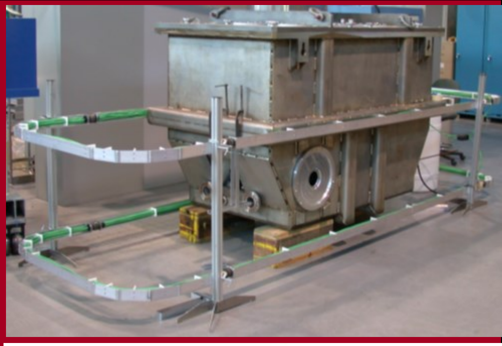
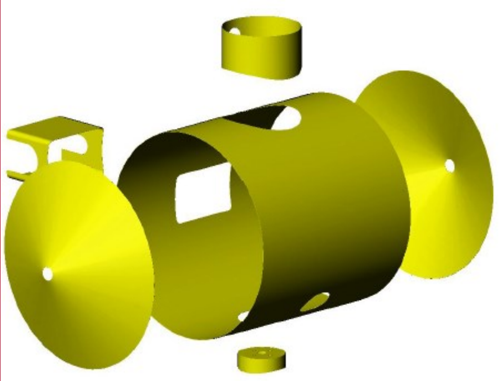
Review of the Magnetic Shielding Design of Low-Beta Cryomodules

Bob Laxdal, TRIUMF





Outline

- Introduction
  - Facilities, projects and proposals
- General considerations
  - Trapped flux and specifications
  - External field – global, local shielding
  - Internal field
    - Magnetization, quench, frozen flux
    - Mitigation – local shields, degaussing, thermal cycle, quench annealing
- FRIB workshop
  - On-going facilites – ISAC-II, ATLAS, IUAC, SARAF, ReA3
  - Developments – FRIB, CEA, Project-X
  - Shielding Materials
- Summary

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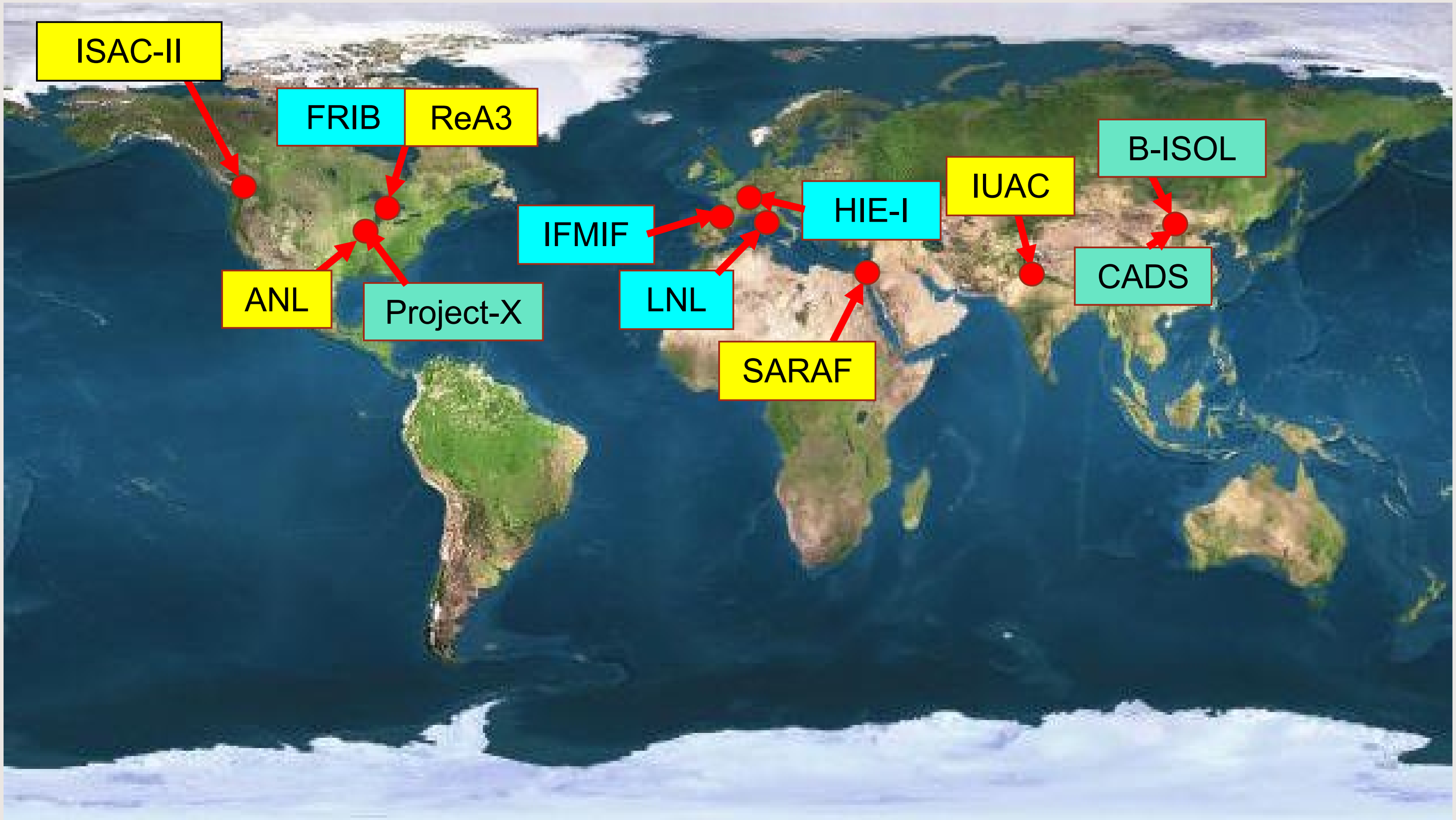
General Comments I

