Accelerator Magnet Technology for future machines

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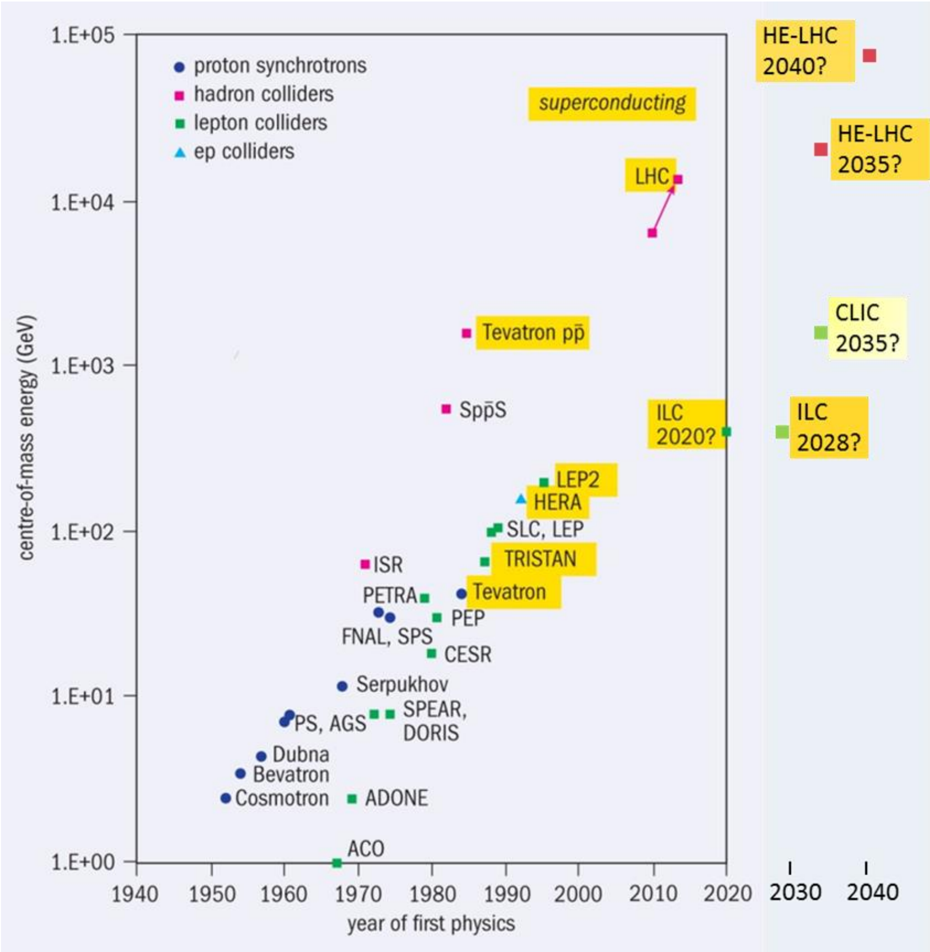
CERN

EUCARD/EUCARD2 week, June 2013

Content

- Progress of accelerators
  - Energy
  - Magnets (dipoles, and dip vs solenoid)
  - Needs
- Sc space
  - Nb-Ti possibility
  - Nb3Sn
  - HTS
- New structures
- New design…
- Normal Conducting Magnets
- Roadmap for the next decade

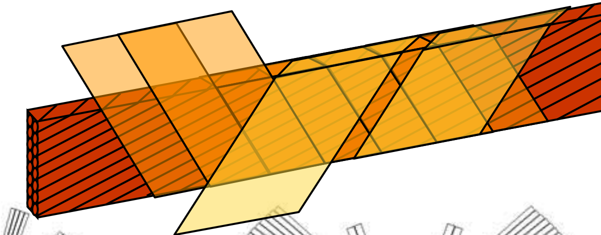
Progress in energy of accelerators

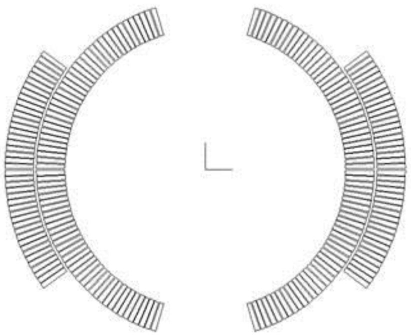


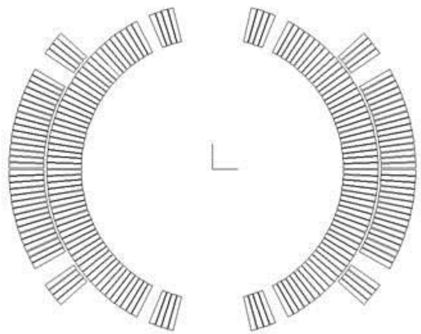
SC is an enabling technology

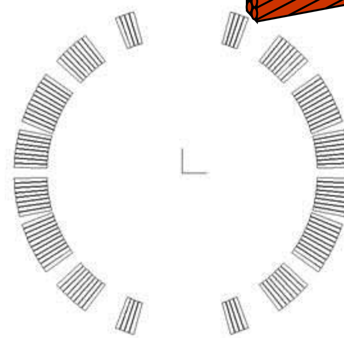
- **Voltage accelrator**
- **Cyclic accelerators**
- **Phase stability**
- **Strong focussing**
- **Colliders**
- **Superconductivity**
- **(Plasma acceleration?)**

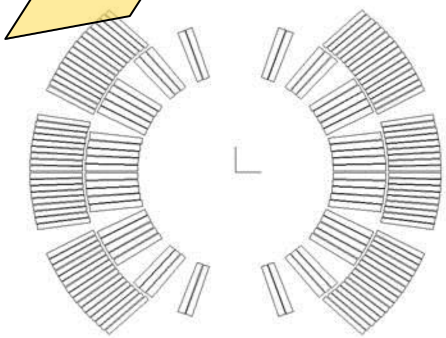
Main dipoles of existing machines SC Coils : all $\cos\vartheta$, all Ruth. cables











Tevatron

HERA

RHIC

LHC

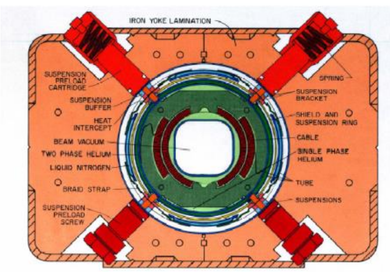
Main dipoles of existing machines but structure quite different

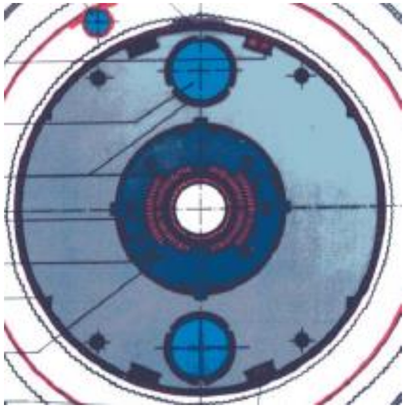
Rutherford cable
Collars Aust. Steel
Warm iron

