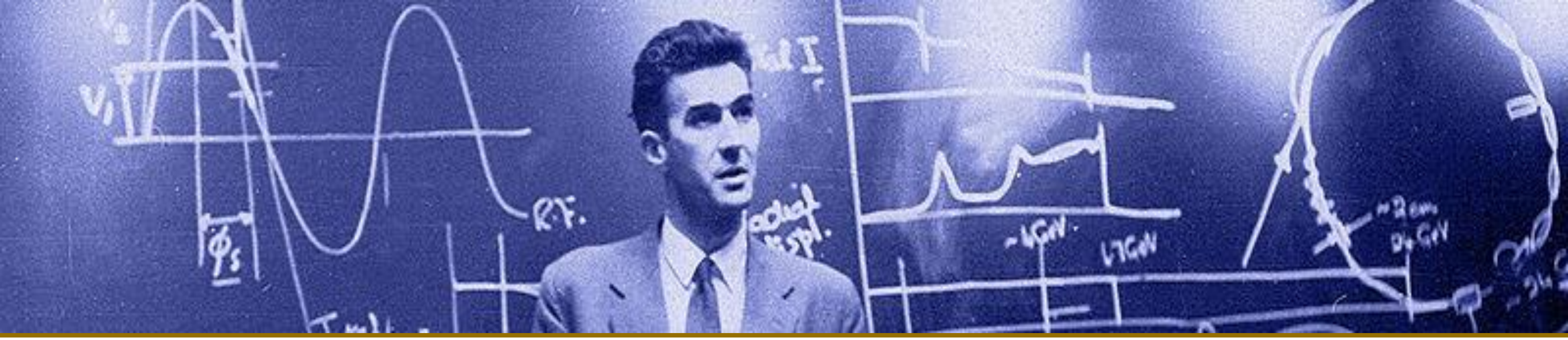
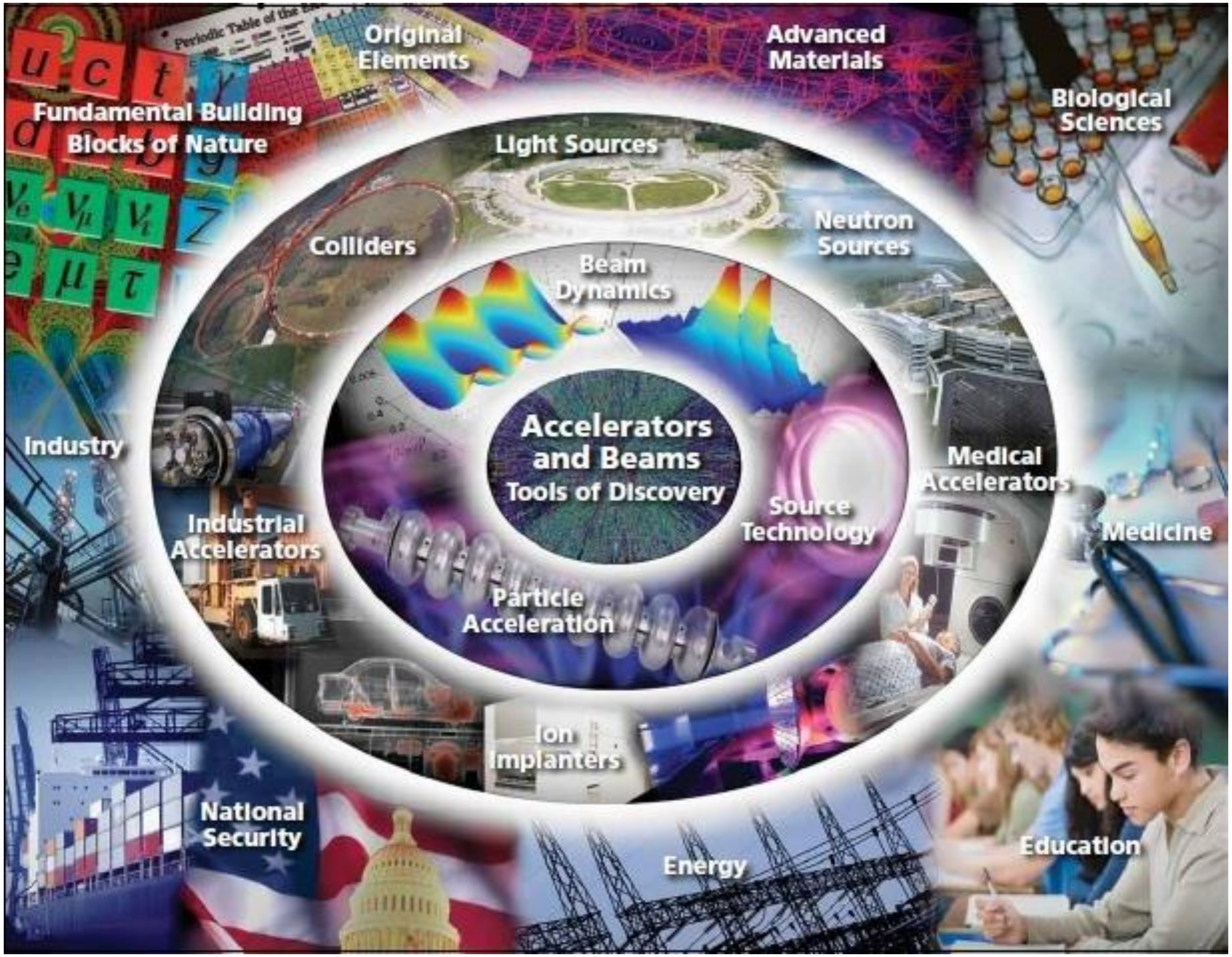


Accelerators at the High Energy Frontier

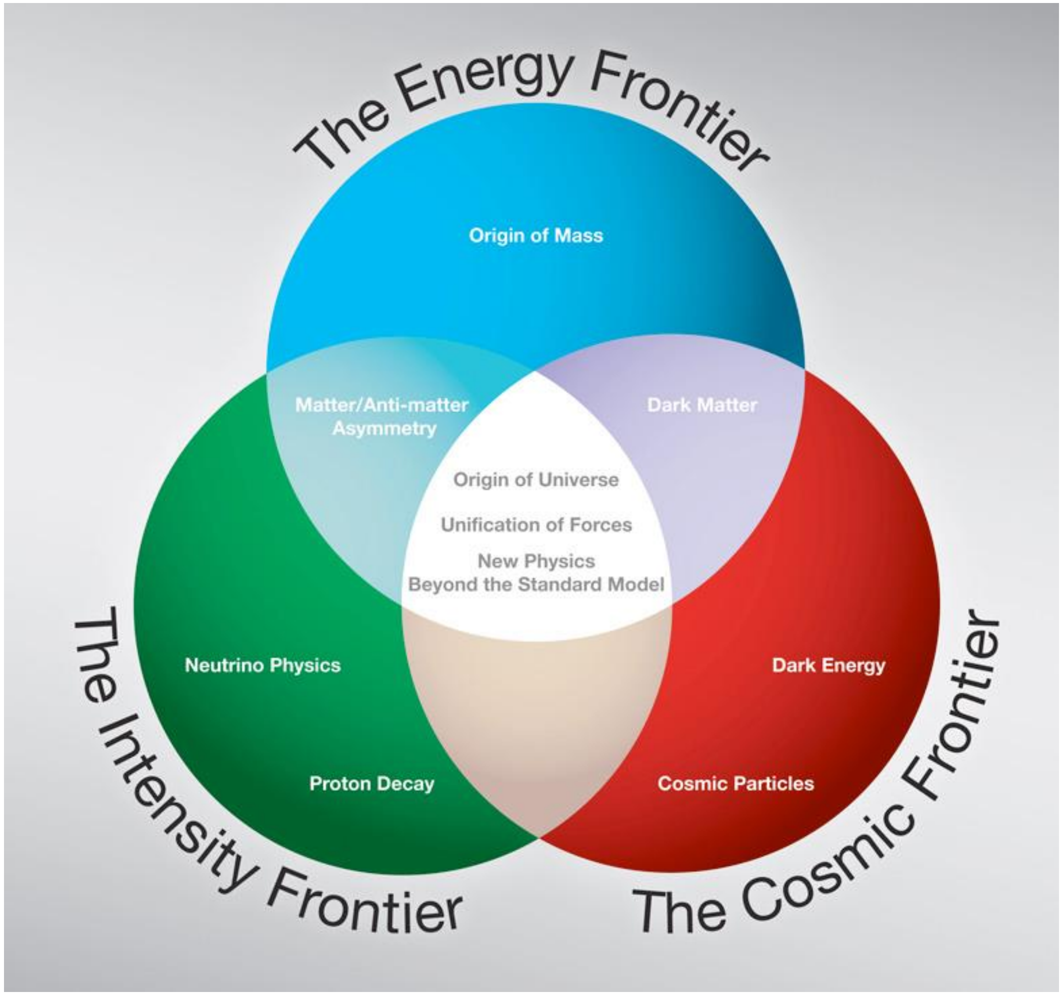
Prof. Emmanuel Tsesmelis
CERN & JAI University of Oxford

