HiLumi HL-LHC PROJECT

Dipartimento di
Fisica «Aldo Pontremoli»
Seminario di Dipartimento

Acceleratori e Superconduttività:
tecnologie per estendere i confini della conoscenza

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Colloquium @ University of Geneva, Physics Section, 24 February 2020

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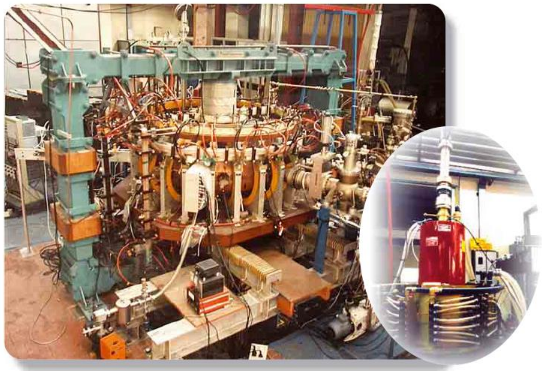
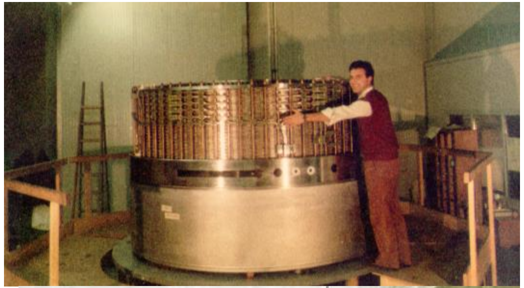
Mio percorso - 1

- Tesi di Laurea in Fisica dei Plasmi (Prof. M. Fontanesi). Misure raggi X sul tokamak THOR nel dipartimento (CNR).
- Ricercatore INFN (art.36) nel gruppo ciclotrone/Fisica del nucleo per il progetto CS (Ciclotrone Superconduttore)
- Ricercatore universitario (primo concorso libero1983) del dipartimento, gruppo CS
- Sono stato l'ultimo assistente del Prof. Resmini (cui è dedicato il Laboratorio LASA)



Mio percorso - 2

- CS: Campi magnetici, dinamica dei fasci e soprattutto l'incontro con la superconduttività
- Bobine superconduttive e misure campo del CS (Prof. Emilio Acerbi) al LASA appena fatto!
- Solenoide SC per Esperimento ZEUS@HERA (E. Acerbi:). La scomparsa di Resmini ci toglie la partecipazione allla costruzione dei dipoli superconduttori di HERA…
- Laboratorio di superconduttività applicata al LASA
  - Solemi – 8 T e 15 T, temperature da 1.4 K a 300 K, misure 30 kA.
  - Studi di materiali avanzati: Nb3Sn, collaborazioni con Industrie, e Enti: CISE, CNR, ENEA, e laboratori (LBNL, ASC-Wisconsin).



Mio percorso – 3

- Internazionalizzazione: Superconduttività per acceleratori & rivelatori.
  - Collaborazione INFN-CERN per i primi dipoli LHC (N. Cabibbo – G. Bellini e poi L. Mandelli): 1989-1998
    - In parallelo a una collaborazione sulle cavità SC per LEPII
  - Primo dipolo LHC (ora su CAST) è dell'INFN. Seguono altri due di cui il primo con lunghezza finale 15 m.
  - Proposta di studiare i quadrupoli speciali per una futura fase II di LHC Upgrade in luminosità…
  - Cavo Superconduttore (con qualifica) design e costruzione del toroide superconduttore di ATLAS con CEA-Saclay.


LHC DIPOLE PROTOTYP
CERN - INFN 1

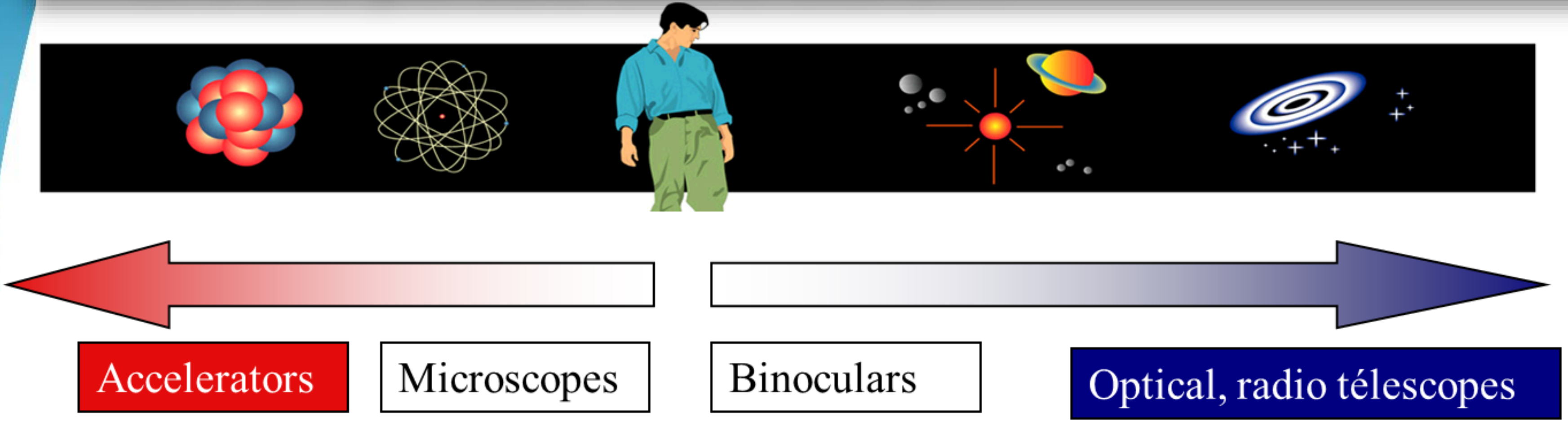

KEYENCE

Mio percorso – 4

- CERN **prima parte: l'avventura LHC 2001-2010**
  - Capo Gruppo Superconduttori e Magneti per LHC (1200 MCHF)
  - Responsile del sistema magnetico per LHC (1700 MCHF) inclusi criostati, interconnessione: incidente!
    - Il lato subdolo della superconduttività: qualita totale, il minimo errore si paga!
  - 2010: lo strumento funziona, anche meglio delle previsioni: **2012 Higgs!**
- CERN – **il nuovo inizio: HiLumi LHC e le nuove tecnologie**
  - Già nel 2007-08 inizio degli studi, riprendendo lo sviluppo del Nb_3Sn.
  - Nel 2010 il piano approntato da Aymar (Linac SC + PS2) va in crisi.
  - Propongo High Luminosity LHC nel 2010. **Avallato e sostenuto dalla ESUPP nel 2013** HiLumi diventa il progetto principale del CERN & HEP. (in **ESFRI 2015**).
  - **Approvato in modo completo dal CERN Council nel 2016** (primo progetto dopo LHC nel 1996).
    - FISICA, TECNOLOGIA innovativa, FORMAZIONE nuova generazione per il post-LHC

LHC the supercollider, sheding light on the universe…

What’s are particle acclerators??



Particle physics looks at matter in its smallest dimensions and accelerators are very fine microscopes or, better, ***atto-scopes!***

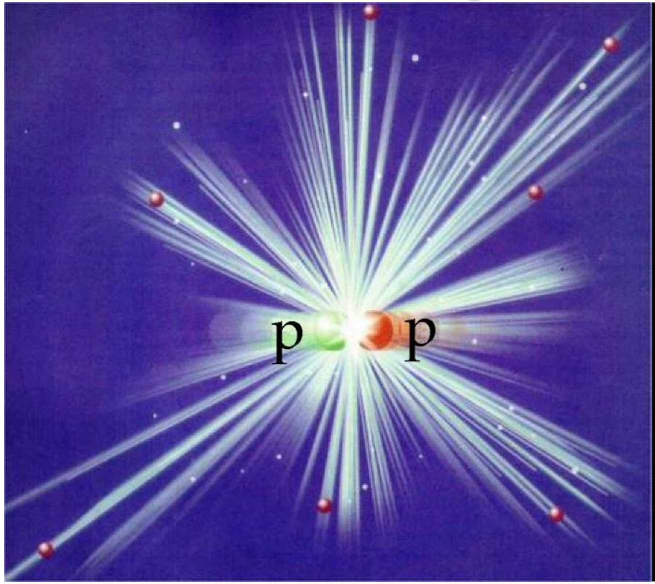
$\lambda = h/p$; @LHC: $T = 1$ TeV $\Rightarrow \lambda \simeq 10^{-18}$ m

Quarks are point-like at < 50 zm!

CERN AC - Z11 - V11/5/98

Accelerators also bring us toward the Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{Gev}$
- T ≅ 1 ps for single particle creation
- T ≅ 1 μs for collective phenomena QGS (Quark-Gluon Soup)



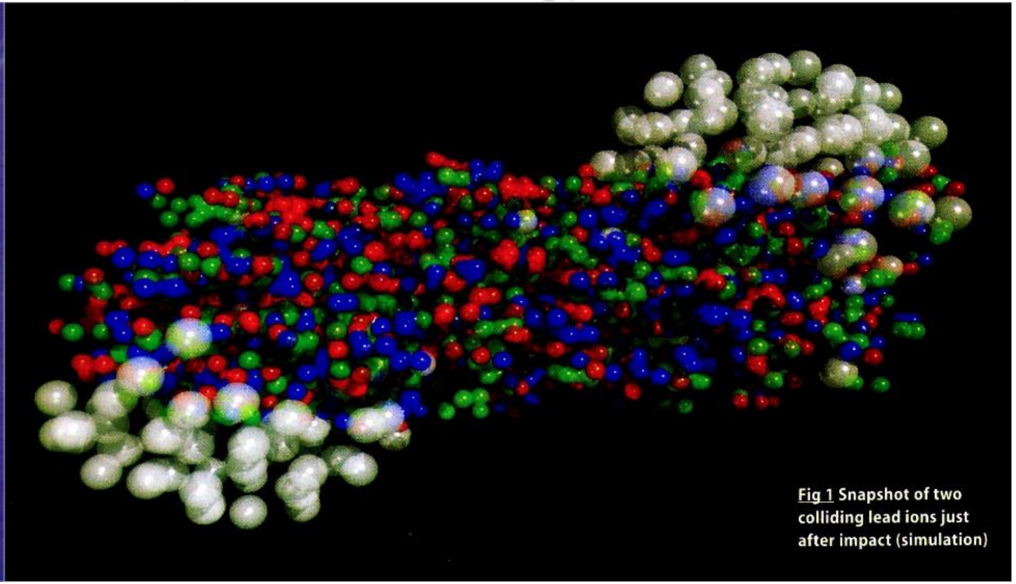
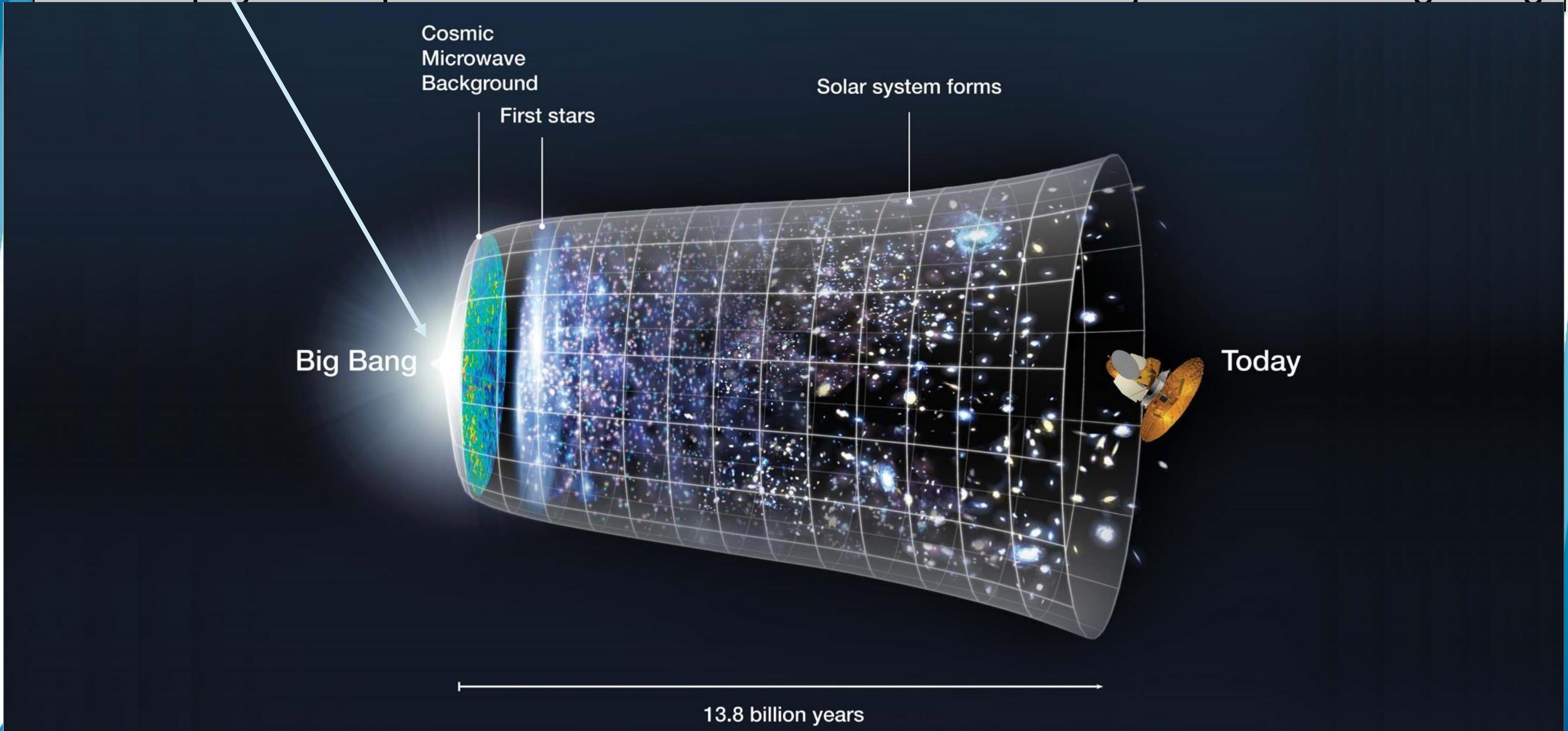


Fig 1 Snapshot of two colliding lead ions just after impact (simulation)

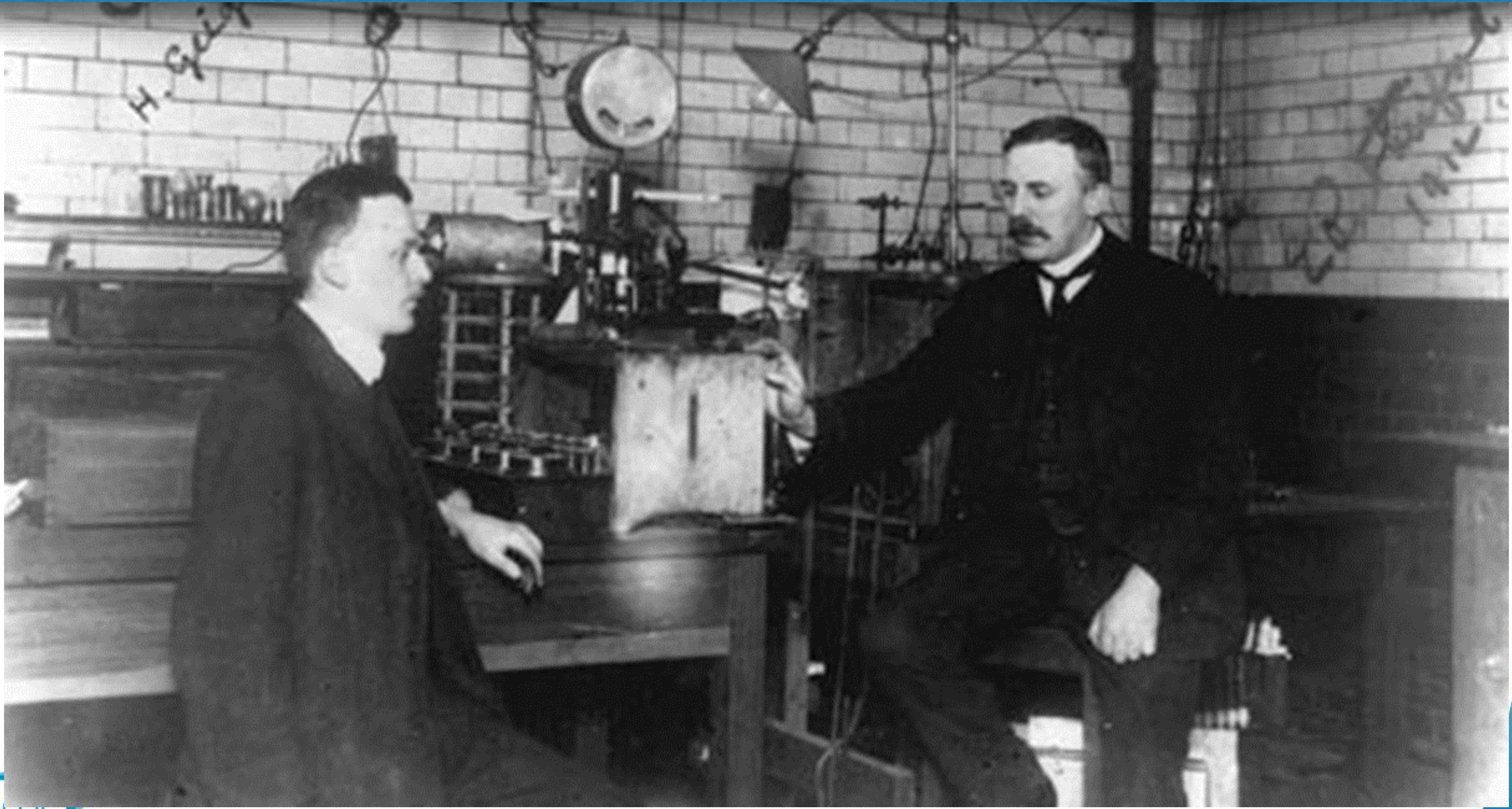
But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about… a much complex task!

The Universe (and all particles within) is 13.8 billion years old

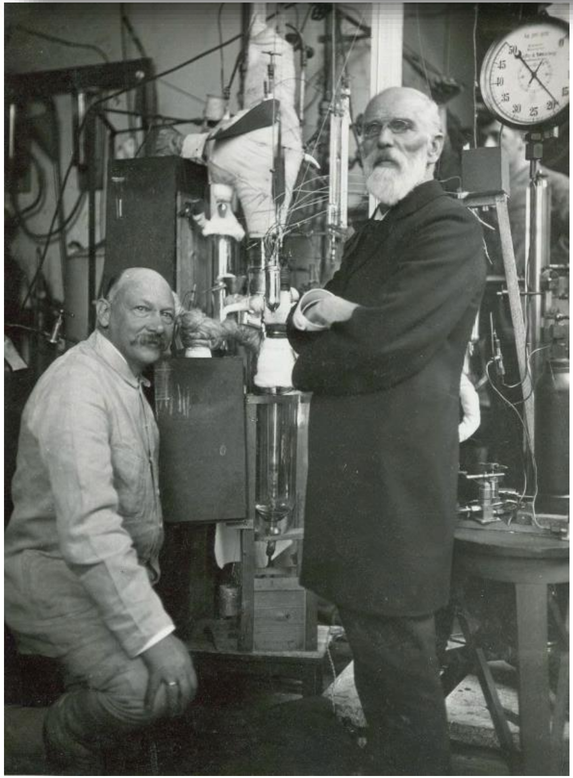
Particle physics reproduces the conditions of the Universe just after the Big Bang



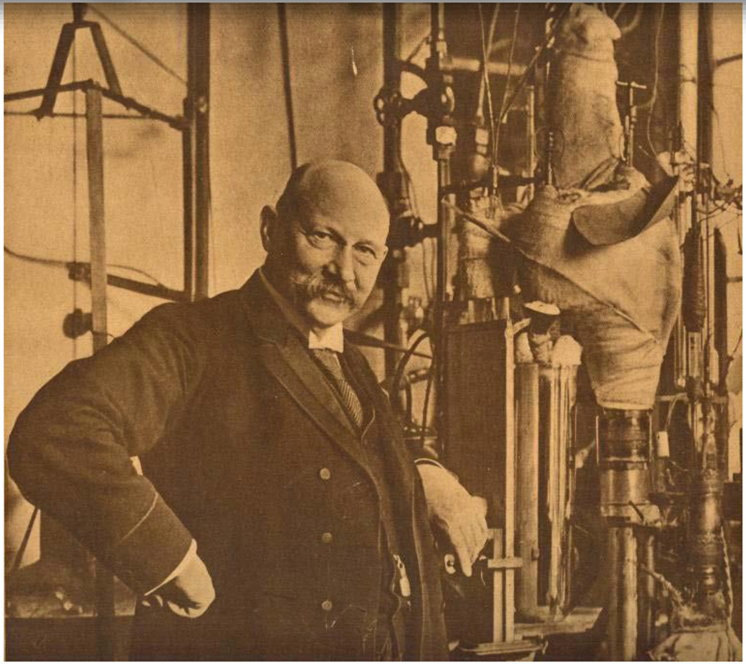
A new frontier: smashing atoms in Manchester 1909-11



A frontier of Physics turning 1800s into 1900s



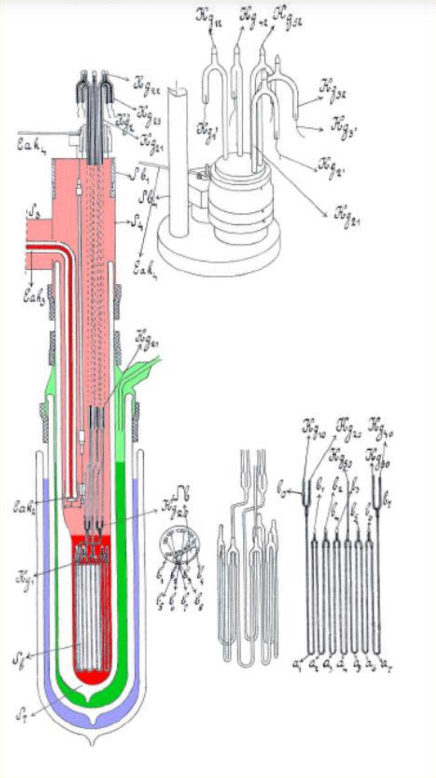
Heike Kamerlingh Onnes with Johannes Diderik van der Waals in front the first Liquid Helium liquifiers



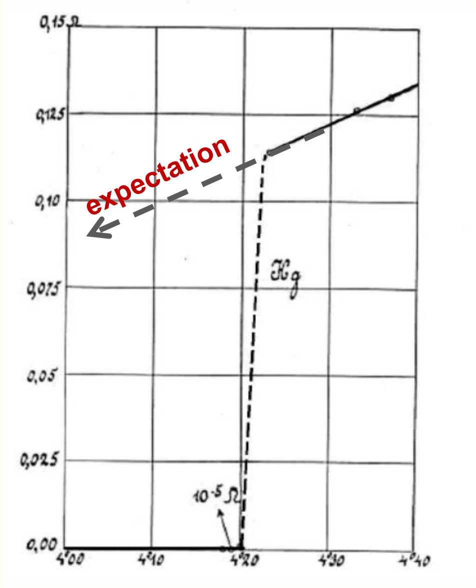
Leiden (NL): Onnes first liquifies helium in 1908. He opened a new territory:

low temperature → low thermal noise

Superconductivity: the gift you don't expect…



Experiment of 26 October 1911 with the historic plot showing the resistance jump at 4.20 K.

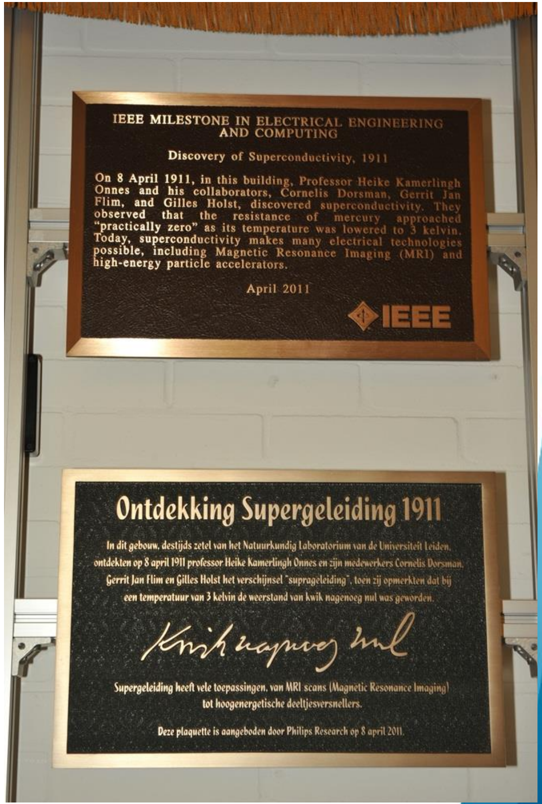


Unexpected, but not discovered by chance… SUPERCONDUCTiVITY was recognized because Onnes was searching, he had a question: and many times the answer is beyond expectation…

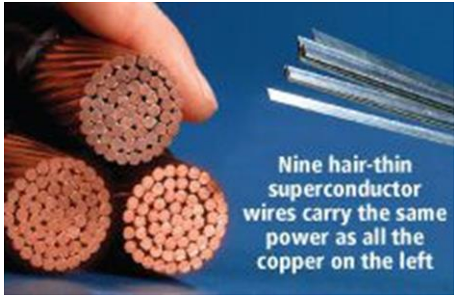
Leiden: high place of history for Physics

10 July 2008: memorial of 100 y from He liquefaction

8 April 2011: memorial of the 100 y discovery of SC

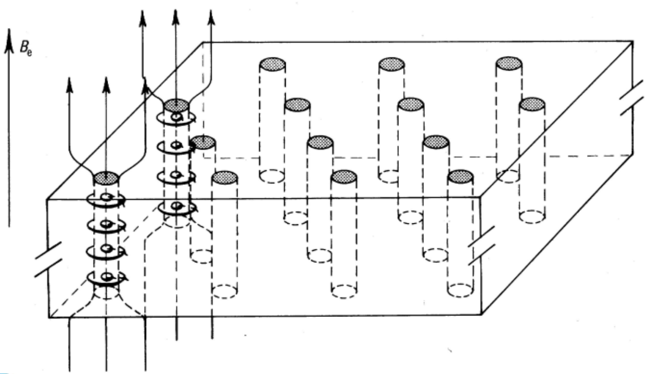


Superconductivity: a new order…



Electrons are individual particles «fermions»
In certain materials, when cooled at very low temperature, electrons couple despite same charge!
The couple becomes a «boson» and it does not interact anymore with the material lattice: no more dissipation, or heating: **«unlimited» zero-dissipation current**!

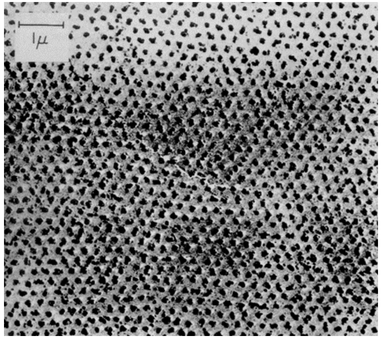
Optimal Nb-Ti properties developed by understanding the processing-nanostructure-J_c feedback cycle

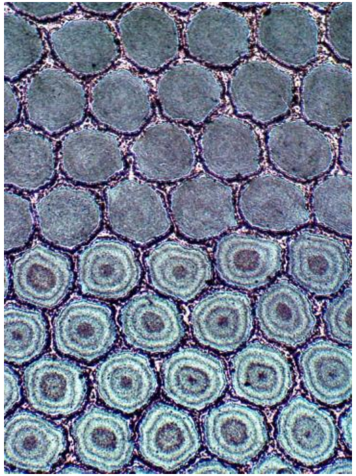


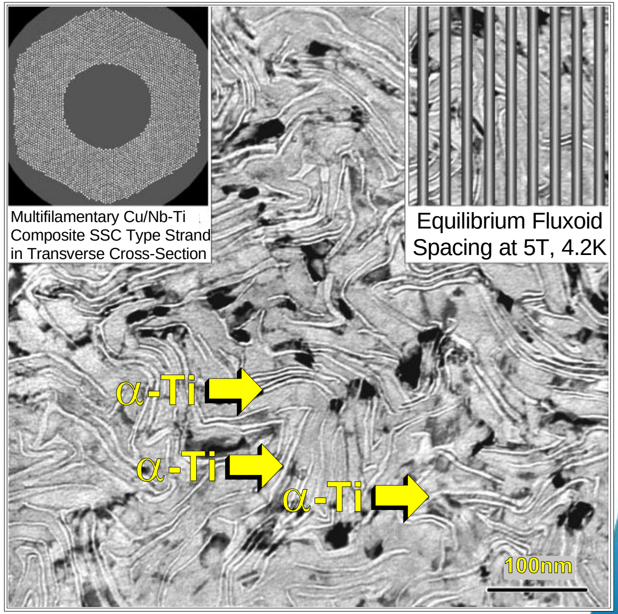
(P, V, T) → (B, J, T)

Precipitate 20-25vol.% α-Ti to pin vortex cores

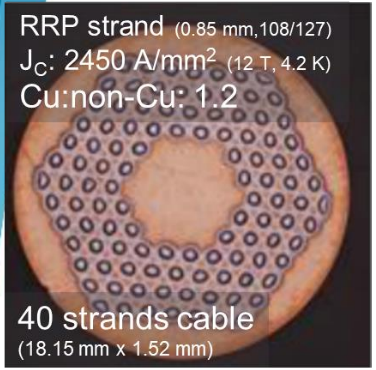
Start with homogeneous Nb-Ti

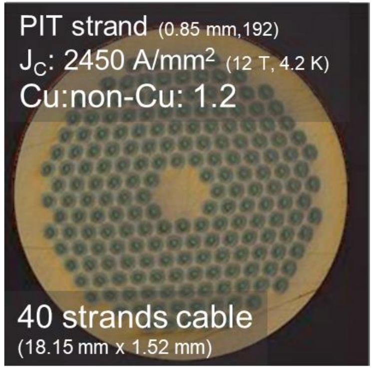


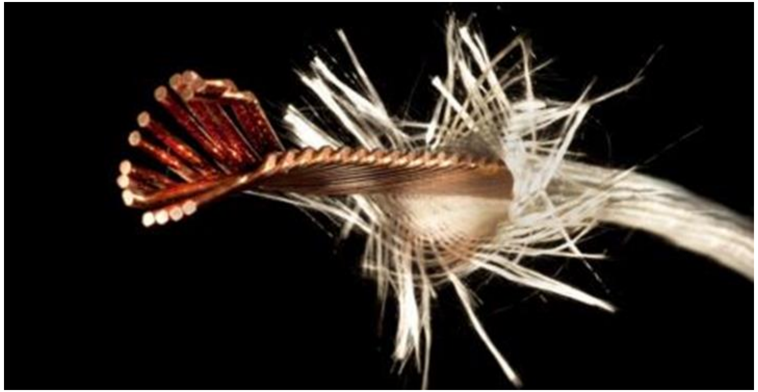


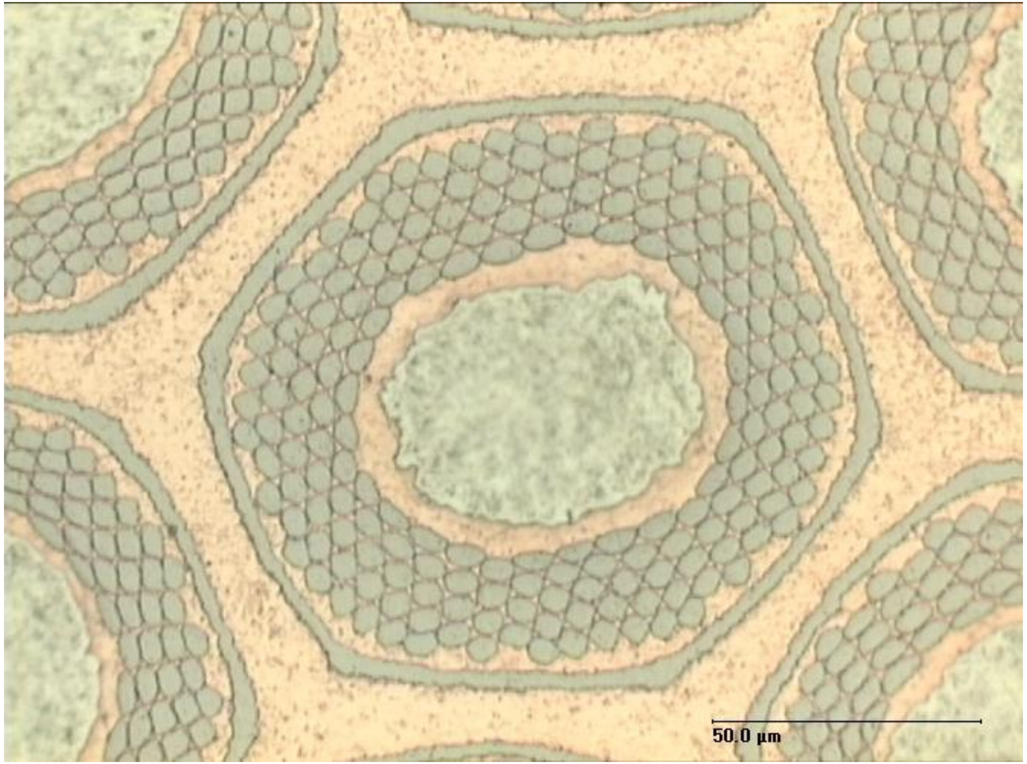


Materiali innovativi: Nb_3Sn ad alta J_c
(J_c 3 times the one of ITER)

