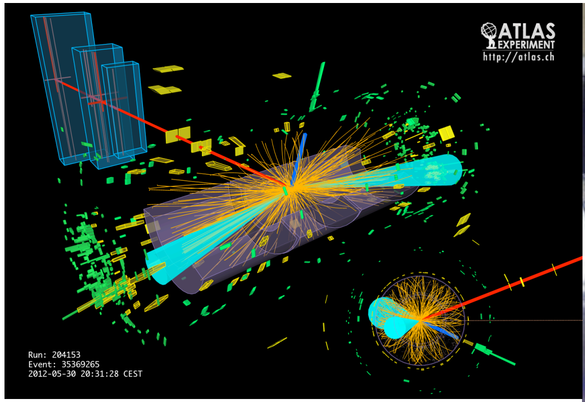
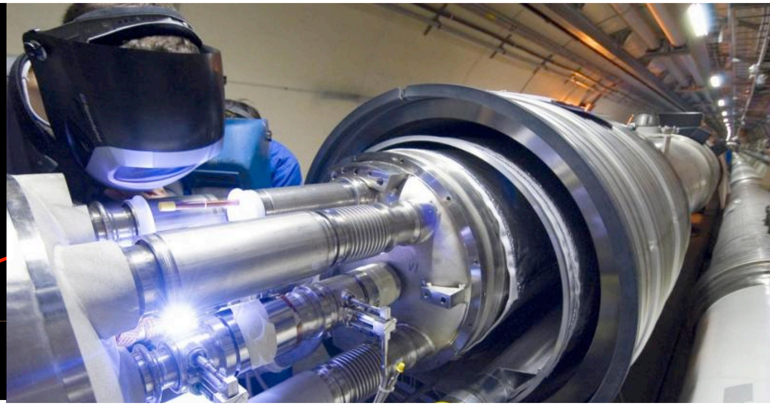
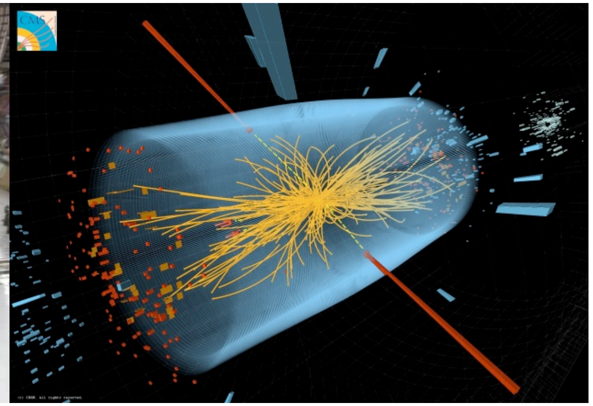


High Field Accelerator Magnets: a Path Towards New Physics ?



Presented by L. Bottura

MT25

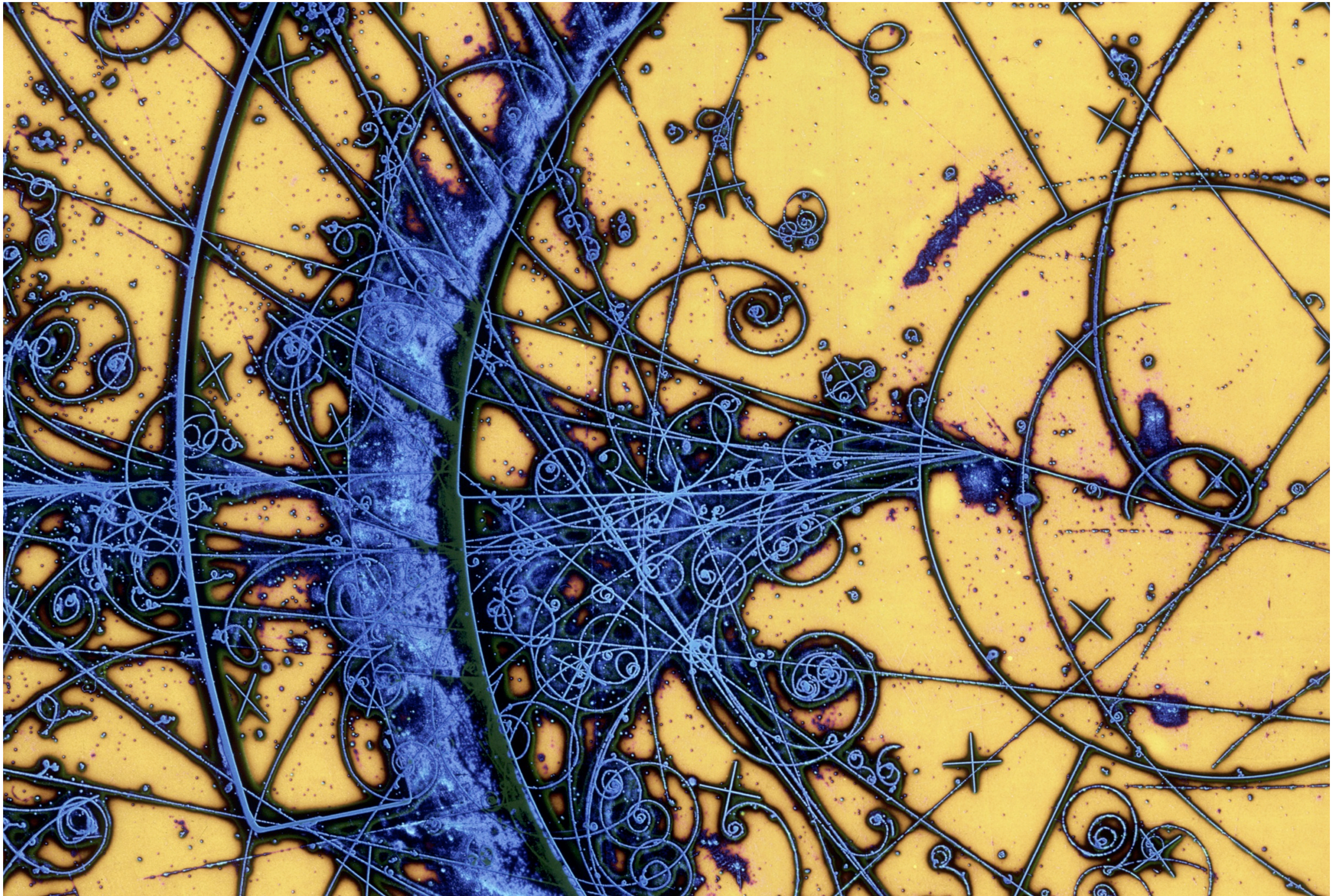
RAI - Amsterdam
August 27-September 1, 2017

CERN

Outline

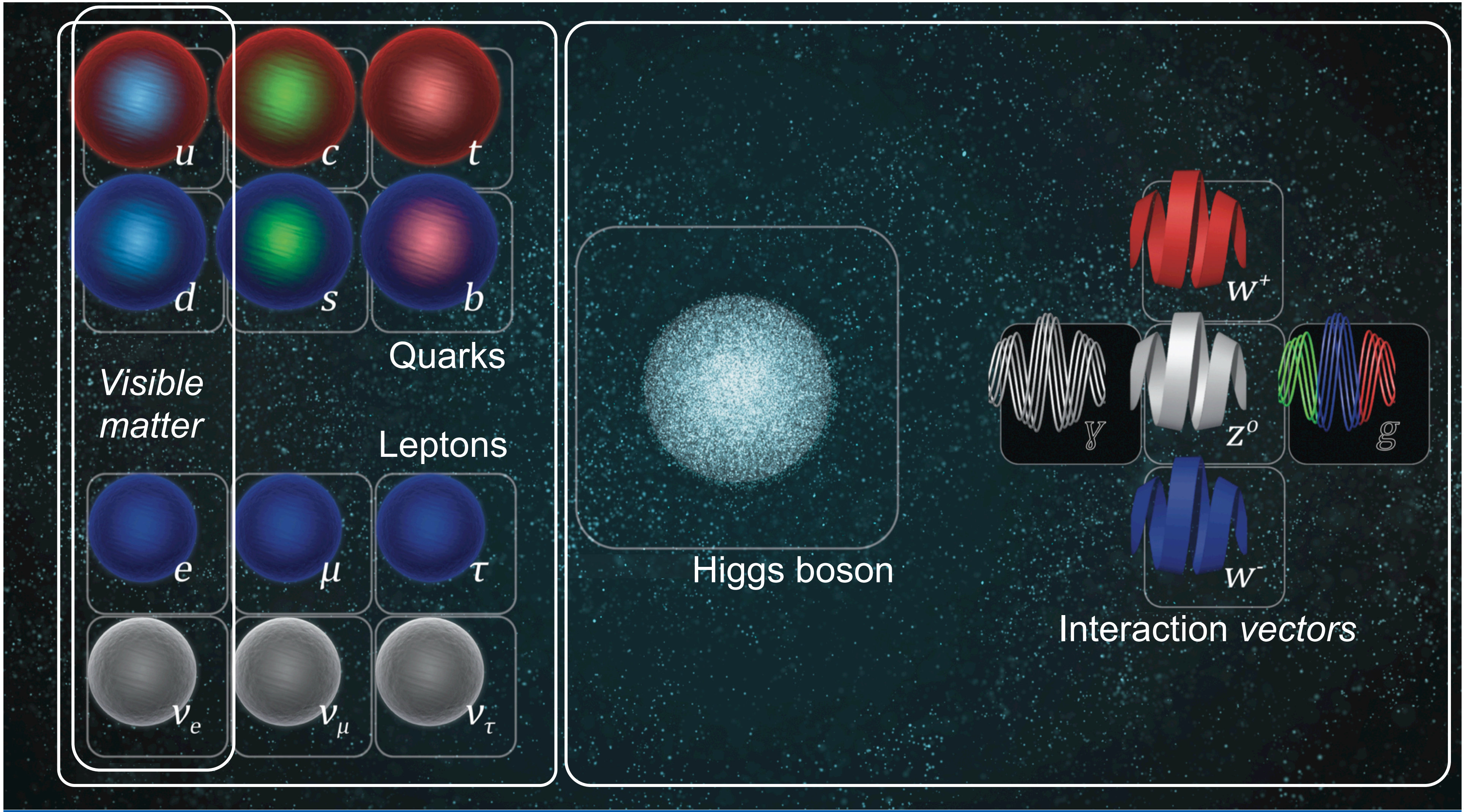
- Where do we stand in HEP ?
- Ingredients of new discovery machines
- Challenges of high magnetic fields
- HL-LHC, the cornerstone
- FCC and its siblings
- Summary and perspective

… and of course many more !



Where do we Stand in HEP ?

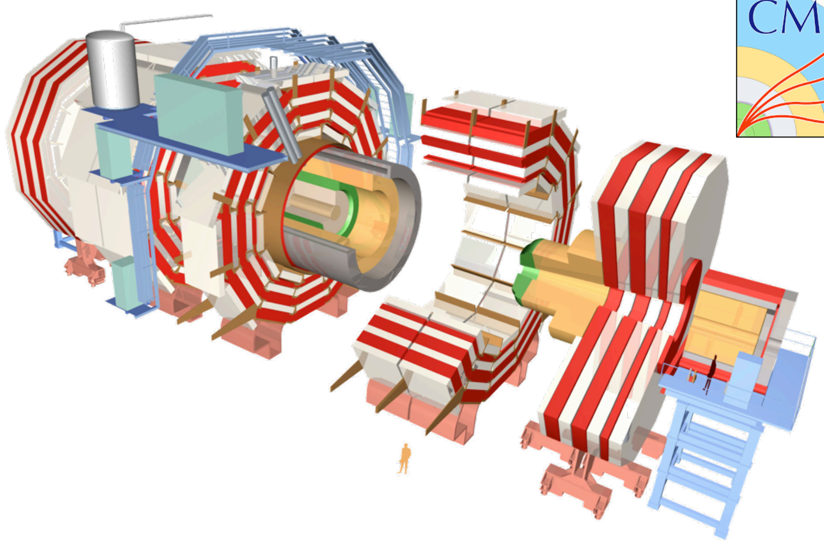
A recipe for all matter (the Standard Model)

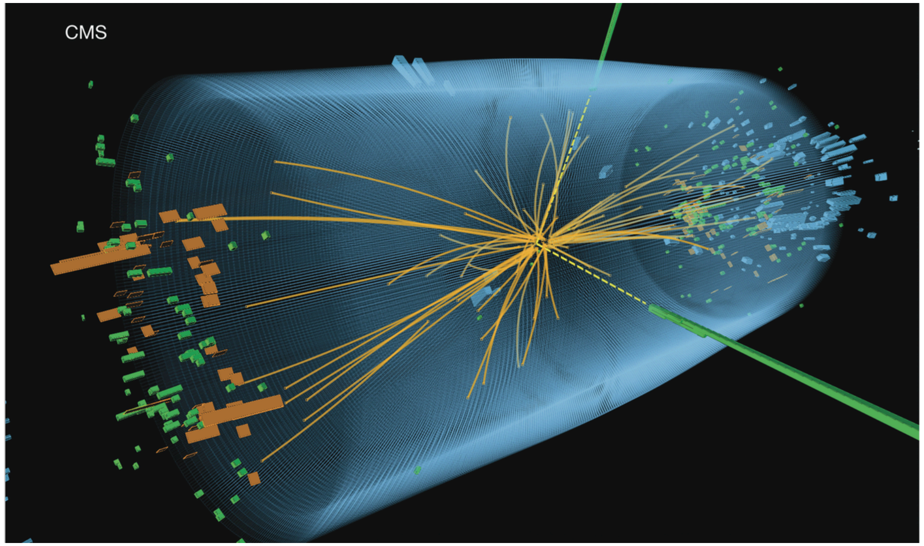


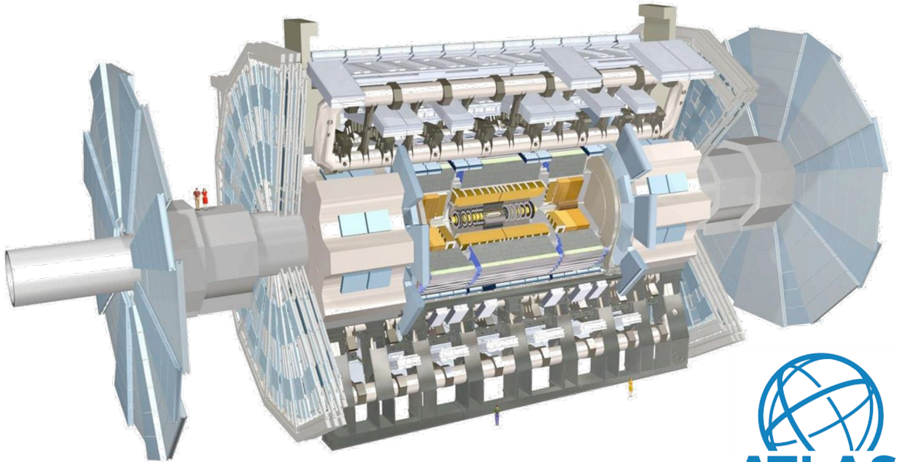
Fermions   Bosons

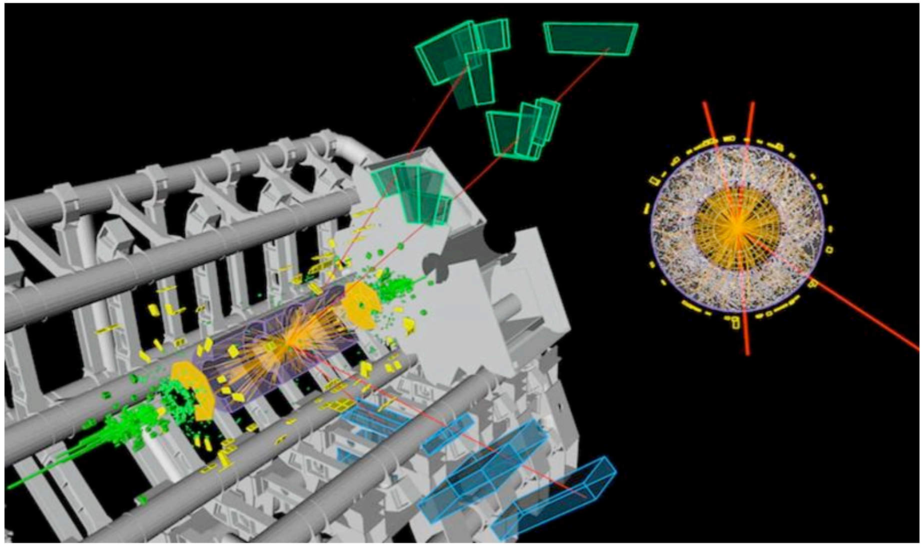
The LHC to produce beams…

… detectors to search for needles…

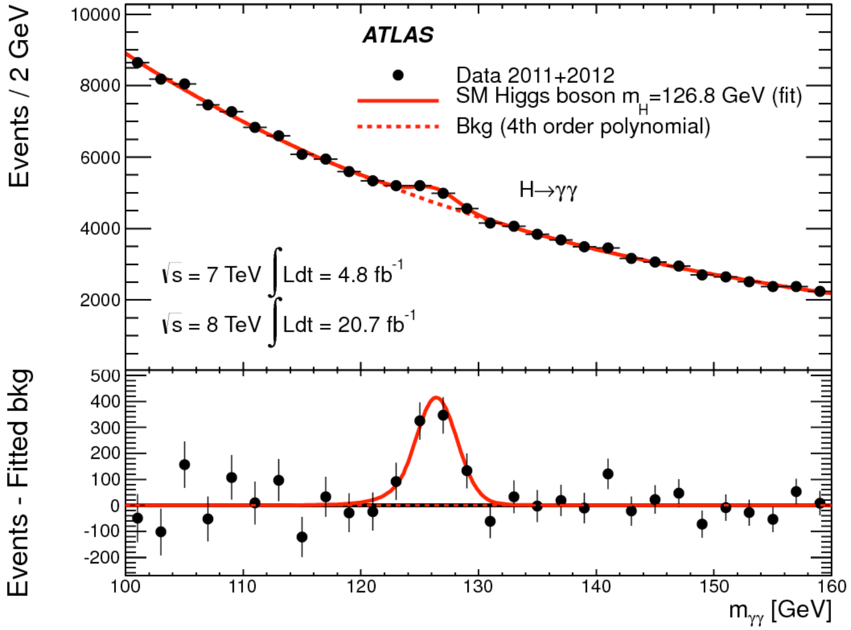


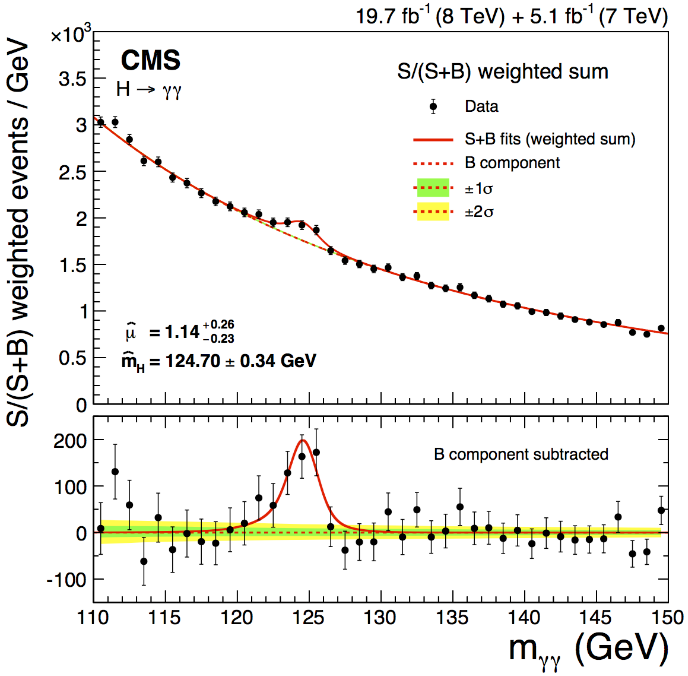




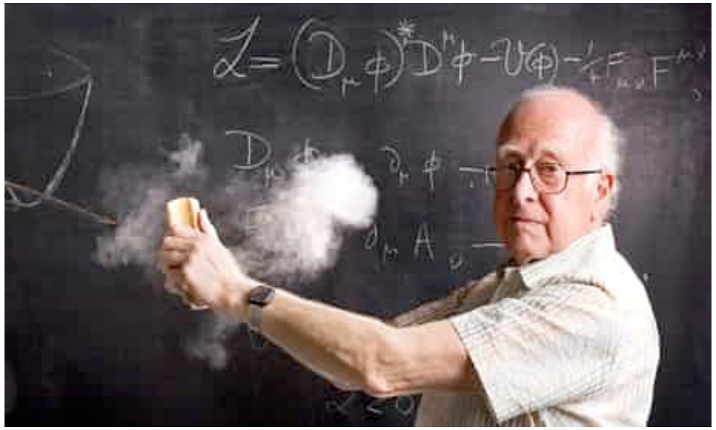


… and finding them





50 years later



R. Brout and F. Englert, PRL 13(9), 321-323, **1964**
P. Higgs, PRL 13(16), 508-509, **1964**
G. Guralnik, C.R. Hagen, T.W.B. Kibble, PRL 13(20), 585-587, **1964**

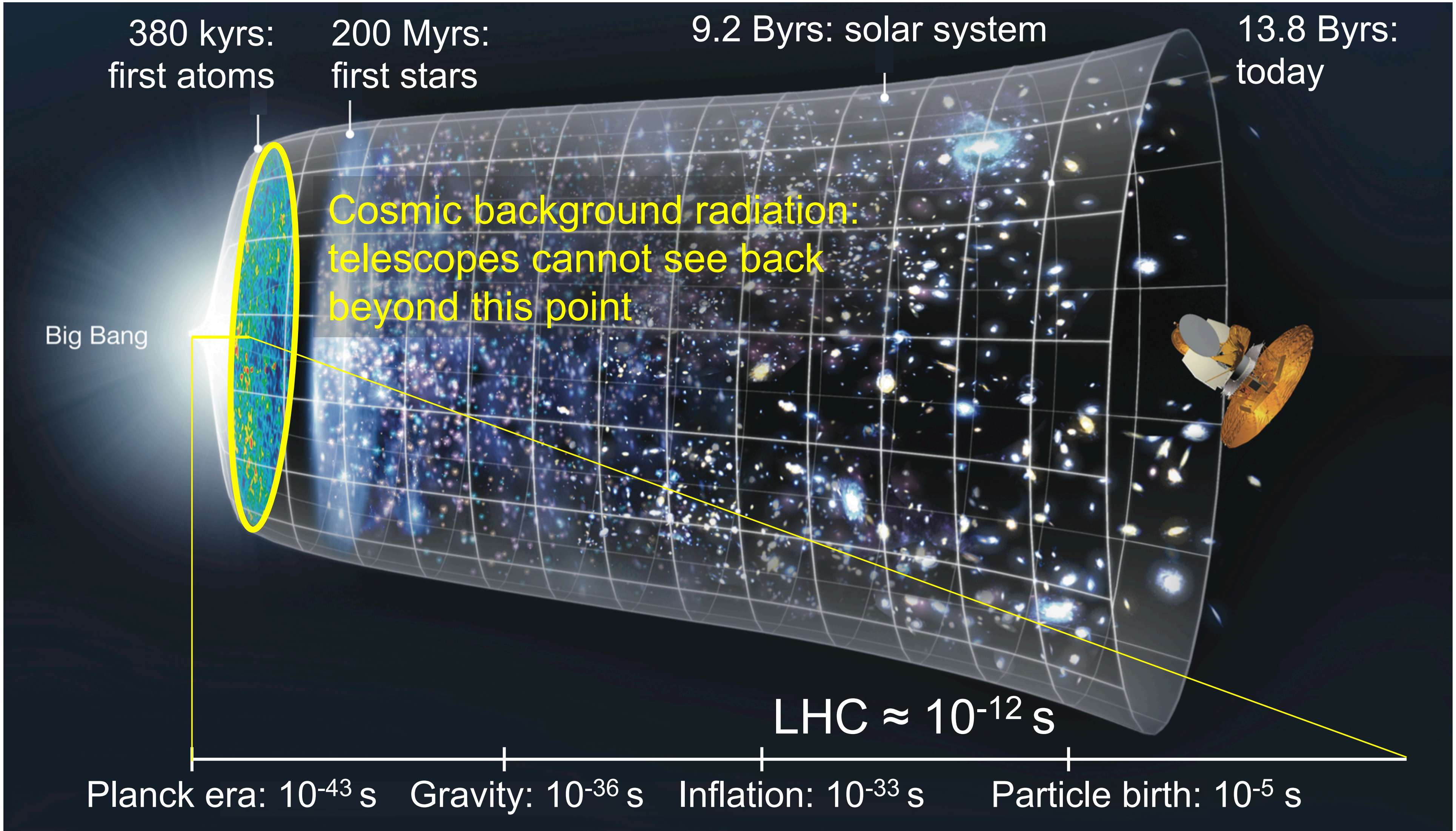
Mysteries – 1/2

The matter we know is only 5 % of the estimated mass of the Universe. Astronomical observations show the universe is dominated by unknown ingredients: dark matter and dark energy. **What are they ?**

