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EUCAS 2019
GLASGOW

Accelerator Technology: Now and the Future

Amalia Ballarino
CERN, Geneva

14th European Conference on Applied Superconductivity
1st-5th September 2019, Glasgow

Accelerator technology

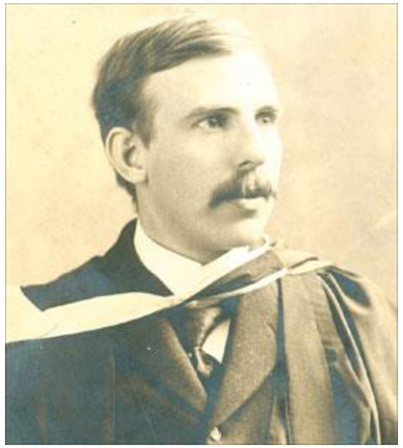
- **Particle accelerators** have been at the forefront of **scientific discoveries** for **more than half a century**

- **Technology progress** has been **innovative and impressive**

- **Charged particles** are accelerated to **high-momenta** to:
  - **Probe matter** at **shorter distances** (MeV: nucleus scale, TeV: sub-nuclear scale)
    Higher energy → Shorter wavelength
  - **Generate new particles**

- Continuous **increase in energy** and intensity to **study known and unknown particles and their interactions**

Particle accelerators



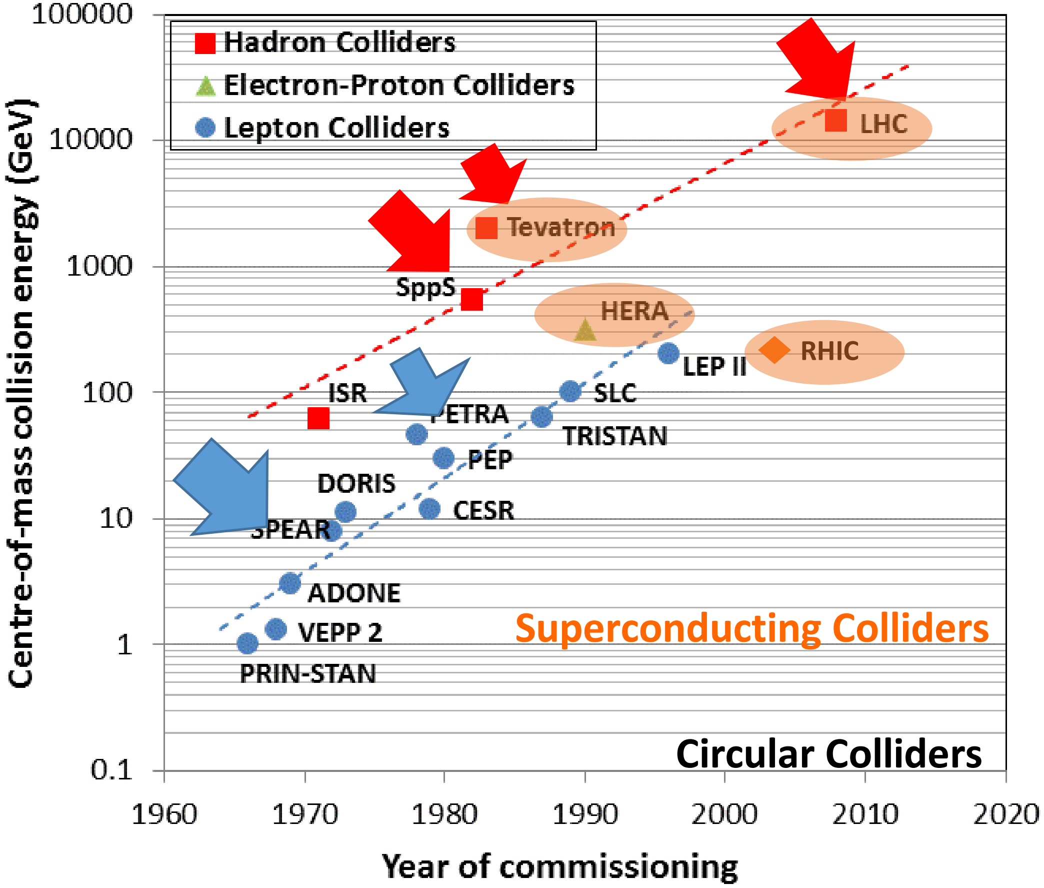
Rutherford, 1911: discovery of nuclear disintegration by α rays

Rutherford, 1927: in his presidential address to the Royal Society of England, made a strong **request for higher energy nuclear probes**:

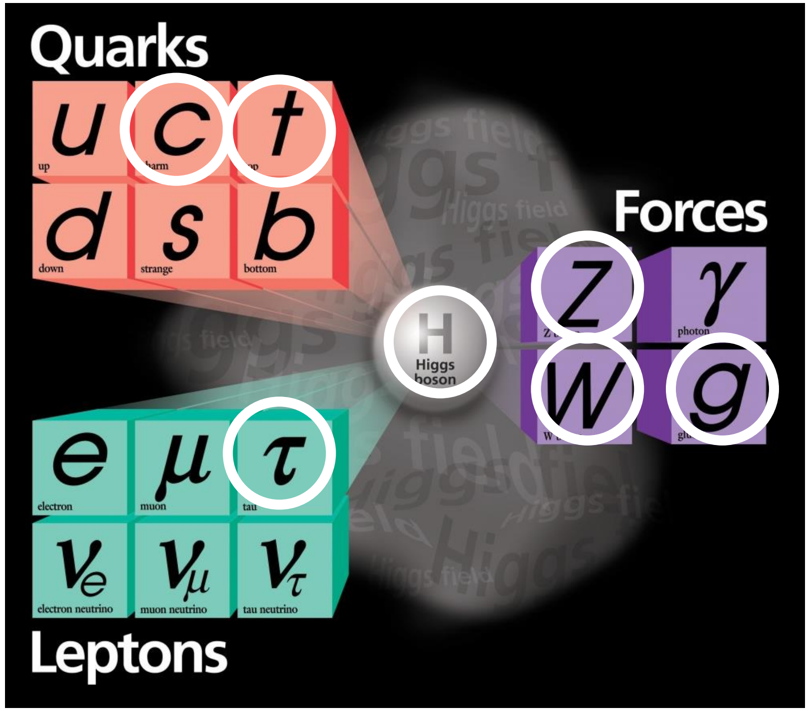
" *It has long been my ambition to have available for study a copious supply of atoms and electrons which have an* ***individual energy far transcending that of the α and β particles from radioactive bodies.*** ***I am hopeful that I may yet have my wish fulfilled***"

Rutherford challenged the physics community to invent **higher-energy particle accelerators**

The quest for higher energies



Standard Model
Particles and forces



Historical trend: Hadron Colliders for discovery physics
Lepton Colliders for precision physics

The present: operation of LHC

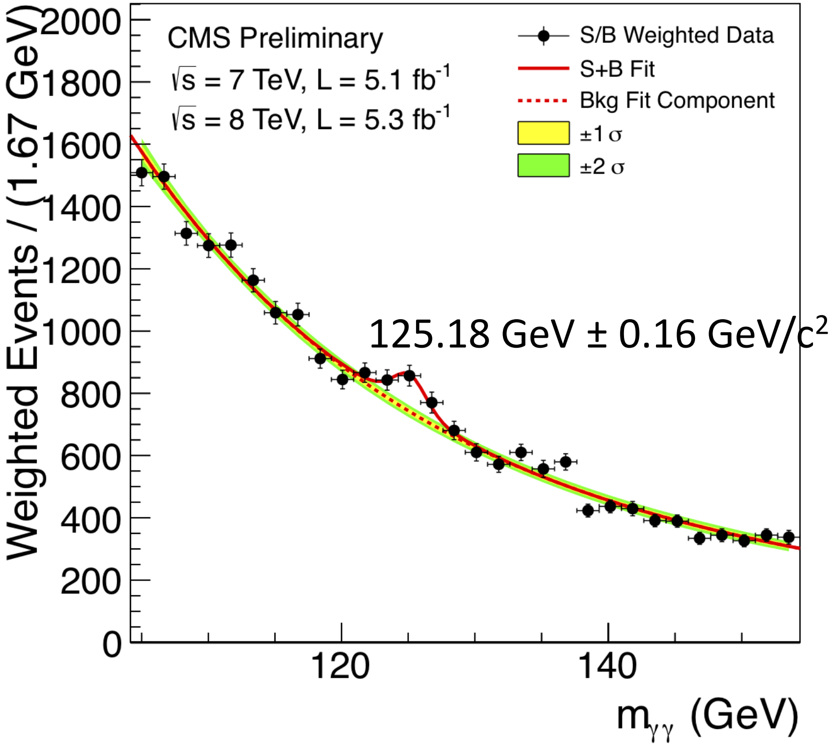
The LHC Findings

- **Last particle predicted by Standard Model,** the **Higgs boson,** discovered at CERN – **July 2012**

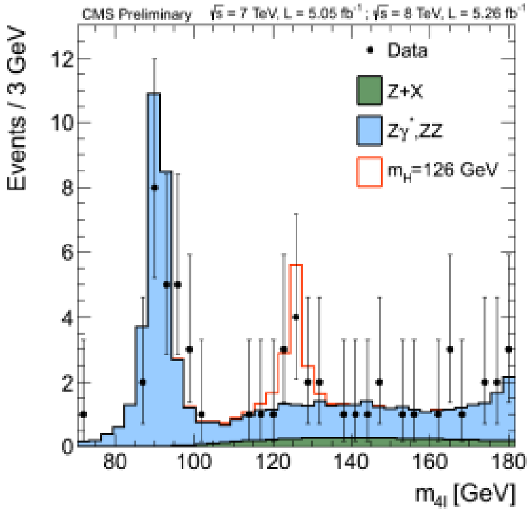
F. Englert

P. Higgs

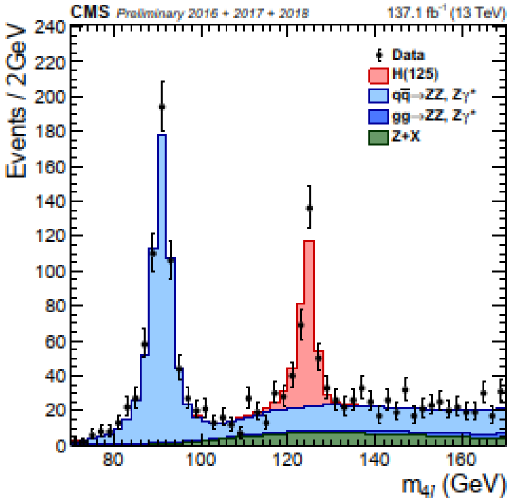
Nobel price in Physics 2013



Discovery (2012)

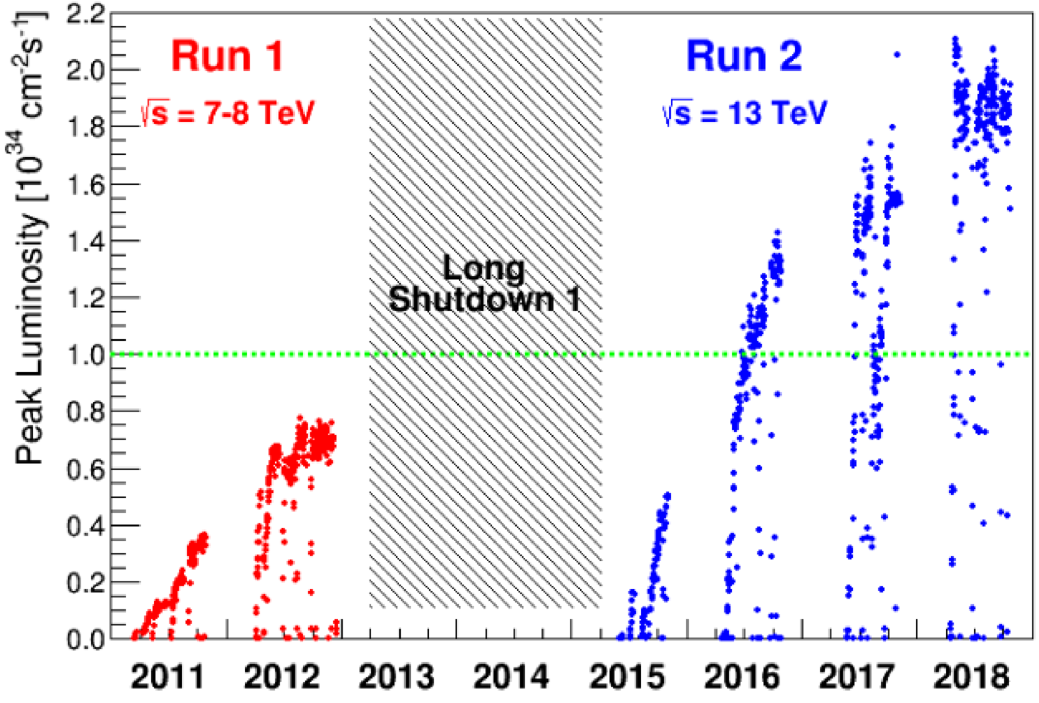


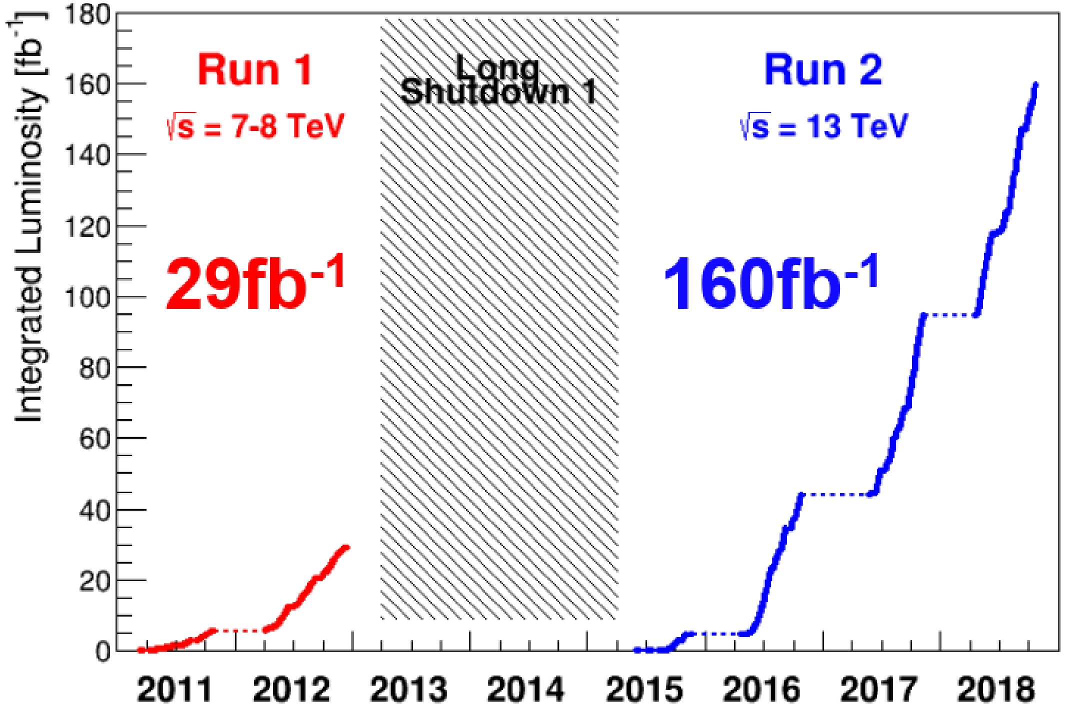
After Run 2 (2019)



Much improved statistics
Main production and decay modes observed

LHC Operation





Design peak luminosity ($1\cdot10^{34}$ cm^{-2}s^{-1}) achieved in 2016 and doubled

LHC total integrated proton-proton luminosity ~ 189 fb^{-1}

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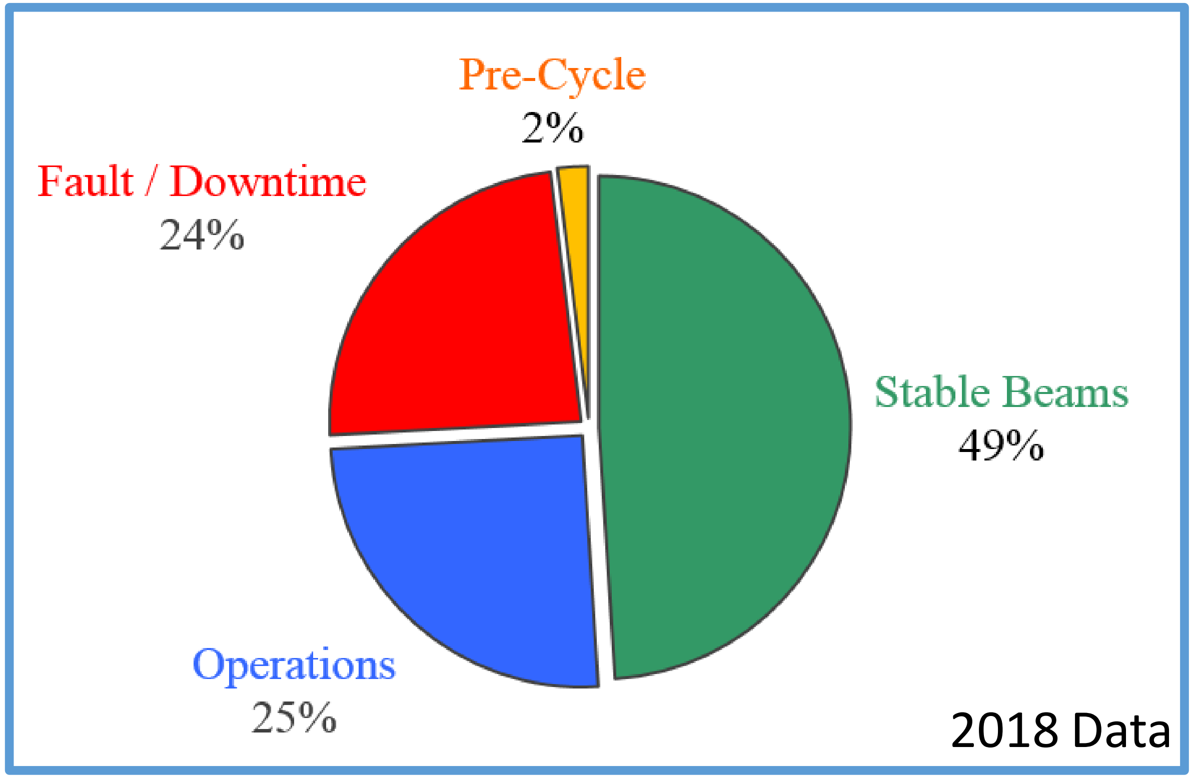
LHC Operation

- Demonstrated **reliable operation** with **6.5 TeV** proton beams
- Very good **control and reproducibility of the beams** → **excellent performance of magnets, RF system, collimation system, alignment**
- **Robust machine configuration**
- **Efficient operation**



~ 75 % Machine availability

Machine beautifully designed and built

LHC Superconducting Technology

~ 8000 Nb-Ti magnets

> 1000 SC Circuits

~ 1200 tons of **Nb-Ti**

~ **36000 tons** of magnets’ cold masses

1.9 K He II operation, ~ **120 tons** of He

16 RF Nb/Cu 400 MHz, 5 MV/m, 4.5 K

HTS (Bi-2223 @ 50 K) Current Leads

transferring ~ **3 MA of current**

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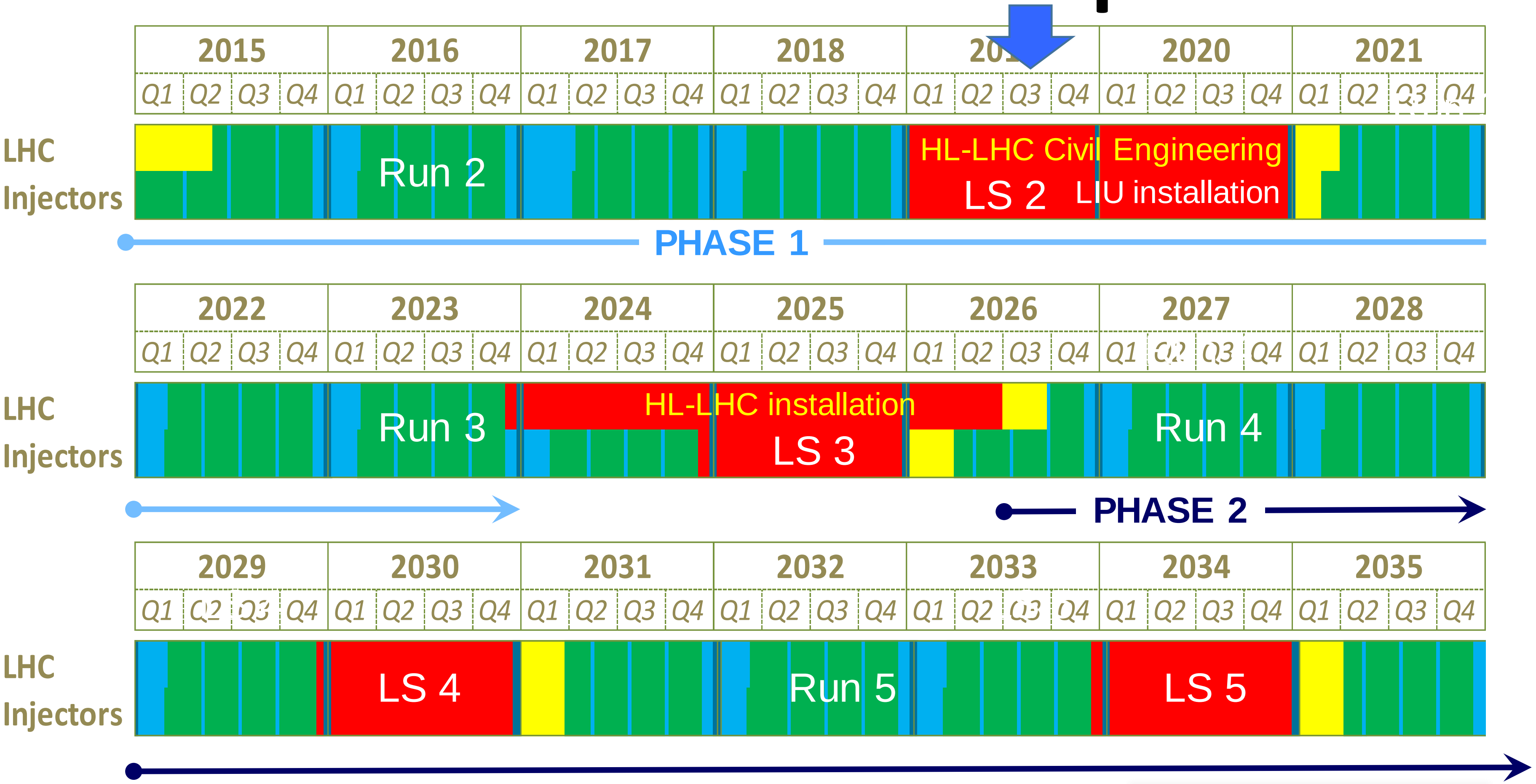
The LHC Roadmap

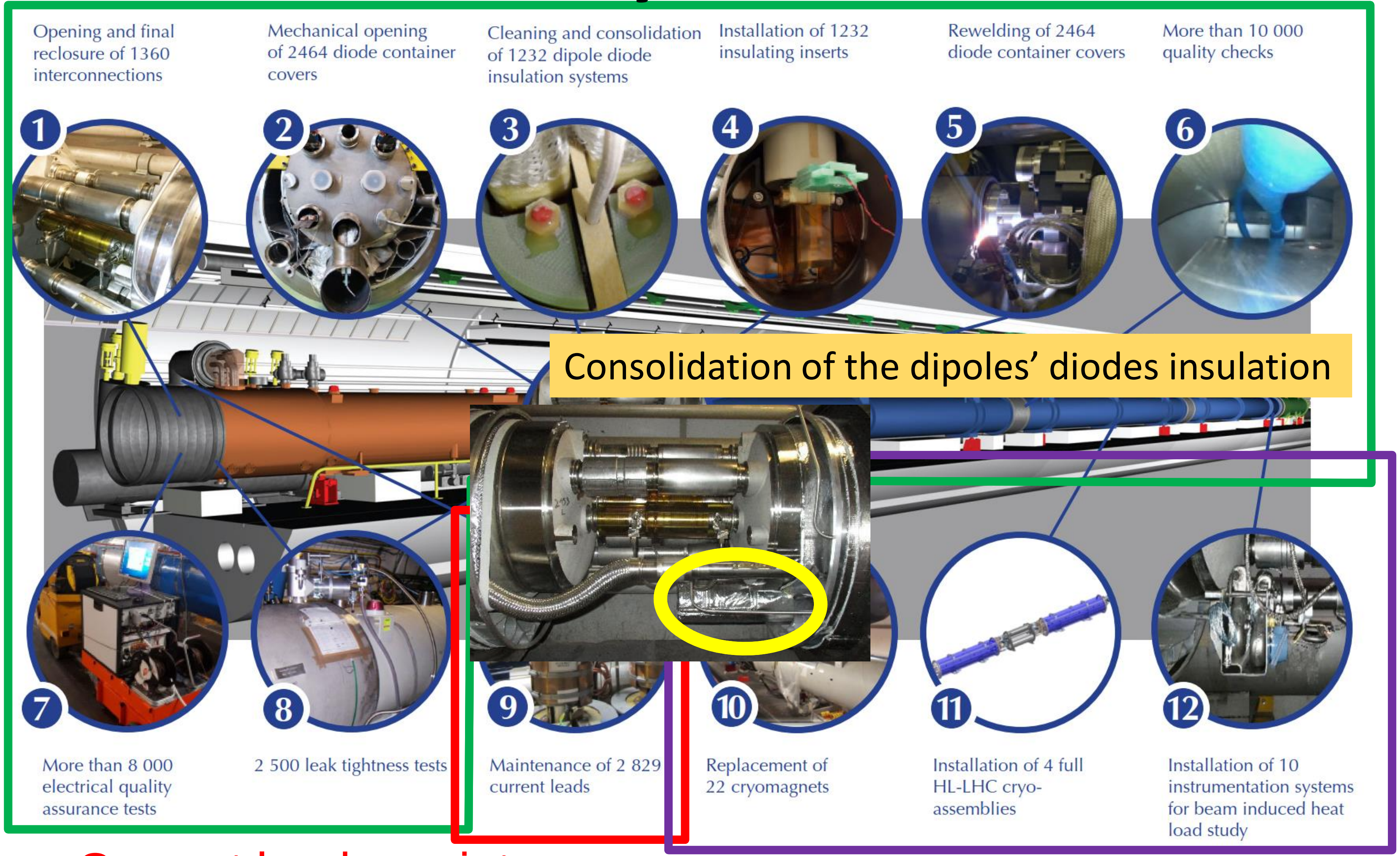


LS2 : 2019 => 24 months + 3 months BC
LS3 LHC: 2024 => 30 months + 3 months BC

🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
🟦 Technical stop

Courtesy of F. Bordry, ATS Director

The LS2 activity in the LHC tunnel



Diodes insulation consolidation

1 Opening and final reclosure of 1360 interconnections

2 Mechanical opening of 2464 diode container covers

3 Cleaning and consolidation of 1232 dipole diode insulation systems

4 Installation of 1232 insulating inserts

5 Rewelding of 2464 diode container covers

6 More than 10 000 quality checks

7 More than 8 000 electrical quality assurance tests

8 2 500 leak tightness tests

Consolidation of the dipoles' diodes insulation

9 Maintenance of 2 829 current leads

Current leads maintenance

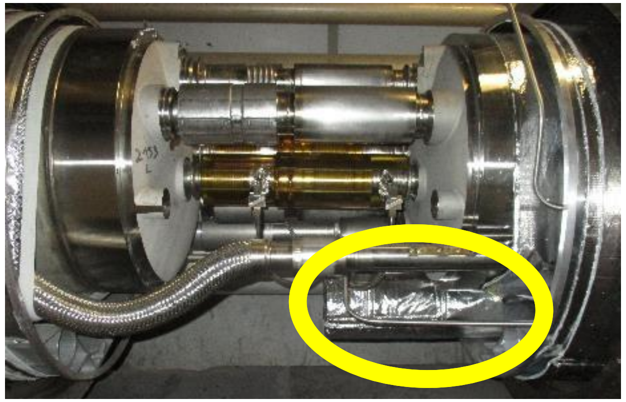
10 Replacement of 22 cryomagnets

11 Installation of 4 full HL-LHC cryo-assemblies

12 Installation of 10 instrumentation systems for beam induced heat load study

Special Interventions

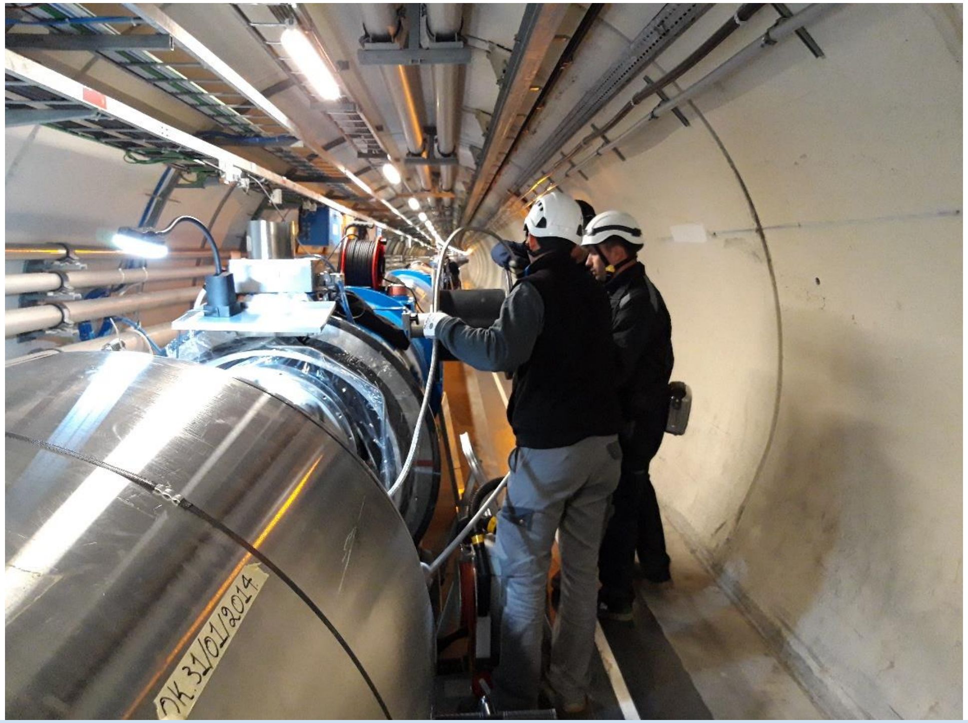
The LS2 activity in the LHC tunnel



Consolidation of the dipole diodes insulation

1232 Diode Boxes
180 People involved
1/3 of the work accomplished

Preparing for 14 TeV operation



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The near future: High-Luminosity LHC
From 2026 onwards

HiLumi
HL-LHC PROJECT

The HL-LHC Upgrade

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 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.

