20 T Block Dipole: Features and Challenges

GianLuca Sabbi, Xiaorong Wang, LBNL

Acknowledgment: Daniel R. Dietderich, LBNL

Emmanuele Ravaioli and Jonas Blomberg Ghini, CERN

ICFA Mini Workshop on High Field Magnets for Future pp Colliders

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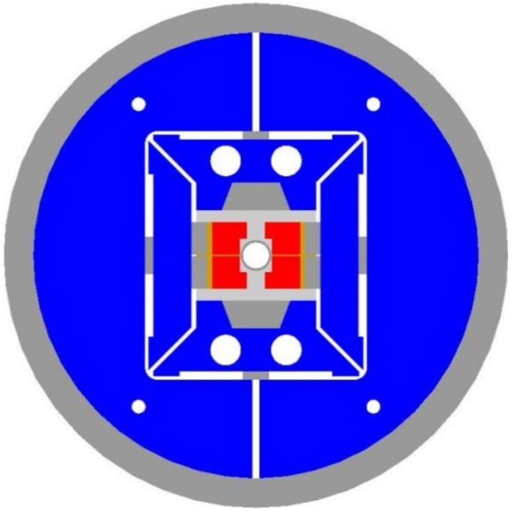
Outline

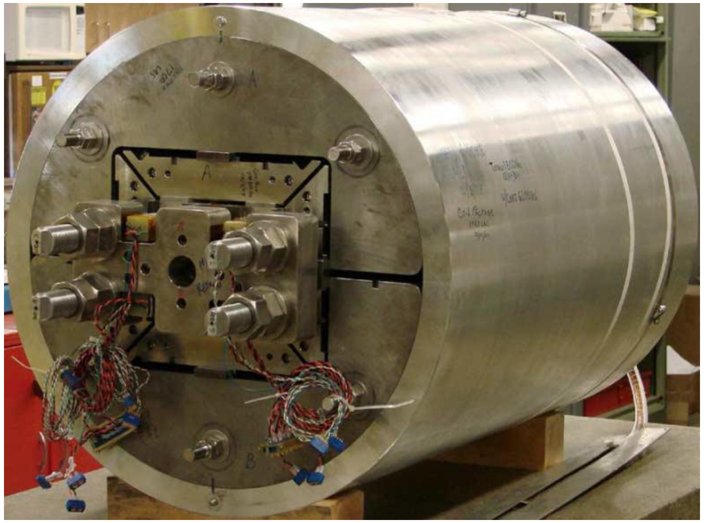
- As requested by the workshop organizer, we performed a preliminary study on the concept

- HD block-coil model dipoles as the starting point
- Conceptual design of a 20 T class hybrid dipole
  - Conductor properties and cable parameters
  - Single aperture design and performance parameters
  - Two-in-one configuration
- Summary

HD2 (single aperture)

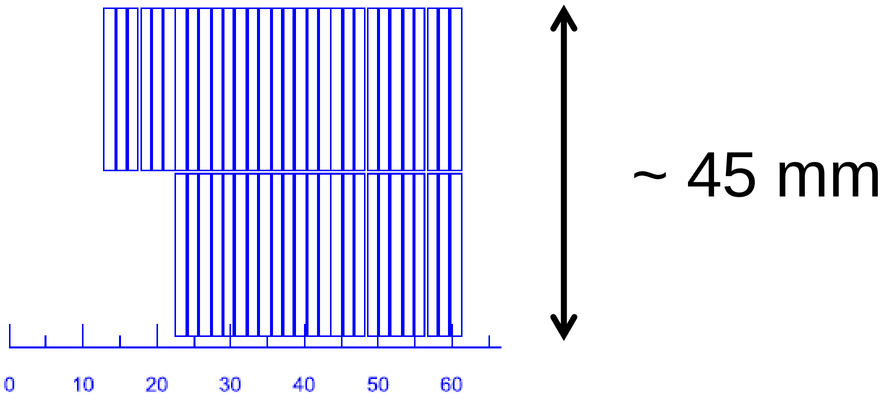
- Achieved 13.8 T at 4.5 K, record field for a dipole with accelerator relevant bore and field quality
  - Solid experience on magnet fabrication, test, analysis
  - See Dr. Sabbi's talk on Monday morning
- A logical basis for the conceptual study of 20 T block dipole (magnetics)