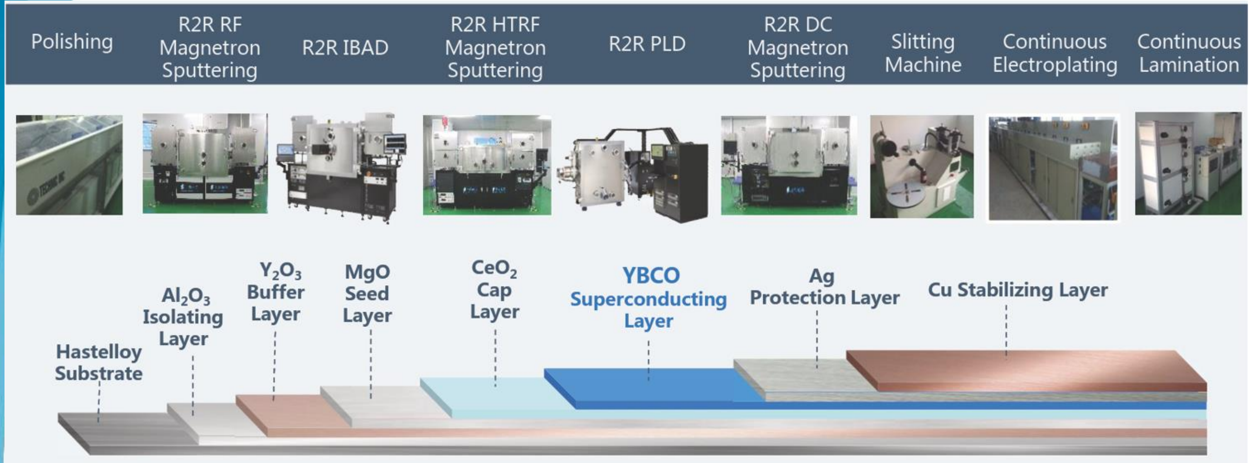


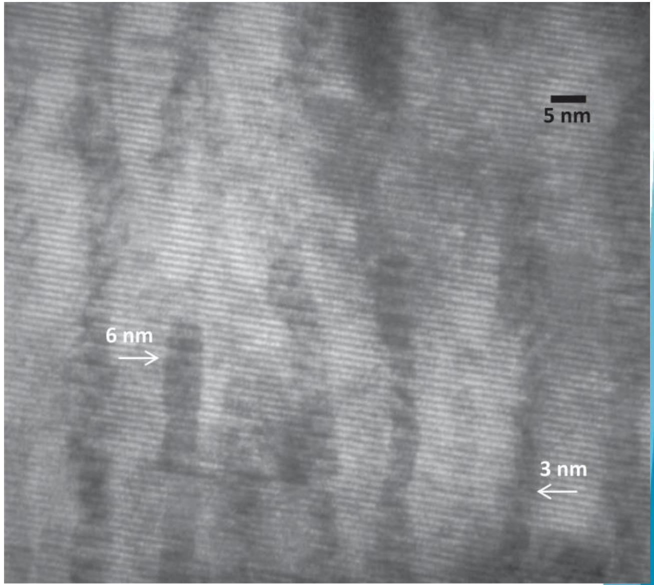






Materiali innovativi: HTS
Bi-2212 e soprattuttoYBCO

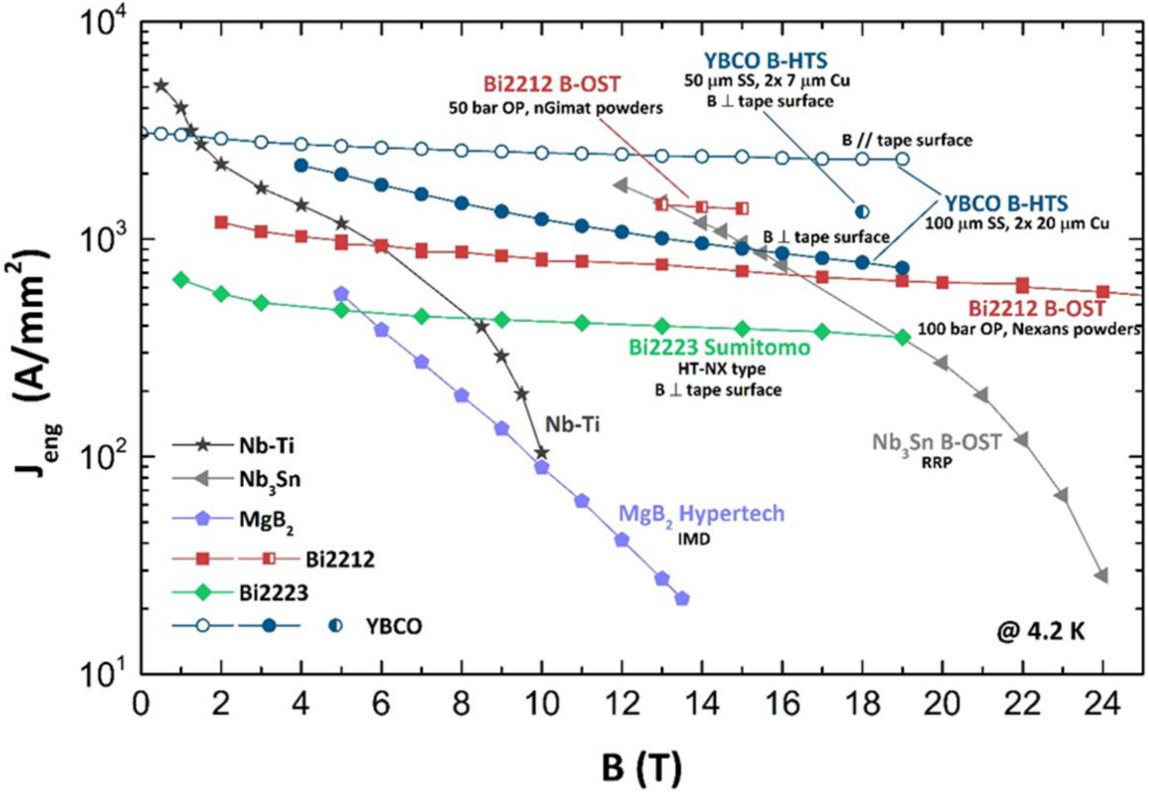




Double disordered YBCO coated conductors of industrial scale: high currents in high magnetic field

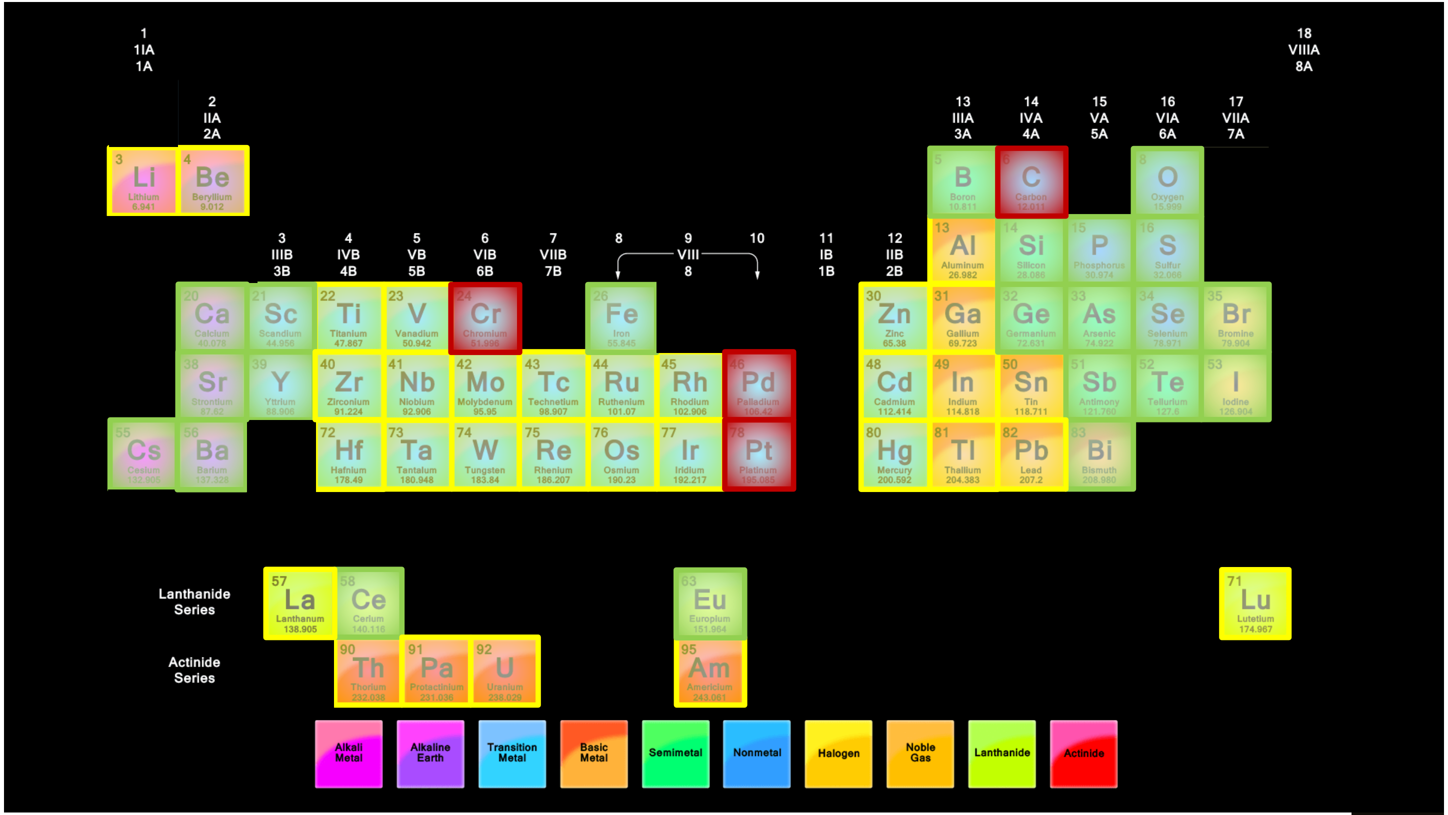
D Abraimov[1], A Ballarino[2], C Barth[3], L Bottura[2], R Dietrich[4], A Francis[1], J Jaroszynski[1], G S Majkic[5], J McCallister[1], A Polyanskii[1], L Rossi[2], A Rutt[4], M Santos[1], K Schlenga[4], V Selvamanickam[5], C Senatore[3], A Usoskin[4] and Y L Viouchkov[1]

Very high critical current in technical SC!



Transverse fields

solenoids

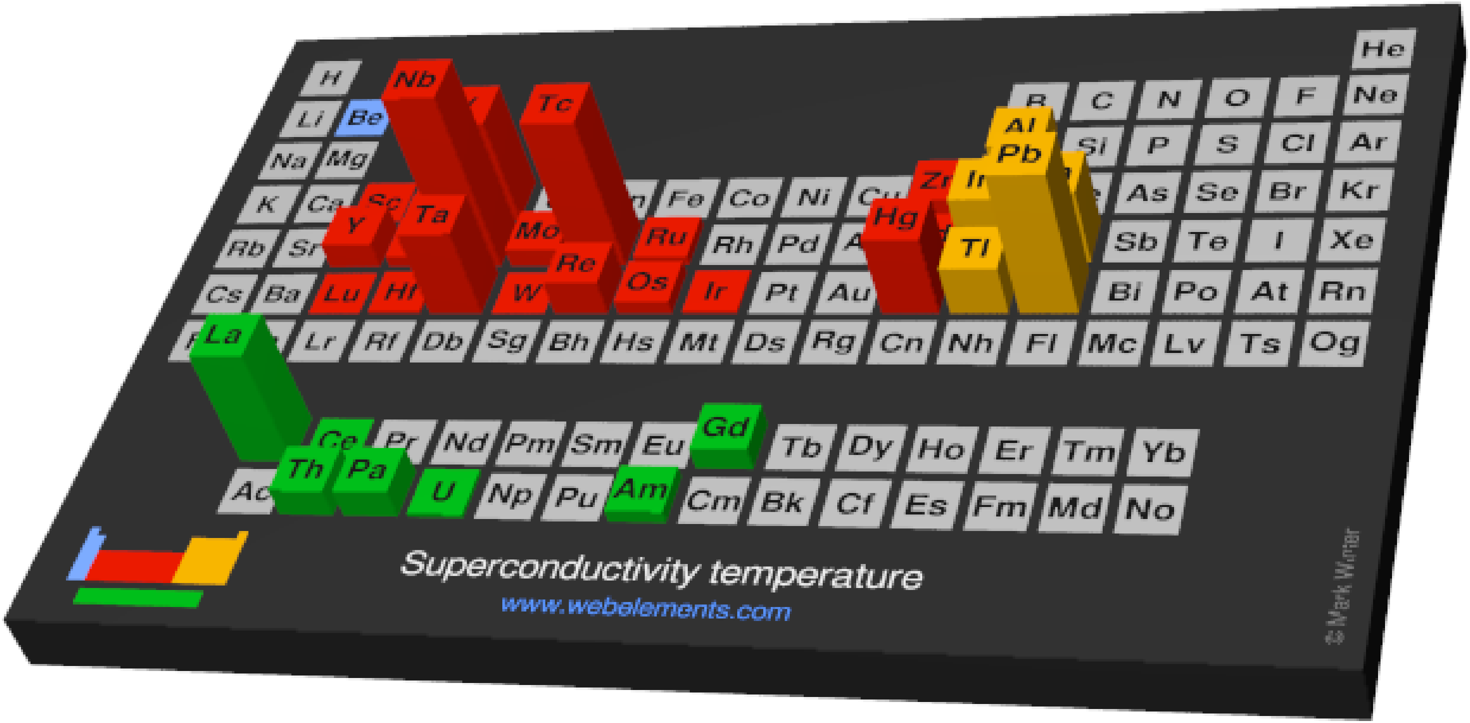


Superconduttori a pressione ambiente

Superconduttori ad alta pressione

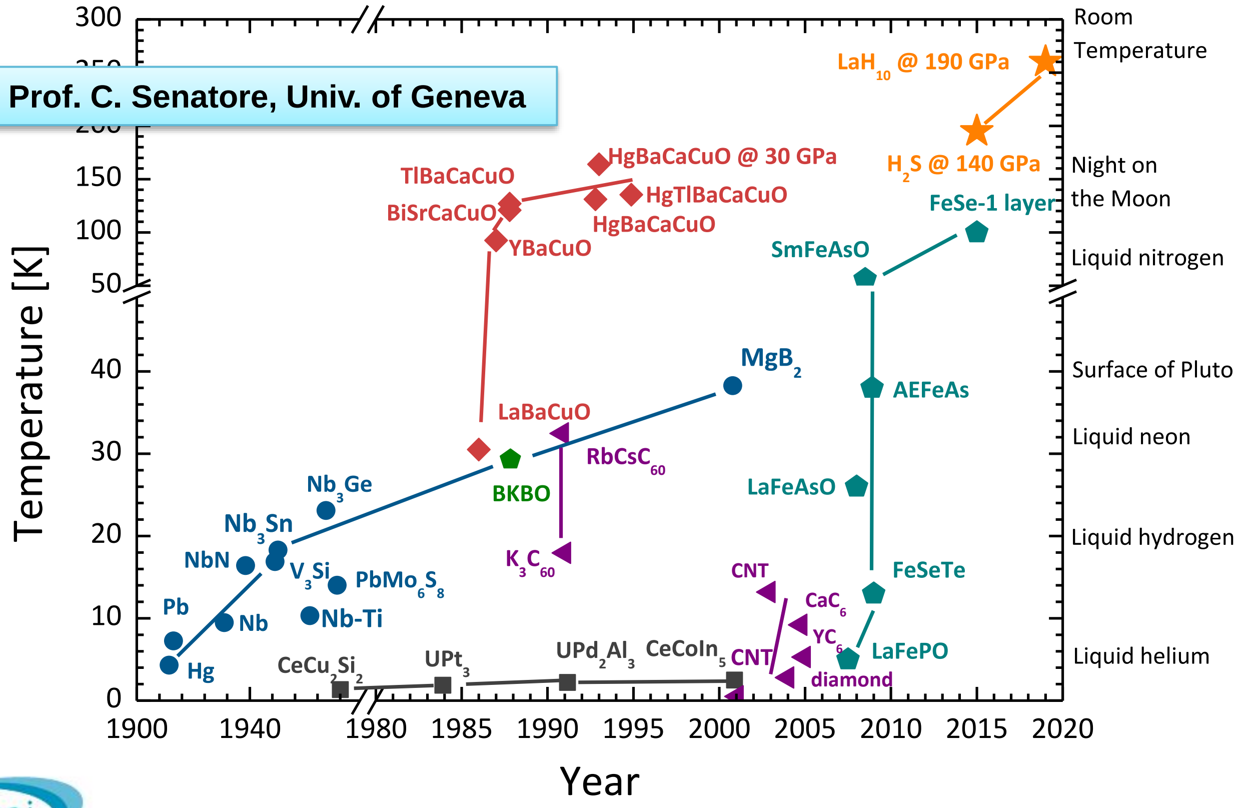
Superconduttori in forma modificata

Critical temperatures on the Mendeleev table

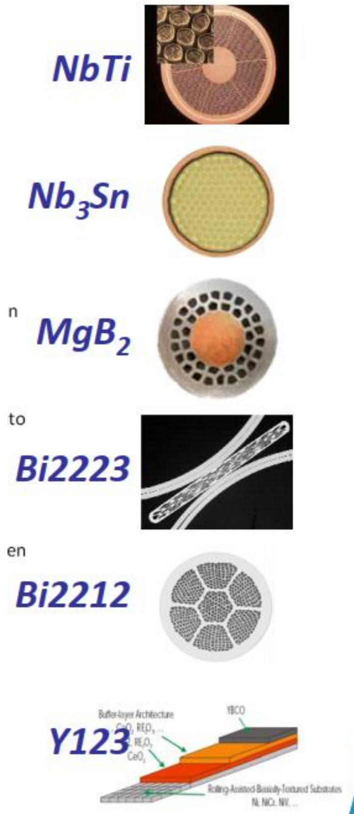


Cortesy of D. Valentinis, KIT, Karlsruhe

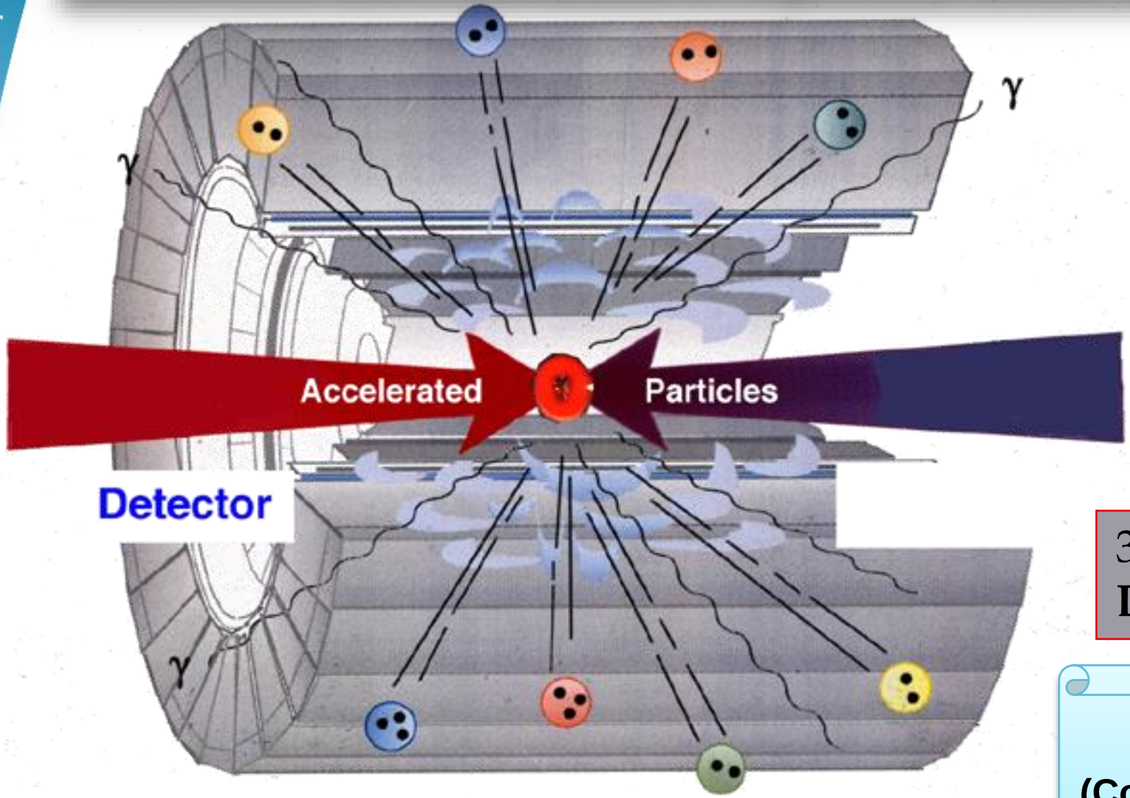
Superconductivity: the endless race toward high temperatures



Courtesy: Prof. C. Senatore, Univ. of Geneva



Method of Particle Physics with Colliders



1) Concentrate energy on particles (**accelerator**)

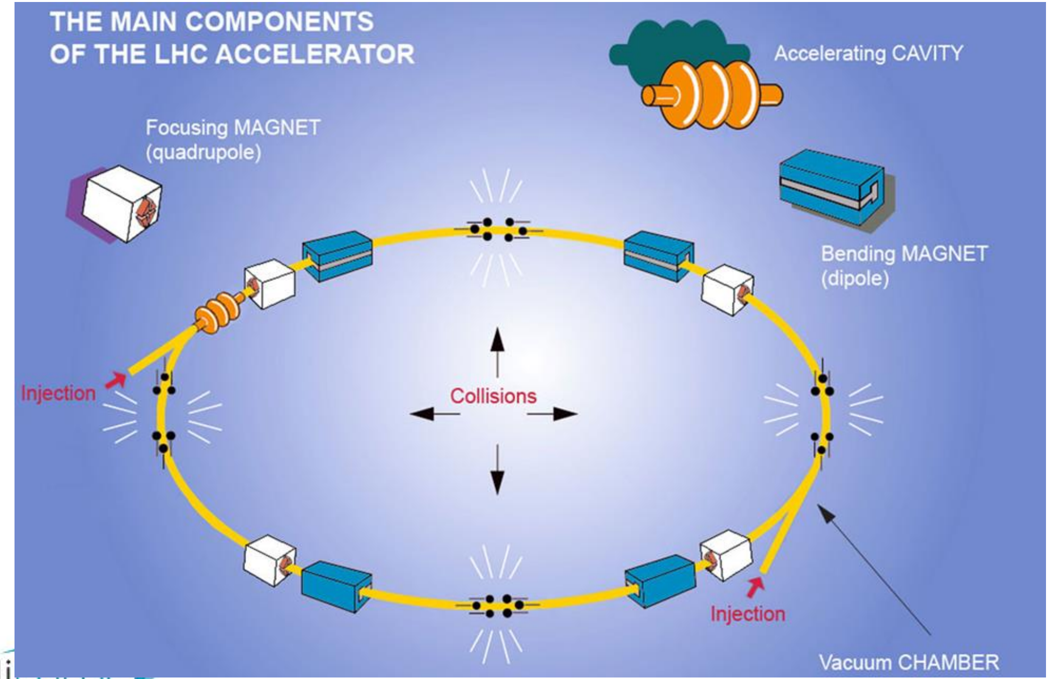
2) **Collide** particles (recreate conditions after Big Bang)

3) Identify created particles in **Detector** (search for new clues)

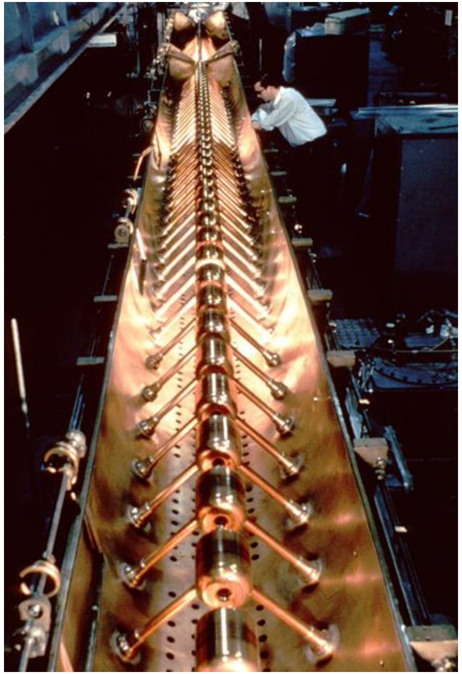
And both Accelerators (Colliders) and detectors need Superconductivity!

Due grandi famiglie: circolari e lineari

Ciclotroni, sincrotroni e anelli d accumulazione: la sezione accelerante è breve ma viene riutilizzata grazie ai magneti dipoli che tengono l’orbita

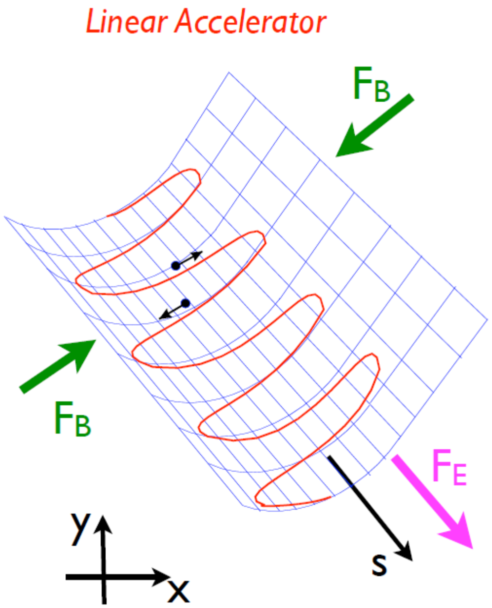


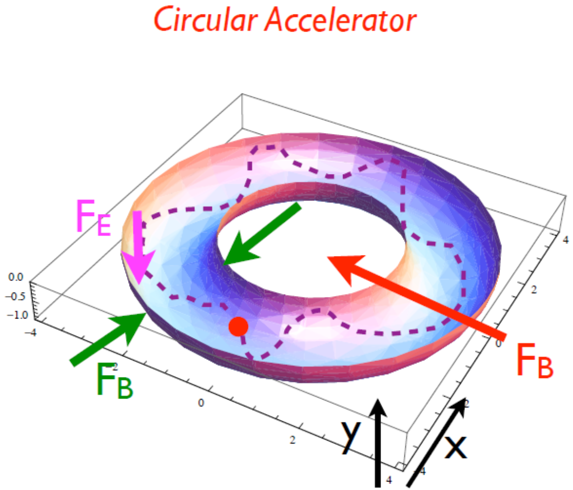
Linac: le sezioni acceleranti si sommano in linea retta



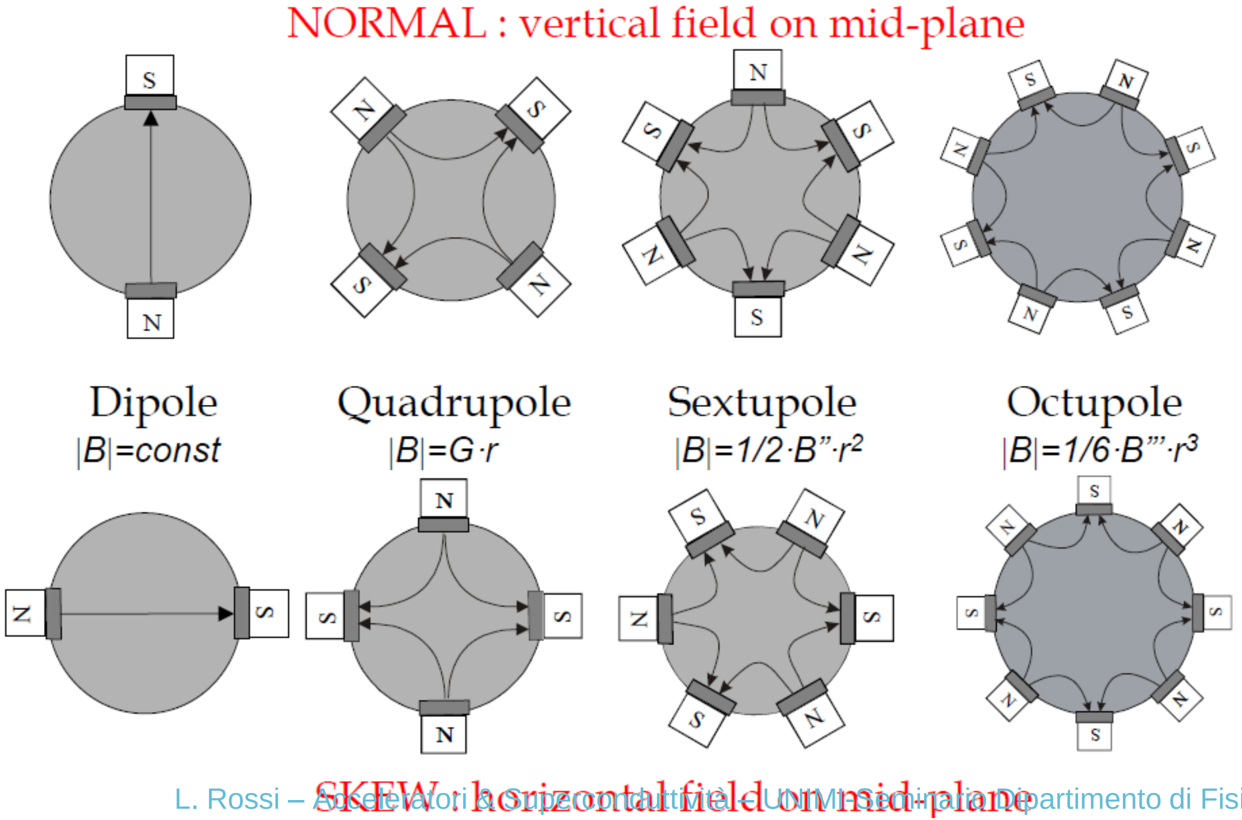
E non basta spedirle dritte o farle girare in tondo: i fasci di particelle devono essere focalizzati.

$$\overline{F(t)} = \underbrace{q\,\Big(}_{F_E}\overline{E(t)} + \underbrace{\overline{v(t)} \otimes \overline{B(t)}}_{F_B}\Big)$$





Un qualsiasi campo è composto di multipoli



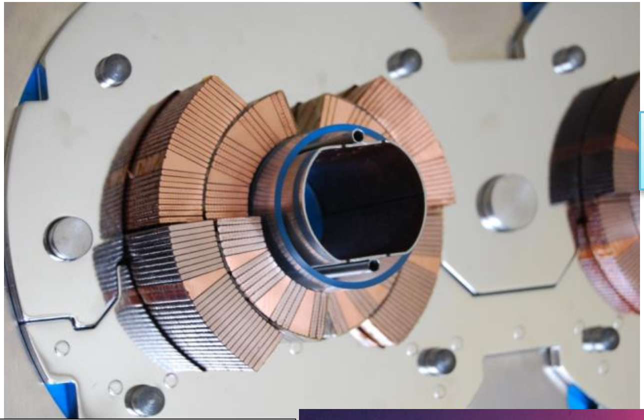
Accelerator magnets : basic

- The basic shape : cosϑ shell
- Shells with const J is a very good approximation
- Field expansion

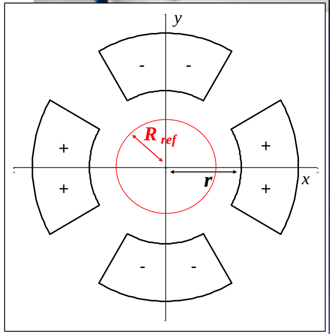
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

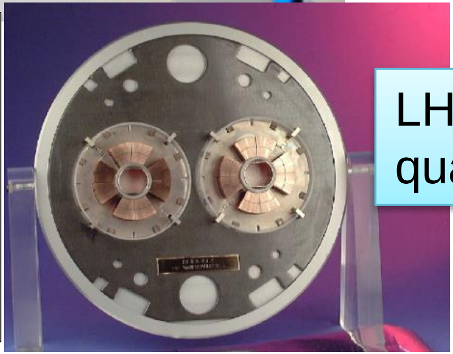
Field quality at 0.1÷1 10^{-4} level

→ Coil accuracy: 10÷50 µm over 15 m !



LHC dipole



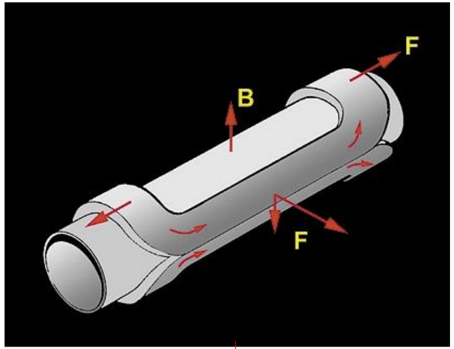


LHC quadrupole

Accelerator Magnets: Basic Design

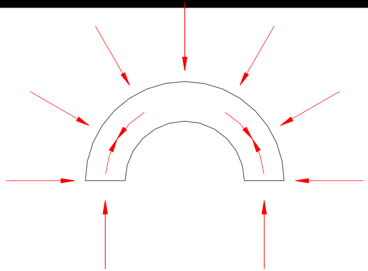
$J_{overall}$ ≈ 500 A/mm² ! e.m. forces are not kept by conductors but tend to torn apart the winding.

Principle



e.m. forces

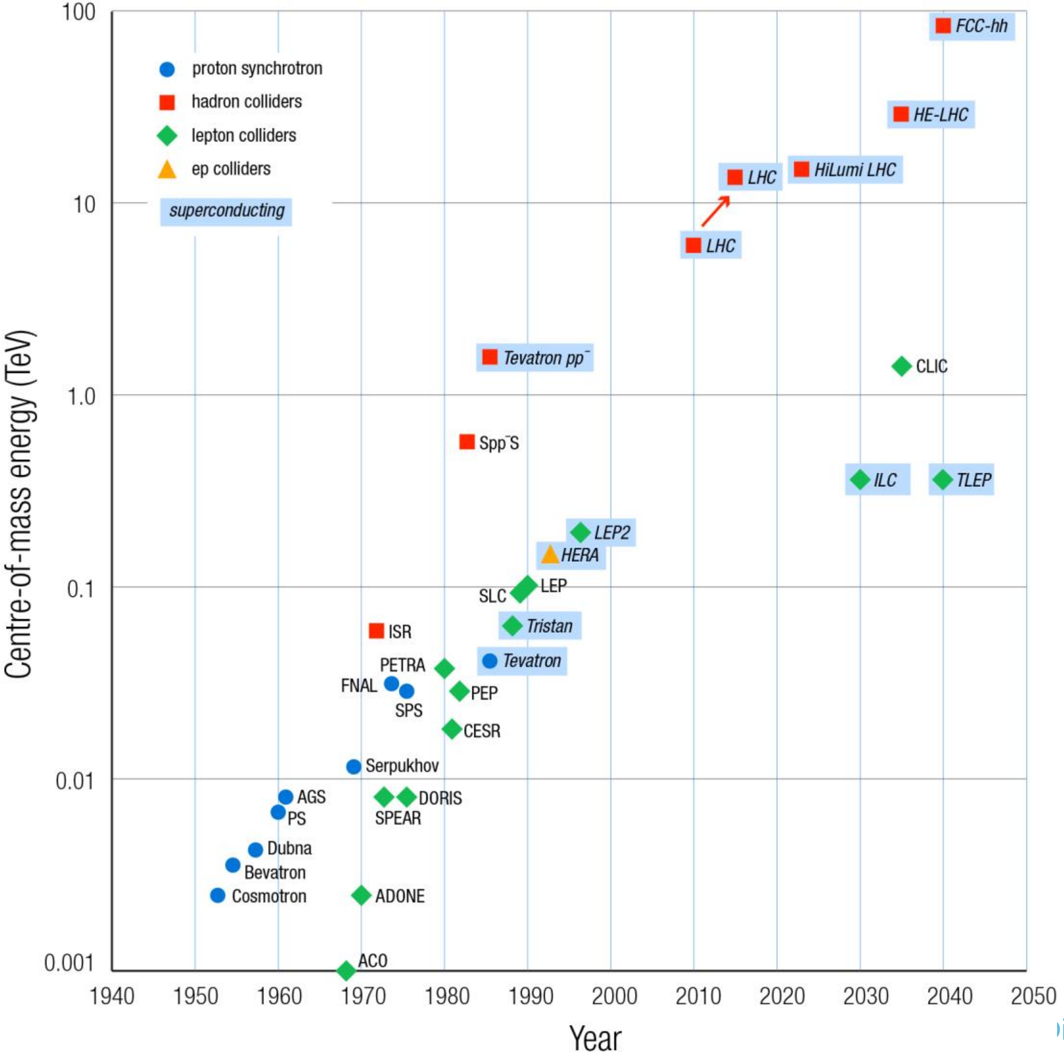
NOT SELF-SUPPORTING



How to contain them

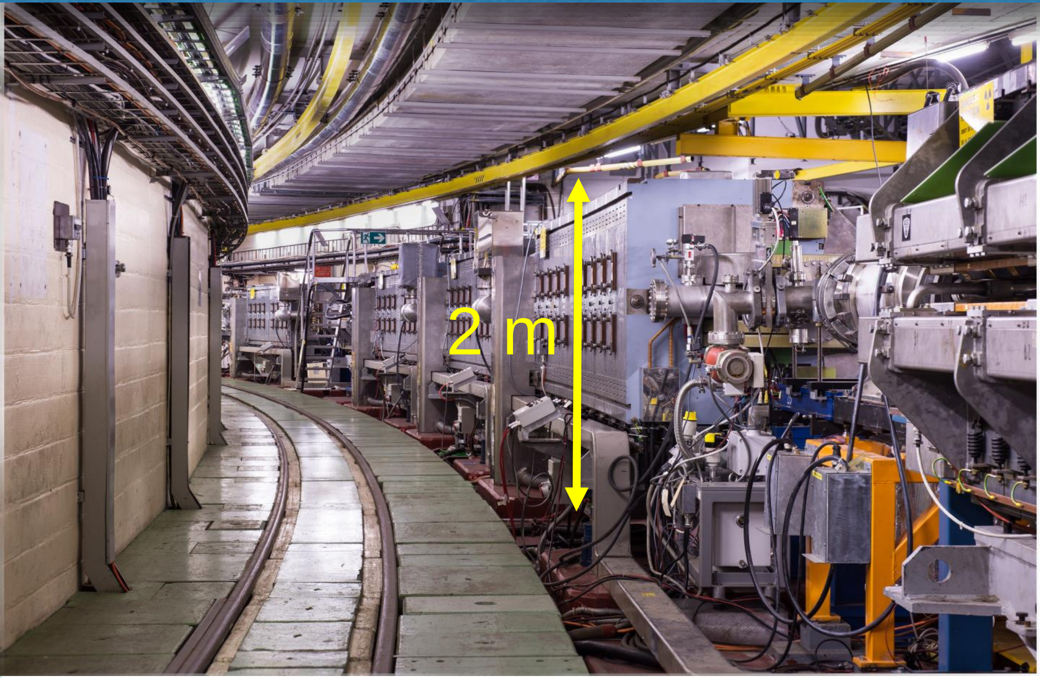
More difficult in twin magnets!

Reality



Dal 1980 (Tevatron al Fermilab) la SC ha dominato la scena permettendo un salto «quantico»

Carrying a lot of current: what a difference for magnets!

