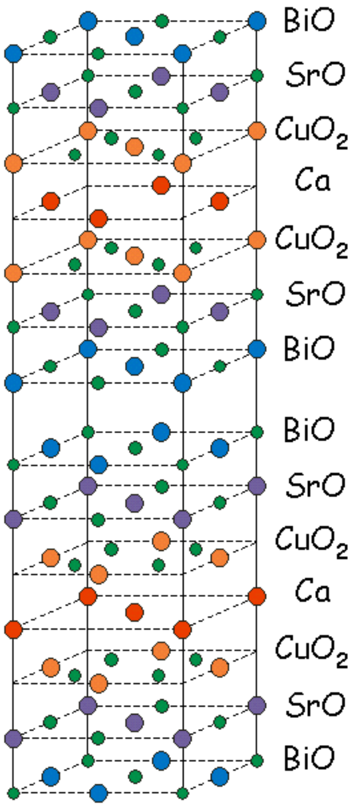
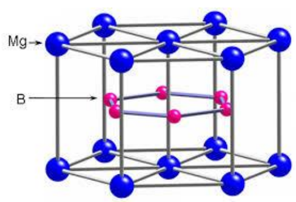
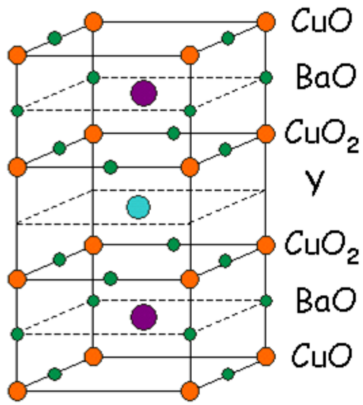
ECFA

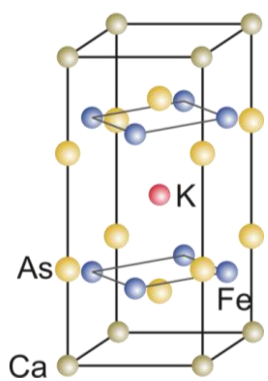
European Committee for Future Accelerators

Towards the use of accelerator HTS magnets in HEP colliders









Luca.Bottura@cern.ch

105th Plenary ECFA meeting

CERN, Geneva, 14-15 November 2019

CERN

Outline

https://en.wikipedia.org/wiki/Technological_applications_of_superconductivity

Wikipedia
The Free Encyclopedia

High-temperature superconductivity (HTS) [edit]

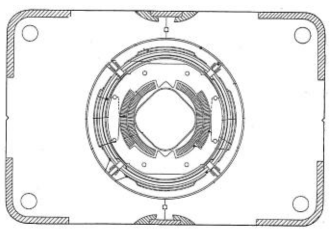
The ~~commercial~~ applications so far for high temperature superconductors (HTS) have been limited.

- The **Challenges** of accelerator magnets at the *energy frontier*
- The status of our **Achievements**
- **Opportunities** for HTS
- A **Perspective** for a development plan

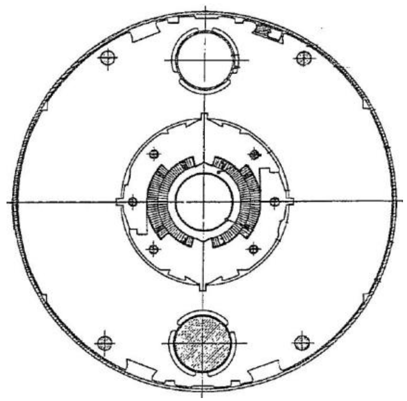
CHALLENGES

I EXPECTED TIMES LIKE THIS- BUT NEVER THOUGHT THEY'D BE SO BAD, SO LONG, AND SO FREQUENT.

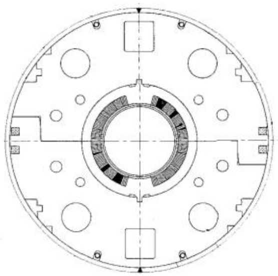
Superconducting dipoles (of the past)



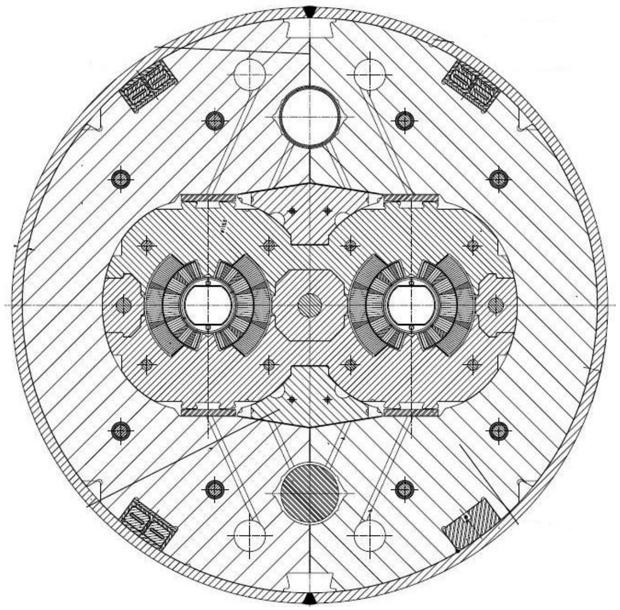
Tevatron
1983-2011
Bore: 76 mm
Field: 4.3 T



HERA
1991-2007
Bore: 75 mm
Field: 5.0 T



RHIC
2000-running
Bore: 80 mm
Field: 3.5 T



LHC
2008-running
Bore: 56 mm
Field: 8.3 T

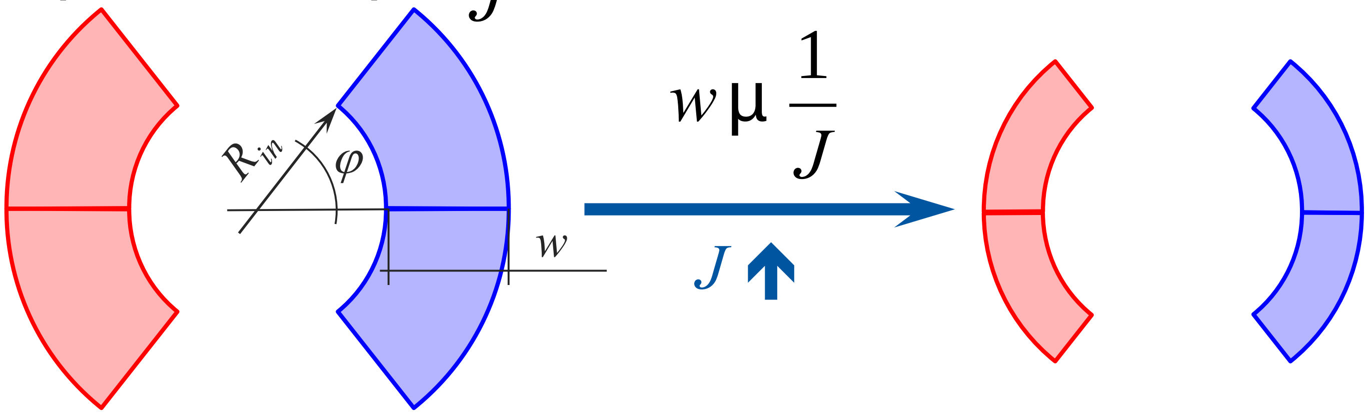
J_C ! J_C ! J_C ! (A. McInturff)

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

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

$$A_{coil} = 2\varphi\left(w^2 + 2R_{in}w\right) \propto \frac{1}{J^n} \qquad n \approx 1\ldots2$$

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



$$w \propto \frac{1}{J}$$

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

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

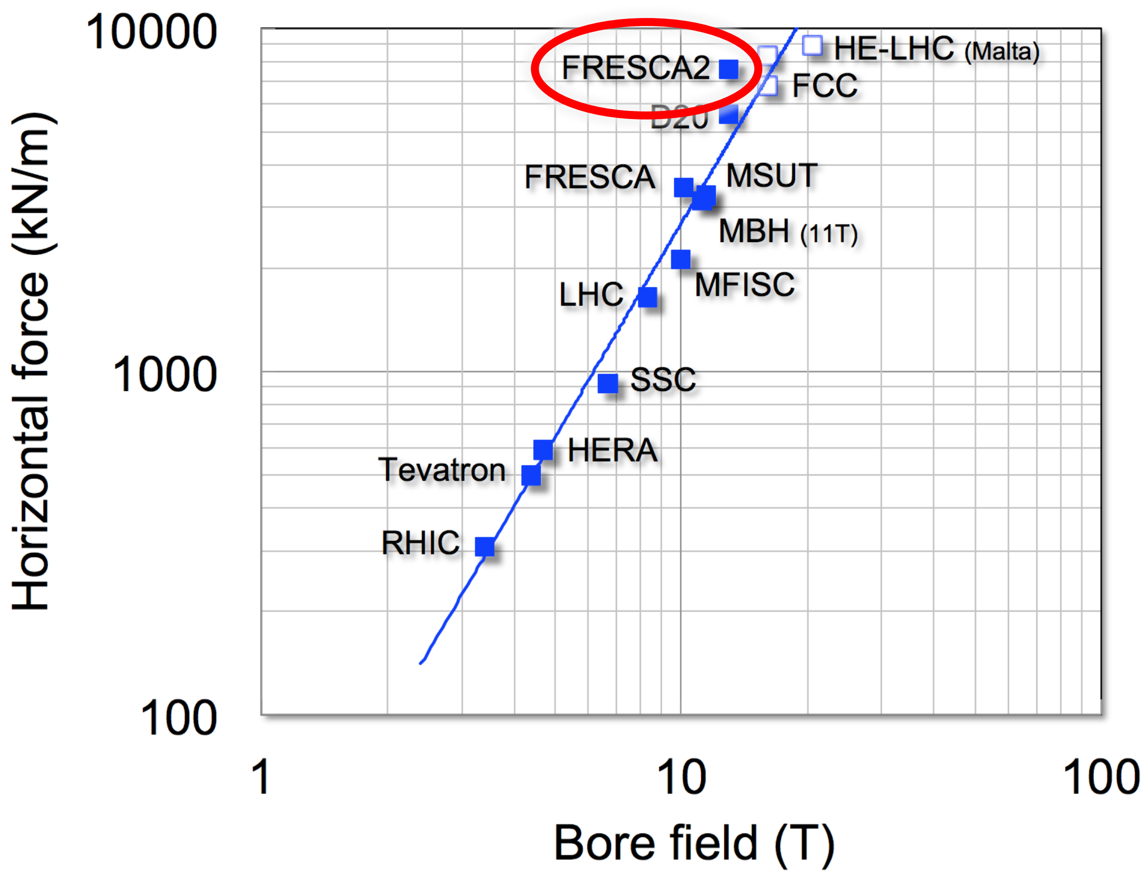
16	
600	Factor 2
38	
7000	Factor 3

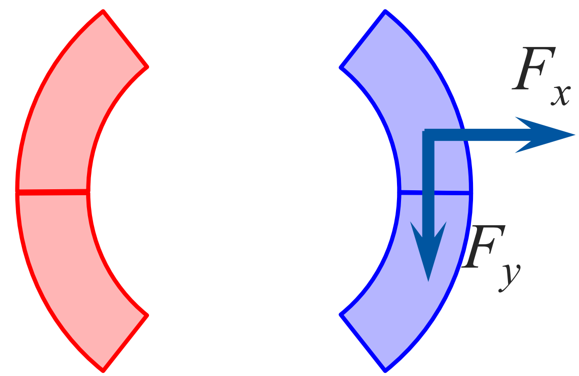
1. We need a high Jc material

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

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

A simple exercise:

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

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

$J_{Cu} \approx$ 1000…1250 (A/mm²)

