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Towards 20 T accelerator magnets: a road to super-high energy colliding beams

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Outline

- **Why do we need Higher Fields in accelerators and how to generate high fields?**
- **SC magnet possibilities and limitations**
- **SC material options**
- **20+ T HTS/LTS hybrid magnets**
- **Conclusions**

Why do we need higher field magnets?

- For a fixed size of a circular collider, its energy is limited by the strength of bending dipole magnets.

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

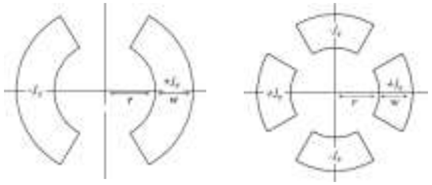
- For both linear and circular machines, their maximum luminosity is determined (among other factors) by the strength of quadrupole magnets used for the final beam focusing.
- We should not forget that our work inspires and fertilizes other fields of science and industry which need and use high field superconducting magnets and related technologies.

Accelerator Electromagnets

- Magnetic fields are generated by electrical currents (Bio-Savart law)

$$B_\theta = \frac{\mu_0 I}{2\pi r}$$

- There are current configurations which produce dipole, quadrupole and higher multipole fields

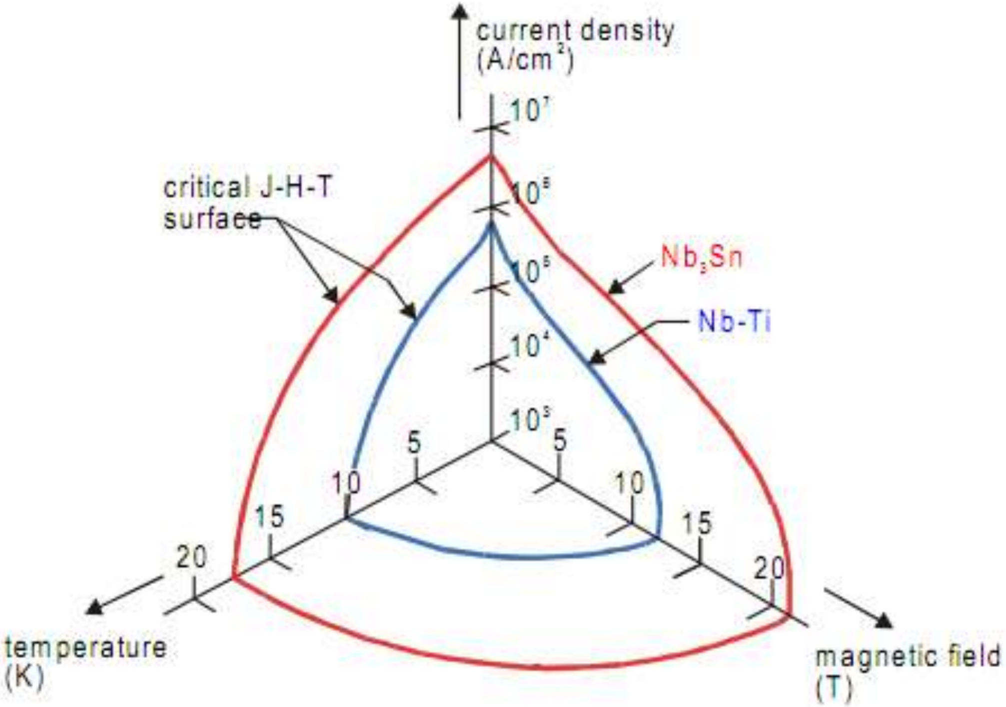


  - **Dipole configuration (60° coil)**
  - **Quadrupole configuration (30° coil)**
- B_D and G_Q are proportional to current density J_e in coil and coil width w

$$B_D = -\frac{\sqrt{3}\mu_0}{\pi} J_e w \qquad G_Q = -\frac{\sqrt{3}\mu_0}{\pi} J_e \ln\left(1 + \frac{w}{r}\right)$$

