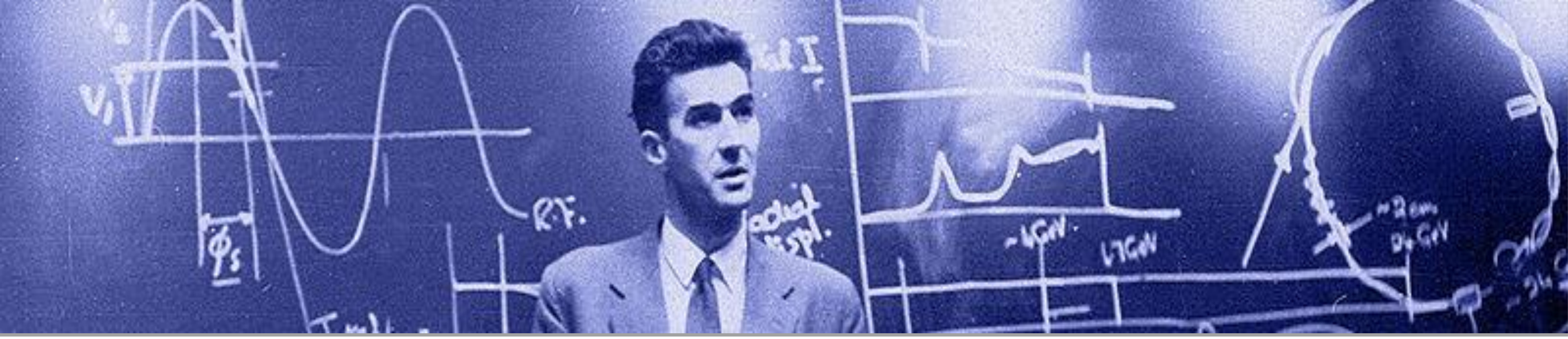
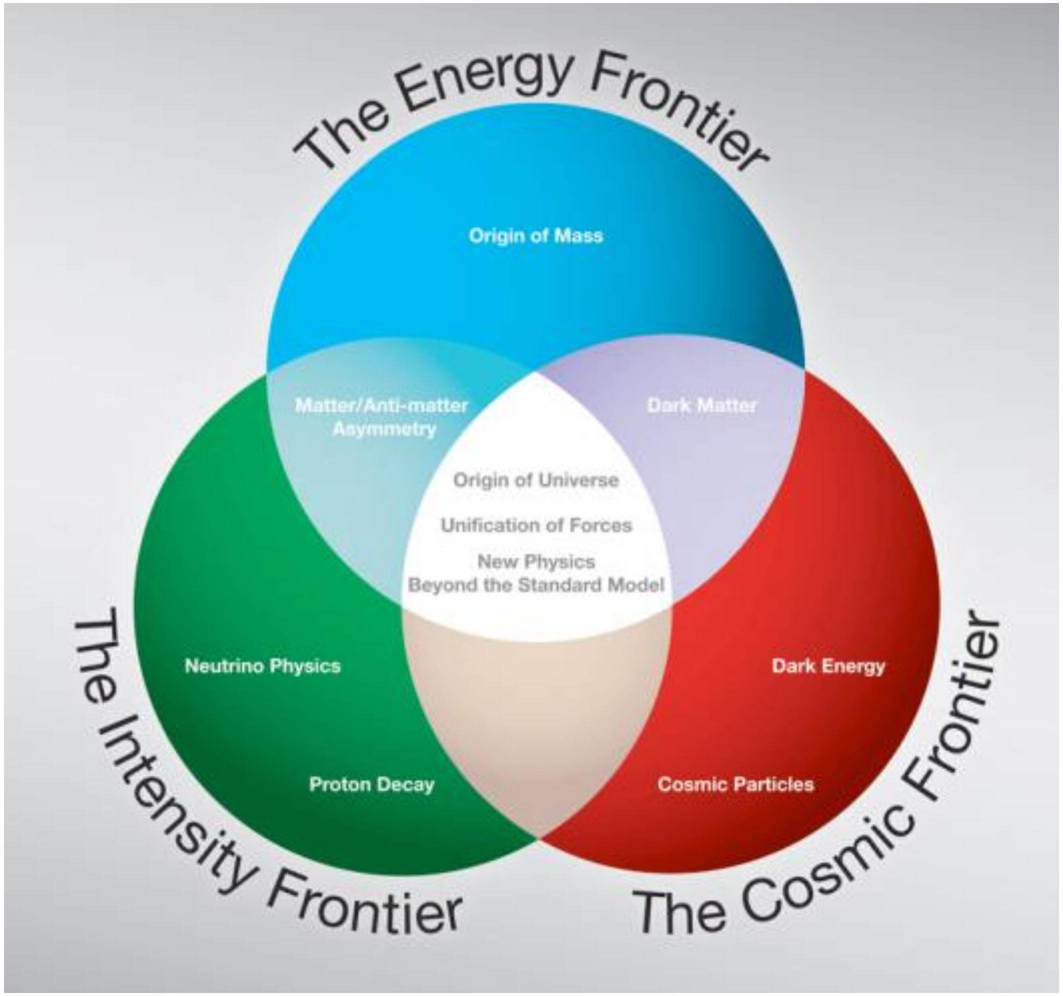


CERN and the High Energy Frontier

Emmanuel Tsesmelis
CERN Directorate-General Unit & JAI University of Oxford

JAI Octoberfest 2014
Royal Holloway, University London
3 October 2014

The Three Frontiers



European Strategy for Particle Physics May 2013 High-priority Large-scale Scientific Activities

- After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority:
  - *The LHC and its Upgrades*
  - *Post-LHC Accelerators*
  - *The International Linear Collider*
  - *(Neutrino Oscillation Physics)*

Consistent with
Building for Discovery - Strategic Plan for U.S. Particle Physics in the Global Context
Report of the Particle Physics Project Prioritization Plan (P5), May 2014

The LHC and its Upgrades

- The discovery of the Higgs boson is the start of a major programme of work to measure the particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier.

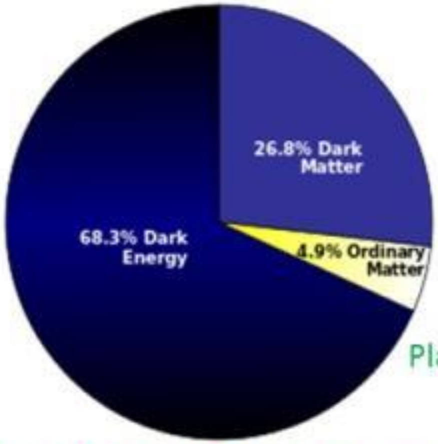
  - *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and the detectors with a view of collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

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 Higgs boson discovery is only the beginning! *What's next?*

- Is it ***the*** Higgs boson…or one of many?
- Measure with precision the properties of the discovered Higgs boson
  - …its properties could give information on Dark Matter
  - …its properties could give first indications on Dark Energy



Planck Space Observatory, ESA (2013)

Our understanding of the Universe is changing!

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}

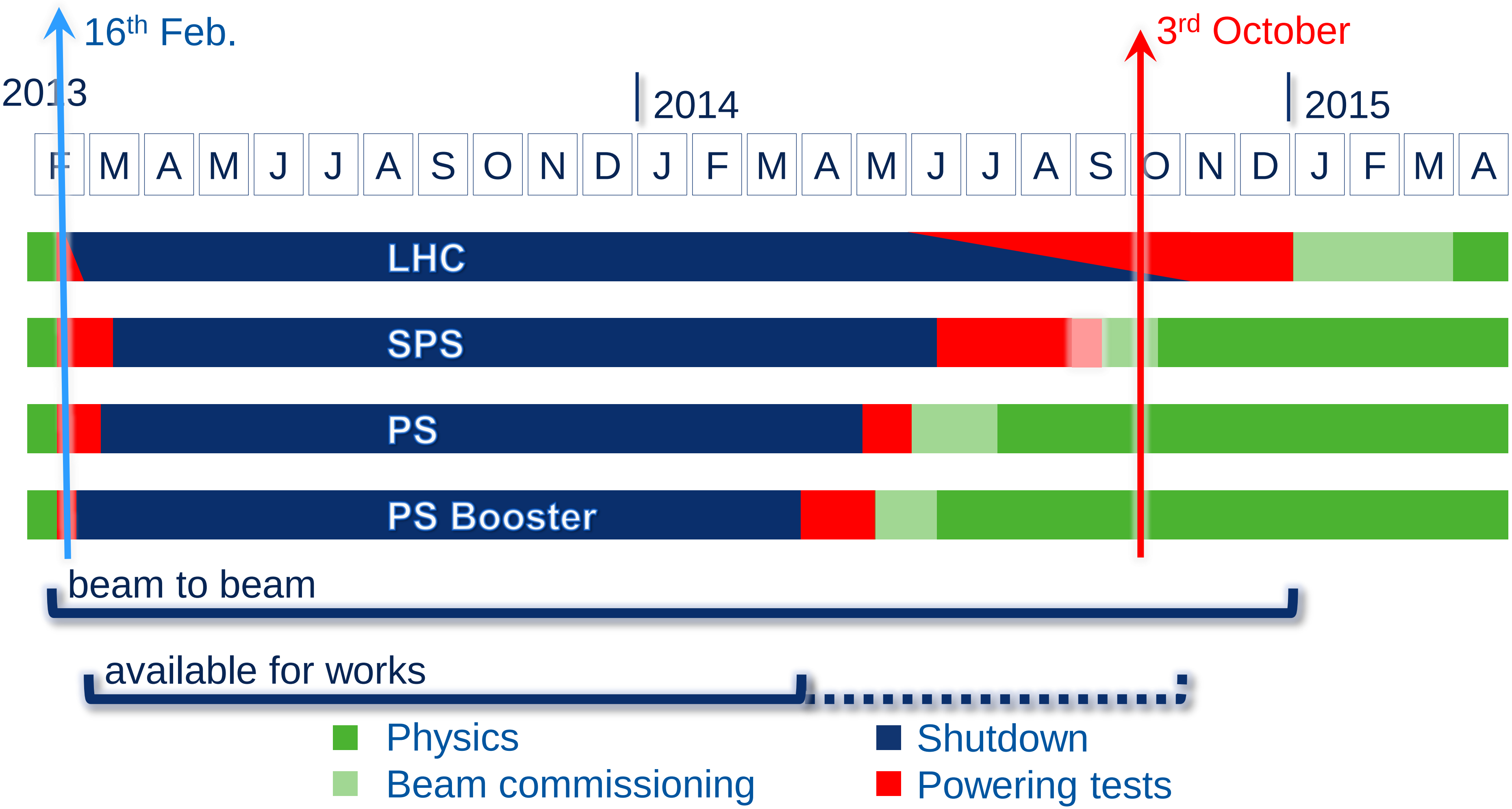
>2035

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
  - Many projects (LINAC4, HIE-ISOLDE, ELENA, nTOF EAR-2, LIU, HL-LHC, ….)

