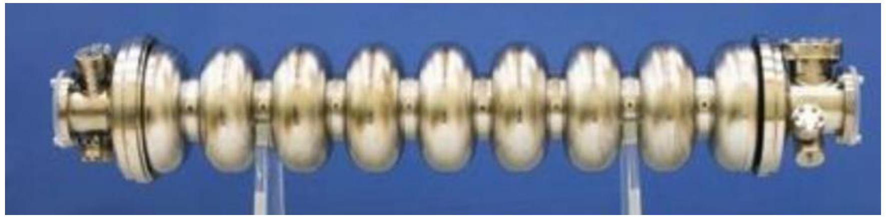
- The two main tasks of an accelerator
  - Increase the particle energy
  - Change the particle direction (follow a given trajectory, focusing “bunches” of particles)
- Lorentz equation:

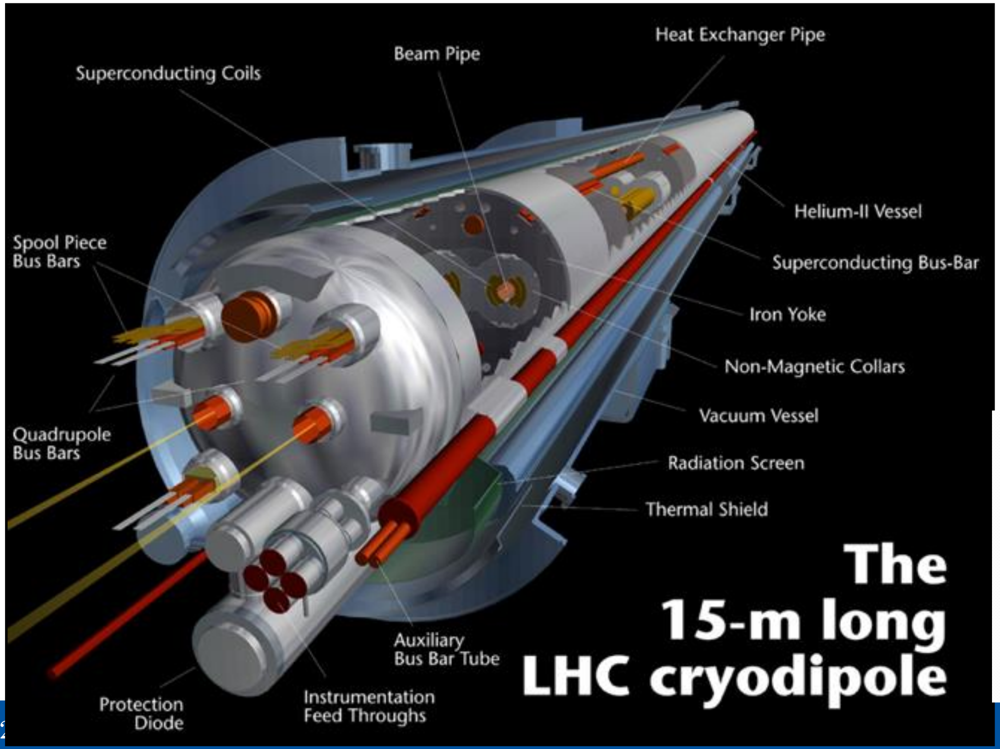
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = q\vec{E} + q\vec{v} \times \vec{B} = \vec{F}_E + \vec{F}_B$$

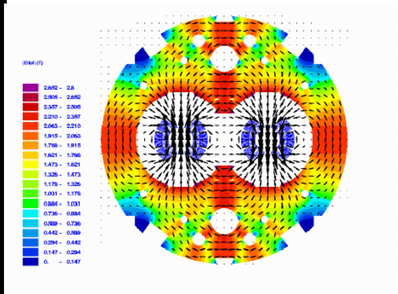
- $F_B \perp v \;\; \Rightarrow F_B$ does no work on the particle
  - Only F_E can increase the particle energy
- F_E or F_B for deflection? $v \approx c \Rightarrow$ Magnetic field of 1 T (feasible) same bending power as en electric field of $3{\cdot}10^8$ V/m (NOT feasible)
  - F_B is by far the most effective in order to change the particle direction











LHC, day of first beam, 10 September 2008

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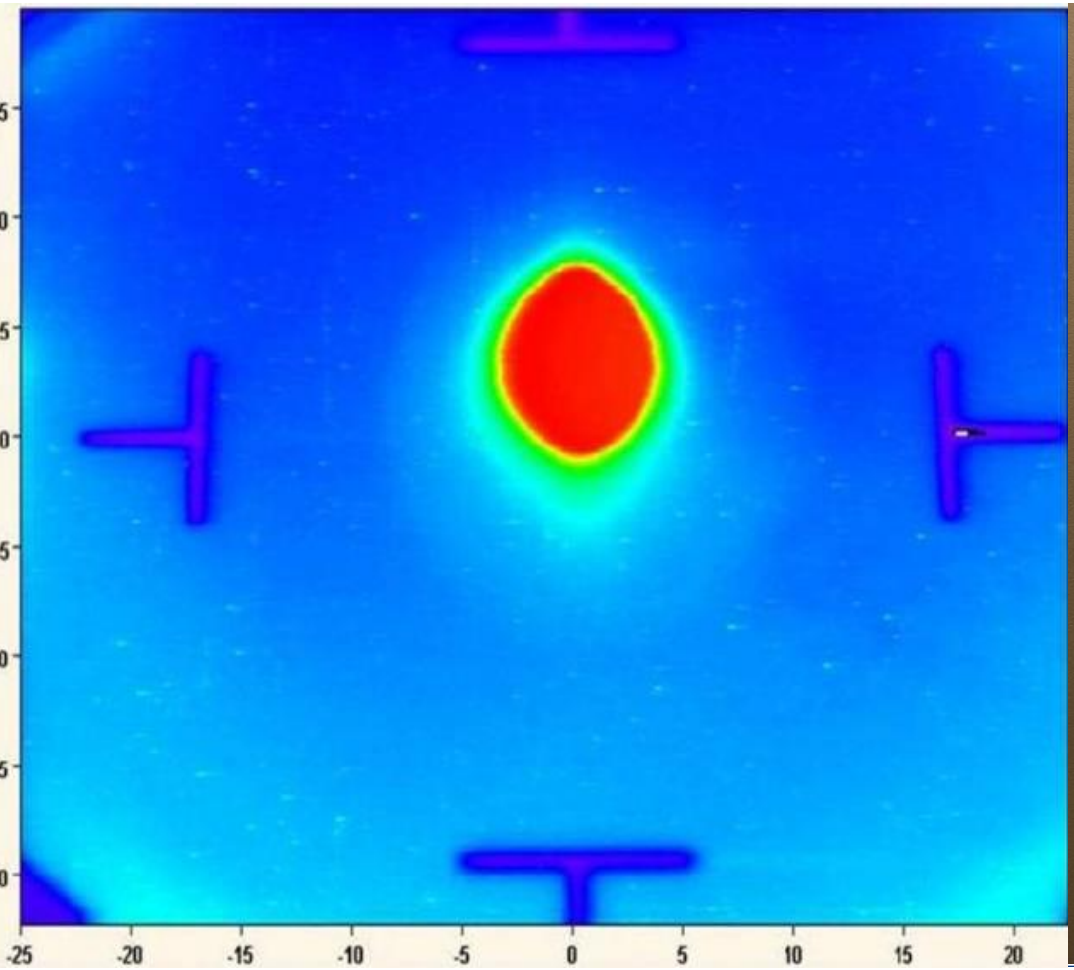

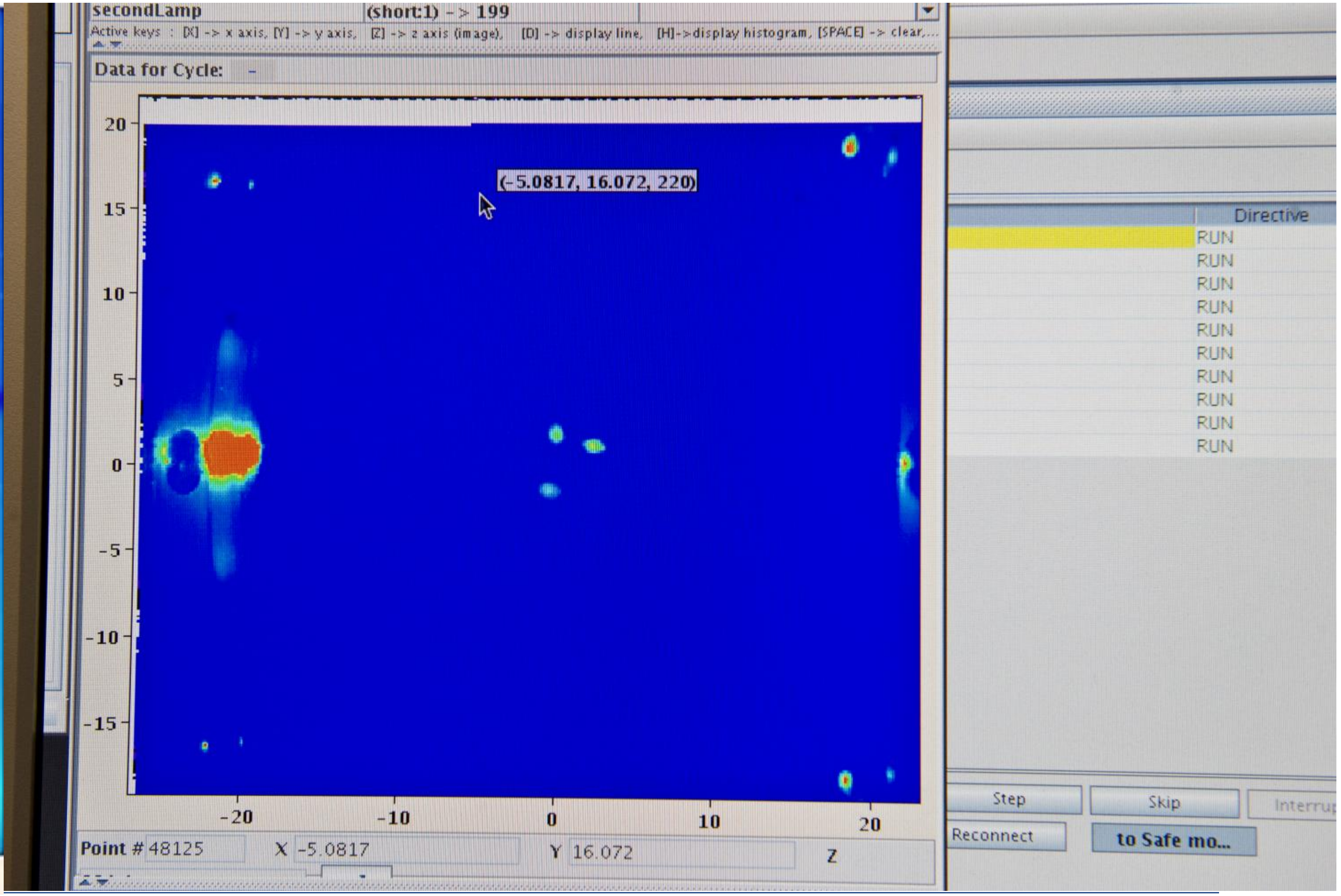
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Active keys : [X] -> x axis, [Y] -> y axis, [Z] -> z axis (image), [D] -> display line, [H]->display histogram, [SPACE] -> clear,...

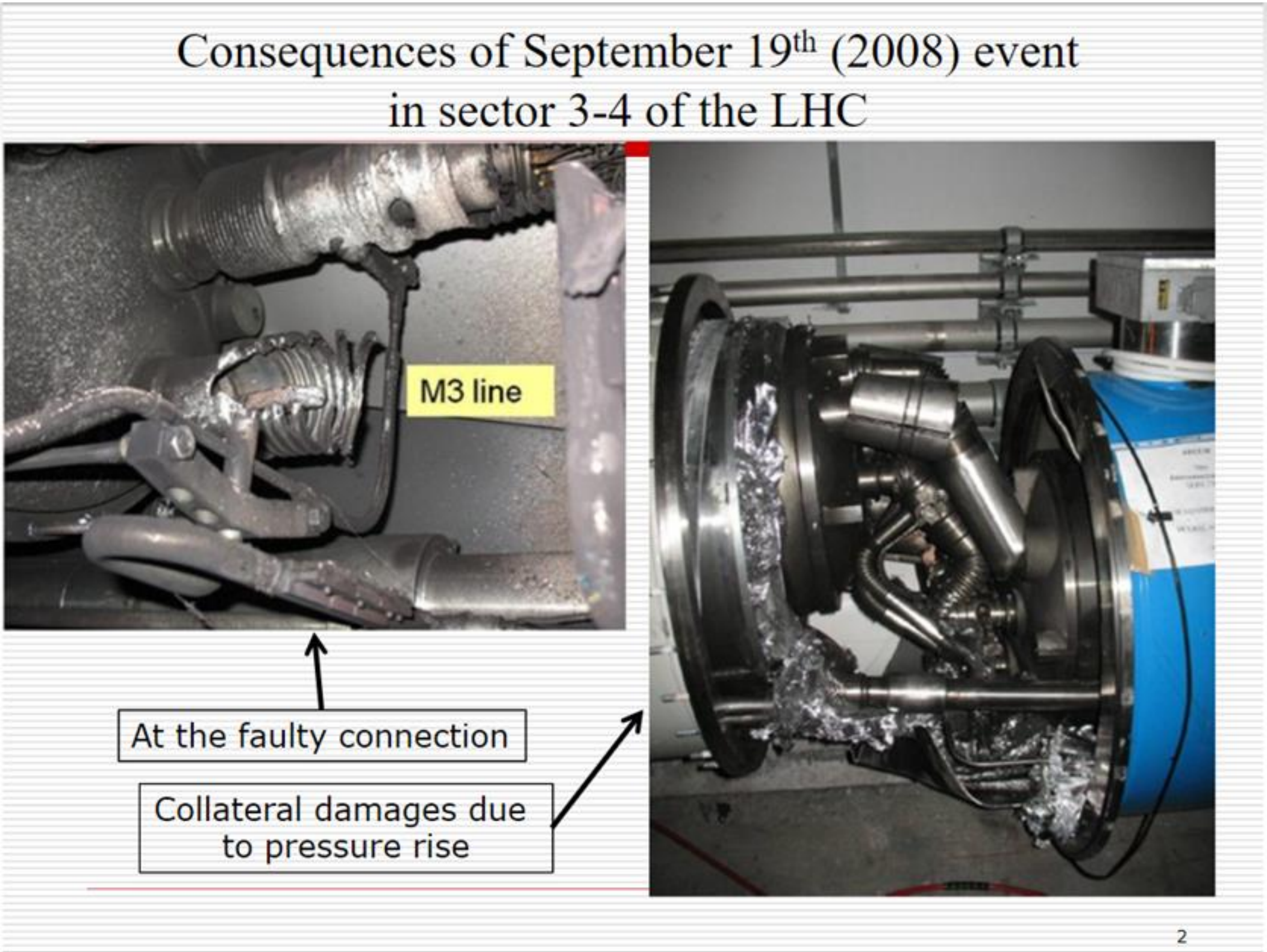
Data for Cycle: -

(-5.0817, 16.072, 220)

Point # 48125 X -5.0817 Y 16.072 Z

19 September 2008
…One of those days…

LHC Accident, 19 September 2008

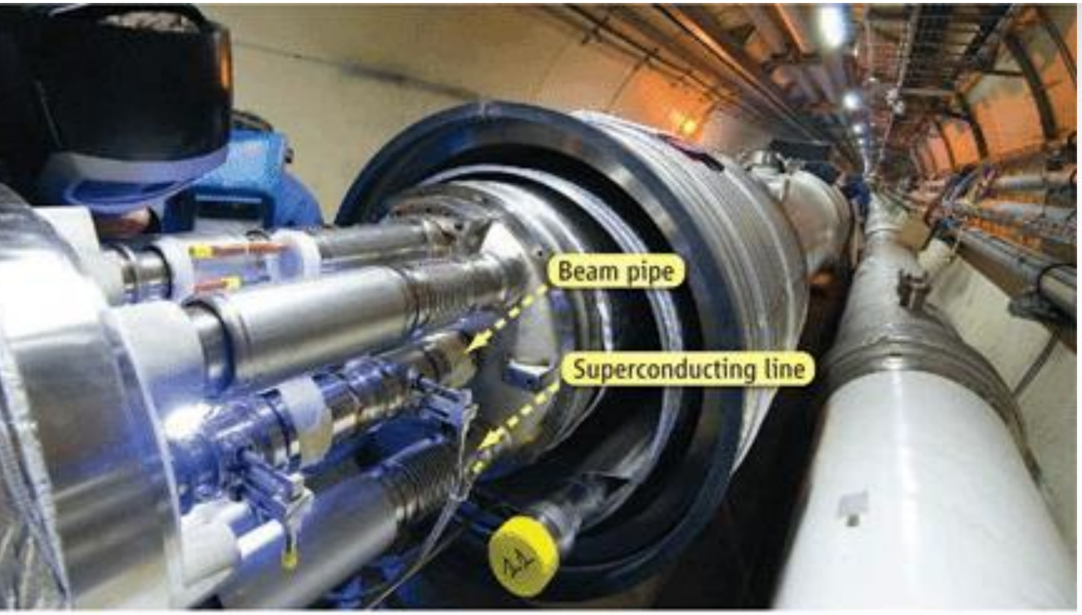


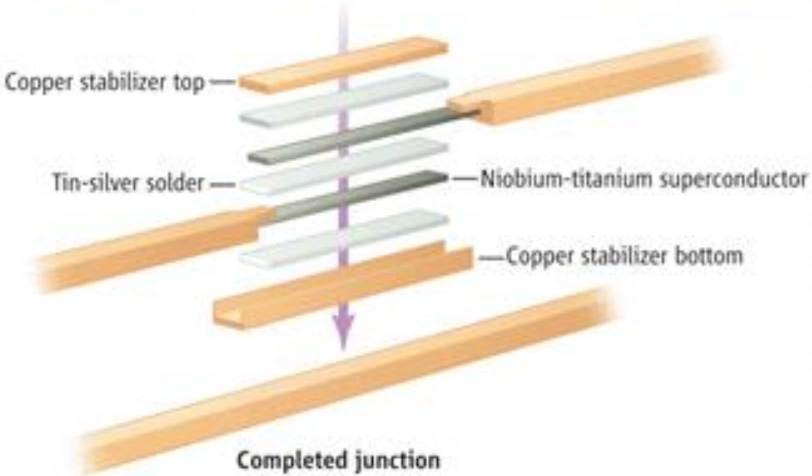
Consequences of September 19th (2008) event
in sector 3-4 of the LHC

At the faulty connection

Collateral damages due
to pressure rise

LHC Accident, 19 September 2008

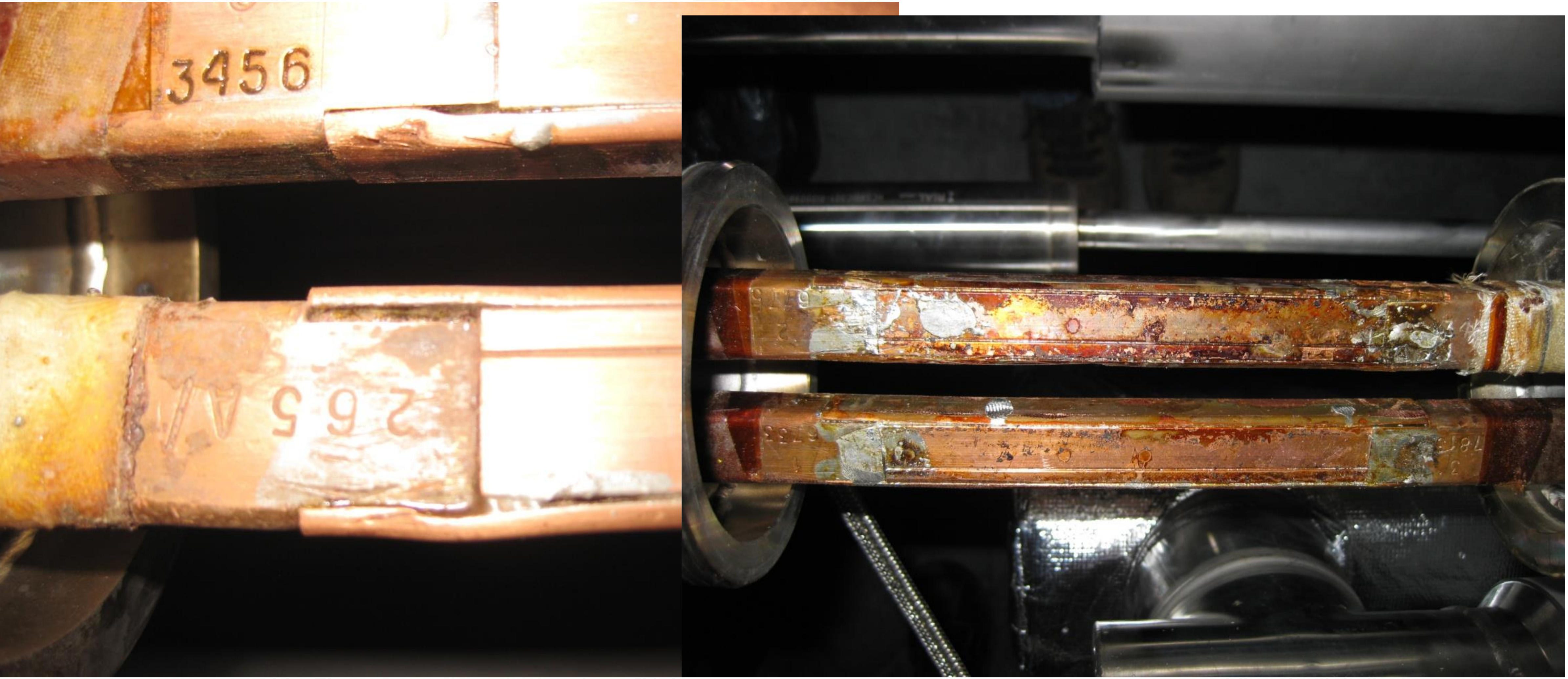




Lessons from LHC He Release and R2E

Sylvain Weisz – DG/PRG

IWLC 2010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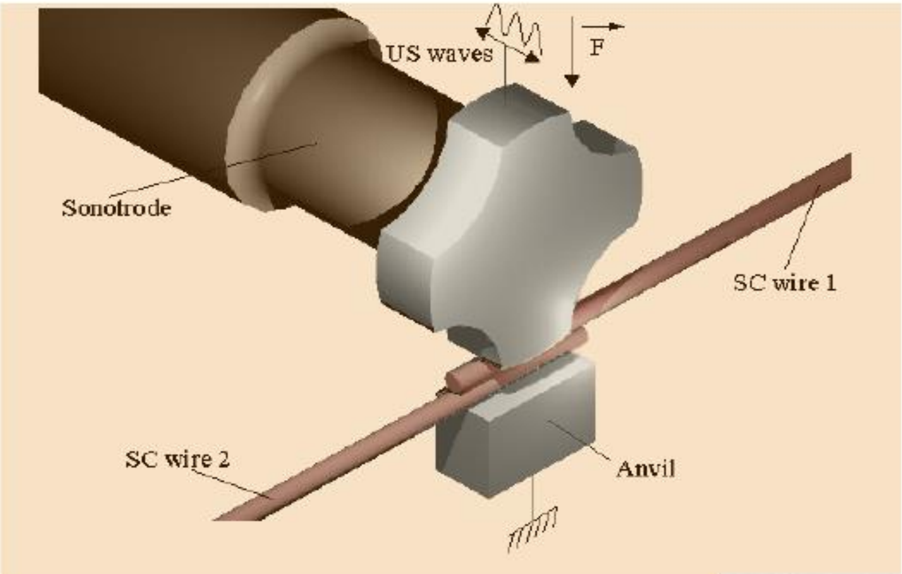
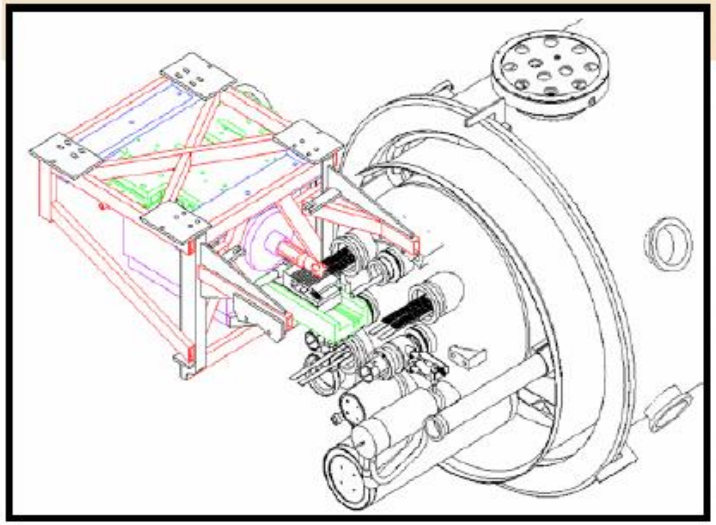
The making of the electrical interconnections in the LHC

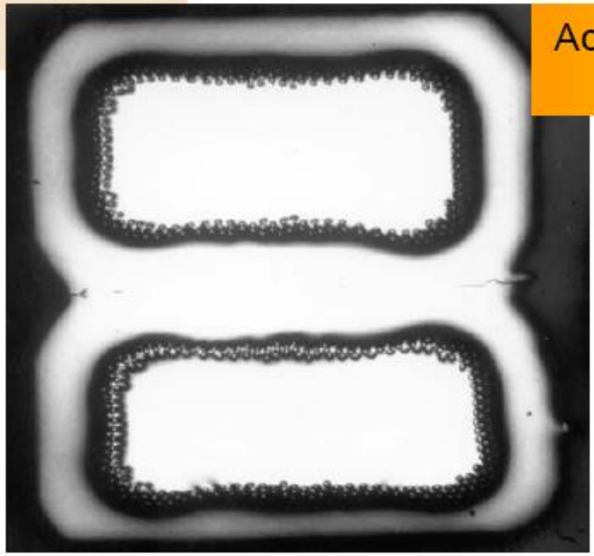
➔ Spool pieces busbars : Junction technology : Ultrasonic welding



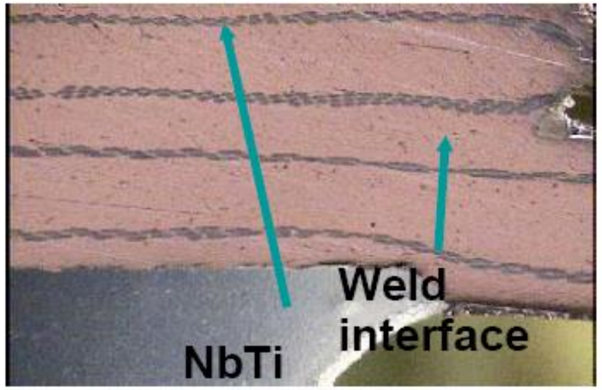
- ➢Clean method (no flux)
- ➢Oxyde destruction by friction
- ➢Contact resistance between 3 and 5 nOhm

- ➢High reproducibility and reliability
- ➢On-line process control
- ➢Mechanical resistance : equivalent to base material
- ➢Fatigue life : more than 500 cycles at room and cryogenic temperatures





Achieved electrical contact resistance : 3 to 5 nOhm in average



Recovery from the accident

Recovery from the accident

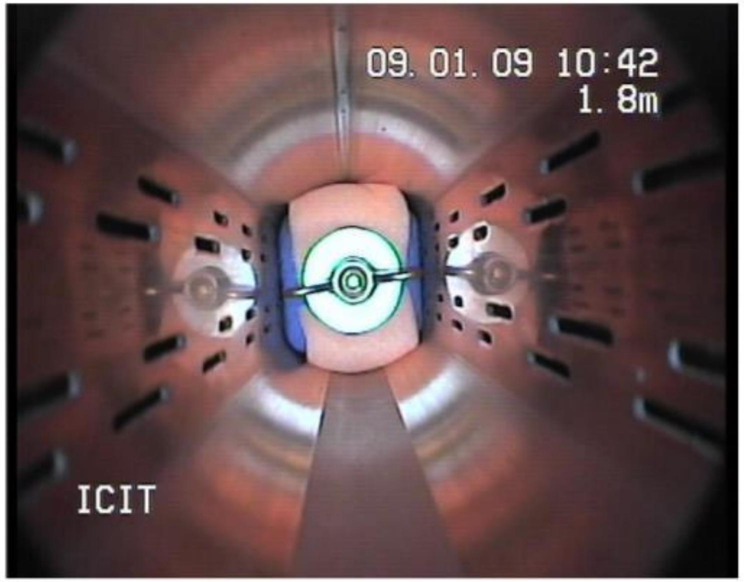
Development of tooling

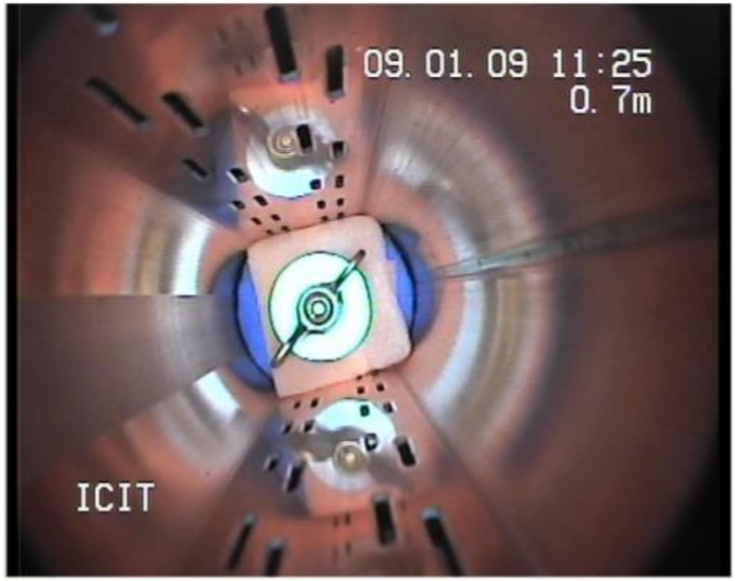
- In parallel to the inspections task, tools were developped to clean the sector
- A vacuum cleaner was developped by the vacuum group !