Ultimate performance established 2015-2016: with same hardware


At present we only have about 190/3000 ∿ 6.5 % of data yield after HL-LHC

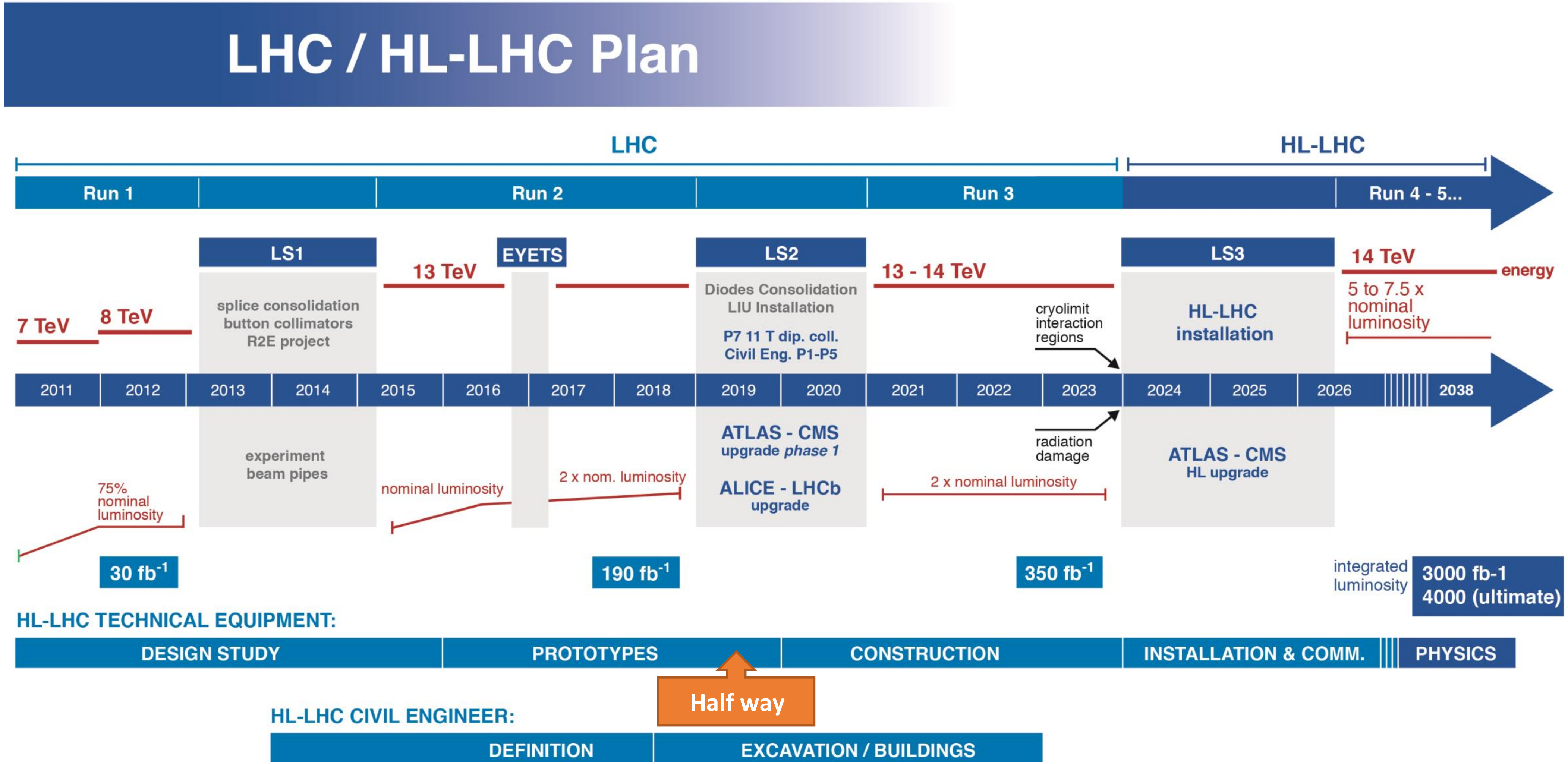
$L_{peak\ ult}$ = 7.5 10 and **Ultimate integrated $L_{int\ ult}$ 4000 fb**

LHC should not be the limit, would Physics require more..

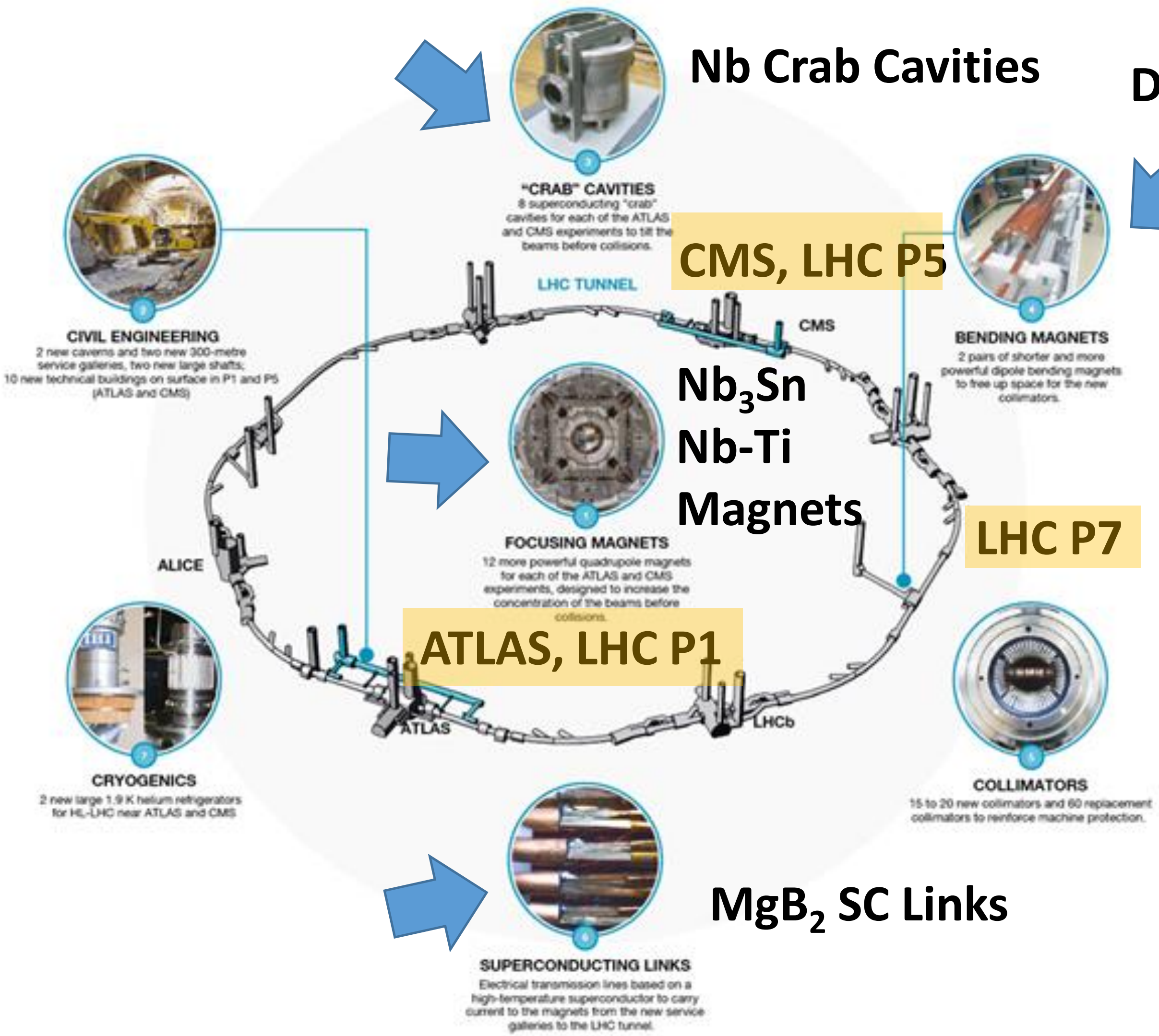
Experiment are designing for this goal.
We need to be compatible with it!

L. Rossi, HL-LHC Project Leader

The HL-LHC Schedule



The HL-LHC SC Technologies



Nb Crab Cavities

Nb_3Sn Dipole Magnets

CMS, LHC P5

Nb_3Sn Nb-Ti Magnets

LHC P7

ATLAS, LHC P1

MgB_2 SC Links

"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.

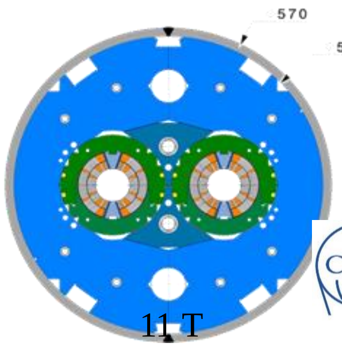
CRYOGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS

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

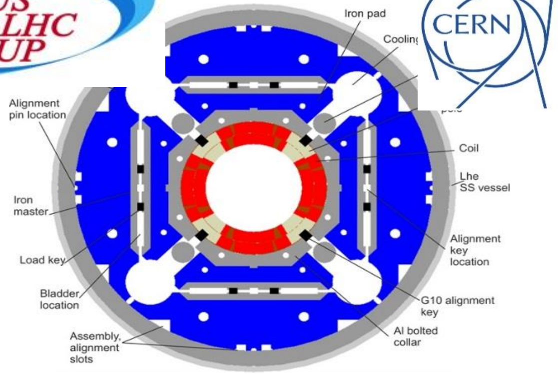
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

The HL-LHC Magnets

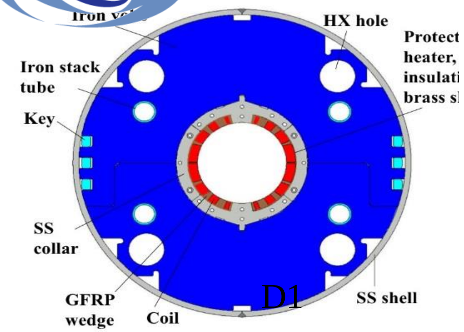
130 new magnets



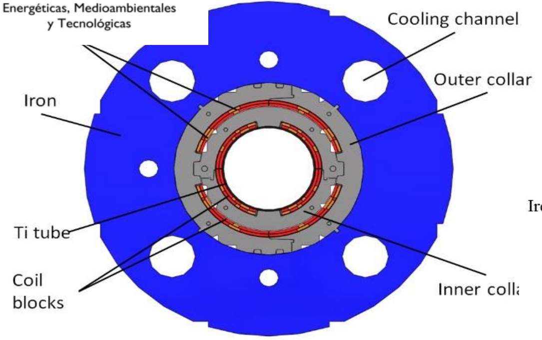
11 T



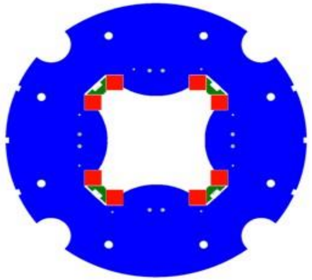
IT Quads



D1

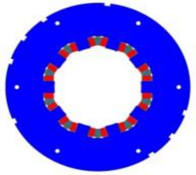


MCBXF

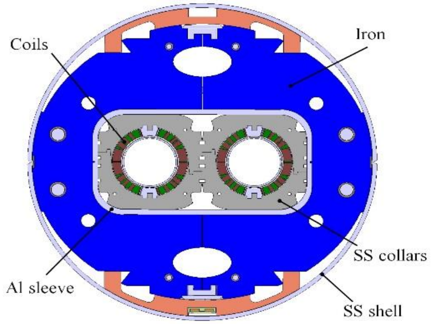


Skew quad

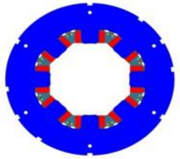
Dodecapole



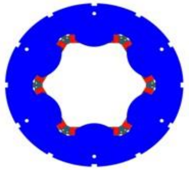
Decapole

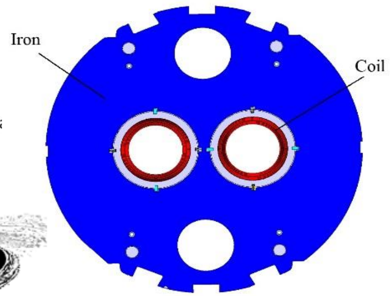


D2



Octupole



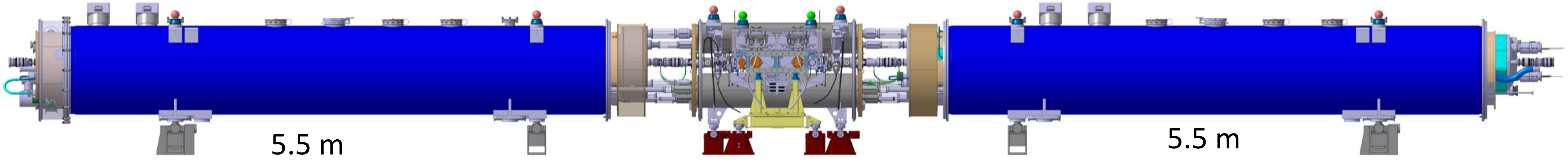


D2 orbit corrector

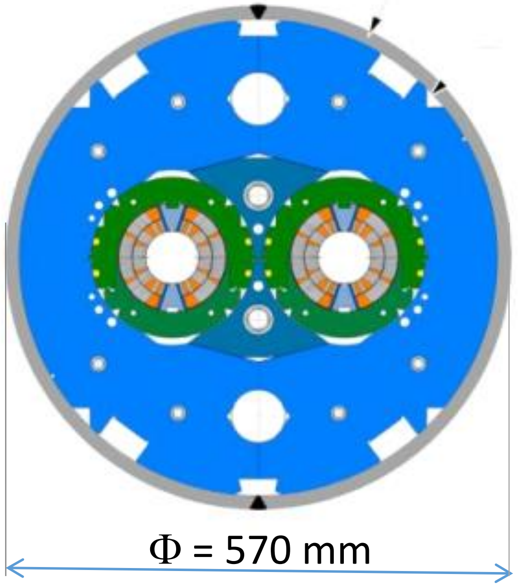
HL-LHC 11 T Nb$_3$Sn Dipoles

By-pass cryostat with **collimator**

F. Savary

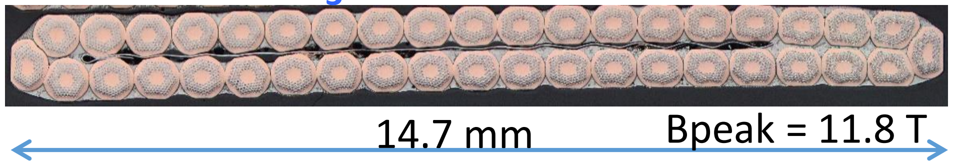


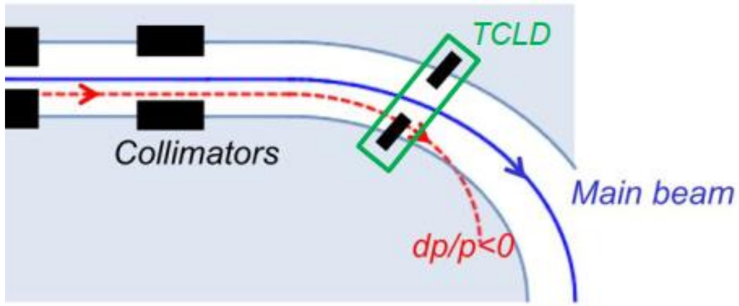
11 T cryo-assembly replacing a 15.6 m 8.3 T LHC dipole in 2020



4 + 2 Nb$_3$Sn Dipoles (5.5 m long)
LHC IP7 – both sides

11 T Nb$_3$Sn Rutherford Cable

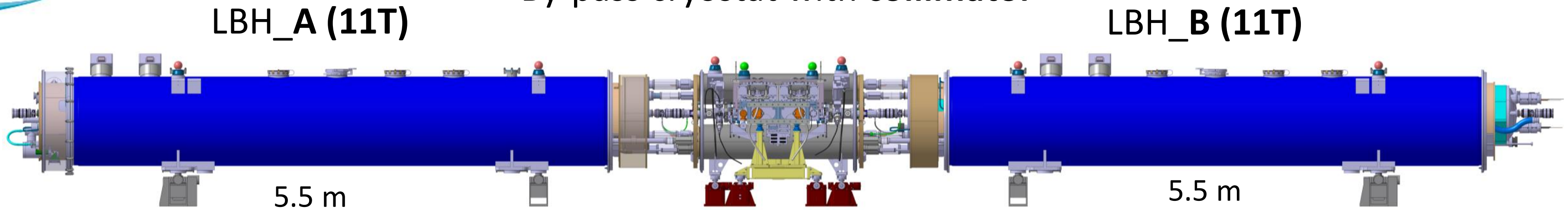


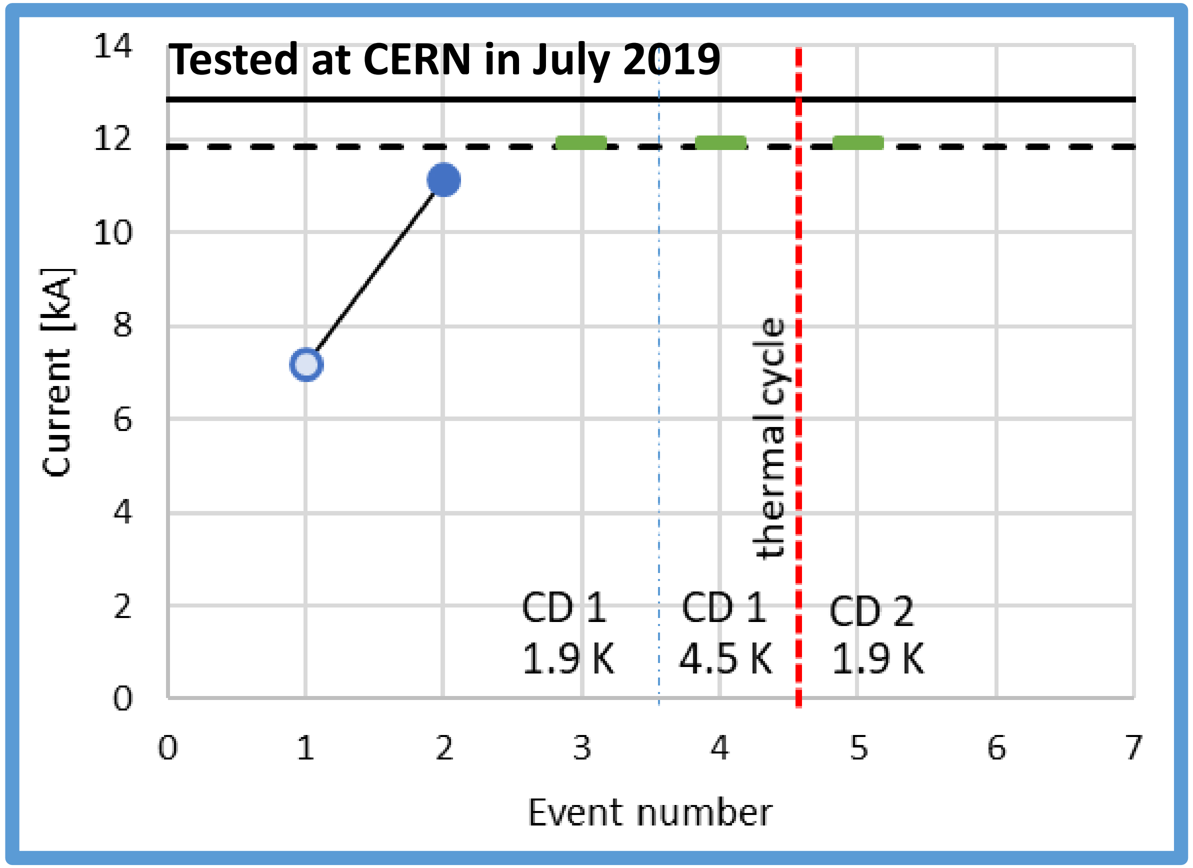


Installation in the LHC Tunnel by mid 2020

HL-LHC 11 T Nb_3Sn Dipoles

By-pass cryostat with **collimator**





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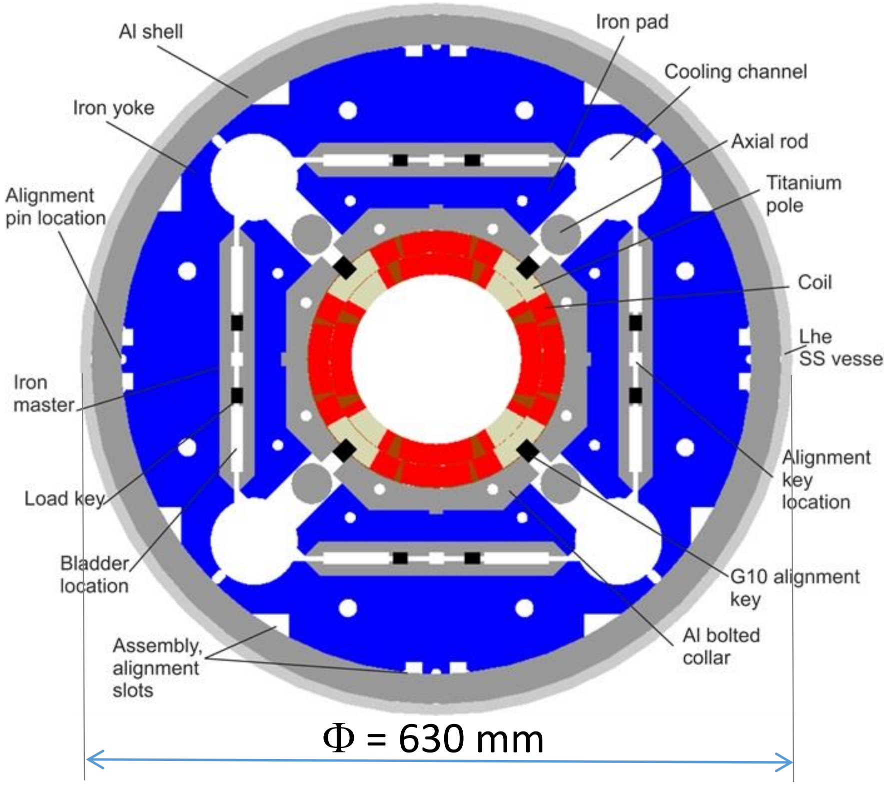
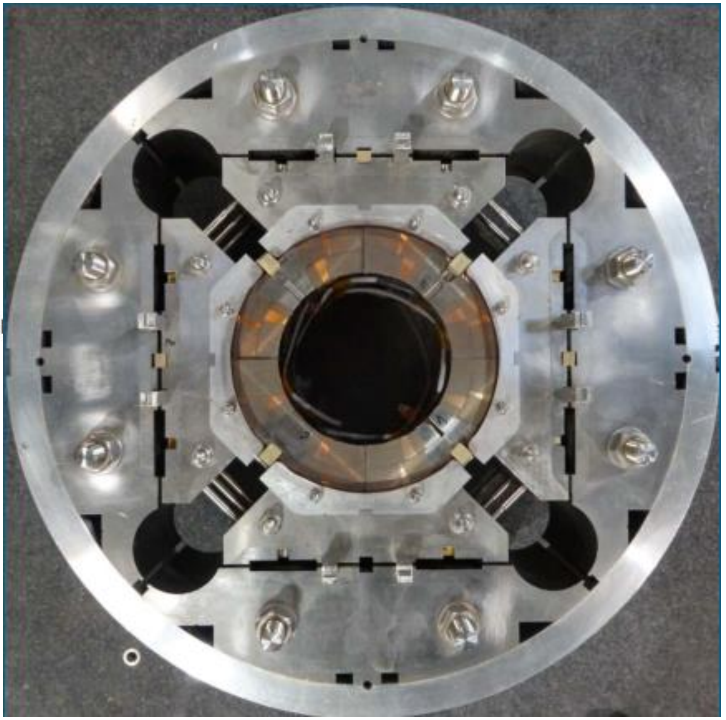
The 11 T Nb_3Sn Dipoles Production at CERN

HL-LHC Focusing Quadrupoles

Low-β Nb_3Sn Quadrupoles for HL-LHC Triplets





Large aperture:
150 mm (70 mm in LHC)

Bpeak:
11.4 T (8.6 T in LHC)
Nb_3Sn (Nb-Ti in LHC)

Number of magnets:
8 + 2 (7.2 m long)
16 + 4 (4.2m long)

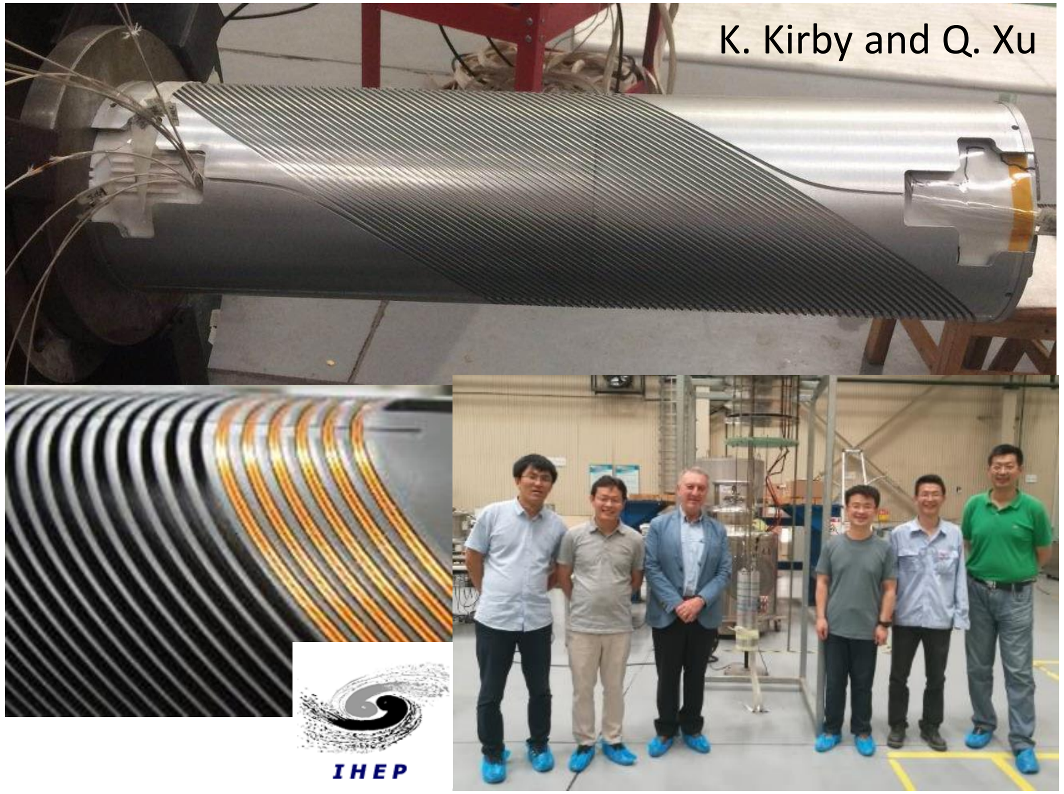
Bladder and keys technology (USA-LARP development)