The most familiar force in our lives, gravity, does not fit in the Standard Model. **Is there a GUT to combine quantum and relativity theories ?**

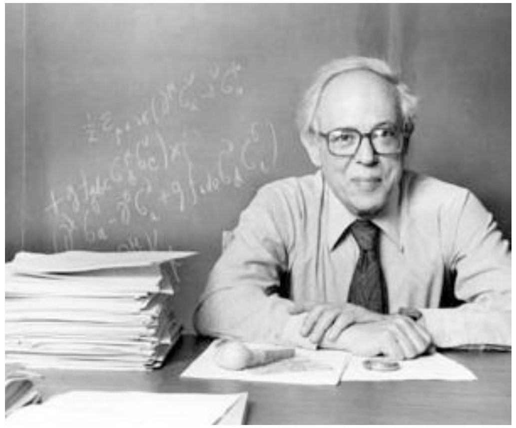
Antimatter should have made up half the early universe, before annihilating with matter to leave just energy. This is manifestly not the case. **Why this asymmetry ?**

Mysteries – 2/2



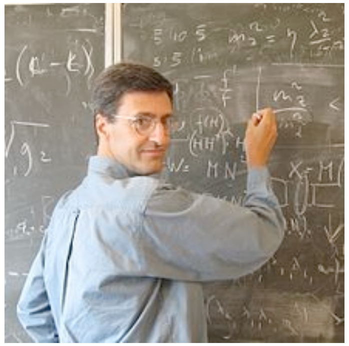
CERN

A state of confusion



"Today we live in the midst of upheaval and crisis. We do not know where we are going, nor even where we ought to be going"

A. Pais, "Physics in Denmark: The First Four Hundred Years" (6 March 1996)



"LHC Run 1 taught us that we live in a metastable state.
I don't refer to the EW vacuum, but to the HEP community.
Confusion is the best moment in science"

G. Giudice, FCC Week 2016, Rome

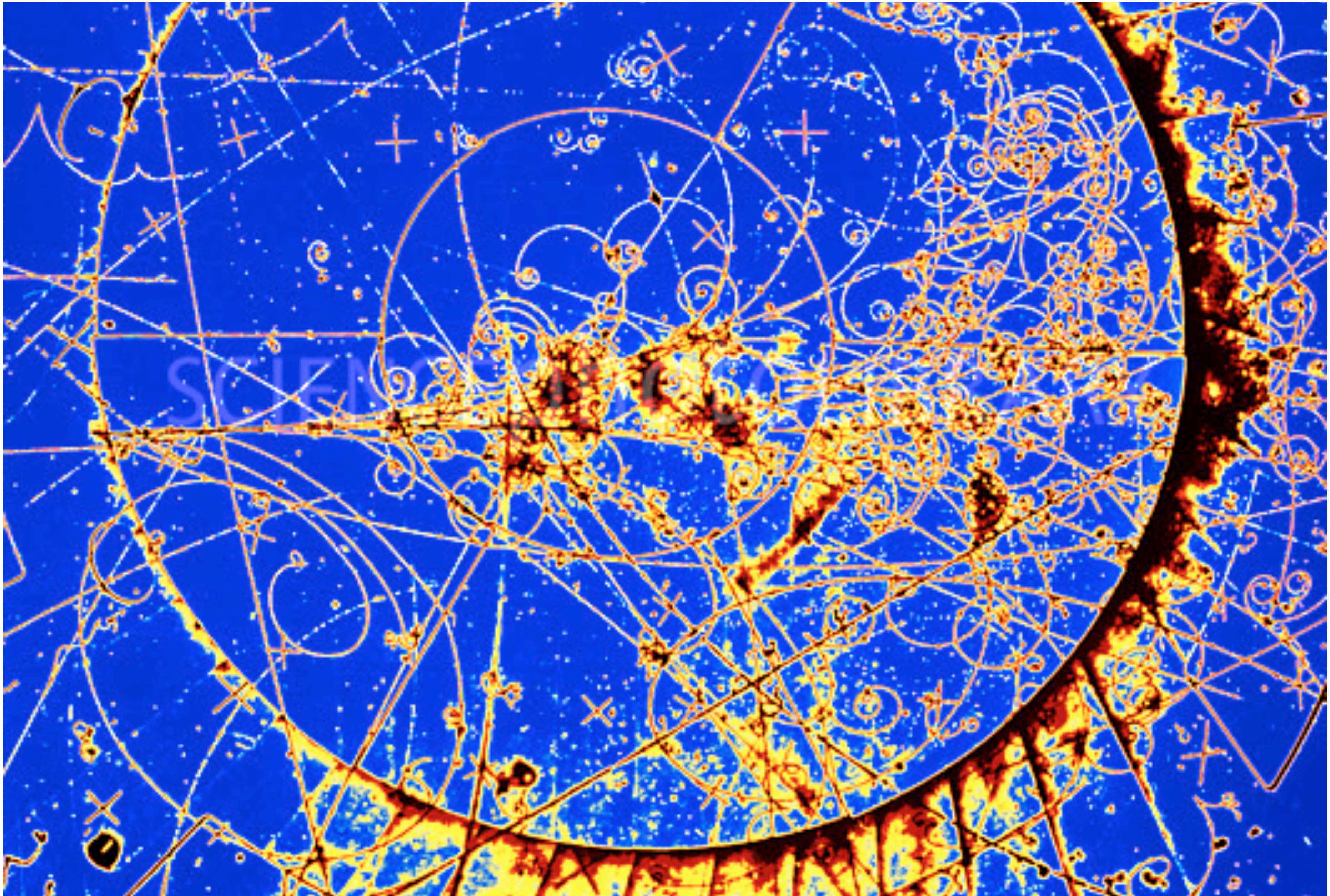
M-theory ?

Supersymmetry ?

Strings ?

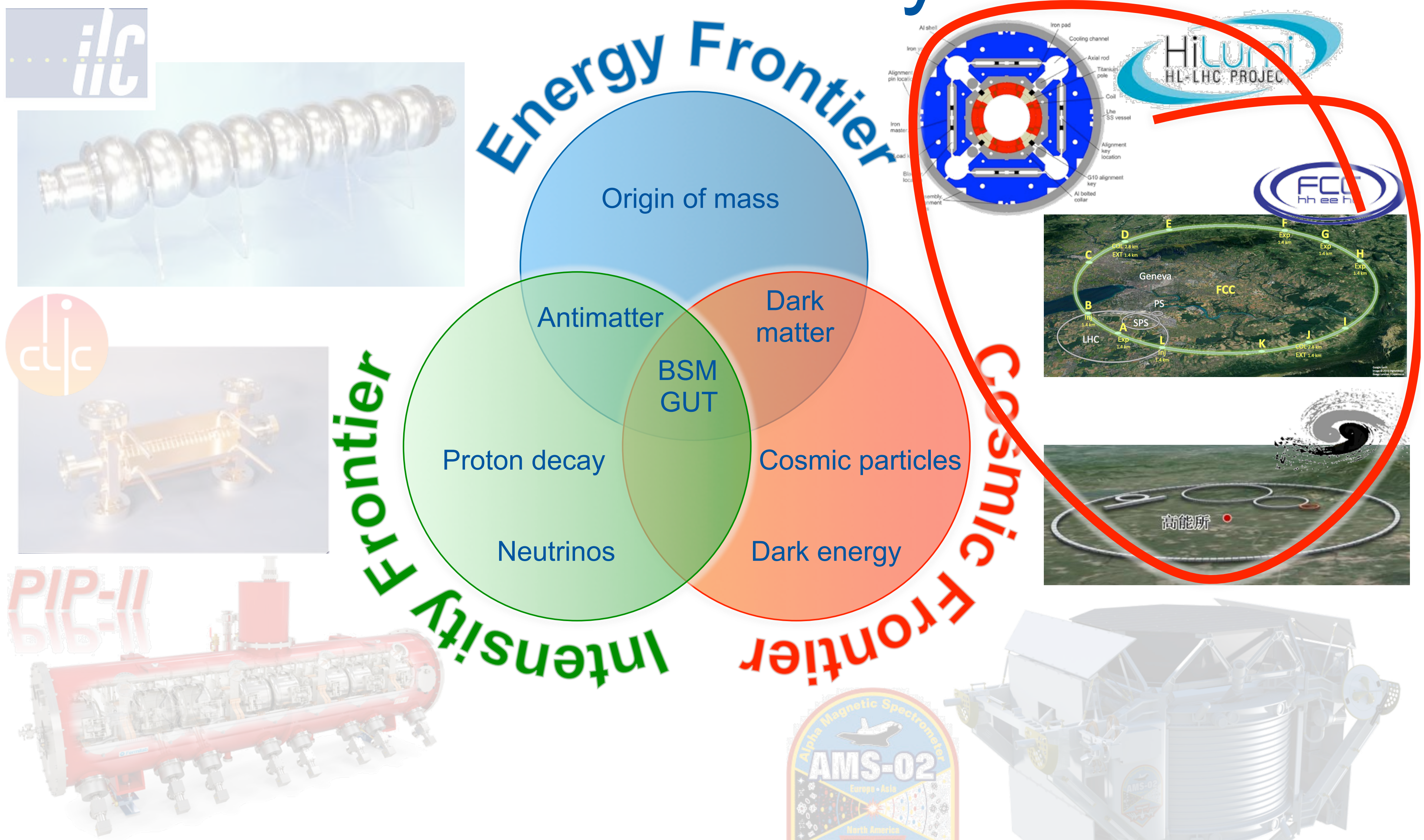
Extra dimensions ?

So, what are we supposed to do ?



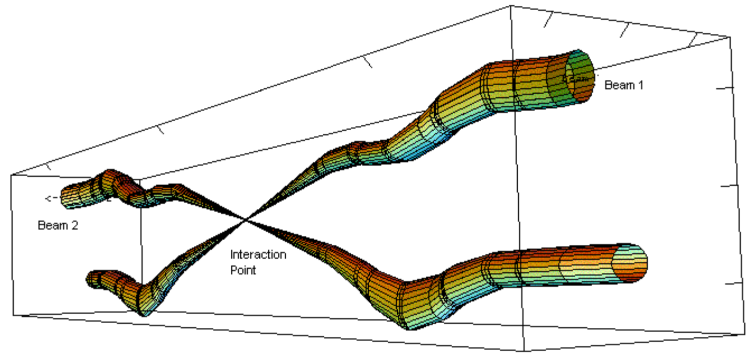
Ingredients of New Discovery Machines

Frontiers of discovery in HEP



Bread and butter of HEP

- More events to increase the statistics of the events (so called **luminosity** at the experiment) ➔ decrease the colliding beam dimension by strong focussing



Relative beam sizes around IP1 (Atlas) in collision

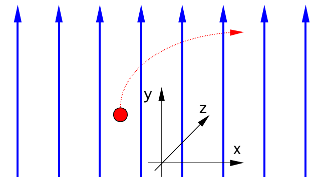
- More collision energy to increase the “physics reach” (generate new particles) ➔ increase the beam **energy**

The need for high fields

- Dipoles:

Beam energy — Bending radius — Dipole field

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



  - Design for the largest feasible and economic B to reduce the accelerator radius

- Final focus quadrupoles

Emittance — Focal length — Beam size at the quadrupole — Lorentz factor

$$\sigma \approx \frac{\varepsilon}{\gamma}\frac{f}{\sigma^*}$$

$$f[m] = \frac{E[GeV]}{0.3\, G\ell_q[T]}$$

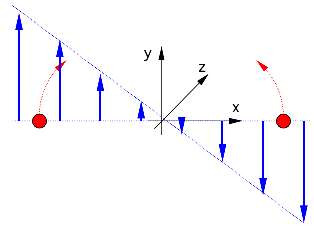
Integrated quadrupole gradient

Peak coil field

$$B \approx \sigma G$$

$$B\ell_q \approx \frac{1}{\sigma^*}$$

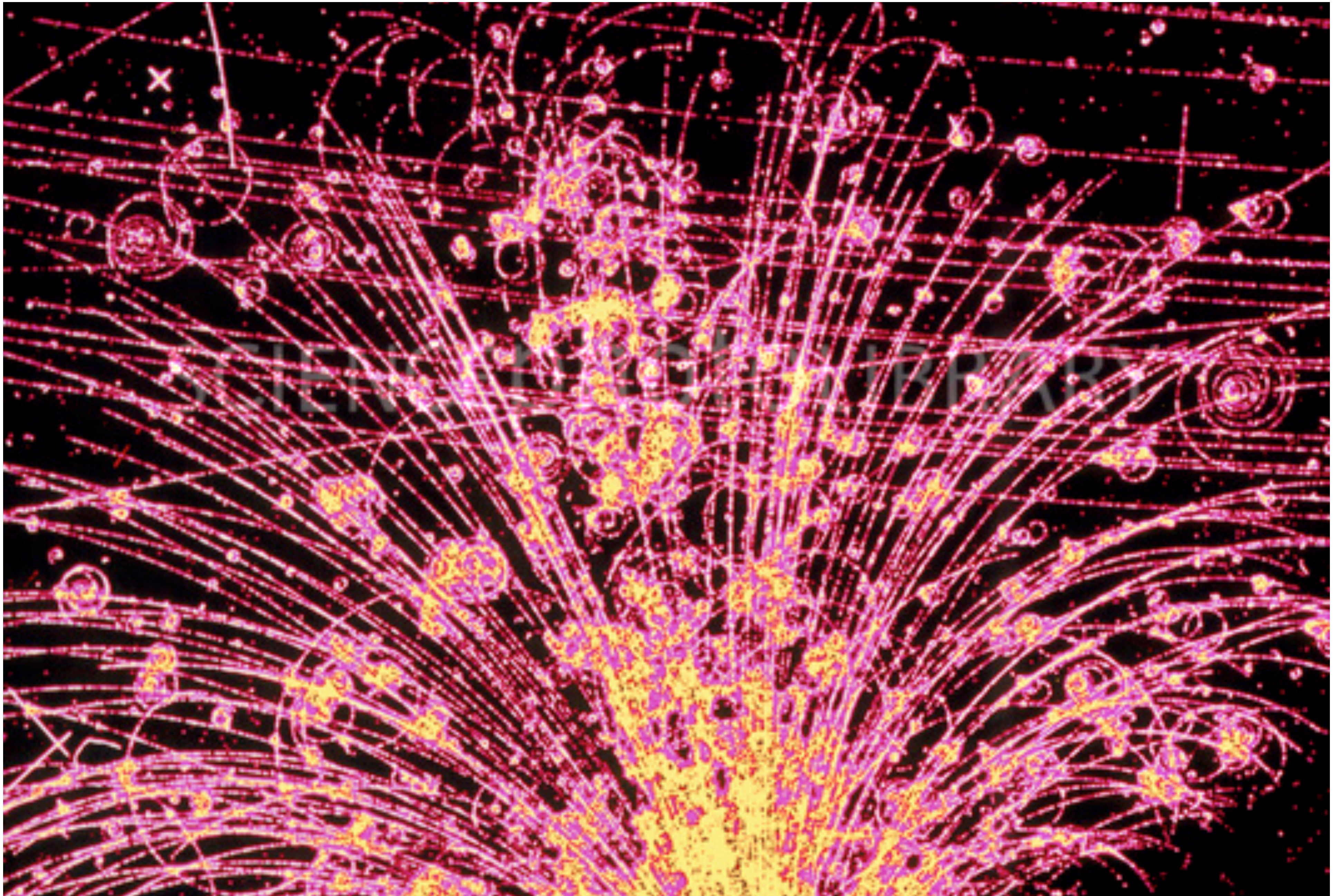
Beam size at the collision point



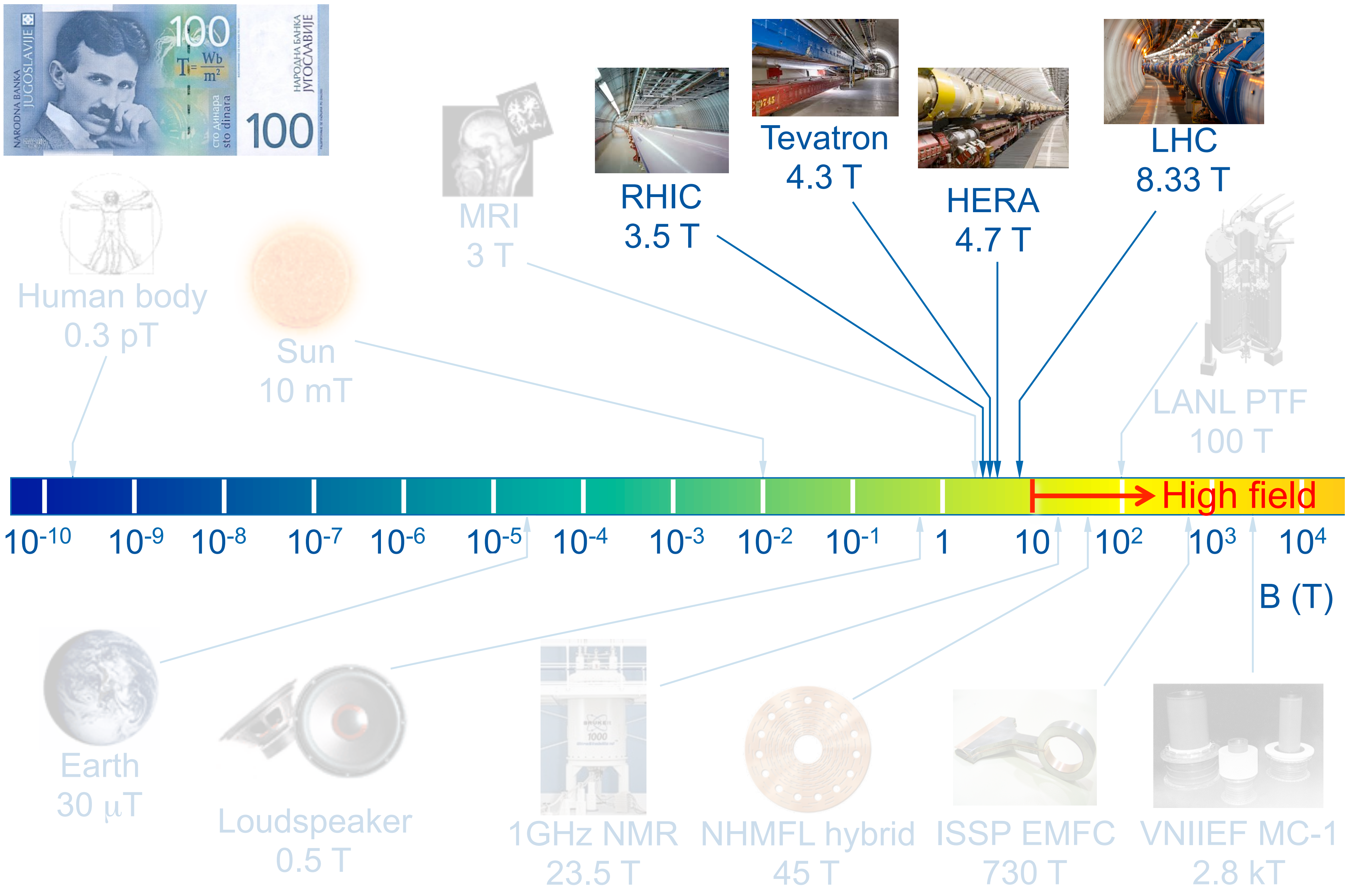
  - Design for the largest feasible and economic integrated field to achieve the smallest beam size at the IP

CERN

High field (SC) accelerator magnets !



Challenges of High Magnetic Fields



Human body
0.3 pT
Sun
10 mT
MRI
3 T
RHIC
3.5 T
Tevatron
4.3 T
HERA
4.7 T
LHC
8.33 T
LANL PTF
100 T
High field
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4
B (T)
Earth
30 μT
Loudspeaker
0.5 T
1GHz NMR
23.5 T
NHMFL hybrid
45 T
ISSP EMFC
730 T
VNIIEF MC-1
2.8 kT

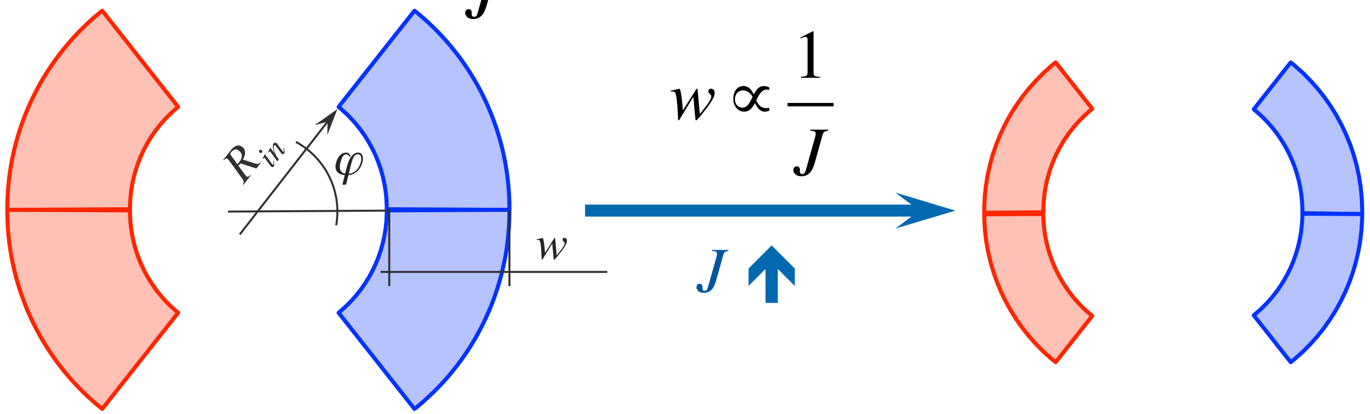
J_C ! J_C ! J_C ! (A. McInturff)

Dipole field generated by a current distribution with constant current density J over a sector of inner radius R_{in}, outer radius R_{out}, coil width $w = R_{out}-R_{in}$ and opening angle φ

$$B = \frac{2\mu_0}{\pi} J\, w \sin(\varphi)$$

$$A_{coil} = 2\varphi\left(w^2 + 2R_{in}w\right) \propto \frac{1}{J^n} \qquad n \approx 1 \ldots 2$$