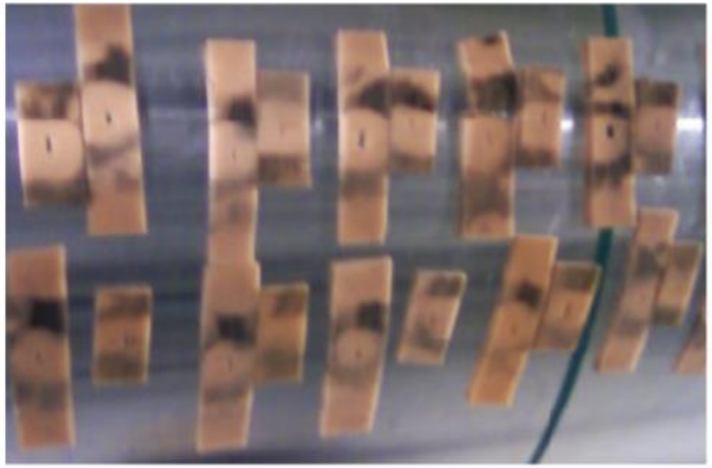
Version 1

Development of tooling

- Chimney sweeping stick for beam screens polluted with soot
- First successful tests before Xmas 2008







Recovery from the accident

- One year allowed to:
  - Protect better the machine from unforeseen events (Machine Protection)
  - automatise several procedures (alignment, protection, set-up, etc…)
  - Study all possible Maximum Credible incidents (system by system) and mitigate effects
  - Develop ramp-up scenarios and monitoring strategies
  - Improve detection and analysis software

Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

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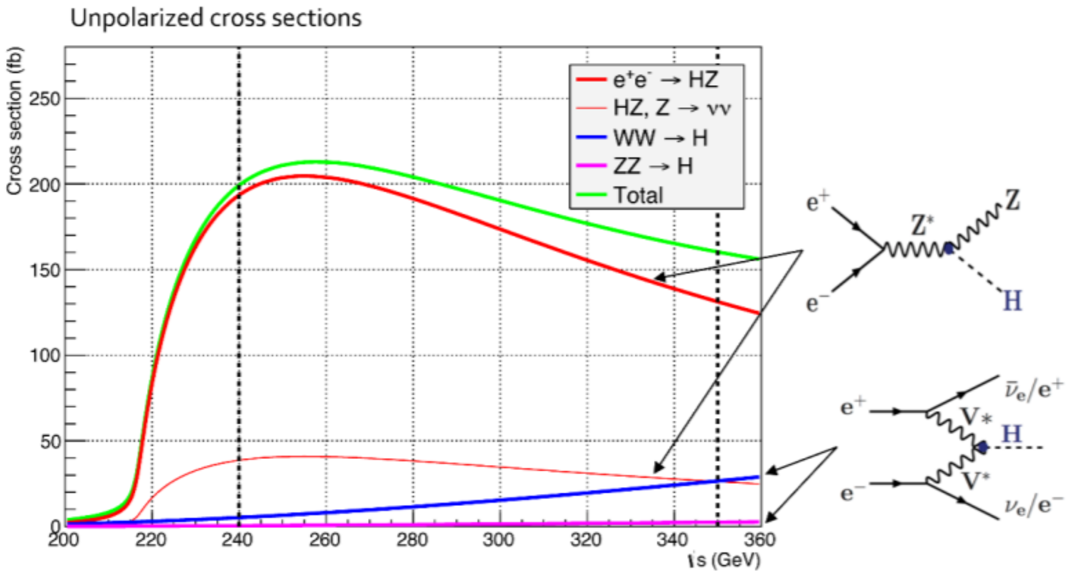
We need more powerful accelerators!

- Many questions remain unanswered yet:
  - What are the constituents of the 95% of mass and energy of the Universe that is not explained by the Standard model?
  - Why is the universe made only of matter, with hardly any antimatter?
  - Why is gravity so weak compared to the other forces?

We need more powerful accelerators!

- Particle physicists analyse “events”, which can be defined as a fundamental interaction between two particles.

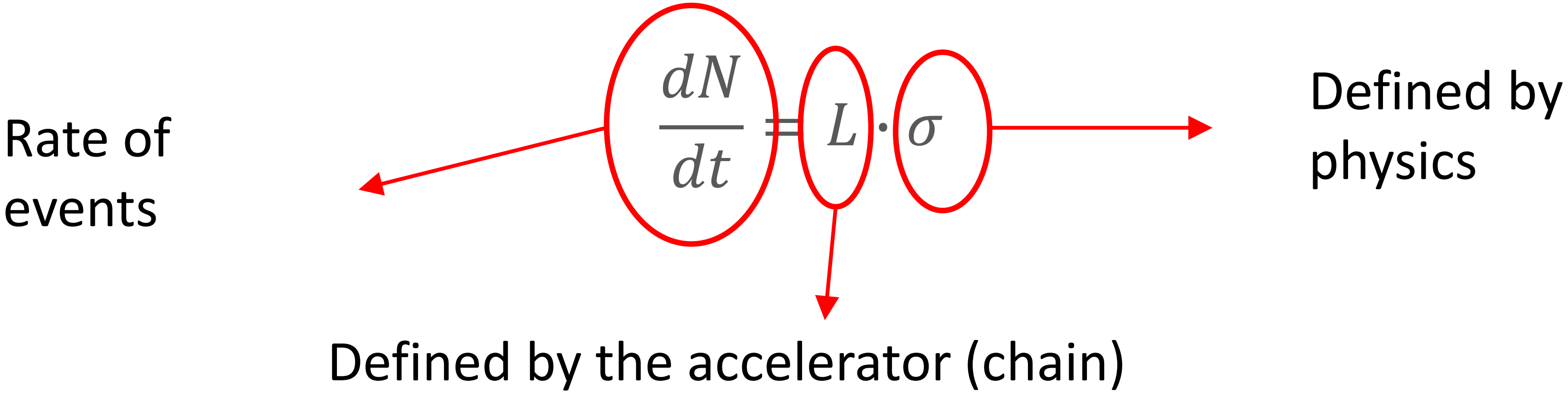
- Particles can interact in many different ways, and each different type of interaction has a given probability “σ” to happen, with a given energy distribution called “cross-section”.



The Higgs boson production cross section as a function of the centre-of-mass energy in unpolarized e+e − collisions, as predicted by the HZHA program, [P. Janot and G. Ganis, The HZHA generator, CERN Report 96/01 (1996)]

We need more powerful accelerators!

- The number of events is the product of the cross section by the Luminosity of the accelerator, which is a measure of how dense is the beam at the interaction point



$$\frac{dN}{dt} = L \cdot \sigma$$

Rate of events

Defined by physics

Defined by the accelerator (chain)

- At the moment no “new” physics, meaning anything not foreseen by the standard model has been revealed at the LHC.

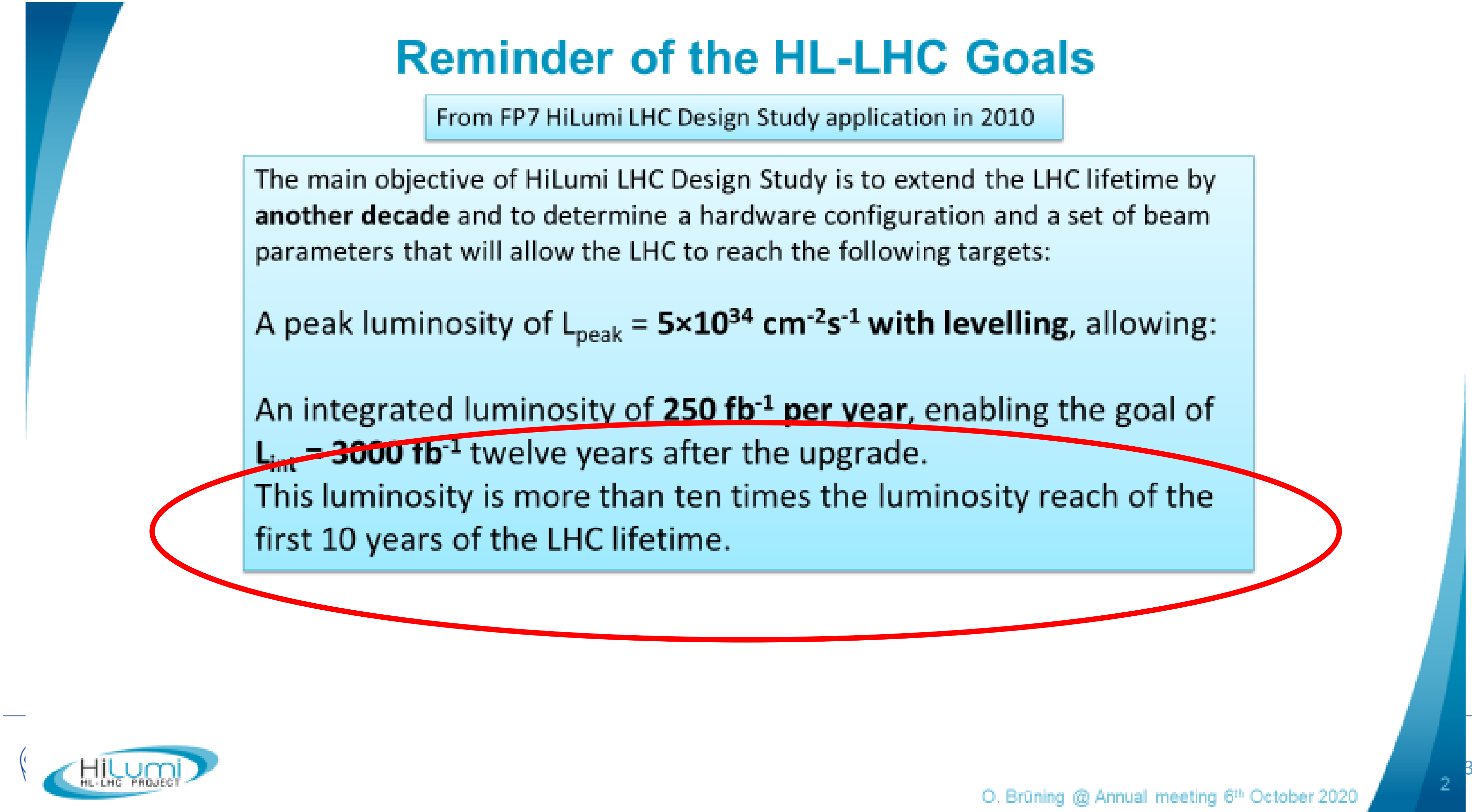
We need more powerful accelerators!

- New physics could be hidden in very rare processes (very small σ) or wait at energies higher than available at the LHC.

$$\frac{dN}{dt} = L \cdot \sigma$$

- The first strategy is therefore to increase the luminosity of the LHC through the High Luminosity LHC project (upgrade of LHC), in order to increase the probability that rare events are seen in the LHC

High Luminosity LHC



Reminder of the HL-LHC Goals

From FP7 HiLumi LHC Design Study application in 2010

The main objective of HiLumi LHC Design Study is to extend the LHC lifetime by **another decade** and to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

O. Brüning @ Annual meeting 6th October 2020

2

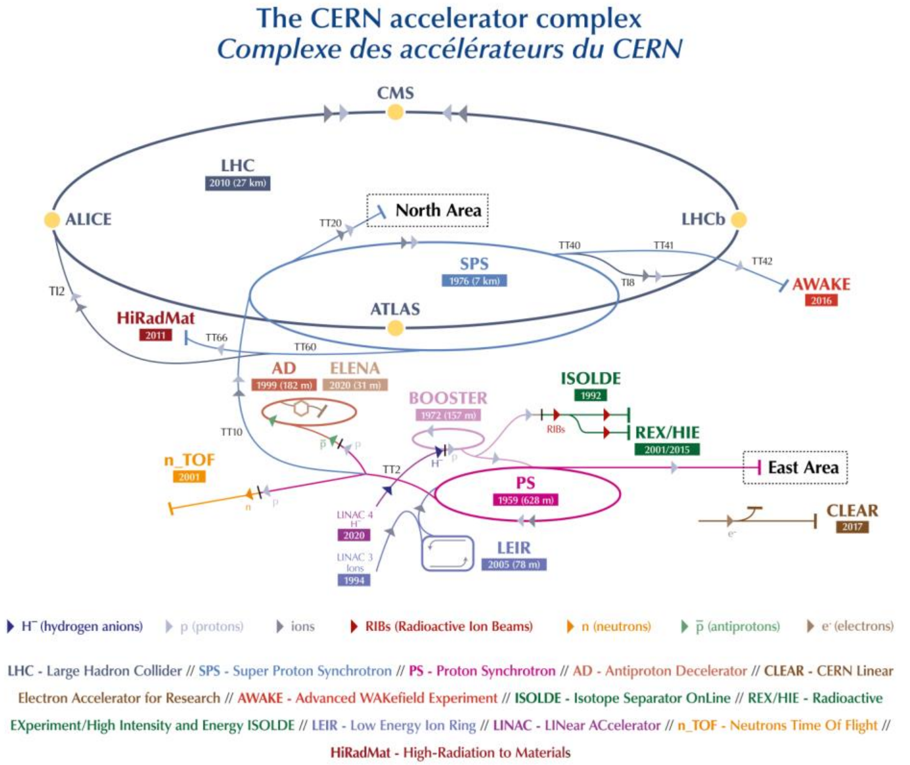
High Luminosity LHC

- How do we increase Luminosity?

- $L = \frac{N^2 f_{rev} N_b}{4\pi \cdot \beta^* \cdot \epsilon_n} \cdot R$ →
  - N_b bunches per beam,
  - N particles in bunches,
  - f_{rev} the revolution frequency,
  - R is a geometric factor,
  - $\beta^* \cdot \epsilon_n$ is proportional to the transverse size of the beam
- More particles, more bunches, higher frequency, smaller size…
- $L_{int} = \int_0^T L \cdot dt$
- More time, better efficiency (improve ORAMS)…

High Luminosity LHC

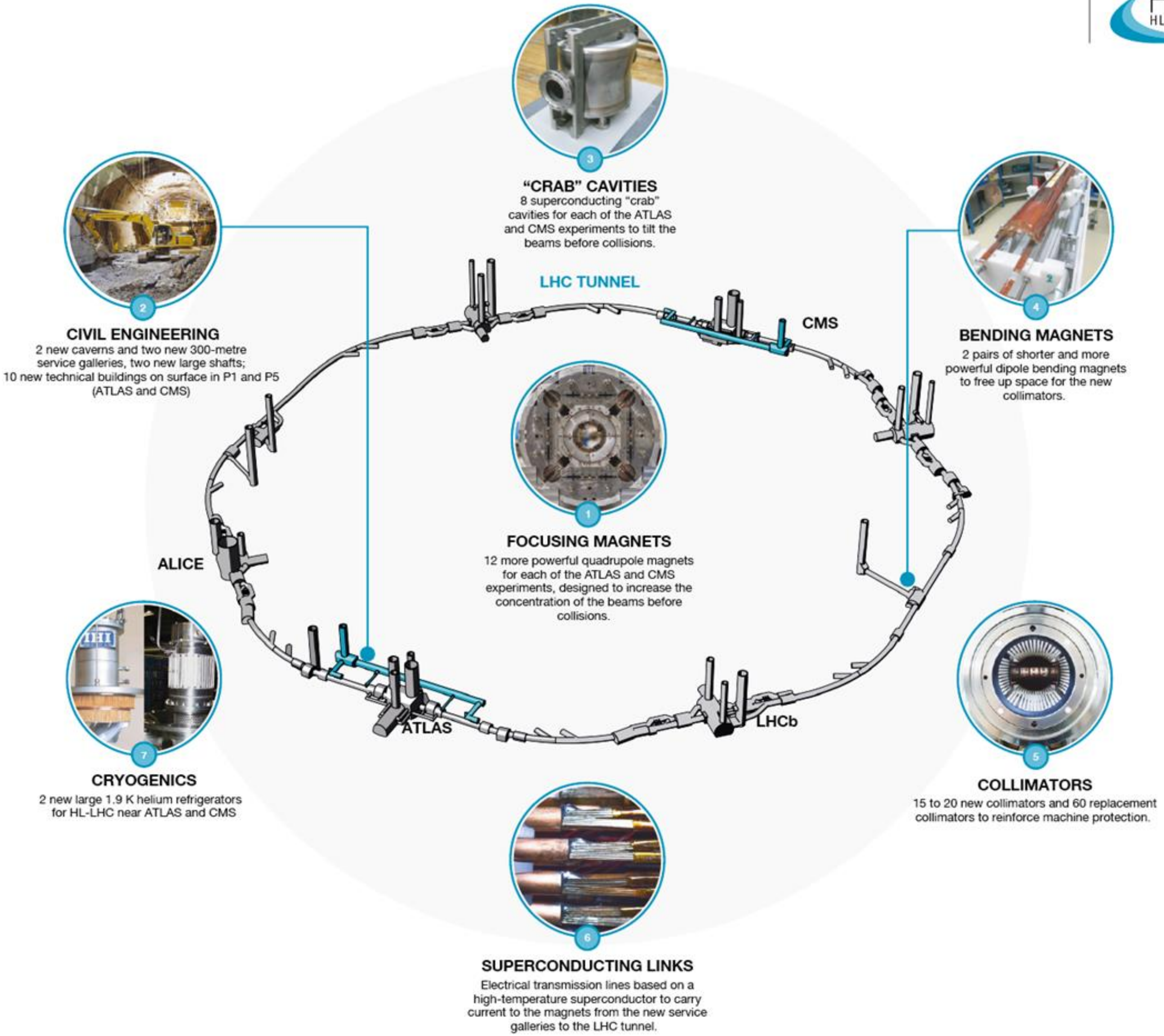
- *More particles, more bunches, higher frequency, smaller size…*
- **More Particles**
  - Requires an upgrade of the injectors (source of particles)
  - Risk to hit stability limits…
- **More bunches, higher frequency**
  - Limited by the size of the machine
  - Risk to hit stability limits
  - High frequency challenging for the experiments
- **Smaller beam size…**
  - Requires changing magnets, protection etc…
  - Risk to hit stability limits…



LHC Beam parameters achieved

Parameter	2018	Design	HL-LHC
Energy [TeV]	**6.5**	7.0	~7.0
No. of bunches	**2556**	2808	2760
Max. stored energy per beam (MJ)	**312**	362	700
β* [cm]	**30→25**	55	15
p/bunch (typical value) $[10^{11}]$	**1.1**	1.15	2.3
Typical normalized **emittance** [μm]	**~1.8**	3.75	2.5
Peak **luminosity** $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	**2.1**	1.0	8.1

High Luminosity LHC



"CRAB" CAVITIES
8 superconducting "crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

CIVIL ENGINEERING
2 new caverns and two new 300-metre service galleries, two new large shafts; 10 new technical buildings on surface in P1 and P5 (ATLAS and CMS)

BENDING MAGNETS
2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

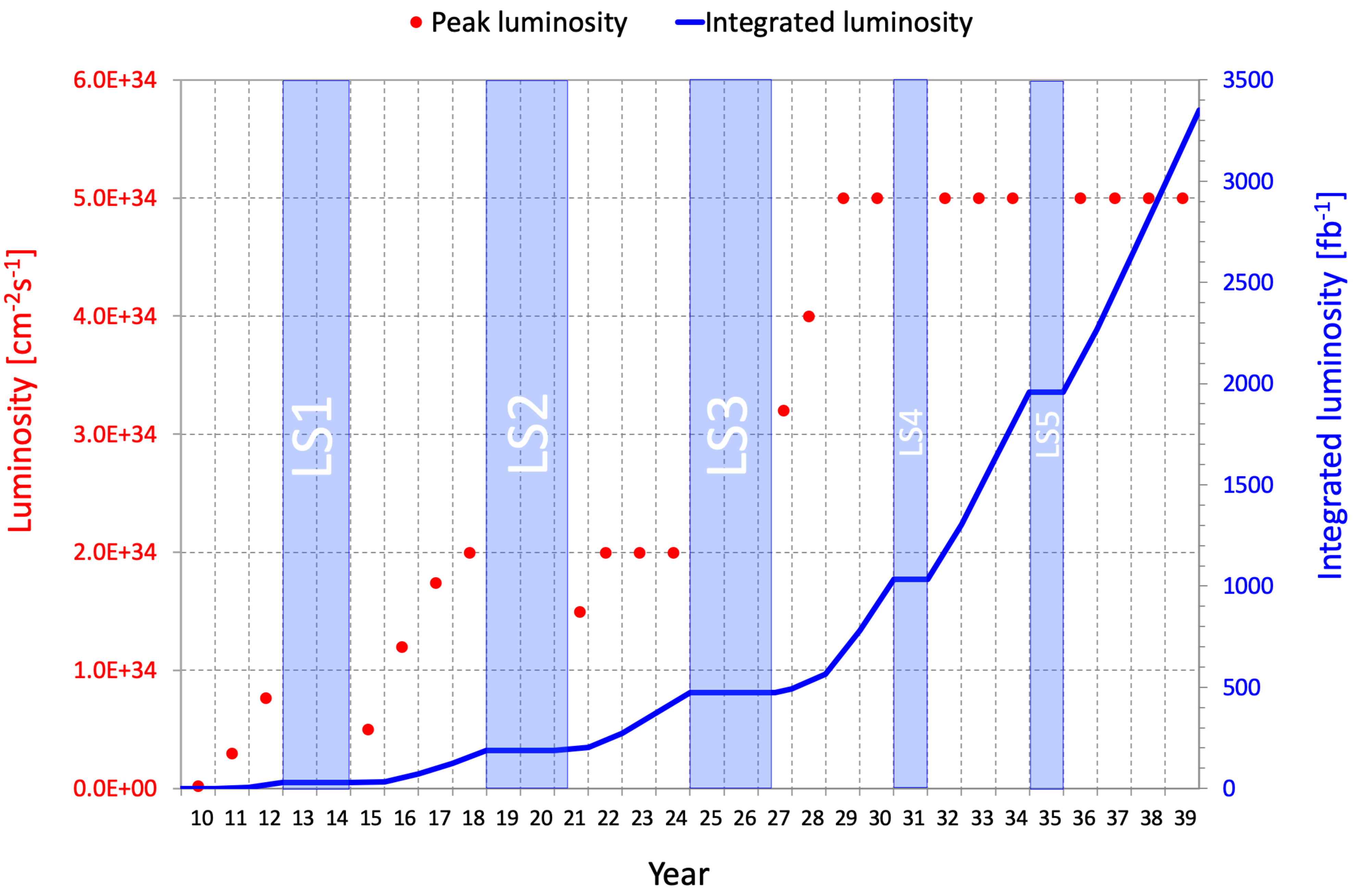
CRYOGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

CERN May 2016

High Luminosity LHC



High Luminosity LHC

- The numbers of the HL-LHC:
  - Cost: ~ 1 BCHF
  - 1.2 km of accelerator components to be replaced
  - 2 new underground (~100 m deep) galleries (~ 300 m long)
  - >15 years from initial design to implementation and commissioning

  - New technologies developed (accelerators):
    - High field magnets (e.g. from 9 to 11 T), new material (from NbTi to Nb_3Sn)
    - Superconducting links (to transport high currents over long distances)
    - New absorbing materials (interacting with beam)

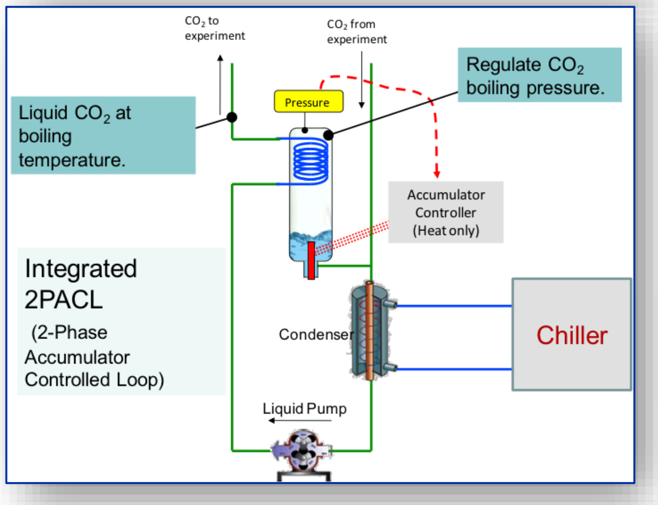
High Luminosity LHC

New Experiment cooling technology:

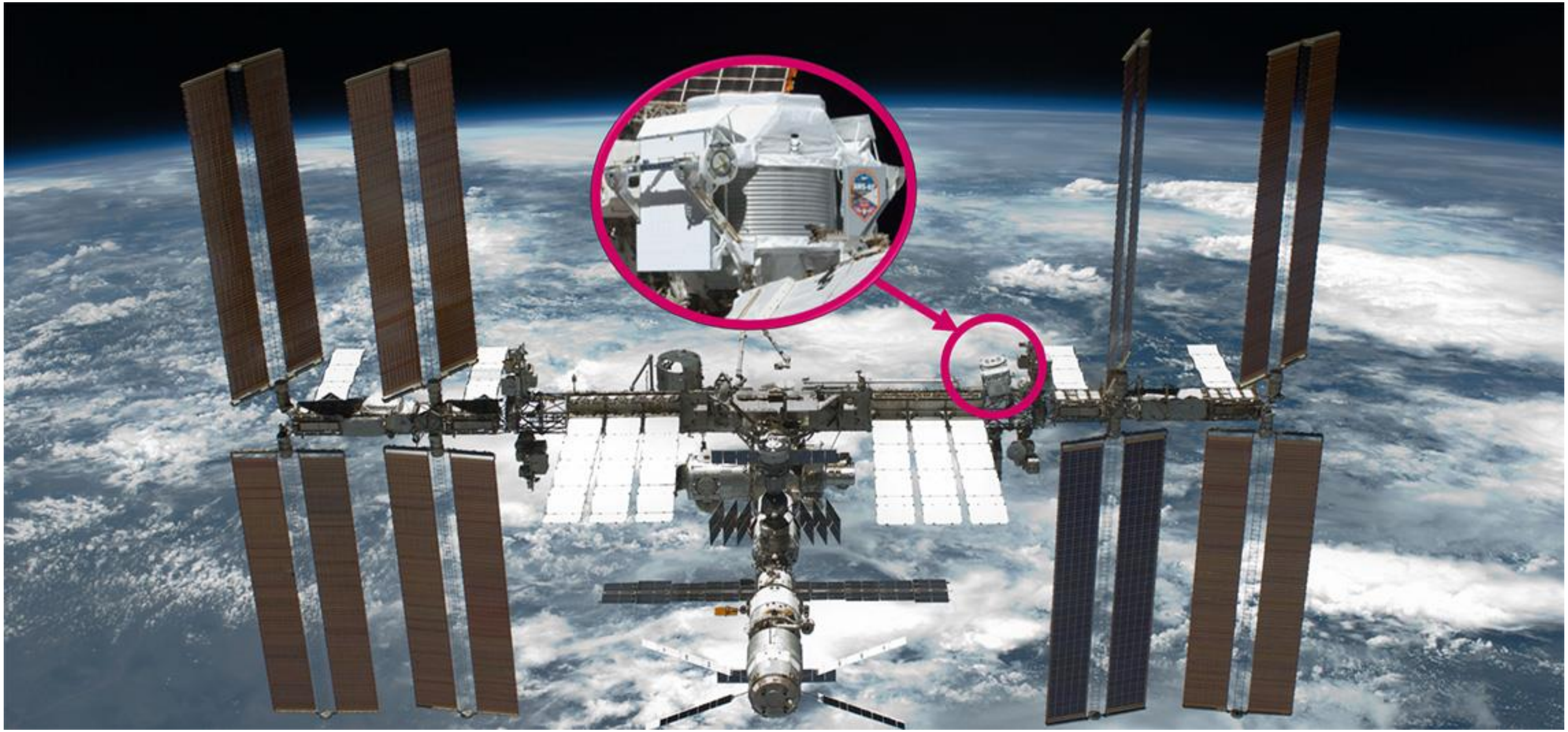
- Experiments need to cool below -40°C for two reasons:
  - Reduce noise
  - Reduce radiation damage
- Today this is achieved through refrigerated fluorinated (CFC) gases, with high impact on the environment (if released…)
- For the HL-LHC, we launched an R&D program to use CO2 as coolant fluid for the full stack