Installation in the LHC Tunnel in 2024

G. Ambrosio and P. Ferracin

Construction of the 1st and 2nd long (7.5 m) IT Quad Proto at CERN
Winding 4th long magnet in USA (2×4.2 m)

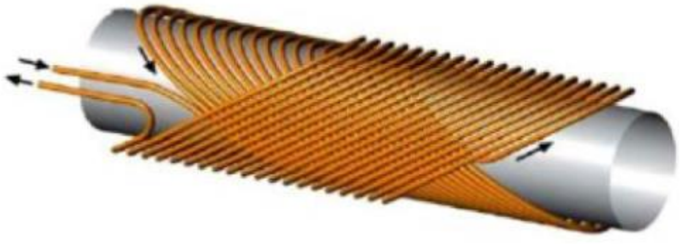
Canted-Cosine Theta Nb-Ti Magnet

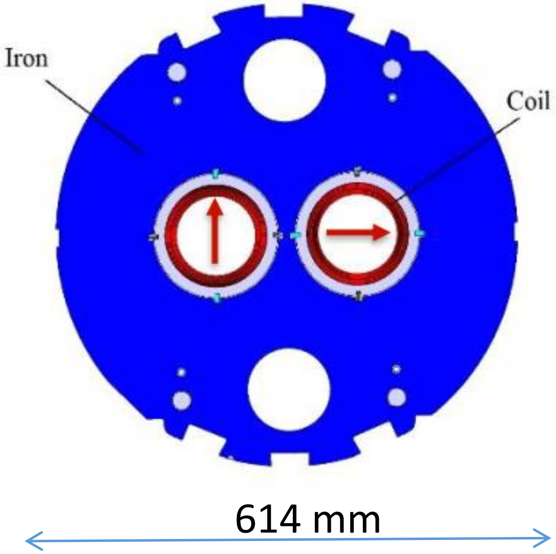


K. Kirby and Q. Xu

HL-LHC Orbit Corrector Dipole, 2.6 T
2.2 m long, 105 mm aperture

Tilted solenoid





Series: 8+4 Magnets

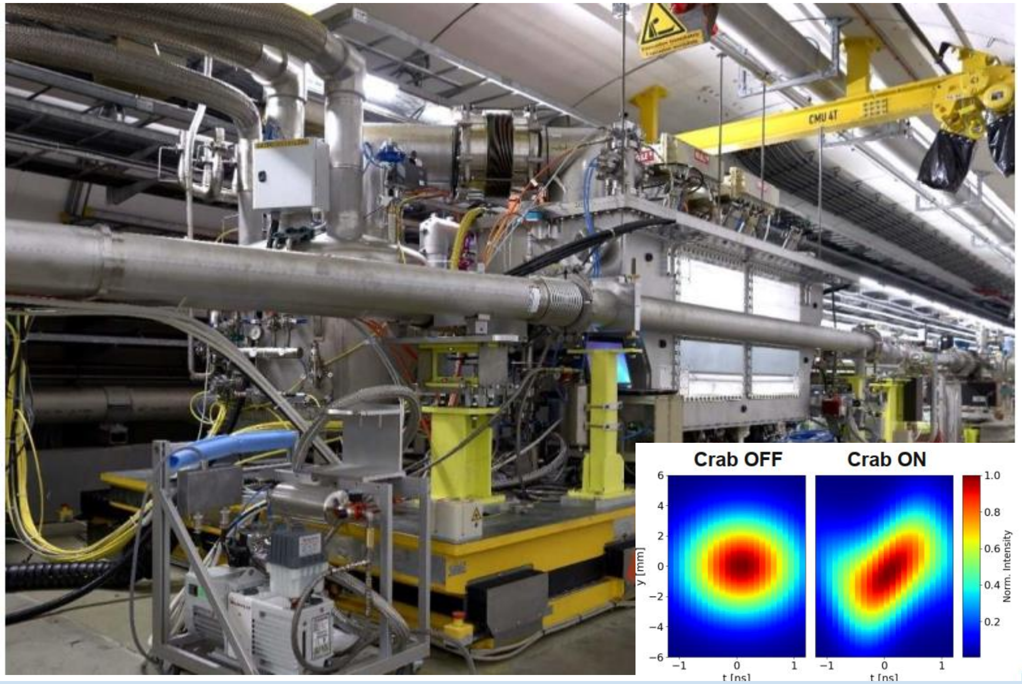
HL-LHC Crab Cavities

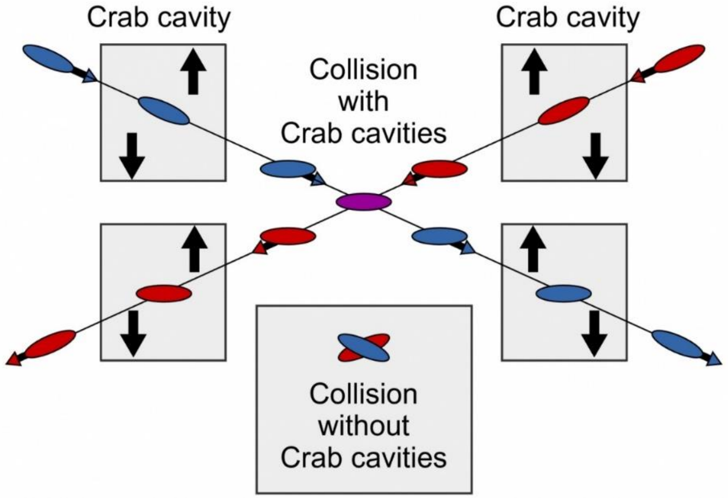
16 SC RF Crab Cavities to be installed at LHC IP1 (ATLAS) and IP5 (CMS)

R. Calaga, O. Capatina

Nb bulk, 2 K – 500 μrad
5 MV/m per cavity, 500 MHz

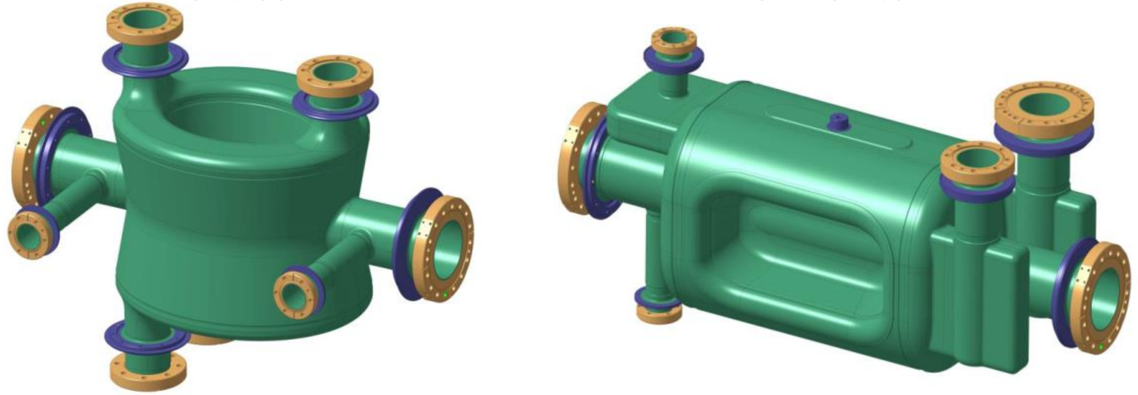
First crabbing demonstration with proton beam (26 GeV) CERN, SPS, May 2018



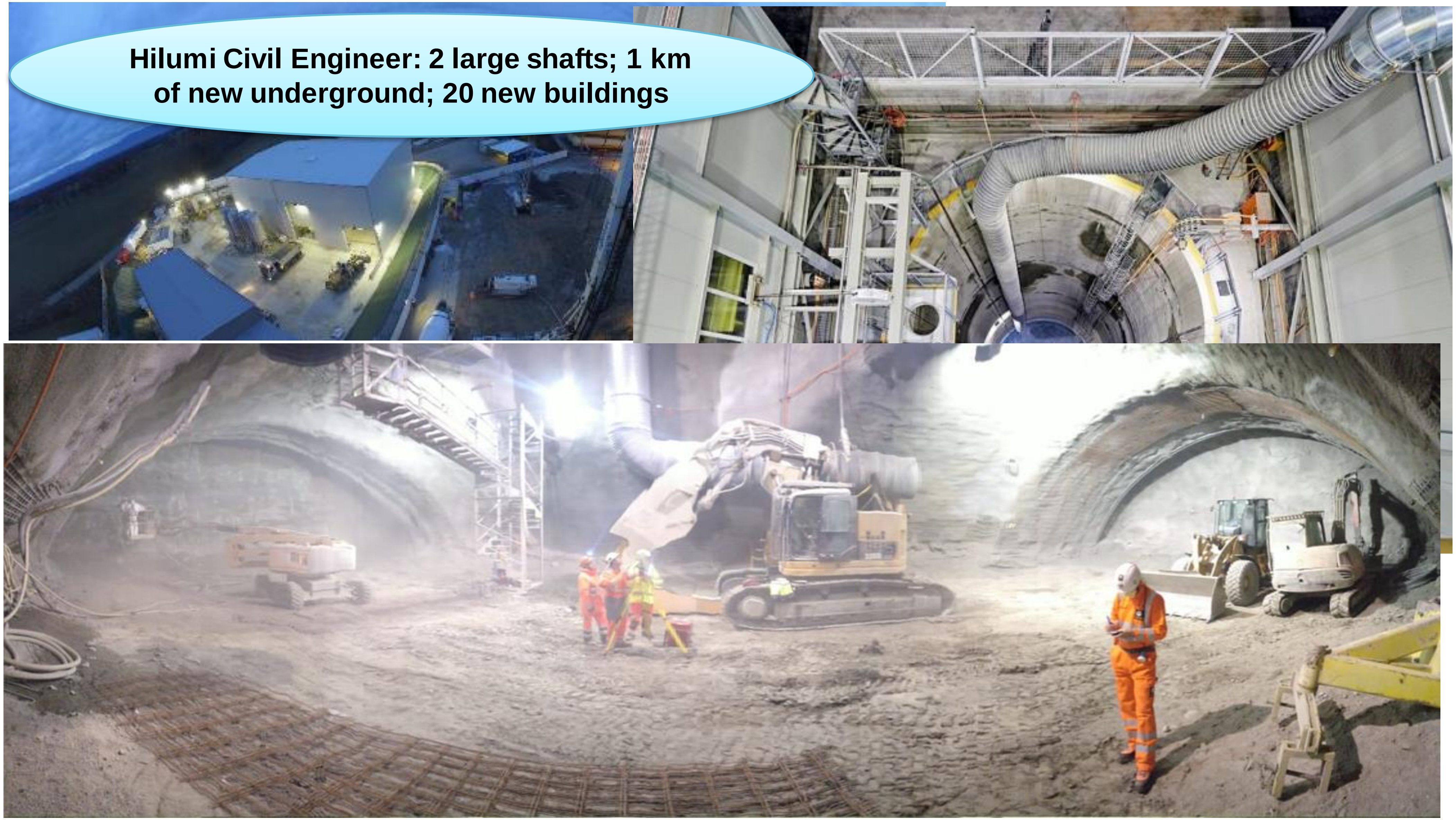


Double Quarter Cavity – P5
Vertical

RF Dipole Cavity – P1
Horizontal



Civil Engineering for HL-LHC

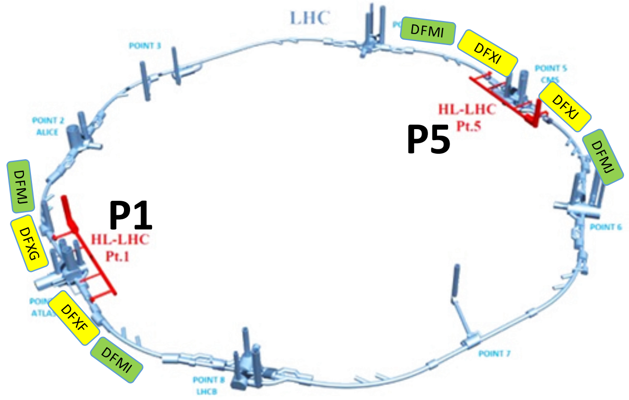


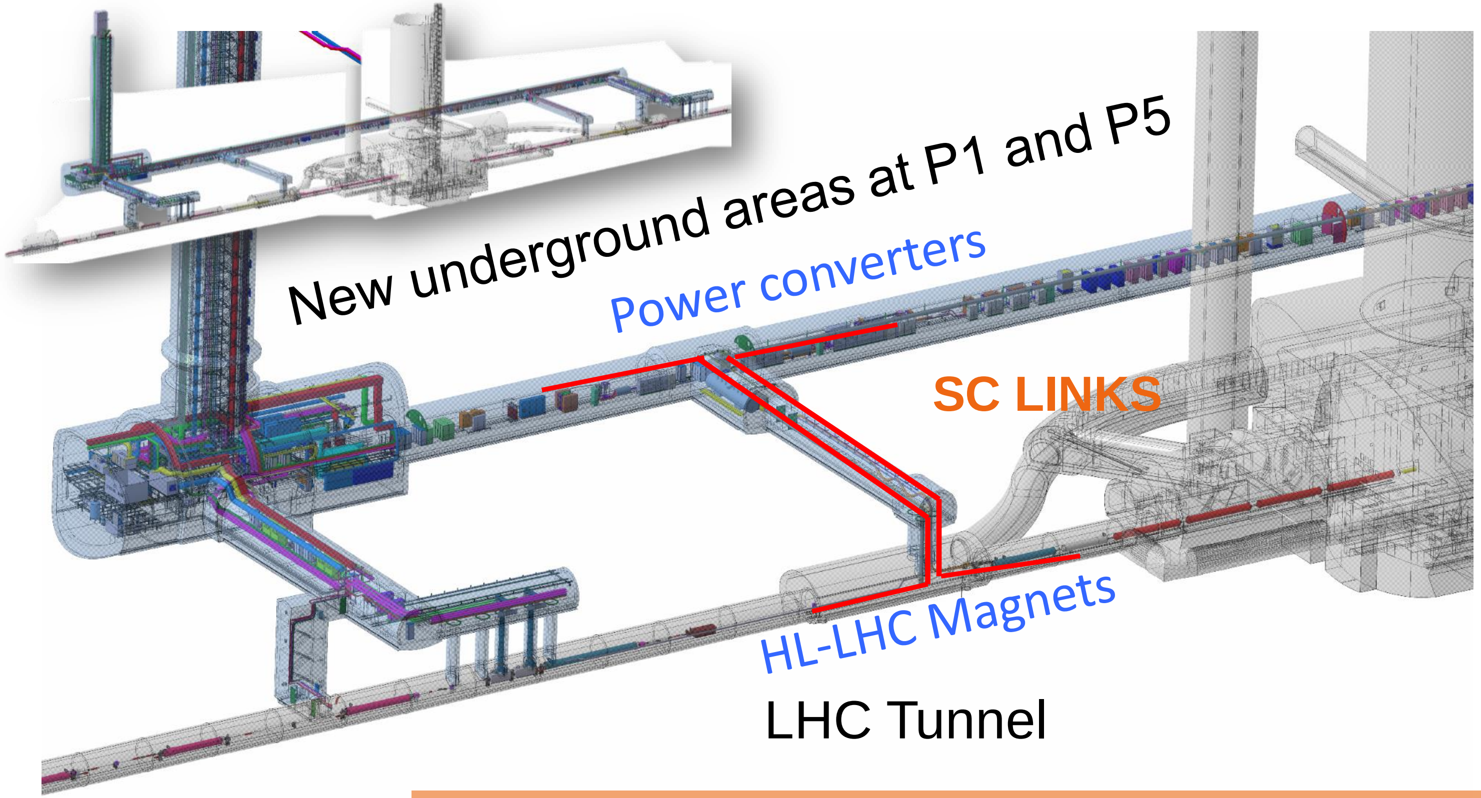
Hilumi Civil Engineer: 2 large shafts; 1 km of new underground; 20 new buildings

HL-LHC MgB_2 Superconducting Links

CERN

UNIVERSITY OF Southampton





MgB_2 + ReBCO

8 + 2 SC Links
Unit lengths ~ 100 - 140 m
DC Current up to ~ 100 kA

Powering the HL-LHC magnets via MgB_2 SC Lines

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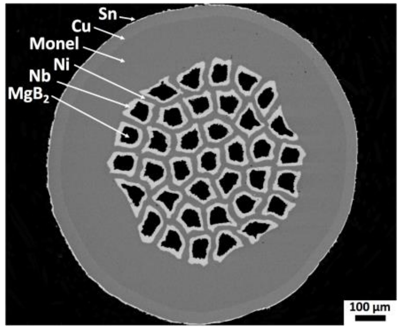
MgB_2 cables for Superconducting Link

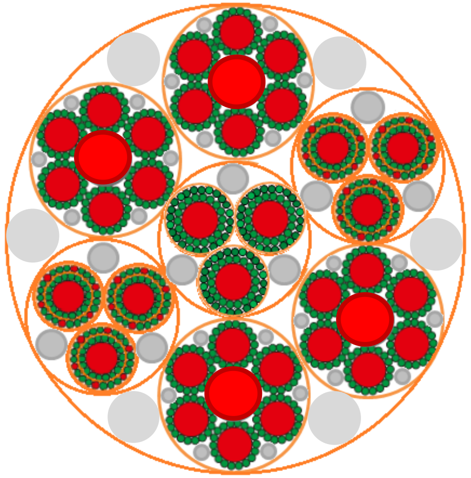
MgB_2 Columbus wire



MgB_2 Wire (Φ = 1 mm)
37 MgB_2 Filaments

~ 1000 km MgB_2

MgB_2 cables assembly



Φ ~ 90 mm
~ 129 kA at 25 K
Forced flow of GHe

Cabling in industry a reacted MgB_2 wire

HL-LHC MgB_2 Superconducting Link

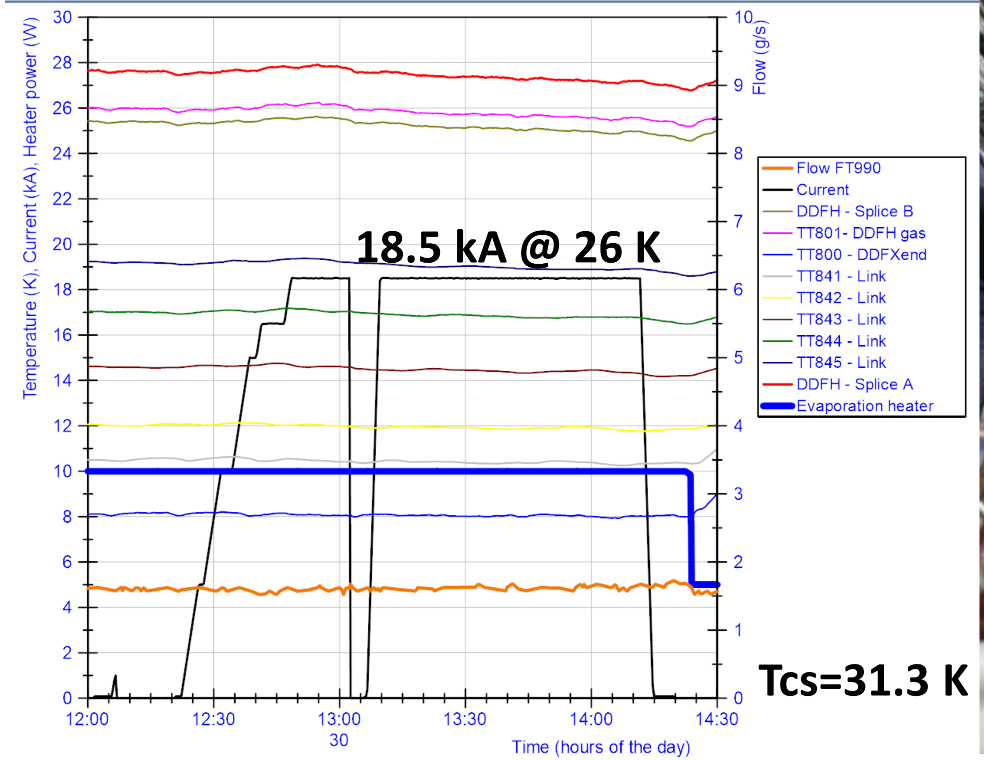
First system test at CERN in March 2019

MgB_2 60 m - 2×18 kA

MgB_2 up to 25 K

2×18 kA ReBCO Current Leads

REBCO up to 50 K



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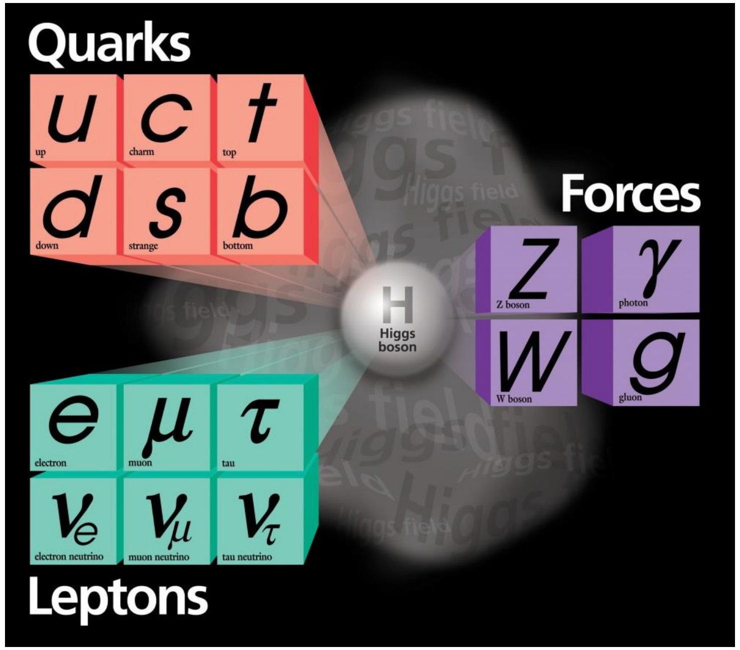
Future accelerators

The LHC Findings

- **Last particle predicted by Standard Model**, the **Higgs boson**, discovered at CERN – **July 2012**
- **Standard model complete**
- **No significant deviations** from Standard Model observed

Standard Model
Particles and forces



Standard Model: self-consistent field theory up to the quantum gravity scale - 10^{19} GeV ?

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Limitations of Standard Model

Experimental observations

Neutrino masses and oscillations

The three neutrinos oscillate and therefore have masses. The Standard Model predicts that neutrinos have no masses

Matter/Antimatter asymmetry

Where is antimatter ?

The SM does not explain the unbalance between matter and antimatter in our universe

Dark matter

About 27 % of universe, but it is not included in Standard Model. Evidence: rotation curves of galaxies, supernovae observations,...

Dark energy

Theoretical observations

The Standard Model does not include gravity

…

Importance of technology development

- **Fundamental research** beyond the frontiers of knowledge brings to **unpredicted discoveries**
- **New colliders under study** cannot promise discovery of a new particle. They **address specific questions**
- **Development of advanced experimental capabilities** is fundamental for enabling future discoveries – and continued of future generations of scientists

Importance of technology development

Galileo Galilei: father of Modern Astronomy

January 1610: discovery of moons orbiting the planet of Jupiter

Evidence for the Copernican understanding of the universe

The Jupiter's moons

Superconducting technologies

- **SC Cavities for acceleration**
  - **Give energy to a charged particle beam**
  - Low Rs → $Q_o \geq 10^{10}$ (wrt to ~ 10^4 for Cu cavities)
  - Smaller power consumption
  - Long pulse acceleration fields
  - Large beam aperture
  - $B < B_c$ → $E_{max} \sim 45$ MV/m (for Nb)

- **SC Magnets for hadron colliders**
  - **Steer and focus a charged particle beam**

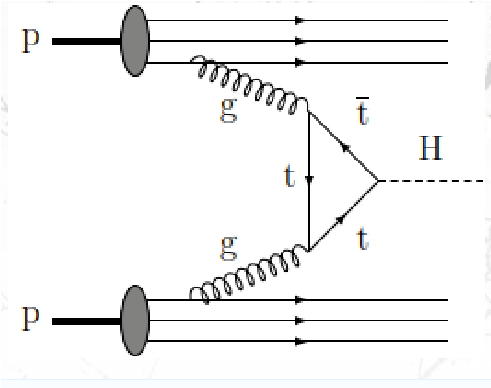
- **Other equipment, e.g. powering equipment**

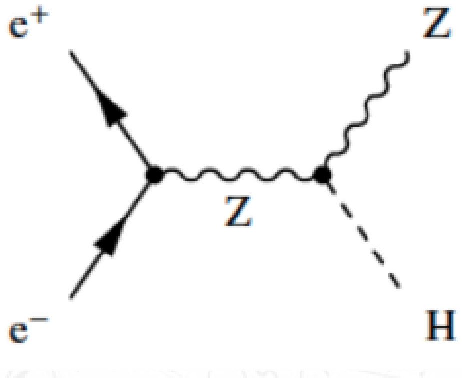
Physics beyond the Standard Model

- **Higgs factories** that operate over a wide range of beam energies for:
  - Precision measurements of Higgs and other particles - that carry the imprint of Higgs, e.g. W (80.4 GeV) and Z (91.2 GeV) bosons and top quark (173.3 GeV);
  - Operation at high (up to 100 TeV) energies

Higgs portal to new physics

Future High Energy Colliders - Studies
Hadron (p-p) vs lepton (e^+-e^-) collisions





p-p collisions

e^+-e^- collisions

pp compound objects

e^+ e^- point like particles

Future High Energy Colliders - Studies

- **Lepton colliders**: great for **precision studies**. Last operational: LEP, almost 20 years ago. They can be also discovery machines

  Linear or **Circular**:

  - **Linear Lepton Colliders**: **higher energies** (for a sufficient linear length)
  - **Circular Lepton Colliders**: limited by energy losses due to synchrotron radiation ($\Delta E \propto \frac{E^4}{m^4 R}$). But **greater collision rates (large luminosity)**. They can be **re-used** as next generation of **high-energy hadron colliders** (**as LEP** – Z_0 factory at 90 GeV and W^+W^- factory at 160 GeV – **and then LHC**)

- **Hadron (proton) Colliders**: **energy reach** via **circular machine.** Highest center of mass energy. Large discovery range

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Future High Energy Colliders - Studies

$e^+ e^-$ (Lepton) Colliders

- ILC
- CLIC

Linear Colliders

- FCC-ee
- CEPC

Circular Colliders

p-p (Hadron) Colliders

- FCC
- SppC
- HE-LHC

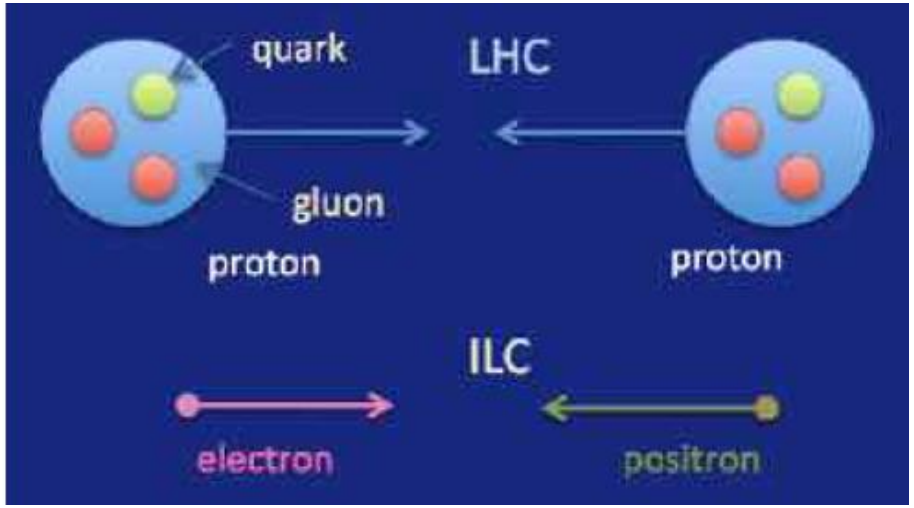
Circular Colliders

Others

- Muon Colliders
- Plasma Colliders

Future accelerators: linear e^+e^- colliders

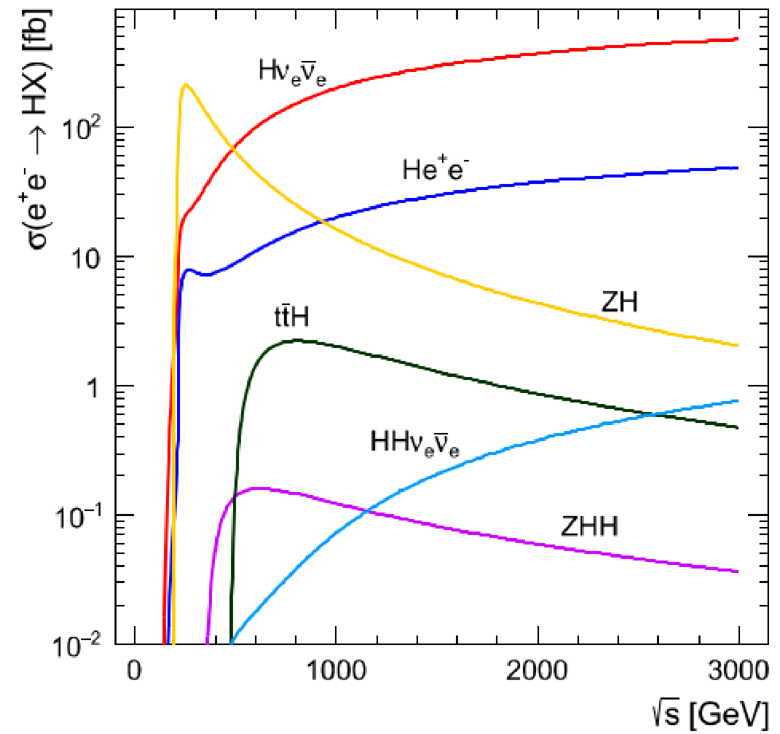
Linear e^+ -e^- Colliders



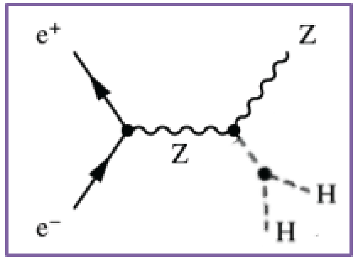
High precision measurements in a clean environment

