Magnet Strategy

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Muon Accelerator Program Review
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Outline

- Magnet Issues for the Muon Collider
- MAP Magnet Objective
- Specific R&D Plans, Cost and Schedules
  - High Field Solenoids for Final Cooling
  - Collider Ring Magnets
  - HCC Magnets
- Comments and Conclusions

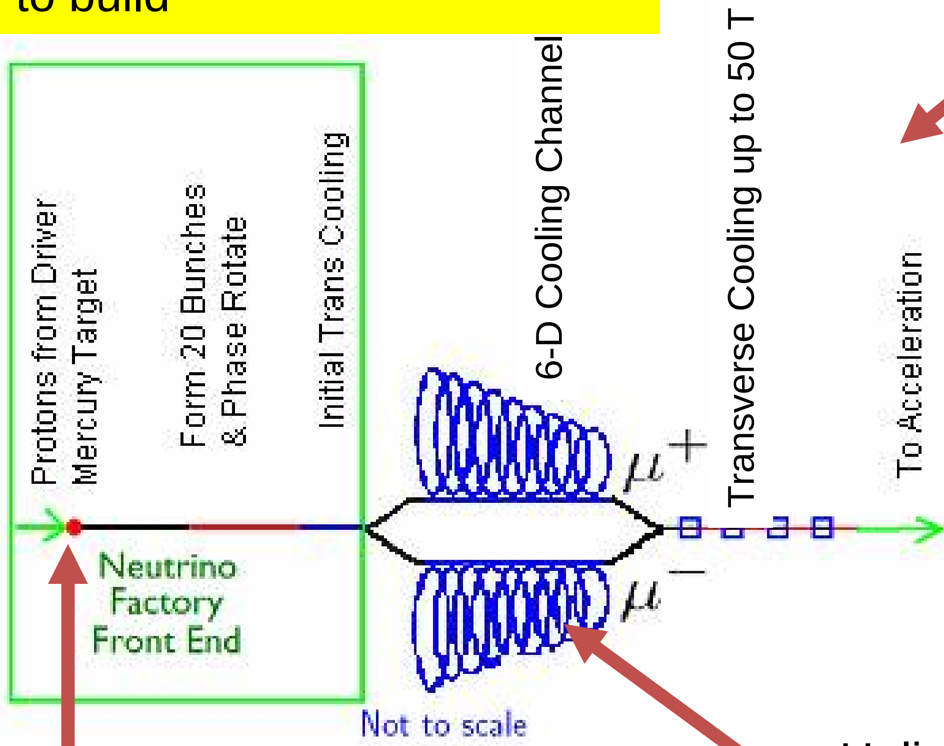
Today's Magnet Presentations

- Magnet Strategy (Lamm)
  – How Magnet Program meets the MAP goals
- Very High Field Superconducting Magnet Collaboration (VHFSMC) Status & Relationship with MAP (Larbalestier)
- Magnet R&D (Tompkins)
  – Present and Future Magnet R&D, how it relates to MAP strategy

Interesting Magnets in Muon Colliders

The good news: Most magnets required for MC accelerator are simple to build

Very high field solenoids



Collider ring/IR Magnets ~10 T, wide aperture/open midplane

Helical cooling channel (HCC) solenoid rings 20 T and above (one of many options-most challenging magnet-wise)

Wide aperture 20 T solenoids

Objectives of Magnet Program

- Practical conceptual design and prototype plan
  - Meets or defines MC design requirements
  - Must be “manufacturable”
    - reproducible and in a reasonable time frame
  - Enough technology development to back up design
    - either through MAP or leveraged from other DOE programs or industrial application

Focus on Difficult Magnets

- High Field Solenoid: 40 T nominal, up to 50 T
  – Mechanical complexity, quench protection
- Colliding Ring Dipoles and Quads
  – Field quality, mechanical support related to wide aperture and/or open midplane
- 6-D cooling Magnets if Helical Cooling Channel (HCC)
  – Logistics of incorporating RF with SC coils