- Many new low and medium beta facilities are being built or are in development
- At low beta there is a need for increased transverse focusing and many designs are choosing high field SC solenoids within cryomodules to provide a more compact, cryogenically efficient, design
  - Proposals include both single and multiple solenoids in a cryomodule
  - Cavities are in close proximity to solenoids

General Comments II

- The concern is that the solenoids will interact with the cavities either quenching the cavities or increasing the surface resistance through trapped flux due to:
  - Magnetization of the environment and through Rf quenches
- Cavity performance is improving as fabrication and processing techniques improve
  - Long cw linacs require high Q (low residual resistance) operation to reduce cryogenic costs
  - Reducing the residual resistance from trapped flux will become increasingly important as cavity performances improve

Low Beta Hadron Linacs Existing or in Development using SC Solenoids

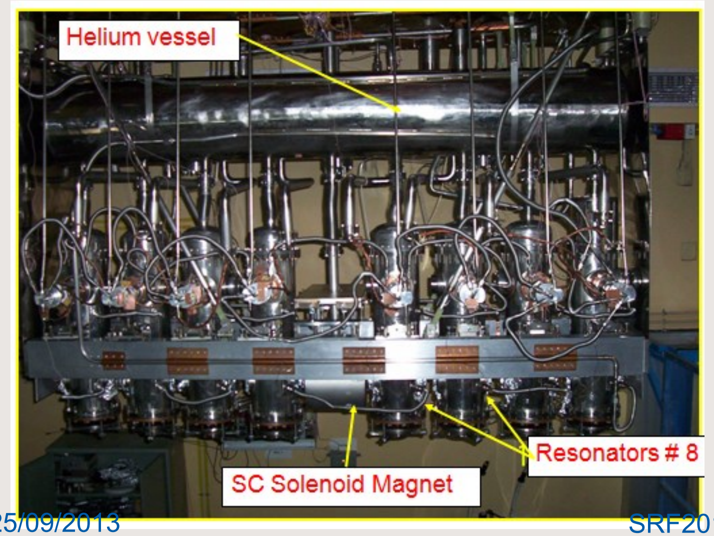


Facilities, Projects and Proposals for Ions

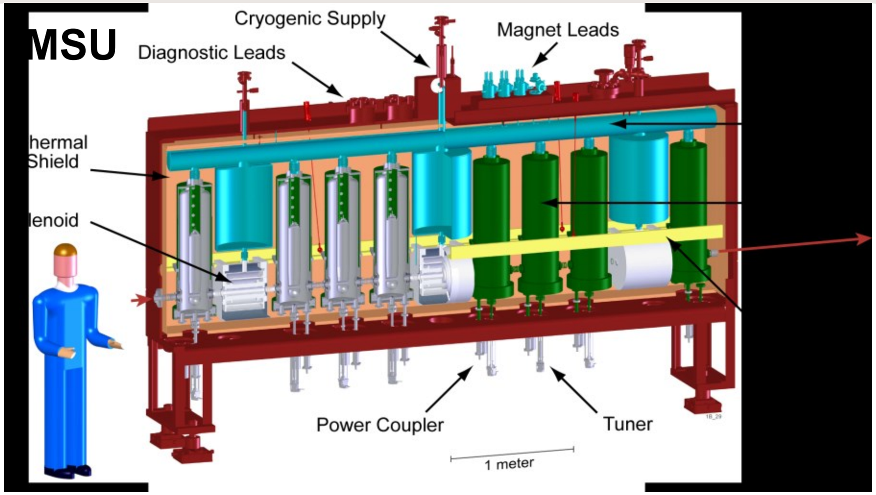
Project	Lab	SC Sol	RT quads	Particle	Structure
ISAC-II	TRIUMF	√		HI	QWR
ALPI	INFN-LNL		√	HI	QWR (sputter,bulk)
Upgrade	ANL	√		HI	QWR
HI-Linac	IUAC	√		HI	QWR
SARAF-I	SOREQ	√		P, d	HWR
ReA3	MSU	√		HI	QWR
FRIB	MSU	√		HI	QWR, HWR
IFMIF	Various	√		d	HWR
Project-X	FNAL	√		H-	HWR, spoke
C-ADS	IHEP, IMP	√		p	HWR, spoke
B-ISOL	CIAE/PKU	√		P,d,HI	QWR, HWR, spoke
HIE-REX	CERN	√		HI	QWR (sputter)
SPIRAL-II	GANIL		√	P,d	QWR
RISP	Korea		√	P, HI	QWR, HWR, Spoke

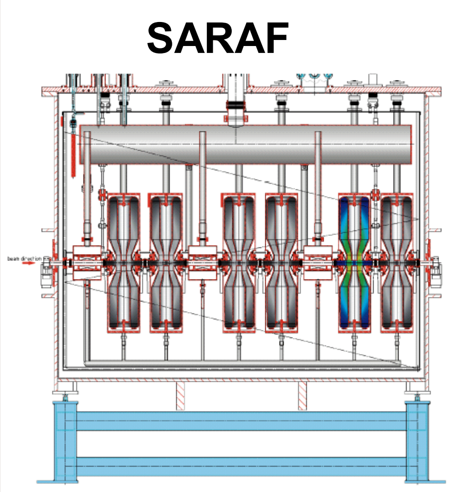
Some existing examples

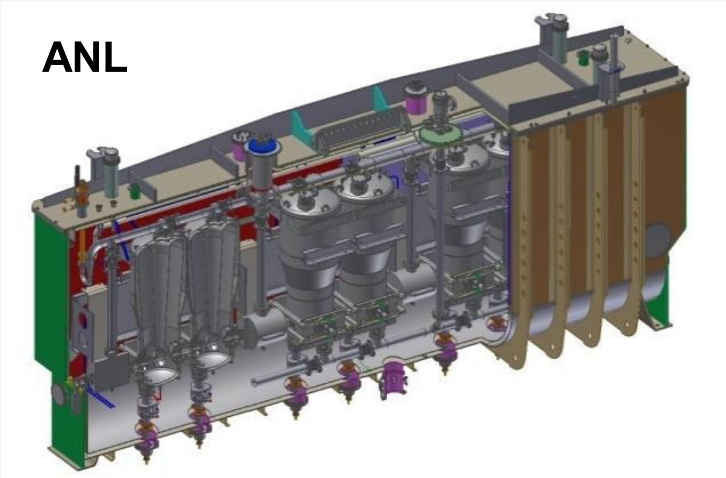
- **TRIUMF ISAC-II Cryomodules –** one 9-Tesla solenoid per cryomodule
- **ANL energy upgrade cryomodule** – one 9-Tesla solenoid per cryomodule
- **IUAC heavy ion cryomodule** – one 6T SC solenoid per cryomodule