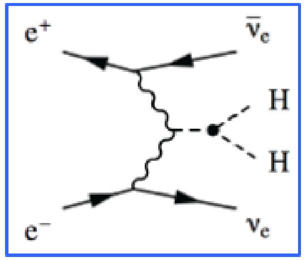
$$E_{cm} = 2\,F_{fill}\,L_{linac}\,G_{RF}$$

Energy reach → High gradient

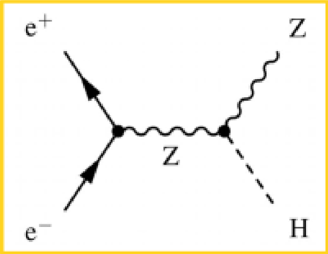


Cross sections for Higgs production processes vs center-of-mass energy

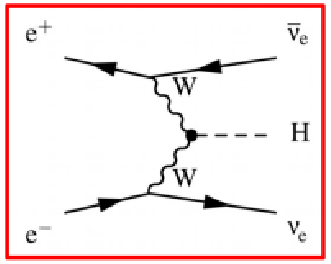




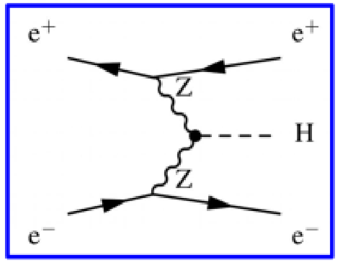
≥ 250 GeV



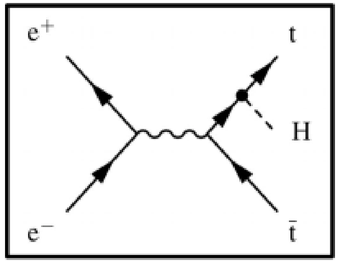
≥ 350 GeV



≥ 350 GeV



≥ 500 GeV



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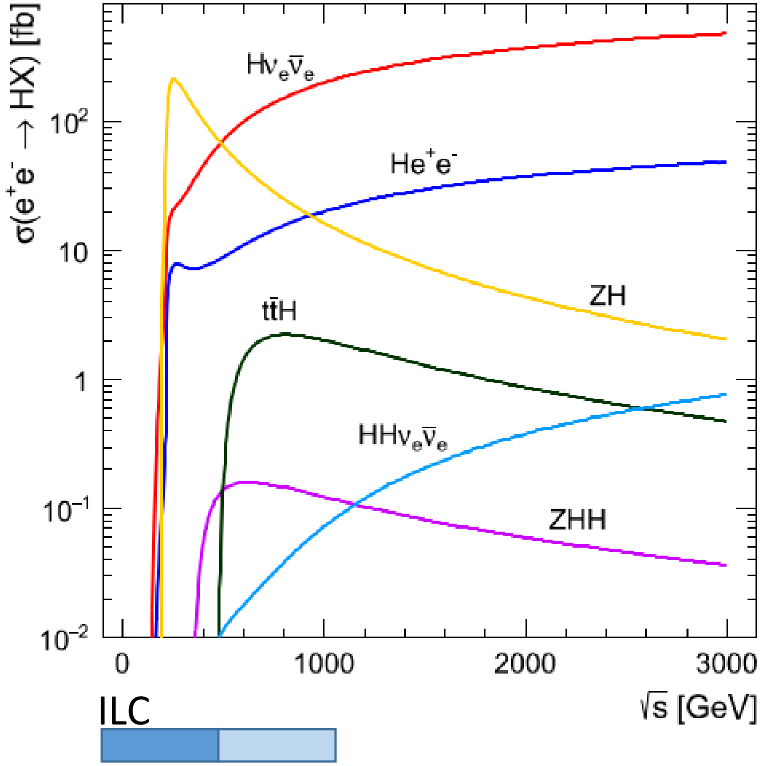
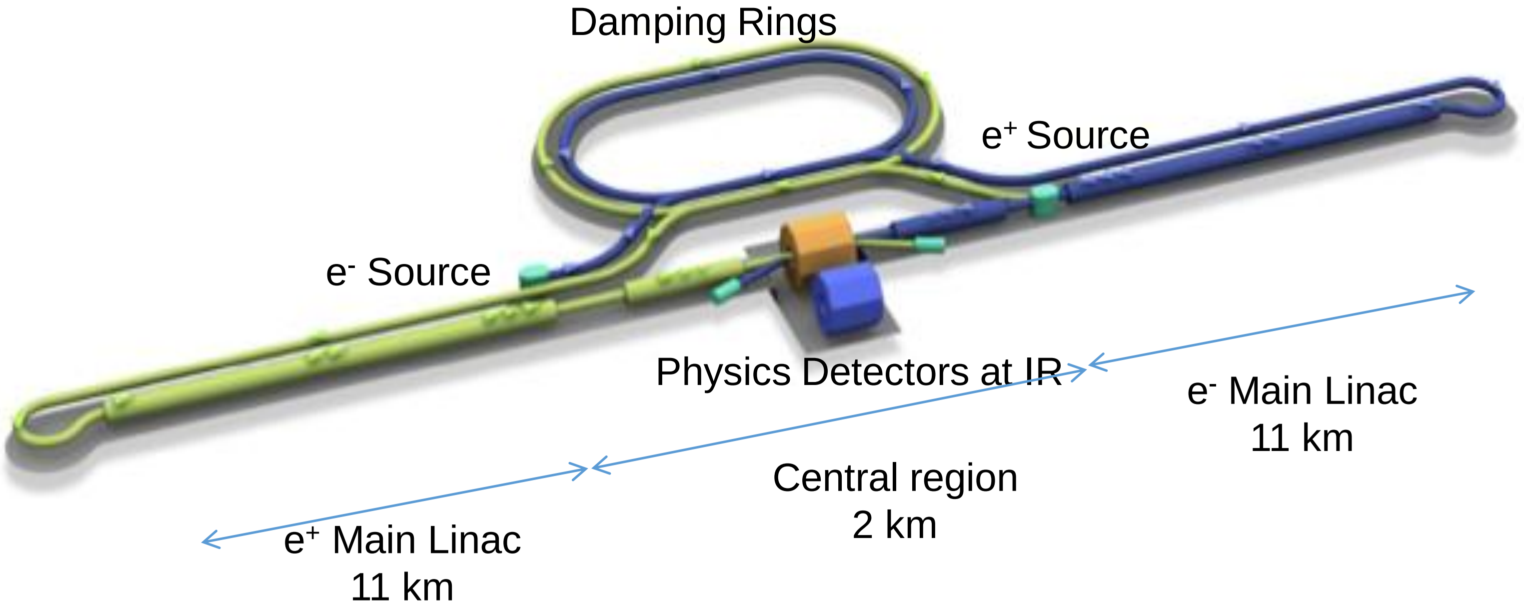
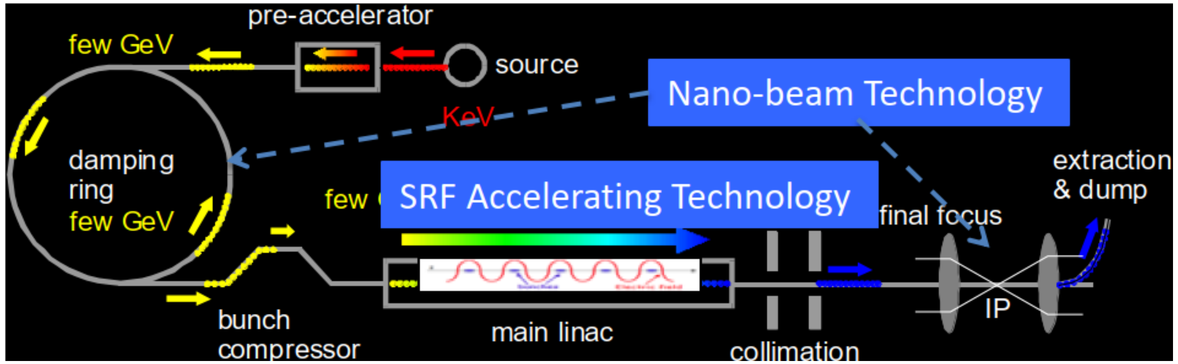
International Linear Collider (ILC)

E_{CM} = 250 GeV – 500 GeV
L = 20 km (250 GeV)
31 km (500 GeV)
Upgradable to 1 TeV (50 km)

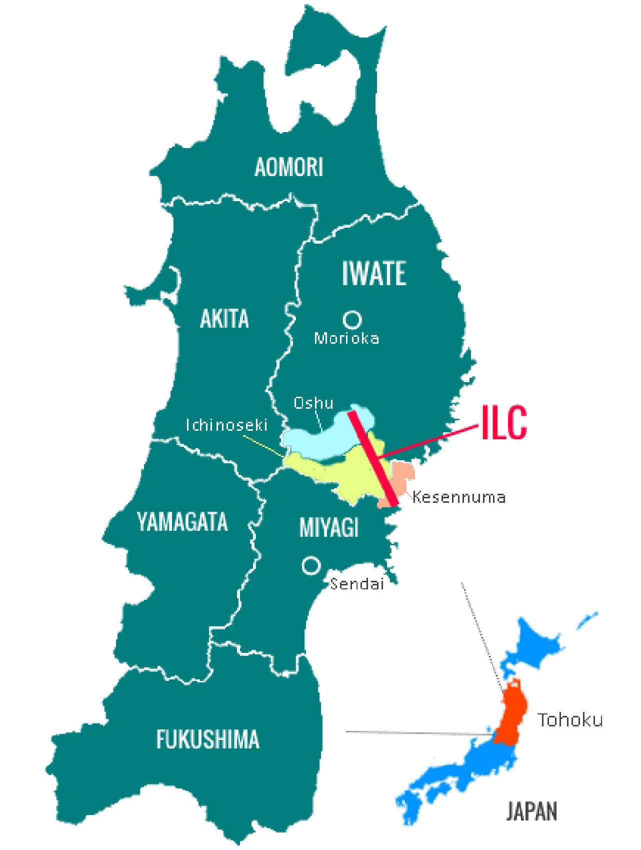


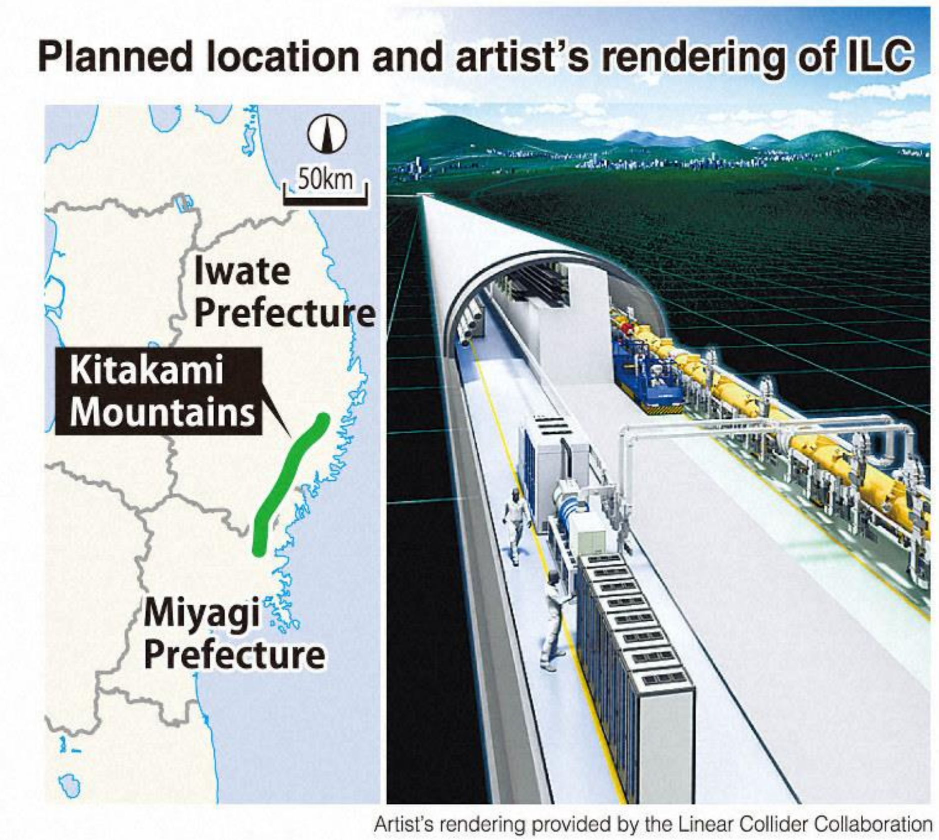




ILC: international facility in Japan

Site in Kitakami region, in northern Japan – close to Sendai and Morioka





Artist's rendering provided by the Linear Collider Collaboration

Geological conditions for a tunnel up to 50 km long

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ILC: Superconducting RF Technology

- **Superconducting RF Nb cavities**

  Standing wave cavities – TESLA Technology

  ~ **16000** Cavities (500 GeV) – Each cavity has **9 Cells** (1.25 m long)

  ~ **1855 Cryo-modules** (each 12 m long, 9 or 8 cavities)

  Production yield ~ 90 % → **Needed industrialization**

- Operating temperature ~ **2 K** (**superfluid helium**). Six cryoplants
- Average field gradient: **31.5 MV/m ± 20 %**
- RF frequency = **1.3 GHz**
- $Q_0 \geq 10^{10}$

State-of-the-art technology considered mature for building ILC

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Recent progress in SC RF Technology (1/5)

- **XFEL (DESY-Germany) – European X ray Free Electron Laser (17.5 GeV)**

800 SC Cavities, 100 cryomodules

9 Cells Nb cavities, 2 K

23.6 MV/m (design gradient), **$Q_0 \geq 10^{10}$, 1.3 GHz**

Cavity **series production** entirely made **in industry**

Coordination of production: **DESY, INFN-LASA**

Cryo-module at **CEA-Saclay**

Cold testing at **DESY**

Average performance: ~ **30 MV/m** with $Q_0 \geq 10^{10}$

Acceptance at 20 MV/m

Vertical test inserts

Operation with beam as from 2017

Successful first large scale industrial production (2012-2015)

Recent progress in SC RF Technology (2/5)

- **FAST, Fermilab (USA)**
  - **FAST Accelerator, 300 MeV e$^-$ beams**

    31.5 MV/m, 1.3 GHz (2017), 2 K

    One cryomodule, **eight cavities**

    Commissioning with beam in Nov. 2017

    Demonstration of ILC RF specification

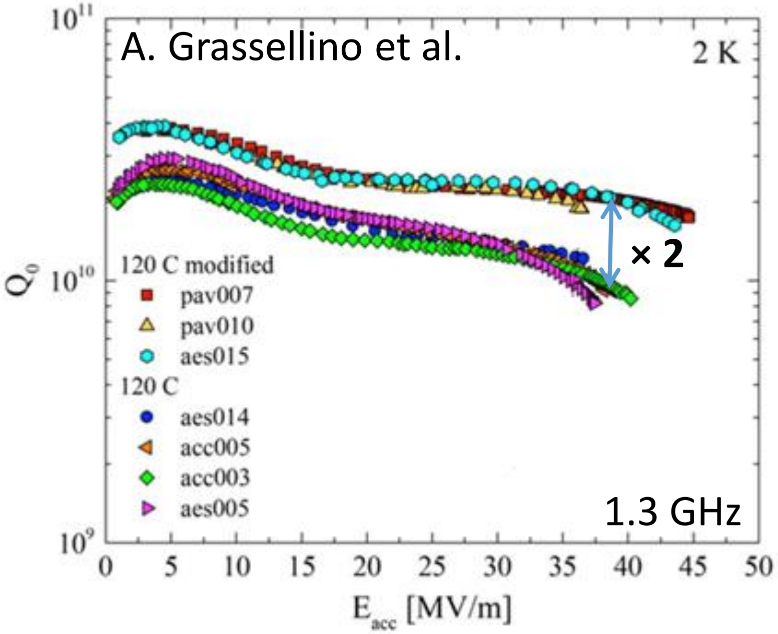
- **N_2 doping: high Q**

  Exposure to **N_2 at ~ 800 °C bake**

  Q >$3\cdot10^{10}$, 35 MV/m
- **N_2 Infusion: high gradient and high Q**

  Exposure to **N_2 at ~ 120 °C bake**

  Q >$1\cdot10^{10}$, 45 MV/m



Supercond. Sci. Technol. **30** (2017) 094004

Recent progress in SC RF Technology (3/5)

- **LCLS2 (SLAC-USA) – Linac Coherent Light Source**

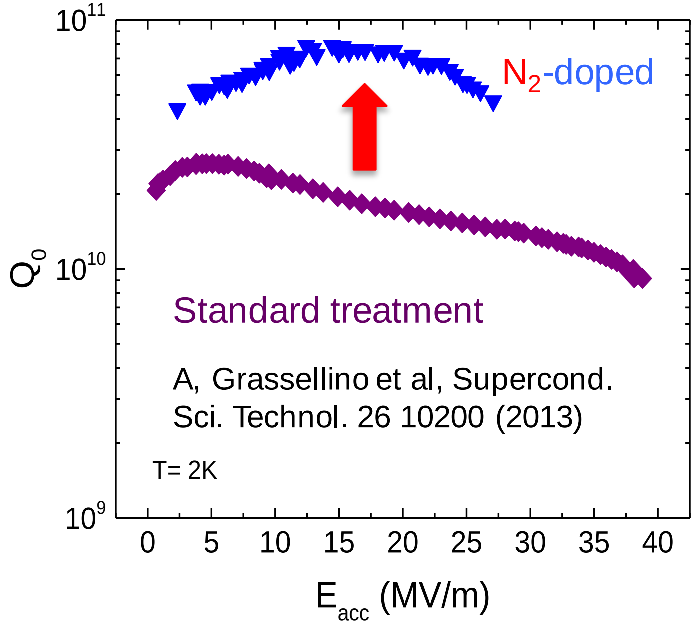
280 SC Cavities, 35 cryomodules

9 Cells Nb cavities, 2 K, 1.3 GHz, CW mode

16 MV/m (operational gradient), $Q_0 \geq 2.7^{10}$

19 MV/m (test gradient), $Q_0 \geq 2.7^{10}$

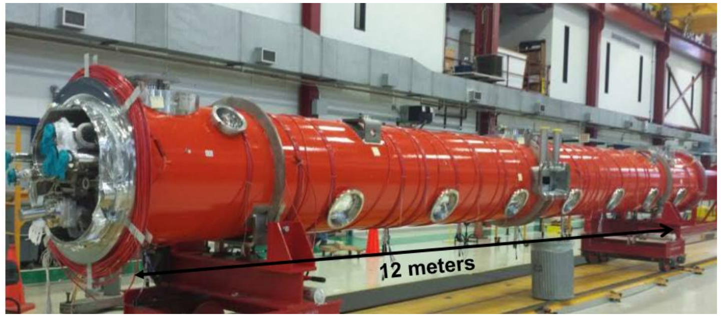
Implementation of **Nitrogen doping**



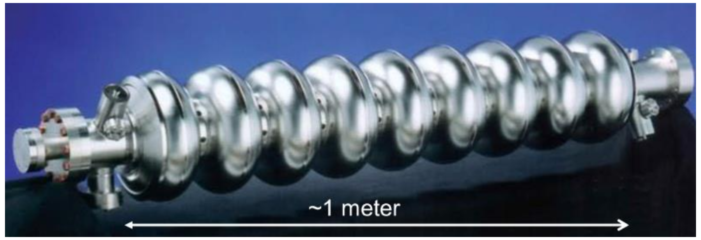
A, Grassellino et al, Supercond. Sci. Technol. 26 10200 (2013)

In production

Cryomodule



RF Cavity



Recent progress in SC RF Technology (4/5)

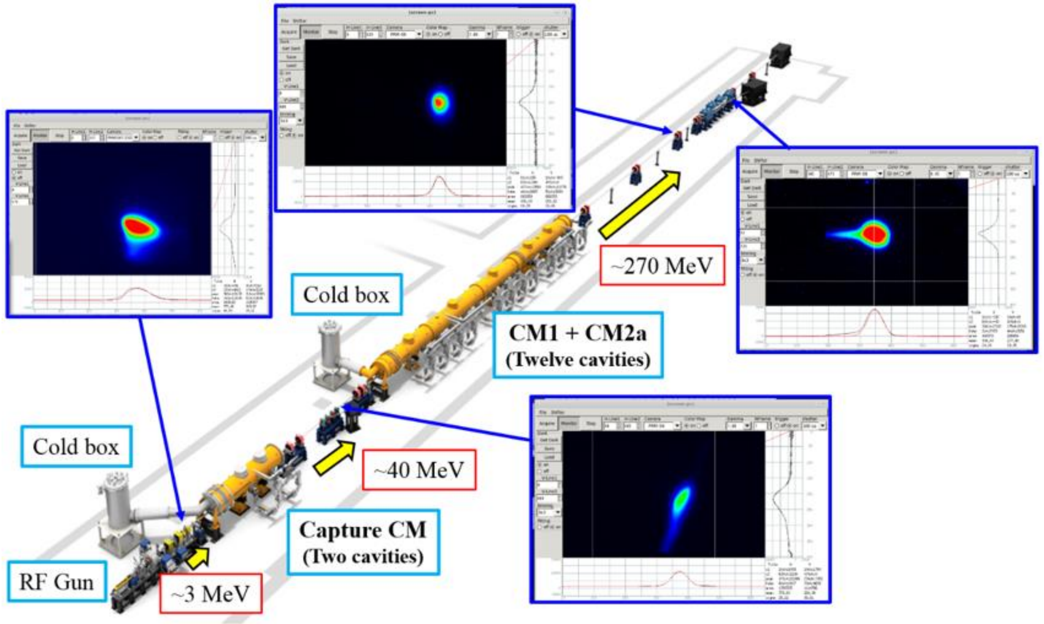
- **STF2 (KEK) – Superconducting RF Test Facility**

February-March 2019: operation with beam
Two half cryomodules (one with **2** and one with **7 cavities**)
9 cell cavities

Beam energy ~ 270 MeV

32 MV/m

Demonstration of ILC RF specification



Progress in SRF Technology for Accelerators

Progress (1988~)

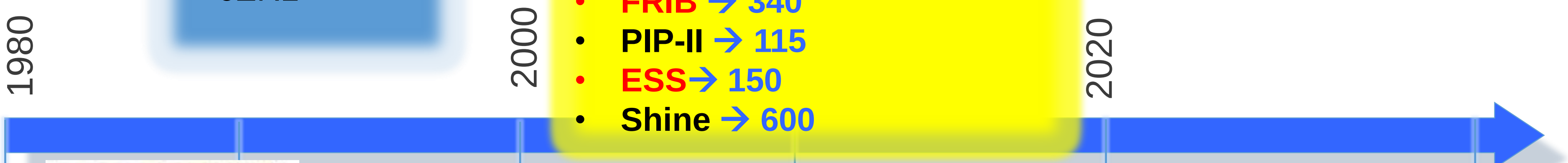
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation: → # cavities

- **SNS: 1 GeV**
- **CEBAF 12 GeV → 80**
- **ISAC-II, ARIEL**
- **Super-KEKB**
- **Eu-XFEL → 800**

Under Construction:

- **LCLS=II → 300**
- **FRIB → 340**
- **PIP-II → 115**
- **ESS→ 150**
- **Shine → 600**



> 2000 SRF cavities made in the last 10 years !

