CERN & the High Energy Frontier

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Corfu Summer Institute
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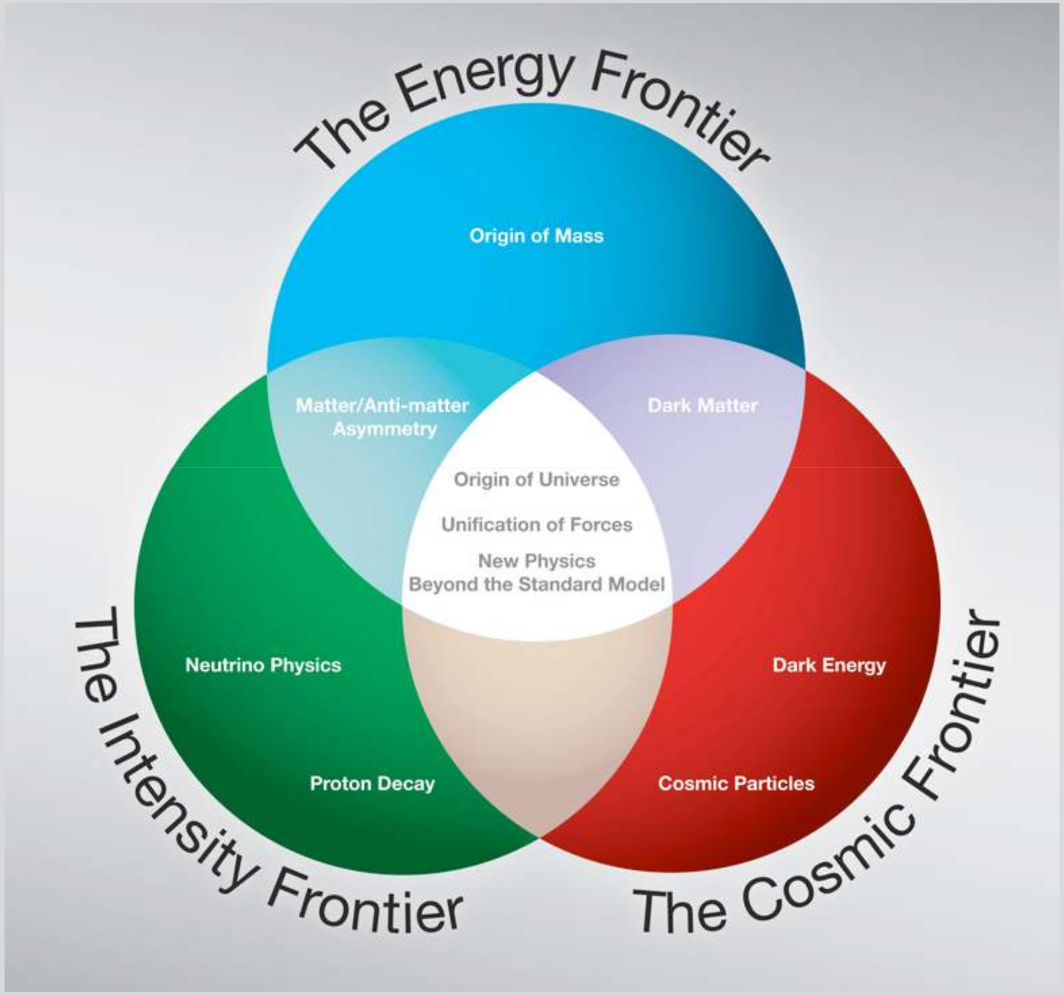
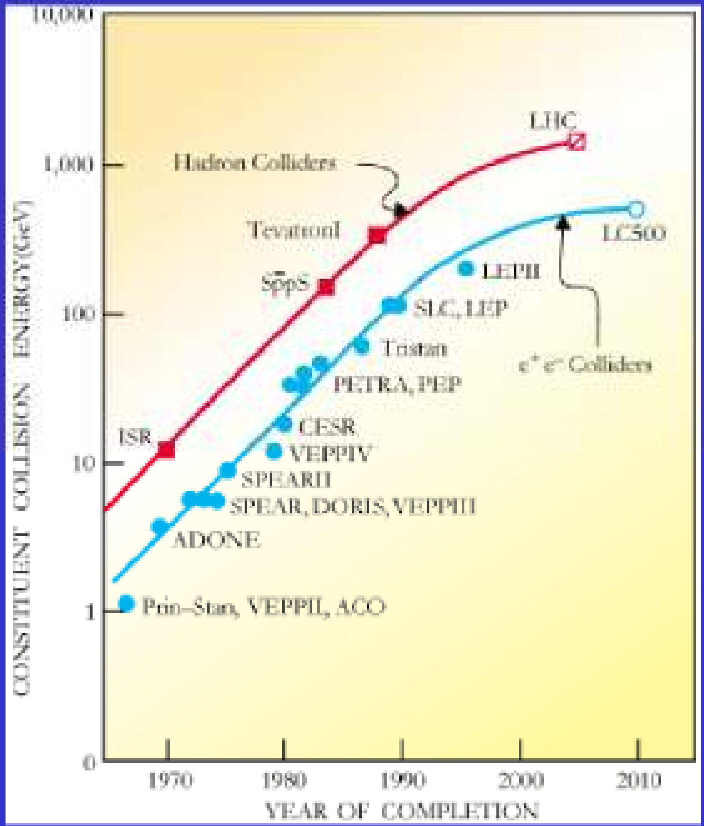
The Three Frontiers



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)!

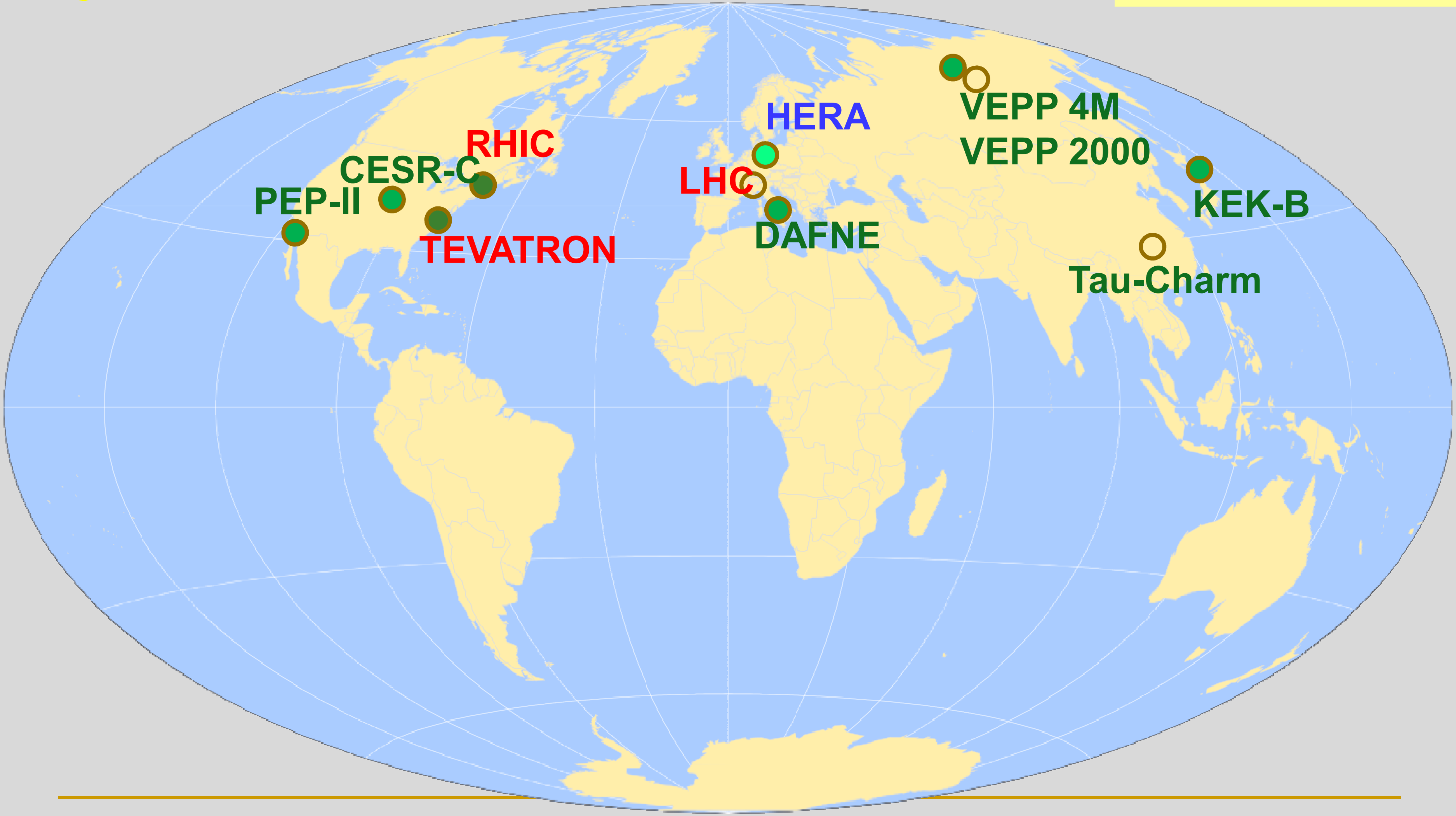
Not enough: Project cost increased by factor 200!