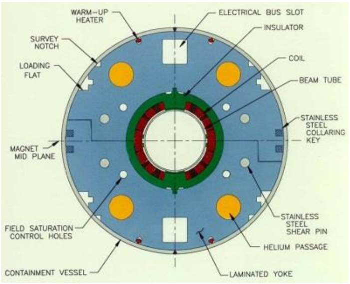
Collars Al alloy
Cold iron

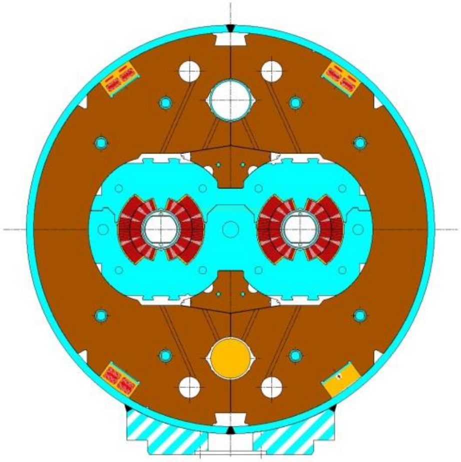
Cold yoke as collar

Collars Aust. Steel + yoke
Twin + HeII









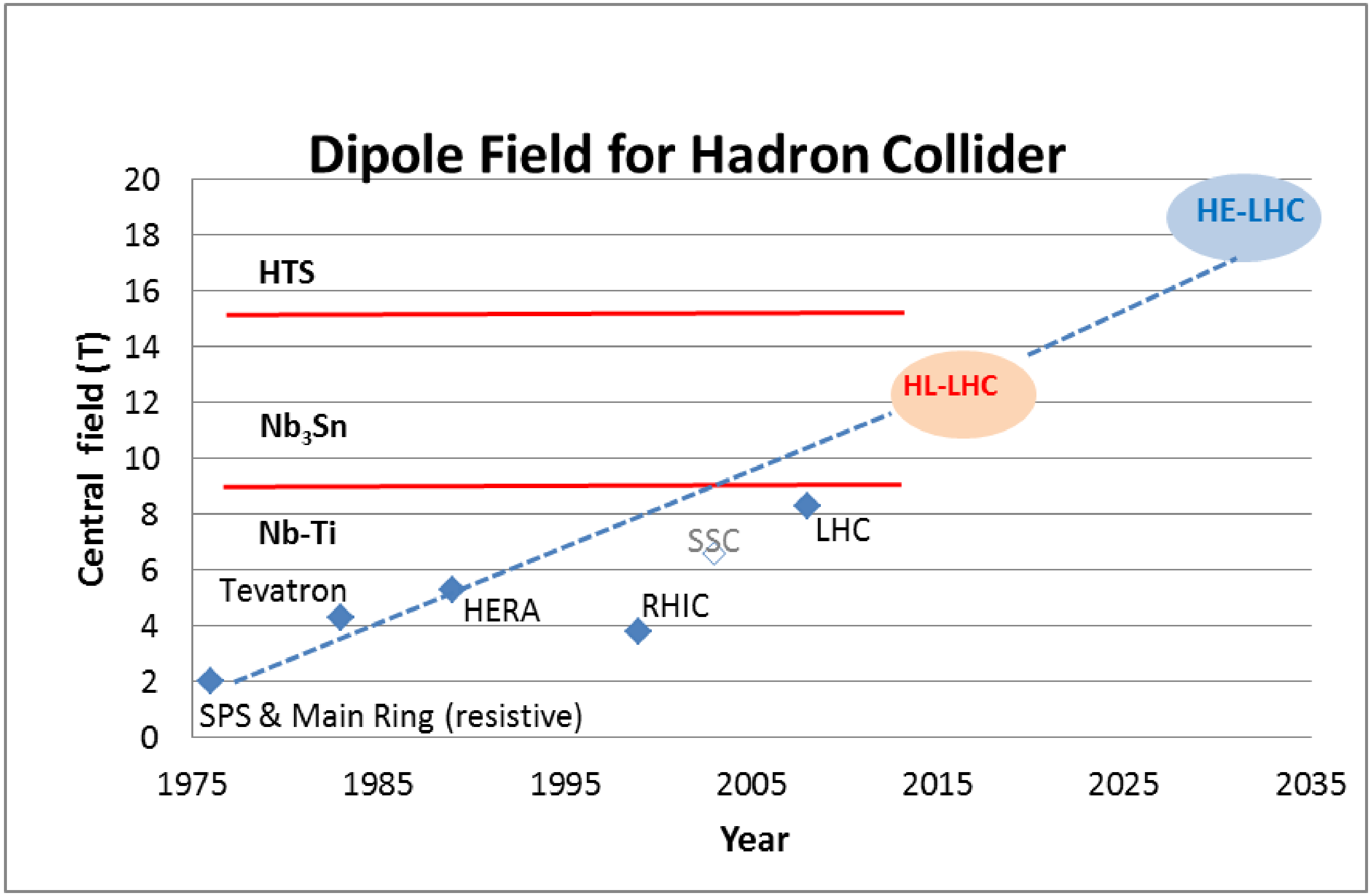
Tevatron

HERA

RHIC

LHC

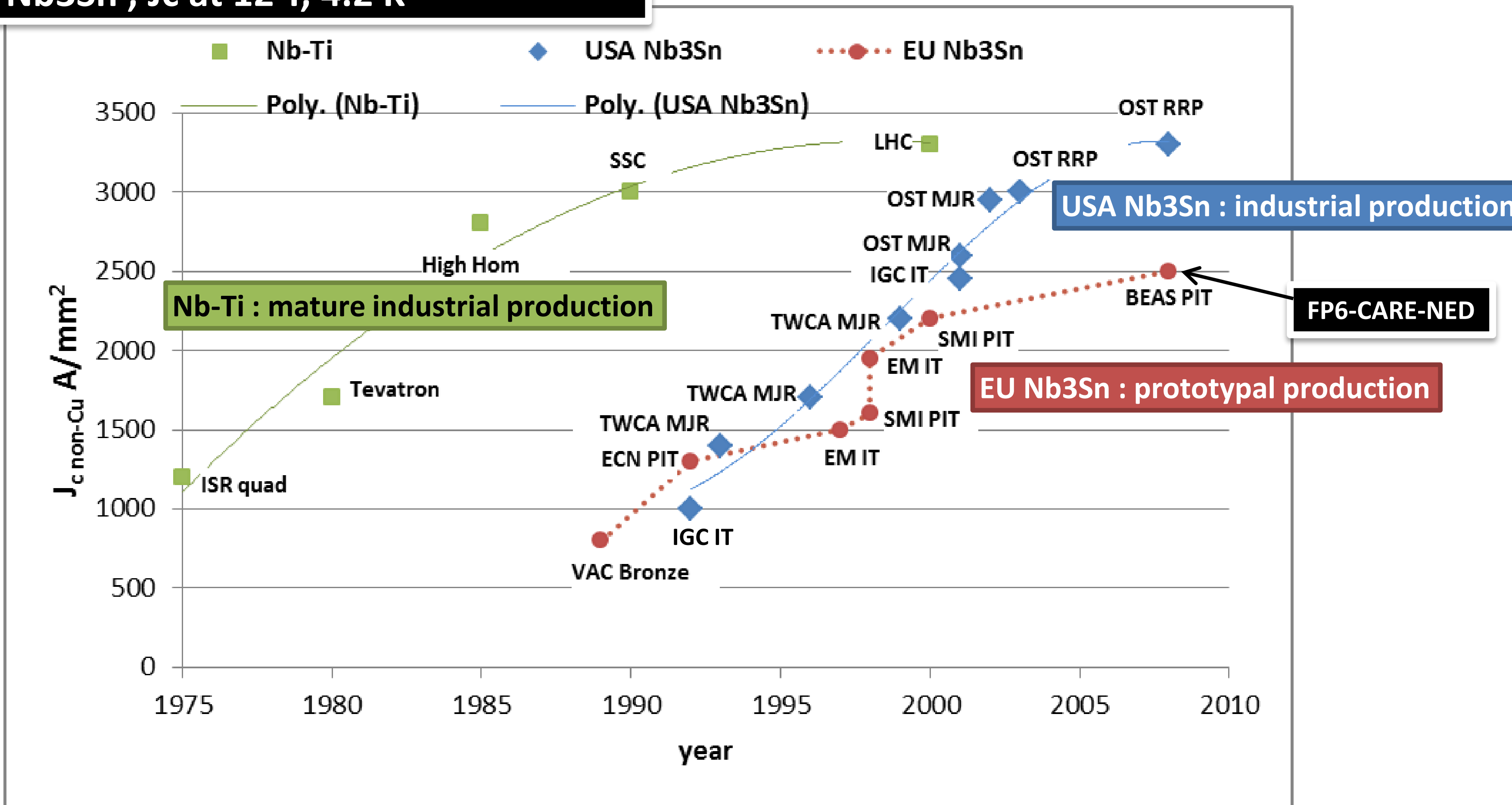
Where we are…
and where we want to go…



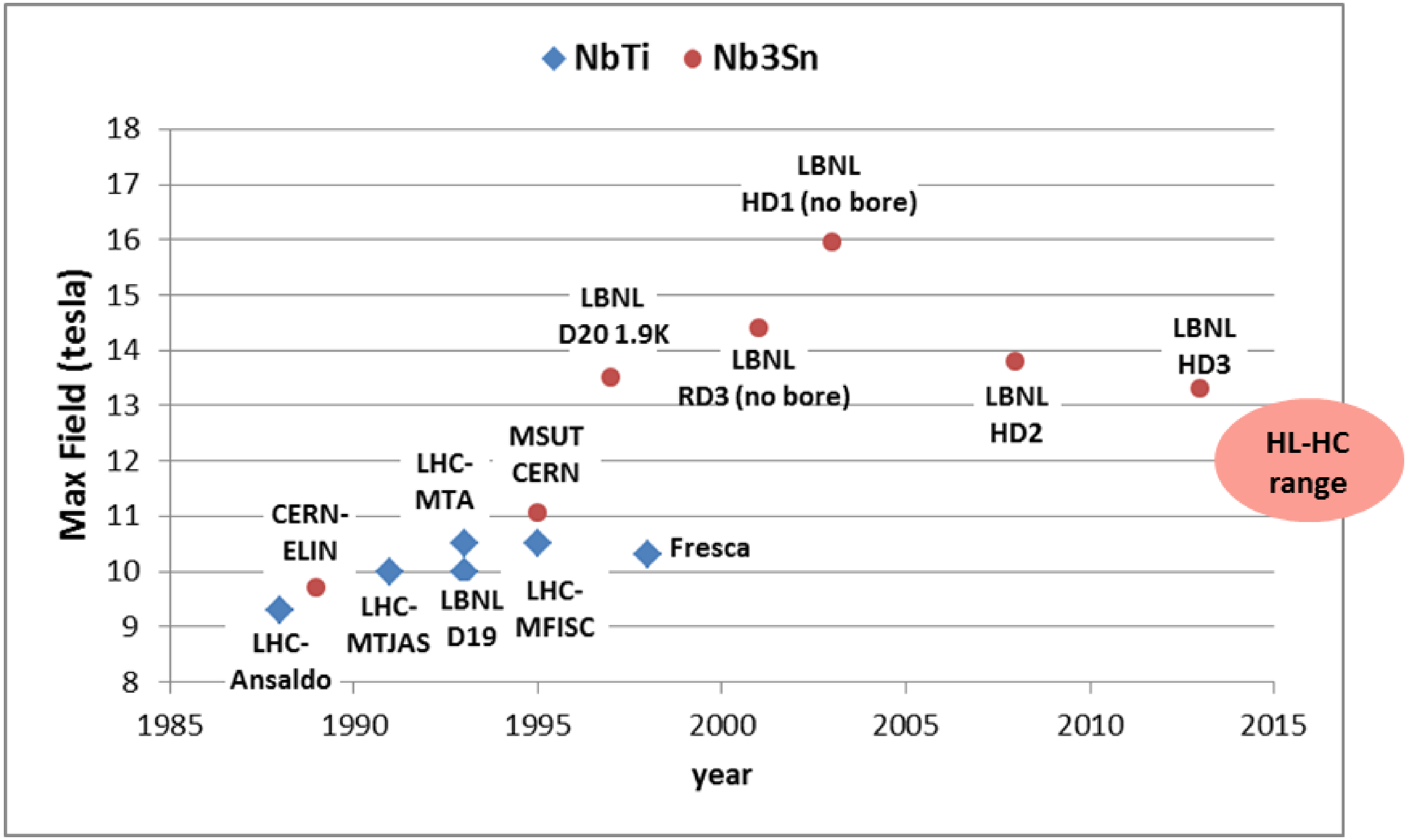
How?

Developing technical, viable, superconductors

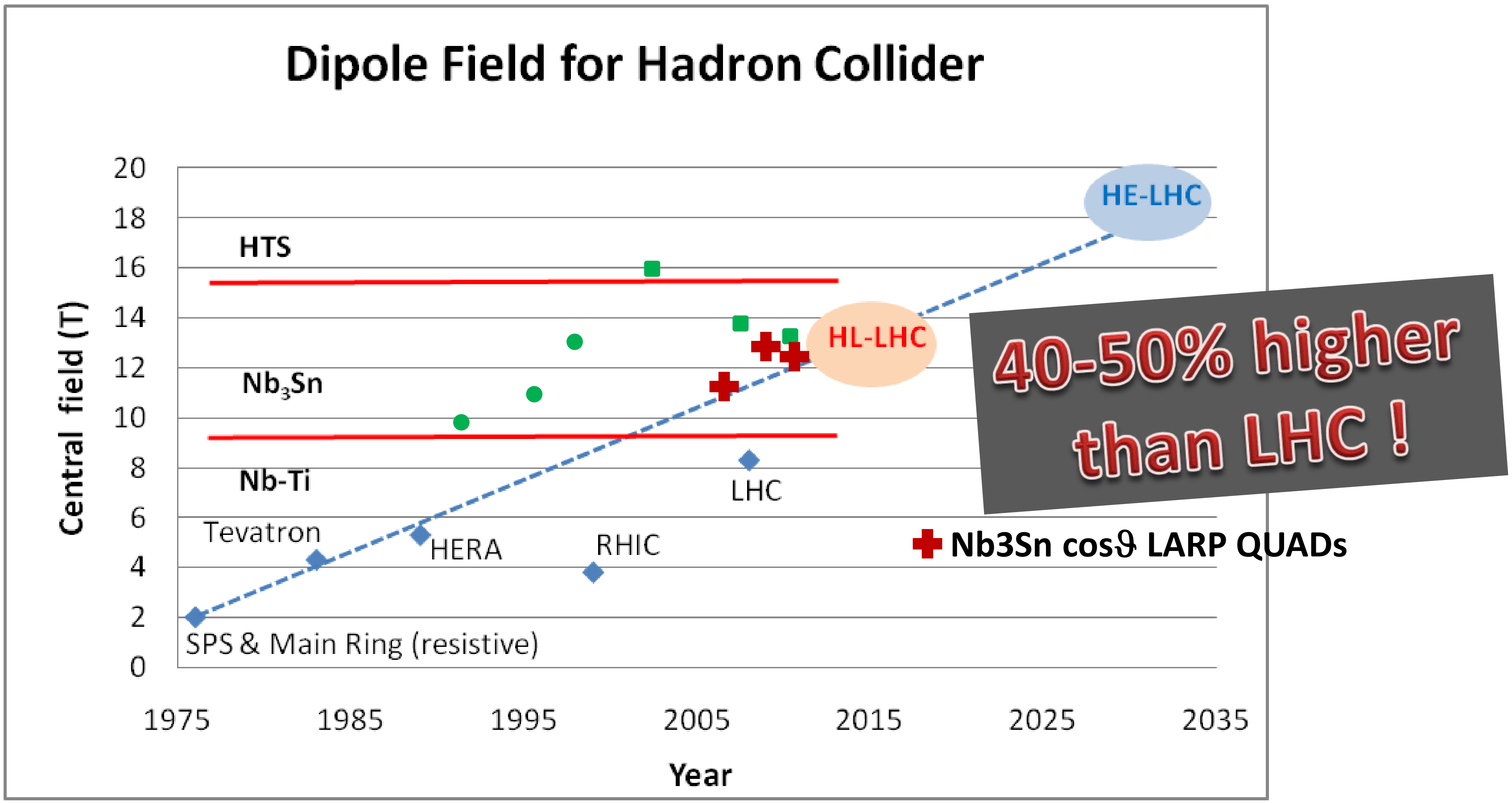
For Nb-Ti : Jc at 5 T, 4.2 K (or 8 T at 1.9K)
For Nb3Sn ; Jc at 12 T, 4.2 K



Best magnet short models results of magnets follow SC



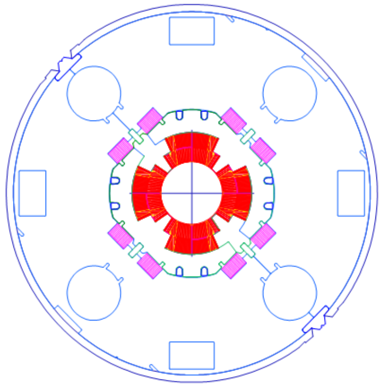
We are near to conquer HL-LHC and the 11-13 T region

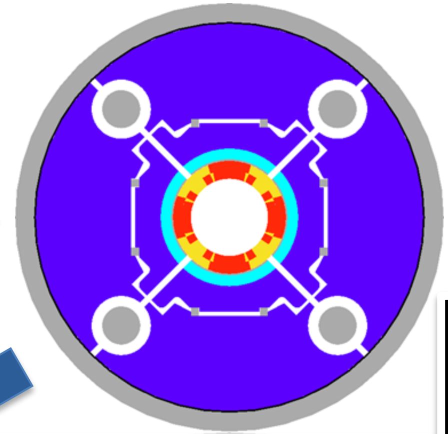


◆ **Nb-Ti operating dipoles;** ● **Nb3Sn cosϑ test dipoles** ■ **Nb3Sn block test dipoles**

LHC low-β quads: steps from present LHC toward HL-LHC

LHC (USA & JP, 5-6 m)
∅70 mm, B_{peak}~ 8 T
1992-2005

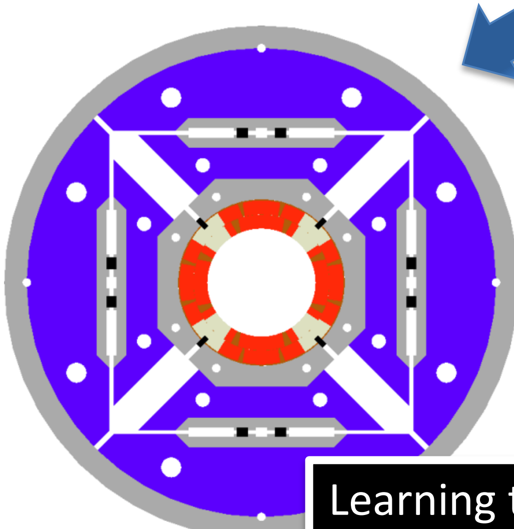


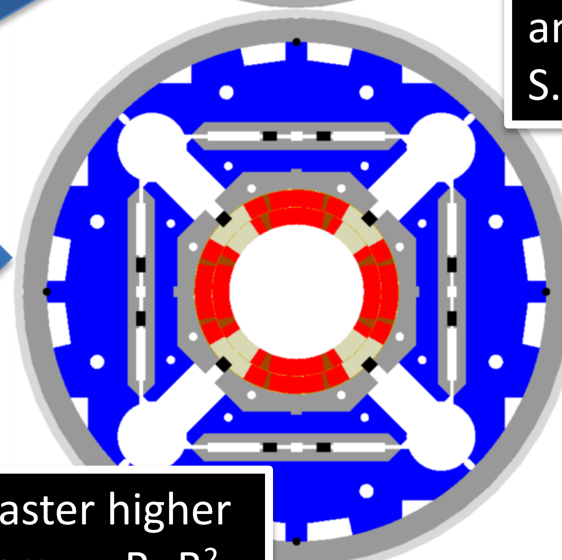


LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010

New structure based on bladders and keys (see talk S. Caspi)

