Pursuing the Origin and Remediation of Low Q_0 observed in the Original CEBAF Cryomodules

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Outline

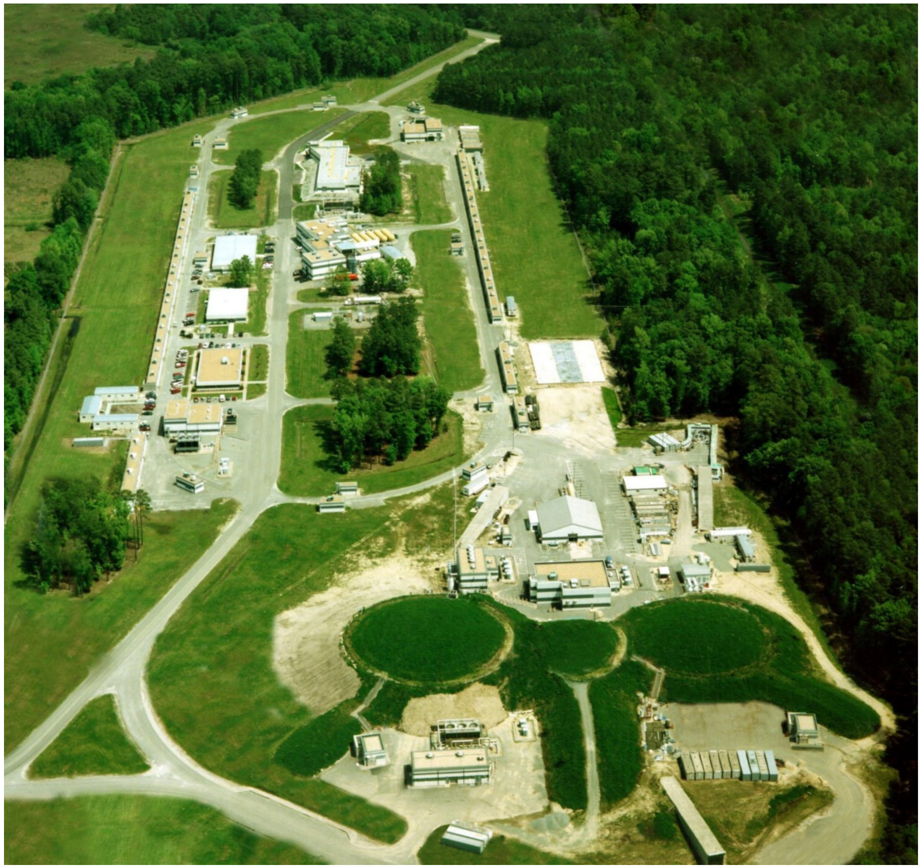
- Introduction
- Low Q_0 issue and prior effort
- New effort
- Results and outlook
- Conclusion

Introduction

CEBAF: Continuous Electron Beam Accelerator Facility

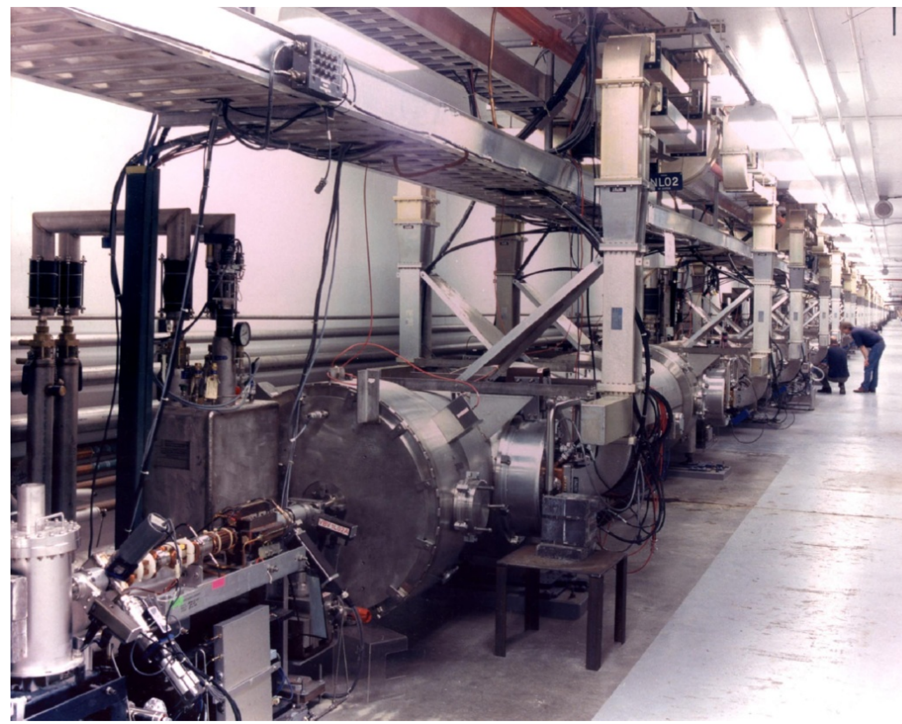
Basic research of atoms's nucleus

Construction 1987-1993
Currently being upgraded



First large-scale application of SRF linac technology

The same SRF technology plus Energy Recovery Linac technology used for JLab's Free Electron Laser



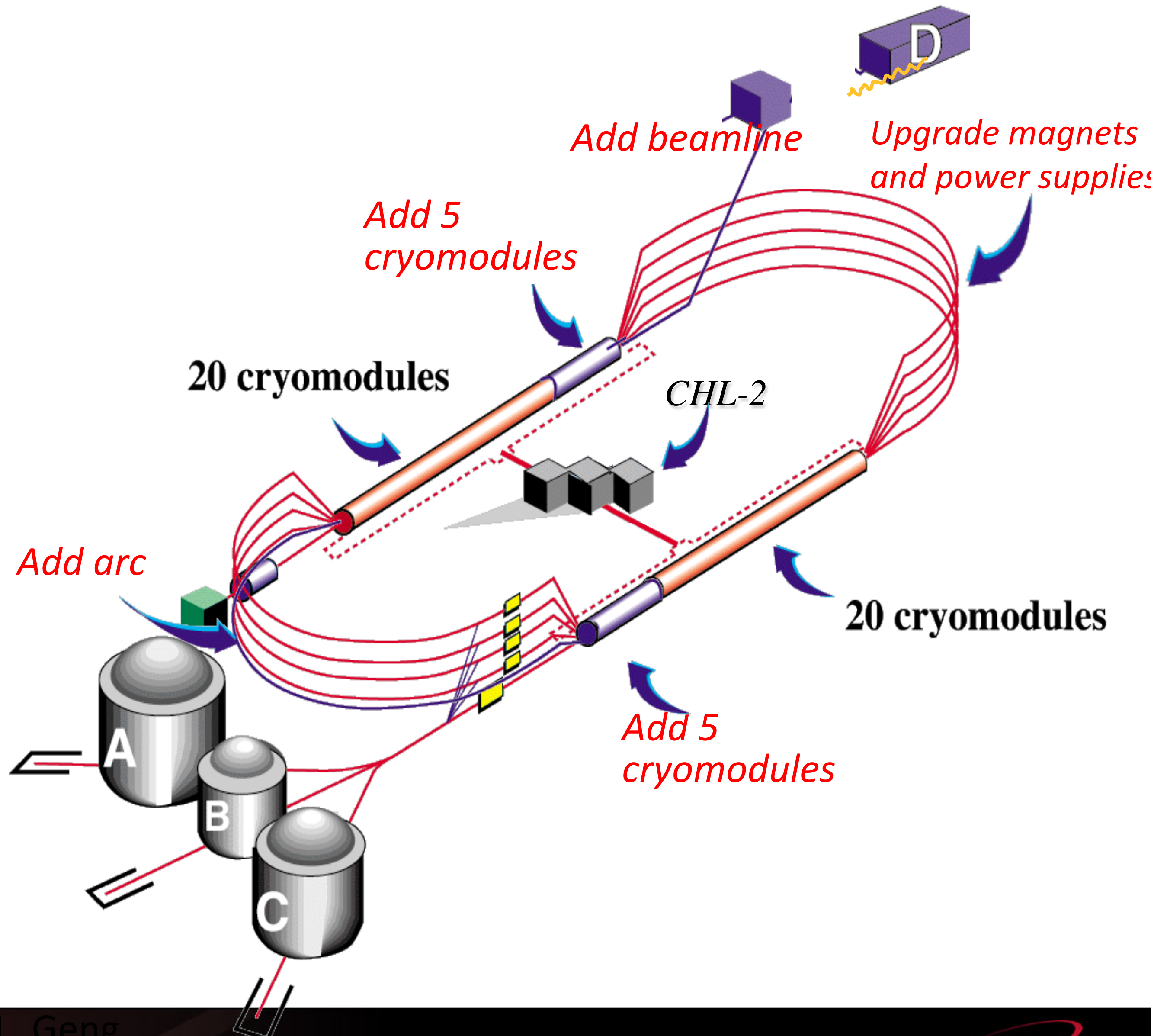
CEBAF Evolution

2.2 GeV per pass acceleration achieved in Feb 2014
10.5 GeV 5.5 pass beam achieved in May 2014

2011 – present
12 GeV Upgrade
Two 1.1 GeV linacs

1995 - 2011
6 GeV improvement
Two 0.6 GeV linacs

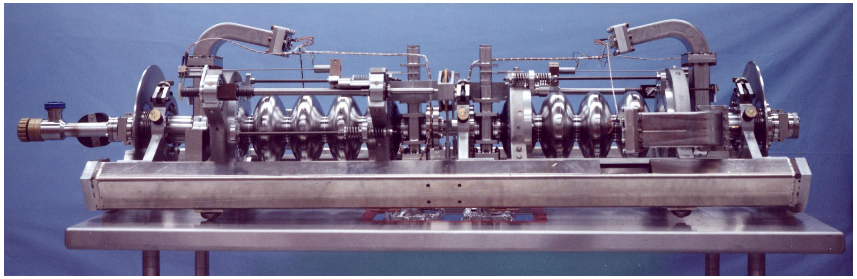
1987 - 1994
4 GeV, 200 μA CW
Two 0.4 GeV linacs