In the range of typical magnet designs considered $n \approx 1.5$

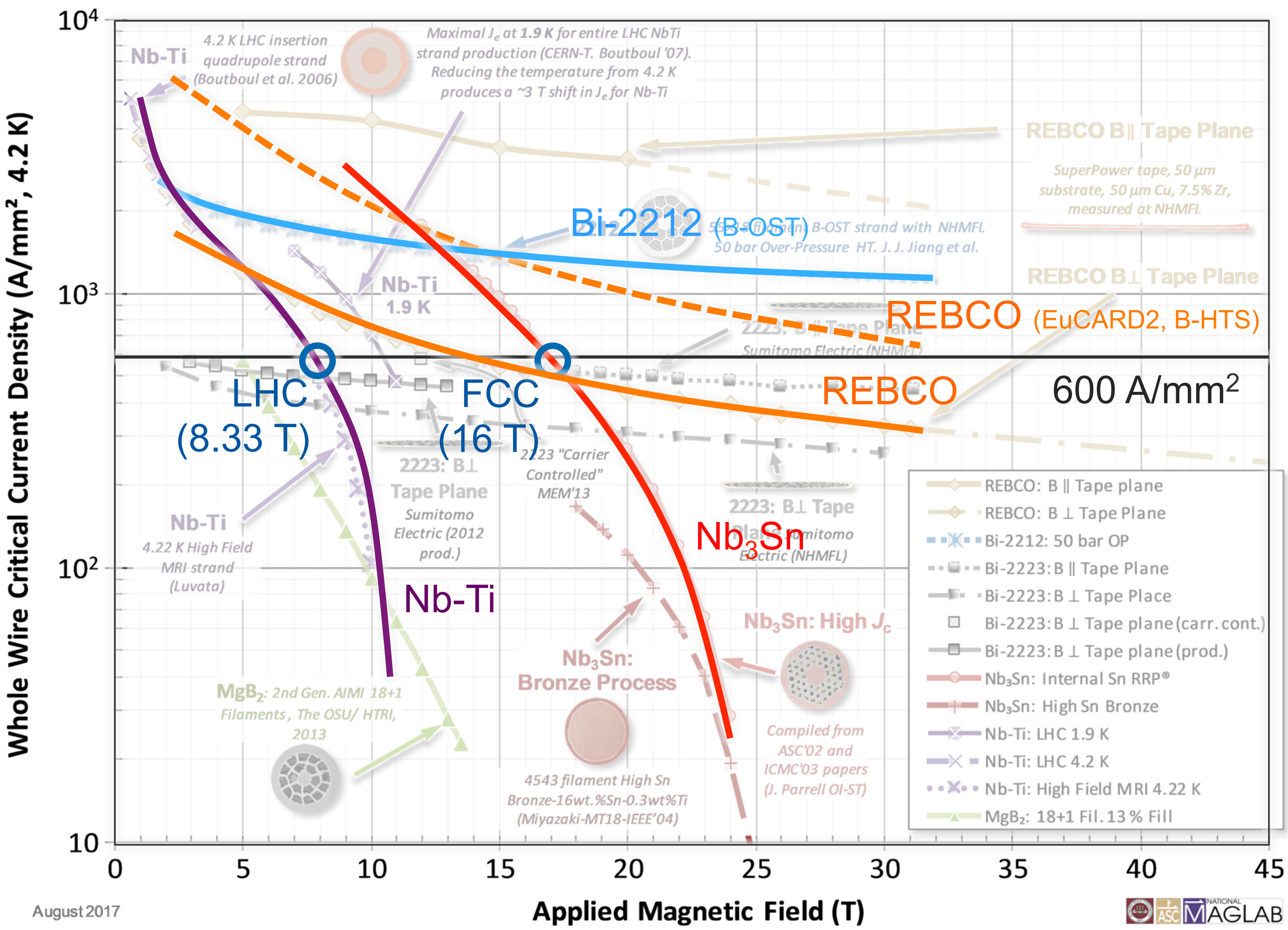


B	(T)	16	16
J	(A/mm²)	300	600
w	(mm)	76	38
A_{coil}	(mm²)	20,000	7000

$$A_{coil} \propto M_{coil} \propto COST$$

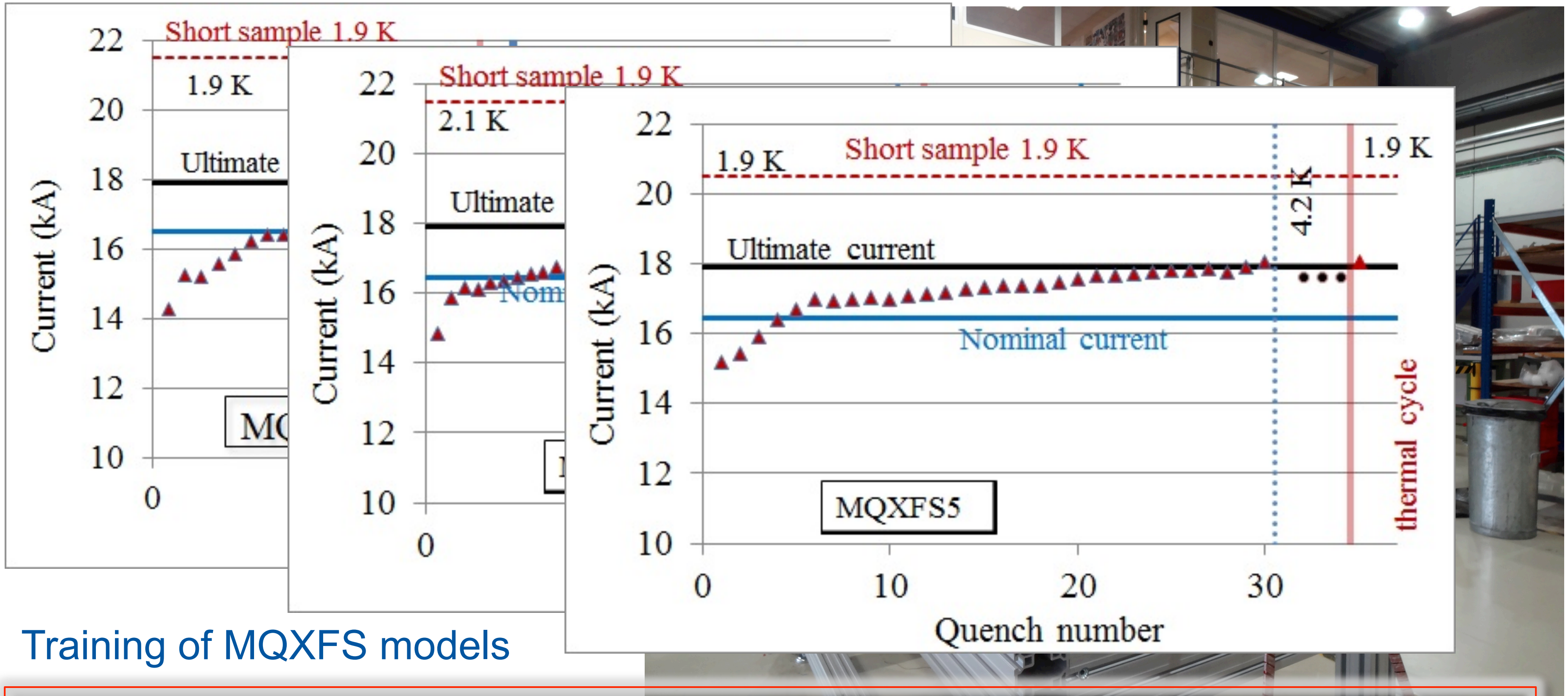
Factor 2 (J: 300 → 600)

Factor 3 (A_{coil}: 20,000 → 7000)



Courtesy of P. Lee, with stimulating inputs from D. Larbalestier and D. Abraimov

Efficient use of J_C



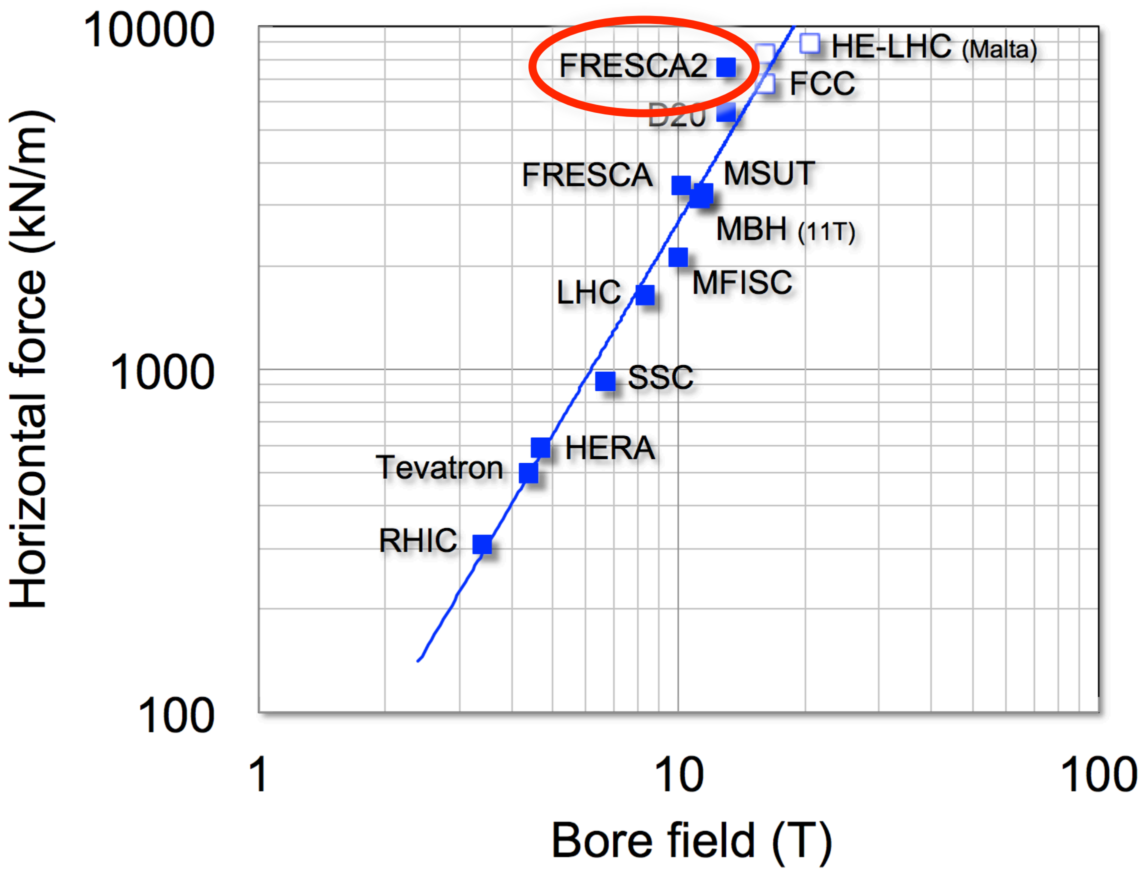
Training of MQXFS models

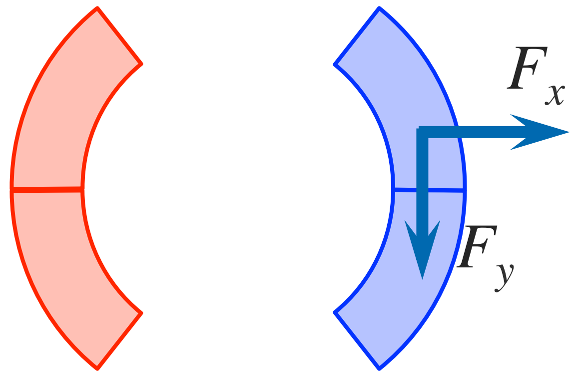
- The grand challenge for high field magnets:
  - Abolish training !
  - Increase J_{op}/J_C (presently at ≈ 40 % for Nb_3Sn at 1.9 K)

Mechanics at high fields

Lorentz forces in the plane of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation), referred to a coil quarter

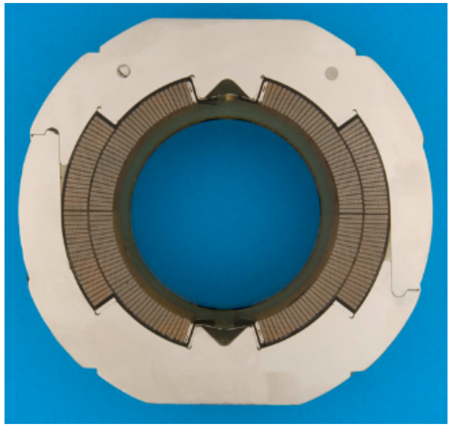
$$F_x = -F_y \approx \frac{4}{3}\frac{B^2}{2\mu_0}R_{in}$$

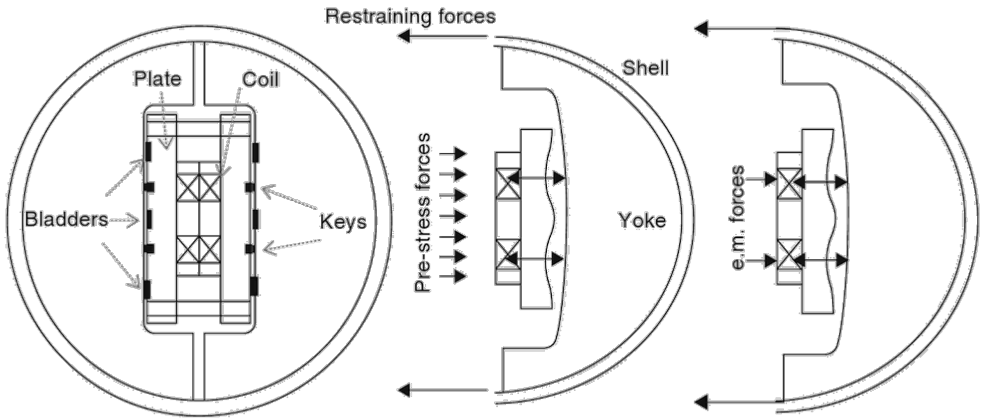




Progression of F_x:
LHC MB(8.33T) ≈ 1.7 MN/m
LHC MBH(11T) ≈ 3.2 MN/m
FRESCA2(13T) ≈ 7.6 MN/m
FCC MB(16T) ≈ 8 MN/m
HE-LHC MB(20T) ≈ 10 MN/m

Old structures, new structures



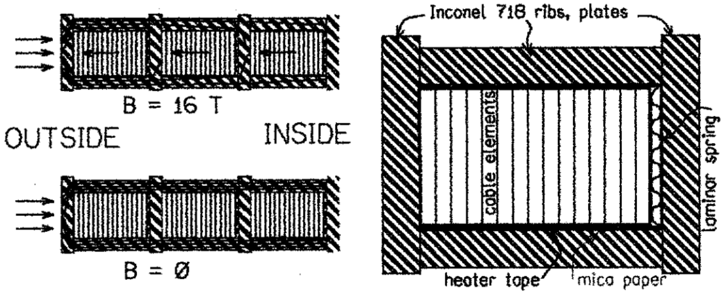


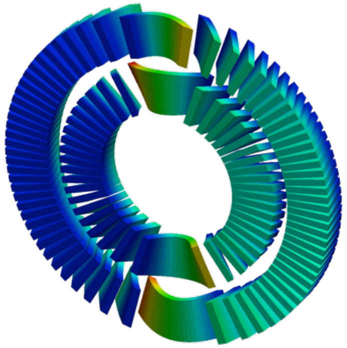
2002, LBNL: Bladder and keys
R.R. Hafalia, et al., IEEE TAS, 12(1) (2002), pp. 47-50.

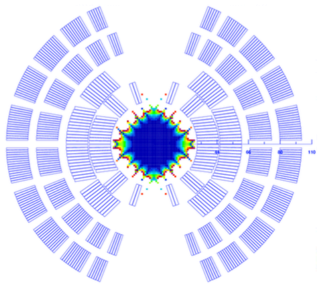
mid 1970’s, FNAL: Collared coils
A. Tollestrup, Proc. Int Conf. on the History of Original Ideas and Basic Discoveries in Particle Physics, Erice (1994).

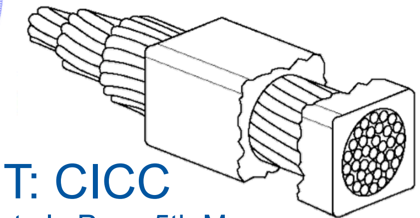
2014, LBNL: CCT
S. Caspi, et al., IEEE TAS (2014), p. 4001804.

2017, FNAL: SM cos(θ)
V. Kashikin, et al., Proc. IPAC, Copenhagen (2017), pp. 3597-3599.







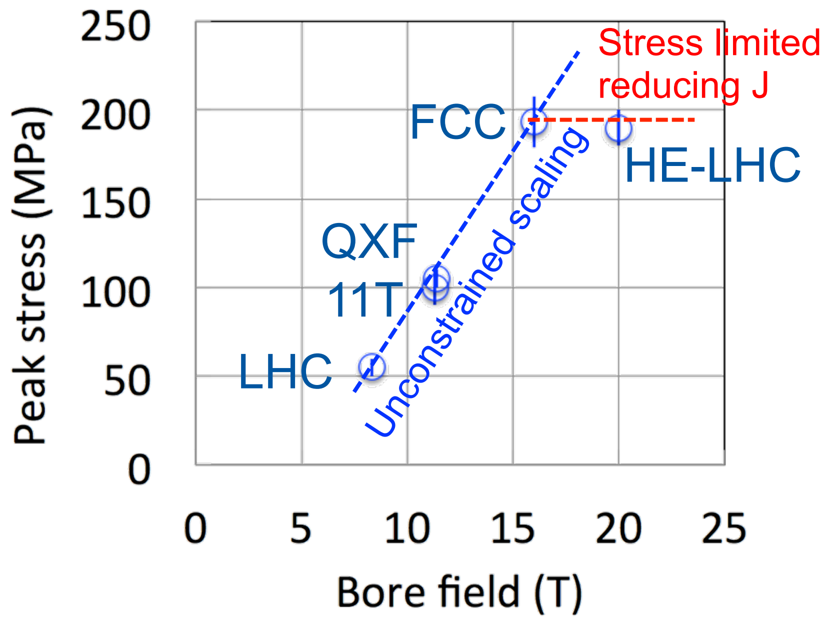


1975, MIT: CICC
M.O. Hoenig, et al., Proc. 5th Magn. Tech. Conf., Frascati(1975), p. 519.

1998, TAMU: Stress management
N. Diaczenko, et al., Proc. PAC, Vancouver (1997), pp.3443-3345.

Stress in high field magnets

$$\left.\begin{array}{l} F \propto B^2 \\ w \propto \dfrac{B}{J} \end{array}\right\} \longrightarrow \sigma \approx \frac{F}{w} \propto JB$$



- The challenge of mechanics:
  - Devise an appropriate support concepts for the coil (bladder-and-key, stress management, canted-cosinus-theta, …)
  - Cope with increasing stress on the conductor
  - Limit mechanical energy release (training)

CERN

Protection at high fields

$$E/l = \frac{\pi B^2 R_{in}^2}{\mu_0}\left[1 + \frac{2}{3}\frac{w}{R_{in}} + \frac{1}{6}\left(\frac{w}{R_{in}}\right)^2\right]$$

Energy per unit length in a sector coil of inner radius R_{in}, outer radius R_{out}, coil width $w = R_{out}-R_{in}$ producing a dipole field B

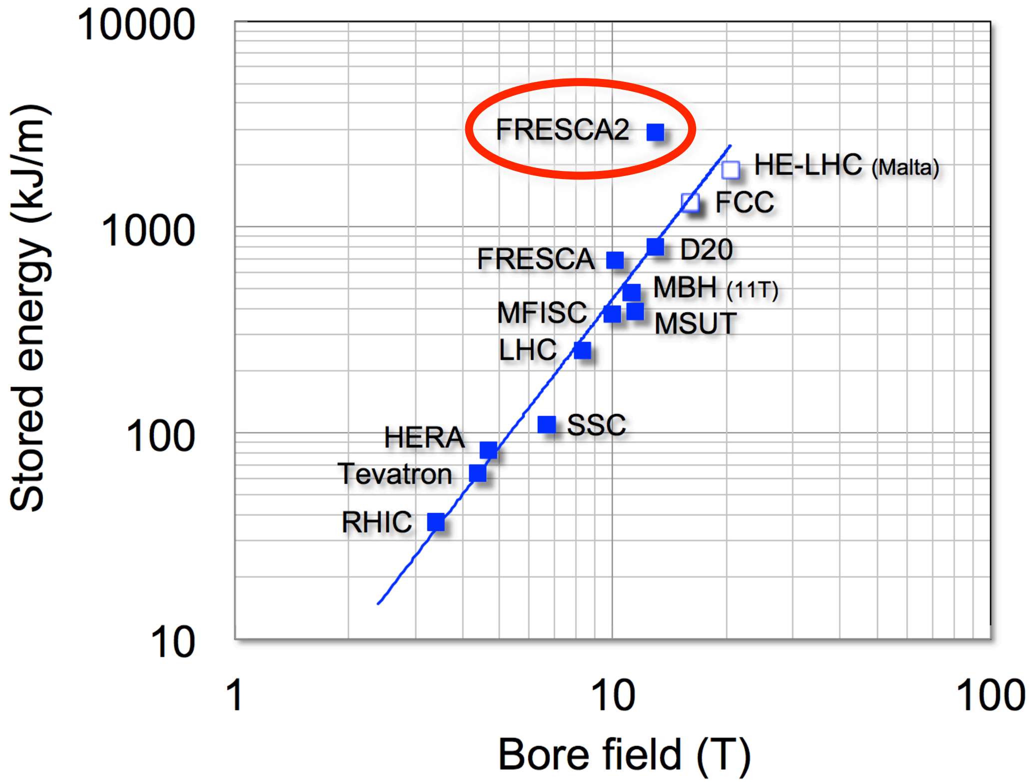
$$V/l \approx \frac{2E/l}{\tau\, I_{op}}$$

Voltage per unit length for an external dump with time constant τ

A simple exercise:

$J_{Cu} \approx$ 1000…1250 (A/mm²)
$dT/dt \approx$ 1000…2000 (K/s)
$\tau_{(300\ K)} \approx$ 0.15…0.3 (s)

$I_{op} \approx$ 15 (kA)
$E/l \approx$ 1000 (kJ/m)
$V/l \approx$ 500…1000 (V/m)



<u>It is not possible</u> to protect accelerator magnet strings using an external dump

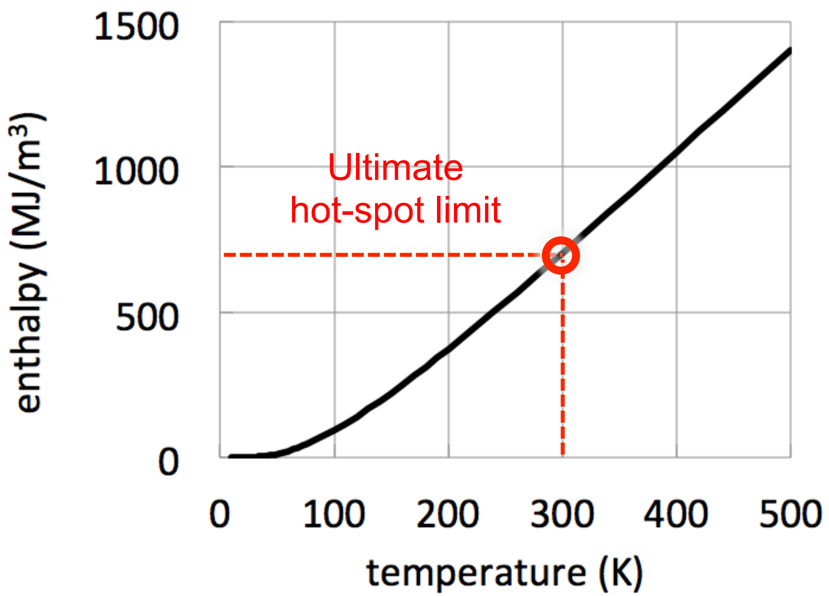
Ultimate protection limit

$$E/l \propto B^2$$

$$A_{coil} \propto \left(\frac{B}{J}\right)^n$$

In the range of typical magnet designs considered $n \approx 1.5$

$$e \approx \frac{E/l}{A_{coil}} \propto J^n B^{2-n}$$



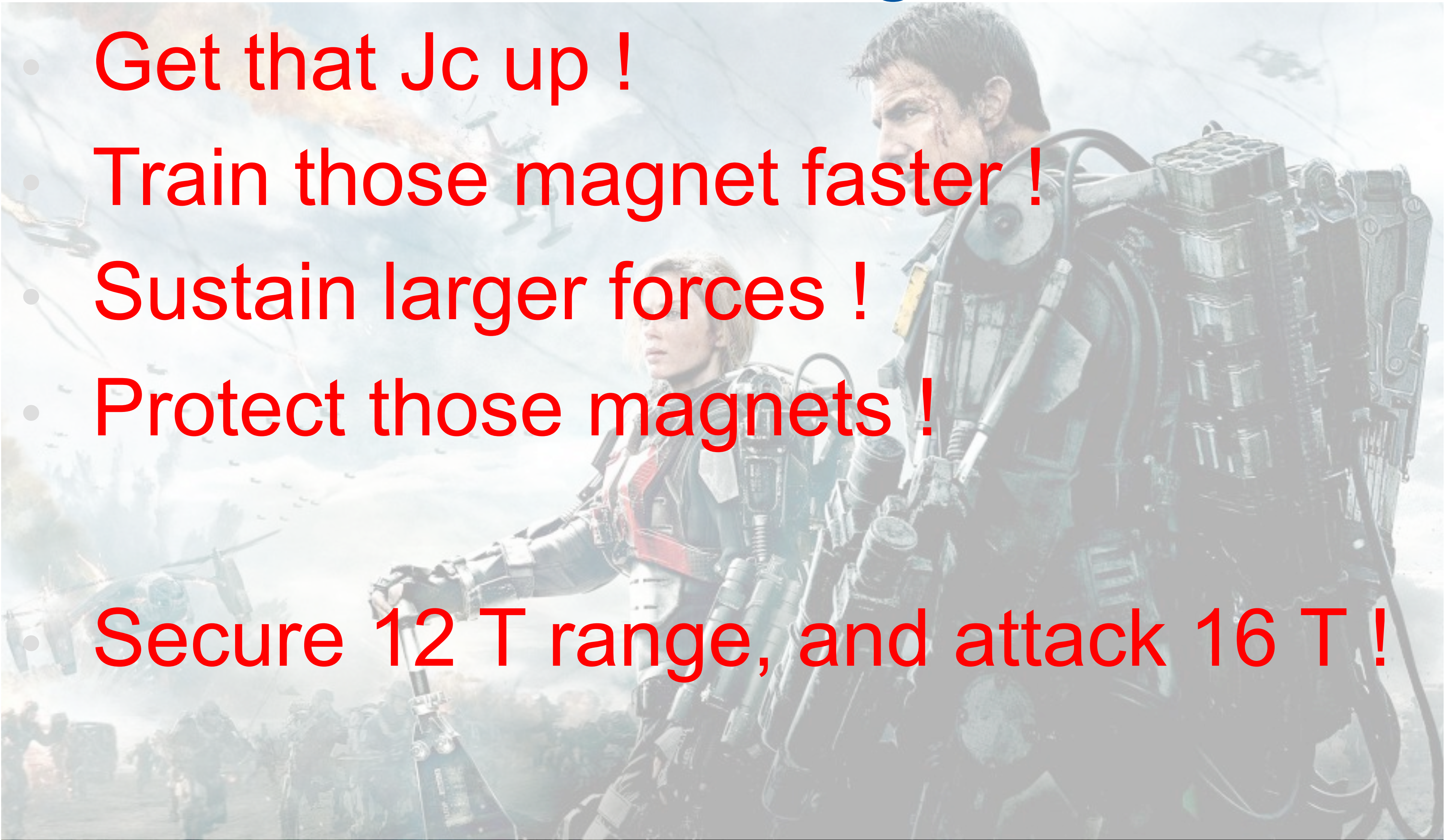
Typical energy densities e:
LHC MB(8.33T) ≈ 50 MJ/m³
LHC MBH(11T) ≈ 85 MJ/m³
FRESCA2(13T) ≈ 100 MJ/m³

- The challenge of protection:
  - Fast detection and internal dump (spread the energy)
  - Material and coil limits (hot-spot, thermal stress, voltage)

The Battle of the High Fields

- Get that Jc up !
- Train those magnet faster !
- Sustain larger forces !
- Protect those magnets !

