AFTER THE HIGGS DISCOVERY:
WHERE IS FUNDAMENTAL PHYSICS GOING

希格斯粒子发现之后：
基础物理学向何处发展

100 TeV Collider Magnets

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Fermilab

1st CFHEP Symposium on circular collider physics
23-25 February 2014
IHEP, Beijing (China)

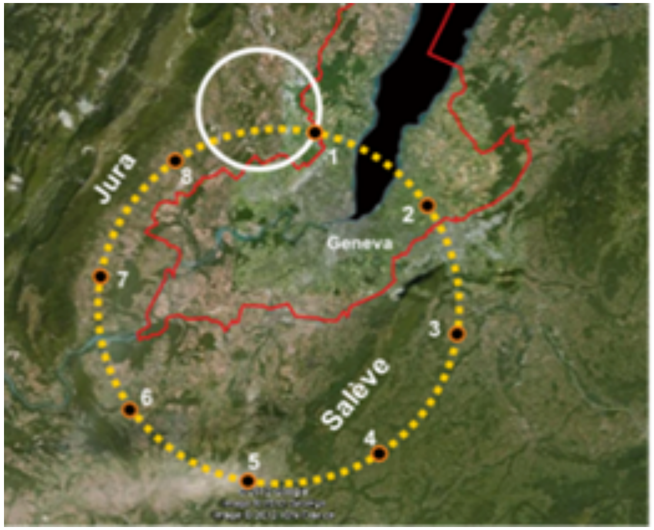
Introduction

$$E[GeV] = 0.3RB\,[m \cdot T]$$

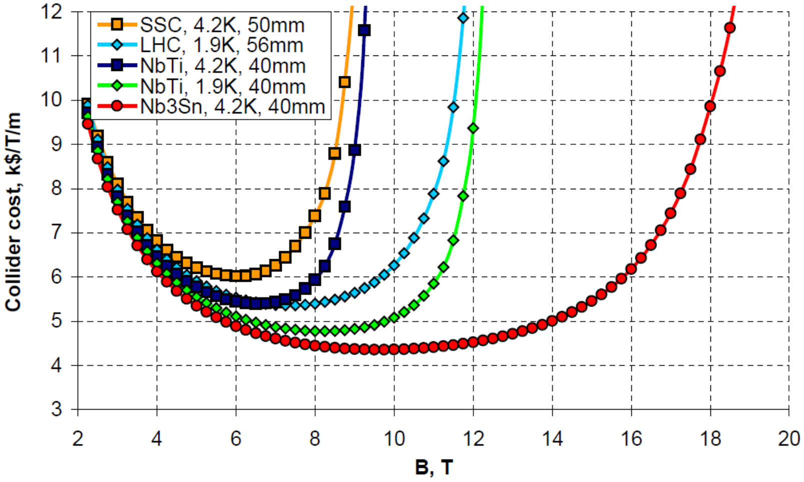
- **Circular collider energy scales with the strength of bending dipole magnets B and the ring size R**
  - **Tevatron: E~1 TeV, B~4 T, C~6 km**
  - **SSC: E~20 TeV, B~6.6 T, C~87 km**
  - **LHC: E~7 TeV, B~8 T, C~27 km**

Proposed post-LHC hadron colliders:

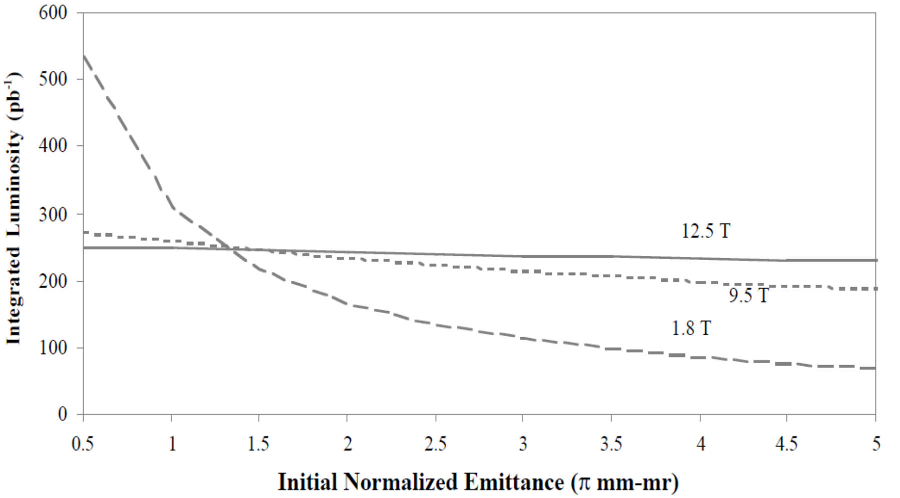
- **HE-LHC: 13-14 TeV => 26-33 TeV, 27 km LHC tunnel, 15-20 T**
- **VLHC: 175 TeV, 233 km tunnel, 10 T (VLHC Design Study, 2001)**
- **VHE-LHC (FCC): 84-104 TeV, 80-100 km tunnel, 15-20 T (planned international design study)**



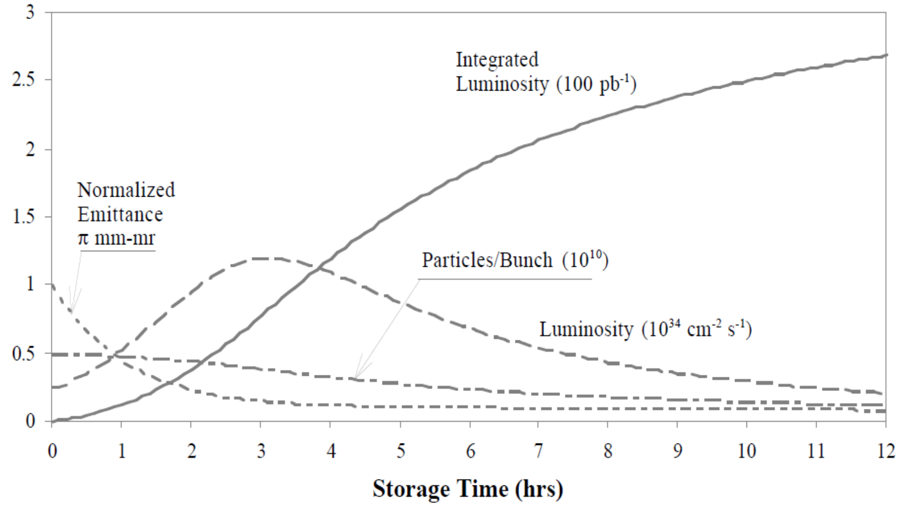
Magnet Strength Considerations



Collider costs as functions of the field in FY2001 dollars.