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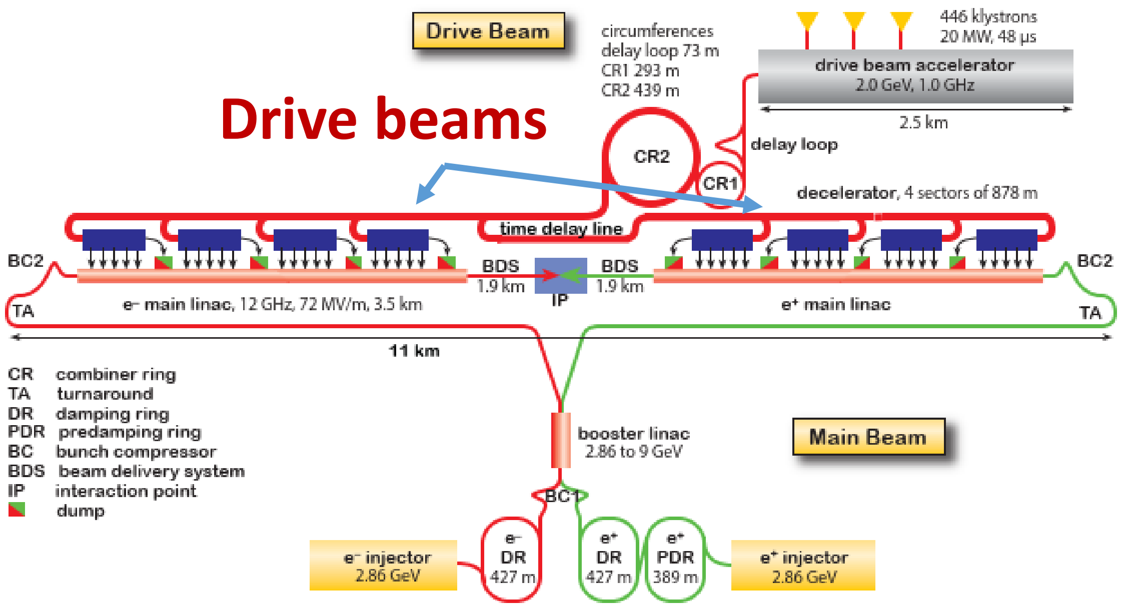
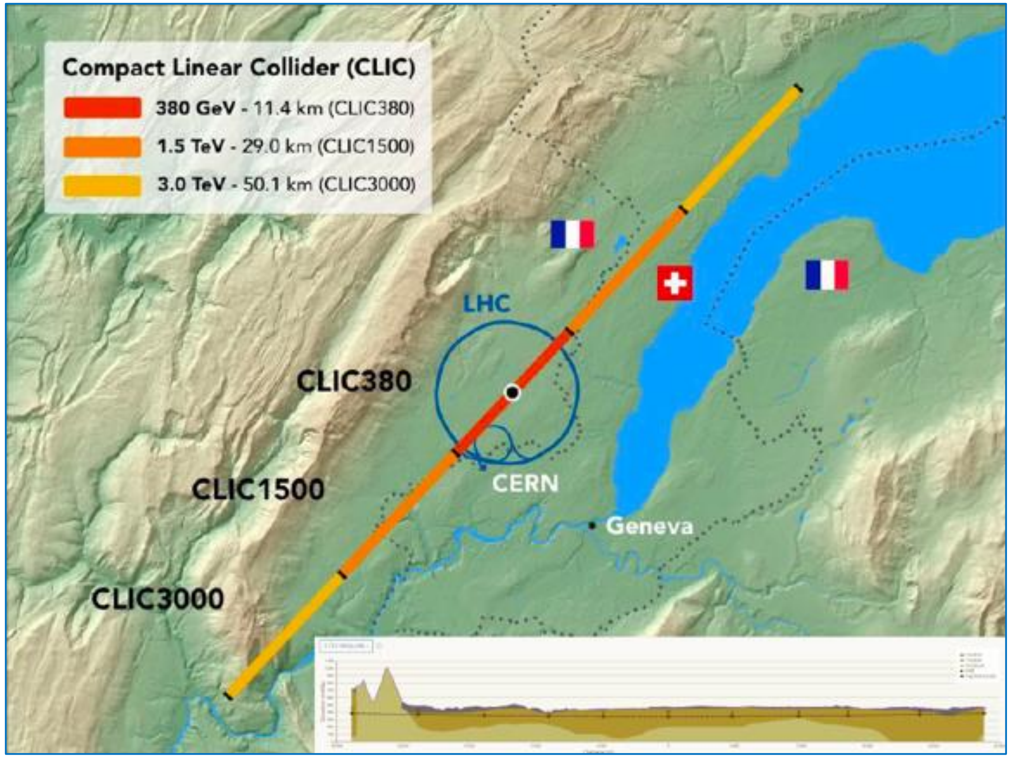
Compact Linear Collider (CLIC)

380 GeV layout



Drive beams

Location



Drive beam replacing the klystron

Normal-conducting 70-100 MV/m, 12 GHz cavities

CLIC Parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-1}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

380 GeV-3 TeV

72 MV/m - 100 MV/m

11.4 km – 50.1 km

Higher energies – Improved sensitivity for rare decays

SC MgB_2 Solenoid for X-band Klystron

CLIC-380 staging scenario X-band (12 GHz) klystron-based accelerating scheme

Beam-focusing solenoid ~ **0.6 T** in a warm bore-diameter of 0.24 m

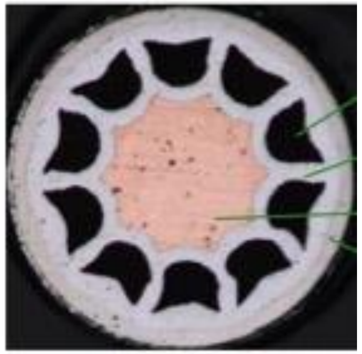
Cu magnet : ~ **20 kW**/Klystron, **~ 100 MW** for ~ 5000 Klystrons

MgB_2 magnet : < **2 kW**/Klystron , **~ 10 MW --> 90 % power saving**

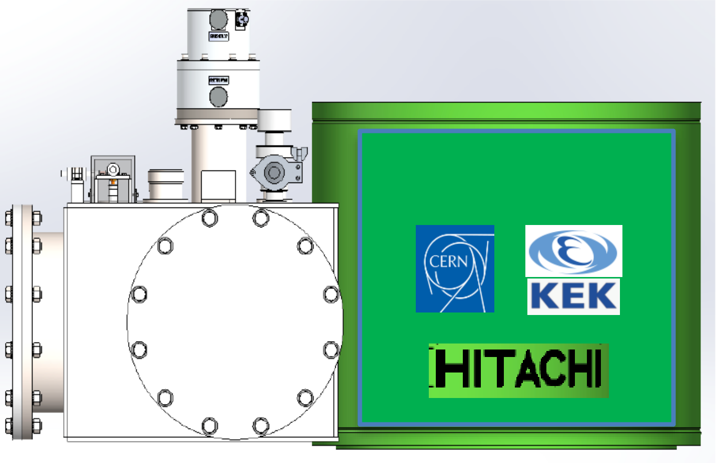
Design Parameters	
Superconductor (T-operation)	MgB_2 (@ 20 K)
Current	50 A
Central field	0.7 T
Stored energy	~ 10 kJ
Cryo-cooler applied	6.7 W @ 20 K 13.5 W @ 80 K
AC Plug-Power	≤ 3 kW (< 1,5 kW/Klystron for a pair)

System successfully commissioned at Hitachi in February 2019

Hitachi in-situ MgB_2 wire



Φ=0.67 mm



Courtesy A. Yamamoto

A. Ballarino

Future accelerators: circular e^+e^- colliders

Future High Energy Colliders - Studies

$e^+ e^-$ (Lepton) Colliders

CLIQ
ILC

Linear Colliders

FCC-ee
CEPC

Circular Colliders

p-p (Hadron) Colliders

FCC
SppC
HE-LHC

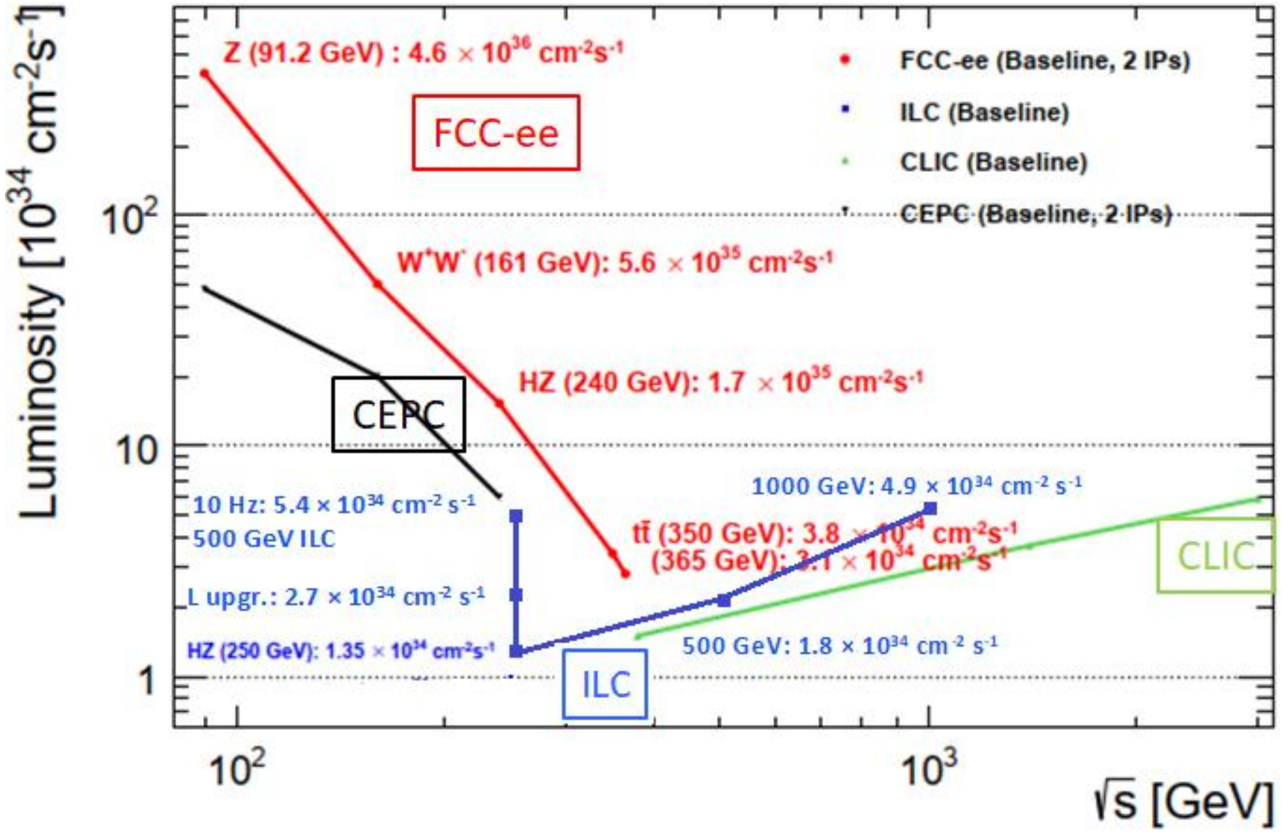
Circular Colliders

Others

Muon Colliders
Plasma Colliders

Circular $e^+ e^-$ Colliders

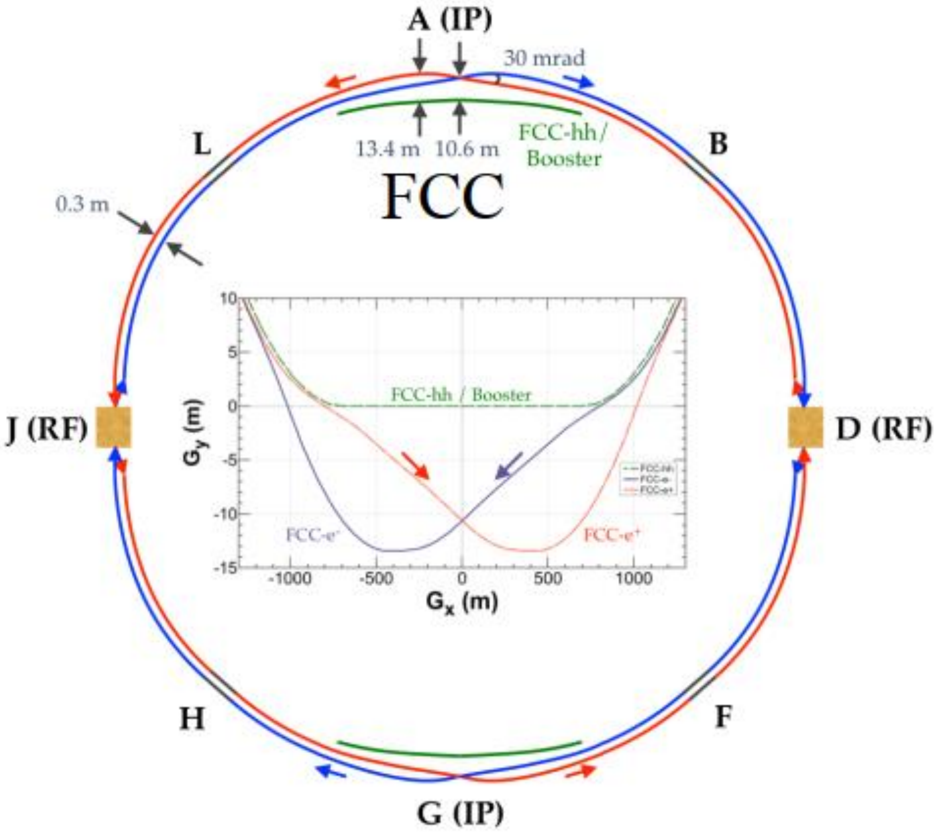
High luminosity



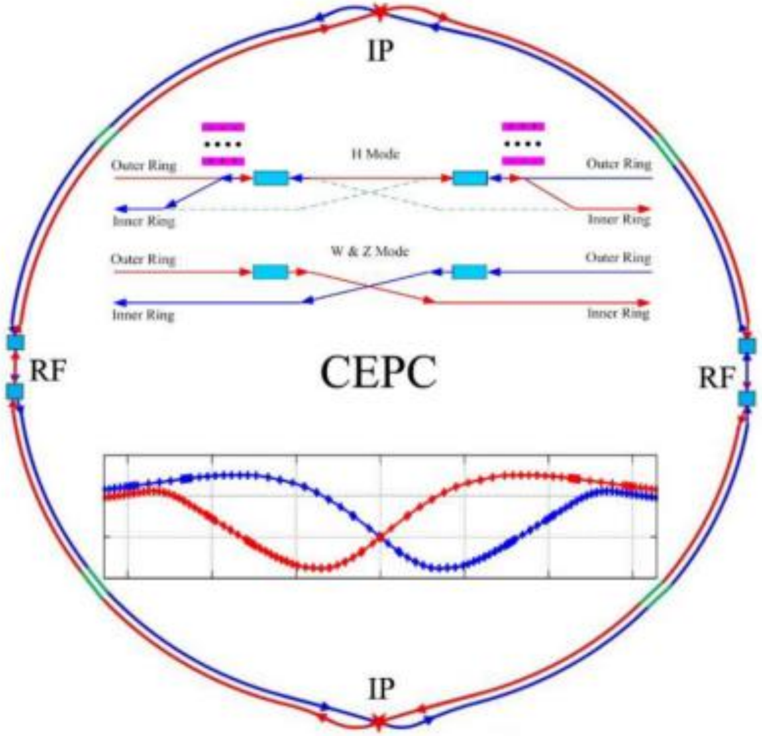
FCC-ee (Z, W, H, tt) as Higgs factory, EW and top factory at highest luminosities

FCC e^+-e^- and CEPC

Double ring colliders – Circumference ~ **100 km – Two IPs**
Two RF straights- Common use of RF for both beams



FCC CDR https://fcc-cdr.web.cern.ch/



CEPC CDR https://arxiv.org/abs/1809.00285

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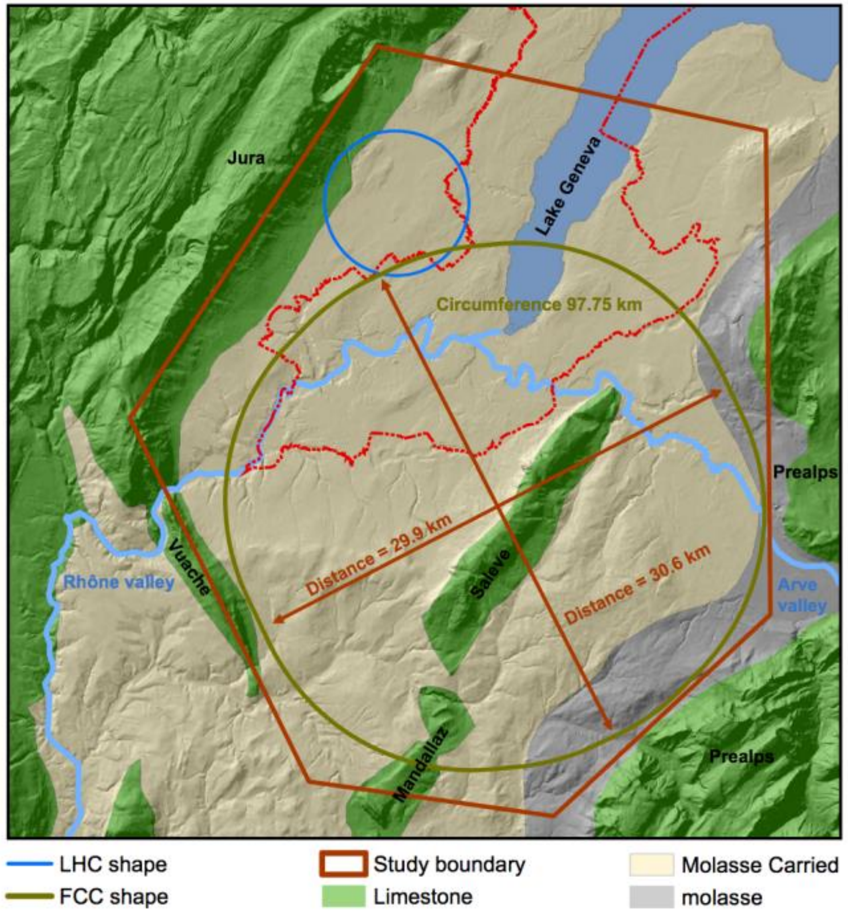
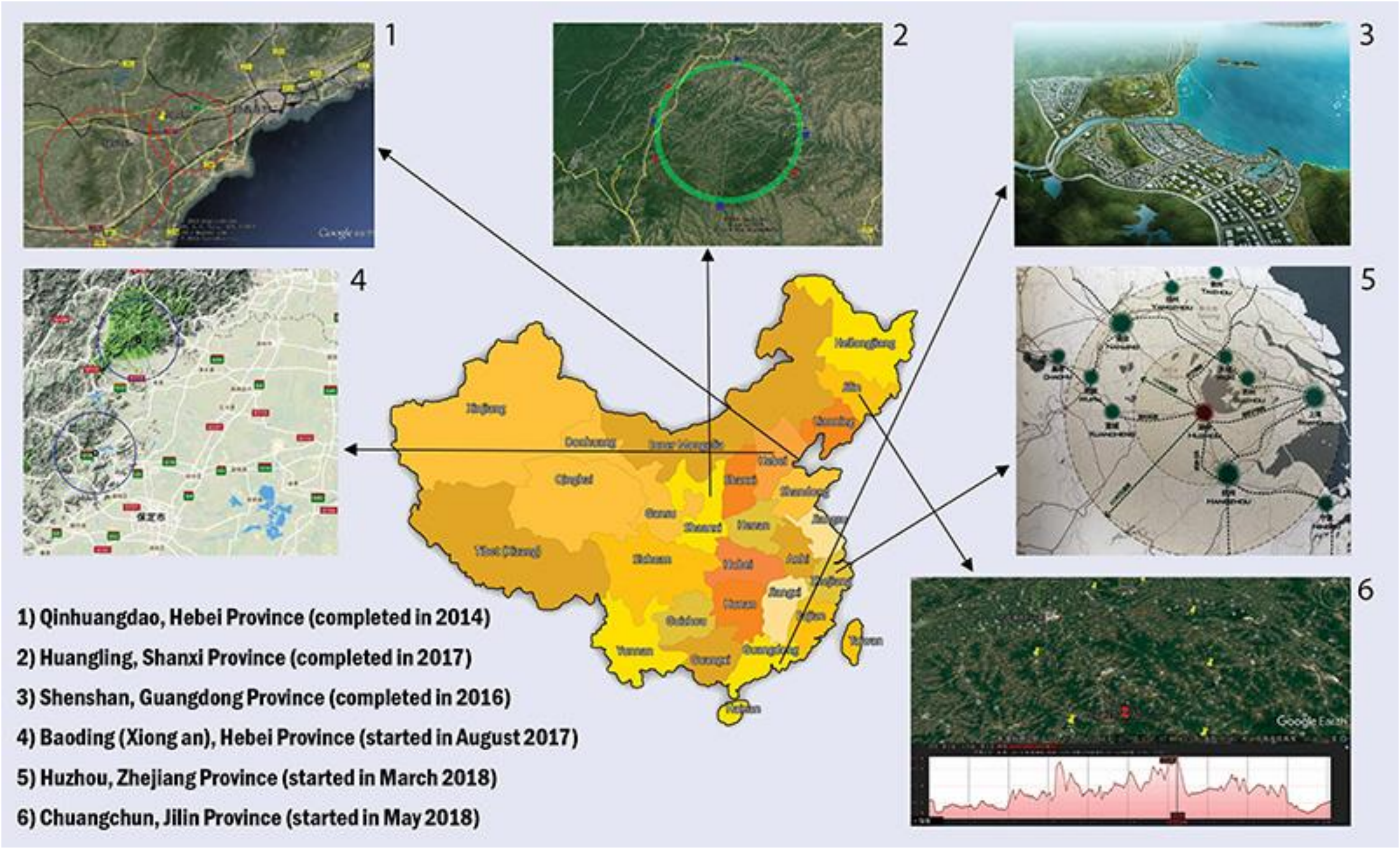
FCC e^+-e^- and CEPC - Location

FCC



CEPC



1) Qinhuangdao, Hebei Province (completed in 2014)
2) Huangling, Shanxi Province (completed in 2017)
3) Shenshan, Guangdong Province (completed in 2016)
4) Baoding (Xiong an), Hebei Province (started in August 2017)
5) Huzhou, Zhejiang Province (started in March 2018)
6) Chuangchun, Jilin Province (started in May 2018)

Image courtesy IHEP

SC RF for FCC e^+-e^-

	Z	W	H	t
E_{beam} [GeV]	**45**	**80**	**120**	**175**
SR energy loss/turn U_0 [GeV]	0.03	0.33	1.67	7.55
Current [mA]	1450	152	30	6.6
$P_{SR,tot}$ [MW]	**50**	**50**	**50**	**50**

c.m.e. 90 GeV → 350 GeV

Baseline: SC cavities @ 400 and 800 MHz:

400 MHz for lower energy/higher beam currents:

Nb/Cu @ 4.5 K

LHC cavities (400 MHz)

800 MHz cavities to reach highest energy/lowest beam currents:

Nb bulk @ 2 K

800 MHz five-cell RF cavity, bulk Nb

Jlab, Oct 2017

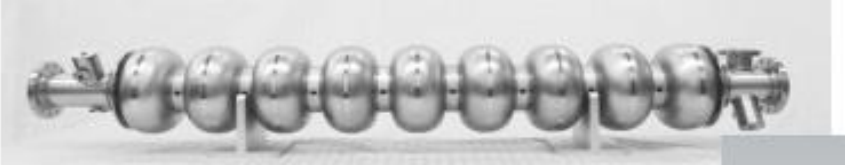
A. Ballarino

FCC e^+-e^- and CEPC – SRF Cavities

	f_{RF} [MHz]	#cavities	#cell/cavity	$V_{RF,tot}$ [MV]	acc. gradient [MV/m]	technology
FCC-ee-H	**400**	136 / ring	4	2000	**10**	**Nb/Cu**
FCC-ee-t	**800**	372	5	6930	**19.8**	**bulk Nb**
CEPC	**650**	240	2	2200	**19.7**	**bulk Nb**

CEPC – Collider Ring: 650 MHz Nitrogen doped fine-grain **Nb bulk** @ 2 K, 2-cell

CEPC – Booster: 1.3 GHz Nitrogen doped, fine-grain **Nb bulk** @ 2 K, 9-cell



RF SC Materials others than Nb

- **Nb_3Sn: primary alternative to Nb**

S. Calatroni talk, EUCAS 2019

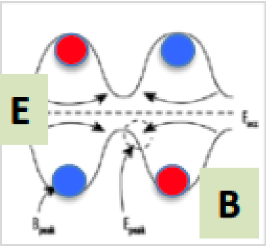
Broader parameter space:

Higher Tc: 18 K

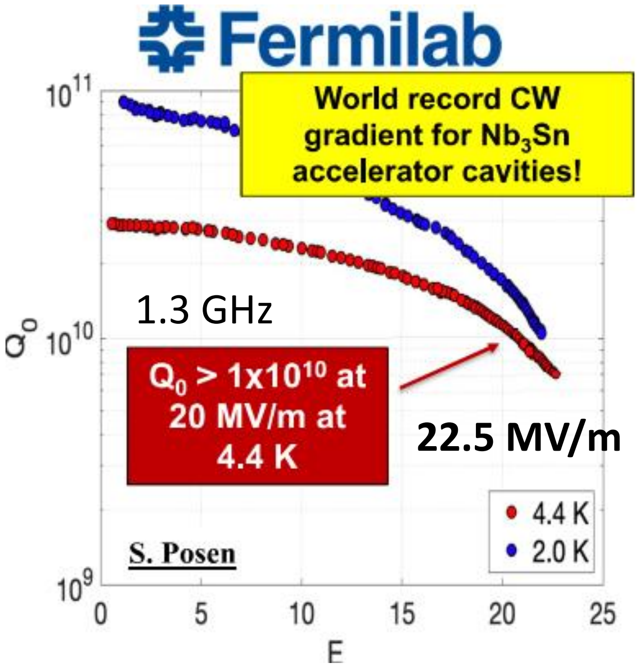
Higher Bsh: 425 mT → Emax ~ 96 MV/m

B_{sh} = practical limit for SRF

- $Bs_{sh\text{-}Nb}$: 210 mT
- $Bs_{sh\text{-}Nb3Sn}$: 430mT
- $Bs_{sh\text{-}MgB2}$: 310mT



State of the art 1.3 GHz performance
16 – 22 MV/m (FNAL record)



Thermal diffusion of Sn vapours
Liquid Sn diffusion
Magnetron sputtering

Electrochemical plating studies at FNAL and Cornell
Magnetron sputtering at CERN

Future High Energy Colliders - Studies

$e^+ e^-$ (Lepton) Colliders

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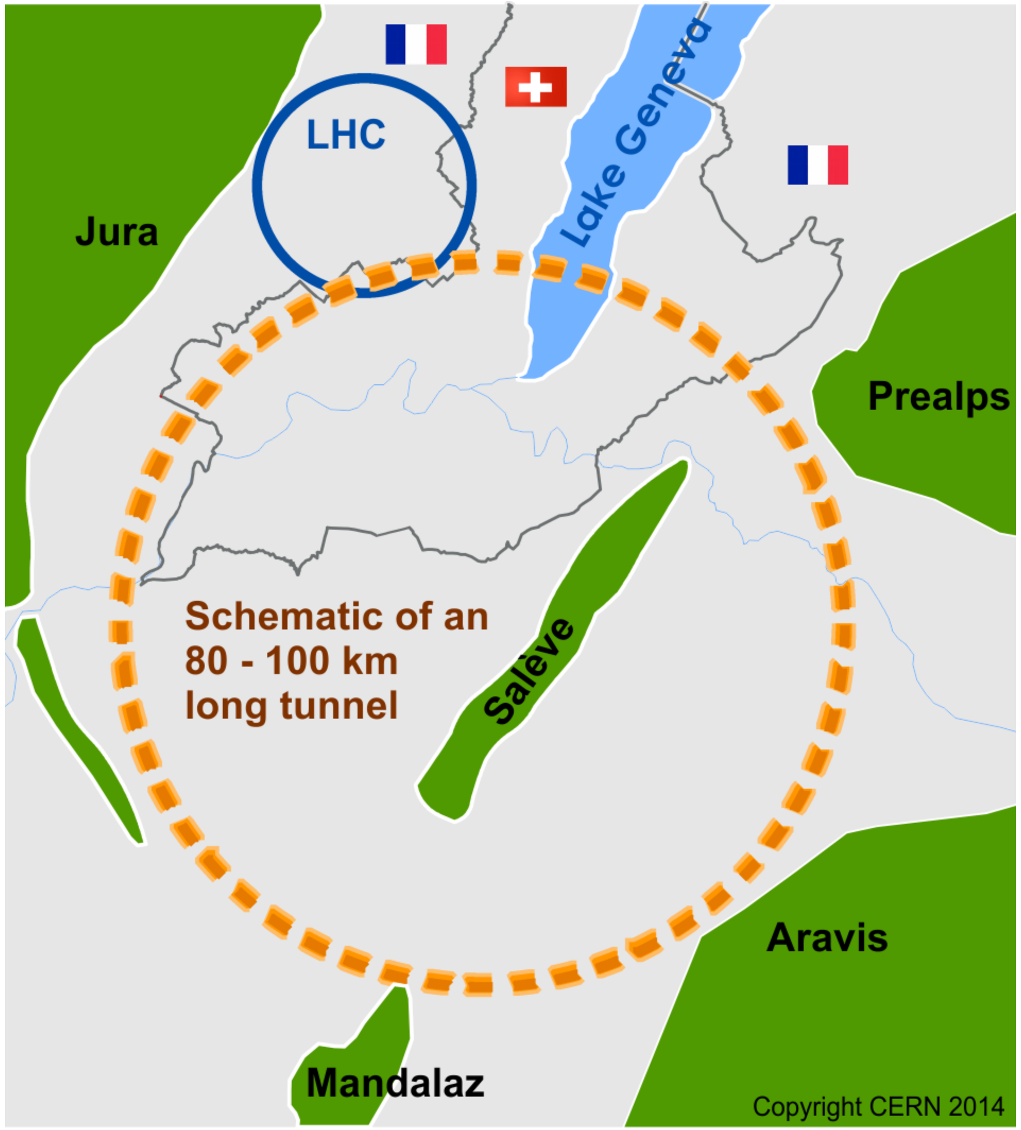
Plasma Colliders

Future Circular Collider (FCC) STUDY



International FCC collaboration with CERN as host lab to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e^+e^-* collider (*FCC-ee*),**
  → potential first step
- ***pp*-collider (*FCC-hh*)**
  → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

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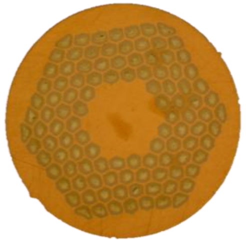
The 16 T Nb_3Sn high-field magnet technology

Nb_3Sn state-of the-art: HL-LHC conductor

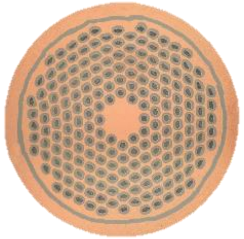
Total procurement ~ **30 tons**

	Lay-out	Sub-El. size [μm]	J_c (12 T), σ [A/mm^2]	J_c (15 T), σ [A/mm^2]	B_{c2}, σ [T]	J_c (16 T), σ [A/mm^2]	J_c (18 T), σ [A/mm^2]	RRR σ -	Effect of 15% Rolling Degradation in % J_c	RRR
RRP 0.7 mm	108 / 127	46	**2637,** *82*	**1371,** *74*	**24.2,** *0.5*	**1064,** *70*	**581,** *61*	**158,** 40	**0**	44
RRP 0.85 mm (75 hrs @ 665 ˚C)		55	**2797,** *53*	**1573,** *43*	**25.9,** *0.3*	**1266,** *41*	**769,** *36*	**135,** 25	**0**	51
RRP 0.85 mm (50 hrs @ 665 ˚C)			**2725,** *61*	**1498,** *47*	**25.4,** *0.3*	**1194,** *44*	**704,** *38*	**226,** 39	**0**	38
PIT 0.85 mm Bundle Barrier	192	39	**2267,** *46*	**1317,** *28*	**26.9,** *0.3*	**1075,** *25*	**681,** *19*	**193,** 17	6	**0**