LARP HQ
∅120 mm,
B_{peak}~ 12.5 T
2008-2014

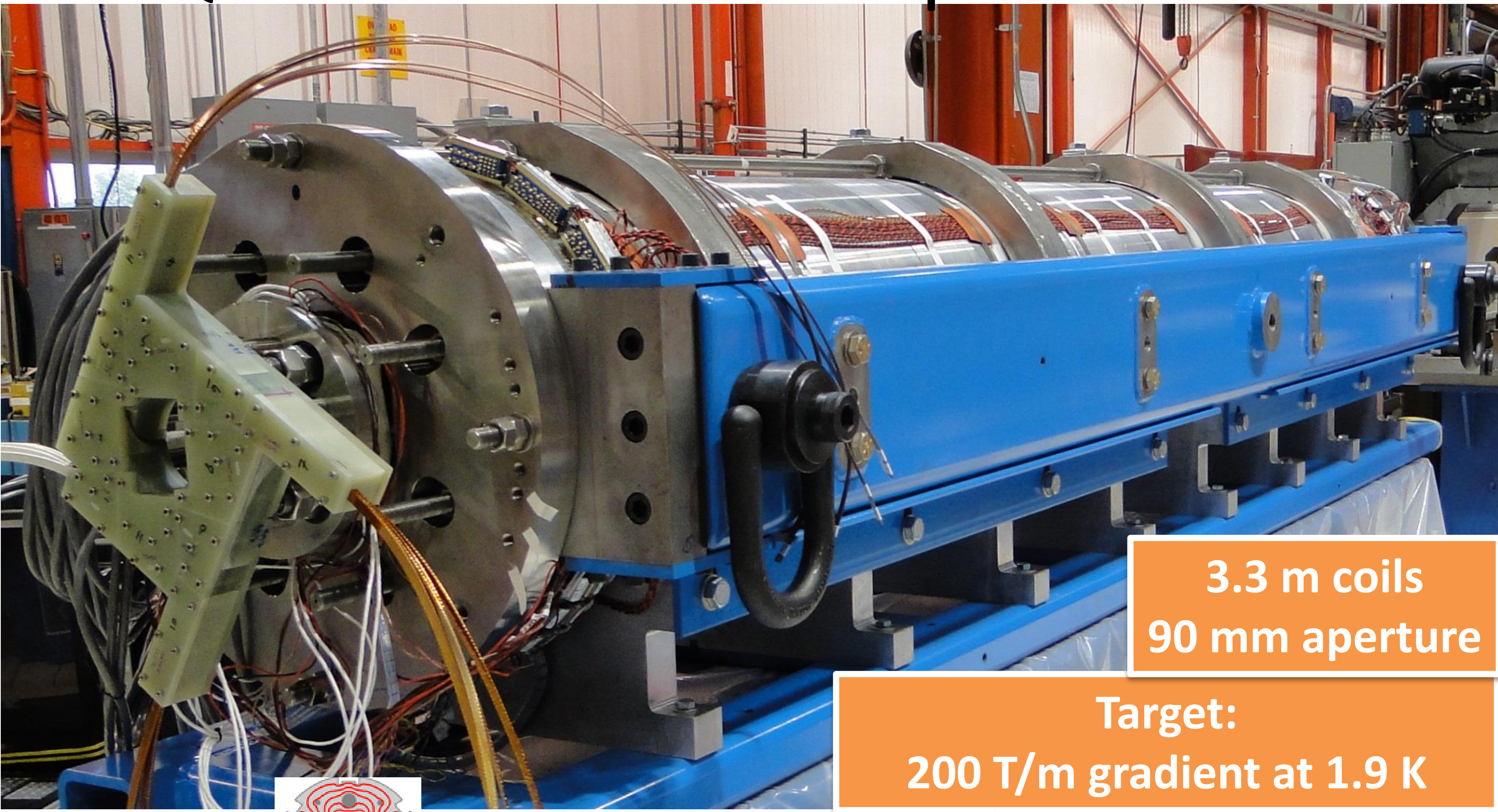




LARP & CERN MQXF
∅150 mm,
B_{peak}~ 12.3 T
2013-2020

Learning to master higher forces and energy ~ $R \times B^2$

LQS of US-LARP as step for HL-LHC



3.3 m coils
90 mm aperture

Target:
200 T/m gradient at 1.9 K

LQS01a: 202 T/m at 1.9 K
LQS01b: 222 T/m at 4.6 K
227 T/m at 1.9 K

LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

High Luminosity LHC

LARP

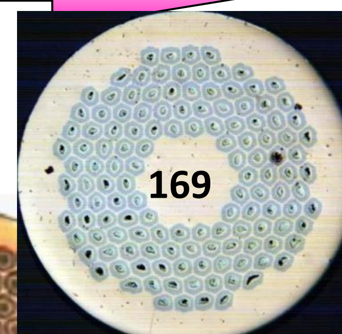
What to do to get into the region of high energy LHC ?

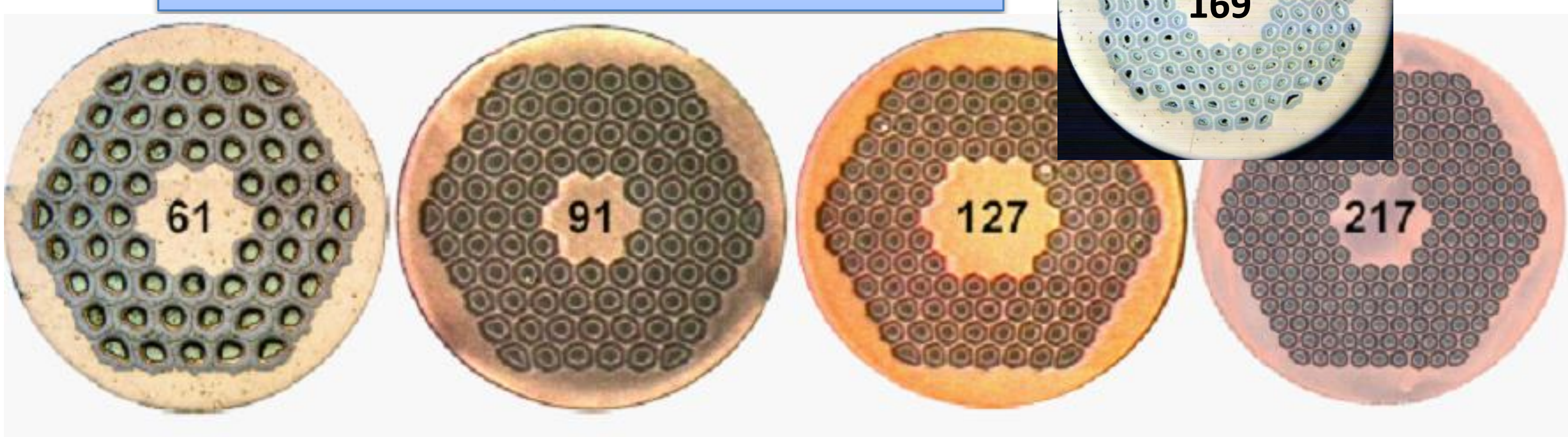
- Superconductors; Nb_3Sn needs to get better

RRP® strands with smaller filaments

Smaller Filament Size

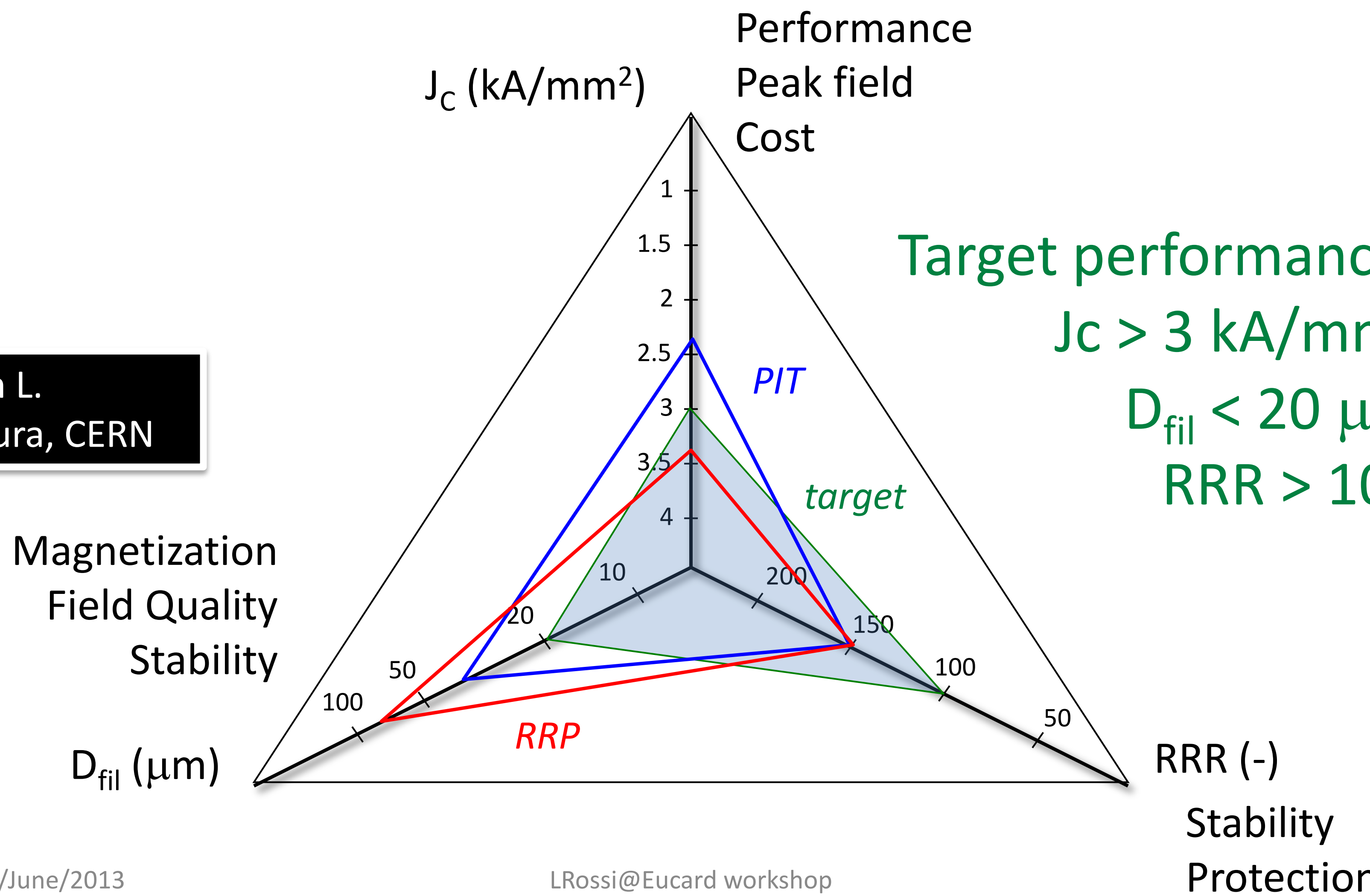
- **Smaller sub-elements can minimize flux jumps and improve stability.**
- **Filament Magnetization decreases**