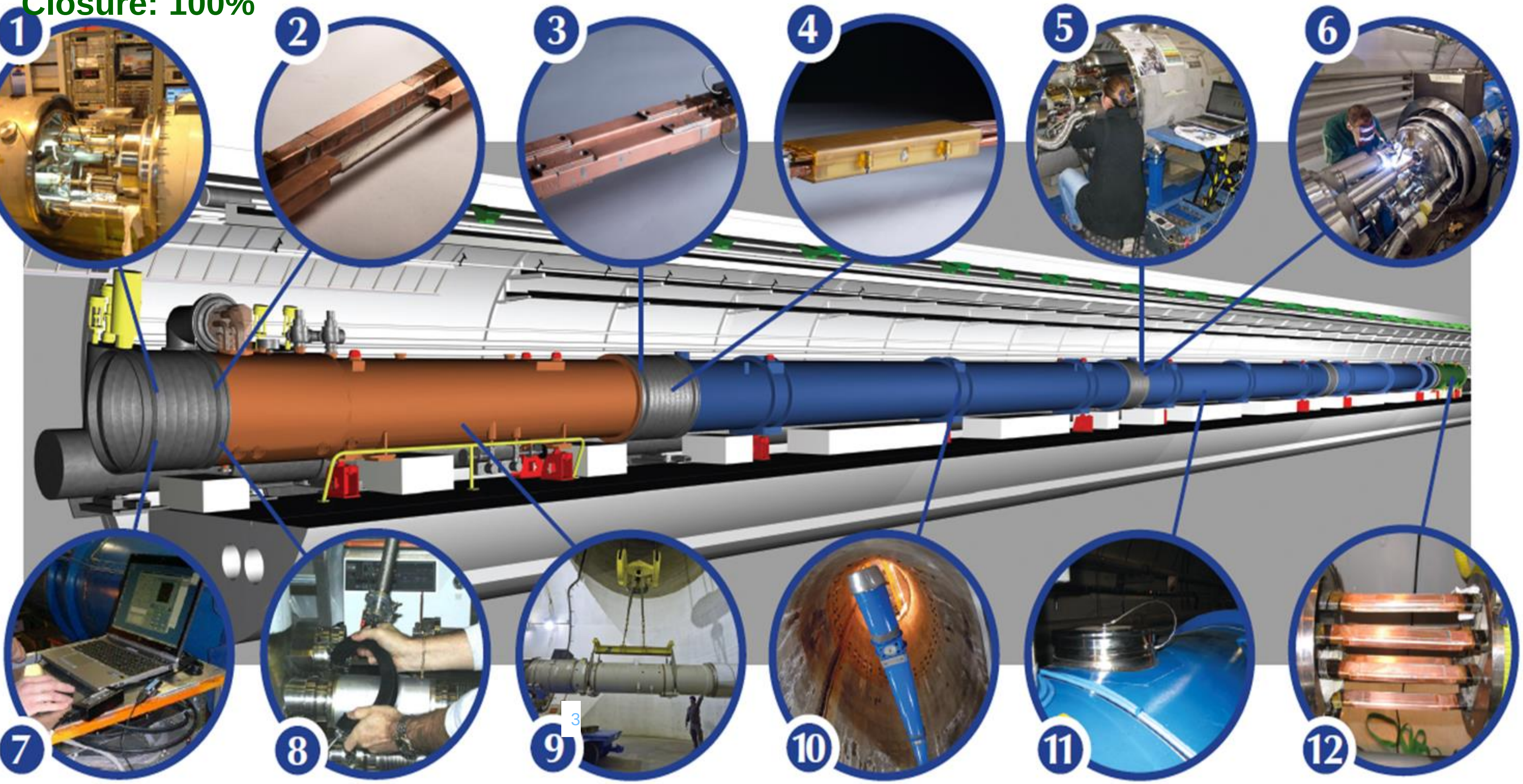
- Compared to previous shutdowns, an exceptional number of:
  - Simultaneous activities (co-activities) – Planning & safety
  - Non-CERN workers (FSU, collaborations, contracts,…) Logistics: Registration, training, transport, parking, access, dosimeter, PPE, catering, accommodation,…)

LS1 from 16th Feb. 2013 to Dec. 2014



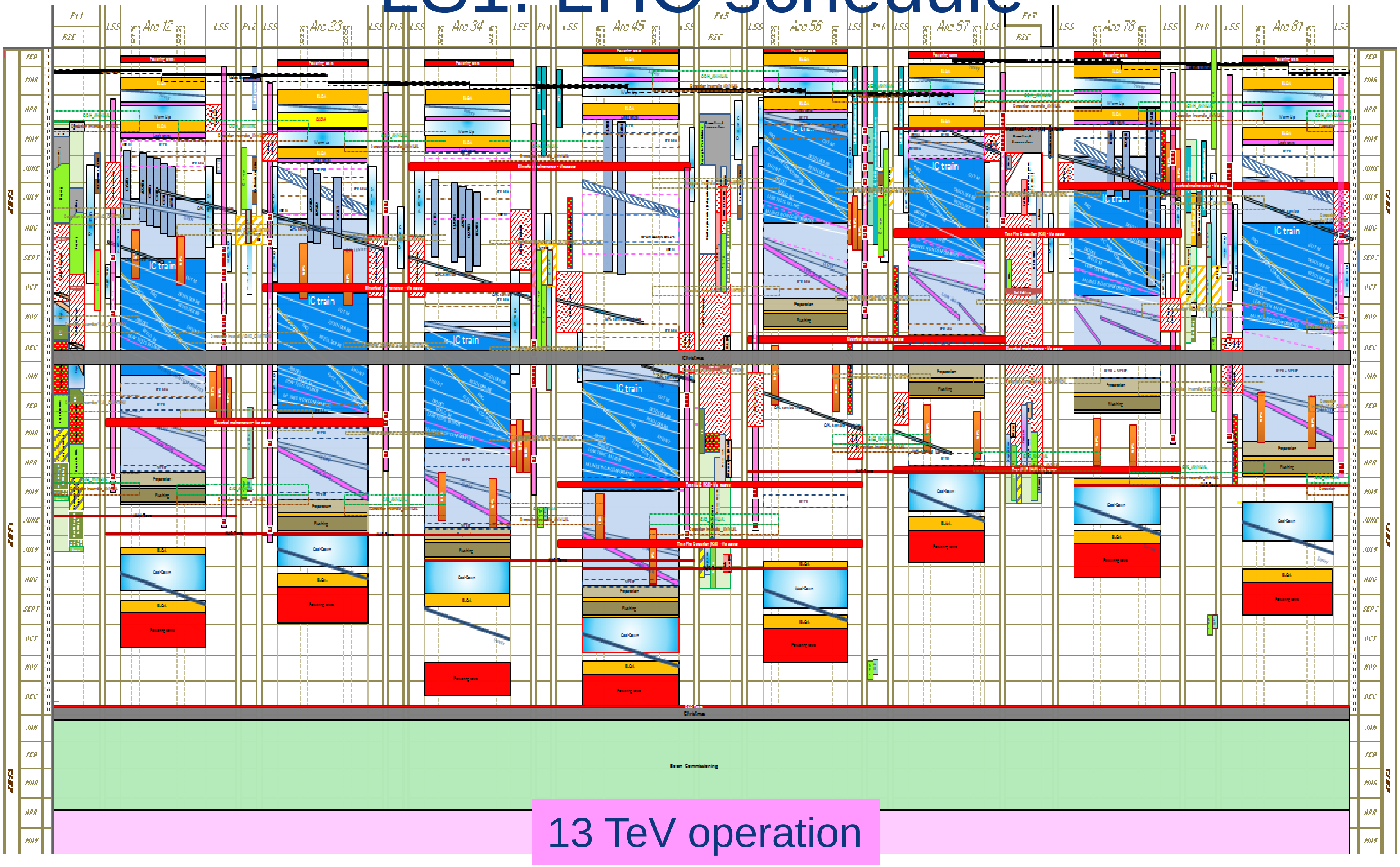
The main 2013-14 LHC consolidations

1. **Opening:100%** — 1695 Openings and final reclosures of the interconnections — **Closure: 100%**
2. **100 % done** — Complete reconstruction of 3000 of these splices
3. **100 % done** — Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. **100 % done** — Installation of 5000 consolidated electrical insulation systems
5. **100 % done** — 300 000 electrical resistance measurements
6. **100 % done** — 10170 orbital welding of stainless steel lines



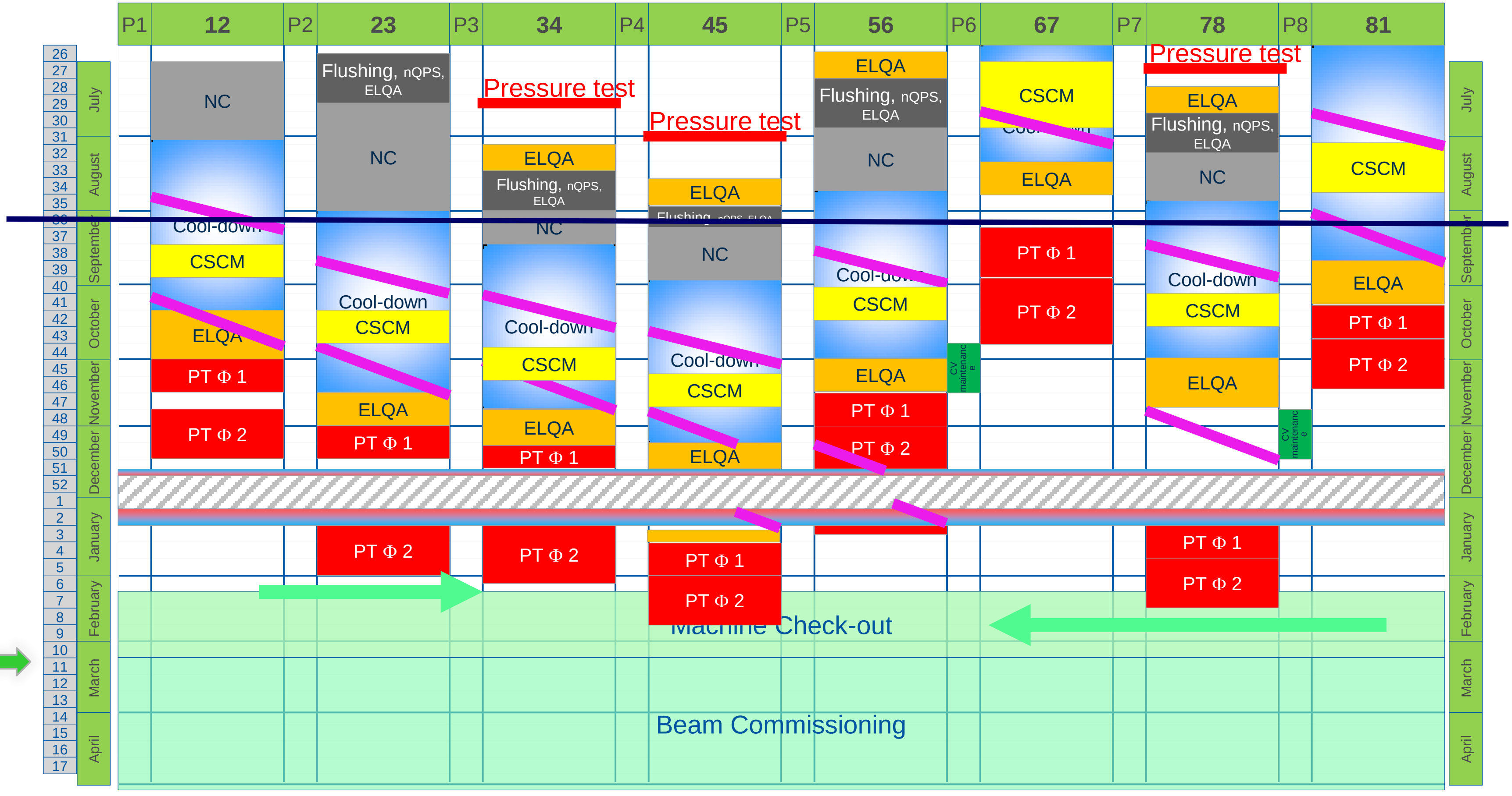
7. **100 % done** — 18 000 electrical Quality Assurance tests
8. **100 % done** — 10170 leak tightness tests
9. 3 quadrupole magnets to be replaced — **Done**
10. 15 dipole magnets to be replaced — **Done**
11. **100 % done** — Installation of 612 pressure relief devices to bring the total to 1344
12. **100 % done** — Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