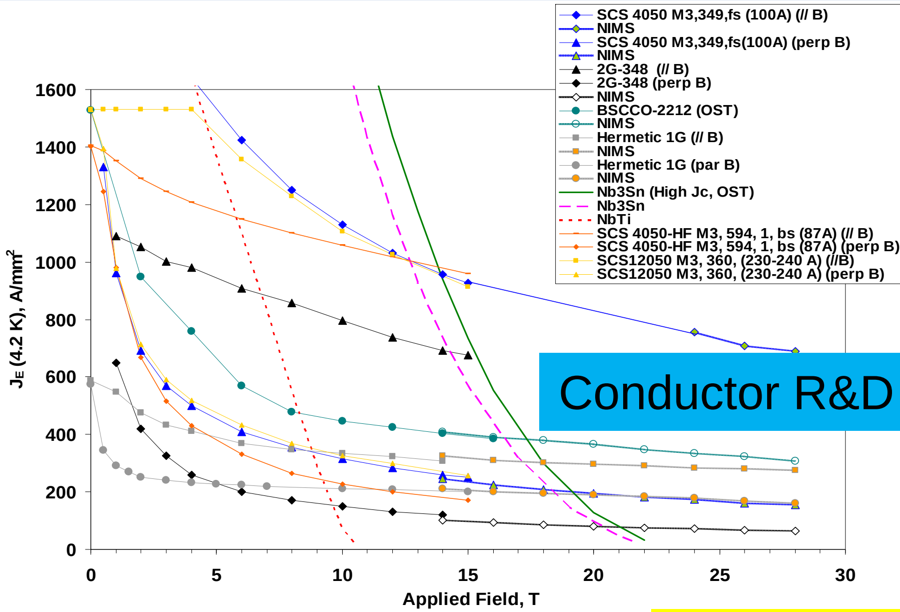
Other Objectives/Issues

- Target Solenoid: 20 T Magnet
  - Energy deposition, radiation damage
- Rapid Cycling magnetic structures for Muon acceleration
  - Power losses
- Cost estimation for magnets:
  - Higher risk specialty magnets
  - Very large number of low risk solenoids
- 10-15 T solenoid R&D
  - Moderate difficultly, issues with field leakage into adjacent RF structures

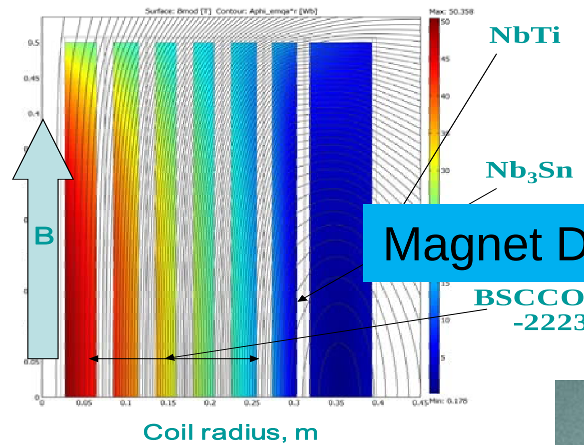
40-50 T Solenoids

- Up to about 50 T, luminosity increases with higher field final cooling solenoids.
- The state-of-the-art for high field superconducting solenoids is about half of this field, i.e. ~25 T
  - Potential for luminosity gain through higher field solenoids
- Goal is to demonstrate feasibility of high field solenoid that meet all muon collider requirements
  - Preliminary studies suggest that a 40 T solenoid meets the field requirements (hence the 40-50 T range)

High Field Solenoid Studies



Conductor R&D

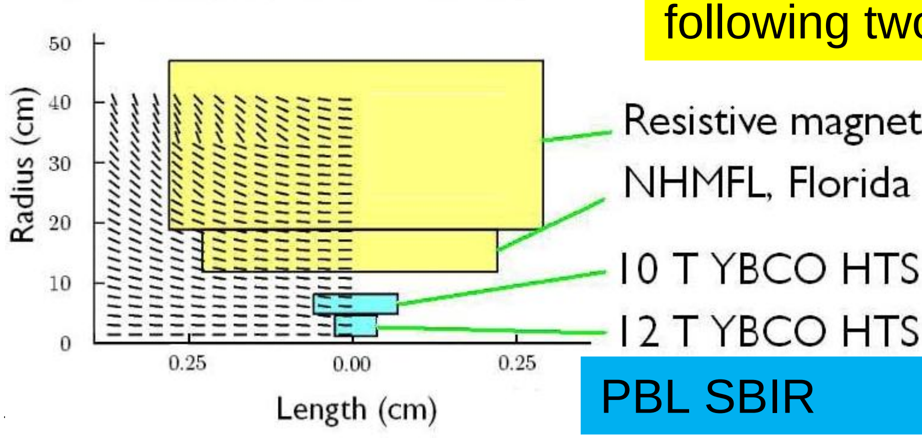


Magnet Design Studies

Instrumentation Development

More details in the following two talks

HTS magnets in 19 T Resistive



PBL SBIR

VHFSMC Supported R&D

Magnet Complexity Grows with Increasing Bore Field

- Several magnet design studies over the past few years point to the difficulties of building high field solenoids
  - Peak hoop stress grows faster than linear with field
    - increase stress means larger % of magnet volume devoted to stress management
  - Volume grows ~field^2 ➔ much more HTS
    - even with hybrid magnets which employ NbTi and Nb_3Sn outserts, most of the volume increase comes from HTS materials