Courtesy of Jeff Parrell (OST) and A. Gosh BNL

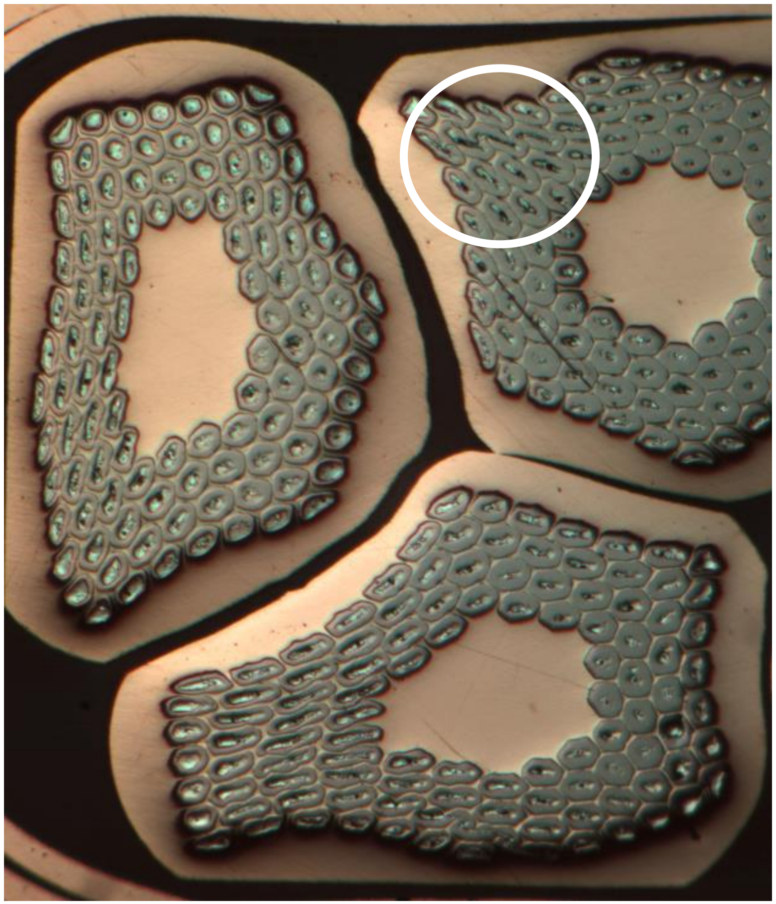
Performance targets for Nb_3Sn

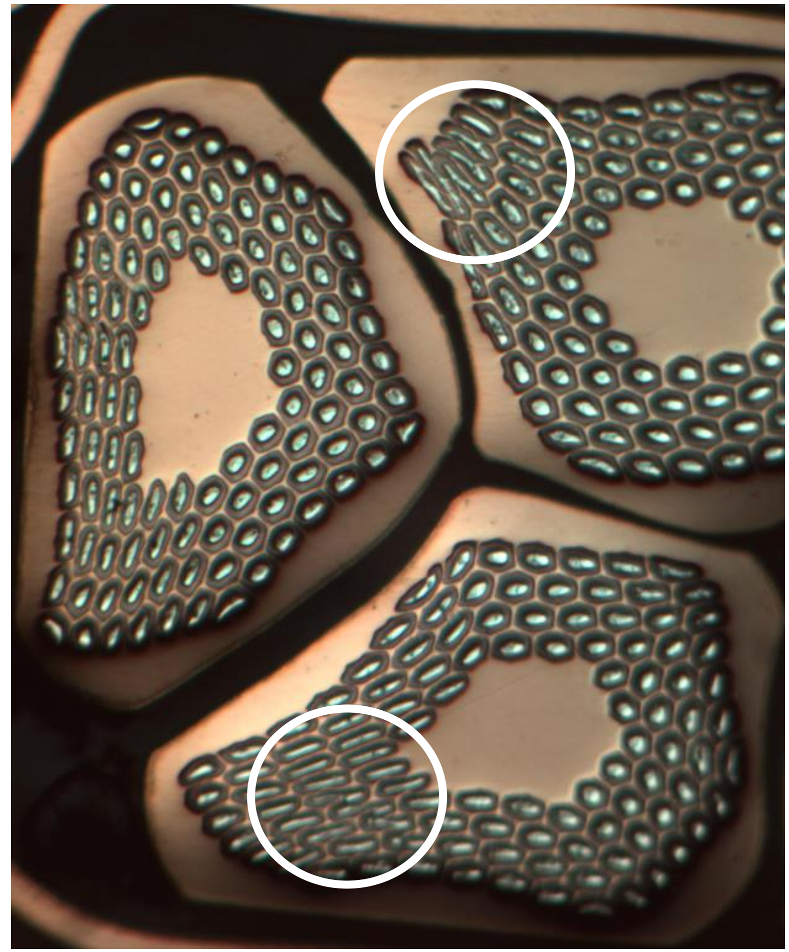


Target performance:
$Jc > 3$ kA/mm^2
$D_{fil} < 20$ μm
RRR > 100

From L. Bottura, CERN

And need to get control of cabling





Width =	17.94 mm
Thickness =	1.49 mm
PL =	109 mm

D.R. Dietderich
LARP-CERN CM20 April 9, 2013

Parameters list of LHC upgrades
(O. Dominguez and F. Zimmermann)

Table 1.1 Parameters of LHC, HL-LHC, HE-LHC, and VHE-LHC

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	40
beam half aperture [cm]	2.2 (x), 1.8 (y)	2.2 (x), 1.8 (y)	1.3	1.3
injection energy [TeV]	0.45	0.45	>1.0	7.0
no. of bunches	2808	2808	1404	4210
bunch population [10^{11}]	1.125	2.2	1.62	1.34
init. transv. norm. emit. [μm]	3.73,	[illegible]	2.10	1.53
initial longitudinal emit. [eVs]	[illegible]	[illegible]	5.67	17.2
no. IPs contributing to tune s[illegible]	[illegible]	[illegible]	2	2
max. total beam-beam tune sh[illegible]	[illegible]	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.412	0.338
rms bunch length [cm]	7.55	7.55	7.7	7.7
IP beta function [m]	0.55	0.15	0.3	1.5

The challenge

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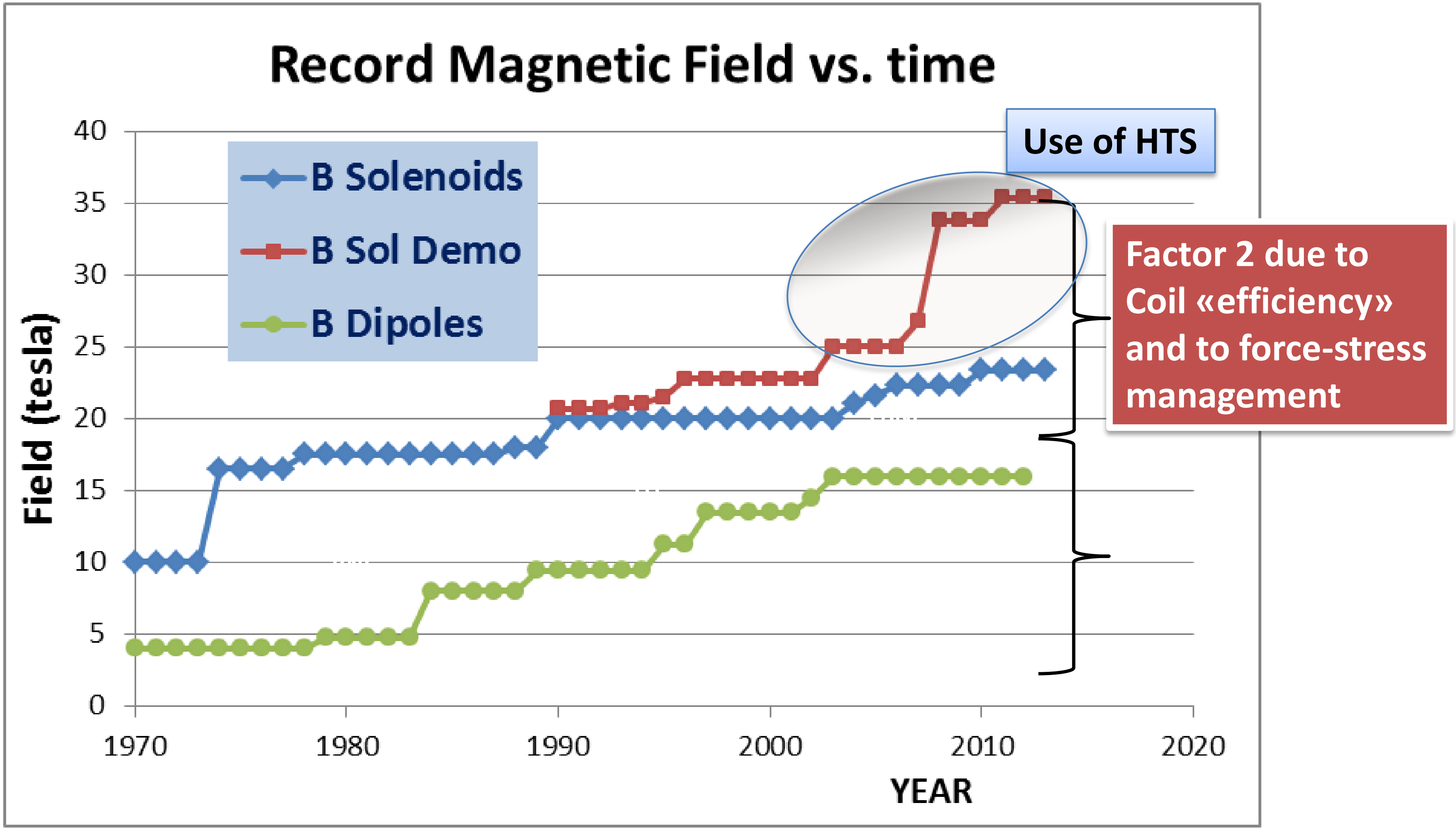
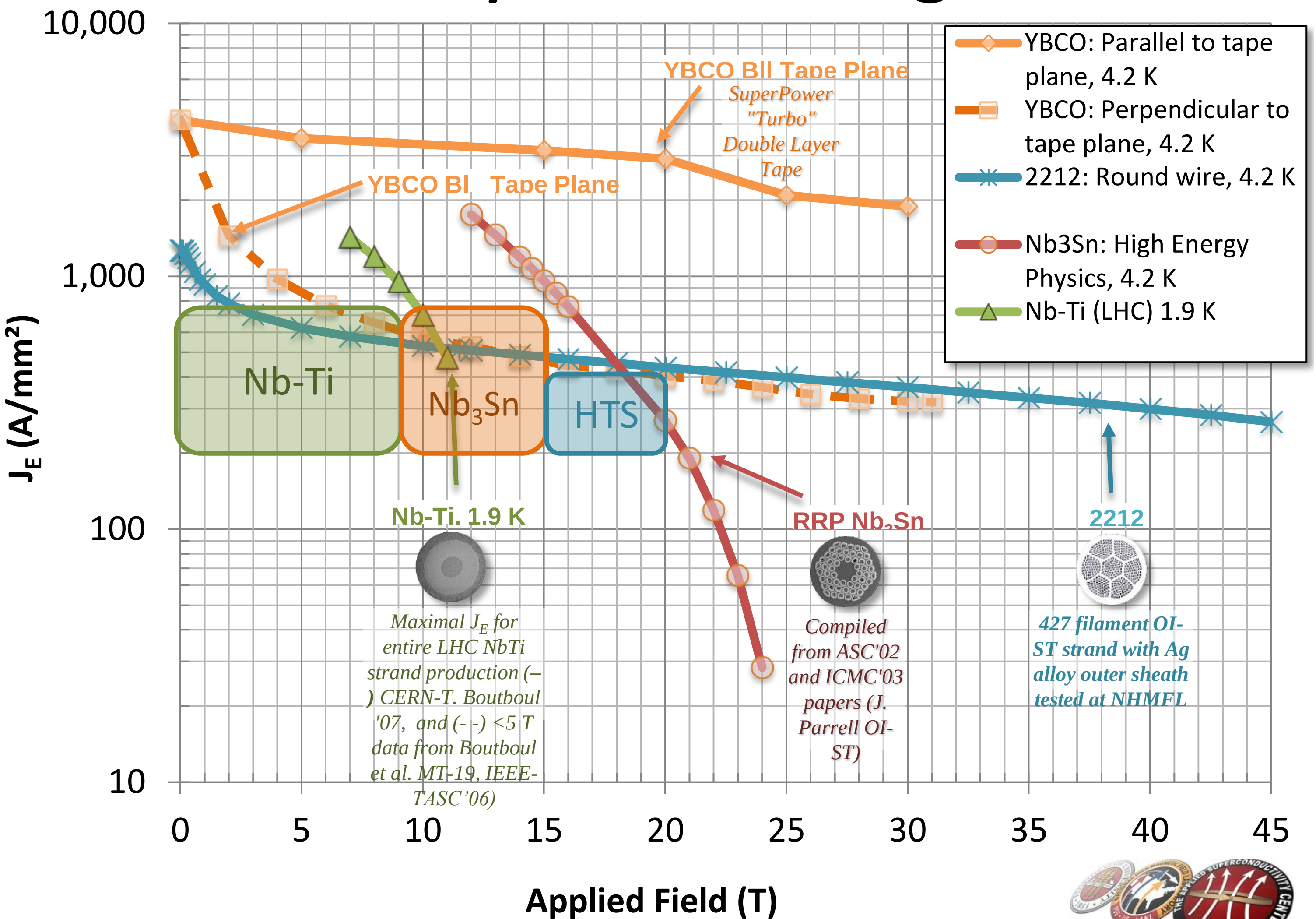
bunch population [10^{11}]	1.125	2.2	1.62	1.34
init. transv. norm. emit. [μm]	3.73,	2.5	2.10	1.53
initial longitudinal emit. [eVs]	2.5	2.5	5.67	17.2
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.412	0.338
rms bunch length [cm]	7.55	7.55	7.7	7.7
IP beta function [m]	0.55	0.15	0.3	1.5
init. rms IP spot size [μm]	16.7	7.1	6.0	6.5
full crossing angle [μrad]	285	590	240	52.3
stored beam energy [MJ]	362	694	601	4573
SR power per ring [kW]	3.6	6.9	82.5	1991
arc SR heat load dW/ds	0.21	0.40	3.5	84
energy loss per turn [keV]	6.7	6.7	201.3	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	1.9	1.6	1.3
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	21.0	78	305
d init. transv. IBS emit. rise time [h]	103	15.4	41	72.2
peak events per crossing	19	140 (lev.)	190	193
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	7.4	5.0	5.0
beam lifetime due to burn off [h]	45	11.6	6.3	15.5
optimum run time [h]	15.2	8.9	7.0	11.8
opt. av. int. luminosity / day [fb^{-1}]	0.47	3.7	1.5	2.1

Need to be addressed

Technology: dipoles vs solenoids in time, a comparison

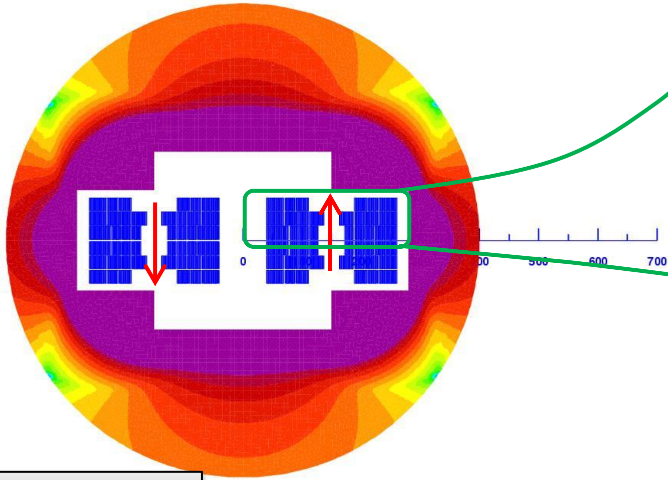


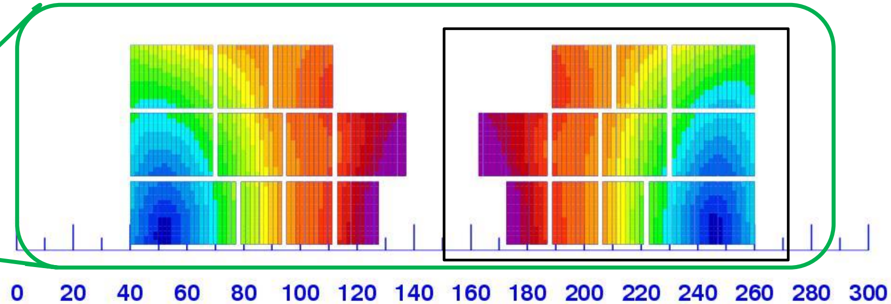
Superconductor space: getting the maximum by minimising the cost