APPEAL-7
University of Oxford
11 June 2016

Introduction



The Three Frontiers

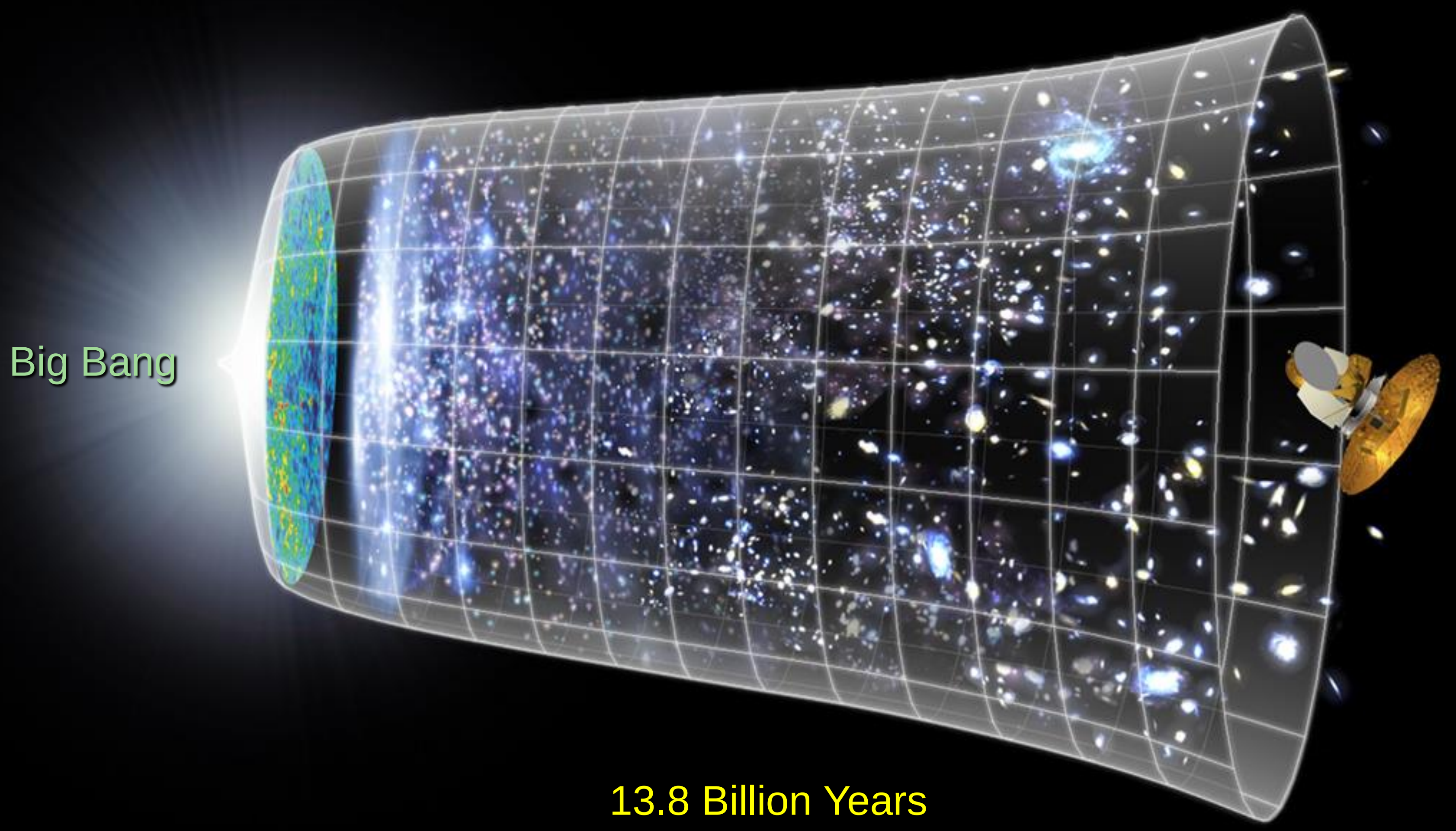


Open Questions in Particle Physics

- What is the origin of particle masses?
- Why are there so many types of matter particles?
- What is the cause of matter-antimatter asymmetry?
- What are the properties of the primordial plasma?
- What is the nature of the invisible dark matter?
- Can all fundamental particles be unified?
- Is there a quantum theory of gravity?

The present and future accelerator-based experimental programmes will address all these questions and may well provide definite answers.

Evolution of the Universe



13.8 Billion Years

10^{28} cm

The Standard Model of Particle Physics

= Cosmic DNA

The matter particles

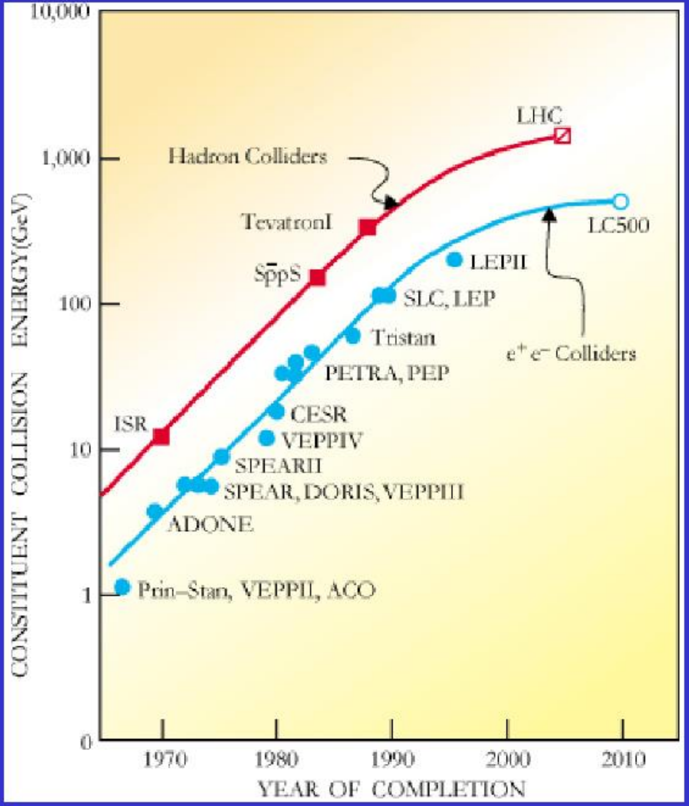
The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

ACCELERATOR DEVELOPMENT

- Historically, HEP has depended on advances in accelerator design to make scientific progress
  - linac → cyclotron → synchrocyclotron → synchrotron → collider (circular, linear)
- Advances in accelerator design and performance require corresponding advances in accelerator technologies
  - Magnets, vacuum systems, RF systems, diagnostics,...
- Accelerators enable the study of particle physics phenomena under controlled conditions
- Costs & time span of today's accelerator projects are high
  - International co-operation and collaboration are obligatory

Colliders – Energy vs. Time



M. Tigner: "Does Accelerator-Based Particle Physics have a Future?" Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!

Not enough: Project cost increased by factor 200!

New technology needed…

Next Decades

Road beyond Standard Model

LHC results will guide the way at the energy frontier

through synergy of

hadron - hadron colliders (LHC,HL-LHC,HE-LHC, FCC)

lepton - hadron colliders (LHeC, FCC)

lepton - lepton colliders (LC (ILC or CLIC) , FCC)

Introduction - Accelerators

- Particle accelerators are designed to deliver two parameters to the HEP user
  - Energy
  - Luminosity
    - Measure of collision rate per unit area
    - Event rate for a given event probability ("cross-section") given by:

$$R = \mathscr{L}\sigma$$

For a Collider luminosity is given by

$$\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

- → Require intense beams and small beam sizes at IP

Today's Accelerators

- HEP typically uses Colliders
  - Counter-propagating beams collide at one or more IPs
- Colliders typically store various particle types
  - Hadrons (protons, ions)
    - Tevatron (p, anti-p), RHIC (p, ions), LHC (p, ions)
  - Leptons (electrons)
    - CESR-c, PEP-II, KEK-B

Today's Accelerators

- Hadron Colliders
  - Protons are composite particles
    - Only ~10% of beam energy available for hard collisions producing new particles
      - Need *O*(10 TeV) Collider to probe 1 TeV mass scale
      - Desired high energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
  - Anti-protons difficult to produce if beam is lost
    - Use proton-proton collisions instead
    - Demand for ever-higher luminosity has led LHC to choose proton-proton collisions
    - Many bunches (high bunch frequency)
    - Two separate rings that intersect at select locations

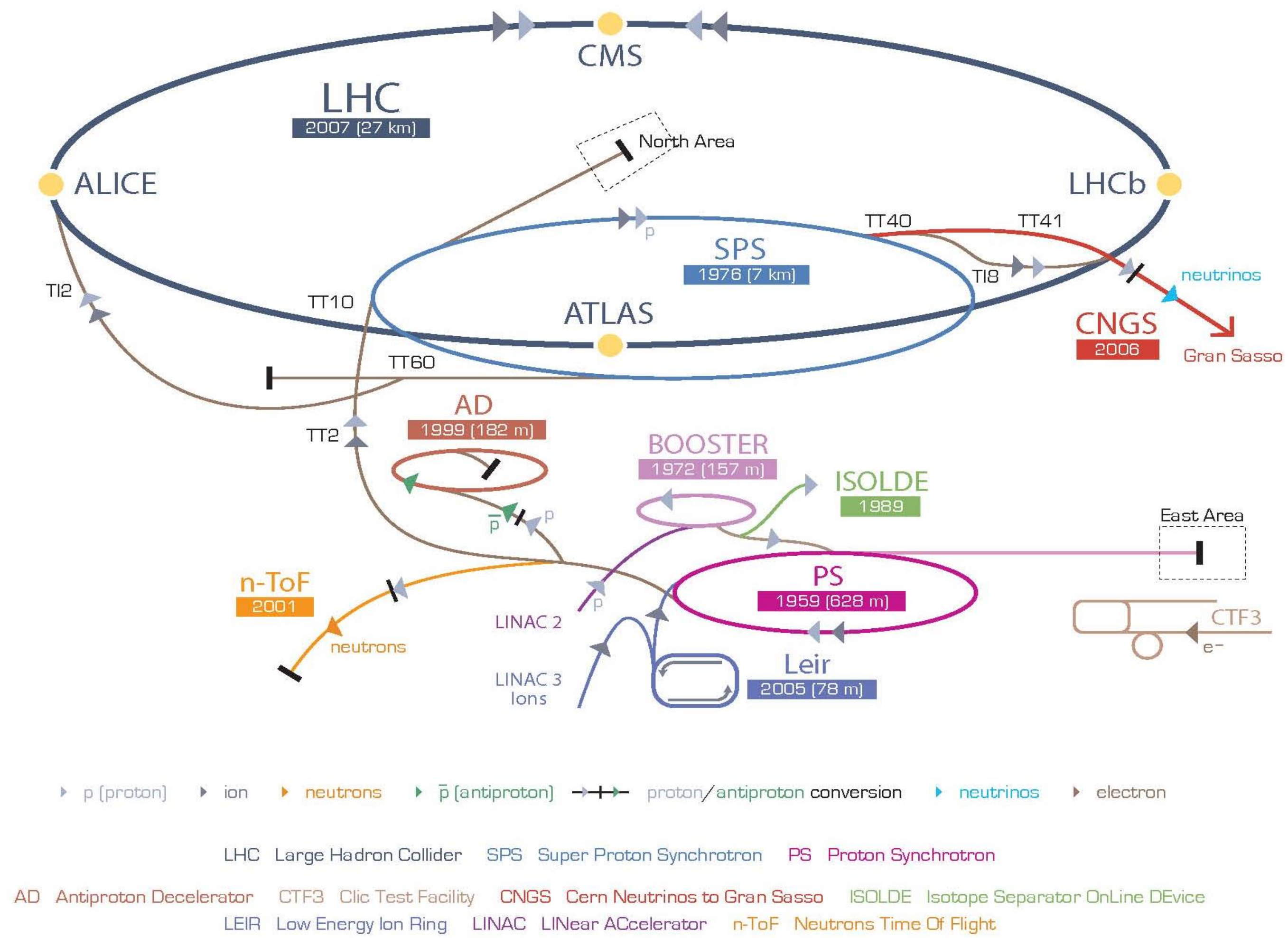
Today's Accelerators

- Lepton Colliders (e+e-)
  - Synchrotron radiation is the most serious challenge
    - Emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}]\, I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

    - For a 1 TeV CM energy Collider in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
      - Would need to replenish radiated power with RF
      - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider (ILC,CLIC)

CERN Accelerator Complex

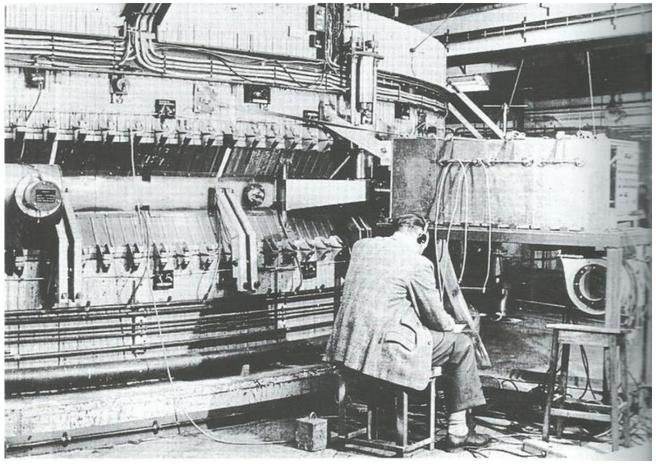


Mark Oliphant & the Synchrotron

"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field...which would be varied in such a way that the radius of curvature remains constant as the particle gains energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."