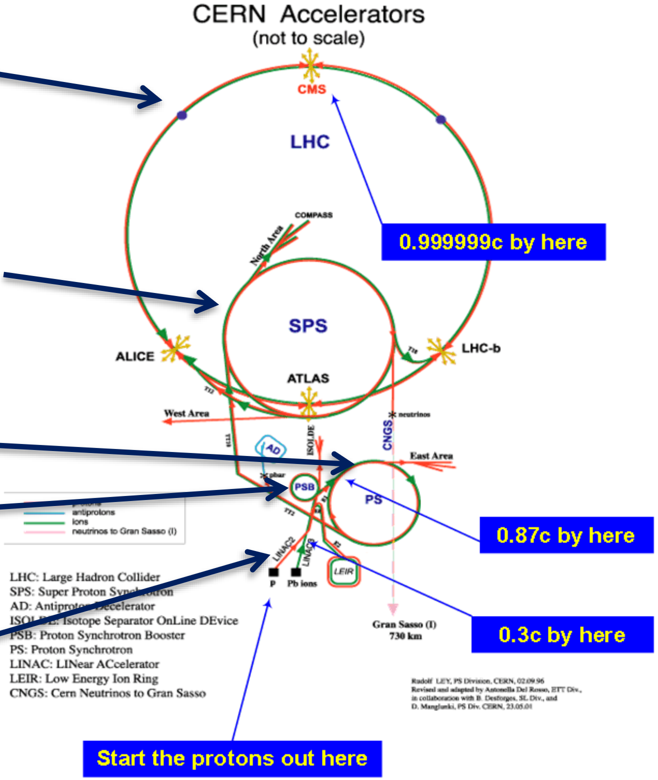


Resistive magnets of PS accelerator at CERN (1.5 tesla)

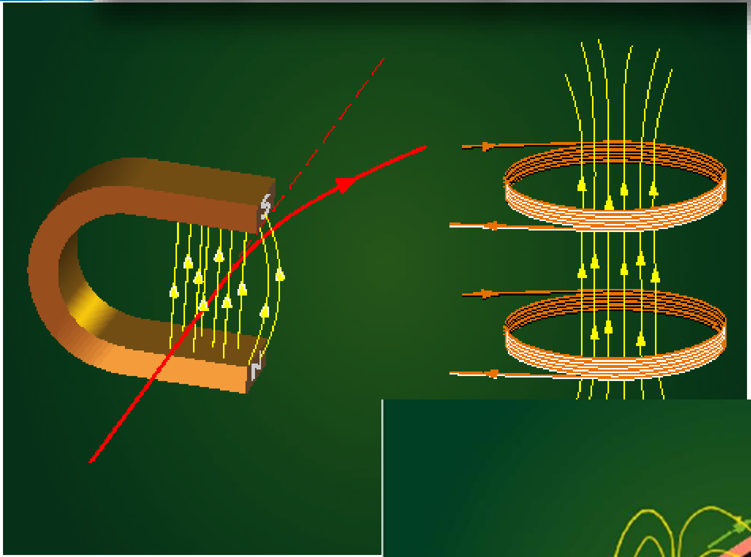
SC magnets at Tevatron at Fermilab (USA) 3 times more powerful!

CERN proton accelerator chain: the force or tradition!

- LHC : 2x(0.45 – 7) TeV
- SPS : 26 – 450 GeV
- PS : 1.4 - 26 GeV
- PSB : 0.05 -1.4 GeV
- Linac: 0-50 MeV

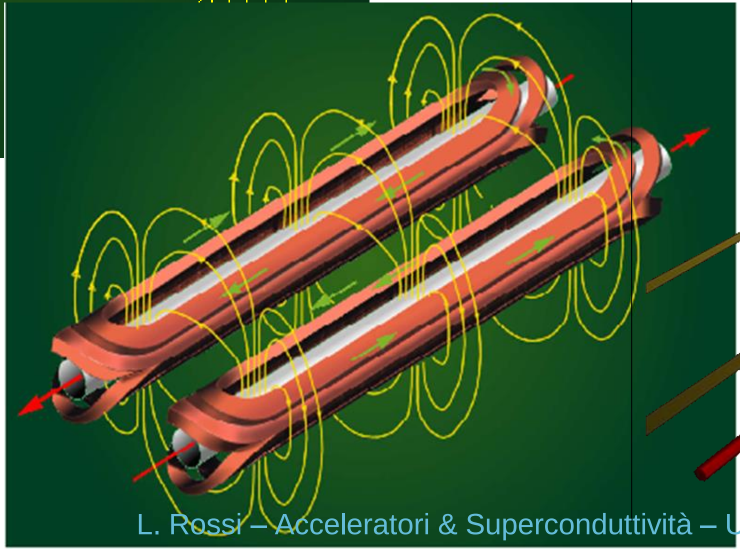


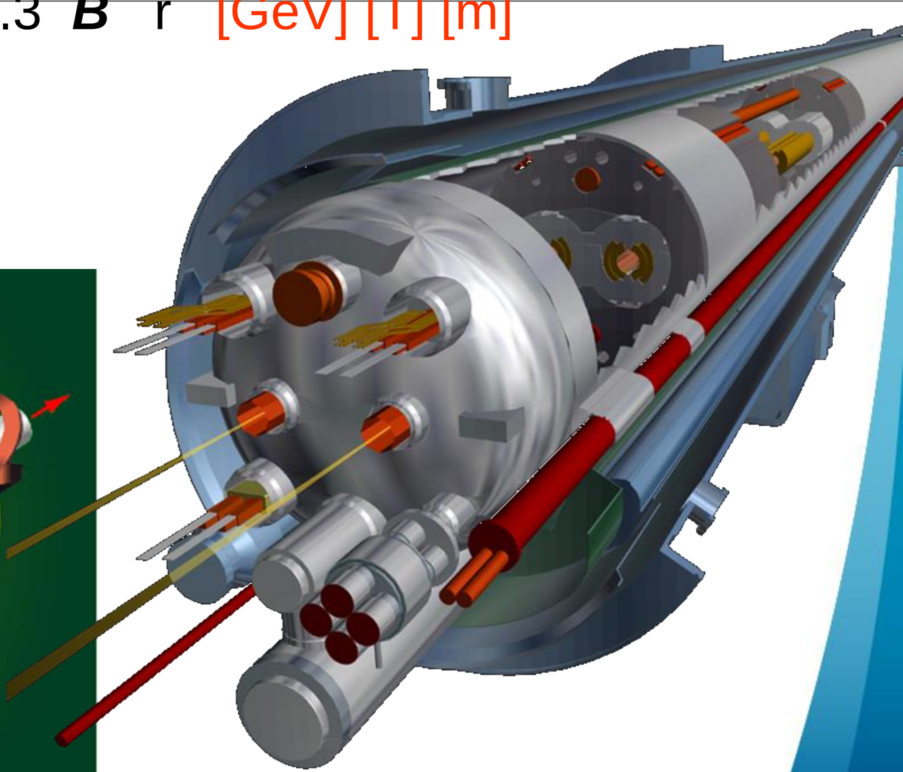
Why looking for higher and higher magnetic field?



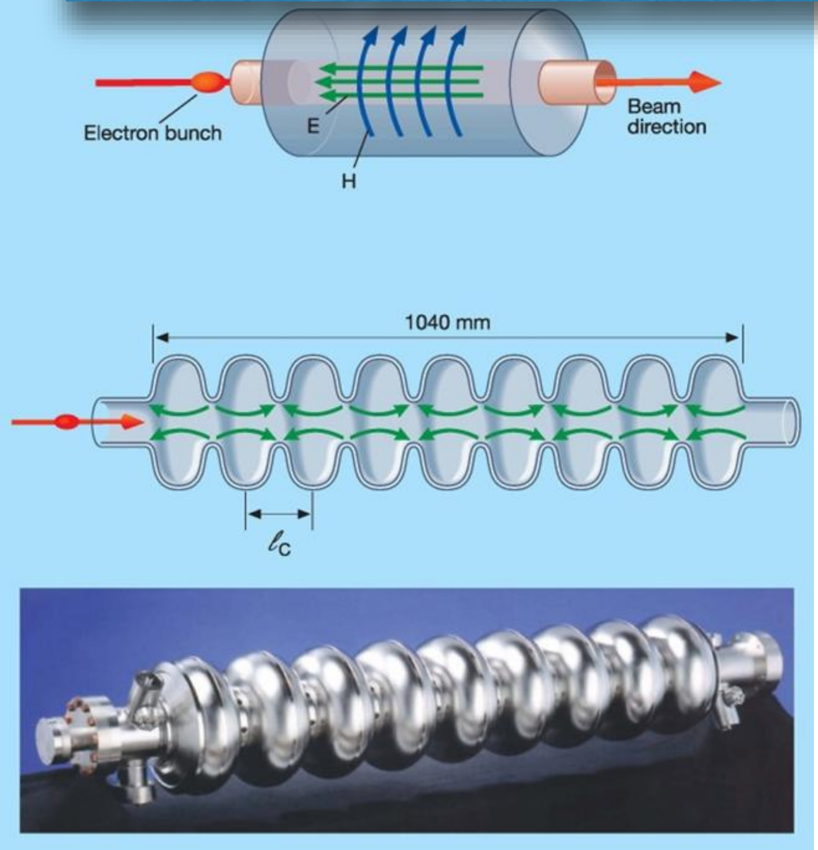
In un acceleratore circolare

$E_{beam} = 0.3\ \boldsymbol{B}\ r$ [GeV] [T] [m]



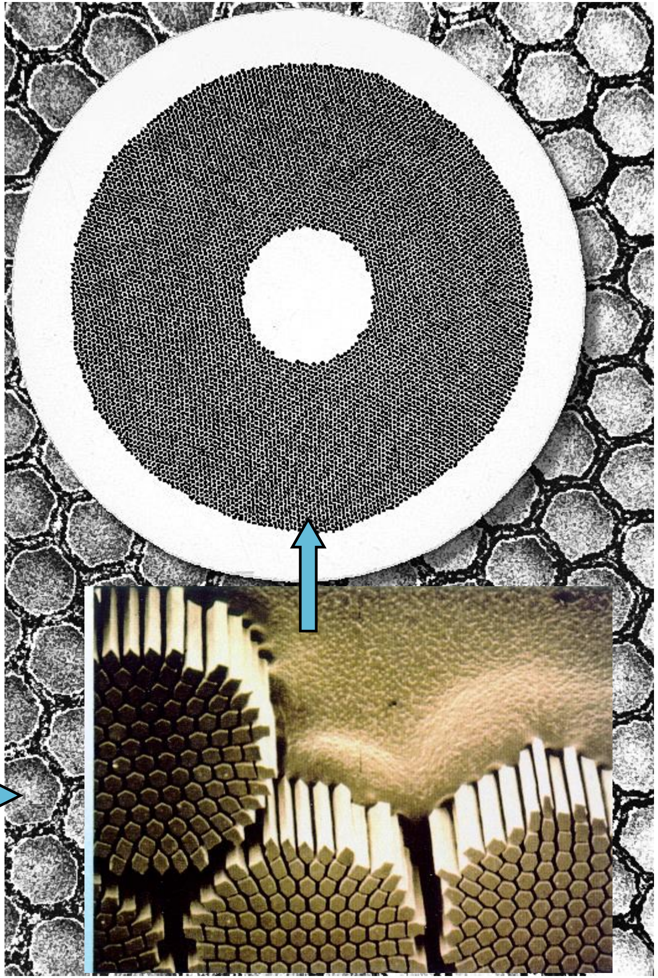


Superconductors (usually pure Niobum) are used to accelerate particles: electric fields in RF cavities

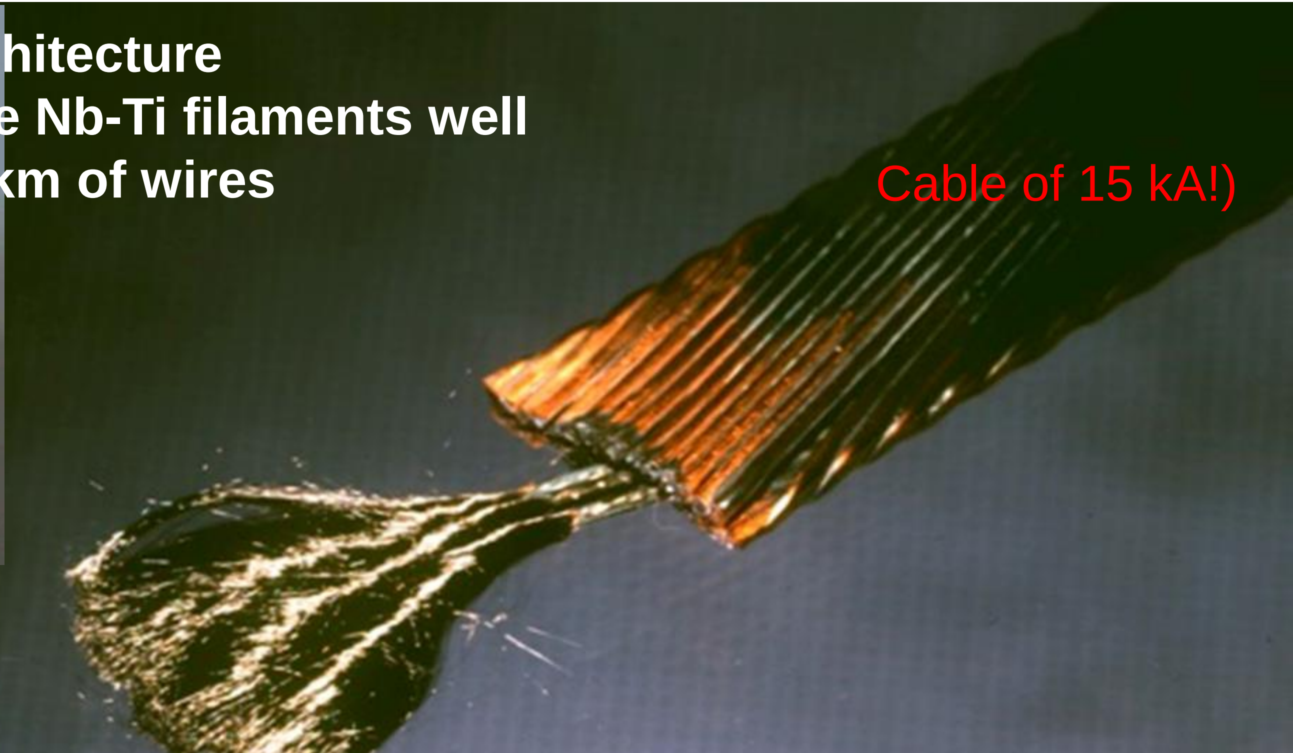


Nb-Ti: dal lingotto HO (alta omogeneità) al filo

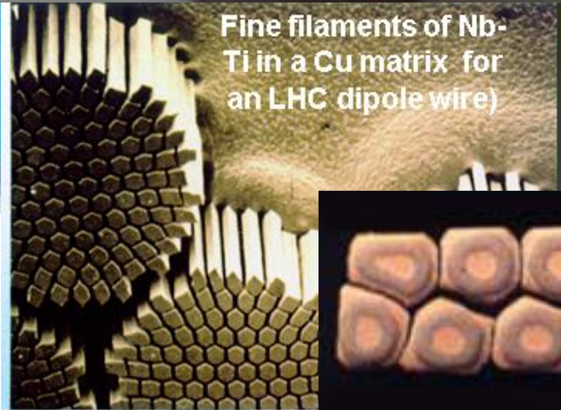
Nb-Ti billets for LHC, courtesy Wah Chang



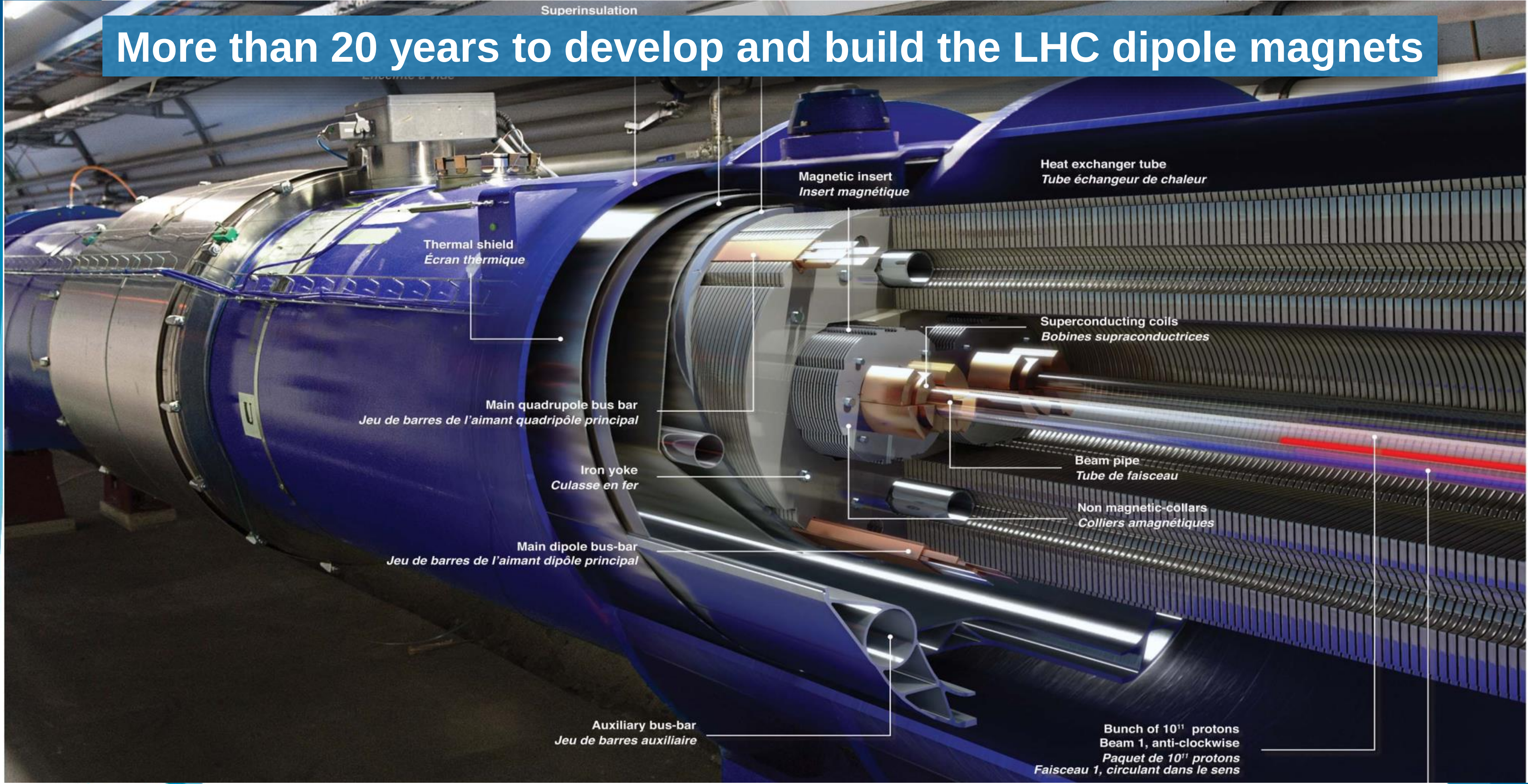
Very complex architecture
Thousands of fine Nb-Ti filaments well separated along km of wires



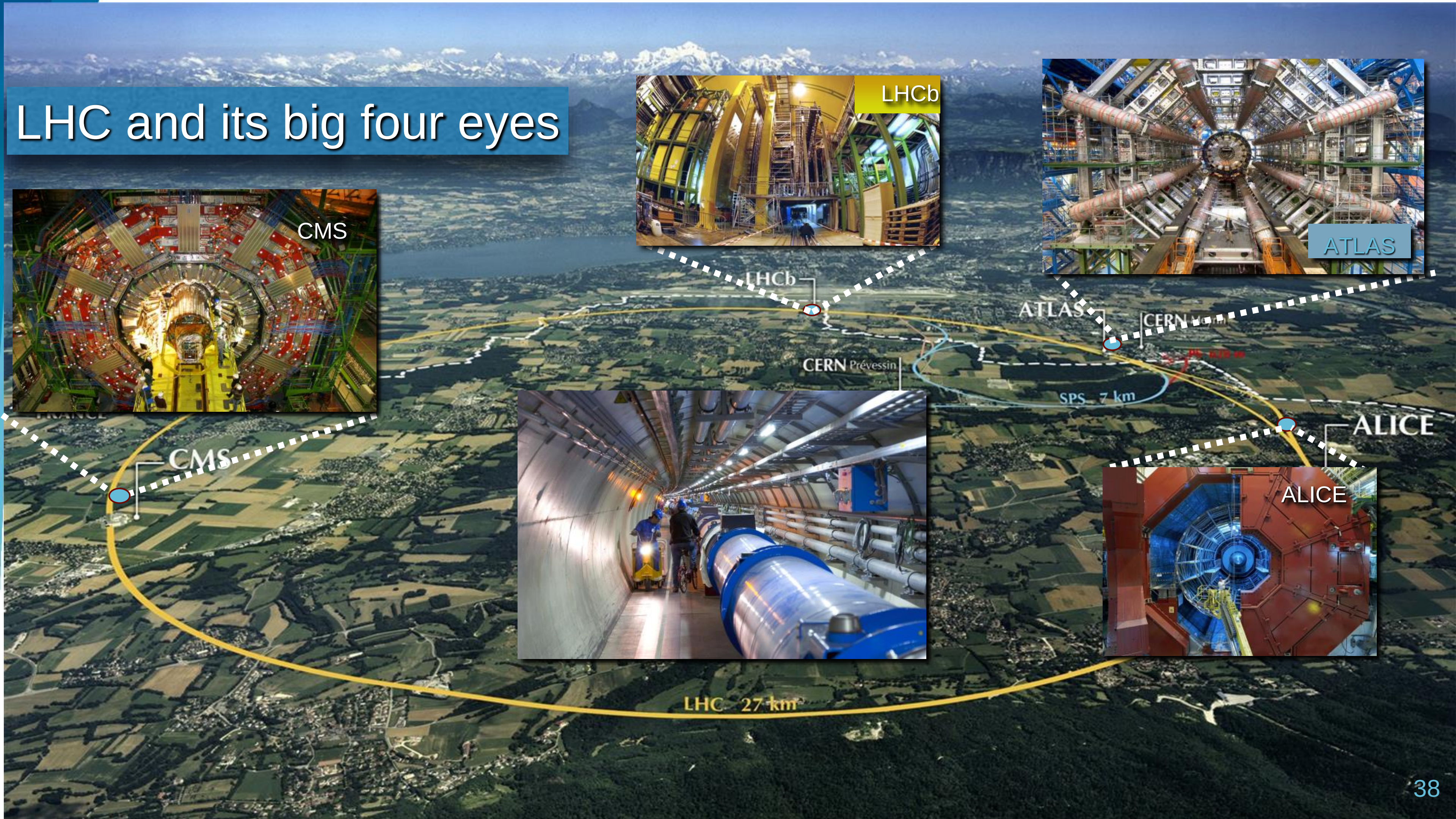
Cable of 15 kA!)

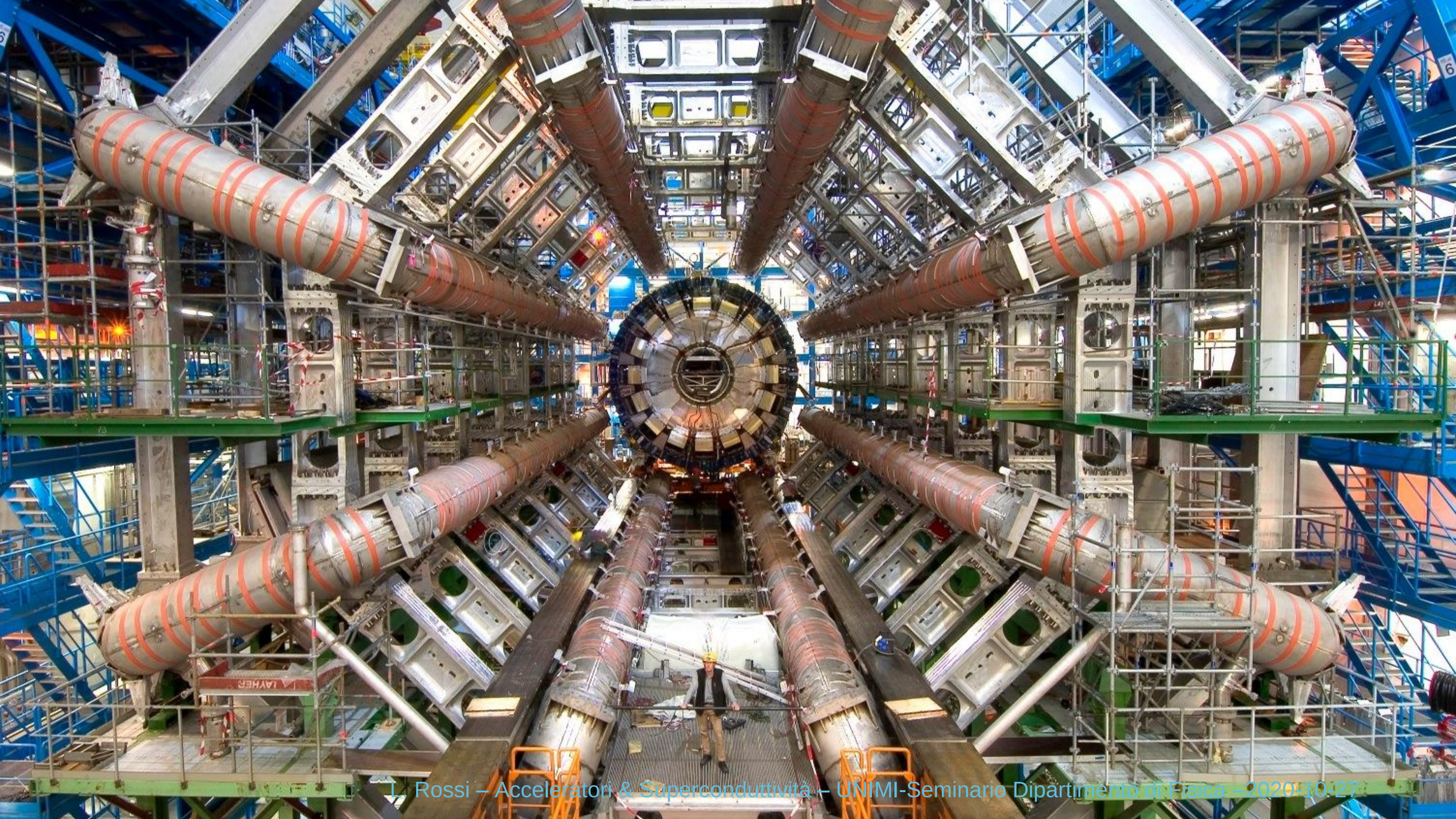


More than 20 years to develop and build the LHC dipole magnets



LHC and its big four eyes





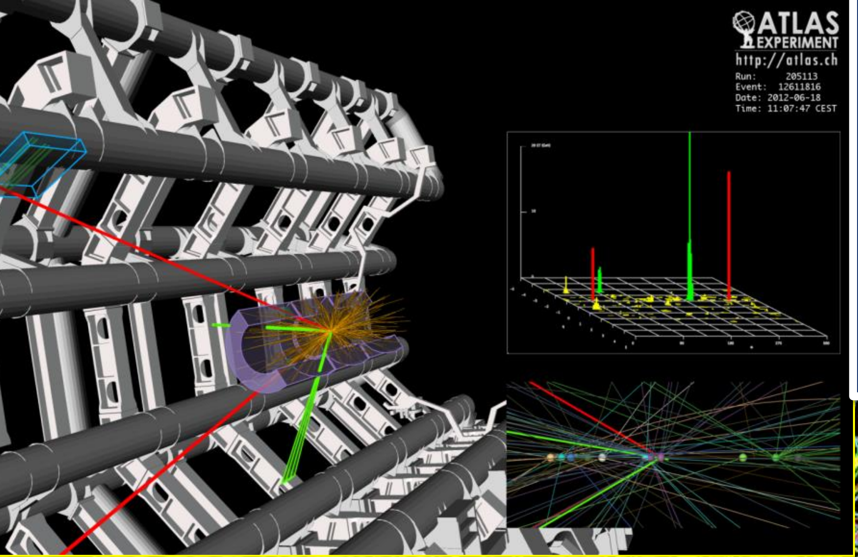
Beams collides 40 MHz

25-50 Pile up

⇒1-2 Billions collisions/s!

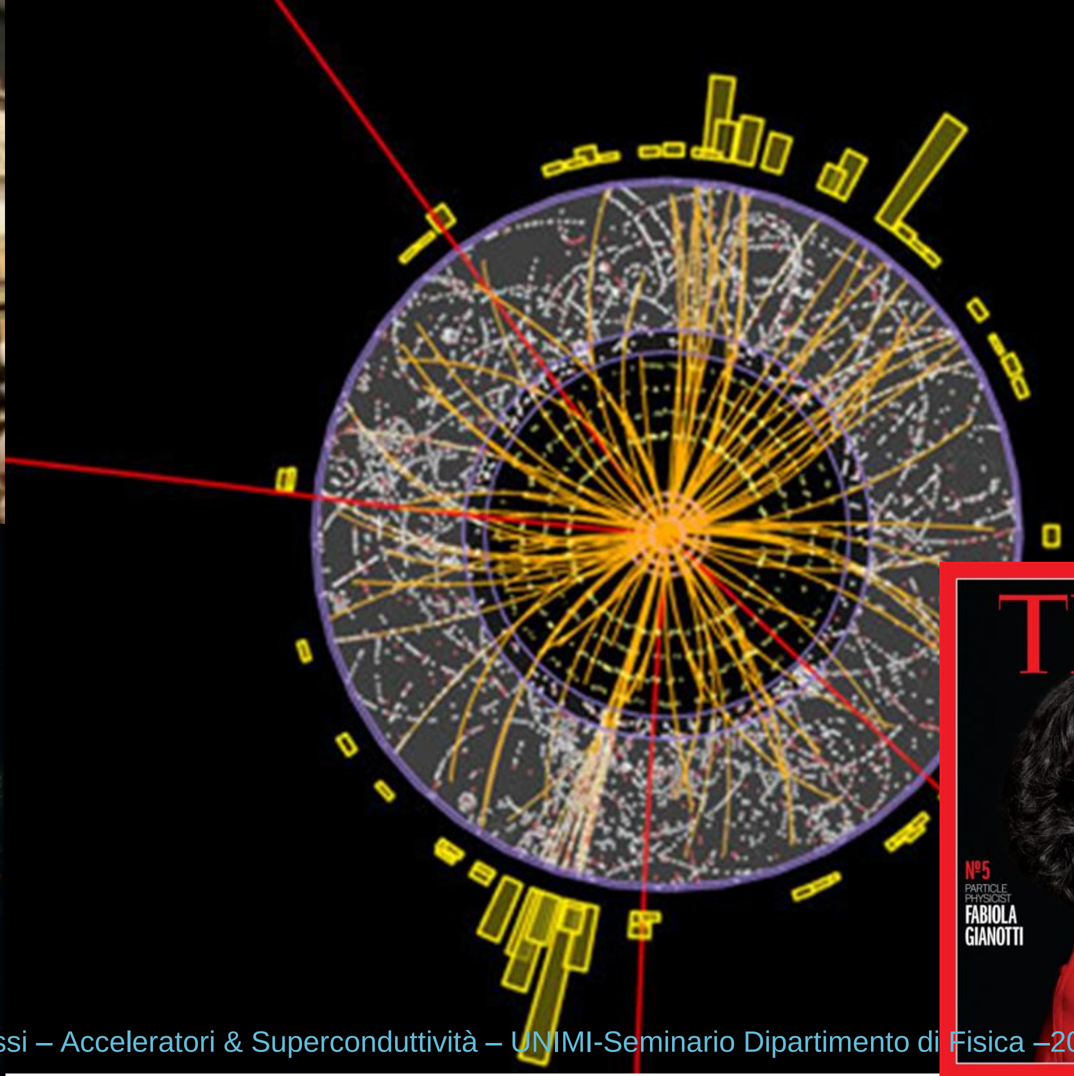
Only 1/10 Bil we “can see” a Higgs boson!

It si really searching for the needle in a haystack!



Z→ μμ event from 2012 data with 25 reconstructed vertices


The Economist
JULY 7TH–13TH 2012
Economist.com
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
A giant leap for science
Finding the Higgs boson



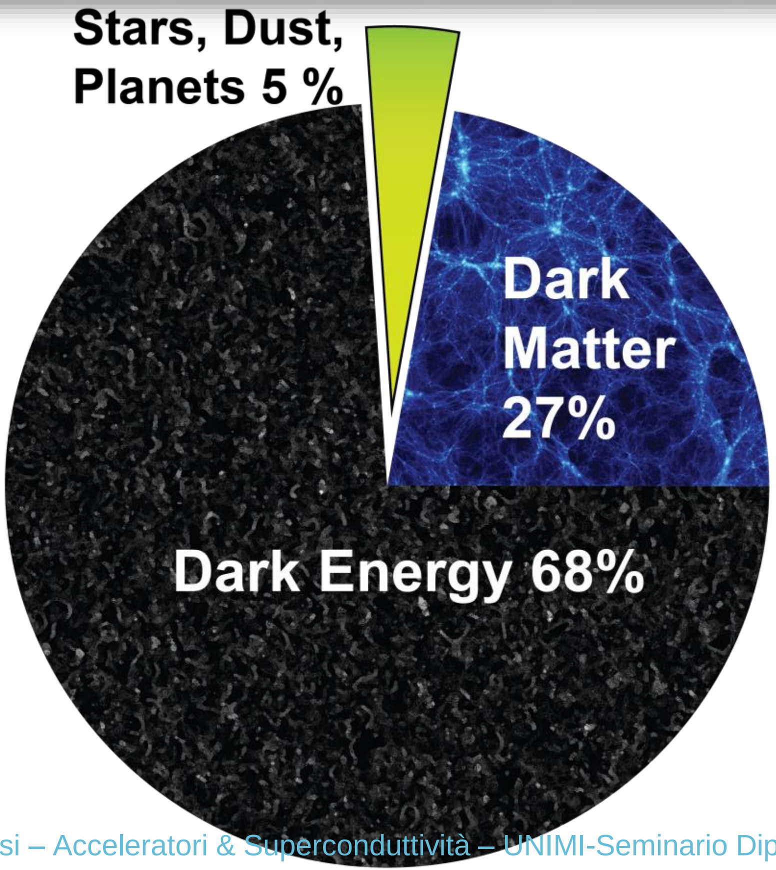

TIME
№5
PARTICLE PHYSICIST
FABIOLA GIANOTTI

Prof. Englert   Prof. Higgs

Prof. Brout

…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**

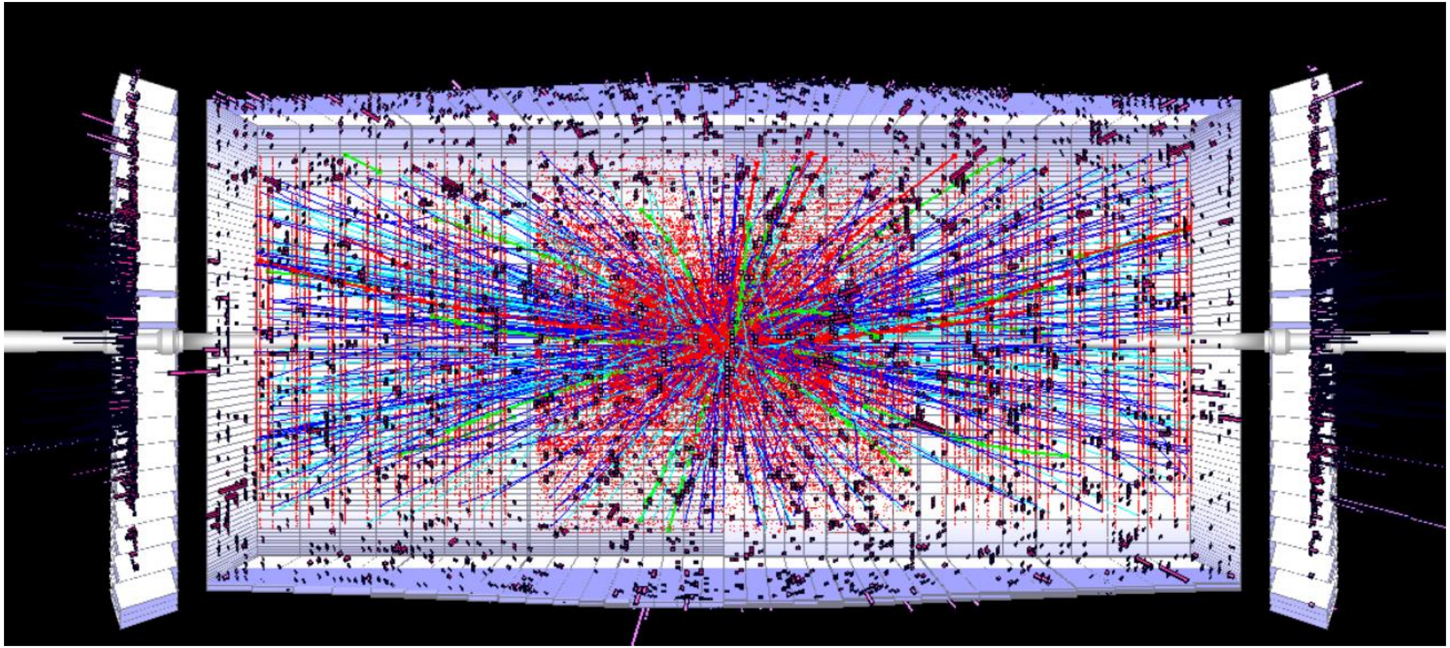
So have we finished our quest? NO!
Cosmology tells us that we still miss the most!