“High Field Solenoid Strategy”

Divide effort into 5 tasks….

1) *Develop functional specifications for the high field solenoid.*
2) *Evaluate/compile information on state-of-the-art of conductors.*
3) *Build HTS and hybrid inserts to prove technology.*
4) *Perform conceptual designs for highest field practical magnet.*
5) *Present plan for building magnets in years 1-3 post plan.*

Magnet Specifications

1) *Develop functional specifications for the high field solenoid.*

Preliminary Specification:

Number of magnets ~ 20	More if field is lower	
Central Magnetic Fields	> 30 T at start,	> 40 T at end
Lengths	~ 1m at start	~ 10 cm at end
Minimum magnet bore	2 cm at start	1 cm at end
Field Quality	0.2% at start	0.2% at end

Time frame: First year (now)

HTS Conductor Studies

2) ***Evaluate state-of-the-art of conductors.***

- The state-of-the-art in HTS conductor is the major factor limiting a practical High Field design. Parameters:
  - engineering current densities > 500 A/mm^2 at 30 T
  - excellent strain tolerance
  - available in long piece lengths
- We expect that there will be continued significant progress in conductor development during the multi-year window for the MAP design study.
- We expect to benefit from conductor studies conducted by other programs such as VHFSMC

HTS Conductor Studies

2) *Evaluate state-of-the-art of conductors. Part II*

- Significant effort in MAP will be devoted to short sample testing of promising materials. Studies include
  - Ic as a function of temperature, field, field orientation
  - strain
  - magnetization
- MAP will focus on materials not covered specifically by other programs
  - for example VHFSMC is studying Bi 2212 wires
- MAP will depend on outside programs such as the VHFSMC and SBIR's to develop new conductor.
- Time frame: First half of program

Insert Program

3) ***Build HTS and hybrid inserts to prove technology.***

- Economical approach to testing out coil technology
- Standalone tests or combined with facility outserts
- Study conductor/cable
    - mechanical properties
    - quench characteristics
    - splice techniques
- Cabling technologies
- Time frame:
    - Now throughout program
- Build~5-6 inserts/year in peak of program
- Detailed program will be dictated by needs of MAP

Note: inserts are not a substitute for building full scale magnets

Conceptual Design

4) *Perform conceptual designs for highest field practical magnet.*

- Key design points
  - utilizing the state-of-the art conductor
  - advanced mechanical support approaches
  - effective insulation schemes
- Quench protection strategies
- Insert development within and beyond MAP; build on results from SBIR
- Time Frame: Second half of program

Fabrication Plan

5) *Develop plan for building full scale magnet after MAP is completed*

- Extension of previous task
- Base on conceptual design
- Develop cost and schedule
- Time Frame: last 2 years of Plan

High Field Solenoid Milestones

- Fabricate small HTS test magnet FY 13
  - This is meant to be a significant technology demonstration.   Required progress:
    - baseline magnet specs
    - continued progress on application of state of the art conductor
    - evolution of insert program, leverage SBIR progress
- Begin conceptual design of >30 T solenoid FY13
    - depends on progress on previous milestone
- Complete conceptual design of >30 T solenoid FY16
    - task 4 and Task 5 completed