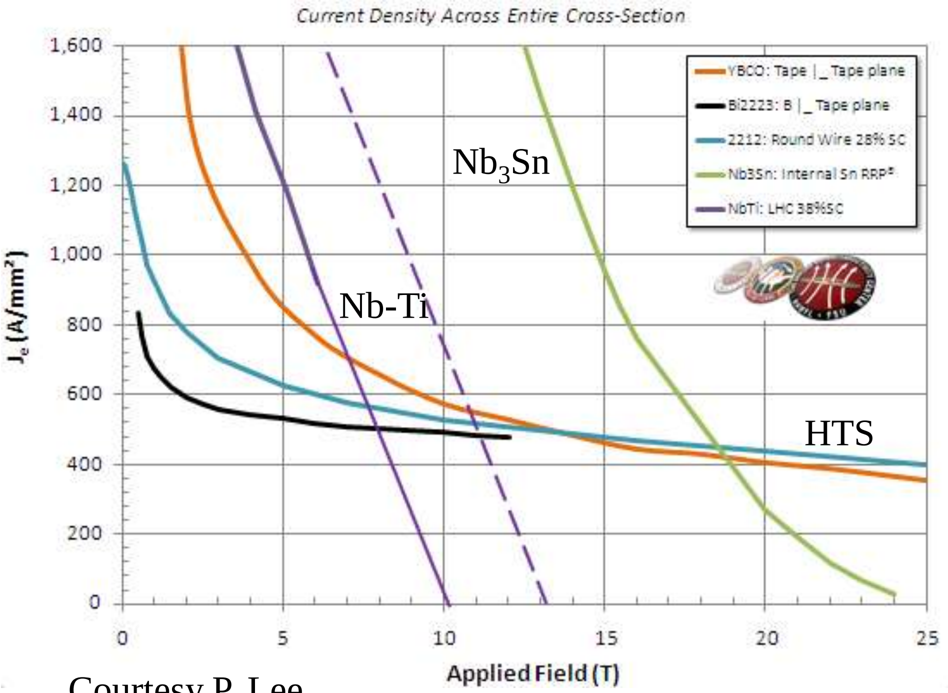
- The current density in coil J_e is a key parameter
  - **Resistive magnets with Cu or Al cable - J_e ~5-50 A/mm^2**
  - **Superconducting magnets - J_e ~500-1000 A/mm^2**
- SC magnets are more compact and have lower operational costs (only power consumption is to keep them cold)

J_e Limit in SC Magnets



- **The highest fields in accelerator magnets have been achieved using SC magnets.**
- **However, superconductivity exists inside the critical surface in (J, B, T) space.**
- **J_e (and B) in SC magnets is limited by the superconductor J_c(B, T).**