HD2 Design

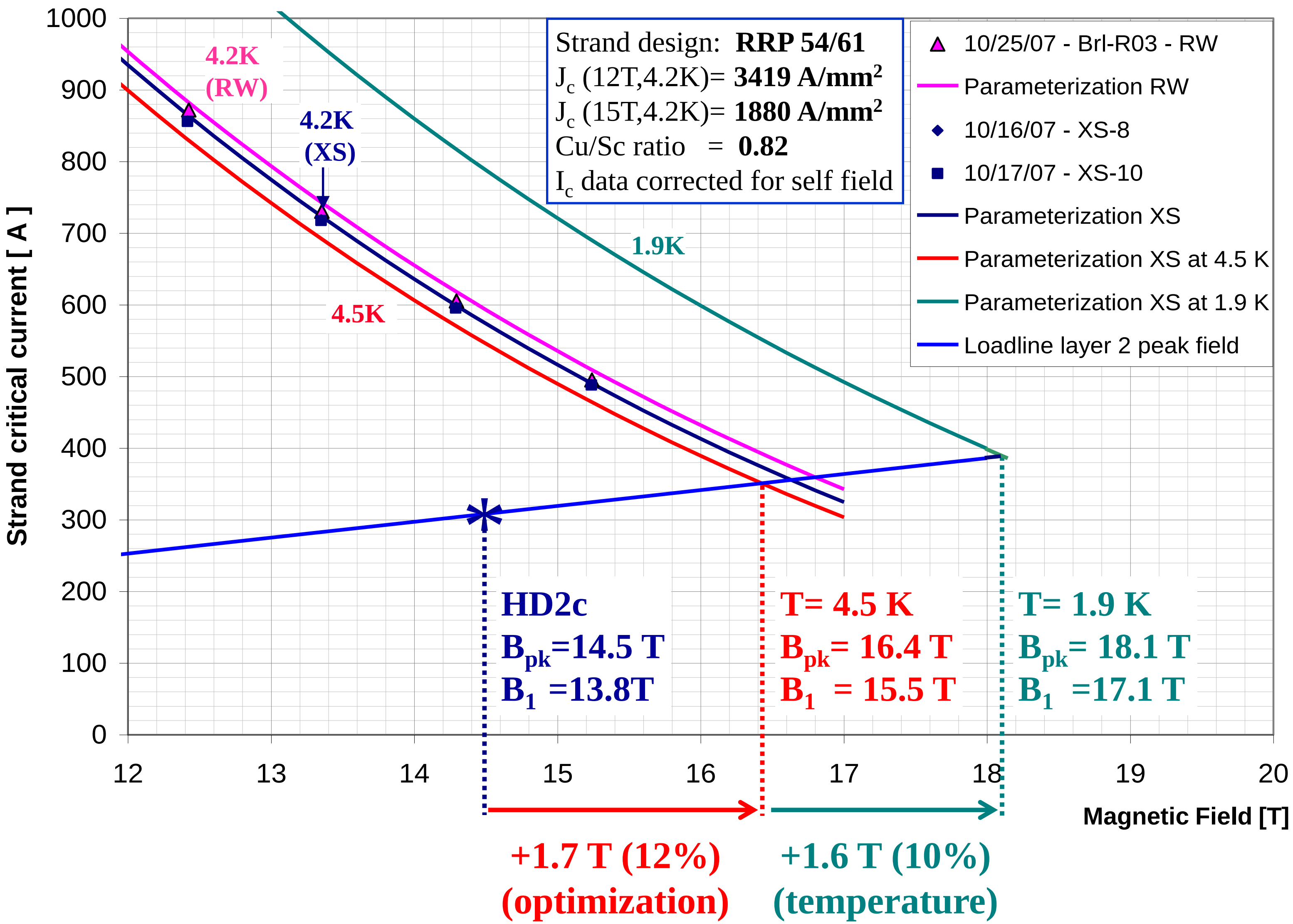
- 2-layer design, clear-bore aperture is 40 mm
- Nb_3Sn Rutherford cable
- Good field quality



Performance at 16 T	Unit	Ref (1ap)
Operating current	kA	18.6
J_e (insulated cable)	A/mm^2	517
Peak field in the coil	T	16.9
Horizontal force (I+/I-)	MN/m	6.3/-6.3
Vertical force (I+/I-)	MN/m	-2.9
Inductance	mH/m	5.1
Stored energy	MJ/m	0.85

A block approach to 20 T dipole field

Performance with available Nb_3Sn

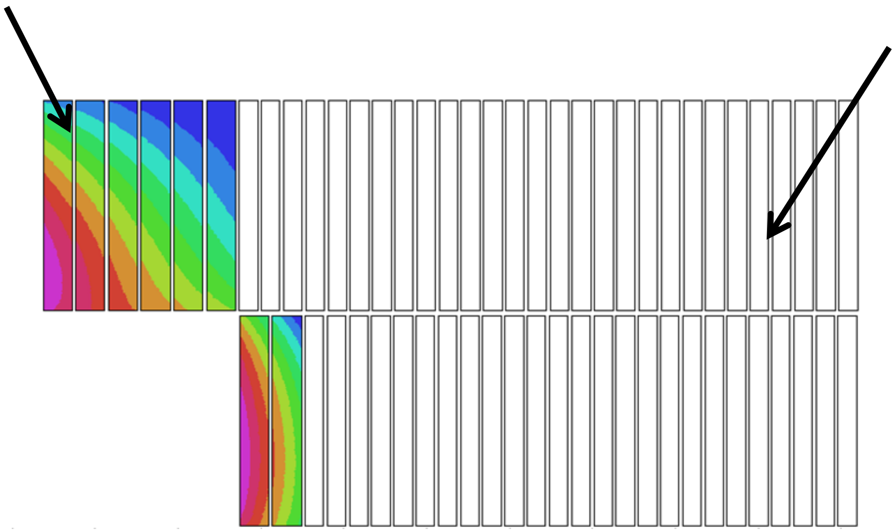


Increase bore field with grading

- An example: grading with only Nb_3Sn strands for HD2
  - 1.2 T increase in dipole field at 4.5 K (from 15.5 to 16.7 T)

1 mm strand diameter

0.65 mm strand diameter



- To reach 20 T bore field, we use Bi-2212 multi-filamentary round wire

Conductor for 20 T class block dipole

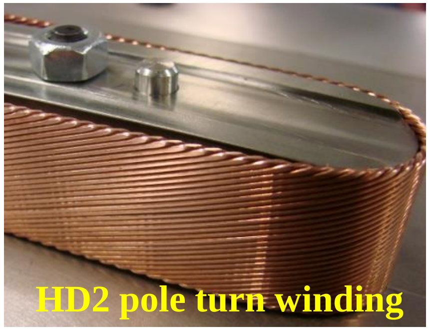
- We use Nb_3Sn strand parameter from HD magnet
- Bi-2212 performance from overpressure reaction
  - Necessary assumption for large dipole coils
  - Optimistic one for operation under high stress

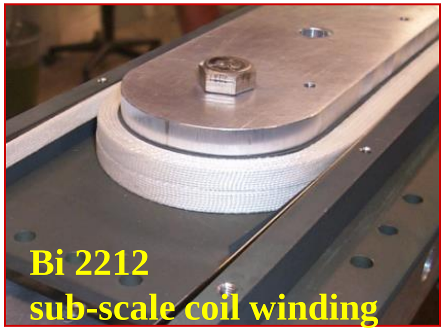
		Nb_3Sn	Bi-2212
Wire diameter	**mm**	**0.8**	**0.85**
I_c (15 T, 4.5 K)	**A**	**490**	**397**
I_c (20 T, 4.5 K)	**A**	**131**	**356**