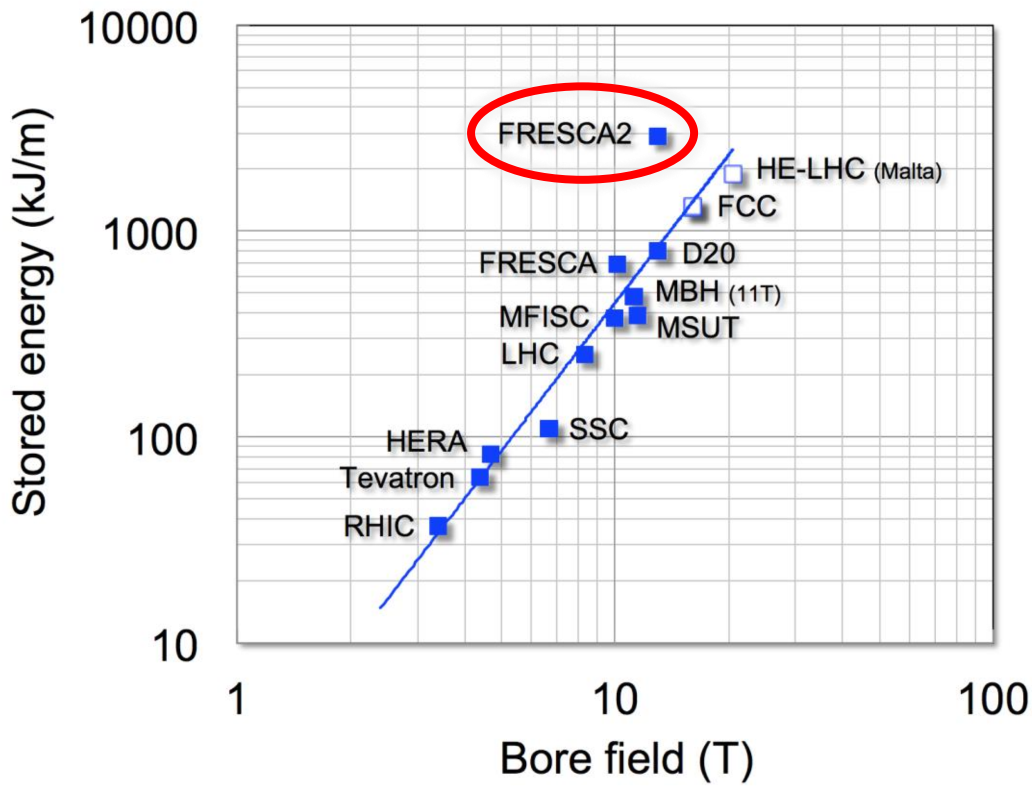
$dT/dt \approx$ 1000…2000 (K/s)

$\tau_{(300\ K)} \approx$ 0.15…0.3 (s)

$I_{op} \approx$ 15 (kA)

$E/l \approx$ 1000 (kJ/m)

$V/l \approx$ 500…1000 (V/m)



It is not possible to protect accelerator magnet strings using an external dump

Reminder

- Accelerator magnets have, alas, a number of other critical requirements, among them:
  - **Field quality**: we need a field homogeneity reproducible (and stable) at o(100 ppm) level to be able to correct errors down to o(1 ppm) level
  - **High current/low inductance**: strings of magnets need to be powered with high precision o(1 ppm) at *reasonable* voltage o(1 kV)
  - **Cryogenic consumption**: the power balance of a superconducting accelerator is largely dominated by the power required to run *the fridge*, the cold heat load should be small o(1 W/m @ 1.9 K) to manage the power requirement
  - **Large scale manufacturing**: accelerators require o(10^3) of magnets, and call for robust production engineering, minimal risk and **cost efficiency**
  - …

ACHIEVEMENT

YOU CAN DO ANYTHING YOU SET YOUR MIND TO WHEN YOU HAVE VISION, DETERMINATION, AND AN ENDLESS SUPPLY OF EXPENDABLE LABOR.

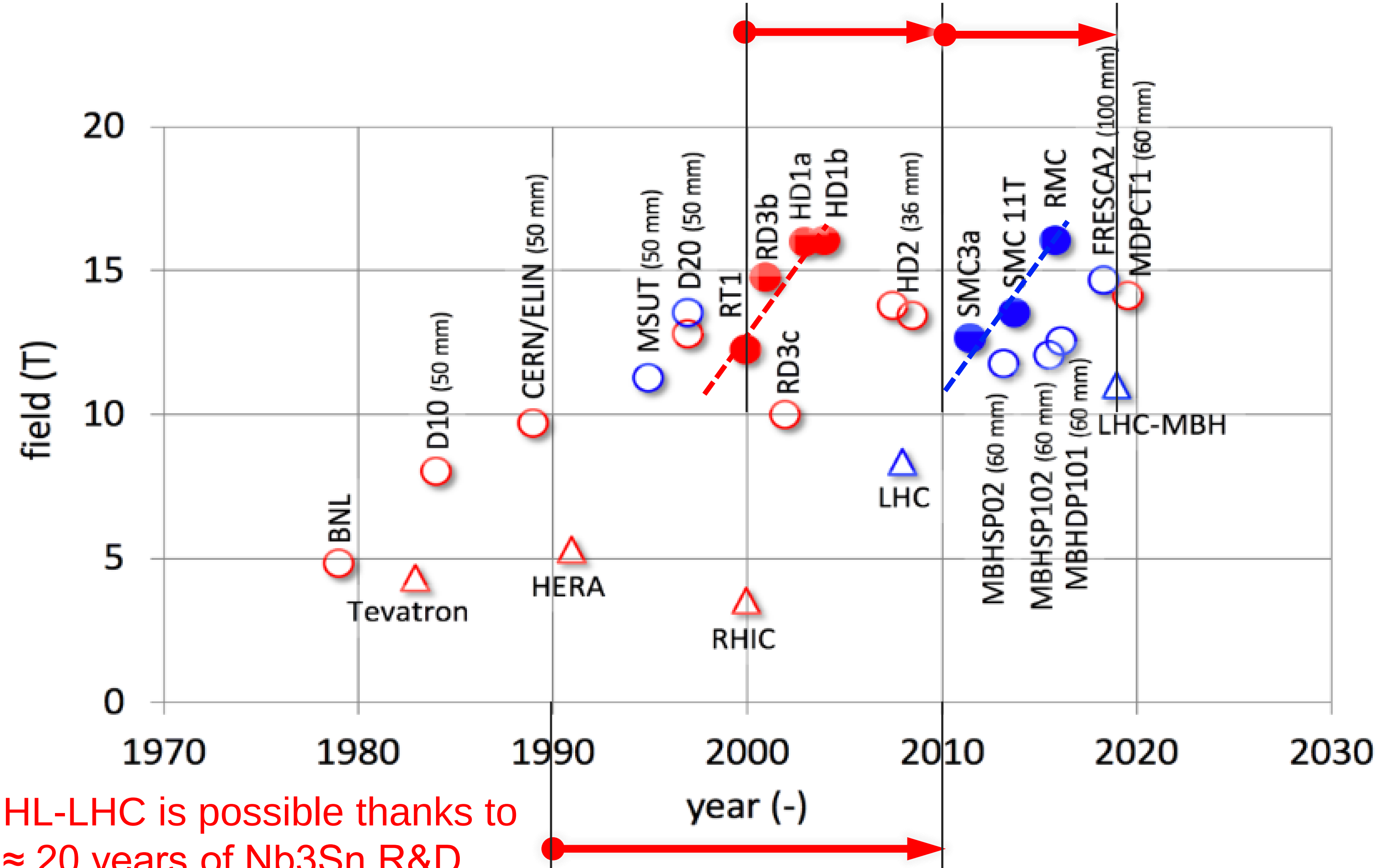
Where do we stand ?

- **The HL-LHC Nb_3Sn program has set a new benchmark**: we have completed the initial model and prototype magnet development for operation in the 11-12 T field range and **the next step is to capitalize on it and get ready for industrialization**.
- We have a few demonstrators showing that Nb_3Sn has the potential to operate at fields beyond 14 T, **the next step is to confirm this potential with model magnets and prototypes**.
- We have not yet had the opportunity to explore the potentials of HTS, **the next step is to develop demonstrators to assess this technology**.

Dipoles

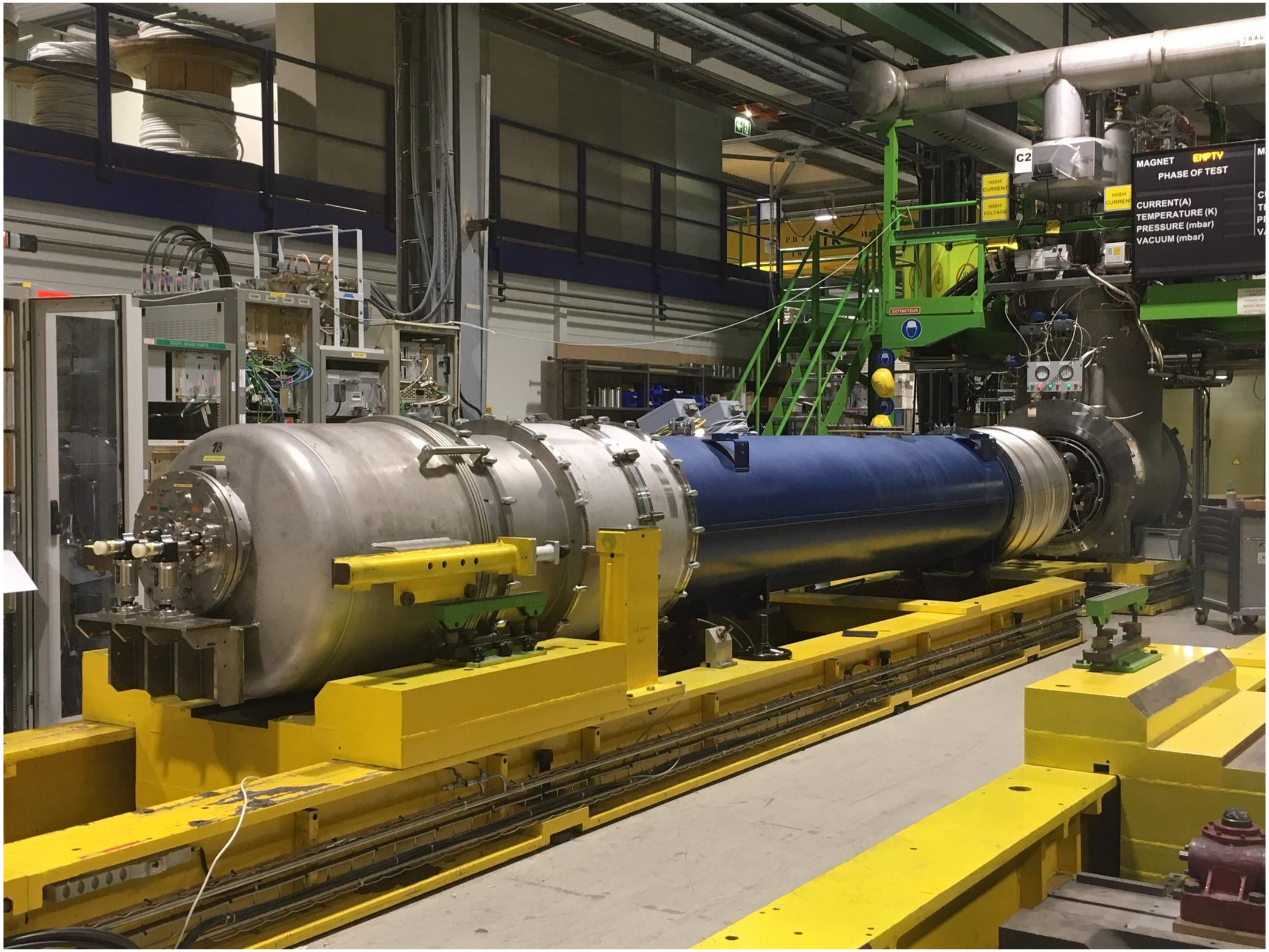
It took ≈ 10 years to establish Nb_3Sn magnet technology