LS1: LHC schedule



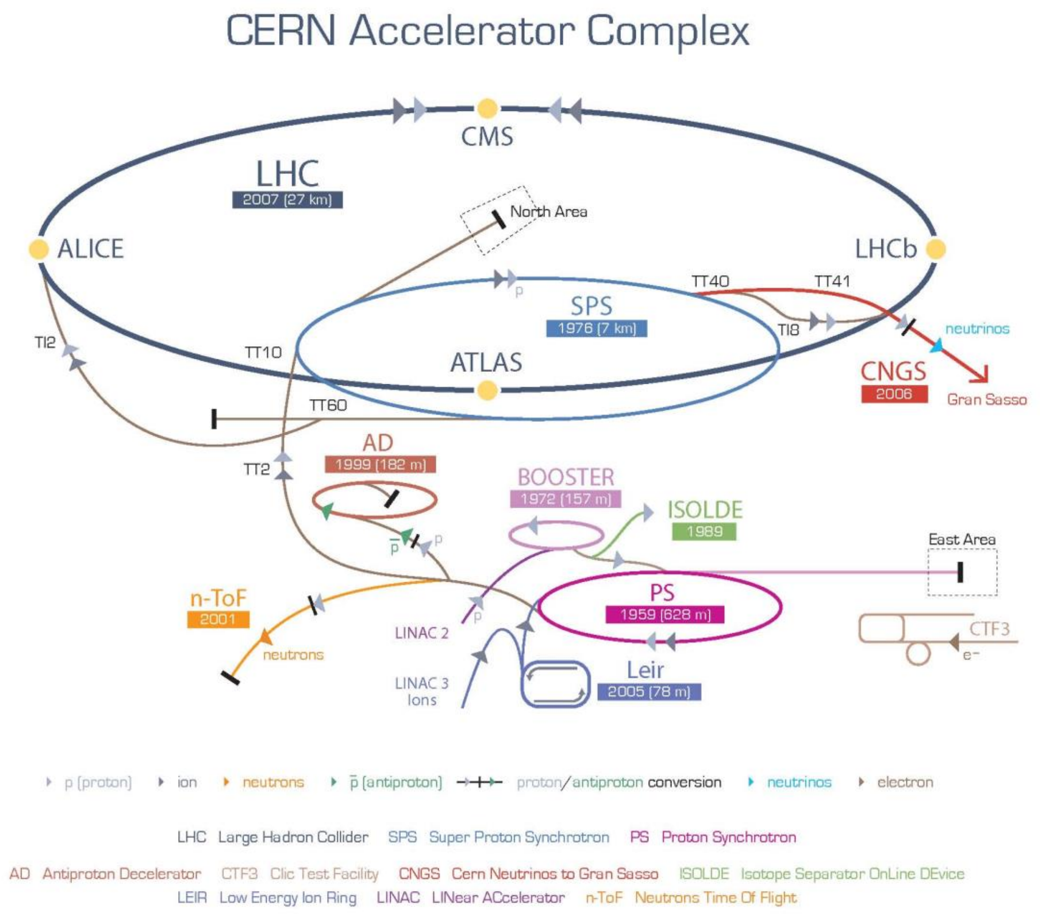
LHC schedule V4.1

Safety First, Quality Second, Schedule Third



1st beam on week 11 (starting 9th March 2015)

CERN Accelerator Complex



LHC Injector Upgrade (LIU)

Improve performance (increase brightness) & reliability

- ⇒ 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…)

Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

The main objective of HiLumi LHC Design Study is 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 **5×10^{34} $cm^{-2}s^{-1}$ with levelling,** allowing:

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

Concept of ultimate performance (Oct.2013, ECFA & RLIUP) under study:
$L_{peak} \cong 7.5\ 10^{34}\ cm^{-2}s^{-1}$ and **Int. L ~ 4000 fb^{-1}**
LHC should not be the limit, would Physics require more…

Baseline Parameters

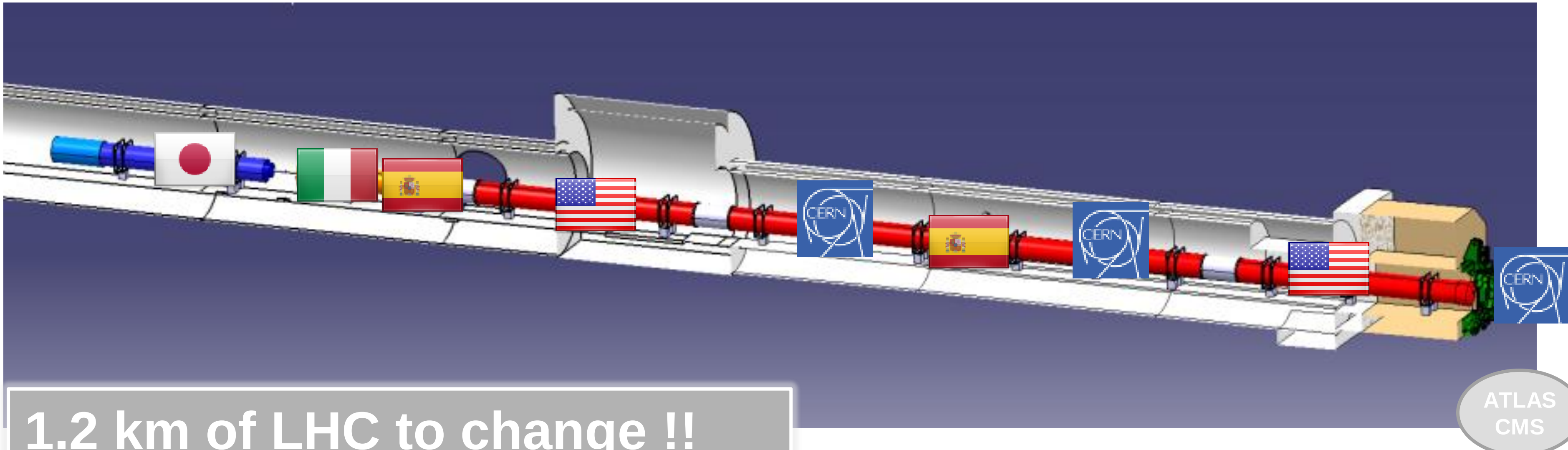
$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\;2}}{4\pi \varepsilon_n \beta^*} R$$

ATS required

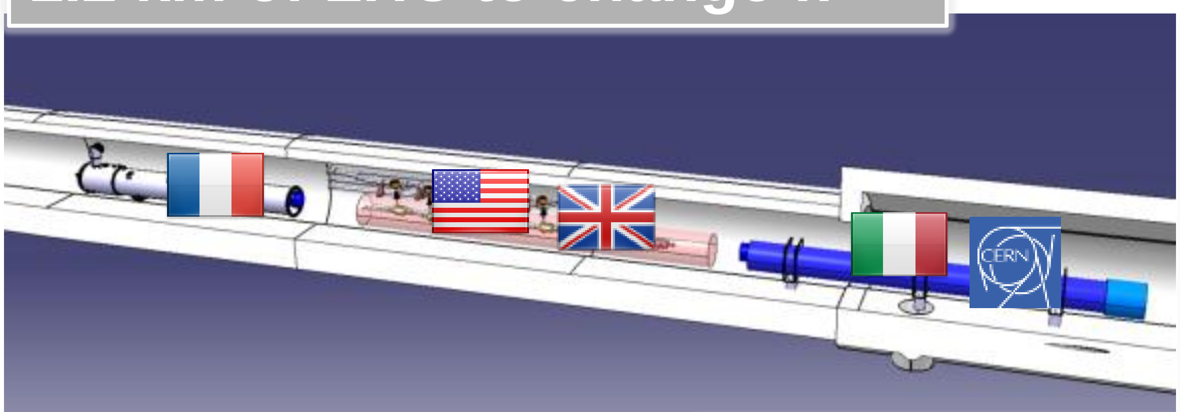
Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 25 ns (BCMS)	HL-LHC 50ns
Beam energy in collision [TeV]	7	**7**	7	7
N_b	1.15E+11	**2.2E+11**	2.2E11	3.5E+11
n_b	2808	**2748**[1]	2604	1404
Number of collisions at IP1 and IP5	2808	**2736**	2592	1404
N_{tot}	3.2E+14	**6.0E+14**	5.7E+14	4.9E+14
beam current [A]	0.58	**1.09**	1.03	0.89
x-ing angle [μrad]	285	**590**	590	590
beam separation [σ]	9.4	**12.5**	12.5	11.4
β^* [m]	0.55	**0.15**	0.15	0.15
ε_n [μm]	3.75	**2.50**	2.50	3
ε_L [eVs]	2.50	**2.50**	2.50	2.50
r.m.s. energy spread	1.13E-04	**1.13E-04**	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	**7.55E-02**	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	**18.5**	18.5	17.2
IBS longitudinal [h]	61 -> 60	**20.4**	20.4	16.1
Piwinski angle	0.65	**3.14**	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	**0.305**	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	**0.829**	**0.829**	**0.838**
beam-beam / IP without Crab Cavity	3.1E-03	**3.3E-03**	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	**1.1E-02**	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [$cm^{-2}\,s^{-1}$]	1.00E+34	**7.18E+34**	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}\,s^{-1}$]	(1.18E+34)	**19.54E+34**	18.52E+34	21.38E+34
Events / crossing without levelling w/o crab-cavity	27	**198**	198	454
Levelled Luminosity [$cm^{-2}\,s^{-1}$]	-	**5.00E+34**	5.00E34	2.50E+34
Events / crossing (with levelling and crab-cavities for HL-LHC)	27	**138**	146	135
Peak line density of pile up event [evt/mm] (max over stable beam)	0.21	**1.25**	1.31	1.20
Levelling time [h] (assuming no emittance growth)	-	**8.3**	7.6	18.0

Collision values

In-kind Contribution and Collaboration for Design and Prototypes



1.2 km of LHC to change !!