- Secure 12 T range, and attack 16 T !

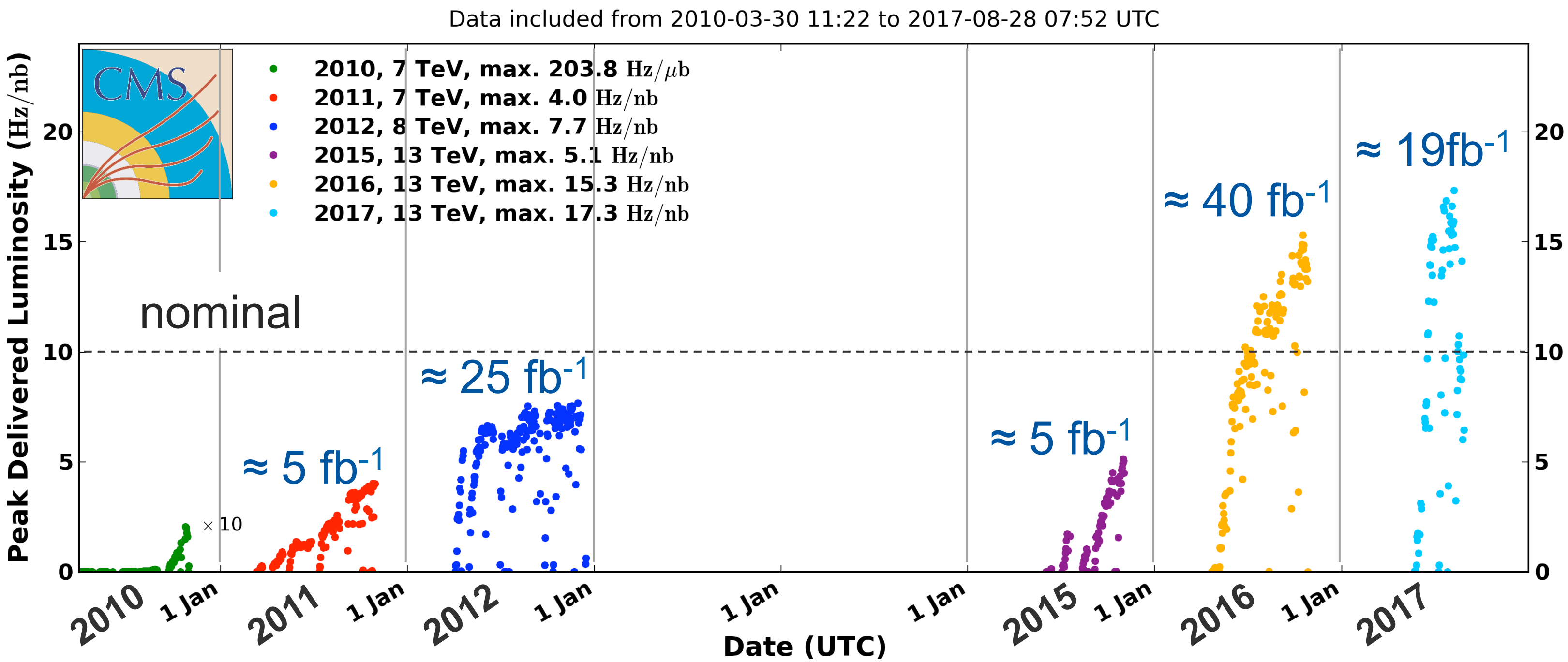


Edge of Tomorrow, Warner Bros., 2014

HL-LHC, the Cornerstone

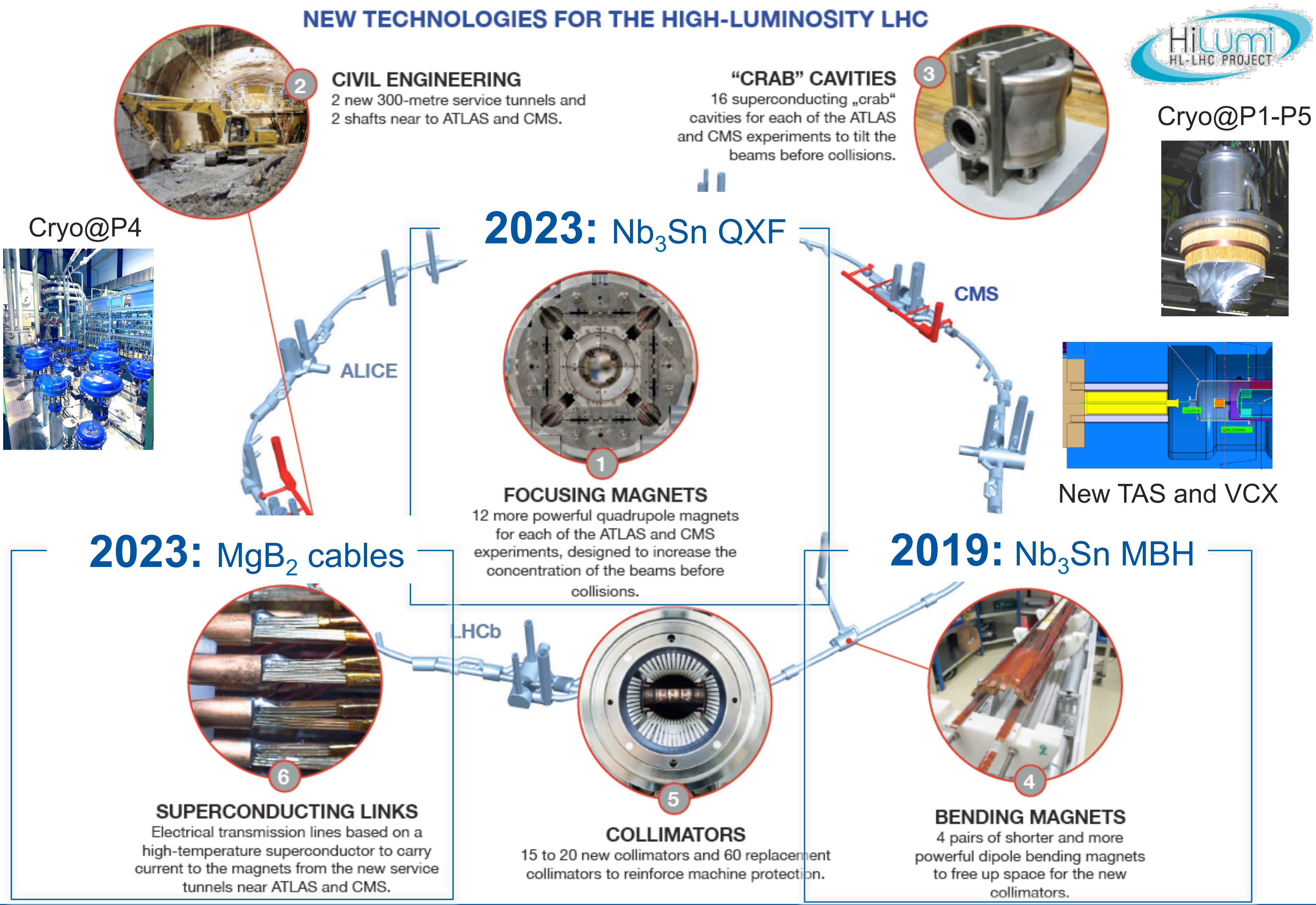
HL-LHC objectives

c.o.m. energy = 13 TeV
L_{max} = 1.73 x 10^{34} $1/cm^2$ s



- HL-LHC:
  - A peak luminosity of 5 × 10^{34} $1/cm^2$ s with *leveling*
  - An integrated luminosity of 250 fb^{-1} per year, with a goal of 3000 fb^{-1} by the end of the LHC lifetime

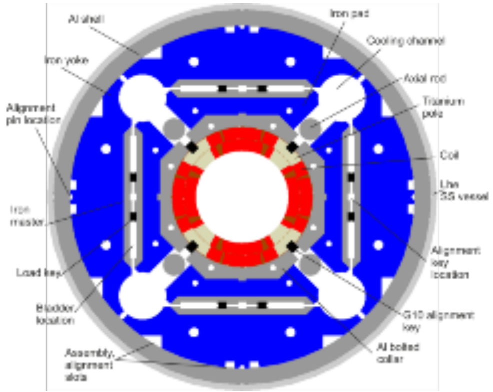
CERN



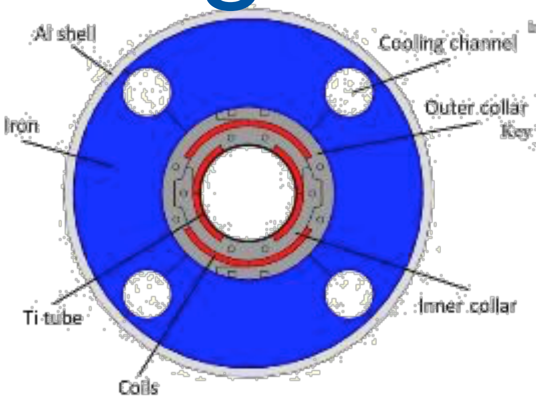
CERN

Courtesy of L. Rossi, HL-LHC

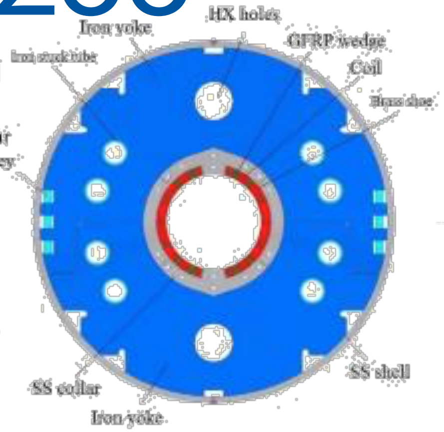
HL-LHC magnet “zoo”



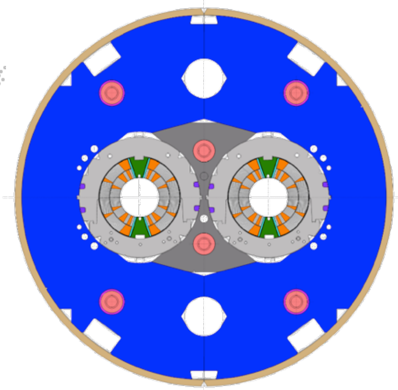
Triplet QXF (LARP and CERN)

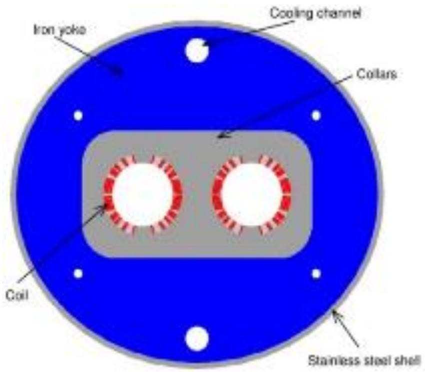


Orbit corrector (CIEMAT)

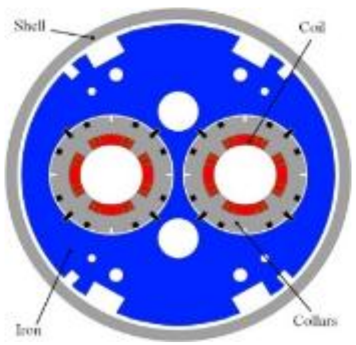


Separation dipole D1 (KEK)

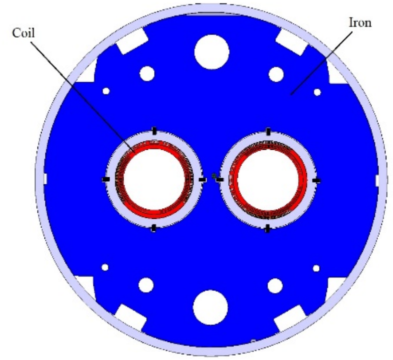

11 T dipole (CERN)



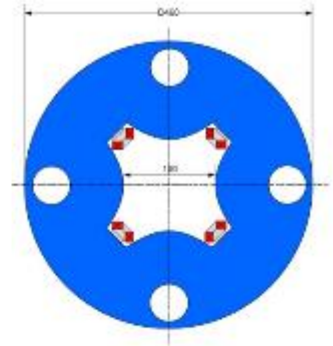
Recombination dipole D2 (INFN)



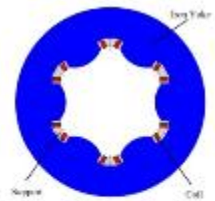
Q4 (CEA)

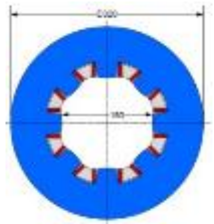


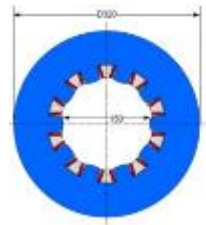
D2/Q4 orbit corrector (CERN)

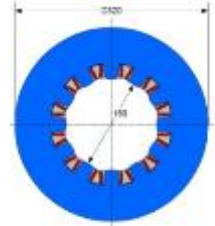

Skew quadrupole (INFN)

Approximately 150 single magnets and 50 cold masses for HL-LHC

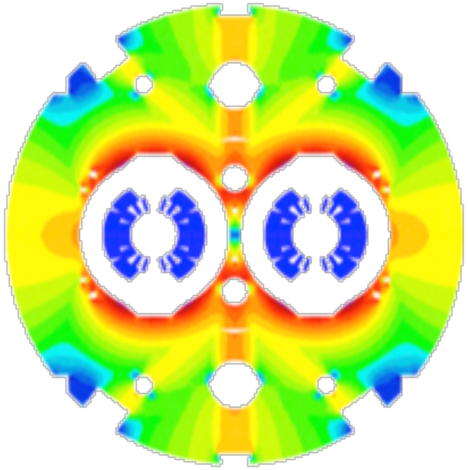

Sextupole (INFN)

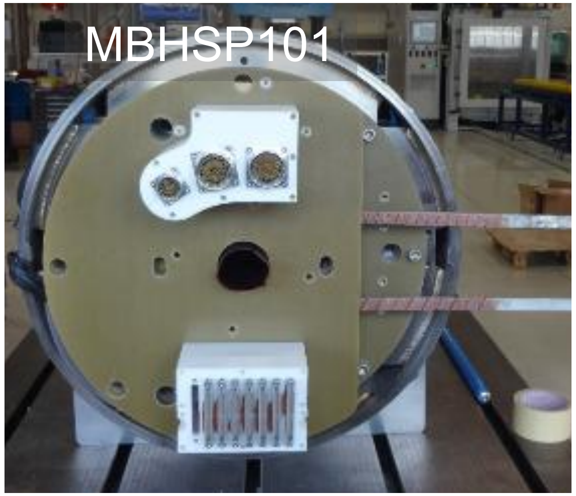

Octupole (INFN)

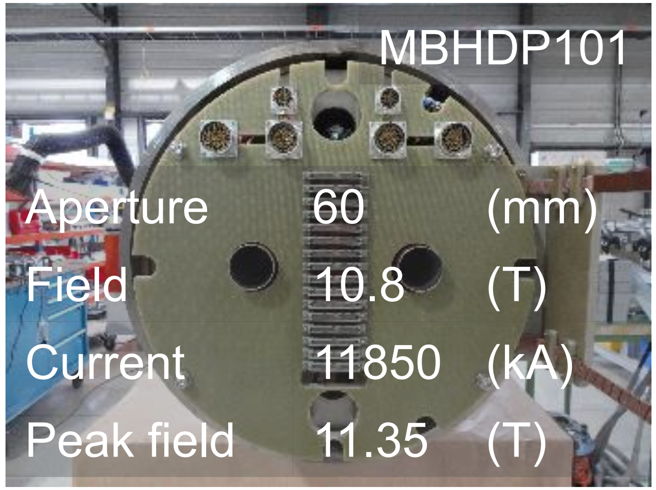

Decapole (INFN)

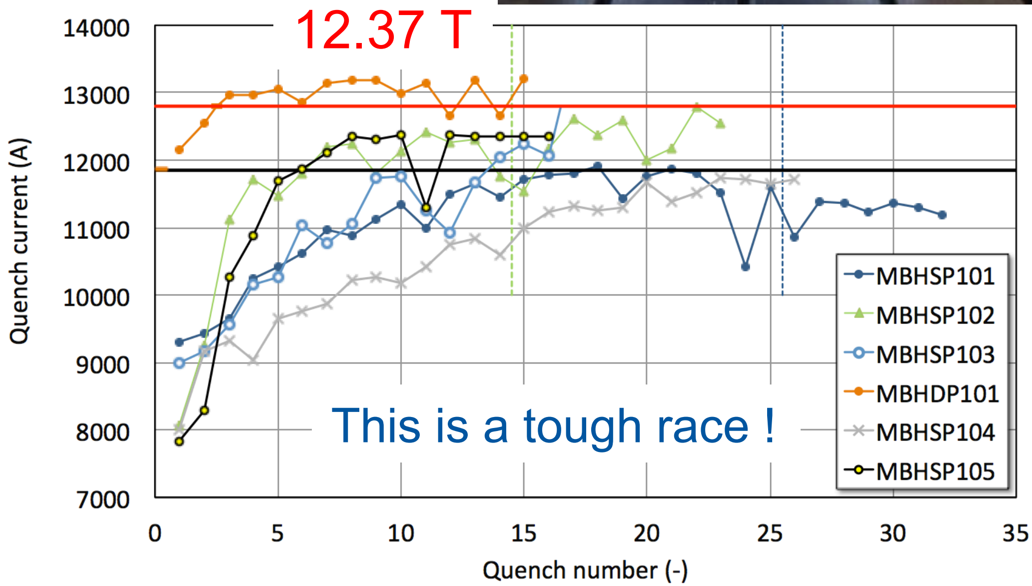

Dodecapole (INFN)

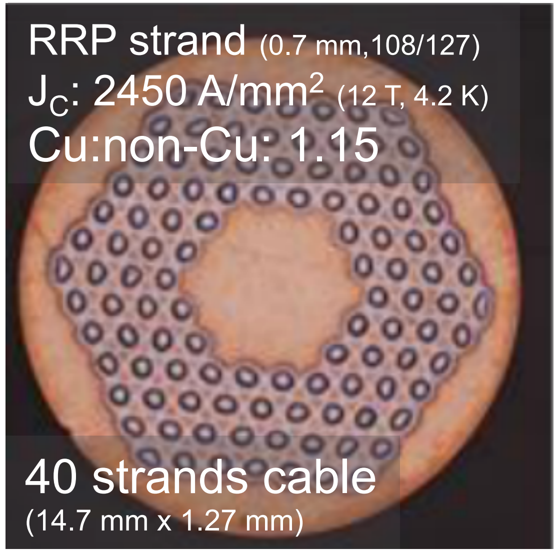
MBH (11T) dipole





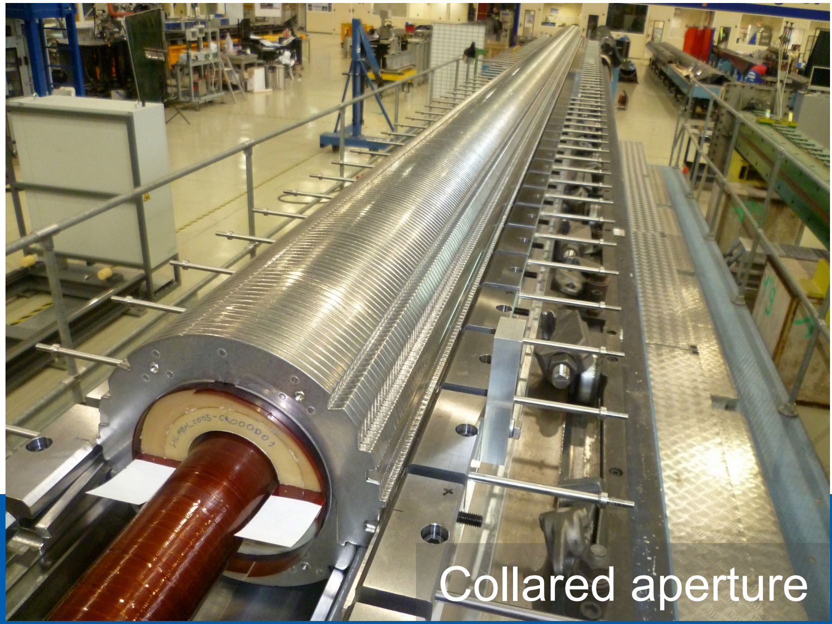




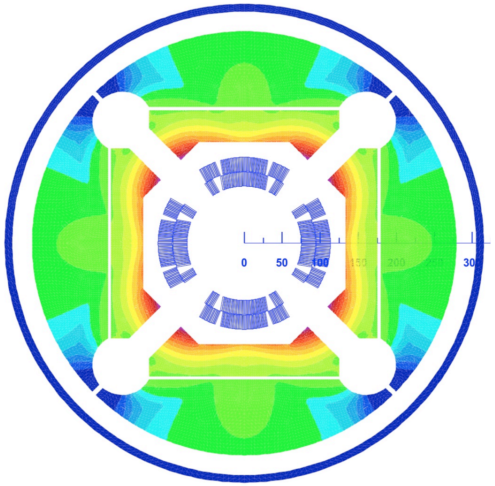


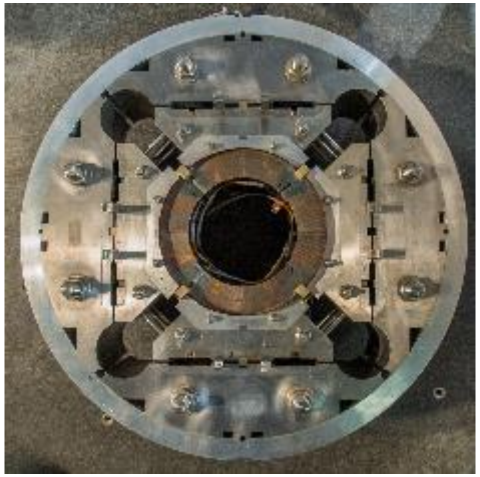
Courtesy of F. Savary, J. C. Perez, G. Willering, CERN