CEBAF SRF Cavities

Together for 12 GeV nuclear physics run

Original CEBAF cavity



- 5-cell, Cornell-Type
- 338 cavities in 42-1/4 moduels
- Design
  - Ea=5 MV/m
  - Q_0=2.4×10^9 @ 5 MV/m
- Achieved
  - <Ea>=7.5 MV/m, <Q_0>=5×10^9@ 5MV/m
  - Helium processing
- Achived
  - <Ea>=12.5 MV/m, <Q_0>=5×10^9@ 5MV/m
  - Refurbishing
- 2x 600 MV
- 5 kW 2K cooling power
- 5 MW liquefier operation power

CEBAF upgrade cavity

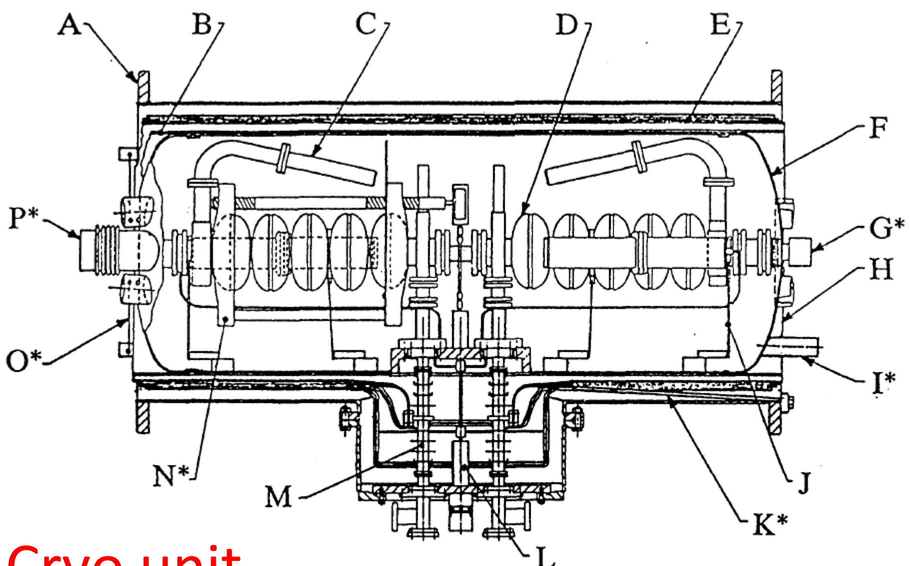
- 7-cell, Low-Loss Shape
- 80 cavities in 10 moduels
- Design
  - Ea=19.2 MV/m
  - Q_0=7.2×10^9 @ 19.2 MV/m
- Achieved
  - <Ea>=22.2 MV/m
  - <Q0 @ 19.2 MV/m>=8.1×10^9
- 2x (600 + 500) MV
- Add ~5 kW 2K cooling power
- Add ~ 5 MW liquefier operation power

Low Q_0 issue and Prior Effort

Original Cavity and Cryomodule

	Design	Vertical testing	Cryomodule testing
<Eacc>	5	>5	>5
Q_0 at 2K at 5 MV/m	2.4×10^9	~ 1×10^{10}	~ 5×10^9

Factor of 2 loss in Q_0



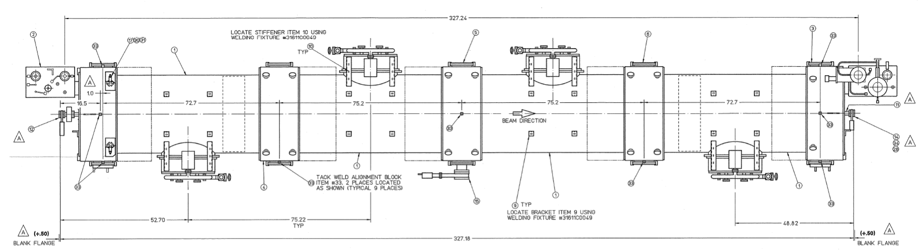
Cryo unit

A. Vacuum Shell Flange
B. Magnetic Shield and Inner Superinsulation
C. HOM Load
D. Cavity
E. Shield Superinsulation
F. Helium Vessel
G. Flange Surface on Isolation Valve
H. 40 to 50 K Radiation Shield
I. Shield Helium Supply Line
J. Outboard Cavity Support
K. Axial Support
L. Rotary Feedthrough
M. Fundamental Power Waveguide
N. Tuning Mechanism
O. Helium Vessel Support Rod
P. 2 K Helium Return

*Asterisked items shown only once to simplify illustration.

Cavity performance spec exceeded !

A factor of 2 loss in Q_0 observed from vertical testing to cryomodule testing ?



4x cryo unit -> cryomodule (8.25 m long)

Unloaded Quality Factor Q_0

$$P_c = \frac{V^2}{\frac{R}{Q} \cdot Q_0}$$

P_c: power dissipation per cavity >>> cryogenic load
V: voltage per cavity
R/Q: determined by cavity shape

$$Q_0 = \frac{G}{R_s}$$

G: determined by cavity shape
R_s: surface resistance (material property)

$$R_s = R_{BCS} + R_{res}$$

R_{BCS}: BCS resistance
$R_{res:}$ Residual resistance

Q_0 can be lowered by extrinsic factors such as field emission

Residual Resistance

- Hydrogen in niobium
  - Hydride precipitation 50-150K >>> “Q-disease”
  - Mitigation
    - Fast cool down
    - Vacuum furnace outgassing
- Frozen flux effect
  - Ambient magnetic field
  - Magnetic component
  - Cryogenic thermal path

Prior Investigation - 1993

- Ambient magnetic field
- Cavity cool down rate
  - original cavities not vacuum furnace outgassed -> prone to “Q-disease”
- Coupler loss

No conclusive finding

W.J. Schneider et al., SRF’93

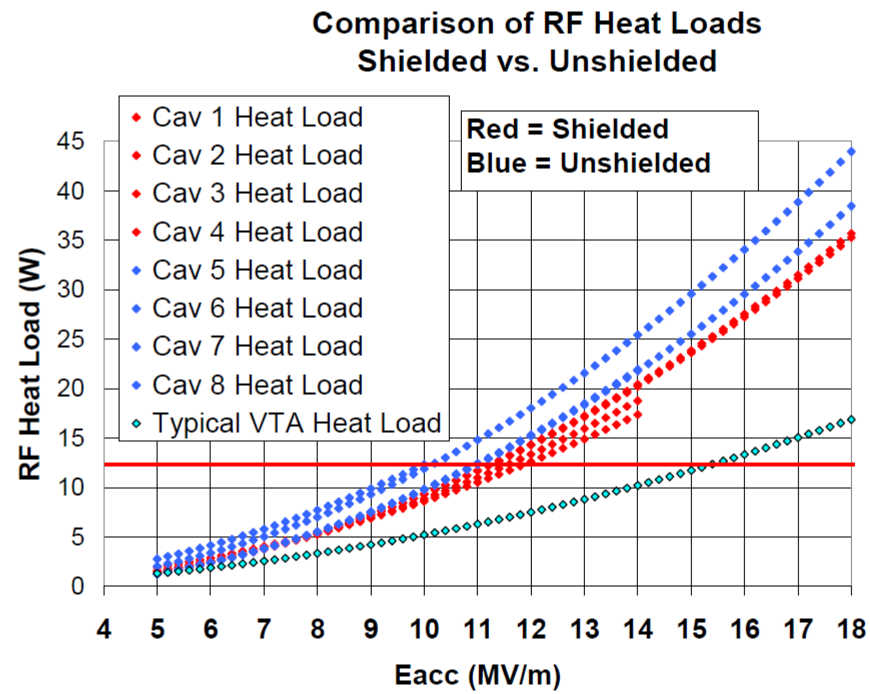
Prior Investigation: 2007-2009

- Cryomodule refurbished
  - 10 weakest modules
  - Goal:
    - Raise voltage for CEBAF energy reach
      - 20 -> 50 MV per module
    - Dynamic heat load budget
      - 100 W per module
    - Cavity performance goal
      - Eacc=12.5 MV/m
      - $Q_0 \geq 6.8\times10^9$ @ 12.5 MV/m at 2K
  - Modern-day processing
    - Vacuum furnace outgassing
      - remove hydrogen
    - HPR
      - reduce field emission

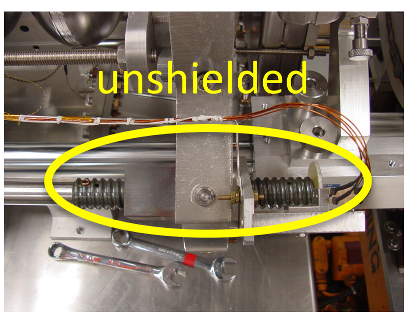
Photo credit: M. Mccrea/Leonard Page

Prior Investigation: 2007-2009

- Result from first 5 modules (C50-1…5)
  - Field emission reduced >>> higher gradient
  - Still a factor of 2 loss in Q_0!!!
- Renewed investigation
  - Identification of magnetized ball-screw
  - Mitigation in C50-6
    - wrap magnetic shielding around ball-screw
  - Inner magnetic shielding explored in C50-8
- None of 80 refurbished cavities met the set Q_0 goal at 12.5 MV/m at 2K



