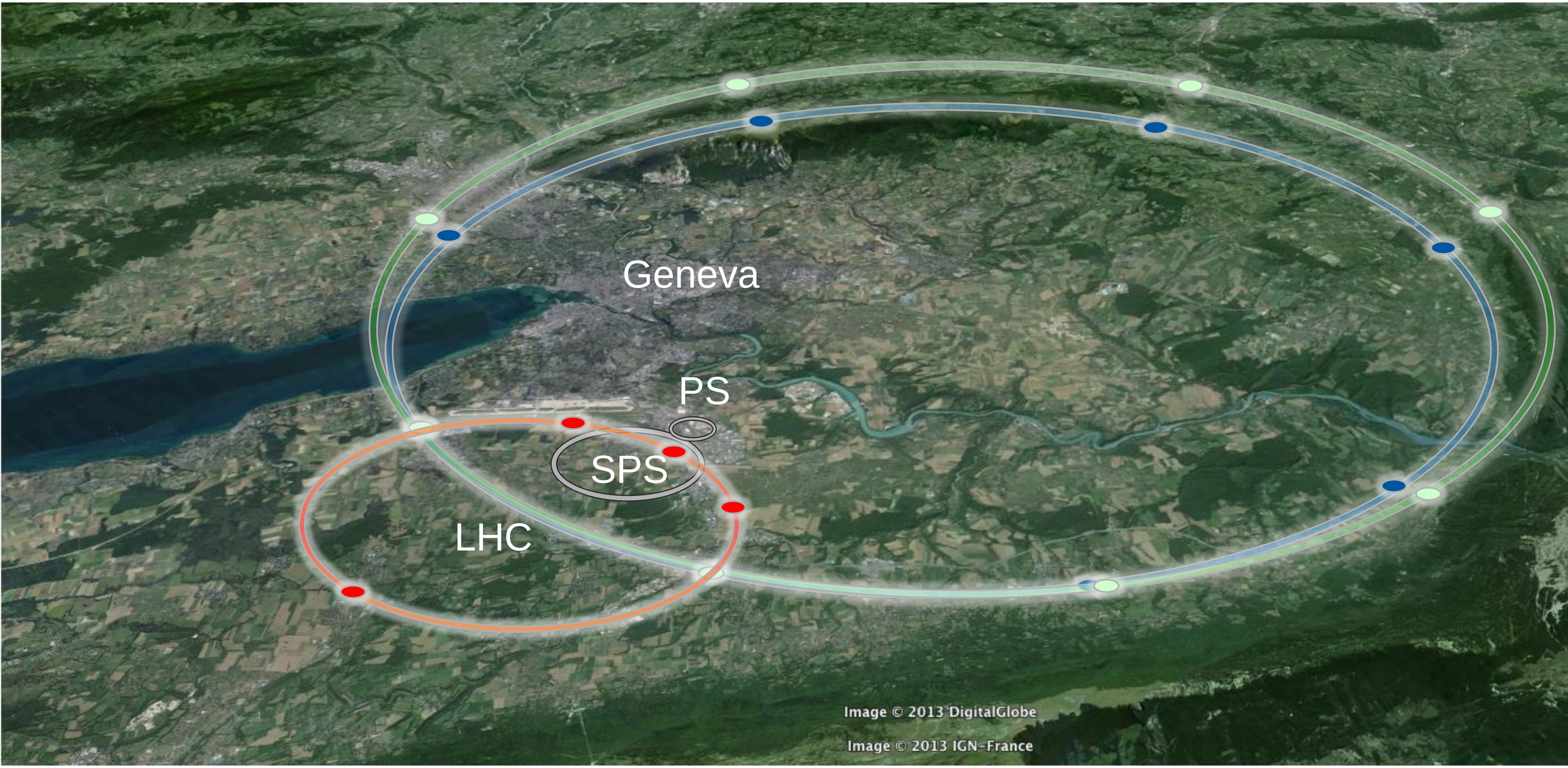
Status of Magnet R&D for the FCC

Presented by Luca.Bottura@cern.ch

Preparation Meeting for the FCC International Collaboration Board

September 9th, 2014

The FCC playground



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS	9000 tons LTS	6000 tons Nb_3Sn
	700 tons HTS	2000 tons HTS	3000 tons Nb-Ti

FCC magnets – LTS option

		B / G (T) / (T/m)	B_{peak} (T)	dB/dt (mT/s)	Bore (mm)	Length (units x m)
FCC	MB	**16**	**16.8**	16	40	**4578** x 14.3
	MQ	375	10	10	40	762 x 6.6
	QX	200	12.5	12.5	90	Optics ?
	D1	12	13	13	60	4x2 x 12
	D2	10	10.5	10.5	60	4x3 x 10
Booster in the FCC	MB	1.1	2	2	50	**4578** x 14.3
injector in the LHC	MB	5	5.25	20	50	1232 x 14.3
injector in the SPS	MB	12	12.5	100	50	892 x 4.7

FCC magnets – HTS option

		B / G (T) / (T/m)	B_{peak} (T)	dB/dt (mT/s)	Bore (mm)	Length (units x m)
FCC	MB	**20**	**21**	16	40	**3662** x 14.3
	MQ	375	10	10	40	610 x 6.6
	QX	200	12.5	12.5	90	Optics ?
	D1	12	13	13	60	4x2 x 12
	D2	10	10.5	10.5	60	4x3 x 10
Booster in the FCC	MB	1.5	2.2	2.2	50	**3662** x 14.3
injector in the LHC	MB	5	5.25	20	50	1232 x 14.3
injector in the SPS	MB	12	12.5	100	50	892 x 4.7

Three directions for R&D

- 16 T dipole for the FCC-hh main arc
  - Challenges: field level with a 40…50 mm bore, field quality, protection, cost
  - Proposal: develop A15-based 16 T dipole technology, with sufficient aperture and accelerator features. Build short model(s) as a worldwide effort
- 20 T dipole for the FCC-hh main arc and special regions
  - Challenges: feasibility, field level, protection, field quality
  - Proposal: demonstrate HTS/LTS 20 T dipole technology in two steps:
    - a field record attempt at breaking the 20 T barrier (no aperture)
    - a 5 T insert, with sufficient aperture (40 mm) and accelerator features
- 1 T … 2 T injectors and booster magnets
  - Challenges: power consumption, compatibility with other collider options (e.g. FCC-ee)
  - Proposal: demonstrate low consumption, compact (HTS based ?) dipole technology

High awareness of potential and impact in other domains of magnet technology and applied superconductivity

FCC Magnet Design and R&D

HH SC magnets

LTS magnets

- Arc dipole designs
- Arc quadrupole designs
- IR magnets design
- A15 material R&D (Nb_3Sn, Nb_3Al)
- 16 T dipole model(s) construction and test

H2020

- Conceptual and engineering design of 16 T dipole

HTS magnets

- Arc dipole designs as hybrid LTS/HTS
- IR and collimation region magnet designs
- HTS material R&D
- 20 T (no bore) insert R&D and test
- 5 T (40 mm) standalone and insert R&D and test

EuCARD

- 6 T insert

EuCARD2

- 5 T dipole

Injectors and booster

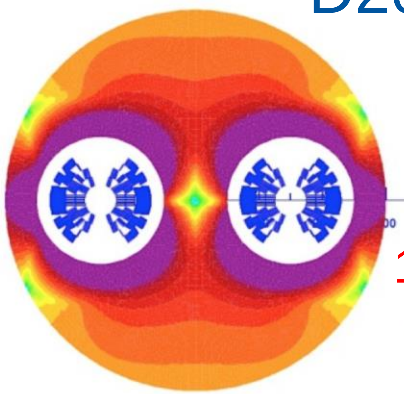
- Compact, low consumption resistive magnets
- Redundancy/fast connectivity, radiation hardness
- Fast cycled 5 T magnets (LHC tunnel)
- Fast cycled 12 T magnets (SPS tunnel)
- Fast cycled 1.5 T magnets for an FCC-hh booster

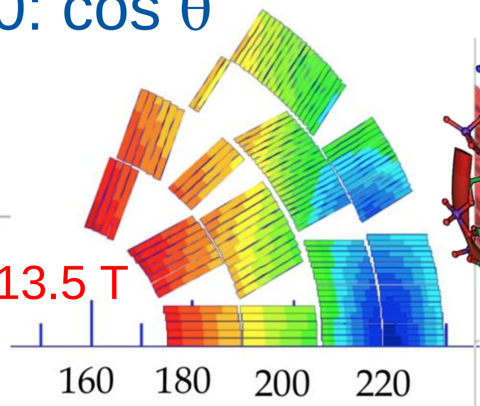
H2020-FET ?