It took ≈ 10 years to make Nb_3Sn accelerator magnets

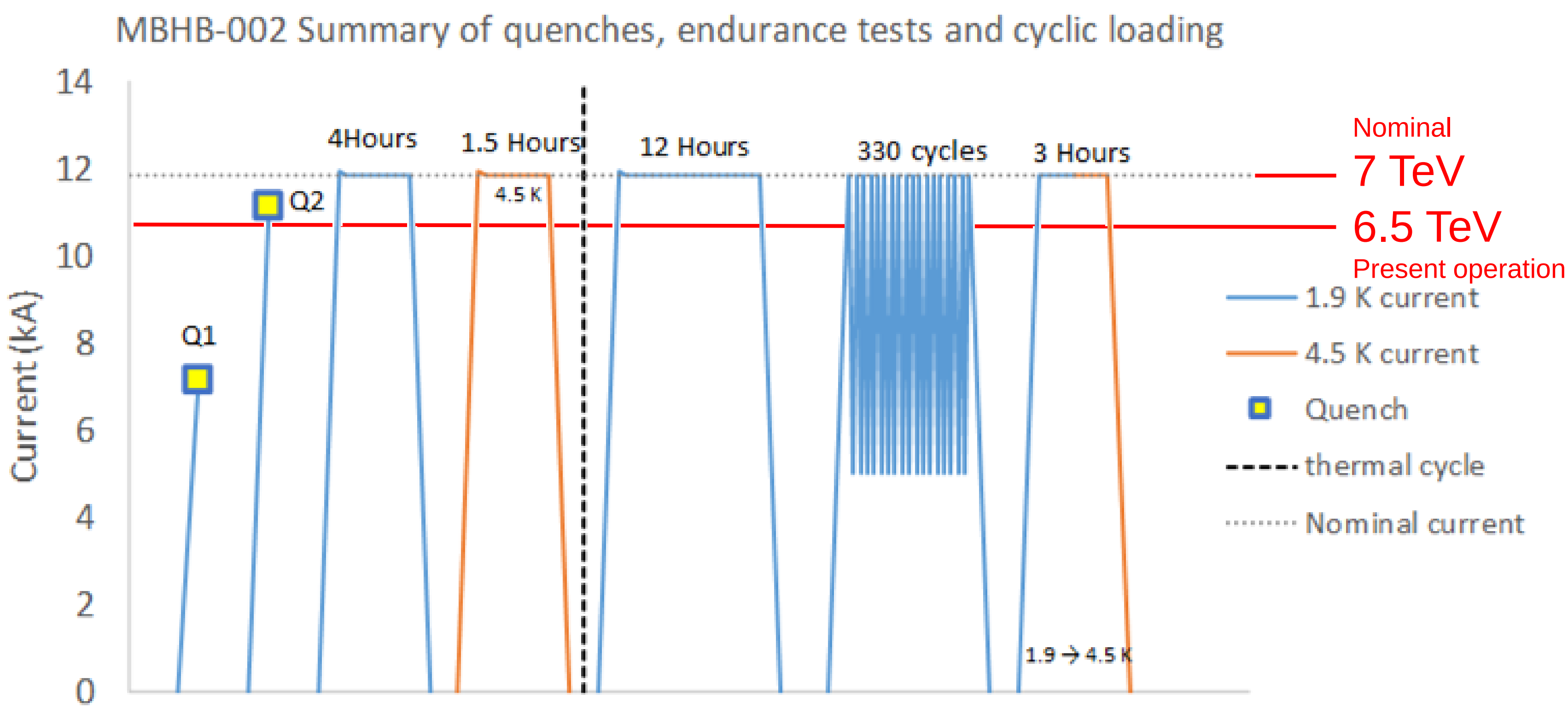


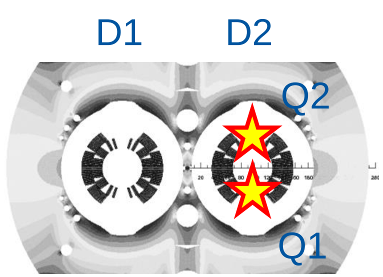
HL-LHC is possible thanks to ≈ 20 years of Nb3Sn R&D

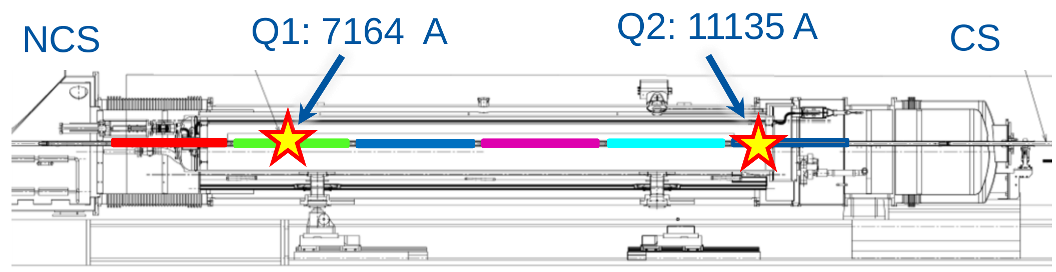
LMBHB0002


C2
HIGH CURRENT
HIGH VOLTAGE
MAGNET
EMPTY
PHASE OF TEST
CURRENT(A)
TEMPERATURE (K)
PRESSURE (mbar)
VACUUM (mbar)

LMBHB002 powering tests



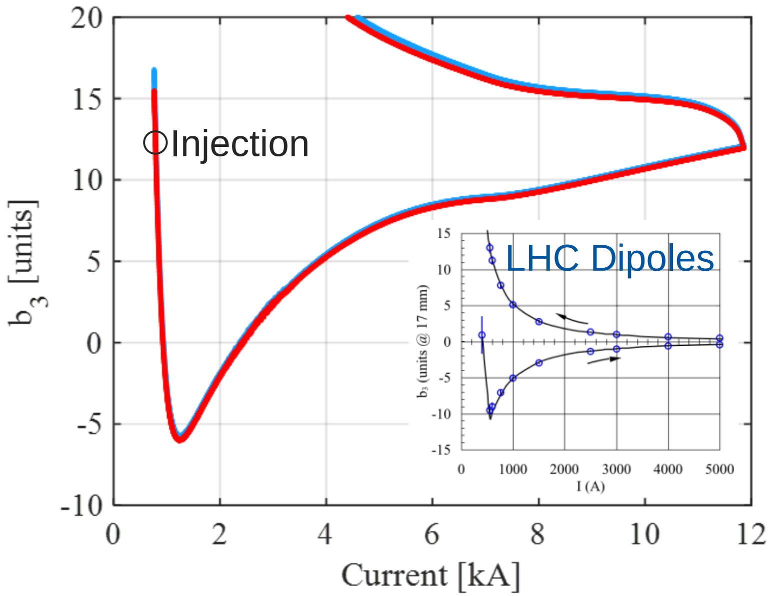




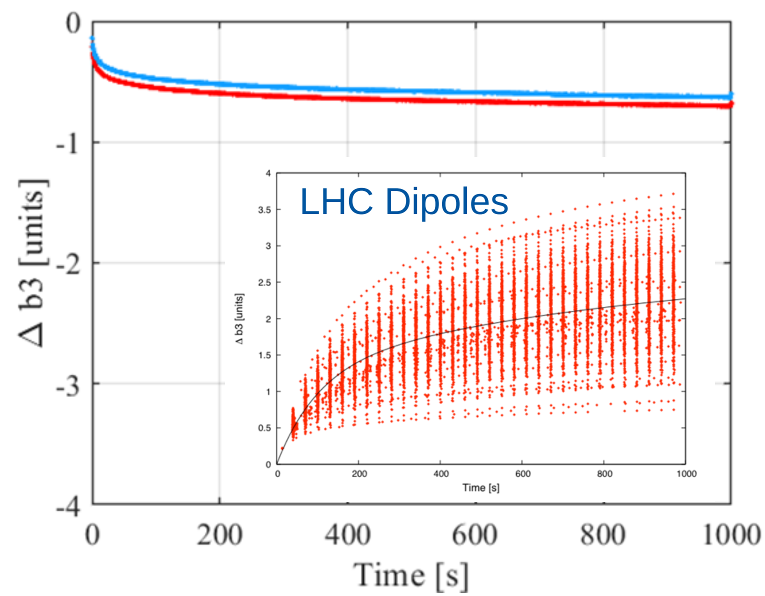
This is an accelerator worthy dipole !

LMBHB002 Field Quality

Persistent Magnetization Currents
(2^{nd} cycle, both apertures)



Time decay at Injection (760 A)



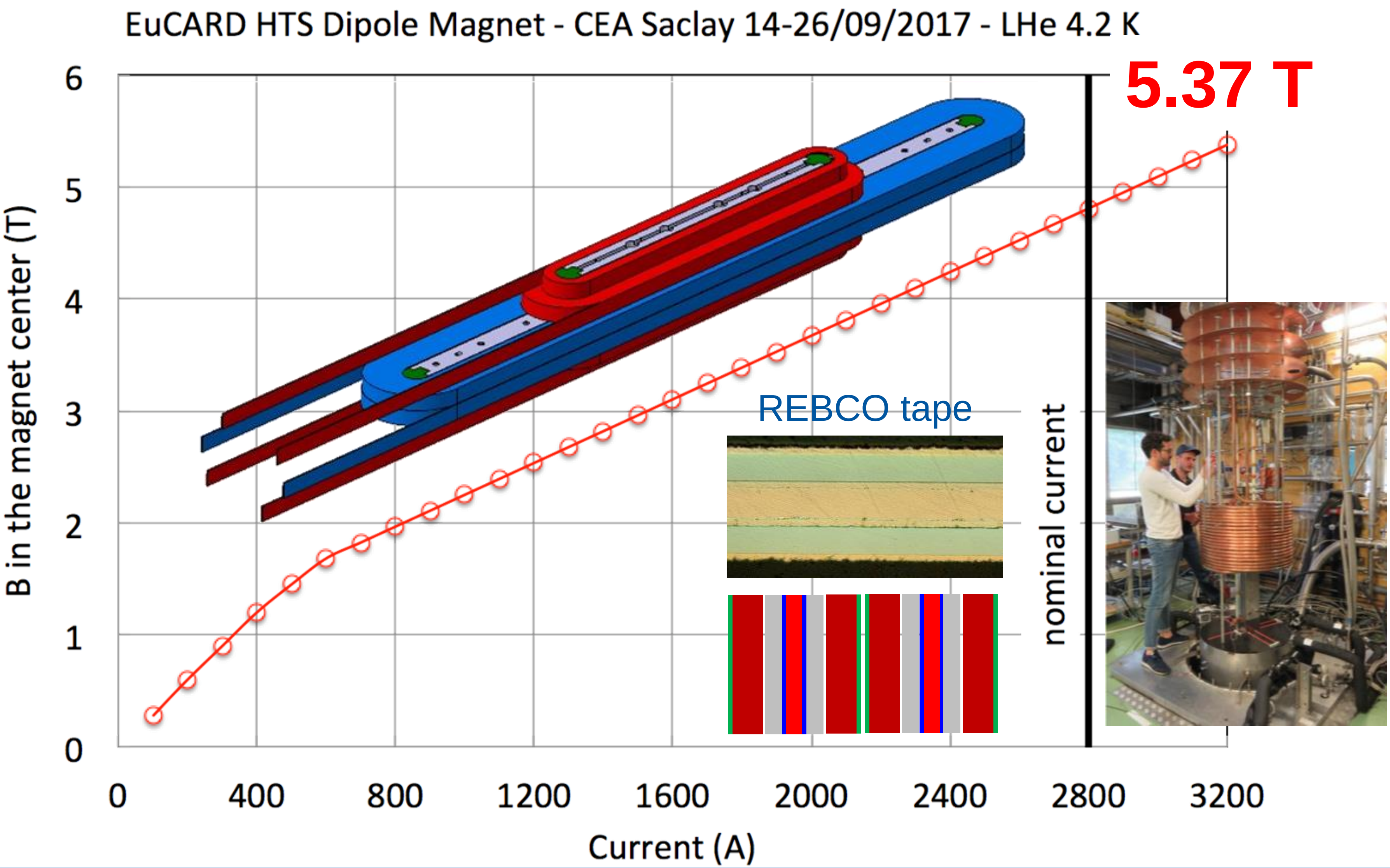
The injection current is on the "wrong side" of the peak of persistent current sextupole due to the inherent magnetic moment of the SC filaments (approximately 50 μm diameter), and ≈ 2.5 times larger than in the LHC Nb-Ti dipoles

b_3 time decay at injection is "reversed" due to the initial point, and relatively small when compared to the LHC Nb-Ti dipoles

This is an accelerator worthy dipole !