The Background

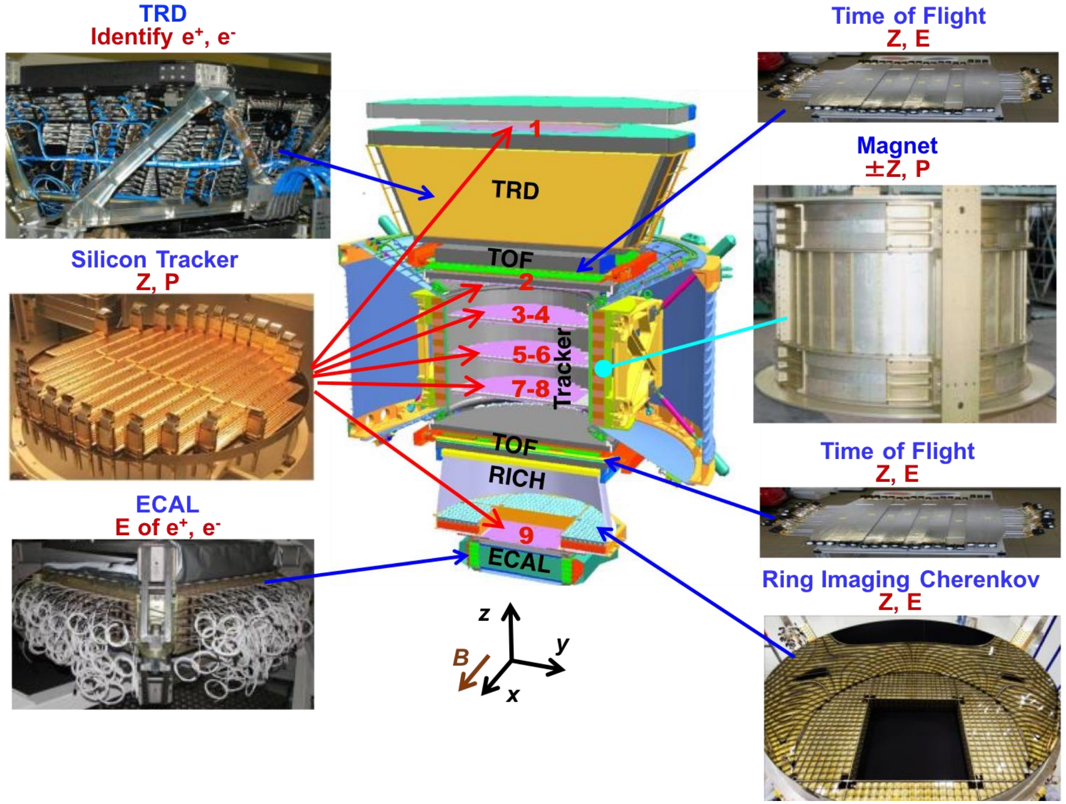
- CO2 has established itself as a promising industrial coolant
- CO2 cooled high energy physics detectors rely on a special concept developed at CERN
- First used for the AMS-02 detector, later for the LHCb VELO and more recently also in the ATLAS IBL and the CMS (phase-I) pixel detector upgrade
- Advantages of Dual-Phase CO2 based cooling systems:
  - proven to be **reliable, efficient and stable** cooling systems
  - **environment friendly** (GWP = 1) compared to conventional systems (GWP ~8000)
  - several **technical/system advantages**

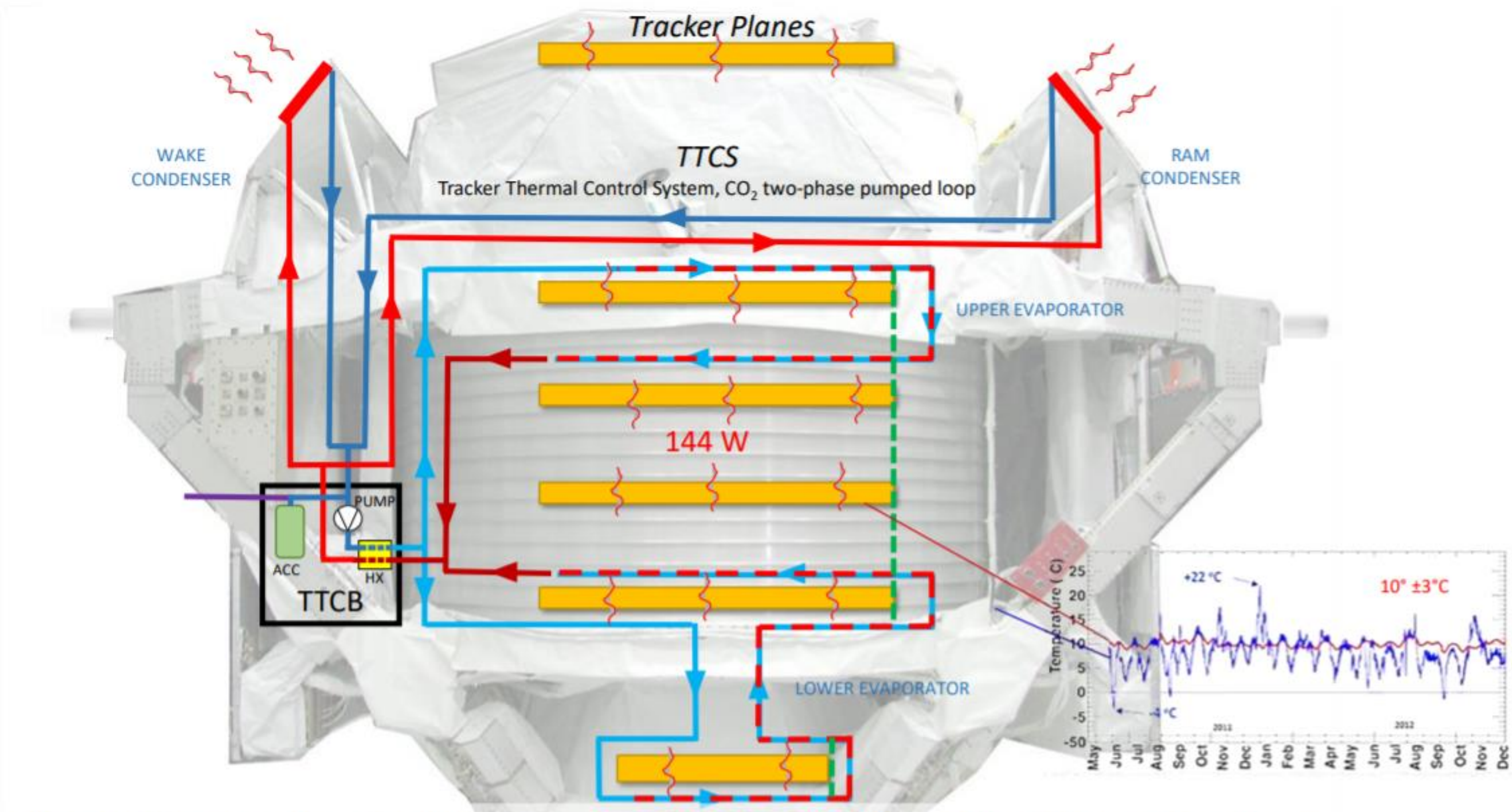


AMS on the ISS



AMS on the ISS





TTCS

Tracker Thermal Control System, CO_2 two-phase pumped loop

The TTCS, a mechanically pumped two-phase carbon dioxide cooling loop

In order to guarantee the tight accuracy of tracker measurement (5-10 µm) the sensors on the different planes, must be kept at a stable uniform temperature

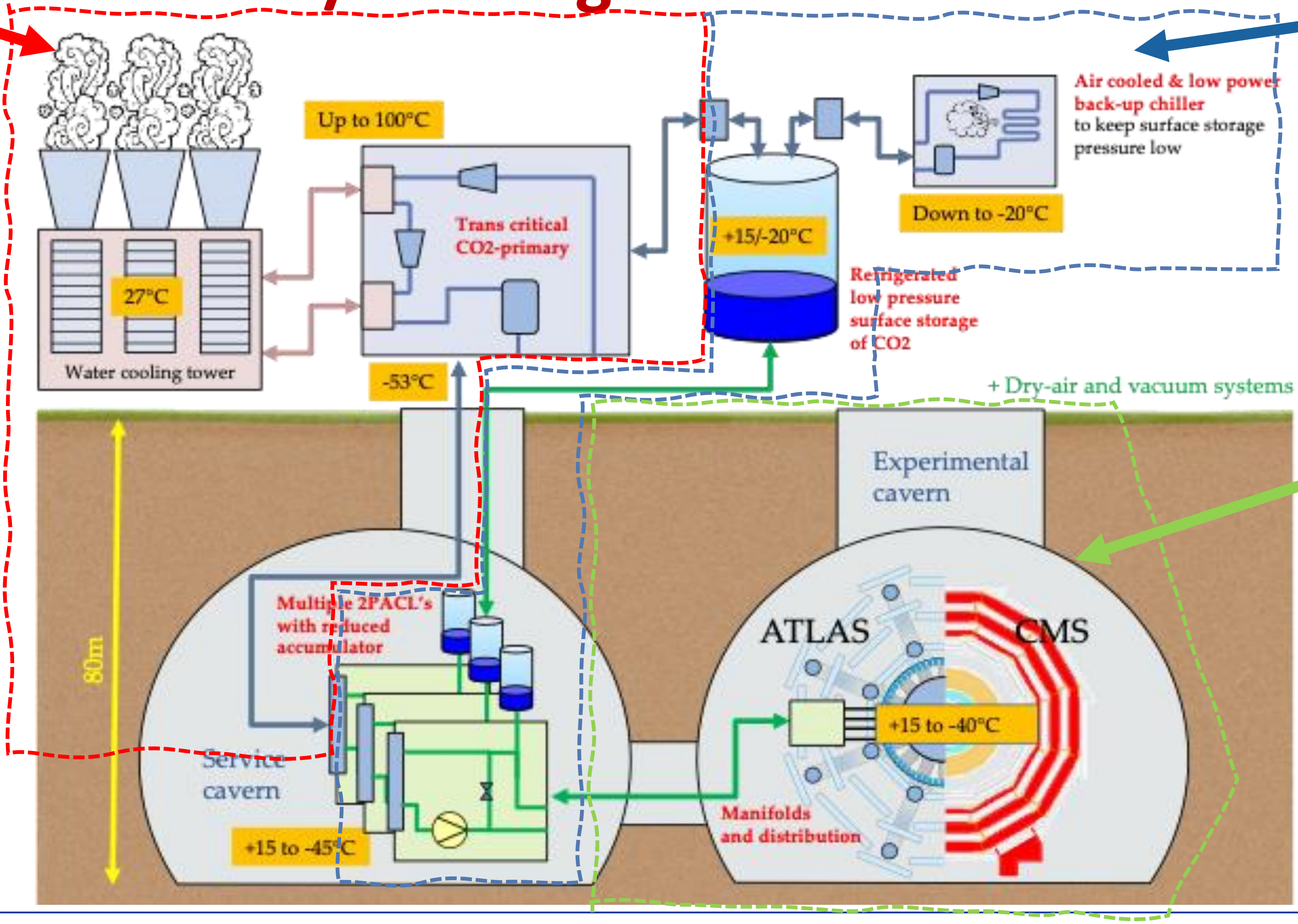
The Scale

1. scaling up in cooling power
2. colder than what was ever done before
3. much larger quantity of CO_2

Primary Cooling

Surface / Underground Installations

- **New Surface Buildings & Related Infrastructure**
- **Long transfer-lines**
- **Space constraints for underground Installations**

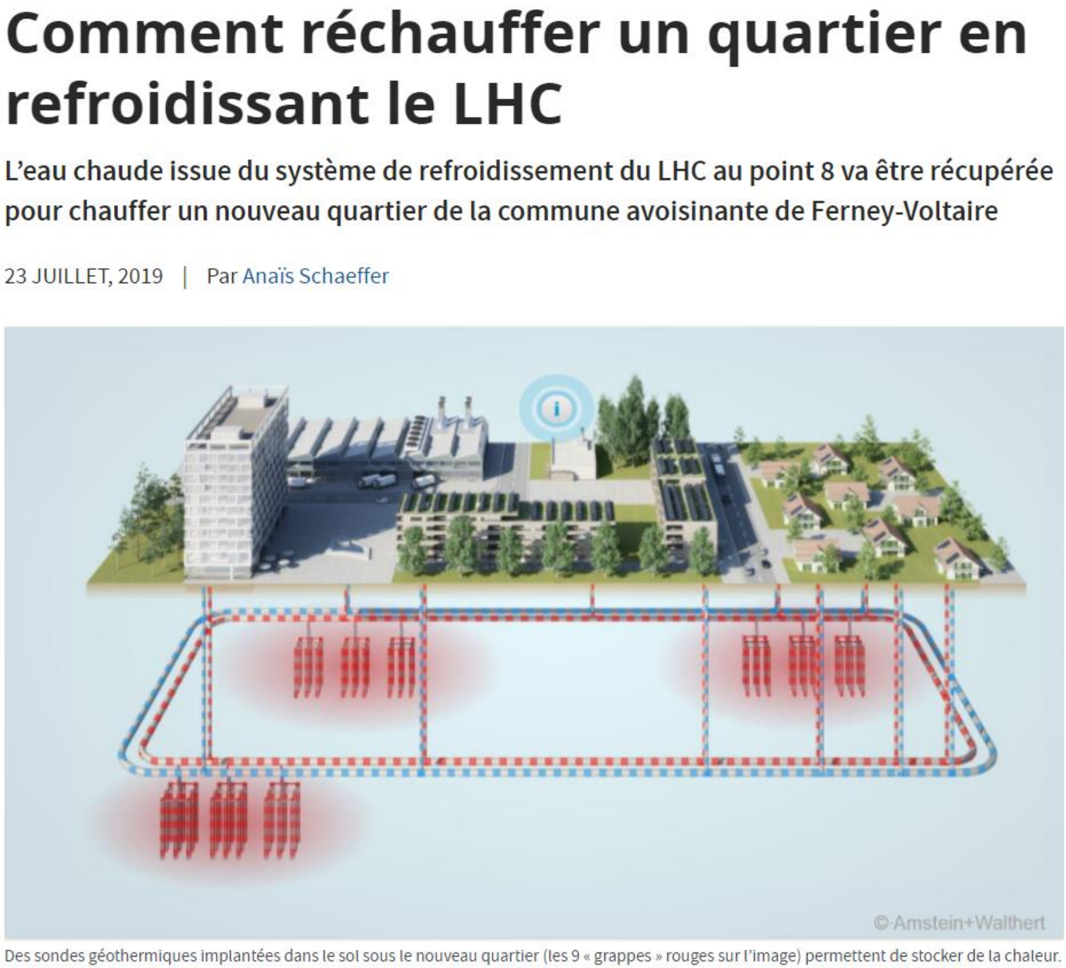


Surface Storage

Experimental Area

- **ATLAS >300kW**
- **CMS >500kW**

Heat Recovery



Comment réchauffer un quartier en refroidissant le LHC

L’eau chaude issue du système de refroidissement du LHC au point 8 va être récupérée pour chauffer un nouveau quartier de la commune avoisinante de Ferney-Voltaire

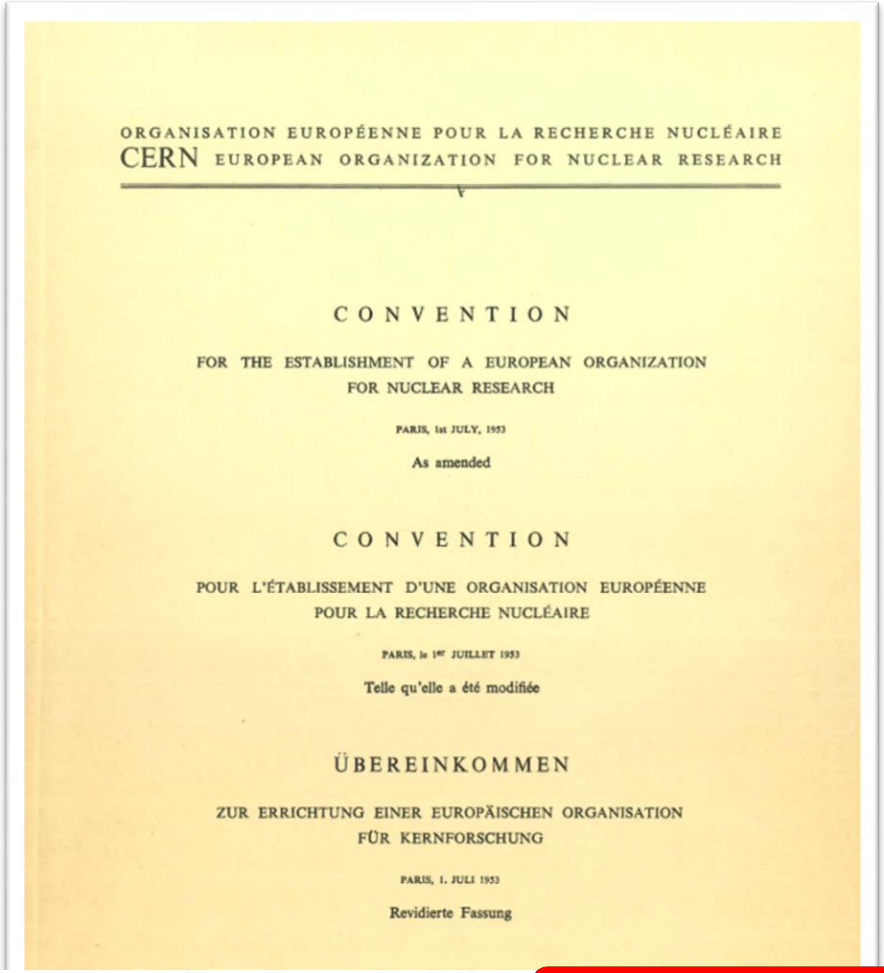
23 JUILLET, 2019 | Par Anaïs Schaeffer

Des sondes géothermiques implantées dans le sol sous le nouveau quartier (les 9 « grappes » rouges sur l’image) permettent de stocker de la chaleur.

bleu, la nouvelle Zone d’aménagement concerté (ZAC) actuellement en construction à Ferney-Voltaire. En rouge, le réseau de récupération de chaleur qui reliera le point 8 à ce nouveau quartier (Image : Territoire d'Innovation)

European Strategy for Particle Physics

The role of CERN



ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CONVENTION

FOR THE ESTABLISHMENT OF A EUROPEAN ORGANIZATION
FOR NUCLEAR RESEARCH

PARIS, 1st JULY, 1953

As amended

CONVENTION

POUR L'ÉTABLISSEMENT D'UNE ORGANISATION EUROPÉENNE
POUR LA RECHERCHE NUCLÉAIRE

PARIS, le 1er JUILLET 1953

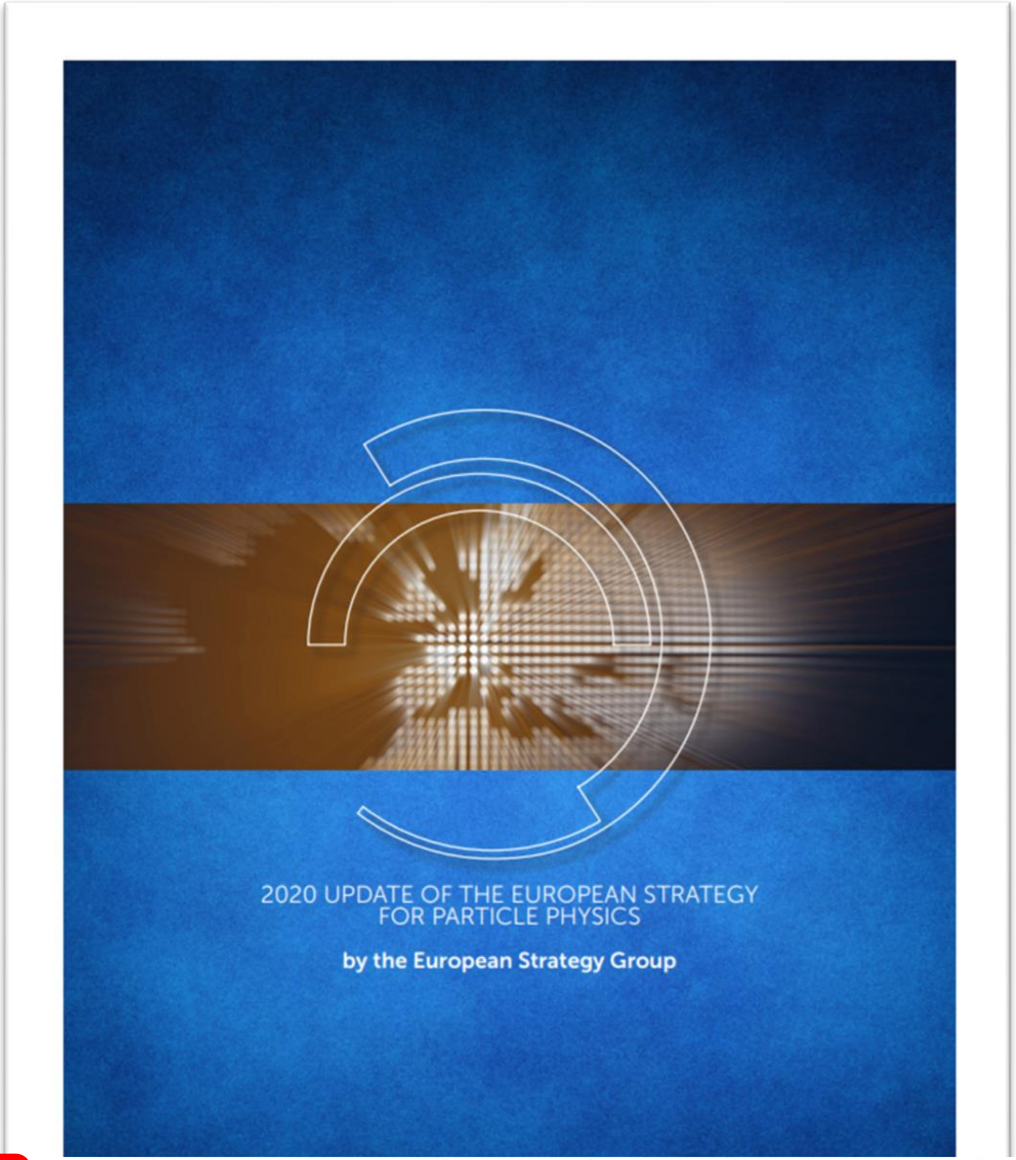
Telle qu'elle a été modifiée

ÜBEREINKOMMEN

ZUR ERRICHTUNG EINER EUROPÄISCHEN ORGANISATION
FÜR KERNFORSCHUNG

PARIS, 1. JULI 1953

Revidierte Fassung



2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group

1. The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available.

2020 Update of the European Strategy for Particle Physics

- *This Strategy update should be implemented to **ensure Europe's** continued scientific and technological **leadership***
- *The successful **completion of the high-luminosity upgrade** of the machine and detectors **should remain the focal point** of European particle physics, together with continued innovation in experimental techniques.*
- *The existence of non-zero neutrino masses is a compelling sign of new physics. **Europe, and CERN** through the Neutrino Platform, **should continue to support long baseline experiments in Japan and the United States.***
- *An **electron-positron Higgs factory is the highest-priority next collider.** For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*

2020 Update of the European Strategy for Particle Physics

- *Accomplishing these compelling goals will require innovation and cutting-edge technology:*
  - *the particle physics community* ***should ramp up its R&D effort*** *focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
  - *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update (~2027).*
- *The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.*

Particle types to accelerate

Not so many choices:

- Need stable charges particles: protons, electrons, (muons), ions – most used: electrons and protons
- Secondary beams: photons, pions, kaons, neutrons, neutrinos, …..

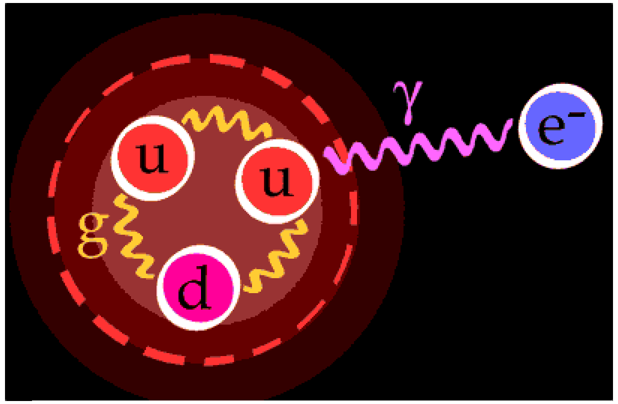
Proton collisions: compound particles

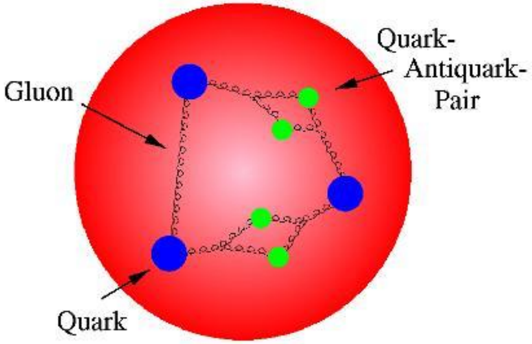
- Mix of quarks, anti–quarks and gluons: variety of processes
- Parton energy spread
- QCD processes large background sources

Electron/positron collisions: elementary particles

- Collision process known
- Well defined energy
- Background from other physics limited

Muons: elementary particle, but lifetime only 2.2 μs





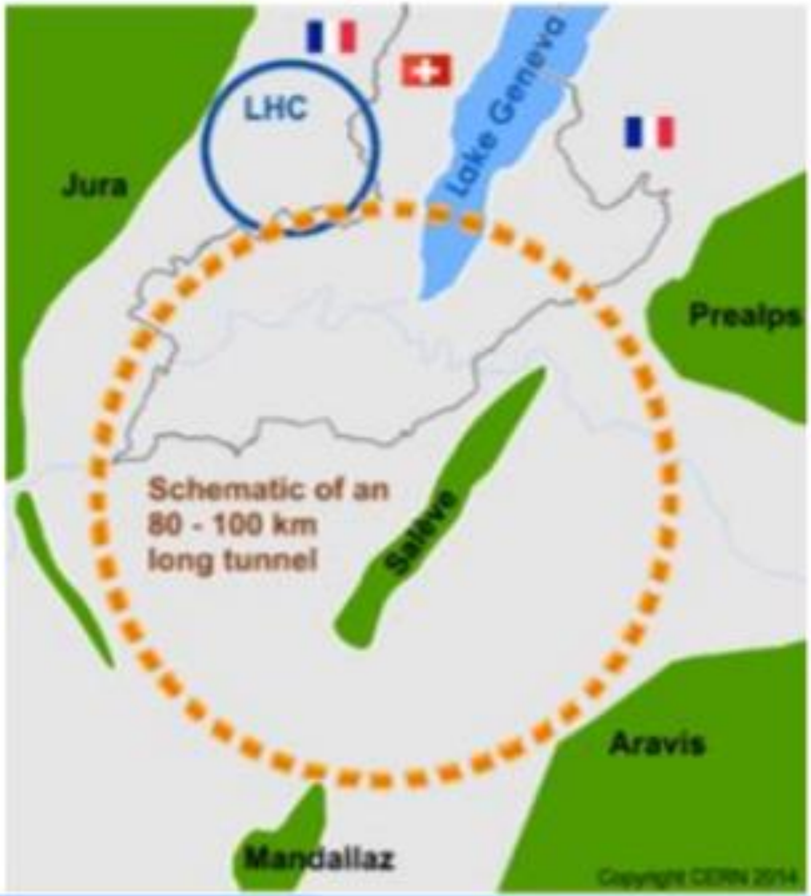
$$\frac{\text{proton mass}}{\text{electron mass}} \approx 2000$$

