

High Field Solenoid Program





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(on behalf of BNL staff and industrial collaborators)



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High Field Solenoid Program

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- Status of PBL/BNL 20⁺ T HTS solenoid
 - Insert already tested for record 15⁺ T field
- Progress in quench protection
 - A major issue in HTS magnets
- Future programs on high field solenoids
- Feedback on conductor and Summary



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10⁺ T,100 mm HTS solenoid (midsert) with 24 pancakes for full length solenoid (ready for test)

PBL/BNL High Field HTS Solenoids



15⁺ T, 25 mm HTS solenoid (insert) with 14 pancakes already tested

Half length 100 mm with 12 pancakes already tested and reached 6⁺ T on axis (9⁺ T peak)



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14 pancake coils with ~25 mm aperture

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(despite anisotropy)



Test Results of HTS Solenoid #2 (¹/₂ Midsert, 12 coils instead of 24)



250 A ==> 6.4 T on axis 9.2 T peak field on coil



Coil could have reached above 10 T peak (original target), but was not ramped up to protect electronics of that time. Full solenoid with 24 pancakes should create >10 T on axis.

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Preparation of Combined Solenoid Test (HTS Insert inside HTS Midsert)



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Combined solenoid is almost ready for test
Would have been tested @77 K but for Sandy
4K test will be performed after the expanded advanced quench protection system is fully tested (construction just completed)





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BNL Quench Protection Strategy

- Things happen slowly in HTS => quench propagation velocities, increasing coil temperature to quench whole coil , etc., etc.
- Use problems (properties) of HTS "of things *happening slowly*" to our advantage.
- In HTS, there is a long pre-quench phase with very small resistive voltage during which the coils can be safely operated.
- Detect this pre-quench phase early on and initiate quench protection action.
- This requires detecting small resistive voltage in presence of large noise and inductive *voltage – challenge in large systems.*
- BNL has made significant advances in electronics to detect start of this pre-quench phase well below 1 mV rather than 50-100 mV.



Use quench protection heaters as the final line of defense

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Expansion of Advanced Quench Detection System at BNL

- So far we have tested solenoids with 12 or 14 pancakes (plus splices).
- The next test (insert + full midsert) will have 14+24=38 pancakes.
- We are ready to go with these two.

Cabinet #1 (32 channels, 1kV)



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Cabinet #2 (32 channels, 1kV) (expandable to 64 and 3kV)



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Significant Progress in Quench Protection R&D at BNL in YBCO Coils



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Solenoid with Multiple (3) Sections (38 pancake coils)

#1 : insert (14 pancakes), #2 and #3 : two half midserts (12 pancakes each)



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- Solenoid is sectionalized to extract energy fast on external dump resistors while keeping voltage low
- Bonus: Can also be used to provide electrical grading

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Superconducting

Novel Quench Protection System for HTS Magnets with Cryo-components

Magnet Division An approach that can make a significant difference in the quench protection of HTS Magnets:



CRYO-SWITCH/BREAKER

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MTECH/BNL SBIR/STTR

MTECH : Cryogenic Power Electronics (PI - M. Hennessy, previously at Intermagnetics General as chief scientist) BNL: Advanced quench detection system and quench protection concepts and experiments

Will use PBL/BNL coil for demo PBL is also a partner

Sectionalize coil with most action remaining inside the cryostat with no additional coldto-warm leads coming out

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Possible High Field Solenoid Program Beyond Present SBIRs

- We have already tested ~25 mm aperture HTS insert solenoid to over 15 T (over 16 T peak field)
- We have already tested half of ~100 mm aperture HTS midsert solenoid (with 12 pancakes) to over 6 T (over 9 T peak field)
- Based on test results from ~100 mm HTS solenoid from other program, the full PBL/BNL midsert should be able to meet the original target of 10 – 12 T
- If every thing goes well, then we should be able to combine the two together to achieve the original target of 20-22 T (was wow at one time)
- A major technical component holding this test has been the construction of expanded quench protection system. That system is now fully built and is currently undergoing final test. Some help from MAP is highly appreciated.