Collider Magnet Issues

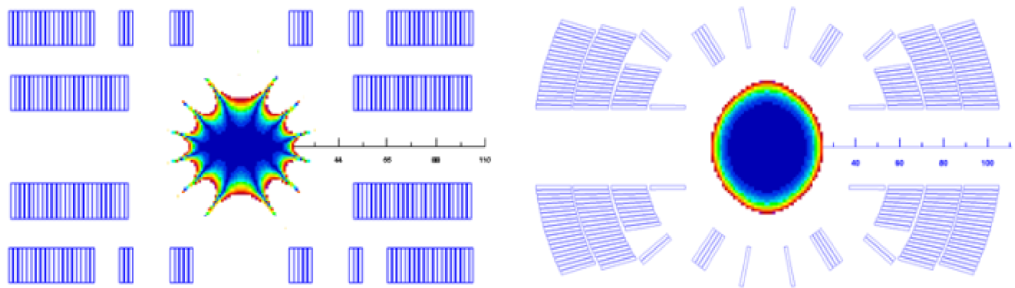
- IR and arc, dipoles and quadrupoles
- Strong arc magnets, reduce ring circumference, increase luminosity
  - Baseline design calls for 10 T fields
- Significant energy deposition issues, electrons from muon decay
  - ~0.1 kW/m in horizontal plane for storage ring
  - Must be intercepted outside of the magnet helium vessel

Magnet Specifications

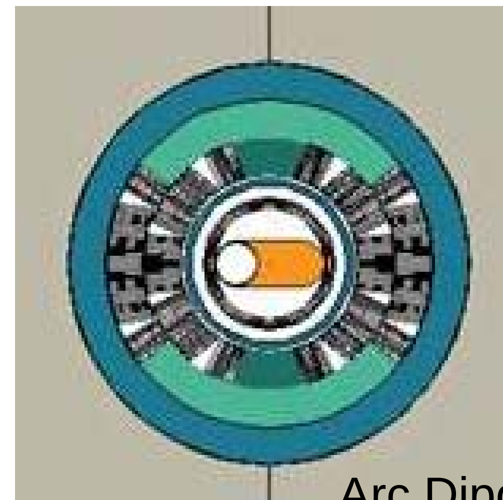
1) *Develop functional specifications*

- i.e. Working with collider ring design group, define parameters for magnet
  - central field
  - field errors/size of “good field region”
  - radiation damage/energy deposition
  - aperture including internal beam absorber
- Field and energy deposition indicate the need for Nb_3Sn conductor

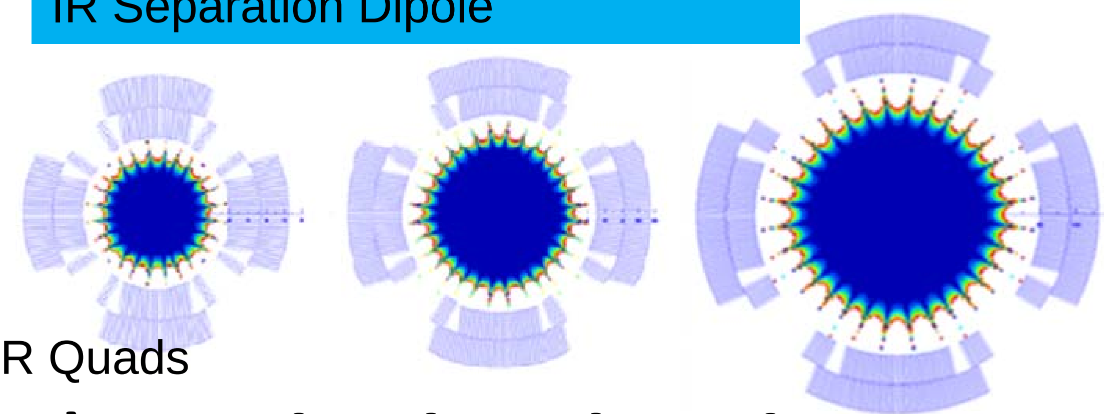
Collider Magnet Concepts



IR Separation Dipole



Arc Dipole



IR Quads

2) Develop baseline designs

Zlobin IPAC 10
Novitski ASC 2010

Note: These studies build on significant Nb_3Sn technology development from LARP and DOE core programs

3) *Technology Development*

- 1 meter long magnets are not part of MAP scope
  - expensive program based on LARP experience
- MAP Plan
  - depend on core programs   FNAL and LBNL
  - benefit from knowledge gained on other projects and programs
    - LARP wide aperture quads for future LHC upgrades in particular
      - 120 mm Nb_3Sn quad models being built now….
  - small R&D projects will be considered depending on design directions, such as radiation hardened insulation

Design Studies

4) *Conceptual design*

- Primary goal is demonstrate feasibility of magnet fabrication
  - issues:
    - details of energy dissipation
    - radiation damage
    - mechanical structure, especially with open plan dipoles
    - field quality (not as big an issue because of muon lifetime)
  - IR dipole looks to be the most challenging