- 2 T HTS FCM with high energy efficiency

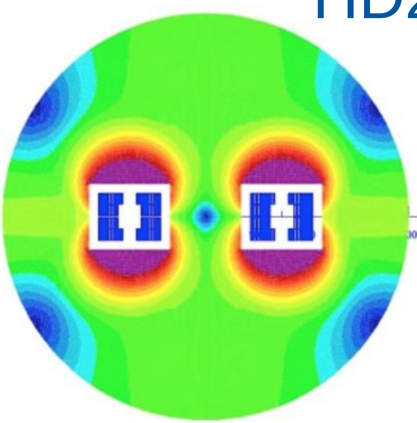
A 16 T dipole (with two bores)

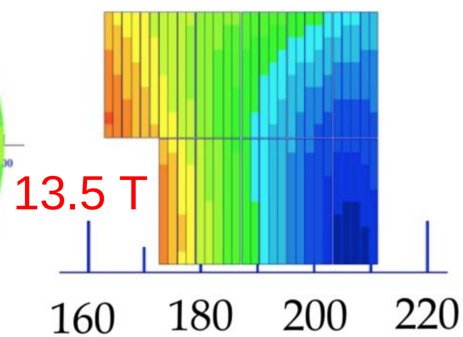
D20: cos θ





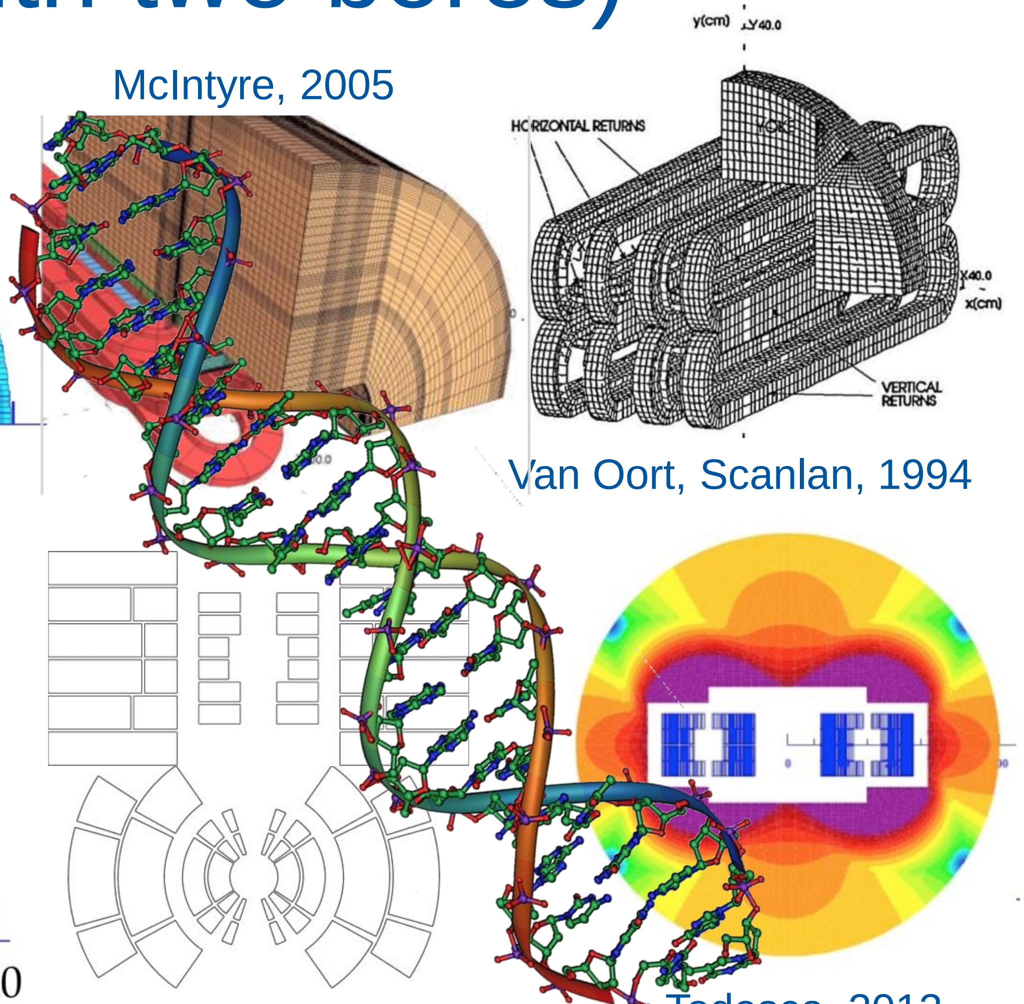
HD2: block





Camouflaged record magnets

E. Todesco (CERN)



McIntyre, 2005

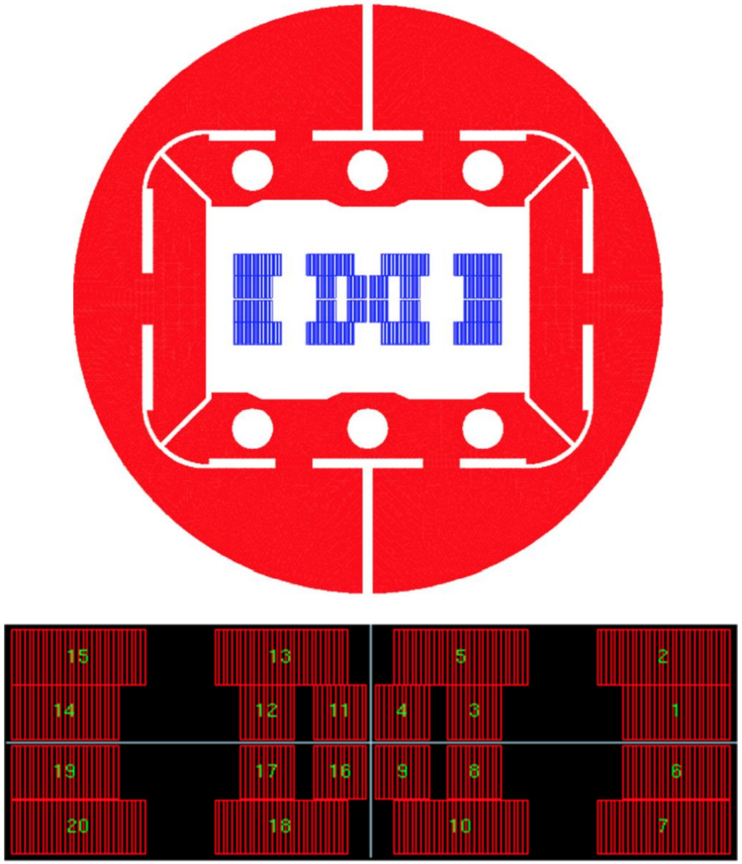
Van Oort, Scanlan, 1994

J. van Nugteren, 2013

Todesco, 2013

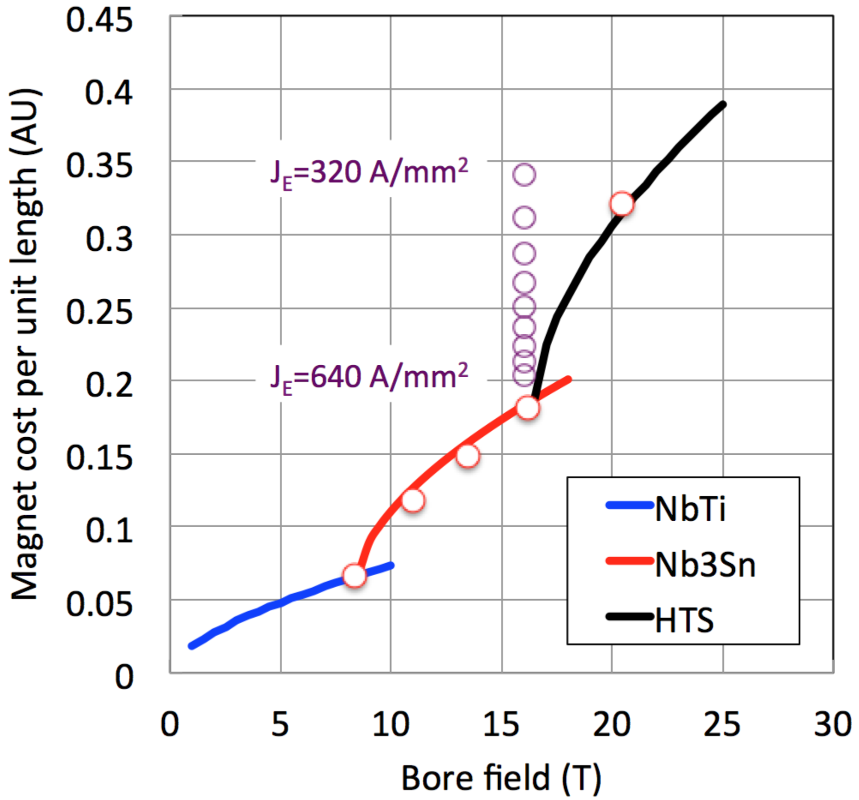
Time for a genetic mutation !