Bi-2212 data from http://magnet.fsu.edu/~lee/plot/plot.htm

Rutherford cable

- Nb_3Sn: HD cable parameter is used
- Bi-2212: extrapolation from previous experience
  - Doubling cable aspect ratio
  - Decreasing winding radius
  - Fall-back option: more layers of narrower cable (adds complexity and cost)

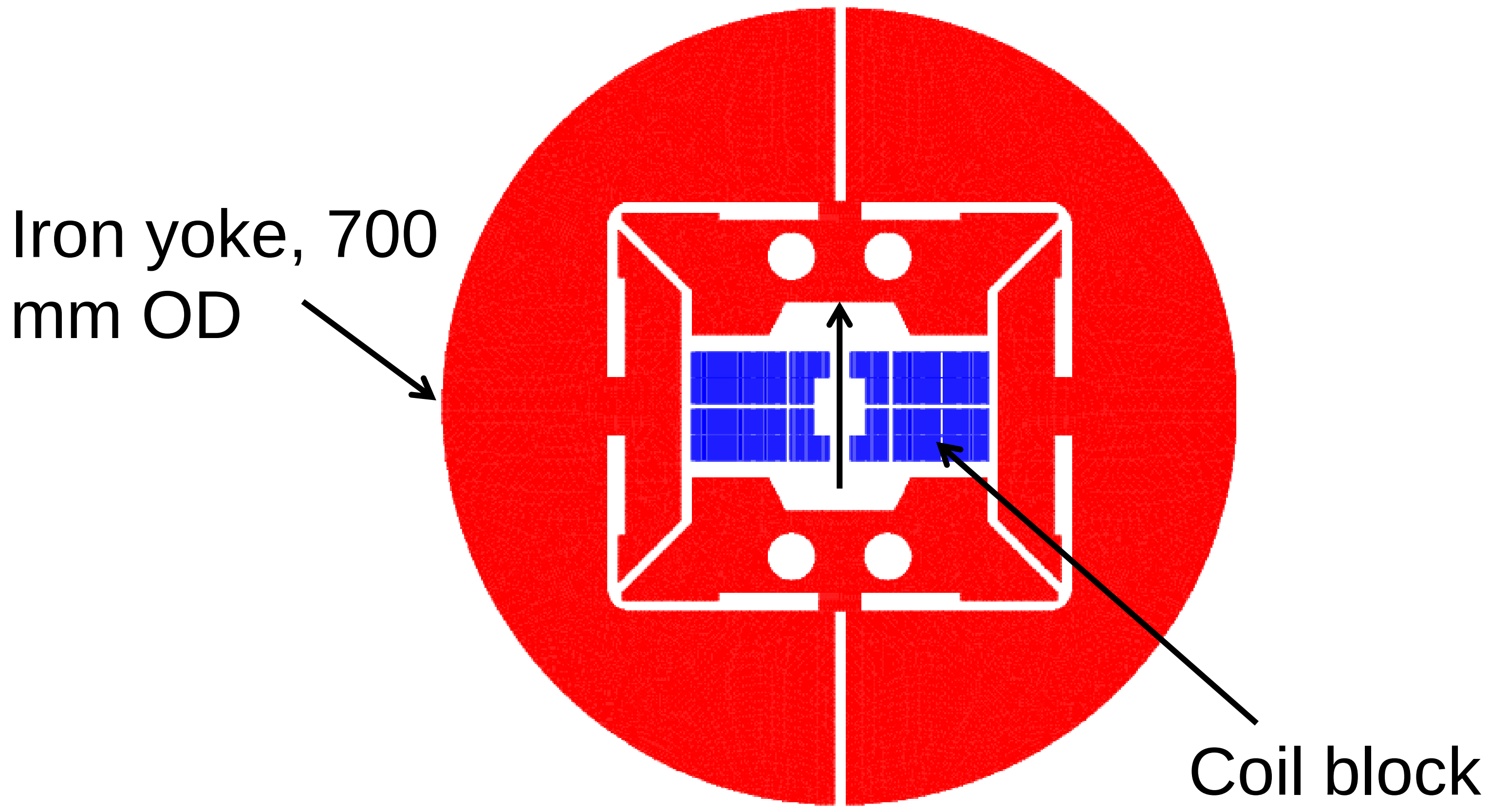




	Nb_3Sn	Bi-2212
Number of strands	**51**	**48**
Cable width (mm)	**22**	**22**
Cable thickness (mm)	**1.40**	**1.49**
Insulation thickness (mm)	**0.11**	**0.11**