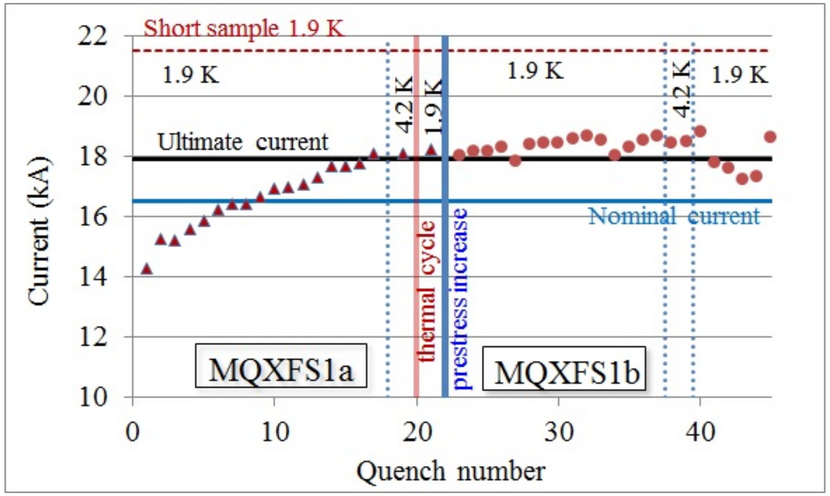
11T production

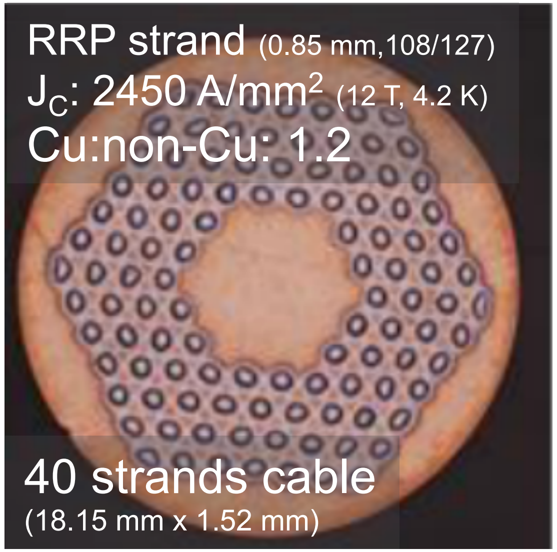


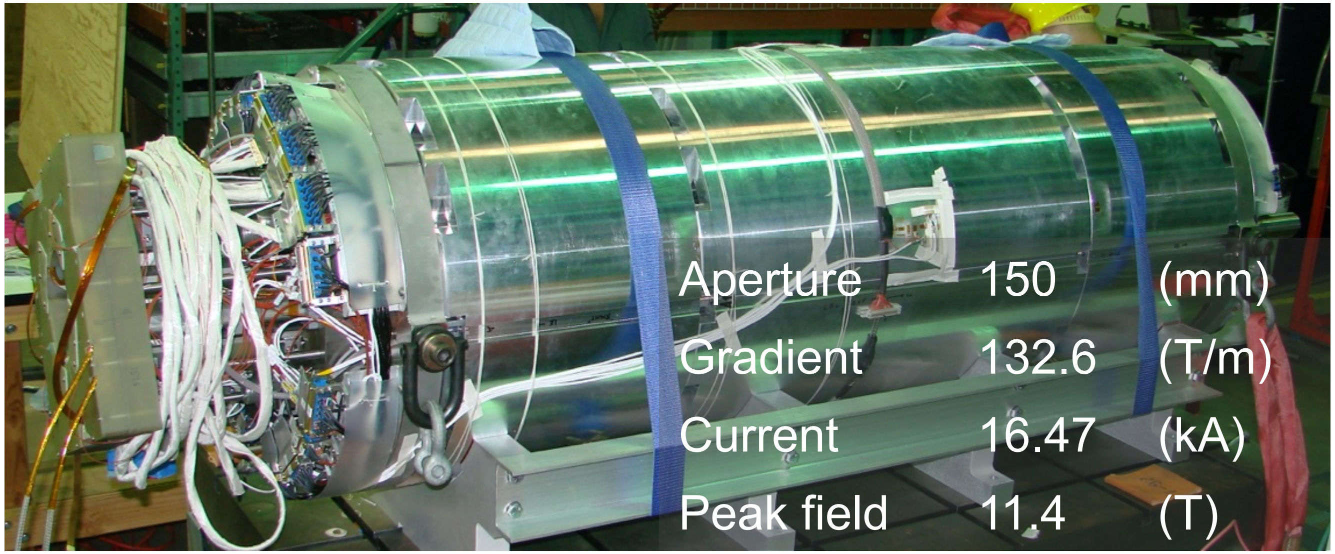
MQXFS1 results





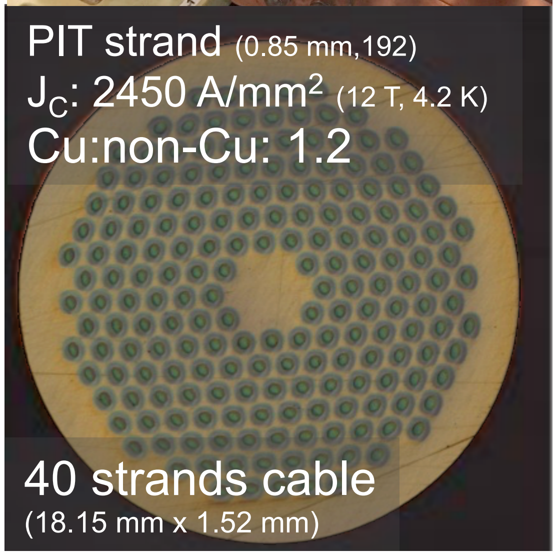


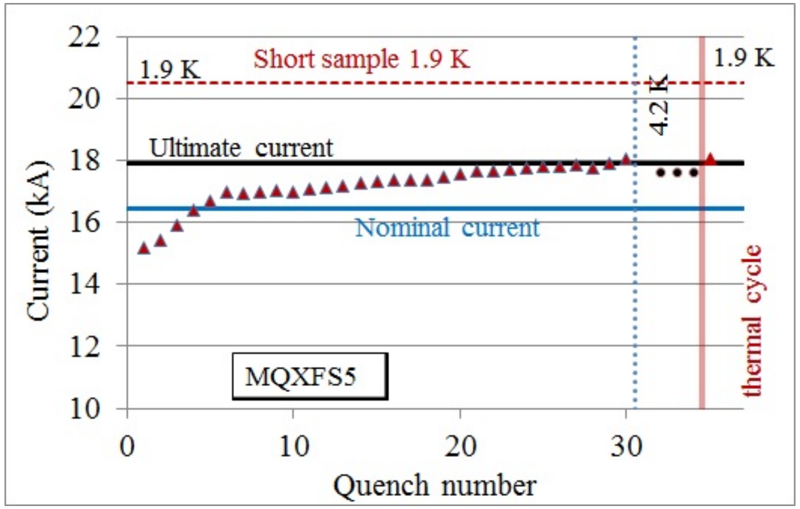


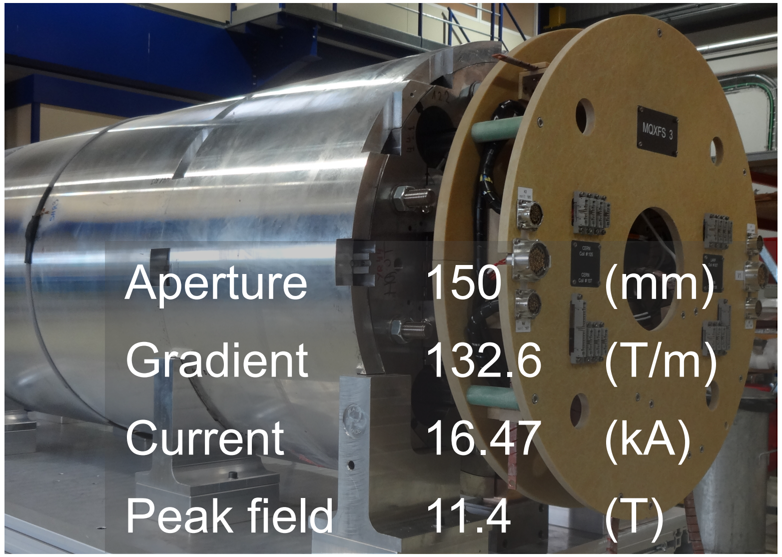


Courtesy of G. Ambrosio, G. Chlachidze, US-LAUP and CERN

MQXFS5 results



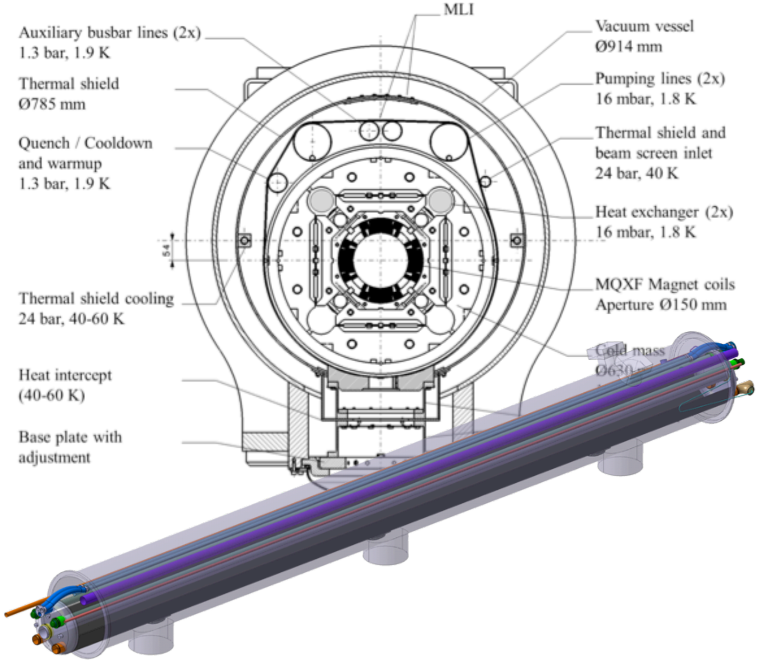


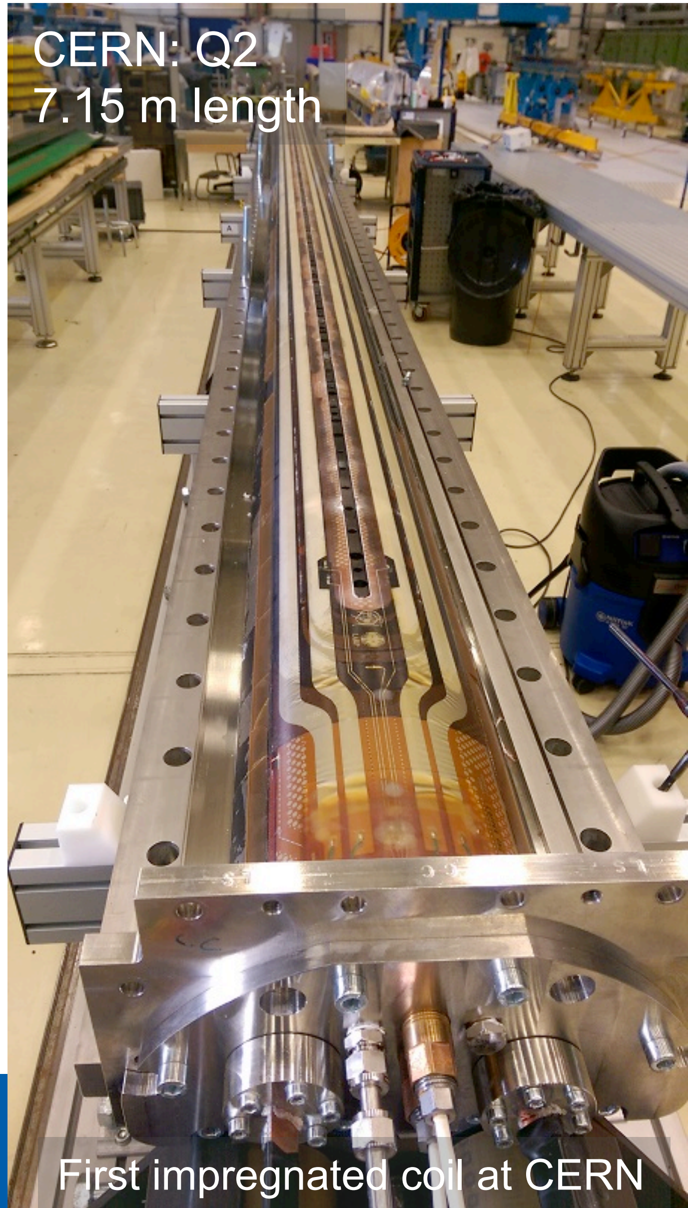


CERN

Courtesy of P. Ferracin, J.C. Perez, H. Bajas, E. Todesco, CERN

LQXF production




CERN: Q2
7.15 m length

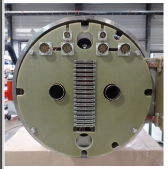
First impregnated coil at CERN


US: Q1/Q3
4.2 m length

Long mirror test at BNL


Coil winding at CERN

HL-LHC Nb_3Sn plan



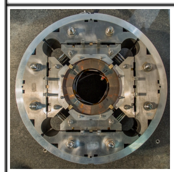
Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
11 T Models Mark I	01.01.2012	31.12.2016												
11 T Models Mark II	30.06.2016	30.06.2018												
11 T Prototype	12.06.2015	20.01.2017												
11 T Production	03.04.2017	14.03.2021												

LHC Run II ≈ 100 fb^{-1}

LS2

LHC Run III ≈ 300 fb^{-1}

LS3

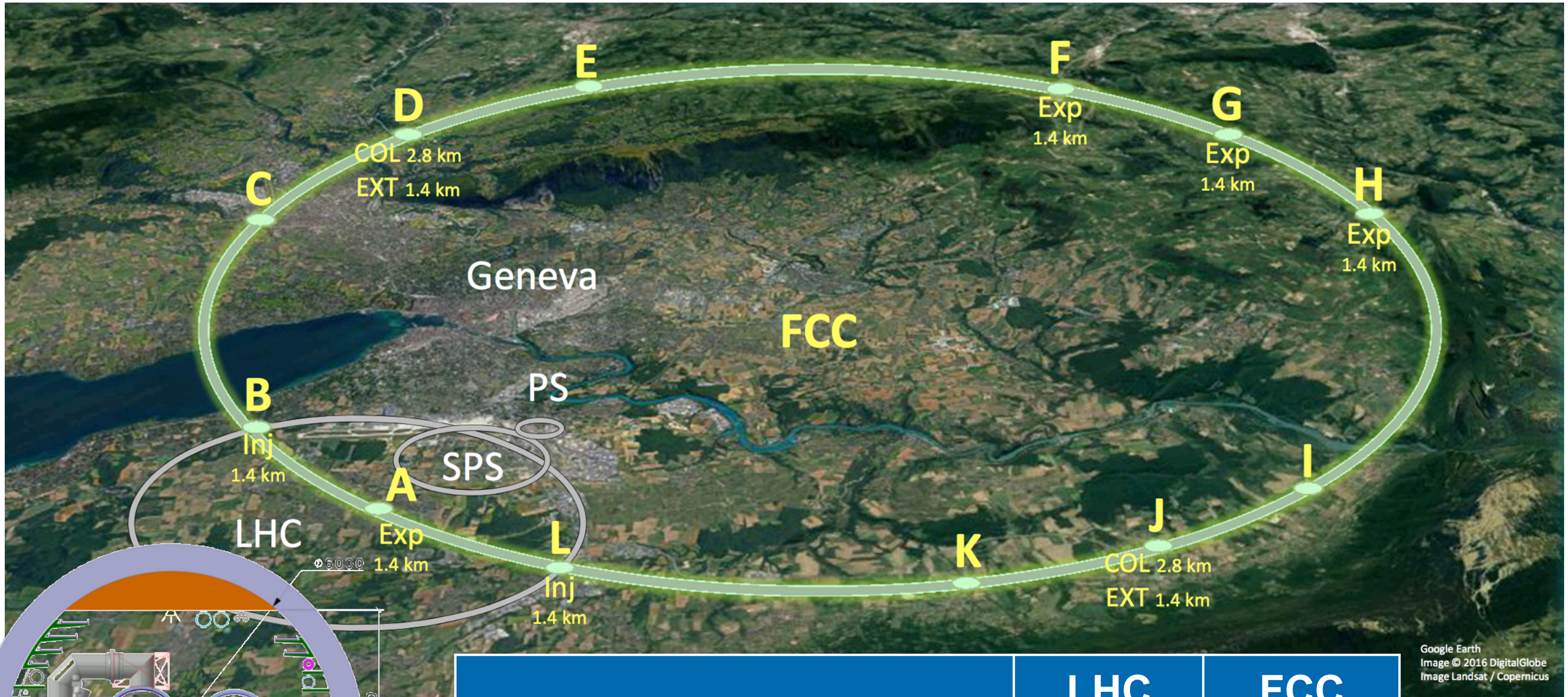


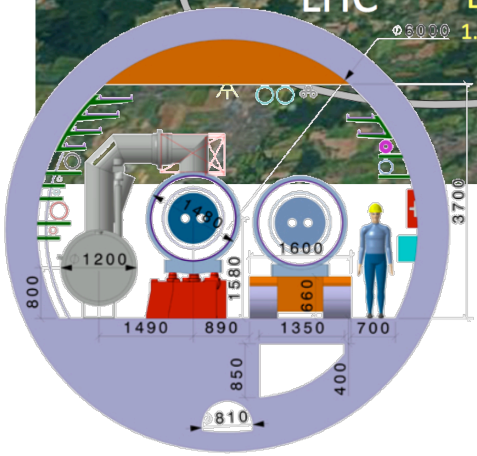
Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
QXF Models CERN/US	26.05.2014	31.12.2017												
QXF Prototypes US	30.06.2015	30.06.2019												
QXF Prototypes CERN	30.06.2016	30.06.2019												
QXF Production US	30.06.2018	31.12.2024												
QXF Production CERN	30.06.2018	31.12.2023												

Opportunity for **first industry experience** on Nb_3Sn accelerator magnets

FCC and its siblings

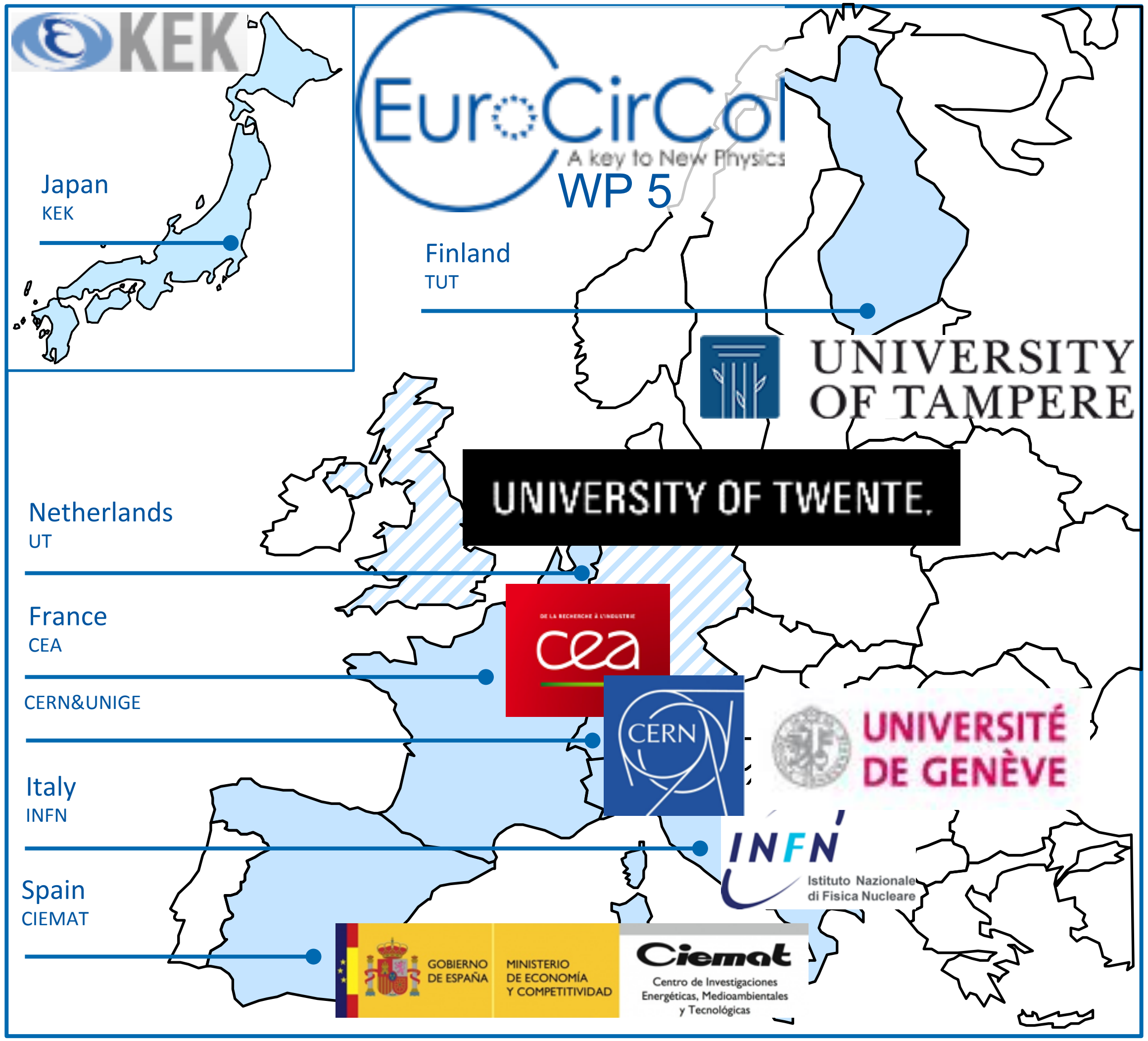
Future Circular Collider





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

CERN/EU program for 16 T dipole



Design a 16 T accelerator-quality model dipole magnet by 2018

FCC Magnet Designs

$T_{op} \approx 1.9$ K

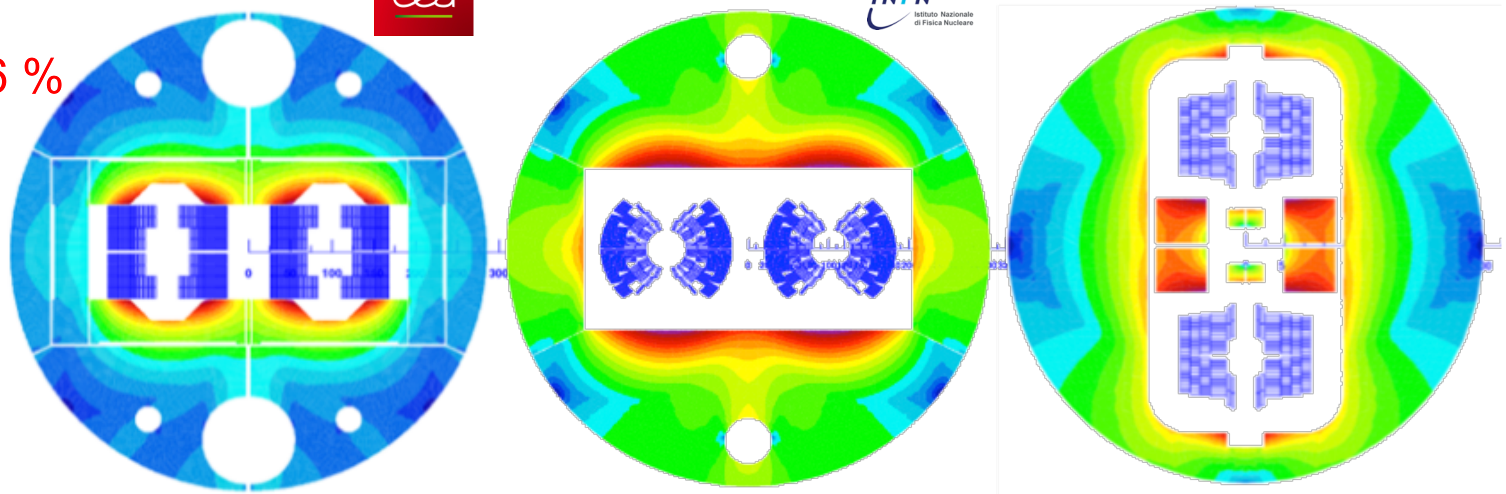
I_{op}/I_C(loadline) $\approx$ 86 %

$V_{dump} < 2.5$ kV

$\sigma_{max} < 200$ MPa

$T_{hot} < 350$ K

$D_{out} \approx 600$ mm



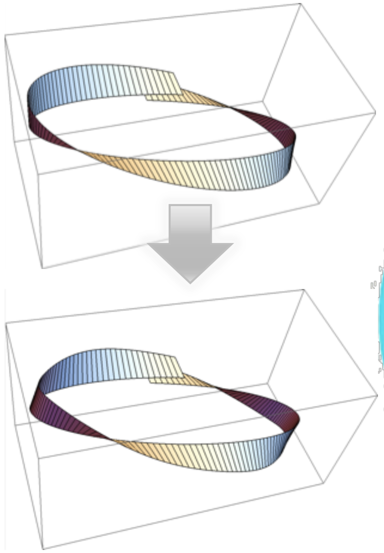
		blocks	cos(θ)	common coil
Current	(A)	11230	10000	16100
Inductance	(mH/m)	40	50	19.2
Stored energy	(kJ/m)	2520	2500	2490
Coil mass	(tons)	7400	7400	9200