New technology needed…

Colliders - 2006

In operation
In construction

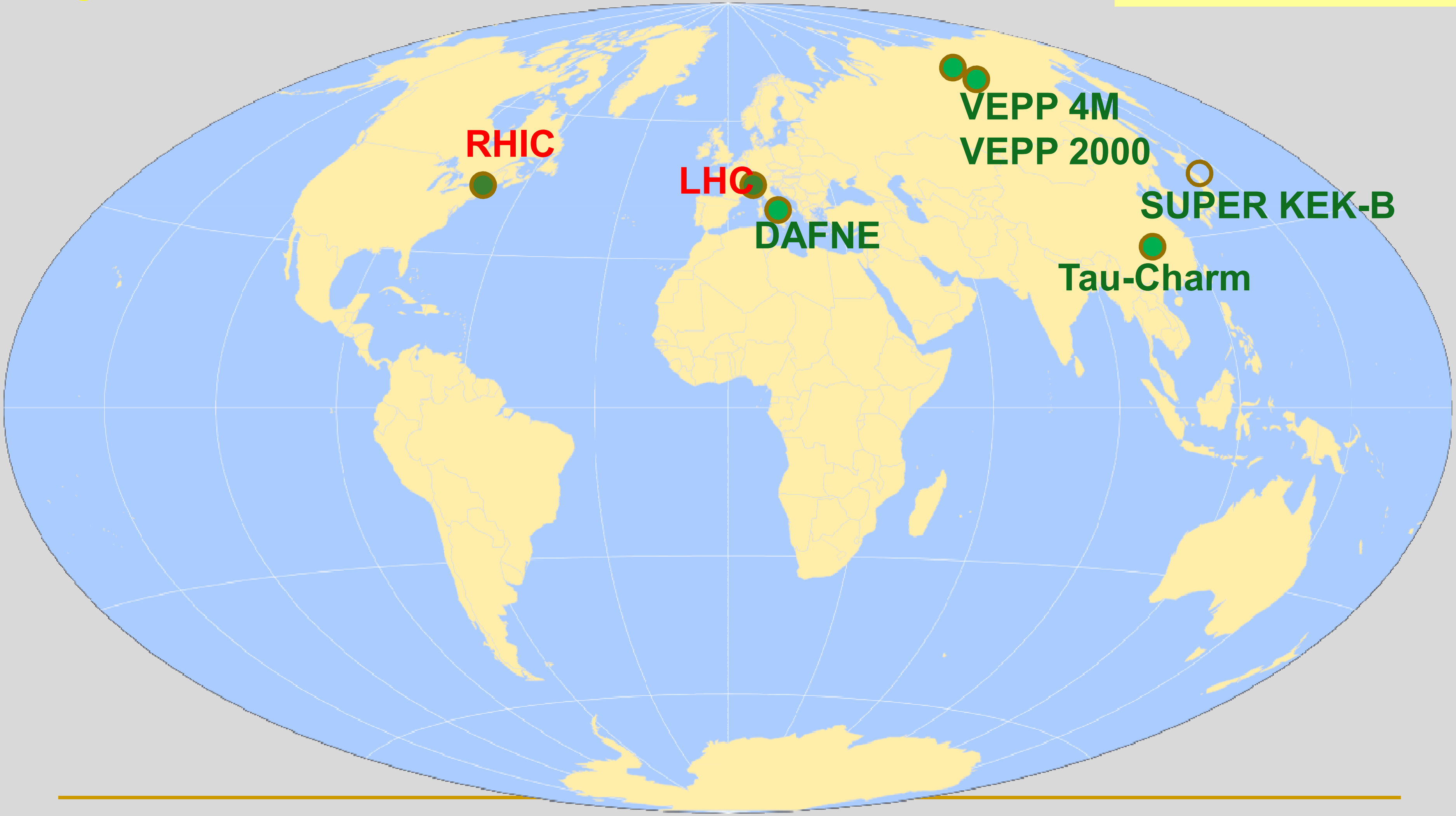
Hadrons
Leptons
Leptons-Hadrons



Colliders - 2012

In operation
In construction

Hadrons
Leptons
Leptons-Hadrons



Next Decades

Road beyond Standard Model

LHC results will guide the way at the energy frontier

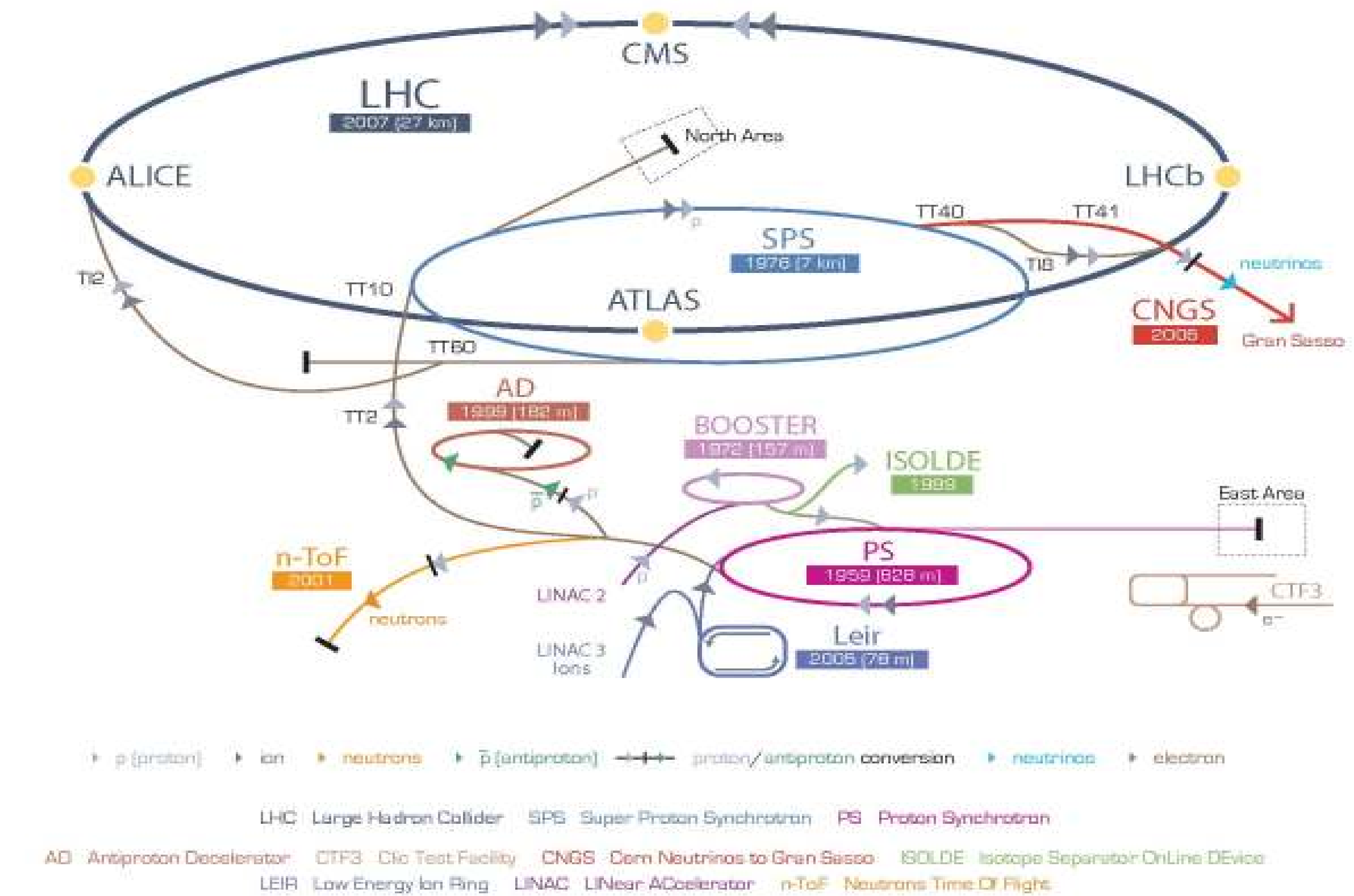
through synergy of

hadron – hadron colliders (LHC,HL-LHC,HE-LHC,VE-LHC)

lepton – lepton colliders (LC (ILC or CLIC), TLEP)

lepton – hadron colliders (LHeC)

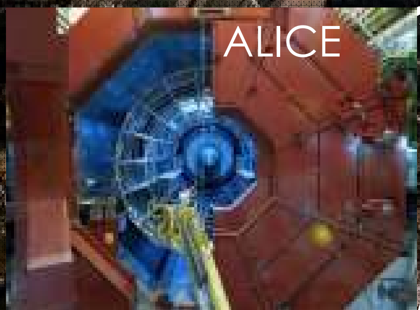
CERN Accelerator Complex

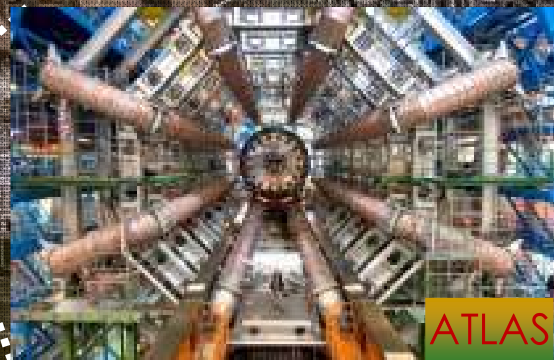


Entered a New Era in Fundamental Science

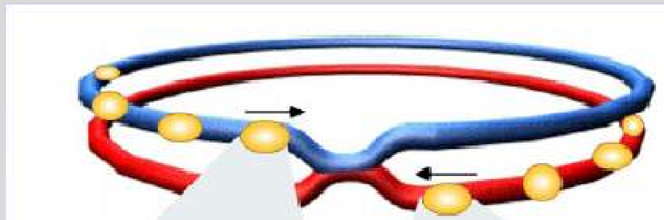
Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

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



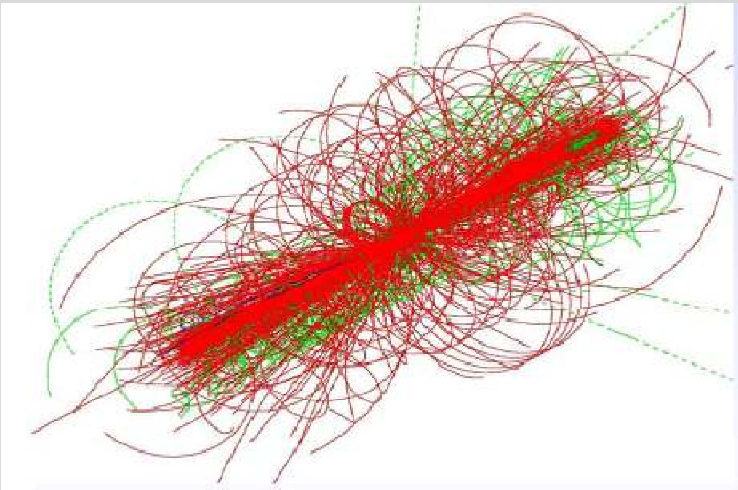


Proton-Proton Collisions at the LHC



Design Energy:
7 + 7 = 14 TeV

2012: 4 + 4 = 8 TeV



- 2808 + 2808 proton bunches

2012: 1400 + 1400 bunches
20 MHz crossing rate

→ = 40 MHz crossing rate

- 10^{11} protons per bunch

- at 10^{34}/cm²/s 2012: 7.7 x 10^{33}
  ≈ 35 pp interactions per crossing
  pile-up

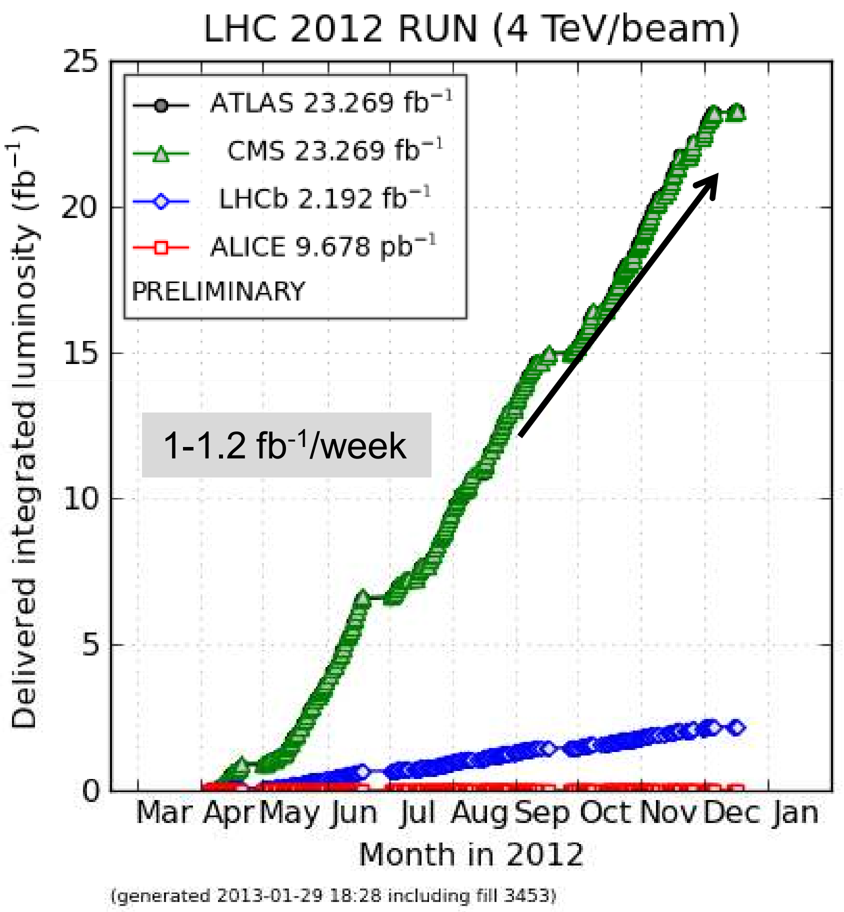
→ ≈ 10^9 pp interactions per second !!!

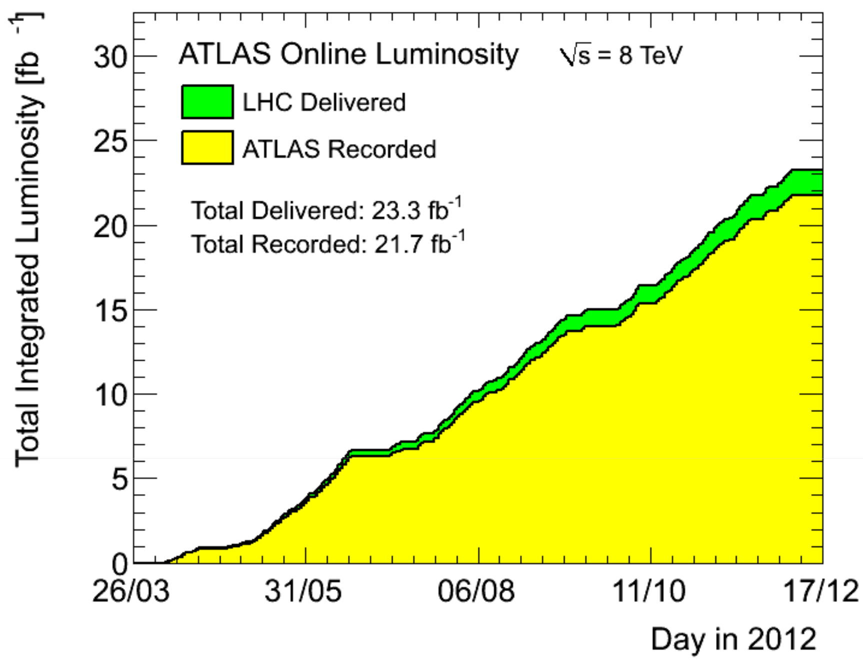
- in each collision
  ≈ 1600 charged particles produced

enormous challenge for the detectors
and for data collection/storage/analysis

Final Numbers for pp Luminosity

Peak Luminosity: 7.73×10^{33}



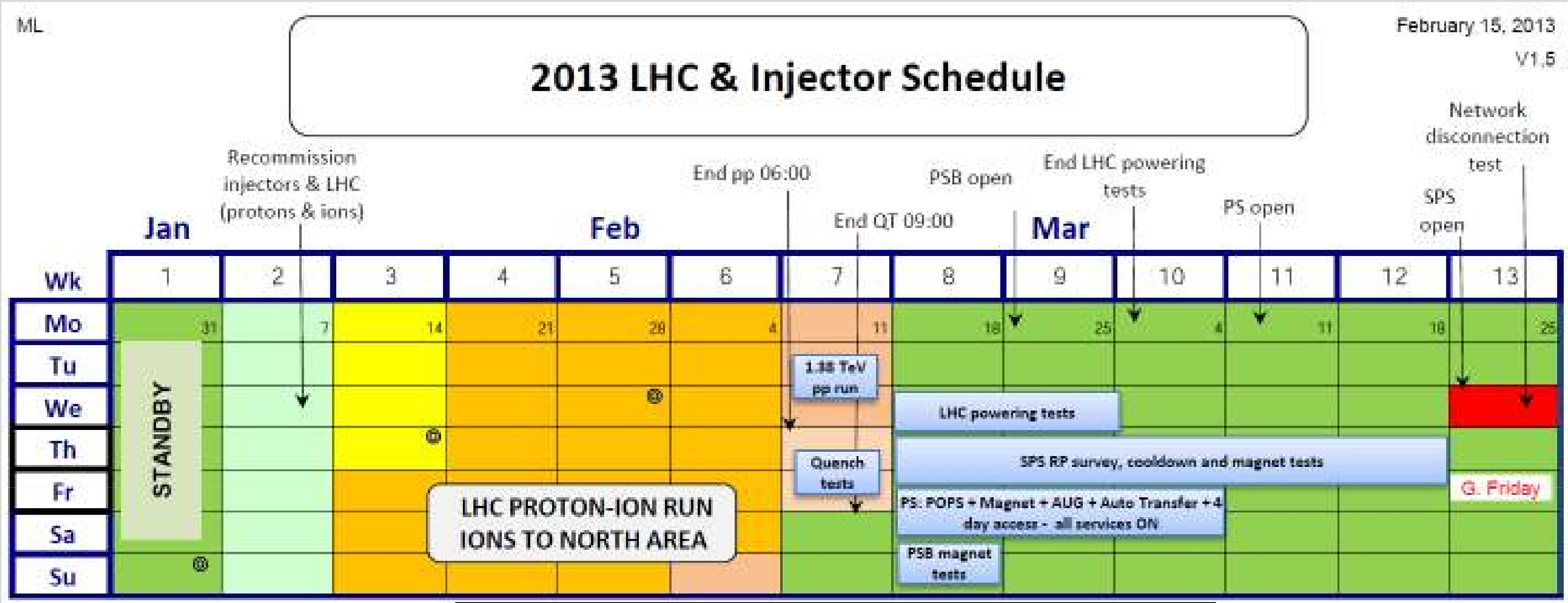


Run Availability

Based on LHC Physics Schedule

Total Run Time	205 days 14 hrs 20 mins	
Cryo Availability	192 days 13 hrs 11 mins	93.7 %
Fault Downtime	50 days 11 hrs 3 mins	24.5 %