- Develop designs far enough along for cost estimate

Collider Magnet Milestone

- Begin conceptual design of collider magnets FY 13
  - Preliminary design work is of course progressing now
  - Final conceptual design depends on
    - specifications based on lattice design
    - continued technology development, mostly outside of MAP

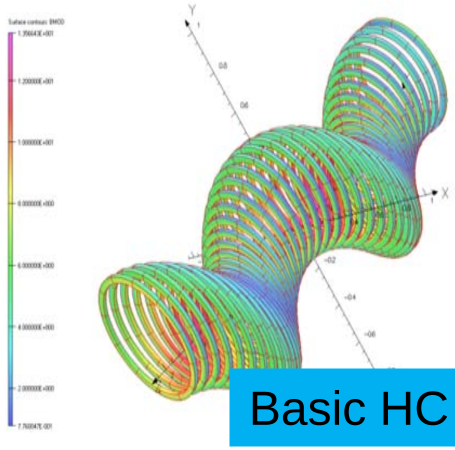
HCC Magnets

- 6- dimensional cooling is one of the highest technological risks of the muon collider
  - $O(10^6)$ cooling required
  - Several technologies are being considered
  - Of these choices, Helical Cooling Channel (HCC) has the most challenging magnets because of the complicated field and close proximity to RF and cooling media.
  - These field can be generated elegantly by using solenoid rings offset in a helical pattern

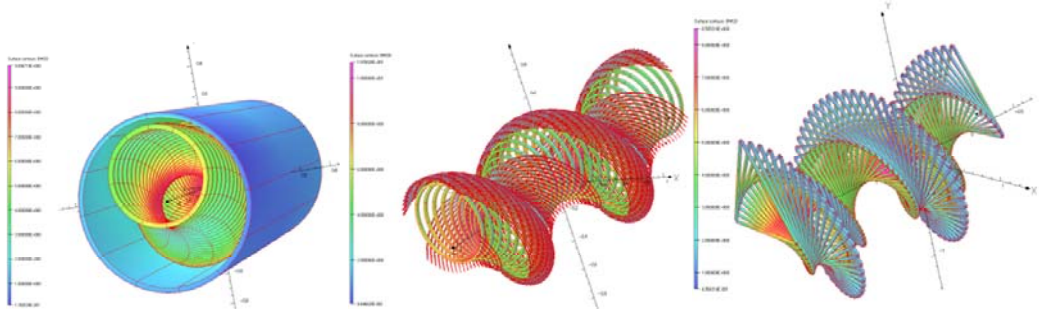
HCC Magnet Strategy

- Over the past few years, studies have been performed between Fermilab and Muons Inc.
  - Paper study cooling channel have been designed and studied.
    - require magnets ranging from ~6 T to 25 T on conductor
  - Cooling efficiency as a function of geometric and conductor parameters
  - Integration of magnets with RF and absorber media
  - Coil fabrication techniques both for high field and low field section of coils

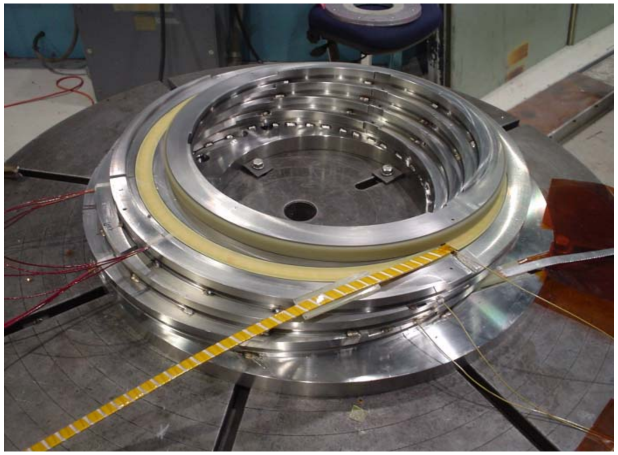
“Helical Solenoid Magnets”