Malta Workshop 14-16 Oct. 2010

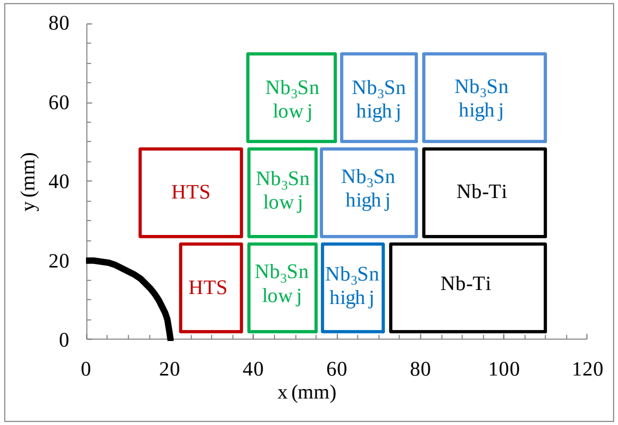
HE-LHC @ 33 TeV





L. Rossi and E. Todesco

Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

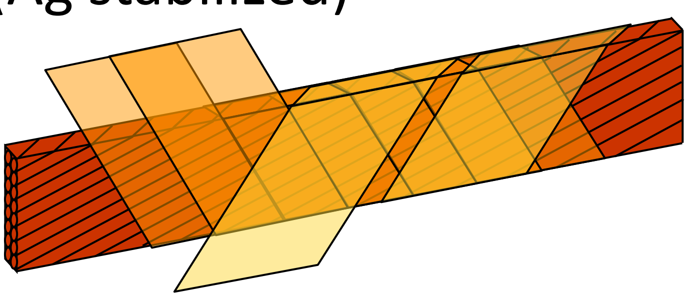


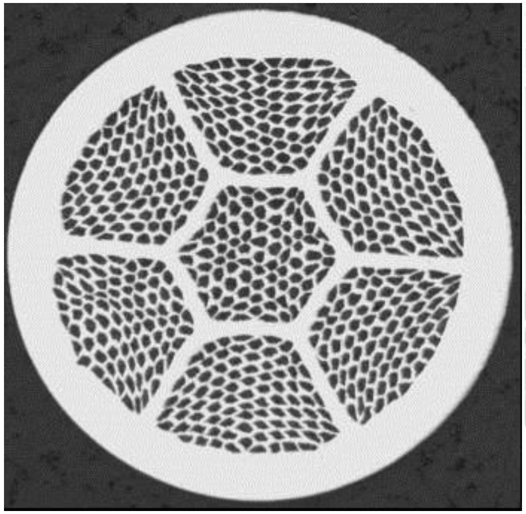
Straw-man desing (only 2D!!!) reasonable characteristics: fits in LHC tunnel, stress < 160 MPa,
Magnet design: very challenging but feasable: 300 mm inter-beam; anticoils to reduce flux
Multiple powering in the same magnet for FQ (and more sectioning for energy): handling energy is a problem

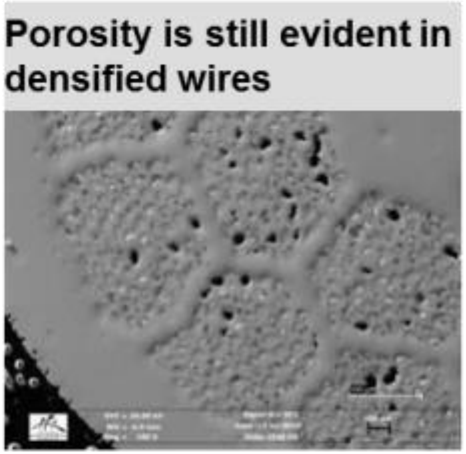
The « new » materials: HTS
Bi-2212

- Round wire, isotropous and **suitable to cabling**!
- HEP only users (good < 20K and for compact cable)
- Big issue: very low strain resistance, brittle
- Production ~ 0,
- cost ~ 2-5 times Nb3Sn (Ag stabilized)

- DOE program 2009-11 in USA let to a factor 2 gain. We need another 50% and more uniformity, eliminating porosity and leakage





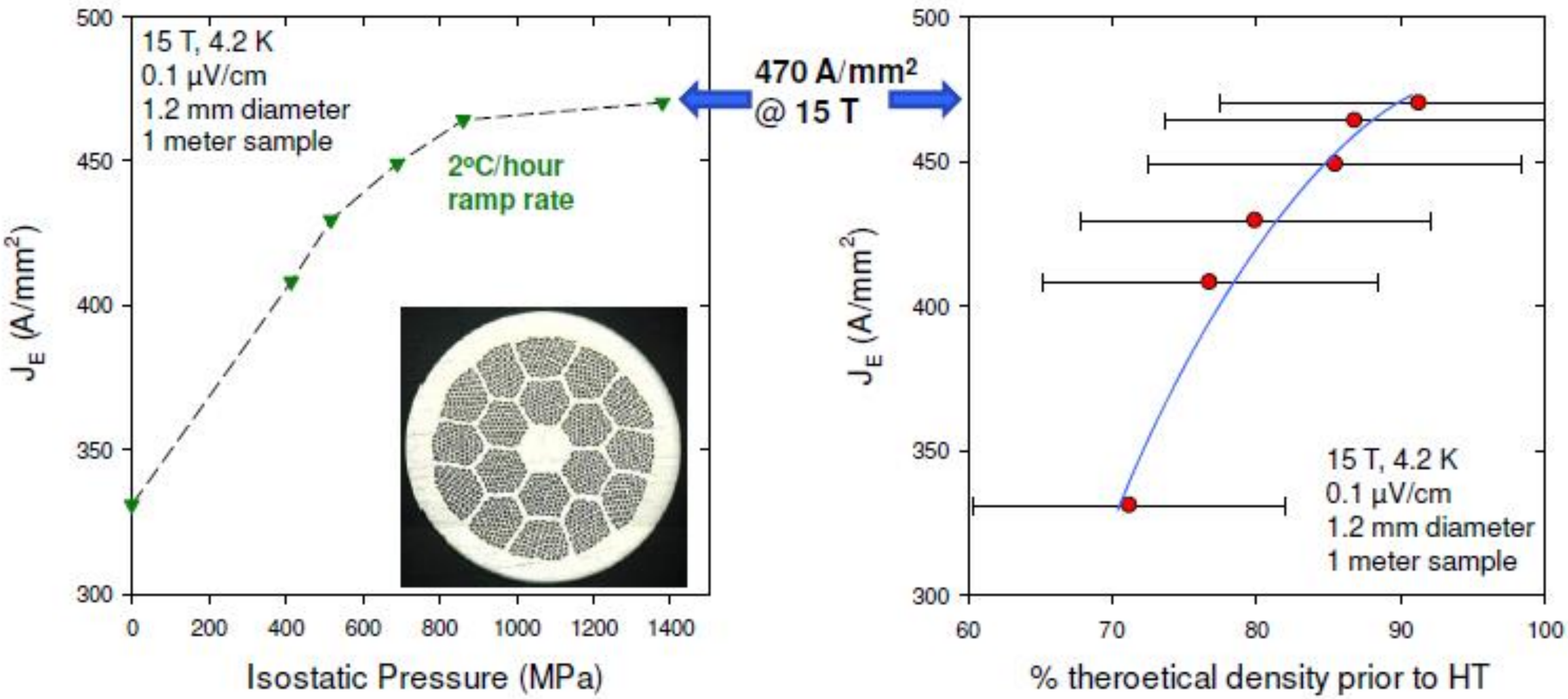


J. Jiang et al 2011

Improvemt are under way…

Oxford Instruments

Compaction + slow heating → improved J_E

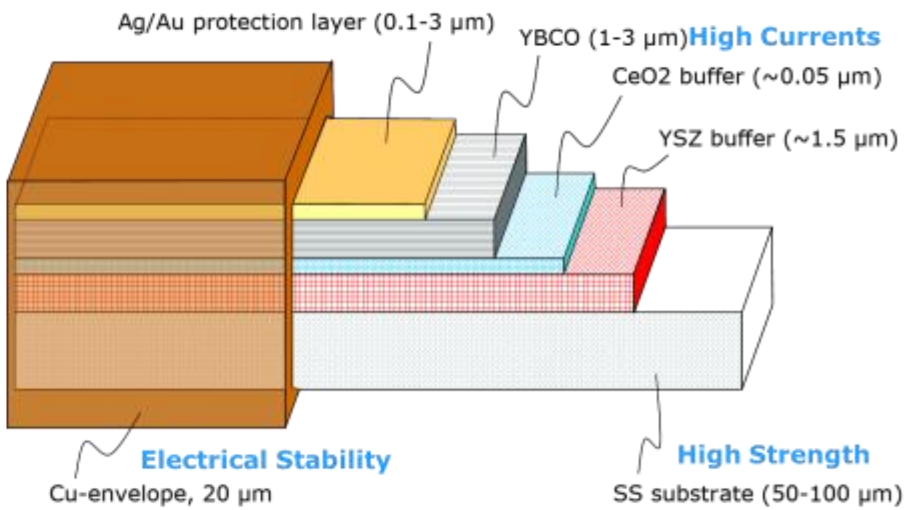


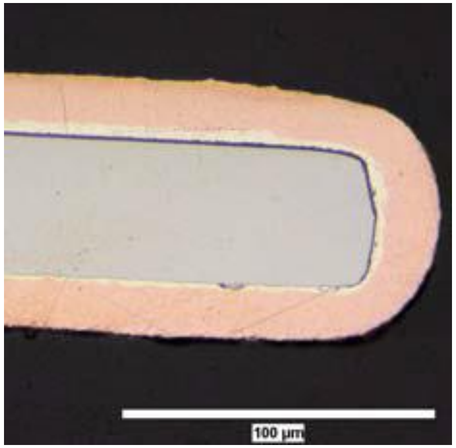
- Combined "best process" result in 15 T J_E values >450 A/mm²

→ Values match the best we've ever obtained, seem reproducible

The « new » materials: HTS YBCO

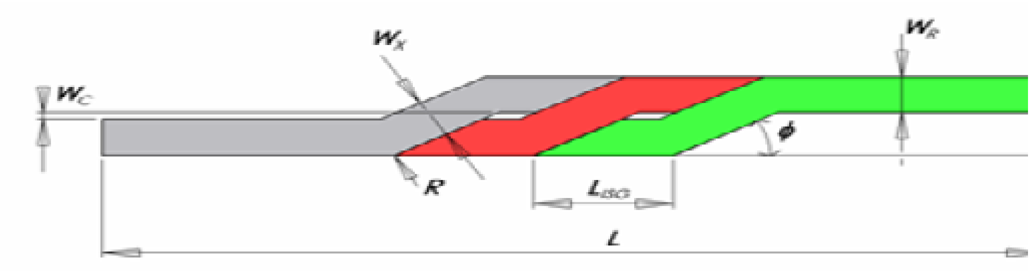
- Tape of 0.1-0.2 mm x 4-10 mm : difficult for compact (>85%) cables
- Current is EXCELENT but serious issue is the anisotropy;
- >90% of world effort on HTS are on YBCO! Great synergy with all community
- Cost : today is 10 times Nb_3Sn, target is same price: components not expensive, process difficult to be industrialize at low cost
- FP7 Eucard is developing EU Ybco

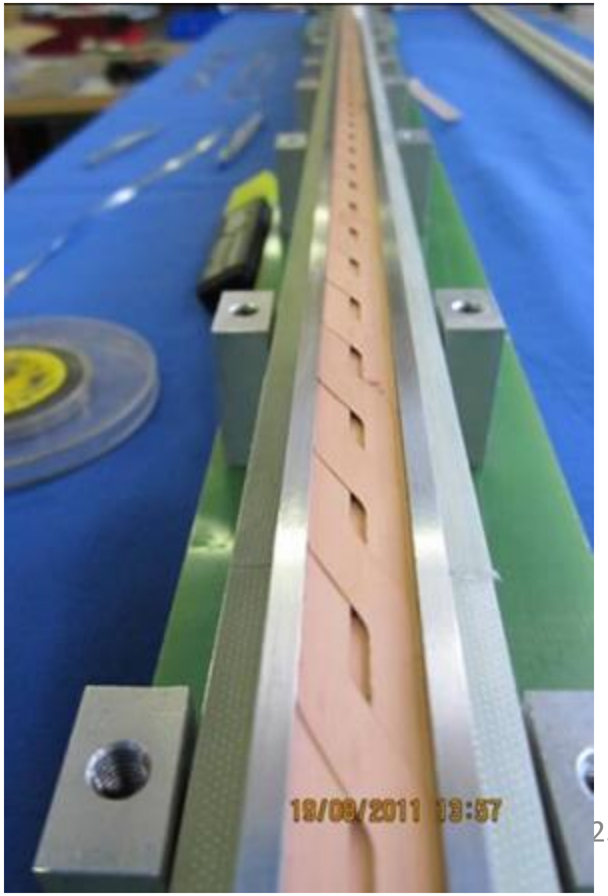




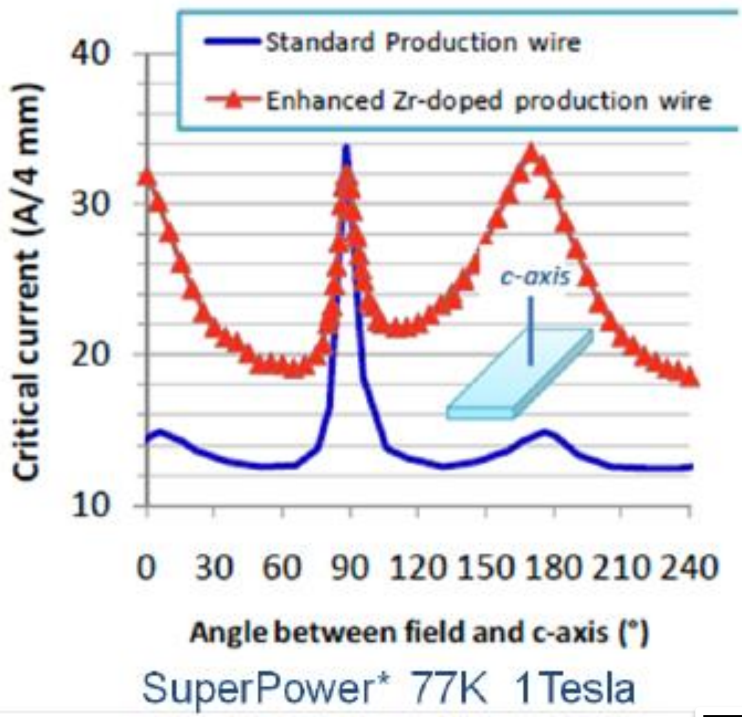
New (old) approach to cabling suitable for tapes

