SC Magnets for High Energy/ High Intensity Frontier Accelerators

G. Apollinari/D. Harding
Fermilab

With help from: D. Larbalestier (FSU), V. Kashikin, A. Zlobin, L. Cooley (FNAL), P. Wanderer, A. Ghosh, R. Gupta (BNL), S. Prestemon (LBL)

Disclaimer: Lack of time has made this a <u>lab-centric</u> effort. Apologies in advance to the various University facilities in the HFM development business. Also, all errors are mine, all the good content is from my helpers !

Content

- Introduction
- Major Achievements and Challenges
- Existing R&D and Test Facilities
- Needed R&D and Test Facilities
- Conclusions

Introduction

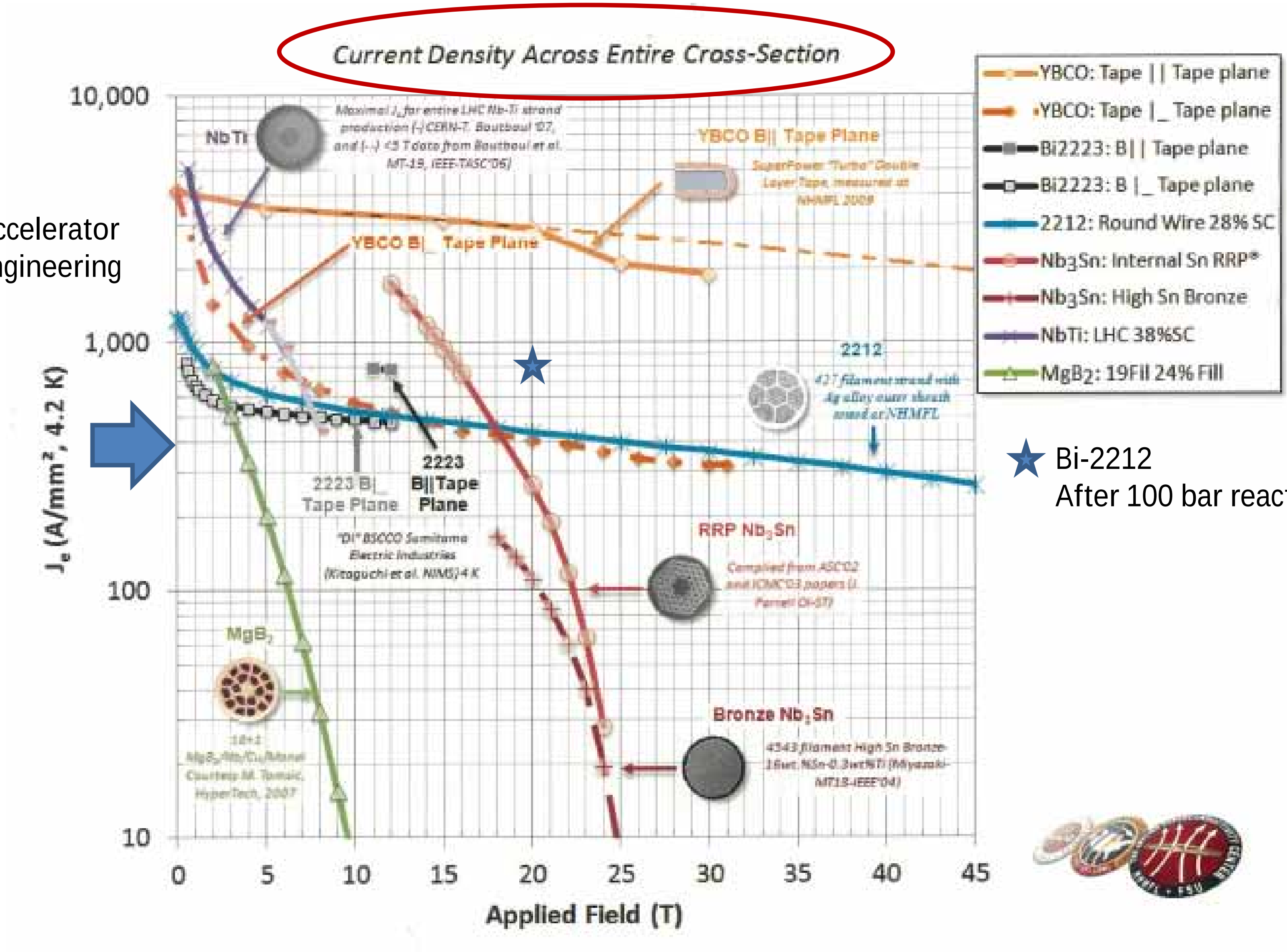
- (NbTi) SC Magnets for accelerator facilities are part of mainstream application since the Tevatron breakthrough in the 1980's.
  - Tevatron (4 T at 4 K)
  - HERA (5T at 4K)
  - RHIC(3.5T at 4K)
  - LHC (8 T at 1.9 K)
- Although production of the magnets has been, both a laboratory (TeV, RHIC) and an industrial (HERA, RHIC, LHC) endeavor, the magnet R&D and the test facilities have always been in the realm of Universities and Research Laboratories.