Mark Oliphant, Oak Ridge, 1943

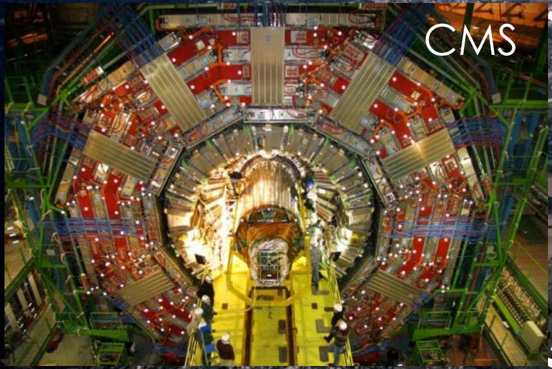
With Ernest Rutherford in 1932



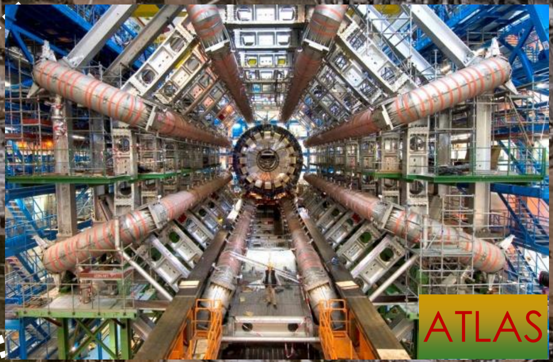
1 GeV machine at Birmingham University

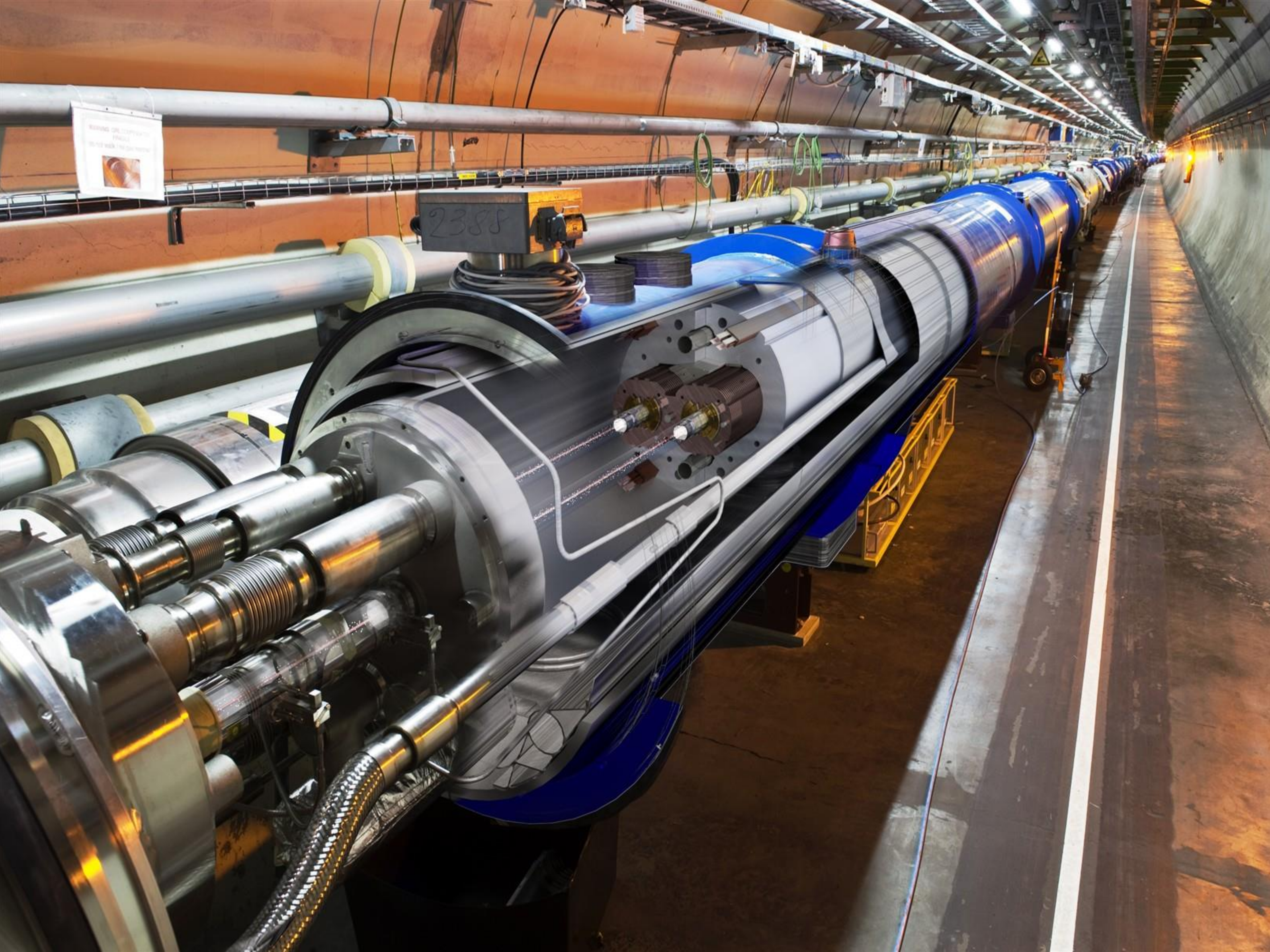
Enter a New Era in Fundamental Science

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.



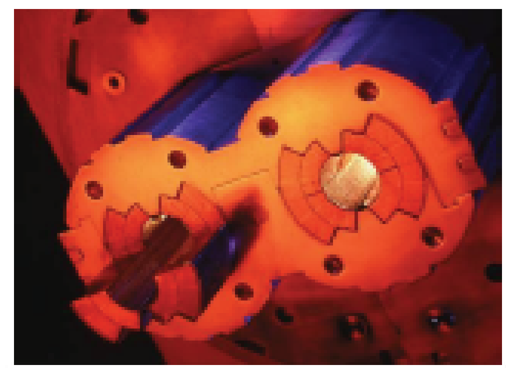
Exploration of a new energy frontier
Proton-proton collisions at E_{CM} = 14 TeV




2388

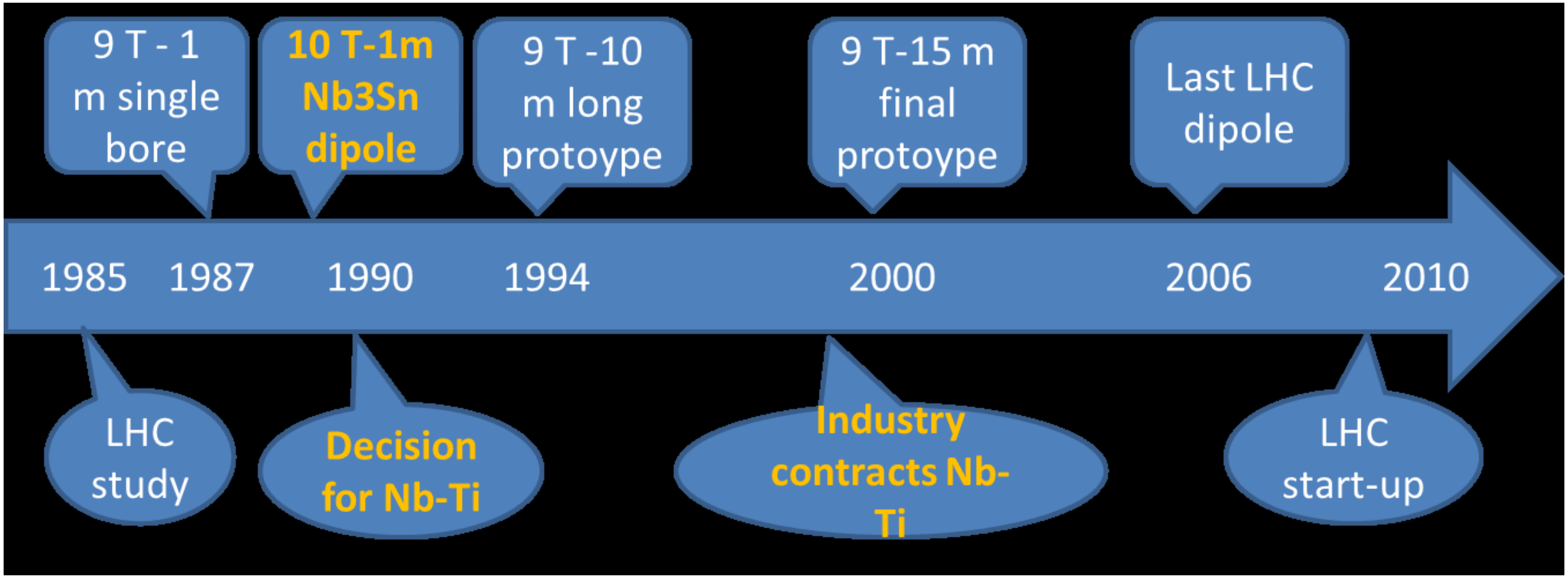
Thirty Years of SC Accelerators

Superconductivity has been an enabling technology



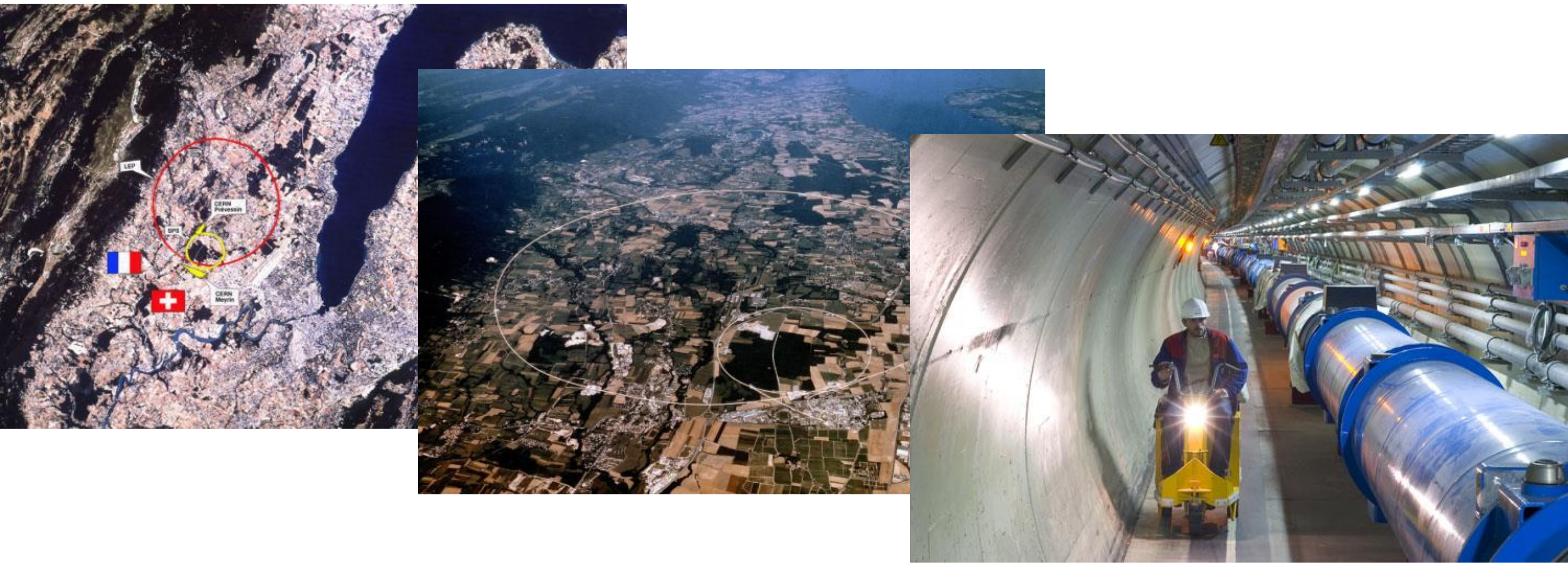
Without SC technology LHC would be 100 km long and 900 MW !