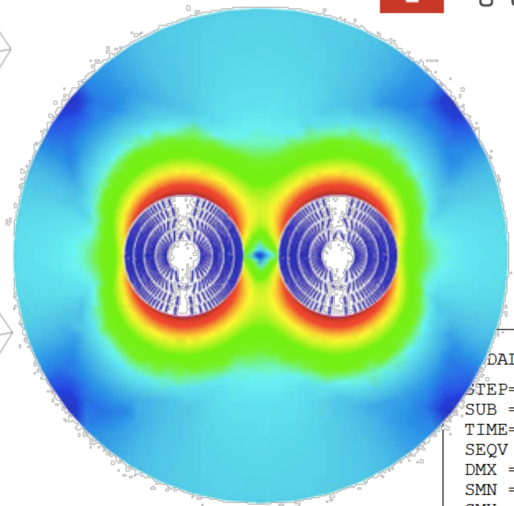
Very efficient use of superconductor (blocks, cos(θ))

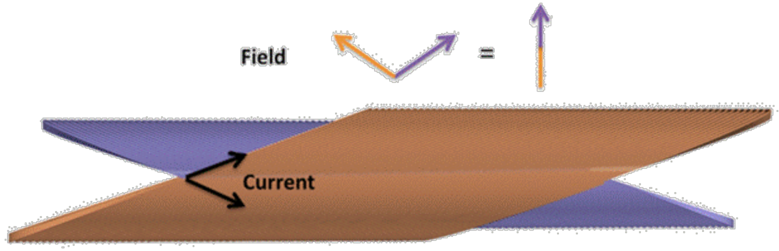
Simplified mechanics and manufacturing ? (common coil)

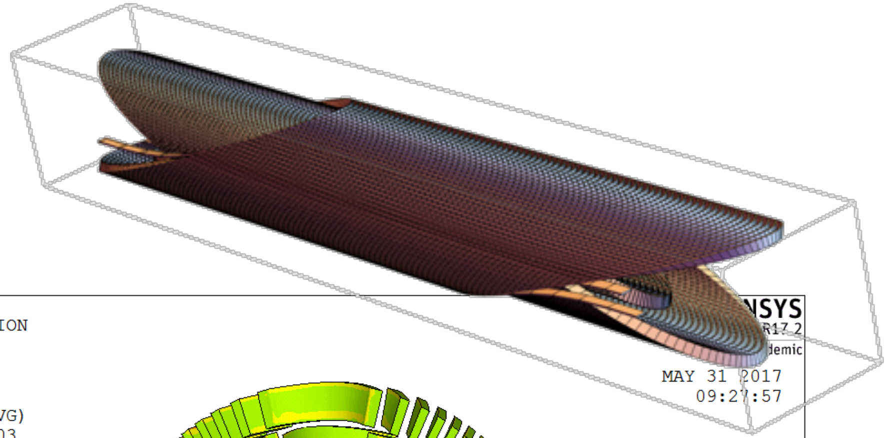
Courtesy of D. Tommasini, CERN

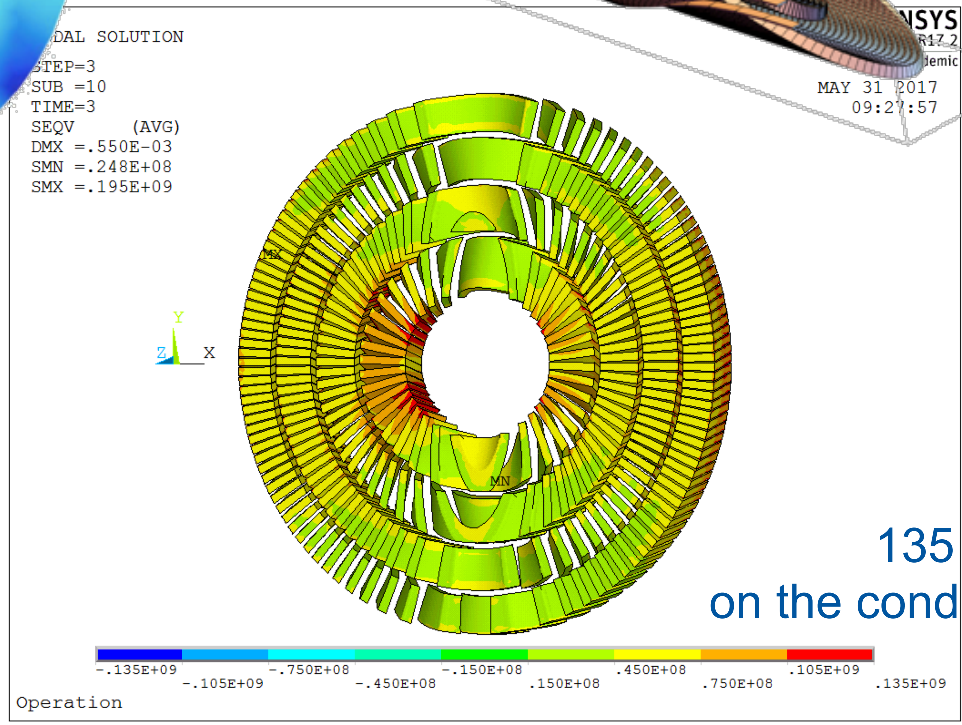
CCT option











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

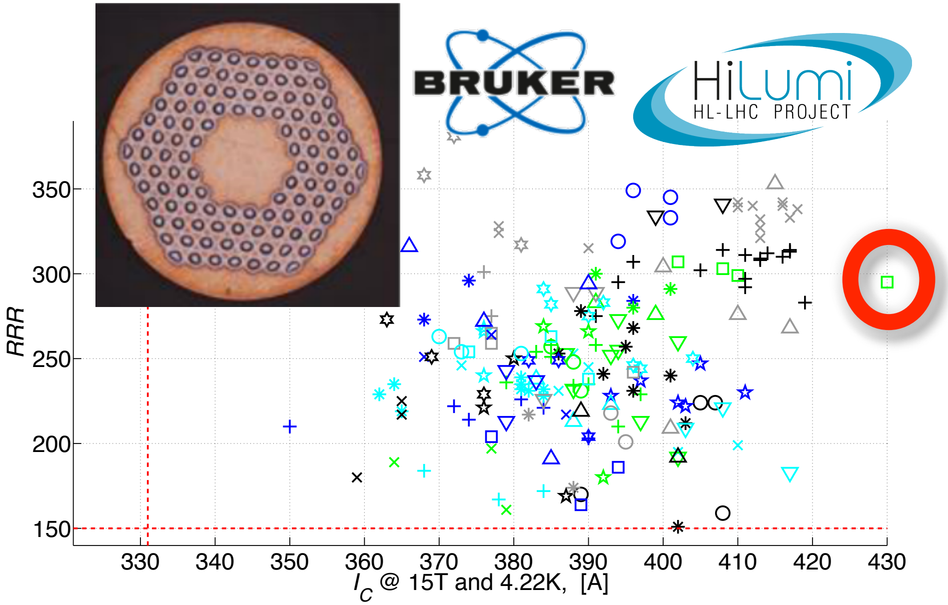
135 MPa
on the conductor

Conductor R&D

ROSATOM · TVEL FUEL COMPANY OF ROSATOM · BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM · NATIONAL NUCLEAR CORPORATION "ROSATOM"

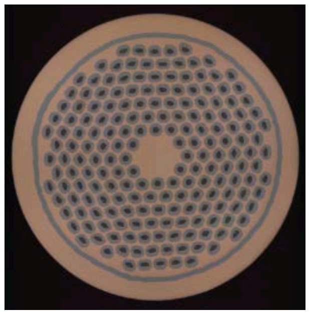
Specification: 1500 A/mm^2 @ 16T, 4.2K

BRUKER · HiLumi HL-LHC PROJECT



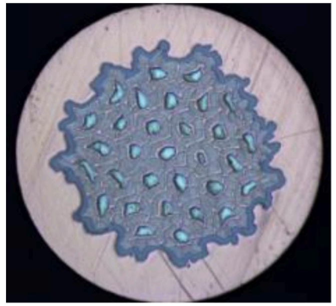
1750 A/mm^2 @ 15T, 4.2K

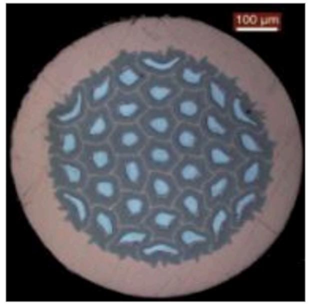
≈ 1400 A/mm^2 @ 16T, 4.2K



1274 A/mm^2 @ 15T, 4.2K

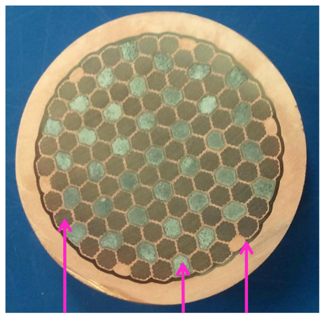
≈ 1000 A/mm^2 @ 16T, 4.2K

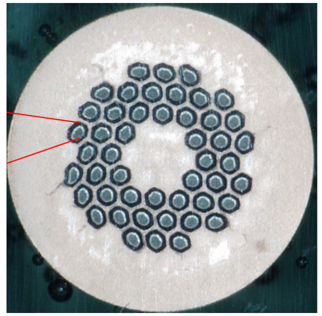




2850 A/mm^2 @ 12T, 4.2K

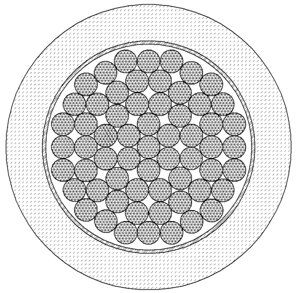
≈ 1250 A/mm^2 @ 16T, 4.2K





JASTEC SUPERCONDUCTOR · FURUKAWA ELECTRIC

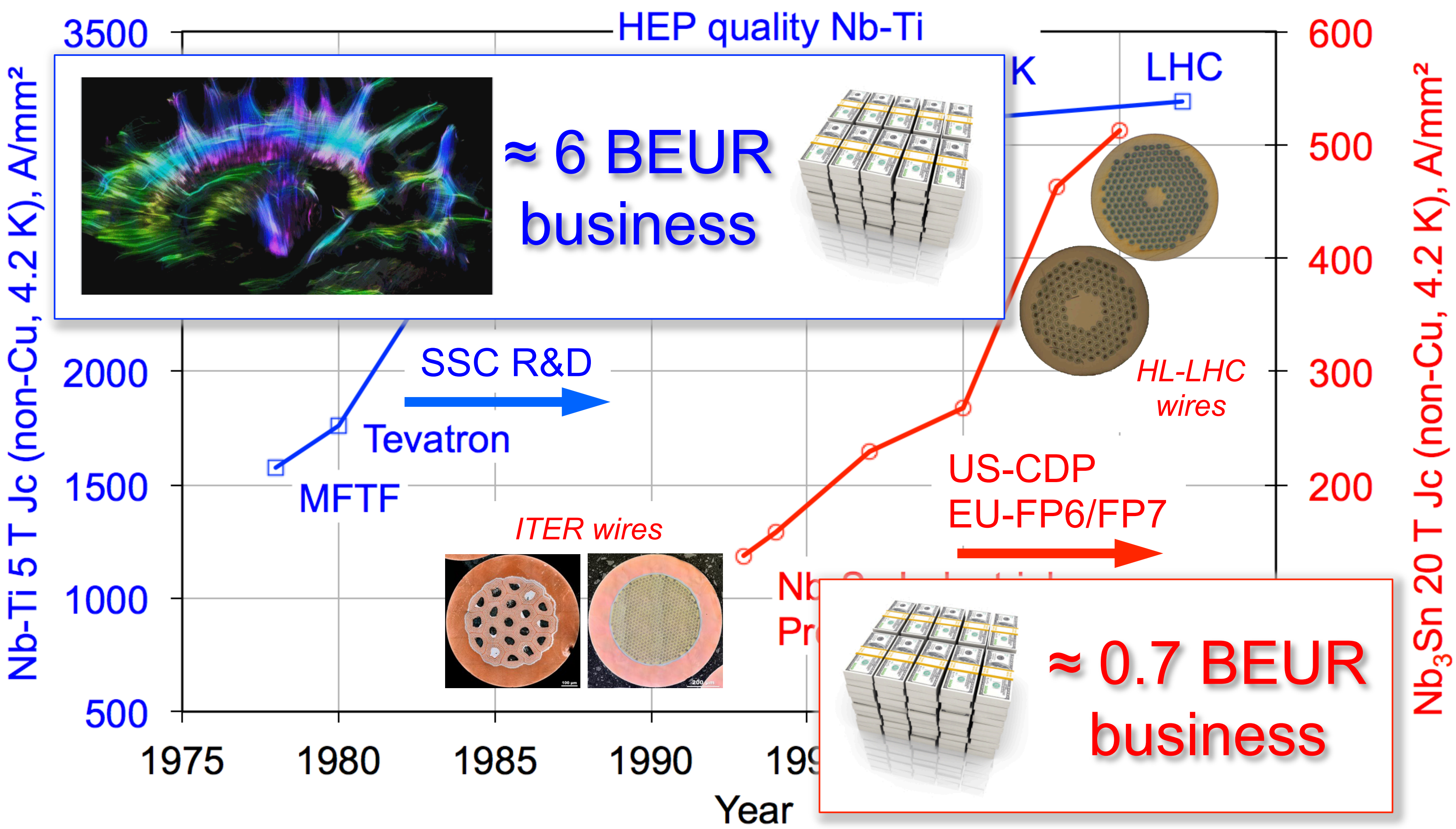
≈ 950 A/mm^2 @ 16T, 4.2K



NFRI National Fusion Research Institute · Kiswire KAT

Results expected later this year

“So I tell you: Ask and it will be given to you” (Luke 11:9)

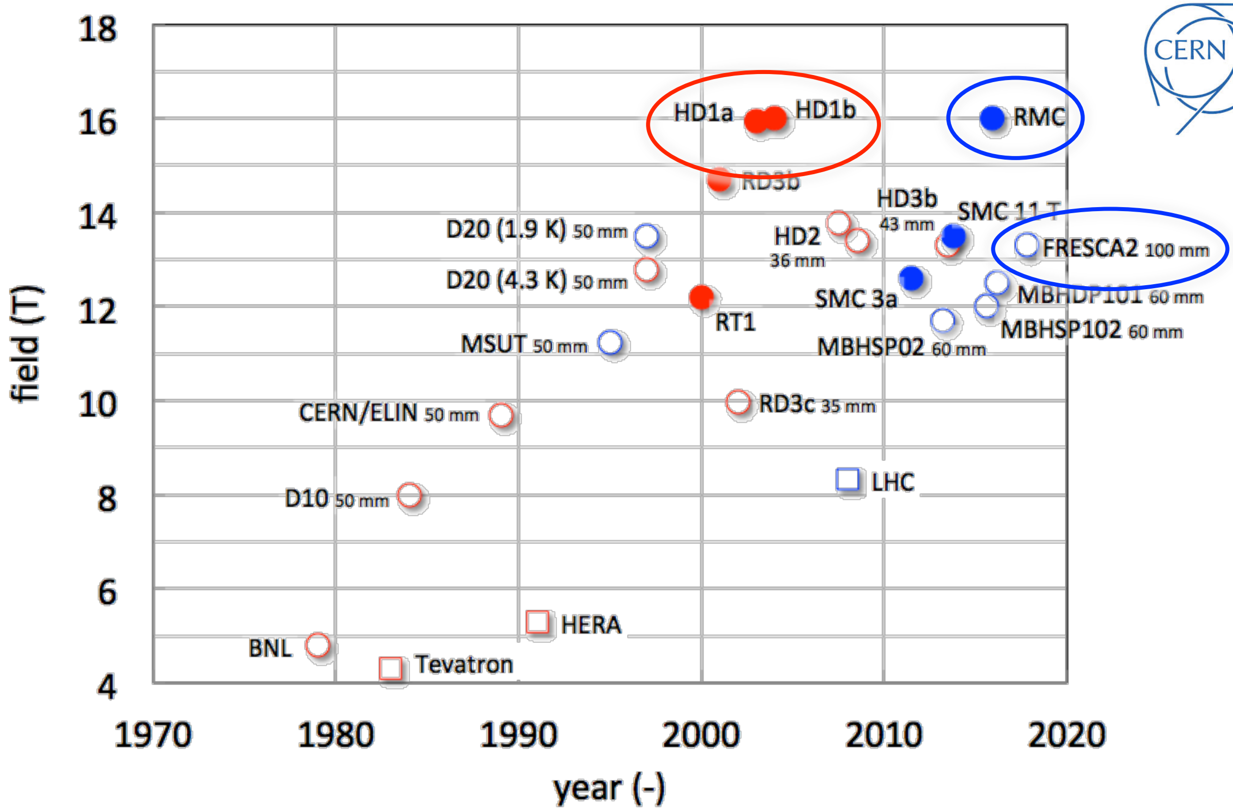


“And this may be known to you: What you do not ask, will not be given to you” (Lucio 1:3)

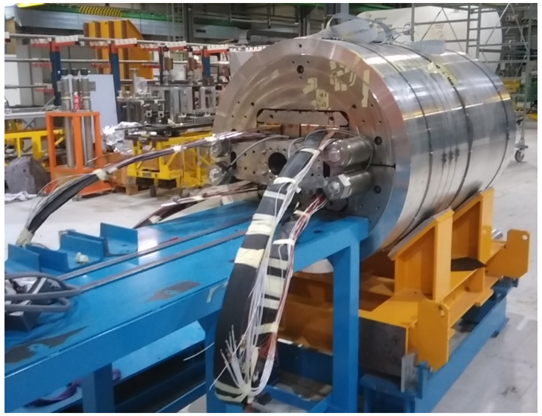
CERN

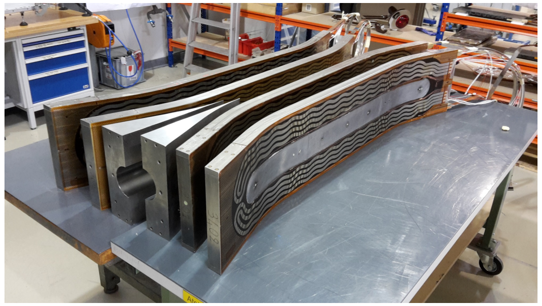
On the unreasonable request of high J_C

High field “Hall of Fame”



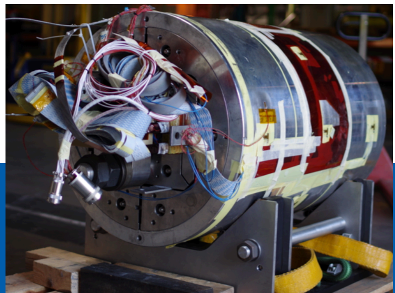
2017: FRESCA2
(13.3 T at 1.9 K, 100 mm)





2003: LBNL HD1
(16 T at 4.2 K)

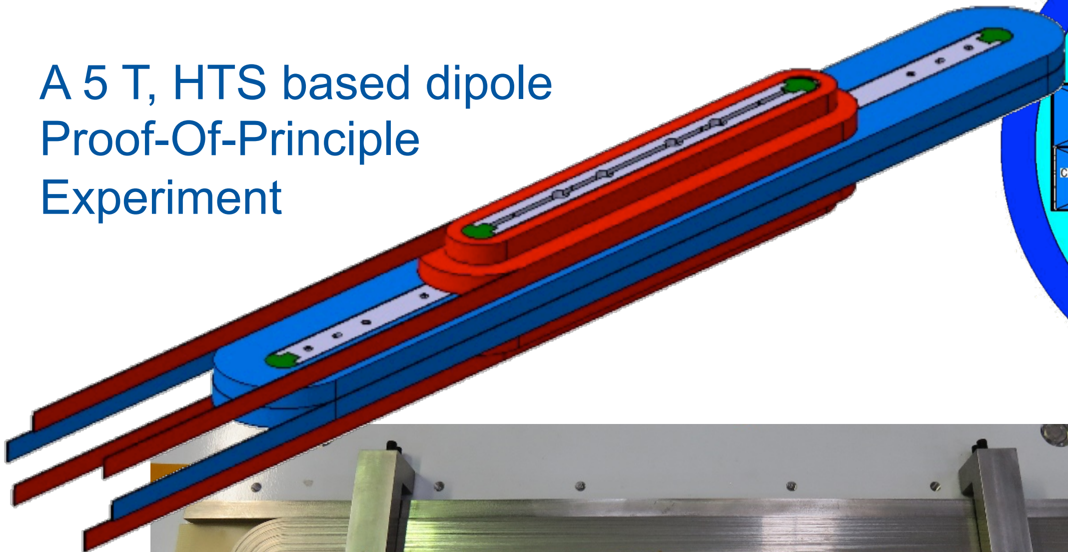
2015:CERN RMC
(16.2 T at 1.9 K)