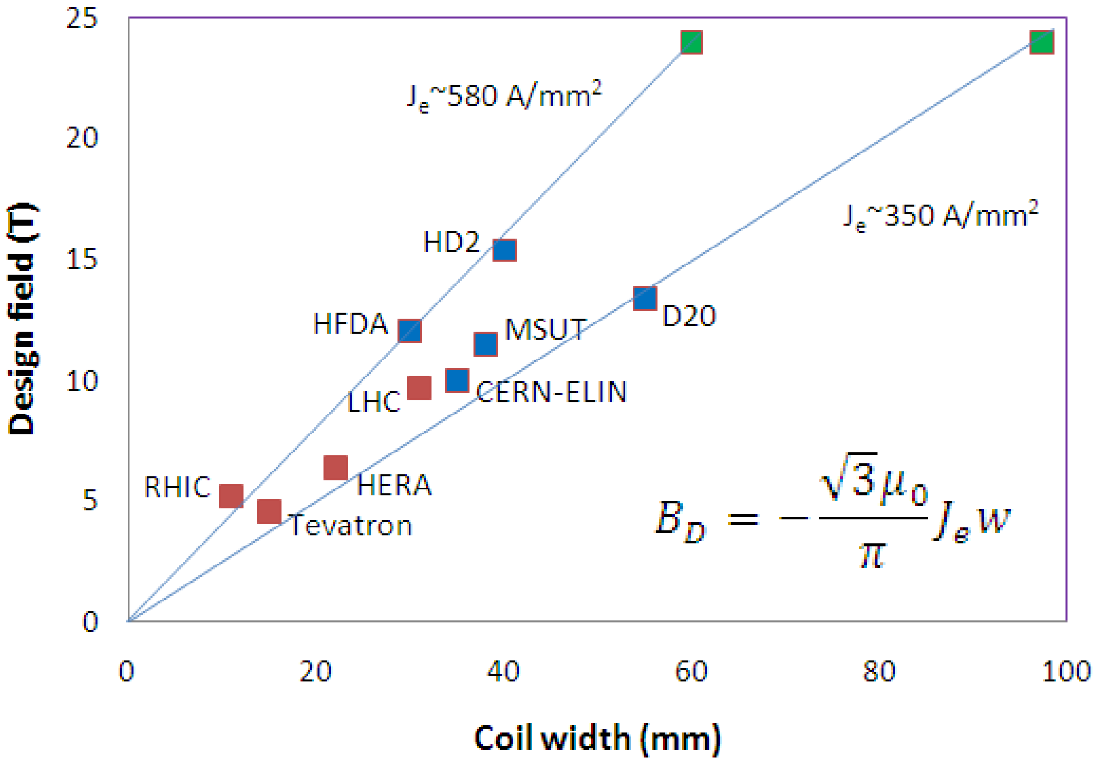
HTS Accelerator Magnets



Courtesy P. Lee,

- **The materials are produced by industry in long length (~1 km)**
- **Nb-Ti**
  - **$B_{c2}(0)$~14 T**
  - **$T_c(0)$~9 K**
  - **=> 10 T magnets**
- **Nb_3Sn**
  - **$B_{c2}(0)$~27 T**
  - **$T_c(0)$~18 K**
  - **=> 16-17 T magnets**
- **BSCCO/YBCO**
  - **B_{c2}(4.2 K)>50 T**
  - **$T_c(0)$~110/90 K**
- **High-field high-temperature superconductors open the possibility of accelerator magnets with B_{nom}>15 T**
  - **B_{des}>18 T assuming typical 20% margin**
- **Due to the lower J_c @ B<18 T (and higher cost) for HTS, a hybrid approach with Nb_3Sn coils in fields <15 T is an attractive option**

Towards 20+ T Magnets



Nb_3Sn section:

B_{des}=13T+20%=15.6T

J_{e_coil}(16T)=580A/mm^2

J_{e_SC}(16T)=800A/mm^2

⇒ w~45 mm

HTS section:

B_{des}=7T+4T=11T

J_{e_coil}(24T)=350A/mm^2

J_{e_SC}(24T)=700A/mm^2

⇒ w~40 mm

Total coil width w_{tot}~85 mm with J_{e_SC}(24T)=700A/mm^2

- **Now J_{e_SC}(24T)~400A/mm^2**

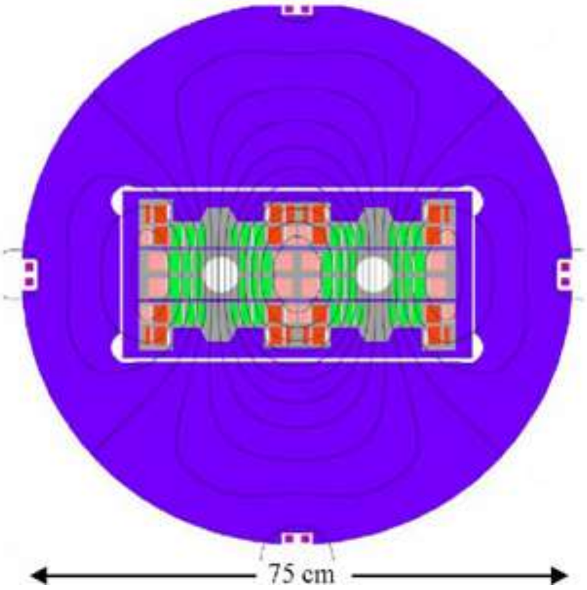
To reduce the coil width to 60 mm J_{e_SC}(24T)~1200A/mm^2