CC : R&D, Design and in-kind **USA**

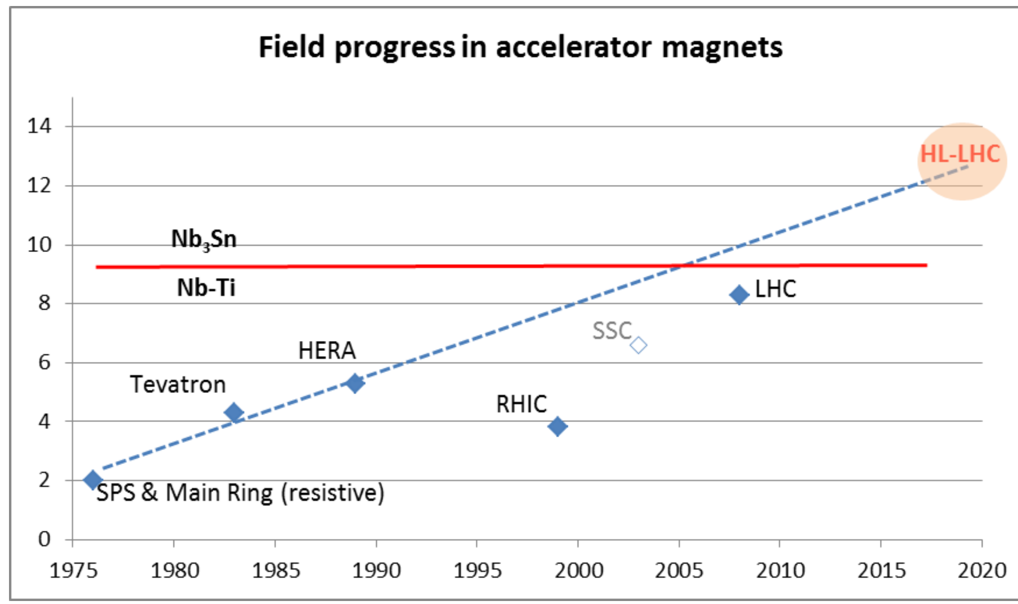
CC : R&D and Design **UK**

Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

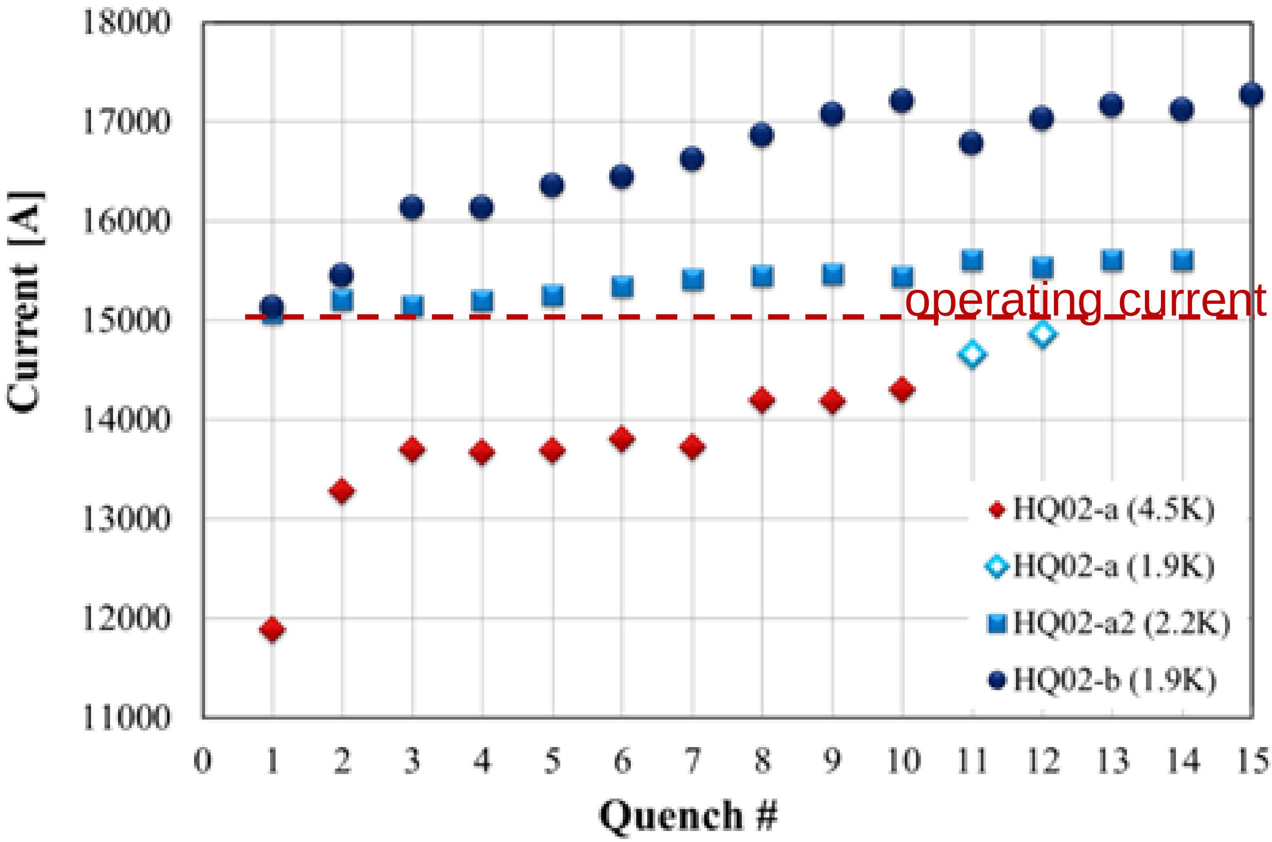
Magnets: Inner Triplet Quads

- LHC dipoles feature 8.3 T in 56 mm (designed for 9.3 peak field).
- LHC IT Quads feature 205 T/m in 70 mm with 8 T peak field.

- **HL-LHC - use of Nb_3Sn**
  - 11 T dipole (designed for 12.3 T peak field, 60 mm).
  - New IT Quads feature 140 T/m in 150 mm, B > 12 T operational field, (designed for 13.5 T).
  - Energy is more than a factor 4 beyond LHC Quads, and even larger than LHC dipoles.

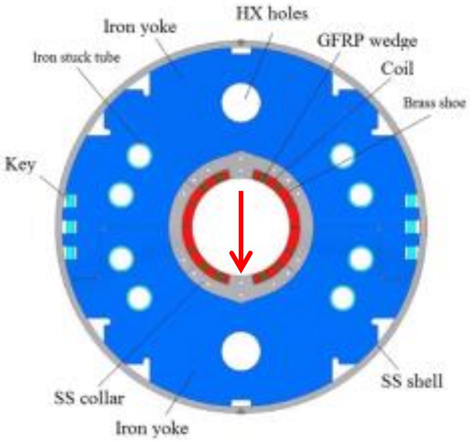


Recent Progress in LARP MQXF (HQ02 120 mm aperture)

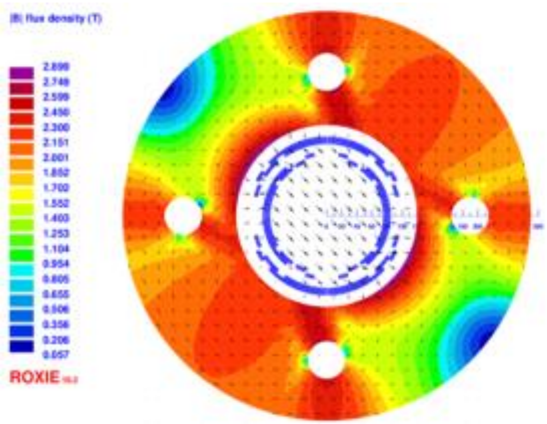


The HL-LHC Magnet Zoo…

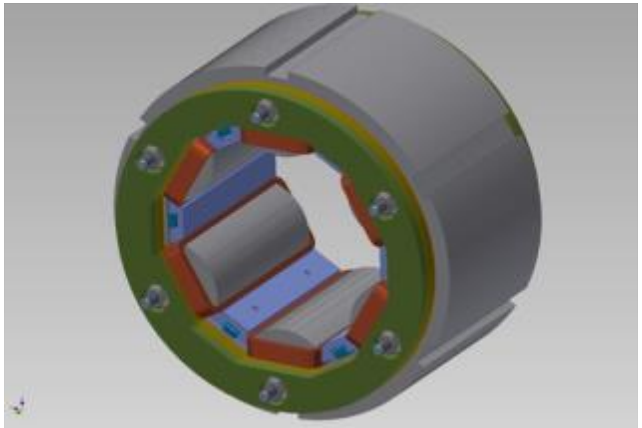
D1 (KEK)

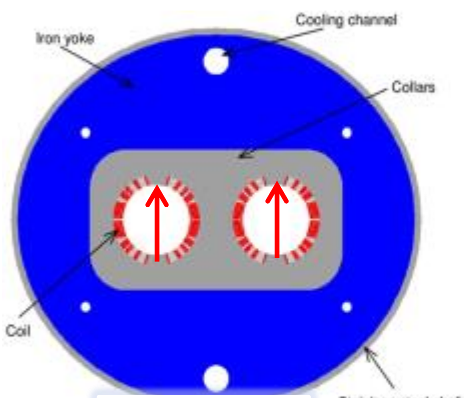


Nested orbit corrector (CIEMAT)

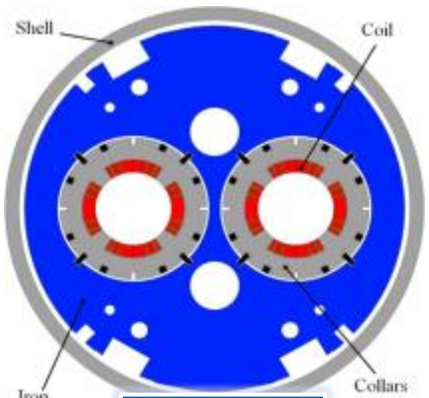


HO correctors: superferric (INFN)

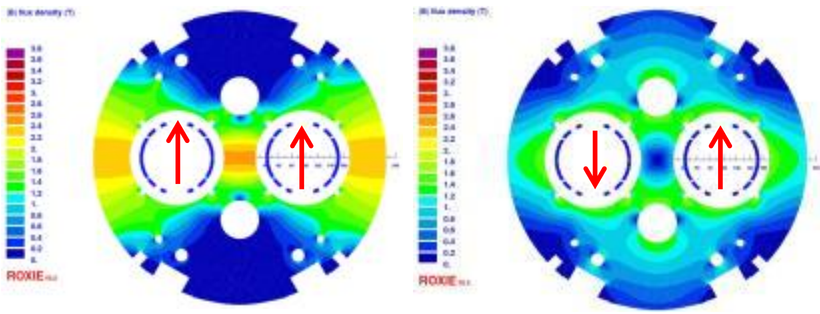




D2 (INFN)