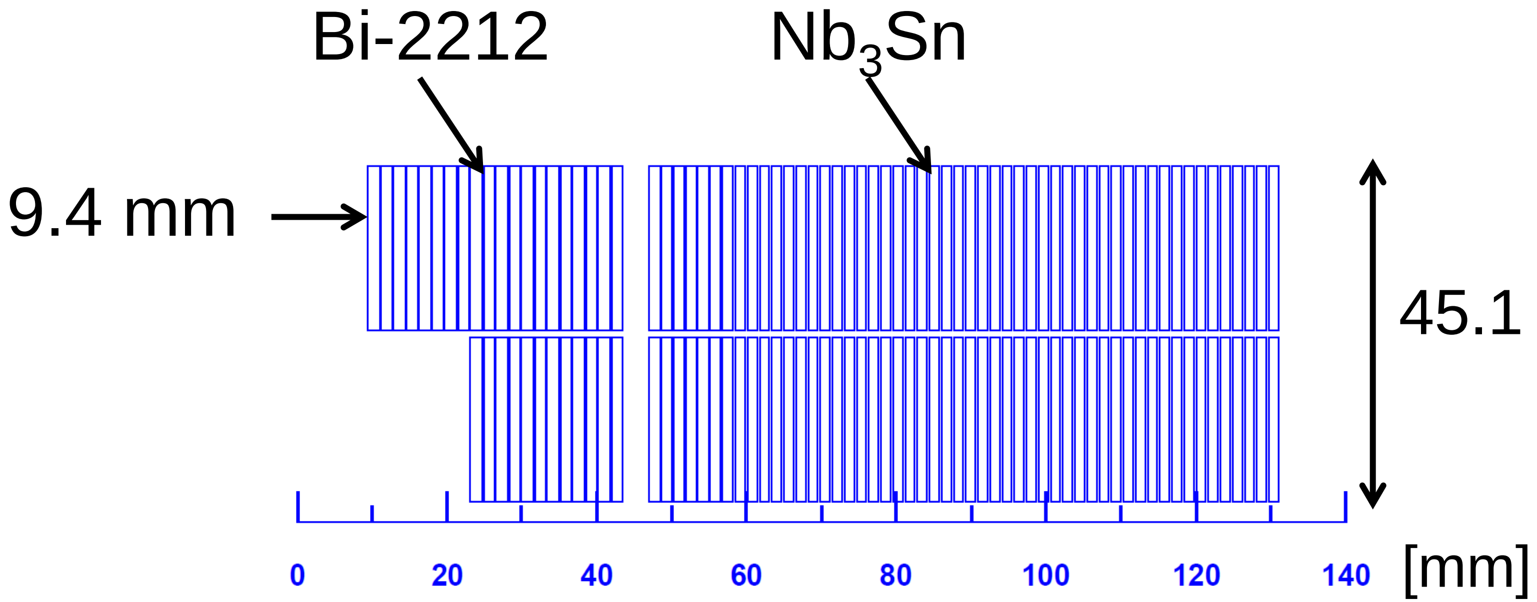
20 T class design, single aperture

- Clear bore diameter 40 mm (similar to HD2)



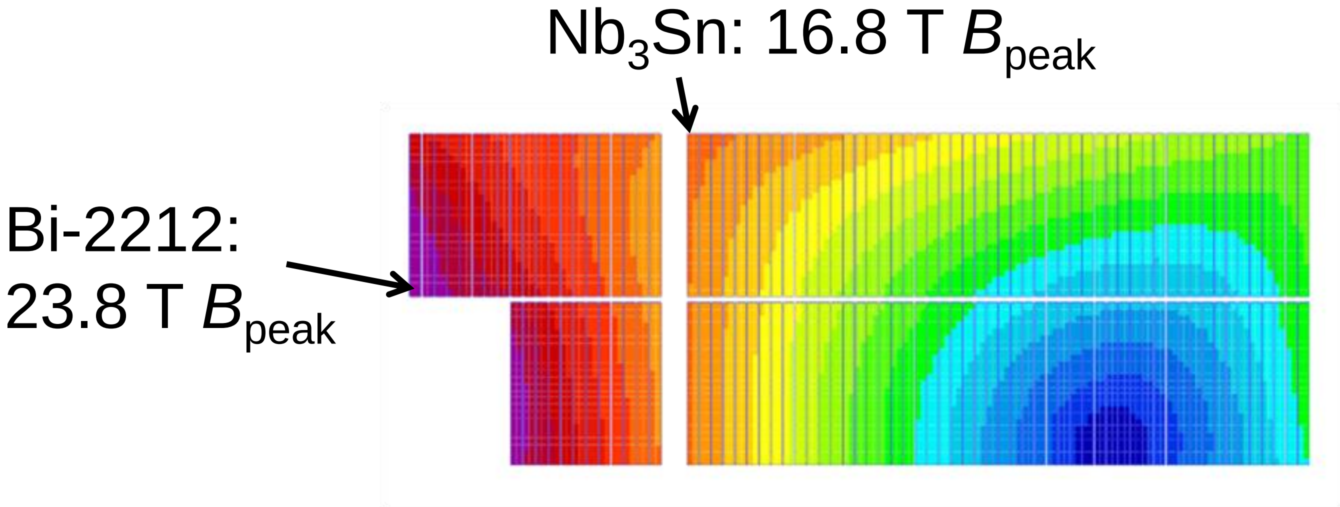
Coil block layout

- 2-layer design, similar to HD
- Small minimum bending radius (9.4 mm) for Bi-2212 cable



Maximum dipole field: 23 T

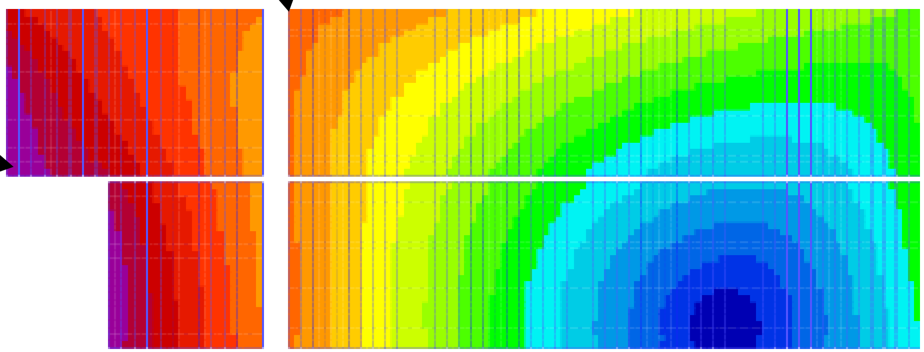
- Current = 15700 A, assuming no I_c degradation due to stress



- Design balanced to reach short sample at the same current in Bi-2212 and Nb_3Sn