M. Drury et al., LINAC'08



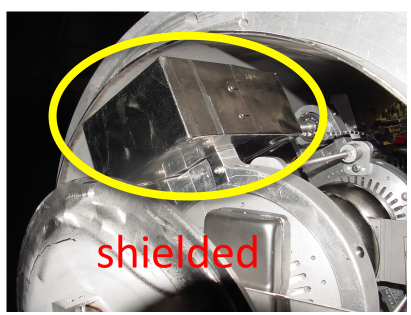


Photo credit: M. Mccrea/Leonard Page

Some improvement due to ball-screw shielding – but insufficient

Encouraging step forward

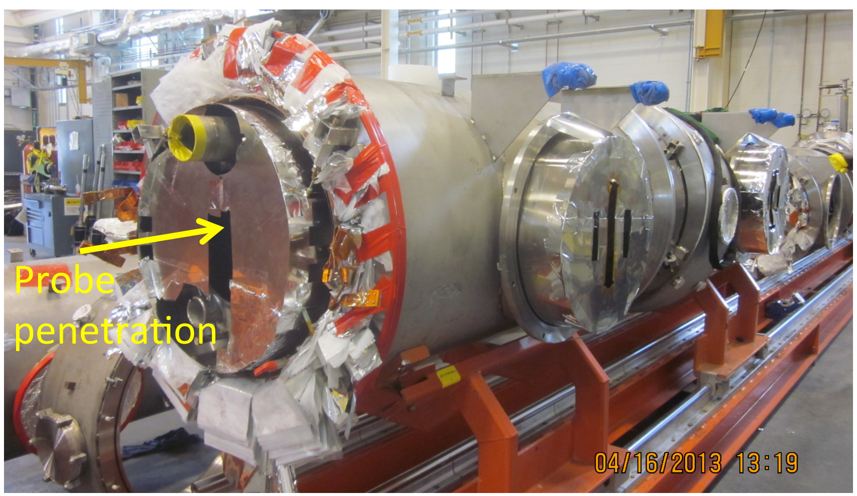
New Effort

New Effort: 2013

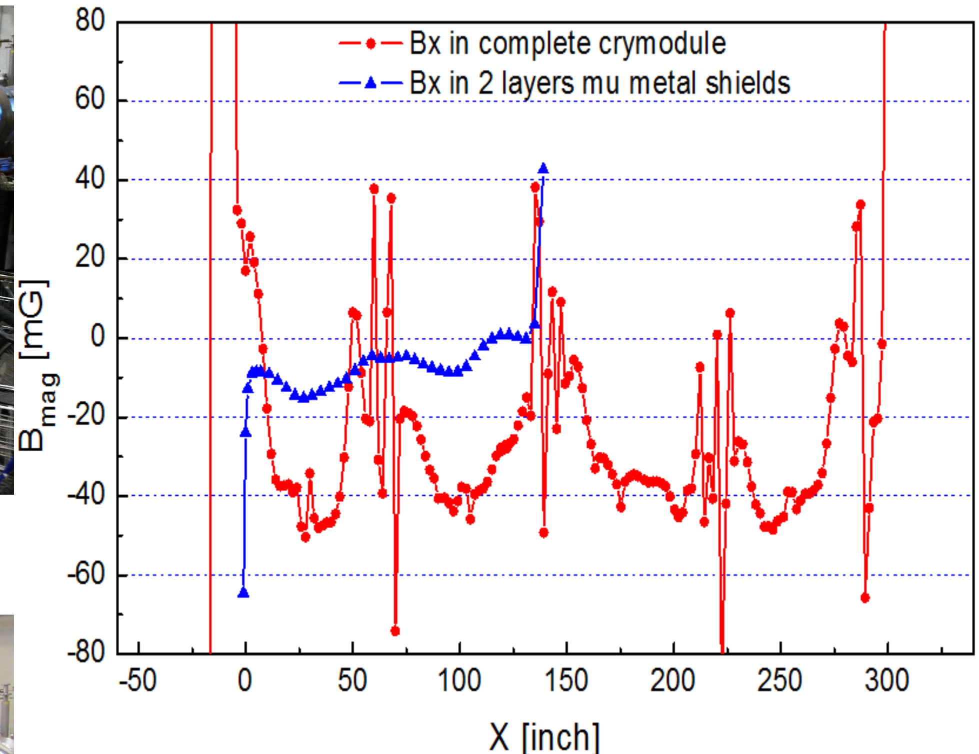
- Latest cryomodule refurbishment
  - Cryomodule pulled out from 9th slot in south linac
  - In parallel to refurbishing activities, systematic studies of following issues:
    - Survey of the as-found cryomodule
    - Magnetic properties of all components contained inside He vessel
    - Shielding effect of the two layer magnetic shields
    - Ambient magnetic field at cryomodule slot in CEBAF tunnel
- Goal:
  - Understand clearly the origin of low Q_0
  - Develop mitigation
  - Implement mitigation where schedule permits

Survey of As-found Cryomodule

Near axis field under as-found condition over entire module

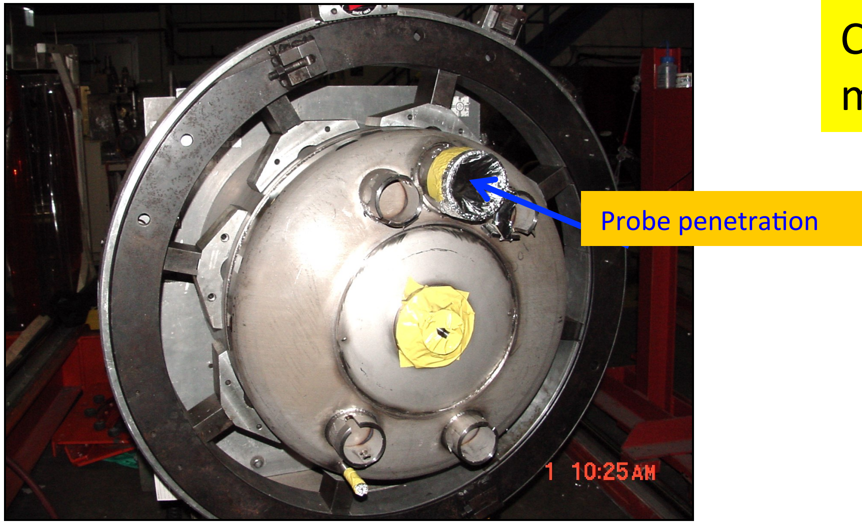


Re-measure after components inside He vessel removed

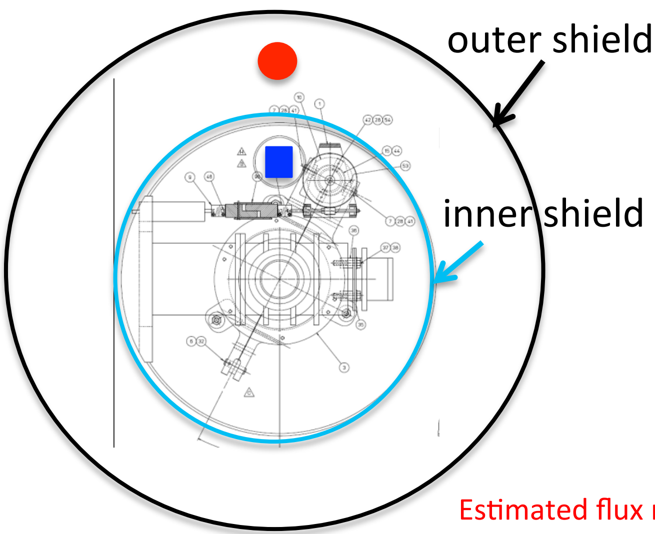


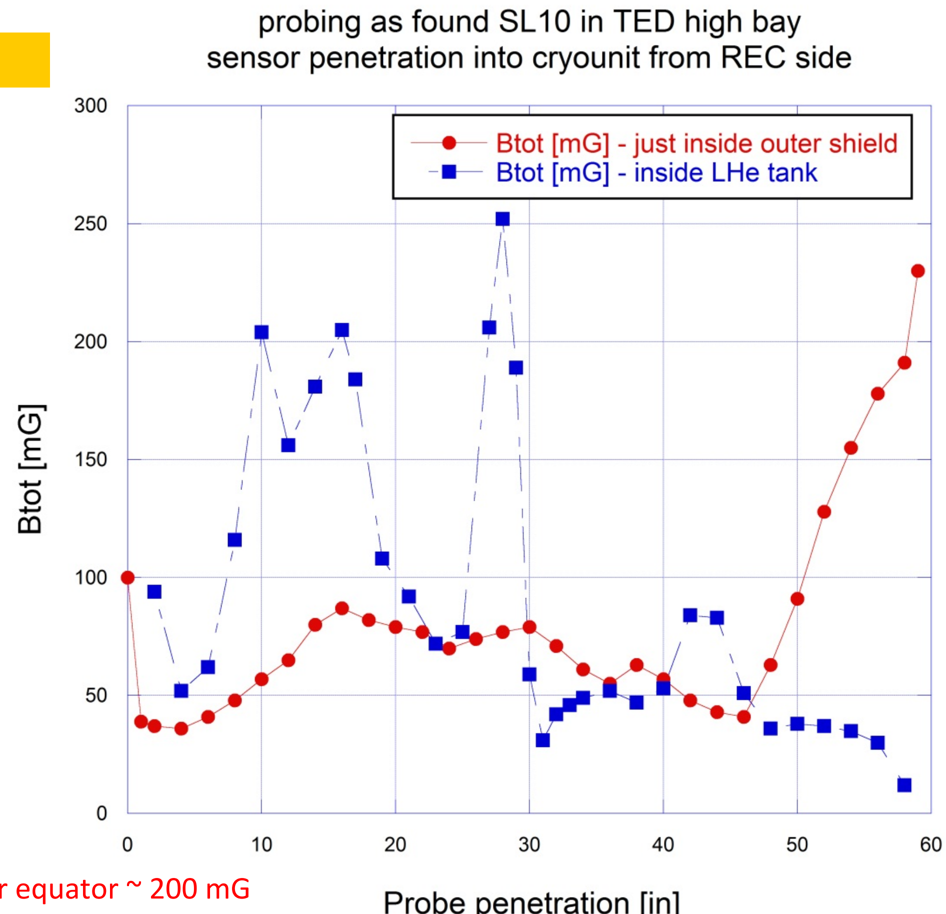
- Clear evidence of presence of magnetized components inside helium vessel
- Responsible for >70% of the measured flux

