Challenges of High Field Magnets

Alexander V. Zlobin
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## Outline

**Muon Collider**

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### Key Points

- Introduction
- Practical superconductors
- MC key systems and magnets
  - Front End, Cooling, Acceleration, Storage Ring and Interaction Regions
- High field magnet challenges
- Summary

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[//doi.org/10.1142/9789811209604_0010]
Practical SC materials for SC magnets include appropriate critical parameters, their reproducibility in long lengths, mass production and affordable cost.

Boundaries are not fixed, they depend on superconductor and magnet technology costs.
Front End - Target & Capture Magnets

- **System functions**
  - Produce muons from protons on target
  - Prepare muon beams for the ionization cooling

- **20 T Capture Solenoid**
  - 15T SC outsert: ~2 m ID, 3 GJ, 100 t
  - 5 T Cu insert: ~0.3 m ID

- **Solenoid decay channel**
  - taper from 20 T to ~2.5 T

- **Technology**
  - Detector or fusion solenoids
    - CMS: 6 m ID, 4 T, 2.6 GJ
    - ITER CS: 0.6 m ID, 13 T, 6.4 GJ

- **Issues and challenges:**
  - Severe radiation environment
  - Possibility of using HTS for the insert
  - Large aperture-high field for Nb₃Sn
  - Continue DS to identify issues and develop solutions
Muon Cooling Systems

Muon Cooling

- Energy dissipation in materials with RF re-acceleration
- Operation in a solenoidal field
- Aperture reduces from ~1m to 50 mm

6D cooling
(a) HFOFO snake
(b) Guggenheim RFOFO
(c) helical cooling channel (shown without a large outer straight solenoid)
(d) rectilinear RFOFO

- $B_{op}$ range from 5 to 20 T
- Aperture range ~50-10 cm
- HTS magnets in 6D Cooling

Final Cooling:
- RF cavities between solenoids
- Bores ID of ~50 mm
- Cooling performance is proportional to $B$
- Ideal range 50-60 T
  - >30T acceptable

V.V. Kashikhin et al., MT
Cooling channel technology development

Issues and challenges:

- High fields
- Possibility of using HTS for the insert
- Large-aperture high-field for Nb$_3$Sn
- Use of accelerator magnet technologies

400-mm 4 T Nb-Ti 4-coil and 50-mm YBCO HS models

4 Double Pancake YBCO insert coils

World Record 32 T LTS-HTS Hybrid Solenoid (NHFML)
Acceleration: Fast Ramping HTS Magnets

• Present baseline - Rapid Cycling Synchrotron
  – magnets operating at ~400 Hz with $B_{\text{max}} > 1.5$ T
• $\text{dB/dt} = 289$ T/s with field amplitude ~0.5 T has been demonstrated using HTS dipole model (H. Piekarz, 2021)
• Next step – increase $B_{\text{max}}$ and $\text{dB/dt}$, study magnet and system limits
• Higher field amplitude – iron free (warm iron) designs

For the 10 T DC dipoles - see section SR and IR magnets below
Muon Collider SR and IR

- MAP Optics Designs for
  - 1.5 TeV CoM
  - 3.0 TeV CoM => 6.0 TeV CoM
  - Higgs Factory (125 GeV CoM)

- Magnet Characteristics
  - Higher B is better, MC luminosity $\propto B_{\text{dipole}}$
  - Large apertures to accommodate thick shielding around beam
  - IR combined function magnets to mitigate $\nu$ radiation

- High fields required for MC call for advanced accelerator magnet technologies beyond traditional Nb-Ti magnets limited to $B_{\text{op}} \sim 8$ T

- Nb$_3$Sn magnets – *baseline approach*
  - $B_{\text{nom}}=10$ T
  - large operation margin >20%
  - mature magnet technology ($B_{\text{op}}<12$ T) thanks to GARD and LARP work during past two decades

- Conductor – *present technology limit*
  - 1 mm high-$J_c$ Nb$_3$Sn strand
  - wide 40-42 strand Rutherford cables
1.5 TeV MC: Arc and IR Magnets

- **Arc magnets**
  - 20 mm $\times$ 10 mm beam aperture
  - Open mid-plane 10T D and large-aperture 200 T/m Q
    - relatively low operation margin ~12%
    - good field quality only in ~30% of coil aperture
    - large dynamic heat load in D ~25 W/m (~5% level)