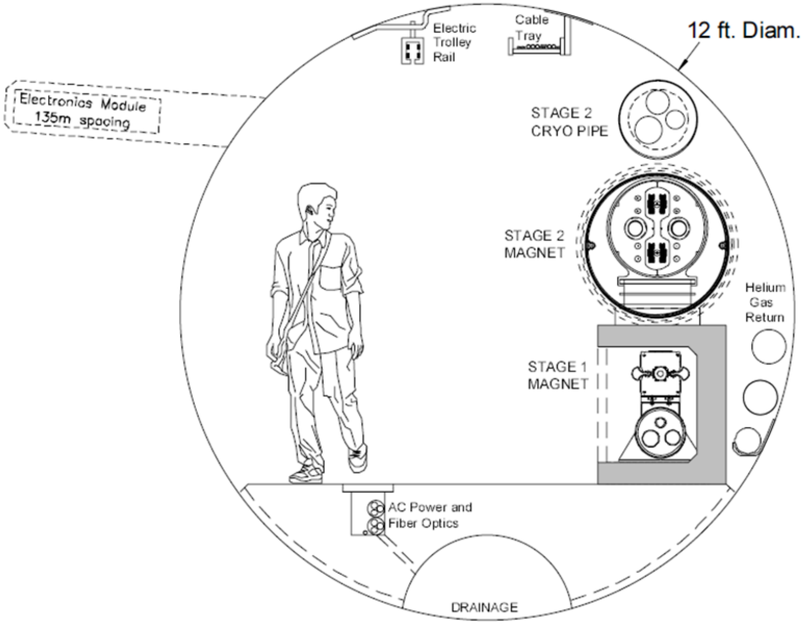
Integrated luminosity of 10 hour store vs. initial rms emittance for RLHC options. The integrated luminosity of the two high-field cases is almost independent of the initial emittance because of synchrotron damping.

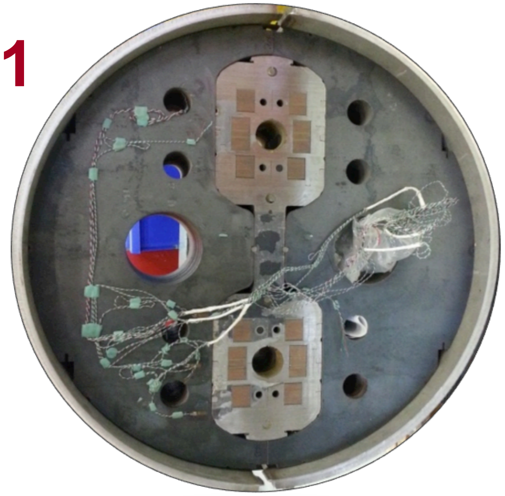


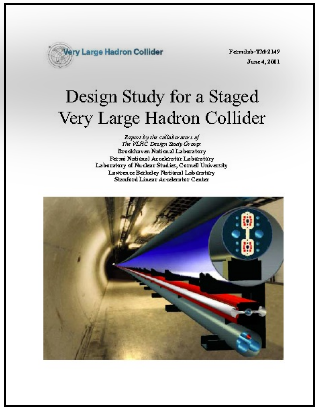
Beam parameters during a store for high-field RLHC.

VLHC Design Study 1997-2001

- **Stage I**
  - **Low-cost NbTi combined function SF magnets**
  - **B~2 T**
- **Stage II**
  - **High-field Nb_3Sn magnets**
  - **B~10 T**






Very Large Hadron Collider

Fermilab-TM-2149
June 4, 2001

Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of
The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center

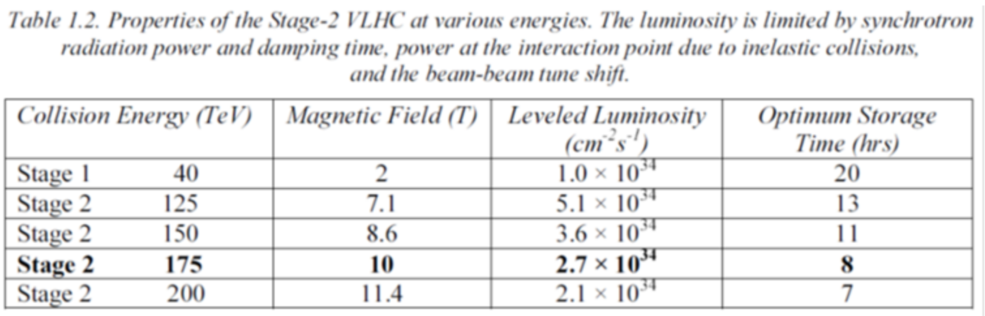
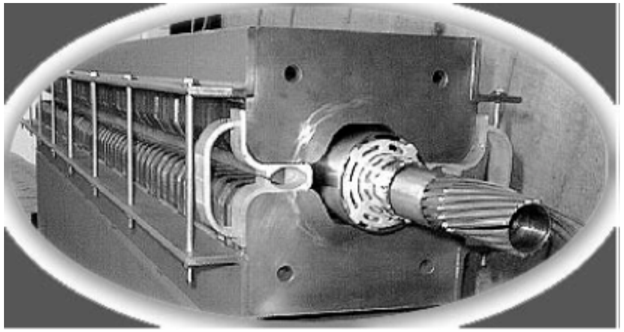
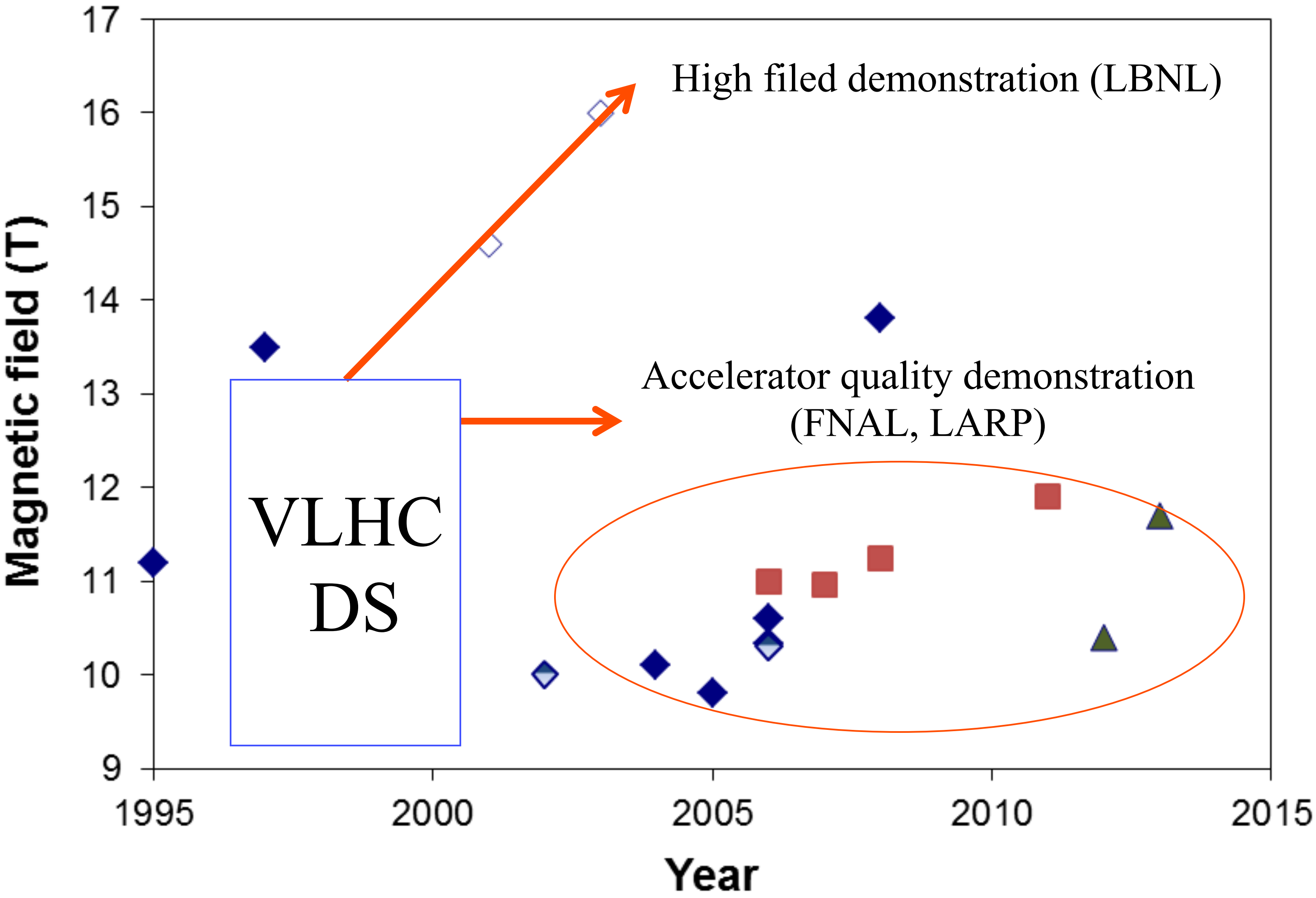