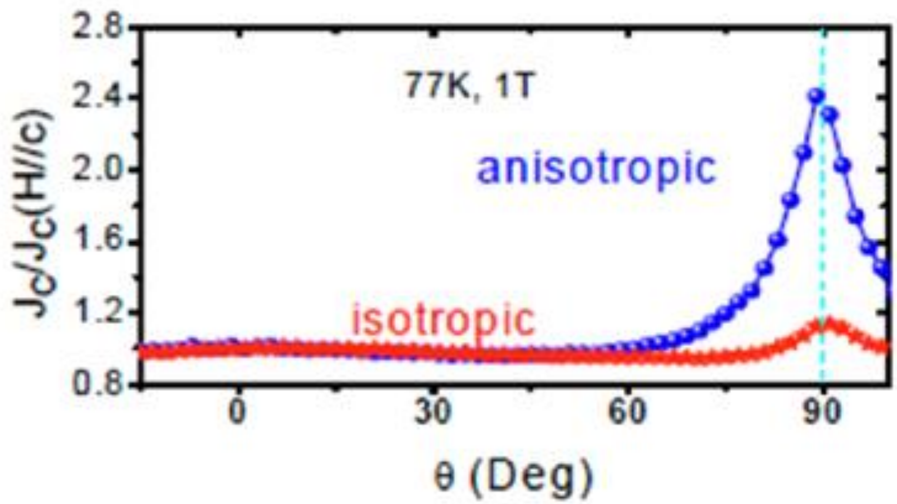
- An old type of cabling (Roebel) suitable for tapes has been recently rivisited (Karlsruhe, New Research Industry NZ)
- Here a first 2 m long test cable done at CERN





Also YBCO is improing: Enhancing Jc in the //c direction





SuperPower, 77K/1T

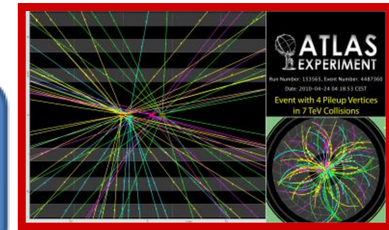
From R. Flukiger, AFF 2013 talk

AMSC, 77K, 1 T

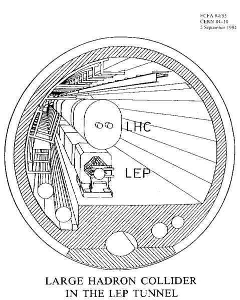
V. Selvamanickam and J. Deckow, DOE Peer Review 2010

M. Rupich, J. McCall, C. Thieme, DOE Peer Review, 2010

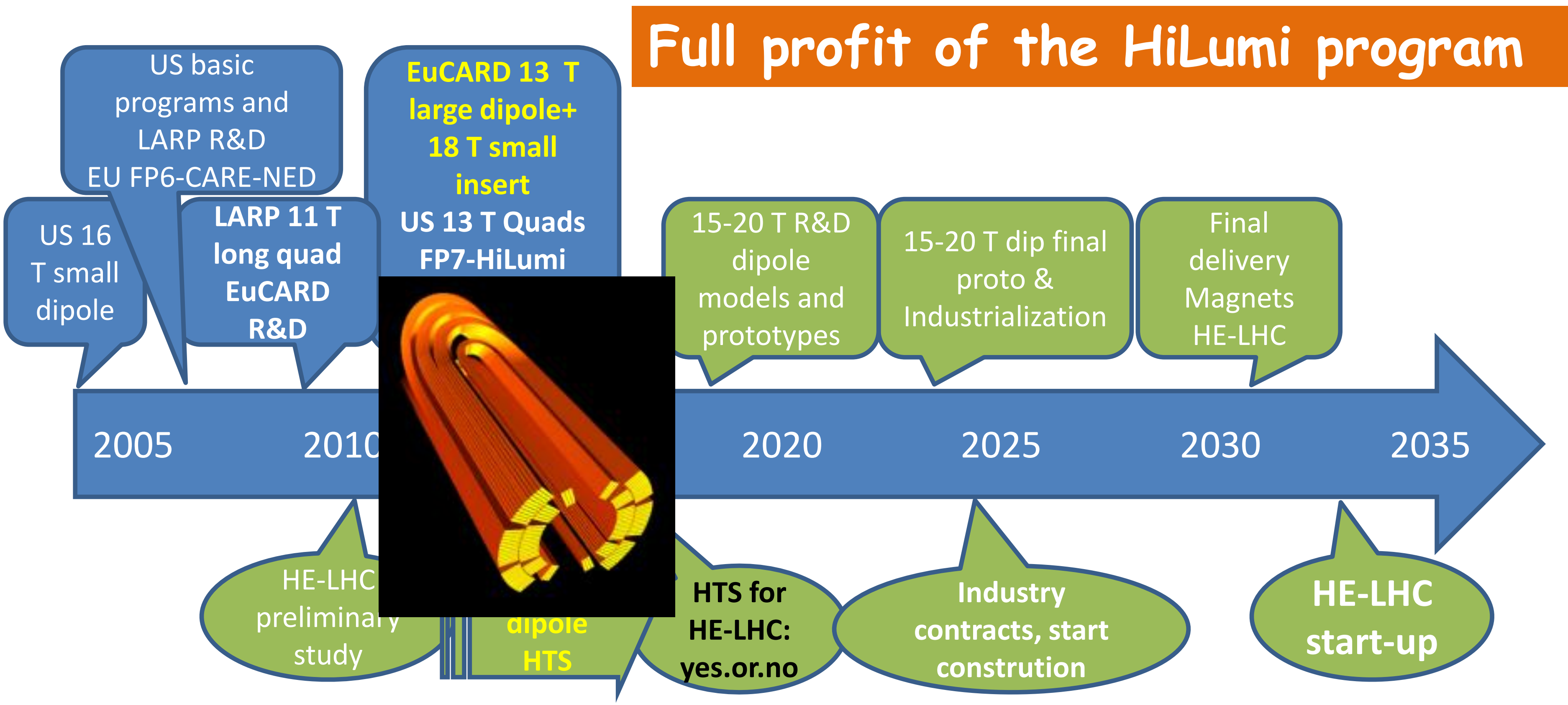
LHC, the construction timeline: a 25 year old project



- 1985 — LHC study
- 1987 — 9 T - 1 m single bore
- 1990 — 10 T-1m Nb3Sn dipole; Decision for Nb-Ti
- 1994 — 9 T -10 m long protoype
- 2000 — 9 T-15 m final protoype; Industry contracts Nb-Ti
- 2006 — Last LHC dipole
- 2010 — LHC start-up

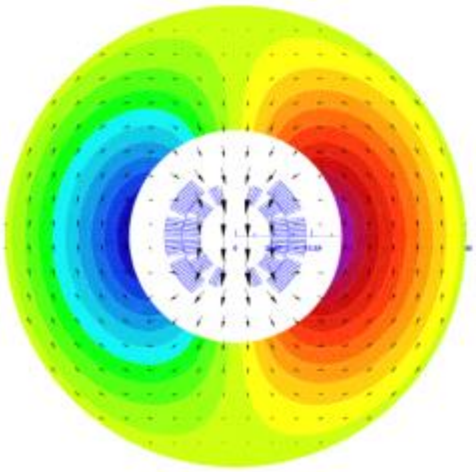


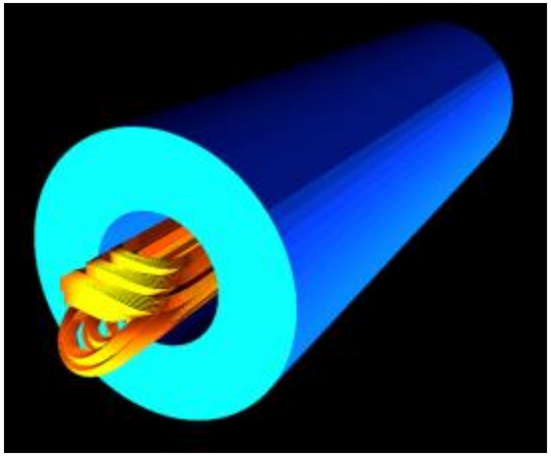
What is the possibile for HE-LHC?



The EU program
The chance for HTS

- FP7-EuCARD2 (2013-16)
- Started on 1 May 2013: **WP-10 Future Magnets**
  - Assessment of YBCO and Bi-2212 for HE-LHC
  - **Development of 10 kA class HTS compact cable**
  - **Prototype of a 5 T real accelerator quality magnet (assessing best structire for HTS ? Outside Eucard2, // program)**
  - Test the coil in a 13-15 T background field to proof 18-20 T principle with 10 kA HTS conductor.

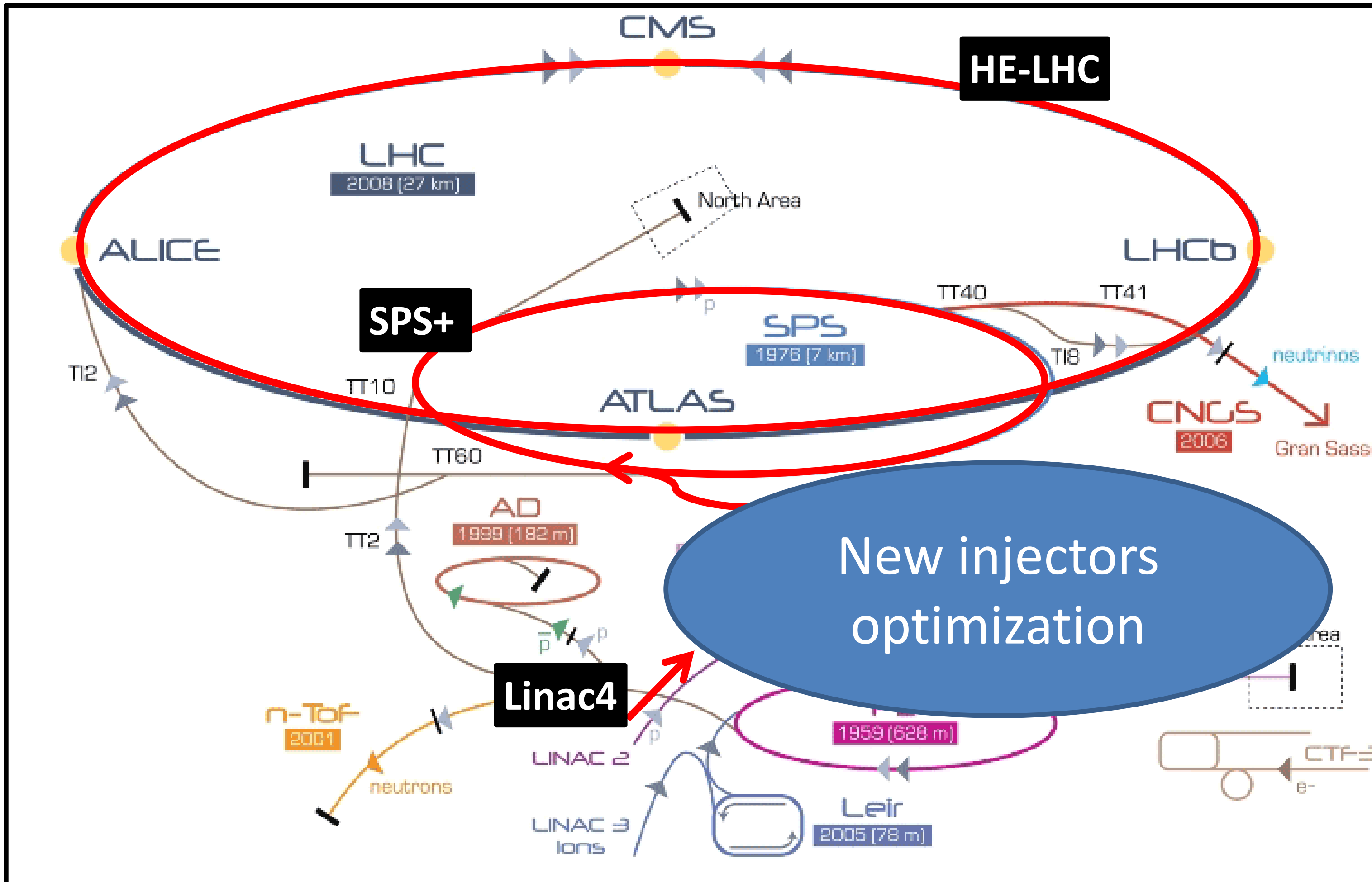




That's all?