16 T design considerations



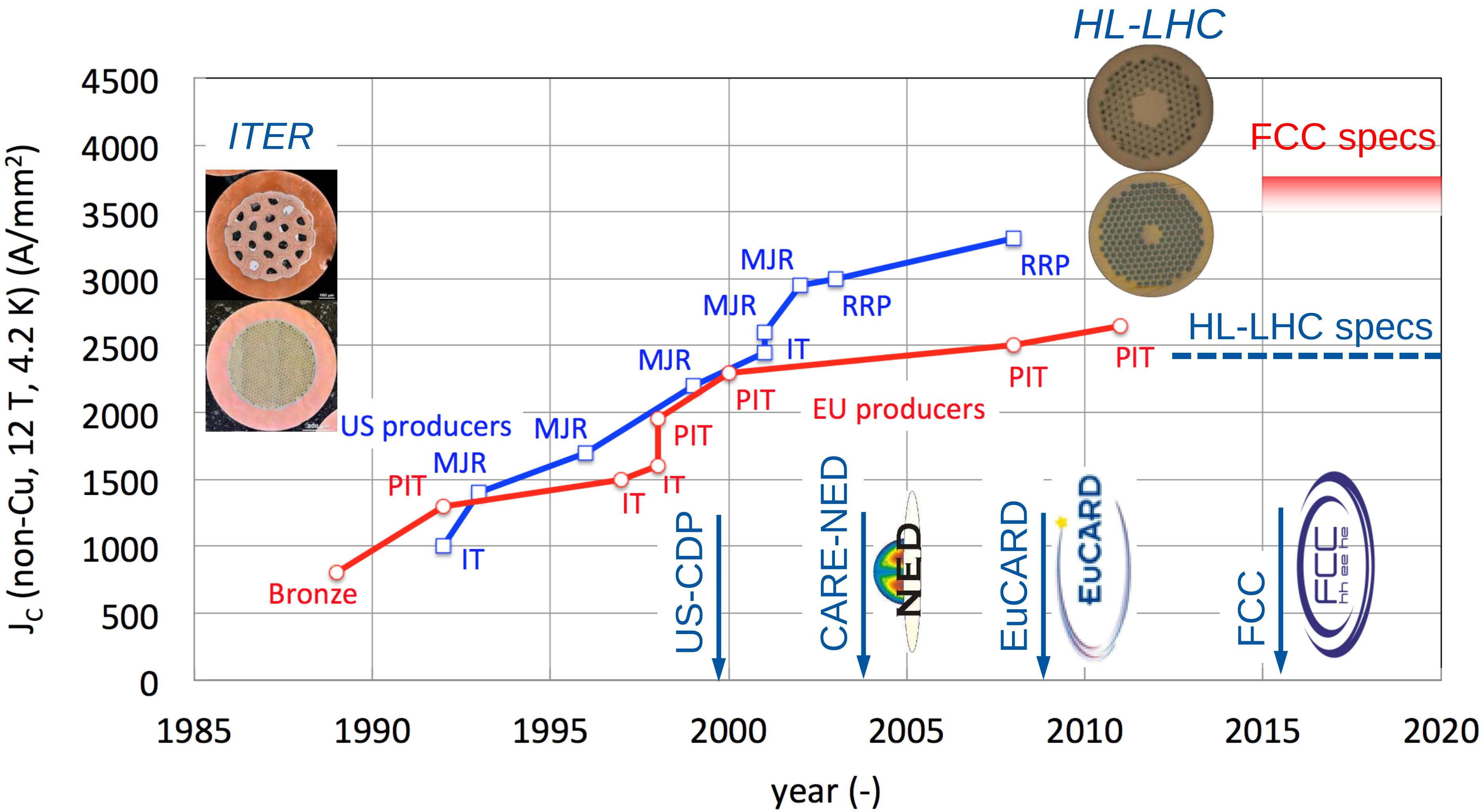
Twin aperture 16 T design proposal
with 150 mm inter-aperture distance
Sabbi, 2014

Cost analysis by D. Schoerling, E. Todesco, and J. van Nugteren

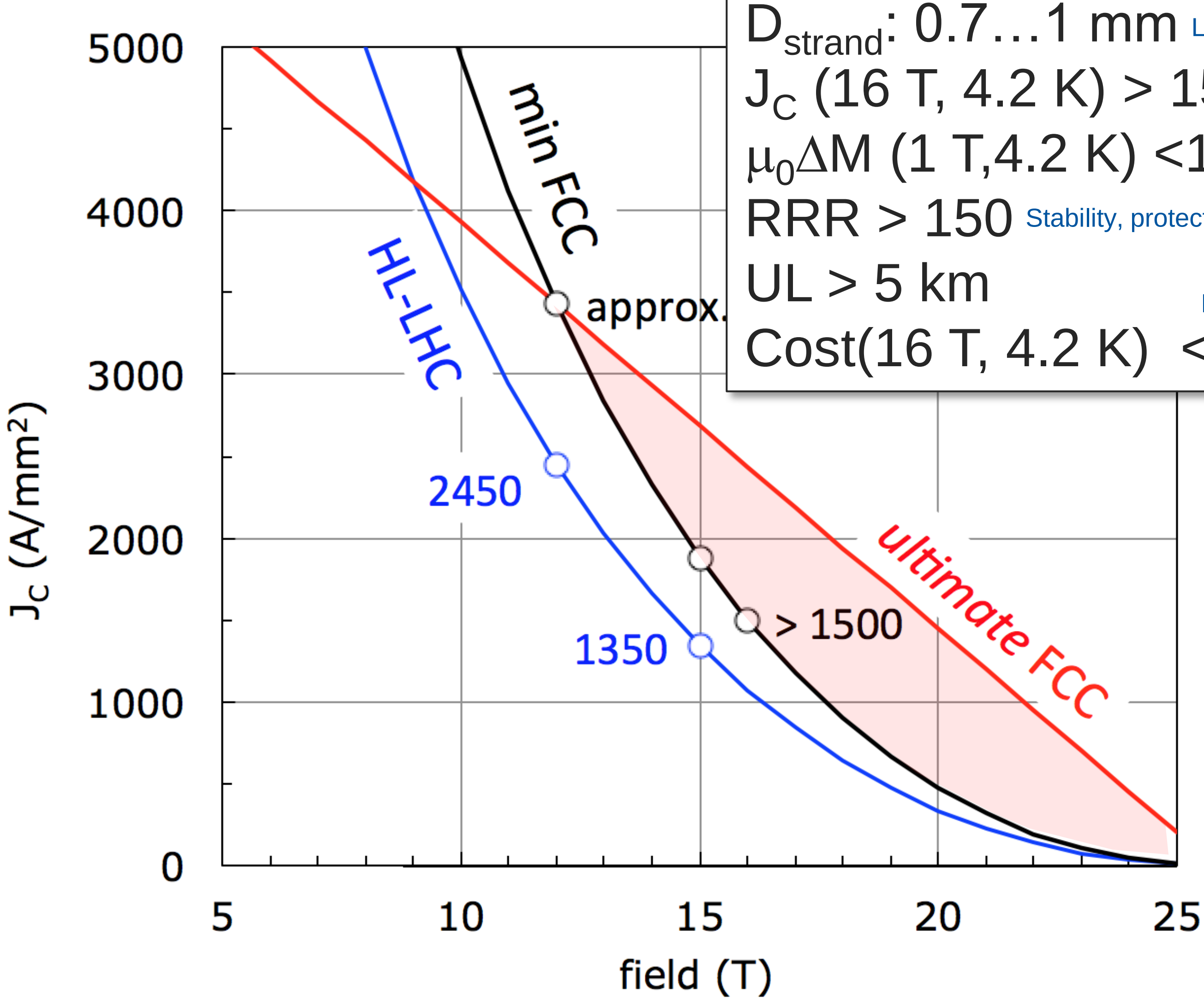


J_C(16 T, 4.2 K) > 1500 A/mm^2

From ITER- to HEP-class Nb_3Sn



FCC Nb_3Sn performance targets



D_{strand}: 0.7…1 mm Large cables, **cabling !**

J_C (16 T, 4.2 K) > 1500 A/mm² Field quality

$\mu_0\Delta M$ (1 T,4.2 K) <150 mT (D_{fil} < 20 μm)

RRR > 150 Stability, protection

UL > 5 km

ITER material cost per kg

Cost(16 T, 4.2 K) < 5 USD/kA m

All single parameters are in reach, their combination is the challenge !