Technologies for Present and Future Frontier Machines

- NbTi
  - Workhorse, in use since 1980
  - Limited to ~8-9 T in accelerator applications
  - Ductile alloy in Rutherford cable, can be used in any accelerator magnets configuration (dipoles, quads, solenoids)
  - Fully industrialized production
- Nb_3Sn
  - Developed between 1998 and 2008 for HEP, magnets in 2010
  - Limited to ~15-16 T
  - Brittle material in Rutherford cable, can be used in any accelerator magnet configuration (dipoles, quads, solenoids)
  - Two competing high J_C strand variants for HEP: “RRP” (restacked rod process, at OI-ST) and “PIT” (powder in tube, at Bruker EAS)
  - Most progress achieved with “Wind & React” technology
  - Major industrialization now (ITER – 600 tons, 11 T, HL-LHC IR)
- All HTS:
  - Expensive, probably used as “insert” coils (HTS coil inside Nb_3Sn coil inside Nb-Ti coil)
- HTS – YBCO
  - Tape conductor, ready to use (no “react”), structural backbone (SS or Hastelloy), good J_C, Roebel cable demonstrated
  - Capable of >> 30 T
    - 34.5 T insert demonstrated
  - Racetrack coils in superferric accelerator magnets (dipoles, quads), pancake coils in solenoid applications
  - Industrial development halted after end of electric power programs, uncertain future
- HTS – Bi-2212/REBCO
  - Round wire, recent breakthroughs in J_C, Rutherford cables possible
  - Capable of >> 30 T
    - 32 T insert demonstrated in 2212
    - 35 T insert demonstrated in REBCO
  - Brittle, will rely on “Wind & React” technology, needs 100 bar pressure for best results
  - Compatible insulation and high-strength components have been verified
  - Industrial development ready to scale, needs secure raw material supply