Table 1.2. Properties of the Stage-2 VLHC at various energies. The luminosity is limited by synchrotron radiation power and damping time, power at the interaction point due to inelastic collisions, and the beam-beam tune shift.

Collision Energy (TeV)		*Magnetic Field (T)*	*Leveled Luminosity ($cm^{-2}s^{-1}$)*	*Optimum Storage Time (hrs)*
Stage 1	40	2	1.0×10^{34}	20
Stage 2	125	7.1	5.1×10^{34}	13
Stage 2	150	8.6	3.6×10^{34}	11
Stage 2	**175**	**10**	$\mathbf{2.7 \times 10^{34}}$	**8**
Stage 2	200	11.4	2.1×10^{34}	7



Nb_3Sn Magnet R&D



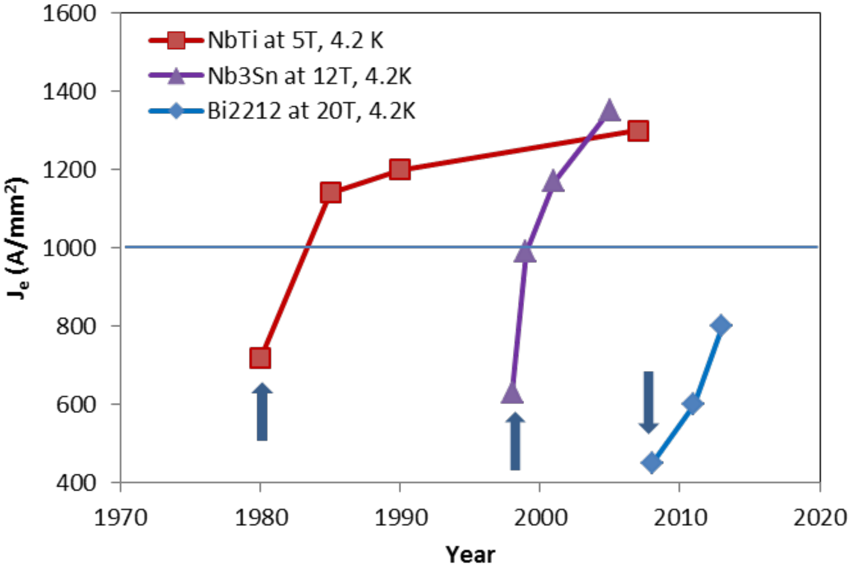
High filed demonstration (LBNL)

Accelerator quality demonstration
(FNAL, LARP)

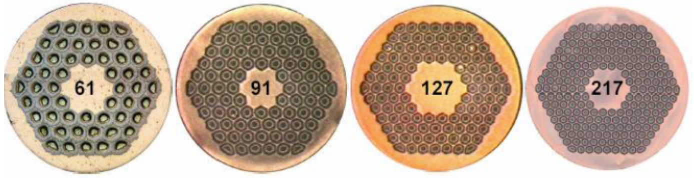
VLHC
DS

Conductor R&D programs

- **Nb_3Sn strand and cable**
  - **Internal tin (CDP in U.S.)**
  - **Powder-in-tube (NED, EU)**
  - **Nb_3Sn Rutherford-type cable development**