Ultimate Nb_3Sn ? Pursue the idea of improved high field pinning (q=1)

(D. Dietrich and R. Scanlan, A. Godeke)

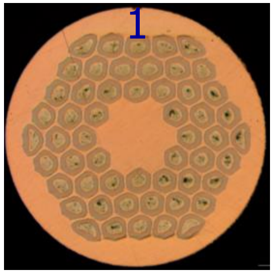
CERN

HL-LHC Nb_3Sn wires

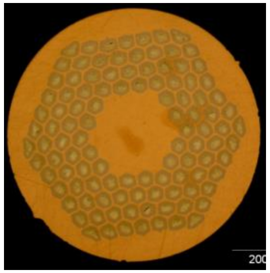
	Sub-element size (μm)					
	Φ_{wire} (mm)	RRP® 108/127	RRP® 132/169	RRP® 192/217	PIT 114	PIT 192
FReSCa2	1	-	58	-	-	48
Hi-Lumi QXF	0.85	-	48	-	-	41
11 T	0.7	46	41	32	44	-

OST RRP®

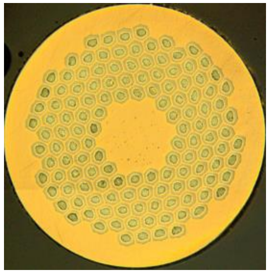
54/61



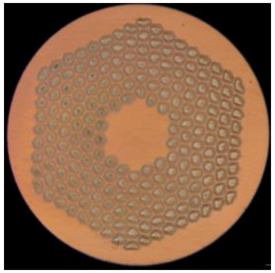
108/127



132/169

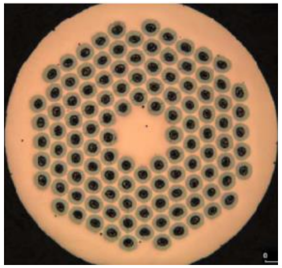


198/217

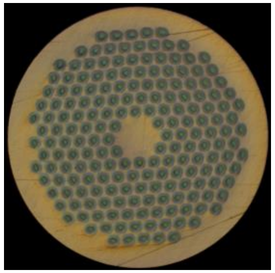


Bruker-EAS PIT

114

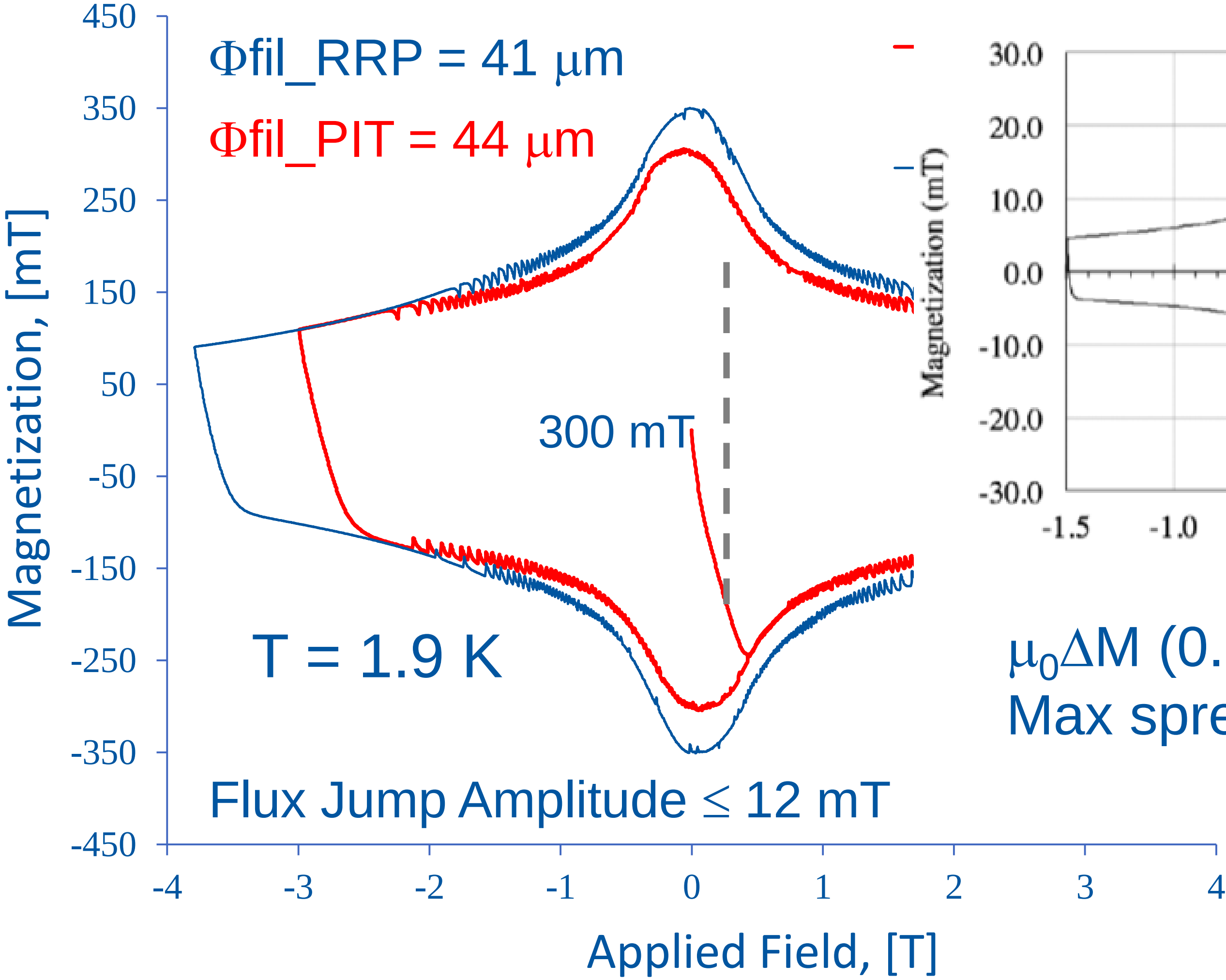


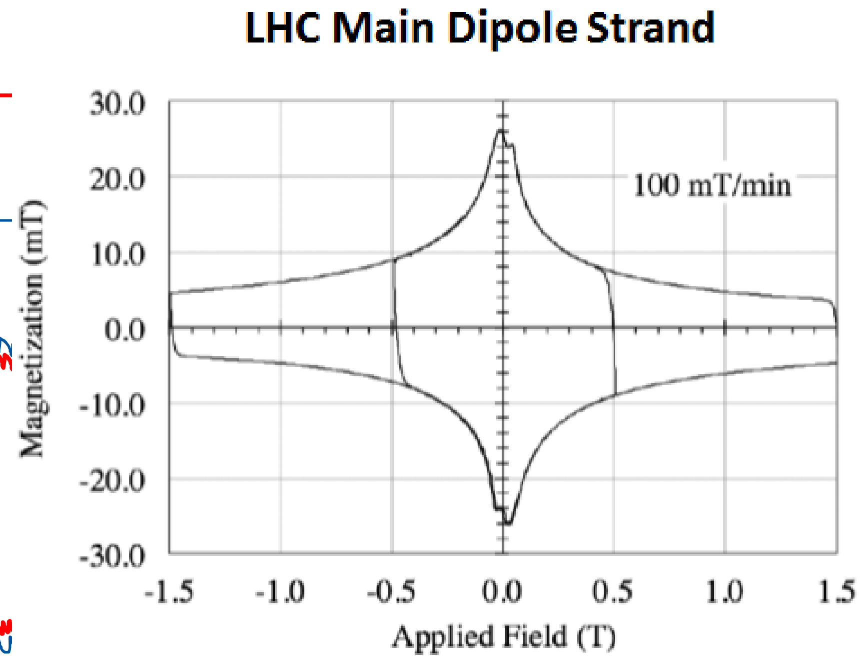
192



Smaller sub-element size

Magnetization of Nb_3Sn

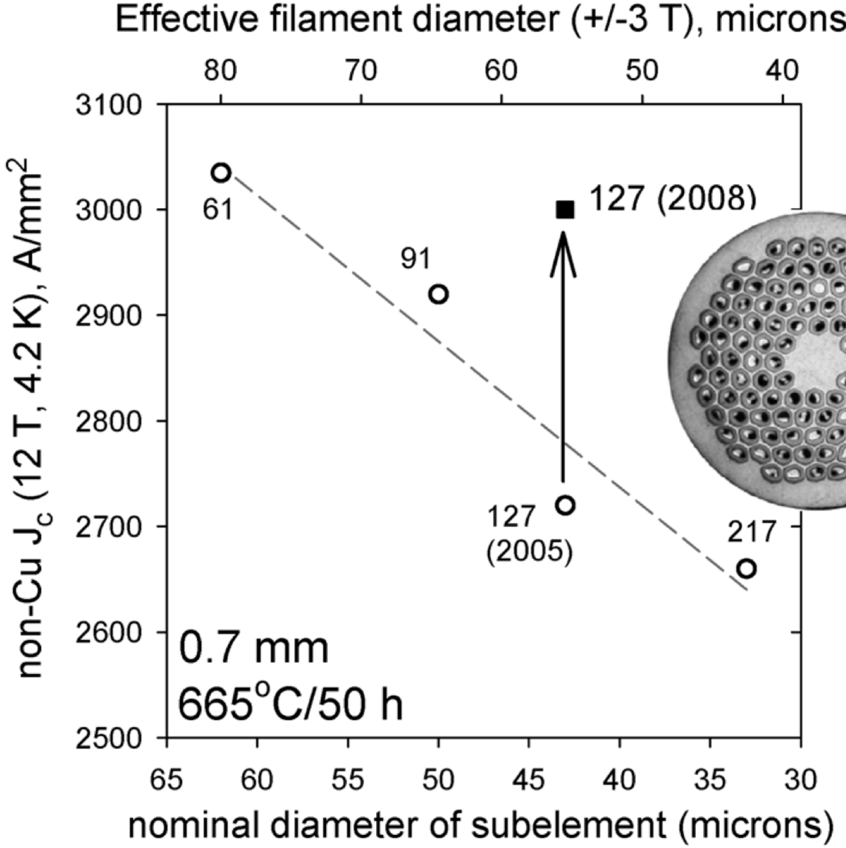




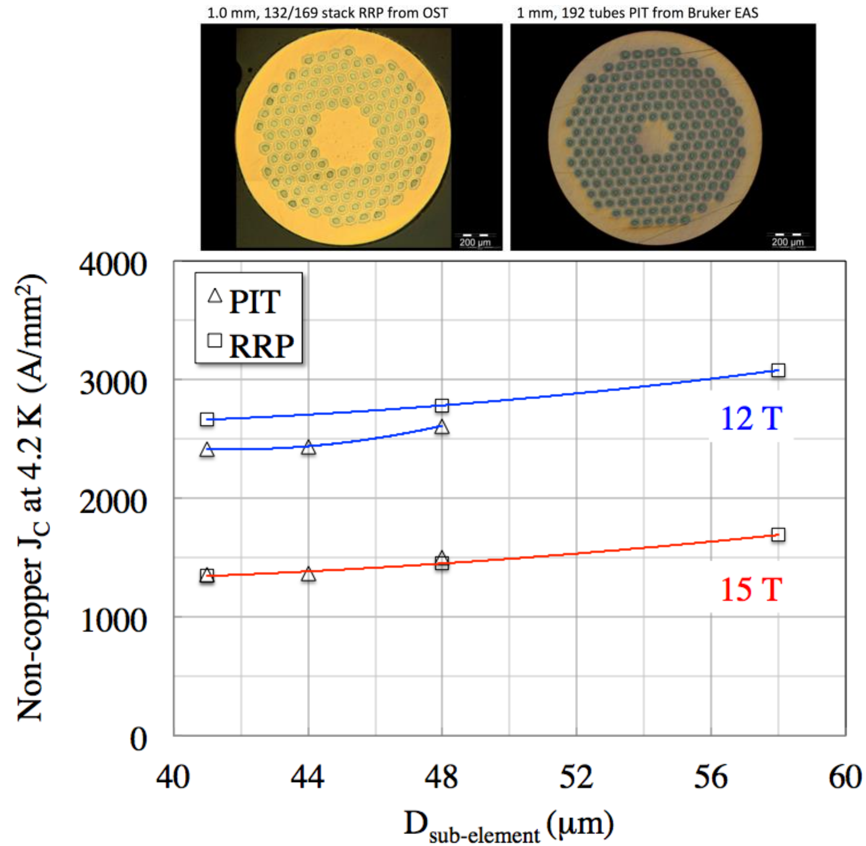
$\mu_0\Delta M$ (0.54 T, 1.9 K) < 30 mT
Max spread ± 4.5 %

The difficulty of fine filaments

Results at OST on RRP wires
IEEE TAS 19(3), (2009) 2573



Results at CERN on RRP and PIT wires
Submitted to IEEE TAS, 2015



Limit at approximately 40 μm for both architectures

Challenges and opportunities

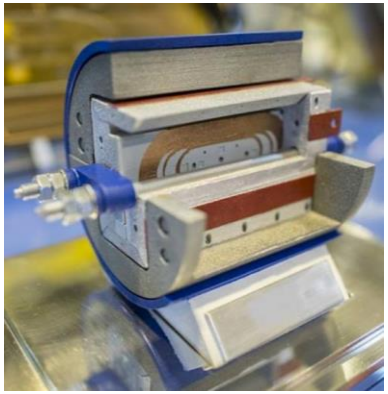