Additional Probing in As-Found Condition



Components inside LHe tank generating excessive magnetic field further confirmed





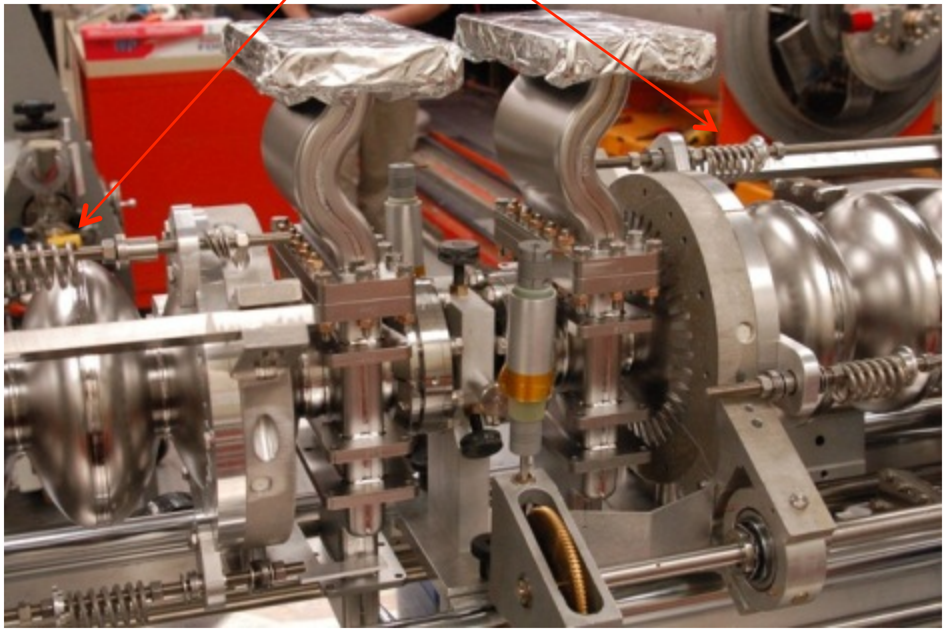
Estimated flux near equator ~ 200 mG
Compatible with observed Q_0 loss

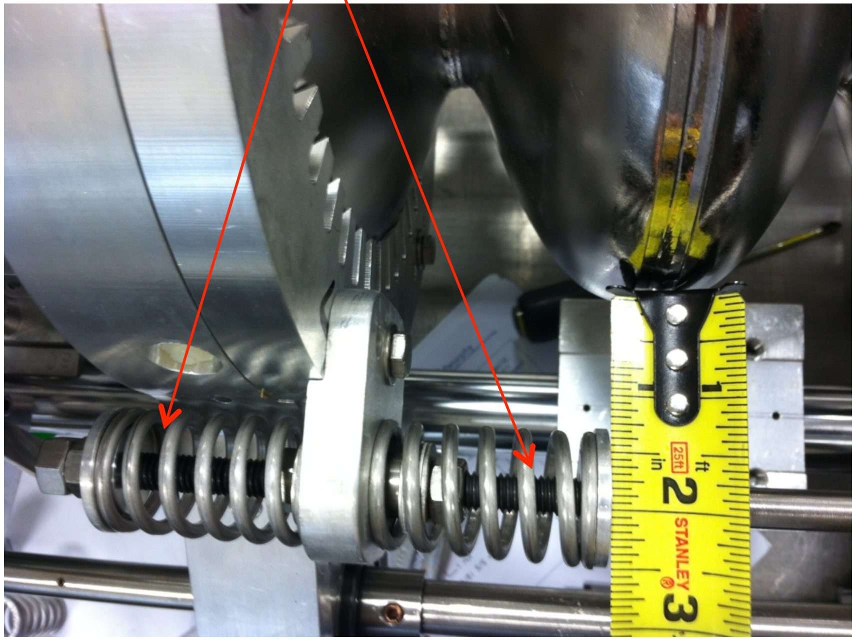
Discovery of Magnetized Strut Springs

High-μ and high remanent field springs from original module

mitigation

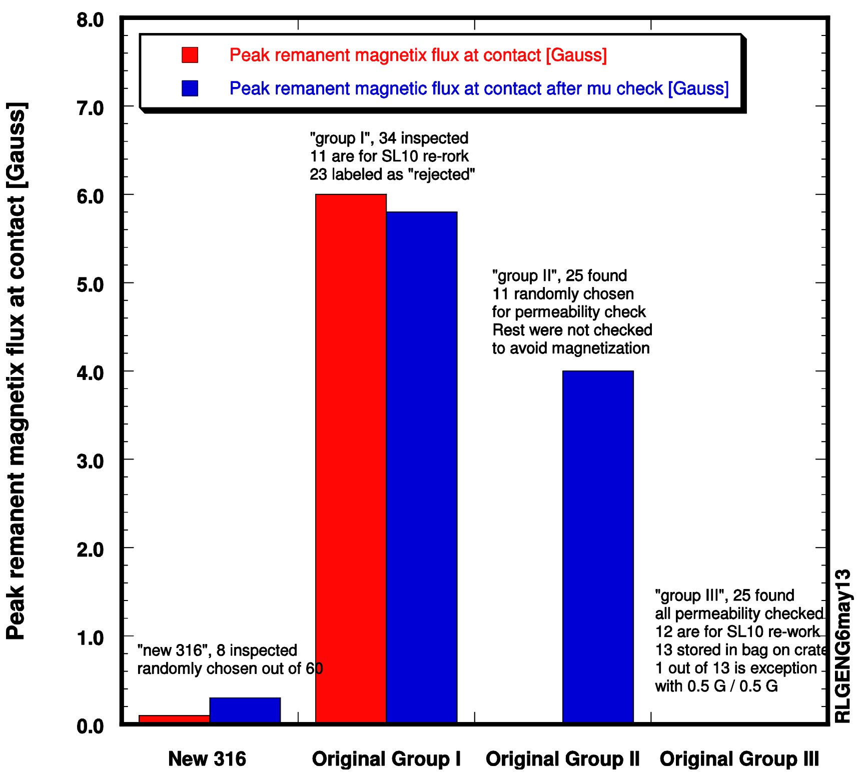
New low-μ and low remanent field Springs acquired and implemented