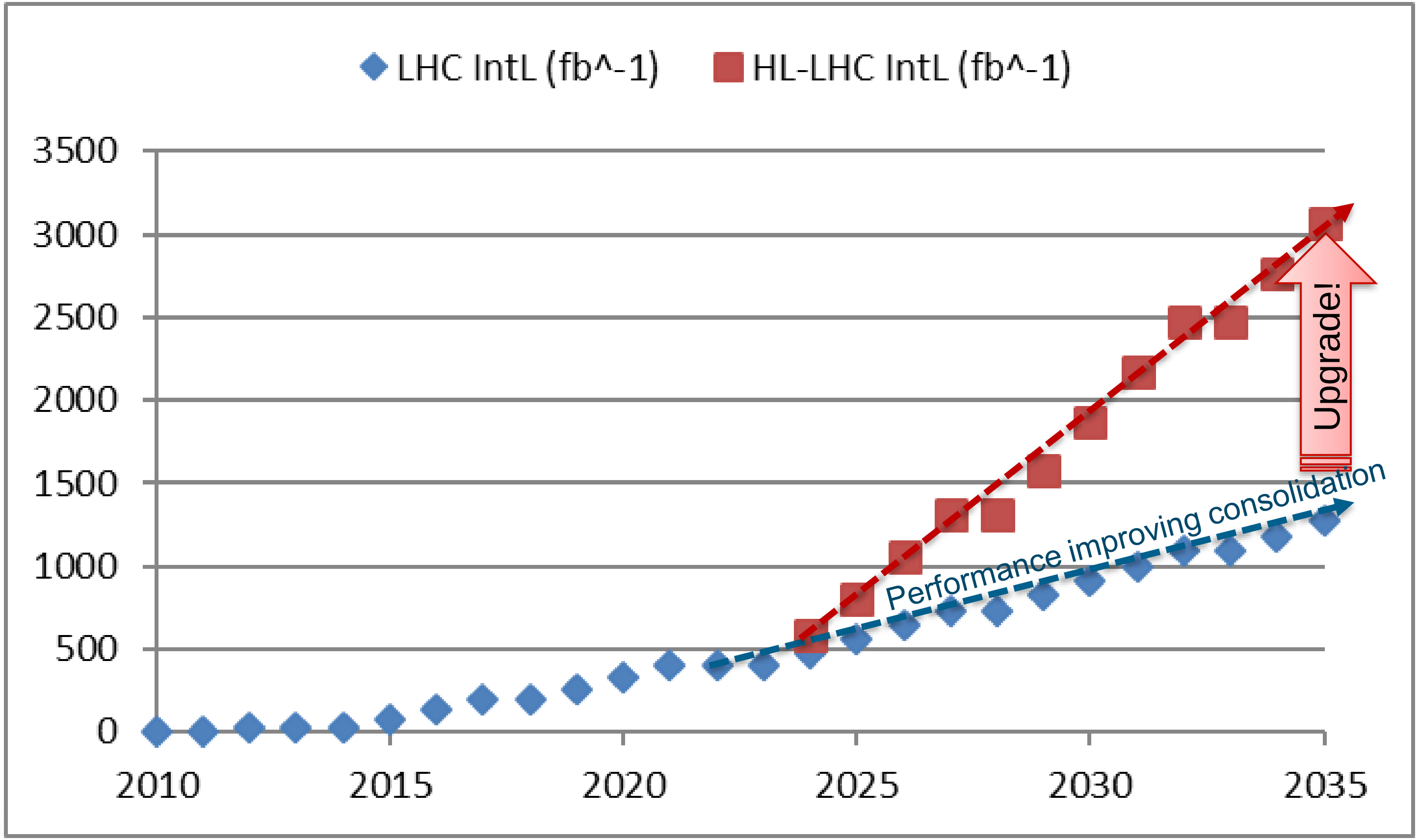
SUPERSYMMERTRY:
A Superworld ahead of us?

Sheding light on Dark Matter?
More light to see more…

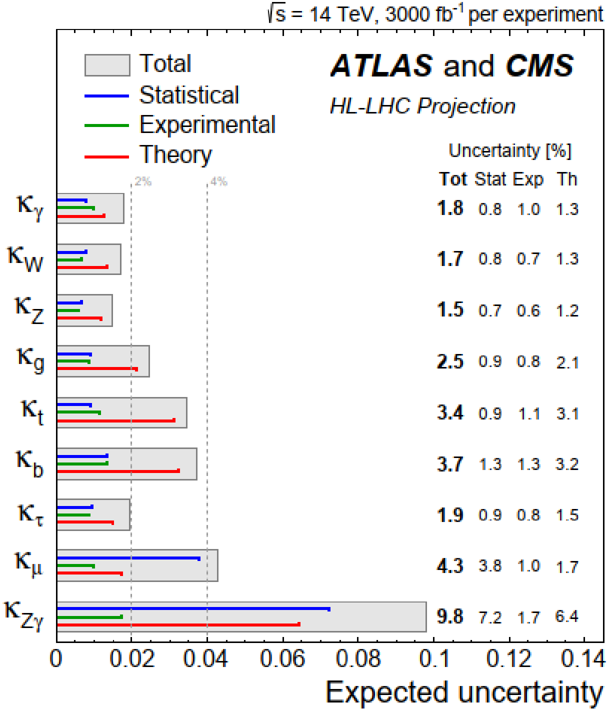
High Luminosity: a bright future for the LHC
Generate more light → machine upgrade
Better eyes to profit of higher luminosity → detector upgrade

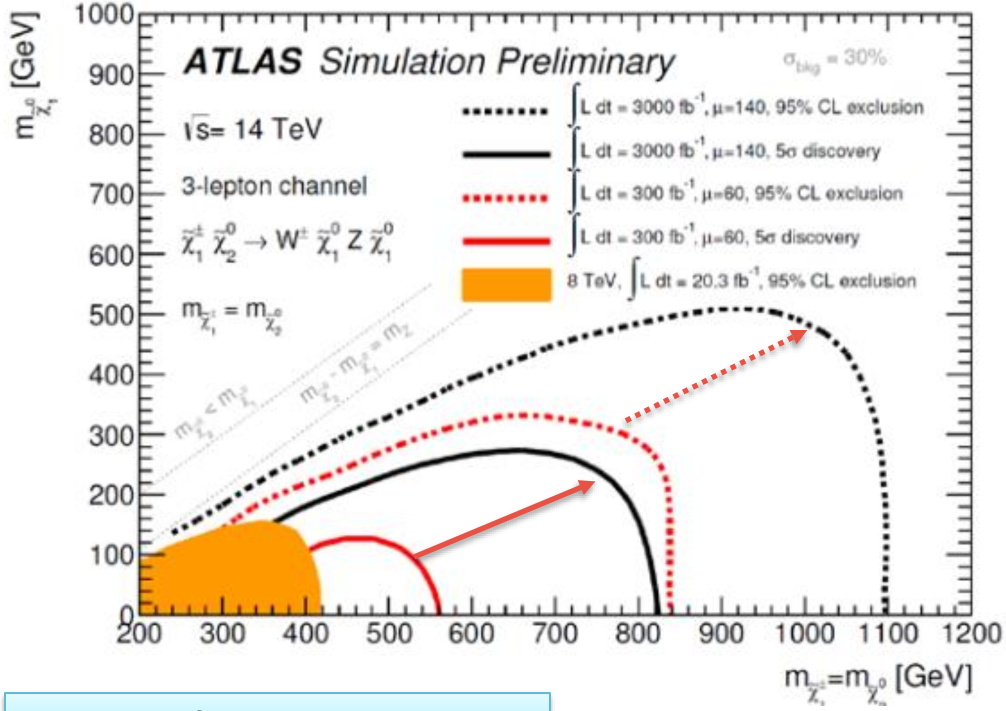


Why not just keep going with cons?



HL-LHC expands the Physics reach of LHC





Courtesy of M. Mangano , CERN

Goal of HL-LHC

From EC-FP7 HiLumi LHC Design Study application of 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 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.

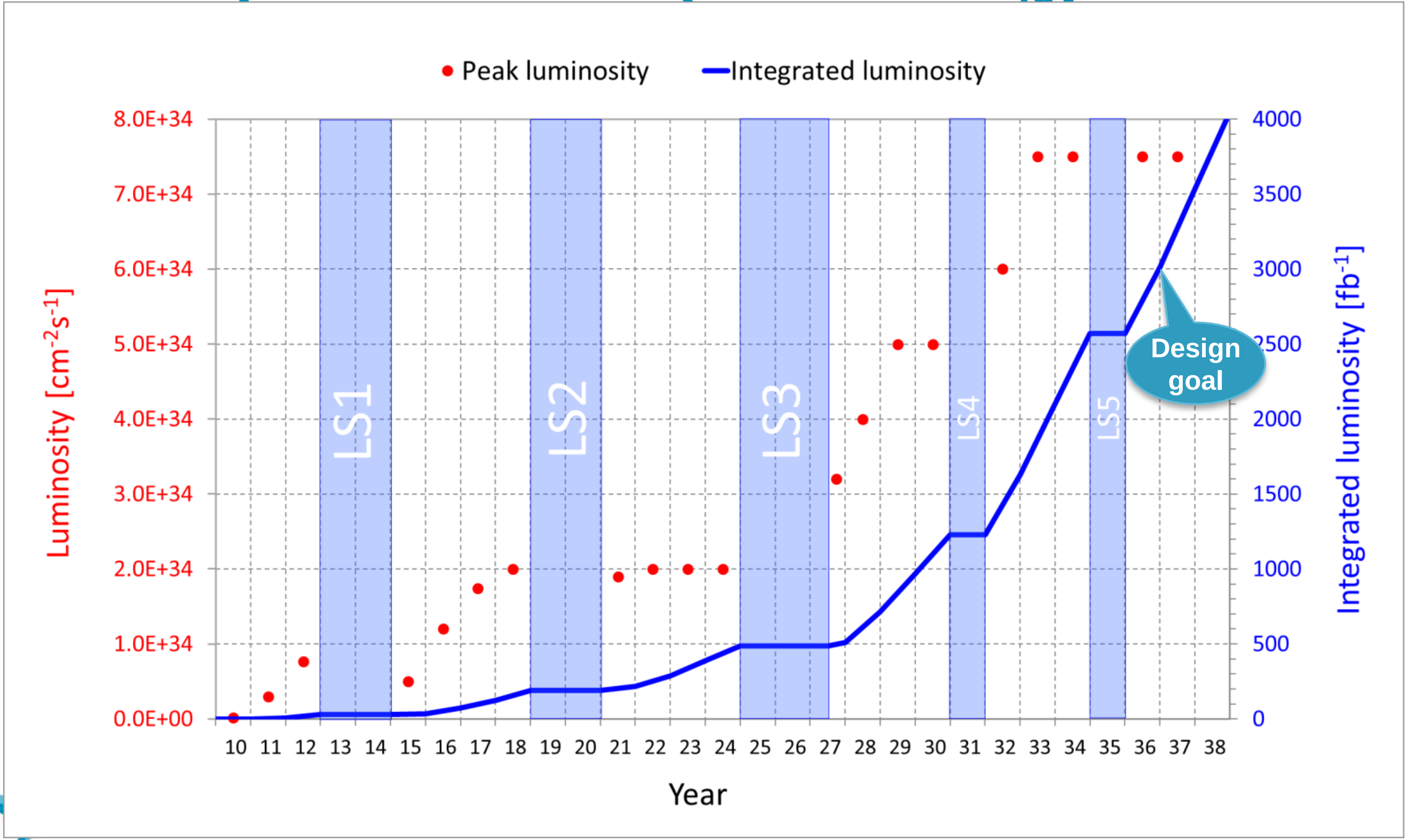
Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult} \cong$ 7.5 10^{34} cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**

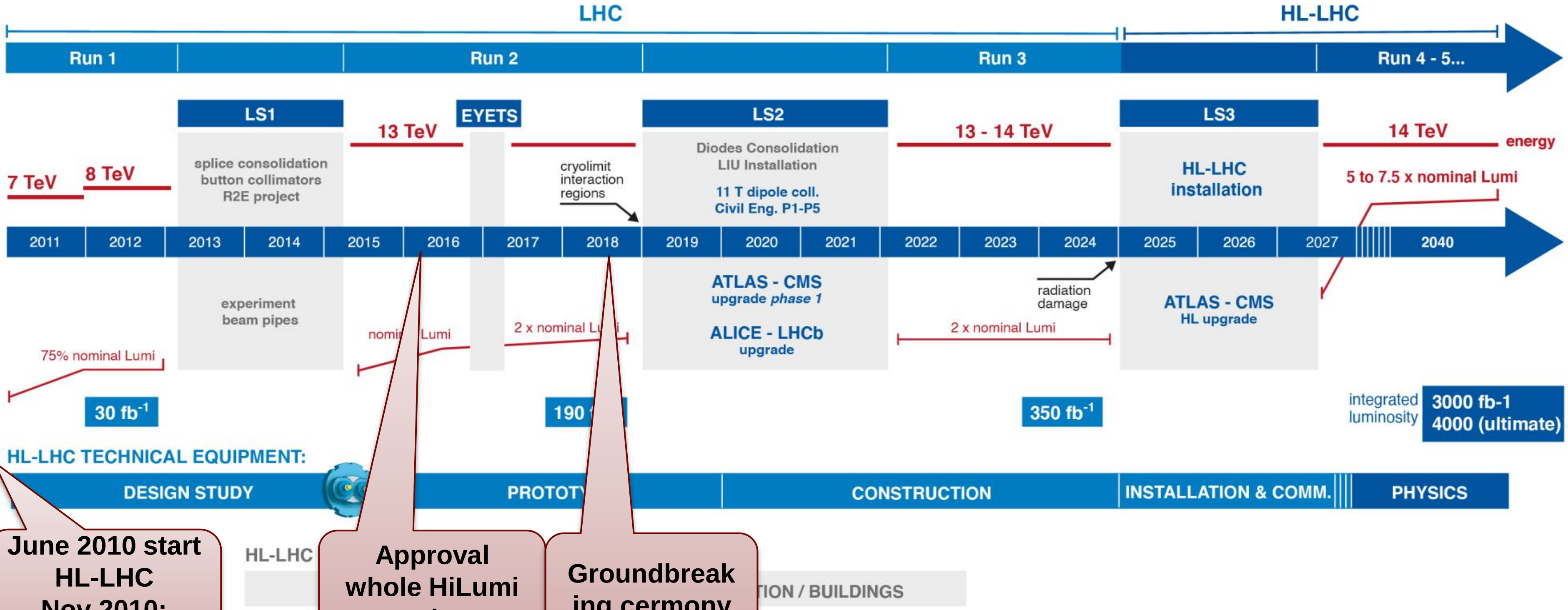
LHC should not be the limit, would

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

HL-LHC performance (ultimate L_{lev} from 2032)



LHC / HL-LHC Plan

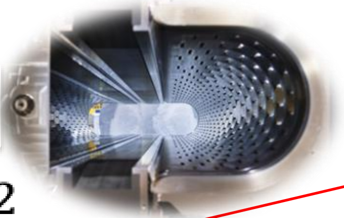


June 2010 start HL-LHC
Nov 2010: application EU

Approval whole HiLumi project

Groundbreaking cermony

Luminosity: which parameters count for LHC?



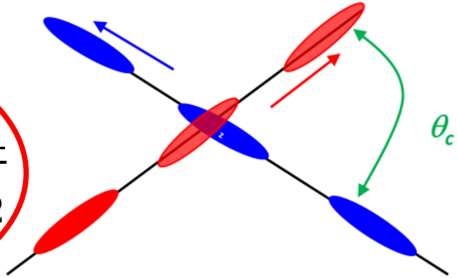
Beam current

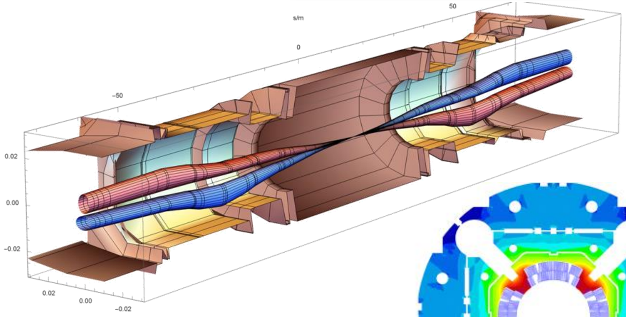
$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

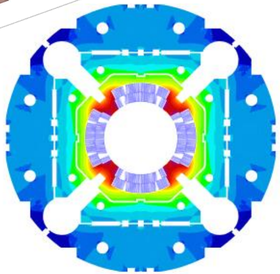
energy

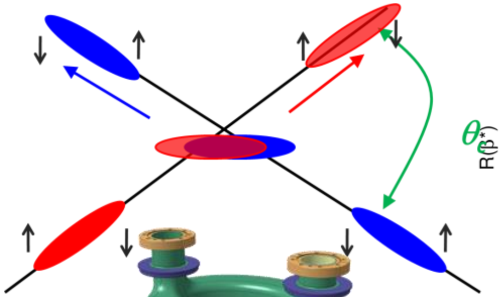
Beam size

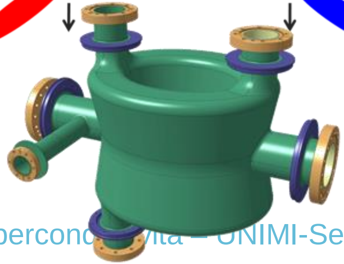
$$R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma\right)^2}}$$

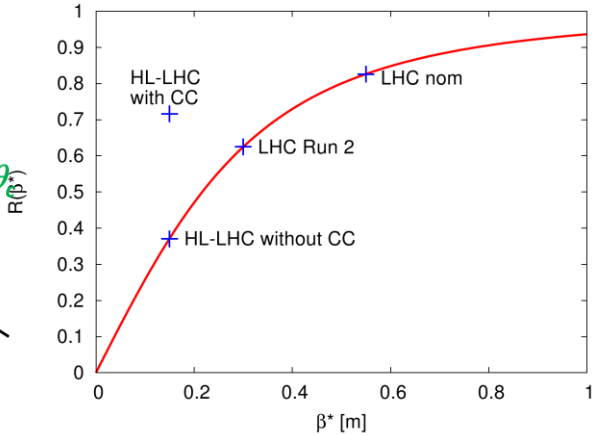




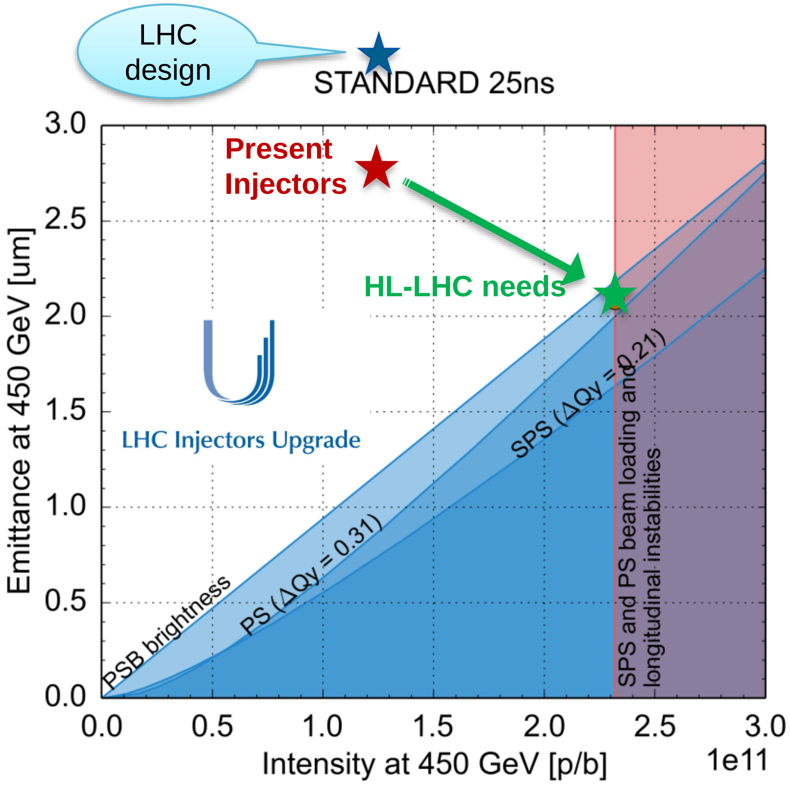




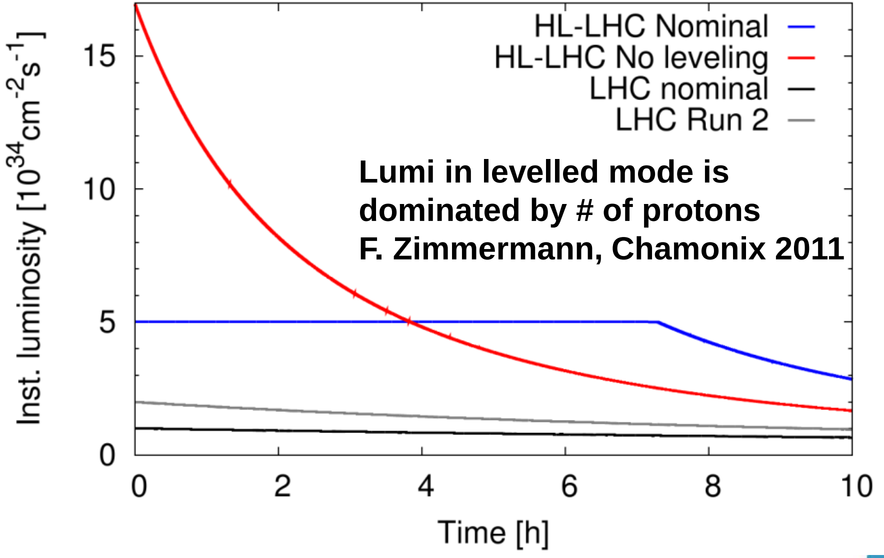




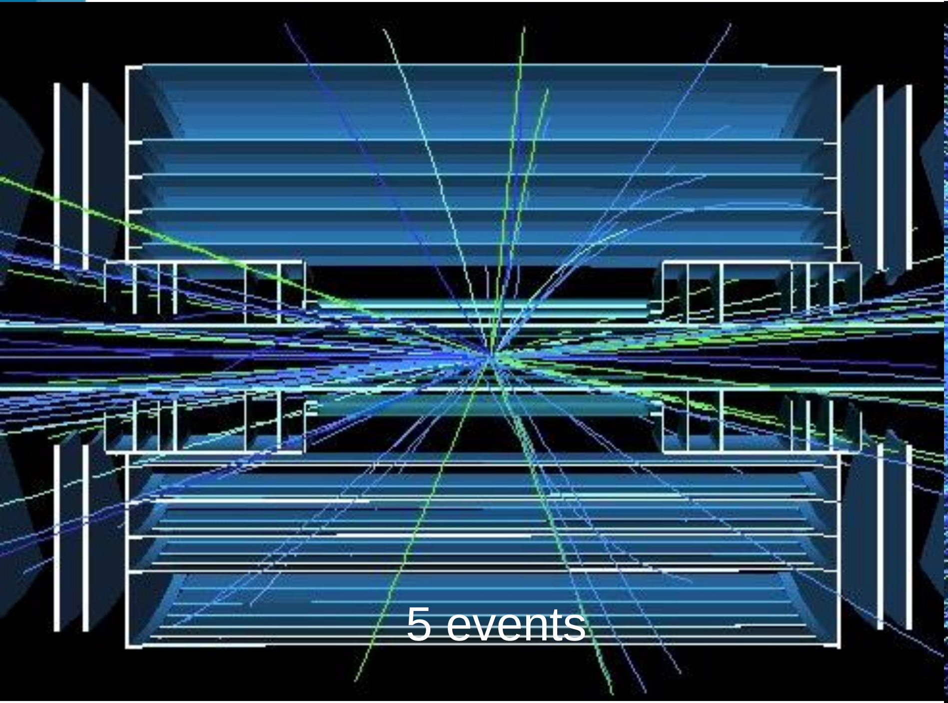
LIU (Intensity) and Levelling mode

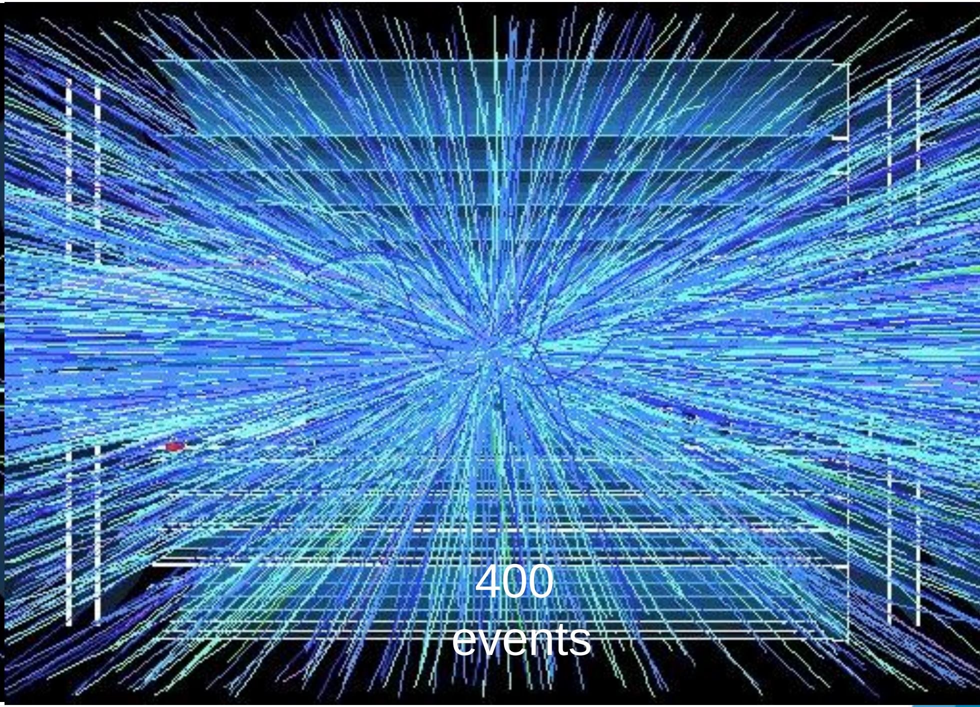


Reducing heat load on the IT triplet (quench and cooling limits)
Limiting pile up in the detectors



Pile up





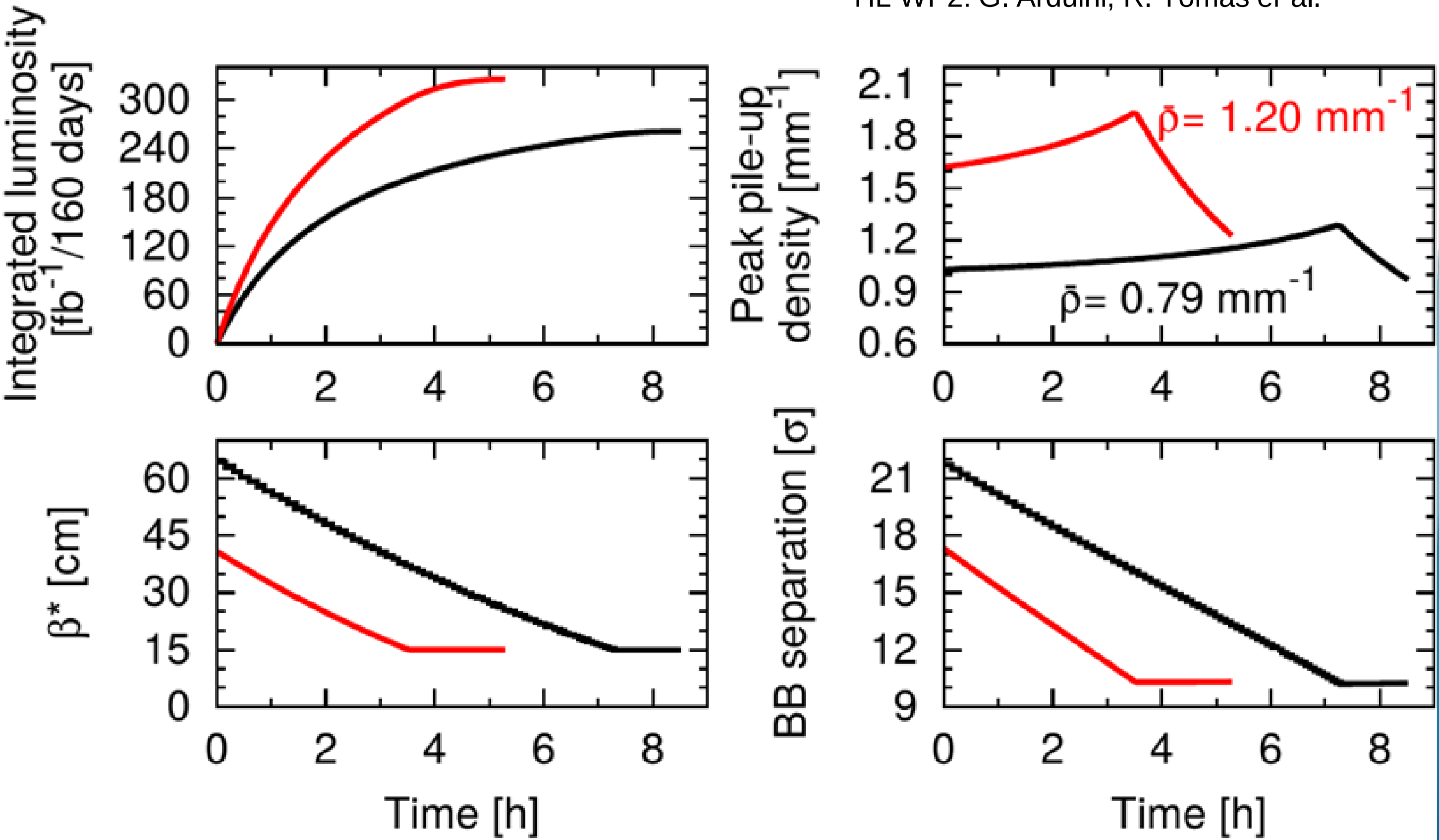
Pushing at the maximum the parameters of HL-LHC we would start the fill at L = **$17x10^{34}$ with 400 events/crossing.**

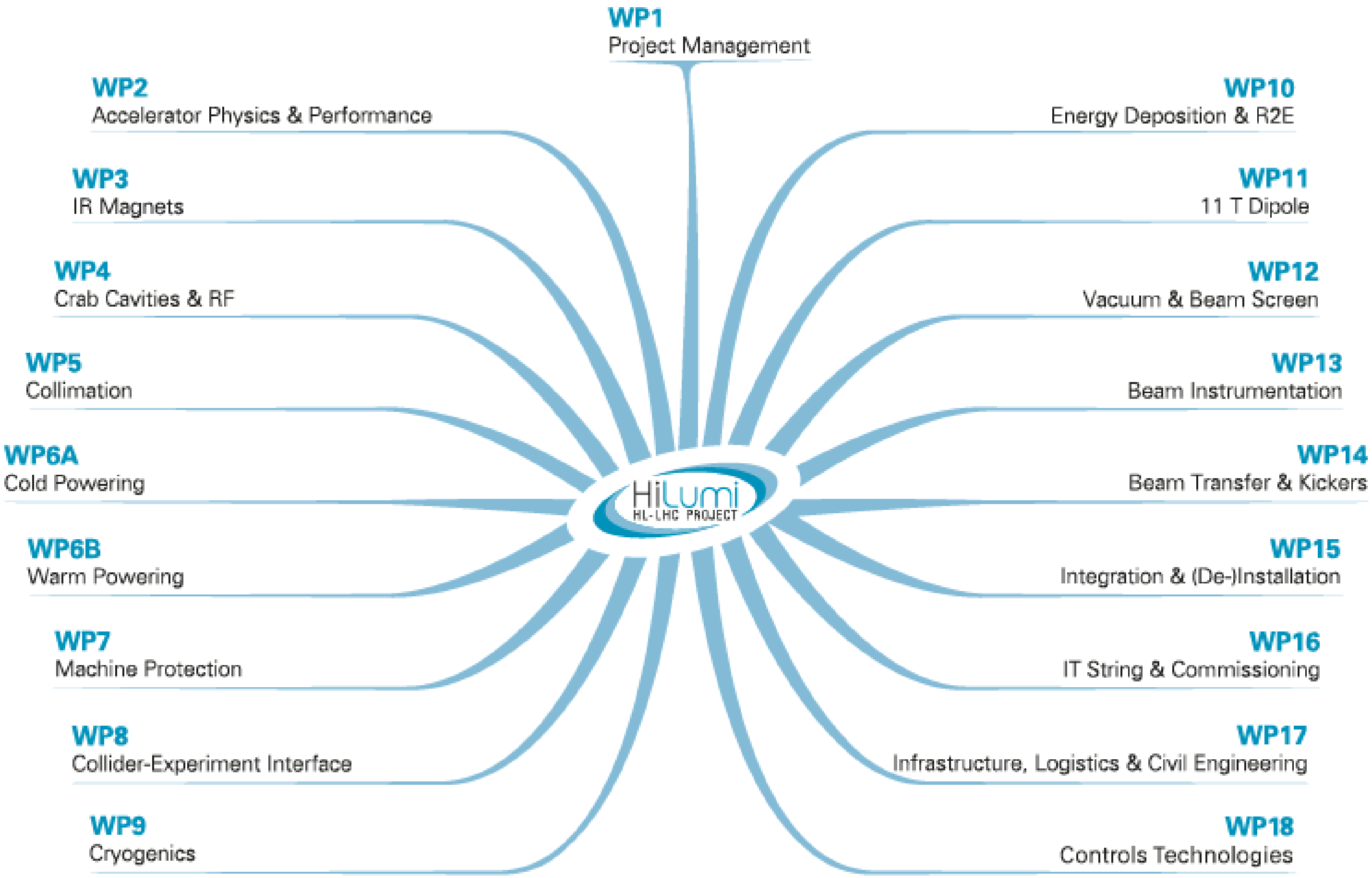
Performance

HL WP2: G. Arduini, R. Tomas er al.