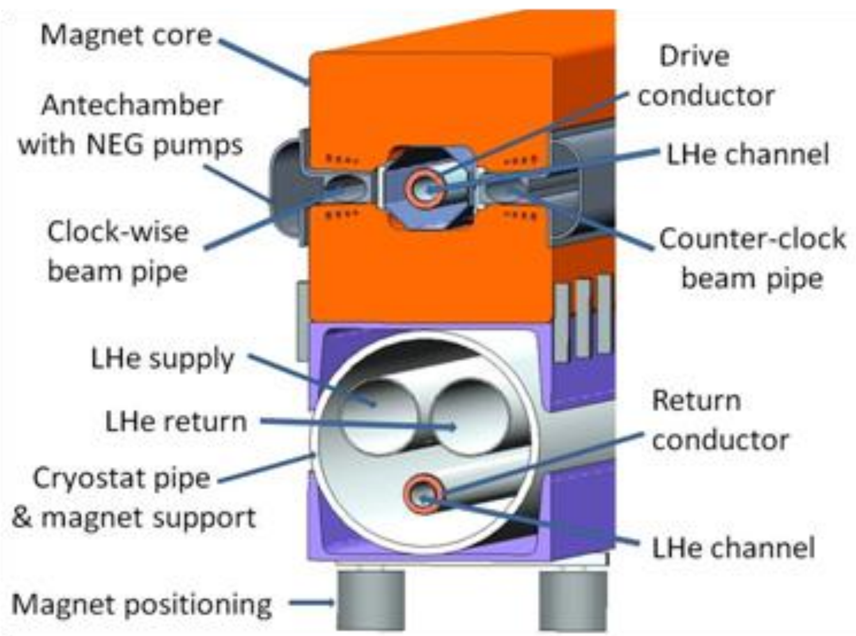
- Not at all:
  - We will need fast cycling magnets for the injection chain of the high energy machine
  - (and high intensity proton synchrotron like FAIR and upgrades)
  - (see next talk by P. Fabbricatore)
- But we need also to try to cope with other accelerator that may share the same tunnel: TLEP, the e+e- circualr Higgs factory

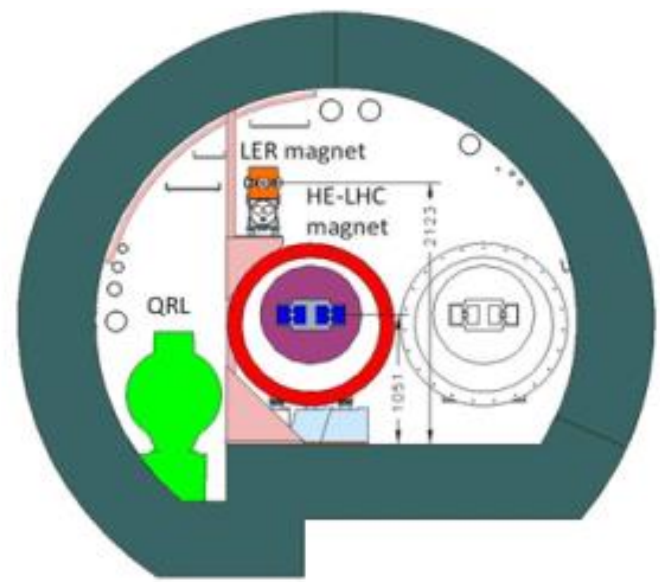
Beyond Linac4: possible SC SPS?



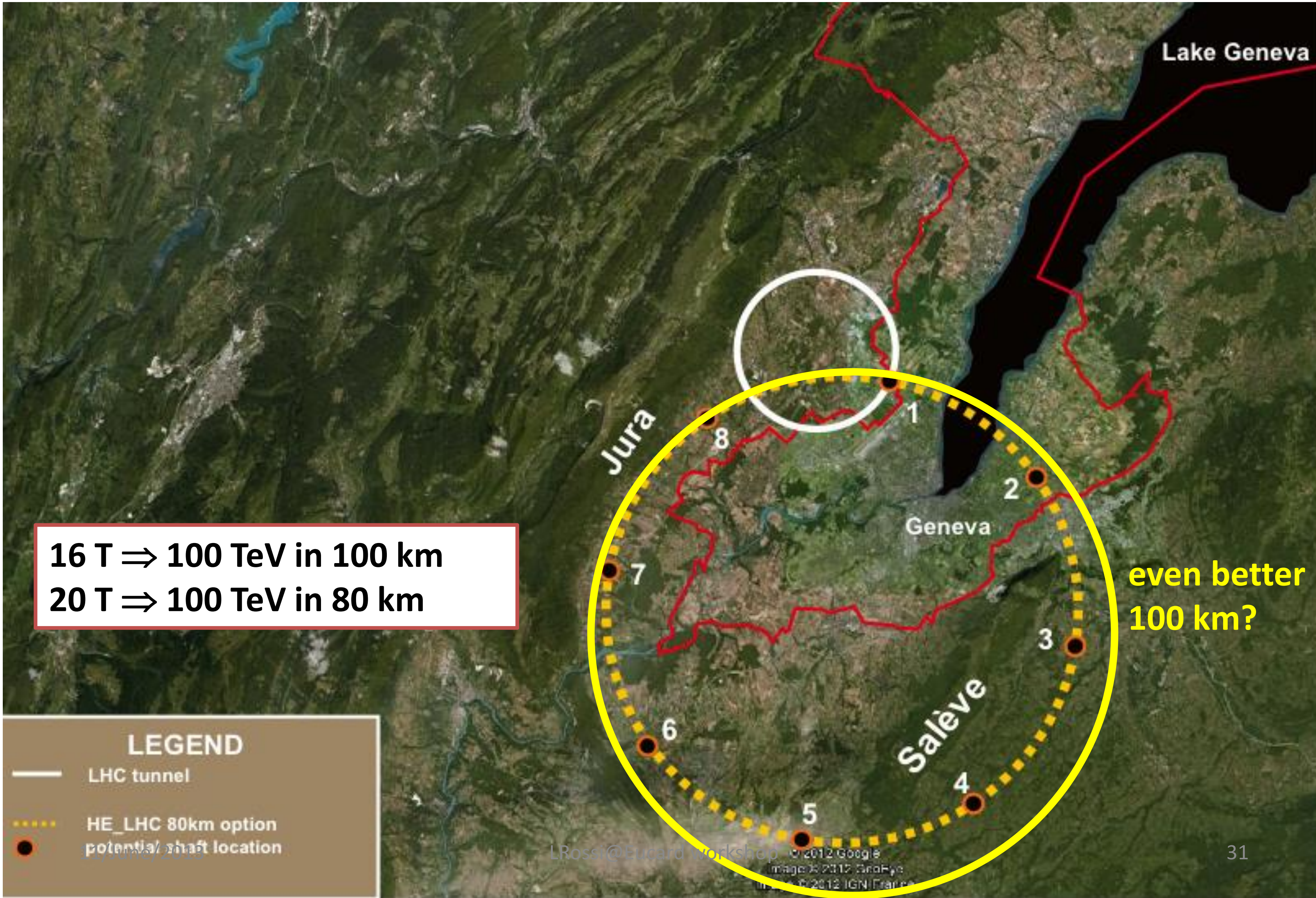
Alternate scenarios for Injectors

- Keeping SPS (and its transfer lines: 6 km!): Low Energy Ring in LHC tunnel with superferric Pipetron magnets (W. Foster).
- Work done by Fermilab (**H. Piekarz**), see Malta workshop proc.
  - **cost of LER is lower than SC-SPS option.**
  - Integration is difficult but no show-stoppers



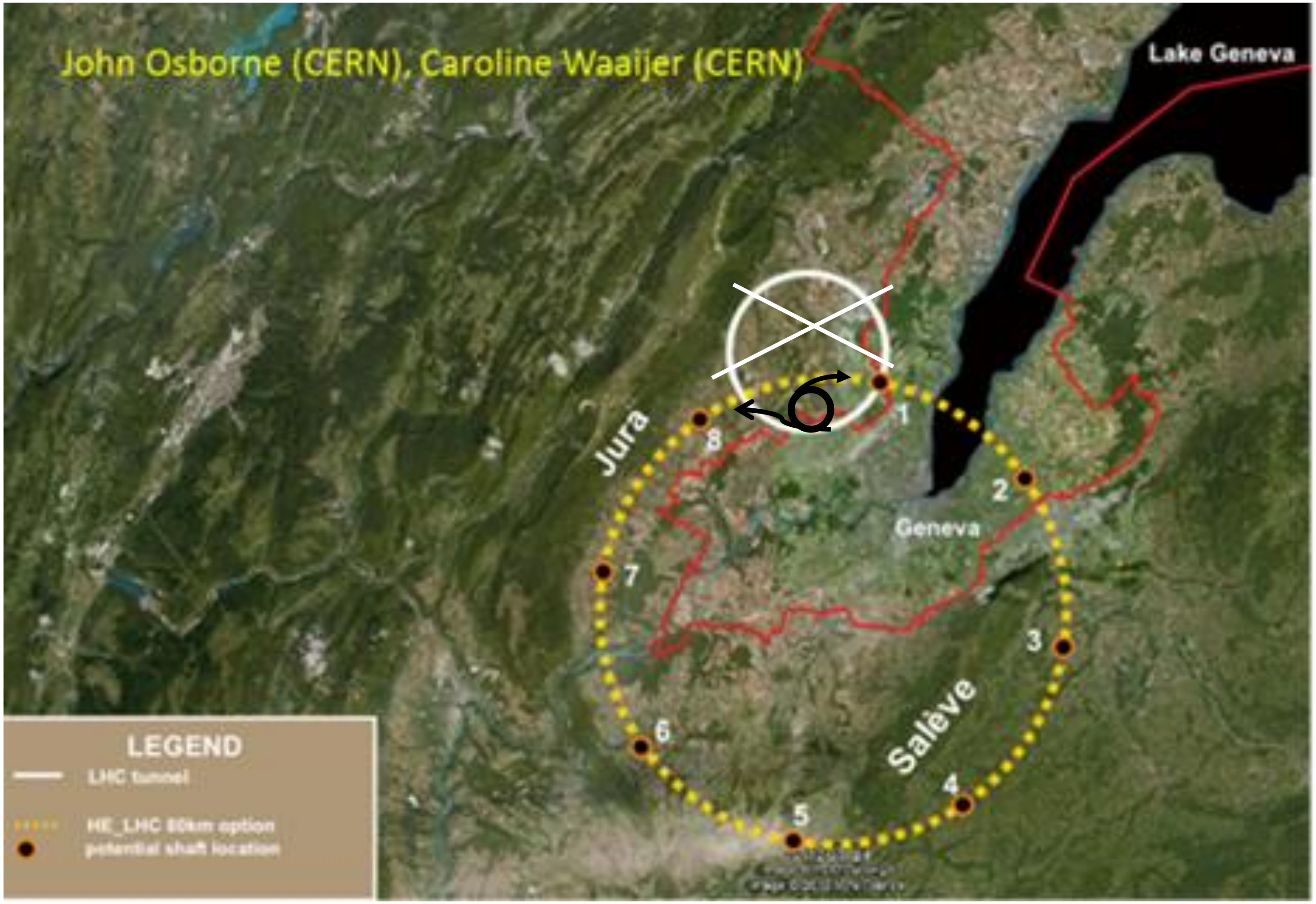


80-km tunnel in Geneva area – VHE-LHC

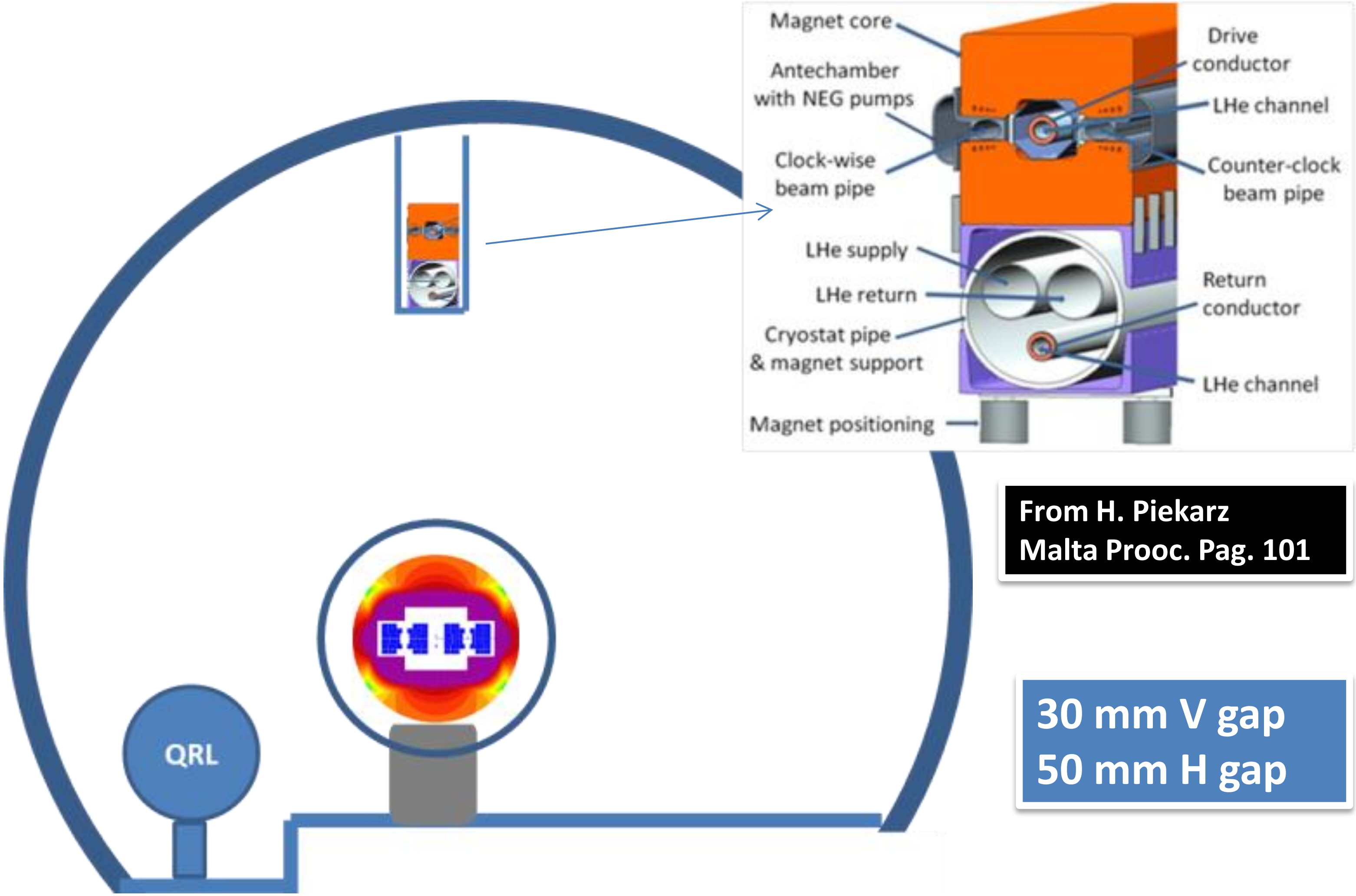


16 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km

For VHE, Injection scheme: SPS+ →LHC → VHE-LHC is too expensive (50 MW power for cryo)