20 T: operation with 13% margin

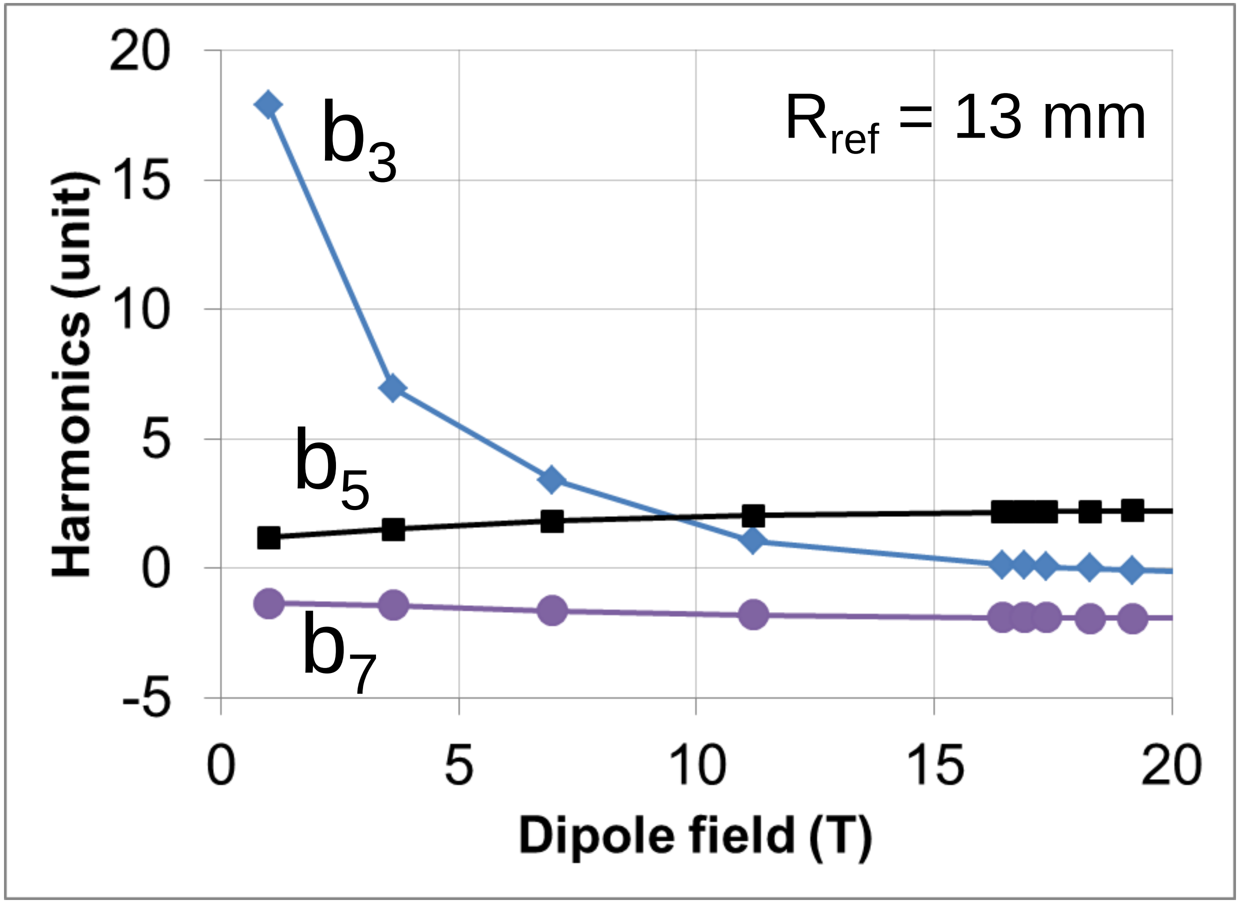
- Current = 13500 A



- Whole-wire current density at operation point (20 T, 4.5 K)
  - Nb_3Sn: 530 A/mm^2, Bi-2212: 500 A/mm^2
- Best Bi-2212 performance with overpressure process is a must for this design

Reasonable field quality

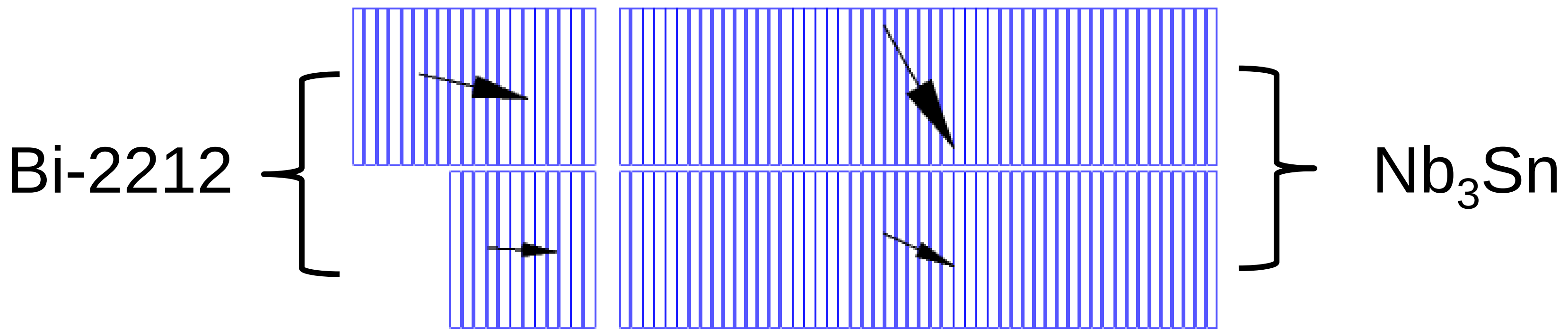
- Considers only the geometric and saturation effects