Physics Run in Proton-Pb



Ending the pPb Run with Records

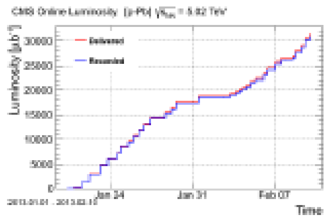
- Sun 10/2 6:04 OP dump of the last Pb-p fill – **lumi requests from experiments surpassed**

ALICE: 31.14 nb^{-1}

ATLAS: 30.25 nb^{-1}

CMS: 30.79 nb^{-1}

LHCb: 2.08 nb^{-1}



- ATLAS records

Peak Stable Luminosity Delivered	1.12×10^{29} $cm^{-2}s^{-1}$	Fill 3544	13/02/10, 00:11
Maximum Luminosity Delivered in one fill	1905.6 ub^{-1}	Fill 3485	13/01/23, 03:30
Maximum Luminosity Delivered in one day	3591.75 ub^{-1}	Saturday 09 February, 2013	
Maximum Luminosity Delivered in 7 days	14679.82 ub^{-1}	Monday 21 January, 2013 - Sunday 27 January, 2013	
Maximum Colliding Bunches	296	Fill 3485	13/01/23, 03:30
Maximum Peak Events per Bunch Crossing	3.06	Fill 3482	13/01/22, 06:07
Maximum Average Events per Bunch Crossing	0.07	Fill 3544	13/02/10, 00:11
Longest Time in Stable Beams for one fill	12.0 hours	Fill 3482	13/01/22, 10:53
Longest time in stable beams for one day	18.0 hours (74.9%)	Tuesday 22 January, 2013	
Longest Time in Stable Beams for 7 days	82.1 hours (48.9%)	Monday 21 January, 2013 - Sunday 27 January, 2013	
Fastest Turnaround to Stable Beams	2.37 hours	Fill 3544	13/02/10, 00:06

8:30 meeting 2013-02-11 EBH 2

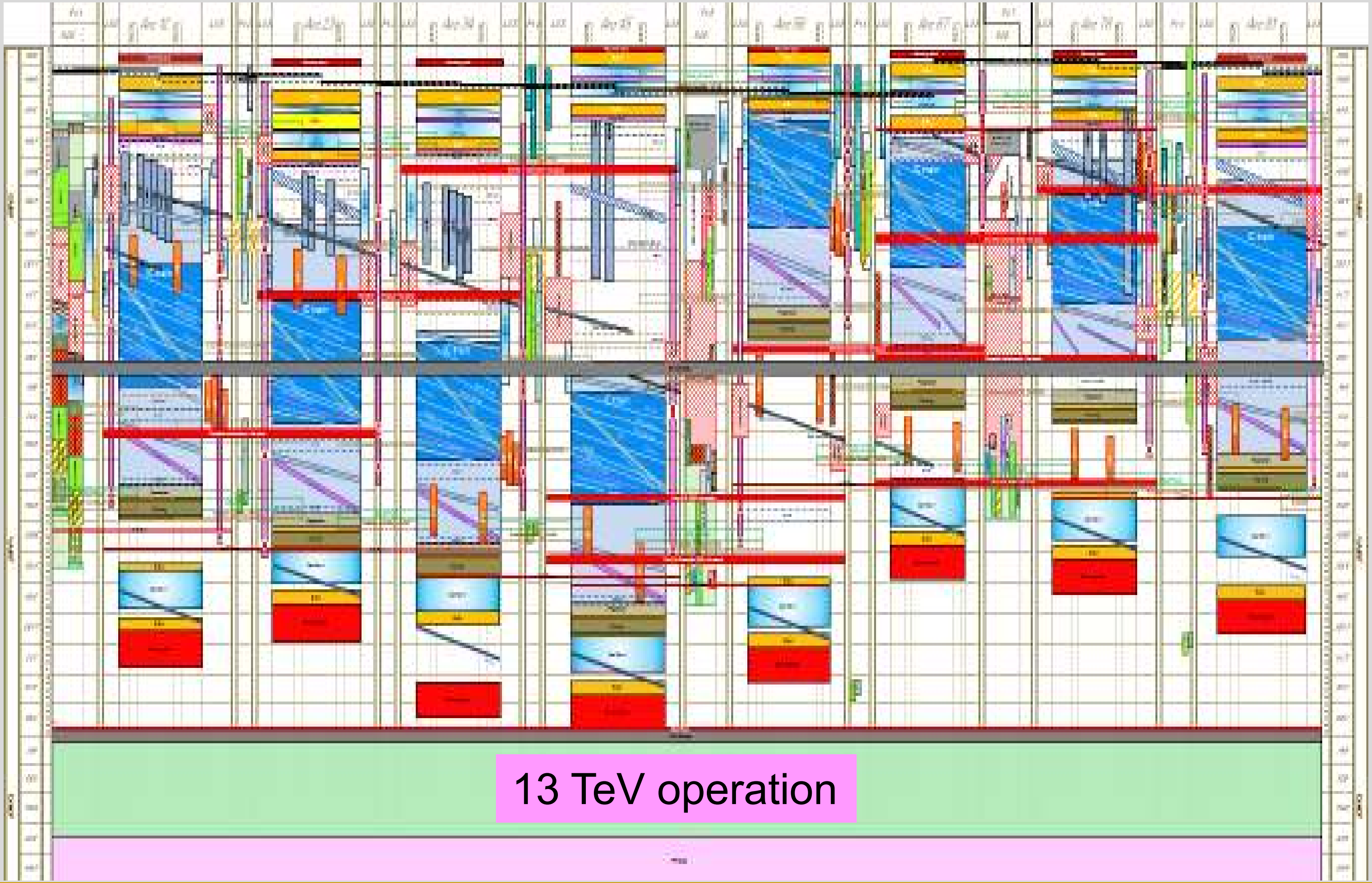
The LHC Timeline

Year	Period	Event	Integrated luminosity
2009		✧ LHC startup, $\sqrt{s}$ = 900 GeV	
2010			
2011		$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns	
2012			~20-25 fb^{-1}
2013	LS1	Go to design energy, nominal luminosity	
2014			
2015			
2016		$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	
2017			~75-100 fb^{-1}
2018	LS2	Injector and LHC Phase-1 upgrade to ultimate design luminosity	
2019			
2020		$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	
2021			~350 fb^{-1}
2022	LS3	HL-LHC Phase-2 upgrade, IR, crab cavities?	
2023			
…			
2030?		$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling	~3000 fb^{-1}

LS 1 (Feb 2013 to Dec 2014)

- Numerous projects and activities:
  - SMACC (Superconducting Magnets And Circuit Consolidation)
  - R2E (Radiation to Electronics)
  - Massive shutdown maintenance after more than 3 years of operation
  - Several major consolidations PSB, PS, SPS, LHC and electricity network
  - A lot of projects (LINAC4, HIE-ISOLDE, Elena, nTOF EAR 2, LIU, HL-LHC, ….)
- Compared to previous shutdowns, an exceptional number of …
  - Simultaneous activities (co-activities) – Planning & safety
  - Non-CERN workers (FSU, collaborations, contracts,…)- Logistics: Registration, training, transport, parking, access, dosimeter, PPE, catering, accommodation,…)

LS1: LHC Schedule



Why Upgrade the Injectors ?

- Need for reliability
  - Accelerators are old [LINAC2 (1978), PSB (1975), PS (1959), SPS (1976)]
  - They operate far from their design parameters and close to hardware limits
  - The infrastructure has suffered from the concentration of resources on LHC during its construction phase
- Need for better beam characteristics

Goals & Means

To increase performance (increase brightness):

⇒ Increase injection energy in the PSB from 50 to 160 MeV
  ⇒ LINAC4 (160 MeV H^-) to replace LINAC2 (50 MeV H^+)

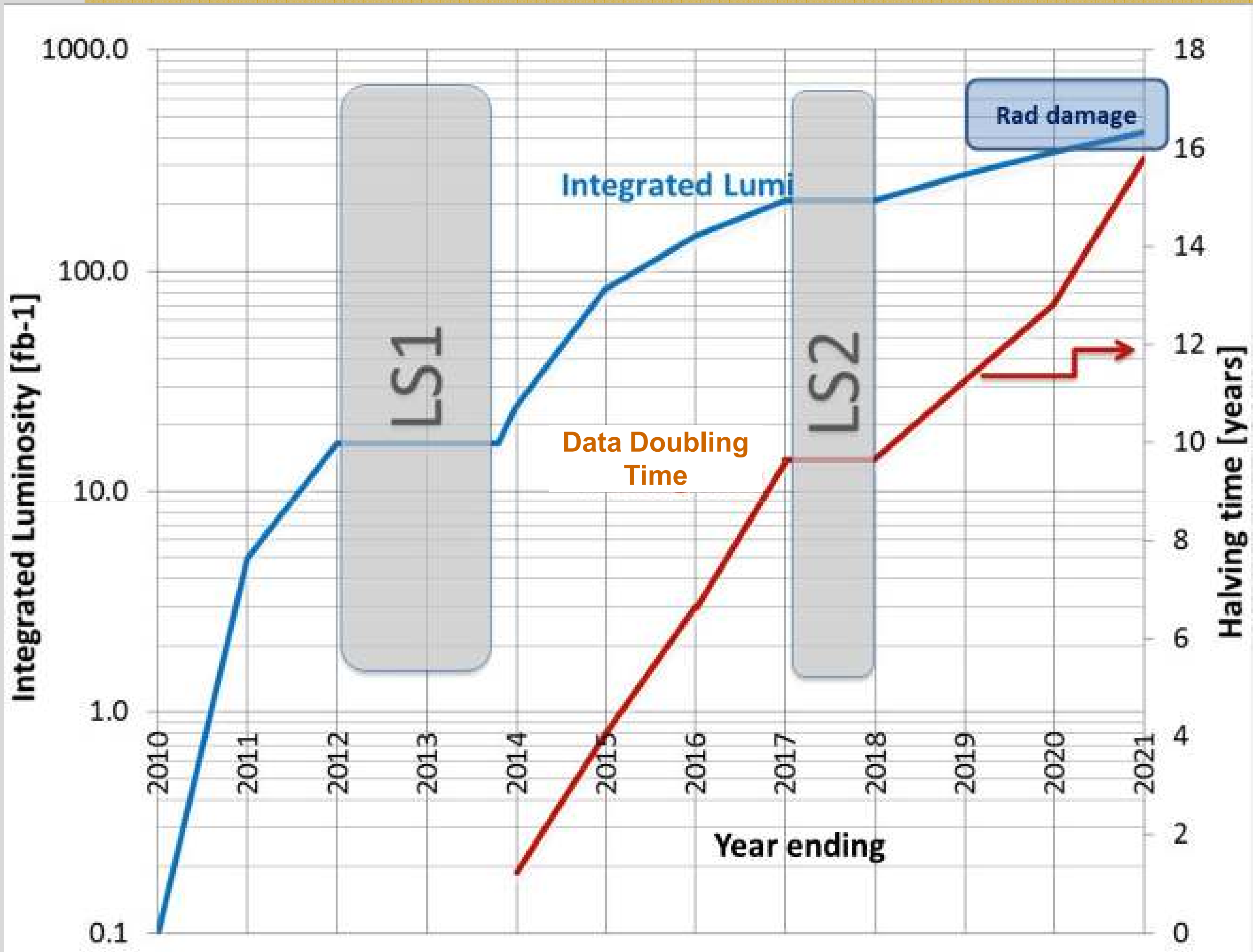
⇒ Increase injection energy in the PS from 1.4 to 2.0 GeV
  ⇒ Increasing the field in the PSB magnets, replacing power supply and changing transfer equipment.