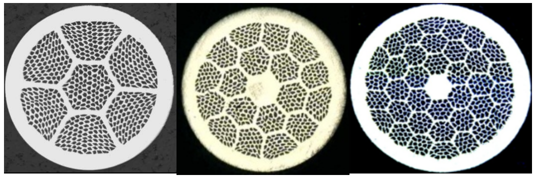


- **HTS conductor and cable**
  - **Bi-2212 R&D (U.S.)**
  - **YBCO (EU)**



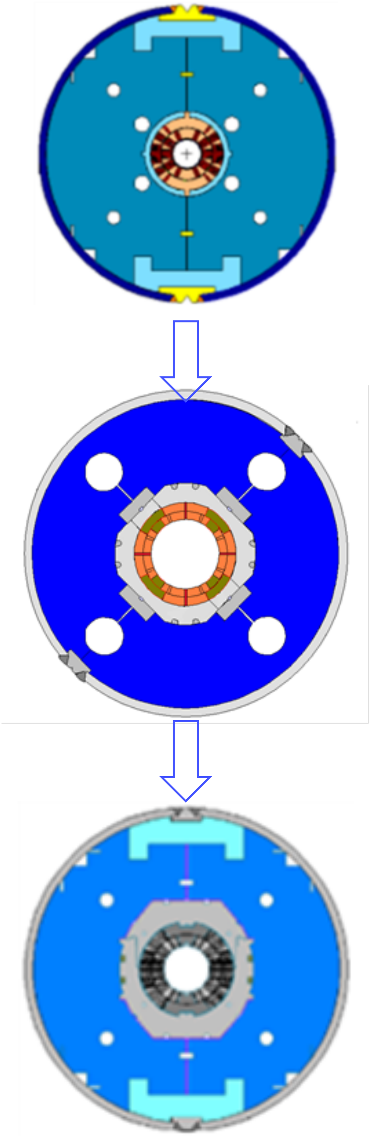
RRP strand, Oxford SC Technologies

- **Objective: improve Je and other parameters for accelerator magnets**

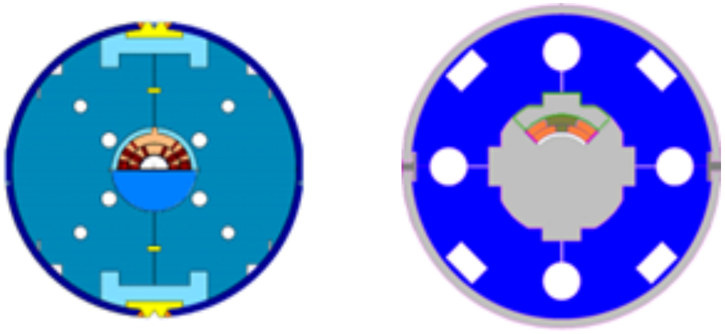


Bi2212 PIT strand, Oxford SC Technologies

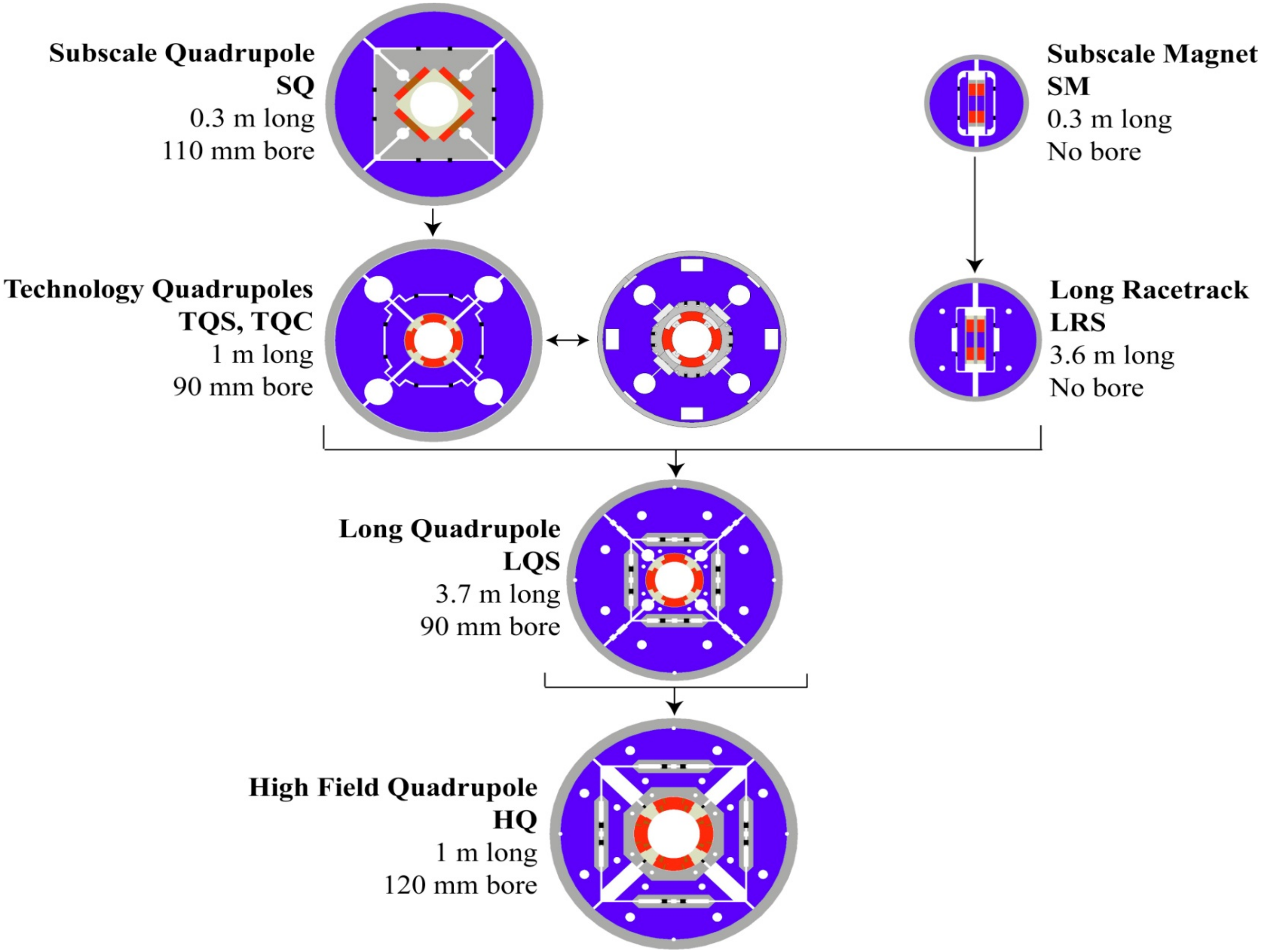
Nb_3Sn accelerator magnet R&D (FNAL)



- Program started in 1999
- 2002-2006 - a series of 43.5-mm Nb_3Sn dipoles with B_{nom}~10 T based on collar-free structure
- 2007-2010 -a series of 90-mm Nb_3Sn quadrupole with G_{max}~217 T/m based on collar structure
- 2011-2014 – A series of 60-mm Nb_3Sn dipoles with B_{nom}~11 T based on collar structure
- 2007-2011 – technology scale up using dipole and quadrupole mirror structures