- HL-LHC
  - Demonstrate Nb_3Sn technology for use in the LHC – 2016
  - Prepare HL-LHC in LS2 – 2018
  - Install HL-LHC in LS3 – 2023
- FCC and linear collider technologies
  - CDR for European Strategy Review – 2017
  - Prototyping of FCC magnets – 2018-2025
  - Production of FCC magnets – 2025-2035

- Secure robust HEP Nb_3Sn for the first large scale use in HEP
- Squeeze out of Nb_3Sn its full potential in terms of J_C and Deff
- Improve quality, affordable production
- How ?
  - A coordinated, worldwide R&D to foster progress and spread technology
  - Material research (on LTS !)
  - Other industrial actors

What is happening in the meantime ?

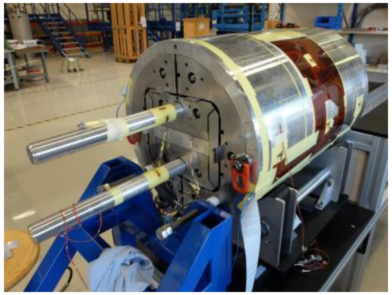
SMC/RMC/FReSCa2 status

Technology development



- SMC-3b (PIT 1.25 mm, 14 strands cable): completed and tested – **12.6 T**
    - SMC-5 wound, test planned in 2014
    - SMC-4 planned
- SMC-11T-1 (RRP 0.7 mm, 40 strands cable rectangular): completed and tested – **13.5 T**
- SMC-11T-2 (same as SMC-11T-1, with mica): completed and tested – 12.2 T

Sub-scale proof



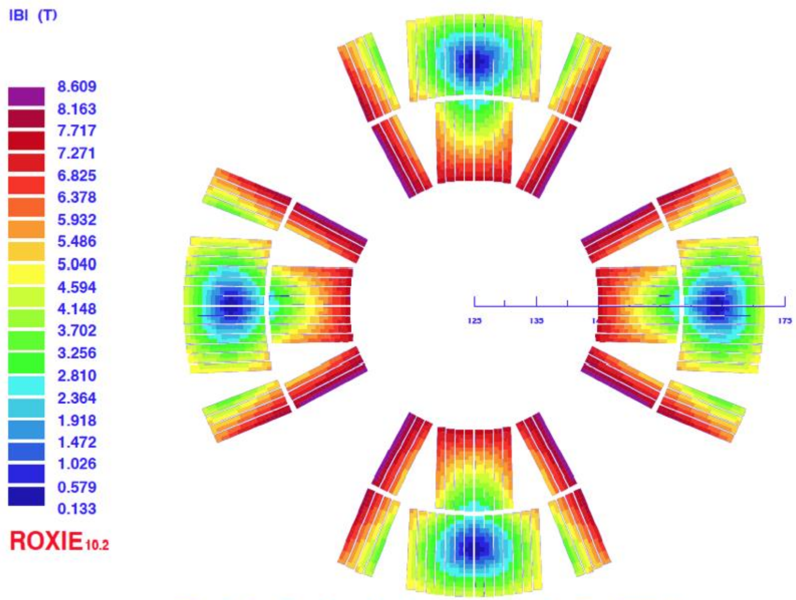
- RMC (PIT 1 mm, 40 strands cable for FRESCA2): heat treated, in impregnation, test in September 2014