⇒ Upgrade the PSB , PS and SPS to make them capable to accelerate and manipulate a higher brightness beam.
  ⇒ Feedbacks, cures against electron clouds, hardware modifications to reduce impedance…)

LINAC4 – Civil Engineering

Building completed in October 2010

HL-LHC: The Need for an Upgrade



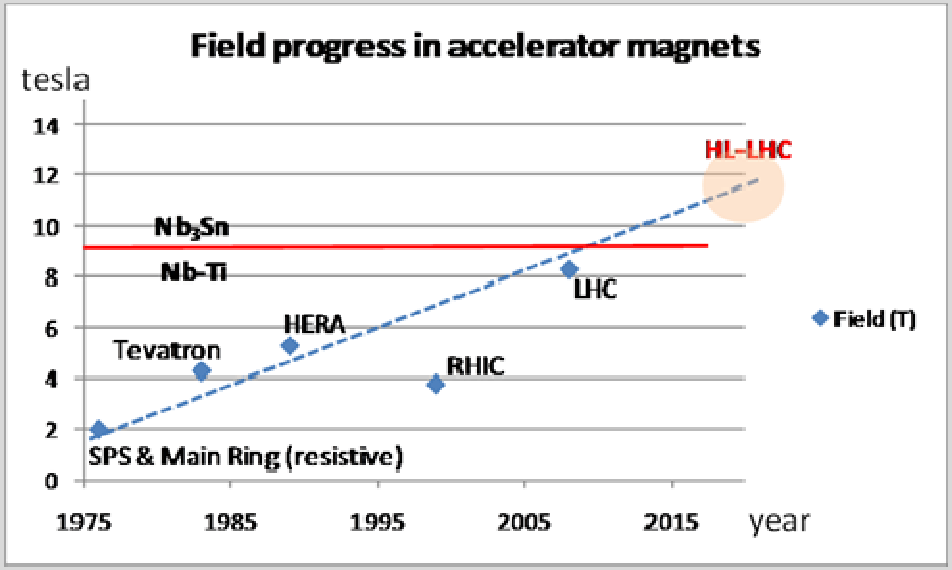
Around 2022 the present triplet magnets reach the end of their useful life (due to radiation damage) …and will anyway need replacing.

In addition, the luminosity of the LHC will saturate by then

Time for an upgrade!

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.

Example HL-LHC Parameters

Parameter	Symbol	Nom.	Nom.*	HL Crab
protons per bunch	N_b [10^{11}]	**1.15**	1.7	**1.78**
bunch spacing	Δt [ns]	**25**	50	**25**
beam current	I [A]	**0.58**	0.43	**0.91**
longitudinal profile		**Gauss**	Gauss	**Gauss**
rms bunch length	σ_z [cm]	**7.55**	7.55	**7.55**
beta* at IP1&5	$\beta*$ [m]	**0.55**	0.55	**0.15**
full crossing angle	θ_c [μrad]	**285**	285	**(508-622)**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	**0.65**	0.65	**0.0**
tune shift	ΔQ_{tot}	**0.009**	0.0136	**0.011**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**10.6**
events per #ing		**19**	40	**95**
effective lifetime	τ_{eff} [h]	**44.9**	30	**13.9**
run or level time	$t_{run,level}$ [h]	**15.2**	12.2	**4.35**
e-c heat SEY=1.2	P [W/m]	**0.2**	0.1	**0.4**
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	**0.32**	0.30	**0.62**
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	**59, 102**	40, 69	**38, 66**
annual luminosity	L_{int}[fb^{-1}]	**57**	58	**300**

Luminosity Levelling

- For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time $\Rightarrow$ low efficiency.

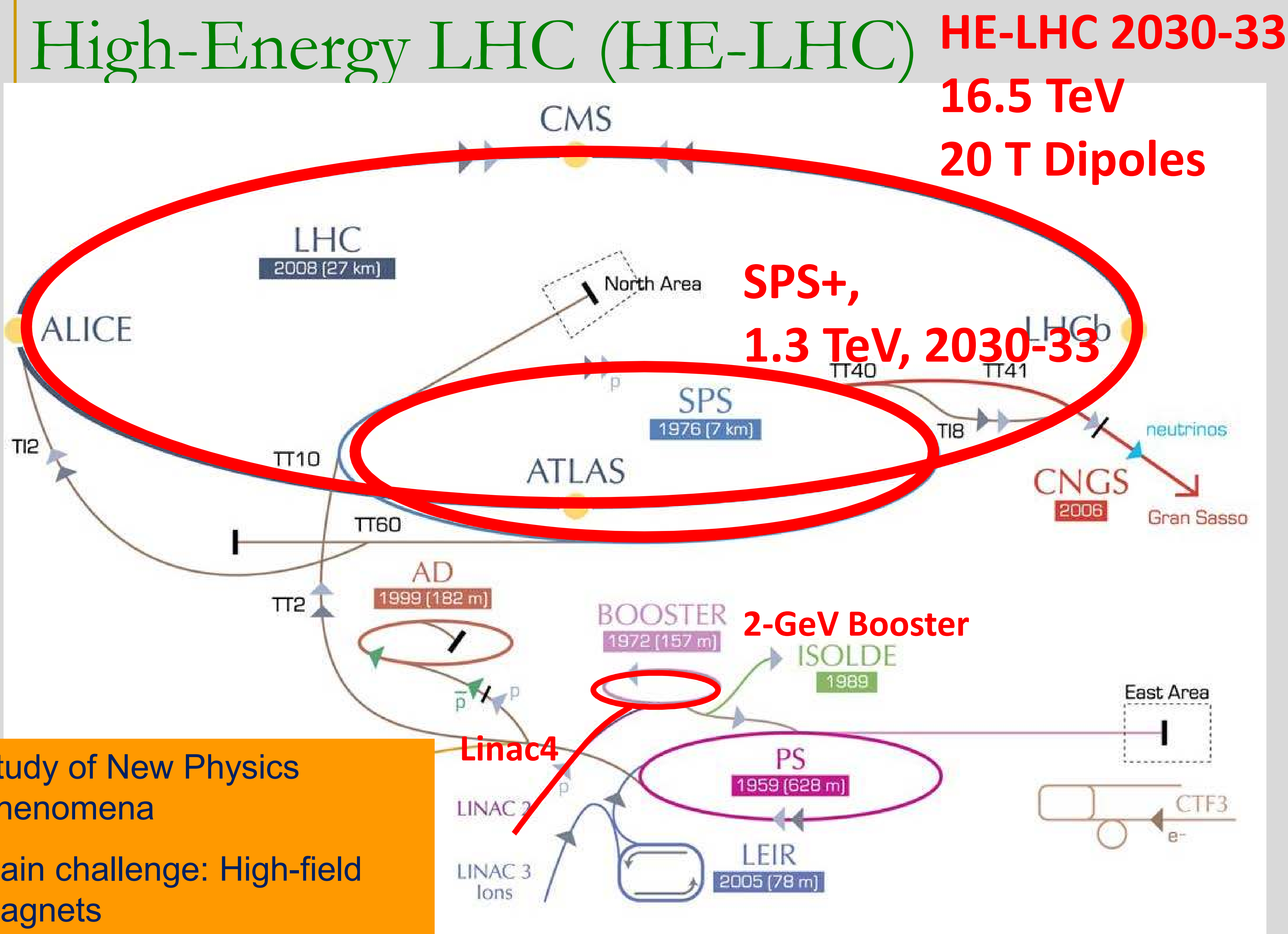
- Estimates show that the useful integrated luminosity is greater with a peak luminosity of 5×10^{34} cm^{-2} s^{-1} and luminosity levelling than with 10^{35} cm^{-2} s^{-1} and a luminosity lifetime of a few hours.

- Luminosity Levelling by
  - Beta*, crossing angle, crab cavities, and bunch length

Particle detector upgrade would become more complicated and expensive for a peak luminosity of 10^{35} due to

- Pile up events
- Radiation effects

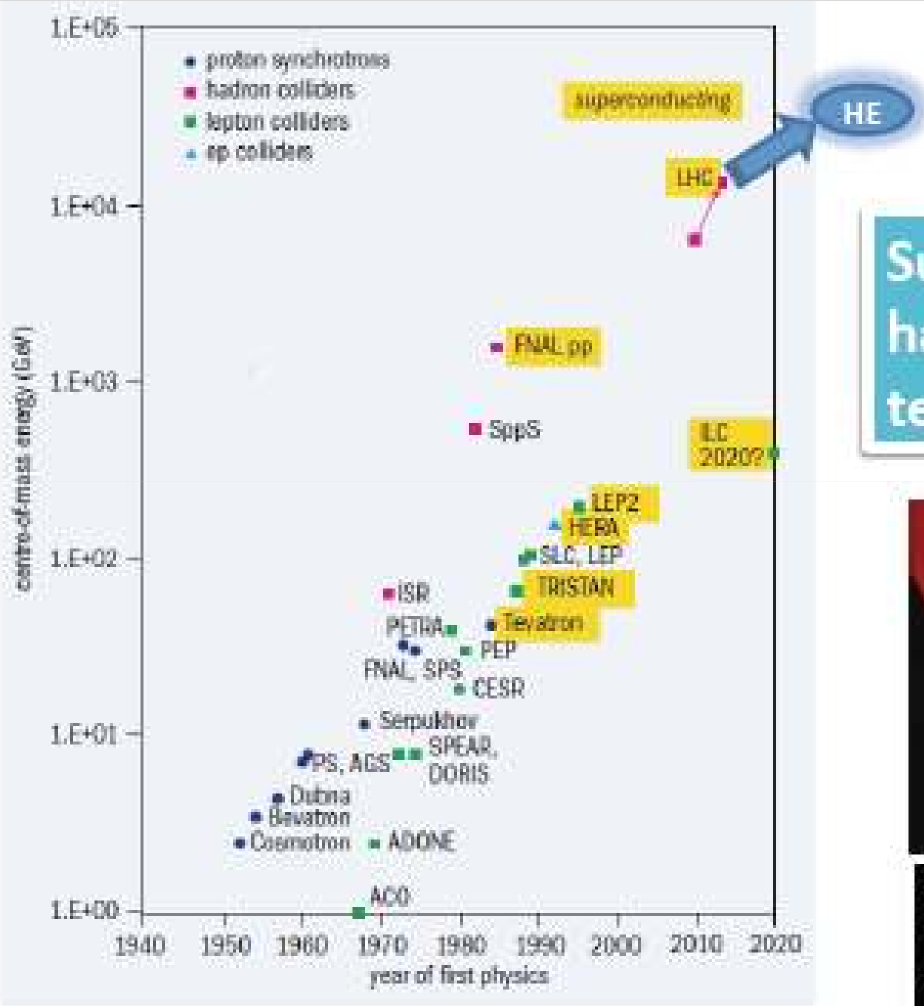
High-Energy LHC (HE-LHC)