Due to many advances in beam bynamics understanding:

- ATS and beam optics controls
- Beam dynamics aperture
- Beam-beam (LR)
- Impedance model
- Noise model
- RF low level

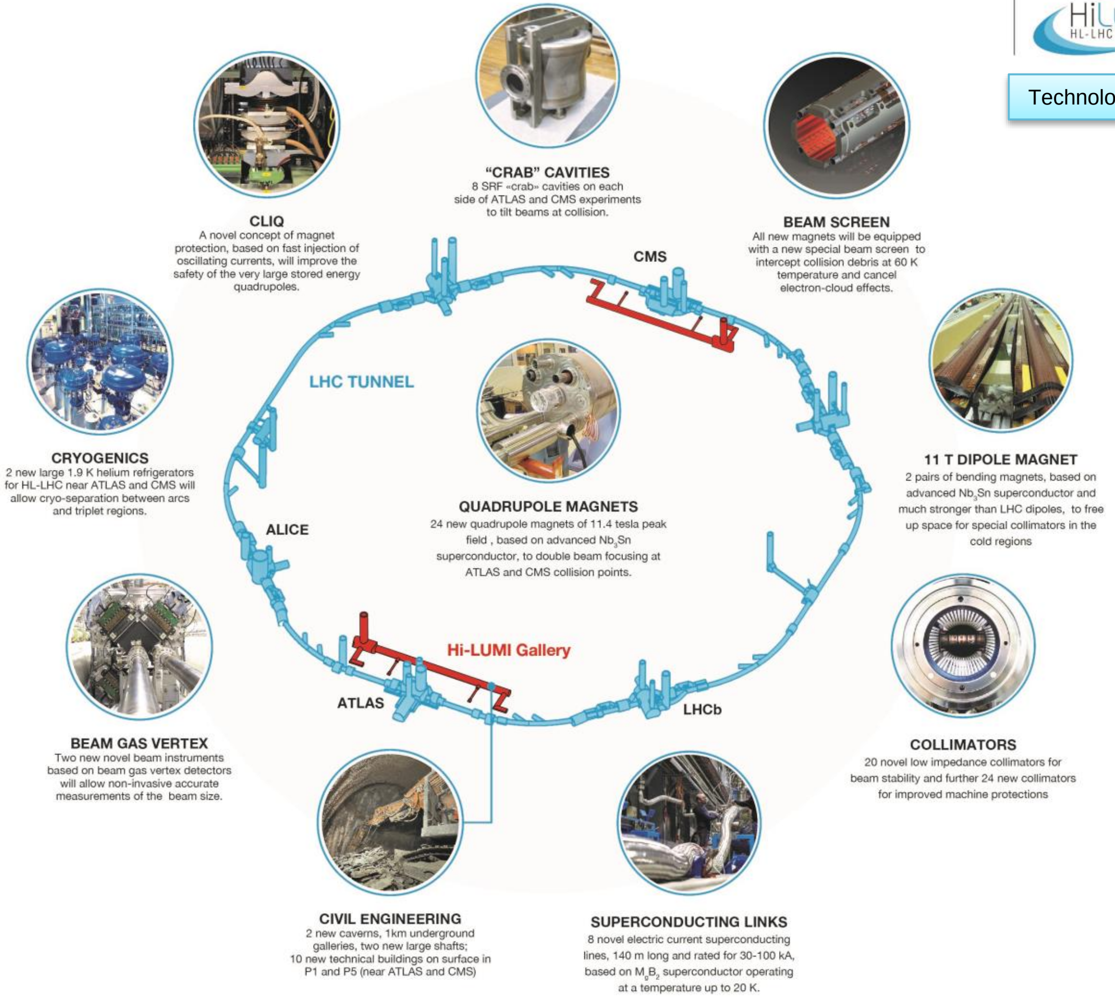



WP1
Project Management
WP2
Accelerator Physics & Performance
WP3
IR Magnets
WP4
Crab Cavities & RF
WP5
Collimation
WP6A
Cold Powering
WP6B
Warm Powering
WP7
Machine Protection
WP8
Collider-Experiment Interface
WP9
Cryogenics
HiLumi
HL-LHC PROJECT
WP10
Energy Deposition & R2E
WP11
11 T Dipole
WP12
Vacuum & Beam Screen
WP13
Beam Instrumentation
WP14
Beam Transfer & Kickers
WP15
Integration & (De-)Installation
WP16
IT String & Commissioning
WP17
Infrastructure, Logistics & Civil Engineering
WP18
Controls Technologies

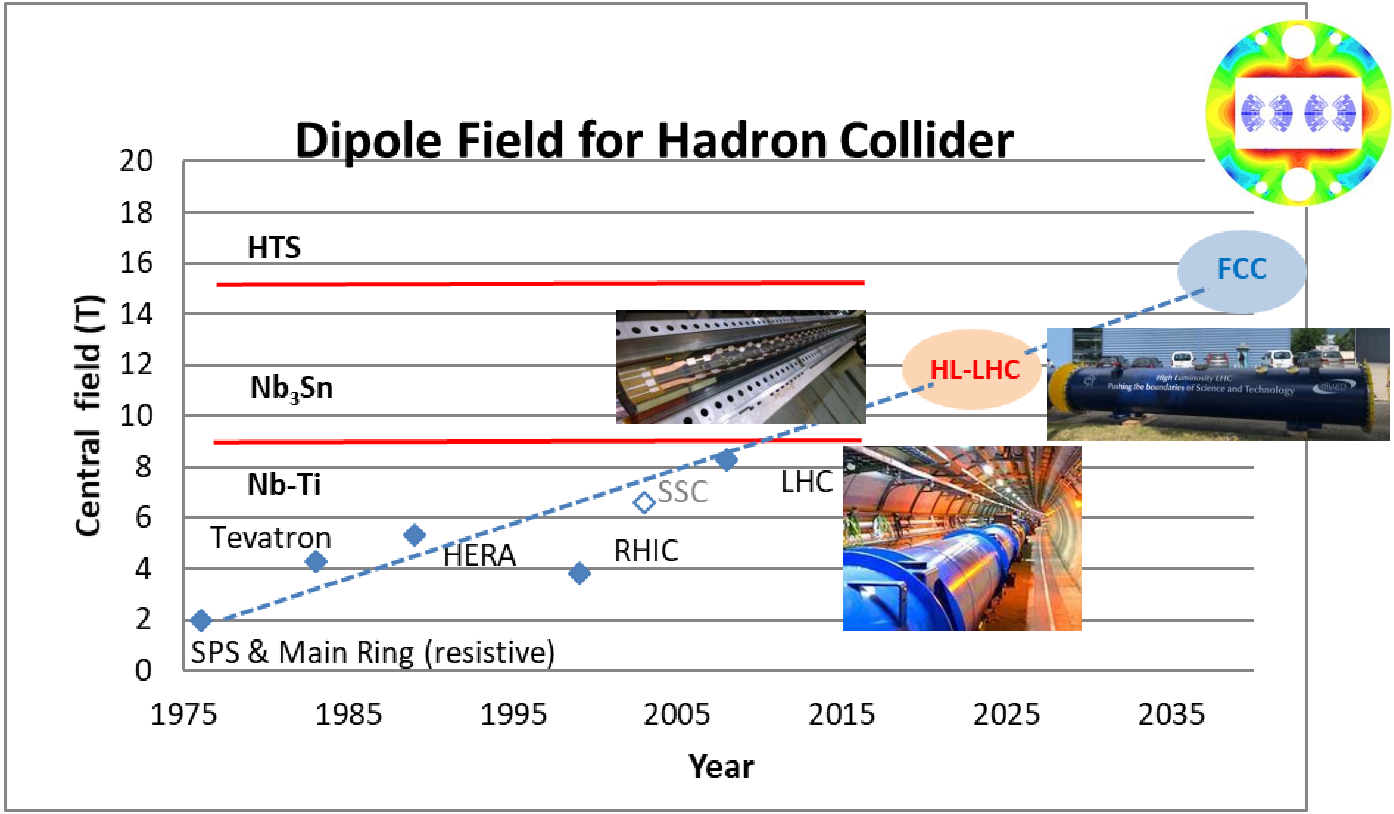
Technology landmarks

No accelerator project has so many absolute novelties and in such a broad technology spectrum

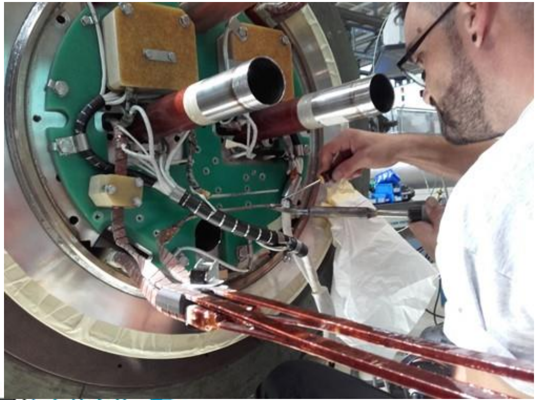
Technology intensive project!

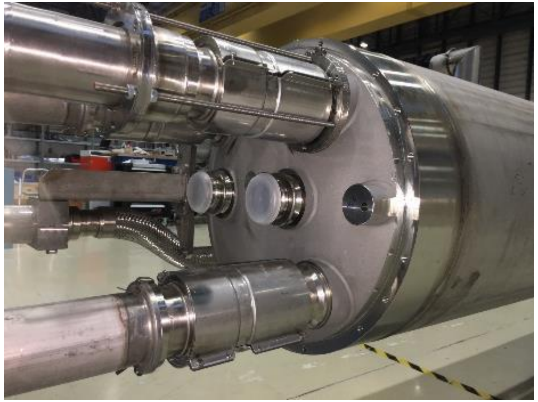


With HiLumi we prepare the new technology for a future leap in hadron colliders…



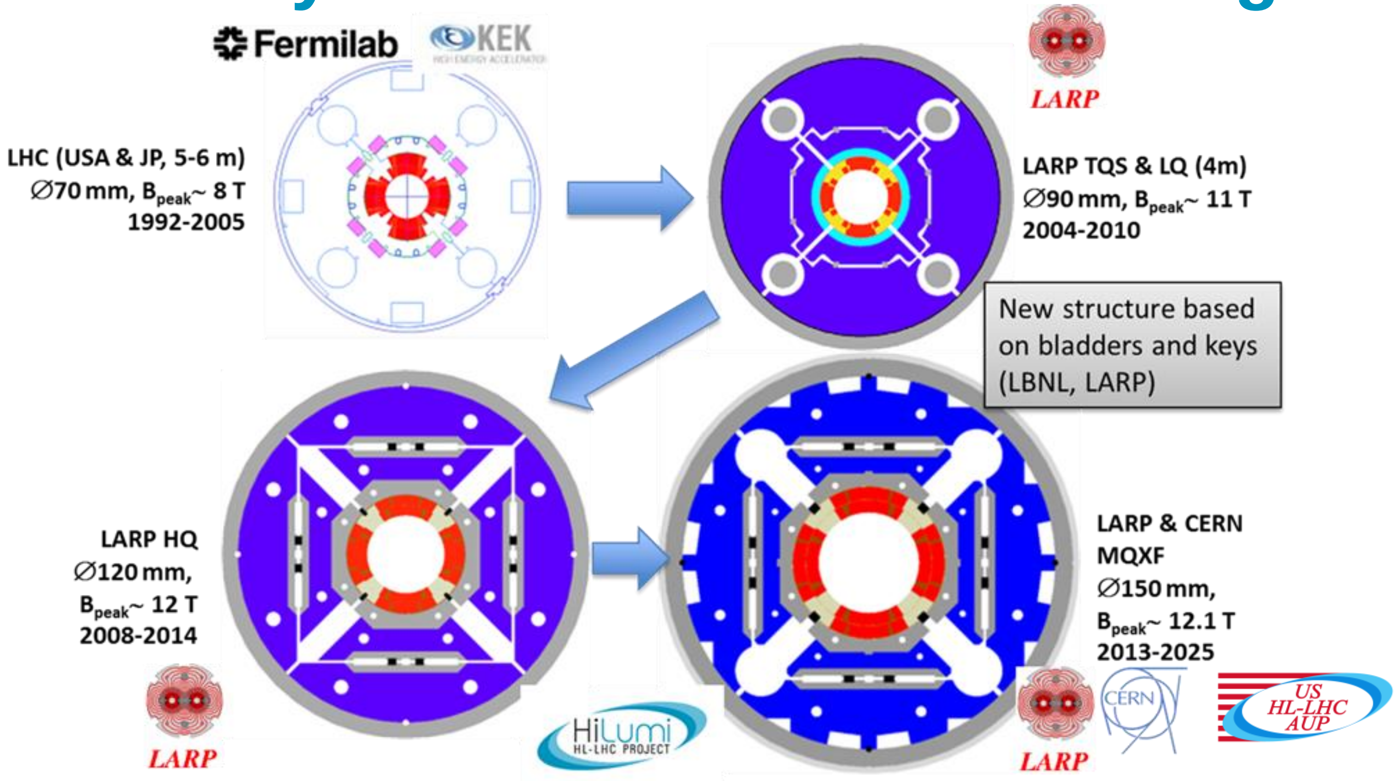
11 T in full swing production: LS2 installation in 2020! great care given the stress sensitivity of Nb_3Sn



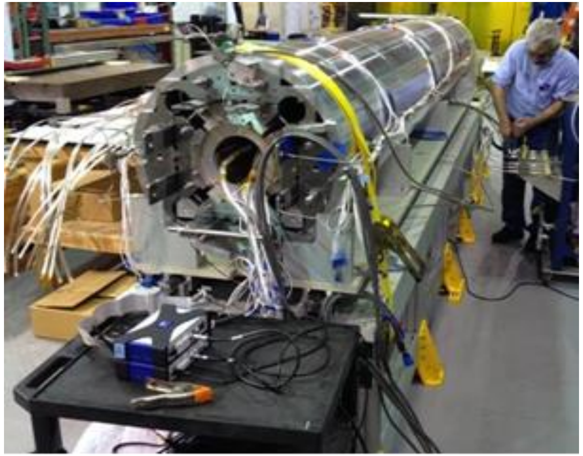


MBH-002 – first out of four 11 T dipoles. Coils after impregnation; magnet on test bench @ SM18 (July 2019)

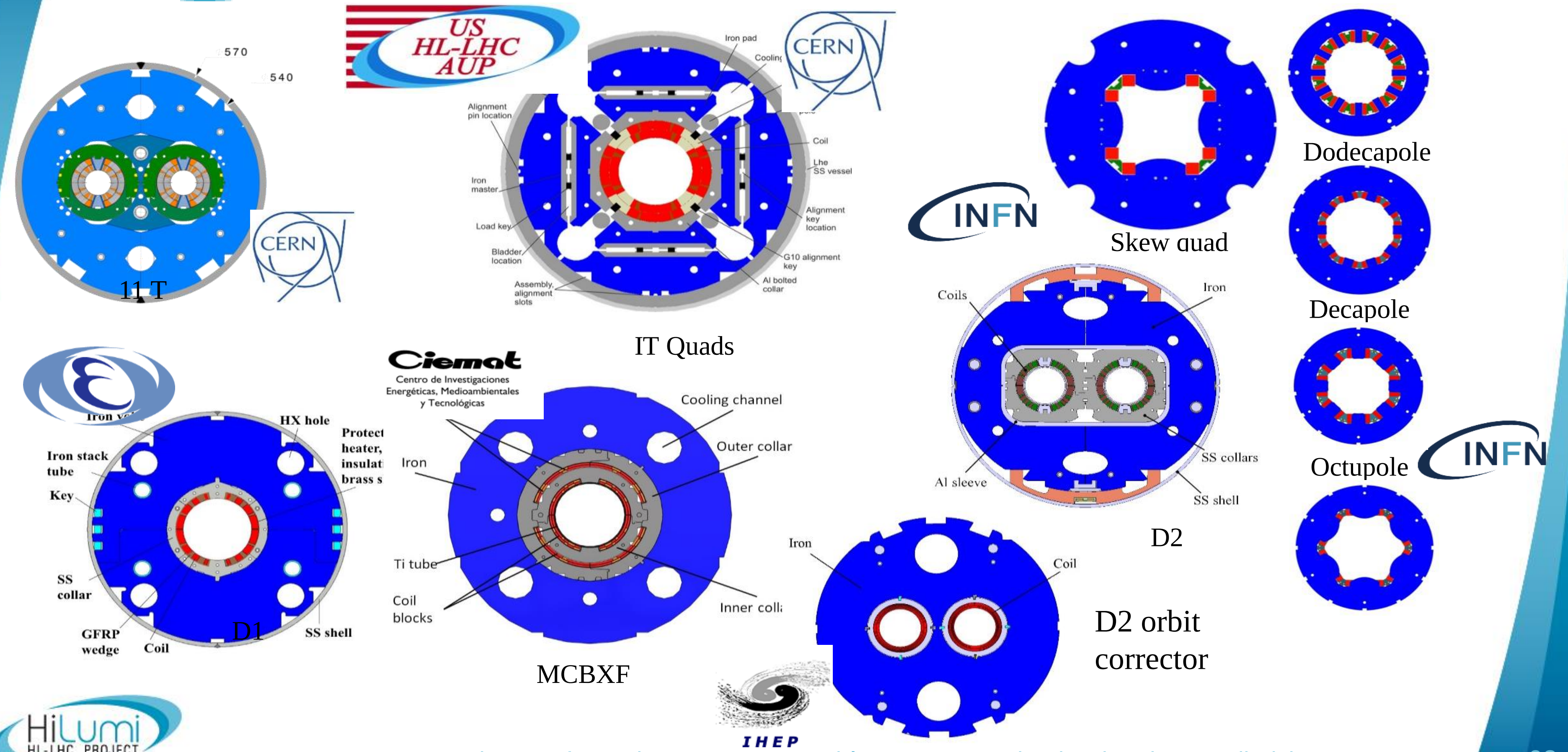
IT quadrupole. Increase in field but also in size wrt LHC. Very relevant also for FCC magnets



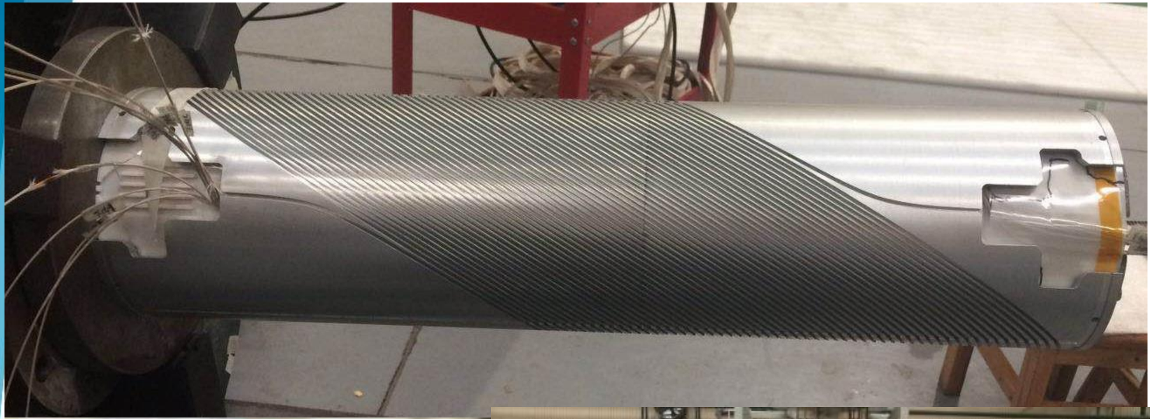
Construction of the 1st and 2nd long (7.5 m!) IT Quad in CERN; in USA winding 4th long magnet

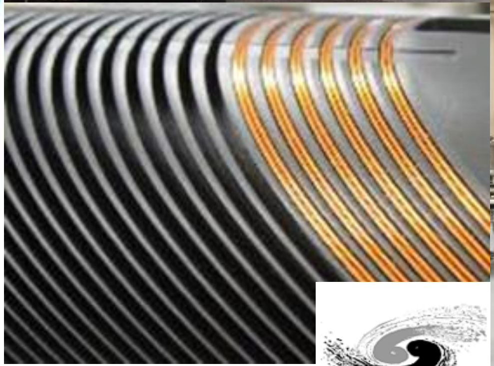


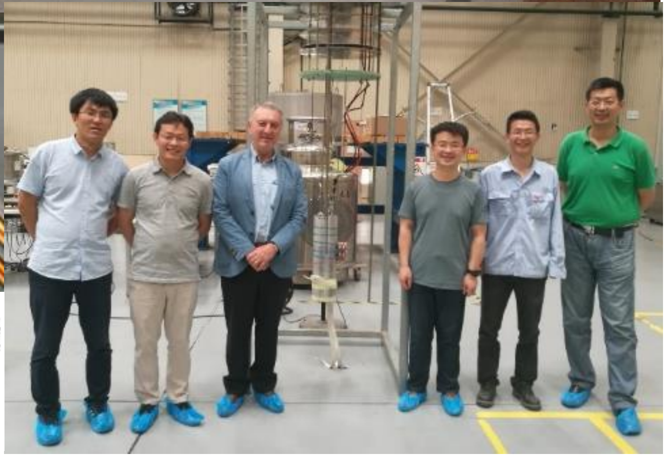
The HiLumi Magnets (~130)



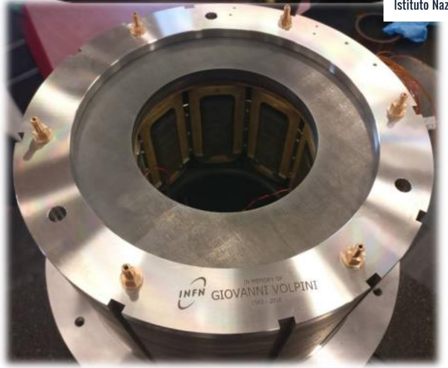
Nb-Ti new technologies: CCT and SF magnets







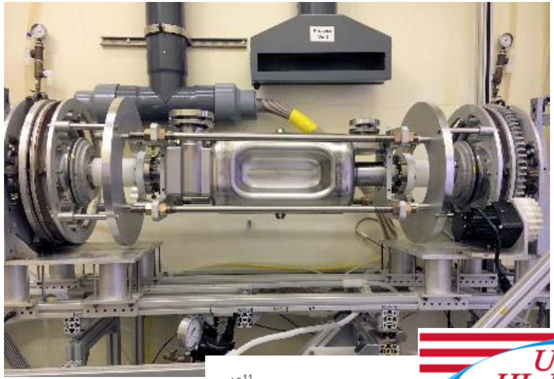
INFN
Istituto Nazionale di Fisica Nucleare



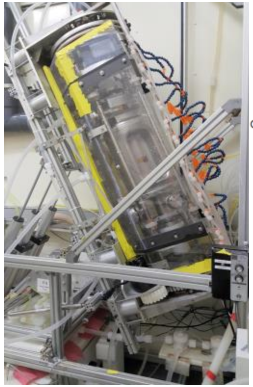
IHEP

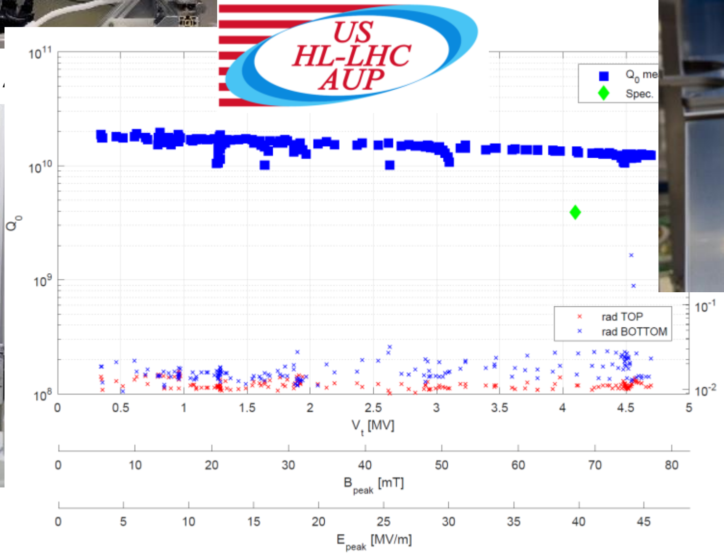
HiLumi
HL-LHC PROJECT

Crab Cavity



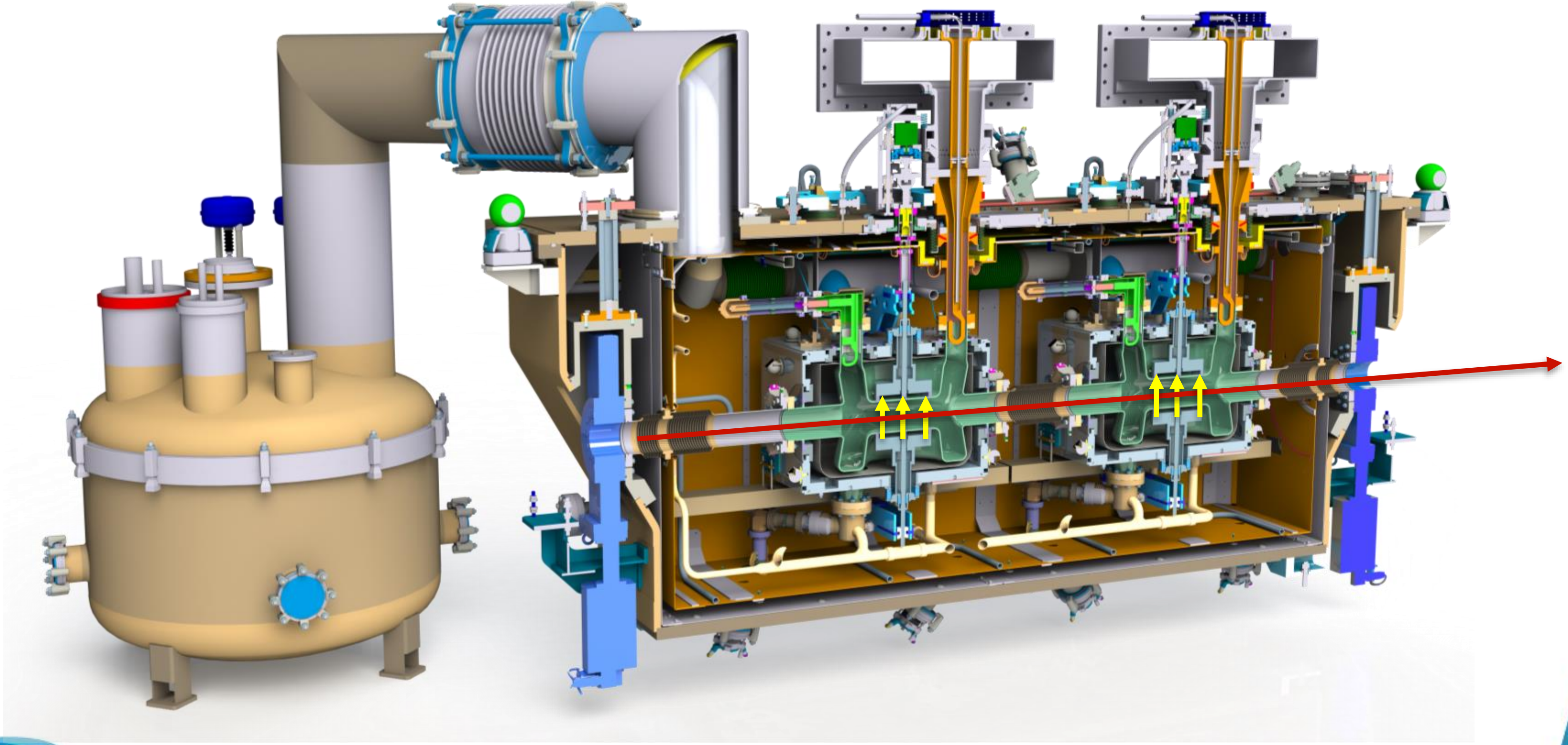
Rotational chemistry at A





CERN DQW prototype for SPS test
Collaboration with UNILANC & STFC - C.I. Daresbury (UK)

The DQW CC in cryomodule for the SPS test



Crab Cavities: progress in design, construction and test infrastructure

New SRF test stand with beam in SPS for HiLumi LHC Crab Cavities

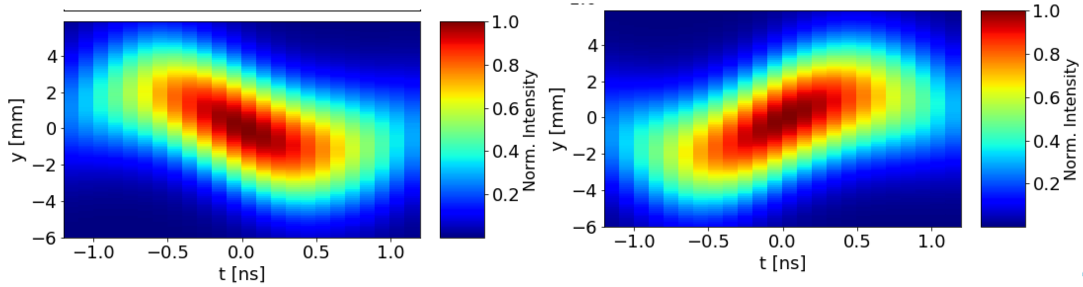
Industrial contracts : launched both from CERN and US-HL-AUP

New CC collaborations

ИЯФ СО РАН

Science & Technology Facilities Council

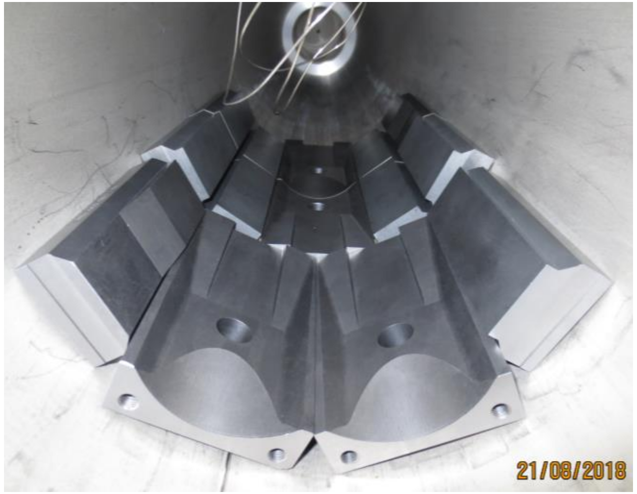
TRIUMF



Transparency of CC to beam demonstrated! MDs very successful (with voltage limitation).

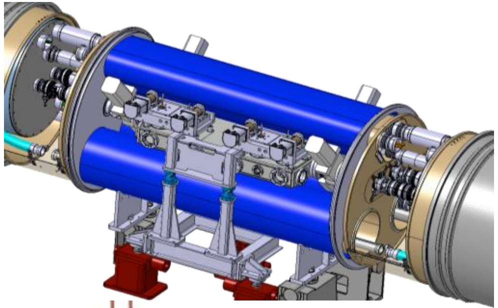
Collimators low-Z : special MoGR Mo-coated upgrade partly in 2020 and then in 2025

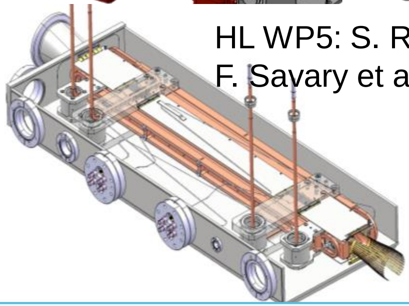
Samples of MoGr (Molybdenum-Graphite) from producer (CERN EN/MME/STI)



HL WP5: S. Redaelli, R. Bruce, S. Gilardoni, M. Calviani, A. Bertrelli, R. Carra et al.

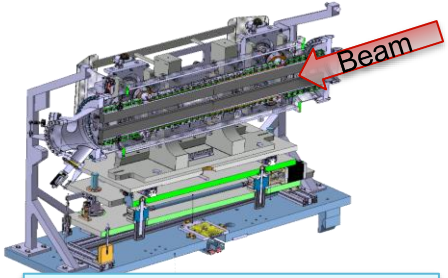
Cold-Warm-Cold bypass to host Collimators in the DS region



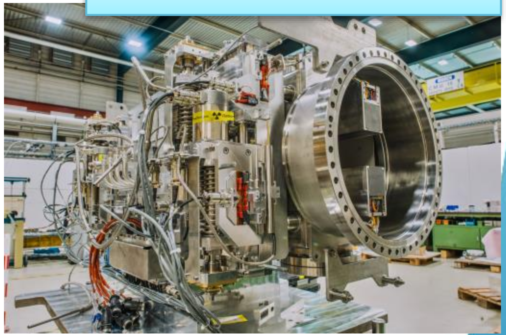


HL WP5: S. Redaelli, F. Savary et al.

New injection protection absorber

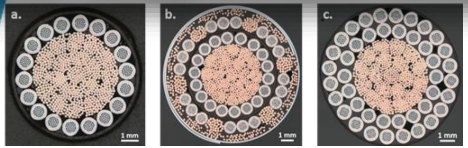


HL WP14: C. Bracco et al.

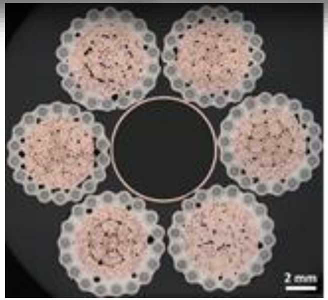


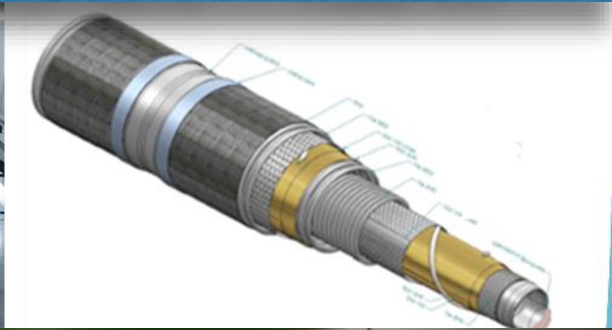
In total some 40 new absorber and collimators devices in LS2 (2020) and LS3 (2025)

New superconducting links for 100 kA current – 130 m



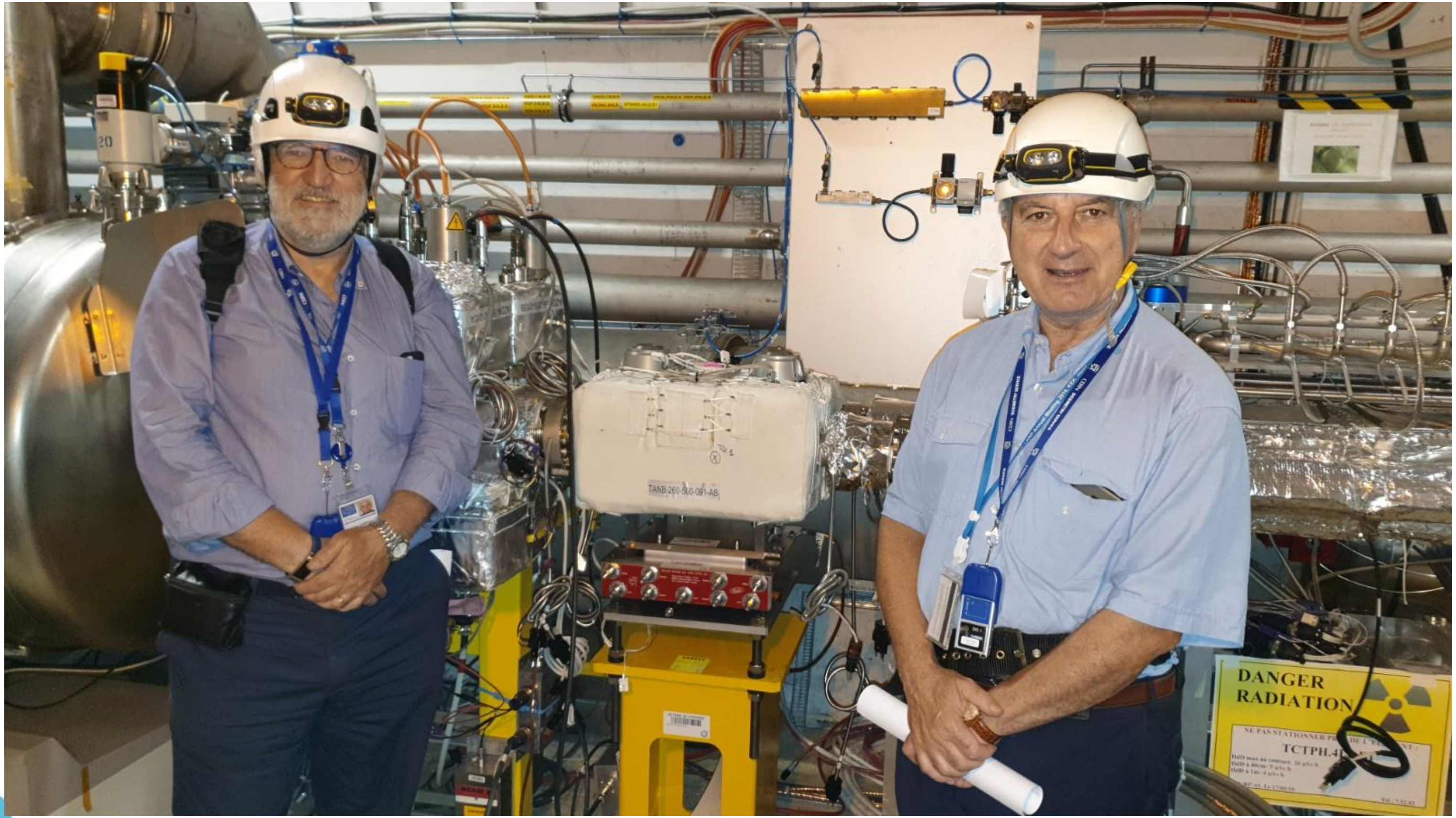
MgB$_2$ superconductor





Amalia Ballarino, CERN

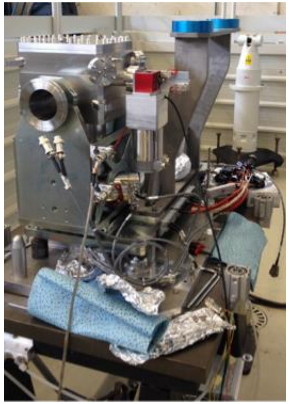
Inspection to the first HL-LHC installed in LHC!