LHC – 25-year Project



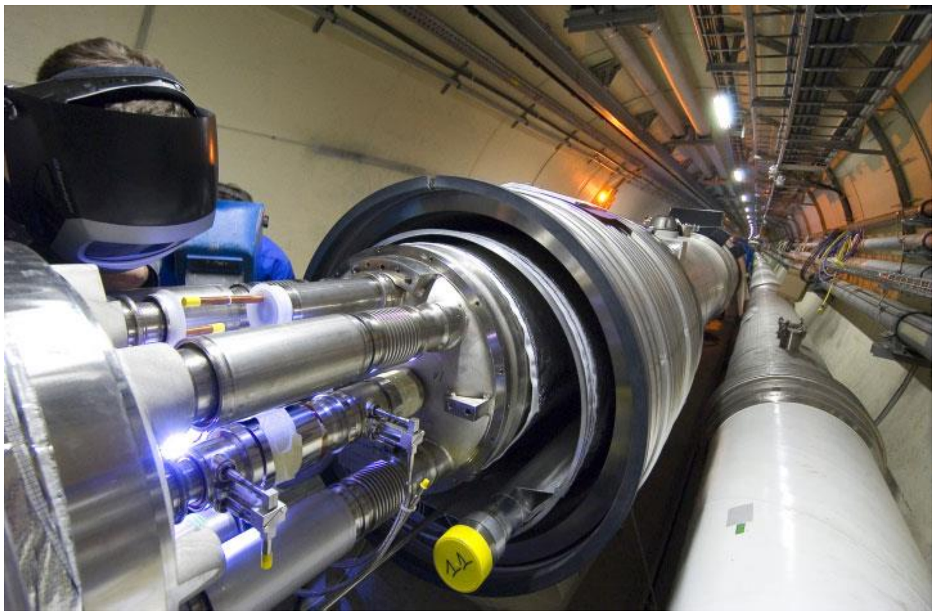
The LHC

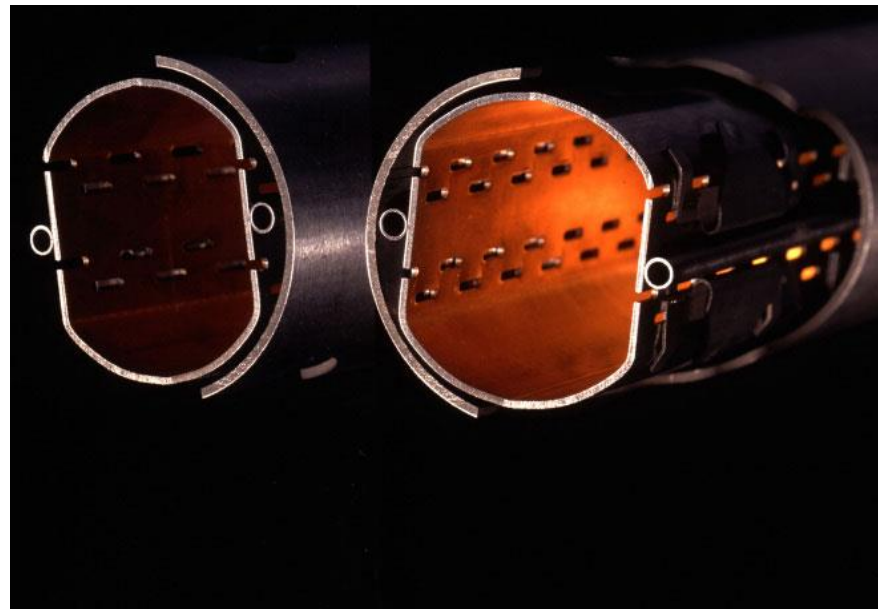
The fastest racetrack on the planet…



Trillions of protons will race around the 27km ring in opposite directions over 11,000 times a second, travelling at 99.999999991 per cent the speed of light.

The emptiest space in the solar system…



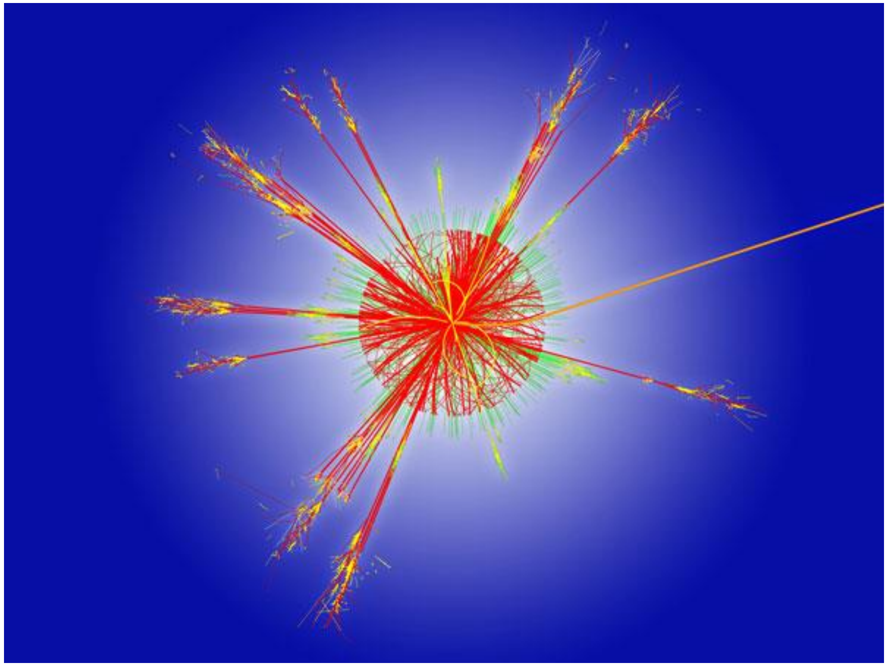


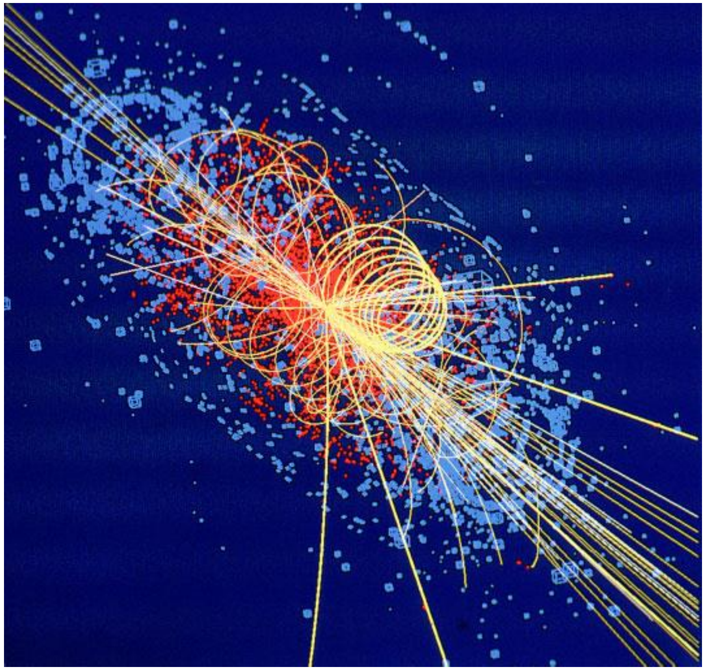
To accelerate protons to almost the speed of light requires a vacuum as empty as interplanetary space. There is 10 times more atmosphere on the moon than there is in the LHC.

One of the coldest places in the universe…

With an operating temperature of about -271 degrees Celsius, just 1.9 degrees above absolute zero, the LHC is colder than outer space.

The hottest spots in the galaxy…





When two beams of protons collide, they generate temperatures 1000 million times hotter than the heart of the sun, but in a minuscule space.

Beam Stored Energy

- 1 electron-volt is 1.6×10^{-19} Joules.
- 3.5 TeV= 560 nJ.
- Hence the full beam of 3×10^{14} protons contains 1.7×10^{8} J, that is 170 Megajoule.
- This energy is comparable to that of an Airbus 380 at 100km/h!
- This will double when the beam will reach 7 TeV!
- An energy of 170 MJ over 90 microseconds corresponds to a power of 2 Petawatt!
  Power=Energy/time

Airbus A380
wikipedia

Charge and Current

- The charge of one electron (or one proton) is 1.6×10^{-19} Coulombs.
- The LHC can store up to 3×10^{14} protons.
- This corresponds to a total charge of 4.8×10^{-5} C, that is 48 micro-Coulombs.
- As it takes 90 microseconds for the particles to travel around the ring this corresponds to a current of 0.54 Amps!
  Current = Charge/duration