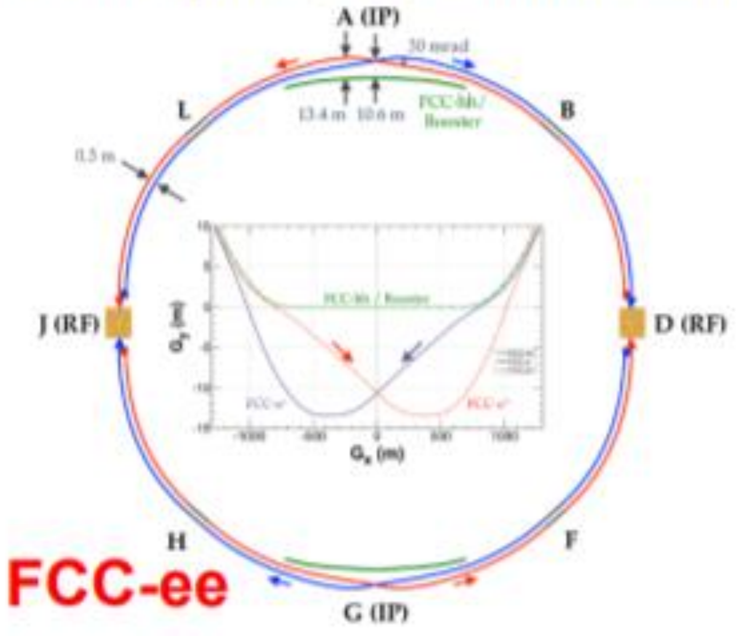
FCC
Future Circular Collider

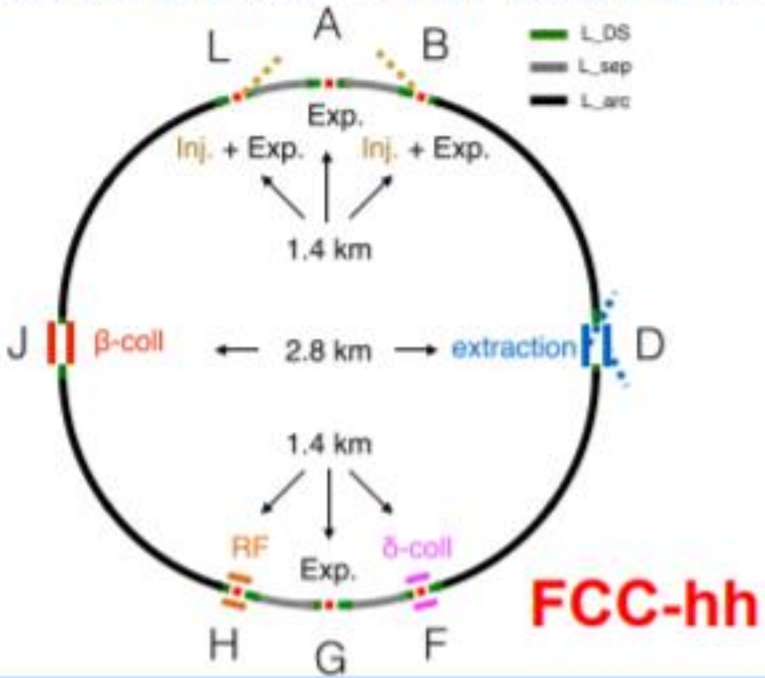
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive long-term program, maximizing physics opportunities

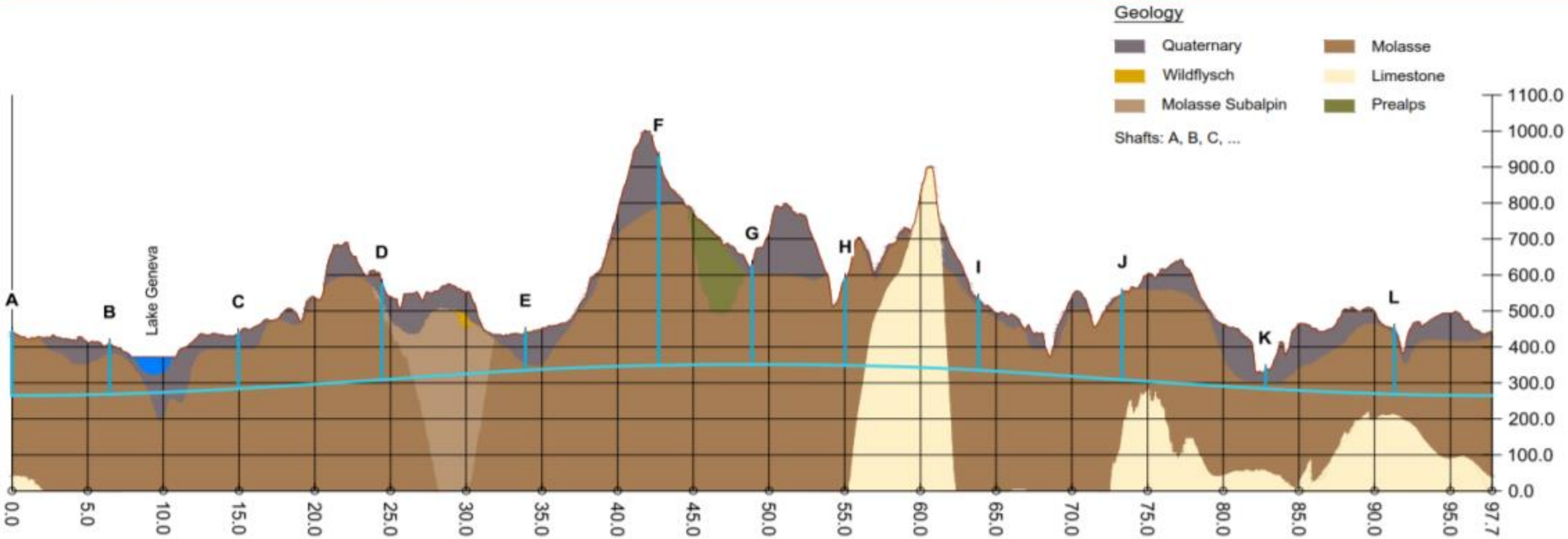
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC

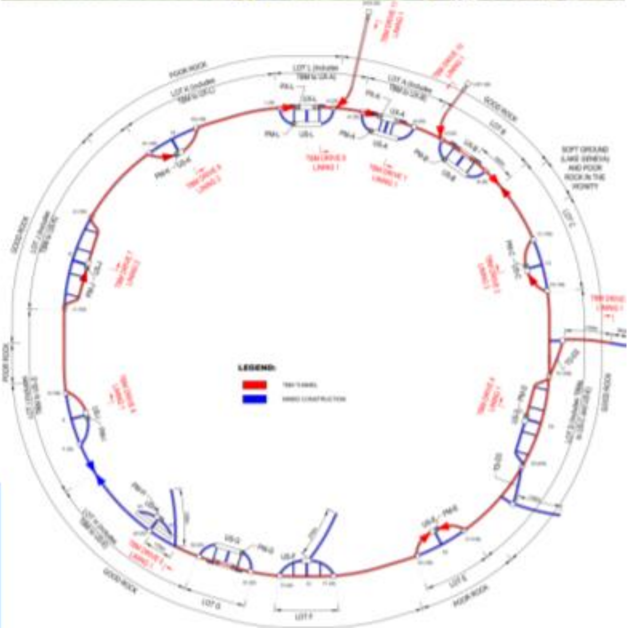






FCC implementation - footprint baseline





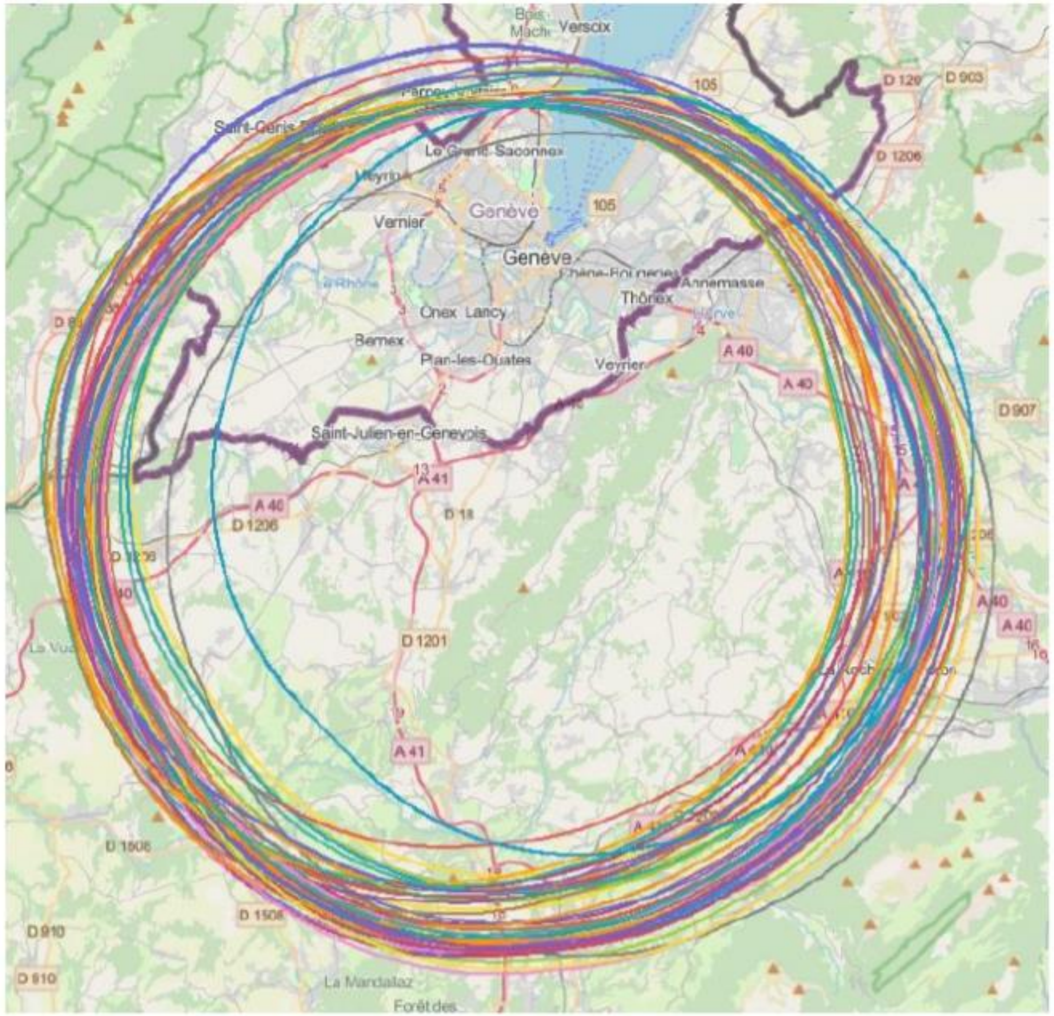
Present baseline position was established considering:

- Molasse rock preferred for tunnelling, avoid limestone with karstic structures
- low risk for construction, fast construction

- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

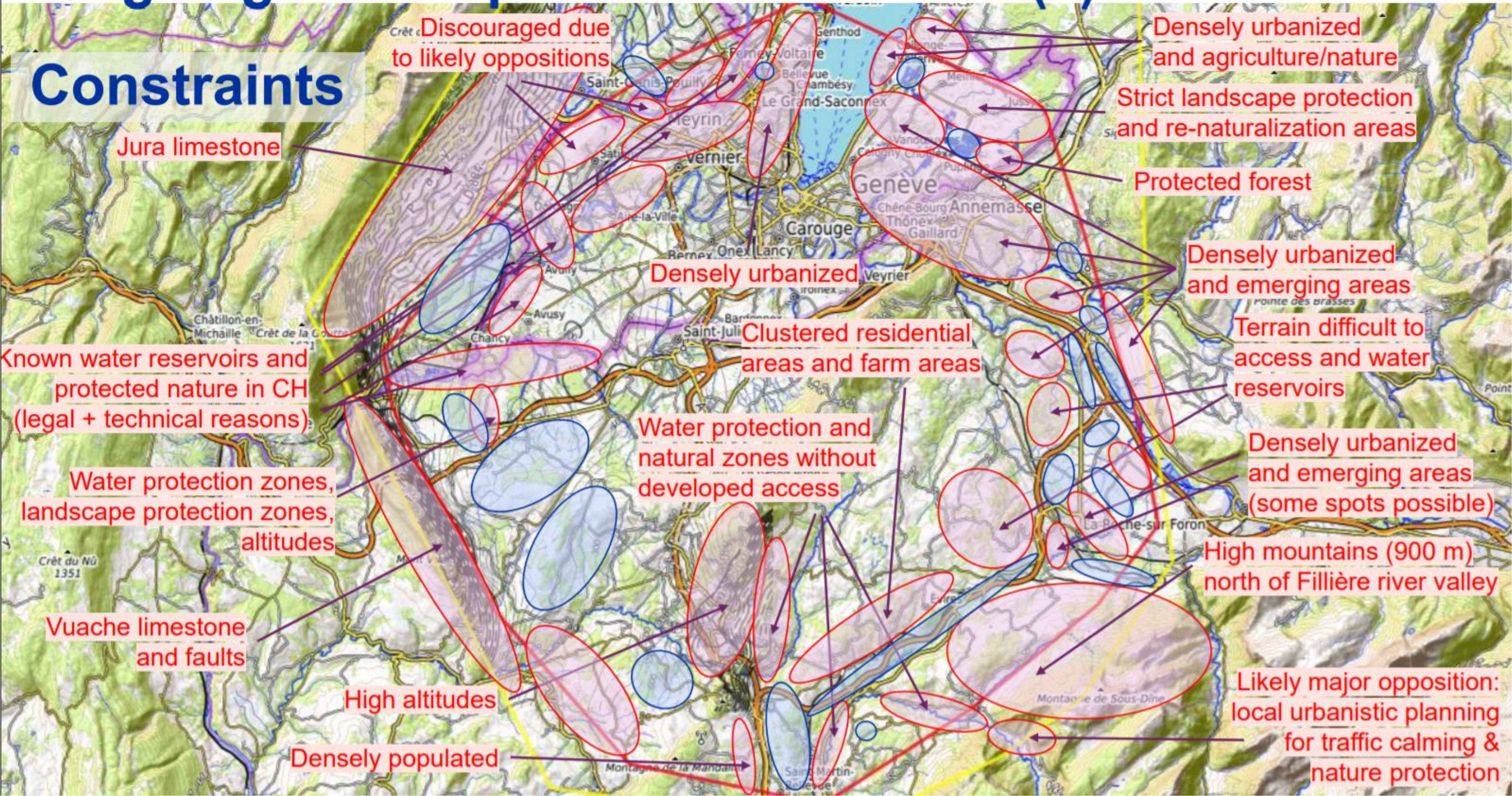
The FCC feasibility Study 2021 - 2025

- Optimise the **layout**, for the ring and the surface sites
- Prepare the **administrative processes** for a potential project approval with the Host States
- Optimise of the **colliders and theirs injector chains**
- Develop and document of the **technical infrastructure**
- Elaborate a **sustainable operational model** for the collider and experiments (human and financial needs, environmental aspects, energy efficiency)
- Consolidate **costs estimates** and **fundings**



Source: CERN

Ongoing work – placements studies (ii)



Constraints

Jura limestone

Discouraged due to likely oppositions

Known water reservoirs and protected nature in CH (legal + technical reasons)

Water protection zones, landscape protection zones, altitudes

Vuache limestone and faults

High altitudes

Densely populated

Densely urbanized

Clustered residential areas and farm areas

Water protection and natural zones without developed access

Densely urbanized and agriculture/nature

Strict landscape protection and re-naturalization areas

Protected forest

Densely urbanized and emerging areas

Terrain difficult to access and water reservoirs

Densely urbanized and emerging areas (some spots possible)

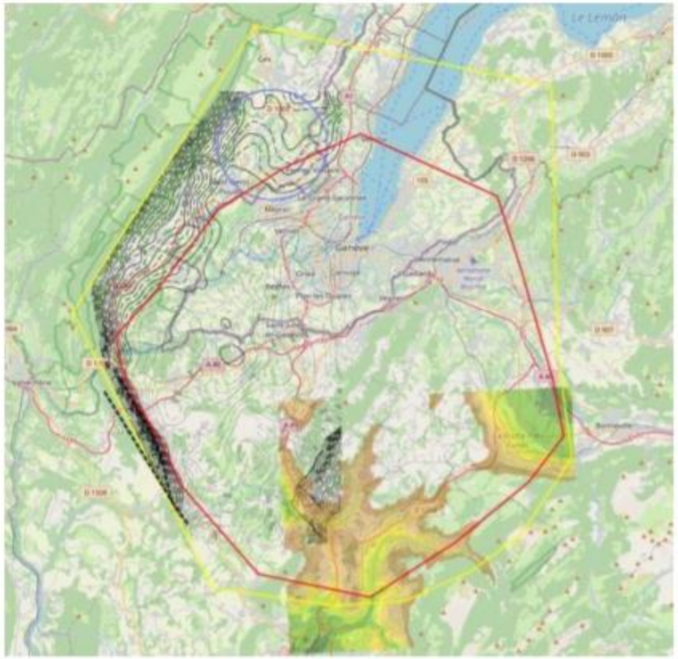
High mountains (900 m) north of Fillière river valley

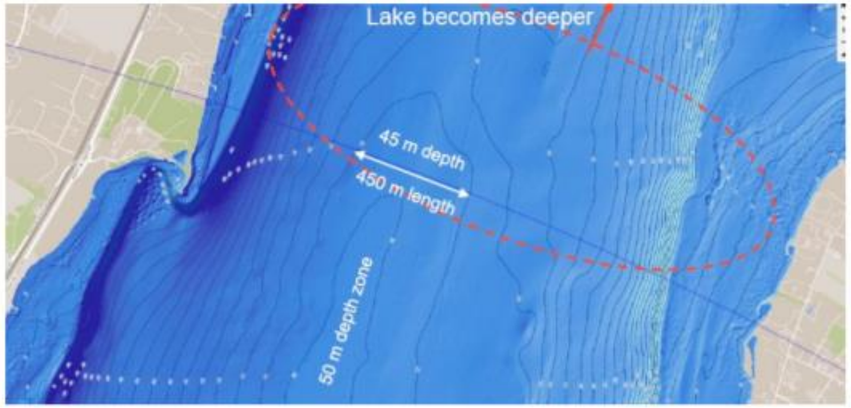
Likely major opposition: local urbanistic planning for traffic calming & nature protection

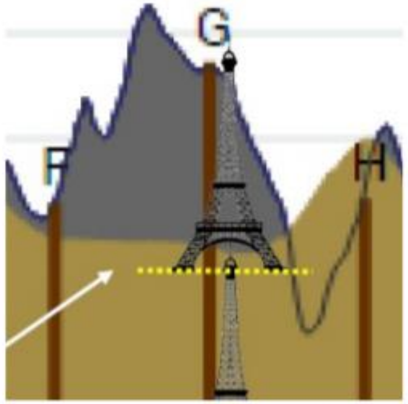
High level needs and constraints

Project risk:

- **Avoid Vuache top of limestone** (200 m above sea level)
- **Avoid Jura top of limestone** (250 m above sea level)
- **Avoid high altitudes** (higher than 700 m above sea level)
- **Shaft depths < 300 m** at **experiment** sites
- **Shaft depths < 400 m** at **technical** sites
- Stay **50 m below lake bed**
- Not too close to Rhône
- Attention at Arve crossing
- Mind overburdens
- Avoid sites at water bearing areas







Source: CERN

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

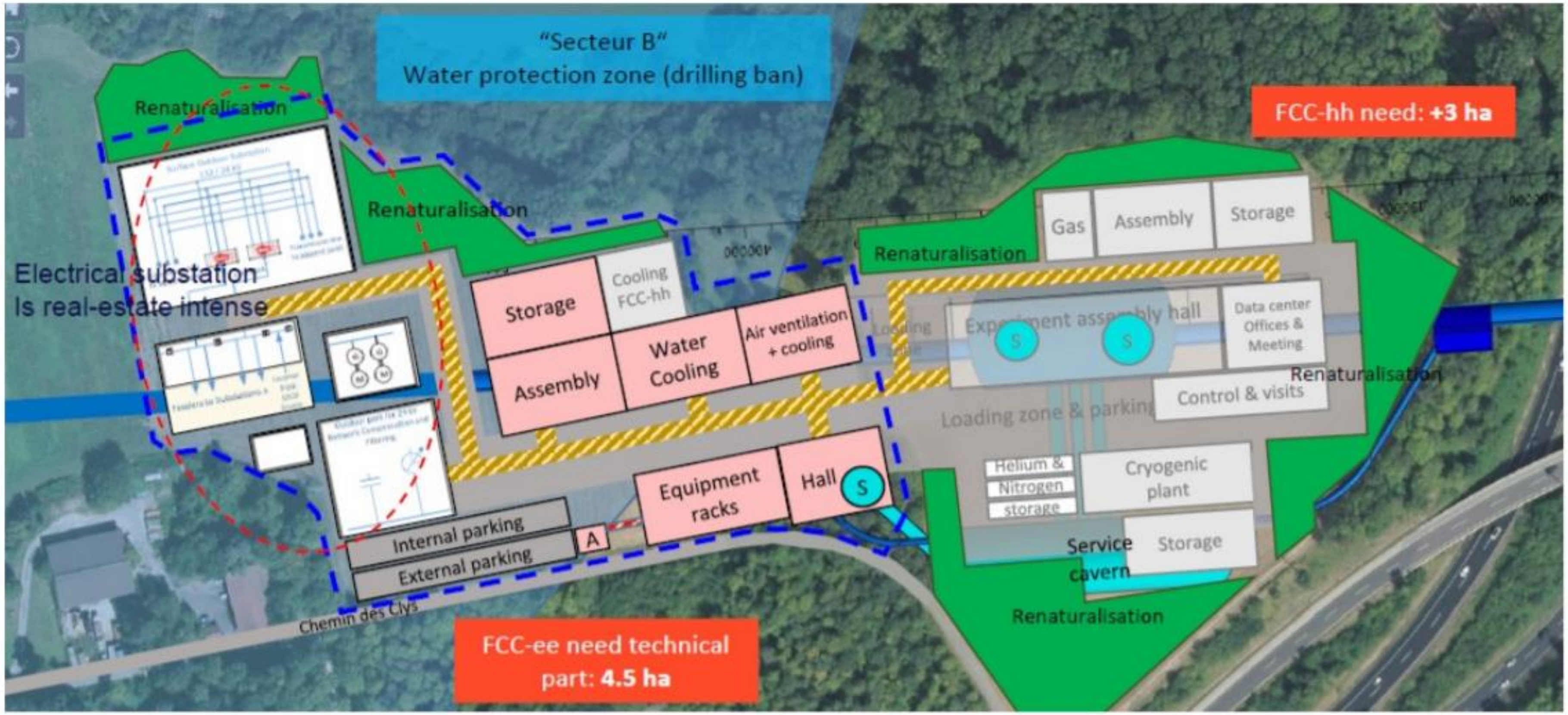
Cerema

Elements of a surface site

Layout exercise reveals that about 7 ha are needed for an experiment site
(Indicated location is not part of a preferred placement scenario)

Many functions:

- Shaft access
- Cryogenics
- Machine powering
- Water cooling
- Ventilation
- Electrical substation
- Workshops
- Storage
- Parkings
- Assembly halls
- Data center



FCC-hh need: **+3 ha**

FCC-ee need technical part: **4.5 ha**

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Fraternité

Cerema

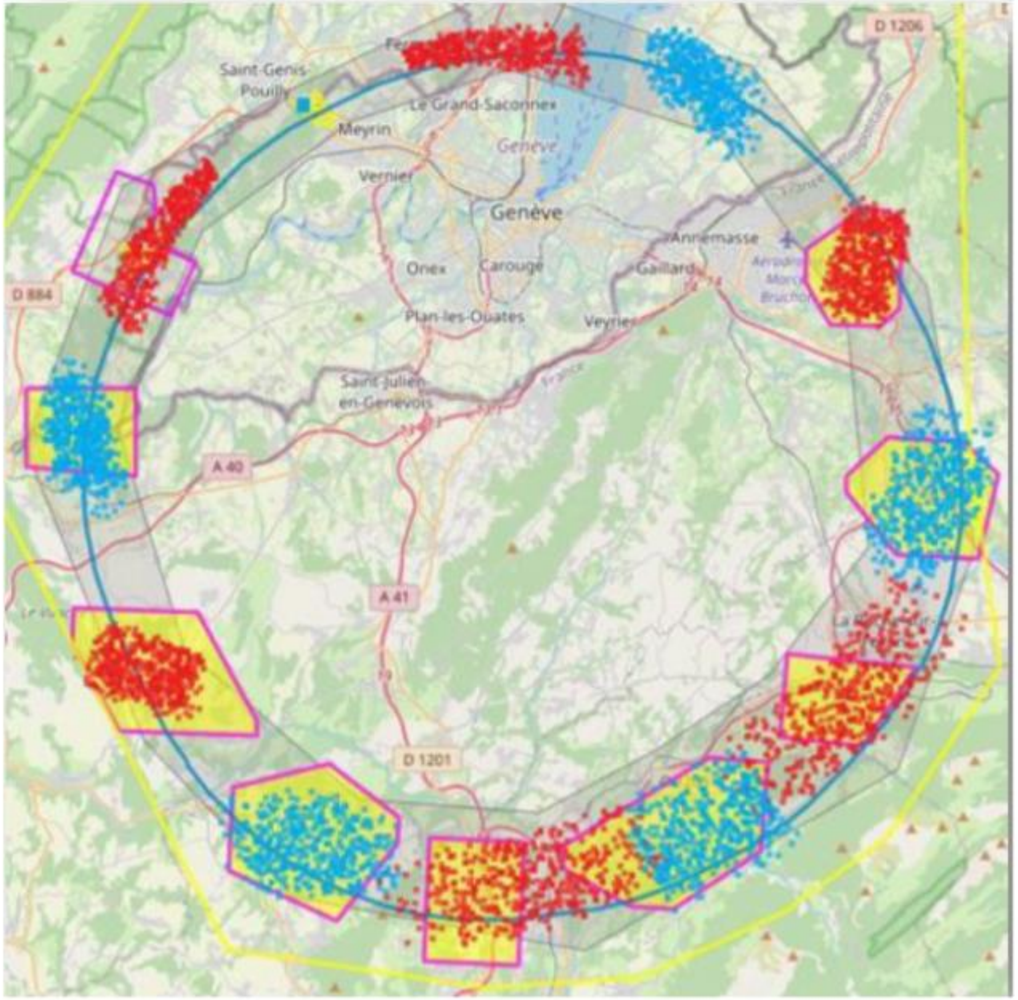
Next steps...

Next steps :

- Work on the developement of the new scenario baseline
- Conduct consultations with stakeholders and partners
- Prepare the high risk area investigations
- Optimise towards a preferred scenario

To bear in mind :

- Territory evolves without stop...
- Constraints continue to increase...

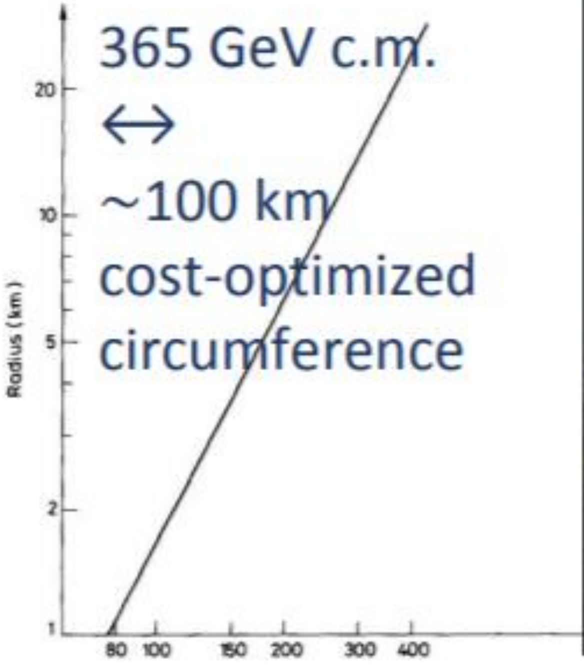


"An e^+-e^- storage ring … of a few hundred GeV in the centre of mass can be built with present technology. ...would seem to be ... most useful project on the horizon." Burt Richter 1976

"Of course, it should not be the size of an accelerator, but its costs which must be minimized."

