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# **Overview on Magnetic Field Management and Shielding in High Q Modules**

Genfa Wu SRF 2015 September 17th, 2015

## Outline

- Magnetic Field Sources
  - Ambient earth field
  - Remnant field from components
  - Thermal electrically induced field
- Magnetic Flux Trapping and Cavity Surface Resistance

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- Design Requirements (Q related)
- Solution
  - Shielding
    - Shielding Material Properties
    - Design
  - Magnetic Hygiene Procedure
  - Fast Cool Down and Flux Expulsion
- Summaries

# What are the sources of magnetic field ?



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#### **Magnetic Sources – Earth Magnetic Field**



LCLS-II tunnel direction is not ideal, not terrible either. (21<sup>o</sup> from the ideal orientation)

Bz = 500 mG \* cos (69-deg) \* cos (60-deg) = 89 mG

US/UK World Magnetic Model -- Epoch 2010.0 Main Field Total Intensity (F)

#### Axial magnetic field is the main focus of the shielding



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#### Magnetic Sources – SLAC Tunnel Wall (Bz)



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### **Magnetic Sources – Cryomodule Components**

- Tuners
- Couplers
- Metal pipes (Helium two phase pipe, GHRP)
- Supports
- Assembly hardware

One example:

6

1. A piezo bearing ball was highly magnetic due to presence of Co. (> 3 G on contact, >200 mG at the cavity)

- 2. It can be de-magnetized to < 5 mG at the cavity
- 3. It is now switched to ceramic



#### Magnetic Hygiene is a must for high Q cavities



#### **Thermal Electromagnetic Field**

• Thermal current induced field is a transient field



This thermal current field can be expelled before complete transition

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Magnetic field needs to be minimized near cavity. How small does it need to be ?



# **Magnetic Flux Trapping and Cavity Surface Resistance**



TABLE I. Cool-downs summary and associated measured residual resistance.

#### The worst case scenario 3-4 mG maximum.

M. Martinello, et al., J. Appl. Phys. 118, 044505 (2015)

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#### **Design Requirement**

- Determined by Q requirement
- Average effect
- May be higher in certain cavity location
- Numbers apply during cavity SC transition

	Average B Field	Q <sub>0</sub>
LCLS-II	< 5 mG	2.7 e10
Cornell ERL	A few mG	2.0 e10
KEK cERL	< 10 mG	1.0 e10
DESY XFEL	< 25 mG	1.0 e10
FRIB	< 15 mG	1-8 e9

 $R_{s} = R_{bcs} + R (H_{ext}) + R_{0}$ 

LCLS-II assumes an average surface resistance R<sub>0</sub>



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How do we achieve such low residual magnetic field ?

- Magnetic shielding
- Magnetic hygiene
- Flux expulsion



## **Magnetic Shielding Engineering Solutions**

- Material Selection
- Global Shield
- Local Shield
  - Layer choices
- Inside and Outside of Helium Vessel
- Active Cancellation
- Magnetic Foil Wrap





#### **Material Properties**

- Large selection of materials
  - Various heat treatment recipes
  - Different material compositions
  - Form factors

Conservative Permeability Design Value ~ 10,000 – 12,000



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## **Engineering Solutions – FRIB**

- Specification
  - Ambient magnetic field < 15 mG</li>
  - Saturation Field ~250 G
- Local Shield
  - Single layer, 1-mm (QWR), 2.2 mm (HWR)
  - A4K or Amumetal (mu > 10,000 @500mG @20K)



FRIB QWR Cryomodule Magnetic Shielding

Courtesy of K. Saito



## **Engineering Solutions – FRIB**

- ReA6-1 Cryomodule Test
  - Local magnetic field on the vessel
    ~ 2 G (on contact)
  - Steel vessel attenuates by a factor of ~2.
  - Residual magnetic field  $\leq$  3 mG









Courtesy of K. Saito

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S. K. Chandrasekeran, TUPB102, SRF 2015

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## **Engineering Solutions – Cornell ERL**

- Main linac cavity Q0 ~ 2e10@16MV/m
- Magnetic field as low as possible ( B < a few mG at cavities)
- Two layers of magnetic shield for injector cryomodule
  - Global magnetic shield outside of thermal shield (0.5 mm A4K, 40/80K)
  - Local cryogenic magnetic shield outside of helium vessel (1mm A4K, 2K)
  - Stainless steel vacuum vessel
- Three layers of magnetic shield for main linac cryomodule
  - Global magnetic shield outside of thermal shield (0.5 mm A4K, 40/80K)
  - Local cryogenic magnetic shield outside of helium vessel (1mm A4K, 2K)
  - Carbon steel vacuum vessel, not demagnetized



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### **Engineering Solutions – Cornell ERL**

 ERL injector cryomodule demonstrated residual B field <3 mG (at room temperature)</li>





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## **Engineering Solutions – Cornell ERL**

- ERL main linac cryomodule magnetic shielding
  - Attenuation factor ~10 for Bz.
  - Inner shield showed negligible internal B field upon receiving.
  - With other cryomodule components included, ambient B field is expected to be ~1 mG.
  - Cool down test soon.