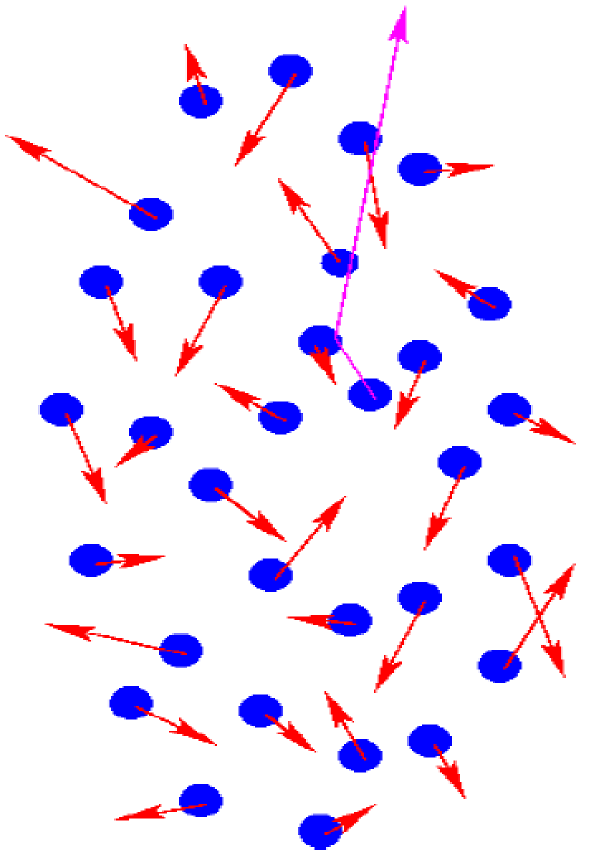
The LHC tunnel

http://cds.cern.ch

Beam Lifetime

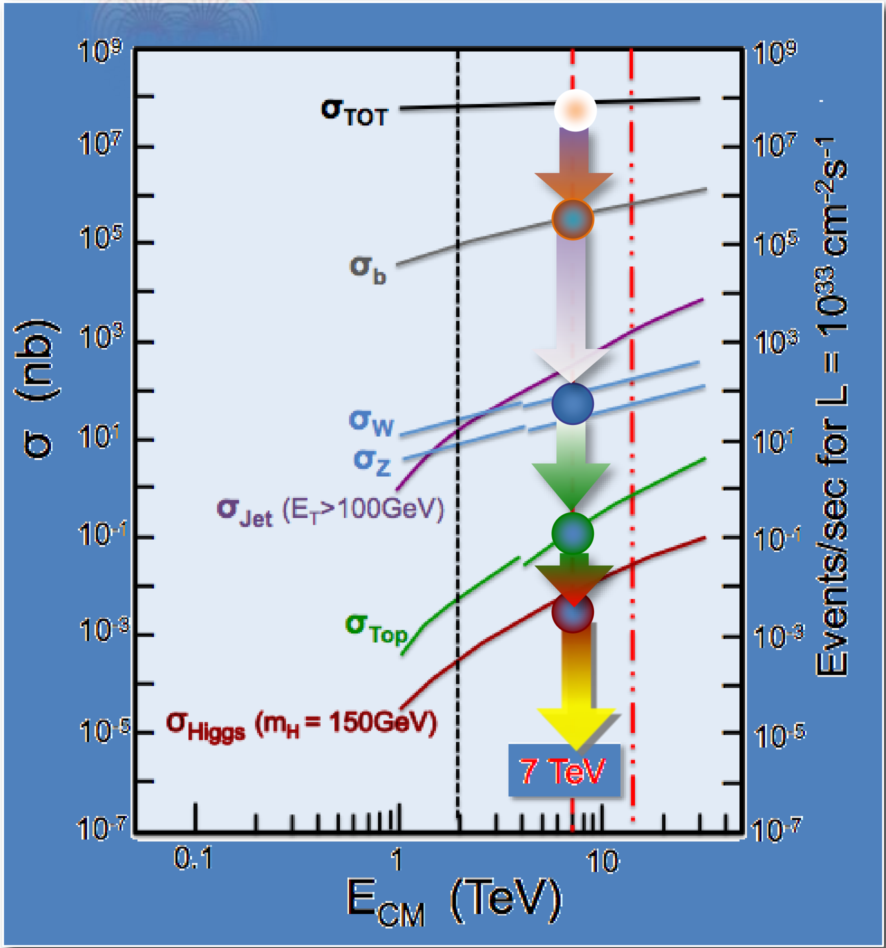
Lifetime

- The beam does not stay for ever in a ring.
- Some particles will scatter on each other and be ejected from the beam.
- Some particles "hit" the walls of the beampipe.
- In some rings the beam lifetime can be only a few minutes.
- In rings where stability is important (such as the LHC or Diamond) the beam lifetime will be several days.

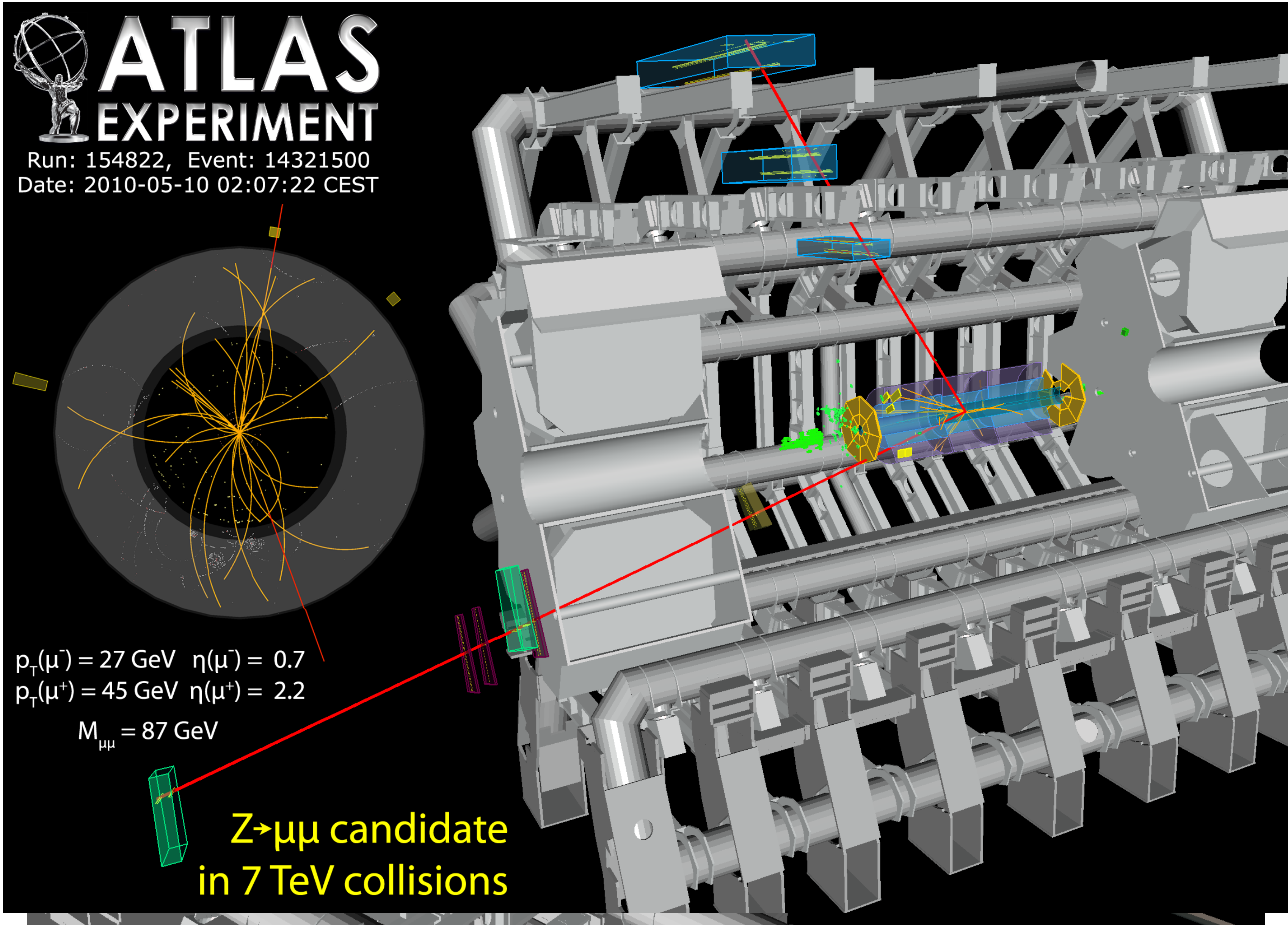


Particle scattering inside a bunch

Needle in a haystack…



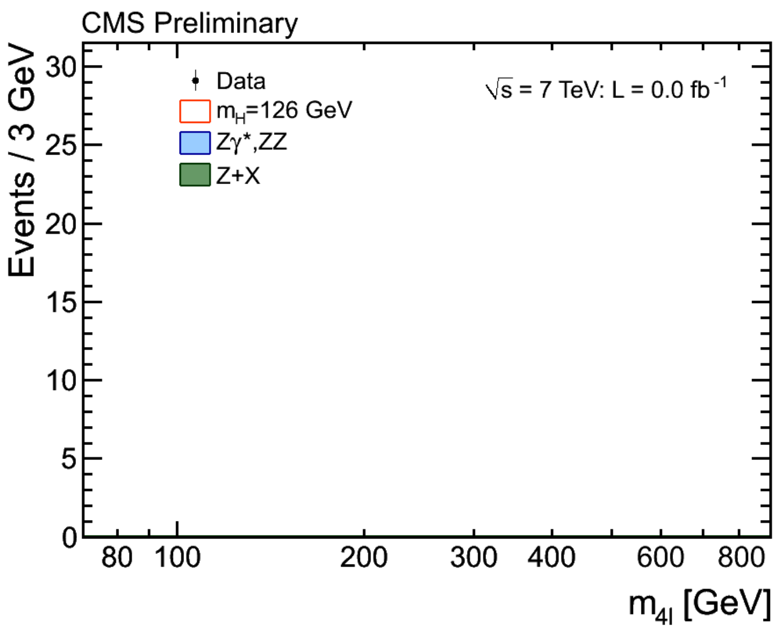
The story so far…

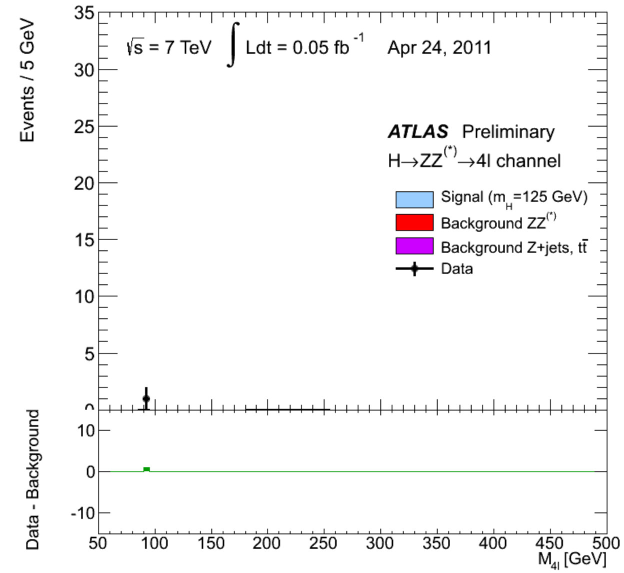


The Higgs is hiding in thousands of trillions interactions…

The Higgs Signal

Accumulation of data





$m_H = 125.8 \pm 0.5 \pm 0.3$ GeV

$m = 0.91^{+0.30}_{-0.24}$

$m_H = 124.3 \pm 0.6 \pm 0.4$ GeV

$m = 1.5 \pm 0.4$ (at 125.5 GeV)

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".*

The Predictable Future - *LHC Timeline*

2009

Start of LHC

Run 1: 7 and 8 TeV centre-of-mass energy, luminosity ramping up to several 10^{33} cm^{-2} s^{-1}, ~25 fb^{-1} delivered

2013/14

LS1 - LHC shut-down to prepare machine for design energy and nominal luminosity

Run 2: Ramp up luminosity to cm^{-2} s^{-1}, ~50 to 100 fb^{-1}) and centre-of-mass energy (1)

2018

LS2 - Injector and L s to go to ultimate luminosity

Ru p luminosity to 2.2 x nominal, reaching ~100 fb^{-1} / year acc e few hundred fb^{-1}

Study of the properties of the Higgs Boson & physics beyond the Standard Model

~20**23**

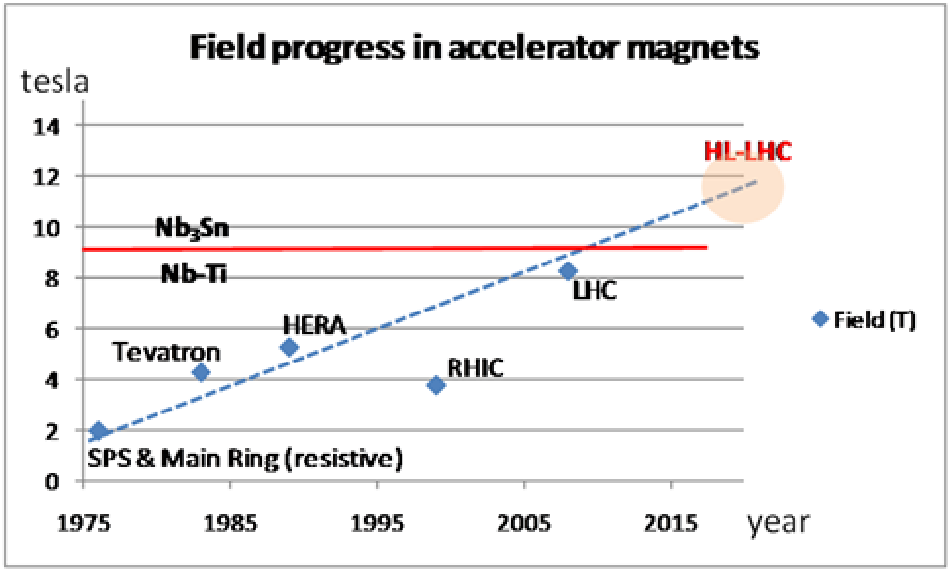
LS3 – High-luminosity LHC (HL-LHC). New focusing magnets and CRAB cavities for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