LARP Magnet R&D



Subscale Quadrupole
SQ
0.3 m long
110 mm bore

Subscale Magnet
SM
0.3 m long
No bore

Technology Quadrupoles
TQS, TQC
1 m long
90 mm bore

Long Racetrack
LRS
3.6 m long
No bore

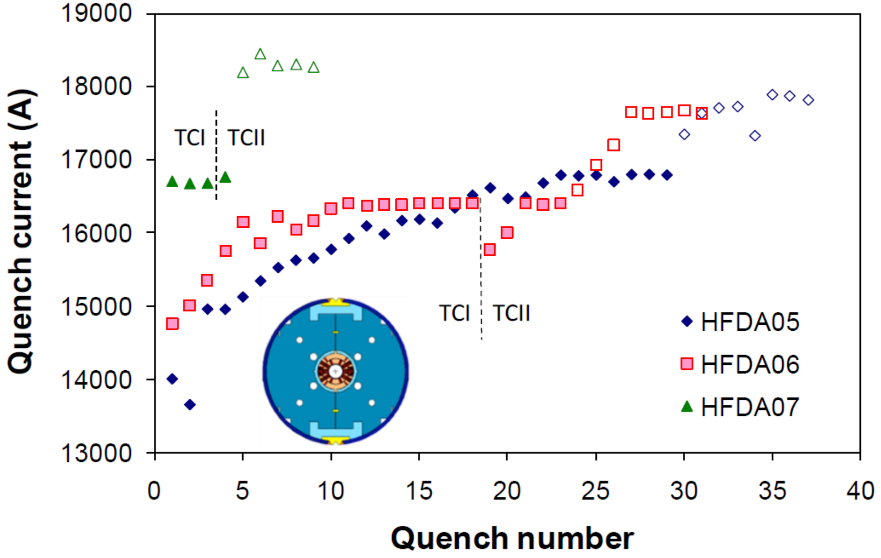
Long Quadrupole
LQS
3.7 m long
90 mm bore

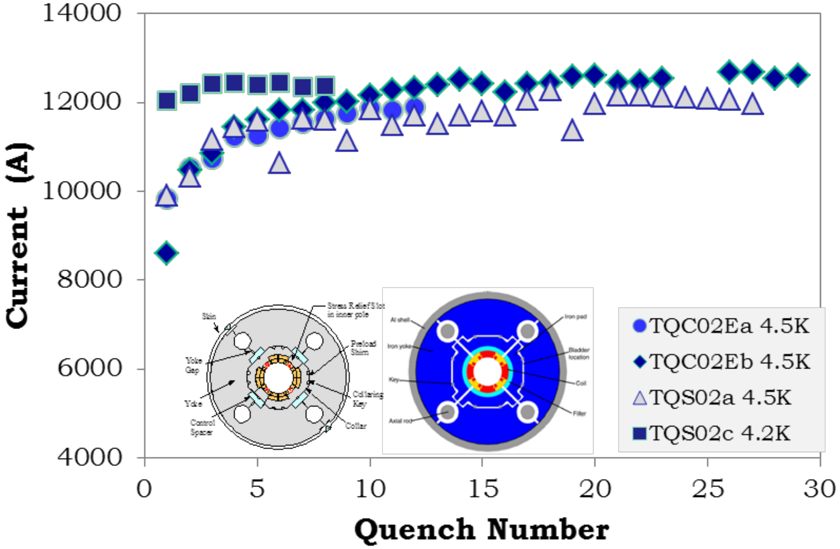
High Field Quadrupole
HQ
1 m long
120 mm bore