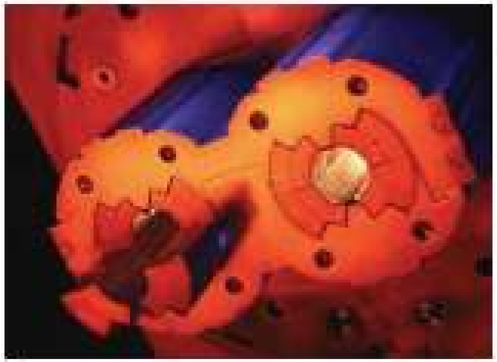
Study of New Physics Phenomena

Main challenge: High-field Magnets

Thirty Years of SC Accelerators

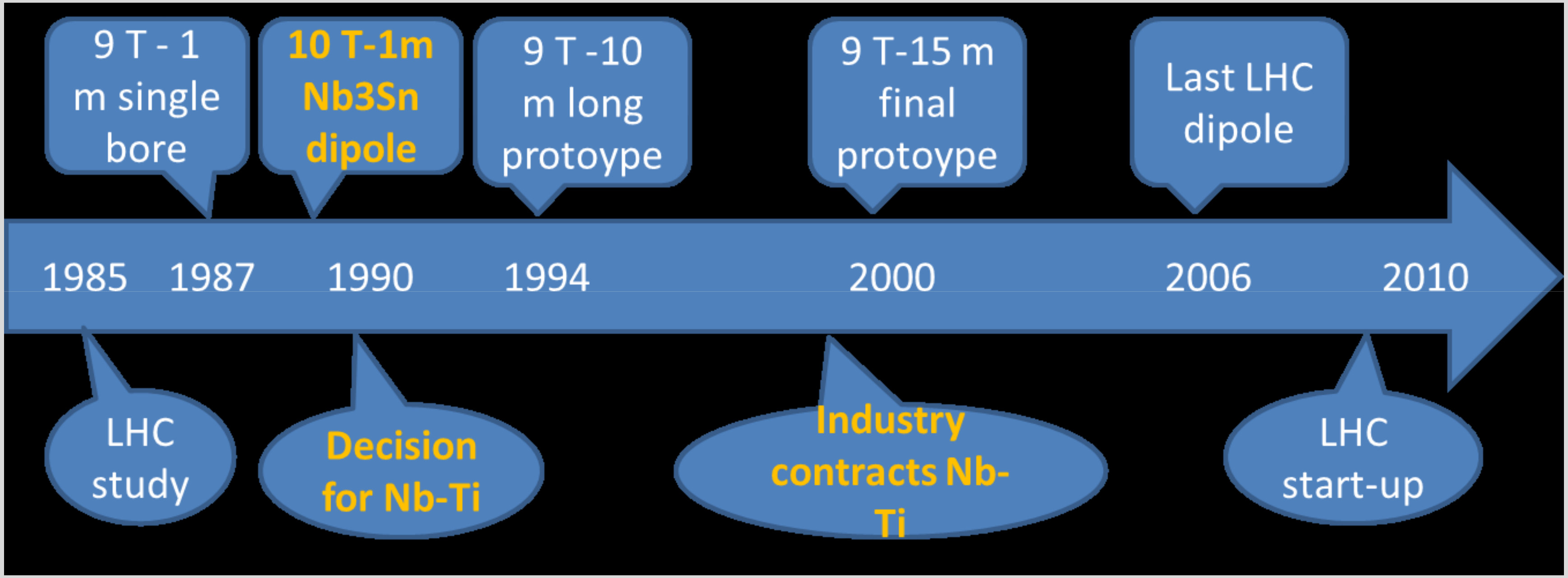


Superconductivity has been an enabling technology

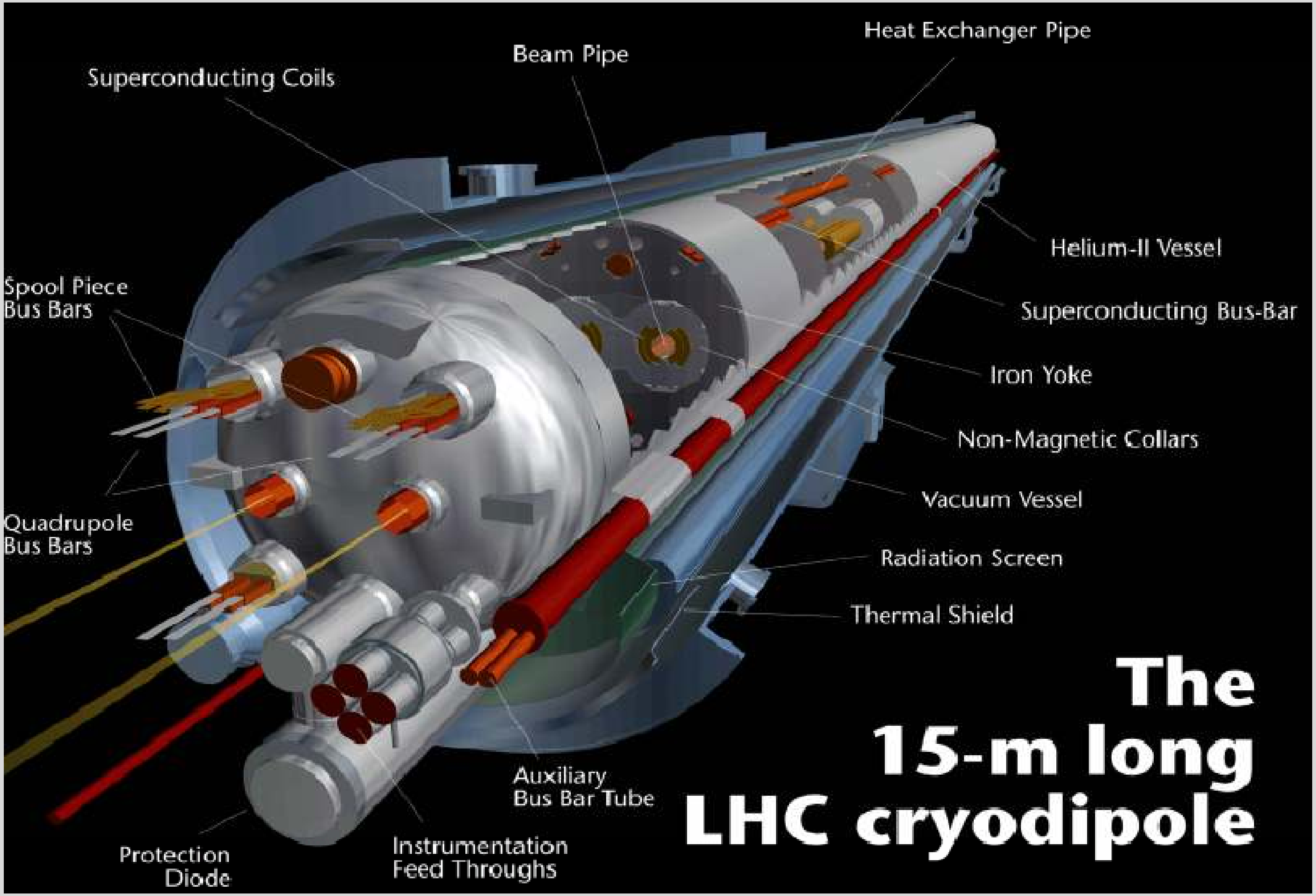


Without SC technology LHC would be 100 km long and 900 MW !

LHC – 25-year Project



LHC Main Bending Cryodipole



8.3 T
nominal field

12 kA
nominal field

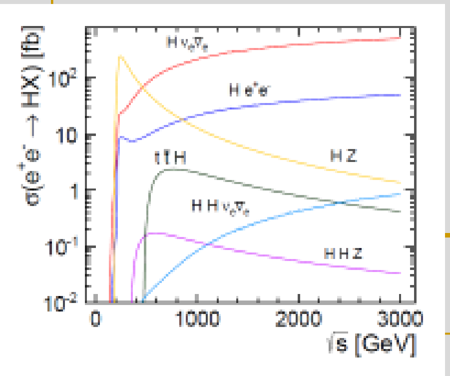
Beyond HE-LHC: New Tunnels 80-100 km Circumference

Very High Energy LHC (VHE-LHC)

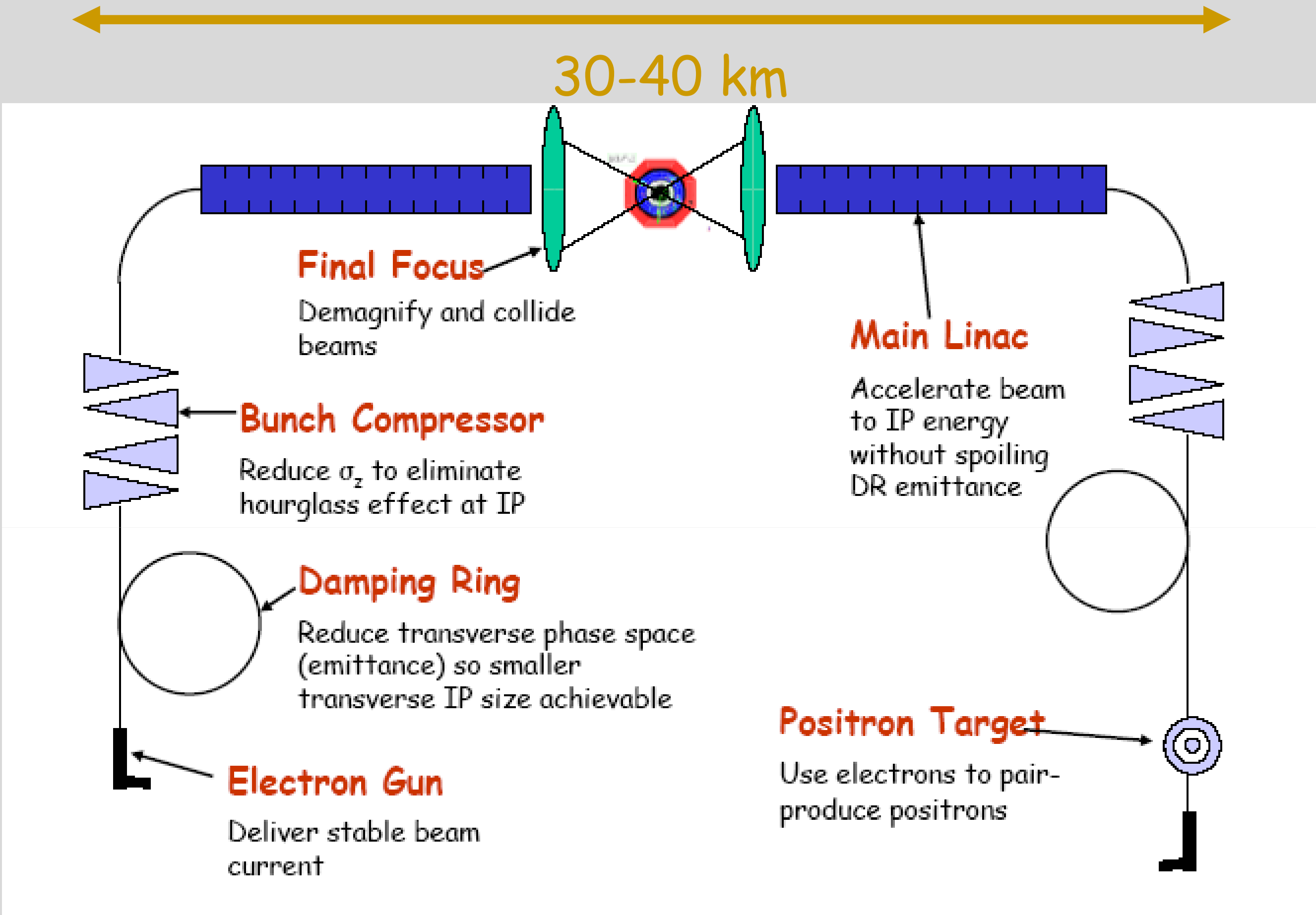
Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)

HIGGS FACTORIES e+e-

- **e+ e-**
  - **Linear Colliders**
    - **ILC**
      - 250 GeV
      - 500 GeV
    - **CLIC**
      - 250 GeV + Klystron based
      - 500 GeV
      - > 500 GeV
  - **Circular Colliders**
    - **CERN**
      - LEP3 at LHC tunnel
      - DLEP – New tunnel, 53 km
      - TLEP – New tunnel, 80 km
    - **Super TRISTAN**
      - 250 GeV– 40, 60 km tunnel
      - 400 GeV
      - 500 GeV