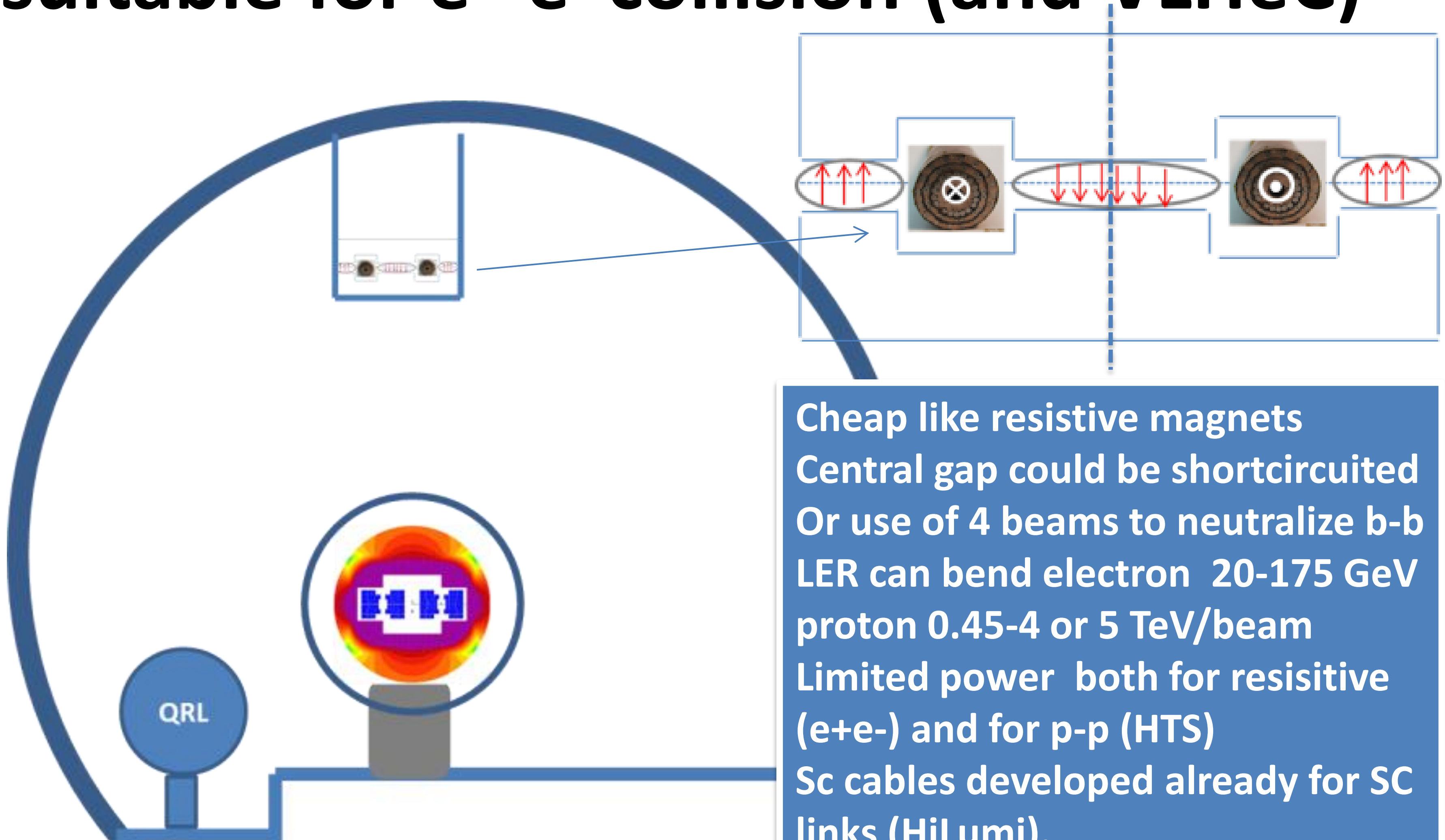
Possible arrangement in VHE-LHC tunnel



From H. Piekarz
Malta Prooc. Pag. 101

30 mm V gap
50 mm H gap

Possible VHE-LHC with a LER
suitable for e^+-e^- collision (and VLHeC)



Cheap like resistive magnets
Central gap could be shortcircuited
Or use of 4 beams to neutralize b-b
LER can bend electron 20-175 GeV
proton 0.45-4 or 5 TeV/beam
Limited power both for resisitive (e+e-) and for p-p (HTS)
Sc cables developed already for SC links (HiLumi).
SR by e- taken at 300 K

A few numbers for proton injector

	PROTONS		
	energy	field	
	[TeV]	[T]	
	0.026	0.117	
SPS	↓	↓	x 17.3
	0.450	2.03	
injector	0.450	0.167	
80 km tunnel	↓	↓	x 9.0
ρ = 9.0 km	4.1	1.5	75 kA

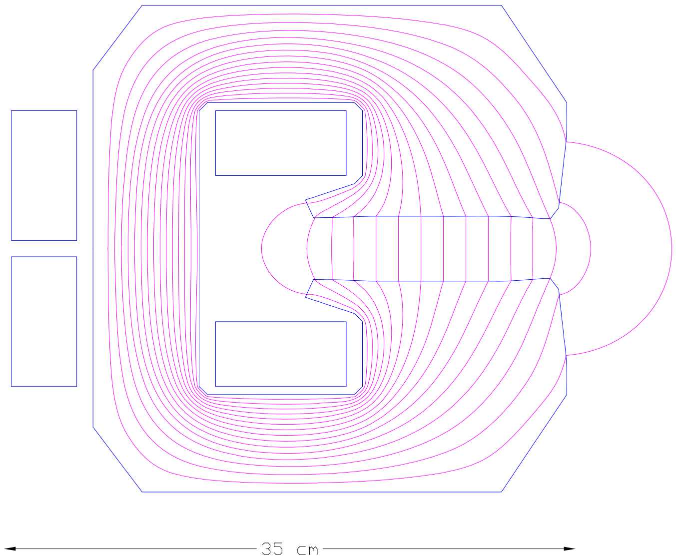
With I = 115-120 kA Bmax= **2 T**

A few numbers to use the same magnet for e+ - e-

	ELECTRONS		
	energy	field	
	[GeV]	[T]	
	3.5	0.016	
SPS	↓	↓	x 5.7
	20	0.090	
e+ / e- machine	20	0.0074	
80 km tunnel	↓	↓	x 8.8
ρ = 9.0 km	175	0.0648	I =3 kA

The injection field is low, 74 Gauss (no diluition). Concern for field quaity.
We think is possîble with «noble» Fe grain oriented but probably also with normal Fe-Si.
Already tested at 100 Gauss. Next magnet (for RCS) will be tested to 50 Gauss.
Diluition can also be a possibilty (not good for p-p injector)

CERN dipole models for LHeC ring-ring



- compact C-type dipole
- cross-section design with “umbrella” pole
- diluted magnetic yoke, since it works with low B
- solid single bars (copper or aluminum) as conductor
- 3 models with different electrical steel:
  - conventional low C, 0.5% Si, H_c < 70 A/m ($)
  - 35M6 grain oriented, H_c < 7 / 25 A/m ($$)
  - Supra 36 NiFe, H_c < 6 A/m ($$$)
- very similar measured results for field quality and cycle-to-cycle reproducibility

interleaved laminations (1/3 electrical steel, 2/3 phenolic resin)

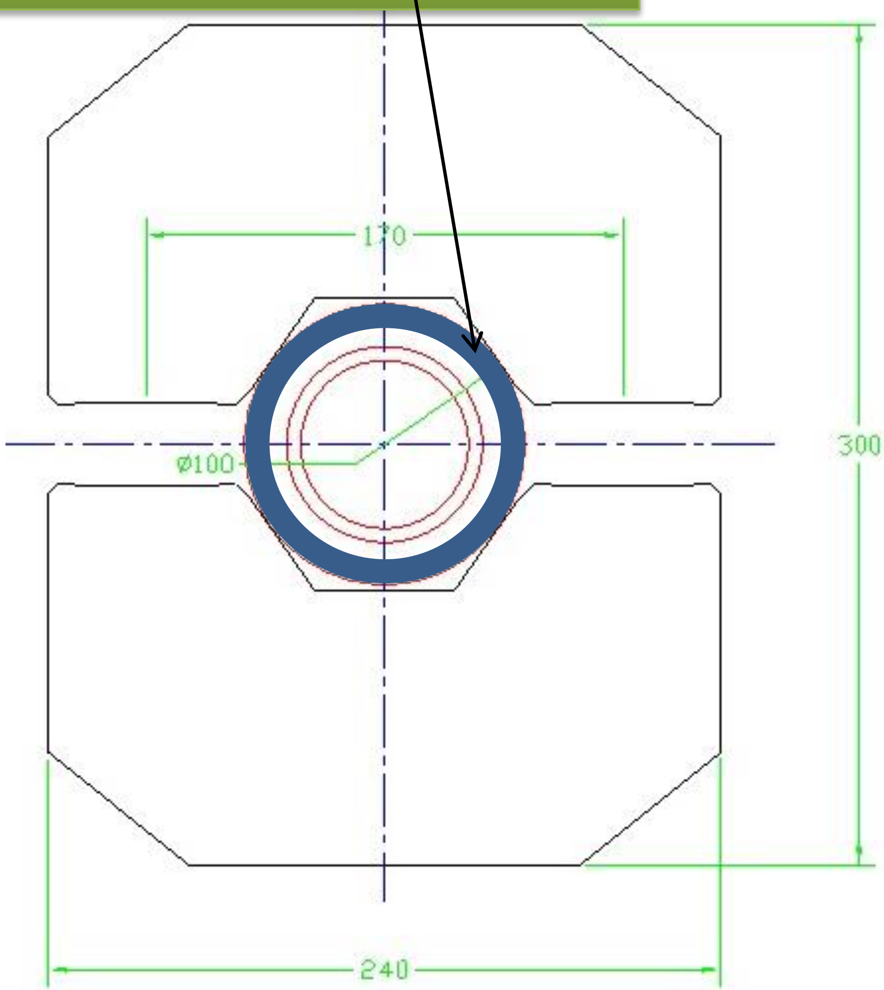
40 mm gap
B = 0.0127 to 0.0763 T

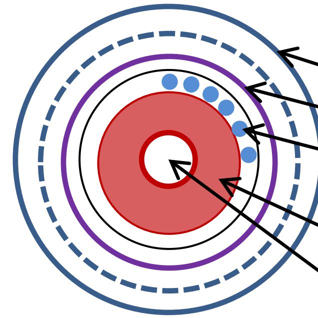
one-turn conductor
I = 216 to 1300 A
air cooled

Courtesy Attilio Milanese, CERN

A Super-Resistive cable

20 mm thick shield around cable
Gaps: 2 x V30xH60 mm





Cable:
inner core of 40 mm Cu (700 mm2)
+ outer core : 2 layers, 150 strands of MgB_2, 1 kA each; Outer size 45 mm.
120 kA =>120 k€/km !
For electrons: us Cu water cooled,
J_{ov} 2.5 A/mm2 (easy): P_{plug}=11 MW/80km

For protons: 800 A/strands
120 kA (for >2.1 T); the central copper is the stablizer
Power: 0.1-W/m at T_{op} = 10 K consumption/cable should be possible:
10 kW of cold power: P_{plug}= few MW
This is for each channel…

Conclusion

- The next step for high field magnet development is HL-LHC
  - We needs to finalize desing, test it, and to do the step from models to long prototypes
- HE-LHC & VHE-LHC are triggering a lot of R&D, ideas and make us to push to the limit each technology:
  - HE-LHC: 1000 tons of Nb-Ti
  - 1500 tons of Nb3Sn
  - 500 tons of HTS !! (Iter Nb3Sn is 400 tobns)
- HTS may have a chance for a large production:
  - If will show ability to meet accelerator quality
  - If the their cost will go down by a factor 5-10 (at least)
- 10-15 years of R& is not a luxury to gain th next future frontier (waiting to change paradigma like plasma accel…)