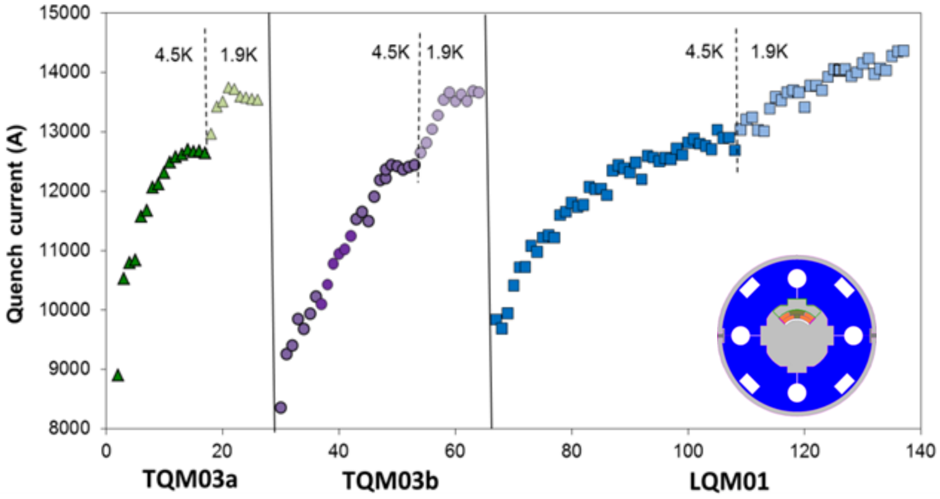
Nb_3Sn technology scale up

4-m long Racetrack, D and Q mirror configurations; 90-mm quadrupoles

Quench performance

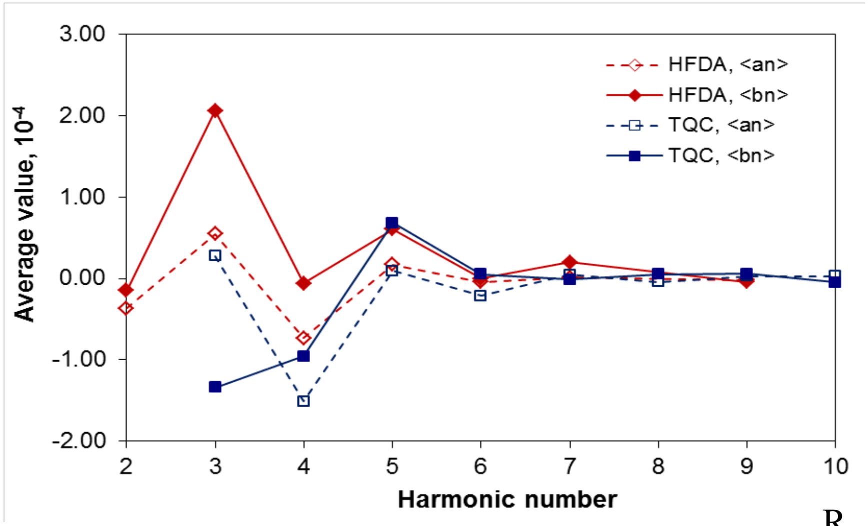


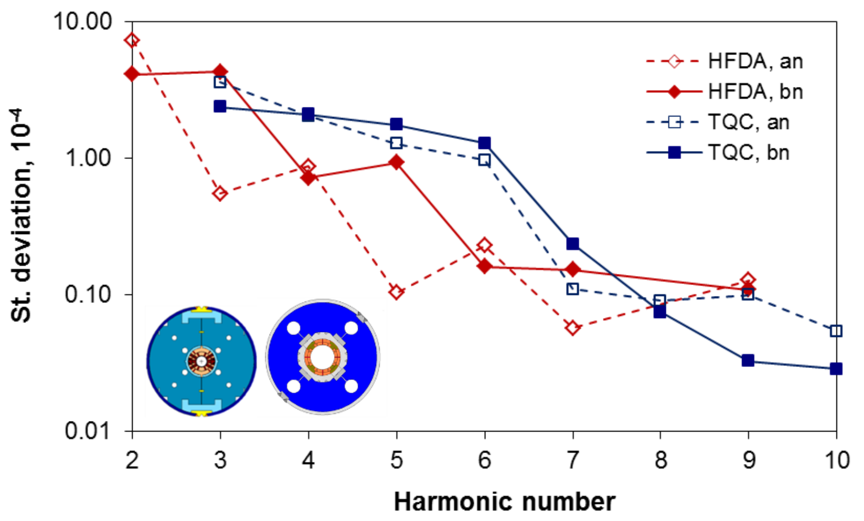




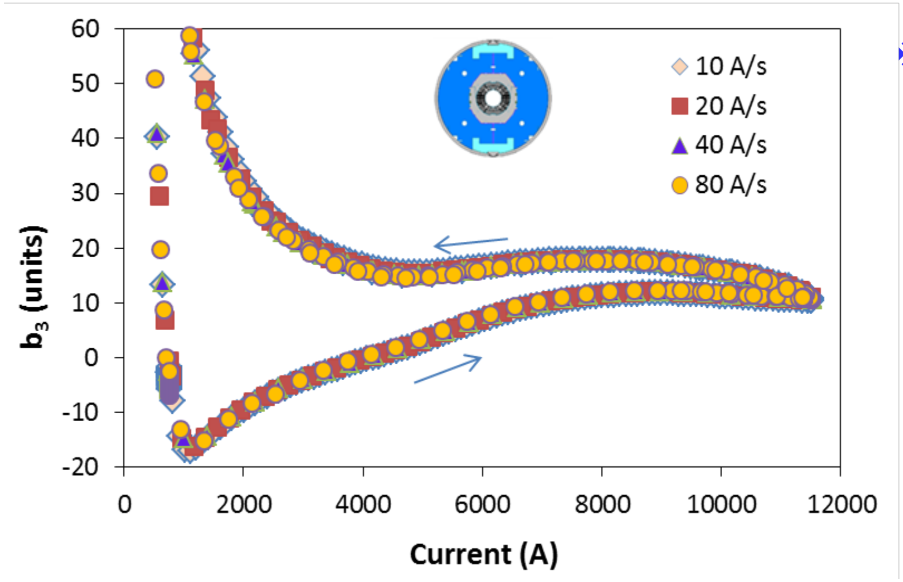
- **Production and test experience**
  - **~100 short D and Q coils**
  - **~20 4-m long coils**
- **Distributed production process**
  - **Handling and transportation**
- **Multiple coil re-use in different configurations and mechanical structures**

Field quality





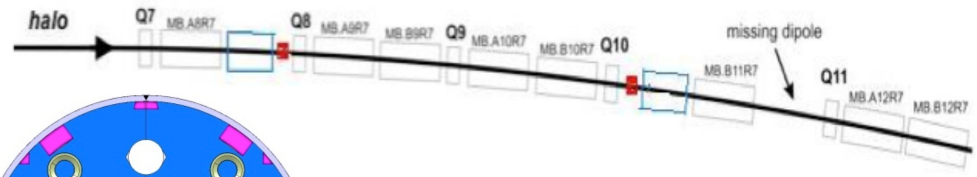
$R_{ref}=0.5R_{coil}$

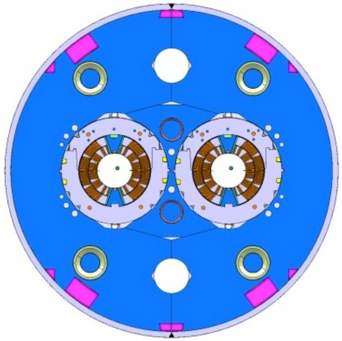


- **Several small series of D and Q models – performance and reproducibility**
  - **Geometries reproducible**
  - **Iron saturation suppressed up to 12 T**
  - **Eddy current effects small**
  - **Persistent current effect large**
    - Passive correction
  - **B_{inj}>1 T**

Focused D&D and Industrialization

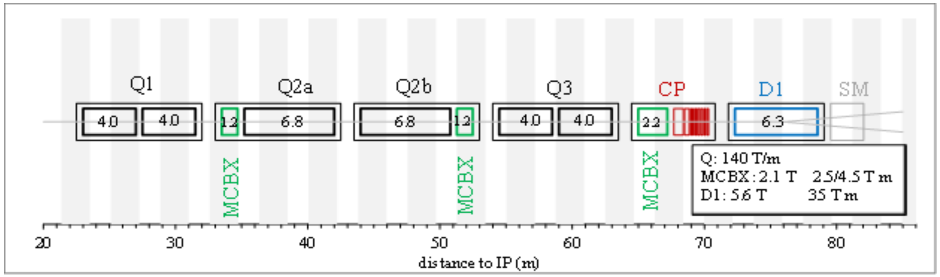
- **11 T dipole (FNAL/CERN)**
  - **2-layer Nb_3Sn cosϑ coils**
  - **Bop=11.25 T in 60 mm bore**
  - **5.5 m long**
  - **Short models 2014-2015**
  - **Long models 2015-2016**