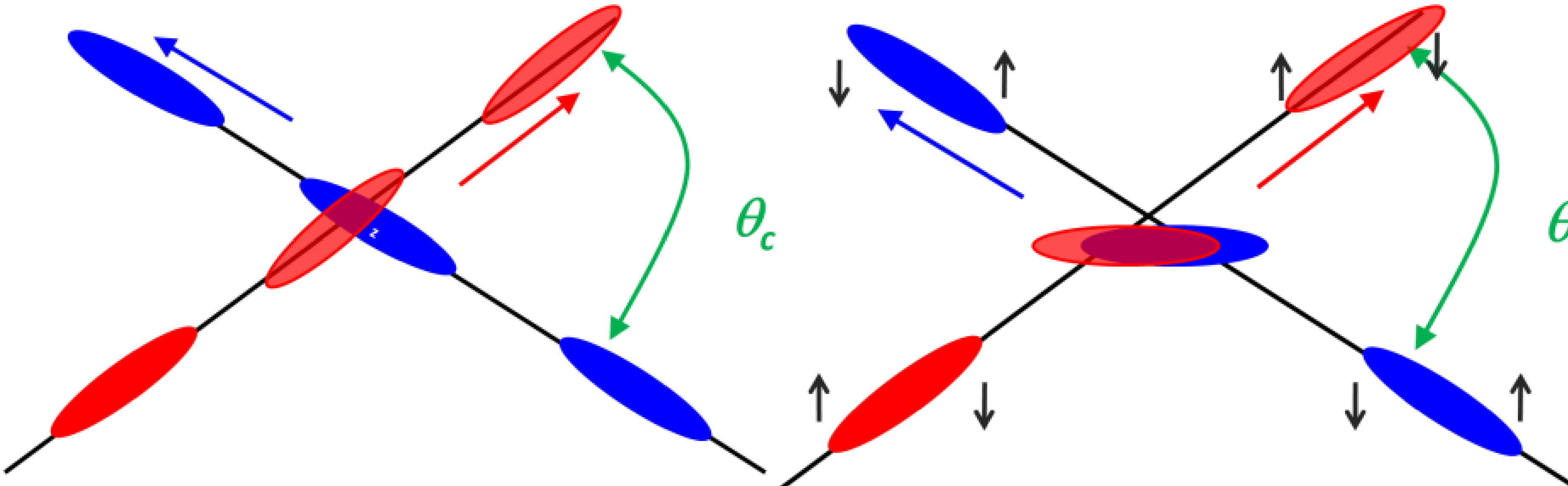


Q4 (CEA)

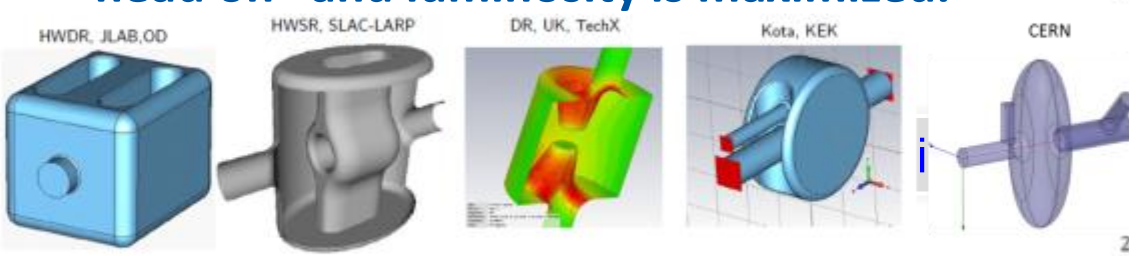


D2 corr

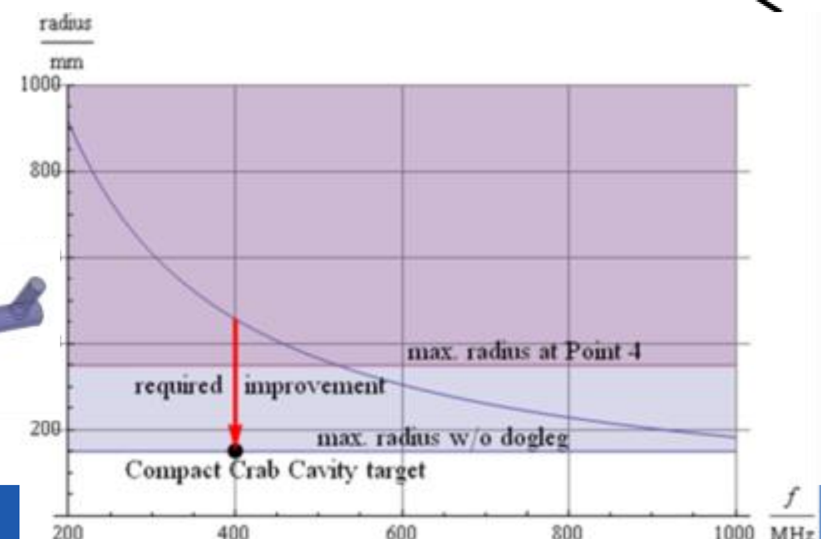
Effect of the Crab Cavities



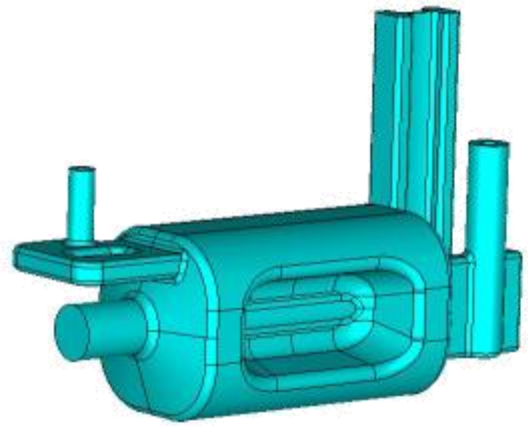
- **RF crab cavity deflects head and tail in opposite directions so that collision is almost "head on" and luminosity is maximized.**



Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

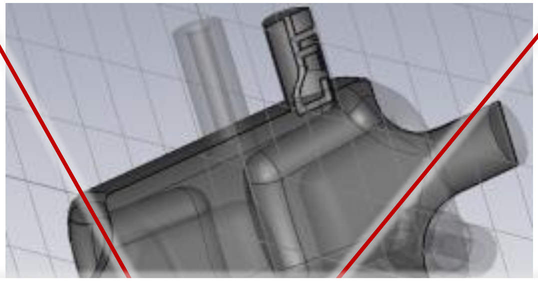


Latest cavity designs towards accelerator

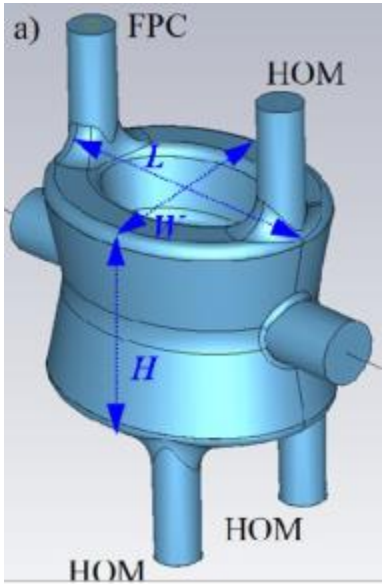


RF Dipole: Waveguide or waveguide-coax couplers

LARP



4-rod: Coaxial couplers with



Double ¼-wave: Coaxial couplers with hook-type antenna

Int. Review on May 2014: Concentrate on two designs with priority (for SPS test)

SPS test is critical: at least one cryomodule before LS2, possibly two, of different cavity type.

R. Calaga, CERN
A. Ratti, LARP
B. G. Burt, UK
O. Capatina, CERN

Post-LHC Accelerator Projects

- To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

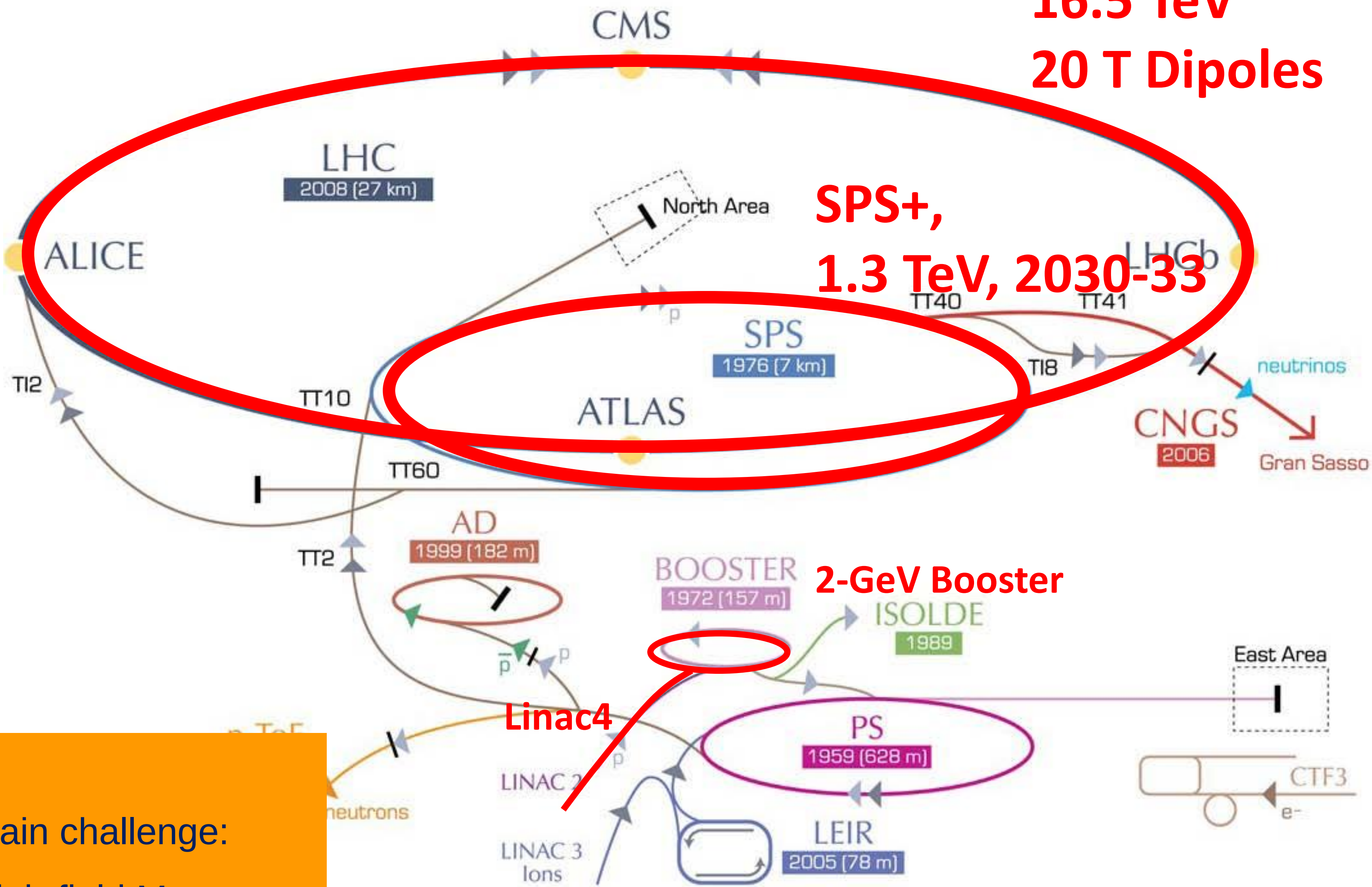
  - *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

High-Energy LHC (HE-LHC)?