Gus Voss, builder of PETRA
IEEE PAC, Dallas, 1995

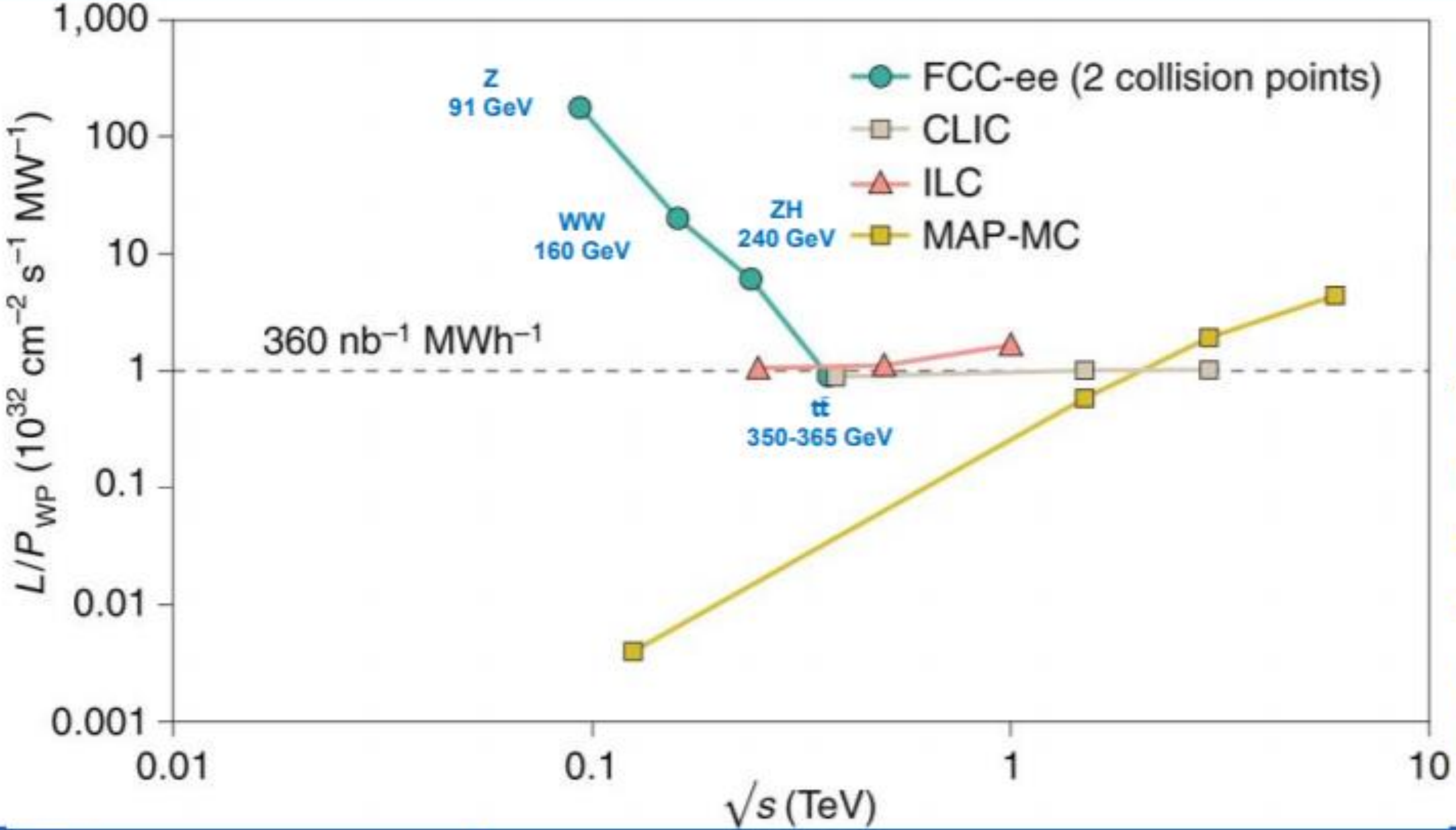
B. Richter, *Very High Energy Electron-Positron Colliding Beams for the Study c Weak Interactions*, NIM 136 (**1976**) 47



365 GeV c.m.
↔
~100 km
cost-optimized
circumference

FUTURE CIRCULAR COLLIDER

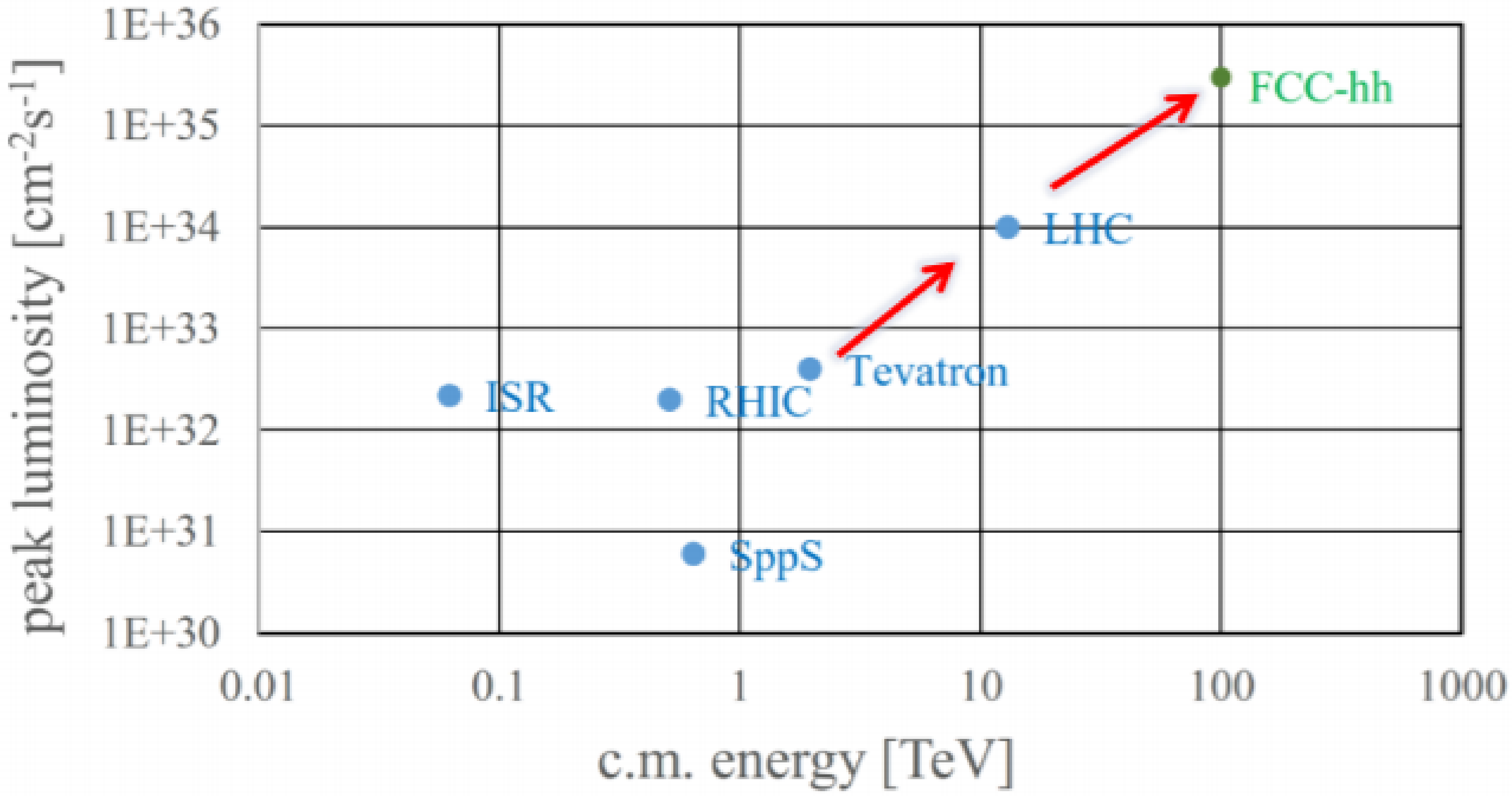
FCC-ee: efficient Higgs/electroweak factory



luminosity *L* per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders

M. Benedikt, A. Blondel, P. Janot, et al., **Nature Physics 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

FCC-hh: big step in performance



order of magnitude performance increase in **energy & luminosity**

100 TeV cm collision energy (vs 14 TeV for LHC)

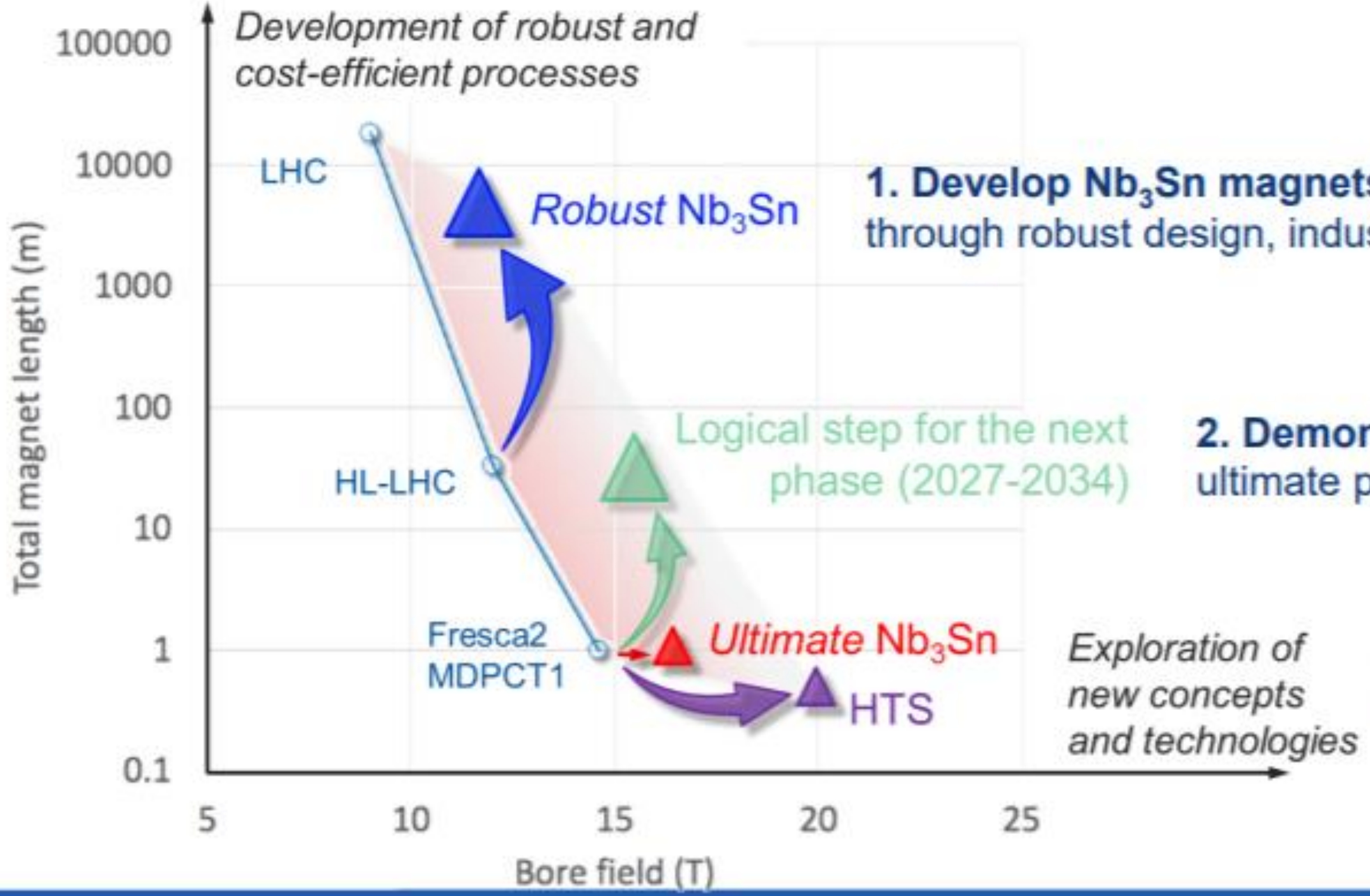
20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

similar performance increase as from Tevatron to LHC

key technology: high-field magnets

High Field Magnet program goals until 2027

L. Bottura

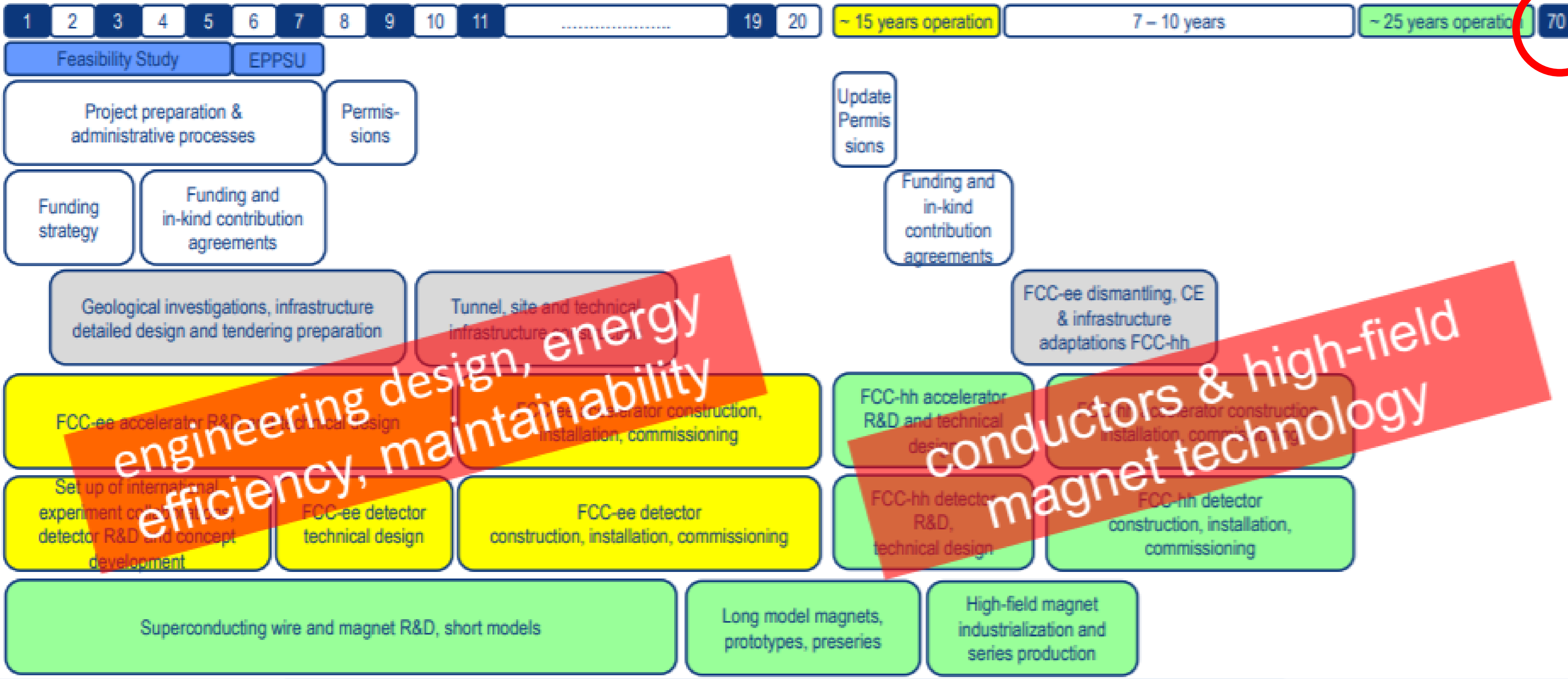


1. Develop Nb_3Sn magnets for collider-scale production, through robust design, industrial processes and cost reduction

2. Demonstrate Nb_3Sn full potential in terms of ultimate performance

3. Provide a proof-of-principle for HTS magnet technology

FCC integrated project technical schedule



1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | .... | 19 | 20 | ~ 15 years operation | 7 – 10 years | ~ 25 years operatio | 70

Feasibility Study

EPPSU

Project preparation & administrative processes

Permis-sions

Update Permis sions

Funding strategy

Funding and in-kind contribution agreements

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and magnet R&D, short models

Long model magnets, prototypes, preseries

High-field magnet industrialization and series production

engineering design, energy efficiency, maintainability

conductors & high-field magnet technology

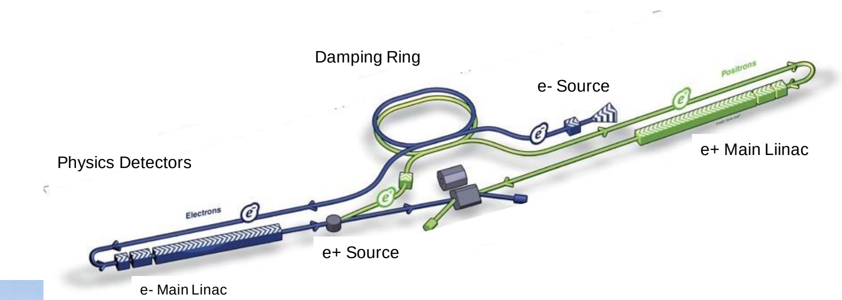
Seneca, Naturales Quaestiones, VII, 25-30

- *There will come a day when these phenomena which now remain in darkness will be brought to light by daily work and by careful investigation over a longer period of time. To investigate such complex phenomena, the work of a single life cannot suffice. It is evident that these phenomena can only be resolved through the work of long, successive generations of men. There will come a day when our posterity will marvel that we have ignored things that will be very clear to them. May the men of our time be happy with the discoveries made, may posterity also have the opportunity to make their contribution to the discovery of the Truth! Many things are reserved for future generations, living in times when the memory of all of us will certainly have faded*

CLIC

Compact Linear Collider

Next: A Higgs factory



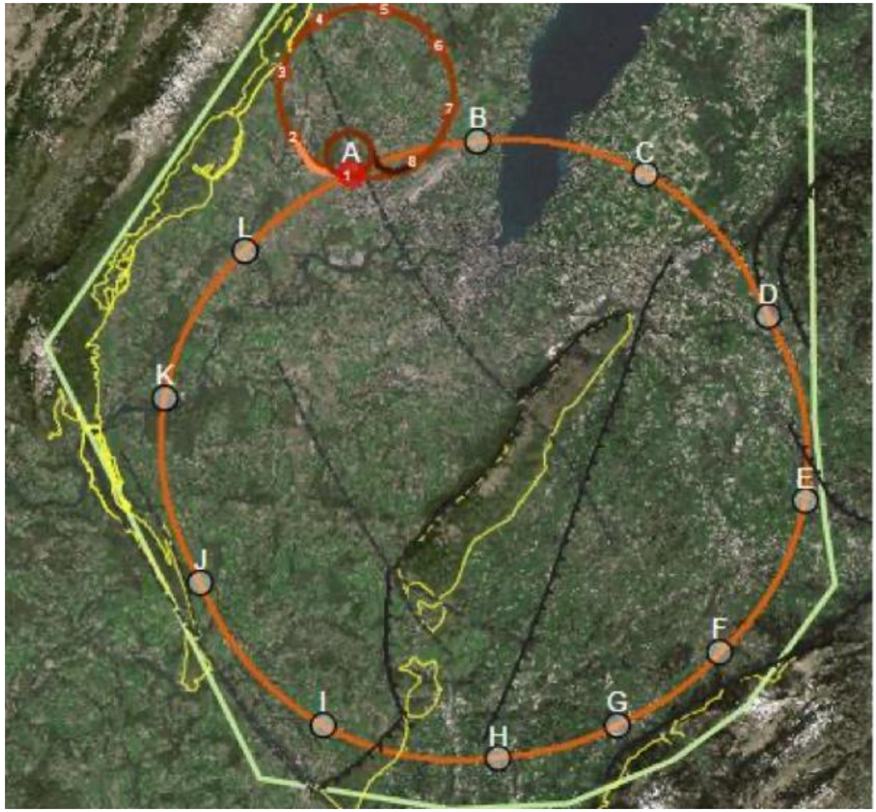
Need e+e– collisions at least at 250 GeV, four alternatives:

ILC in Japan (linear)

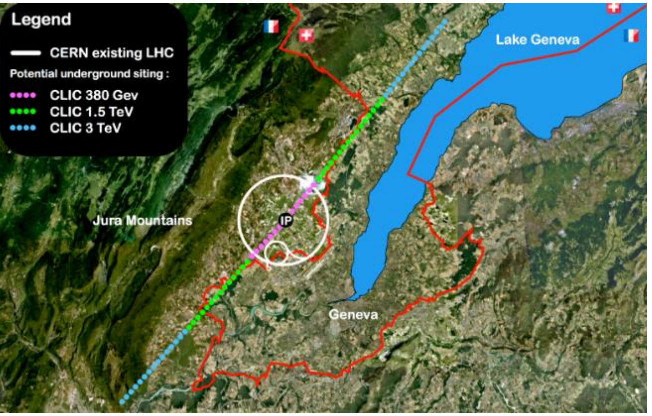
FCC at CERN (ring)

CLIC at CERN (linear)

CEPC in China (ring)



Linear colliders: 13 (Higgs) –> 50 (max) km
Rings ~100km, can be used for protons after



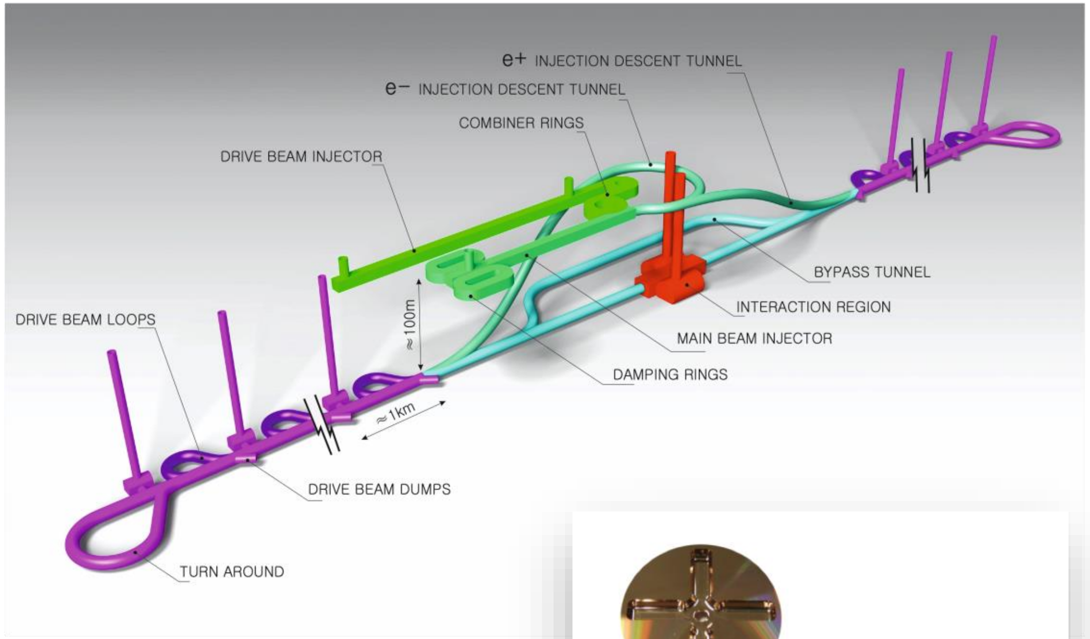
Circular vs Linear

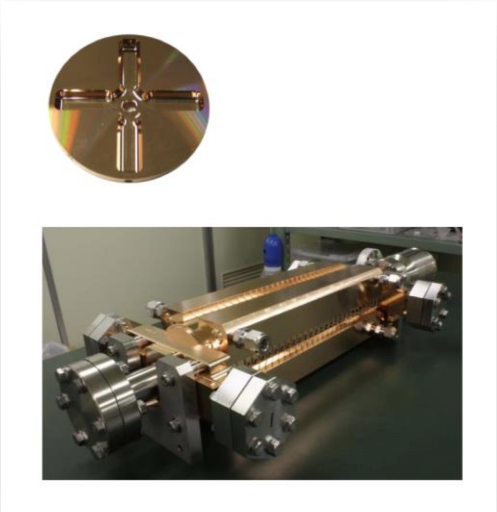
- *Circular colliders are preferred for protons (and heavier particles).*
  - In a Linear collider the energy would be limited by the electric field gradient one can reach in accelerating structures → prohibitive length for significant energies
  - Has the advantage of re-colliding bunches several times, making a better use of particles generated…
  - The Energy is limited by the B field that can be reached in bending

- For Electrons both linear and circular are possible.
- In Circular colliders the energy/intensity is limited by synchrotron radiation

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

Proposed e^+e^- linear colliders – CLIC





Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

The Compact Linear Collider (CLIC)

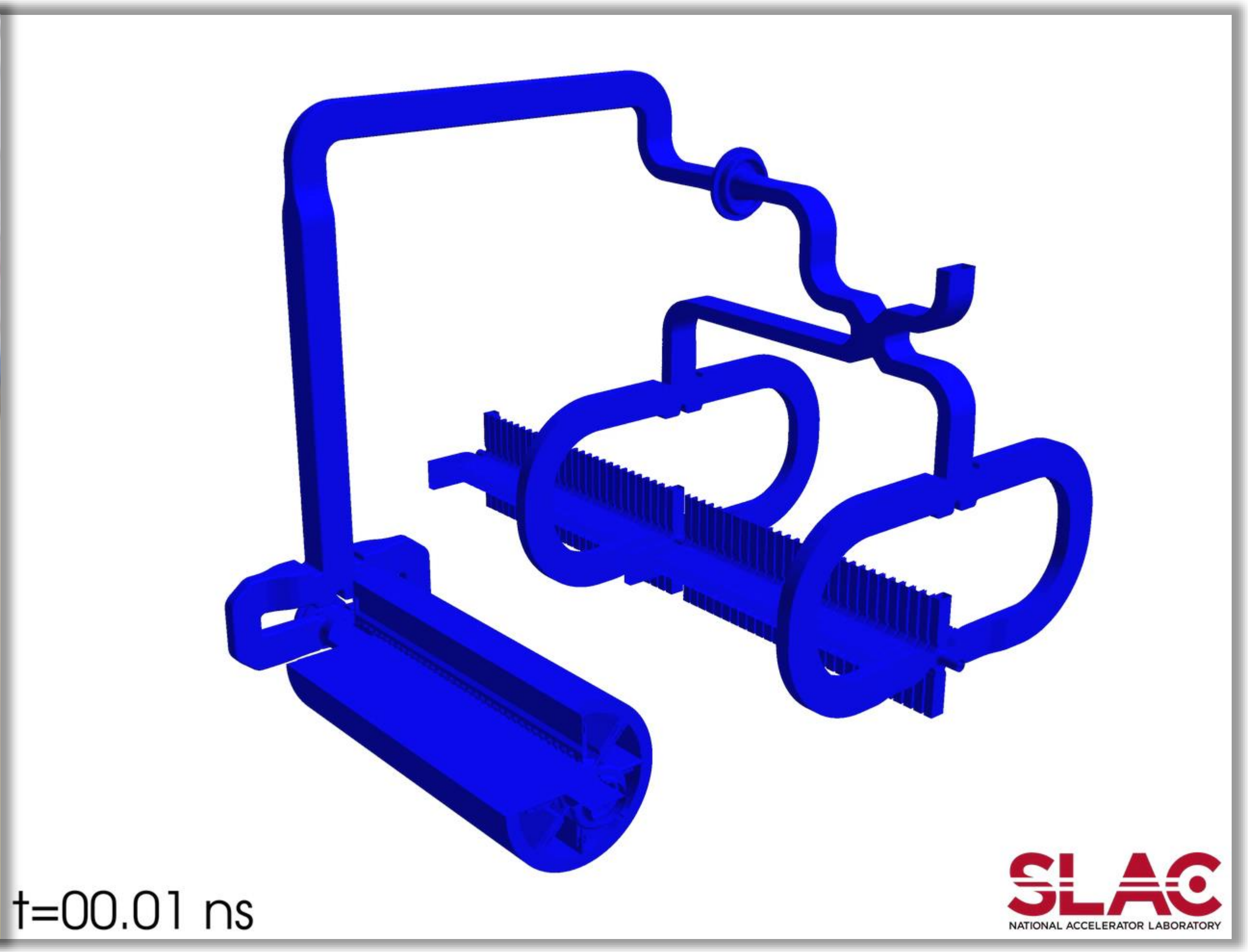
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

- CDR in 2012. Updated project overview documents in 2018 (Project Implementation Plan). See resource slide.