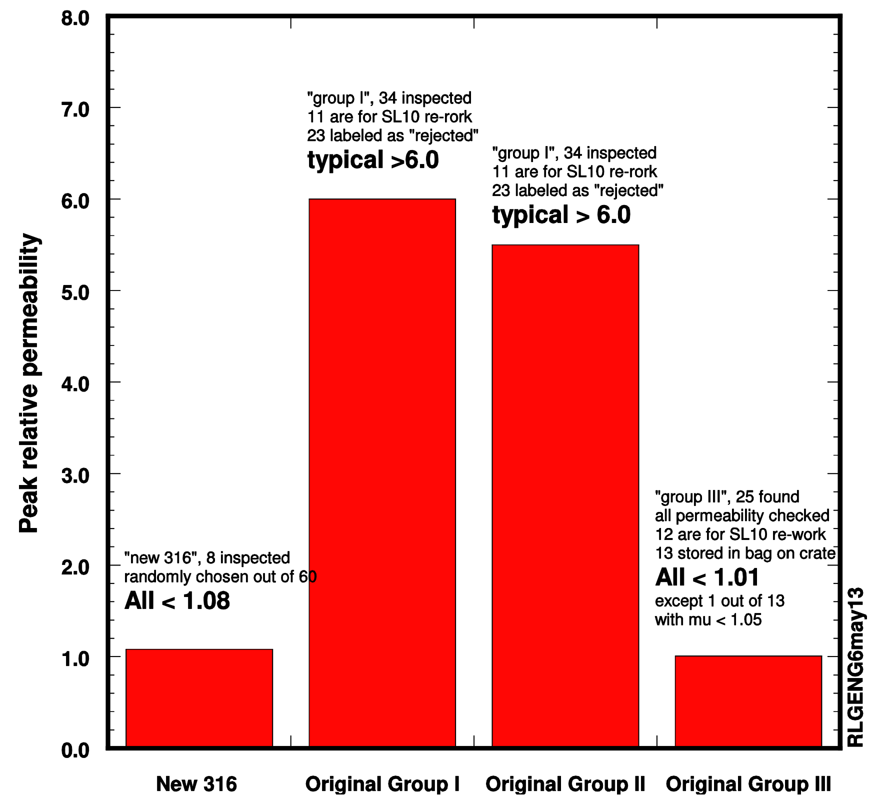


Comparison of New & Old Springs

Remanent magnetic flux density of 4 groups of strut springs

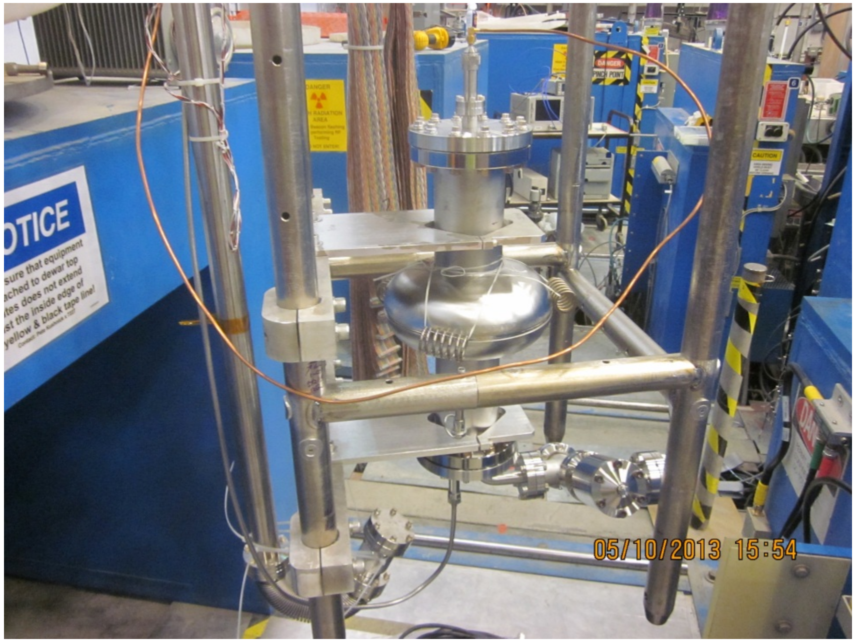


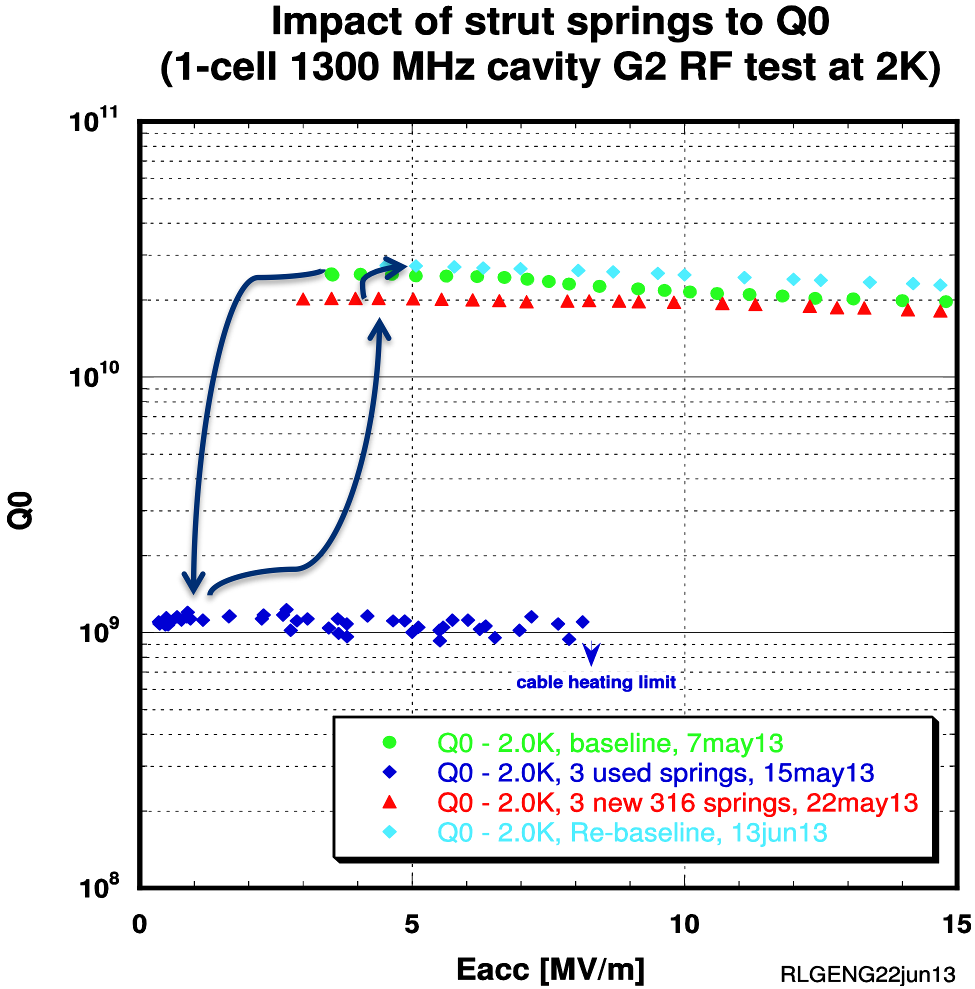
Peak magnetic permeability of 4 groups of strut springs



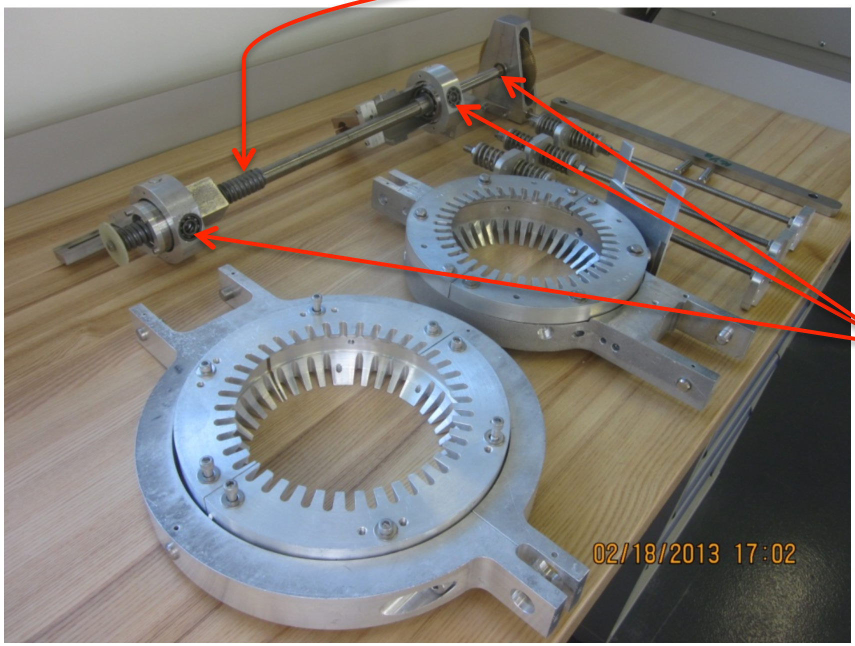
Further Assessment of Springs

New 316 springs far better !





2nd & 3rd Offending Components

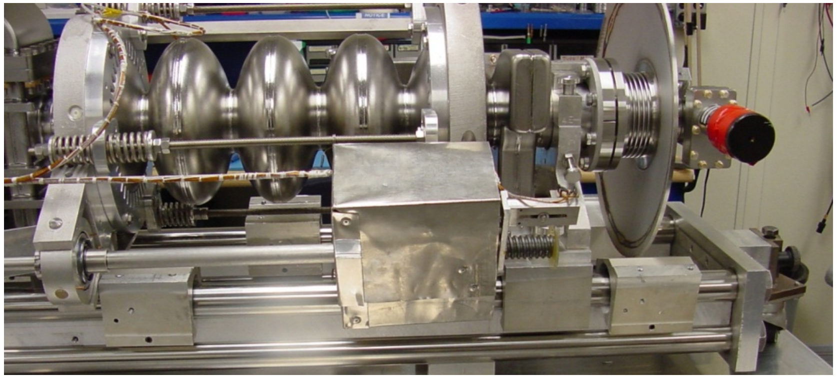


- Threaded rod
  - Bpk 1.7 G
  - High permeability
- Ball bearings of all sizes
  - Bpk 0.5 G
  - High permeability

Bpk: Peak remanent magnetic flux at contact

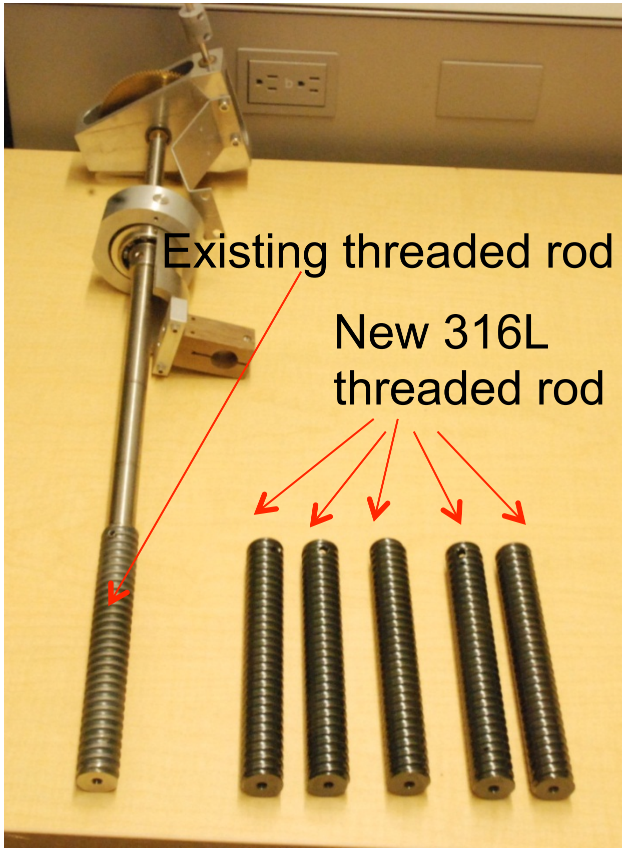
Mitigation of Magnetic Tuner Components

Shielding of ballscrew in earlier C50 modules
Result: visible but very small Q0 imporvement