HE-LHC >2035

16.5 TeV

20 T Dipoles



Main challenge:

High-field Magnets

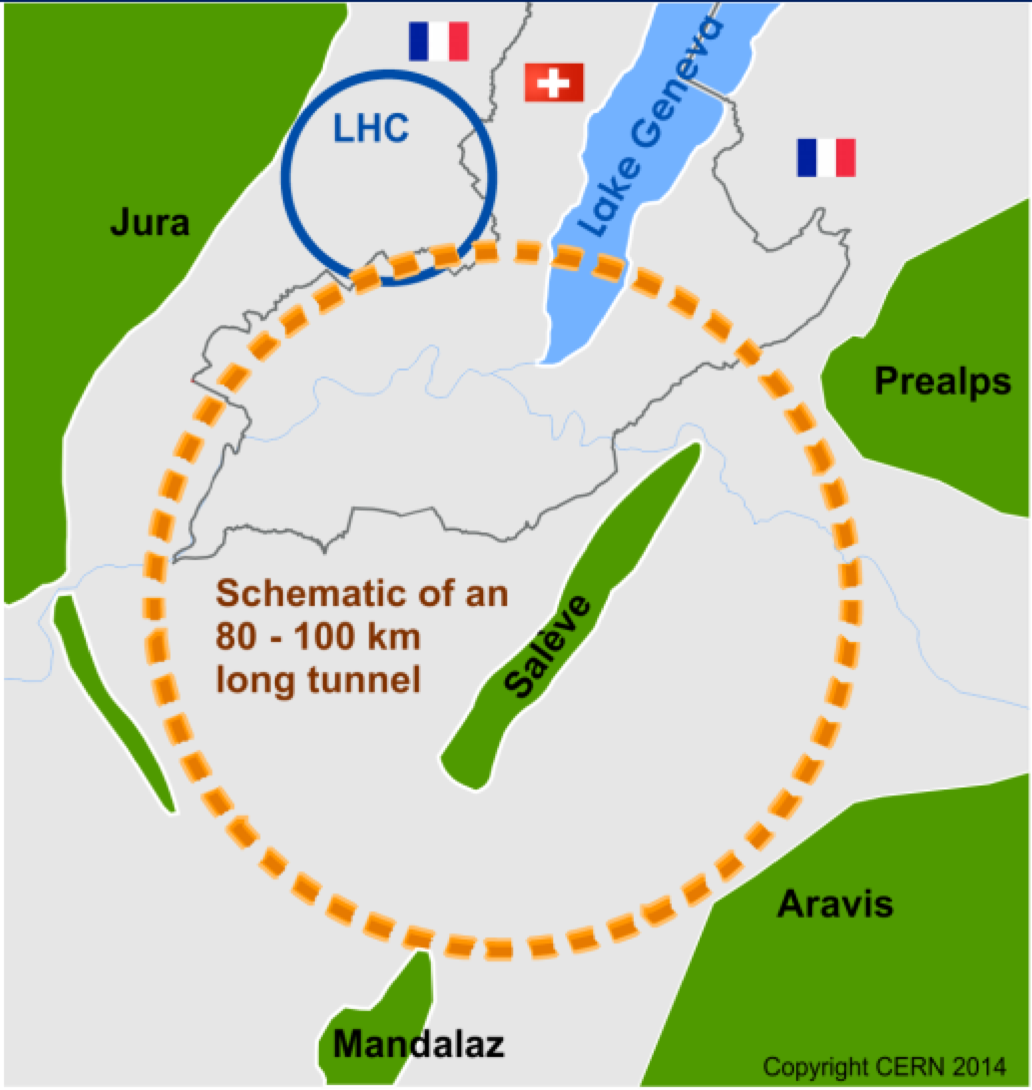
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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



FCC motivation: pushing energy frontier

High-energy hadron collider *FCC-hh* as long-term goal

- **Seems only approach to get to 100 TeV range** in the coming decades
- High energy and luminosity at affordable power consumption
- **Lead time design & construction > 20 years** (LHC study started 1983!)

  → **Must start studying now to be ready for 2035/2040**

Lepton collider *FCC-ee* as potential intermediate step

- Would provide/share **part of infrastructure**
- Important **precision measurements** indicating the energy scale at which new physics is expected
- Search for **new physics in rare decays of *Z, W, H, t*** and rare processes

Lepton-hadron collider *FCC-he* as option

- High precision **deep inelastic scattering and Higgs physics**

Most aspects of collider designs and R&D non-site specific.
Tunnel and site study in Geneva area as ESU requests.

FCC-hh parameters – starting point

Energy	**100 TeV c.m.**
Dipole field	**~ 16 T (Nb_3Sn), [20 T option HTS]**
Circumference	**~ 100 km**
#IPs	**2 main (tune shift) + 2**
Luminosity/IP$_{main}$	**$5x10^{34}$ cm^{-2}s^{-1}**
Stored beam energy	**8.2 GJ/beam**
Synchrotron radiation	**26 W/m/aperture** (filling fact. ~78% in arc)
Long. emit damping time	**0.5 h**
Bunch spacing	**25 ns [5 ns option]**
Bunch population (25 ns)	$1x10^{11}$ p
Transverse emittance	2.2 micron normalized
#bunches	10500
Beam-beam tune shift	0.01 (total)
β*	1.1 m (HL-LHC: 0.15 m)

} already available from SPS for 25 ns

FCC-ee parameters – starting point

Design choice: max. synchrotron radiation power set to 50 MW/beam

- **Defines the maximum beam current at each energy**
- **4 physics operation points (energies) foreseen *Z, WW, H, ttbar***
- **Optimization at each operation point, mainly via bunch number and arc cell length**

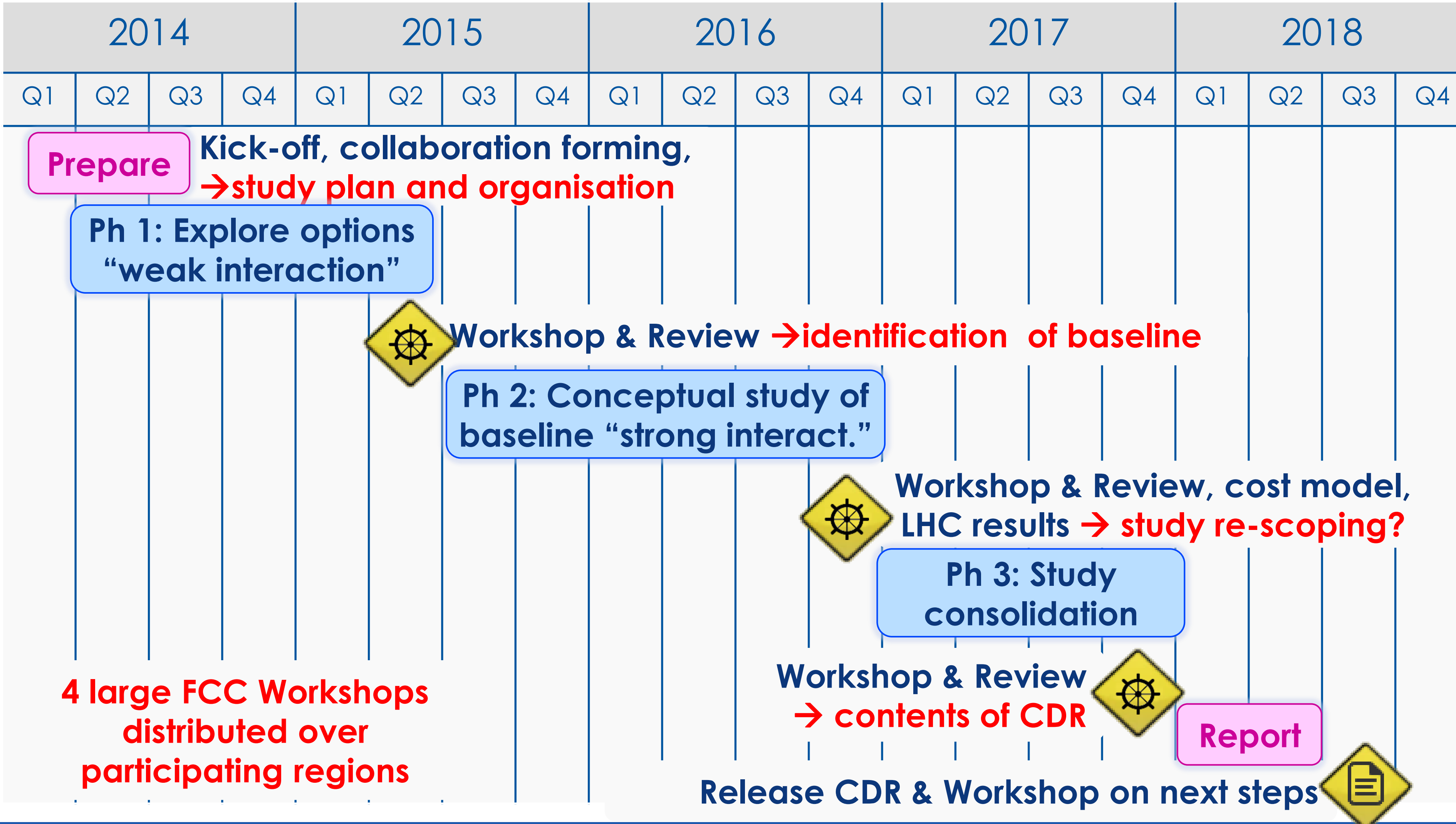
Parameter	***Z***	***WW***	***H***	***ttbar***	***LEP2***
E/beam (GeV)	**45**	**80**	**120**	**175**	**105**
L (10^{34} $cm^{-2}s^{-1}$)/IP	**28.0**	**12.0**	**5.9**	**1.8**	**0.012**
Bunches/beam	**16700**	**4490**	**1330**	**98**	**4**
I (mA)	1450	152	30	6.6	3
Bunch popul. [10^{11}]	1.8	0.7	0.47	1.40	4.2
Cell length [m]	300	100	50	50	79
Tune shift / IP	0.03	0.06	0.09	0.09	0.07

FCC-he parameters – starting point

- **Design choice: beam parameters as available from *hh* and *ee***
  - Max. $e^{\pm}$ beam current at each energy determined by 50 MW SR limit.
  - **1 physics interaction point, optimization at each energy**

collider parameters	$e^{\pm}$ scenarios			protons
species	$e^{\pm}$ (polarized)	$e^{\pm}$	$e^{\pm}$	*p*
beam energy [GeV]	**80**	**120**	**175**	**50000**
luminosity [$10^{34}cm^{-2}s^{-1}$]	**2.3**	**1.2**	**0.15**	
bunch intensity [10^{11}]	0.7	0.46	1.4	1.0
#bunches per beam	4490	1360	98	10600
beam current [mA]	152	30	6.6	500
$\sigma_{x,y}$* [micron]	4.5, 2.3			