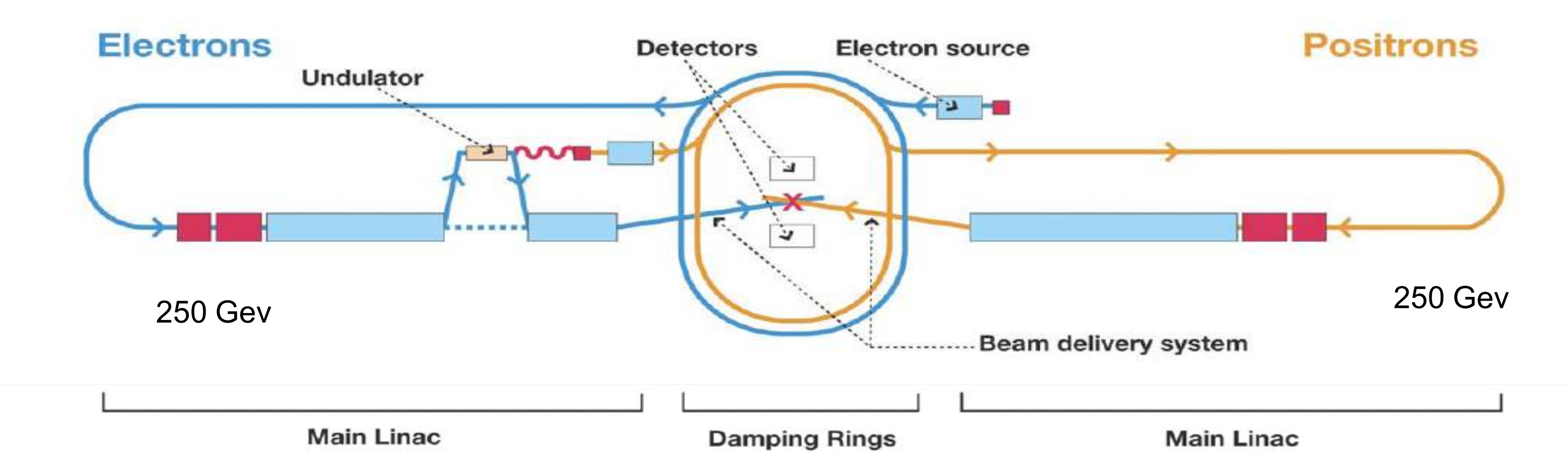


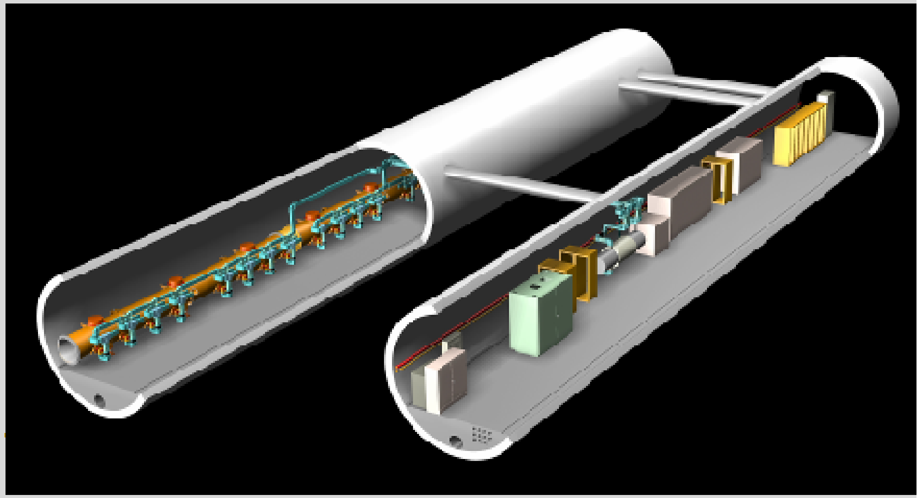
A Generic Linear Collider



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

International Linear Collider Baseline Design

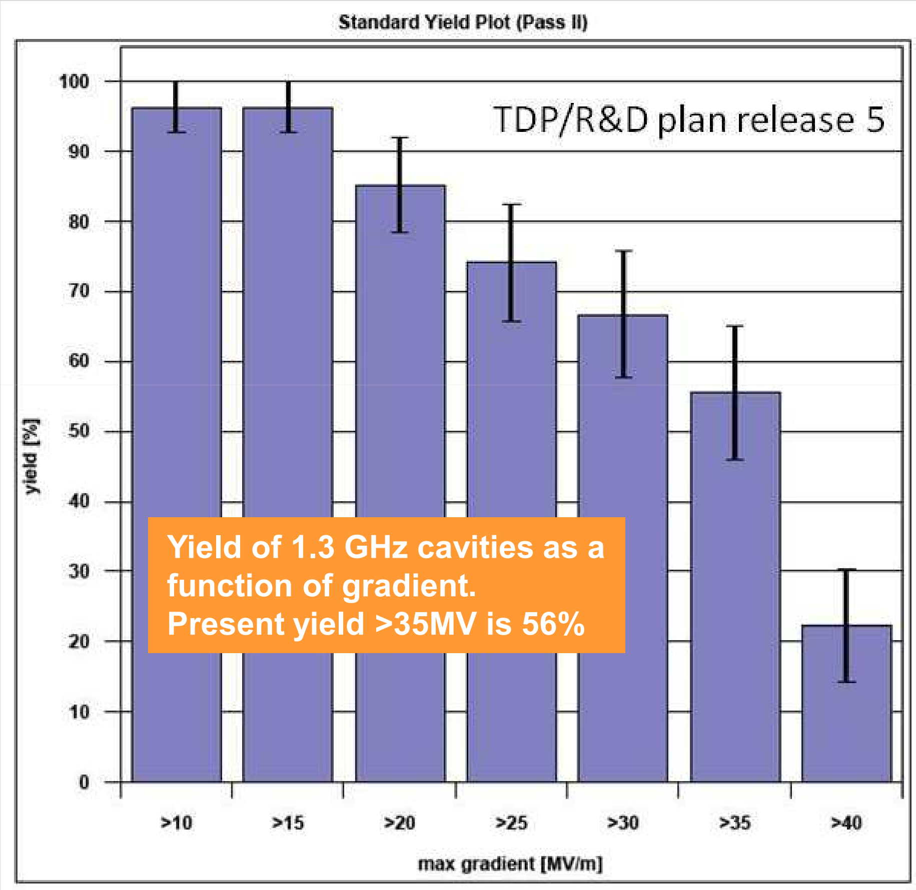




e+ e- Linear Collider

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 : σ_x 350 – 620 nm; σ_y 3.5 – 9.0 nm	
Total power	~230 MW
Accelerating Gradient	31.5 MeV/m

Global Effort on ILC R&D



First world-wide coordinated effort under ICFA for R&D, with strengths in all regions

CLIC Conceptual Design

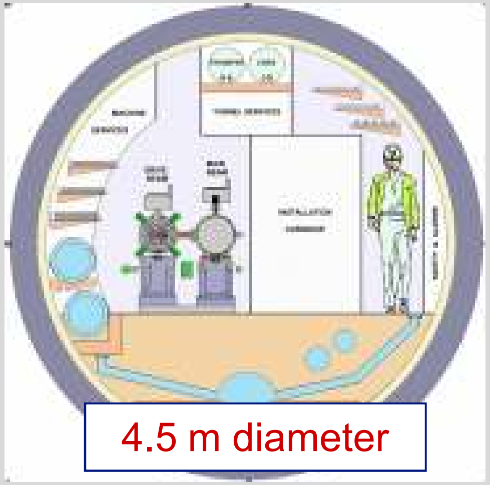
- Site independent feasibility study aiming at the development of the technologies needed to extend e+ / e- linear colliders into the multi-TeV energy range.
  - E_{cm} range complementary to that of the LHC & ILC
    - $E_{cm} = 0.5 – 3$ TeV
  - $L >$ few 10^{34} cm^{-2} s^{-1} with low machine-induced background
  - Minimise power consumption and costs

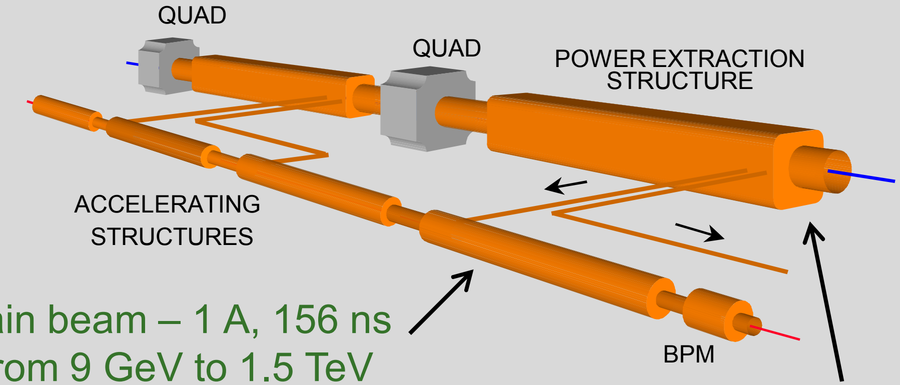
Basic Features

- **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





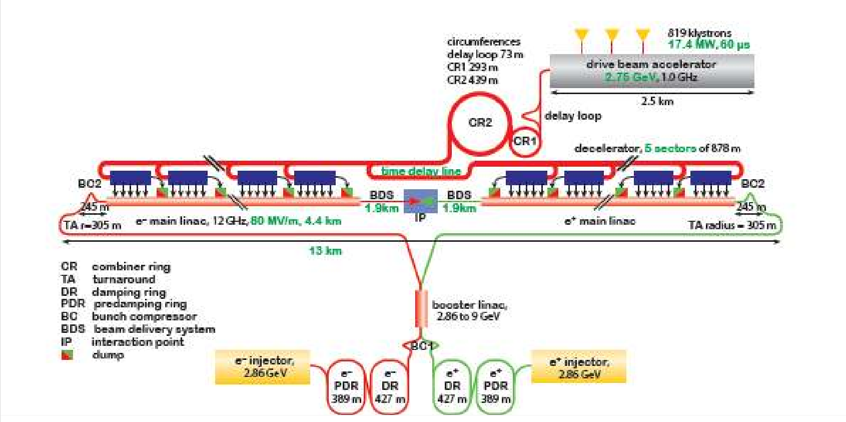
Main beam – 1 A, 156 ns from 9 GeV to 1.5 TeV 100 MV/m

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

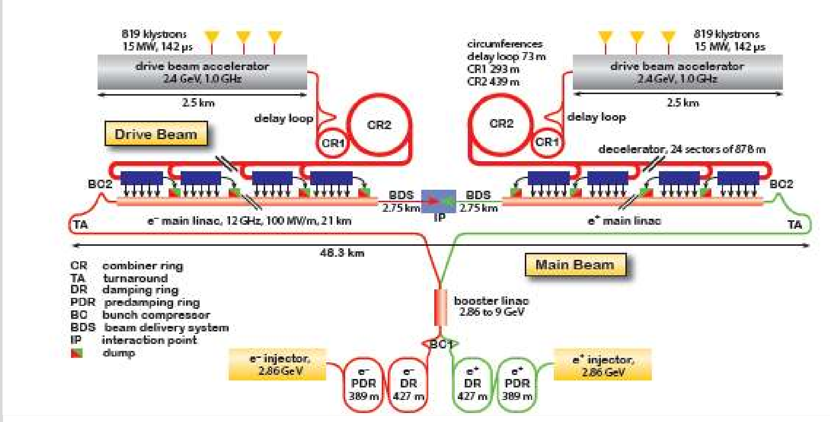
12 GHz – 64 MW

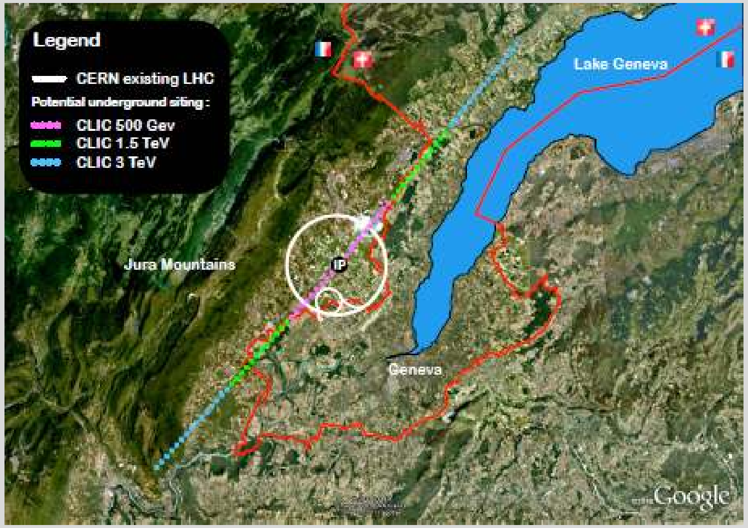
Proposed CLIC Lay-outs

Centre-of-mass energy 500 GeV



Centre-of-mass energy 3 TeV



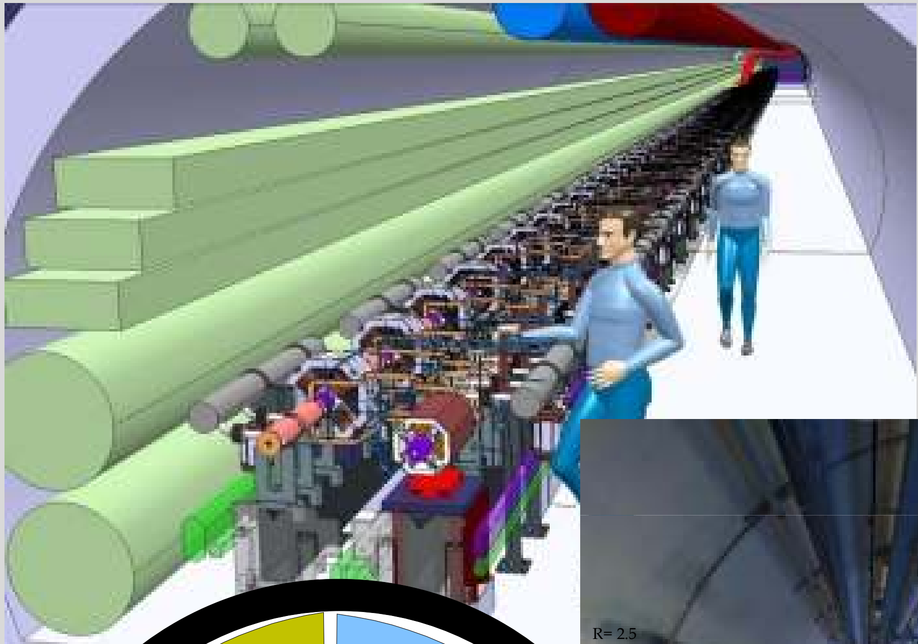


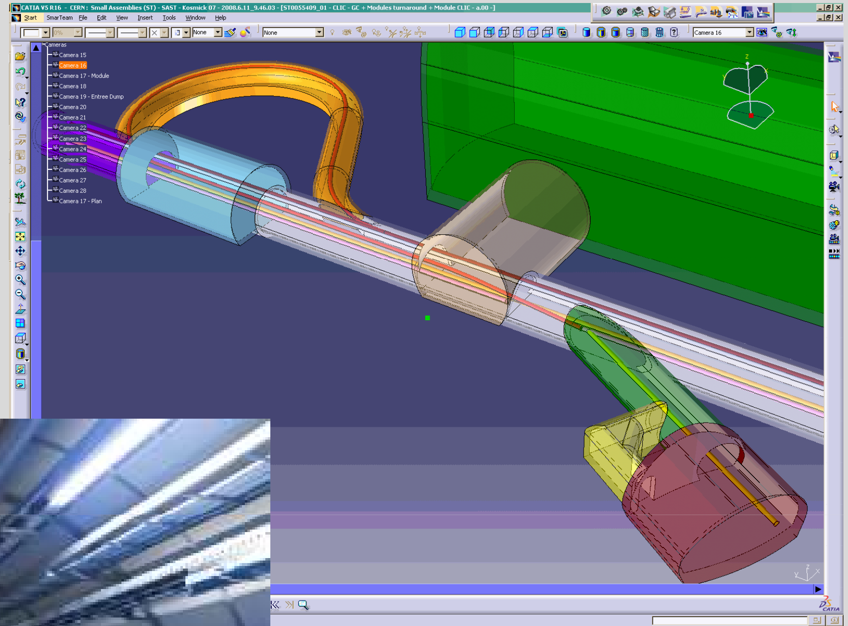
CLIC footprints near CERN

CLIC Parameters

Center-of-mass energy	3 TeV
Peak Luminosity	$7 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	41.7 km
Bunch charge	$4 \cdot 10^{9}$
Beam pulse length	200 ns
Average current in pulse	1 A
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size bef. pinch	53 / ~1 nm
Total site length	48.25 km
Total power consumption	390 MW