>2035

Beam Focusing
High-Field SC Magnets

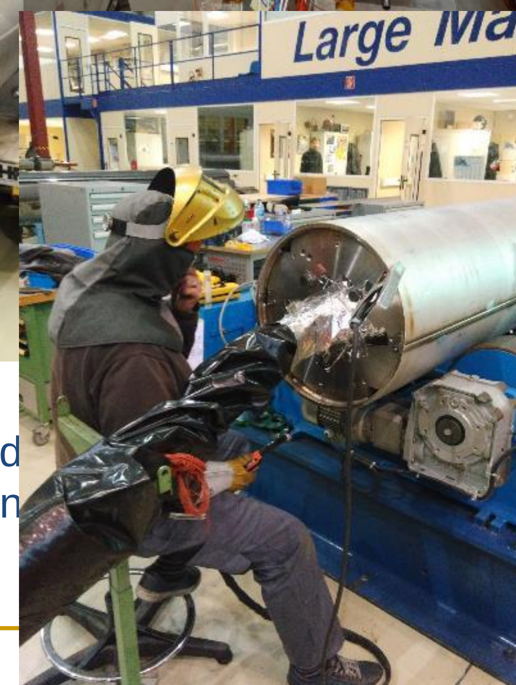
- 13 T, 150 mm aperture quadrupoles for the inner triplet:
  - LHC: 8 T, 70 mm.
- More focus strength, β* as low as 15 cm (55 cm in LHC).
  - In same scheme even β* down to 7.5 cm considered.
- Dipole separators capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)



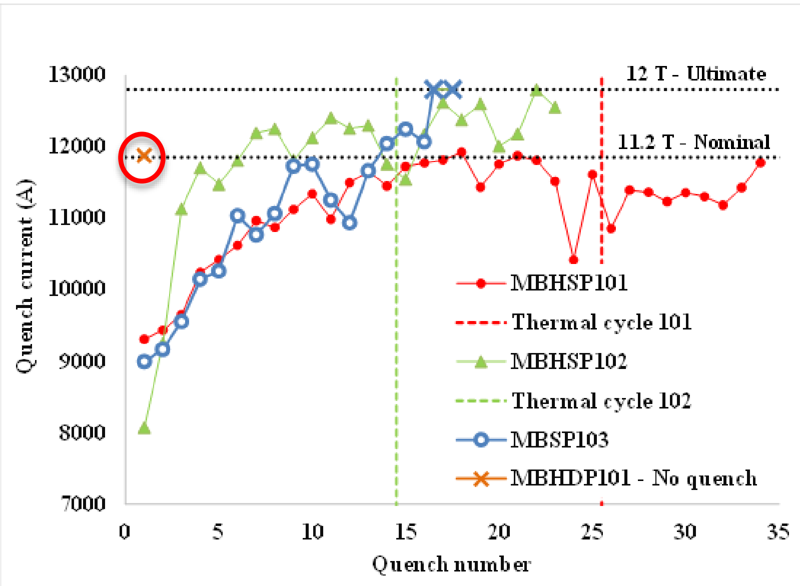
Goal:

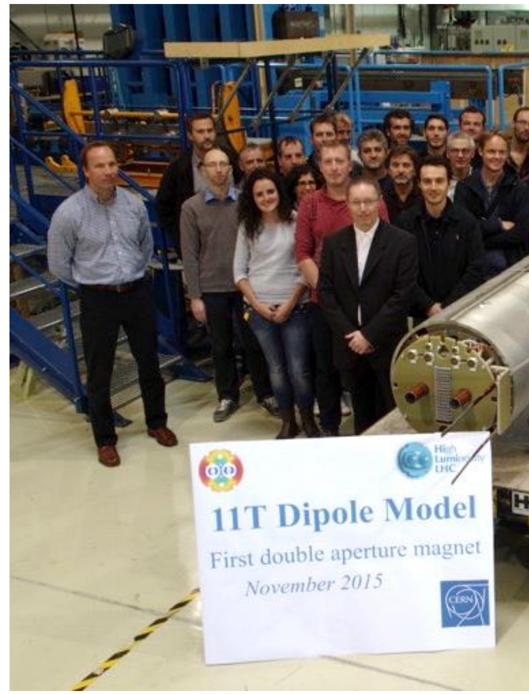
Enable focusing of the beams to β^*=0.15 m in IP1 and IP5.

11 T Dipole for HL-LHC (Dispersion suppressor collimation)
First assembly in Two-In-One magnet of short coils (1.8 m)
Nb_3Sn technology



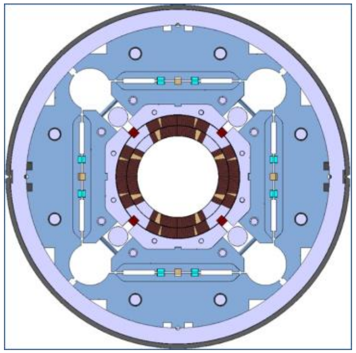
Single apertures n. 102 & 103 reached 12 T after some training that started at ~ 9 T.

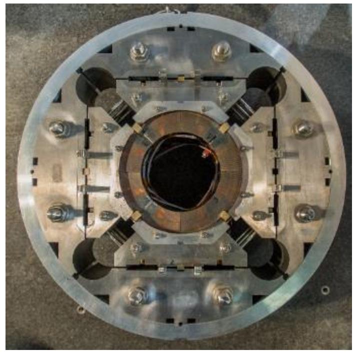




- Cold powering test started on Wednesday 9th December : Result in red
- No quench up to 11.3 T, above nominal! Test stopped because of quen
connection (**NOT in the magnet**).

First short model magnet MQXFS1 (1.5 m)
Inner Triplet Quad final cross section (Ø =150 mm)



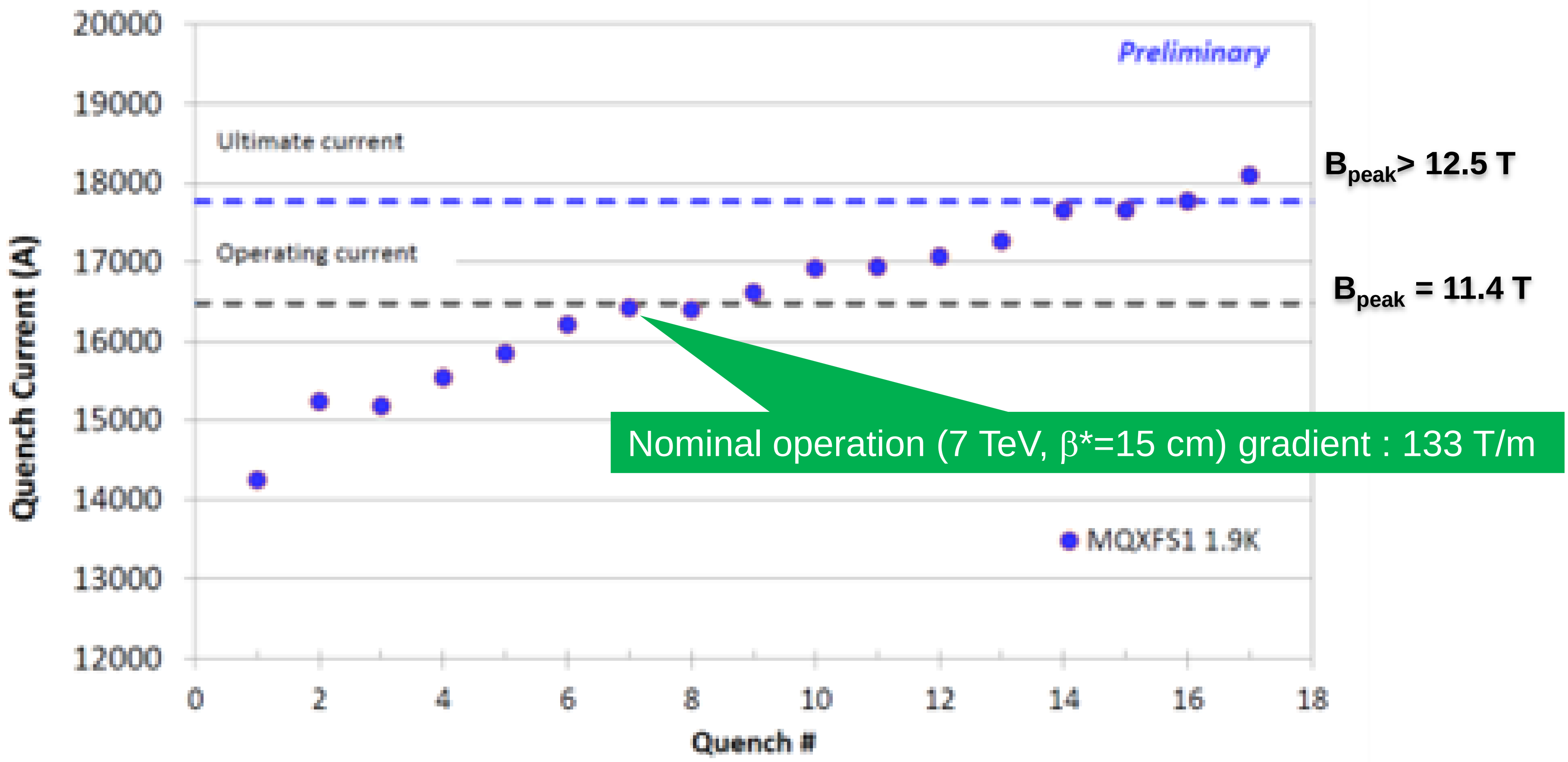


CERN - US LARP collaboration

Design and Nb_3Sn coils by CERN and LARP together (50%-50%)