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## Magnetic Shield for cERL Main Linac cavity system



Magnetic shield (Cryophy, 1.57 mm thickness)



The shape of the shield was decided to be square, rather than cylindrical to simplify the alignment & to avoid any mechanical stress added while bending.



#### Simulation

- Using the permeability data obtained @ LHe temp.
- Average magnetic field inside the cavities is less than 10 mG, which satisfies the requirement.
- Locations near various holes for couplers and so on show weak shielding(Max. being 18mG).



## **Engineering Solutions – LCLS-II**

- No Global Shield
- Local Shield
  - Two layers with end caps that enclose the HOM couplers, FPC 2K flange and beam pipes
  - Inner surface of the shield is electrically isolated using g-10 support bars, that disrupts thermal current as much as possible.
  - METGLAS foil (10 layer) covers and minimizes open ports, extends the port covering. (Poster: **TUPB099**)
- Active cancellation
  - To reduce the longitudinal magnetic field component that is present despite of double layer and endcaps. (due to the geometric factor of long cylinders of magnetic shield)
  - Serves as an insurance policy in case of a high magnetic field was present and fast cool down cannot effectively expel magnetic field in a cryomodule
  - Provides possible demagnetization option in case the vacuum vessel becomes magnetized again after cryomodule is tested.



#### **Engineering Solutions – LCLS-II Magnetic Shield Design**

- Magnetic Shielding for the pCM is CryoPerm 10.
- The baseline permeability is >12,000@45K.
- Design allows the access to tuner motor and piezos.





## The Challenge of Longitudinal B field and Edge Effect

- Geometric factor limits the attenuation of longitudinal B field
  - Longitudinal Field
  - Edge Effect



A.C. Crawford, http://arxiv.org/abs/1507.06582

S : attenuation factor

$$\begin{split} S_{\perp} &\simeq \frac{\mu \cdot d}{D} + 1 \\ S_{\parallel} &\simeq \frac{4N(S_{\perp} - 1)}{1 + D/2L} \text{ closed cylinder} \\ S_{\parallel} &\simeq 4NS_{\perp} \text{ open cylinder} \end{split}$$



http://tesla.desy.de/TTF\_Report/CDR/pdf/cdr\_chap4.pdf

Shield unit couples with neighboring units. Active cancellation helps reduce Bz.



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How do we achieve such low residual magnetic field ?

- Magnetic shielding
- Magnetic hygiene
- Flux expulsion



## **Magnetic Hygiene Solutions – LCLS-II**

- Permeability is not enforced
  - Any tool that measures permeability will magnetize the components inadvertently. De-magnetization may not be cost effective for many parts.
  - Permeability measurement is intrinsically inaccurate for non flat and irregular surfaces.
- Remnant Field
  - Measurement is done for all components that is within 3-in distance from cavity.
  - Measurement is done at contact and 1-in distance.
  - Working specification is provided for parts screening
- Demagnetization
  - Parts will be demagnetized or rejected based on the value and demagnetization labor cost. ( Be careful with the tools )
  - Demagnetization of vacuum vessels
  - Demagnetization of assembled cryomodules

Technical Division Controlled Document:

464233 - REV 1 - Specification and Measurement Procedures of Magnetic Properties of Parts for LCLS II Cryomodule Assembly

# Magnetic Hygiene Solutions – LCLS-II

- Demagnetization of vacuum vessel
  - Internal magnetic field was greatly reduced.



#### Carbon steel vacuum vessel may have strong remnant field

A. C. Crawford, http://arxiv.org/abs/1409.0828

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## **Magnetic Hygiene Solutions – LCLS-II**

- Demagnetization of a mock up cryomodule
- Invar rod and/or magnetic shield had some remnant field
- Combining cancelation coil and cryomodule demagnetization, the magnetic shield can meet the requirement any moment in a cryomodule life time

A.C. Crawford, http://arxiv.org/abs/1507.06582



#### Cryomodule demagnetization is feasible and effective

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#### **Flux Expulsion**



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#### Flux Expulsion during Fast Cool Down

• Movie was removed to reduce the size



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#### Flux Expulsion during Fast Cool Down



Excellent cool down. Cell #1  $\Delta$ T = 8K Cell #5  $\Delta$ T = 20K Cell #9  $\Delta$ T = 15K

#### Large thermal gradients were achieved

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#### Successful Magnetic Field Management Demonstrated



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#### Summary

- A magnetic shield design combined with passive and active shield can realize a minimum remnant magnetic field during cavity superconducting transition.
- A comprehensive magnetic hygiene plan can prevent high field component being close to cavity
- Fast cool down can be effective as demonstrated in horizontal test.
- Fast cool down from 45K in a cryomodule will be tested when a pCM is tested.



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