Proposal for FCC Study Timeline



FCC Kick-Off Meeting February 2014

341 registered participants

MoU Status 8 September 2014

- **20 MoUs signed,** 15 further agreed, pending signatures

- ALBA/CELLS, Spain
- BINP, Russia
- CBPF, Brazil
- CIEMAT, Spain
- Cockcroft Institute, UK
- CSIC/IFIC, Spain
- DESY, Germany
- EPFL, Switzerland
- Hellenic Open U, Greece
- JAI/Oxford, UK
- KEK, Japan
- King’s College London, UK
- MEPhI, Russia
- Sapienza/Roma, Italy
- TU Darmstadt, Germany
- TU Tampere, Finland
- U. Geneva, Switzerland
- U. Iowa, USA
- U. C. Santa Barbara, USA
- U Silesia, Poland

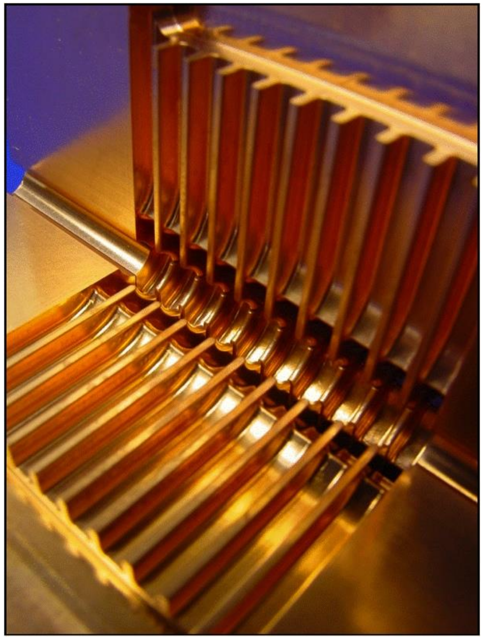
International Linear Collider (ILC)

- There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the ILC has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.
    - *Europe looks forward to a proposal from Japan to discuss a possible participation.*

See talk by P. Burrows – *Status of the ILC Project*

ILC (and the Compact Linear Collider CLIC)

CLIC

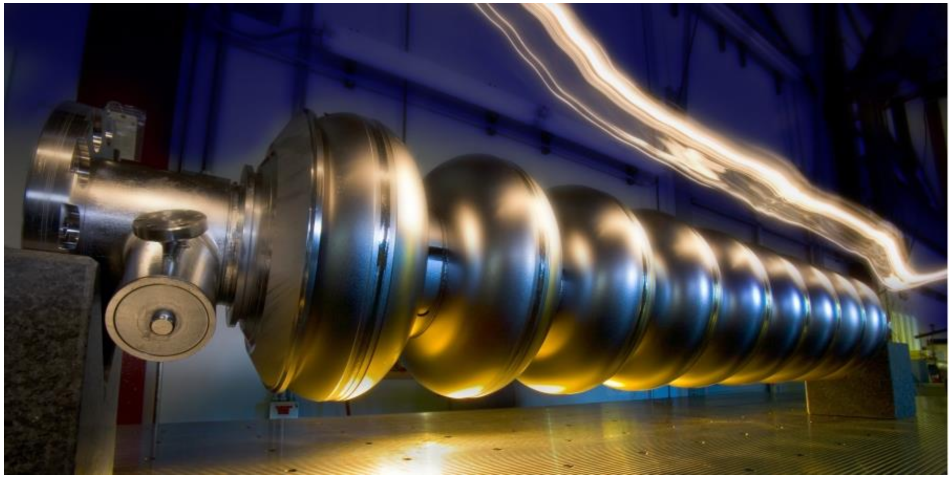


- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- √s up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

Linear e^+e^- colliders

Luminosities: few 10^{34} $cm^{-2}s^{-1}$

ILC



- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- √s ≤ 500 GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

CLIC Lay-out at 3 TeV

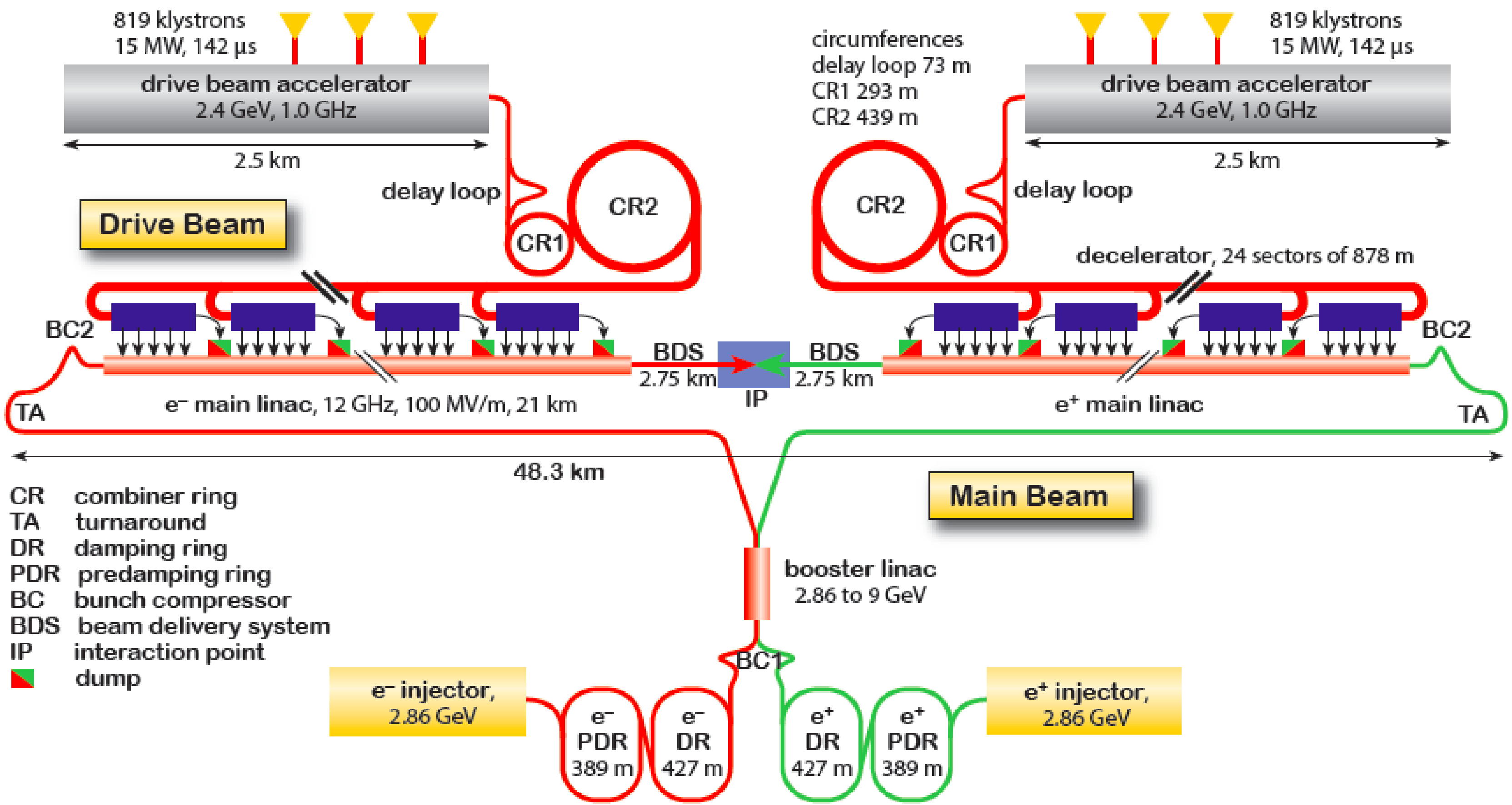
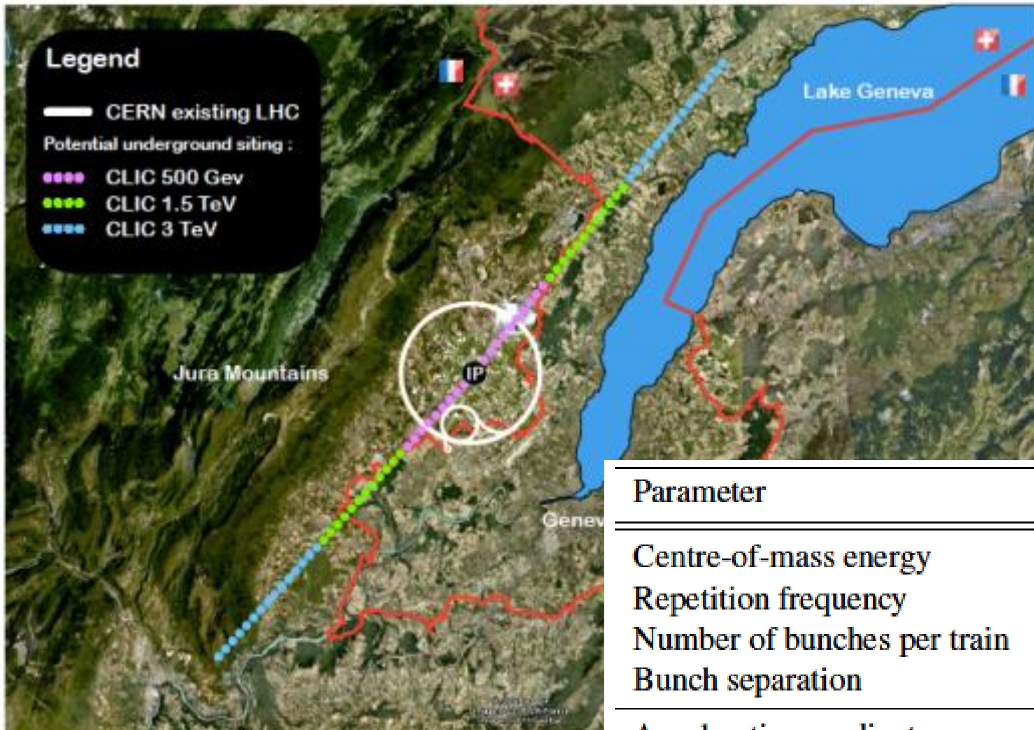


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

CLIC Implementation



← Possible lay-out near CERN

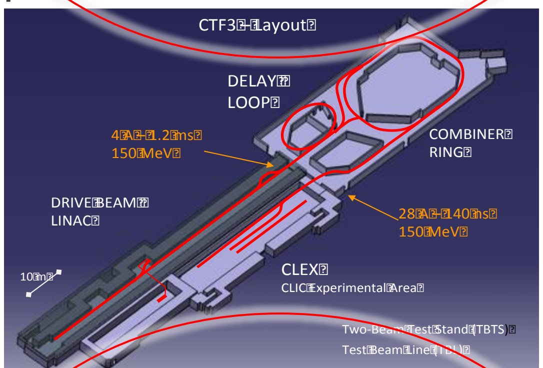
↓ CLIC parameters

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

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

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



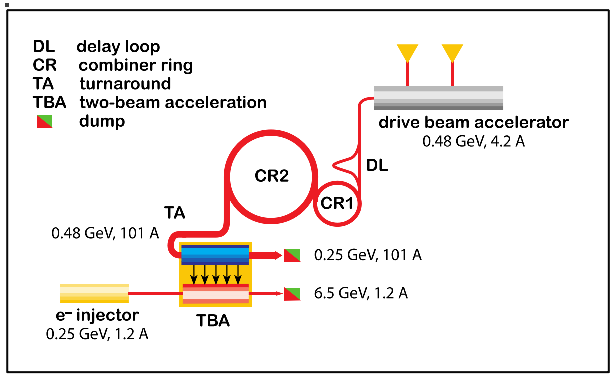
2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

4-5 year Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.