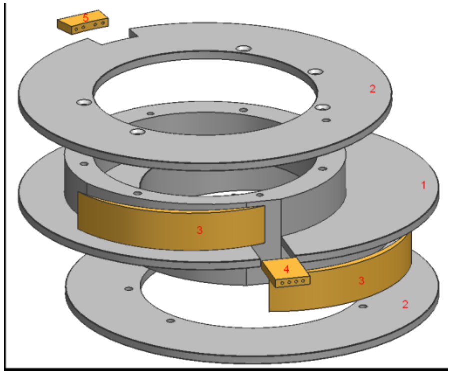
Basic HC Design

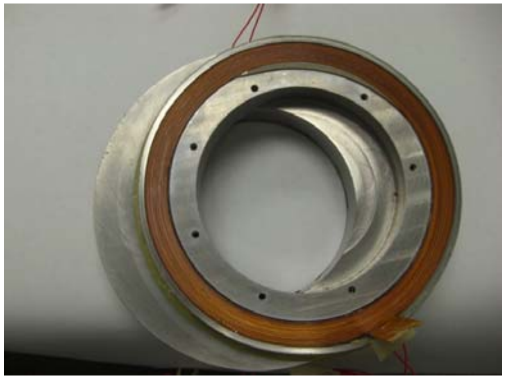


Correction Schemes



Model Magnet Program NbTi





Model Magnet Program HTS

HCC MAP Program

- Continue to support magnetic design studies to determine if HCC is the best solution of the muon collider
- Continue on a low level magnet development program: Key issues:
  - Economical and reliable coil fabrication
  - NbTi, Nb_3Sn and HTS coil technology
  - Quench protection for very long strings of solenoid rings

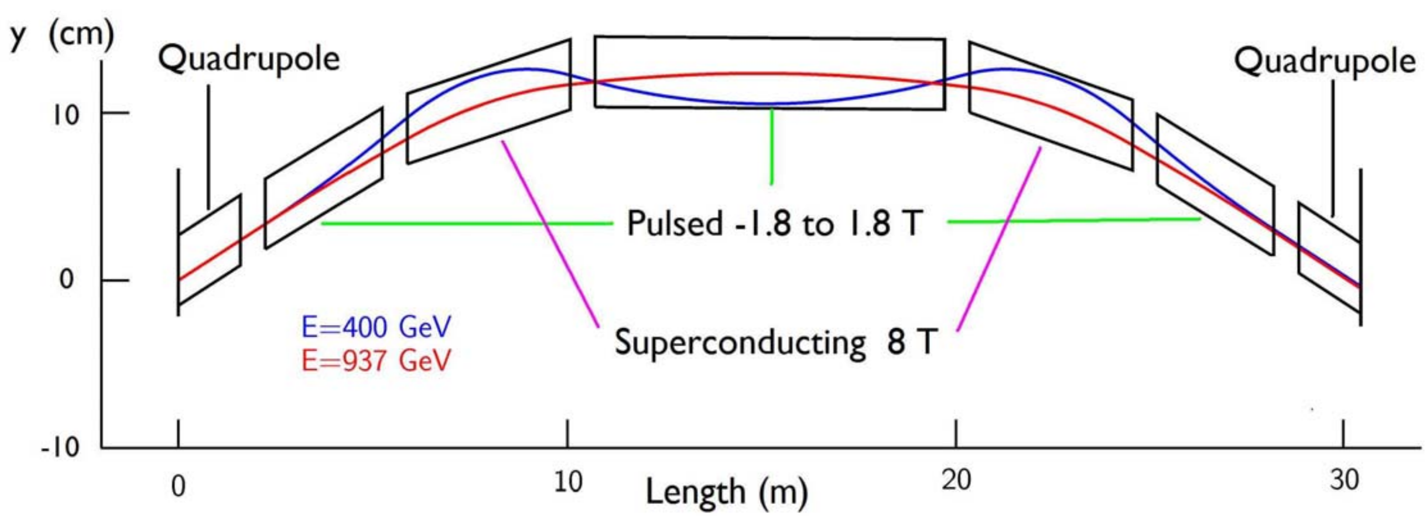
HCC MAP Program II

Future of program completely depends on technology decision in the next few years

- If HCC is not chosen
  - Program closed
- If HCC is adapted for all or part of Cooling
  - Continue magnet demonstration program
- Either way
  - Effort will segue to magnet support of 6-D demonstration (which is the only relevant milestone)