Tunnel Integration

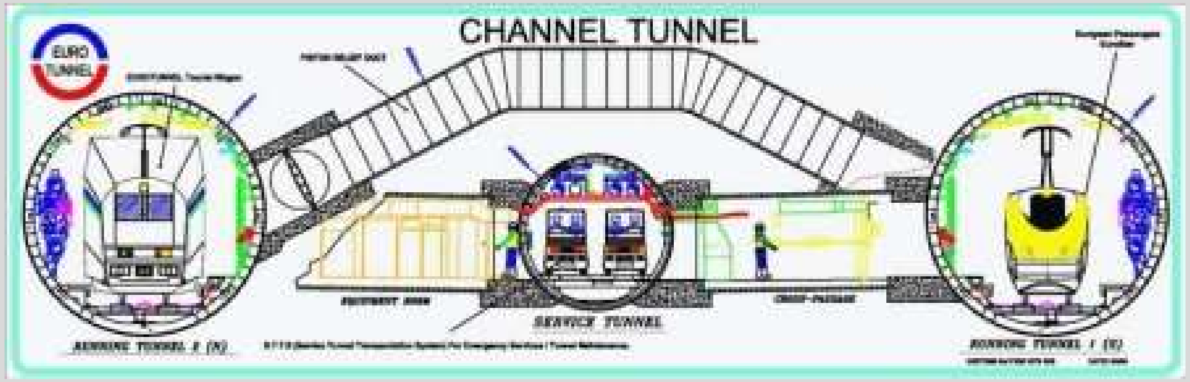




(Courtesy John Osborne)