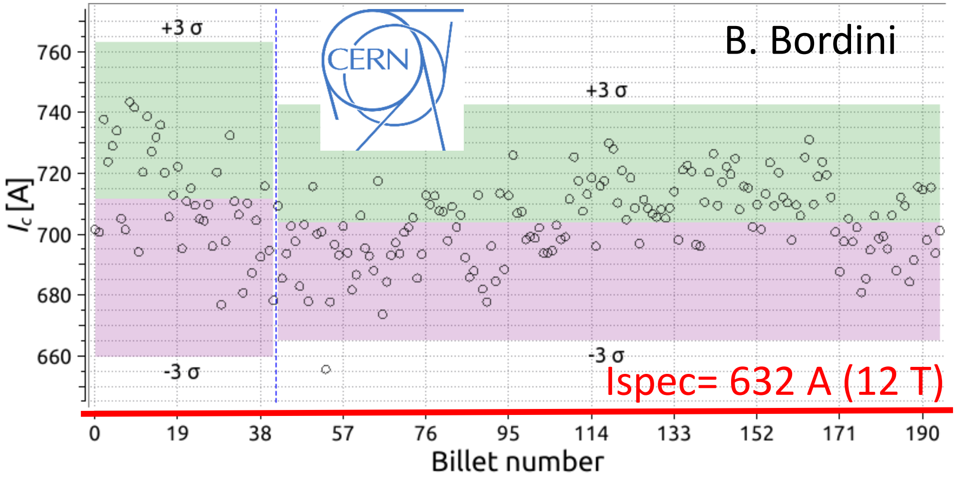
RRP 108/127

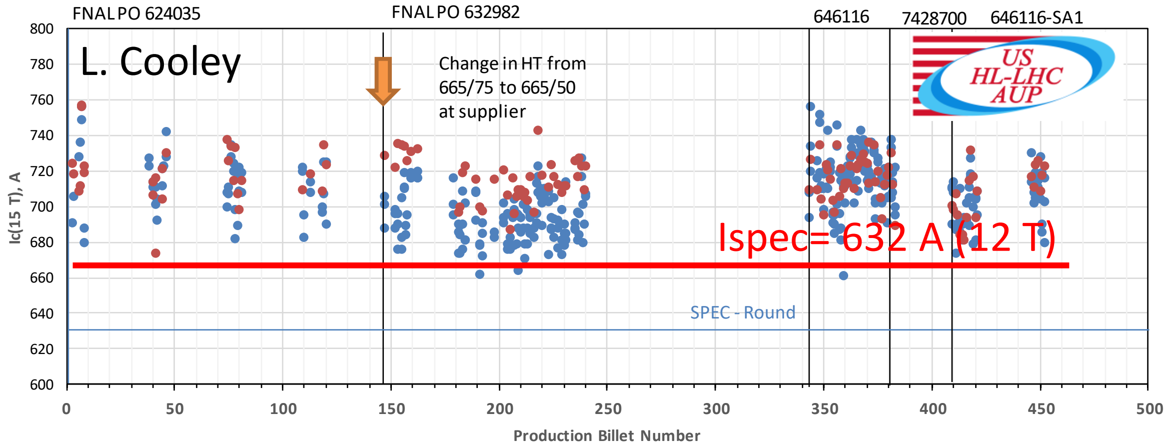


PIT 192 Bundle Barrier



BRUKER





A. Ballarino

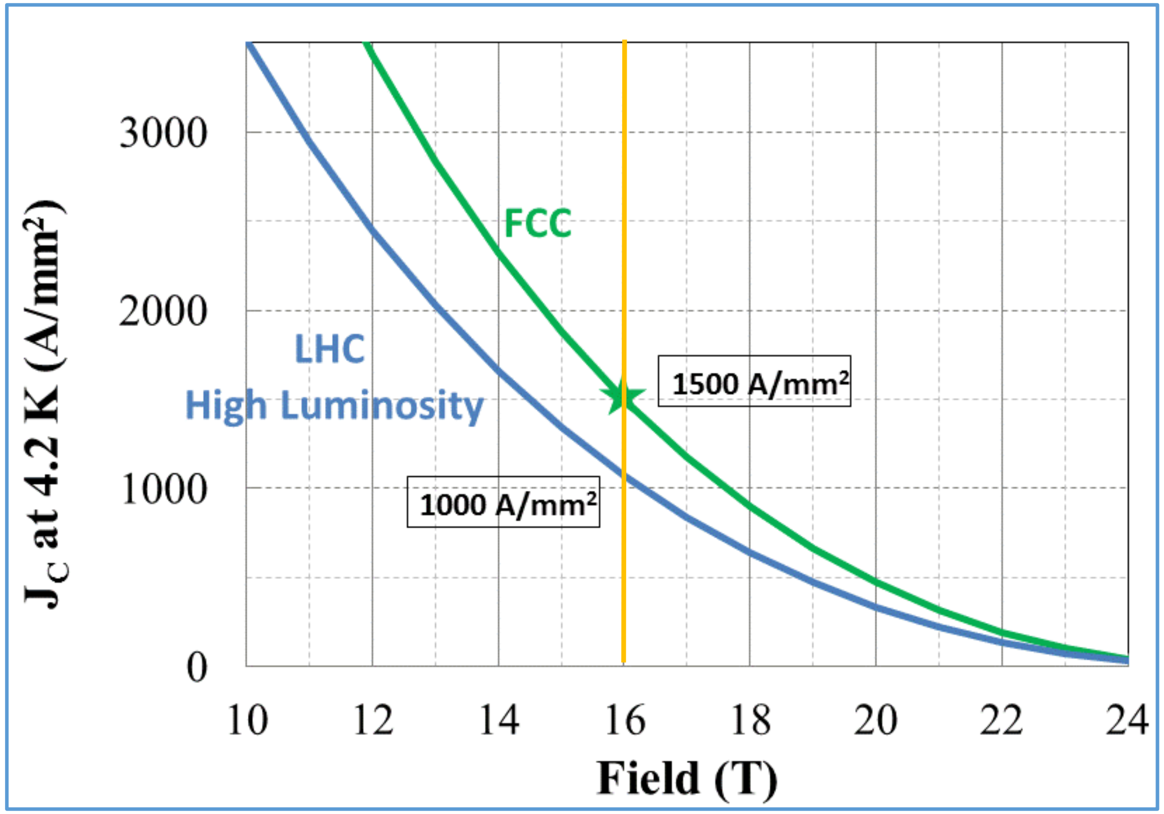
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation 4-LO-PL4 given at EUCAS, 01 – 05 September 2019, Glasgow, (UK).

FCC Nb_3Sn Targets

Wire diameter	mm	~ 1
Non-Cu Jc (16 T, 4.2 K)*	A/mm^2	≥ 1500
μoΔM(1 T, 4.2 K)	mT	≤ 150
σ(μoΔM) (1 T, 4.2 K)	%	≤ 4.5
Deff	μm	≤ 20
RRR	-	≥ 150
Unit length	km	≥ 5
Cost	Euro/kA m**	~ 5

*Je ~ 600 A/mm^2 ** 16 T, 4.2 K
*Cu:non Cu =1.5

FCC Jc target vs HL-LHC performance



Needed: 7000 tons - 9000 tons superconductors

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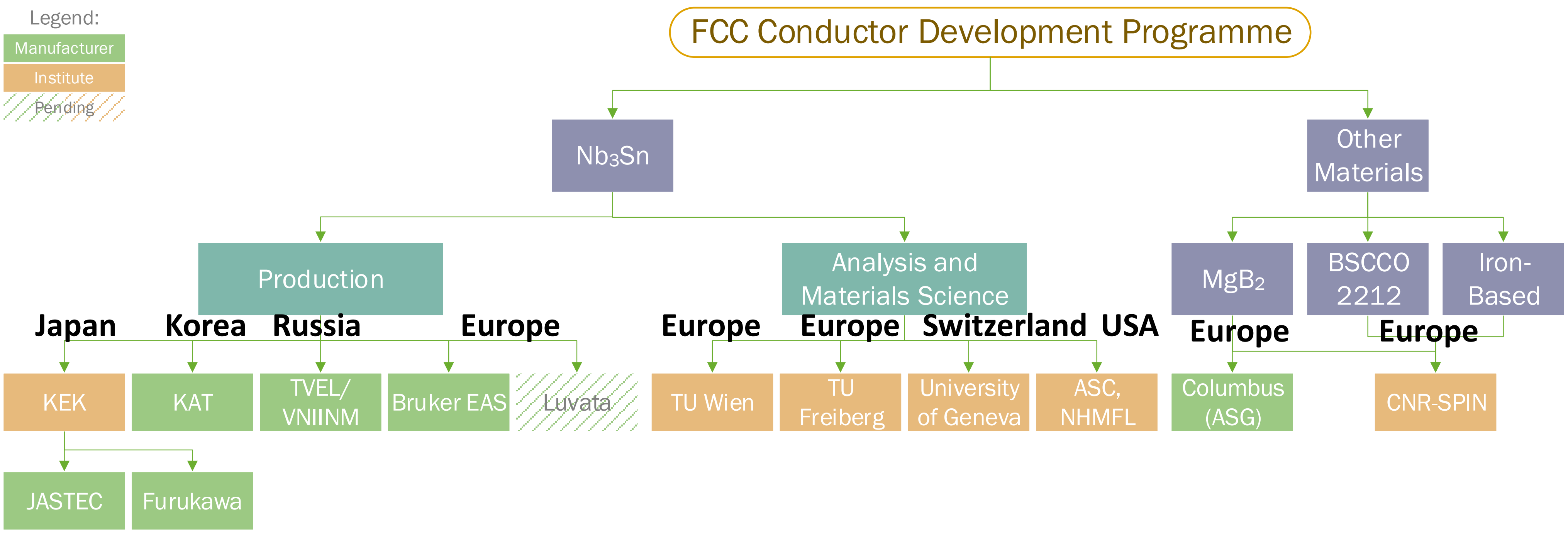
CERN FCC Conductor Development Program

A world-wide effort



Legend:
- 🟩 Manufacturer
- 🟧 Institute
- ▨ Pending

FCC Conductor Development Programme

- Nb_3Sn
  - Production
    - Japan: KEK
      - JASTEC
      - Furukawa
    - Korea: KAT
    - Russia: TVEL/ VNIINM
    - Europe: Bruker EAS, Luvata
  - Analysis and Materials Science
    - Europe: TU Wien
    - Europe: TU Freiberg
    - Switzerland: University of Geneva
    - USA: ASC, NHMFL
- Other Materials
  - MgB_2
    - Europe: Columbus (ASG)
  - BSCCO 2212
  - Iron-Based
    - Europe: CNR-SPIN

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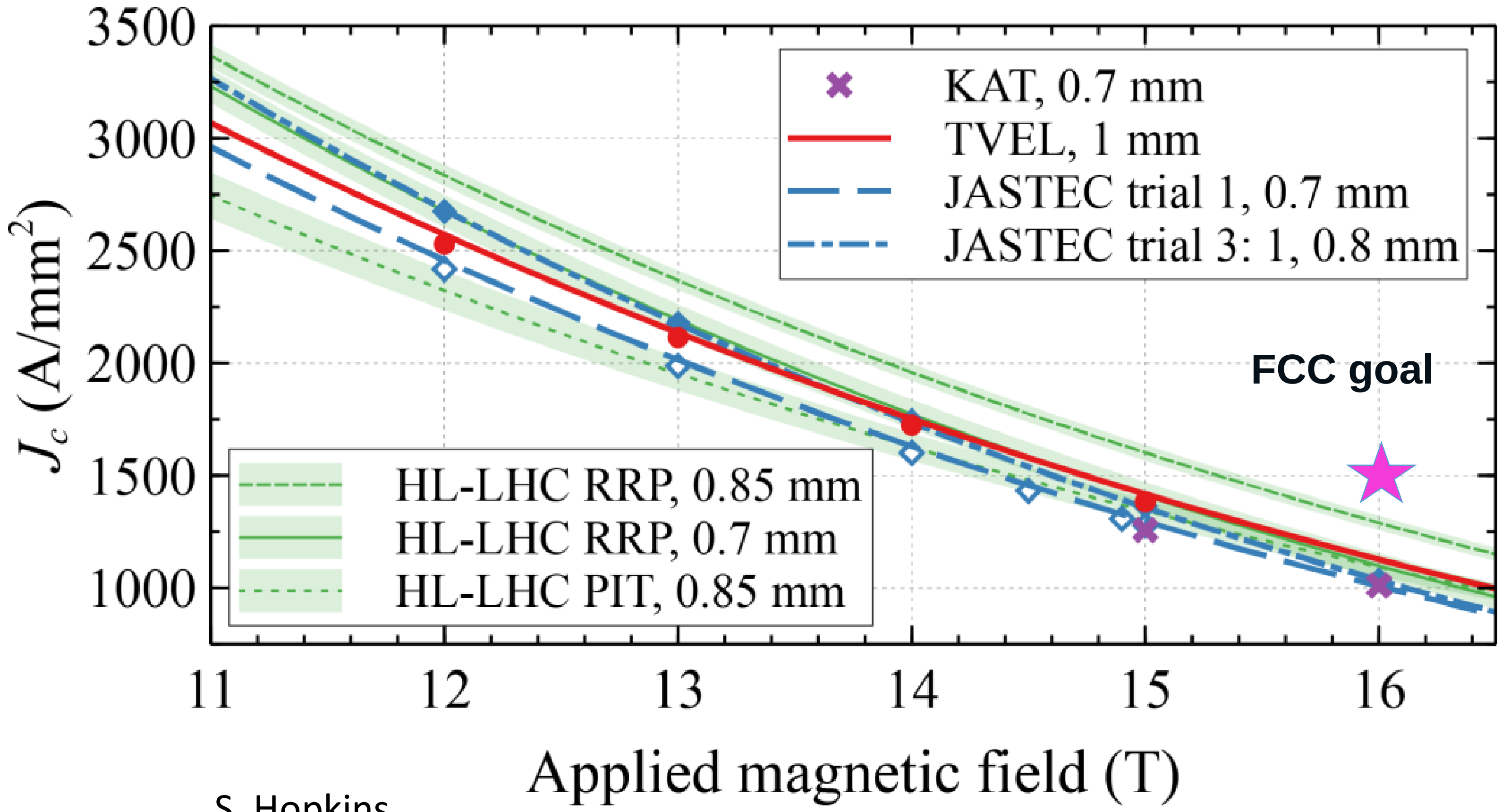
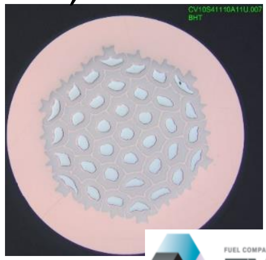
CERN FCC Conductor Development Program

Results after ~ 2 years of R&D development

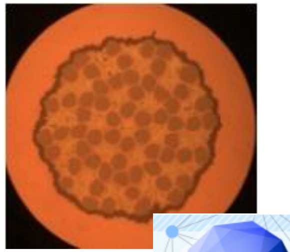


S. Hopkins

TVEL, Φ = 1mm



KAT, Φ = 1 mm



Jastec, Φ = 0.8 mm

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Nb_3Sn New Developments (1/3)

Internal Oxidation Process at Fermilab

Record Jc in multi-filamentary **ternary APC wires**: **Jc (16 T, 4.2 K) > 1500 A/mm²**

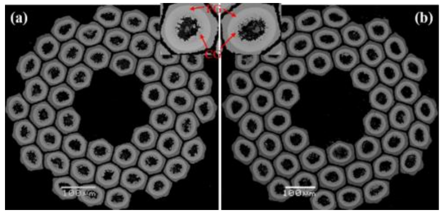
Oxygen source: SnO_2 powder

Nb-1wt%Zr -7.5 wt% Ta

Birr = 27 T

Bc2 = 27.8 T

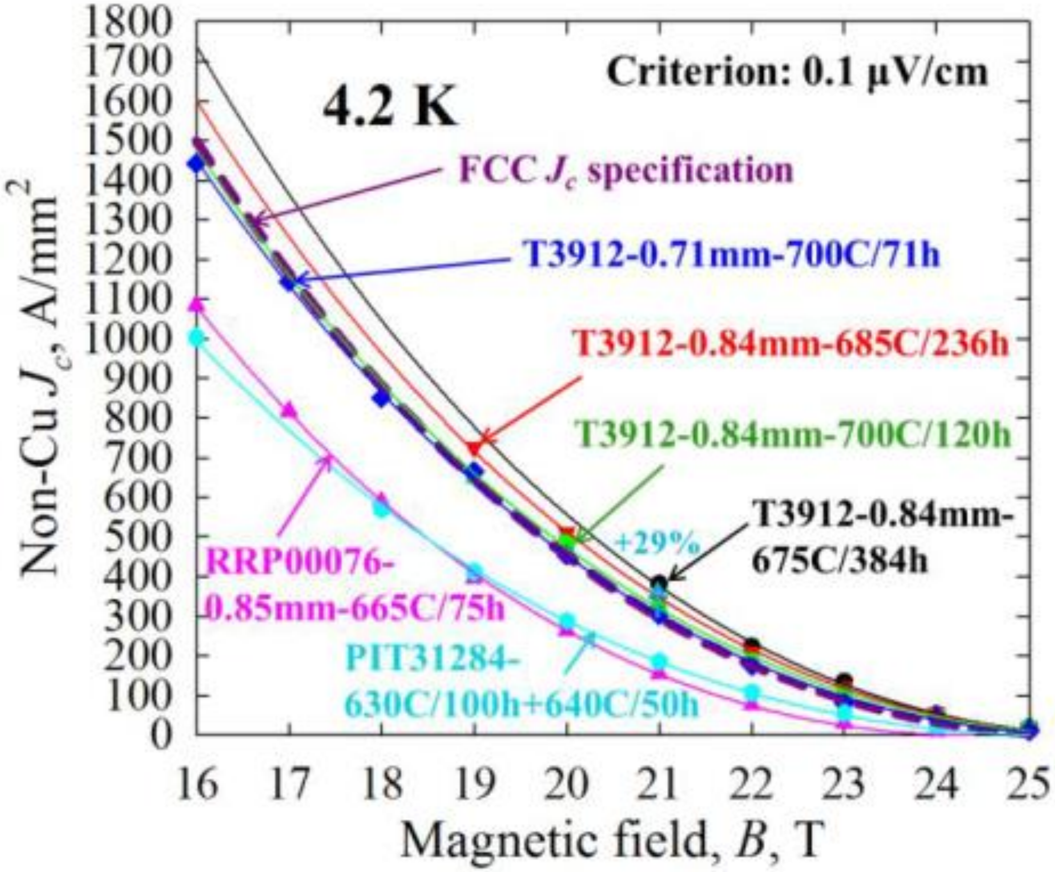
Fermilab
Hypertech
Ohio State University



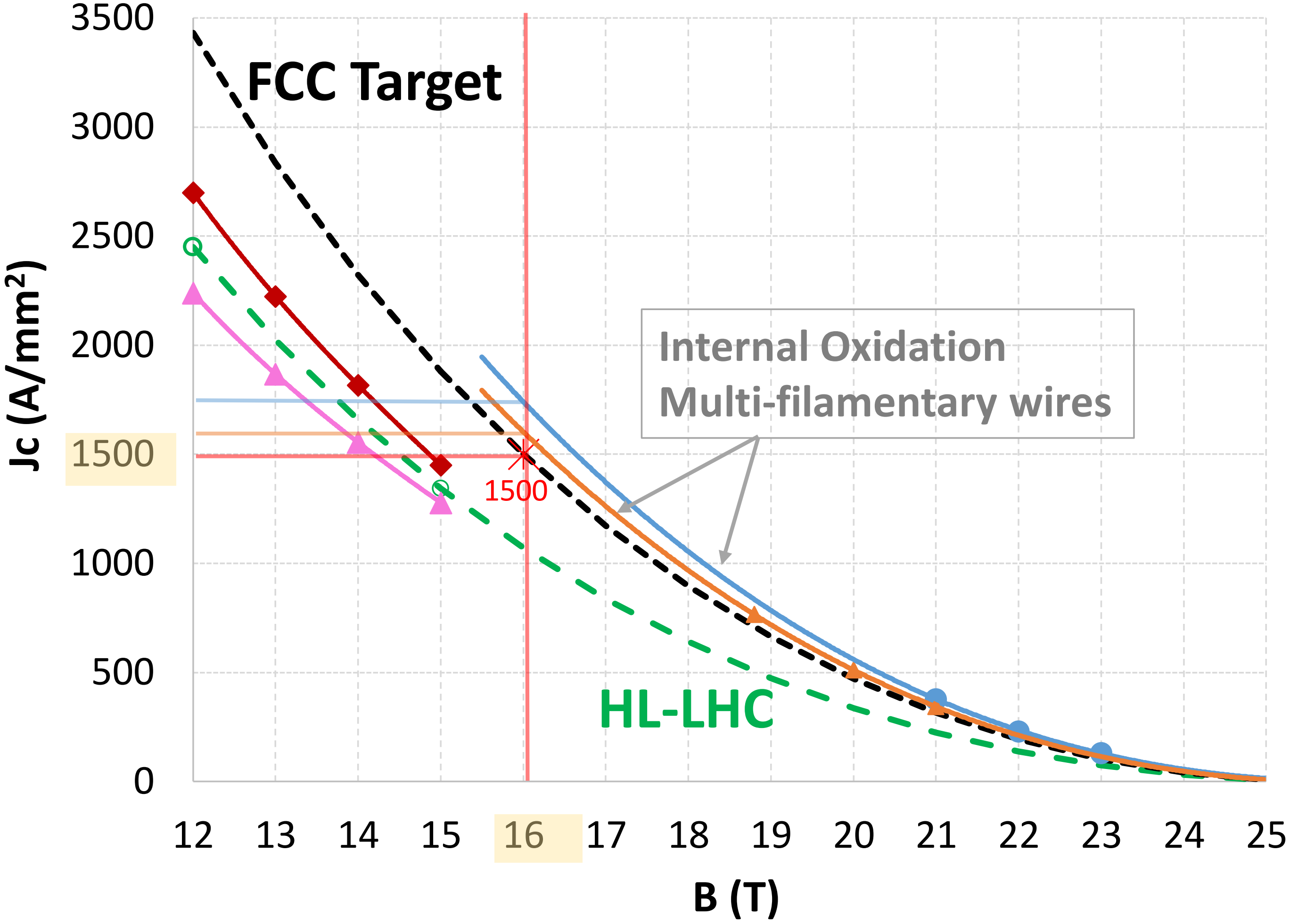
Φ= 0.71 mm Φ= 0.84 mm

Room for further process optimization

X. Xu et al, arXiv:1903.08121, 2019



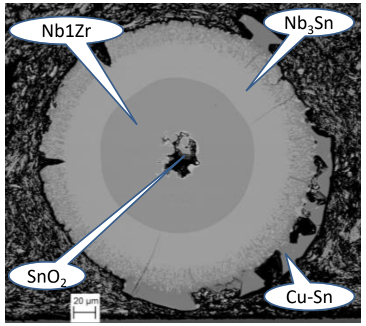
Nb_3Sn: new developments

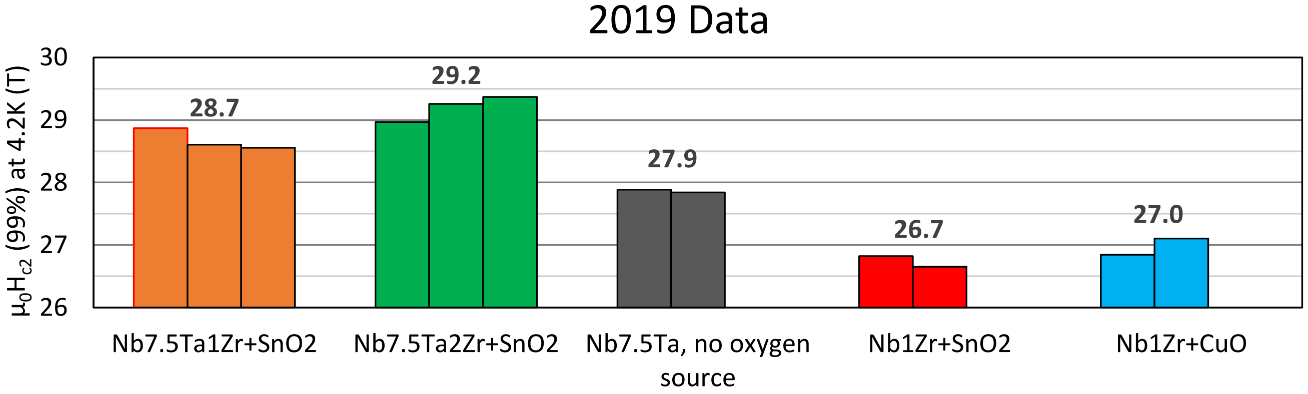


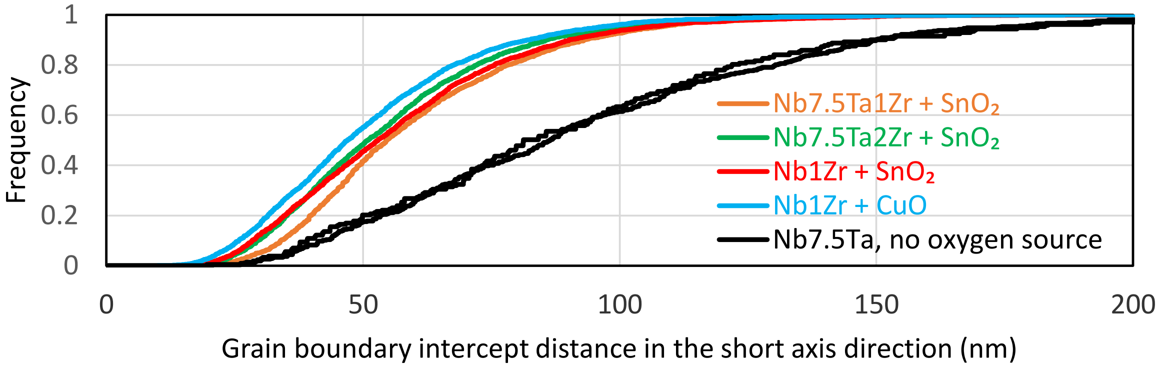
A. Ballarino

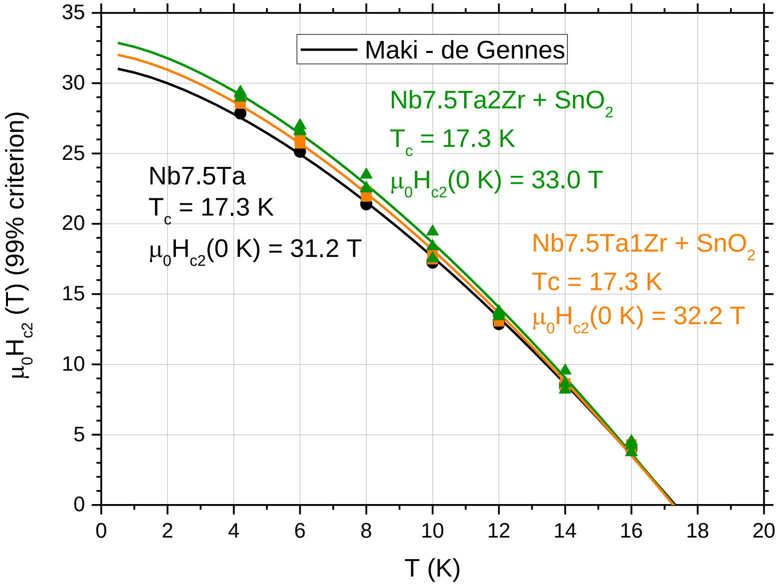
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Nb_3Sn New Developments (2/3)





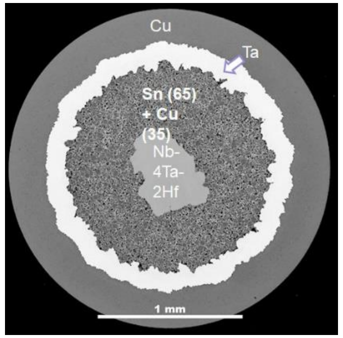




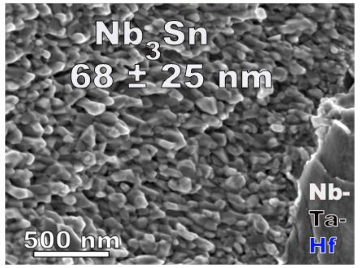
F. Buta and C. Senatore

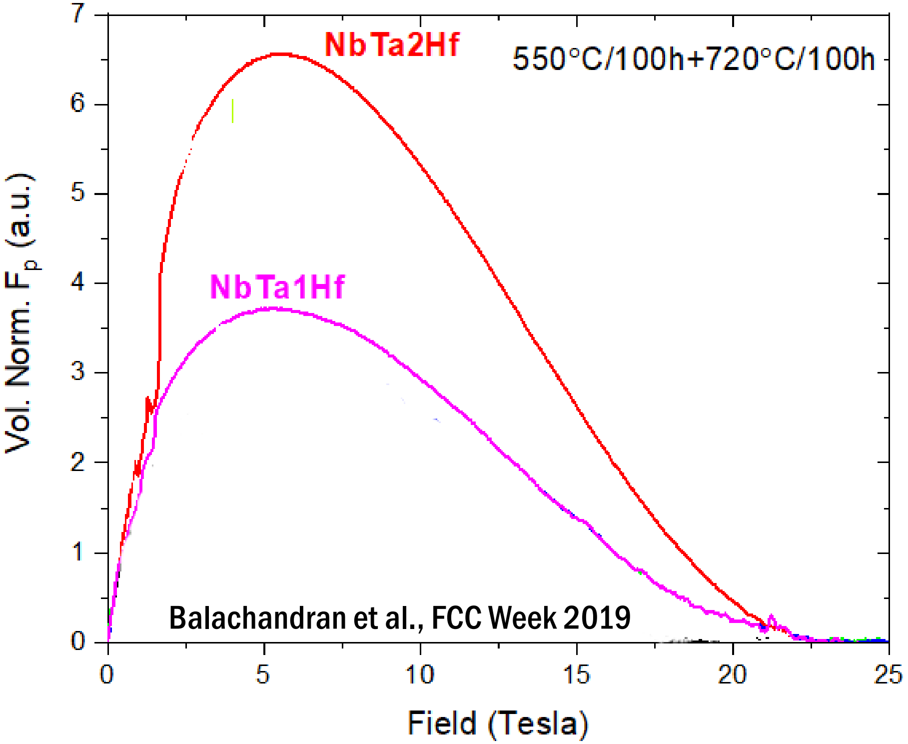
Nb_3Sn New Wire Developments (3/3)