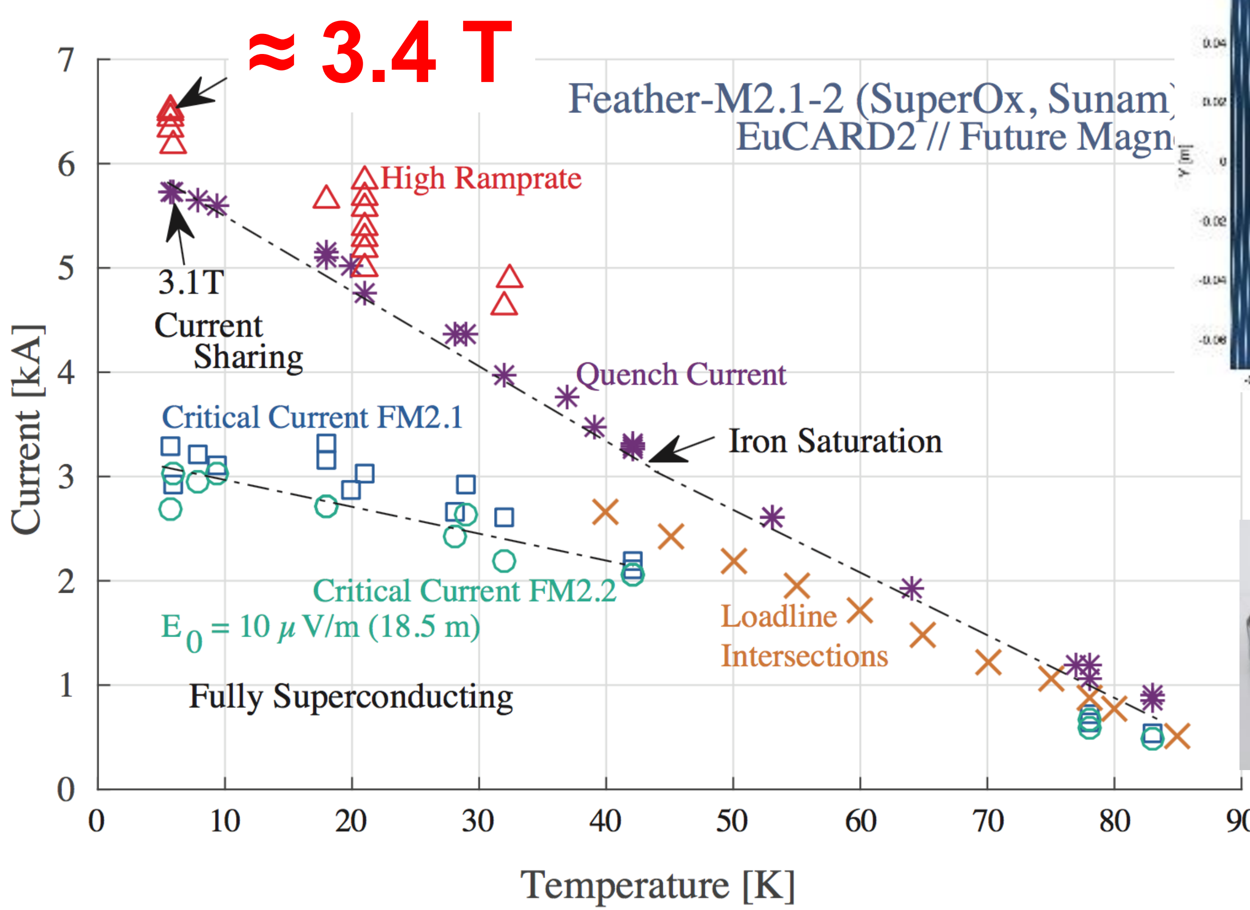
LTS vs. HTS

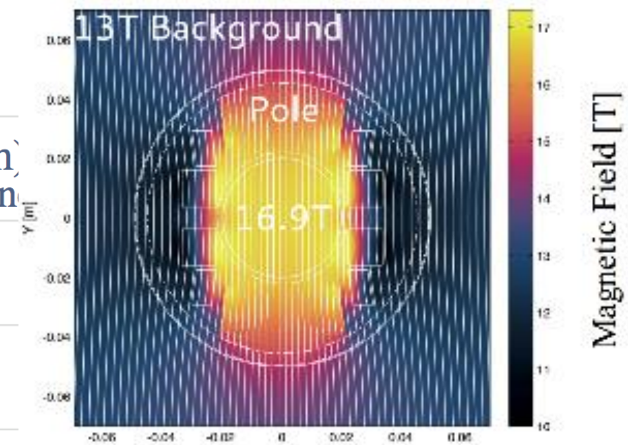
EuCARD - HTS insert



Courtesy of M. Durante, CEA

EuCARD2 – FeatherM2.12

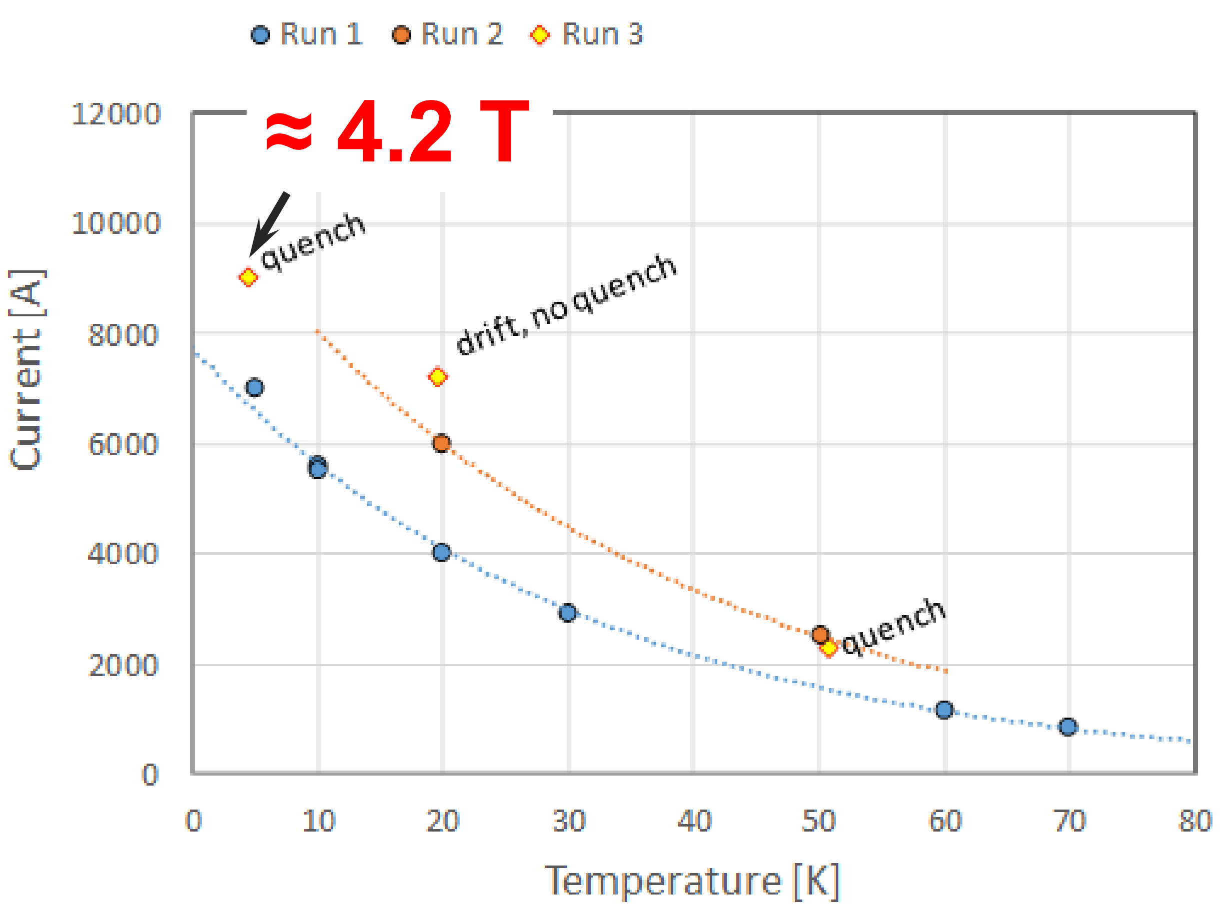




Aligned block design

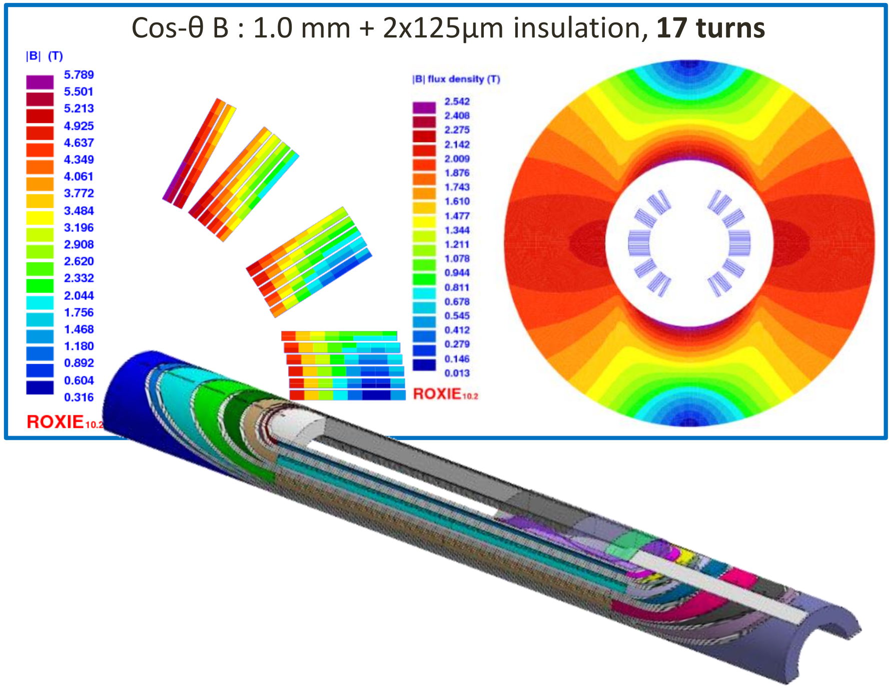
Roebel cable

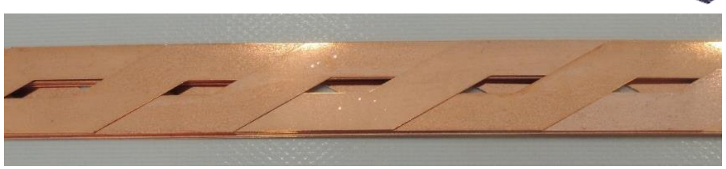
EuCARD2 – FeatherM2.34

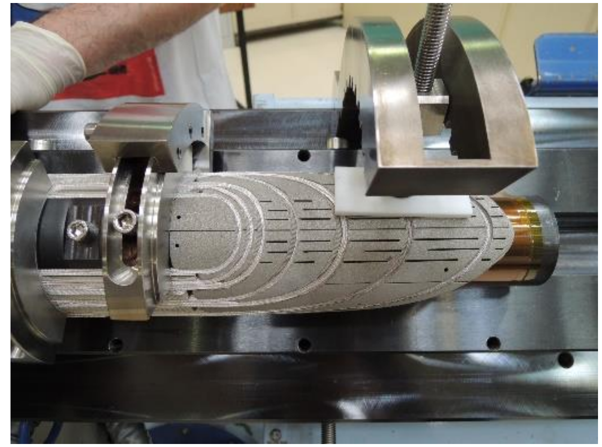


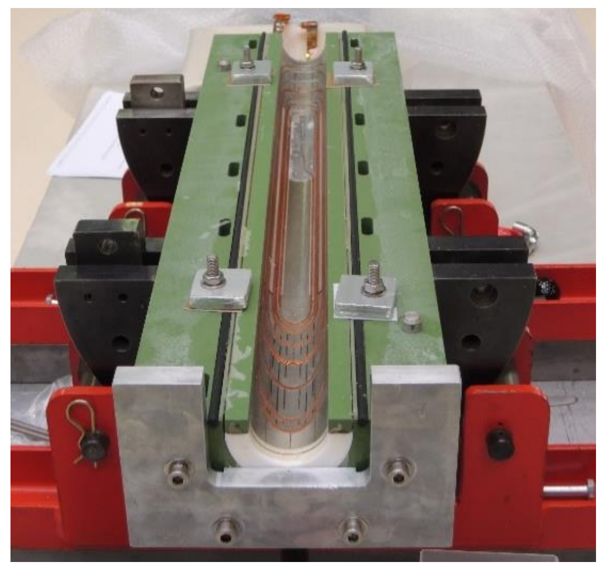
We are taking baby-steps

EuCARD2 – cos-theta









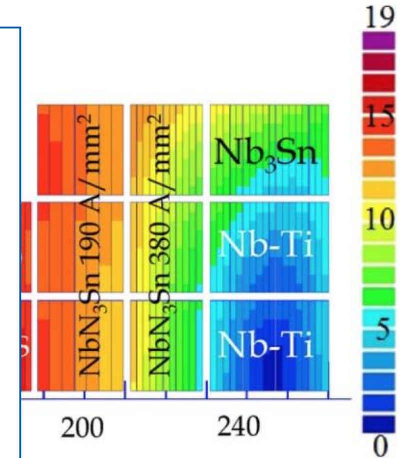
I AM DR. ADEWOLE AREMU- DIRECTOR OF THE UNION BANK OF NIGERIA- I WISH TO SPEAK TO YOU MOST URGENTLY ABOUT A MATTER REGARDING A SUM OF $39,000,000 US DOLLARS…