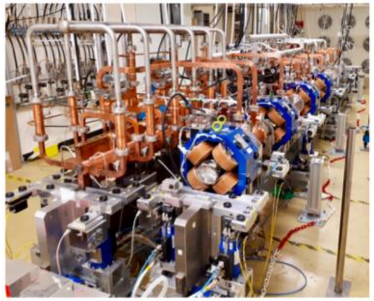
- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

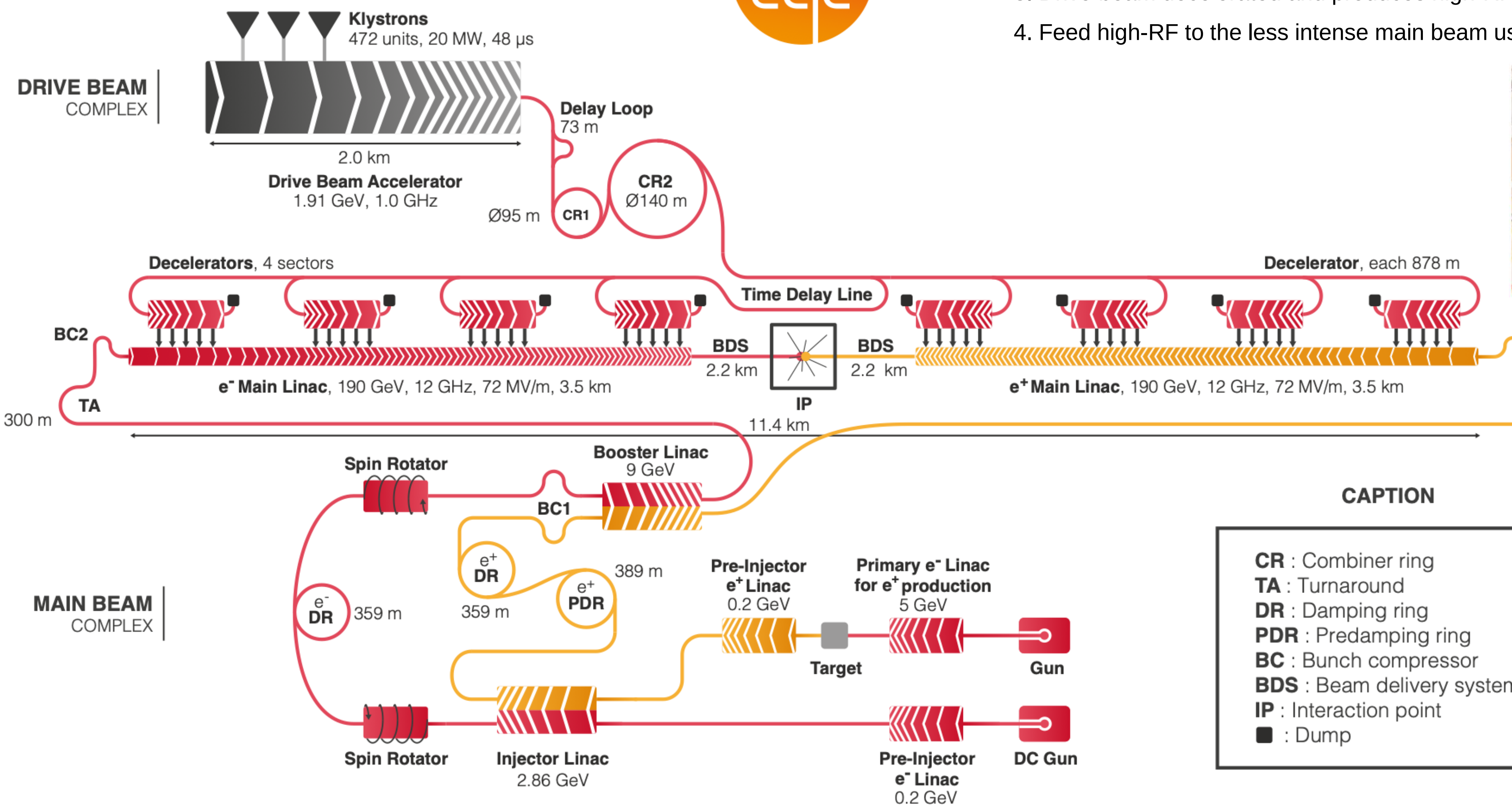
- Comprehensive **Detector and Physics** studies

Two-Beam acceleration



1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides

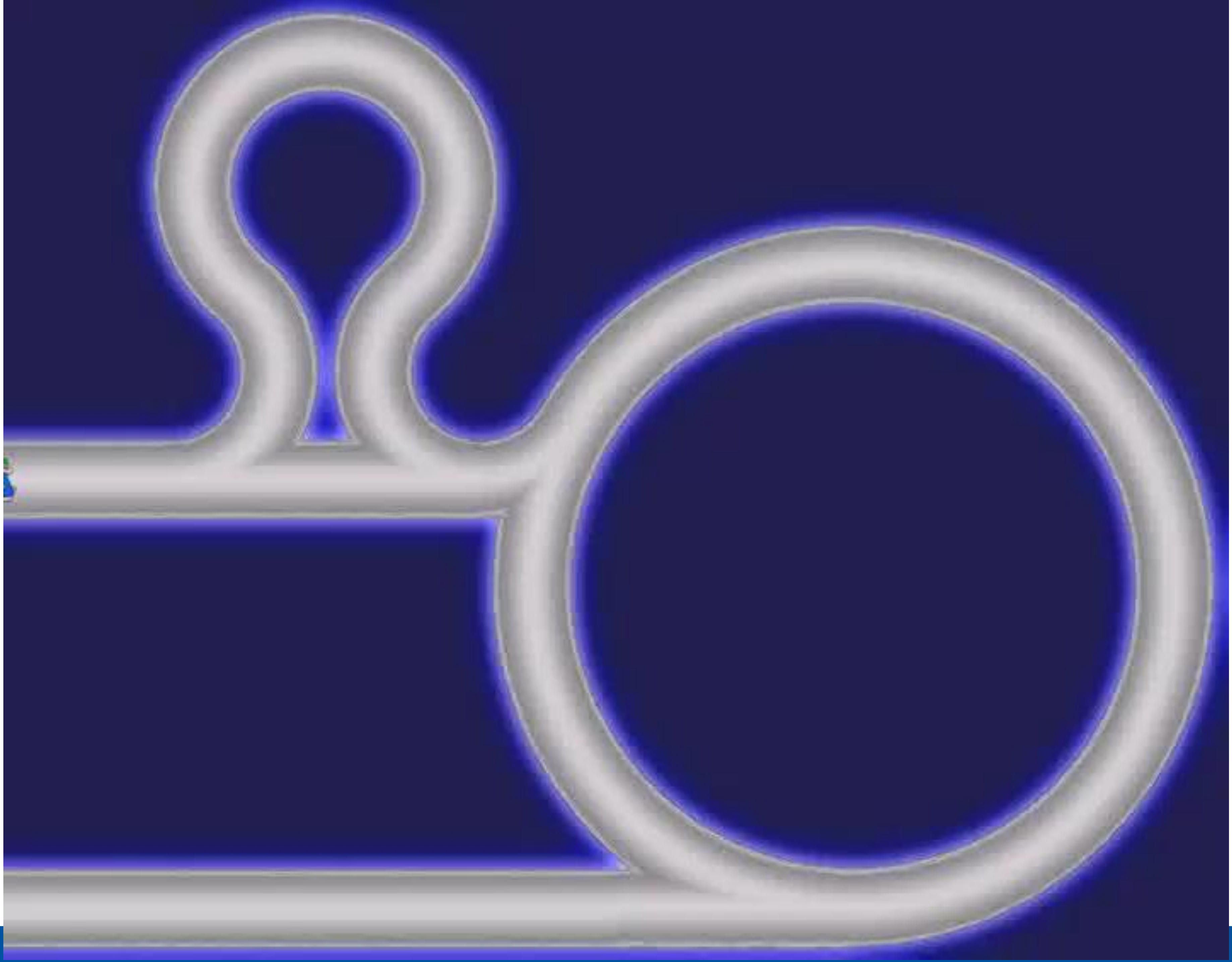


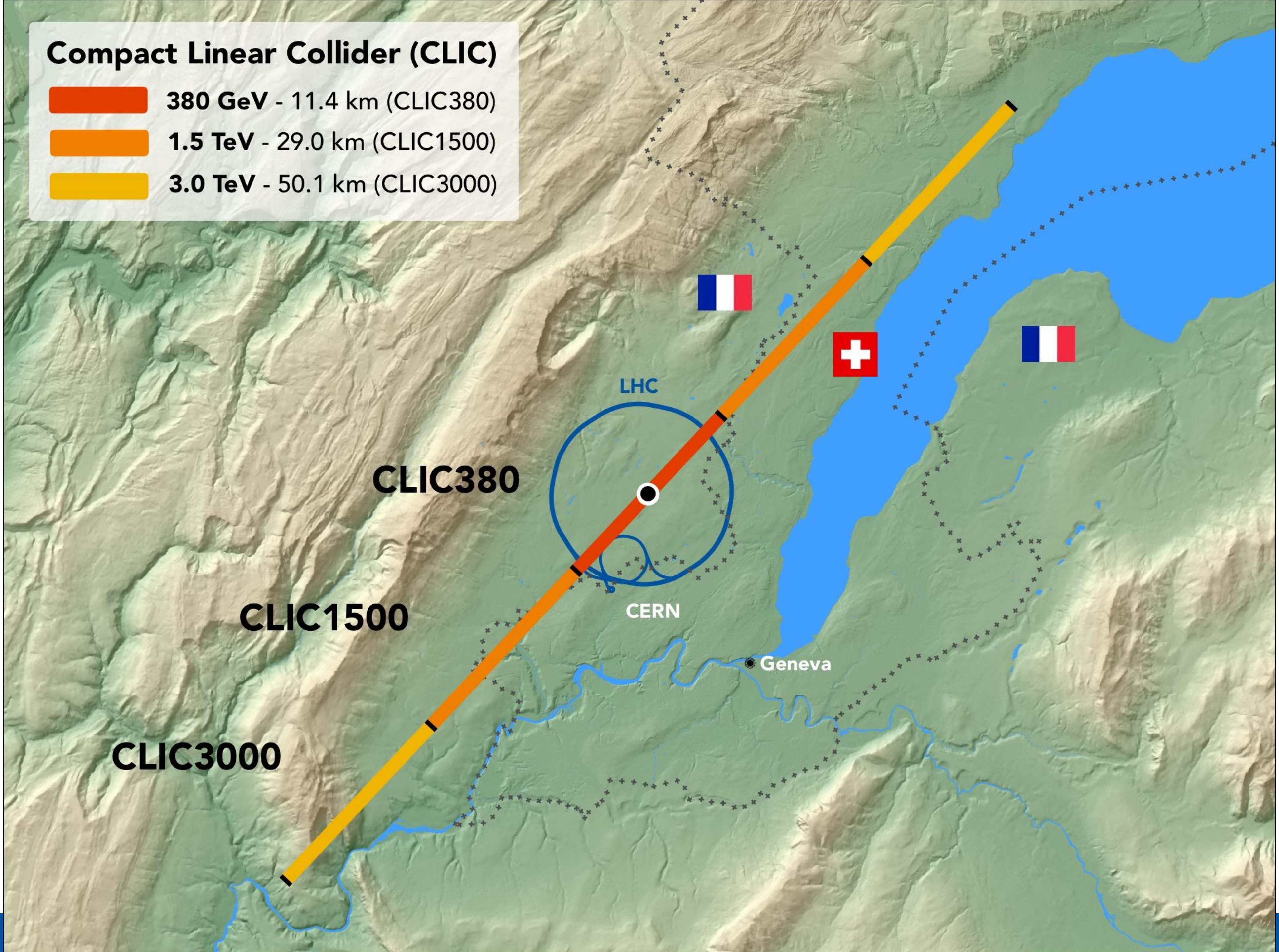


CAPTION

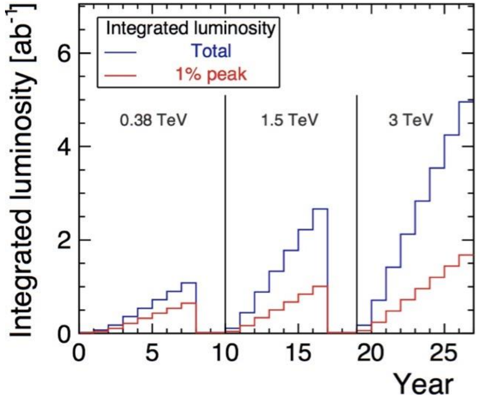
CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

380 GeV

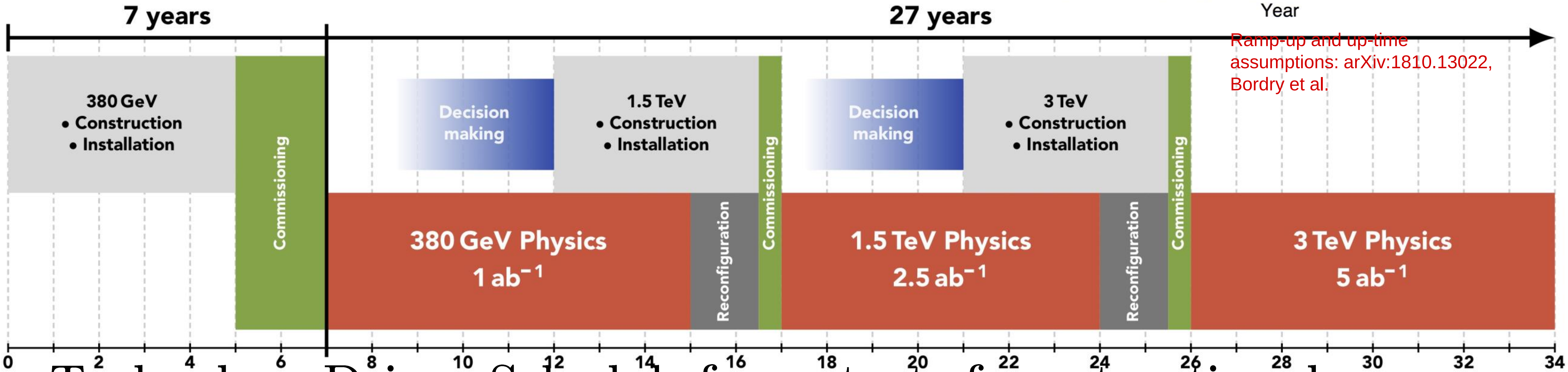



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
CLIC380
CLIC1500
CLIC3000
LHC
CERN
Geneva

CLIC timeline



Ramp-up and up-time assumptions: arXiv:1810.13022, Bordry et al.



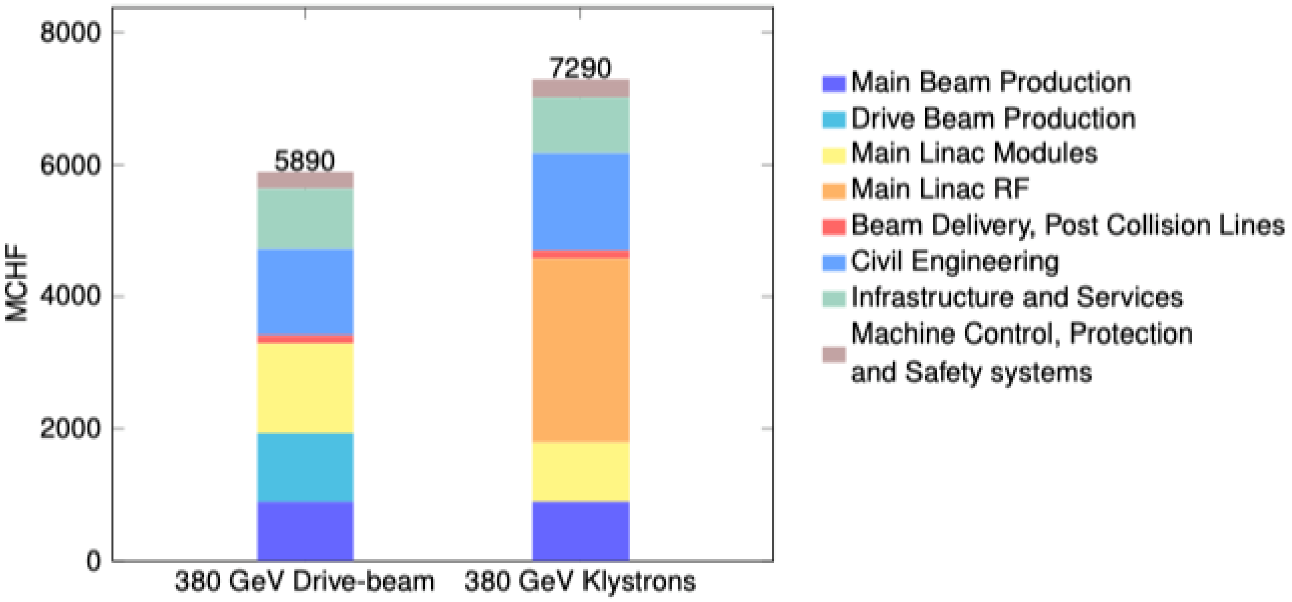
- Technology Driven Schedule from start of construction shown above.
- A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)

Cost - I

Machine has been re-costed bottom-up in 2017-18

- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated

Domain	Sub-Domain	Cost [MCHF]	
		Drive-Beam	Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**



CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

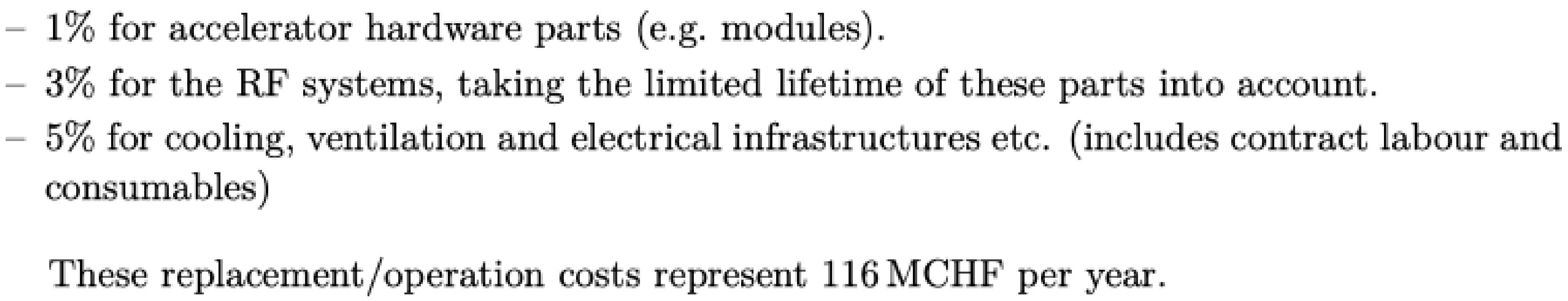
CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

Cost - II

Other cost estimates:

Construction:
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction (~1700 FTE x 7 years…)

Operation:
- 116 MCHF (see assumptions in box below)
- Energy costs



- 1% for accelerator hardware parts (e.g. modules).
- 3% for the RF systems, taking the limited lifetime of these parts into account.
- 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

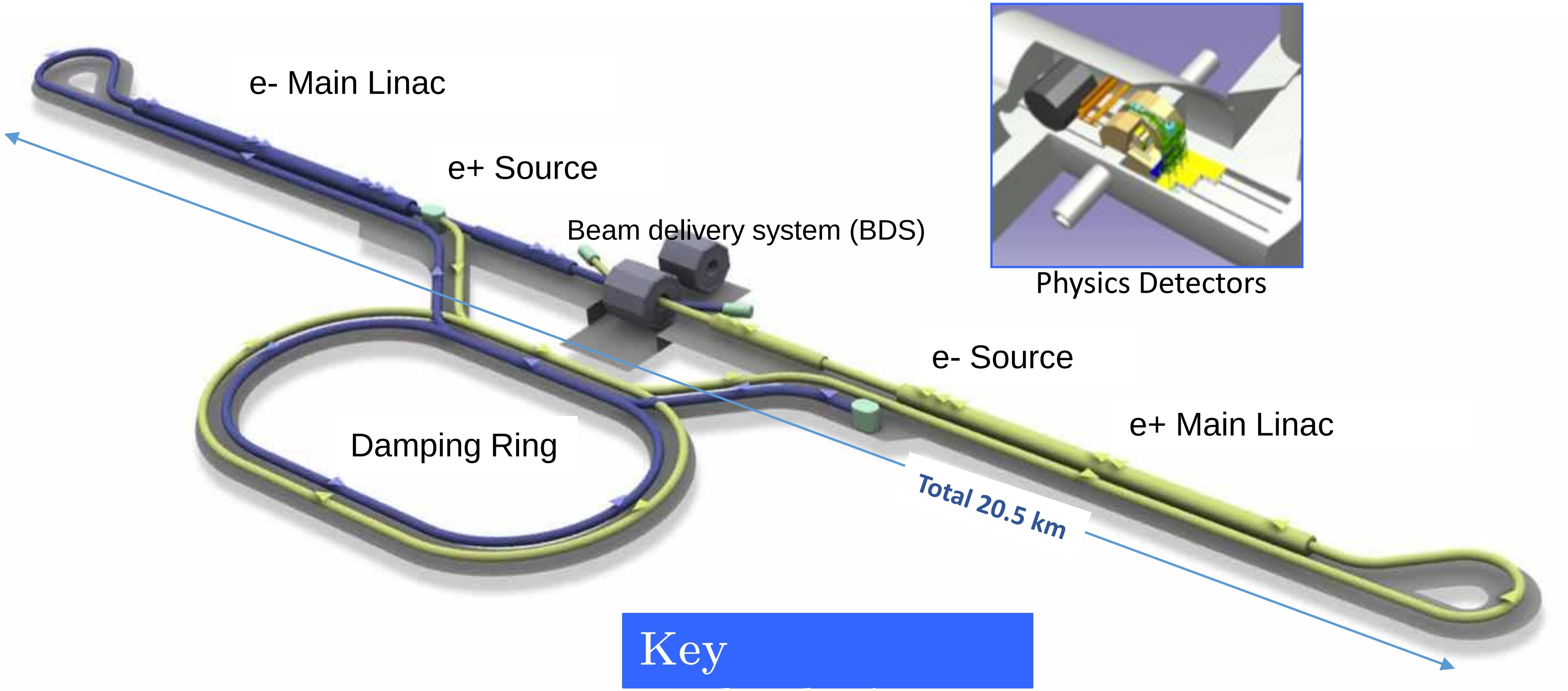
These replacement/operation costs represent 116 MCHF per year.

ILC

International Linear Collider

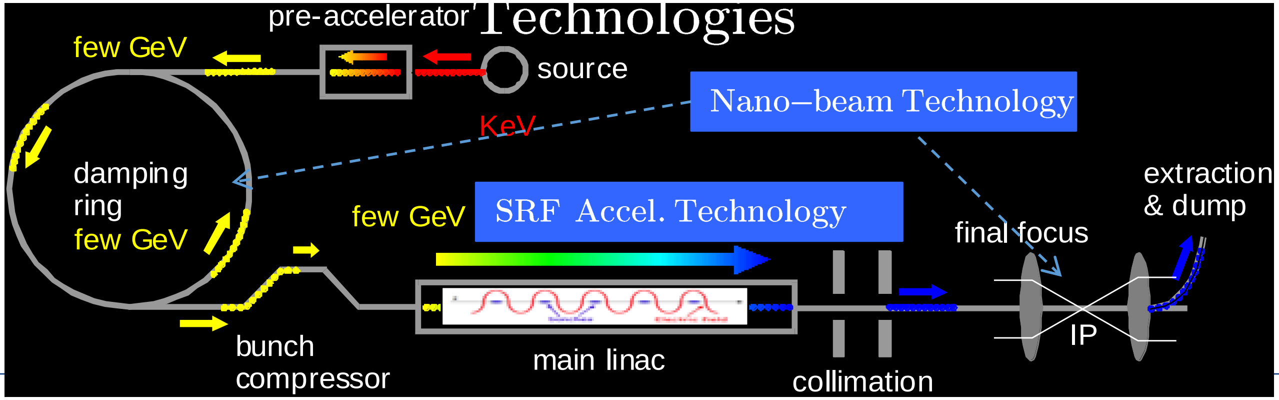
ILC Candidate Location: Kitakami, Tohoku

Design outline: ILC250 accelerator facility

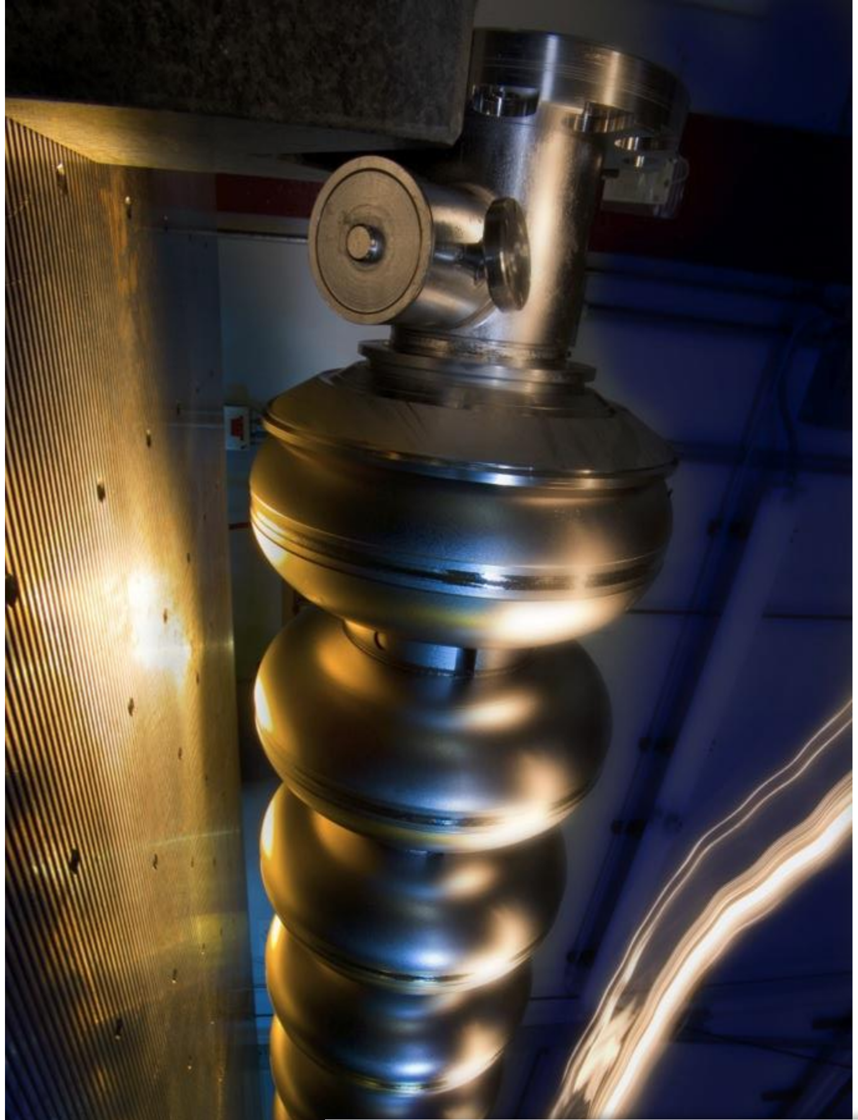


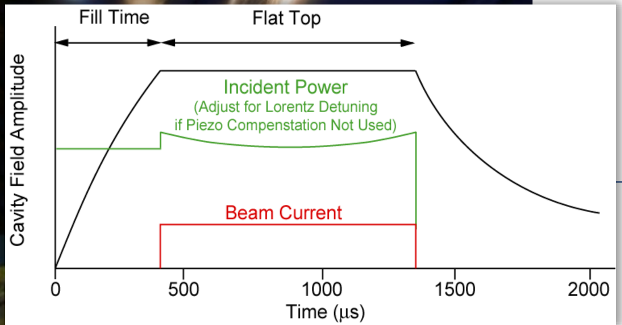
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10 ^{10}

Key Technologies



- Costs ~5 B$, power ~120 MW
- Will concentrate on SRF
- Nanobeam similar as for CLIC but a few words about ATF





ILC: SCRF

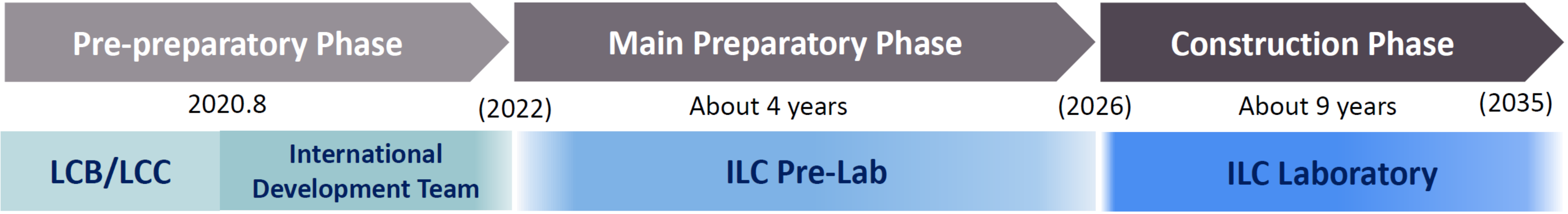
Ultra–high Q_0 (~10^{10})

- Almost zero power (heat) in cavity walls (in SC RF the main efficiency issues related to fill factors and cryogenics)
- Standing wave cavities with low peak power requirements
- Long beam pulse (~1 ms) – favorable for feed–backs within the pulse train

Low impedance

- beam generates low “wakefields”
- relatively large structures (1.3 GHz)

Overall timeline



Pre-preparatory Phase

Main Preparatory Phase

Construction Phase

2020.8

(2022)

About 4 years

(2026)

About 9 years

(2035)

LCB/LCC

International Development Team

ILC Pre-Lab

ILC Laboratory

ILC IDT (~1.5 years)

- Prepare the work and deliverables of the ILC Pre–laboratory and work out, with national and regional laboratories, a scenario for their contributions
- Prepare a proposal for the organisation and governance of the ILC Pre–laboratory

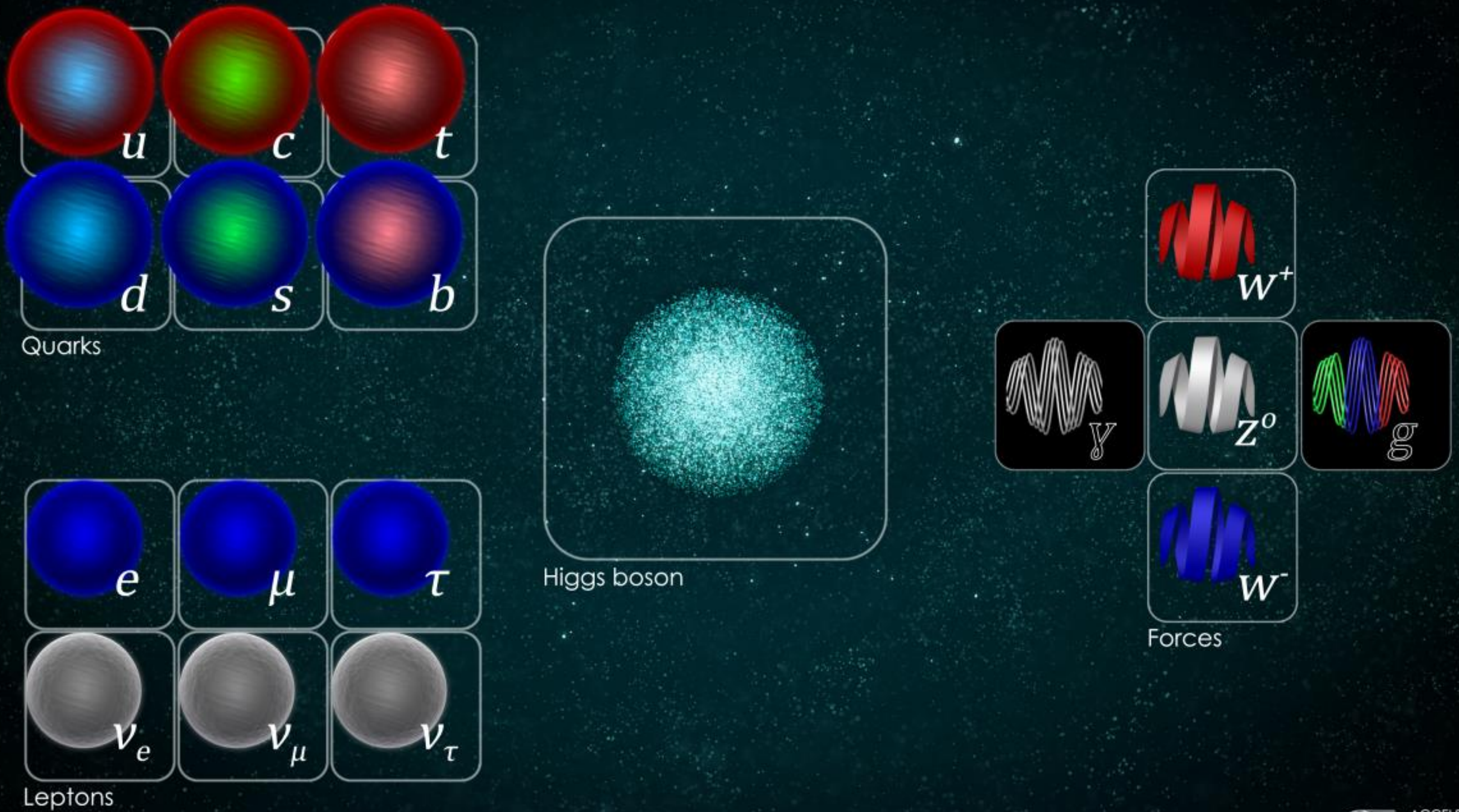
ILC Pre–laboratory (~4 years)

- Complete all the technical preparation necessary to start the ILC project (infrastructure, environmental impact and accelerator facility)
- Prepare scenarios for the regional contributions to and organisation for the ILC.