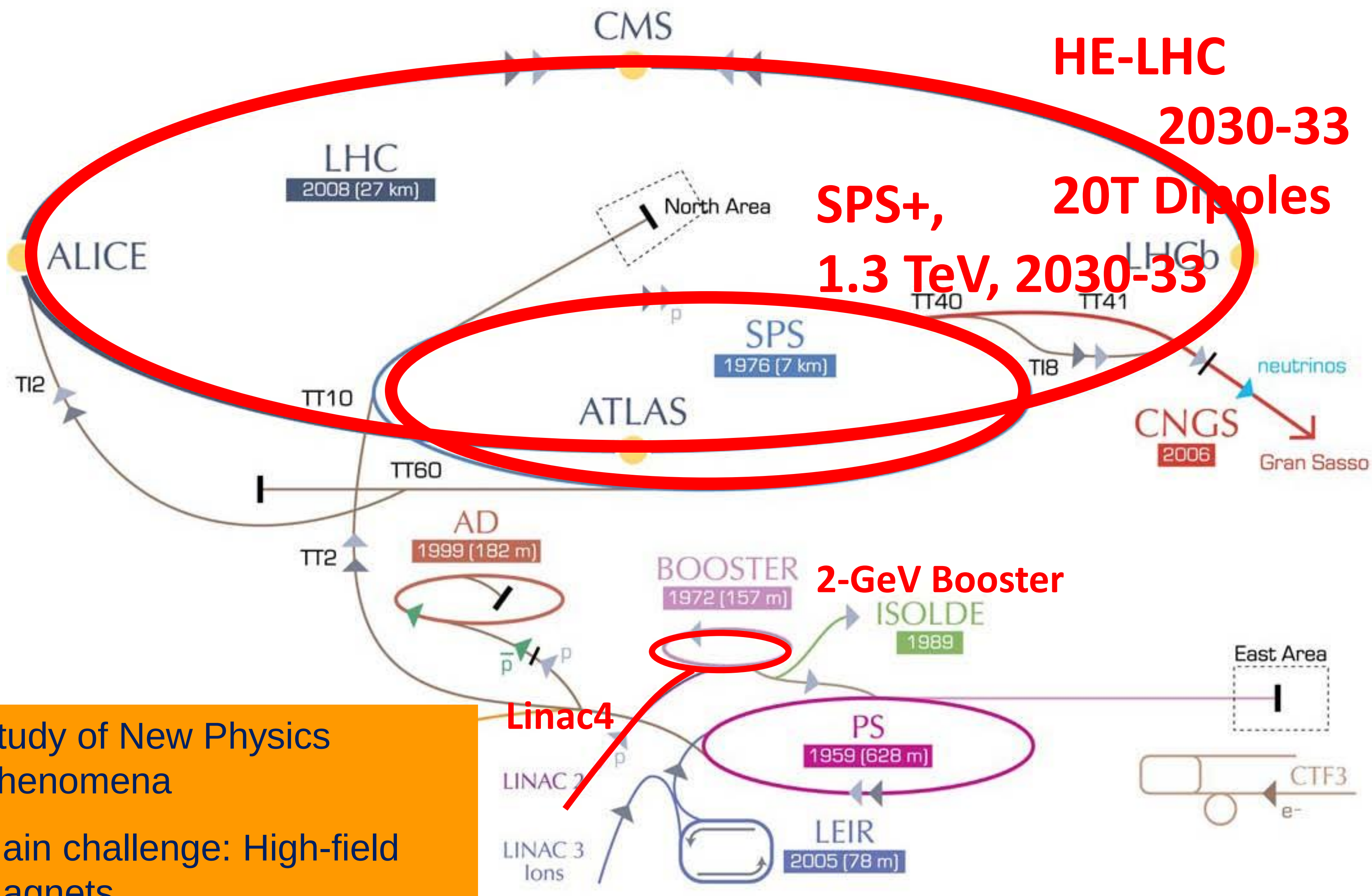
Full collider characteristics.
Final length will be 3 to 5 times more

First short model magnet MQXFS1 (1.5 m)
Result of the first energization @ FNAL



Next: thermal cycle and memory test (and more…)

High-Energy LHC (HE-LHC)



Study of New Physics Phenomena

Main challenge: High-field Magnets

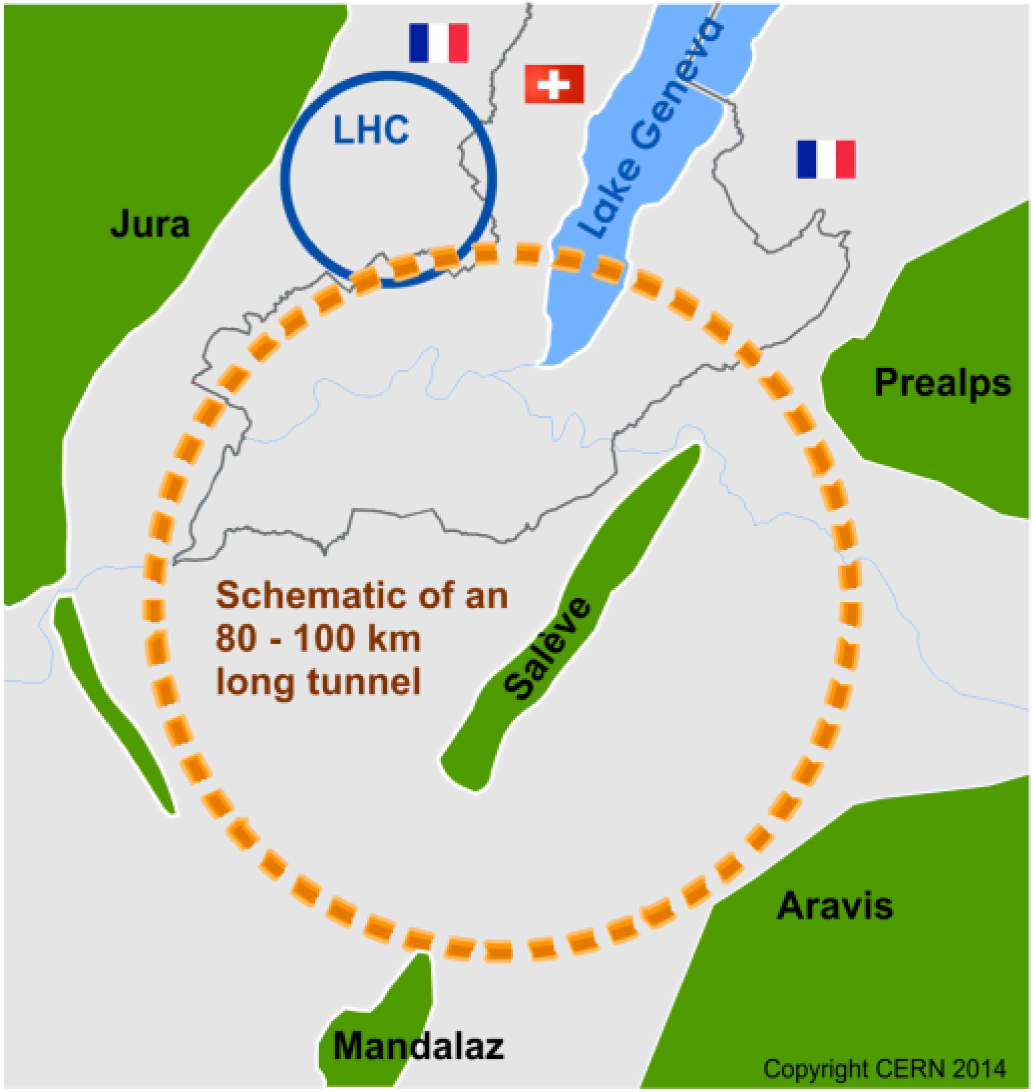
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

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

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

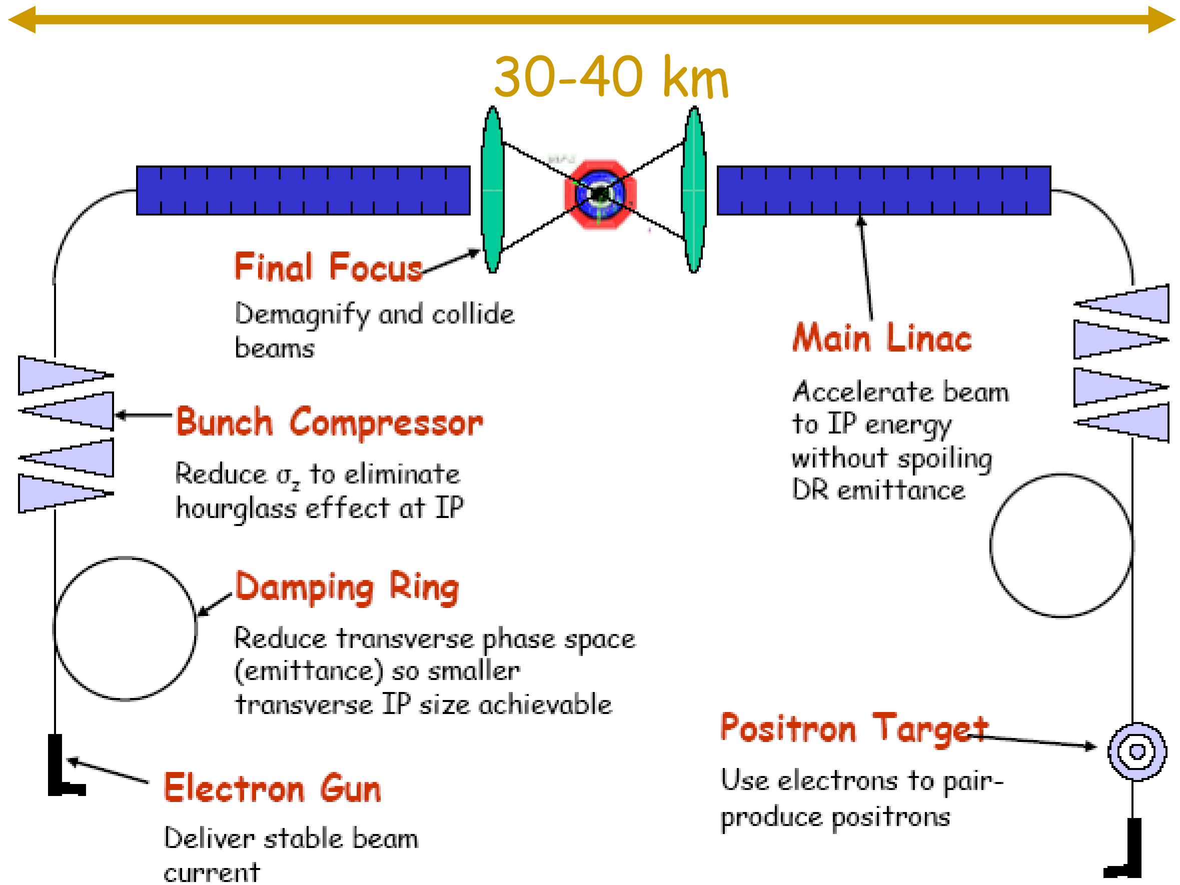
- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



Collaboration Status (11/2015)

- 72 Institutes (research centers & universities)
- European Commission
- 26 countries

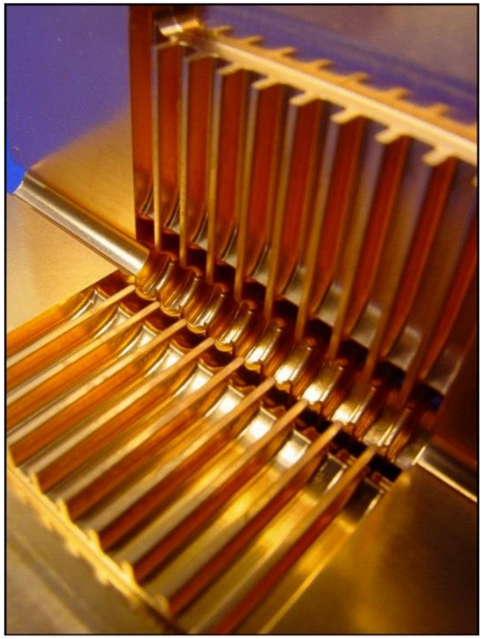
A Generic Linear Collider



The machine which will complement and extend the LHC best, and is closest to be realized, is a Linear e+e- Collider.