1. Ultra-high fields

20 T “Malta

Graded LTS an

E. Todesco, IEEE TAS



3(4), 2018, 4008509

Let us make a simple exercise:
A 20 T dipole with 50 mm bore

J_E = 600 A/mm^2

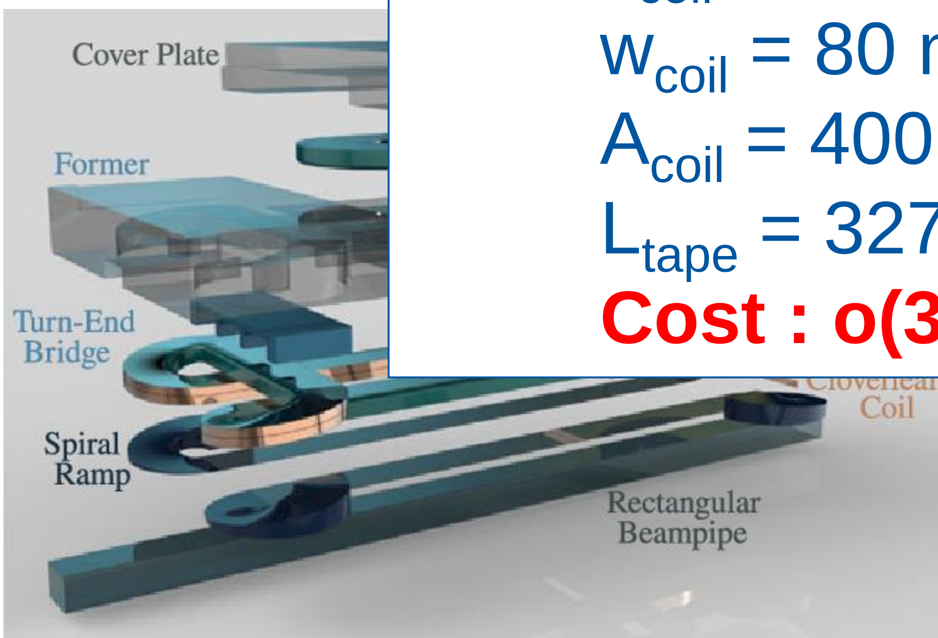
J_{coil} = 400 A/mm^2

w_{coil} = 80 mm

A_{coil} = 400 mm^2

L_{tape} = 327 km

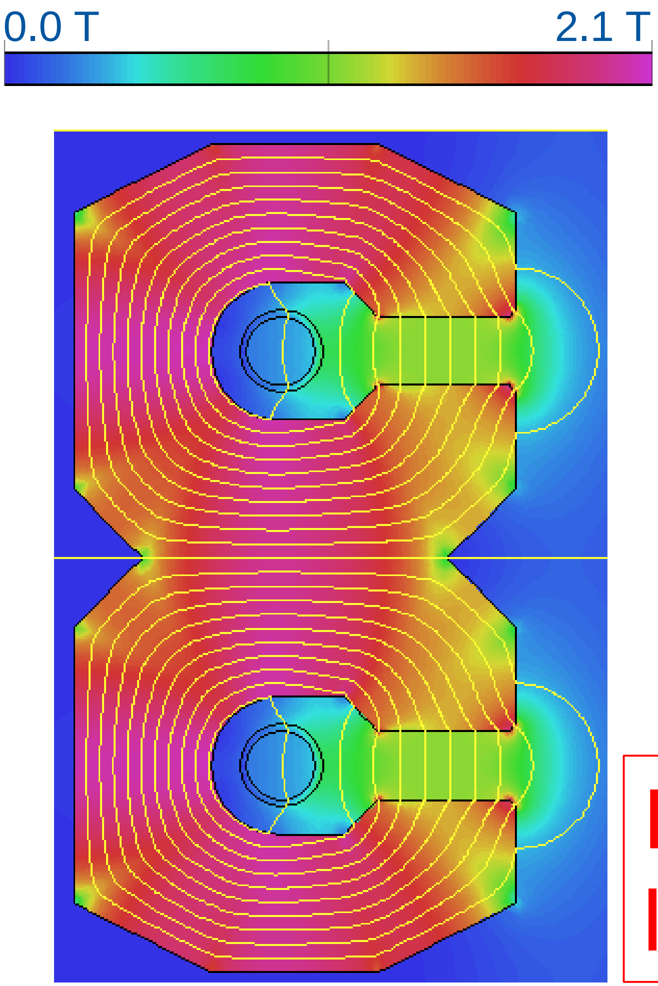
Cost : o(30 MEUR)



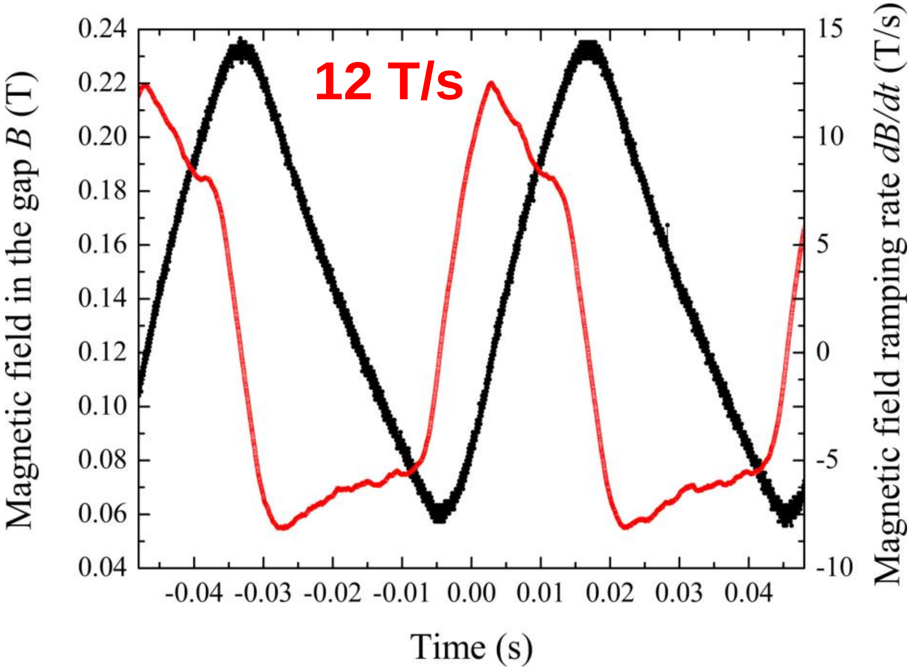
HTS can break the LTS supremacy

These are only two relevant examples …

2. Operating margin



H. Piekarz, NIM PR-A, 943(1), 2019, 162490

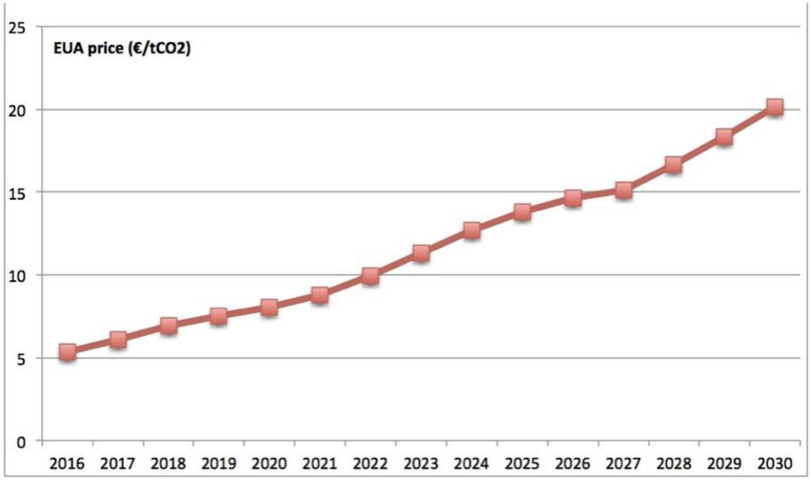


HTS can tolerate large heat loads (including radiation)

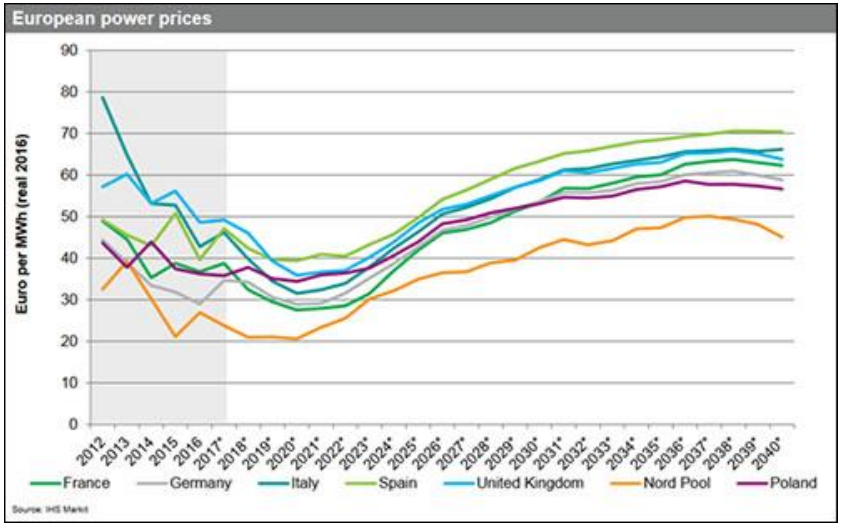
A study of an FCC-hh booster
A. Milanese, TUOCB01, IPAC 2014

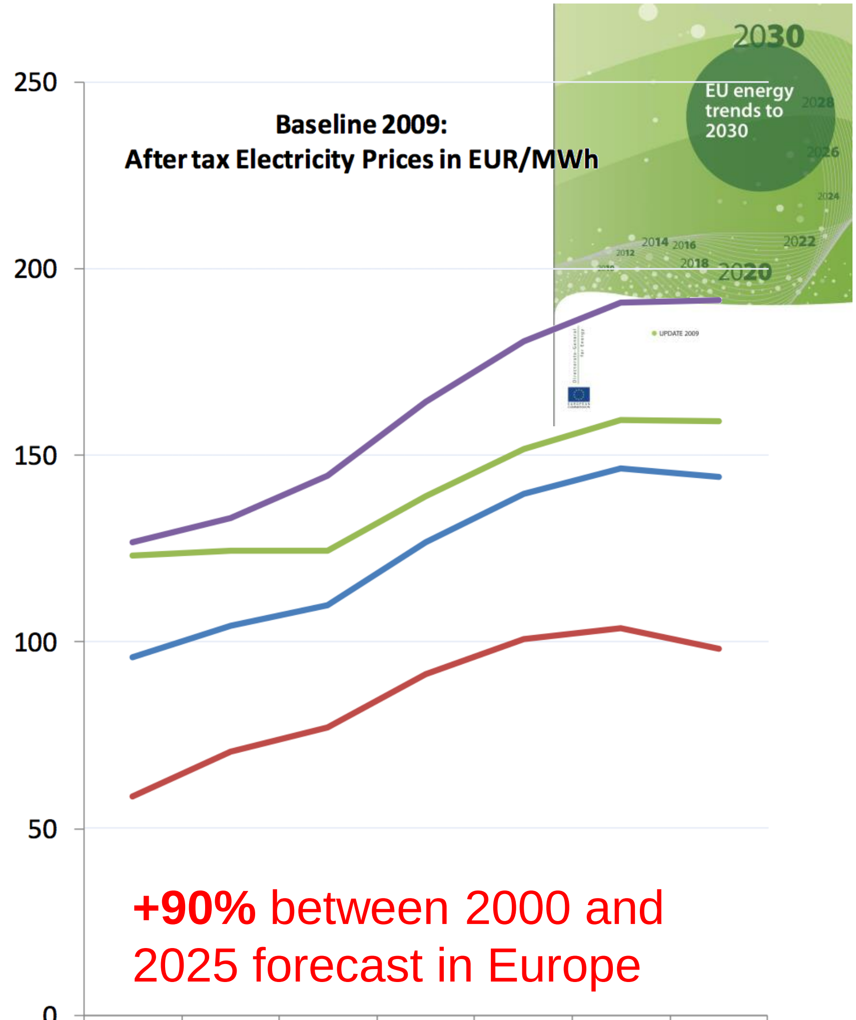
These is only a relevant example …

Electricity price



Source: Thomson Reuters Point Carbon



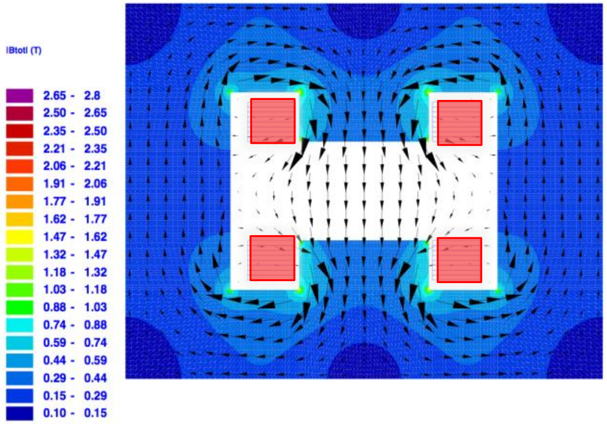


	2000	2005	2010	2015	2020	2025	2030
Average	96	104	110	127	140	146	144
Industry	59	71	77	92	101	104	98
Services	123	124	124	139	152	159	159
Households	127	133	144	164	180	191	192