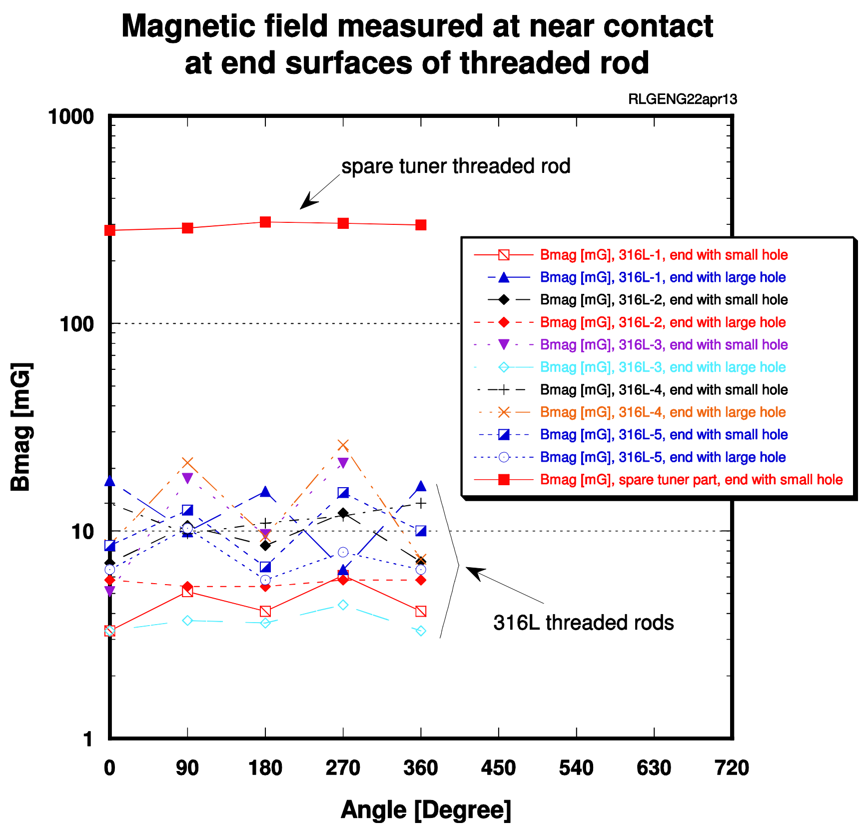


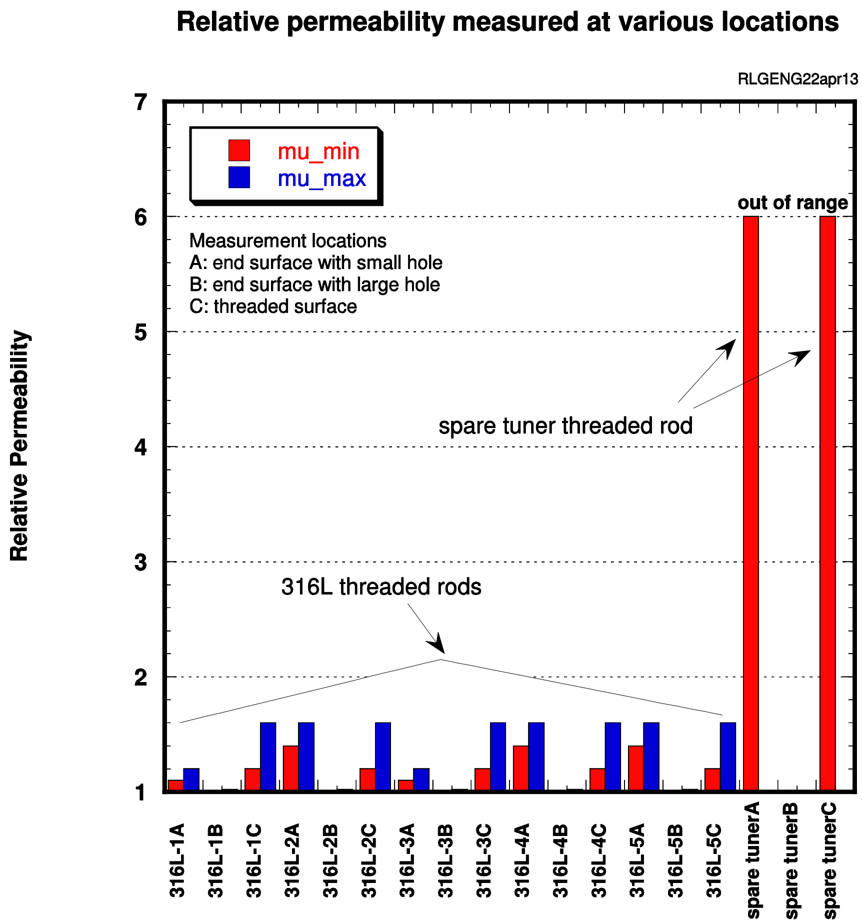
- Degauss the following tuner components
  - Threaded rod
  - Ball screw block
  - All ball bearing (including those in gear box)
- Practice "clean magnetic" handling practice after degaussing

New 316L threaded rod in hand

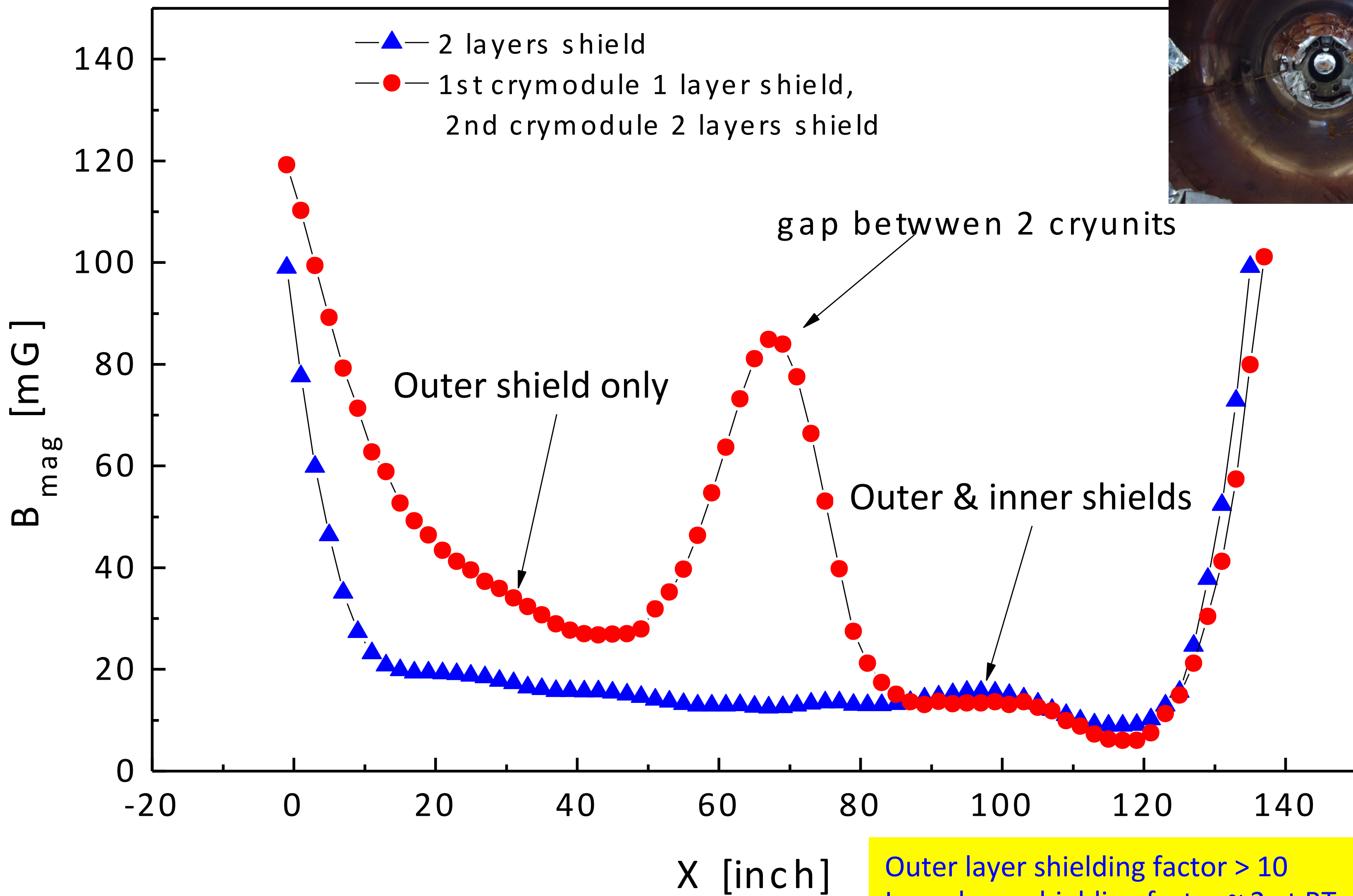


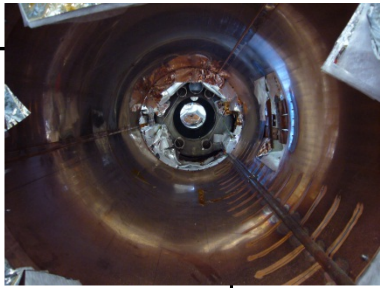
Comparison of New & Old Threaded Rods





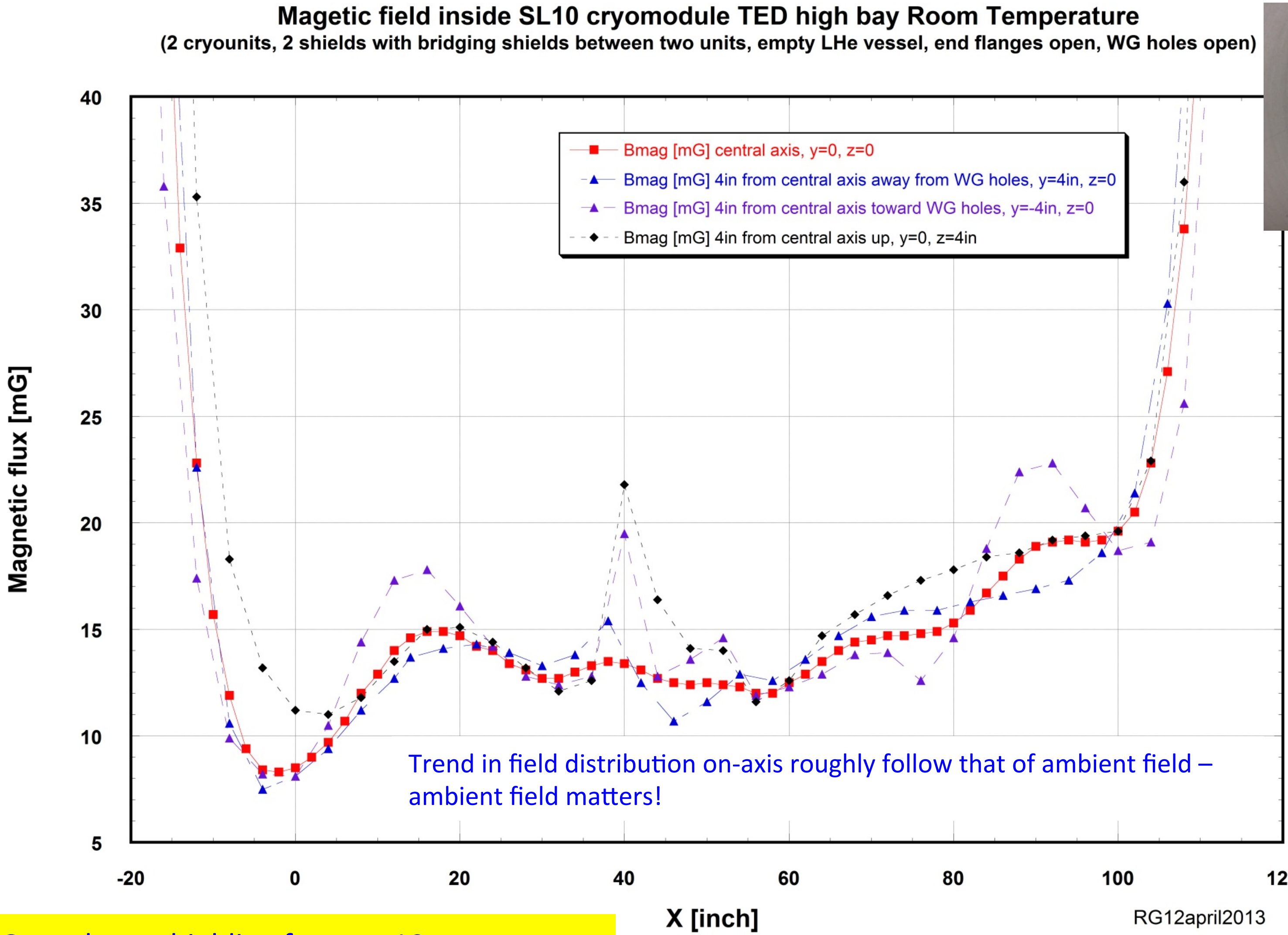
Preliminary Assessment of Magnetic Shields