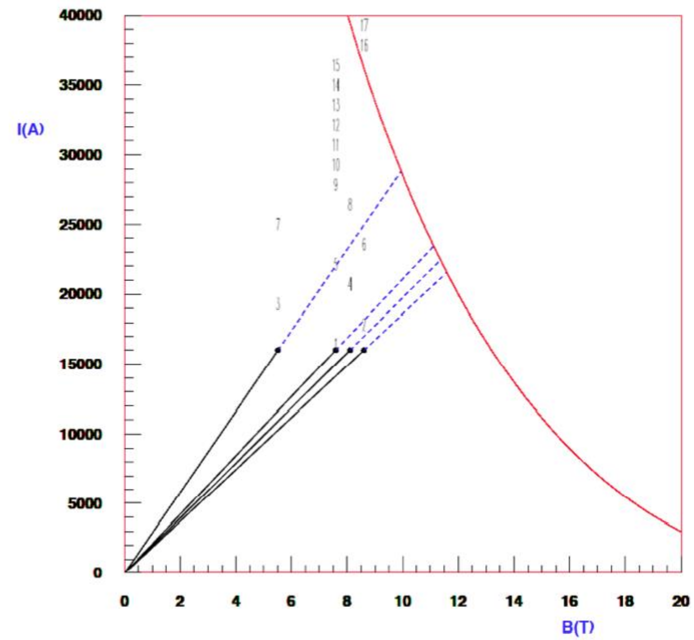
- FReSCa2 – 13 T operational field, ≈ 15 T ultimate field (mechanical limit): two Cu pancakes wound at CEA-Saclay, first pancake heat treated and instrumented, second pancake heat treated and in instrumentation

Main quadrupoles

375 T/m
40 mm

Load-Line @1.9 K





- G(16 kA) = 383 T/m
- Bp(16 kA) = 8.6 T
- wp(16 kA) = 75 %

- T_{marg}= 5.9 K
- Bc = 11.6 T

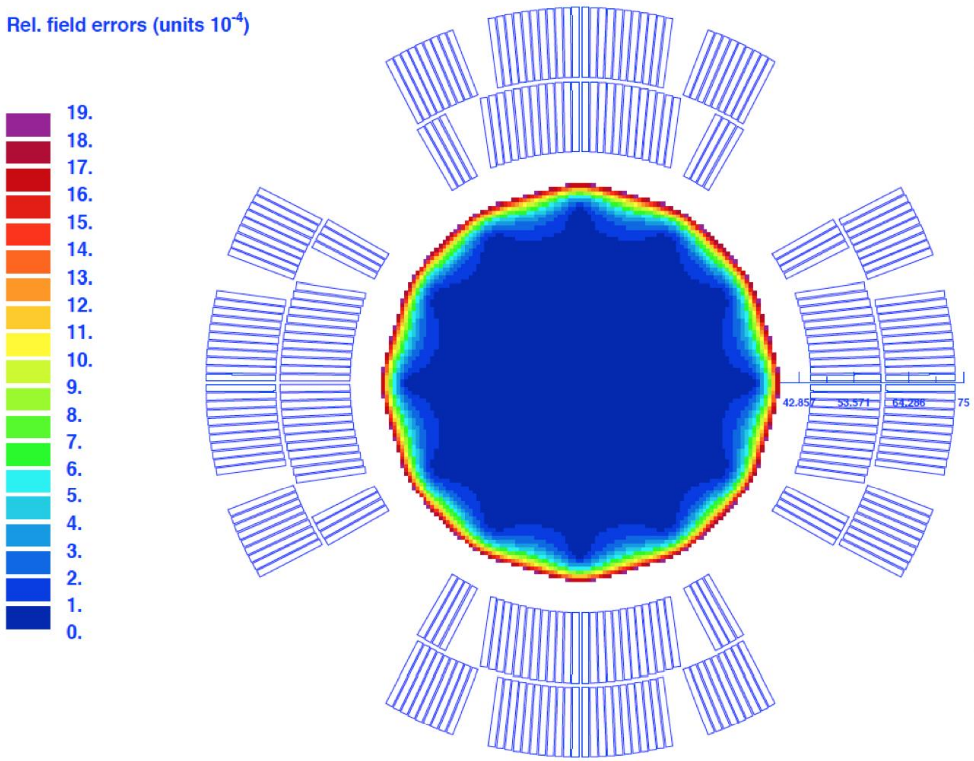
Comfortable operating margin

By courtesy of M. Karppinen (CERN)

IR quadrupoles

200 T/m
90 mm

Coil X-section



Field errors with iron saturation at 200 T/m

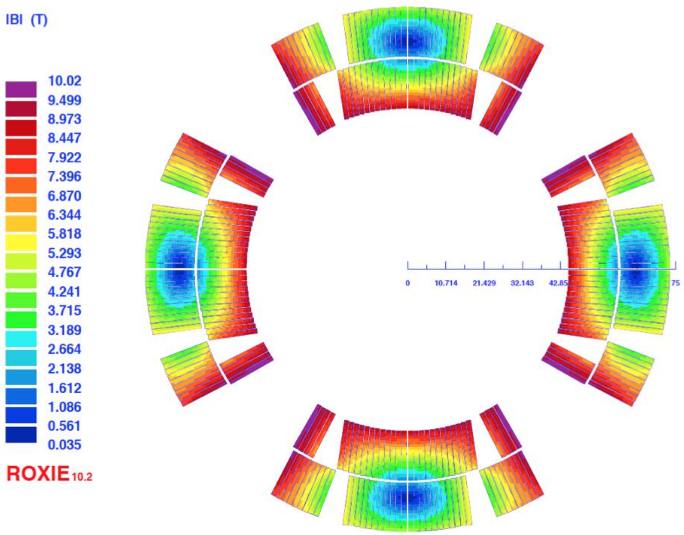
- Aperture Ø90 mm
- 36 turns (IL 16, OL 20)
- No grading
- I-L insulation 0.7 mm
- Mid-plane insul. 0.2 mm
- FQ_{r30mm}(200 T/m):
  - b6 = 0.8 units
  - b10 = 0.18 unit
- L_{diff} = 4.26 mH/m
- E_{mag} = 401 kJ/m

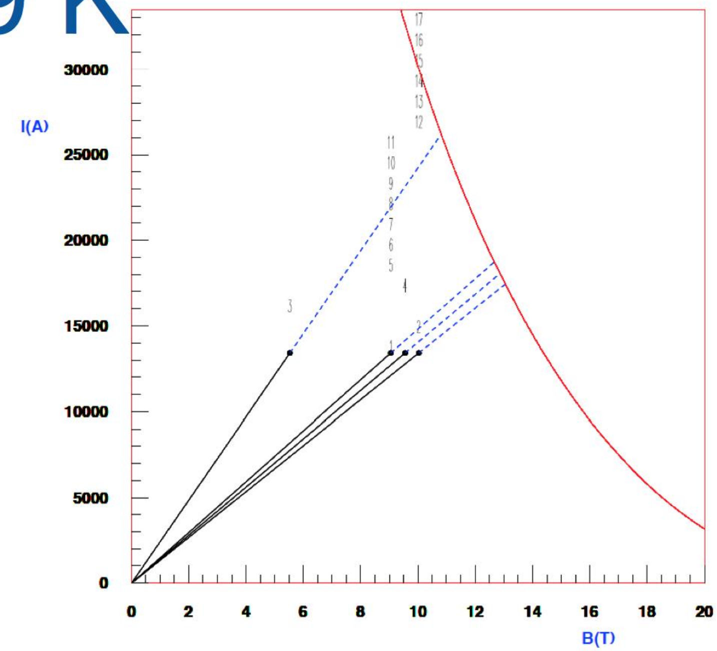
By courtesy of M. Karppinen (CERN)

IR quadrupoles

200 T/m
90 mm

Load-Line @1.9 K





- G(13.4 kA) = 200 T/m
- Bp(13.4 kA) = 10 T
- wp(13.4 kA) = 77 %
- wp(13.4 kA, 4.3K) = 83 %