Alloying Nb-Ta with Hf – no Oxygen source - at ASC

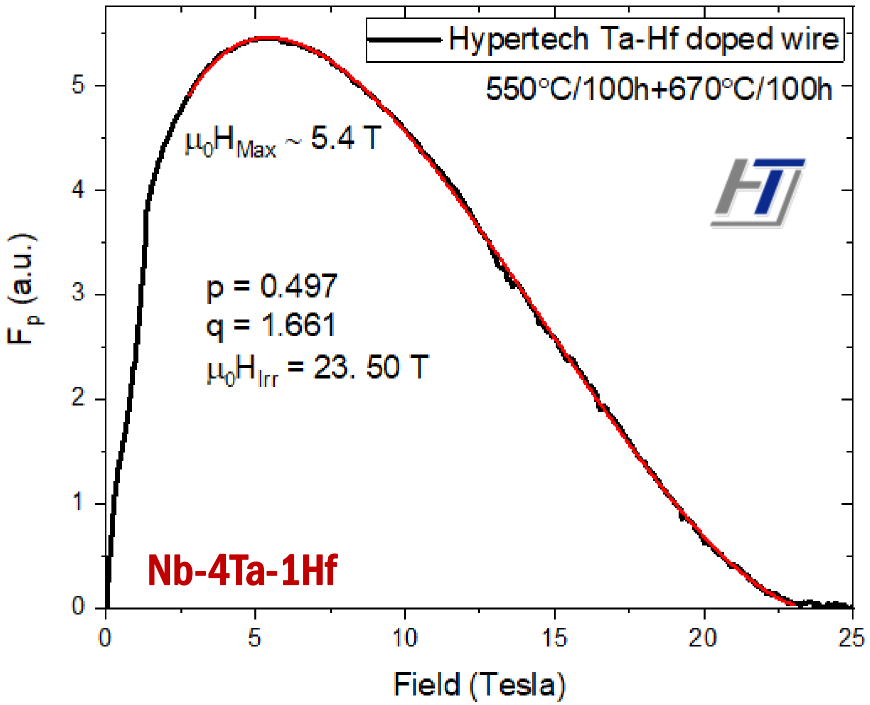


Ta-Hf





Ta-Hf at FSU
Mono-filamentary wires



Ta-Hf at Hypertech
Multi-filamentary wires

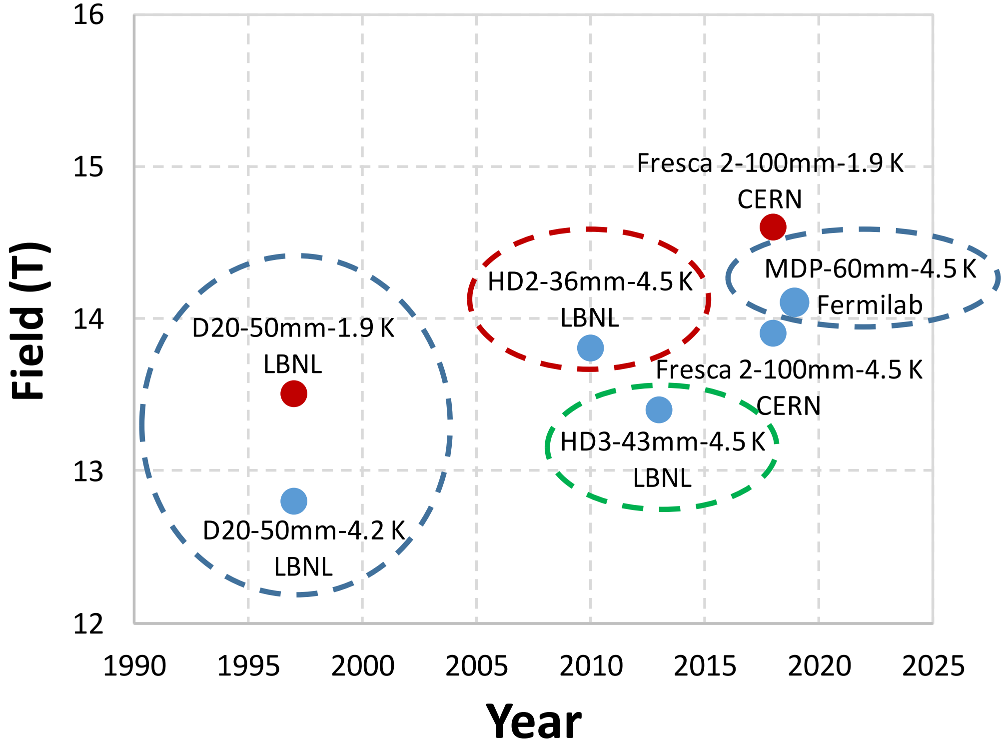
S. Balachandran *et al., Supercond. Sci. Technol.* 32 (2019) 044006

FCC 16 T Magnets

Challenges of Nb_3Sn high-field magnets:

- **Conductor performance/development**
  - Jc at 16 T;
  - Mechanical performance of wires
- **Electrical insulation**
- **Mechanical design of magnets**
- **Field quality**
- **Training and training memory**
- **Quench protection**
- **Magnet thermal management**
- **Manufacturing**
- **Cost**

Nb_3Sn Dipoles – Record fields (> 12 T)



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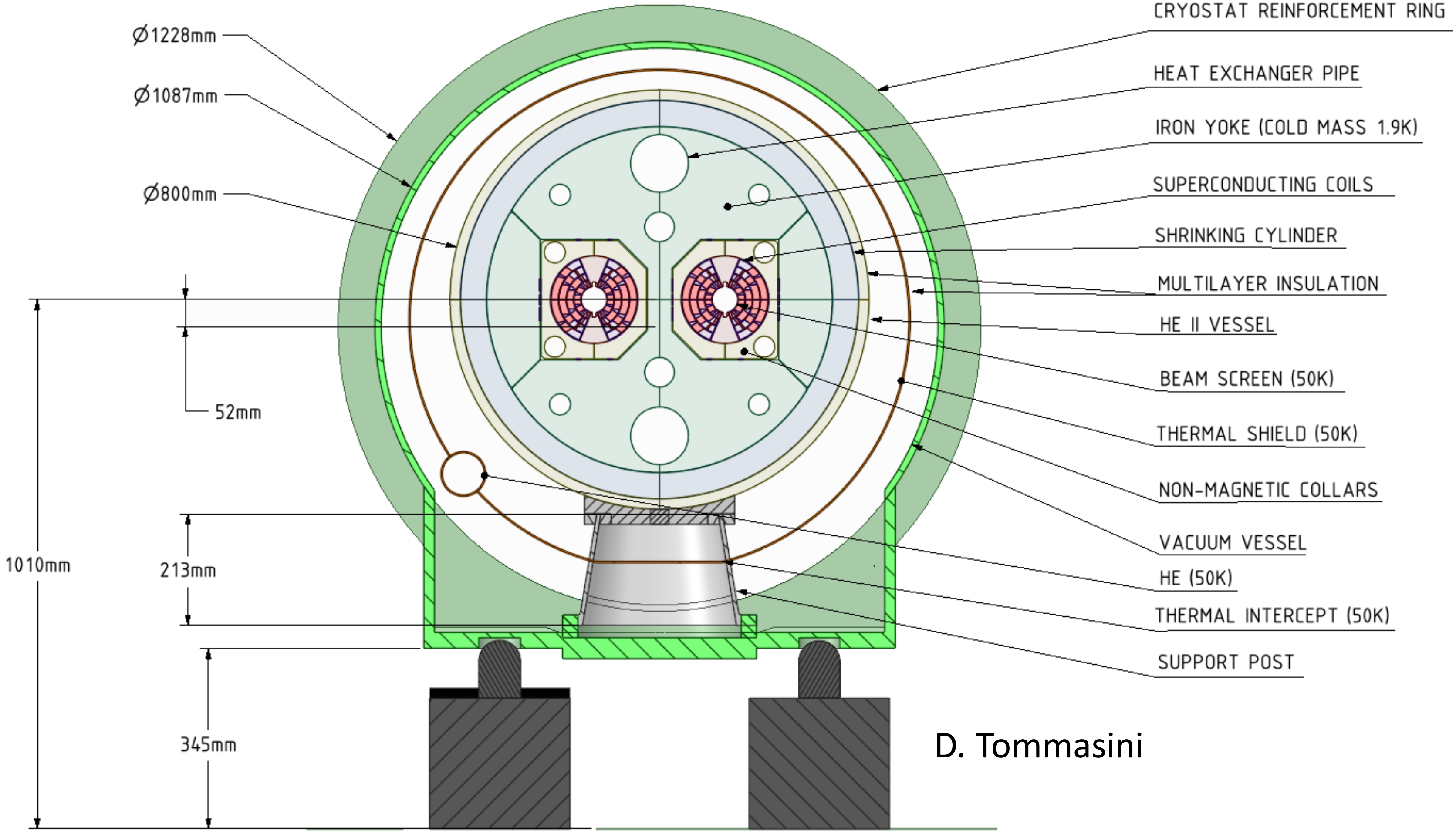
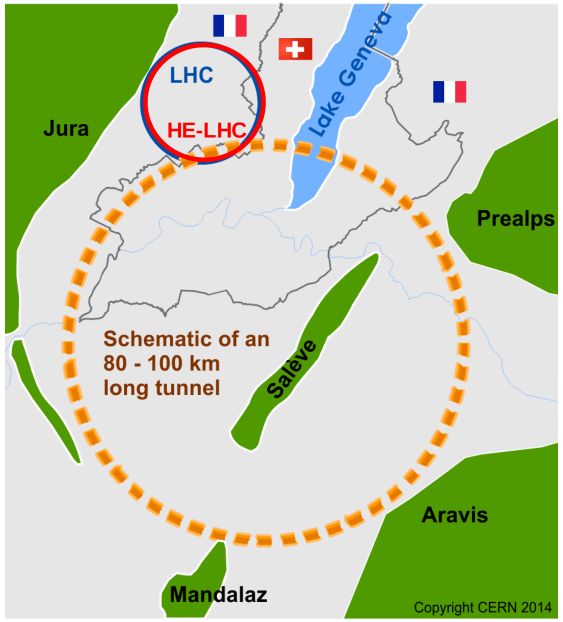
FCC 16 T Dipole Magnet

Φ = 1228 mm



D. Tommasini



HE c.m.e 27 TeV
LHC tunnel, 16 T Magnets

Size compatible with possible integration in LHC tunnel for HE-LHC

A. Ballarino

High-Field Magnet Program

EU EuroCirCol WP5 (CEA, CERN, CIEMAT, UNIGEneva, KEK, INFN, TampereU, UTwente)

- Feed the FCC CDR with design and cost model of 16 T magnets.

CERN FCC 16 T Magnet Development, supporting:

- conductor development & procurement
- R&D magnets and associated development
- model magnets

US Magnet Development Program (ASC/NHMFL, BNL, FNAL, LBNL)

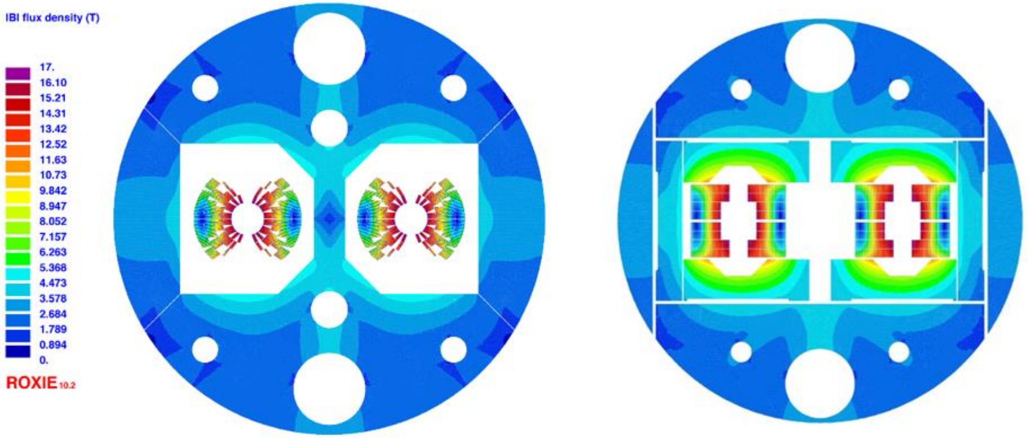
- 14-15 T cosine-theta magnet
- Design, manufacture, and test of a 2-layer 10 T CCT magnet.
- Novel diagnostics and advanced modeling techniques.

16 T Nb_3Sn Dipoles for FCC – Design options

CERN Collaborations

INFN
Cosine-theta demonstrator

CEA
Block coil demonstrator

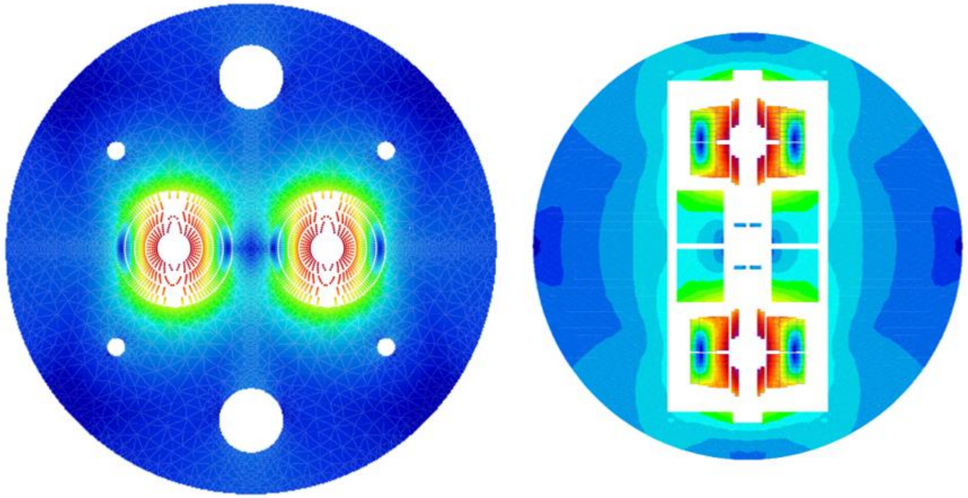


Cosine-theta

Block-coils

PSI
Canted-Cosine-Theta

CIEMAT
Common coil demonstrator



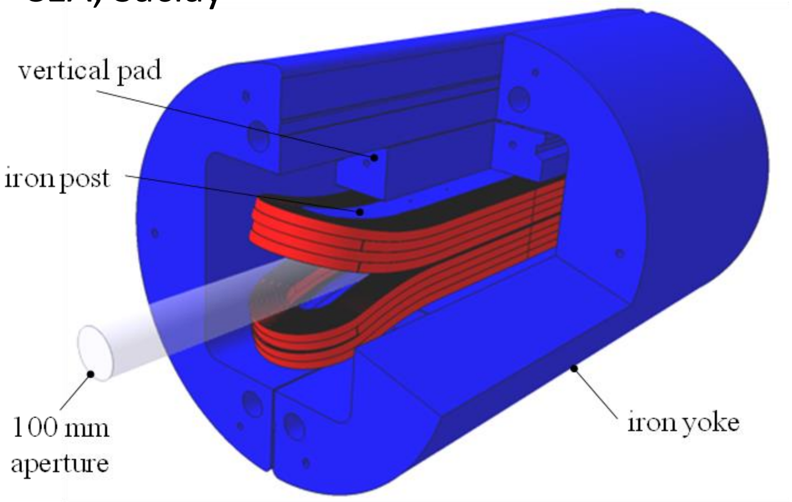
Canted cosine-theta

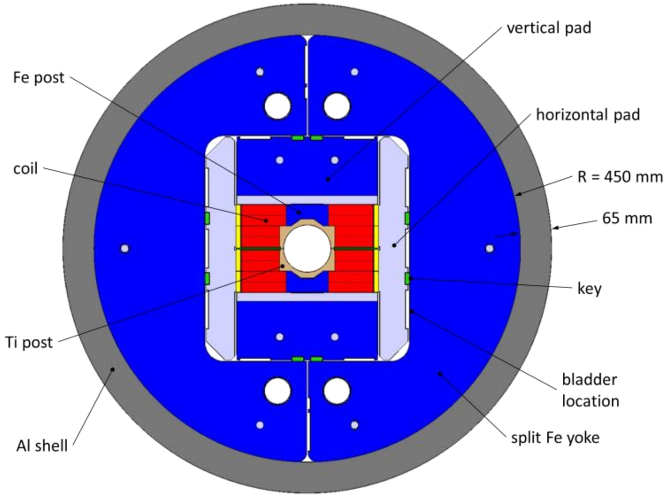
Common-coils

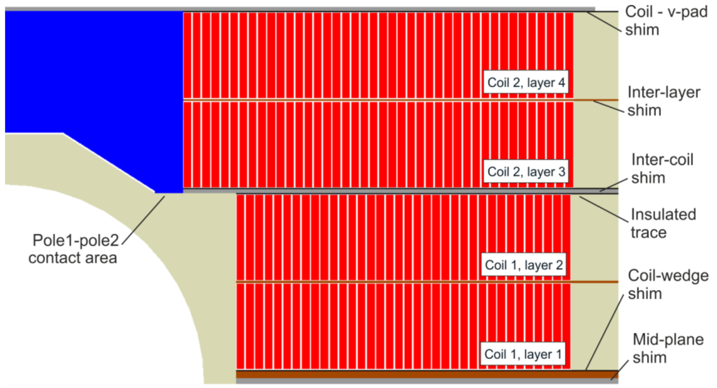
CERN world-wide magnet R&D Program

Fresca 2 Nb$_3$Sn Dipole

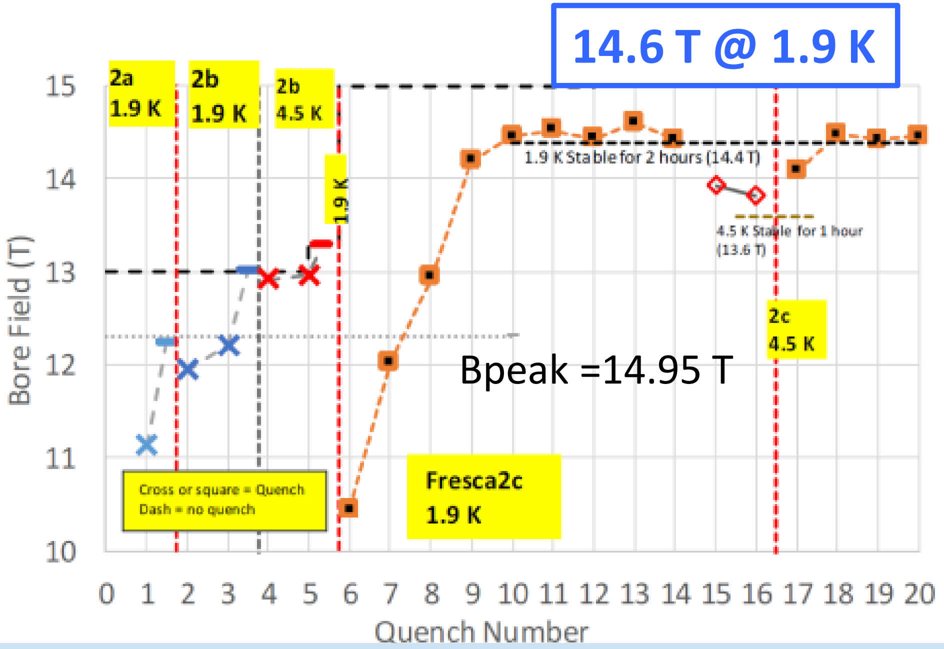
CERN
CEA, Saclay







Tested at CERN in April 2018



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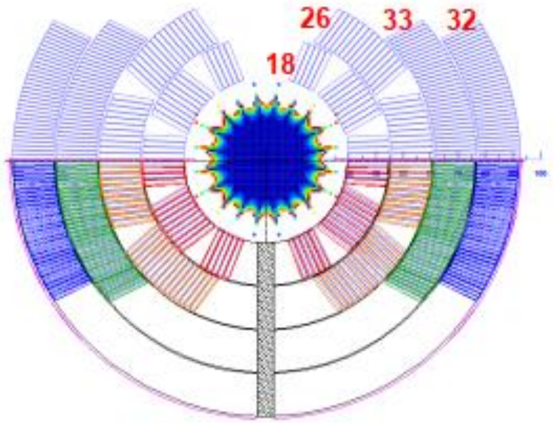
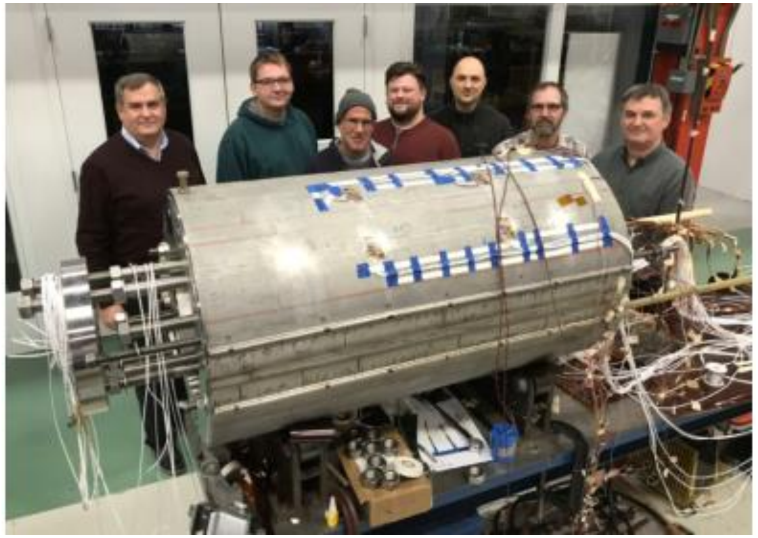
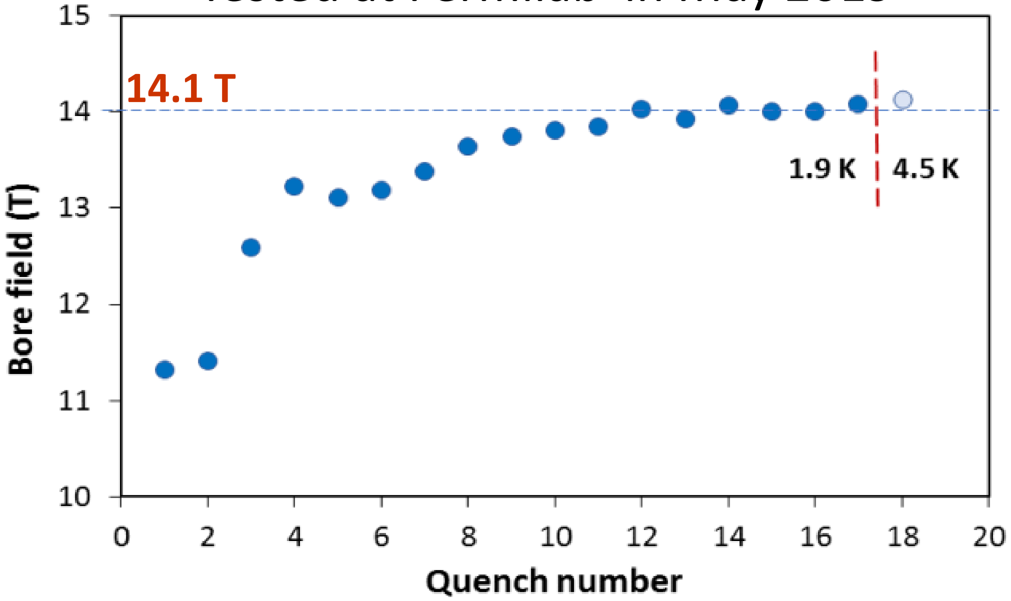
US-MDP Dipole Magnet Demonstrator

cosθ magnet
60 mm aperture
4-layer graded-coil





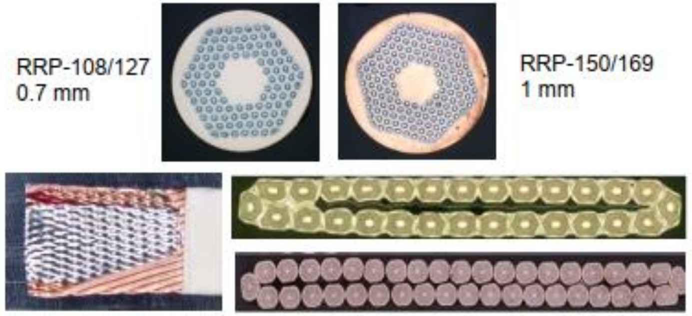
Tested at Fermilab in May 2019



Length = 1 m
OD cold mass < 610 mm

Record field for accelerator quality dipole magnet

Nb_3Sn RRP® Conductor



Maximum design stress: **200 MPa** at **15 T** and **4.2 K**

Conservative pre-load of < 150 MPa **for 14 T** qualification

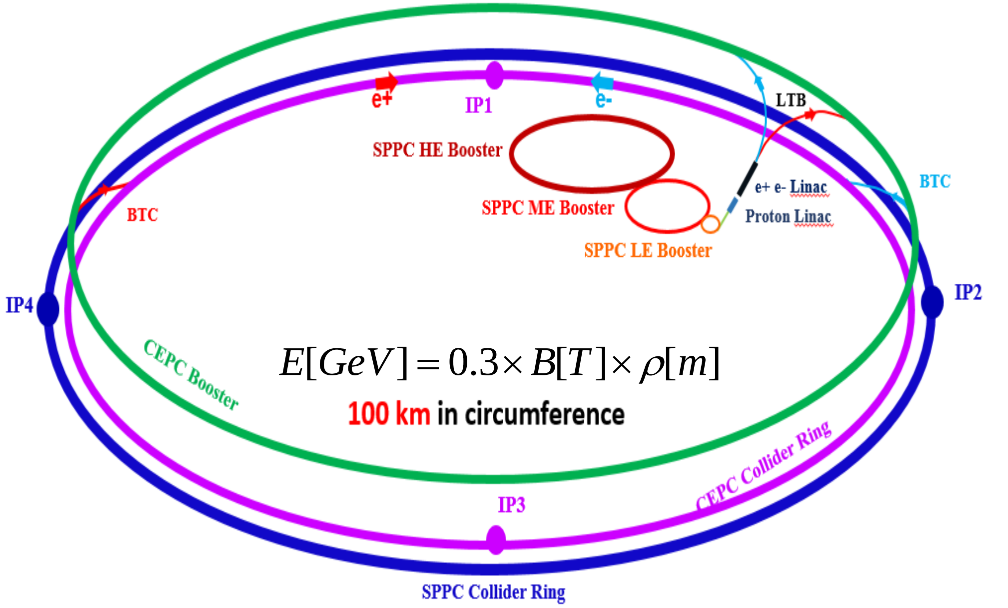
Magnet conductor limit for the wire J_c(12T,4.2K)~2.65 kA/mm^2

Courtesy A. Zloblin

SPPC

Main dipoles

- *Field strength: 12-24 Tesla to get 75-150 TeV in a 100-km tunnel*
- *Baseline Iron-Based Superconductor (IBS), Nb_3Sn/ReBCO as option*
- *Aperture diameter: 40~50 mm*
- *Field quality: 10^{-4} at the 2/3 radius*