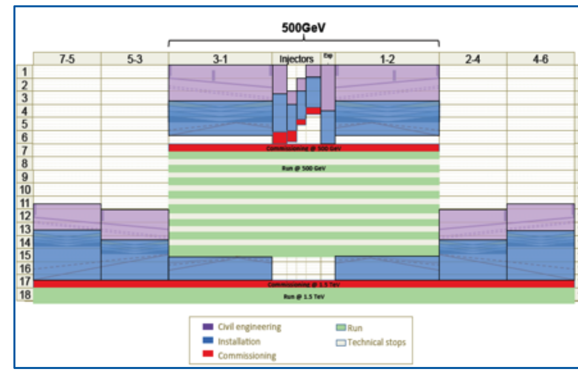


2024-25 Construction Start

Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



Commissioning

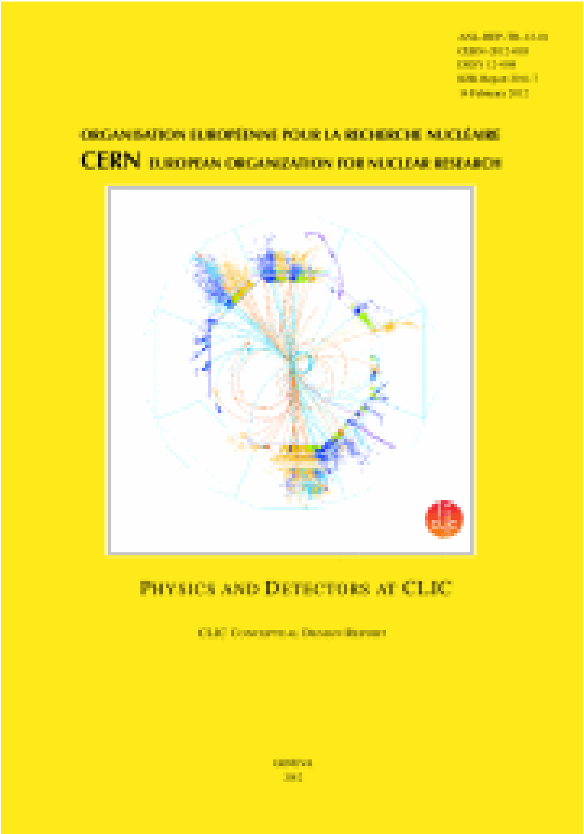
Common work with ILC related to several acc. systems as part of the LC coll., also related to initial stage physics and detector developments

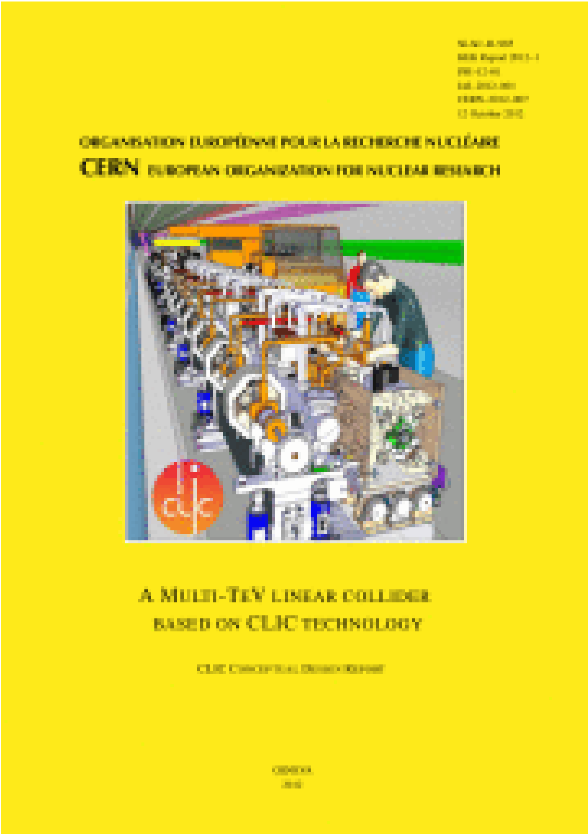
Common physics benchmarking with FCC pp and common detect. challenges (ex: timing, granularity), as well as project implementation studies (costs, power, infrastructures …)

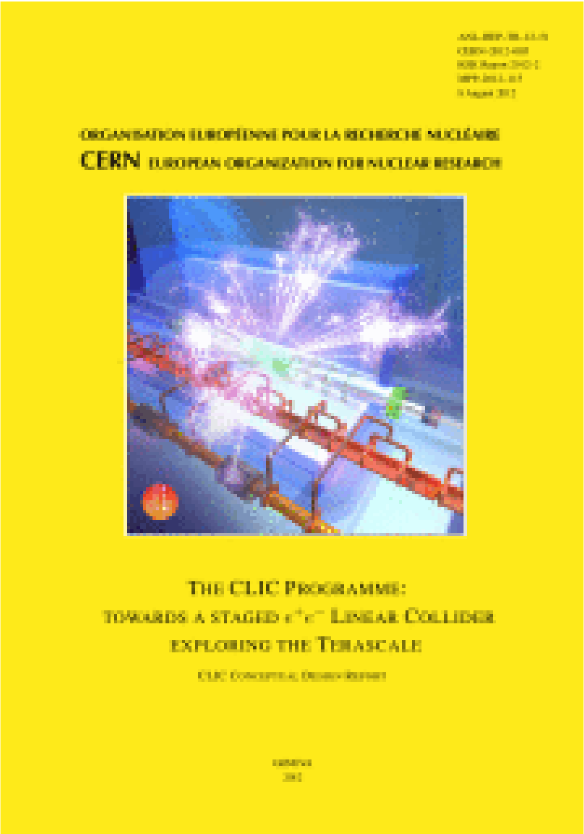
CERN

John Adams Institute for Accelerator Science

CLIC CDR and cost study (2012)







- **3 volumes CDR: physics & detectors, accelerator complex, strategy, cost & schedule**
- **Collaborative effort: 40+ institutes worldwide**

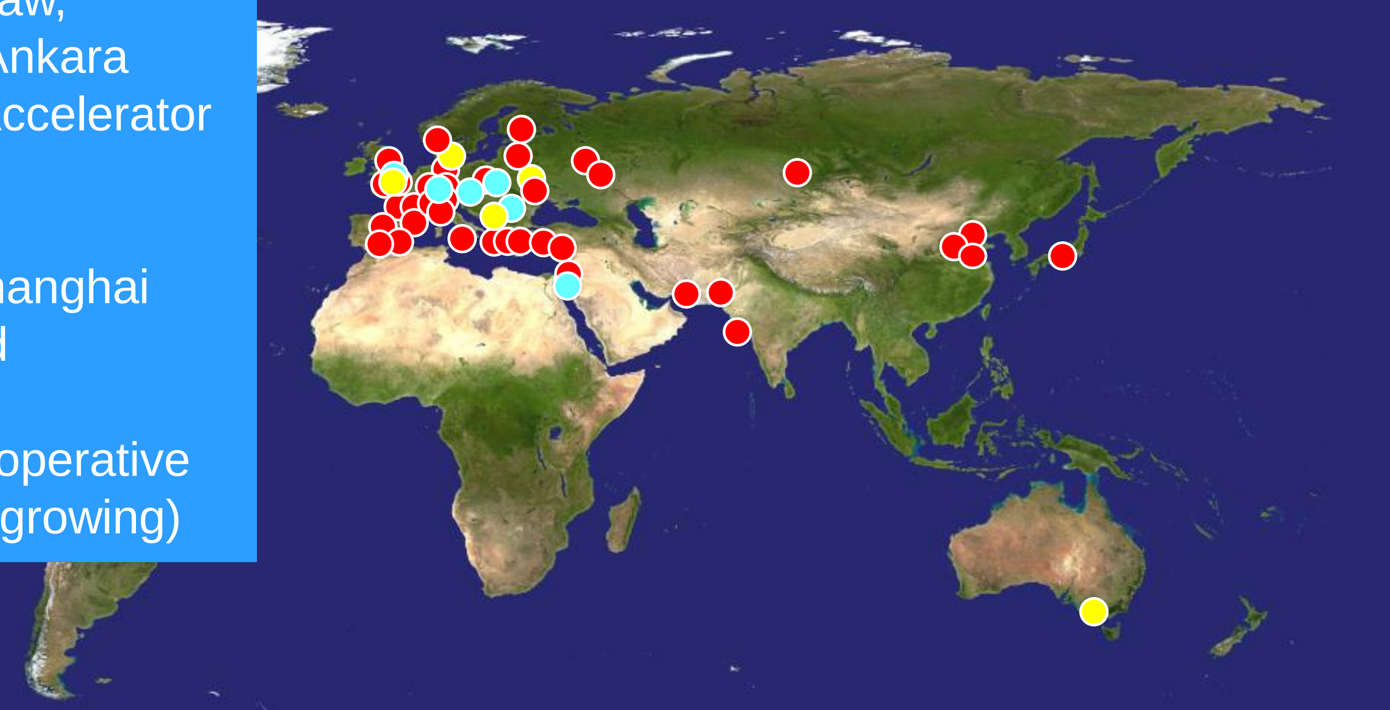
Collaboration

Seven new collaboration partners joined in 2013 (The Hebrew University Jerusalem, Vinca Belgrade, ALBA/CELLS, Tartu University, NCBJ Warsaw, Shandong University, Ankara University Institute of Accelerator Technologies (IAT)).

In 2014 two (SINAP Shanghai and IPM Tehran) joined

Detector collaboration operative with 23 institutes (also growing)

untries – over 70 Institutes



Detector collaboration

Accelerator + Detector collaboration

Summary

- Highest priority of particle physics community is to fully exploit physics potential of the LHC.
- The updated European Strategy for Particle Physics incorporates a number of new accelerator projects for the future. (Updated May 2013)
  - 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.
- Many open questions from the LHC could be addressed by:
  - An electron-positron collider (ILC and/or CLIC)
  - New studies – 100 km hadron / lepton collider – FCC
- These new initiatives will lead particle physics well into the next decades of fundamental research.