Nb_3Sn section: dipole aperture >120 mm and B_{max}~16 T

- **New challenging R&D goal for Nb_3Sn dipole magnets**

24 T Dipoles for LHC Energy Upgrade

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



Bi2212 + Nb_3Sn

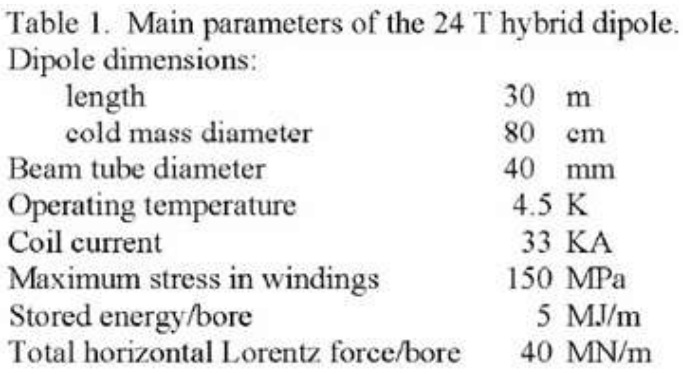
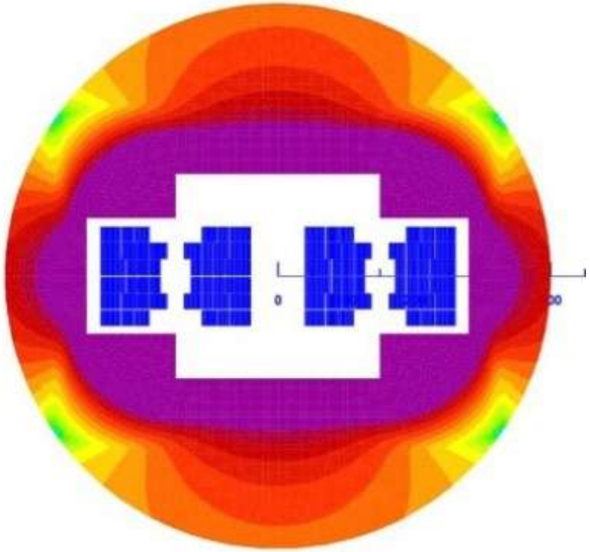


Table 1. Main parameters of the 24 T hybrid dipole.

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

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



Bi-2212+Nb_3Sn+Nb-Ti

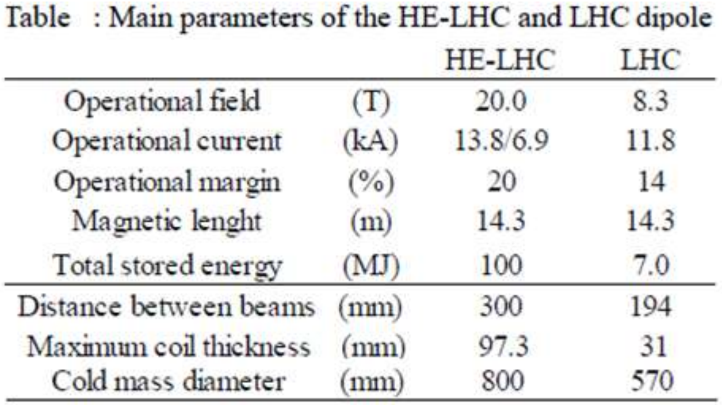
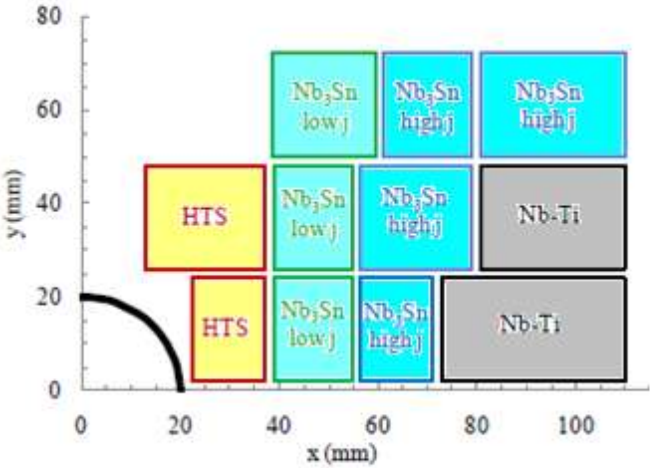


Table : Main parameters of the HE-LHC and LHC dipole

		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 Magnet Cost Expectation



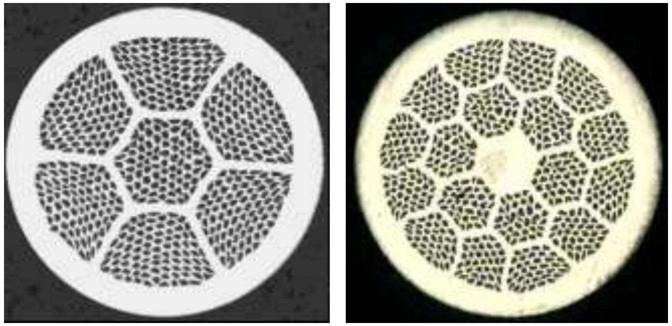
L.Rossi, E.Todesco (CERN), HE-LHC'2010

Table : Estimate of the cost of the conductor for a 14.3 m coil length two-in-one dipole.