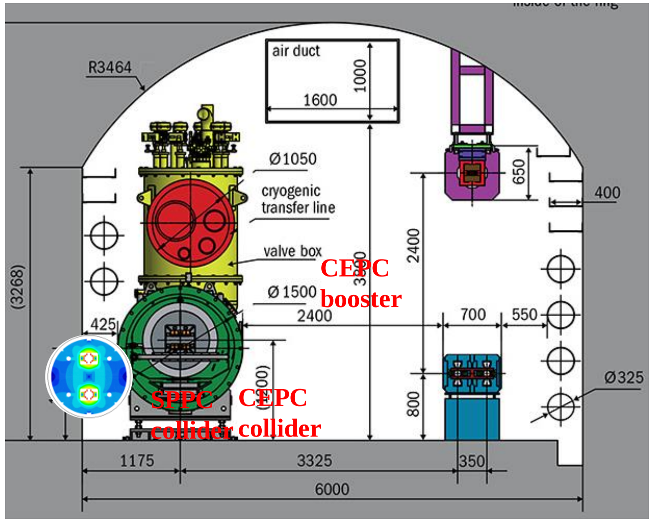


$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

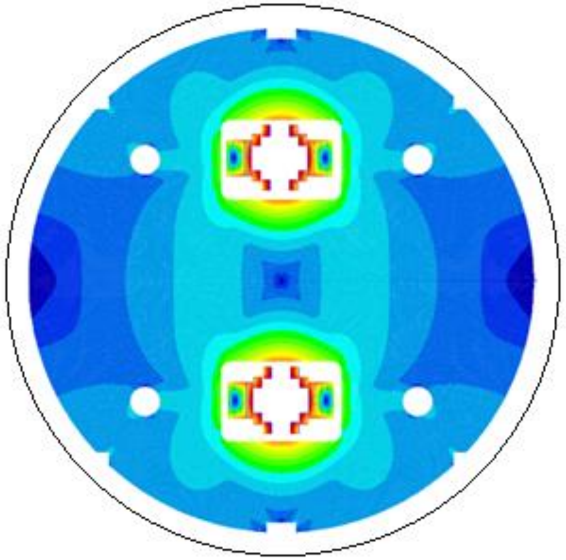
100 km in circumference

Q. Xu

Site study of the CEPC-SPPC



6-m width Tunnel for CEPC-SPPC

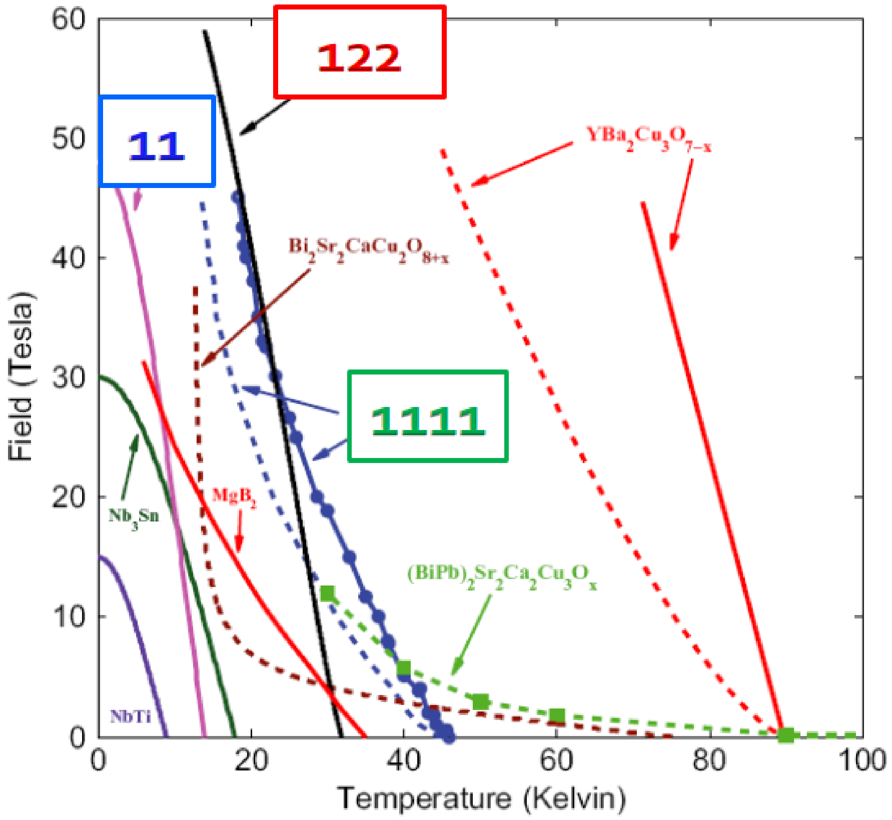


SPPC 12-T Dipole with IBS

A. Ballarino

Iron based superconductors for SppC

Upper Critical Fields



C. Tarantini et al., PRB 84, 184522 (2011)

Conceptual design with expected J_e of IBS in 2025

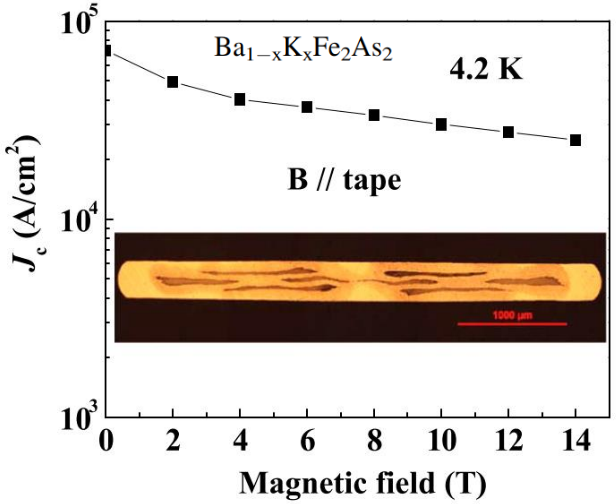
Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0.802	1	200	4.2	12	3800	111

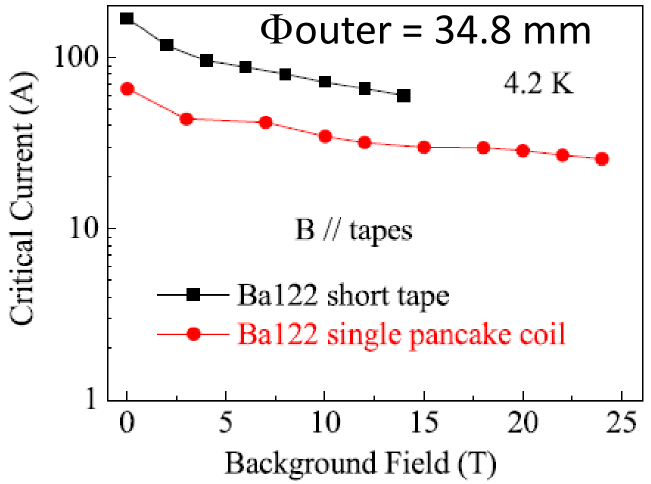
- For 100-km SPPC, **3000 tons of IBS** is needed
- Target cost of IBS: **20 RMB /kAm @12 T**
- Total cost for IBS conductors: **~10B RMB**

Y. Ma, D. Wang et al

Fabrication of IBS solenoid coil and test at 24T

Supercond. Sci. Technol. 2019(32) 04LT01

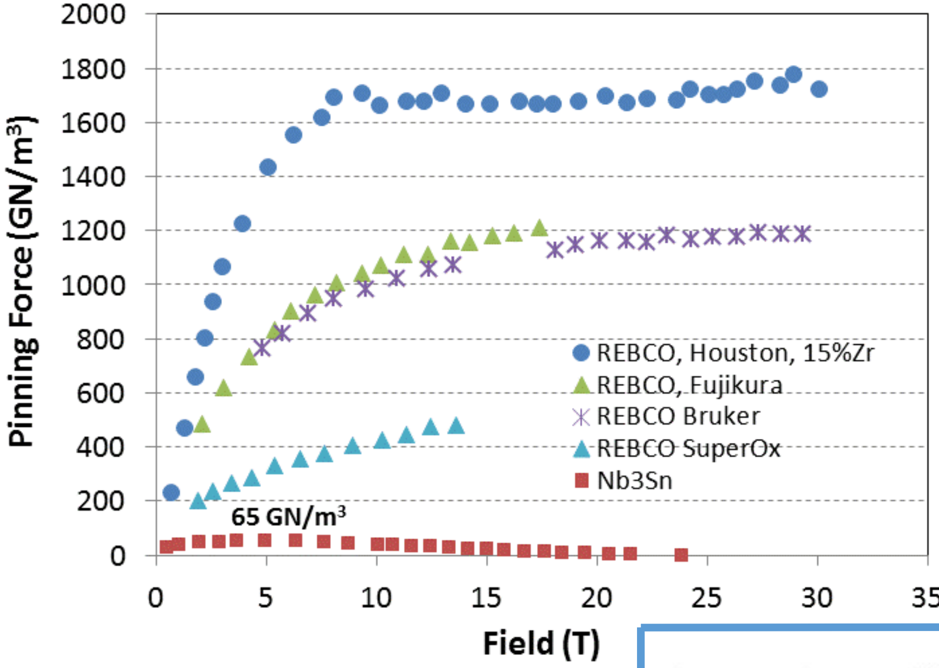




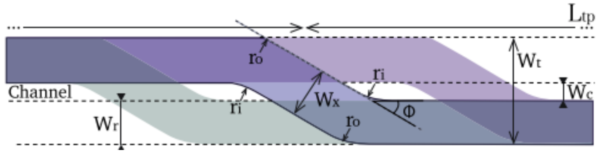
High upper critical field and low anisotropy

HTS Conductor: REBCO (16 T and beyond)

Fantastic Jc at 4.2 K in high magnetic fields !



Measured at CERN

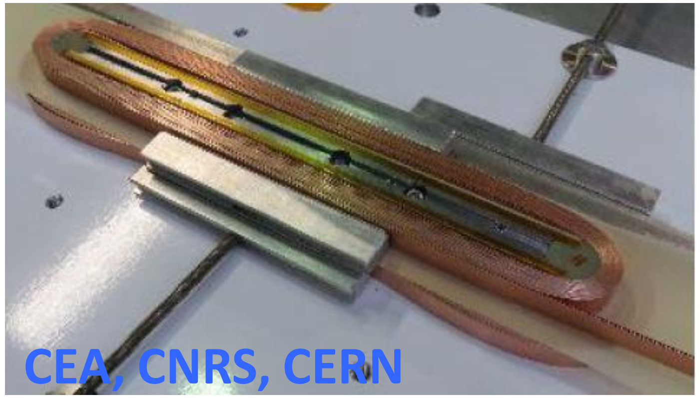


Eucard 2 Feather 2, Roebel cable, 3.35 T at 5.7 K

Supercond. Sci. Technol. **31** (2018) 065002

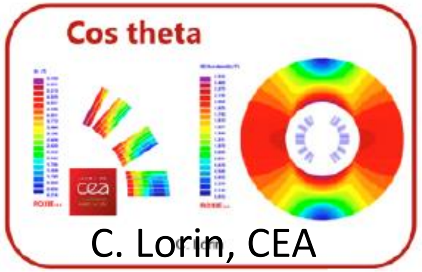
J. Van Nugteren, G. Kirby et al.

Eucard 1 Insert, 4-tape stack cable, 5.37 T at 4.2 K

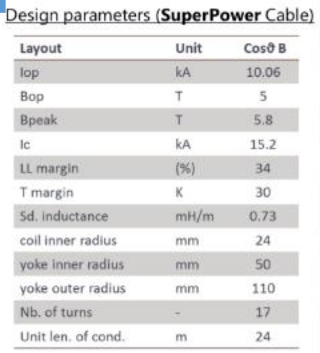


Tested in stand-alone at CERN

**Eucard 2, cosθ dipole, Roebel cable
5 T at 4.2 K, to be tested in 2019**



C. Lorin, CEA

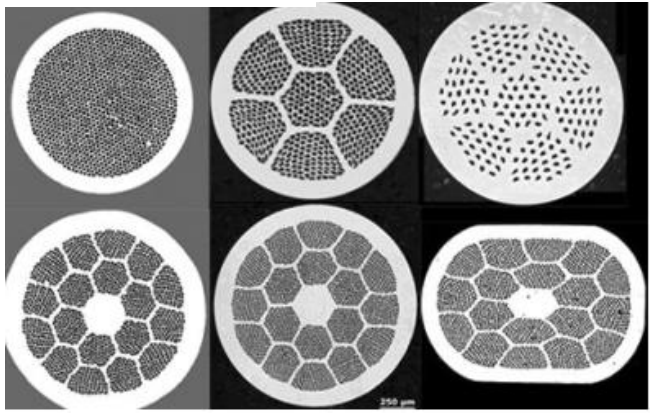


Design parameters (**SuperPower** Cable)

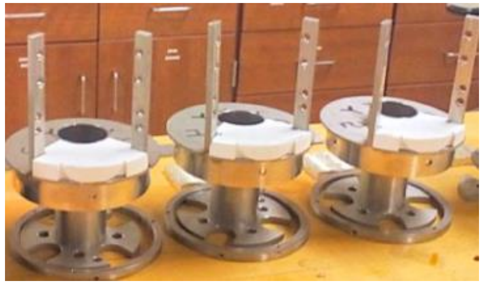
Layout	Unit	Cosθ B
Iop	kA	10.06
Bop	T	5
Bpeak	T	5.8
Ic	kA	15.2
LL margin	(%)	34
T margin	K	30
Sd. inductance	mH/m	0.73
coil inner radius	mm	24
yoke inner radius	mm	50
yoke outer radius	mm	110
Nb. of turns	-	17
Unit len. of cond.	m	24

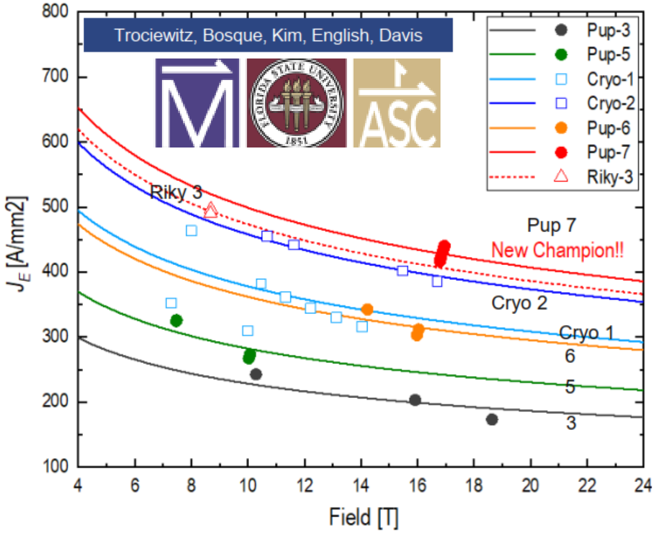
A. Ballarino

BSCCO 2212



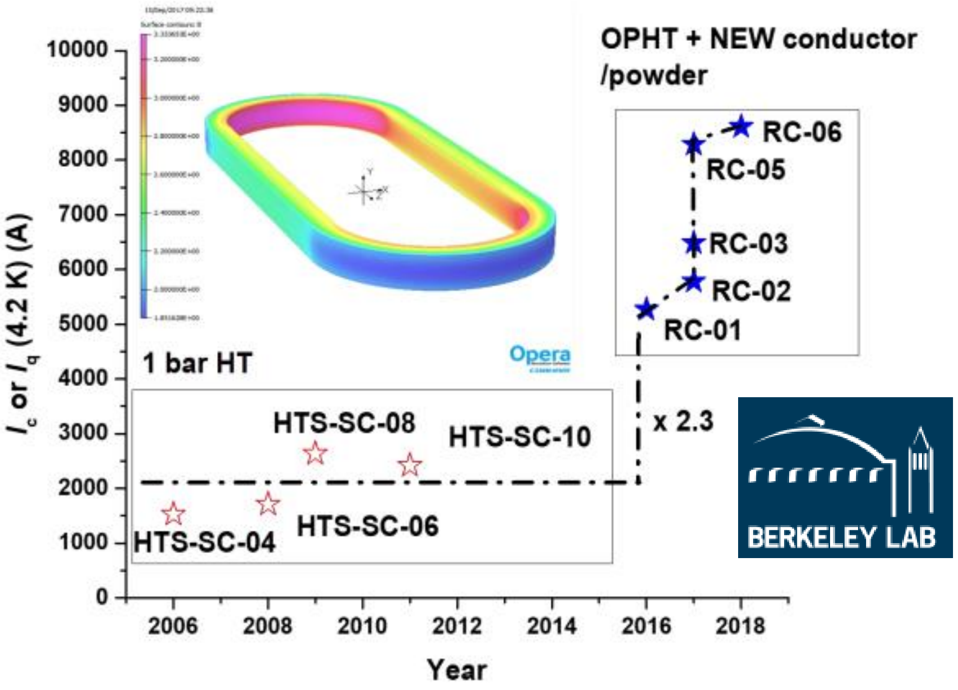
HT at 50 atm





LBNL: Racetrack and CCT

Technology for ~ 20 T dipoles



Best conductor properties depend sensitively on cooling rate: these 20% fill factor conductors have J_E (16 T) = 1300 A/mm^2 and J_c = 6500 A/mm^2 with RRR (Ag) > 100 and no need for diffusion barrier

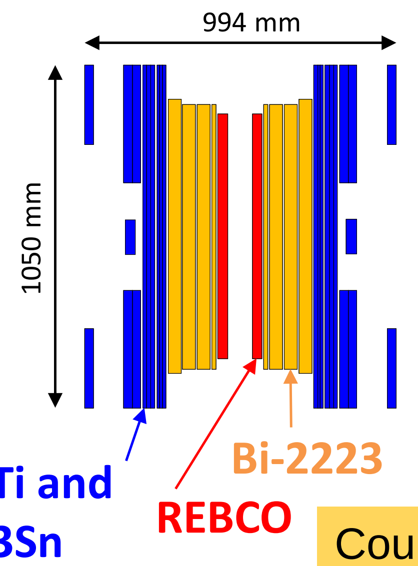
D. Larbalestier, FCC Week 2019, Brussels

Towards a 1.3 GHz (30.5 T) NMR magnet:

400 MHz (9.39 T) NMR with superconducting joints between REBCO conductors

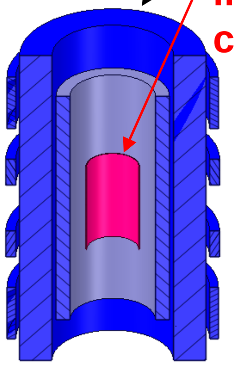
JST MIRAI · SUMITOMO ELECTRIC · RIKEN · JASTEC · JEOL · NIMS · CHIBA UNIVERSITY · Tokyo Tech

The development of a persistent-mode 1.3 GHz NMR magnet in the JST-Mirai project[1]

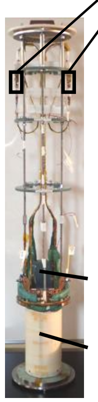


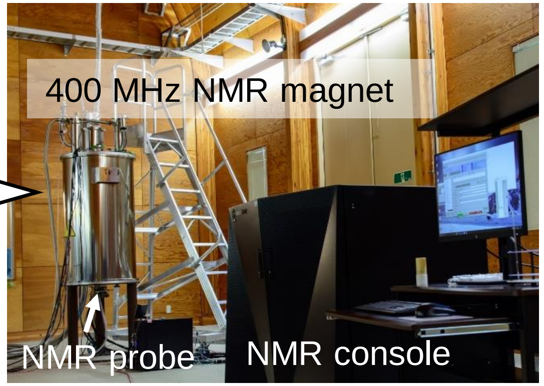
Courtesy of RIKEN

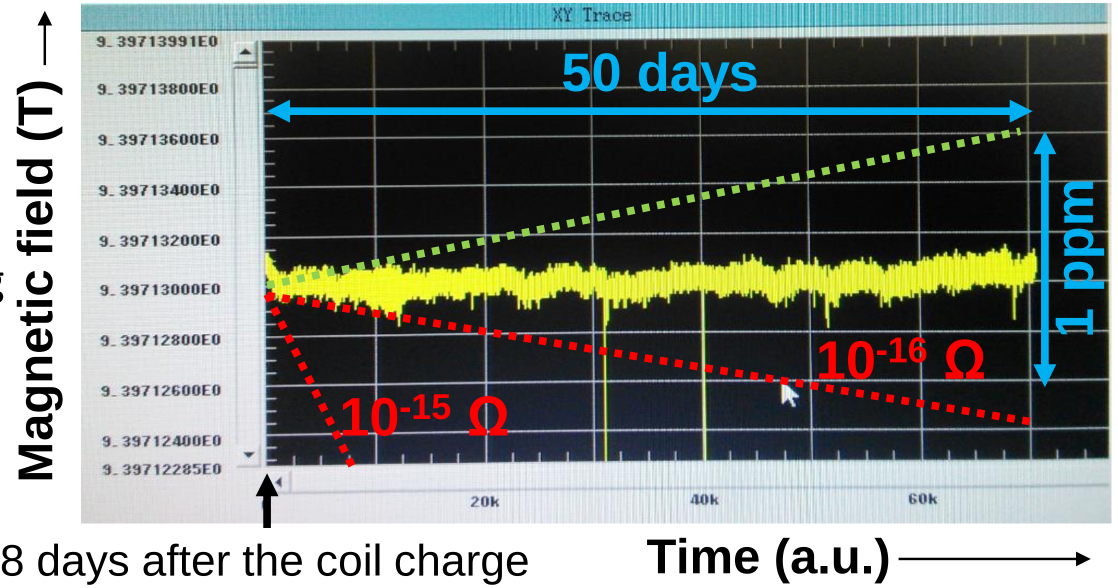
A first step:
Persistent-mode 400 MHz (9.39 T) NMR with superconducting joints between REBCO conductors



Intermediate grown superconducting (iGS) joints by SEI[2]







The superconducting joints perfectly functioned in the persistent-mode NMR magnet.[3]

1. H. Maeda et al. *IEEE TAS* 29 (2019) 4602409
2. K. Ohki et al., *Supercond. Sci. Technol.* 30 (2017) 115017
3. T. Yamazaki et al., Presented at ENC2019.

Other technologies: Muon Colliders

- **Muons**:

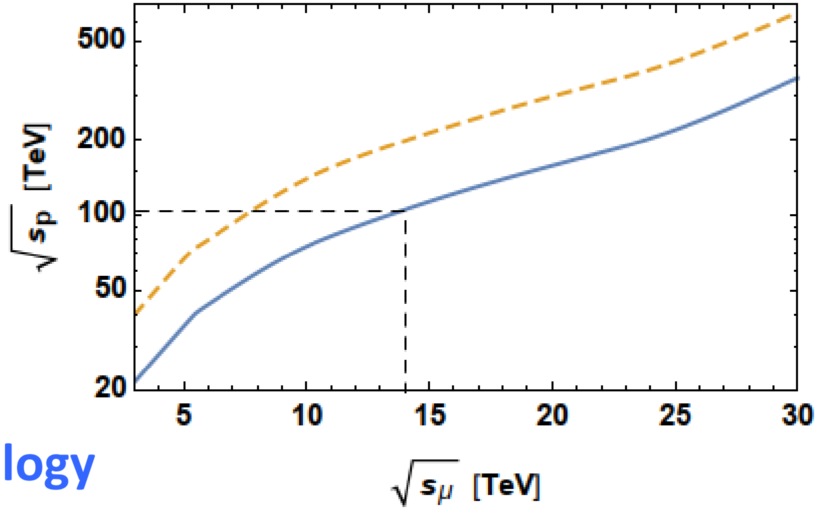
  Very large mass (207 time that of electrons)

  Sort lifetime (2.2 μs at rest)

- **Muon Colliders**:
  - Very high energies (no synchrotron radiation)
  - Challenge of luminosity (short lifetime of muons)

30 T – 40 T Solenoids for transverse beam cooling → HTS Technology

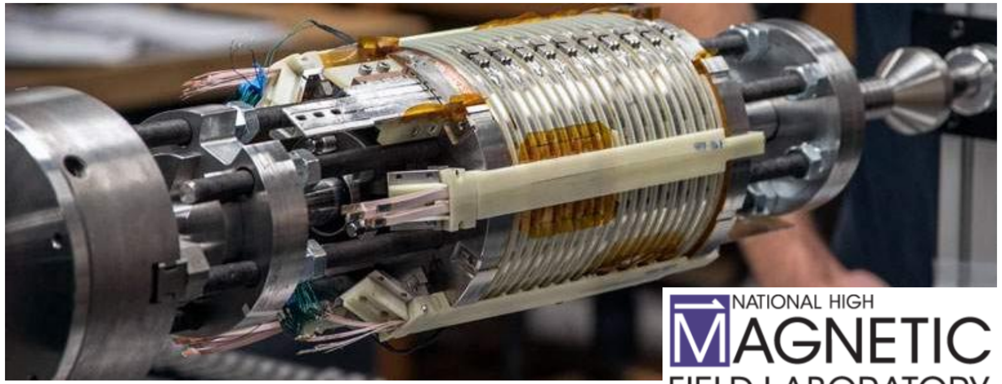
14 TeV μ Collider → 100 TeV proton collider



Input to the European Particle Physics Strategy Update

The Muon Collider Working Group

32 T Record Field Solenoid (2017) at NHMFL
ReBCO, Bore diameter = 34 mm bore



NATIONAL HIGH MAGNETIC FIELD LABORATORY

Development of demanding technologies and innovative concepts are required

Conclusions

- For future **linear colliders** focused on Higgs factories **technology and SRF** are considered **mature**
- Future **circular lepton colliders** are combining concepts and **techniques developed**, implemented and demonstrated **by past and present circular colliders. Mature beam physics and technology**
- Future **hadron colliders** are based on high-field Nb_3Sn and/or HTS magnets, whose development represents a **challenging R&D** requiring **longer term planning** and funding
- Continuous **R&D effort** is **very important** for all future accelerators. Effort is on cost reduction, energy saving and proving technological feasibility of challenging targets

Thank you for your attention !

*"Along with "**Antimatter**"*
*and "**Dark matter**"*

we have recently
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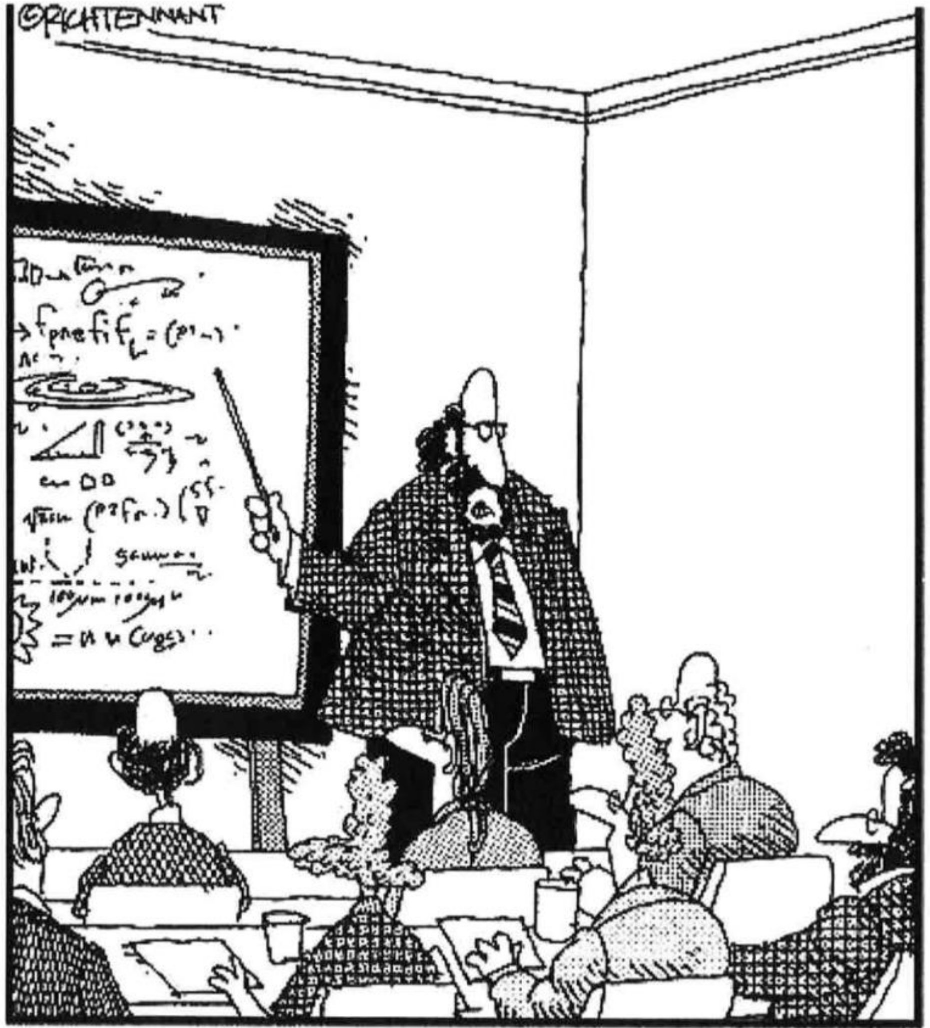

"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."