ILC (and the Compact Linear Collider CLIC)

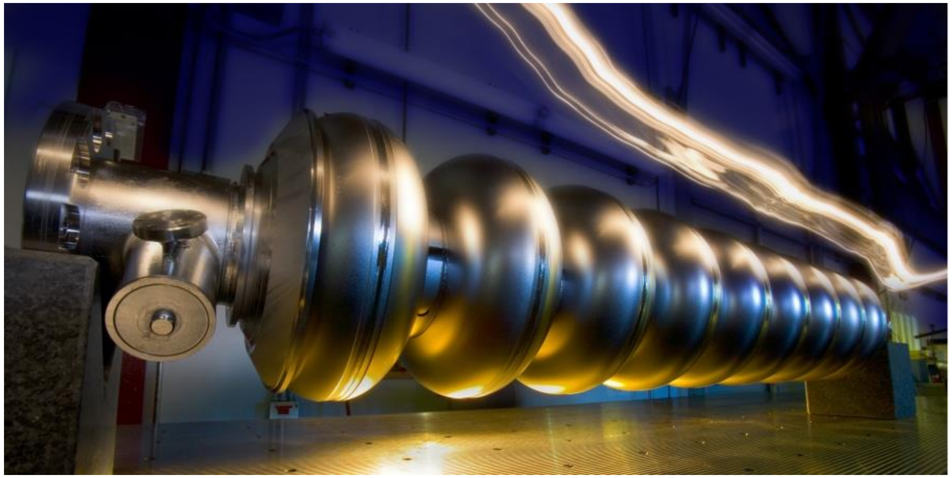
CLIC



•2-beam acceleration scheme at room temperature
•Gradient 100 MV/m
•$\sqrt{s}$ up to 3 TeV
•Physics + Detector studies for 350 GeV - 3 TeV

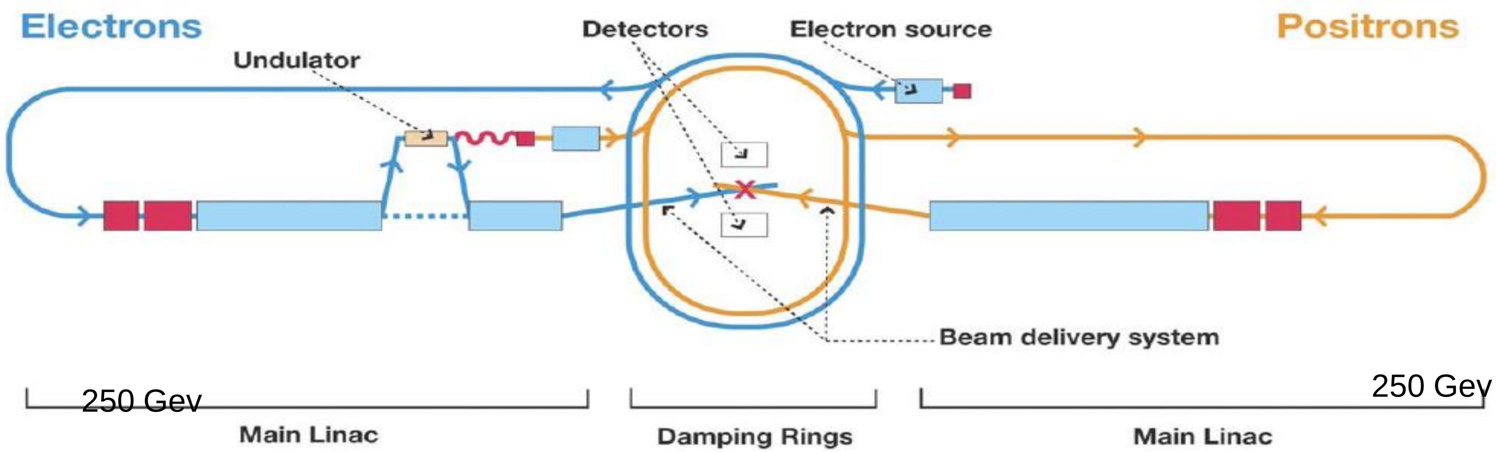
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

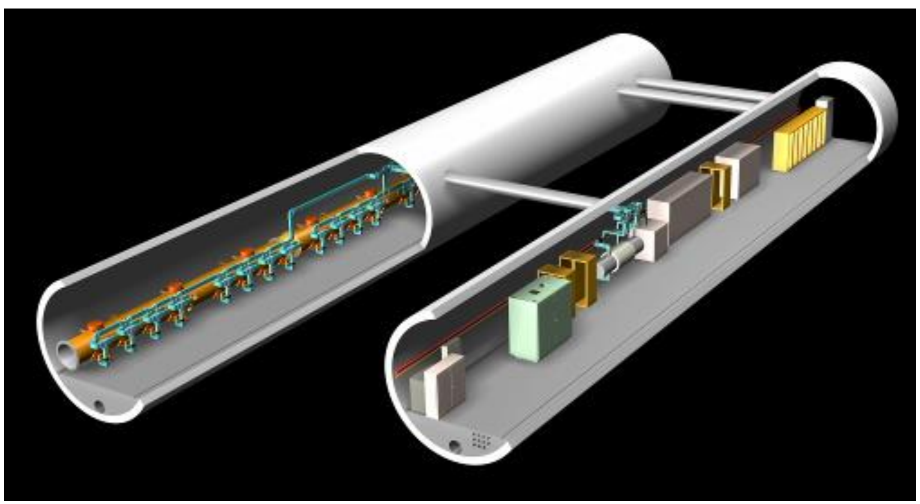
ILC



•Superconducting RF cavities (like XFEL)
•Gradient 32 MV/m
•$\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
•Focus on ≤ 500 GeV, physics studies also for 1 TeV

International Linear Collider Baseline Design





e+ e- Linear Collider

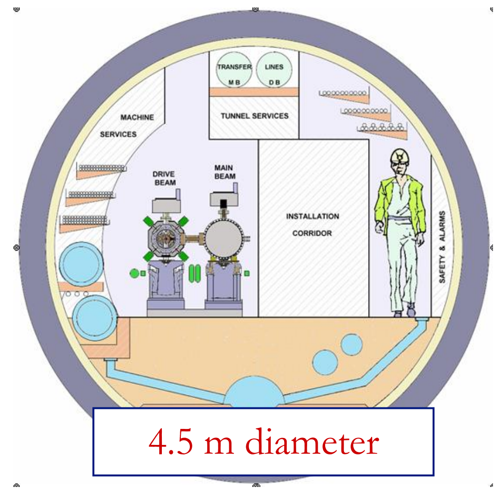
Energy 250 GeV x 250 GeV
# of RF units 560
# of cryomodules 1680
# of 9-cell cavities 14560
2 Detectors push-pull
peak luminosity 2 10^{34}
5 Hz rep rate, 1000 -> 6000 bunches
IP : s_x 350 – 620 nm; s_y 3.5 – 9.0 nm
Total power ~230 MW
Accelerating Gradient 31.5 MeV/m

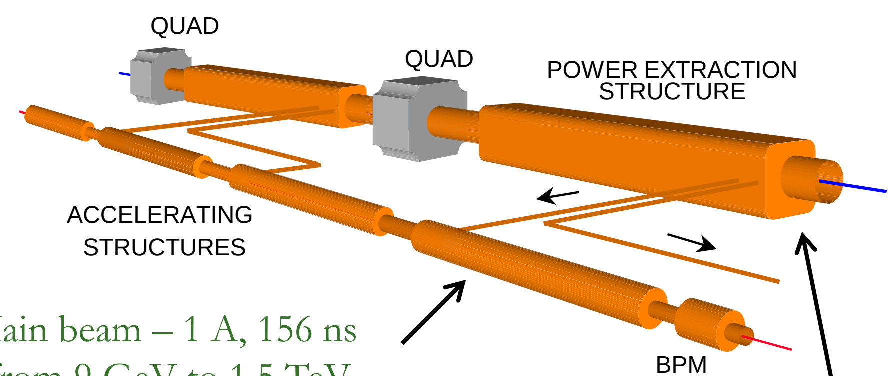
Basic Features

- **High acceleration gradient: > 100 MV/m**
  - "Compact" collider – total length < 50 km at 3 TeV
  - Normal conducting acceleration structures at high frequency

- **Novel Two-Beam Acceleration Scheme**
  - Cost effective, reliable, efficient
  - Simple tunnel, no active elements
  - Modular, easy energy upgrade in stages

CLIC TUNNEL CROSS-SECTION



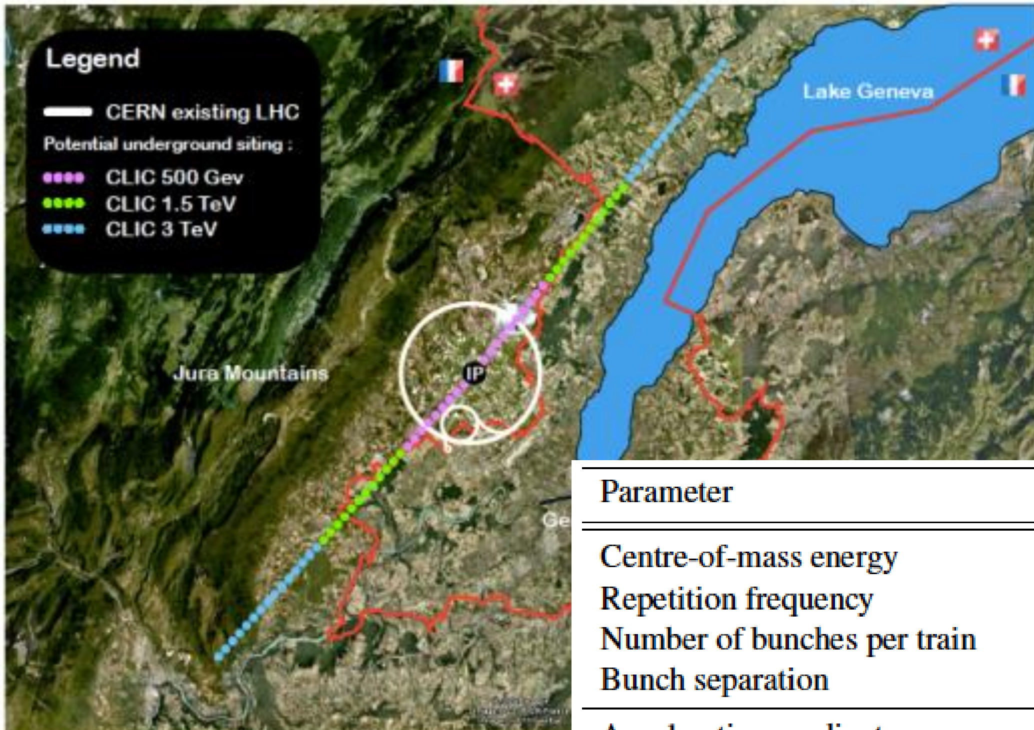


Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV
100 MV/m

Drive beam - 95 A, 240 ns
from 2.4 GeV to 240 MeV

12 GHz – 64 MW

CLIC Implementation



← Possible lay-out near CERN

Note: the design is currently being re-optmised, e.g. to include 350 GeV as the first stage

↓ CLIC parameters

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	μm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

THE SUB-FERMI SCALE (2010-2040)?