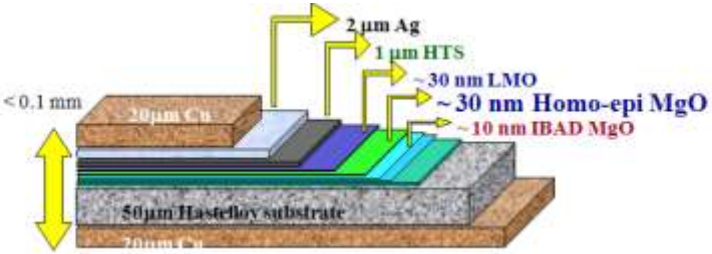
	(\$/kg)	m^3	Kg	M\$	%	Field (T)
Nb-Ti	200	0.12	960	0.19	5%	8
Nb_3Sn - h	800	0.16	1300	1.0	28%	13
Nb_3Sn - l	800	0.10	850	0.7	18%	15
HTS	3000	0.07	620	1.9	49%	20
Total		0.45	3730	3.8		

- **Cost estimate for the generic shell-type hybrid HTS/Nb_3Sn 20 T magnet gives comparable numbers**
- **Taking into account the cost of conductor, components and assembly labor the magnet cost per T*m (w/o cryostat):**
  - **8.3 T LHC NbTi dipole – 7-8 k\$/T/m**
  - **20 T HTS/LTS dipole – 16-17 k\$/T/m**
- **The possibility of operation of 20 T magnets at 4.5 K instead of 1.9 K (LHC) reduces the cost difference**

Practical HTS Strands



- **$Bi_2Sr_2CaCu_2O_x$ => Bi-2212**
- **Multifilament round 0.7-1.0 mm wire with Ag matrix**
- **SC fraction ~25-30%**
- **Traditional PIT process (OST)**
    - **Unit length >1 km**
- **Complex high-temperature final heat treatment in O_2**
- **Brittle after heat treatment, sensitive to longitudinal and transverse load**
- **Isotropic properties**



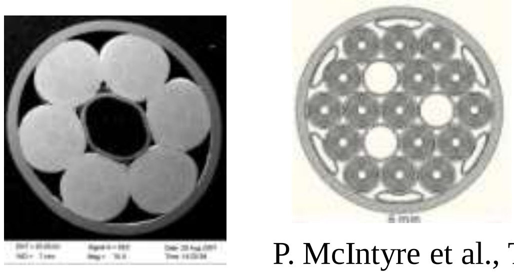
- **$YBa_2Cu_3O_y$ => YBCO-123**
- **4-12 mm wide tape, 50% is high strength superalloy (Hastelloy) and ~40% is Cu coating**
- **YBCO fraction ~1%**
- **Complex multilayer deposition process and final Cu electroplating (SP)**
    - **Unit length ~500-1000 m**
- **No final heat treatment**
- **Brittle but can withstand substantial load**
- **Large Ic variation along the tape**
    - **limit unit length to 50-200 m**
- **Highly anisotropic**

Present J_e(24T) is ~400A/mm^2 for both materials. It needs to be increased by a factor of 2-3 for 20 T accelerator magnets.