- **IR magnets**
  - $B_{op}$=8 T (D), $B_{op}$~11 T (Q)
  - $B_{des}$=14-15 T with 2-layer coils
  - 20-30% (Q) and 45% (D) operation margin

- **W masks and inner absorbers**

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Q1, 80 mm  Q2, 110 mm  Q3-5, 160 mm  B1, 160 mm

Open mid-plane in D does not work well

Novitski et al., TAS 2011

V.V. Kashikhin et al., IPAC2012
3 TeV MC: Arc and IR Magnets

• Arc magnets
  – 150 mm aperture D and combined Q/D
  – Elliptical liner with shifted 56 mm × 26 mm bore
  – $B_{\text{op}}=10.4$ T with ~30% margin at 4.5 K => 2-layer coils
  – $B_{\text{op}}$~8-9T and $G_{\text{op}}$~80T/m with ~20% margin ($B_{\text{coil}}$ ~18 T) at 4.5 K => nested Q/D with 4-layer coils

• IR magnets
  – $B_{\text{op}}$=8 T (D), $B_{\text{op}}$~11 T (Q)
  – Aperture 80-180 mm
  – $B_{\text{des}}$=14-15 T with 2-layer coils
  – 20-30% (Q) and 45% (D) operation margin

• Tungsten masks and inner absorbers
125 GeV HF: CCS, MS, Arc and IR Magnets

- **CCS, MS and Arc magnets**
  - Coil ID 160 mm (Arc) and 270 mm (MS, CCS)
  - $B_{op}=10$ T with ~30% margin at 4.5 K ($B_{max} \sim 14$ T) with 2-layer $D$ coils
  - $G_{op} \sim 36$ T/m with ~60-80% margin at 4.5 K ($max \, B_{coil} \sim 15$ T) with 2-layer $Q$ coils

- **IR magnets**
  - IR magnet aperture is large 320-500 mm (!)
  - $B_{des} \sim 17-18$ T requires 6-layer coils for quench protection and to limit maximum coil stress
  - 20-50% operation margin in IR magnets

- **W masks and inner absorbers**

N.V. Mokhov et al., ArXiv, JINST, 2018
Nb$_3$Sn Magnet model R&D

- **R&D issues:** mechanical structure, quench performance, field quality, quench protection, etc.
Stress Management needed

- **Stress management on the coil level is critical**
  - synergy with MDP on SMCT technology development and demonstration
Stress Management for high-field large-aperture magnets

- **US-MDP 120 mm ID 12-15 T dipole demonstrators with Nb₃Sn SMCT coils**
  - results in 3-4 years

**Design studies**

**Technology development**


I. Novitski et al, MT-27.
Higher Field Magnets

- Higher fields in MC SR => higher $L$ or lower Proton Driver power
- Magnet target parameters:
  - $B_{op}=15-20$ T ($B_{max}\sim14.5$ T Fresca2 and MDPCT1, aperture 60-100 mm)
  - 20% margin => $B_{des}=18-25$ T !!!
- 15-20 T magnet issues
  - Large stored energy and Lorentz forces => Quench protection and stress management
  - Cost ~ coil width)
- Magnet R&D directions
  - Increase $\text{Nb}_3\text{Sn}$ and HTS conductor $J_E$
  - Develop high-current $\text{Nb}_3\text{Sn}$ and HTS cables
  - Solve stress management and quench protection problems
  - Demonstrate quench performance and field quality for large-aperture $\text{Nb}_3\text{Sn}$ and HTS magnets
Summary

- Front end: 20 T solenoid – detector or fusion technology, design studies
- Magnet cooling – 50 T solenoid
- Acceleration – fast cycling dipole, increase B and f
- Magnet studies for 0.125, 1.5 and 3 TeV MC SR are complete by MAP
  - SR and IR magnets for 6 TeV machine – *small extension of the 3 TeV concepts*
- 10 T Nb$_3$Sn magnets – *MAP baseline approach*
  - magnet technology is *available* from LARP-HL-LHC and MDP
  - *focused R&D* for large-aperture Nb$_3$Sn dipoles and nested Q/D
- Higher field magnets
  - 15 T Nb$_3$Sn magnets with coil ID~20(40) cm, B$_{des}$~18 T – *new class of Nb$_3$Sn accelerator magnets with stress management*
  - 20 T HTS/LTS magnets (10 T HTS insert) with ~20 cm bore, B$_{des}$$>$25 T – *new magnet technology based on HTS => significant R&D effort is needed***