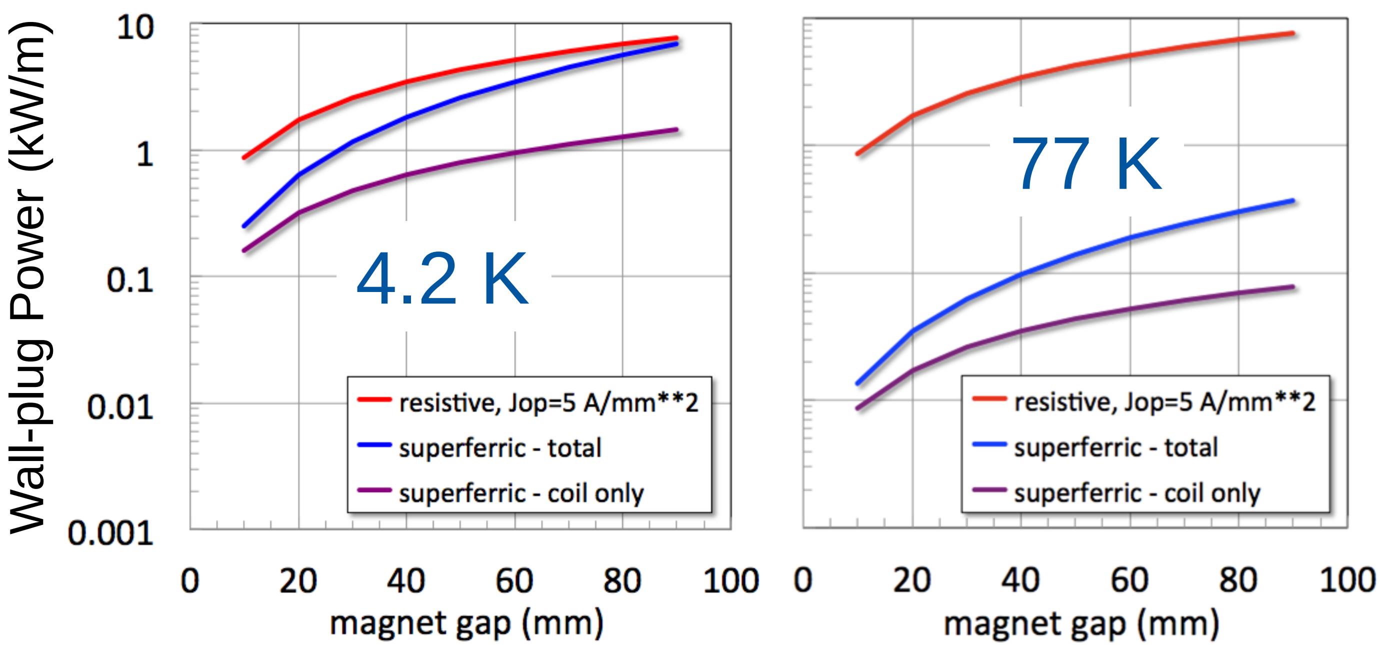
+90% between 2000 and 2025 forecast in Europe

It is unlikely that electricity price will decrease

3. Energy efficiency



A superconducting magnet will be competitive if we achieve a wall-plug power per unit magnet length *much below* 1 kW/m



HTS can offer a significant energy benefit

This is only a study case …

Opportunities for HTS

- HTS for field (or high J_E)
  - Attain fields o(20 T) and J_E o(1000 A/mm^2), initially providing ad-hoc solutions for specific functions or regions (e.g. function similar to the HL-LHC 11 T Nb_3Sn dipole)
- HTS for operating margin
  - Potential for solutions where radiation tolerance, heat removal and temperature margin are paramount to reliable operation (e.g. nuclear physics)
- HTS for low consumption
  - Large installations for HEP are naturally very *power-hungry*. HTS can provide solutions for energy efficiency, as a retro-fit or for future projects (e.g. injectors, boosters, detector magnets)

CERN

If only the cost was lower !


© DESPAIR.COM
PERSPECTIVES
YES, BUT EVERY TIME I TRY TO SEE THINGS YOUR WAY I GET A HEADACHE

The leading questions

- What is the potential of HTS materials to **extend the performance reach** of high-field superconducting accelerator magnets ?
  - Basic material and conductor properties
- Are HTS conductors, cables, coils **suitable** for accelerator magnet applications ?
  - Cable concept
  - Winding and mechanics
  - Quench detection and protection
  - Field quality
- What **engineering** solutions are required to build such magnets, including consideration of material and manufacturing **cost** ?
  - Splice and joint technology
  - Insulation and impregnation

HTS development matrix

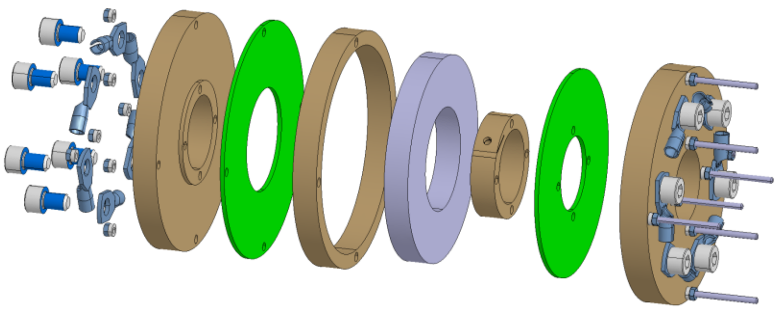
A first attempt at structuring a development program for HTS accelerator magnets

		Basic material and conductor properties (Ic(B,T,α,ε), RRR, k, M, R, …)	Cable concept (stacks, Roebel, transposition, defects, current sharing…)	Splice and joint technology	Insulation / impregnation	Quench detection and protection	Winding and mechanics	Field quality
Conductor R&D	Tape/Wire							
	Cables							
	Joints							
Magnet technology	Small coils (I, PI, NI)							
	Demo coils							

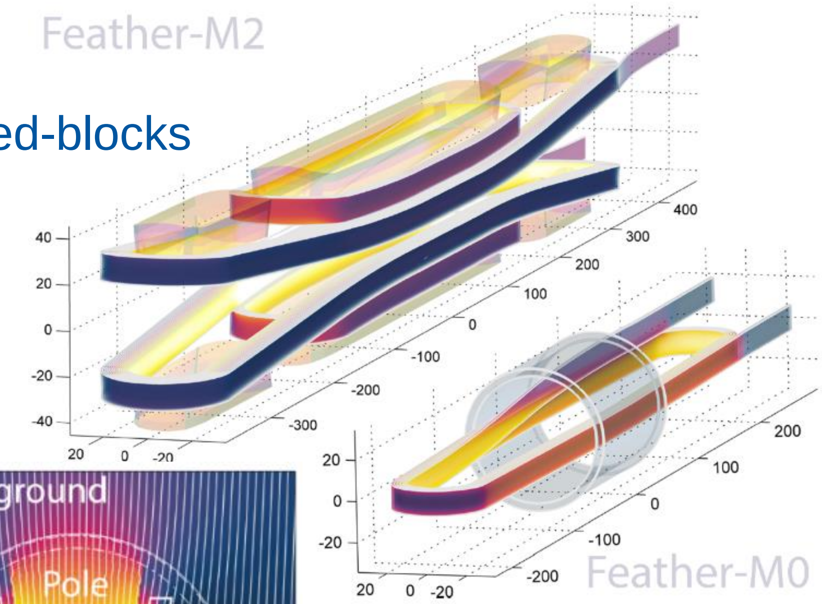
The vehicles (in addition to material, conductor and cable tests …)

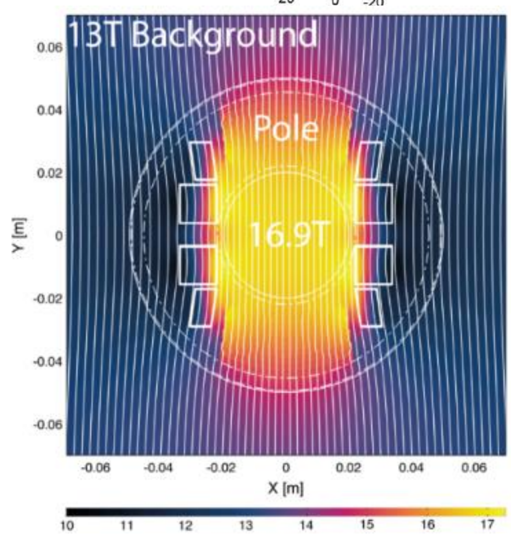
Small coils to test basic magnet properties and technology variants

Insert coils to test in-field behavior and performance reach



Aligned-blocks





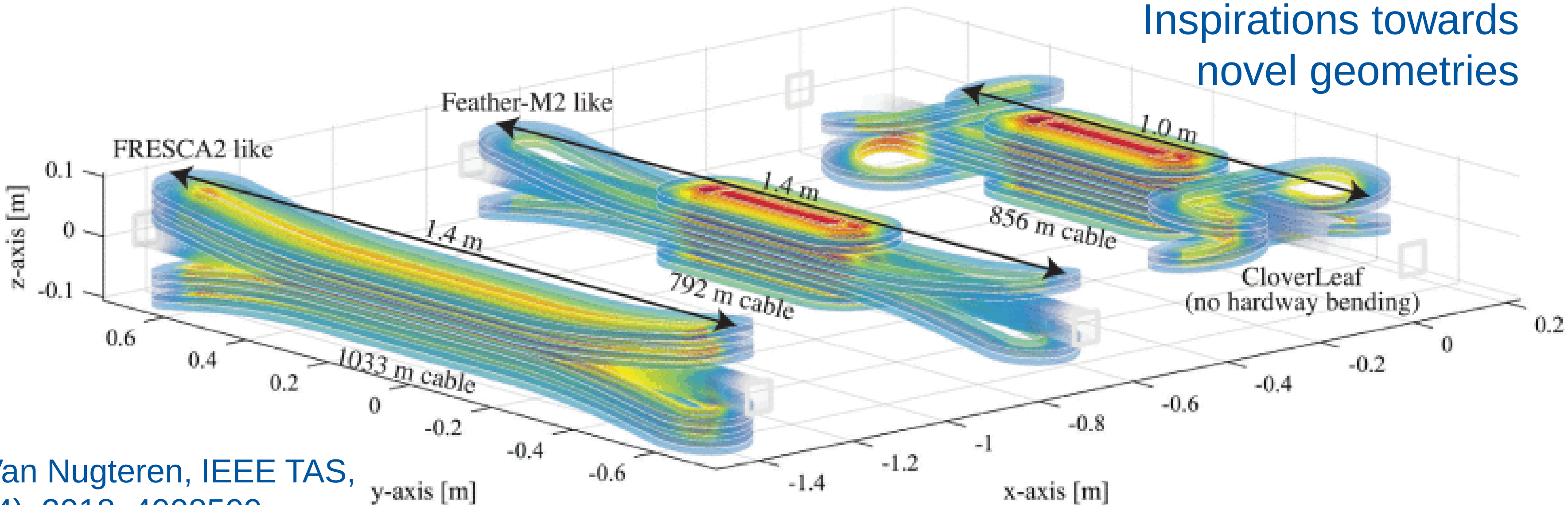
Field generated by Feather-M2 as **insert** in a magnet providing **background field** FRESCA2 (13 T)