HTS cables

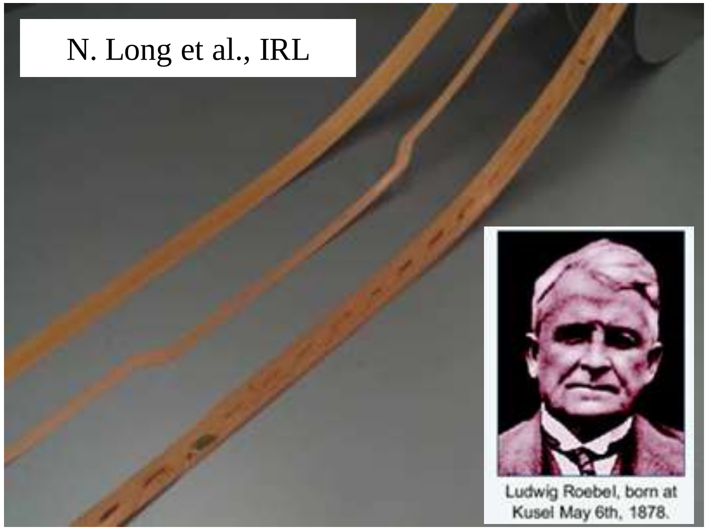
E. Barzi et al., Fermilab

- **Rutherford cable works well for round Bi-2212 wire**
  - **High packing factor ~85%**
  - **I_c degradation after cabling <20%**
  - **Sensitive to transverse pressure**
  - **R&D at Fermilab and LBNL**
- **Alternative option**
  - **Round cable inside metal tube to reduce transverse and axial load on Bi-2212 strands**
  - **Low packing factor**



P. McIntyre et al., TAMU

- **YBCO tape cannot be cabled using the Roebel method**
  - **Large packing factor**
  - **I_c degradation and sensitivity to transverse pressure are being studied**
  - **Under development by Karlsruhe (Germany) and General Cable and Industrial Research,Ltd (NZ)**
    - **15/5 YBCO Roebel cable self-field I_c>10 kA**



N. Long et al., IRL

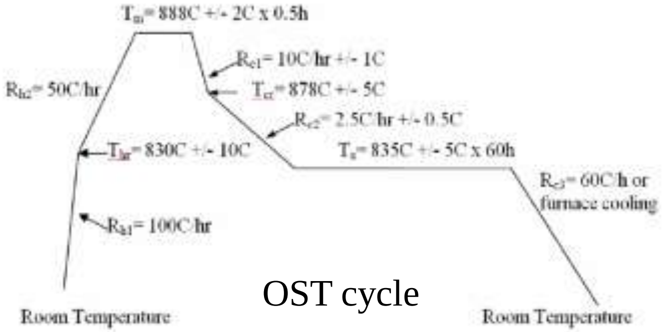
Ludwig Roebel, born at Kusel May 6th, 1878.

10-kA HTS cable R&D is critical for 20 T accelerator magnets.

HTS Coil technology

Bi-2212 coils:

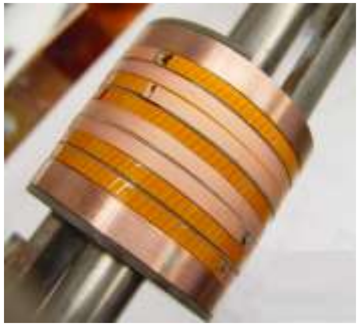
- ❖ Cos-theta and block-type coil geometry possible
  - o R&D using solenoids and small racetrack coils made of single strand and Rutherford cables
- ❖ W&R approach
- ❖ Complicate multi-step HT cycle
  - o Temperature variations ±1-2 C
- ❖ Liquid BSCCO can leak through the Ag matrix during reaction
  - o Coil performance is ~50-70% of short sample limit
- ❖ Insulation/structure/conductor chemical compatibility



OST cycle

YBCO coils:

- ❖ Block-type coil geometry with relatively small bending radii
  - ❖ R&D using solenoids and small racetrack coils based on single tapes so far
- ❖ R&W approach
- ❖ Coil performance is ~80-90% of short sample limit
  - o Tape splicing may degrade the coil performance



A. Godeke et al., LBNL

V. Lombardo et al., Fermilab

The key step is HTS Coil technology R&D based on high-current HTS cables and realistic mechanical structures.

Conclusions

- **Accelerator magnets with nominal fields of 20+ T look feasible (technically and economically) thanks to recent progress with HTS materials.**
- **Focused and well coordinated R&D efforts are needed to develop and demonstrate this technology including**
  - **HTS conductor properties (BSCCO, YBCO) and processing**
  - **high-current HTS cables compatible with accelerator magnet operating conditions**
  - **robust coils and mechanical structures capable to generate accelerator field quality under high Lorentz forces**
  - **Short and long magnet performance**
- **Nb_3Sn accelerator magnet R&D is still important**
  - **Nb_3Sn coil will generate ~70% of the total field and play an important role in magnet quench protection and cost**
  - **focus on large aperture (>130 mm) 15-16 T magnets**
- **If successful, these technology will provide excellent opportunities for HE-LHC and especially for Muon Collider.**

Acknowledgements

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