Stored energy and Lorentz forces at 20 T

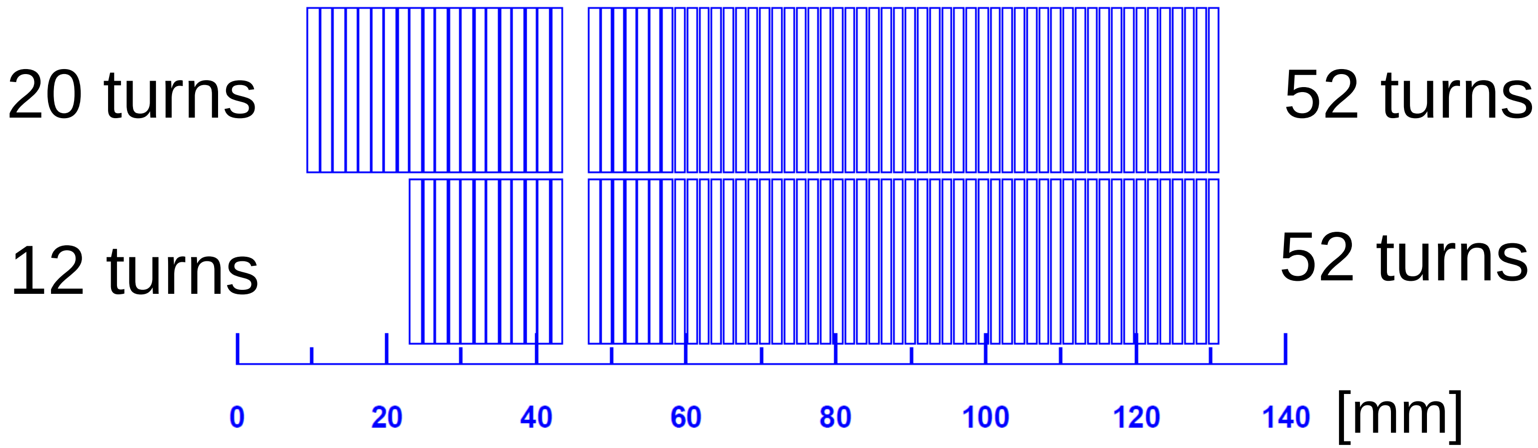
- Stored energy 0.89 MJ/m
  - 9.8 mH/m inductance

- Forces on the centroid of coil blocks



	Bi-2212	Nb_3Sn
Horizontal (MN/m)	**6.9**	**5.2**
Vertical (MN/m)	**-1.1**	**-6.1**

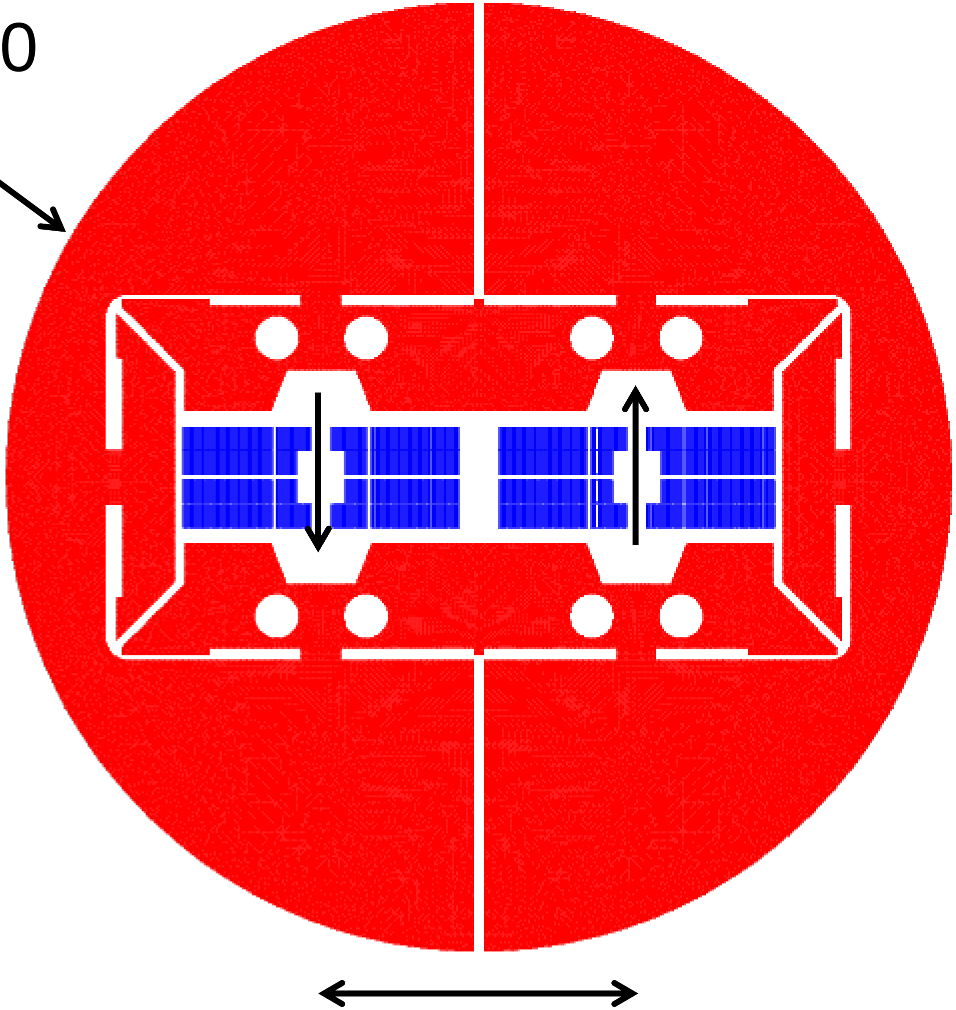
Required conductor amount



	Nb_3Sn	Bi-2212
Number of turns (1 quadrant)	104	32
Strand length per 1 m coil (km)	21.2	6.1
Strand weight (kg)	106	35