This is the right **scale for R&D !**

The models

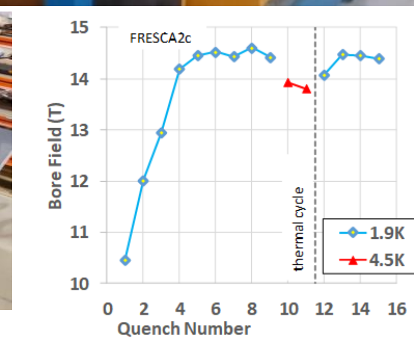
- Specific issues (e.g. winding geometry, field quality, …) may require to realize small magnets with aperture and intermediate field (range of 5 to 10 T)
- Given the charting nature of this R&D, it is important to approach problems gradually, especially in terms of force and energy density
- This is best achieved testing at variable temperature

Inspirations towards novel geometries



J. Van Nugteren, IEEE TAS, 28(4), 2018, 4008509

The test beds

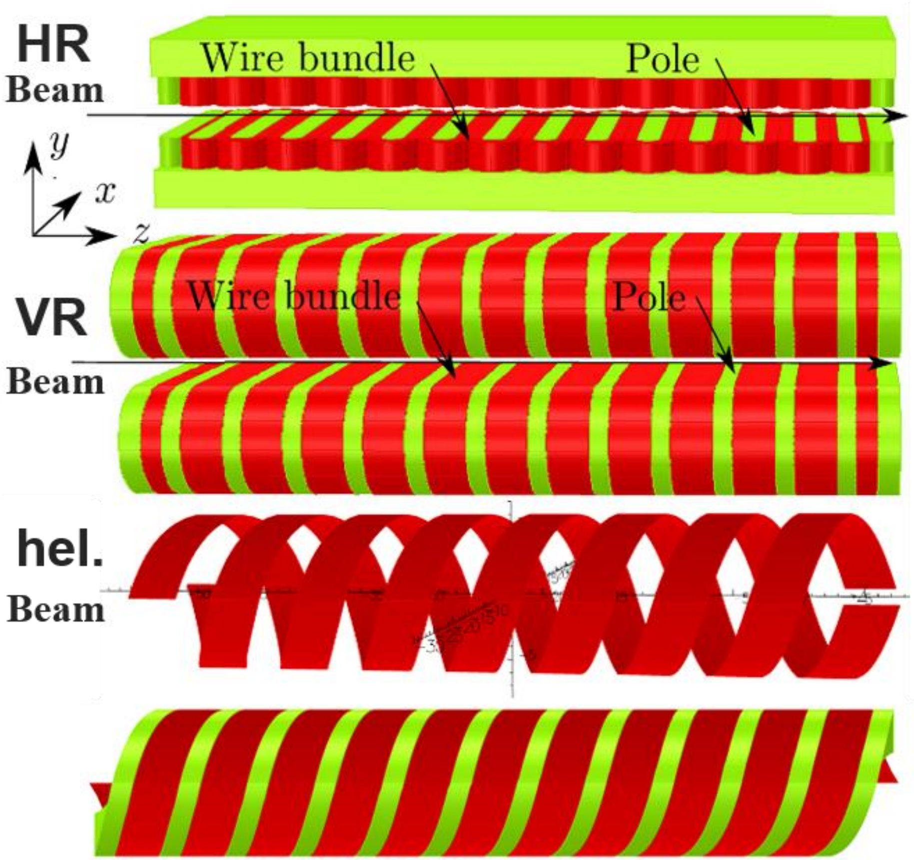


1984: SULTAN at EPFL/SPC (Villigen)
11T at 4.5…100 K, 92x142 mm

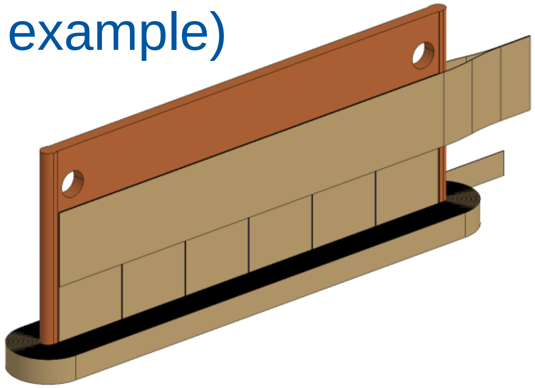
2018: FRESCA2 (CERN/CEA) at CERN
14.6T at 1.9 K, 100 mm

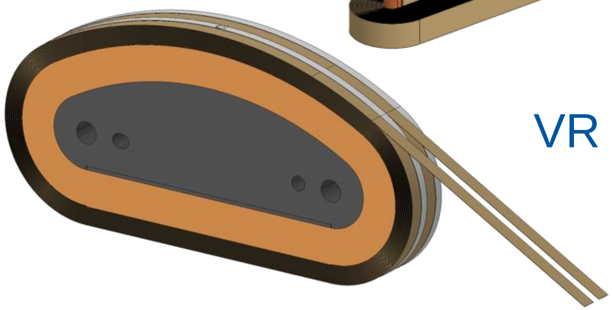
This is **not enough** on the long term !

The demonstrations (one example)



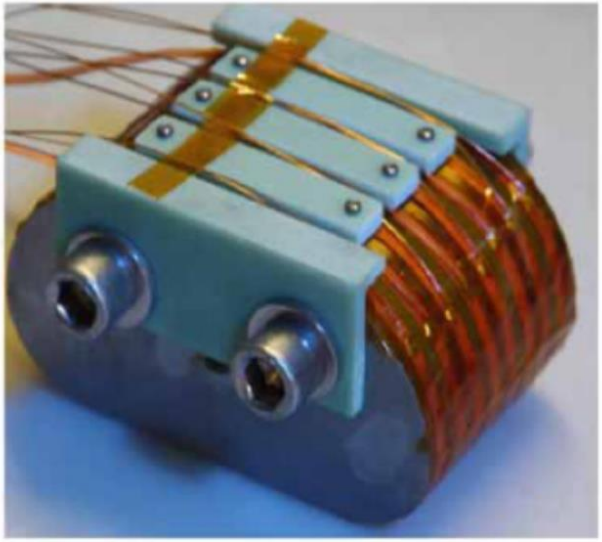
HR coil





VR coil

HTSCU H2020 Proposal
$B_{gap} \approx 3$ T
Gap ≈ 15 mm

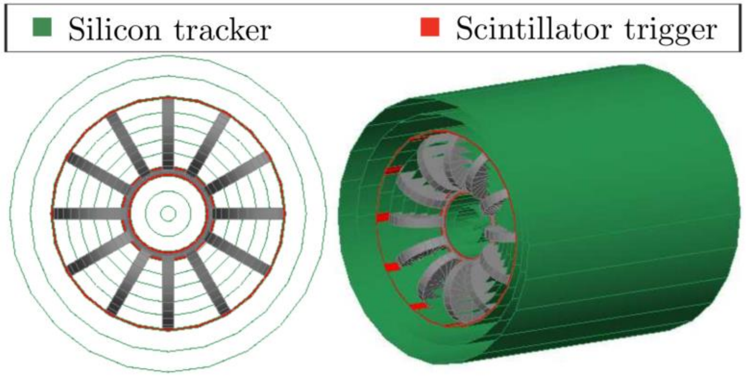


C. Boffo
IDMAX10

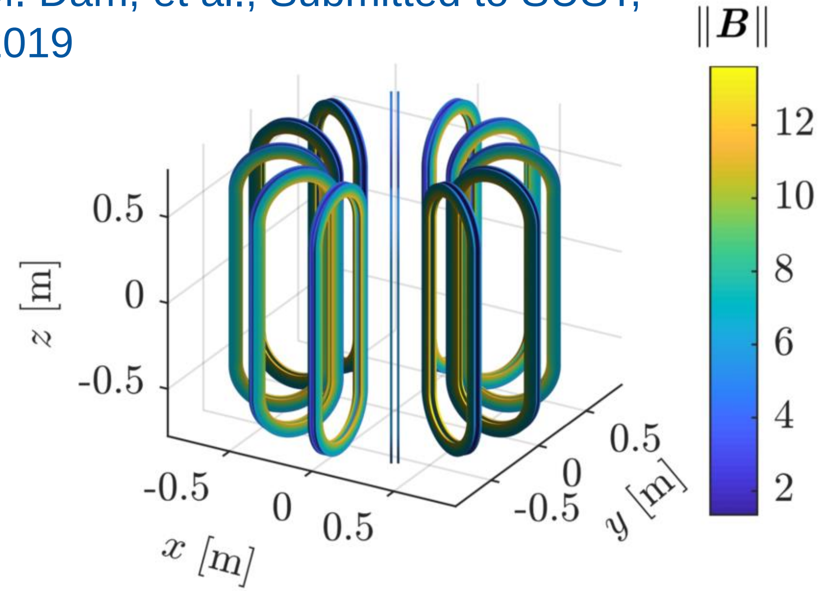
This is the right scale for a beam test !

The demonstrations (other examples)

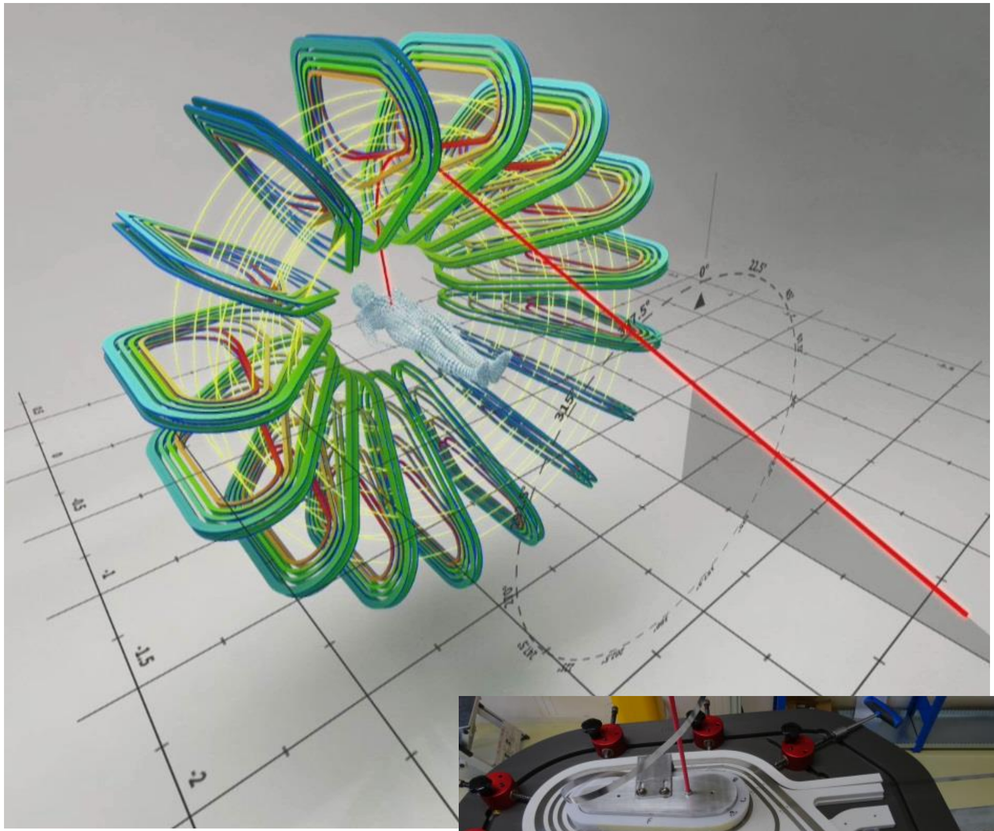
HDMS detector in space



M. Dam, et al., Submitted to SUST, 2019



GaToroid for ion therapy



Magnet configuration and sub-size demonstrator

A piece of history

Proc. ICEC-12, 64-73, 1988

THE IMPLICATIONS OF HIGHER CRITICAL TEMPERATURE SUPERCONDUCTIVE MATERIALS

P. Komarek

This allows the conclusion, that the breakthrough of fusion power will not depend on the availability of new superconductors […]

By no means the time frame would be sufficient to replace the He cooled conductors […] Capital cost savings would be only marginal […]

- I started working on SC cables and magnets in 1986, as a member of the newly formed NET Team (precursor of ITER). Baseline were LTS Nb-Ti and Nb_3Sn. In March 1987 **HTS went viral**
- I graduated in nuclear engineering in February 1986. In April 26th 1986 **Chernobyl reactor 4 exploded…**

(b) Magnetic fusion power systems

… only ~ 3 % of the total capital costs;
… radiation shield, due to the higher heat removal
… only a good radiation resistivity of the new materials,
… veral 10^{11} rad, so that such savings must be quoted as
… ls. Here the larger cross sections due to reduced strength
… ues.
… *6 % roughly*, which is in agreement with another recent study[5].