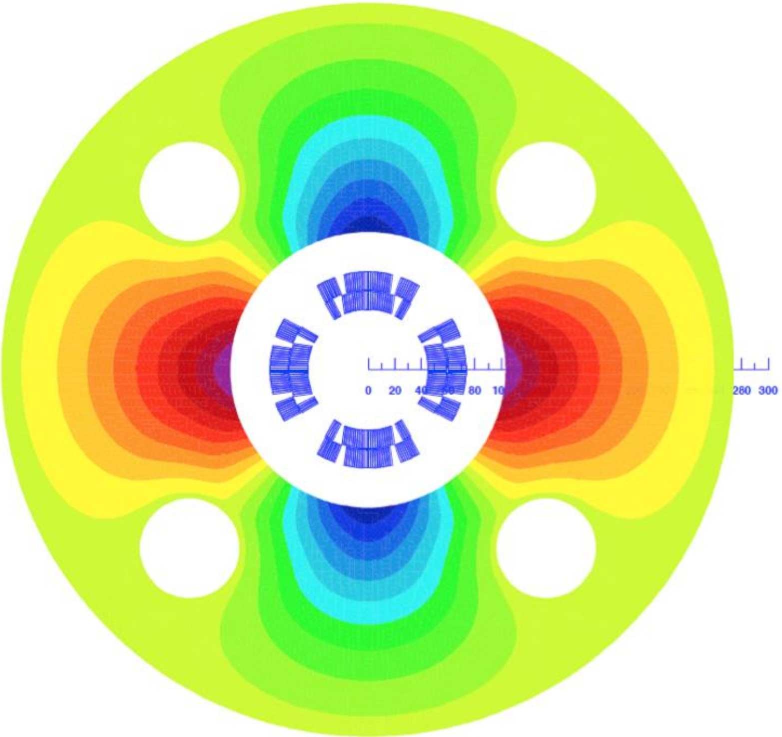
- T_{marg}= 5.4 K
- Bc = 13 T

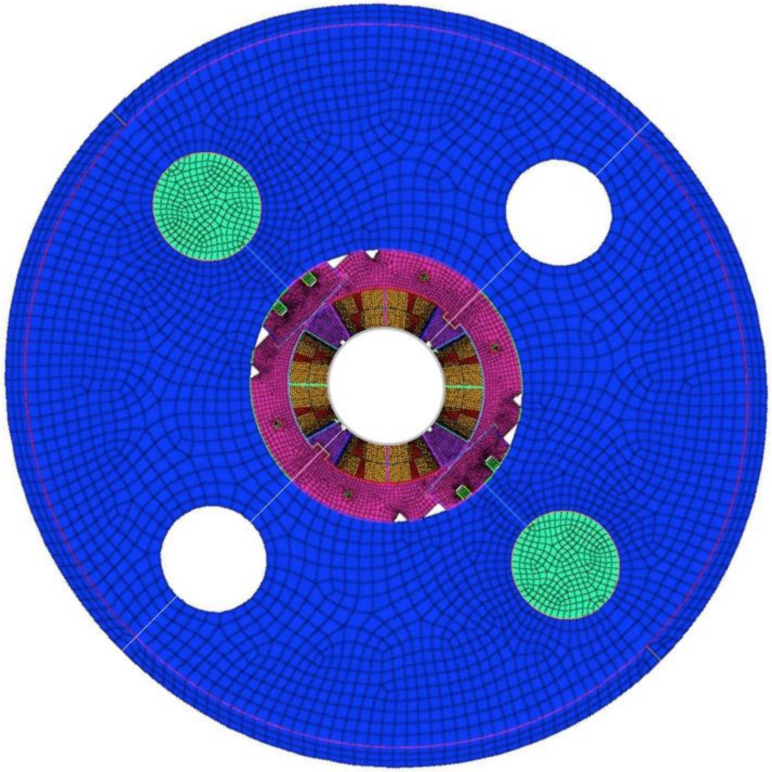
Comfortable operating margin

By courtesy of M. Karppinen (CERN)

IR quadrupoles

200 T/m
90 mm

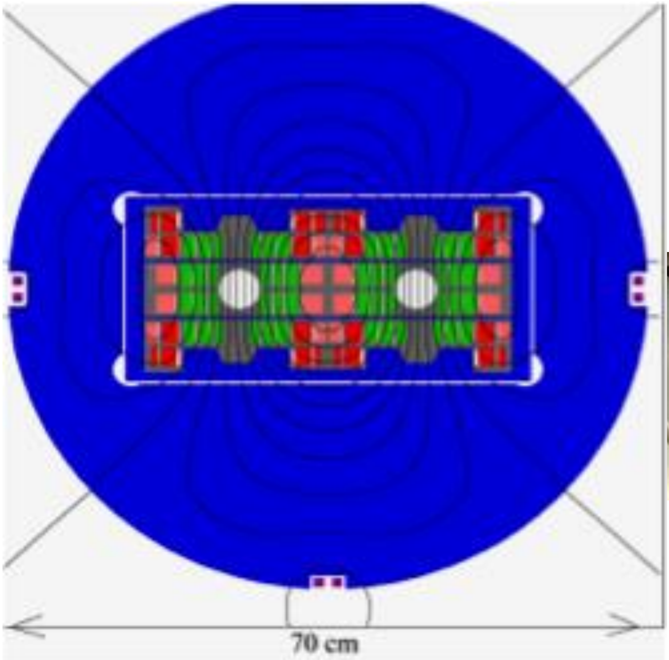




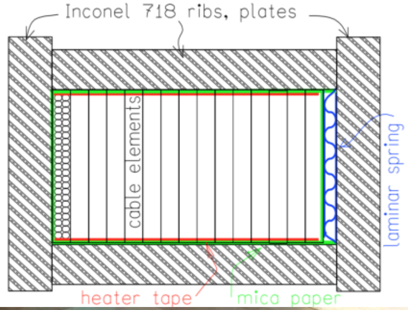
Novel (horizontal) collaring concept that could be more easily extrapolated to large series production

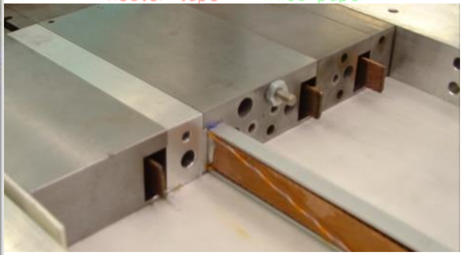
Ideas for 20 T

A 24 T LHC *Tripler*
P. McIntyre (TAMU)

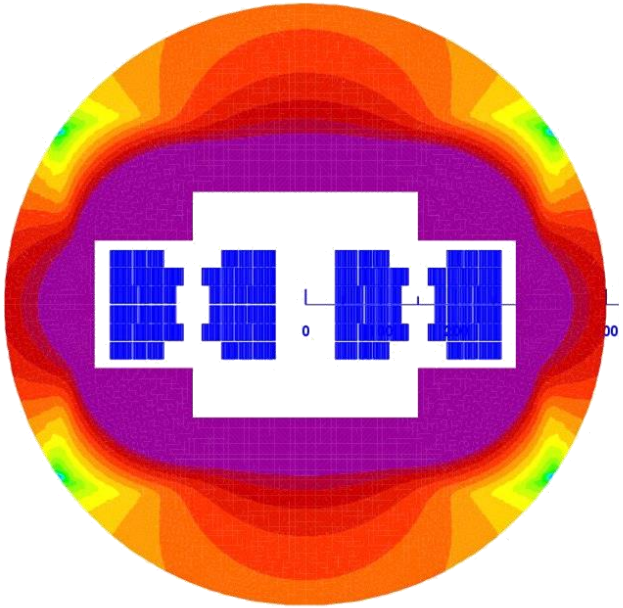


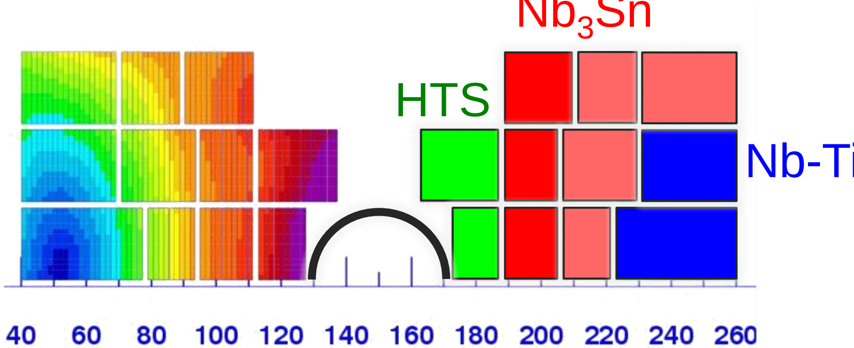
Stress managed winding





A 20 T HE-LHC dipole
E. Todesco, L. Rossi (CERN)