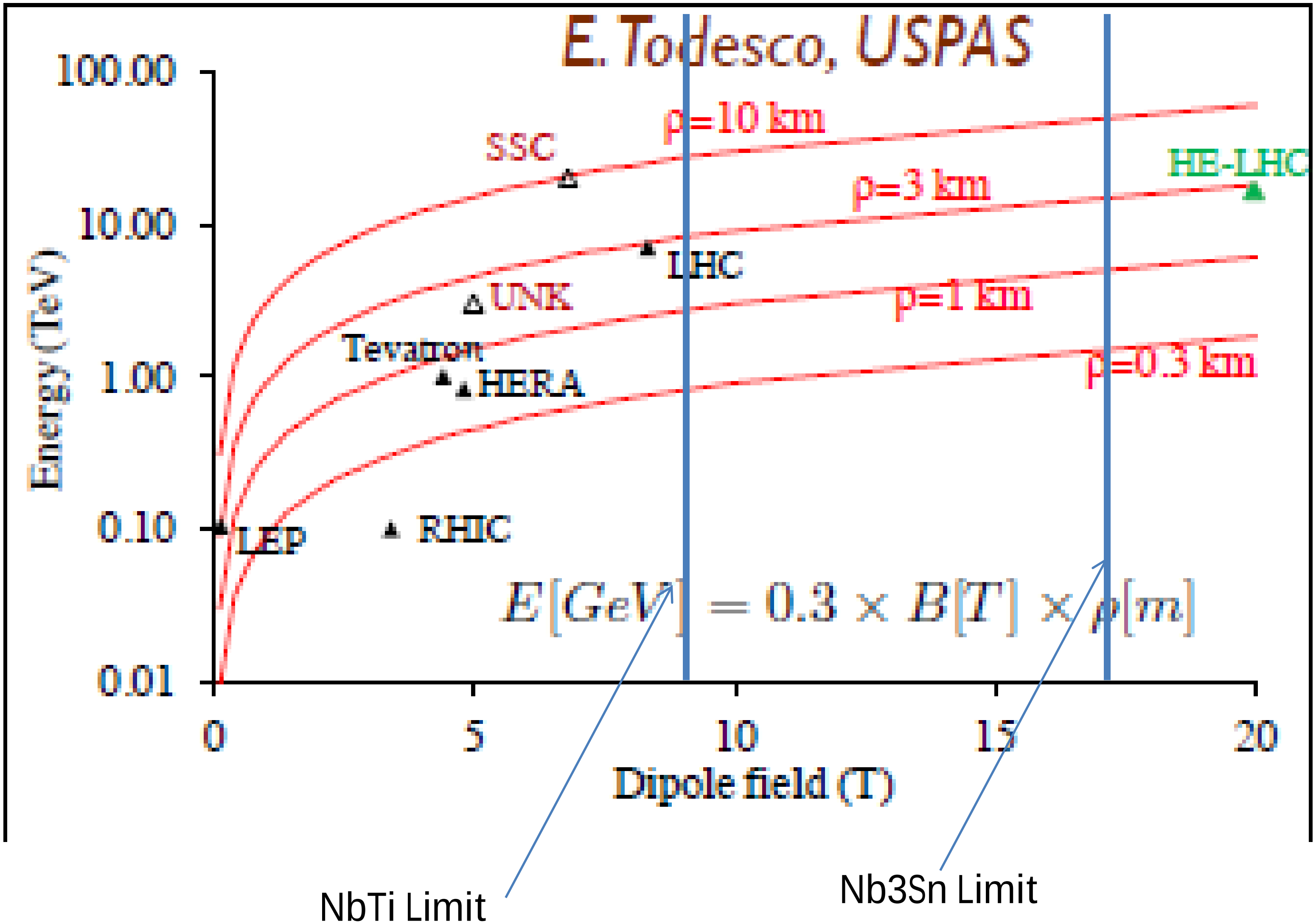
J_E vs. Field

Arrow:
Feasible accelerator magnet engineering



★ Bi-2212
After 100 bar reaction

Collider ring R & E versus Field



HFM Development Path

Every new material in the area of High Field Magnets must follow a very specific path:

- R&D on basic strand/materials
- R&D on cable/tape
- Assembly and development of model coils and mechanical structures
- Assembly and development of large coils and magnets*

* For circular or multi-pass machines with or without energy-ramping features, magnets must be “accelerator quality” magnets.

“Accelerator quality” is a broad term that includes properties beyond the field strength: appropriate aperture for beam, alignment properties, control of high-order multipoles during energy ramp, appropriate length, heat load and quench management, etc.

All these necessary features can obviously limit the ultimate fields achievable compared to a magnet that does not have to satisfy “accelerator quality” demands.

Major achievements and Challenges

- Most recent achievements on “accelerator quality” magnets have taken place using the Nb_3Sn technology:
  - LARP (LBL, BNL, FNAL): first demonstration of Long (3.5m) Nb3Sn quadrupole magnets with 90 mm aperture and 220 T/m
  - 11 T effort(FNAL): 10.4 T achieved in first 2 m long model with LHC Main Dipoles features.

- Activities on HTS have been limited to small coils, mostly due to lack of appropriate equipment and R&D Facilities.
  - YBCO Coils (BNL, NHMFL): Achieved 16 T in stand alone mode (BNL) and 35 T in 31 T background (FSU) in several small coils. All superconducting LTS/REBCO HTS 32 T user magnet under construction at NHMFL (2015 for use). Quench protection demonstrated at BNL down to ½ mV level (versus 100 mV in standard NbTi magnets)
  - Bi-2212 (BNL, LBNL, FNAL, NHMFL): Small racetracks achieve full short sample performance (LBNL), while 10 bar processed coil achieved 34 T in 31 T (FSU). Recent breakthrough in J_C of single wire implies special high-pressure furnace to extend capability to cables and coils

(Example of) Existing Facilities for Nb_3Sn

- As mentioned previously, most equipment for generic Nb_3Sn "accelerator quality" magnets already exists in various laboratories
  - Cabling machine
  - Winding Machines
  - Reaction Oven
  - Impregnation and Assembly Fixtures
  - Test Setup down to 1.8 K (and up to ~3.6 m long magnets)

11 T Model @ FNAL – A. Zlobin

"Fermicentric" Examples

Present and Future Frontier Machines on the radar scope

- Energy Frontier
  - HL-LHC (~2022) and/or VLHC/80 km ring (~2030-2035?)
    - Will use Nb_3Sn for 11T dipoles and ~250 T/m IR quadrupoles
    - Development facilities mostly exist FNAL/LBL/BNL. **Need for Production facilities (probably to be met by US-LHC project once approved)**
  - HE-LHC (~2030)
    - Will use HTS (YBCO or Bi-2212) magnets or HTS inserts for ~ 20T dipoles
    - **Need for HTS Cable R&D Facilities and Magnet Development Facilities**
  - Higgs Factory/Muon Collider (2030-2035?)
    - Cooling section will rely on ~30-50 T solenoids based on HTS
    - Collider section will rely on ~12-15 T Nb_3Sn dipoles and quadrupoles
    - **Need for HTS Cable R&D Facilities and Magnet Development Facilities**
  - ILC (~2020)
    - No need for HFM foreseen at this time
- Intensity Frontier
  - Project X (~2018)
    - No need for HFM foreseen at this time
  - Neutrino Factory (~2025?)
    - Will use NbTi/Nb_3Sn technology