… at the electric power demand for He-refrigeration of a
… 3 % of the gross electric power output. By LN_2 cooling
… *ease the overall efficiency of the plant by this 3 %, a*

… tors and so also for the superconducting materials, are
… ($\geq$ 11 T), as well as operation under pulsed or a.c.
… ctor tailoring, which the material must be suited for and
… he overall current density, due to the requirements of stabilizer, structure and coolant. Moreover, a capability of condutors for much higher magnetic fields does not necessarily result in improvements, because limits are simultaneously given by plasma and first wall performances due to the higher fusion power density associated with the higher magnetic field.

This allows the conclusion, that the breakthrough of fusion power will not depend on the availability of the new superconductors, but its commercial application can later on benefit significantly from the new technology by the better economy.

(c) Other areas with superconductors as indispensable component

Very similar statements as above one can make for MHD-generators[2], so that those are not treated here further.

Large future particle accelerators are now planned exclusively with superconducting dipoles and quadrupoles for the particle guidance. Confidence for that has been achieved by the successful operation of such an accelerator at FNAL, USA and the well proceeding construction of the HERA accelerator with similar size at DESY, FRG. Much larger accelerators as SSC in USA and LHC at CERN are already in the development phase using NbTi magnets up to their limits or even Nb_3Sn magnets. Considering the potential of LN_2 cooled conductors, one can make following statements:

- By no means the time frame would be sufficient to replace the He cooled conductors for projects already in the development phase now.
- Capital cost savings would be only marginal, because the He-refrigerators represent not more than about 5 % of these costs and on the other hand additional equipment for vacuum pumping would become necessary in the case of LN_2 cooling.
- Attractive savings can be seen for the electricity costs, where for SSC or LHC an electric power of about 20 - 50 MW_{el} in continuous operation mode is needed for LHe cooling, which would be reduced to less than 1 MW_{el} in case of LN_2 cooling.

AREAS WHERE SUPERCONDUCTORS HAVE TO COMPETE WITH CONVENTIONAL TECHNOLOGY

(a) Electrical engineering

This is an area where superconductor application has been investigated since the early time of its development, but in spite of many successful prototype experiments, no commercial implementation could take place yet.

Capitalization of energy losses in electric power systems
For comparison with conventional technology, besides reliability the costs are a major decision factor. Within that the potential saving of energy is usually seen by a factor in the capital costs which is called capitalization

67

CERN

A roadmap from LTS to HTS

- HTS is only in its infancy, but it is the **disruptive high-field magnet technology**, it requires a *revolution* rather than an *evolution.* Let us dream, but remain pragmatic
  - By 2026 – The LHC High-Luminosity Upgrade is the spring-board for new magnet technology and will prove first use ever of Nb_3Sn in a running accelerator (2021 ?). This will be the **new performance benchmark** (**12 T**)
  - 2020-2027 – Address (i) the issue of large-scale and **cost-efficient industrial production** (at the HL-LHC benchmark) and (ii) explore the ***ultimate*** **Nb_3Sn performance** (**16 T**). A solid and comprehensive R&D accompanies this two-prongs development activity
  - 2020-2025 – Upgrade the infrastructure for production and test (in particular **high-field test stations for both LTS an HTS**)
  - 2020-2030 – HTS R&D, spanning from material science to electromechanical engineering. Address in priority the **basic magnet science questions** to explore with small-scale demonstrators whether and how the HTS potential can be exploited, including **considerations of cost**

HTS is the only way to surpass LTS

But…

On a medium term I do not see HTS without LTS

GET TO WORK

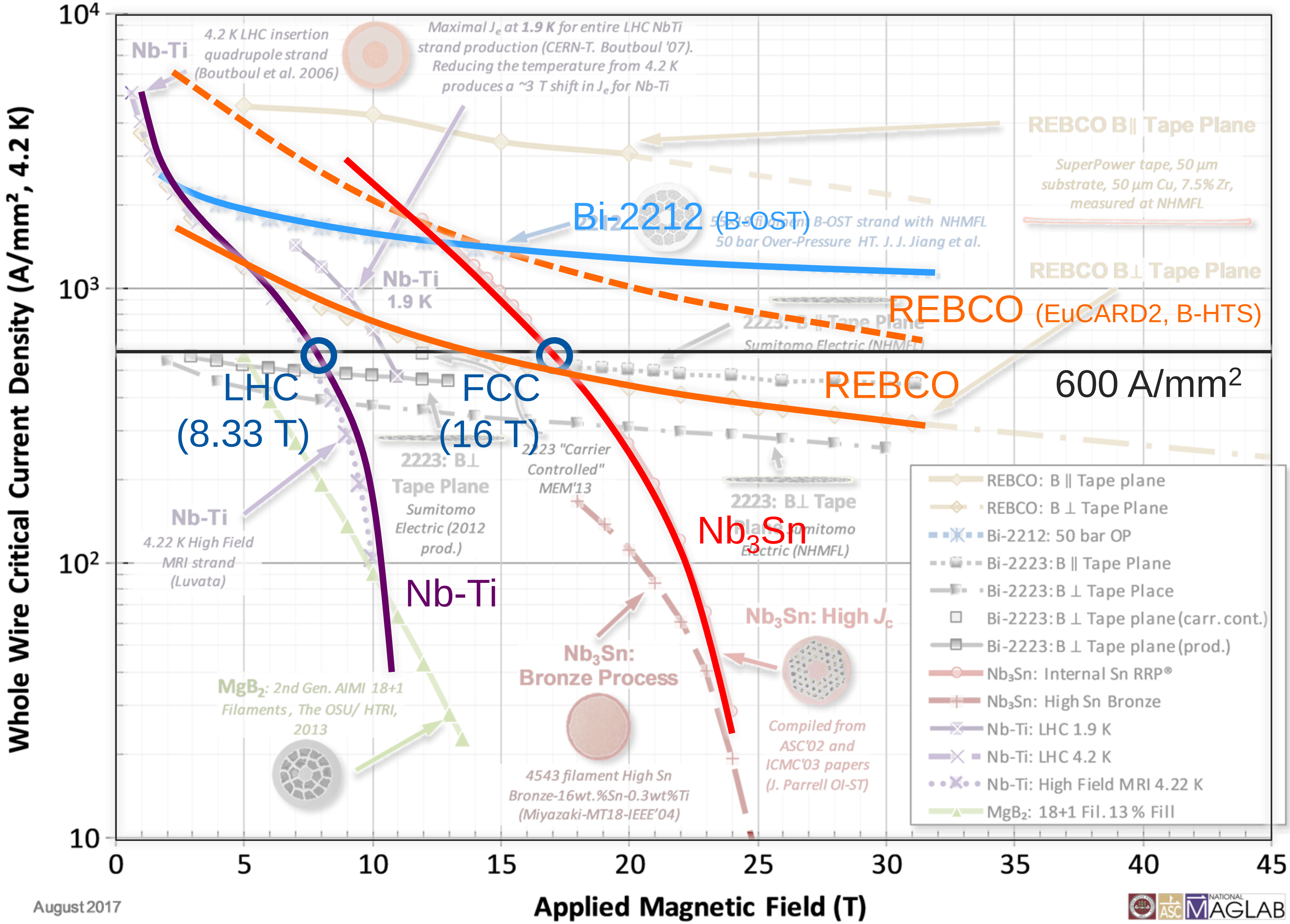
You Aren't Being Paid to Believe in the Power of your Dreams.

Elements of a program (10 years)

- Answer to the basic questions on material selection, potential for high fields, suitability for accelerators, and relevant engineering solutions

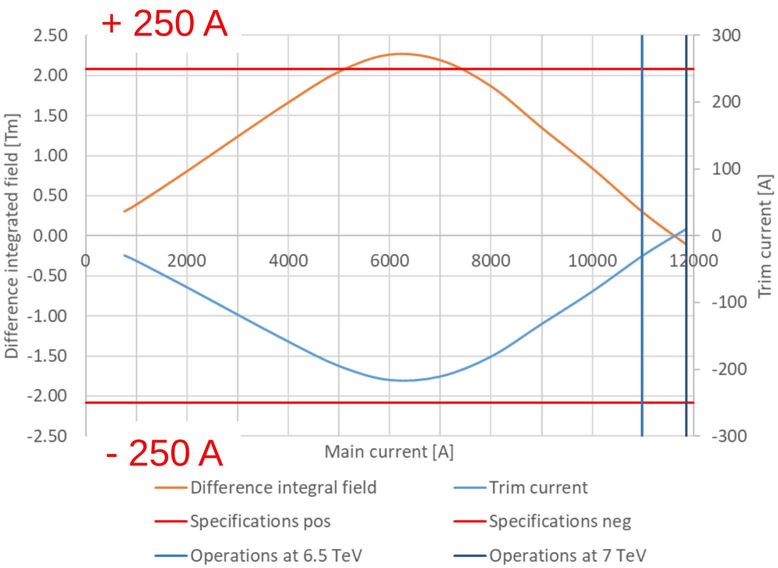
Year	Duration	Activity	Quantity	Cost
0	10	Conductor R&D: material research, tape and wire development and production, cable development and production, characterization	1 to 10 km/y	2 MEUR/y
0	5	Small coils: test of different technologies	5…10/year	1 MEUR/y
2	7	Demonstrators	2…5/year	1 MEUR/y
5	5	Scale-up models	1/year	5 MEUR/y

This is where HTS has the cutting edge

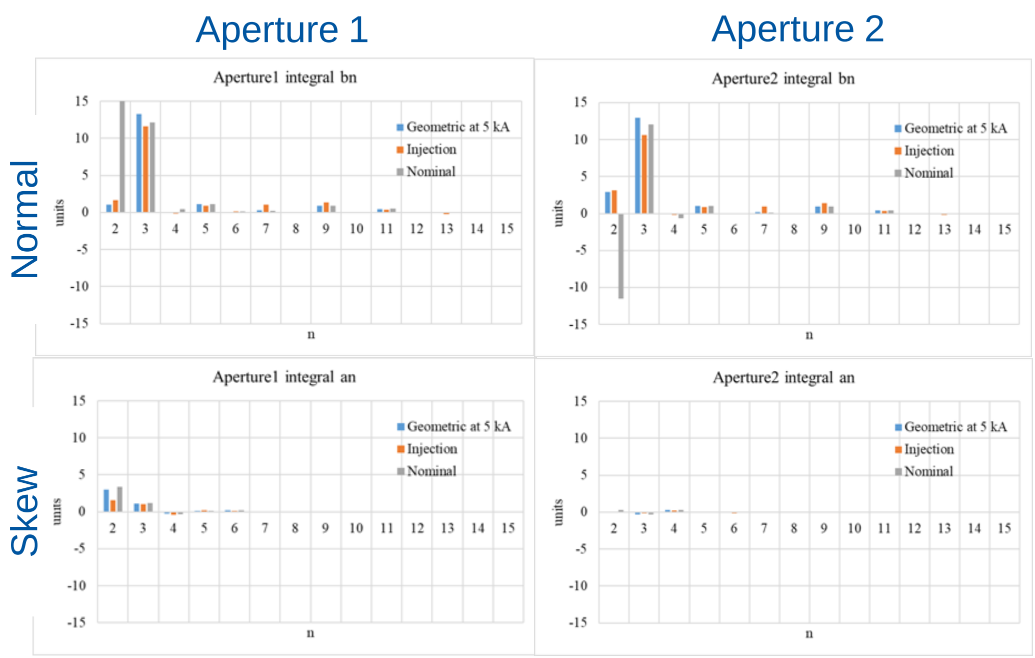


LMBHB002 Field Quality

Transfer Function difference MB vs. MBH



Geometric Multipoles (@17 mm)



A trim current is injected in the 11 T dipole circuit to match LHC dipole transfer function (based on average of integral field measurements for the 2 apertures)

b_2 (normal quadrupole) arises from iron saturation and is as expected (~±14 u);

b_3 (normal sextupole) is a bit larger than expected (~7 u).

This is an accelerator worthy dipole !