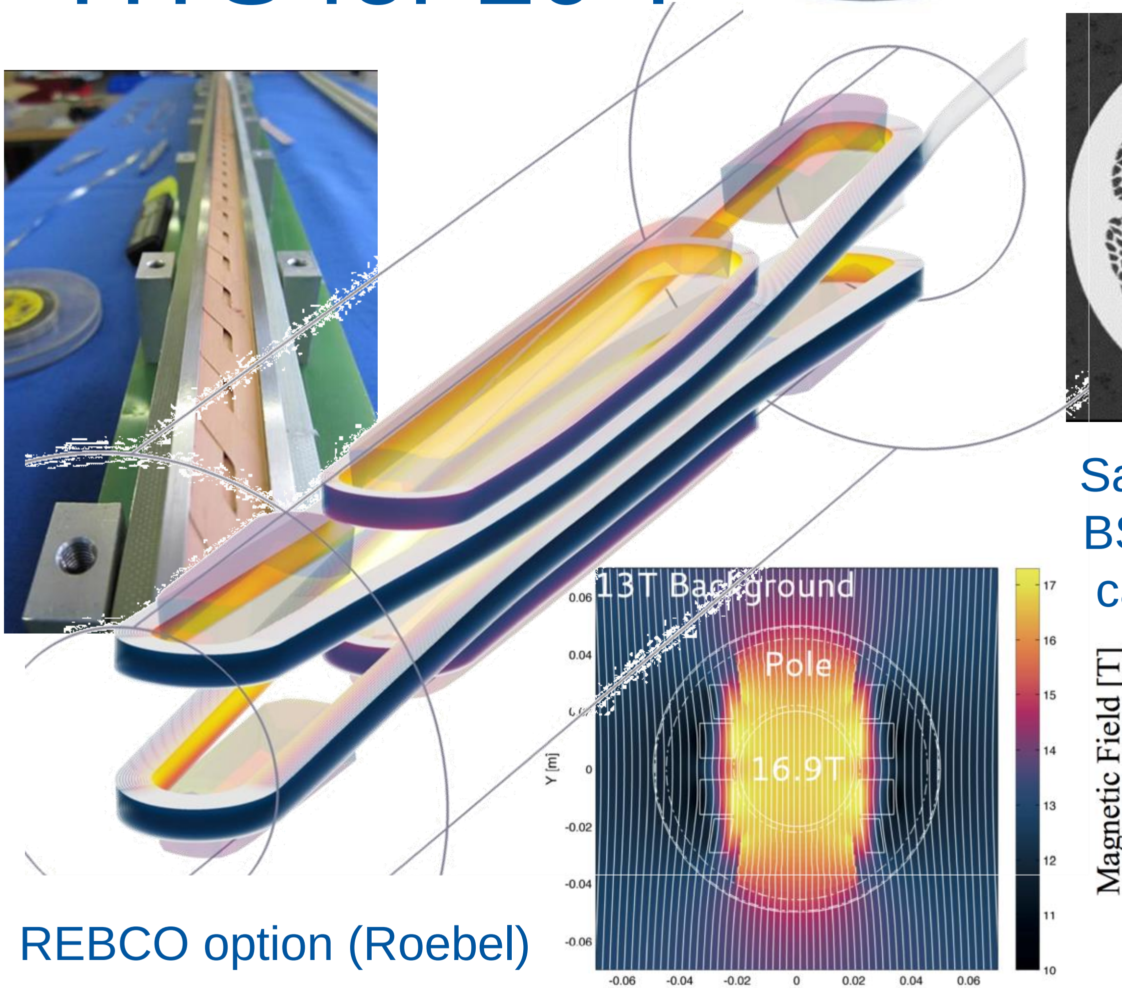




Cost optimized, graded winding

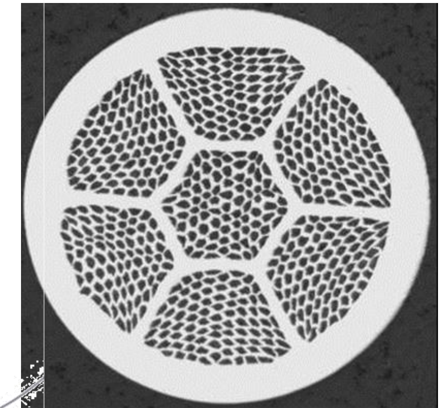
All options are based on an LTS winding (outsert), and an HTS field booster (insert)

HTS for 20 T

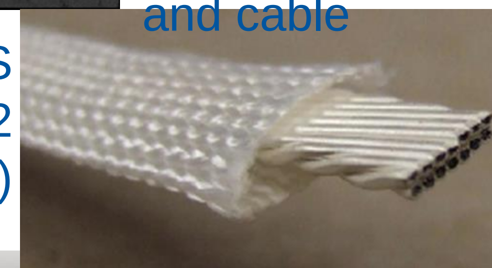


REBCO option (Roebel)

EuCARD2 program, targeting a 5 T, 40 mm aperture demonstrator, in collaboration with EU laboratories and industry



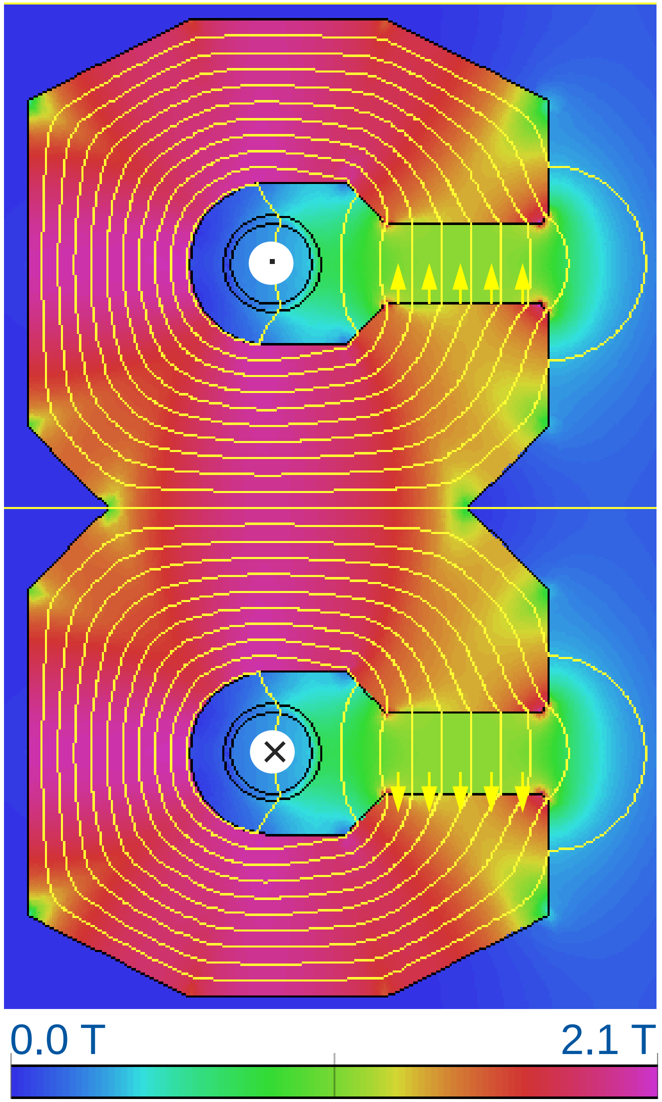
BSCCO-2212, CERN provides precursor powders, US BSCCo program produces wire and cable



Sample of US BSCCO-2212 cable (LBNL)

US-BSCCo program, testing alternative materials and coil configurations (CCT, LBNL)

HEB magnets in a 100 km tunnel



- **HTS, transmission line,** iron dominated, superferric, 2-in-1 dipole
- Tentative parameters:
  - vertical full gap 50 mm
  - good field region ±20 mm
  - overall diameter of “super-cable”, including cryostat, 100 mm
- 50 kA-turns for 1.1 T (3.4 TeV)
- At low current, the apertures could be used in bipolar operation as a lepton booster

Study by A. Milanese, IPAC 2014