Bi-2212-based Magnets Needs - Solenoids

- R&D facilities at Labs to drive conductor and cable development
  - Goal: Build and test small coils to make serious new marks that will prove Bi-2212 round-wire technology for next steps.
    - Why? Coils and cable tests will best reveal conductor weaknesses
  - Cost: $1-2M per year of capital and M&S:
    - Conductor: $10-100 per meter. **Needs to be brought down !**
    - Specialized reaction furnaces at strand and cable level: tens to hundred k$
    - Small coil materials (steels, insulation, etc.)
    - Cable test capability dedicated to HEP needs (or appropriate time dedicated to HEP at comparable existing facility)
- Investment for real coils at ~30T level
  - Goal: Run sizeable program over ~5 years to develop MAP-like focusing solenoid.
  - Cost: ~$10M:
    - Conductor and cables – present target is pancake coils wound from Rutherford cable
    - Large furnace at 25 to 100 bar pressure, 900 °C: $2.5M facility
      - Stewardship opportunity – future NMR magnets
    - Solenoid Test Facility improvements
      - Must have “outsert” to test prototype “insert” coils

YBCO-based Magnets Needs – Solenoids

- R&D Facilities at Labs to drive conductor development
  - Goal: Characterize shortcomings of YBCO “electricity” conductors when used in solenoids, to steer conductor development more toward HFM needs
    - Why? R&D on other conductor architectures is not feasible in industry at present
  - Chief areas:
    - J_E(field angle) at < 10 K and 5-10 T or higher
    - J_E (length) at < 10 K, characterization of conductor drop-outs
  - Main costs:
    - Conductor: between $25/m and 100$/m
    - Large-bore magnets with ~10 T background fields, or horizontal split-pair magnets, to accommodate rotation and mechanical test devices, hundreds k$
- R&D Facilities for coil manufacturing and testing
  - Goal: wind pancake coils using YBCO tape and test them to limits
    - >$10M program at NHMFL for 35 T user magnet
    - Need “outsert” magnet and solenoid test facility improvements
    - Test mechanical properties, quench protection, joints and splices, coils under “real” mechanical loads and “real” current densities

HTS(YBCO/Bi-2212)-based Magnets Needs – Dipoles and quads

- Conductor-specific R&D facilities
  - YBCO – tape-based magnet engineering facilities
    - Goal: evaluate tapes and Roebel cable in magnets
    - Need special winding facilities
  - Bi-2212: over-pressure reaction furnace facilities
    - Goal: use existing Rutherford cables with new over-pressure approach
    - Need special reaction furnaces
- R&D Facilities for Cable Testing
  - Goal: evaluate and remove conductor weaknesses in real cables
    - Dipole vertical test with cable probe insert, upgrade of facility like that at BNL
- R&D Facilities for Magnet Testing
  - Goal: develop highly sensitive quench protection system for HTS Coils
    - New dedicated HTS Magnet test system with usual "bells & whistles" or upgrade of existing magnet system facilities with significant investments in leads, quench detection electronics, power supply, strain gauges, level sensors, etc.
- R&D Facilities for Insert Testing
  - Goal: User-like, large aperture magnets to provide ever-increasing fields for "inserts" application
    - Nb_3Sn dipoles and quad coils up to ~11-14 T fields as "outsert" background for HTS (YBCO or Bi-2212) inserts up to ~20T

High level Summary Needs

- Facilities needs for Nb_3Sn R&D are mostly covered on US soil.
- Challenge in next ~10 years is to develop facilities for HTS R&D as happened in 2000-2010 for Nb_3Sn R&D

<u>Specifically</u>

- Engineering Facilities Needs
  - Facilities (cryostat) to test long (>4 m) accelerator magnets on US soil with high currents (up to 29-30 kA) and at 1.9 K
  - Facilities to test long/large solenoids for MAP applications
- R&D Facilities Needs (mainly for HTS magnets)
  - High Pressure furnaces for cable and coils based on Bi-2212
  - Variable angle, length, load test capabilities for YBCO J_E at temperature and fields of intended operation (10+ T, <10 K)
  - Magnet assembly equipment (winding machine, coil manufacturing tooling, etc) for HTS magnets
  - “Outsert” magnet facilities to develop insert concepts