Test on crystal collimation (for baseline)

<u>Scope</u>: further improvement of ion cleaning after 2016 re-baselining.
Studying if, for ions*, this can be an "adiabatic" upgrade of the IR7 system.*
2017: ***improved by up to x60 collimation cleaning*** *of Xe beams!*

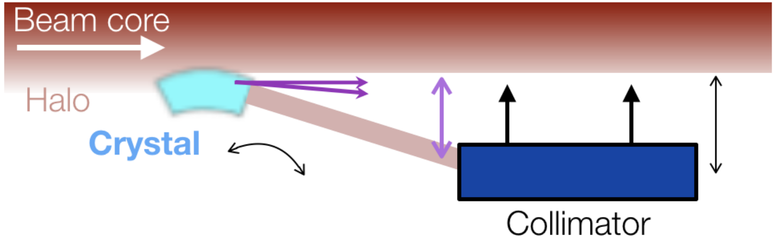
Courtesy EN/SMM



Courtesy UA9 collaboration/PNPI

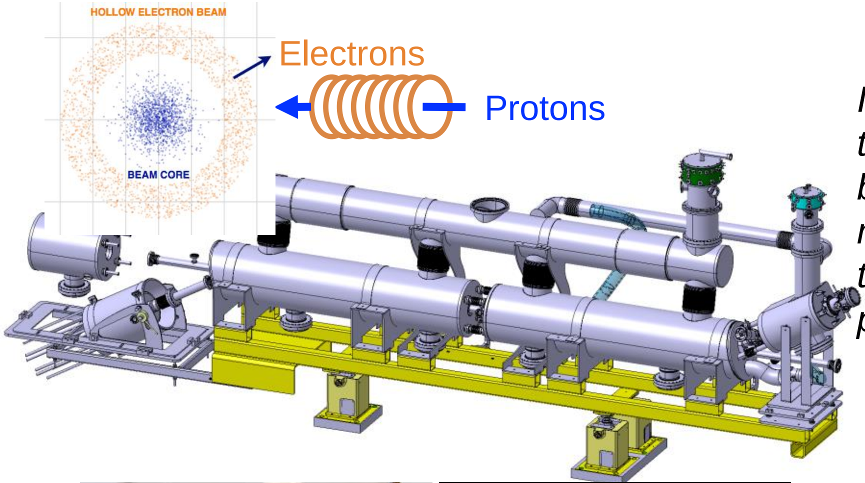
4 mm = 50 μrad,
or 10 x 15m long LHC dipoles
or 300 T at 7 TeV

Two goniometers installed on B1 in LS2; two more on B2 in 2017, upgraded in 2018.
4 operational crystals for collimation.



HL WP5: S. Redaelli, S. Gilardoni, M. Calviani al.

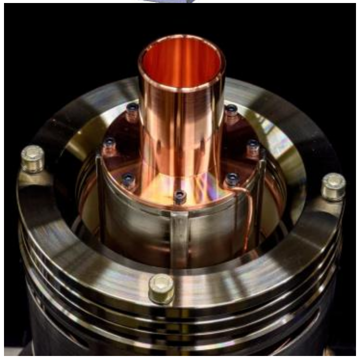
E-lens in HL-LHC for halo control - 30 MJ in the halo



It would allow controlling actively the halo, through a hollow electron beam (overlapped over three meters to the proton/ion beams) that selectively excites halo particles.

HL WP5: S. Redaelli, D. Perini, A. Rossi et al.

Cathode

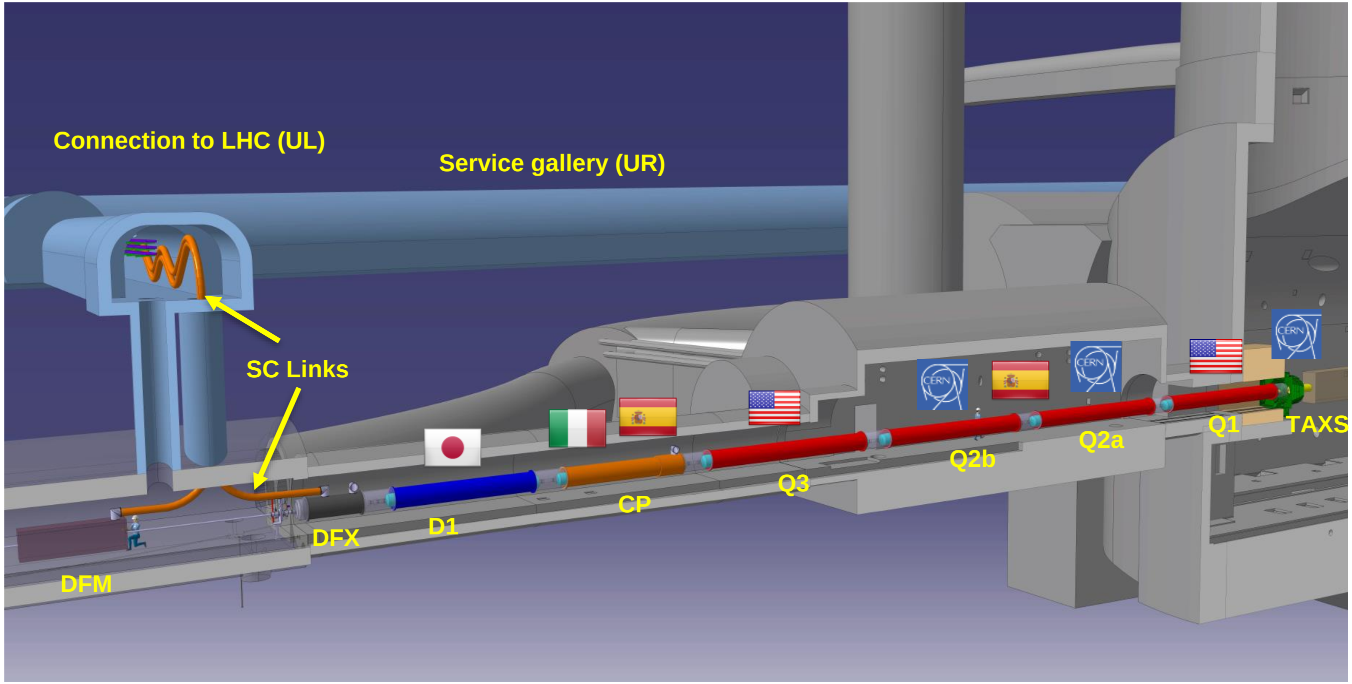


Electron gun

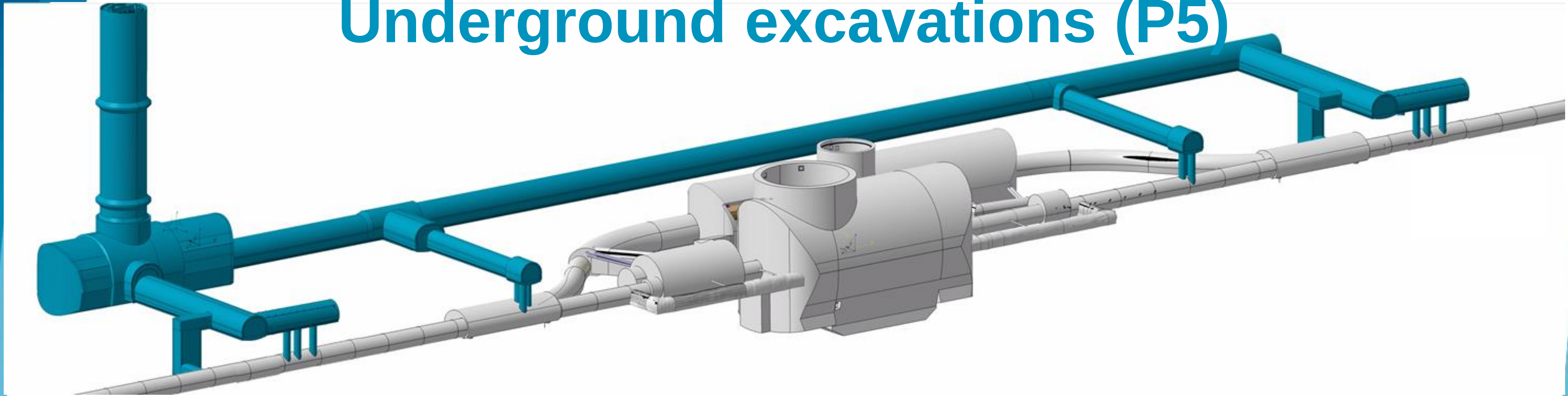
Design nearly complete.
Surpassed target e-beam current of 5A, now final cathode design (smaller) under test at FNAL.

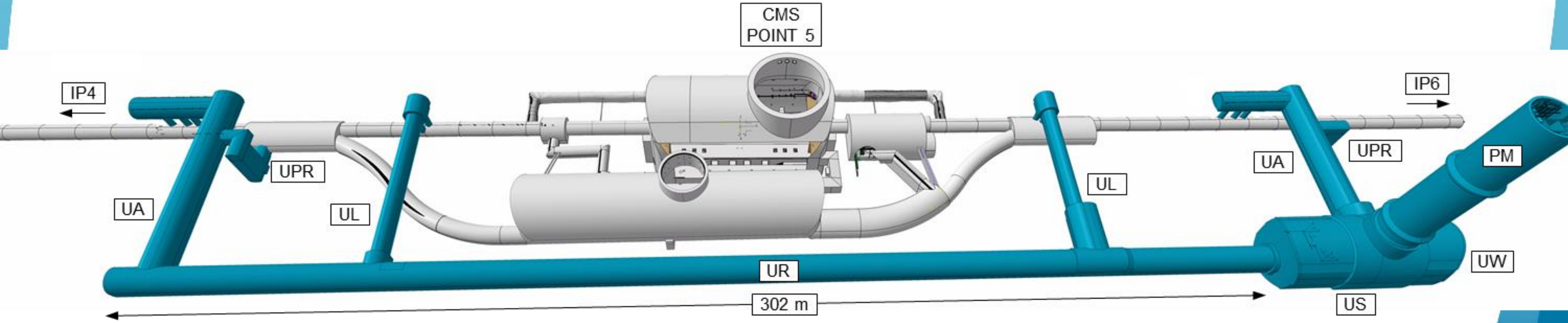
Ready to built it, heading to integrated into the baseline.

High Luminosity LHC IT region



Underground excavations (P5)





HL-LHC P1 surface: new platform with spoils

PIT at HL-LHC P1 (ATLAS)


936
LIEBHERR

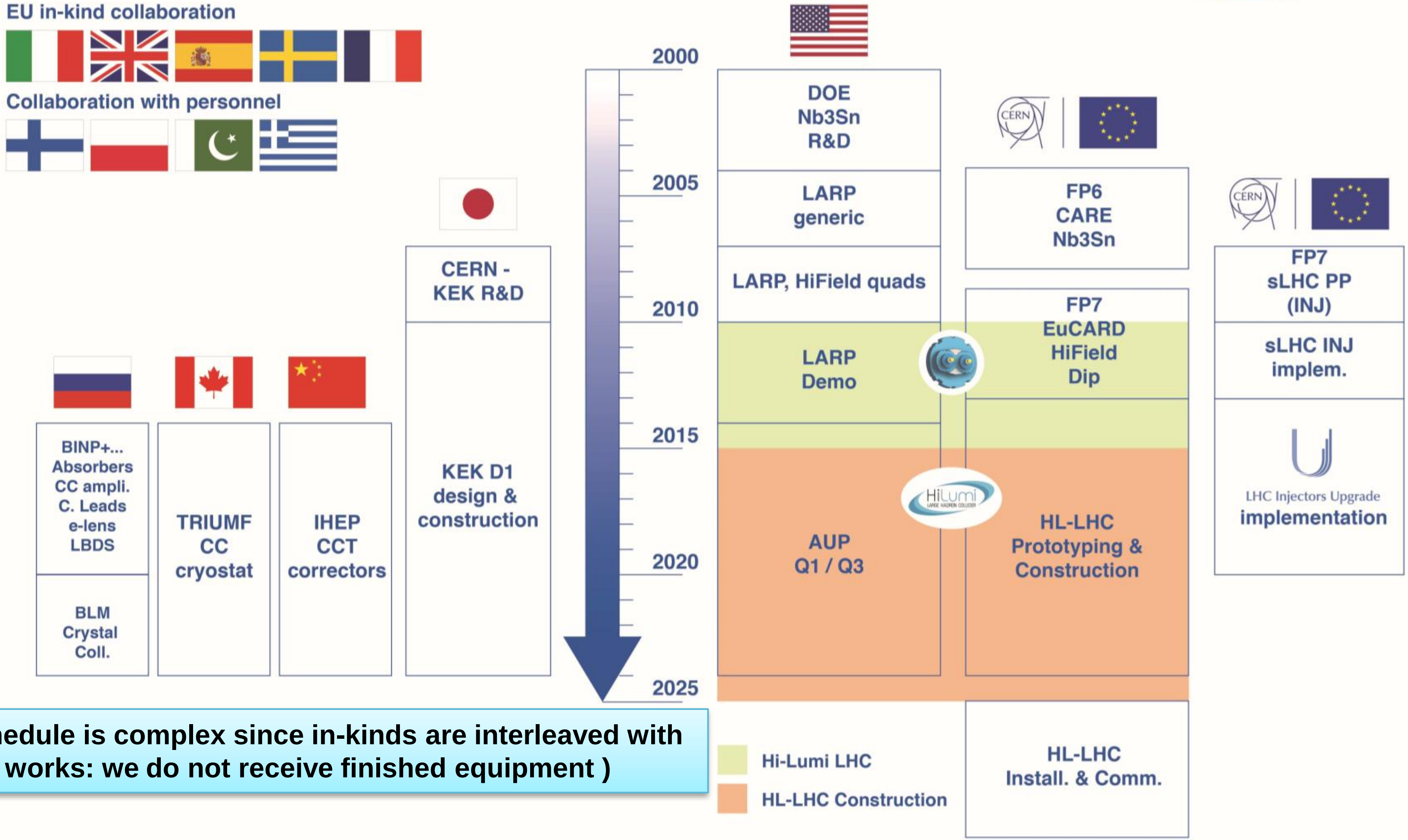

22

HL-LHC Excavation at P5

UR55 (long gallery for EPC)

US57 Cryogenic cavern)

IN-KIND CONTRIBUTIONS



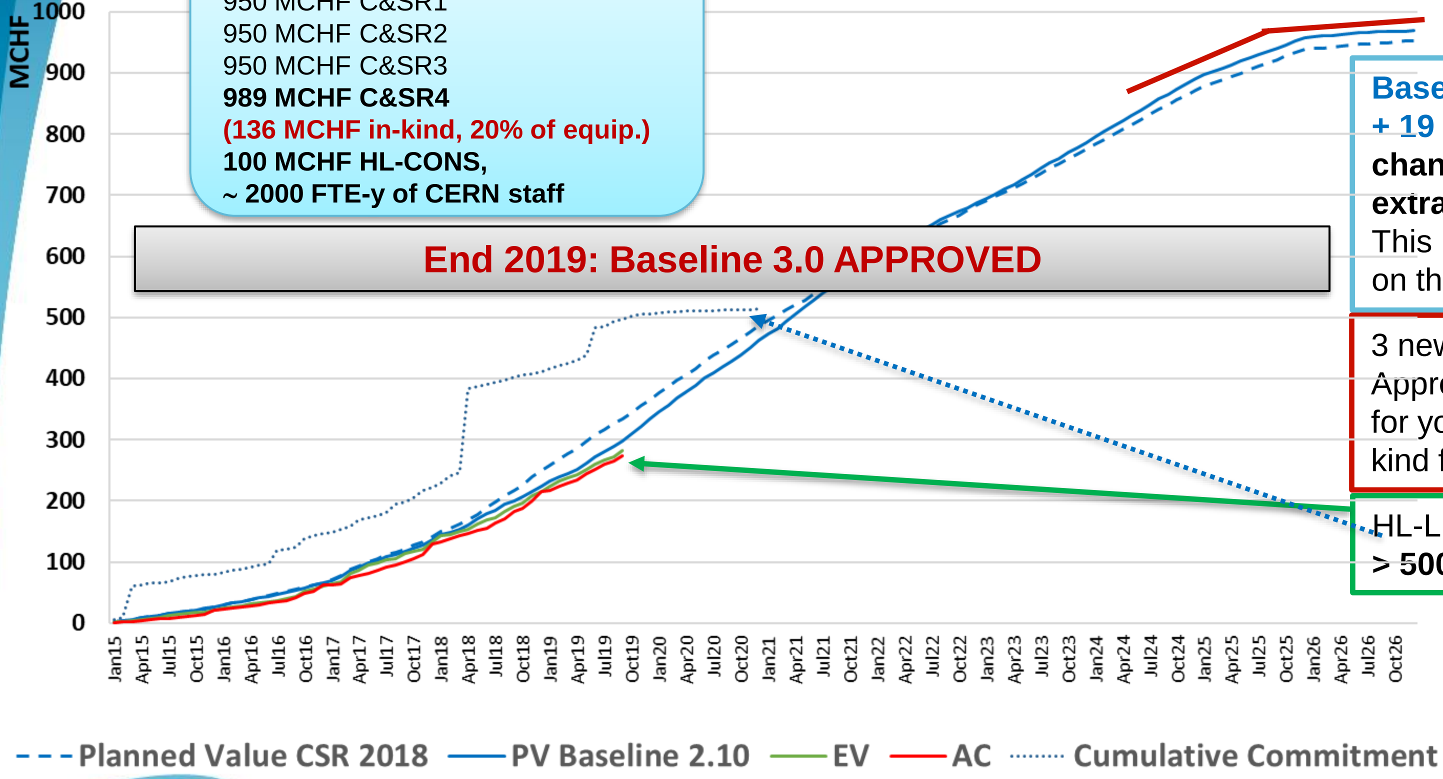
HiLumi: a global project since the start

Schedule is complex since in-kinds are interleaved with our works: we do not receive finished equipment)

Budget profile for HL-LHC at C&SR4

Cost-to-Completion
950 MCHF C&SR1
950 MCHF C&SR2
950 MCHF C&SR3
989 MCHF C&SR4
(136 MCHF in-kind, 20% of equip.)
100 MCHF HL-CONS,
~ 2000 FTE-y of CERN staff

End 2019: Baseline 3.0 APPROVED



Baseline 2.10:
+ 19 MCHF, as balance between change of scope and (projected) extra-cost.
This is total extra-cost accumulated on the initial baseline from 2015.

3 new equipment: **Baseline 3.0**
Approved by ED but exposed here for your C&SR assesment (60% in-kind from Russia): **+ 20 MCHF**

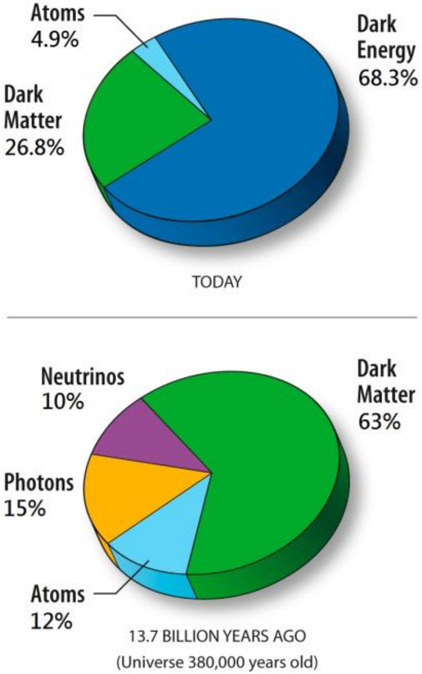
HL-LHC; nearly 3**00 MCHF spent;**
> 500 MCHF (>HALF) committed.

Residual cost uncertainty: **45 MCHF**
(min 26, max 72 MCHF)

HiLumi HL-LHC PROJECT

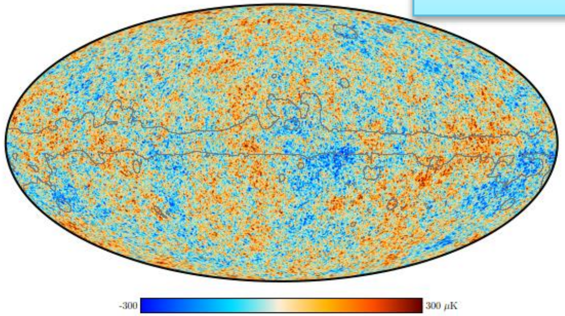
Do we need BSM physics? Yes.., and HiLumi LHC is not enough

Data we definitely cannot explain! matter-antimatter asymmetry,
dark matter
dark energy
inflation



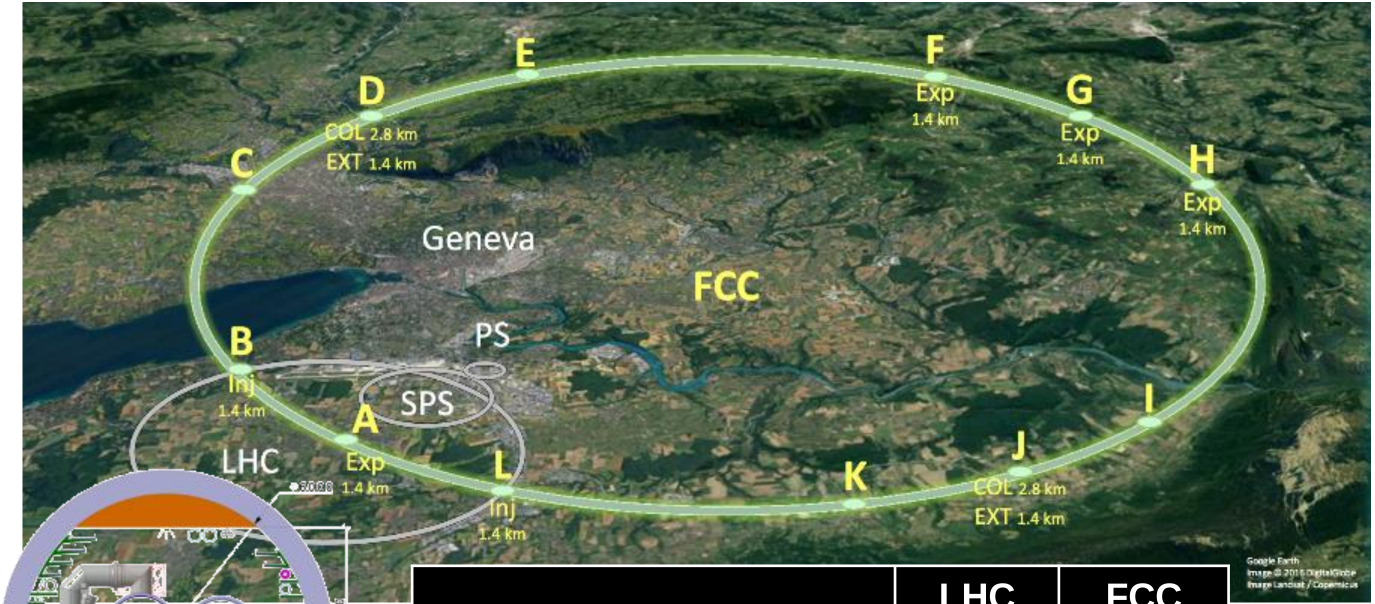
$$\text{SM} + \text{gravity} \neq \text{cosmos}$$

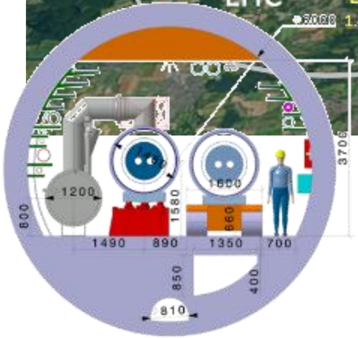
Pilar Hernández, U. of Valencia
Granada Symposium, May 2019



Can we understand this with BSM particle physics ?

Future Circular Collider

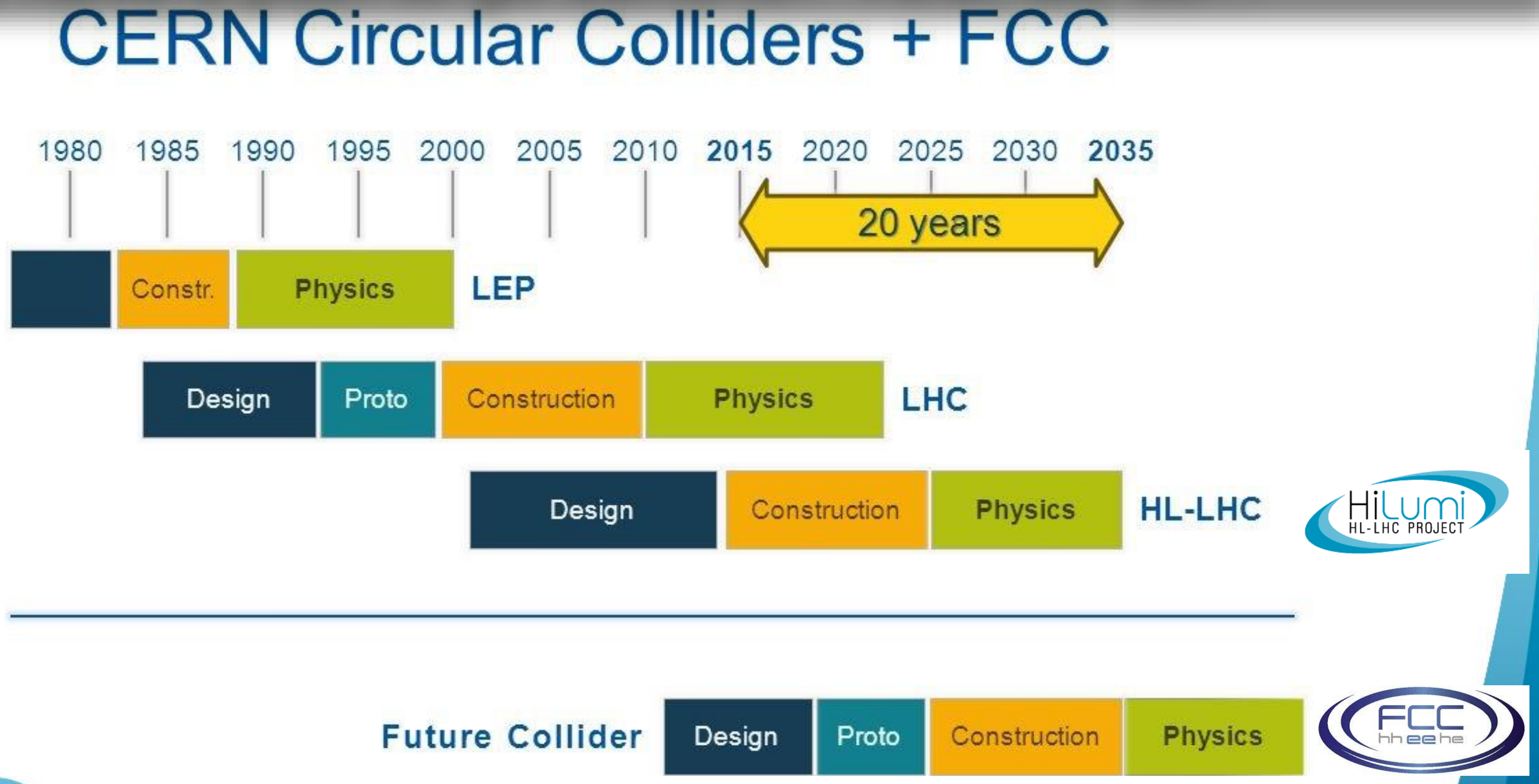


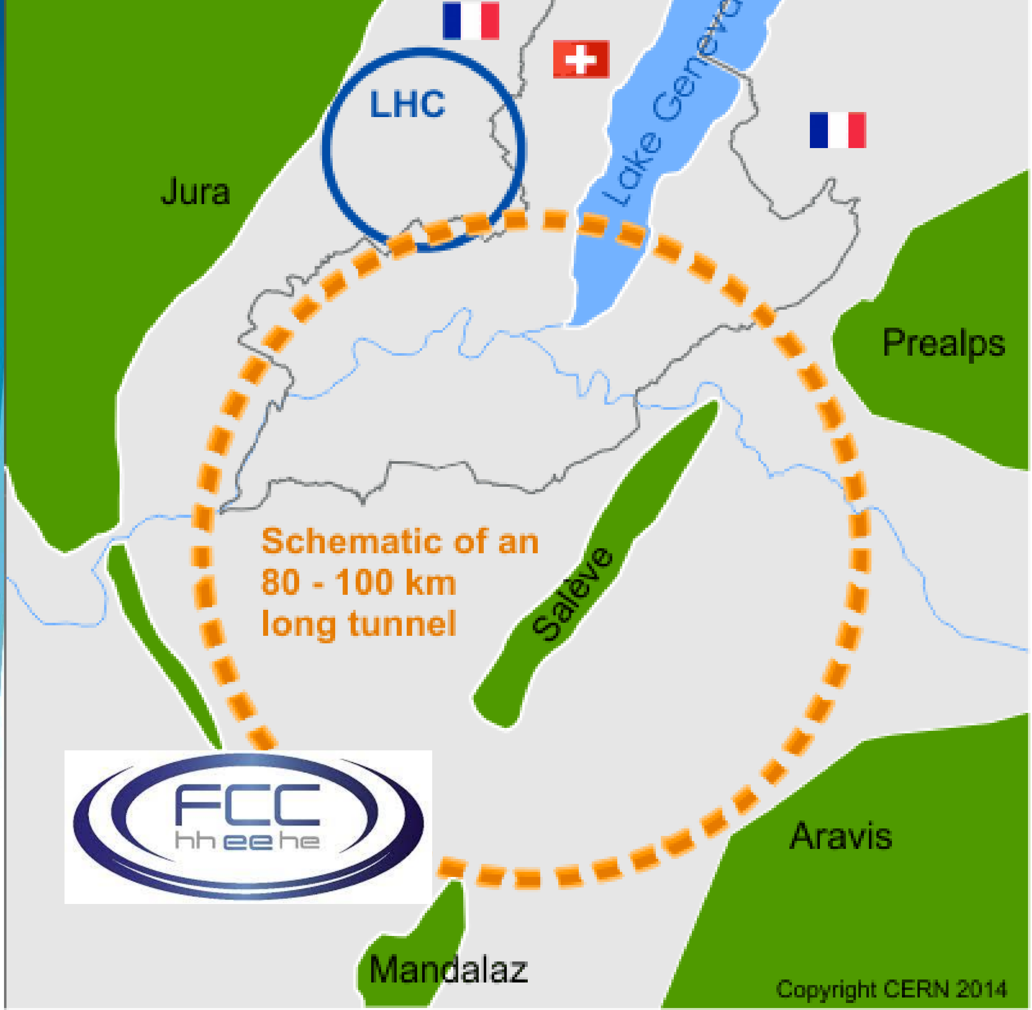


	LHC	FCC
Circumference (km)	26.7	97.5
Dipole field (T)	8.33	16
C.o.M. energy (TeV)	14	100

Courtesy of M. Benedikt, FCC

Do we have a plan to go behond? YES, we do...





Circular collider in new tunnel

80- 100 km circumference

Circular proton-proton collider
100 TeV collision energy (p+p)

Circular electron-positron collider (VLEP)
(***350 GeV c.m.*** energy, t-tbar threshold)

Lepton-Hadron collider (like HERA)
(***50 TeV p + 100 GeV e***)

Alternatively:

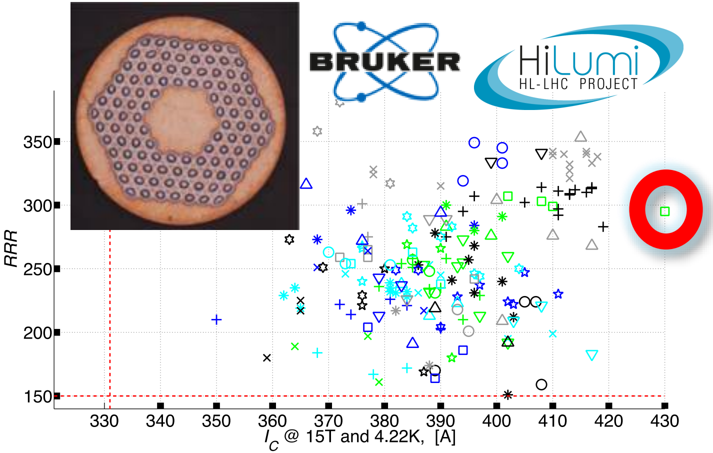
30 TeV p-p collider in LHC tunnel ?
(***16 T magnets***)

Conceptual design report ~late 2018

Competition? Yes, guess form whom…

Conductor R&D

Specification: 1500 A/mm² @ 16T, 4.2K

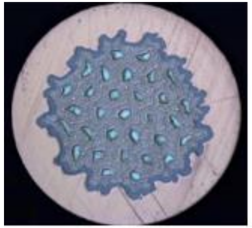


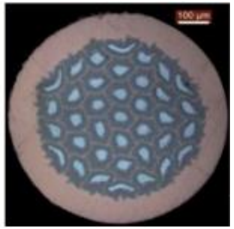
1750 A/mm² @ 15T, 4.2K

≈ 1400 A/mm² @ 16T, 4.2K

1274 A/mm² @ 15T, 4.2K

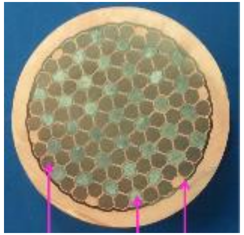
≈ 1000 A/mm² @ 16T, 4.2K

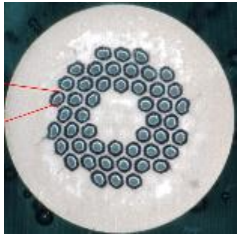




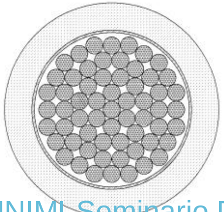
2850 A/mm² @ 12T, 4.2K

≈ 1250 A/mm² @ 16T, 4.2K





≈ 950 A/mm² @ 16T, 4.2K



Towards the ultimate performance of Nb_3Sn

Performance target for FCC-hh J_c(4.2K,16 T) = 1'500 A/mm²

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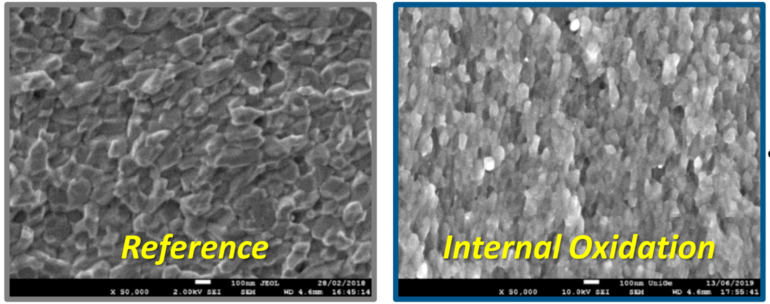
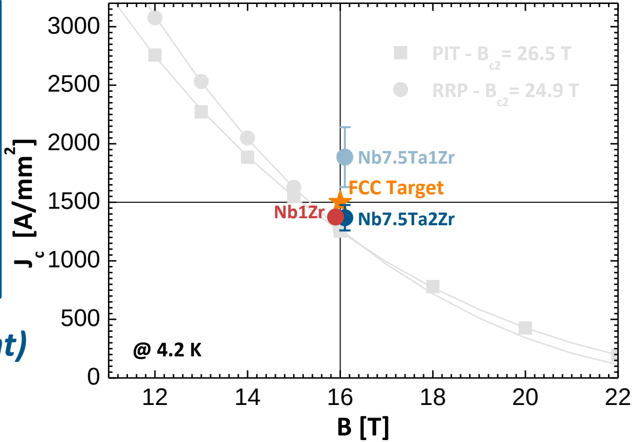
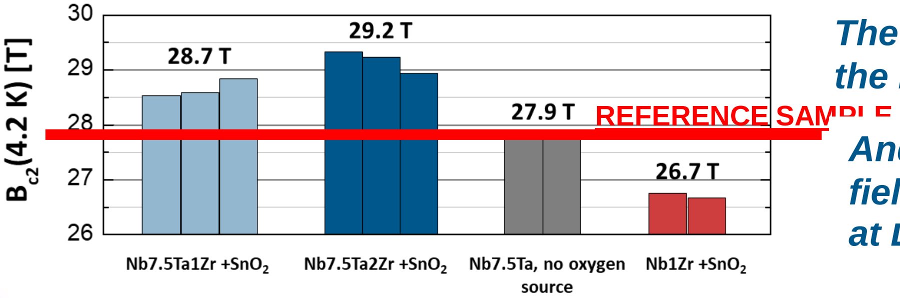
DQMP
http://supra.unige.ch





Grain refinement from 120 nm (left) to 60 nm (right)

Enhanced grain boundary pinning



The potential to reach and exceed the FCC-hh specs

And record-high upper critical field !!
at LNCMI-Grenoble

FCC Magnet Designs

$T_{op} \approx 1.9$ K

I_{op}/I_C(loadline) ≈ 86 %

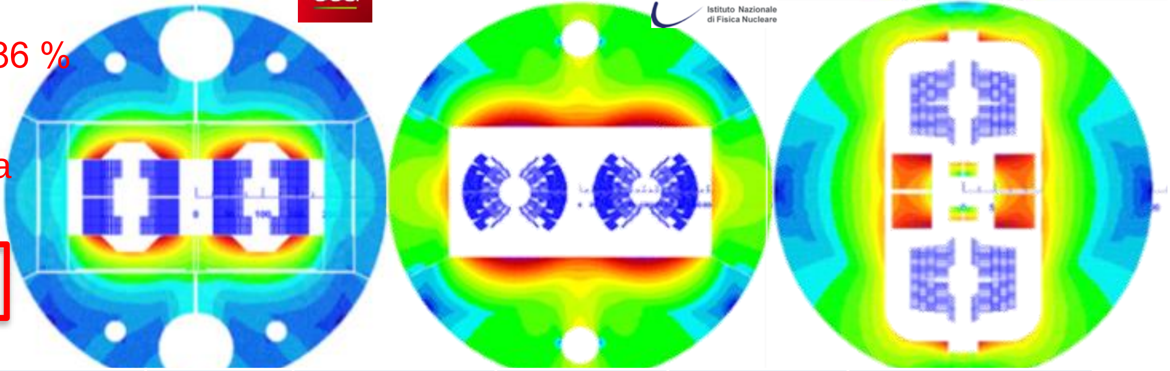
$V_{dump} < 2.5$ kV

$\sigma_{max} < 200$ MPa

$T_{hot} < 350$ K

$D_{out} \approx 600$ mm

HE-LHC !