Outer layer shielding factor > 10
Inner layer shielding factor ~ 2 at RT

Preliminary Assessment of Magnetic Shields

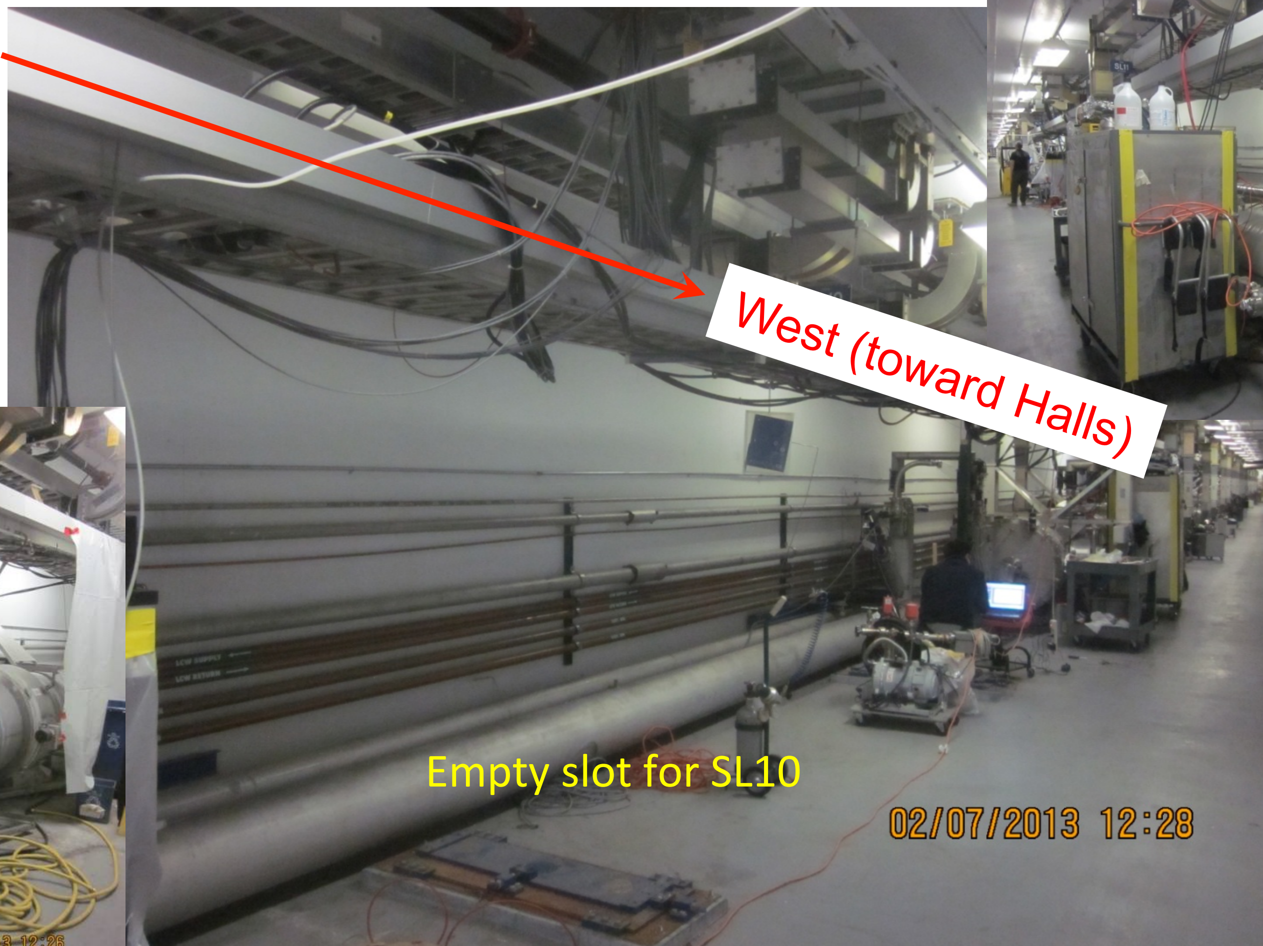


Trend in field distribution on-axis roughly follow that of ambient field – ambient field matters!

Outer layer shielding factor > 10
Inner layer shielding factor ~ 2 at RT

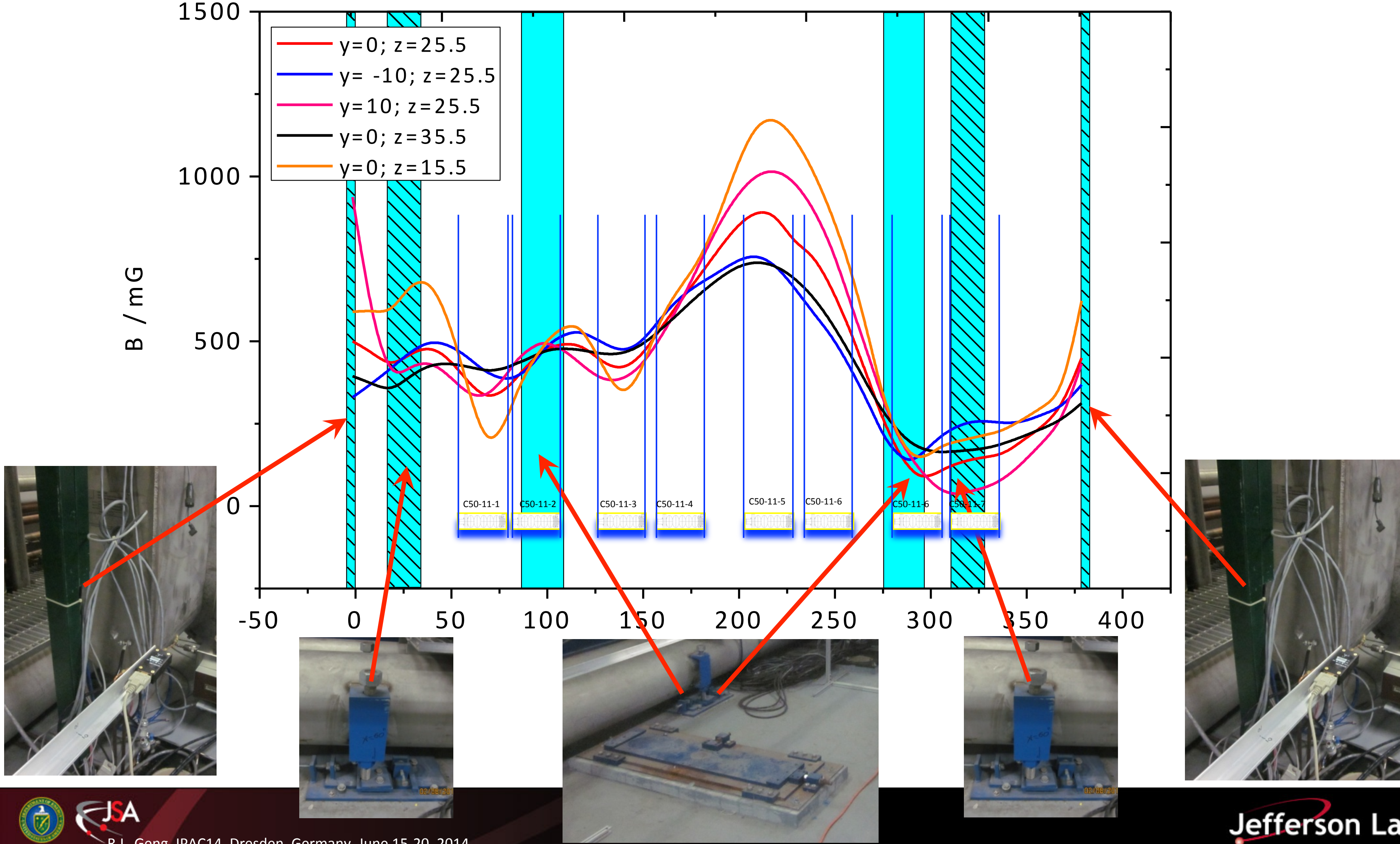
SL10 Ambient Magnetic Field Survey

February 7-8, 2013 in CEBAF Tunnel



SL10 Ambient Field Survey Results

Coordinate adjusted , Mid-point between SL9 and SL10 at x=0
X direction point to West, Y direction point to South; Z direction point upward