Next step …



- The next step, assuming above is successful, will be to test the combined solenoid in the background field to achieve a combined field of about 30 T
- One possibility is to test above at NHMFL. But that is turning out to be very complicated due large forces and protection of HTS and NHMFL solenoids
- It is also not practical to carry large quench protection electronics from BNL to NHMFL and marry with NHMFL system
- Even if all above is technically and logistically possible, the cost is coming out to be very high when everything needed to be done is considered
 - > See next slide for creating an alternate possibility





NbTi Solenoid for E-lens at BNL (200 mm i.d., 6 T, recently tested)

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Magnet Division

Parameters	Value
Wire, bare	1.78 mm X 1.14 mm
Wire, insulated	1.91 mm X 1.27 mm
Wire I_c specification (4.2 K, 7 T)	>700 A
Turn-to-turn spacing (axial)	1.98 mm
Turn-to-turn spacing (radial)	1.42 mm
Number of layers (main coil)	22 (11 double layers)
Additional trim layers in ends	4 (2 double layer)
Length of additional trim layers	173 mm on each end
Coil inner diameter	200 mm
Coil outer diameter	274 mm
Coil length	2360 mm
Yoke length	2450 mm
Maximum design field	6 T
Current for 6 T	~440 A
Peak Field on the conductor @ 6 T	~6.5 T
Computed Short Sample @4.2 K	~7.0 T
Stored energy @ 6 T	~1.4 MJ
Inductance	~14 Henry
Yoke inner diameter	330 mm
Yoke outer diameter	454 mm
Operating field (on the axis)	1 T to 6 T
Relative field errors on axis	<6 X 10 ⁻³

- Two of these solenoids were recently tested to 6.6 T (test stopped 10% above design field)
- Design, technology and some leftover material available for use





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PBL/BNL STTR on Developing High Field Solenoid for MAP (PI: Weggel)

- Strategy: Leverage existing assets (HTS coils, quench protection system hardware, leftover material from e-lens NbTi solenoid)
- Build NbTi solenoid with Phase I STTR funding
- Merge two HTS solenoids with above NbTi in early part of Phase II for field approaching 30 T in an all superconducting solenoid
- Add more HTS coils, structure, quench protection hardware, etc. in the later part of Phase II with a goal to achieve higher fields



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Superconducting Magnetic Energy Storage (SMES)

High field, large aperture, HTS solenoid with ambitious targets:

Key Target Parameters: 25 T, 100 mm, 2.5 MJ, 12 mm YBCO



Participants: ABB, USA (Lead), SuperPower (Schenectady and Houston), and BNL (Material Science and Magnet Division)

Funded by arpa-e as a "high risk, high reward" project.

Many challenges still remain but so far we have been getting good test results.

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A HTS Insert for a 20 T Superconducting Pion-Capture Solenoid for a Muon Collider

Superconducting Magnet Division

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- In capture solenoid system, field varies from 20 T to 1.5 T over ~15 m
- In original design, 20 T section consists of 14 T s.c. and 6 T resistive
- Resistive insert consumes ~12 MW power making operation expensive
- The solenoid system must tolerate ~4 MW dissipation of beam power
- Therefore, investigation of the use of HTS insert is highly attractive
- HTS will be compact and will reduce the size of s.c. solenoid



Not enough resources to build or test something meaningful in Phase I

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Major Opportunity to Increase High Field Performance of REBCO

- REBCO is highly anisotropic with performance in coil is limited by field perpendicular (or within 20°) value of Ic
- Recent BNL measurements of production samples of SuperPower show that 4K perpendicular field Ic varies as much as 2X

Measurements presented in BNL Magnet Division Internal Note by Arup Ghosh, "Ic Measurements of ReBCO Tapes at 4.2 K in Perpendicular Field.

- See afternoon presentation by SuperPower (Univ of Houston)
- Once we understand the source, we may find a way to incorporate that in production.
- Here we have an opportunity for increasing effective Ic by a factor of two or more.
- An opportunity for DOE/HEP to support REBCO and get a high impact outcome.
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Sample Num	Comments	Tape Width, mm	lc_Perp(8T)	lc(77K)	lc(8T)/lc(77K)
1	PERP TEST	12	726	330	2.200
2	PERP TEST	12	800	312	2.564
3	PERP TEST	12	1119	341	3.282
4	PERP TEST	12	1324	404	3.277
5	PERP TEST	12	1401	383	3.658
6	PERP TEST	12	773	365	2.118
7	PERP TEST	12	956	337	2.837
8	PERP TEST	12	1369	439	3.118



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SUMMARY

- Significant demonstrations have been made on quench protection. More work is still needed but as of now we are running ahead of schedule.
- Significant progress in high field solenoid area has been made with a line share of impressive results coming with DOE SBIR/STTR funding.
- Record field obtained in HTS magnet and a critical test coming soon.
- The technology developed is critical to MAP but useful elsewhere too.
- HTS will play an essential role in developing very high field magnets. There is still potential for significantly higher performance.
- Fast forward one year from now (at least for BNL):
 - > where we will be and what we will be discussing?

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