Two-in-one configuration

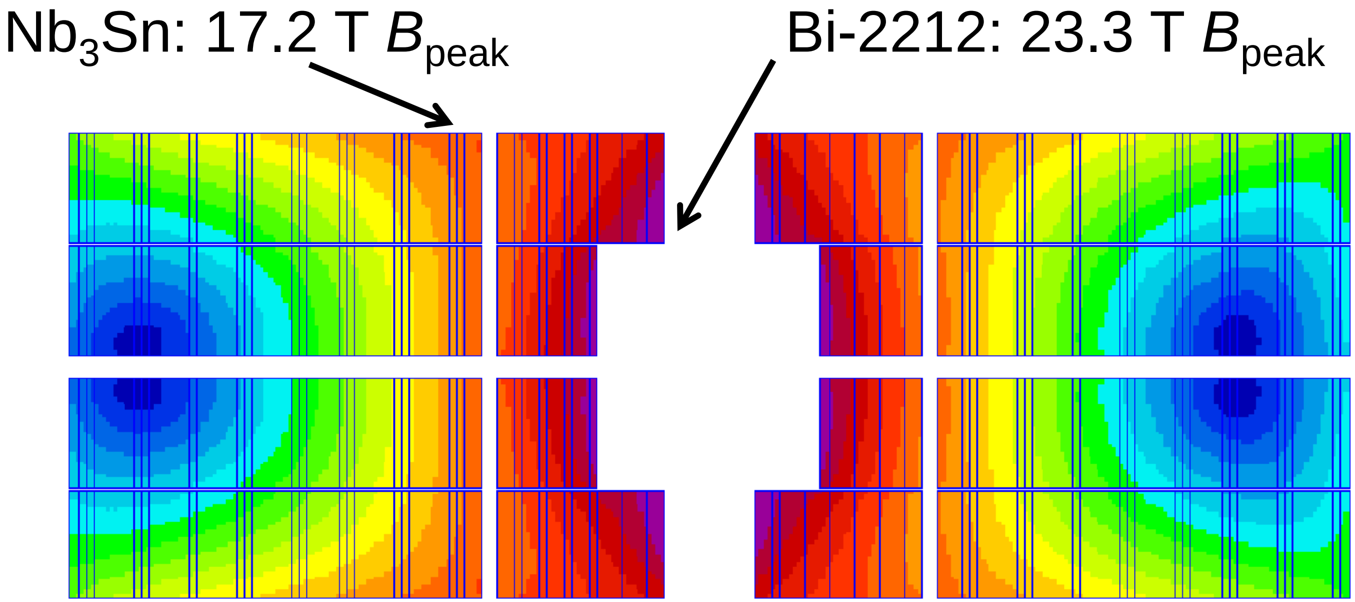
Iron yoke, 900 mm OD



Beam separation: 300 mm

Characteristics

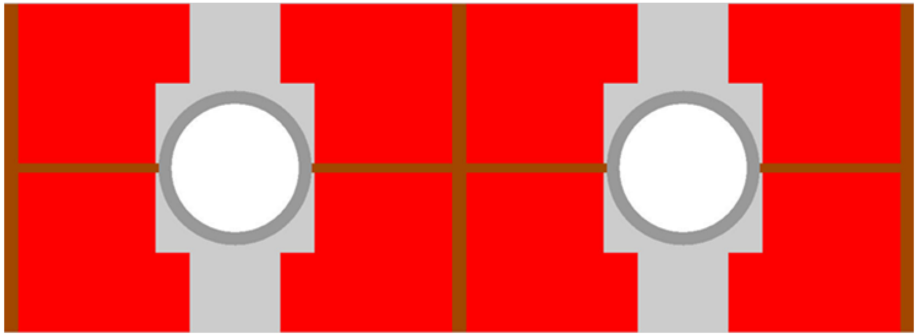
- Maximum dipole field 22.6 T at 14430 A, 11% margin when operating at 20 T



- Further optimization in geometry (separation and yoke radius) and operating margin

Compact configuration for 2-in-1

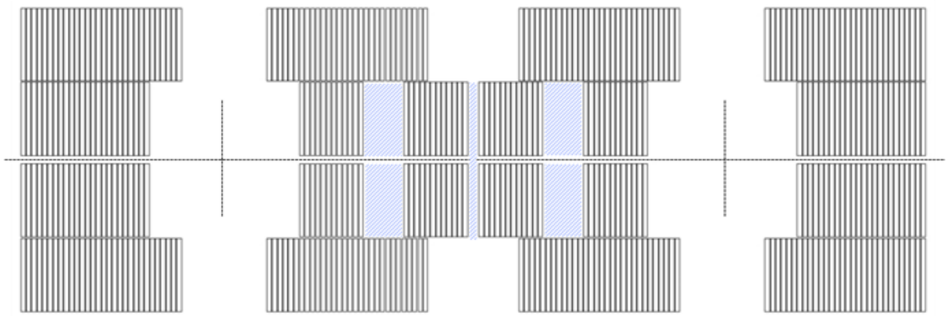
- The two block coils can be brought (almost) in contact
- Very compact configuration for 2-in-1



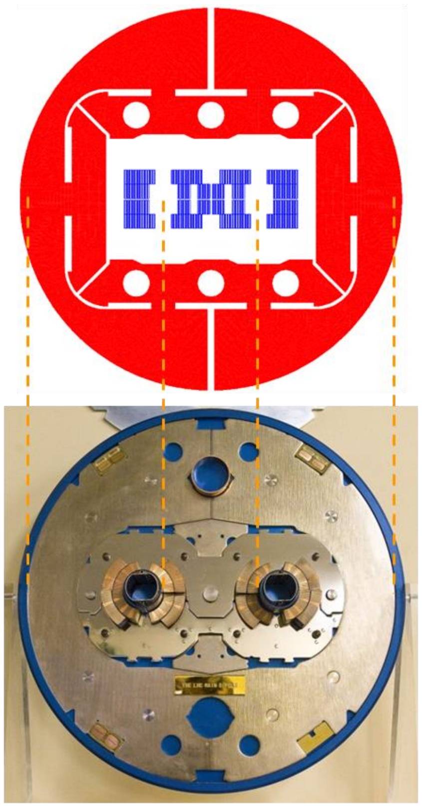
- Field increases, but field quality degrades due to left-right asymmetry
  - 32 units of b_2 at 20 T