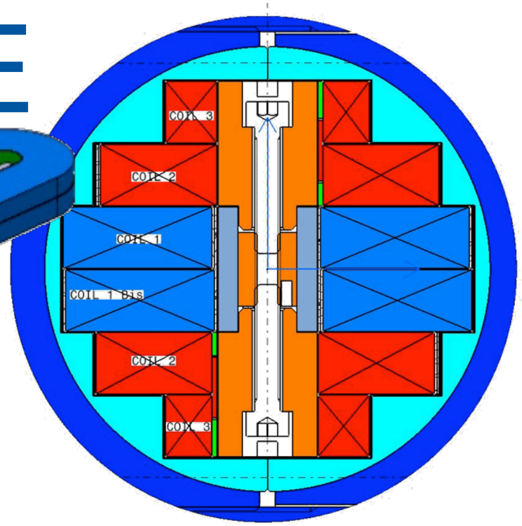


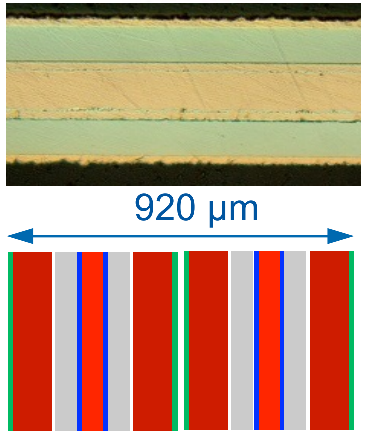
A digression on HTS R&D

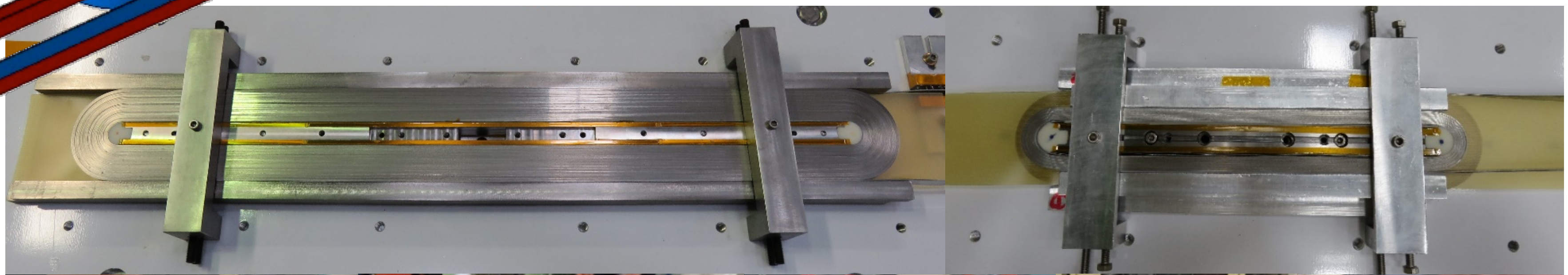
Racetrack POPE

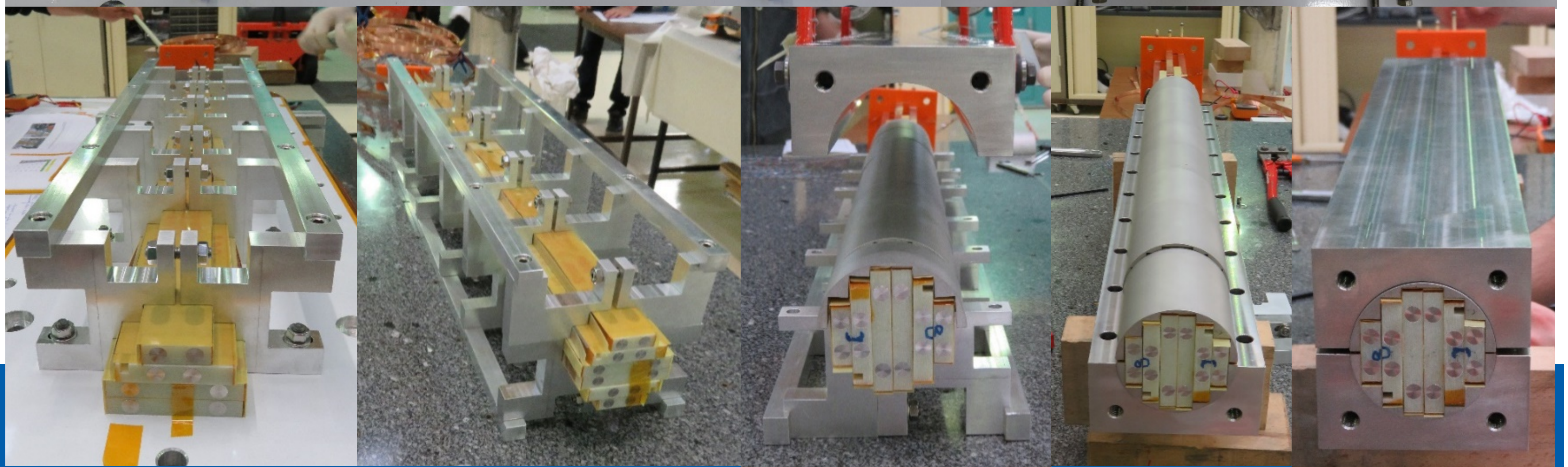
A 5 T, HTS based dipole
Proof-Of-Principle
Experiment



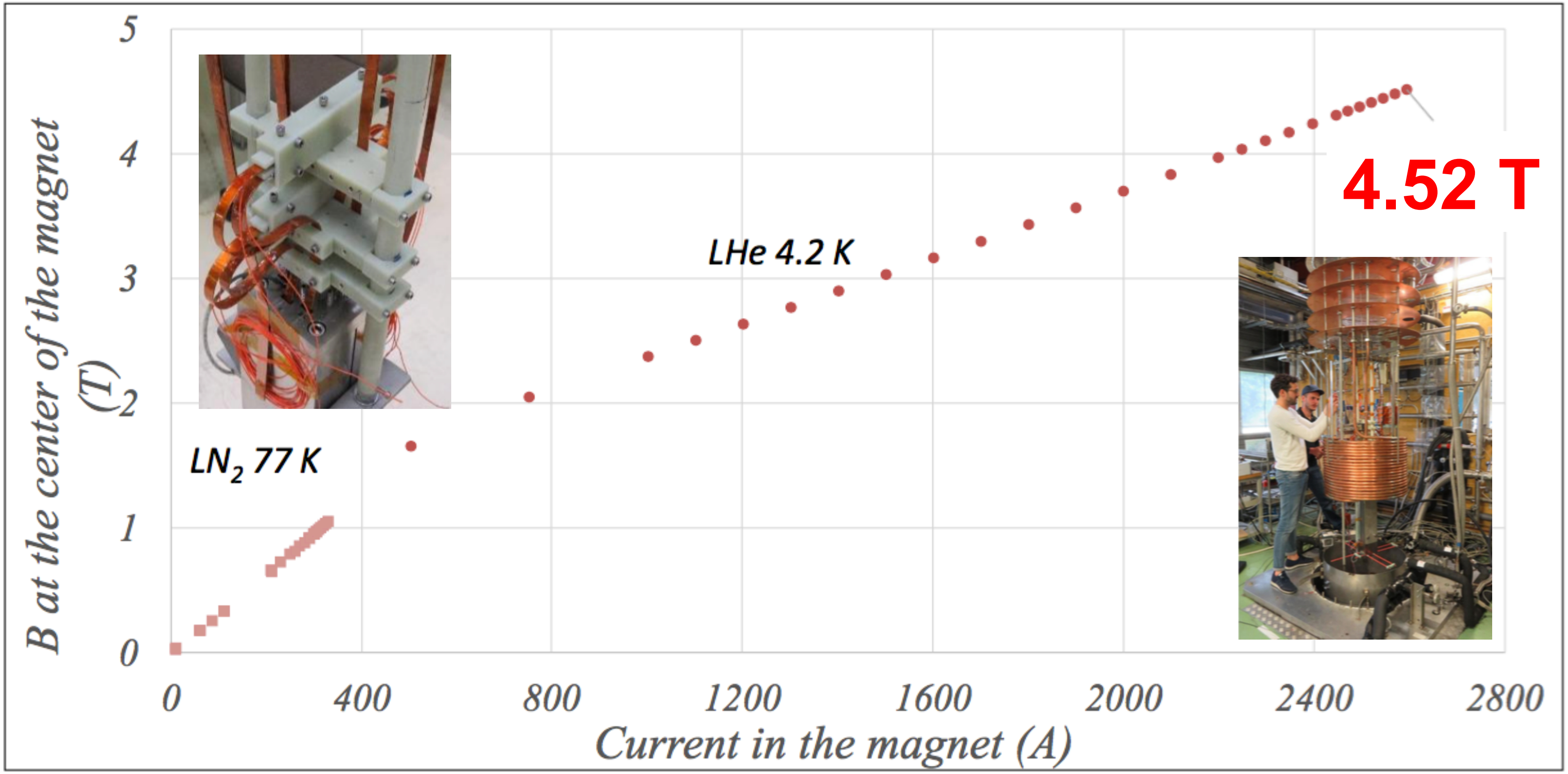






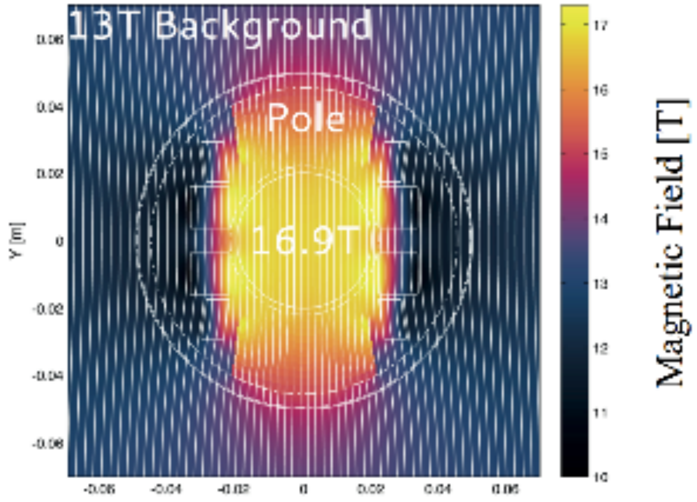


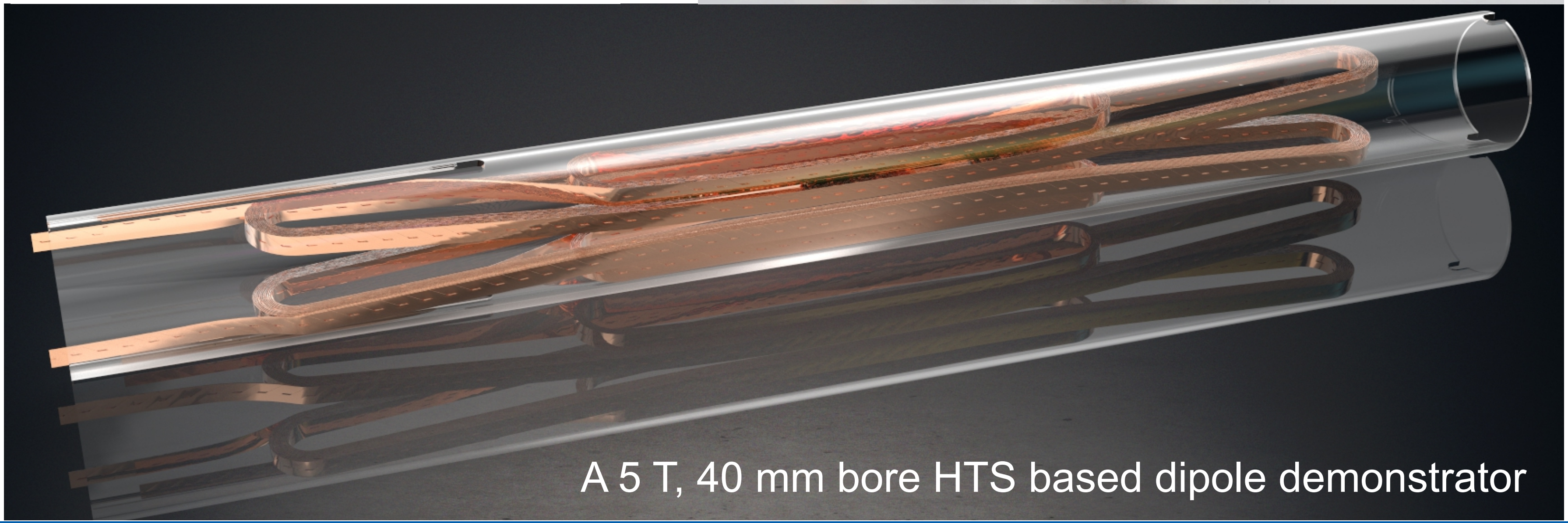
Racetrack POPE results



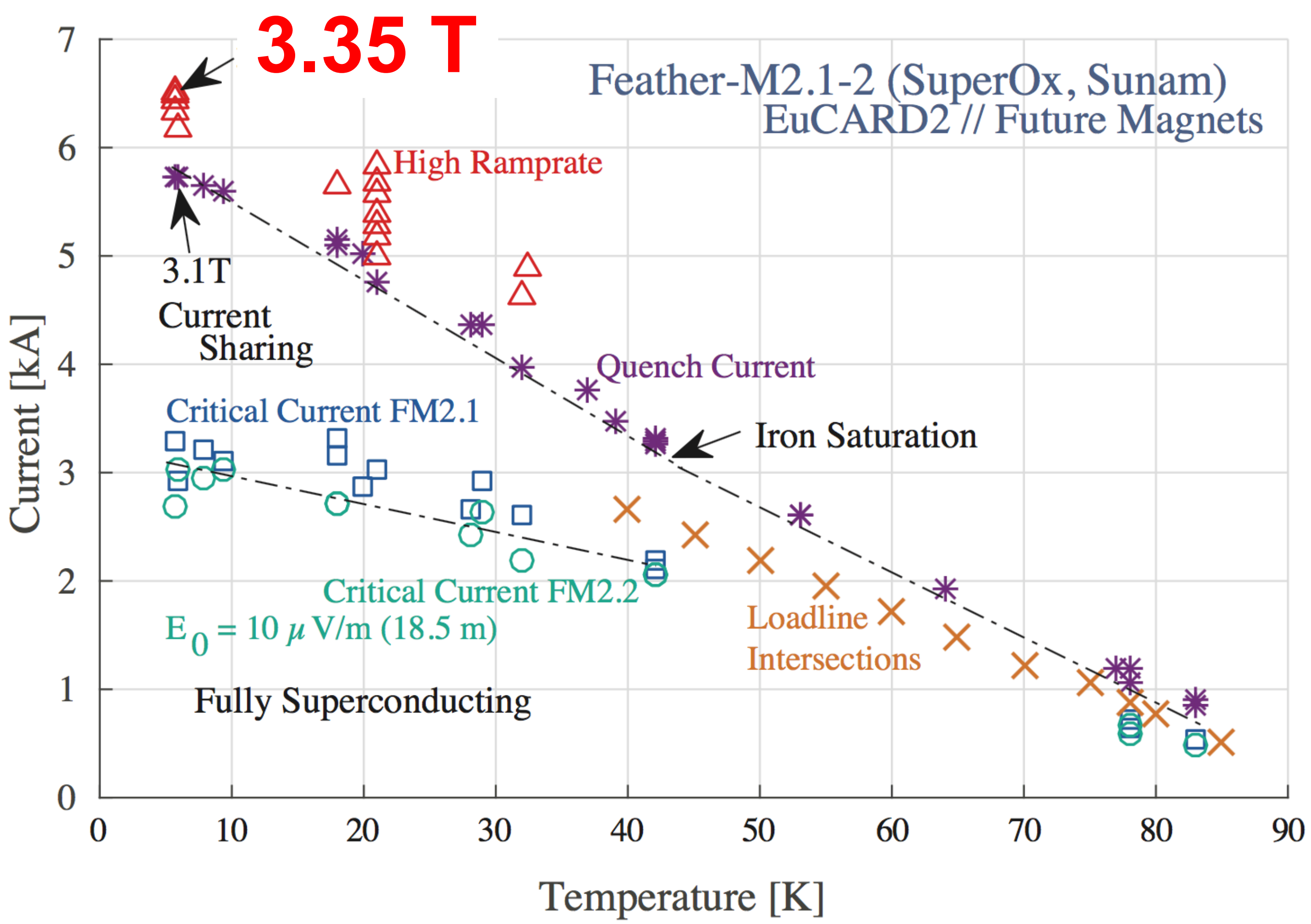
Courtesy of M. Durante, CEA

Short dipole demonstrator



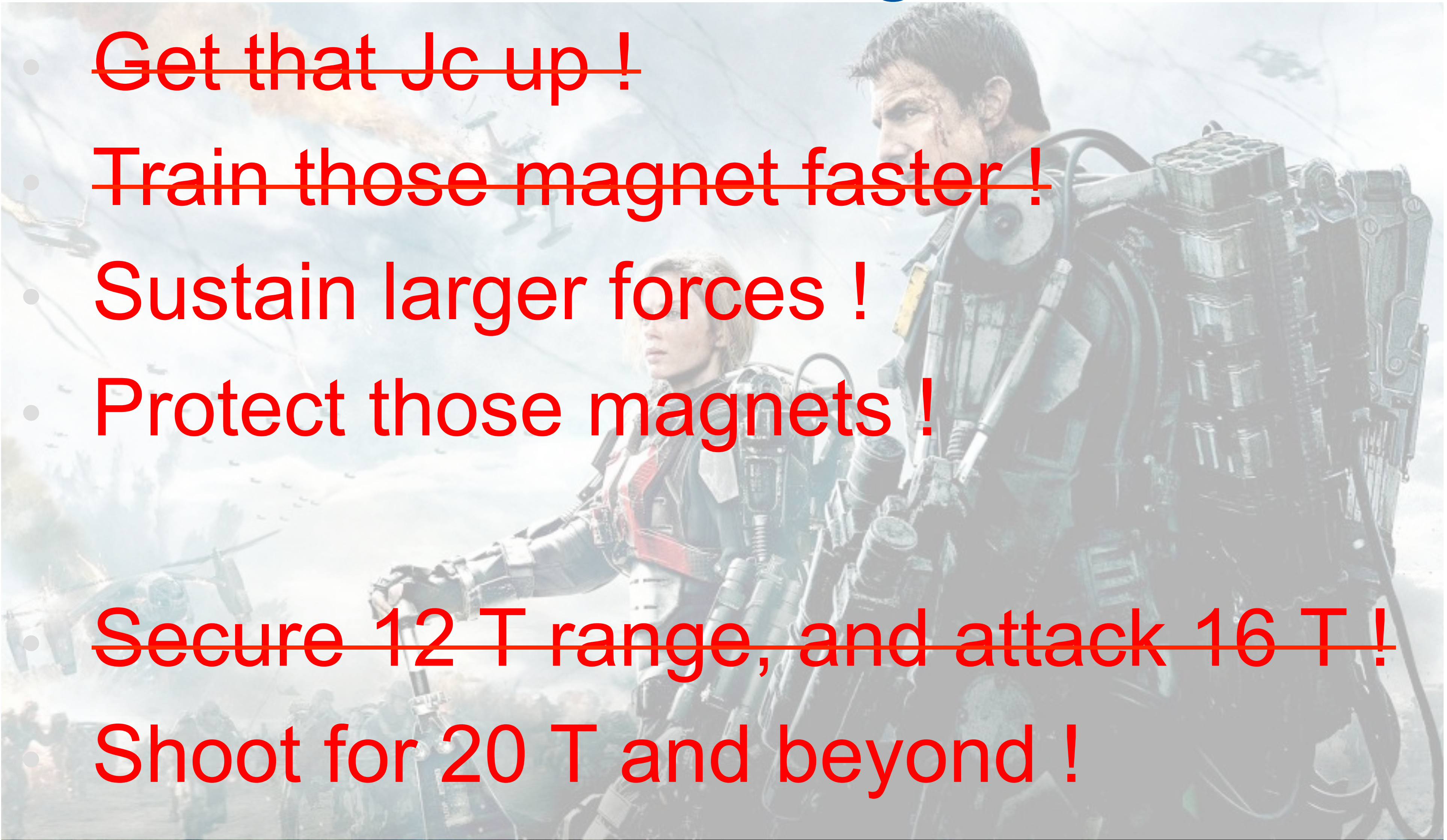


Dipole demonstrator results



Courtesy of J. Van Nugteren, H. Bajas, CERN

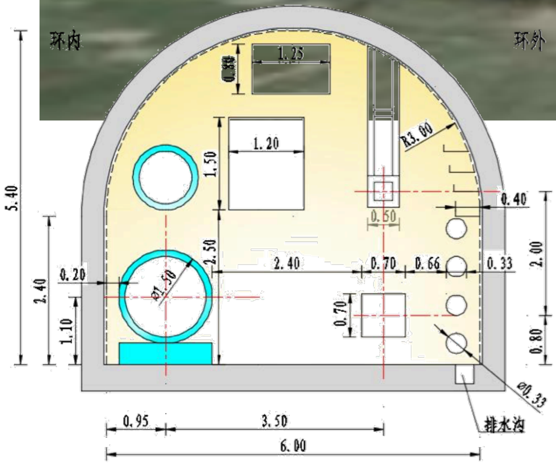
The Battle of the High Fields



- ~~Get that Jc up !~~
- ~~Train those magnet faster !~~
- Sustain larger forces !
- Protect those magnets !

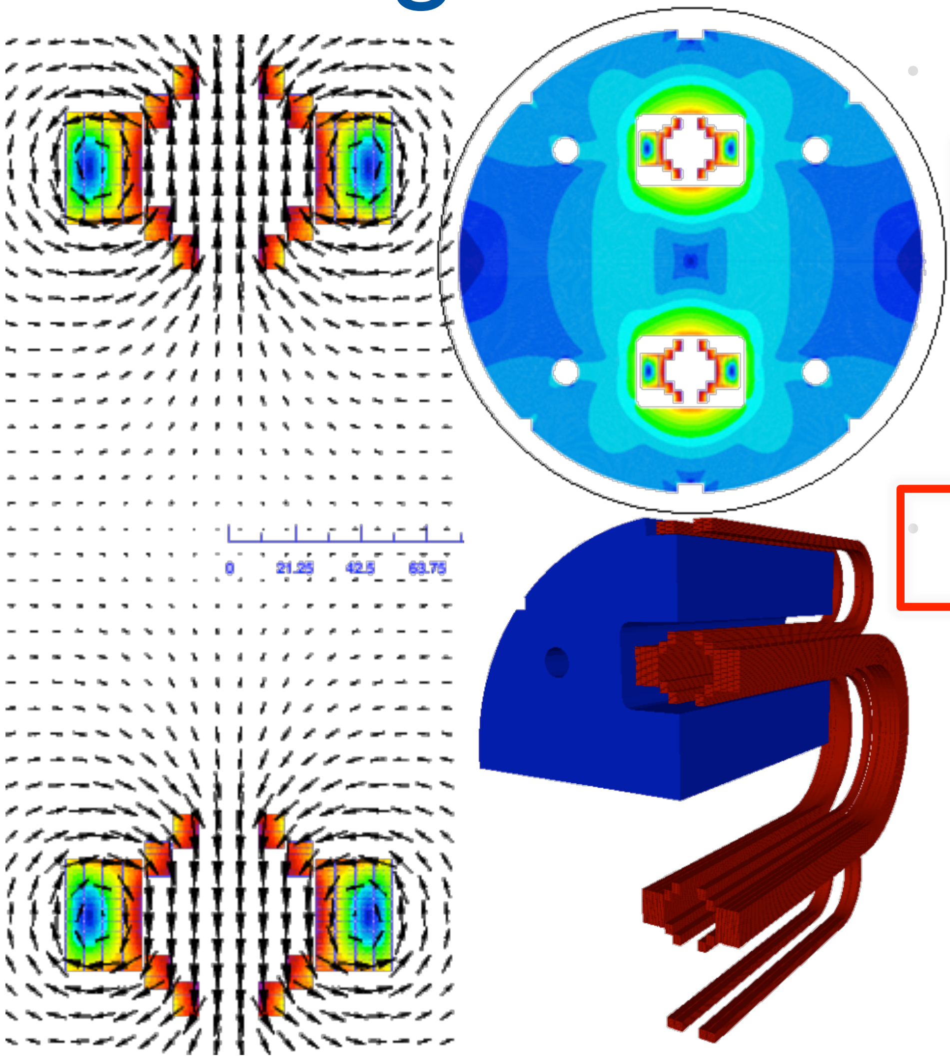
- ~~Secure 12 T range, and attack 16 T !~~
- Shoot for 20 T and beyond !