ILC laboratory

- Construction and commissioning of the ILC (~9–10 years)
- Followed by the operation of the ILC
- Managing the scientific programme of the ILC

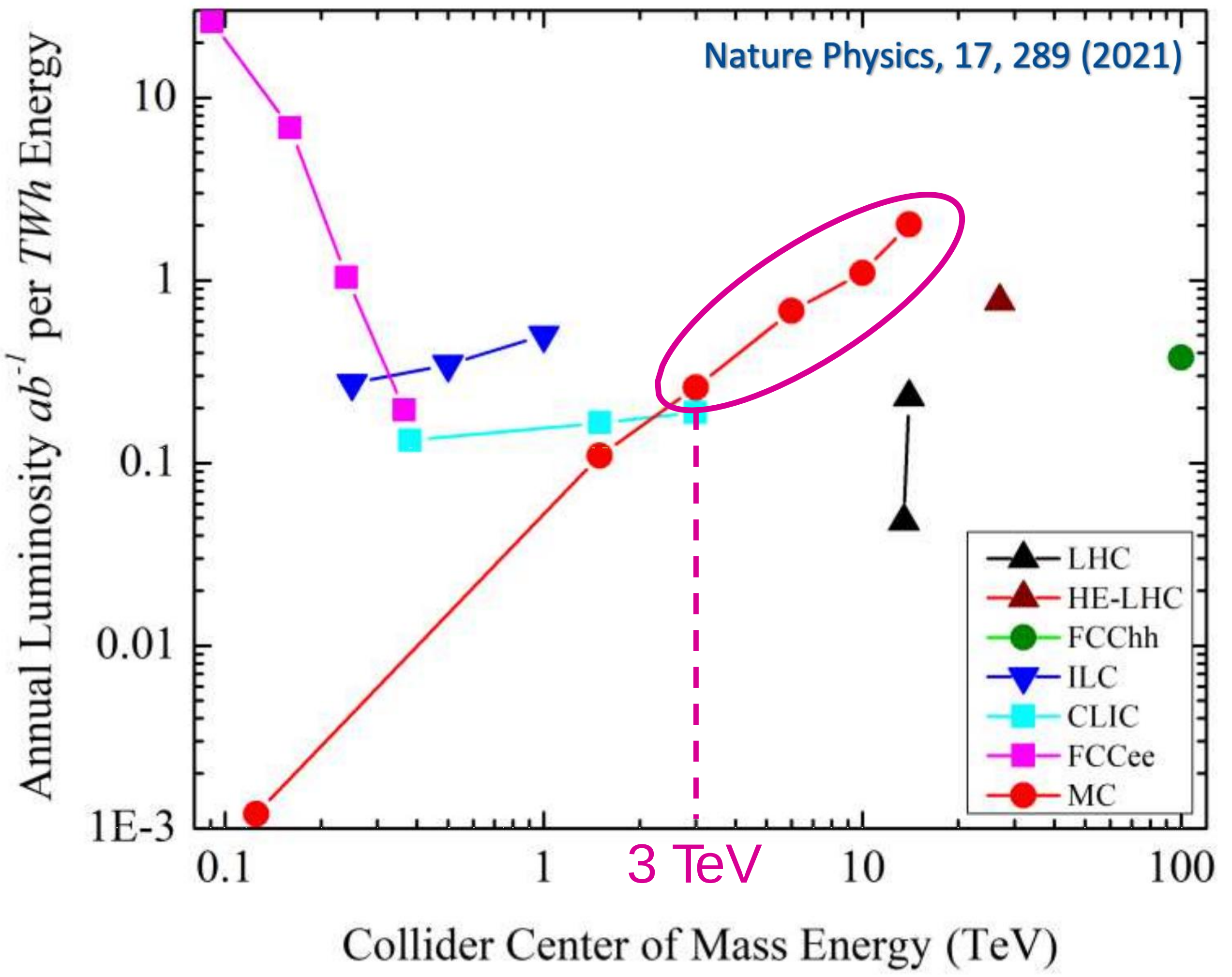
Muon Colliders



ACCELERATING SCIENCE

Introduction

Power efficiency



$$m_\mu = 105.7\ MeV/c^2$$
$$\tau_\mu = 2.2\ \mu s$$

Idea

Protons → target

→ **pions**

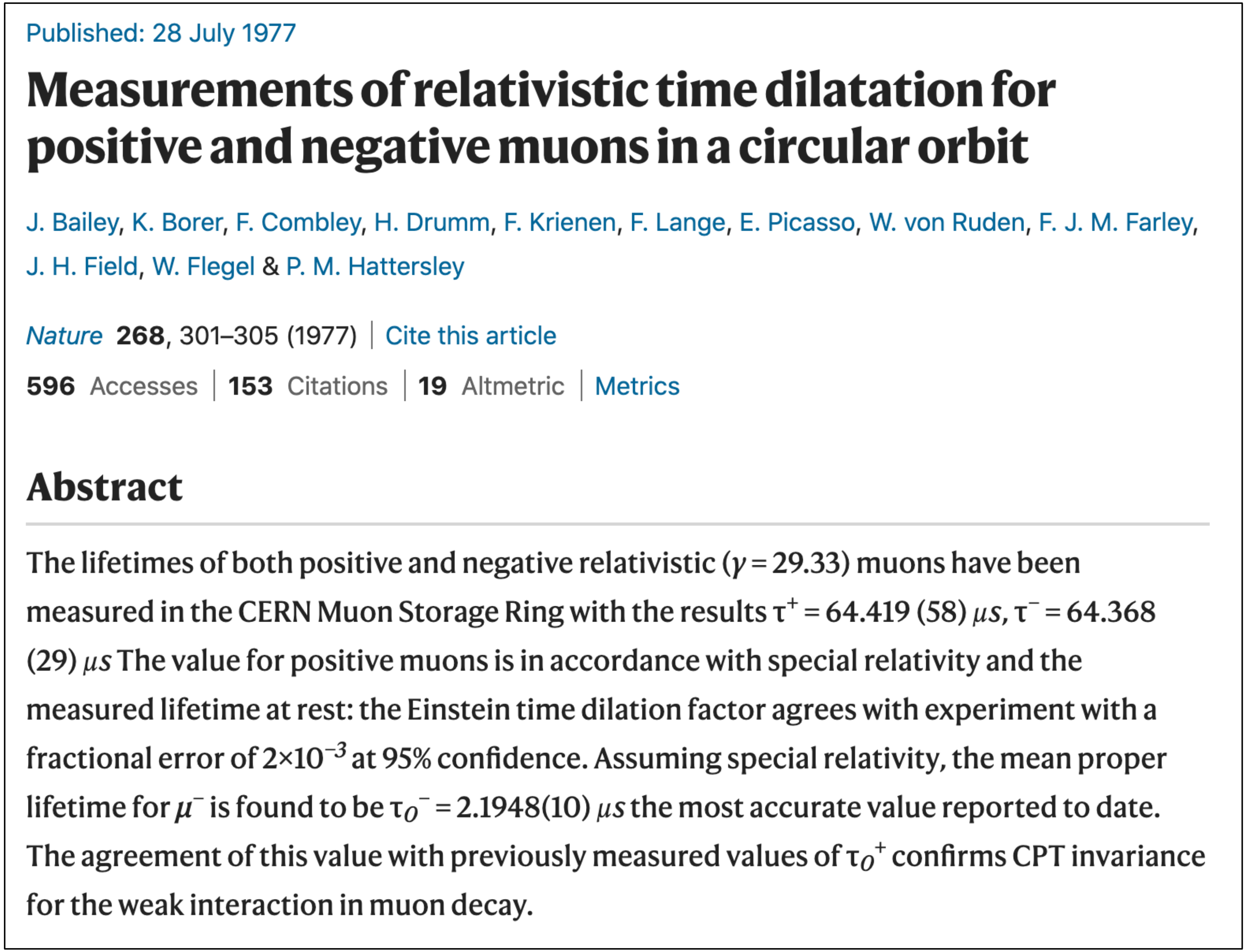
→ **muons**

→ ***μ- μ+* collider**

4 main challenges

$$(\mu^- \rightarrow e^-\nu_\mu\overline{\nu_e})$$

– Muon production
– Fast muon cooling
– Fast acceleration
– Neutrino radiation



Published: 28 July 1977

Measurements of relativistic time dilatation for positive and negative muons in a circular orbit

J. Bailey, K. Borer, F. Combley, H. Drumm, F. Krienen, F. Lange, E. Picasso, W. von Ruden, F. J. M. Farley, J. H. Field, W. Flegel & P. M. Hattersley

Nature **268**, 301–305 (1977) | Cite this article

596 Accesses | **153** Citations | **19** Altmetric | Metrics

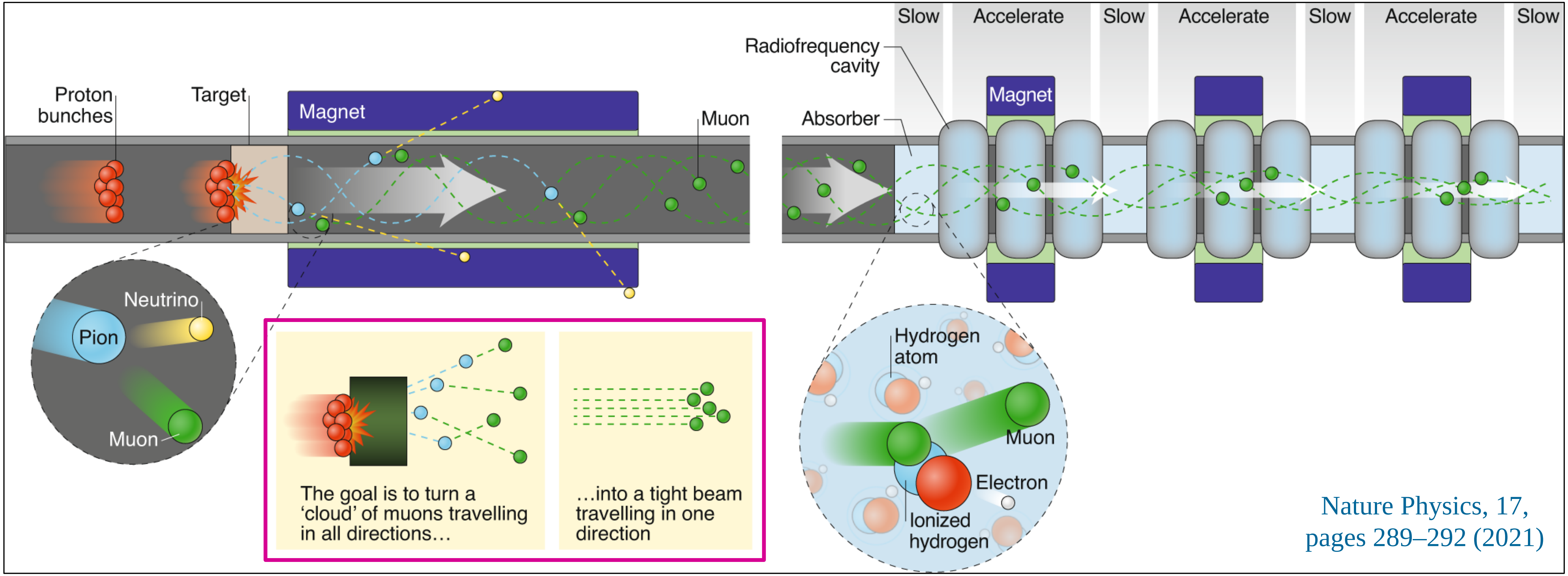
Abstract

The lifetimes of both positive and negative relativistic ($\gamma = 29.33$) muons have been measured in the CERN Muon Storage Ring with the results $\tau^+ = 64.419$ (58) μs, $\tau^- = 64.368$ (29) μs The value for positive muons is in accordance with special relativity and the measured lifetime at rest: the Einstein time dilation factor agrees with experiment with a fractional error of 2×10^{-3} at 95% confidence. Assuming special relativity, the mean proper lifetime for μ^- is found to be $\tau_0^- = 2.1948(10)$ μs the most accurate value reported to date. The agreement of this value with previously measured values of τ_0^+ confirms CPT invariance for the weak interaction in muon decay.

$$\boxed{\tau = \gamma \, \tau_0}$$

~ 150 ms
at 7 TeV

Muon production and cooling

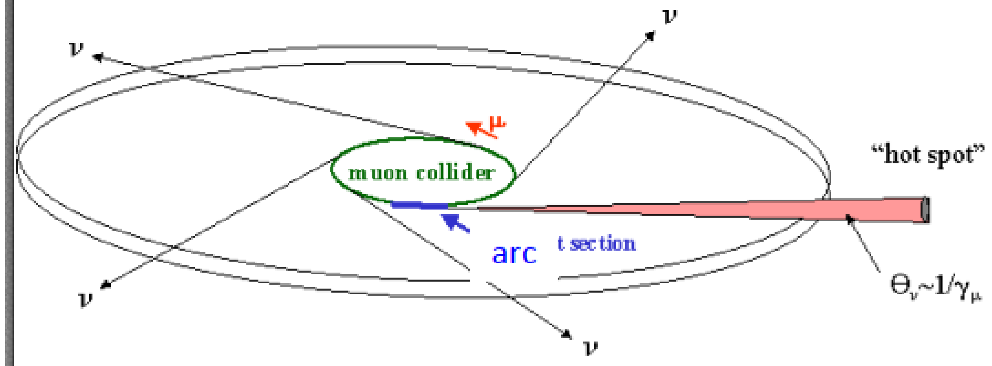


The goal is to turn a 'cloud' of muons travelling in all directions…

…into a tight beam travelling in one direction

Nature Physics, 17, pages 289–292 (2021)

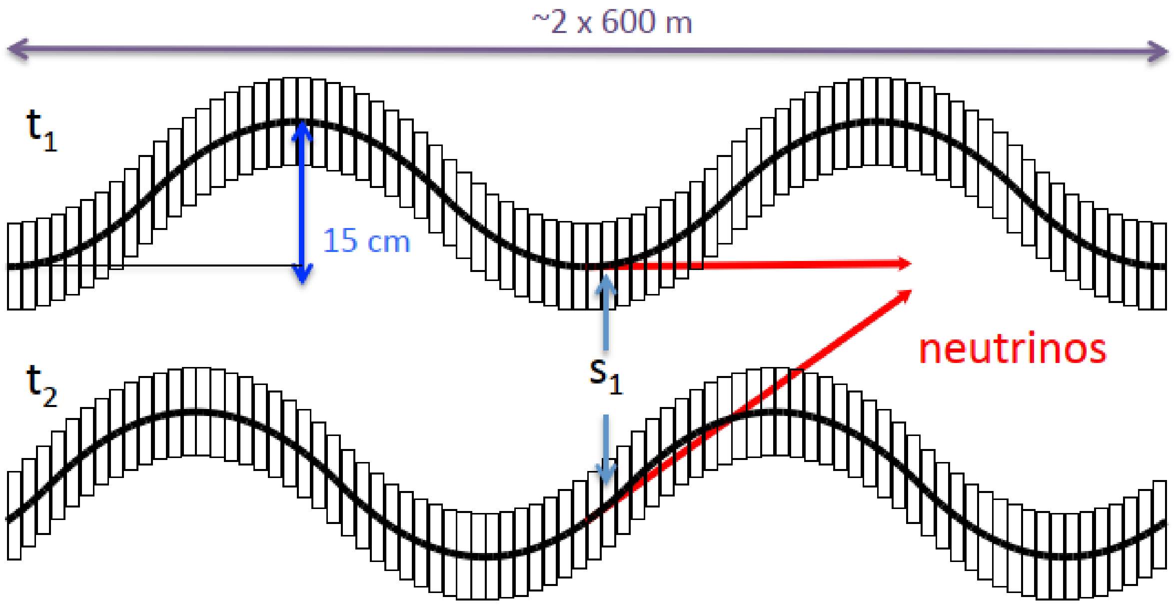
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 µSv/year
LHC achieved < 5 µSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



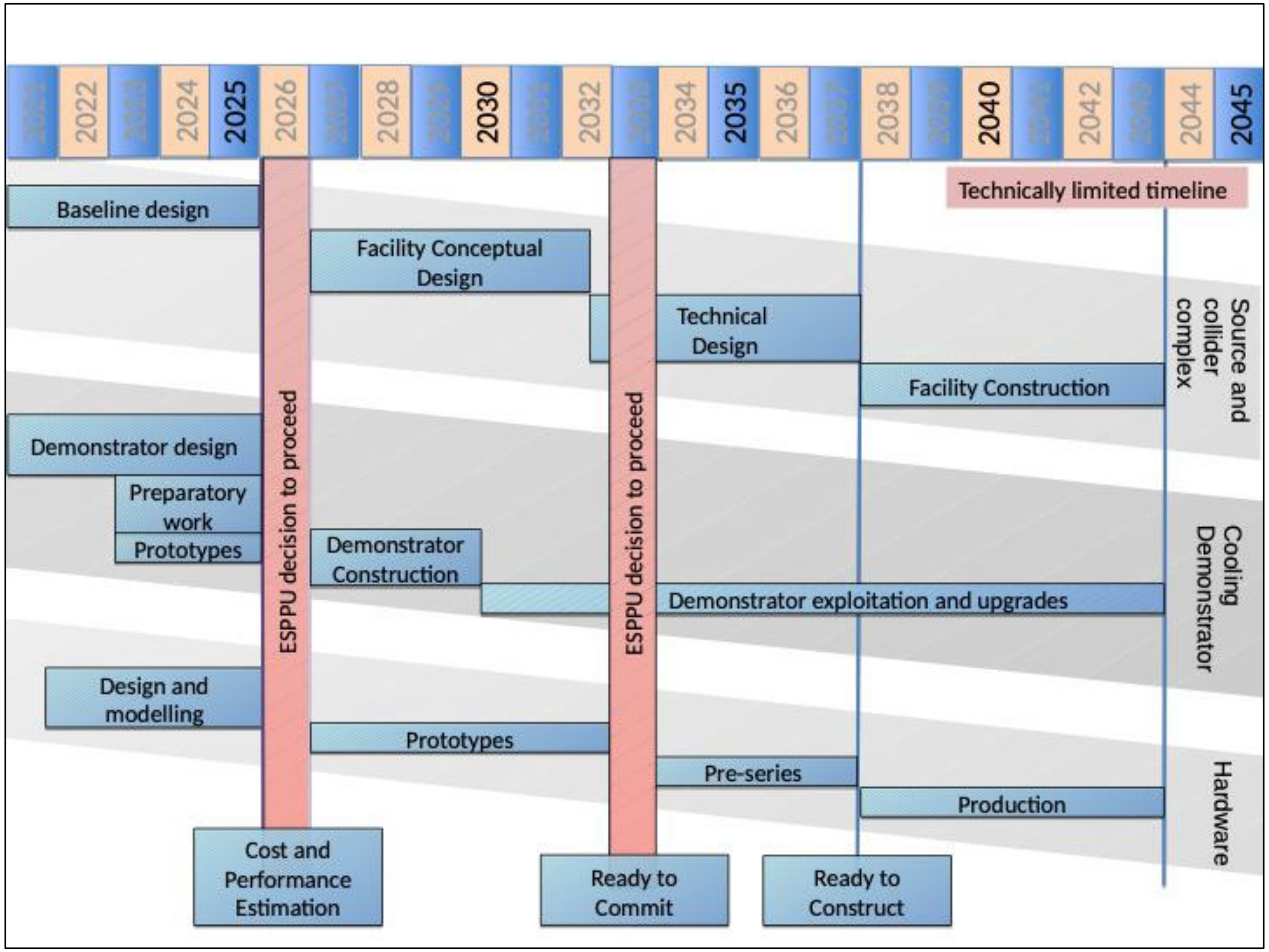
Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

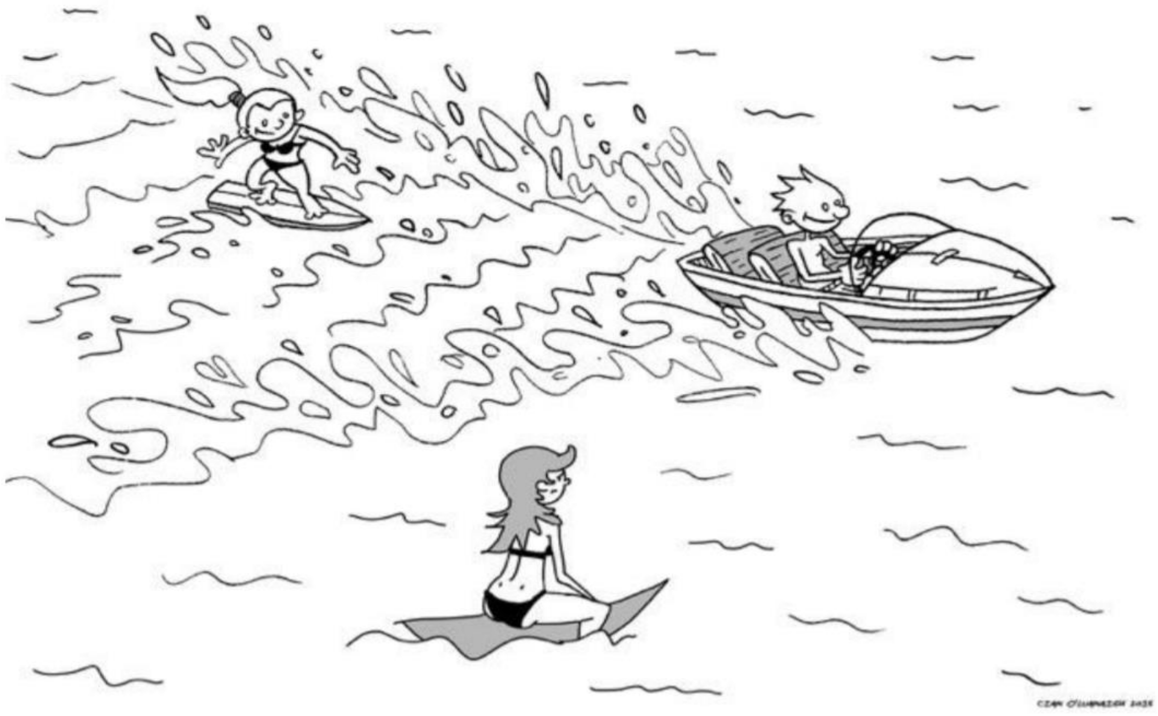
A technically limited timeline
for 3 TeV construction by 2045



Plasma Acceleration

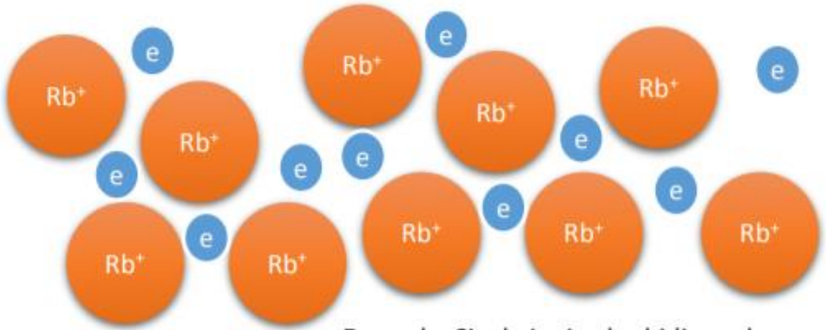
Wakesurfing….

- https://www.youtube.com/watch?v=08hpljs49Ec



Plasma Wakefield

What is a plasma?



Example: Single ionized rubidium plasma

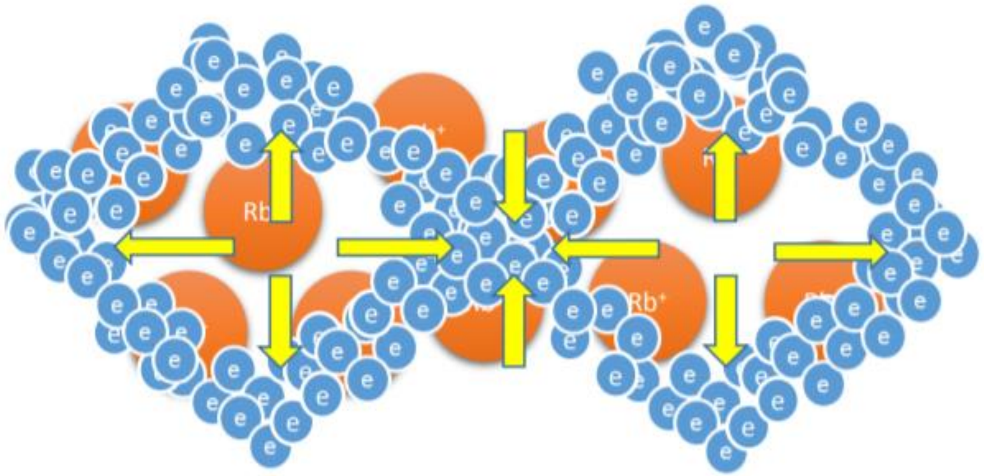
Plasma is already ionized or “broken-down” and can sustain **electric fields up to three orders of magnitude higher gradients** → order of **100 GV/m.**

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?