Asymmetric Coils for Compactness

- This effect can be corrected with an asymmetric coil configuration



- Example for a 16 T design: smaller beam separation and similar overall envelope as present LHC
- To be investigated for the 20 T case



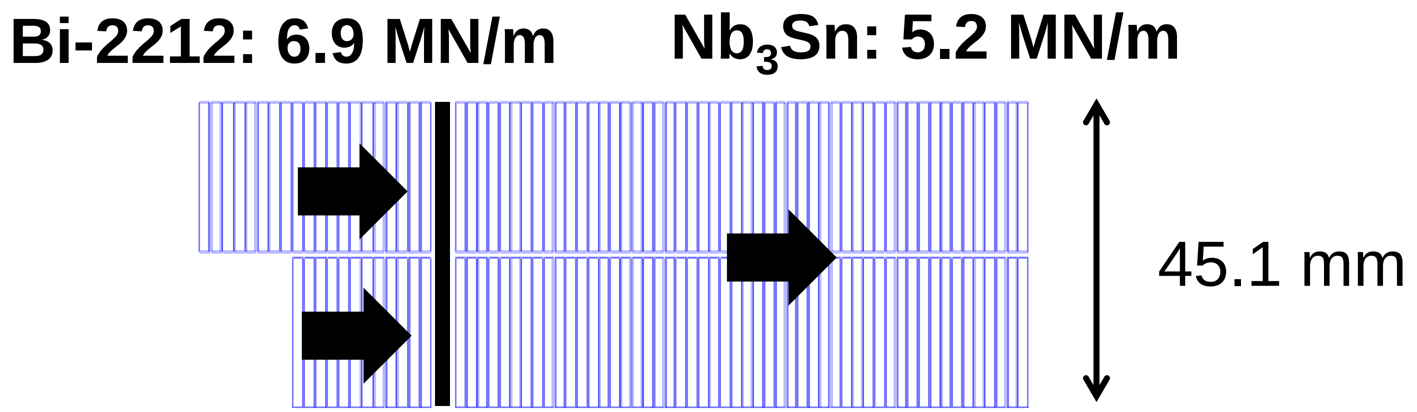
Challenges to be addressed

Demonstrate the feasibility of Bi-2212

- Best short-sample performance with overpressure process is crucial to reach 20 T operation dipole field
- Demonstrate the short-sample performance in cables and coils
- See Dr. Shen’s talk on Tuesday

Manage transverse stress on cable

- 270 MPa Lorentz stress at 20 T

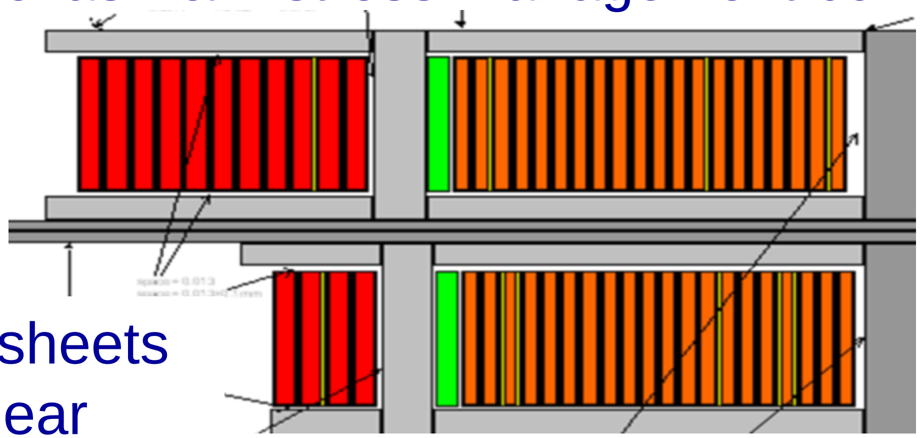


- Nb_3Sn limit: ~ 200 MPa, H Felice *et al.*, J. Phys.: Conf. Ser. 234, 032010, 2010
- Bi-2212 limit: ~ 60 MPa, Dietderich *et al.*, IEEE TAS, 11(1), p. 3577, 2001
- Critical to pre-load without causing irreversible degradation

Possible mitigation

- Replace Nb_3Sn in the low field region with NbTi
- Support matrix of ribs and plates (Texas A&M concept)
  - We allocate space between sub-coils for internal structure
  - Potential to reduce stress in half, still too high for Bi-2212

Texas A&M stress management concept



Mica sheets for shear stress relief

Foil springs for pre-load

Quench detection and protection

- We have tools to protect the Nb_3Sn part
  - Recently demonstrated CLIQ (Coupling-Loss Induced Quench) technique
  - Can limit maximum temperature within acceptable level (350K)

- Quench detection can be an issue for Bi-2212 insert
  - High stability margin and slow propagation
- The coupling behavior between the insert and outsert requires investigation

Engineering challenges

- Flared ends are required by aperture and field
- Hard-way bends in the cables
  - HD magnet: limiting quenches near the bends

- Demonstrate nested coils
  - Leads/splices, mechanical support, production method, tolerances
  - Flared ends with Bi-2212 cables

Summary

- A block design concept for a 20 T dipole field at 4.5 K
  - Based on experience from HD magnet development
- Conductor
  - Nb_3Sn conductor and cable available today
  - Best Bi-2212 short-sample performance with overpressure reaction to be demonstrated on cable and coil level
- Significant challenges to be addressed
  - Flared ends, fabrication of nested coils
  - Stress management and quench protection
- Significant fundamental and collaborative R&D to do before one could consider building a demonstrator