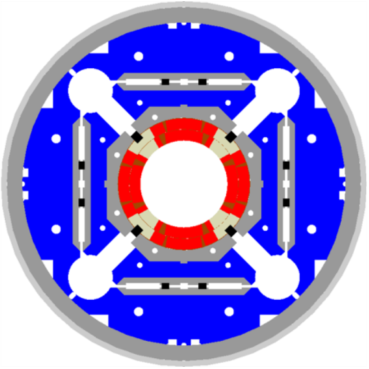




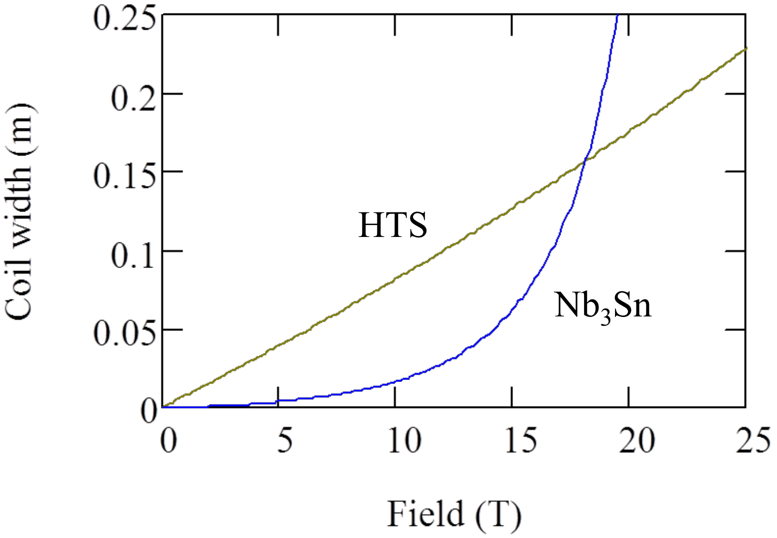
5.5 m Nb_3Sn | 0.8 m Collim. | 5.5 m Nb_3Sn

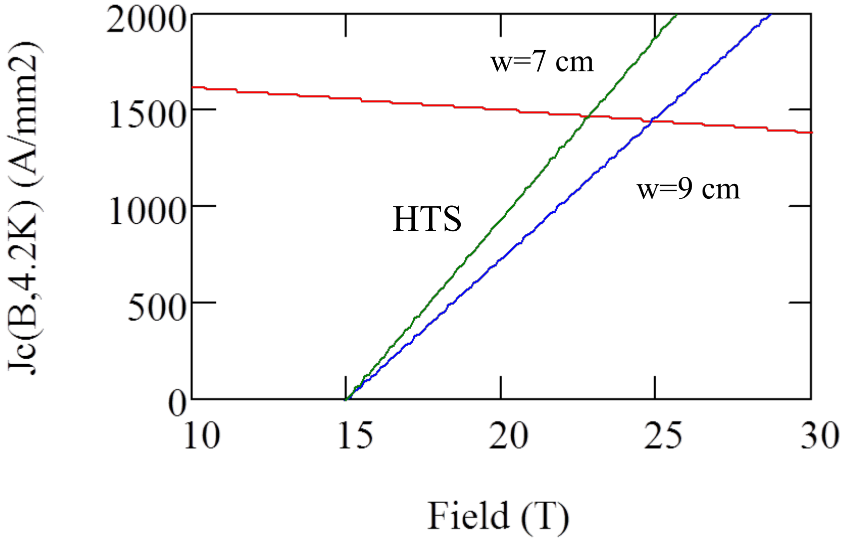
- **QXF (LARP/CERN)**
  - **2-layer Nb_3Sn cos2ϑ coils**
  - **Bop=12 T (Gop=140 T/m) in 150 mm bore**
  - **Q1/Q3 (LARP) 4.0 m long**
  - **Q2a/b (CERN), 6.8 m long**
  - **Short models 2014-2016**
  - **Long models 2015-2017**
- **Ready for production (industrialization) by 2017**





Towards Higher Field Magnets

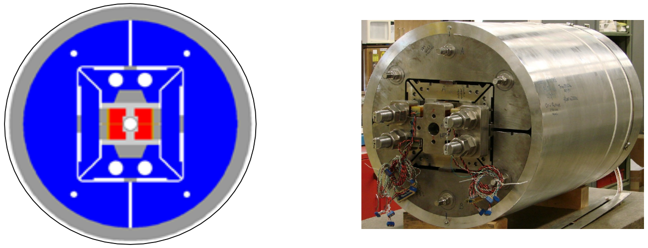




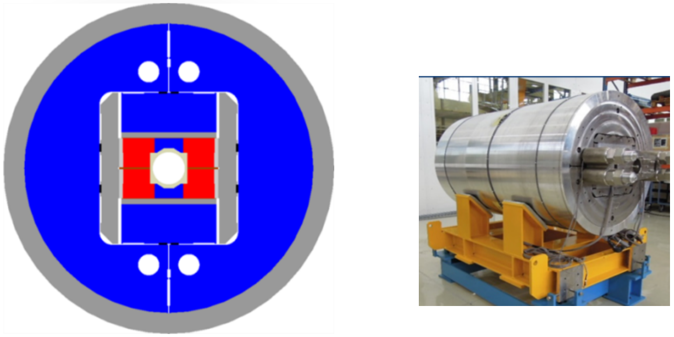
- **B_{op}=15-20 T + 20% margin => *B_{des}=18-25 T!***
- **15-20 T magnet issues**
  - **Large stored energy and Lorentz forces (~*B^2*)**
  - **Size, Cost (~*coil W*)**
    - **15 T Nb$_3$Sn magnets: w=15 cm**
    - **20 T HTS/LTS magnets: w_{tot}~20-25 cm**
      - ***10 T HTS insert: w~7-9 cm***
      - ***15 T Nb$_3$Sn section: w~15 cm, ID~20-25 cm***

15+ T Nb_3Sn Demonstrator Dipoles

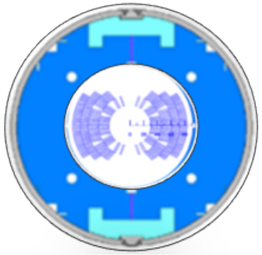
- **HD2 (LBNL) 2004-2009**
  - Block coil, aperture 35 mm
  - Bdes=15/17 T at 4.3/1.9 K
  - B_{max}=13.3-13.8 T, 10% degradation



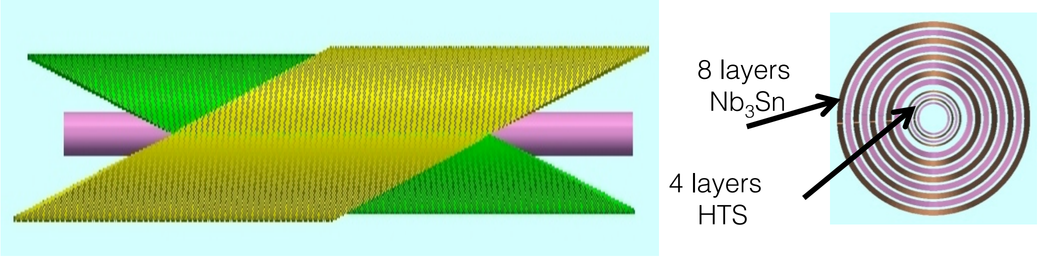
- **FRESCA2 (CERN) 2012-2016**
  - Block coil, aperture 100 mm
  - Bdes=16.5/18 T at 4.5/1.9 K
  - Magnet tests: 2016