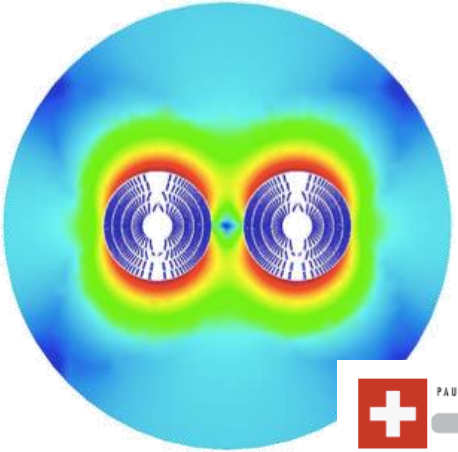
		blocks		cos(θ)		common coil
Current	(A)	11230		10000		16100
Inductance	(mH/m)	40		50		19.2
Stored energy	(kJ/m)	2520		2500		2490
Coil mass	(tons)	7400		7400		9200

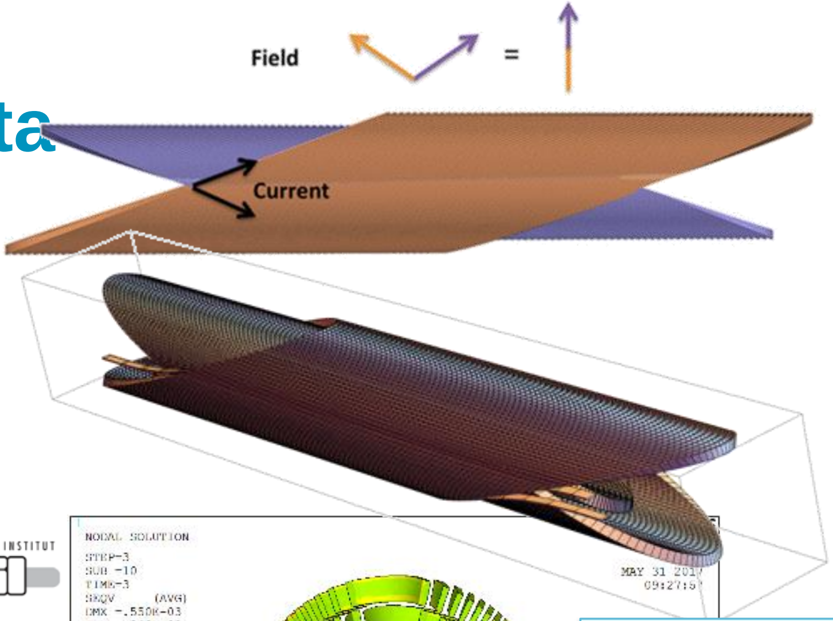
Very efficient use of superconductor

Simplified mechanics and manufacturing ?

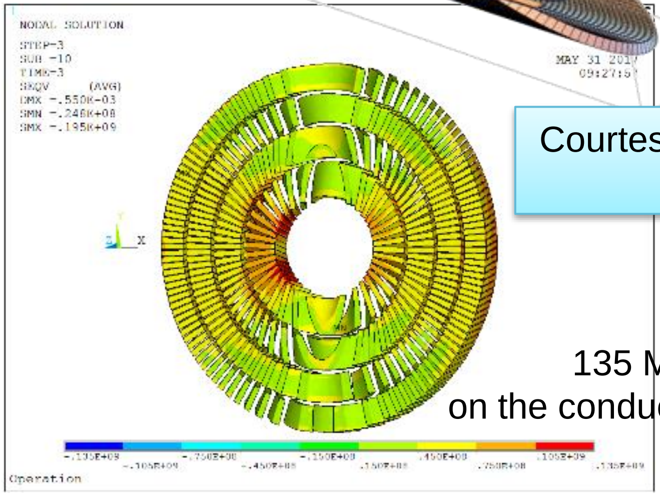
Courtesy of D. Tommasini, CERN

CCT option
Canted CosTheta





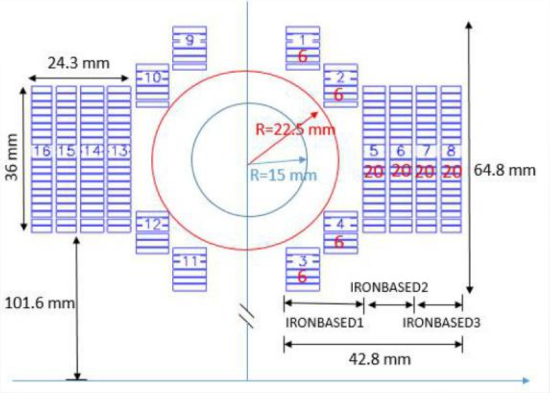
		CCT
Current	(A)	18055
Inductance	(mH/m)	19.2
Stored energy	(kJ/m)	3200
Coil mass	(tons)	9770

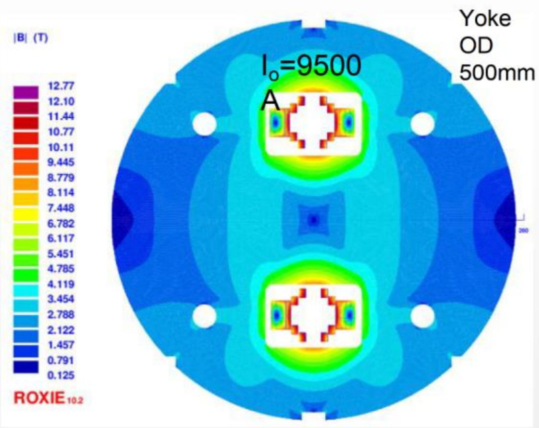


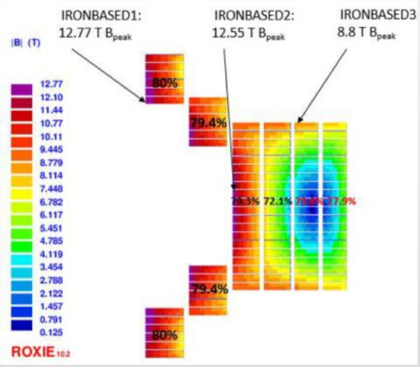
Courtesy of B. Auchmann, PSI and CERN

high-field magnet R&D for SppC

The 12-T Fe-based Dipole Magnet



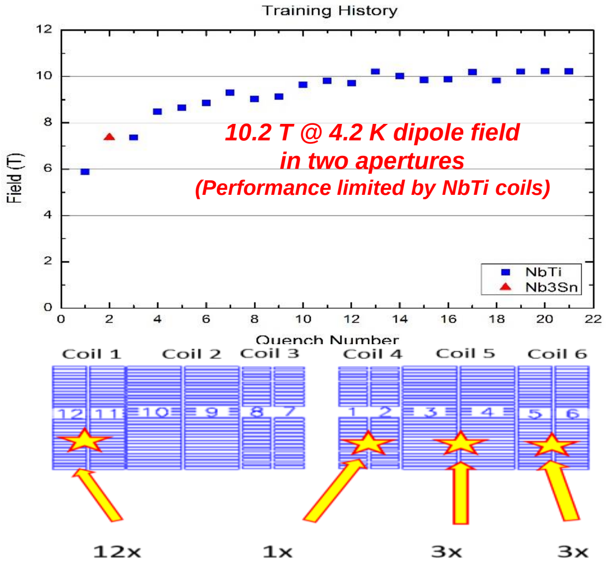




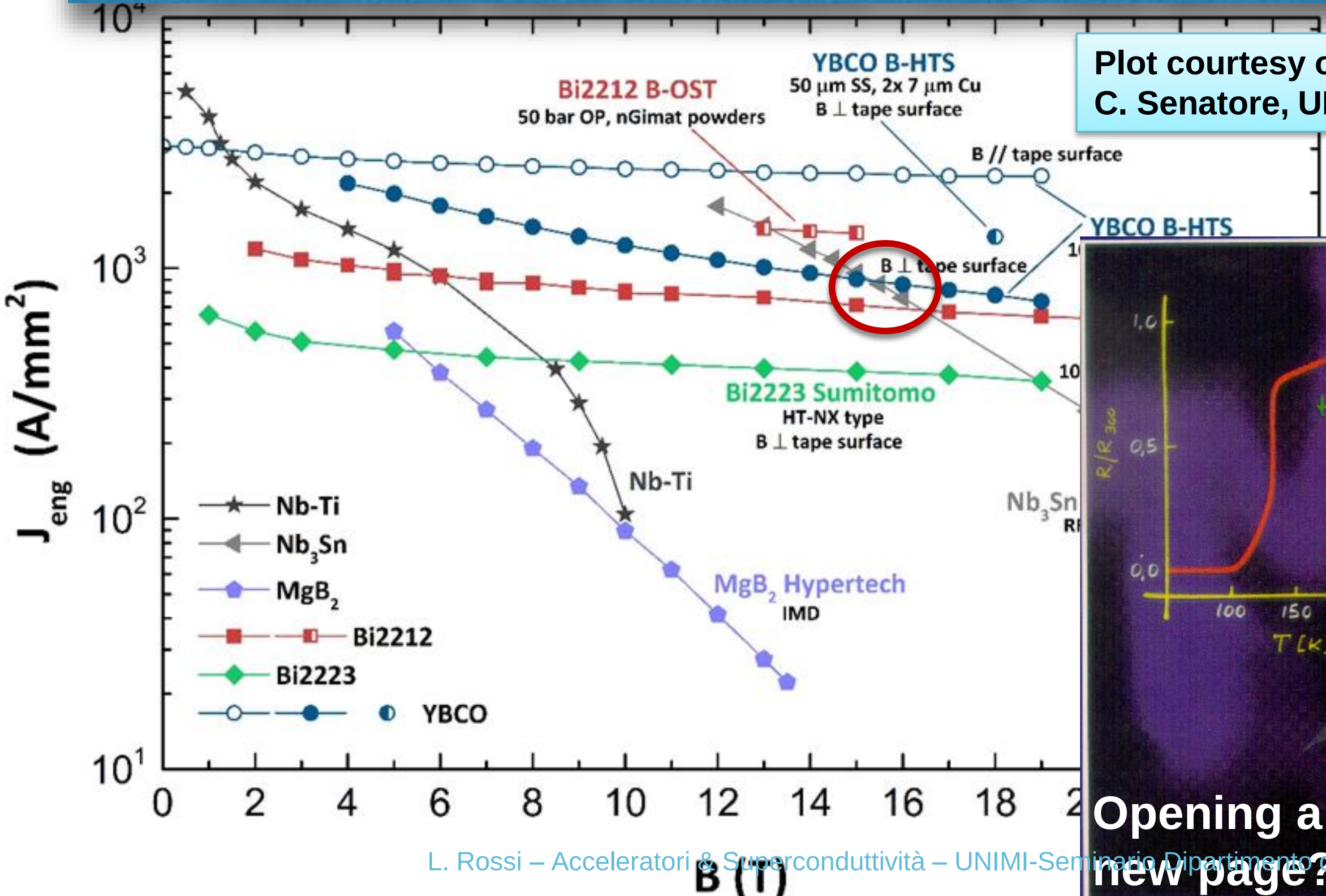
Design with expected J_e of IBS in 2025

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0.802	1	200	4.2	10	4000	111

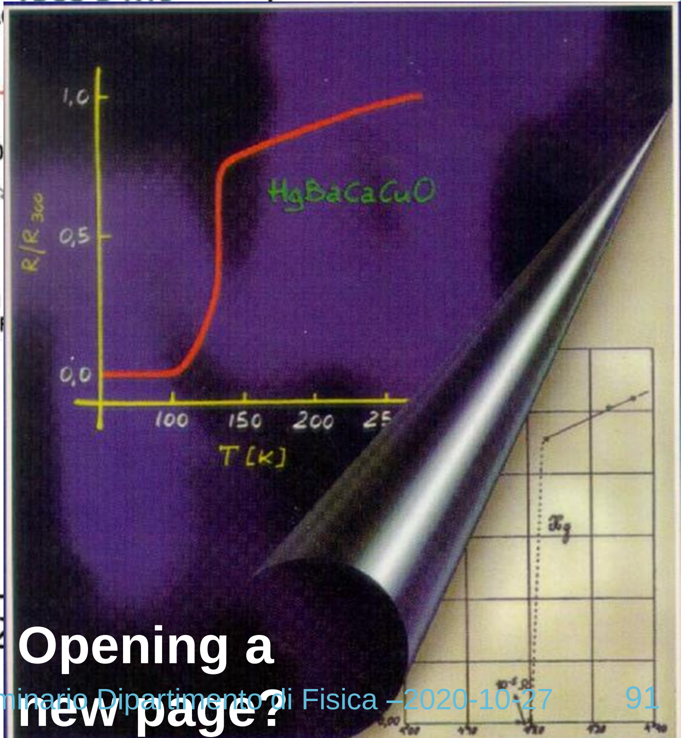
- For 100-km SPPC, **3000 tons of IBS** is needed
- Target cost of IBS: **20 RMB /kAm @12 T**
- Total cost for IBS conductors: **~10B RMB**



High Temperature Superconductors – HTS: next technology step

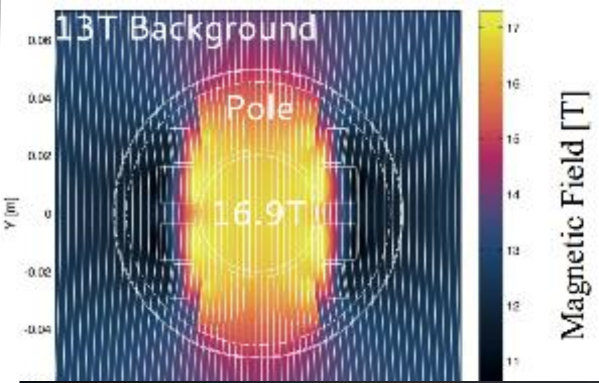


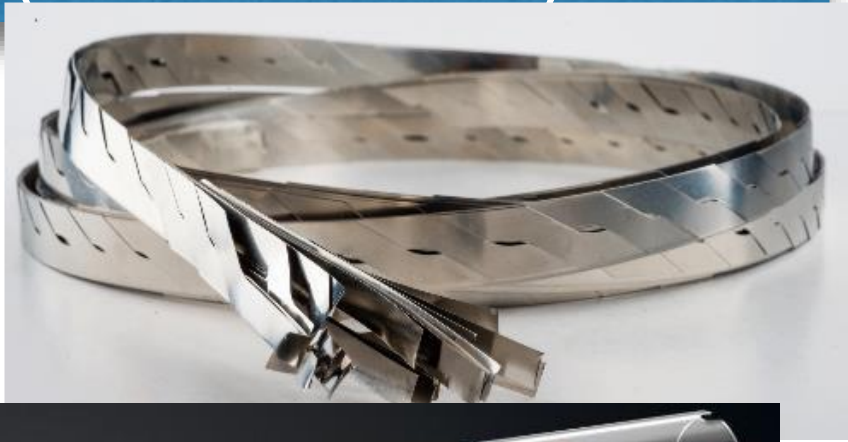
Plot courtesy of
C. Senatore, UNIGE

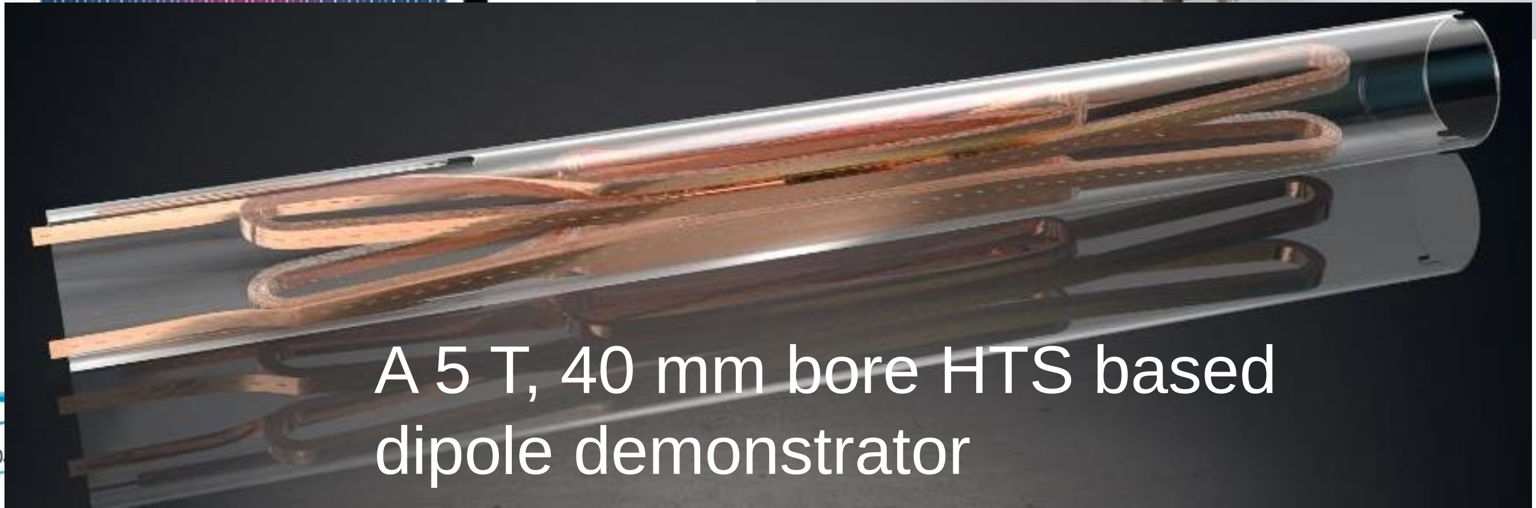


Opening a new page?

High Temperature Superconductors – HTS
The dream of 20-25 tesla! (2 x HilumiLHC!)





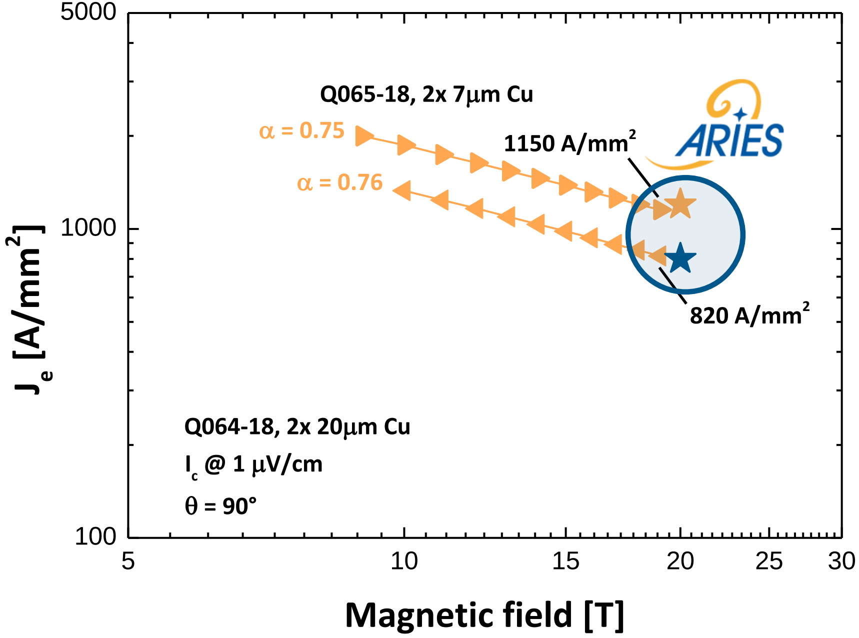


A 5 T, 40 mm bore HTS based dipole demonstrator

Trying the magnets of the future… 20 tesl or more...

Engineering current density $J_e(B,T=4\ K)$

Performance target



Measured by C. Senatore team

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http://supra.unige.ch

Tape Q065-18 (with 2x 7μm Cu) reached a very high performance of 1150 A/mm² at 4.2 K, 19 T, 90°

HiLumi HL-LHC PROJECT

How our technolgies contribute to society?
Not only the web: new eyes…

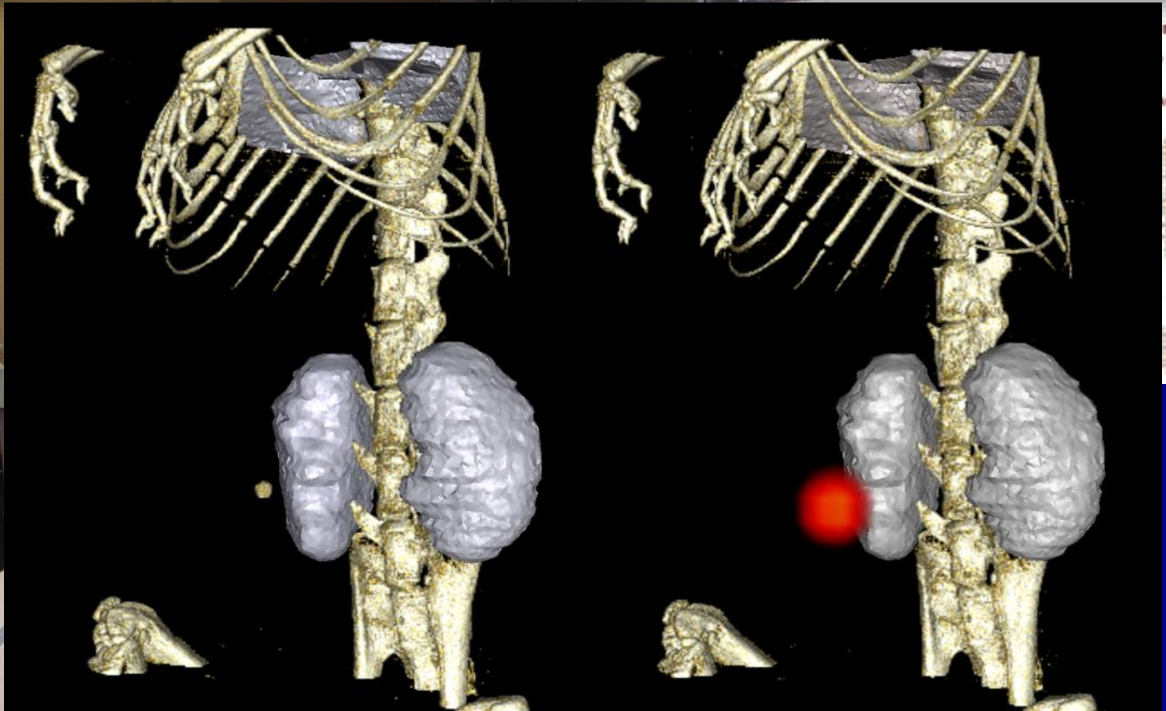
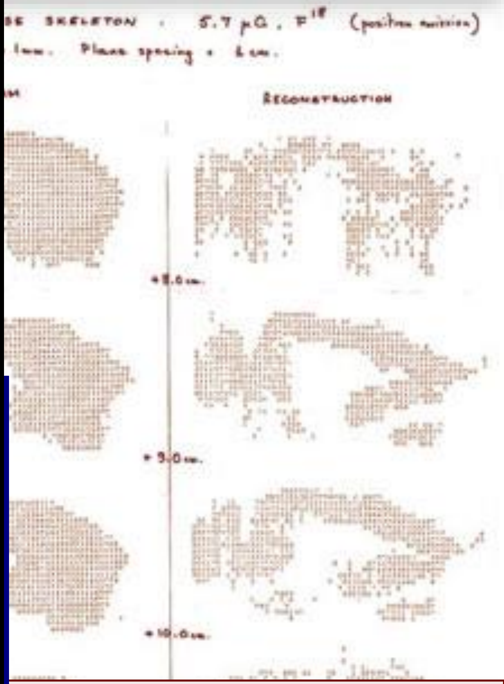
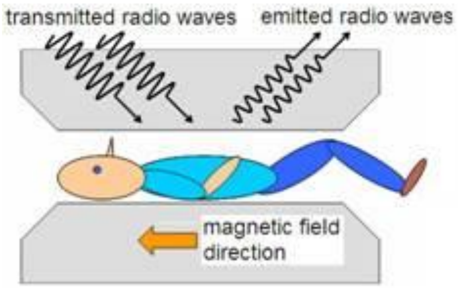


Image by PET and MRI combined

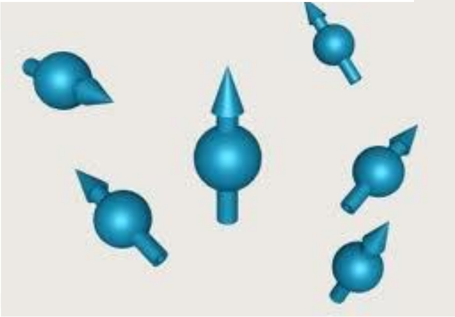


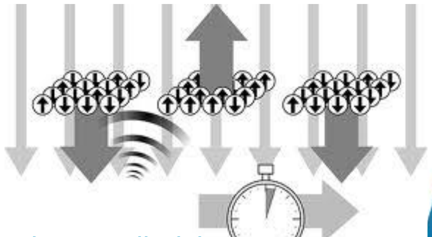
First PET image: CERN, circa 1975

New medical «eyes»: MRI, 2000 large systems/year

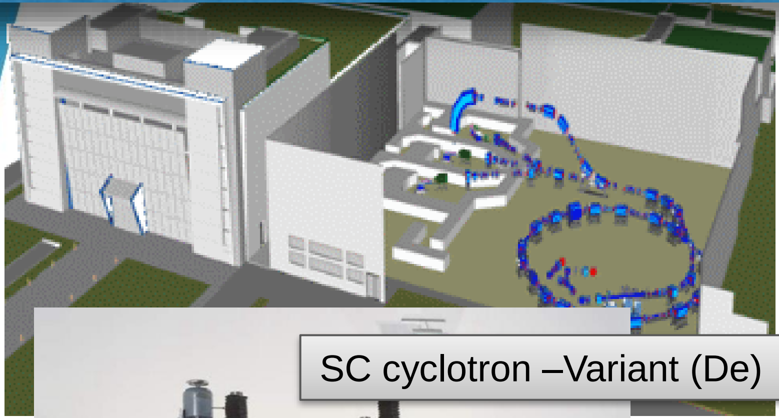


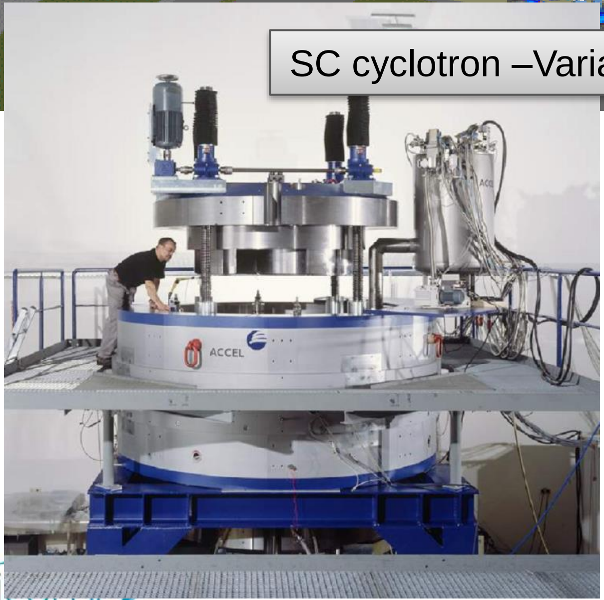
An example of an MRI brain scan
Image courtesy of Scott Camazine, MD





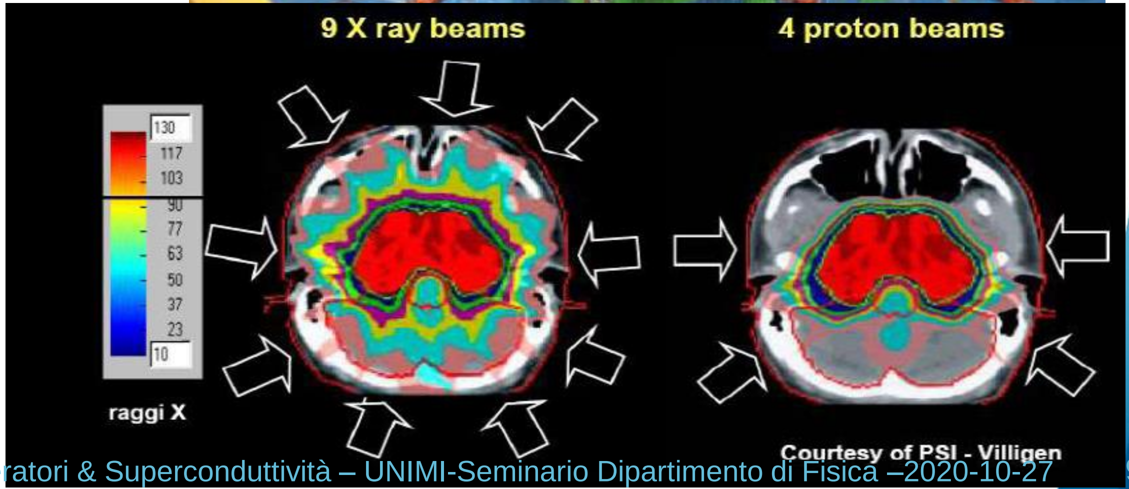
Hadron therapy



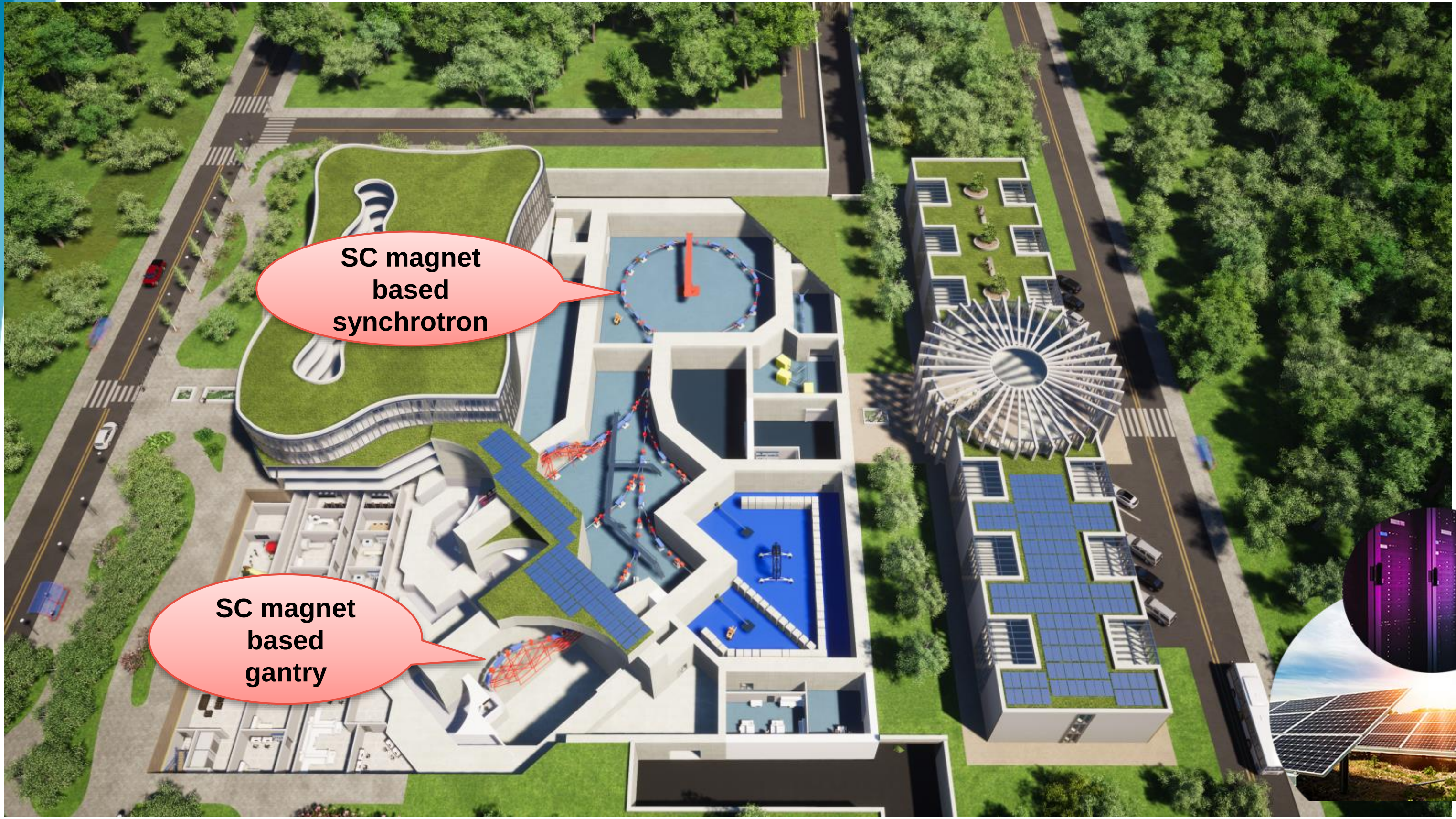


SC cyclotron –Variant (De)

Synchrotron in Pavia (CNAO), It

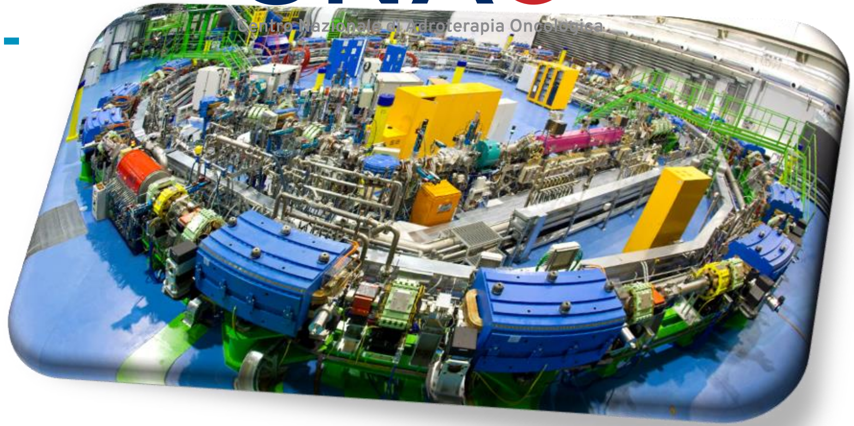


SEEIIST – First Green Infrastructure in line with Horizon Europe Cancer Mission



collaboration CERN-CNAO-MedAustron-INFN on C-ion GANTRY

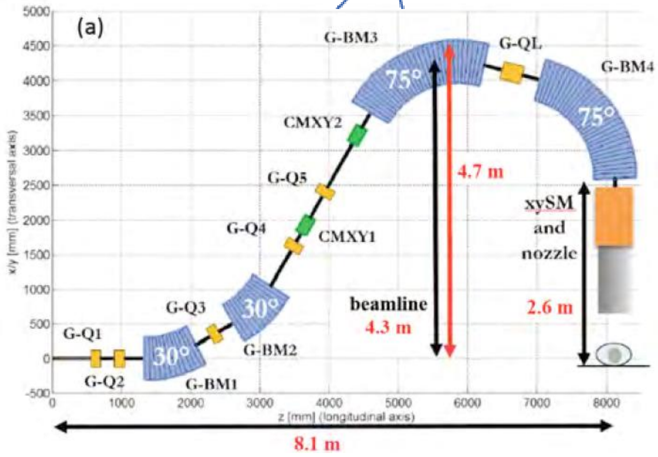
- Improve the efficiency (medical effectiveness and treatment time) of the present facilities
  - CNAO (Pavia, IT)
  - MedAustron (Vienna, AT)
- Design a gantry compatible with the present layout without large civil engineering and infrastructure investment
- Leveraging the design capability and technology infrastructure of HEP community (CERN) to strenghten the medical technology in EU.
  → NIMMS program at CERN led by M. Vretenar

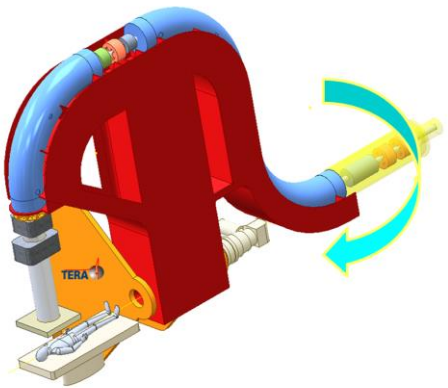


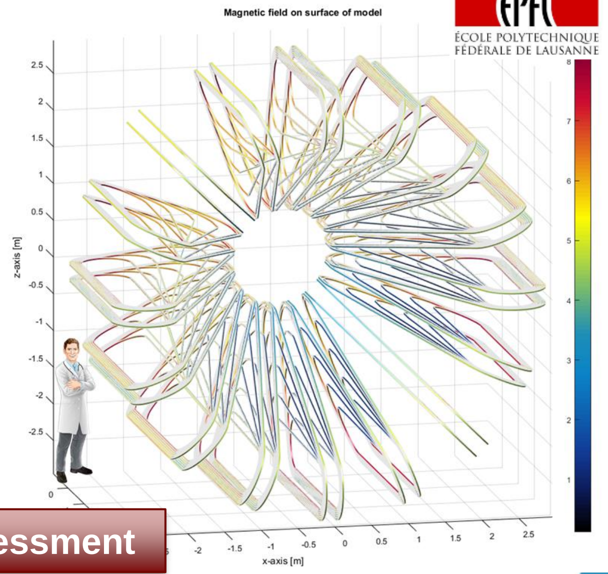
Collaboration CERN-CNAO-MedAustron-INFN on C-ion SC GANTRY

Light rotating ga

Toroidal gantry





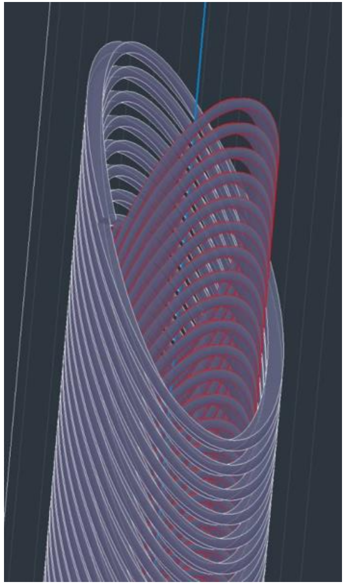


End 2020: decision on design based on Internation panel assessment

Nb-Ti CCT: p-gantry and HiLumi LHC

LBNL: CCT coil prototype for large acceptance proton gantry ∅ = 400 mm: Successfully tested to 3.5 T; segmented former

HiLumi LHC: CERN has designed, built and tested a dual 3 T, 2 m long - ∅ = 90 mm, straight CCT. Now IHEP Beijing producing 2x13 units



The EC H2020 funded (??) program

- HITRI presented in Nov.2019 (not funded)
  - Heavy Ion Therapy Research Infrastructure
  - Scope: design study mainly (if not purely) for SEEIIST
  - Not approved (March 2020): weak in medical part and use… (Physics part OK)
- **HITRI*plus* (Hitri+)**
  - Medical part improved, scope expanded not only to SEEIIST (still most prominent project in EU). Physics part same as HITRI
  - **WP8 on Magnet Design**
    - overview and assessment of various conductors (LTS, HTS, various types of cables) and magnet layouts (cosϑ, CCT, racetracks – spit coils or flare ends – etc…). Both for Synchrotrons (main dipole and extraction channel) and Gantry
    - Design construction and test of 1 demontrator ~500 mm long (either LTS or HTS)
    - Very much CCT oriented!
  - **Applied in May 2020; assessment expected by 19th October!**
- **I.FAST**
  - Is the *omnibus* program following CARE, Eucard, Eucard2, ARIES to integrate accelerator R&D across EU labs
  - **WP8 on Innovative Superconducting Magnets**
    - scope is fostering technology innovation: → exploring HTS cable and magnet layout
    - General consensus to go toward CCT: CORC® ?, stacked tapes? Roebel? Or Bi-2212 Rutherford cable? Other magnet layout not excluded
    - The WP8 fosters also a panel among various lab to steer HTS for accelerator magnets in EU and the development of a HTS cable suitable for low losses - large size - fast cycling - synchrotrons (led by GSI)
    - Applied in May 2020; assessment expected by 19th October!