New Mitigation Procedure

(in order of precedence)

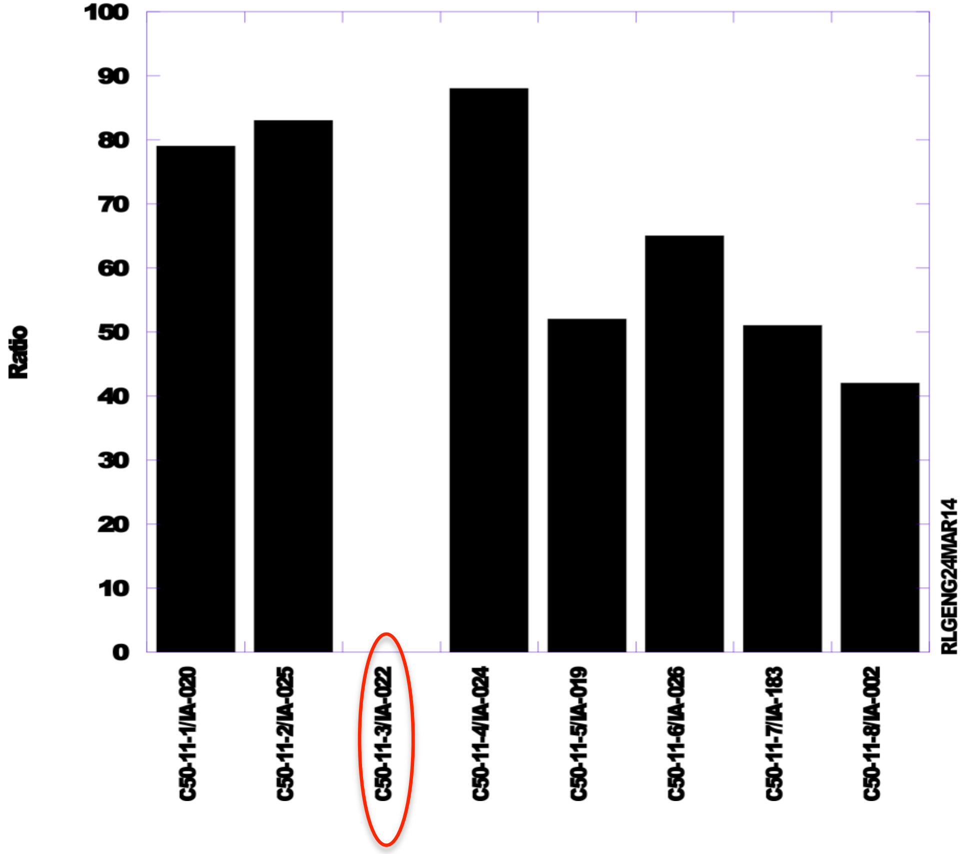
- Replace magnetized components inside He vessel
  - New 316 SS strut springs (implemented)
  - New 316L SS threaded rods (to be implemented)
    - For C50-11
      - Degaussing all other known magnetized components
        - threaded rod, ball bearing
      - Wrap ball-screw with shielding box
- Improve magnetic shielding
- Mitigate ambient field in CEBAF tunnel

Further study in future

Results and Outlook

Q_0 (at 5 MV/m) Preservation

Ratio of Q_0 at 5 MV/m at 2K cryomodule test vs. vertical test

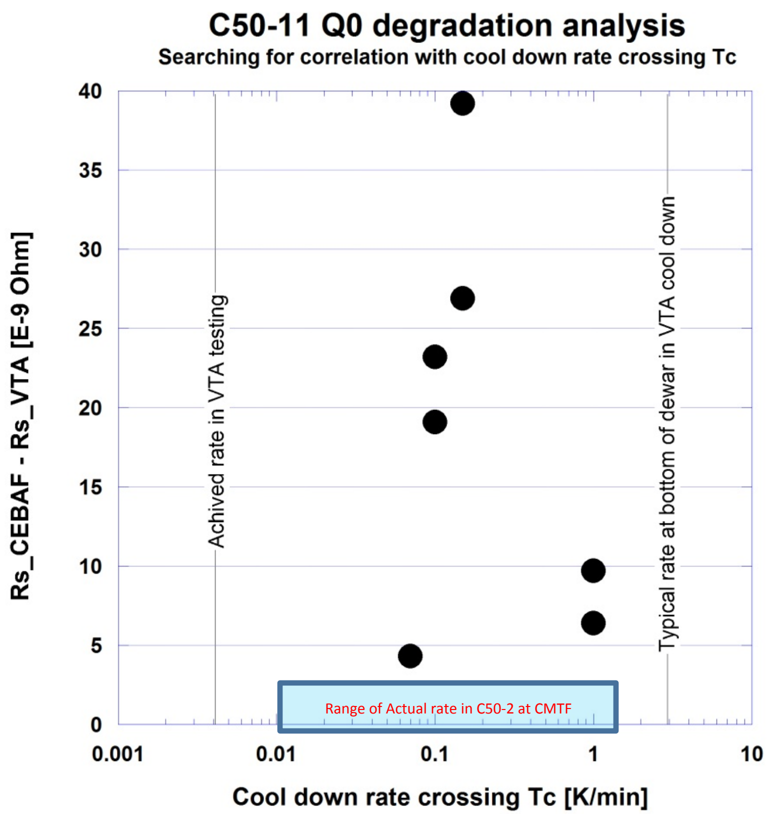


Cavity #3 not measured due to tuner issue

- 3 cavities preserved Q_0 at 5 MV/m at 79-88%
  - Encouraging first result
- Last 4 cavities still at 50%
- It is noted ball-screw shielding box for first 4 cavities different than for last 4 cavities
  - Still consistent with findings
- No correlation with ambient magnetic field in range of 0-1 G
  - Good news, mitigation in magnetic shielding or ambient field may not be needed
  - Further studies needed

Exploration of In-Situ Remediation for Improving Q_0

- Such a remedy could provide a cost-effective interim solution before an expensive cryomodule refurbishment opportunity arrives
- Any saving in cooling power can be used to enhance the acceleration voltage and improve the robustness of the energy reach of CEBAF.



- 1-cell testing studies started in August 2013
  - 30% loss in Q0 from cryogenic thermal annealing below Tc
  - 30% loss in Q0 from slow crossing Tc
  - 30% gain by partial warm up followed by rapid cool down
- Typical cool down rate crossing Tc at dewar bottom ~ 3K/min
- Lowest achieved 1-cell cavity cool down rate crossing Tc ~ 4mK/min
- Good match with actual cool down rate in CEBAF cryomodule

Possible Q_0 Recovery by “Mobile Magnetic Shield”

Shield (Si steel or LCS)

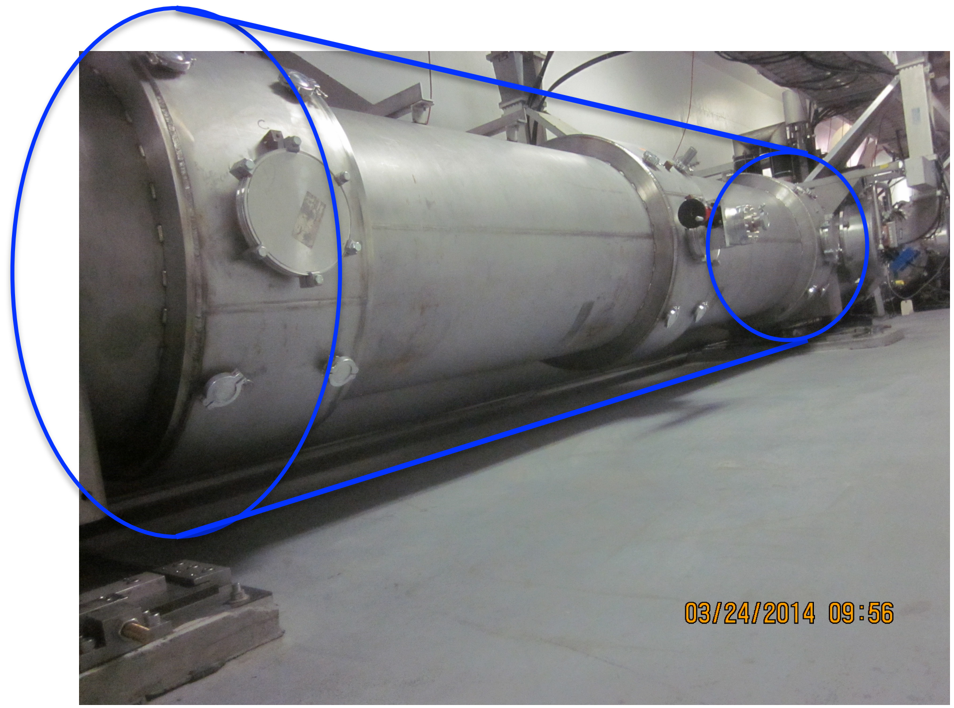
Warm up to 15K Put on shield Cool down to 4K	4K	4K

Move shield

4K	Warm up to 15K Put on shield Cool down to 4K	4K

Move shield

4K	4K	Warm up to 15K Put on shield Cool down to 4K



Conclusion

- Origin of low Q_0 in original CEBAF cryomodules further understood
  - Magnetized strut springs with large remanent magnetic flux the leading culprit
- New mitigation procedure developed and partially implemented
  - Best case Q_0 at 5 MV/m at 2 K preservation of 88% achieved
- Experimented techniques of manipulating trapped flux by thermal cycling cavities in-situ in CEBAF tunnel
  - A possible interim solution for improving Q_0 before expensive refurbishment opportunity arrives
- Any gain in Q_0 alleviates pressure of increasing demand for more cooling power
  - Useful to enhance acceleration voltage and robustness of CEBAF energy reach