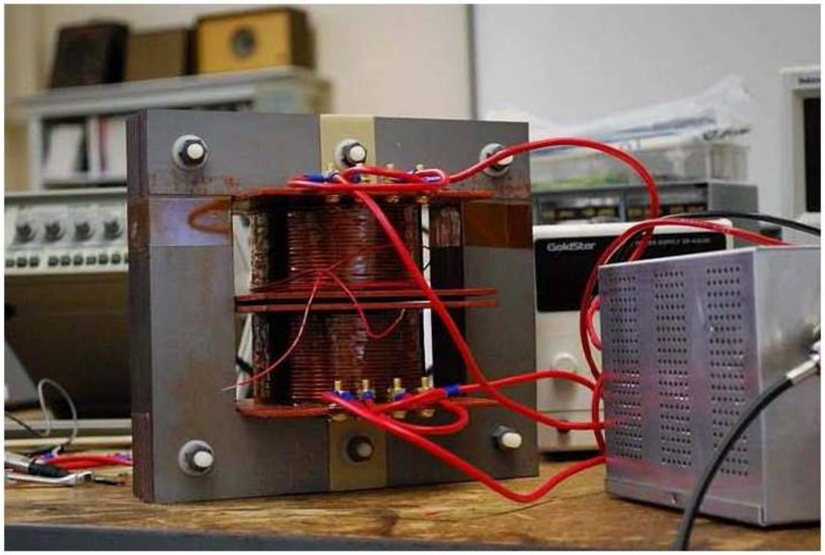
Rapid Cycling Dipoles

- Muon synchrotrons to 750 GeV in the Tevatron tunnel.
  See PAC07, D. Summers et al., arXiv:0707.0302 for details.
- Low mass, high γ muons allow small beams and magnets.
  Survival of muons is reasonable.
  Grain oriented silicon steel for low loss, high field dipoles.
  There is time to refill RF cavities during acceleration.
  Low duty cycle leads to low losses in the 400 Hz magnets.
  Fixed 8T superconducting and $\mp$1.8T dipoles are interleaved.



Rapid Cycling Dipole Results

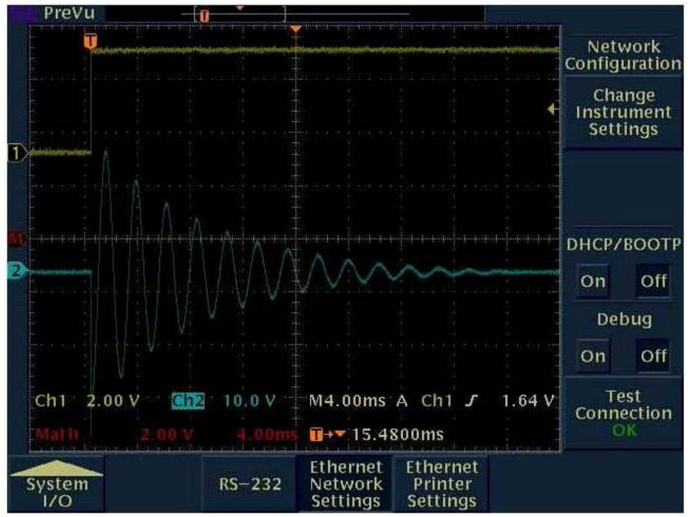
Grain Oriented Silicon Steel Dipole Prototype



- 1.5 x 46 x 46 mm gap, Slotted "EI" Transformer Laminations

IGBT power supply test: 400 Hz, 400V, 50 Amps

- Tektronics TDS3054B 500 MHz Oscilloscope



- Results: LC circuit should ring for twice the time.
  Magnet only linear to 1.2 T DC. Lossy, saturated T-joint?

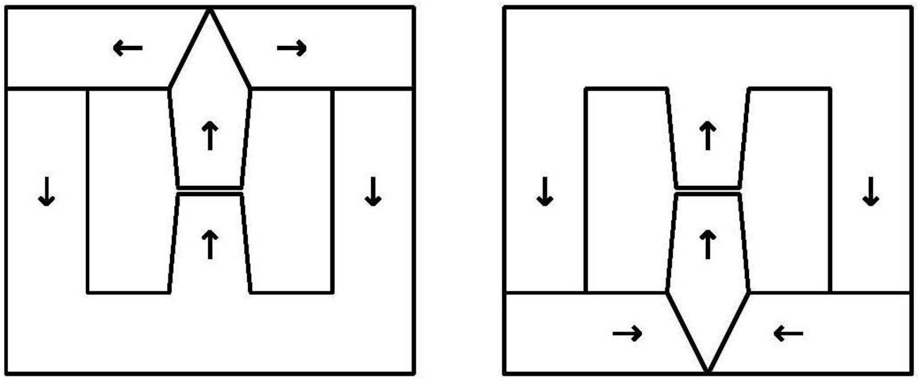
Prototype Built

Prototype Tested

D. Summers U. Mississippi

Rapid Cycling Dipole Program

- Build a 1.5mm gap, 46mm long dipole with mitered joints.