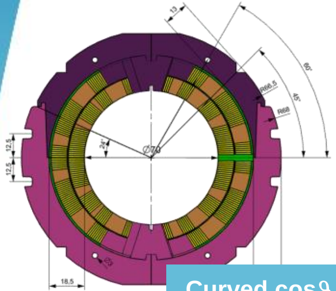
The EU roadmap for enabling a full SC C-ion facility: synchrotron + gantry

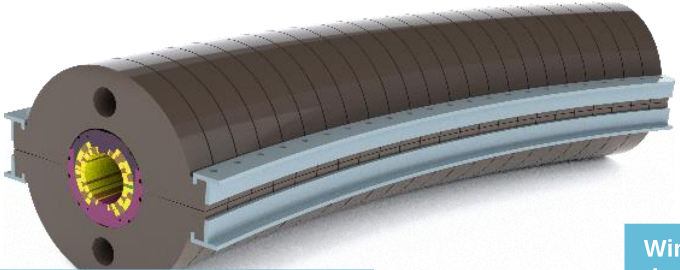
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CERN-CNAO-MedAustron-INFN collab. for Gantry													
SEEIIST													
H2020-HITRIPlus & I.FAST			LTS										
			HTS										
HE program for R&D ??			HTS			?	?	?	?	?	?		
	Conceptual study		Proto & Design		Construction		Installation & Commissioning						

Disclaimer: roadmap to be reviewed with stakeholders
At time of freezing this presentation, the result (approval or not) of the H20220 applications, both I.FAST and HITRI+, is not yet known (but it should be by the time of delivering this talk …)

HiLumi HL-LHC PROJECT

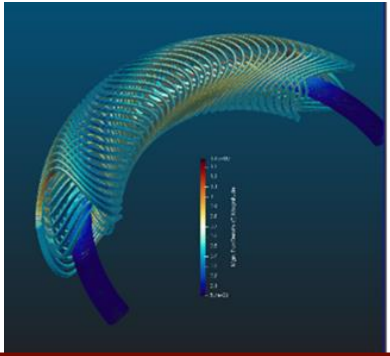
A few ideas (just as list.

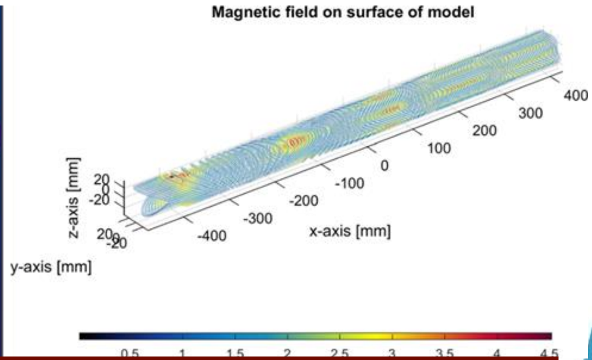




Curved cosϑ dipole with H-split yoke with assembly clamps - Courtesy Mikko Karppinen, CERN

Winding plate of the HTS 0.5 m wide HTS demonstrator toroid for the Ga-Torroid; courtesy E. Felcini and G. de Rijk, CERN





The challenge is not the field level, rather designing for ramping field and cryocooled magnets…

HITRI+ WP8 Magnet Design (with construction and test of a demonstrator)

Member	Person-months	Total costs	EC funds	Institute matching funds
CEA	20	192,500	86,625	105,875
CERN	10	161,250	70,538	90,713
CIEMAT	22	145,000	65,250	79,750
INFN	32	357,000	160,650	196,350
PSI	2	29,750	13,388	16,363
UU	8	79,750	35,888	43,863
Wigner RCP	12	39,250	17,663	21,588
SEEIIST	8	65,625	15,094	50,531
Total	114	1,070,125	465,094	605,031

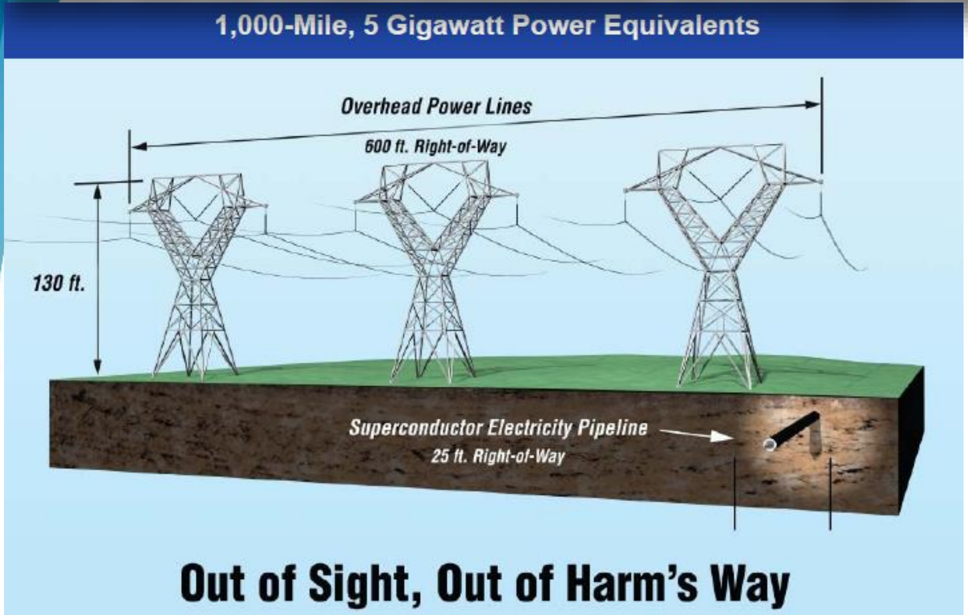
INFN is the WP8 – Magnet Coordinator
CEA is the deputy coordinator

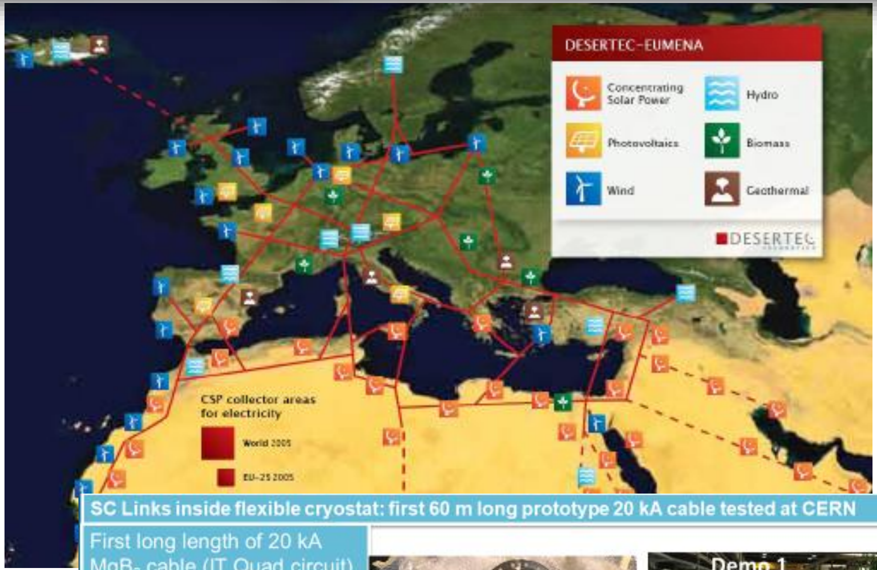
I.FAST WP8 Innovative SC Magnet. Demonstrator in Industry!!!

Members	Person-months	EC funding	Institute matching funds	TOTAL Funds
CEA	10	42,188	76,705	118,892
CERN	11	190,153	345,732	535,884
Wigner RCP	24	24,638	44,795	69,433
INFN	14	112,613	204,750	317,363
CIEMAT	12	26,438	48,068	74,506
UU	5	31,500	57,273	88,773
PSI	6	28,688	52,159	80,847
BNG	10	64,313	116,932	181,244
Scanditronix	10	59,938	108,977	168,915
Elytt	15	59,938	108,977	168,915
Sigmaphi	15	59,938	108,977	168,915
Grand Total	**132**	**700,340**	**1,273,345**	**1,973,685**

INFN is the WP8 – Magnet Coordinator
CEA is the deputy coordinator

SC and Renewable Energy Technology: Transmission





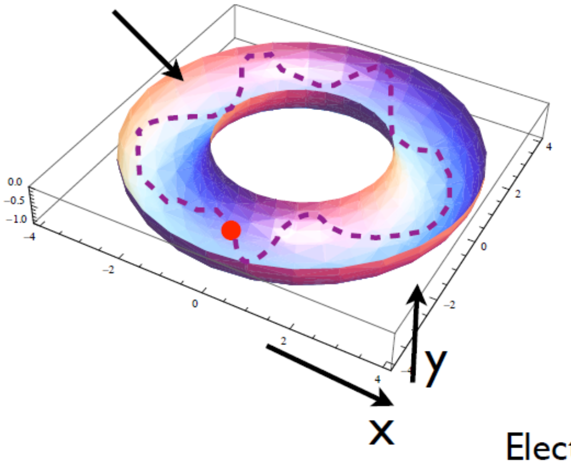
HiLumi cable is considered for long line-high power and for Data Storage Center (tens of MW!)

Research: Stimulating innovation…

Spero che le ricerche su acceleratori & superconduttività siano all’altezza del passato e che abbiano un futuro luminoso come quello di LHC

Thanks

How an accelerator works ?



Goal: *keep enough* ***CHARGED*** *particles confined in a well defined volume to accelerate them for a sufficiently long time* ***(ms - hours)***

How ? Lorentz Force!

$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

Electric field accelerates particles

Particles of different energy (speed) behave differently

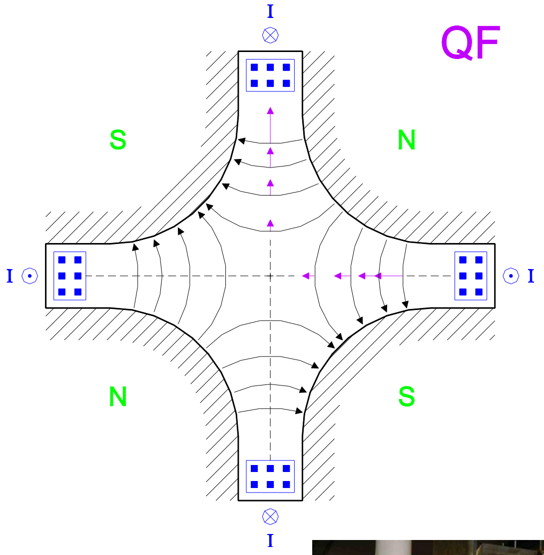
Magnetic field confines particles on a given trajectory

An ***accelerator*** *is formed by a sequence (called* ***lattice****) of:*

a) Magnets → Magnetic Field

b) Accelerating Cavity → Electric Field

A questo ci pensano i magneti quadrupoli…

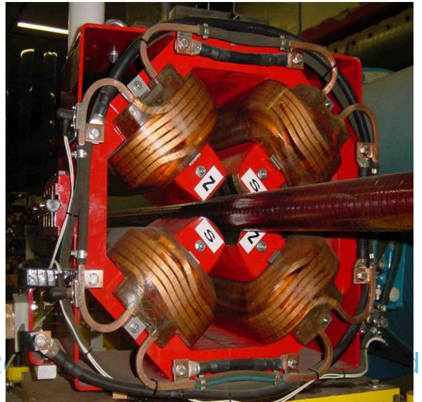


$$F_x = -g.x$$

$$F_y = g.y$$

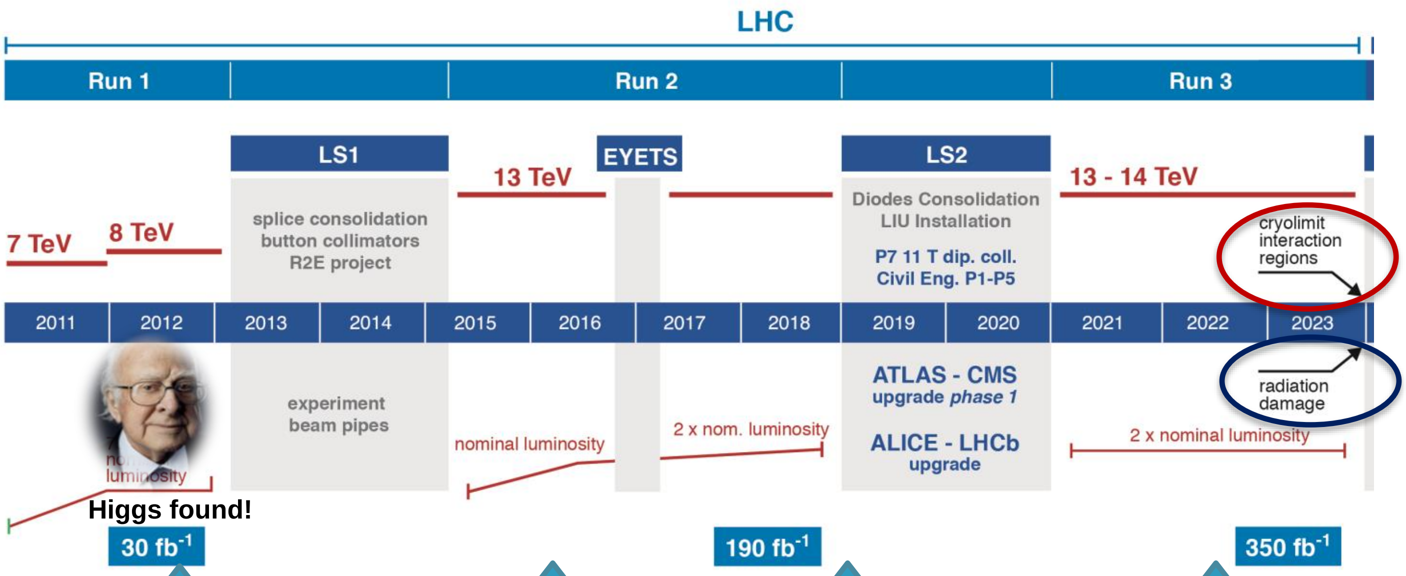
Force increases linearly with displacement.

Unfortunately, effect is opposite in the two planes (H and V).



Remember: this quadrupole is focusing in the horizontal plane but defocusing in the vertical plane!

LHC / HL-LHC Plan



$0.75\ 10^{34}\ cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

$1.4\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

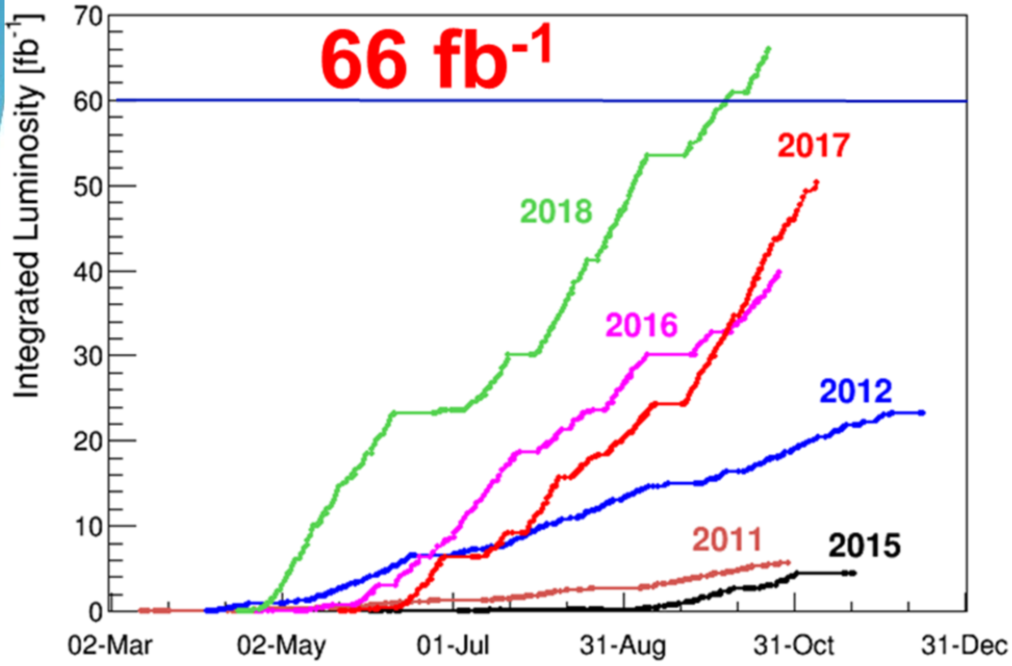
$2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

$2\ 10^{34}\ cm^{-2}s^{-1}$
with levelling, 25 ns b.
pile up ~60 continuous

Technical limitation on the istantaneous lumi:
1. **Collider** (cryolimit in the triplet region) at 2×10^{34} cm^{-2}s^{-1} twice the nominal design luminosity)
2. **Experiments** (pile up in the detectors). Designed for PU 40 they are actually dealing with 60 (average)!

Technical limitation on integrated lumi:
1. **Collider** (radiation damage to the IT magnets – correctors and quadrupoles)
2. **Experiments** (radiation damage in the Inner Tracker)

Performance: Integrated Luminosity

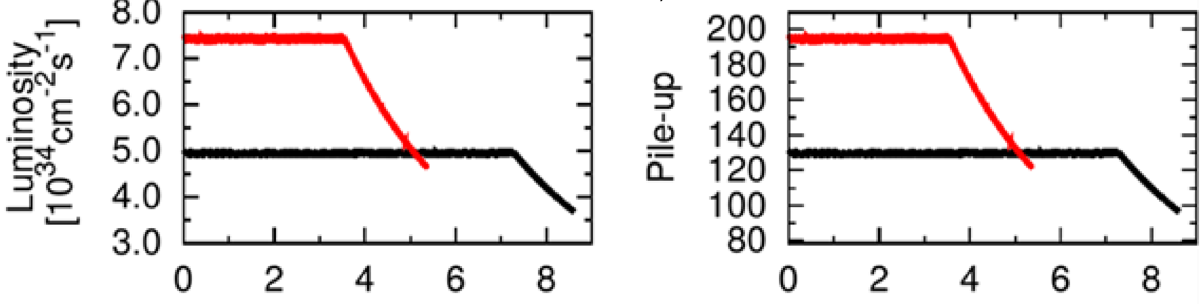


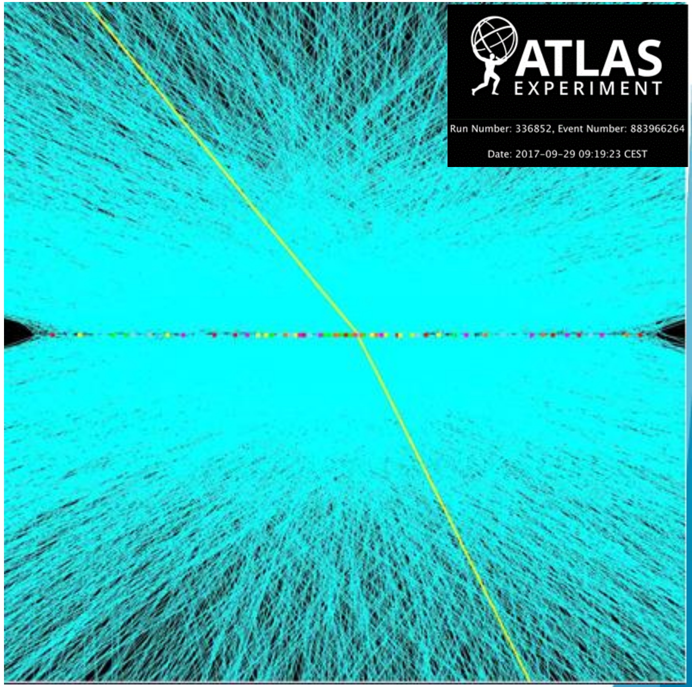
Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66.0
Total Run1 + Run 2	189.3

Original goal of Run1+Run2 = 150 fb^{-1}:
Δ = + 20%

Improving the data quality

R. Tomas, CERN



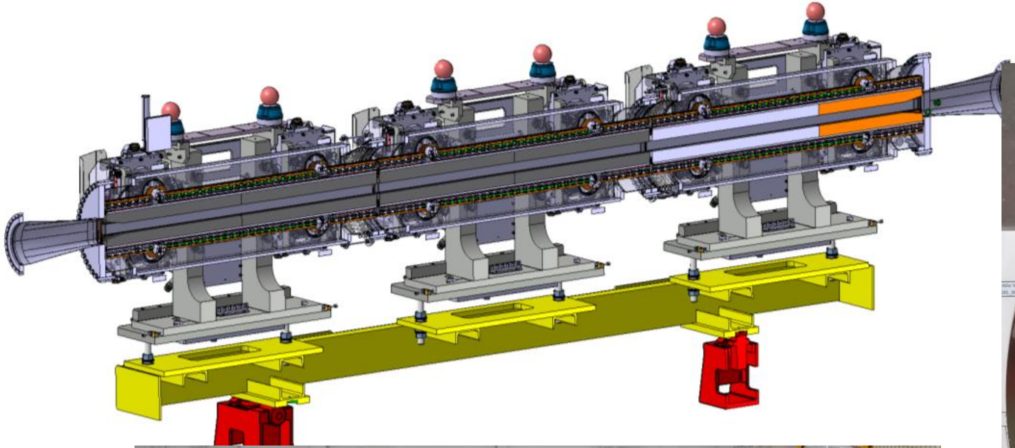


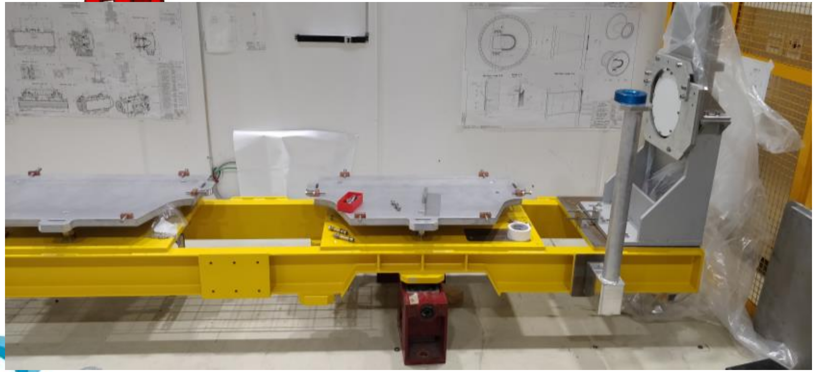
Collision with μ = 65

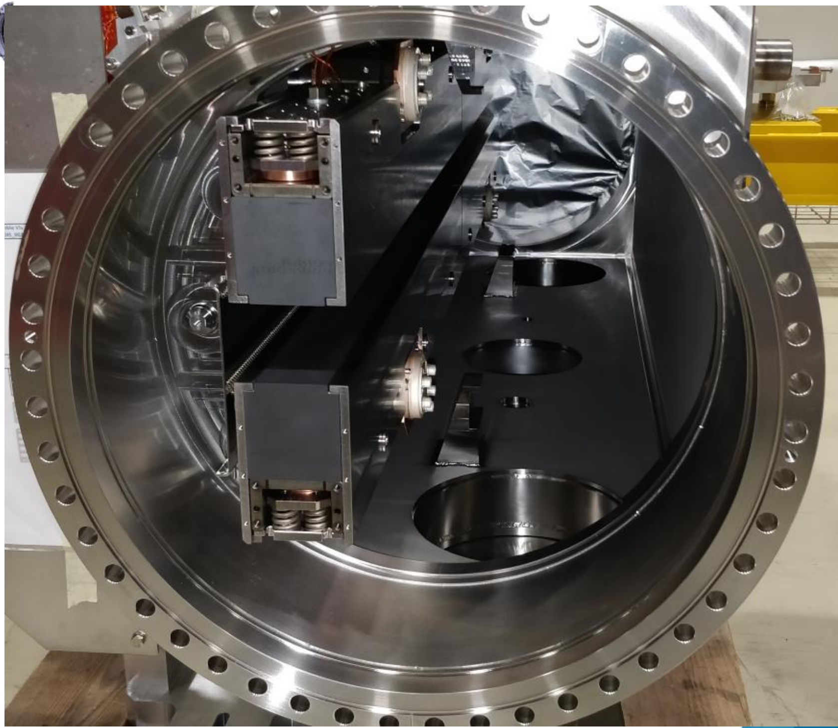
Levelling helps to limit total pile up:
μ_{ave}= 140 (ultimate: μ_{ave}= 200). Experiments ask to reduce the pile up linear density (number of events/lenght) and need to introduce time stamping
$\Rightarrow$ carefully control and variation of:

- β* (beam size at collision), main levelling knob
- Bunch tilt (Crab cavities)
- Crossing angle
- Longitudinal bunch length

HL-LHC equipenment for LS2: new TDIS module – 1 out of 3 – ready (necessary to inject LIU beam into LHC

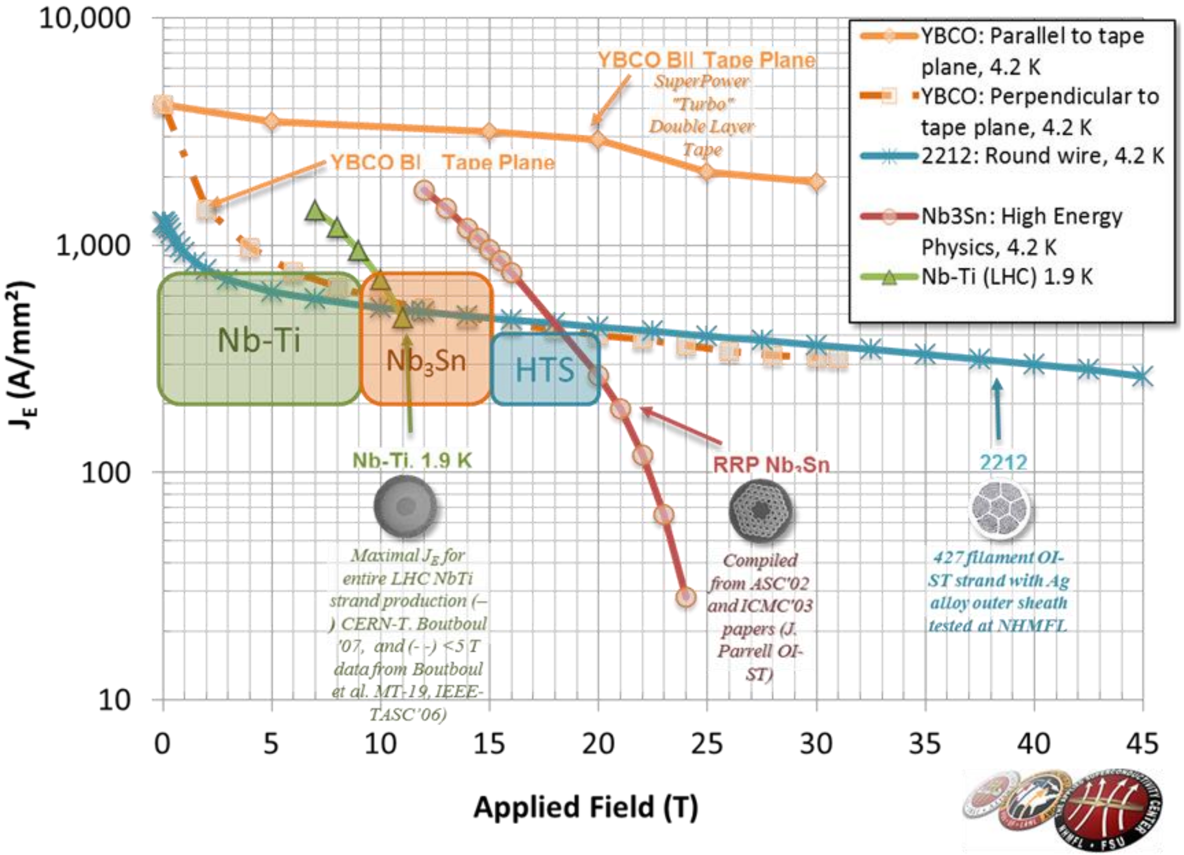






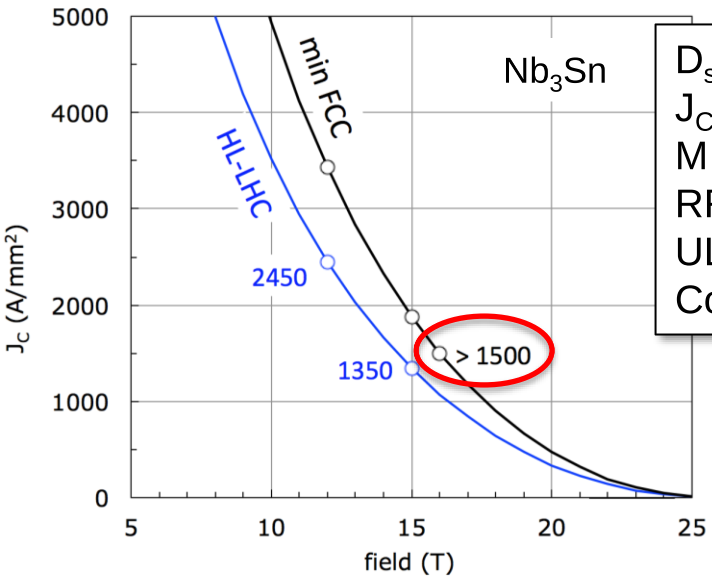
HiLumi HL-LHC PROJECT

Are we stuck with 15-16 T of FCC? NO!



Nb_3Sn: the workhorse of the "near Future"

Solid objectives for the FCC conductor R&D

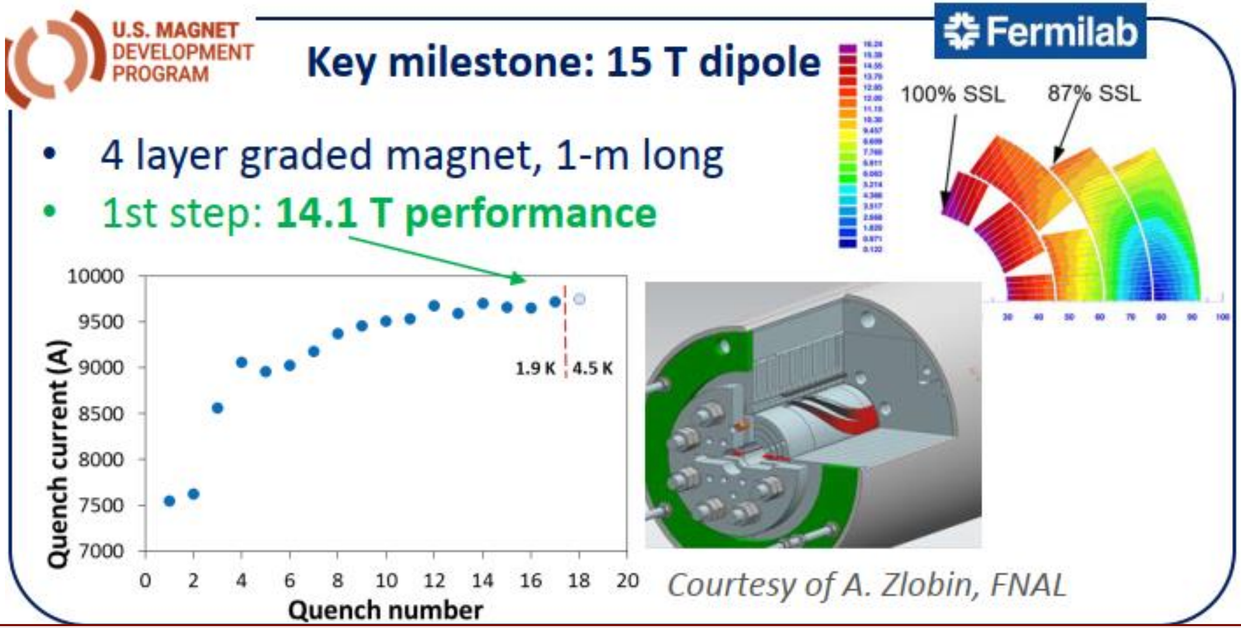


D_{strand}: 0.7…1 mm
J_C (16 T, 4.2 K) > 1500 A/mm²
M (1 T,4.2 K) <150 mT (D_{fil} < 20 μm)
RRR > 150
UL > 5 km
Cost(16 T, 4.2 K) < 5 USD/kA m

Presentation given at "50+10 years"
Panel Session at the ASC,
Charlotte (US), August 10th-15th, 2014

The goal is ambitious but not impossible.
Cost wil be probably the most challenging

Recent very successful 14 T magnet reached by US MDP cosϑ dipole at FNAL



But the route is long… a 16 T 100 km accelerator is not yet at hand and a long R&D is necessary.
In May 2020 in Budapest gthe new ESPP will be approved…