- **HFD? (FNAL) - proposal**
  - Cos-theta coil, aperture 60 mm
  - Bdes=15 T at 4.5 K
  - Magnet tests: 2016



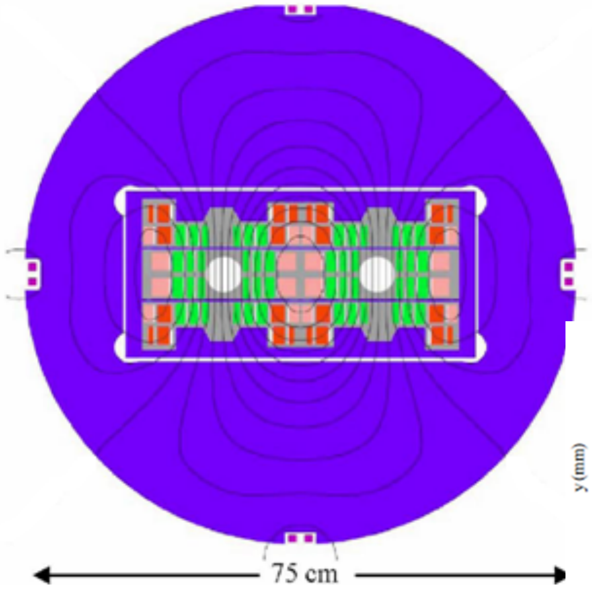
- **CCT (LBNL) - proposal**
  - Canted cos-theta coil
  - Bdes=19 T at 4.5 K
  - Magnet tests: TBD



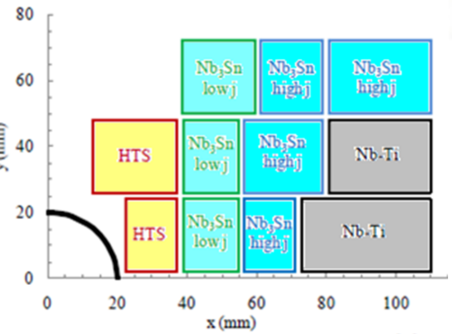
24 T HTS/LTS Dipole Concepts

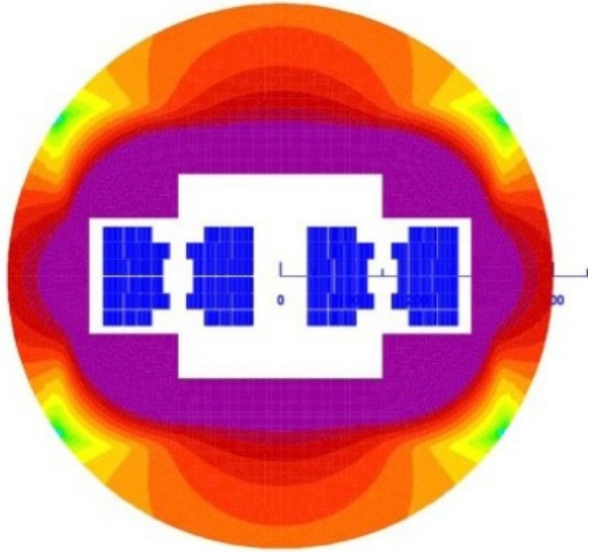
P. McIntyre et al.(TAMU), PAC' 2005

L. Rossi, E. Todesco (CERN), HE-LHC'2010



Bi2212 + Nb_3Sn





Bi-2212+Nb_3Sn+NbTi

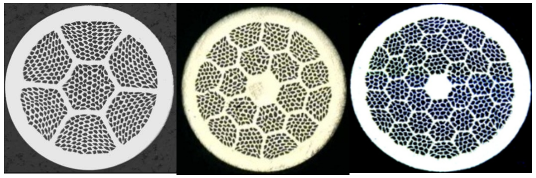
Table 1. Main parameters of the 24 T hybrid dipole.

Dipole dimensions:		
length	30	m
cold mass diameter	80	cm
Beam tube diameter	40	mm
Operating temperature	4.5	K
Coil current	33	KA
Maximum stress in windings	150	MPa
Stored energy/bore	5	MJ/m
Total horizontal Lorentz force/bore	40	MN/m

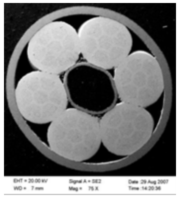
Table : Main parameters of the HE-LHC and LHC dipole

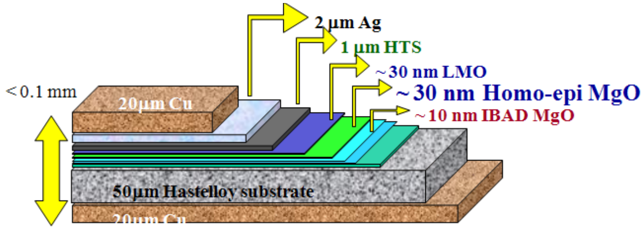
		HE-LHC	LHC
Operational field	(T)	20.0	8.3
Operational current	(kA)	13.8/6.9	11.8
Operational margin	(%)	20	14
Magnetic lenght	(m)	14.3	14.3
Total stored energy	(MJ)	100	7.0
Distance between beams	(mm)	300	194
Maximum coil thickness	(mm)	97.3	31
Cold mass diameter	(mm)	800	570

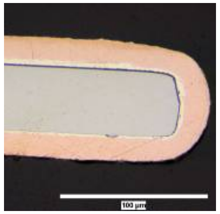
HTS Strand and Cable R&D Issues



- $Bi_2Sr_2CaCu_2O_x$ => Bi-2212
- 0.7-1.0 mm wire with Ag matrix
- SC fraction ~25-30%
- Traditional PIT process (OST)
    - Unit length >1 km
- Complex heat treatment in O_2
- Brittle after heat treatment
- Isotropic properties







- $YBa_2Cu_3O_y$ => YBCO-123
- 4-12 mm wide tape with Cu stabilizer
- YBCO fraction ~1%
- Complex multilayer deposition process and final Cu electroplating (SP)
    - Unit length ~500-1000 m
- No final heat treatment
- Brittle but withstand substantial load
- Highly anisotropic
- Large Ic variation along the tape

High-Je high-Ic cables

HTS coil technology demonstration

Summary

	10-12 T	13-15 T	18-20+ T
Superconductor	Nb_3Sn	Nb_3Sn	HTS/LTS
Strand	+	+	+/-
Cable	+	+	-
Technology	+	+	-
Field demonstration	+	+/-	-
Accelerator quality	+	-	-
Scale up	+	-	-
Focused development	+/-	-	-
Industrialization	-	-	-
R&D effort needed	$	$$	$$…$