Super proton-proton Collider



	LHC	FCC	SppC
Circumference (km)	26.7	97.5	100
Dipole field (T)	8.33	16	12…24
C.o.M. energy (TeV)	14	100	70…125

CN high-field magnet R&D

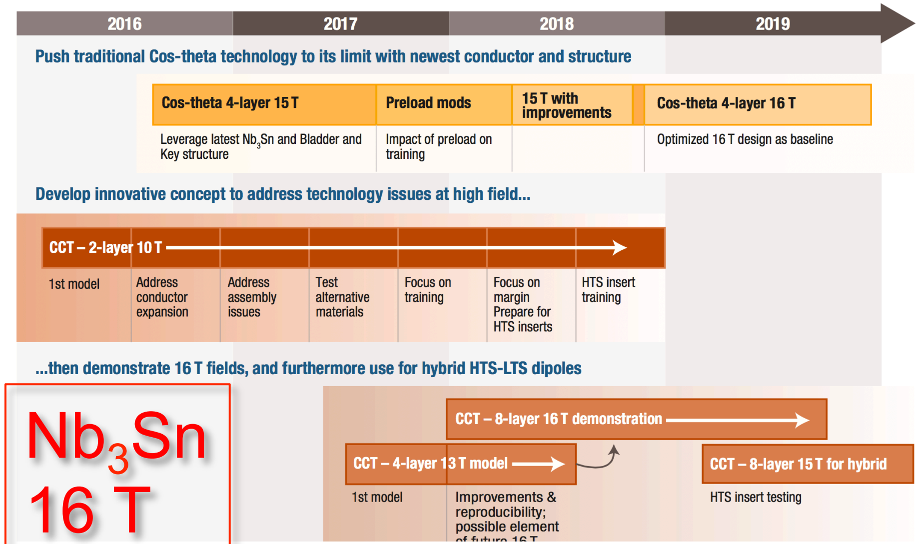


Conceptual design of common coil 12T dipole

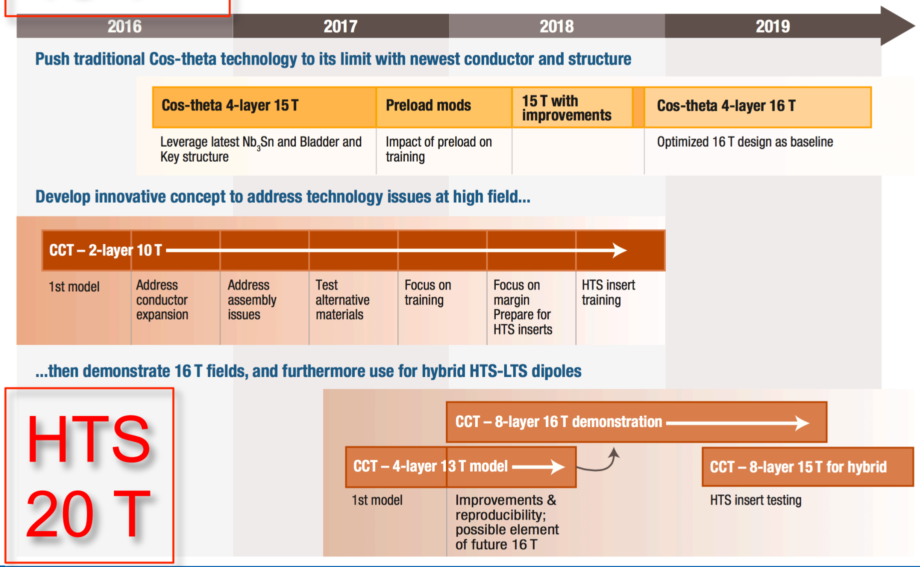
- Baseline design
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV
- Upgrade phase
  - Dipole magnet field: 20…24T, IBS technology
  - Center of Mass energy: >125 TeV
- Development of high-field superconducting magnet technology
  - Starting to develop required HTS magnet technology before applicable iron-based wire is available
  - ReBCO & Bi-2212 and LTS wires be used for model magnet studies and as an option for SppC: stress management, quench protection, field quality control and fabrication methods

Top priority: reduce cost!
Instead of increasing field

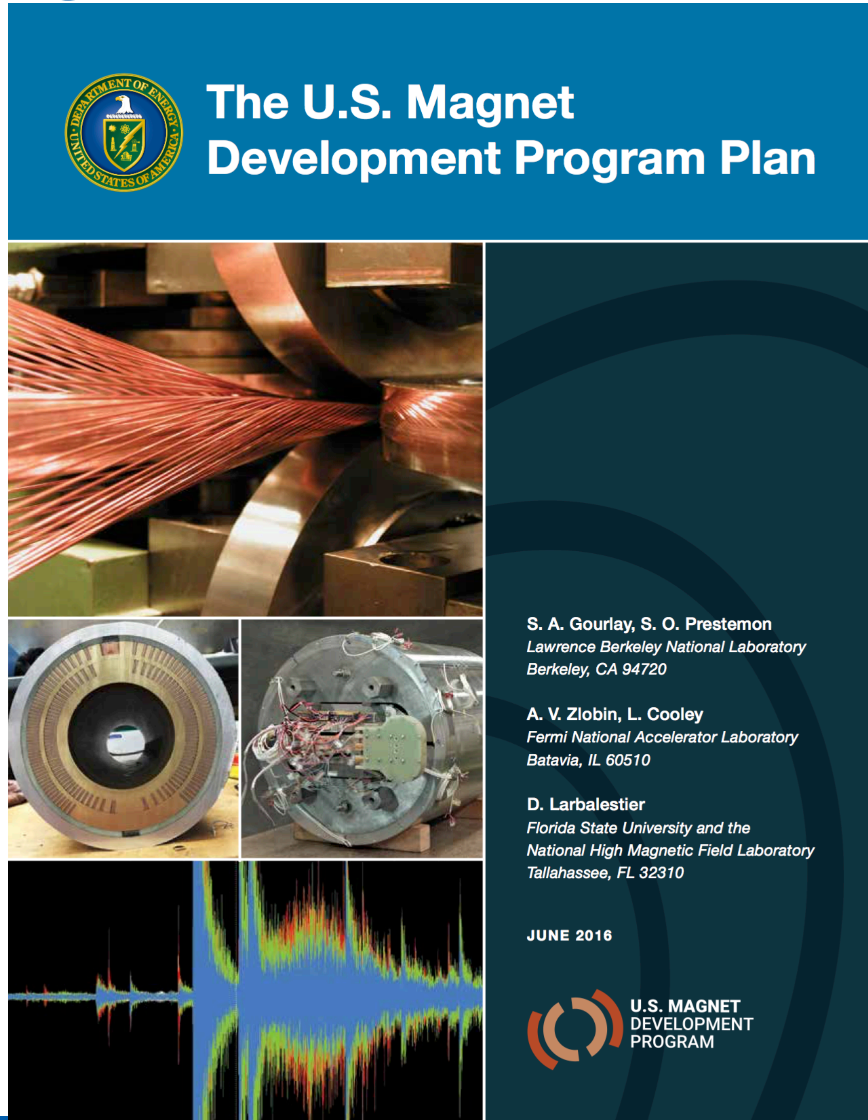
US high-field magnet R&D



Nb_3Sn
16 T



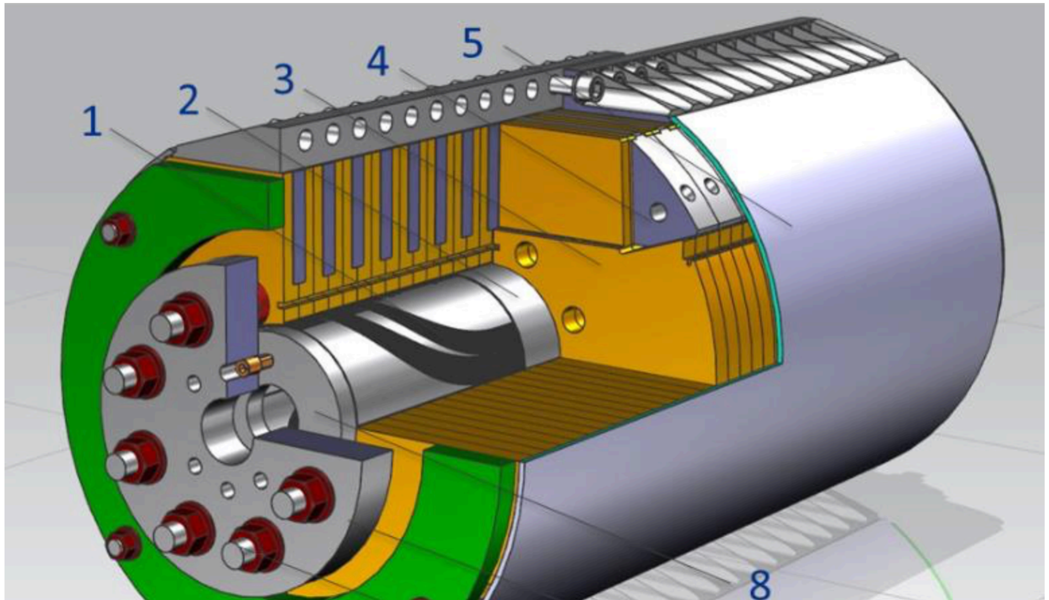
HTS
20 T



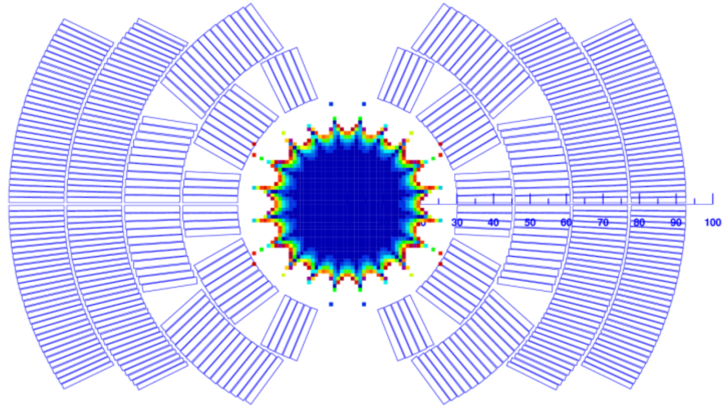
CERN

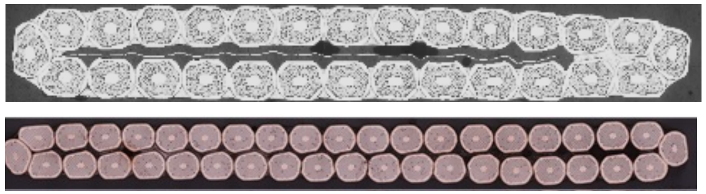
Courtesy of S. Gourlay, US-MDP

Cos-theta, 4 layers, 15 T dipole

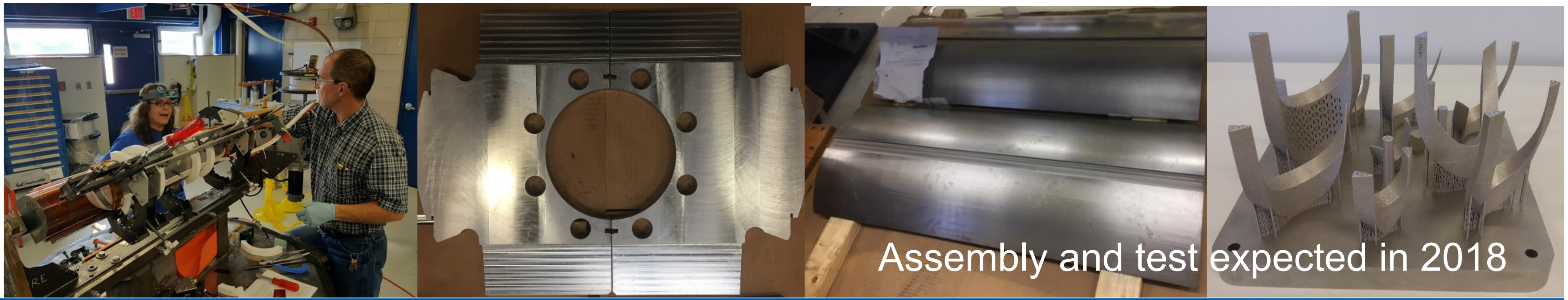


Simplify assembly, reduce cost





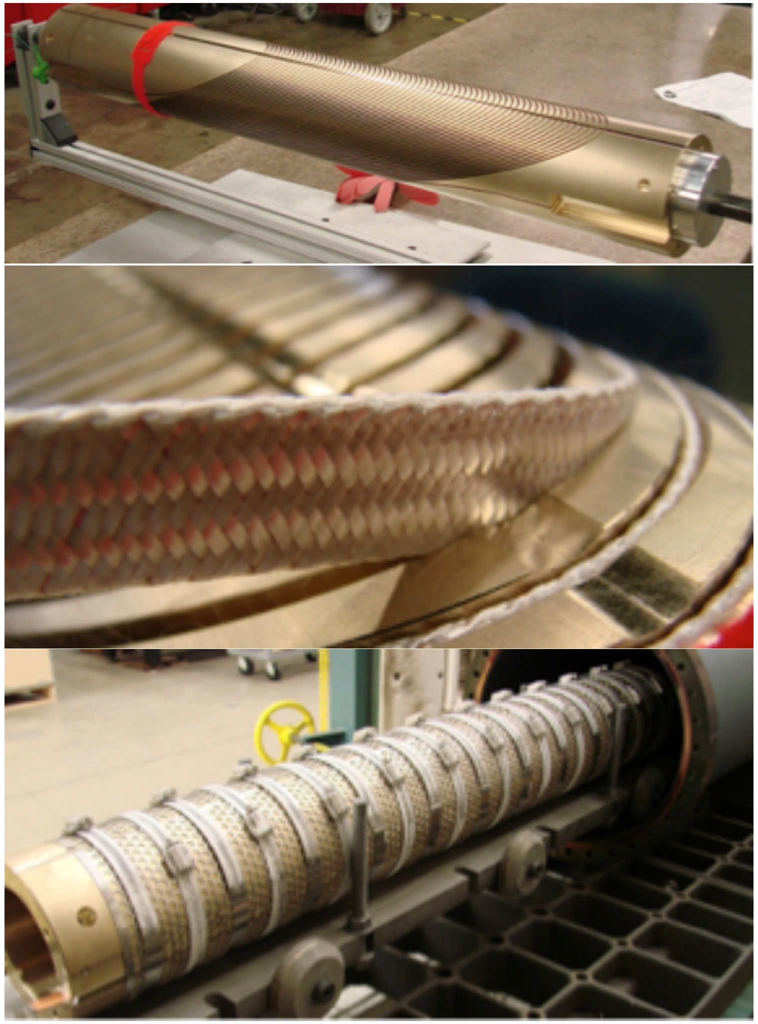
L1-L2: 28 strands, 1 mm RRP 150/169
L3-L4: 40 strands, 0.7 mm RRP 108/127



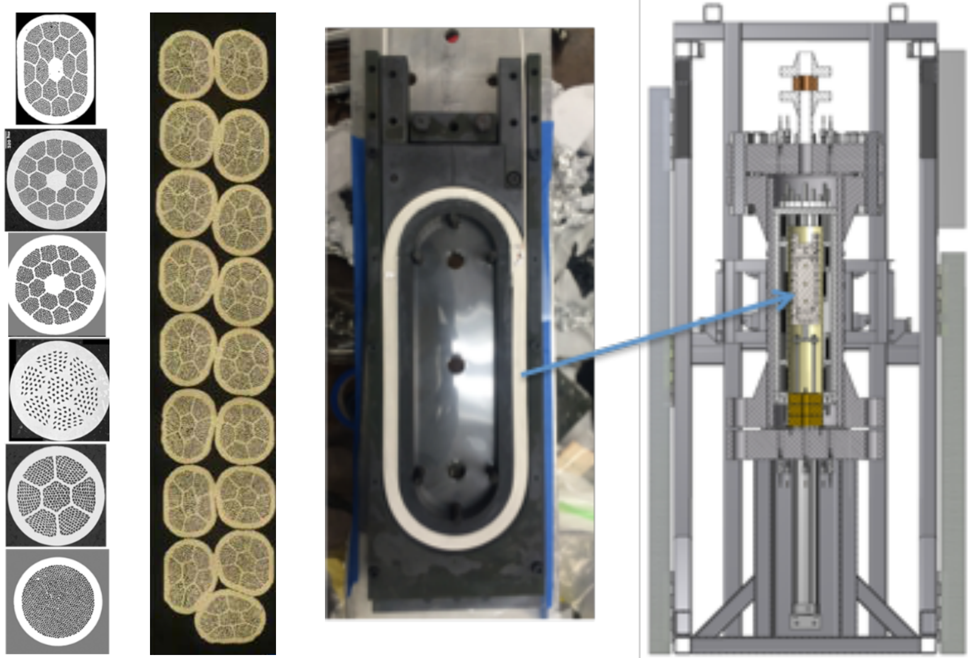
Assembly and test expected in 2018

US CCT and HTS programs

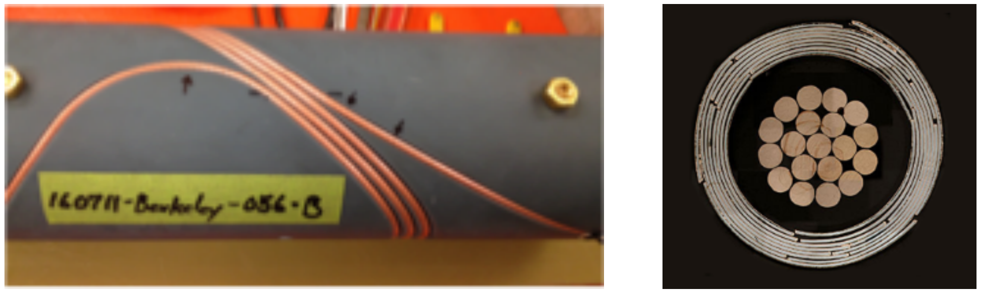
Nb_3Sn cable in CCT geometry



Bi-2212 cable in racetrack



REBCO CORC in CCT geometry



Courtesy of S. Prestemon, LBNL

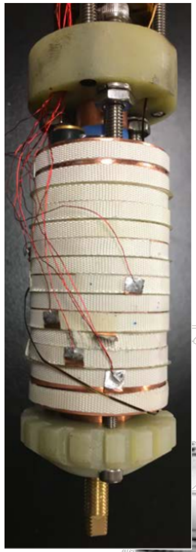
Summary and perspective

An *executive summary*

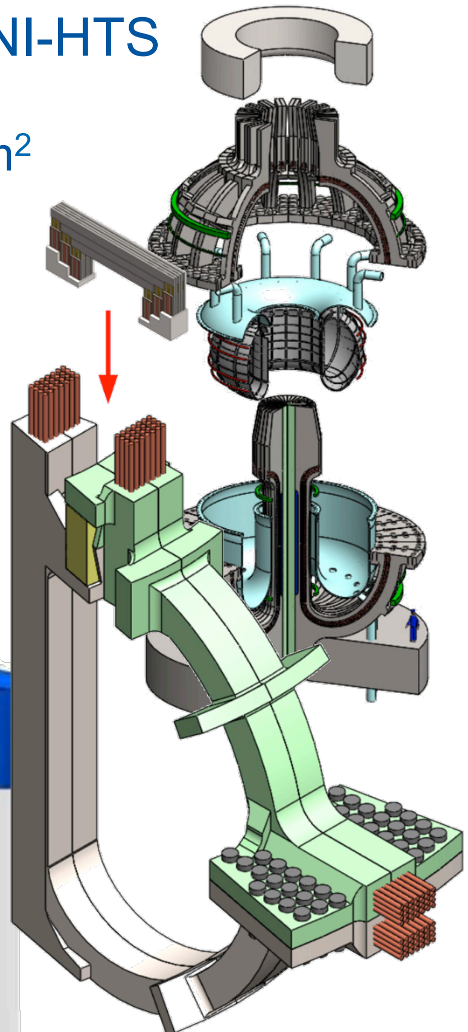
- The LHC High-Luminosity Upgrade is the **spring-board** for new magnet technology, and provides an interesting opportunity for industry
  - Production in 2018-2022
  - First use ever of Nb_3Sn in a running accelerator
- The **next step** is the development of magnets for an "FCC"
  - Model activities are planned in EU laboratories (and US) in 2018-2022
  - Prototyping in industry (full length, ≈10 magnets), in 2022-2025
  - This is the logical sequence of the HL-LHC production, profiting from Nb_3Sn technology established in laboratories and industry
- HTS is only in its infancy, but is the **disruptive high-field magnet technology** of the future
  - Requires high-tech R&D, spanning from material science to electromechanical engineering, 5 years program defined
  - HTS is the high-risk/high-return investment of the future

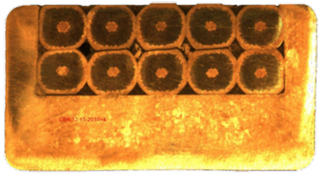
Is all of this useful ?

Fusion: MIT ARC reactor
B_t = 9.2T
HTS cable (20 T at 20 K)

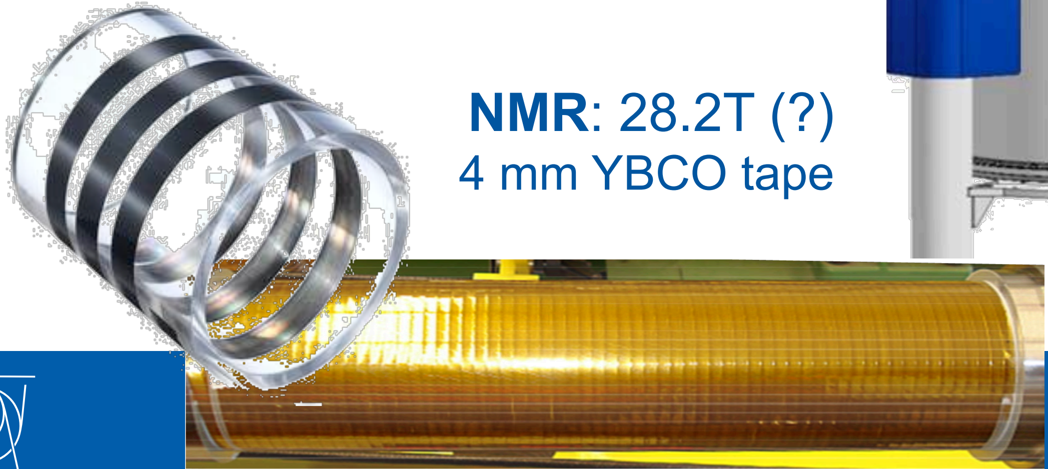


HF science: NI-HTS
42.5 T
J_E > 1000 A/mm^2





MRI: 11.7T Iseult MRI
Nb-Ti conductor (1.9 K)

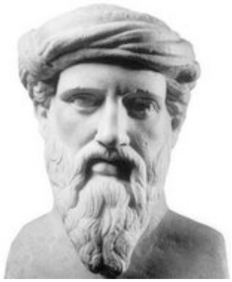


NMR: 28.2T (?)
4 mm YBCO tape

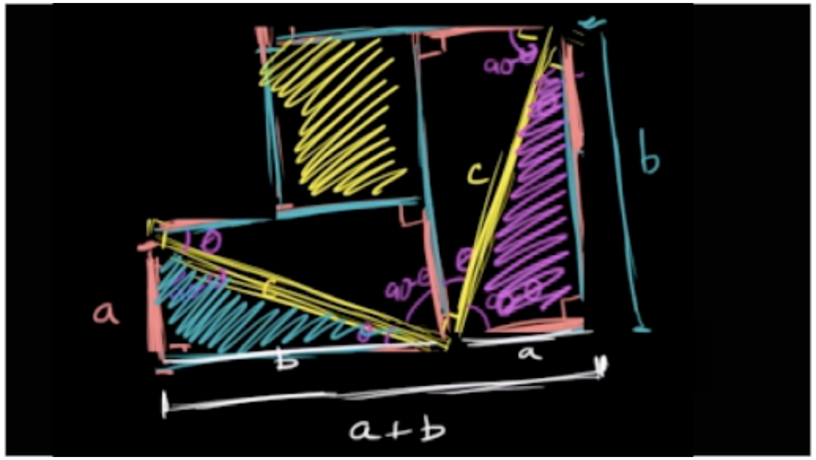
Now, is all of this really useful ?

Pythagoras theorem

(ca. 570–495 BC)



$c^2 = a^2+b^2$



A piece of cardboard and a twig of olive

Hamiltonian of the Standard Model of Physics (ca. 1961-2012 AD)

Discover the physics of applications to come, and not yet thought of…

… Provide an immediate return in new technology and industrial aplications, …

… Give a nest to the scientists of the future where they educate and train…

… Witness a living and successful experiment in cross-culture relations…

A 5 BEUR accelerator and a few tens of thousands of scientists

… a quest for an intimate order in Nature

Credits and grateful acknowledgements

To those that have conceived, engineered, realized, and tested
the wires, cables and magnets discussed here:

Present and “significant previous” CERN contributors:

B. Auchmann, H. Bajas, T. Boutboul, M. Bajko, A. Ballarino, B. Bordini, A. Devred, P. Ferracin, L. Fiscarelli, J. Fleiter, P. Hagen, S. Izquierdo Bermudez, M. Karppinen, G. Kirby, F. Lackner, D. Leroy, A. Milanese, L. Oberli, J. C. Perez, C. Petrone, H. Prin, D. Richter, G. De Rijk, F. Savary, Ch. Scheuerlein, D. Schoerling, S. Tavares, E. Todesco, D. Tommasini, G. Willering

Our present post-docs:

A. Chiuchiolo, E. Nillson, J. Van Nugteren, R. Ortwein, E. Rochepault, G. Vallone

The CERN TE-MSC Group, as well as TE-CRG, TE-EPC, TE-MPE for their support

The main sponsors of the programs described here

L. Rossi (HL-LHC Project) and M. Benedikt (FCC Study)

Our EU collaborators at:

CEA Saclay, CIEMAT Madrid, CNR SPIN Genova, INFN Milano (LASA) and Genova, KIT, RAL, University of Geneva, University of Southampton, University of Tampere, University of Twente, University of Vienna and ATI

Worldwide collaborators at:

ASC at NHMFL, Bochvar, BNL, FNAL, IHEP, KAIST, KEK, LBNL, US-DOE, US-LAUP and US-MDP

Our industrial partners:

ASG, BNG, Bruker-EAS, Bruker OST, Bruker-HTS, GE, Furukawa Electric, JASTEC, KAT Kiswire, OI, Sunam, SuperPower, SuperOx, TVEL ChMP