- Build a full 12mm gap, 300mm long mitred joint dipole.

  Build an IGBT power supply for the 12mm gap dipole.

  Calculate eddy current hexapole moment with OPERA-3D.

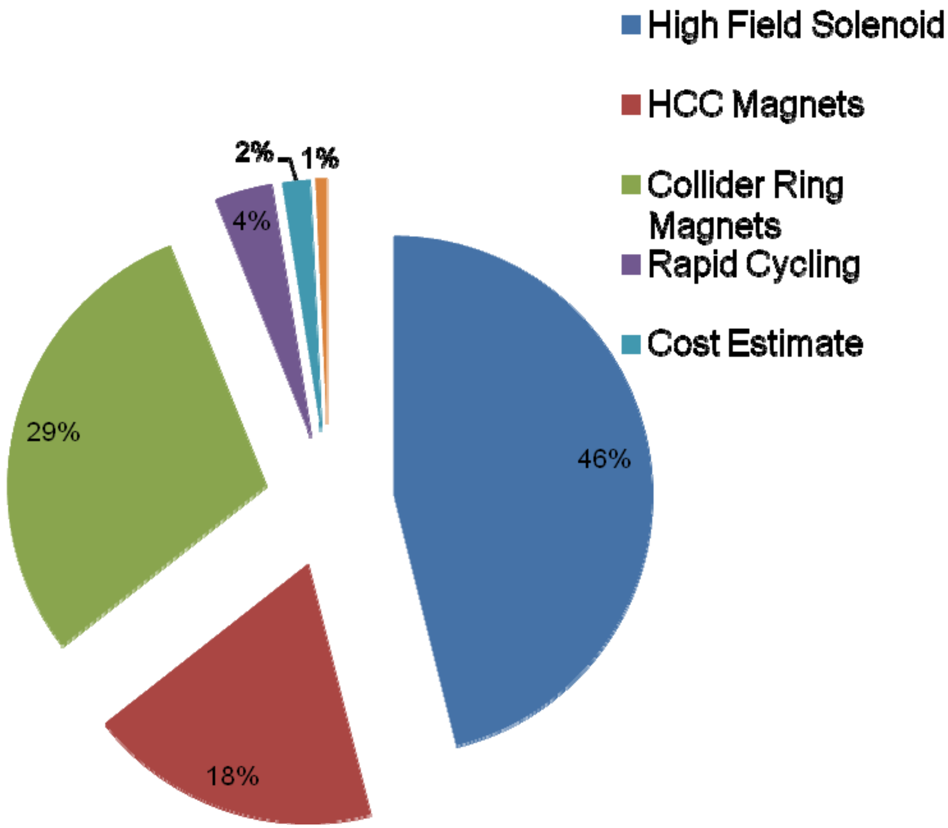
  Get a finite element program for grain oriented silicon steel.

  10μm lamination accuracy, small 12mm gaps: B fields OK?

  Does grain orientation cause trouble with field quality?

  Simulate, optimize, and measure field quality.

Proposed Resource Allocation



Task	FTE
High Field Solenoid	25.1
HCC Magnets	10.9
Collider Ring Magnets	15.2
Rapid Cycling	1.9
Cost Est	0.9
Travel	
TOTALS	53.9

Comments

- As this is an R&D program, within a larger R&D program, there must be some flexibility in planning
  - Program must adapt to evolving ideas in the muon collider design
  - Program must adapt to anticipated and unanticipated technology breakthroughs
  - Possibility to redistributing funds in later years with the broader magnet view as best needed.

Examples of future decisions

- Technology decision for 6-D
  - might scrap HCC altogether=>focus on 6-D magnet/RF integration
  - Hybrid 6-D focus on HCC in higher energy regime=> Nb_3Sn or HTS
- Development of HTS materials or high field solenoid technology might argue for a more significant demonstration in the later years
- Refinement of IR design and LARP breakthrough in Nb_3Sn might affect IR dipole technology decision

Conclusion

- There are significant magnet challenges for the Muon Collider
- A strong magnet program within MAP is essential to building a convincing muon collider design
  - Program targets key magnets with the highest technical risk. (highest % of resources to "high field solenoid")
  - Reliance on DOE programs outside of MAP for support particularly for conductor development and collider magnet R&D
  - Additional resources needed for any significant magnet demonstration within MAP