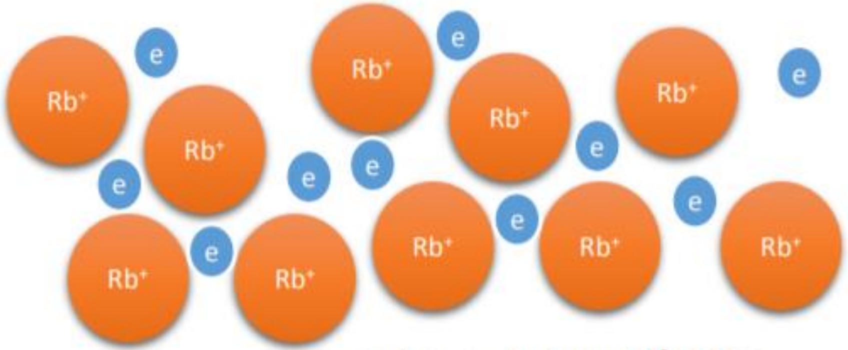


Fields created by collective motion of plasma particles are called plasma wakefields.

How to Create a Plasma Wakefield?

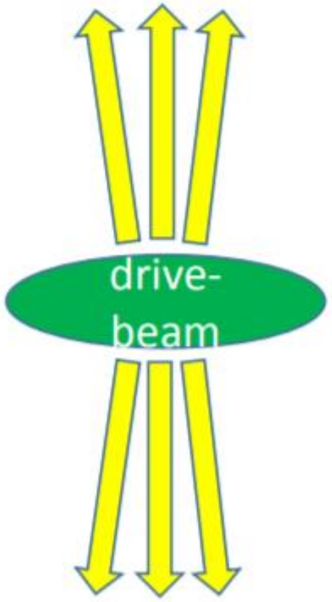
What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:



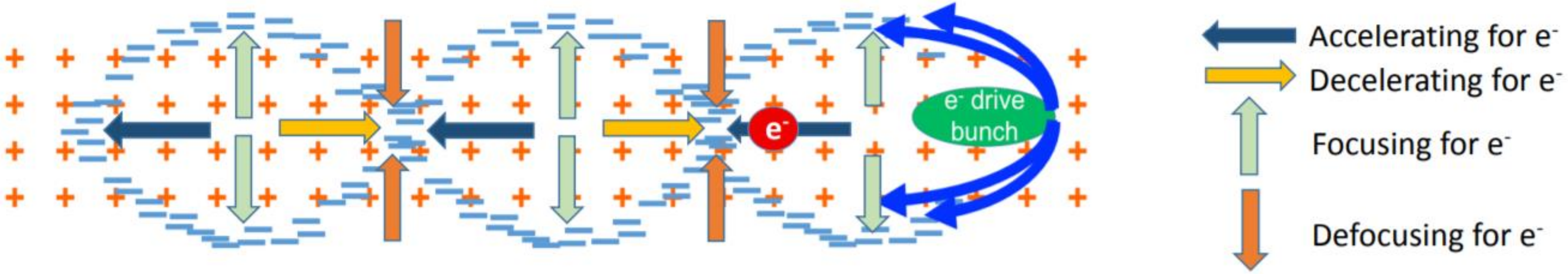
Single ionized rubidium **plasma**

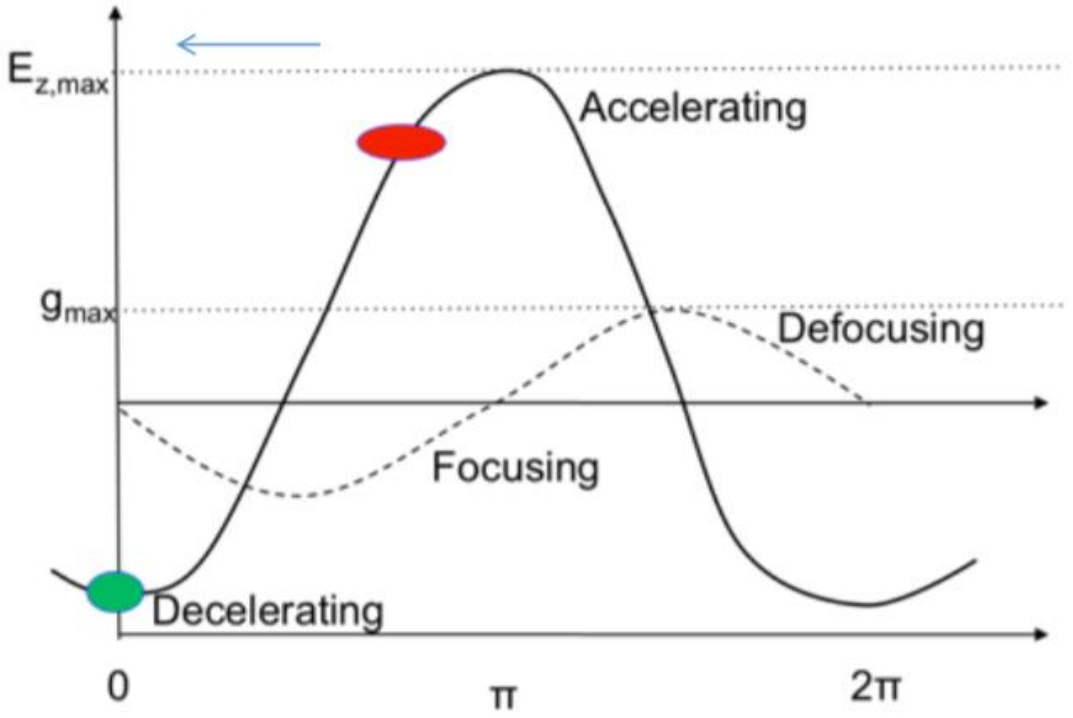
Charged particle bunches carry almost purely transverse electric fields.



Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.** The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

Where to Place the Witness Beam (Surfer)?





High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

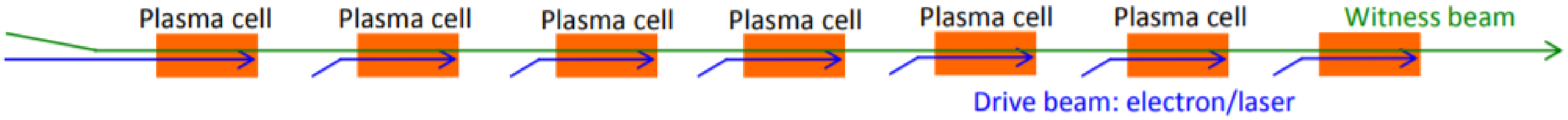
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:

Electrons: 10^{10} particles @ 1 TeV ~few kJ

To reach TeV scale:

- **Electron/laser driven PWA**: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….

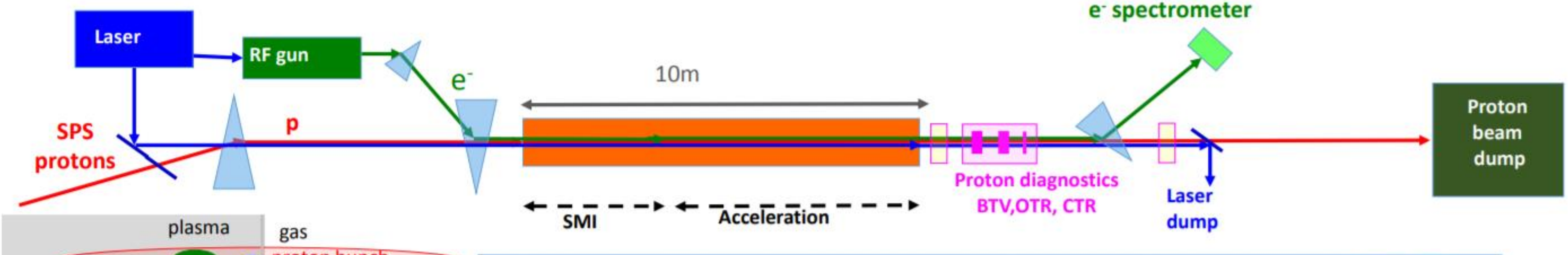


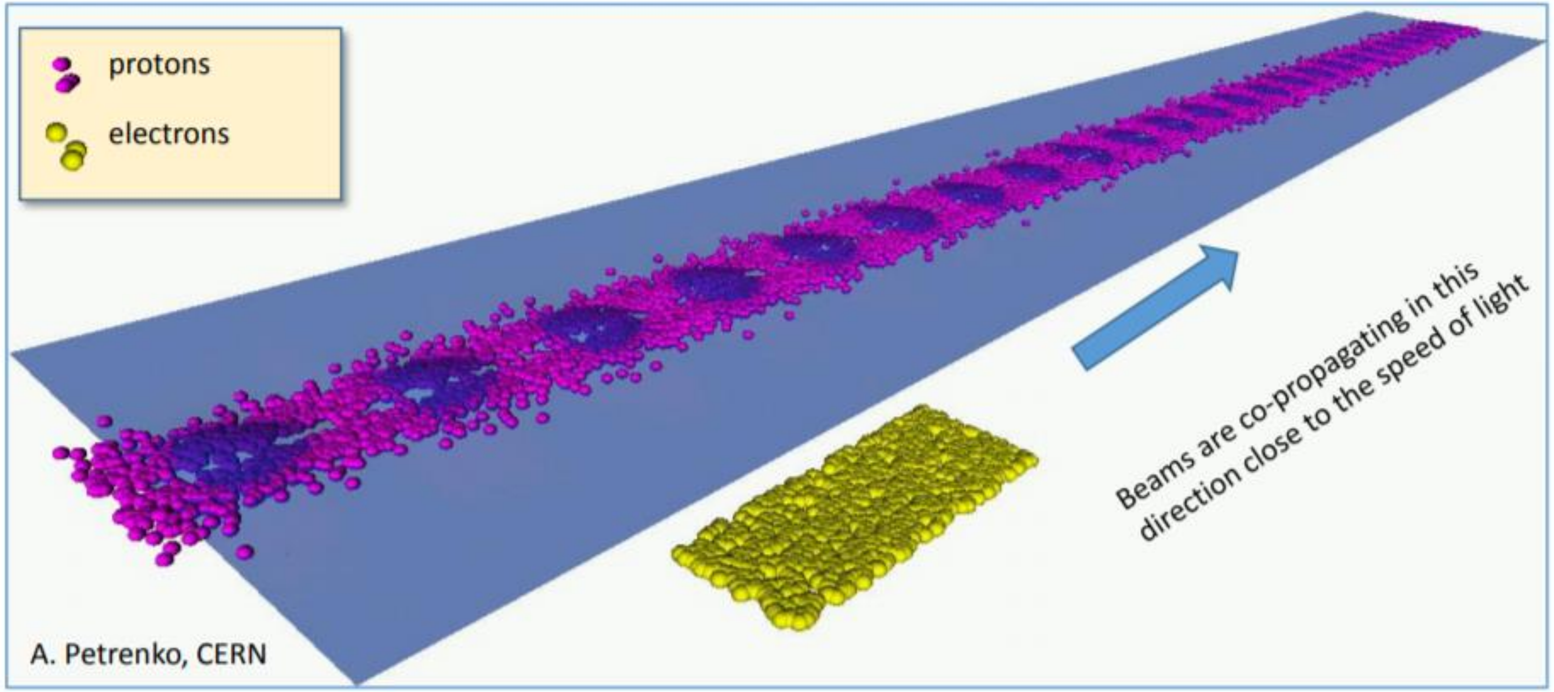
- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

AWAKE Experiment: Electron Acceleration 2017/18

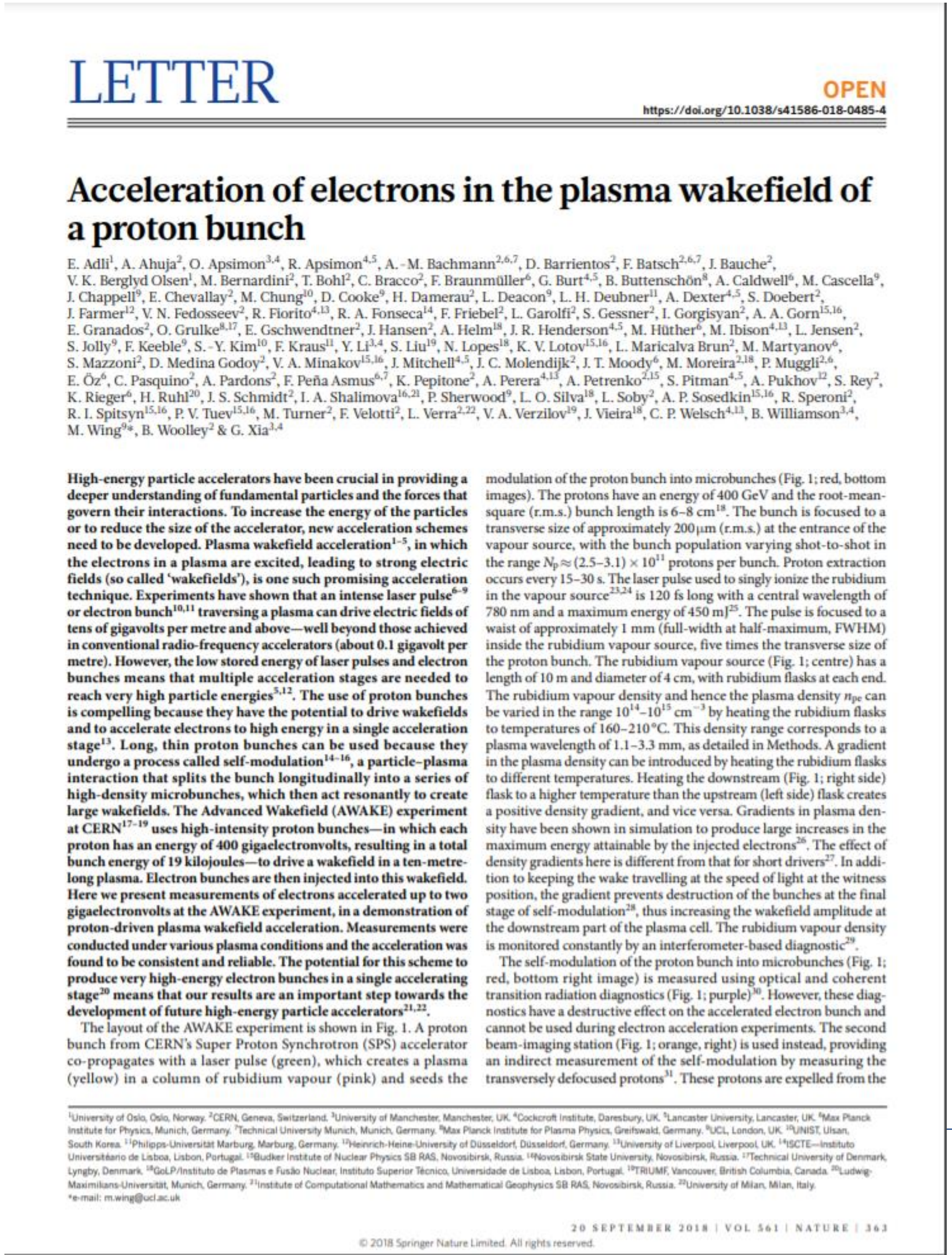
Phase 1: 2016/17: Understand **the physics of the seeded self-modulation** processes in plasma.

Phase 2: 2017/18: **Probe the accelerating wakefields** with externally injected electrons.





A. Petrenko, CERN



LETTER

OPEN

https://doi.org/10.1038/s41586-018-0485-4

Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli[1], A. Ahuja[2], O. Apsimon[3,4], R. Apsimon[4,5], A.-M. Bachmann[2,6,7], D. Barrientos[2], F. Batsch[2,6,7], J. Bauche[2], V. K. Berglyd Olsen[1], M. Bernardini[2], T. Bohl[2], C. Bracco[2], F. Braunmüller[6], G. Burt[4,5], B. Buttenschön[8], A. Caldwell[6], M. Cascella[9], J. Chappell[9], E. Chevallay[2], M. Chung[10], D. Cooke[9], H. Damerau[2], L. Deacon[9], L. H. Deubner[11], A. Dexter[4,5], S. Doebert[2], J. Farmer[12], V. N. Fedosseev[2], R. Fiorito[4,13], R. A. Fonseca[14], F. Friebel[2], L. Garolfi[2], S. Gessner[2], I. Gorgisyan[2], A. A. Gorn[15,16], E. Granados[2], O. Grulke[8,17], E. Gschwendtner[2], J. Hansen[2], A. Helm[18], J. R. Henderson[4,5], M. Hüther[6], M. Ibison[4,13], L. Jensen[2], S. Jolly[9], F. Keeble[9], S.-Y. Kim[10], F. Kraus[11], Y. Li[3,4], S. Liu[19], N. Lopes[18], K. V. Lotov[15,16], L. Maricalva Brun[2], M. Martyanov[6], S. Mazzoni[2], D. Medina Godoy[2], V. A. Minakov[15,16], J. Mitchell[4,5], J. C. Molendijk[2], J. T. Moody[6], M. Moreira[2,18], P. Muggli[2,6], E. Öz[6], C. Pasquino[2], A. Pardons[2], F. Peña Asmus[6,7], K. Pepitone[2], A. Perera[4,13], A. Petrenko[2,15], S. Pitman[4,5], A. Pukhov[12], S. Rey[2], K. Rieger[6], H. Ruhl[20], J. S. Schmidt[2], I. A. Shalimova[16,21], P. Sherwood[9], L. O. Silva[18], L. Soby[2], A. P. Sosedkin[15,16], R. Speroni[2], R. I. Spitsyn[15,16], P. V. Tuev[15,16], M. Turner[2], F. Velotti[2], L. Verra[2,22], V. A. Verzilov[19], J. Vieira[18], C. P. Welsch[4,13], B. Williamson[3,4], M. Wing[9]*, B. Woolley[2] & G. Xia[3,4]

High-energy particle accelerators have been crucial in providing a deeper understanding of fundamental particles and the forces that govern their interactions. To increase the energy of the particles or to reduce the size of the accelerator, new acceleration schemes need to be developed. Plasma wakefield acceleration[1–5], in which the electrons in a plasma are excited, leading to strong electric fields (so called 'wakefields'), is one such promising acceleration technique. Experiments have shown that an intense laser pulse[6–9] or electron bunch[10,11] traversing a plasma can drive electric fields of tens of gigavolts per metre and above—well beyond those achieved in conventional radio-frequency accelerators (about 0.1 gigavolt per metre). However, the low stored energy of laser pulses and electron bunches means that multiple acceleration stages are needed to reach very high particle energies[5,12]. The use of proton bunches is compelling because they have the potential to drive wakefields and to accelerate electrons to high energy in a single acceleration stage[13]. Long, thin proton bunches can be used because they undergo a process called self-modulation[14–16], a particle–plasma interaction that splits the bunch longitudinally into a series of high-density microbunches, which then act resonantly to create large wakefields. The Advanced Wakefield (AWAKE) experiment at CERN[17–19] uses high-intensity proton bunches—in which each proton has an energy of 400 gigaelectronvolts, resulting in a total bunch energy of 19 kilojoules—to drive a wakefield in a ten-metre-long plasma. Electron bunches are then injected into this wakefield. Here we present measurements of electrons accelerated up to two gigaelectronvolts at the AWAKE experiment, in a demonstration of proton-driven plasma wakefield acceleration. Measurements were conducted under various plasma conditions and the acceleration was found to be consistent and reliable. The potential for this scheme to produce very high-energy electron bunches in a single accelerating stage[20] means that our results are an important step towards the development of future high-energy particle accelerators[21,22].

The layout of the AWAKE experiment is shown in Fig. 1. A proton bunch from CERN's Super Proton Synchrotron (SPS) accelerator co-propagates with a laser pulse (green), which creates a plasma (yellow) in a column of rubidium vapour (pink) and seeds the modulation of the proton bunch into microbunches (Fig. 1; red, bottom images). The protons have an energy of 400 GeV and the root-mean-square (r.m.s.) bunch length is 6–8 cm[18]. The bunch is focused to a transverse size of approximately 200 μm (r.m.s.) at the entrance of the vapour source, with the bunch population varying shot-to-shot in the range $N_p \approx (2.5\text{–}3.1) \times 10^{11}$ protons per bunch. Proton extraction occurs every 15–30 s. The laser pulse used to singly ionize the rubidium in the vapour source[23,24] is 120 fs long with a central wavelength of 780 nm and a maximum energy of 450 mJ[25]. The pulse is focused to a waist of approximately 1 mm (full-width at half-maximum, FWHM) inside the rubidium vapour source, five times the transverse size of the proton bunch. The rubidium vapour source (Fig. 1; centre) has a length of 10 m and diameter of 4 cm, with rubidium flasks at each end. The rubidium vapour density and hence the plasma density n_{pe} can be varied in the range $10^{14}\text{–}10^{15}\ \text{cm}^{-3}$ by heating the rubidium flasks to temperatures of 160–210 °C. This density range corresponds to a plasma wavelength of 1.1–3.3 mm, as detailed in Methods. A gradient in the plasma density can be introduced by heating the rubidium flasks to different temperatures. Heating the downstream (Fig. 1; right side) flask to a higher temperature than the upstream (left side) flask creates a positive density gradient, and vice versa. Gradients in plasma density have been shown in simulation to produce large increases in the maximum energy attainable by the injected electrons[26]. The effect of density gradients here is different from that for short drivers[27]. In addition to keeping the wake travelling at the speed of light at the witness position, the gradient prevents destruction of the bunches at the final stage of self-modulation[28], thus increasing the wakefield amplitude at the downstream part of the plasma cell. The rubidium vapour density is monitored constantly by an interferometer-based diagnostic[29].

The self-modulation of the proton bunch into microbunches (Fig. 1; red, bottom right image) is measured using optical and coherent transition radiation diagnostics (Fig. 1; purple)[30]. However, these diagnostics have a destructive effect on the accelerated electron bunch and cannot be used during electron acceleration experiments. The second beam-imaging station (Fig. 1; orange, right) is used instead, providing an indirect measurement of the self-modulation by measuring the transversely defocused protons[31]. These protons are expelled from the

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[1] University of Oslo, Oslo, Norway. [2] CERN, Geneva, Switzerland. [3] University of Manchester, Manchester, UK. [4] Cockcroft Institute, Daresbury, UK. [5] Lancaster University, Lancaster, UK. [6] Max Planck Institute for Physics, Munich, Germany. [7] Technical University Munich, Munich, Germany. [8] Max Planck Institute for Plasma Physics, Greifswald, Germany. [9] UCL, London, UK. [10] UNIST, Ulsan, South Korea. [11] Philipps-Universität Marburg, Marburg, Germany. [12] Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany. [13] University of Liverpool, Liverpool, UK. [14] ISCTE—Instituto Universitéario de Lisboa, Lisbon, Portugal. [15] Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia. [16] Novosibirsk State University, Novosibirsk, Russia. [17] Technical University of Denmark, Lyngby, Denmark. [18] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal. [19] TRIUMF, Vancouver, British Columbia, Canada. [20] Ludwig-Maximilians-Universität, Munich, Germany. [21] Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Novosibirsk, Russia. [22] University of Milan, Milan, Italy.
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CERN Bulletin

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More articles at *http://home.cern/cern-people*

SUCCESS FOR AWAKE

The experiment successfully accelerated electrons with plasma wakefields generated by protons, a world first

The final part of the AWAKE experimental facility, with the accelerating plasma cell and the scintillating screen used to detect the accelerated electrons and infer their energy. (Image: Maximilien Brice, Julien Ordan/CERN)

Early in the morning on Saturday, 26 May 2018, the AWAKE collaboration at CERN successfully accelerated electrons for the first time using a wakefield generated by protons zipping through a plasma. A paper describing this important result was published in the journal *Nature* on 29 August. The electrons were accelerated by a factor of around 100 over a length of 10 metres: injected at an energy of around 19 MeV, they reached an energy of almost 2 GeV.

AWAKE ("Advanced WAKEfield Experiment") is a proof-of-principle "Research and Development" project investigating the use of protons to drive plasma wakefields for accelerating electrons. While traditional accelerators use radio-frequency cavities, in wakefield accelerators, the particles get accelerated by "surfing" on top of a plasma wave (or wakefield).

"Wakefield accelerators have two different beams: the beam of particles that is the target for the acceleration, known as 'witness beam', and the beam that generates the wakefield, known as the 'drive beam'," explains Allen Caldwell, spokesperson of the AWAKE collaboration.

(Continued on page 2)

A WORD FROM...

NOW GOING LIVE – THE LEARNING HUB AT CERN

Education and training are essential parts of CERN's core mission, whether for high school teachers, summer students or our many public visitors. One particularly important audience for training is you – the CERN personnel. That's why we offer a wide range of learning opportunities, varying from the technical skills we need to carry out our jobs to the behavioural competencies we need to make our working lives run smoothly and the courses that enable us to stay safe.

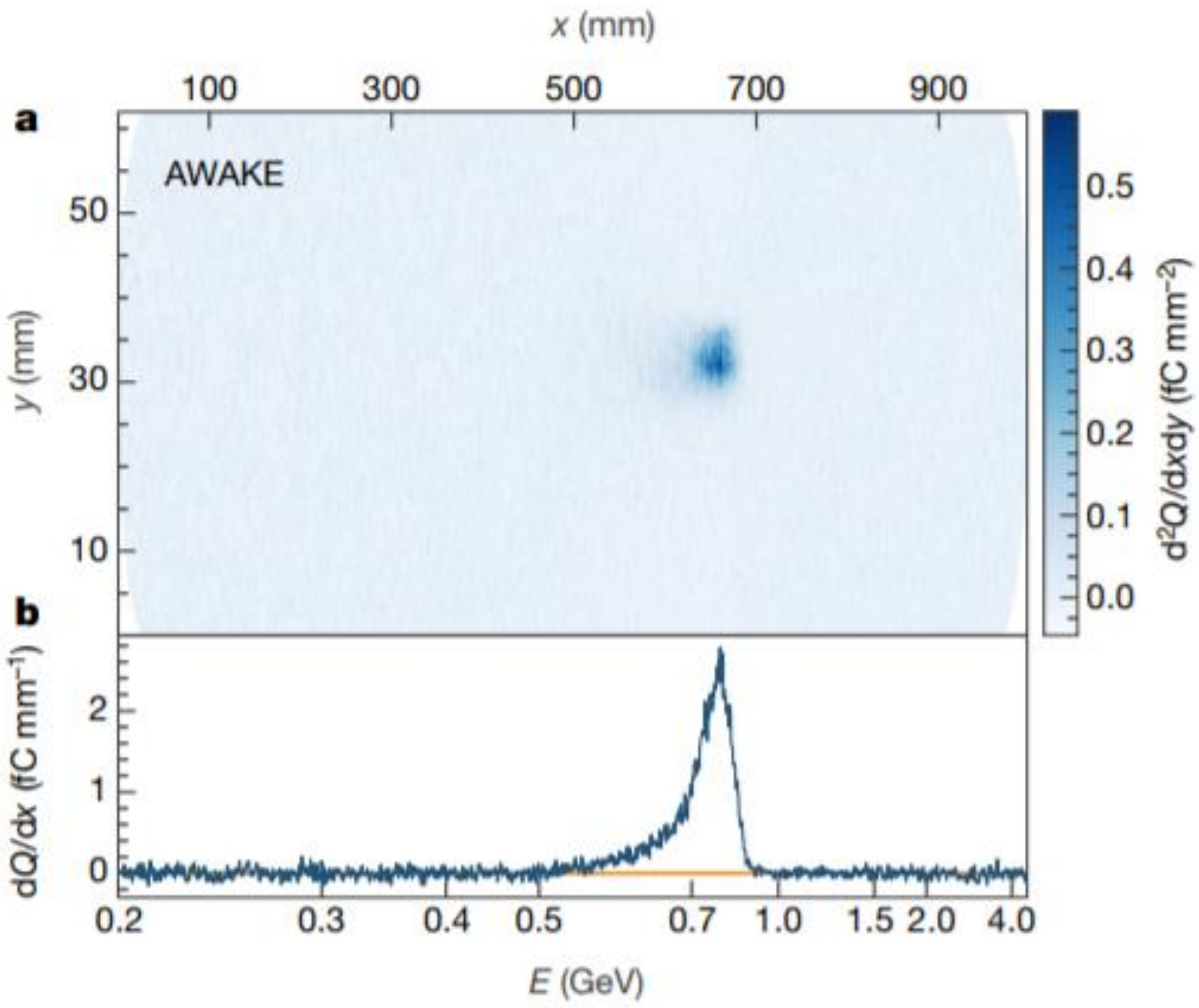
(Continued on page 2)

In this issue

Preliminary results

- Peak energy gain 800 MeV

- Lot of work to do….



Conclusions

- High Energy Physics is an exciting playground for Engineers…
- The future is bright: all possible projects are extremely interesting, and will continue providing surprises!
-

Thank you for your attention!