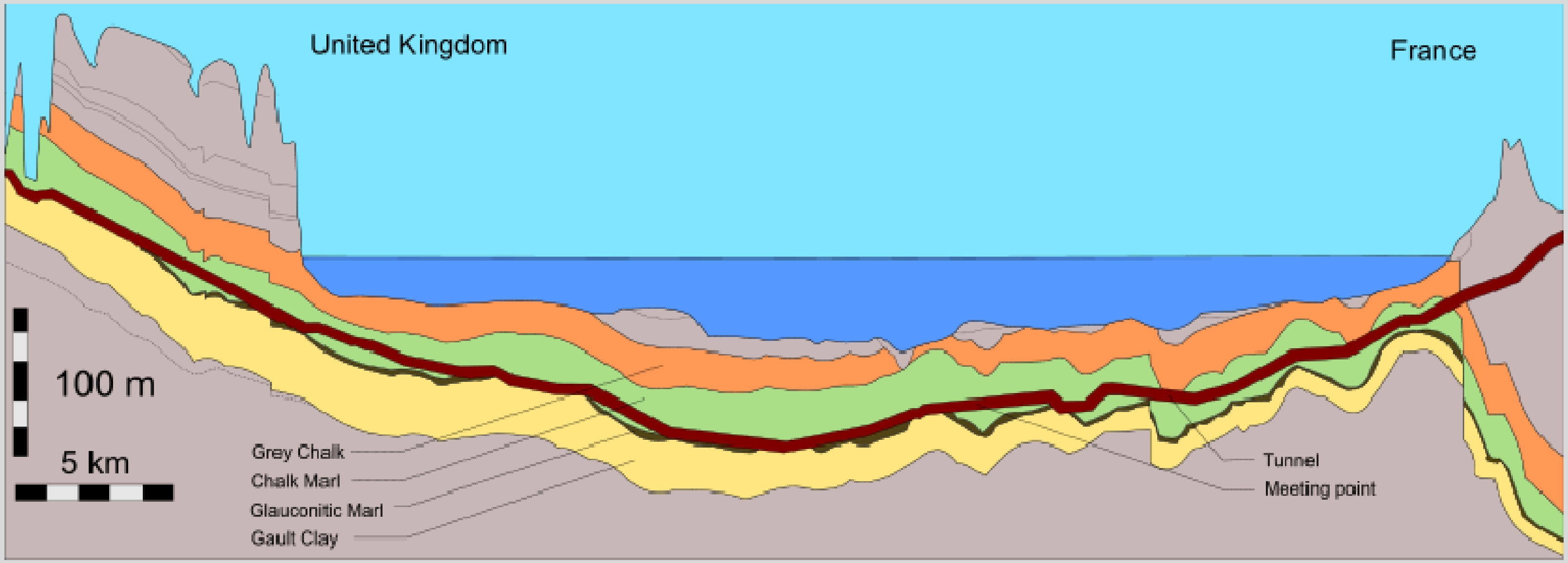
Standard tunnel with modules

For CLIC & ILC - Similar World Projects: Channel Tunnel

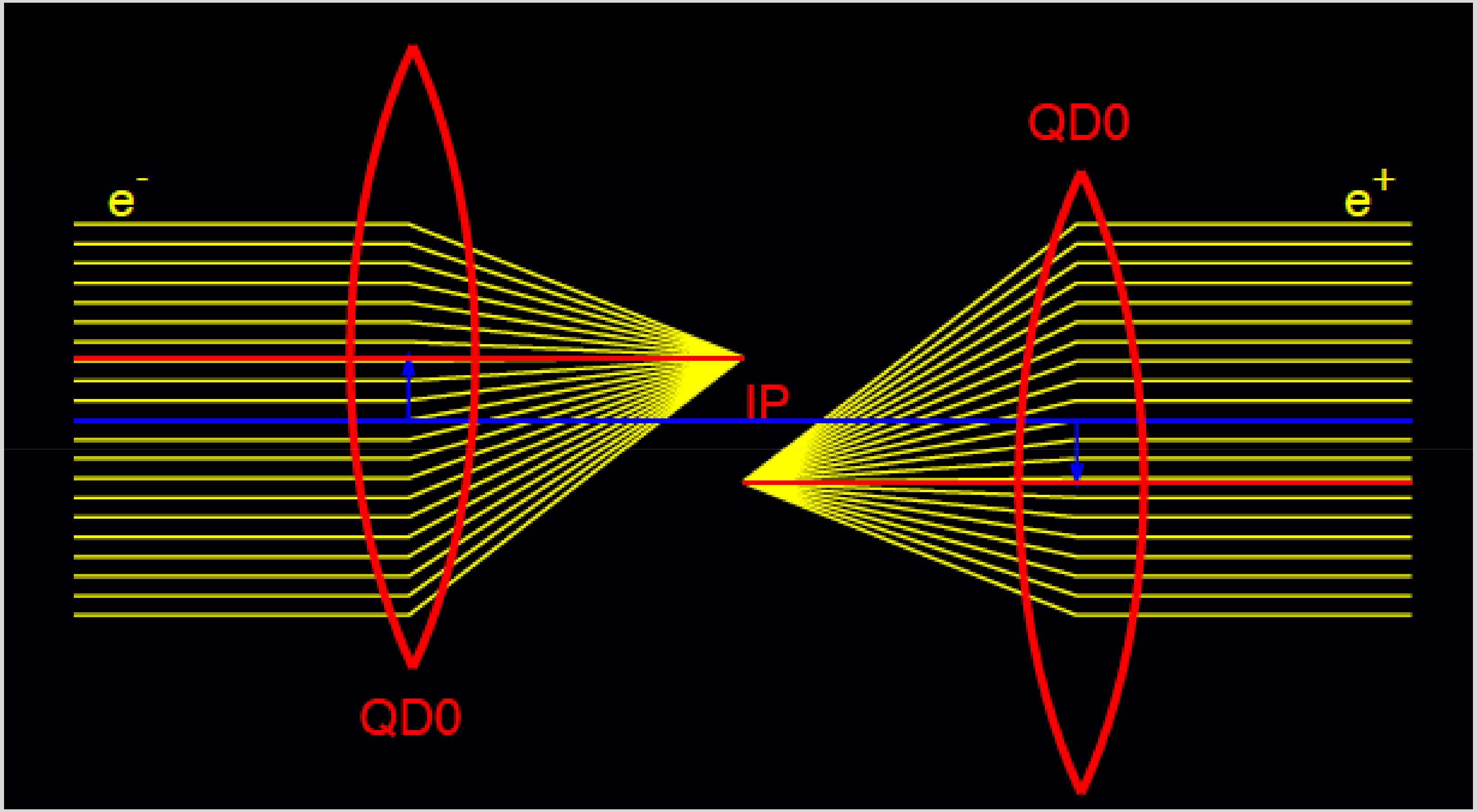


7.6mØ 4.8m Ø 7.6mØ

50Km

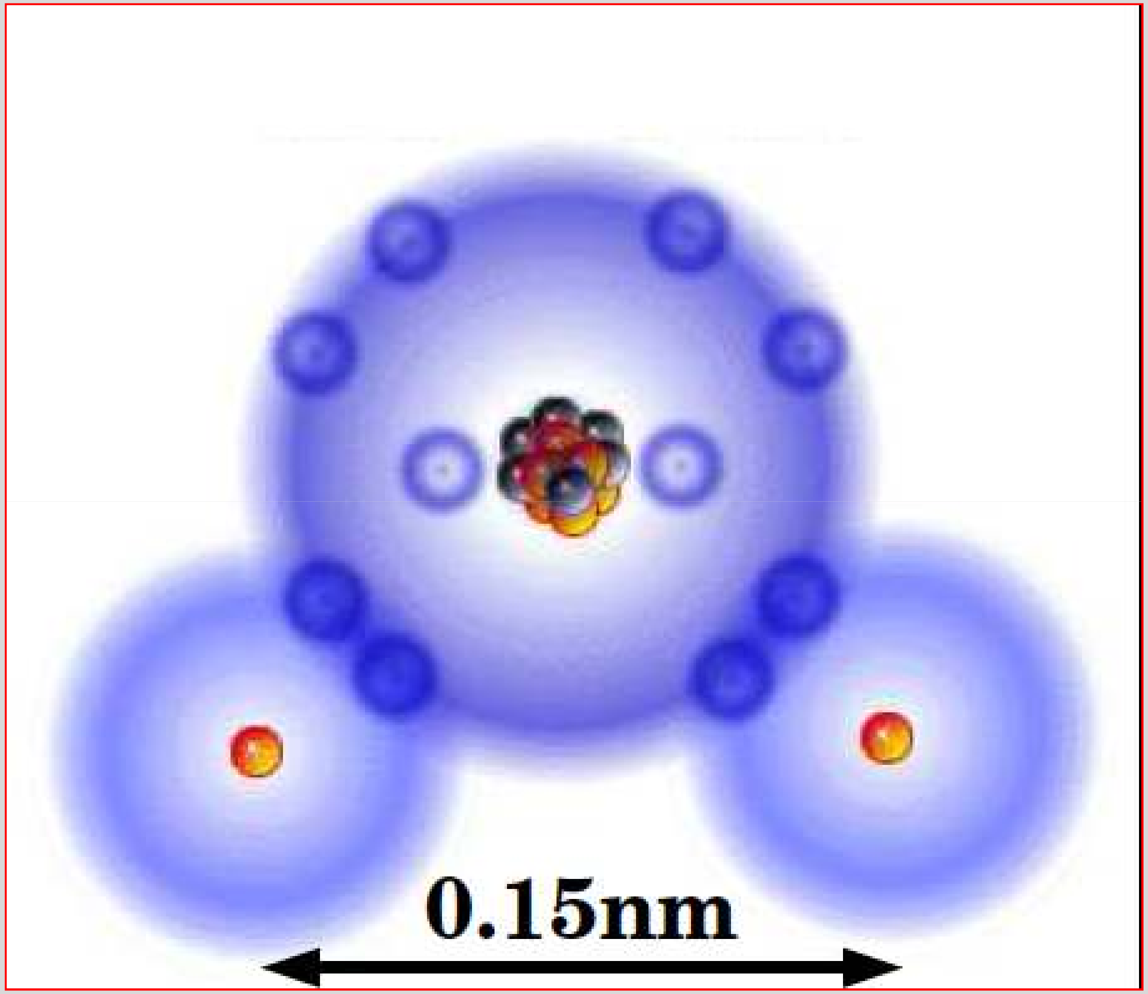


Other Technological Challenges



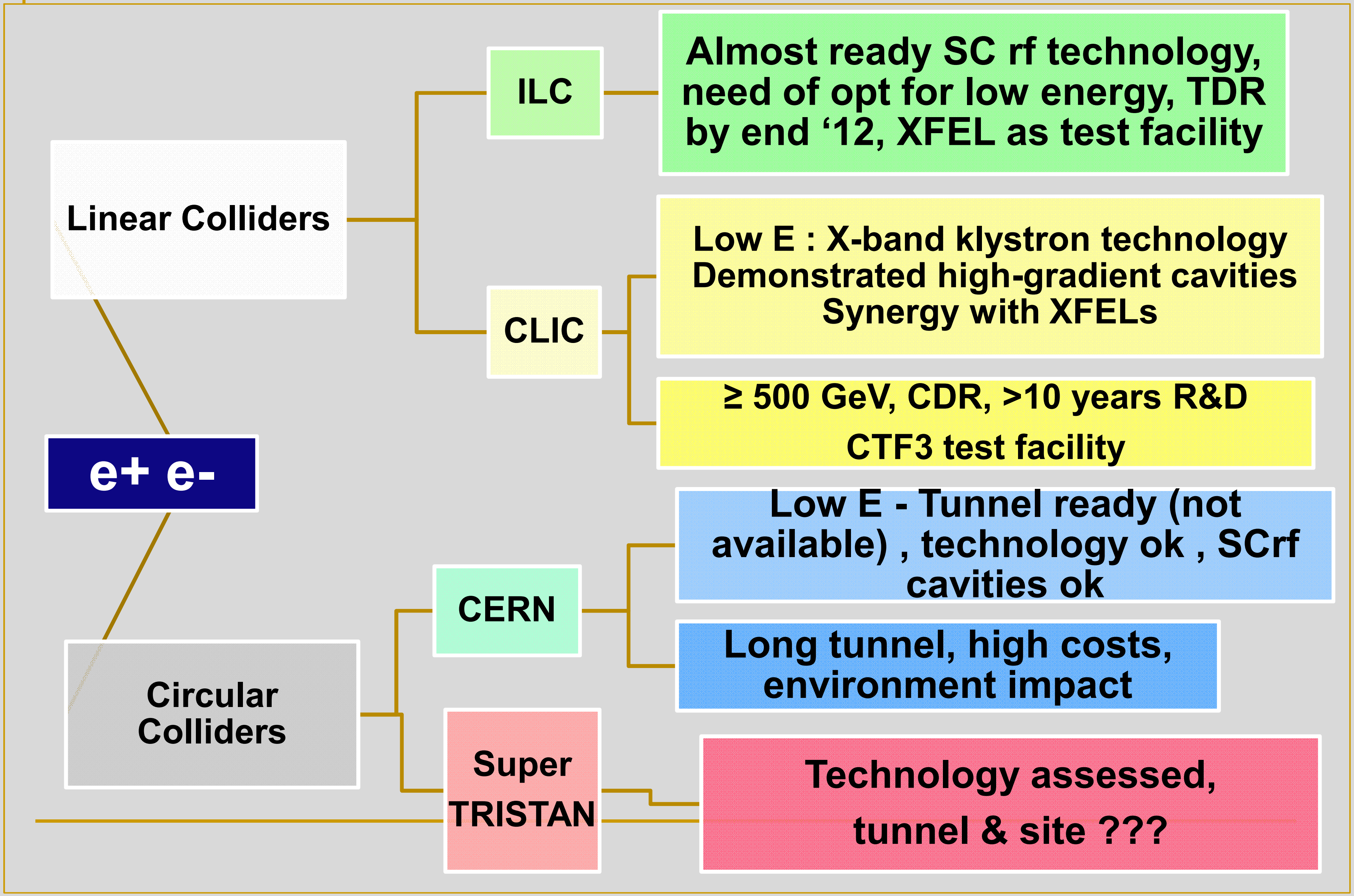
The final focusing quadruple should be stabilized to 0.15 nm
for frequencies about 4 Hz

Other Technological Challenges



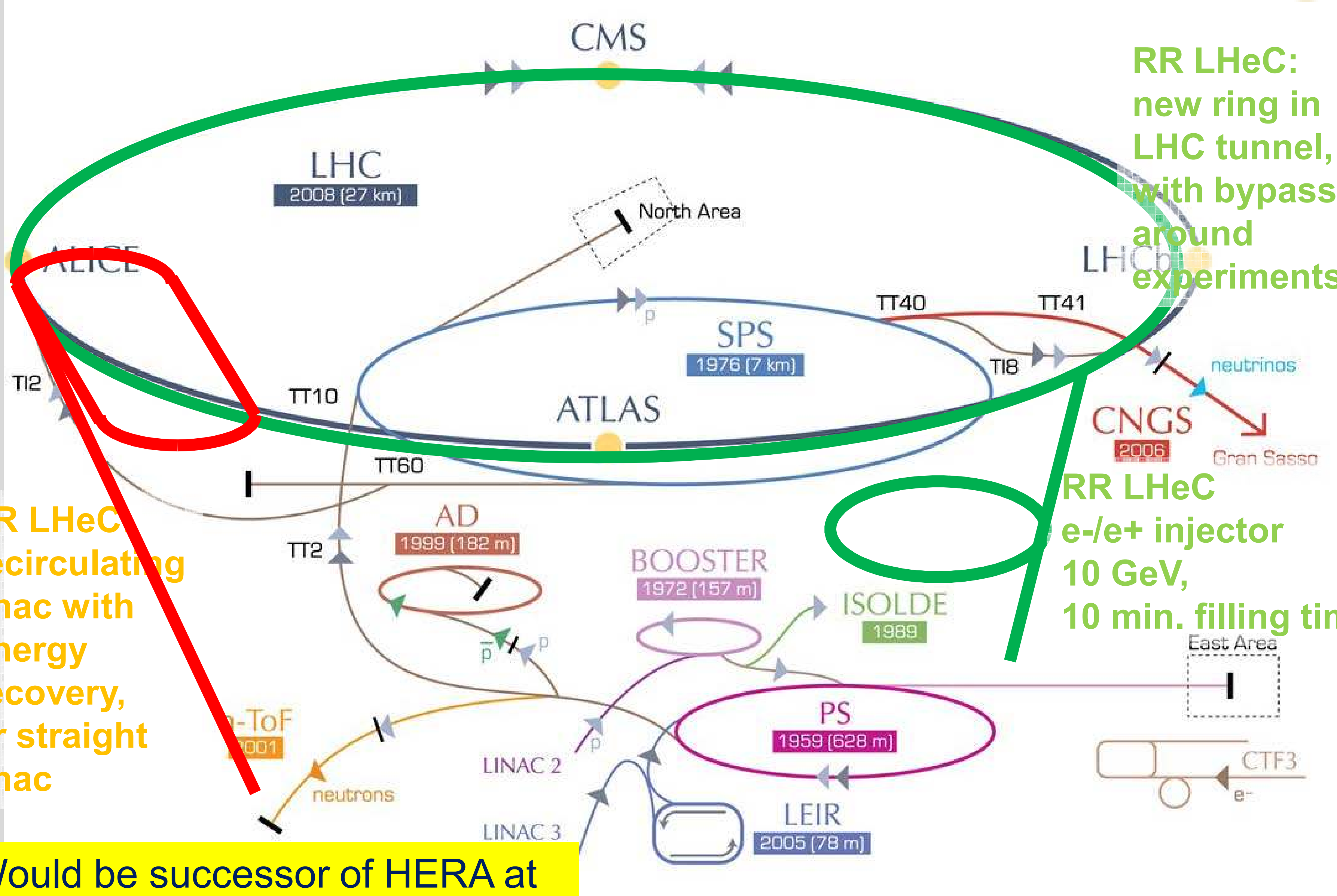
0.15 nm, small as a H_20 molecule !

HIGGS FACTORIES e+e- R&D & Main Issues



QCD, Leptoquarks?

LHeC options: RR and LR



RR LHeC:
new ring in LHC tunnel, with bypasses around experiments

RR LHeC
e-/e+ injector
10 GeV,
10 min. filling time

LR LHeC:
recirculating linac with energy recovery, or straight linac

Would be successor of HERA at higher centre-of-mass energy

Key Messages

- All projects need continuing accelerator and detector R&D
- All projects need continuing attention concerning a convincing physics case
  - Close collaboration experiment and theory is mandatory
- So that community is ready to make right decision when the time comes to identify the next energy frontier accelerator (collider)

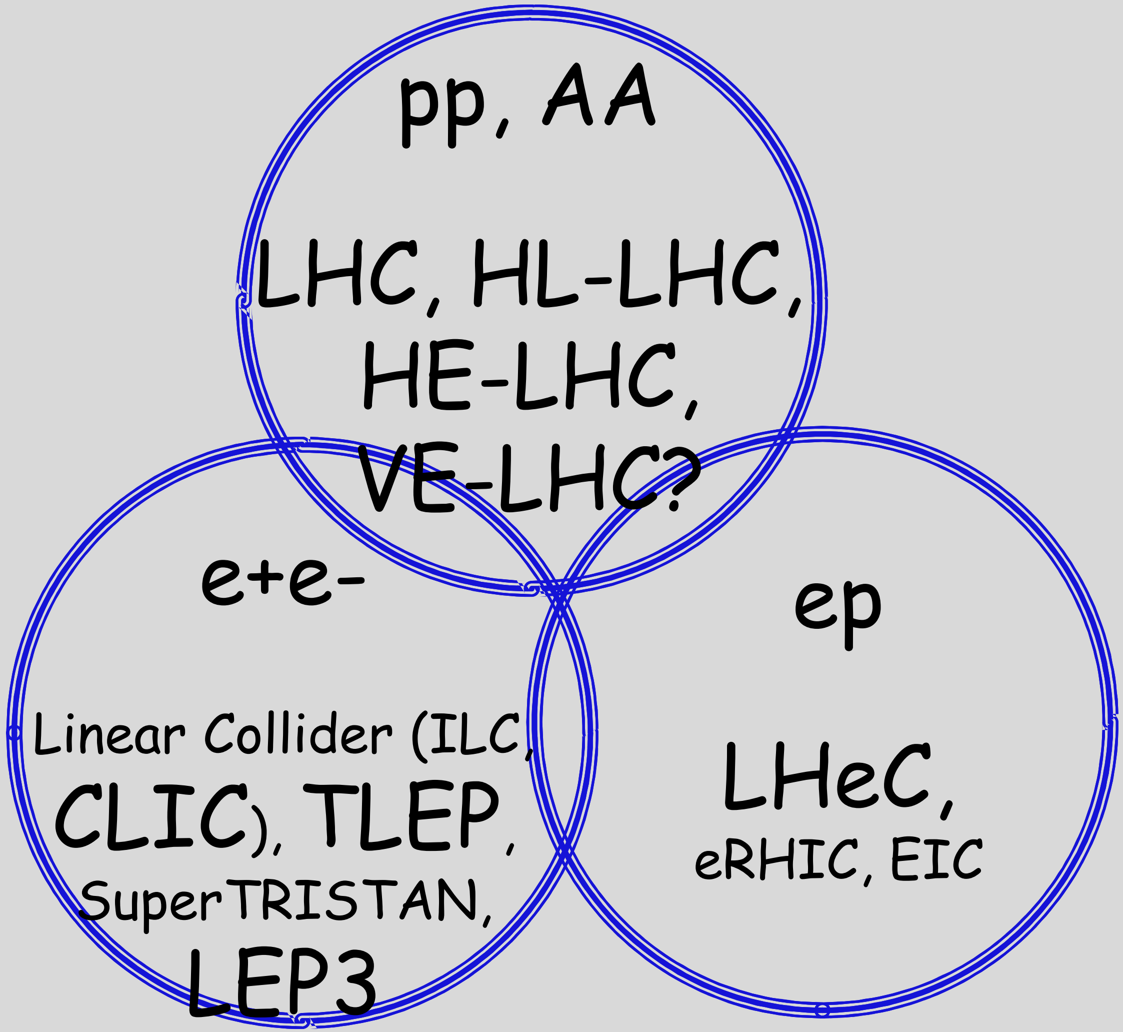
Today, we need to keep our choices open. The way forward –

- **Physics results from the LHC.**
- **Update of the European Strategy for Particle Physics (2012-2013).**

European Strategy for Particle Physics Updated May 2013

- Europe's top priority should be exploitation of full LHC potential, including the high-luminosity upgrade of the machine & detectors with view to collecting ten times more data than in initial design.
  - LHC and HL-LHC
- CERN should undertake design studies for accelerator projects in global context, with emphasis on proton-proton & electron-positron high-energy frontier machines.
  - HE-LHC, VHE-LHC, CLIC, ILC, TLEP, …
- There is strong scientific case for an electron-positron collider, complementary to the LHC, that can study properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.
  - ILC & synergy with CLIC
- Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.
  - SPS North Area at CERN could be equipped with a neutrino beam for an experiment and/or dedicated detector test facility.

THE SUB-FERMI SCALE (2010-2040)?



Summary

- Highest priority of the particle physics community is to fully exploit the physics potential of the LHC.
- The current European Strategy for Particle Physics incorporates a number of new accelerator projects for the future. (Update in progress)
  - The need to renovate the LHC injectors is recognised and relevant projects/studies have been authorised.
  - The main motivation to upgrade the luminosity (HL-LHC) & energy (HE-LHC) of LHC is to explore further the physics beyond the Standard Model while at the same time completing the Standard Model physics started at LHC.
- Further down the line, many of the open questions from the LHC could also be addressed by:
  - An electron-positron collider (ILC or CLIC)
  - New studies – 80 km hadron / lepton collider – VHE-LHC, TLEP
  - (A hadron-electron collider LHeC is also under design)
- These new initiatives will lead particle physics well into the next decades of fundamental research.