Others with multiple solenoids







Facility	Shielding	Active
ISAC-II Phase I and II	1mm and 1.5mm global	9T solenoid – bucking coil
ATLAS upgrade	1mm global	9T solenoid – bucking coil
SARAF	1 mm global	6T solenoid
IUAC	1 mm global	8T solenoid

Residual magnetic field goals

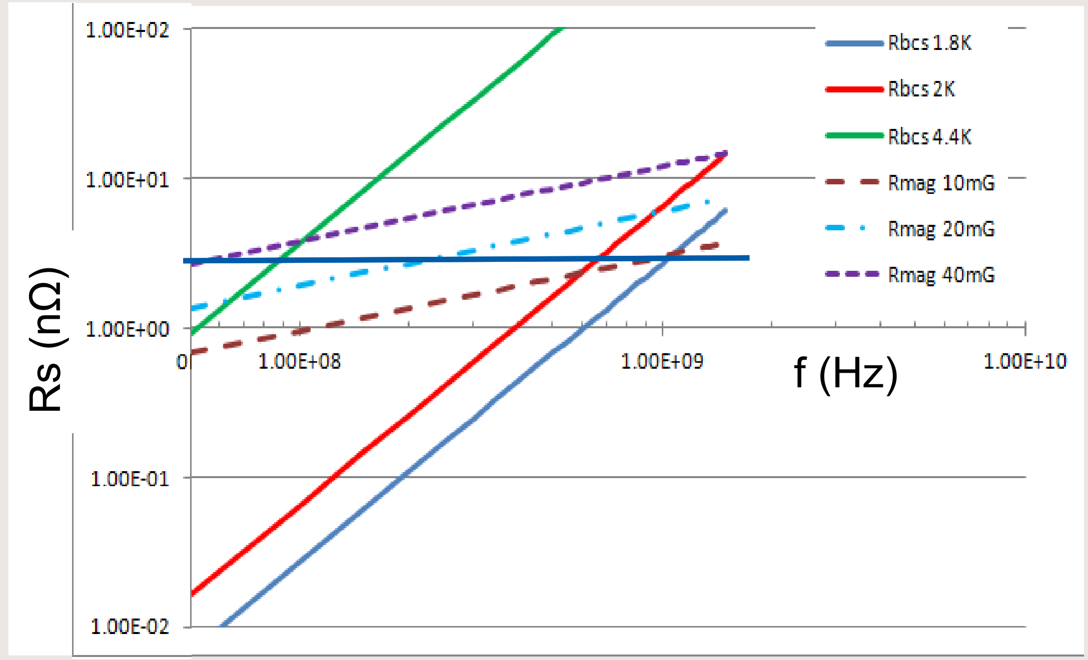
$$\frac{R_m}{H_{ext}} = \frac{R_n}{H_{c2}} = \frac{1}{H_{c2}}\sqrt{\frac{\omega\mu_0}{2\sigma\cdot \mathrm{RRR}}}$$

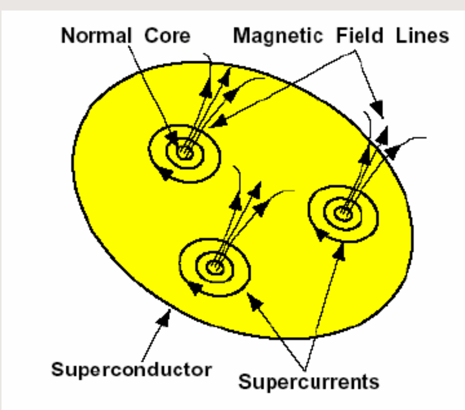
For bulk Nb H_{c2}=4000, σ=6.6 x 10-6 mhos, RRR=300

then $\frac{R_m}{H_{ext}}\left[\frac{\mathrm{n}\Omega}{\mu\mathrm{T}}\right] = 60\sqrt{\frac{f[\mathrm{GHz}]}{RRR}} = 3.5\sqrt{f[\mathrm{GHz}]}$

$$R_{BCS}[\mathrm{n}\Omega] \approx 2\times 10^5 \frac{1}{T}\left(\frac{f[\mathrm{GHz}]}{1.5}\right)^2 \exp\left(-\frac{17.7}{T}\right)$$

$$R_s = R_{BCS} + R_0 + R_m$$





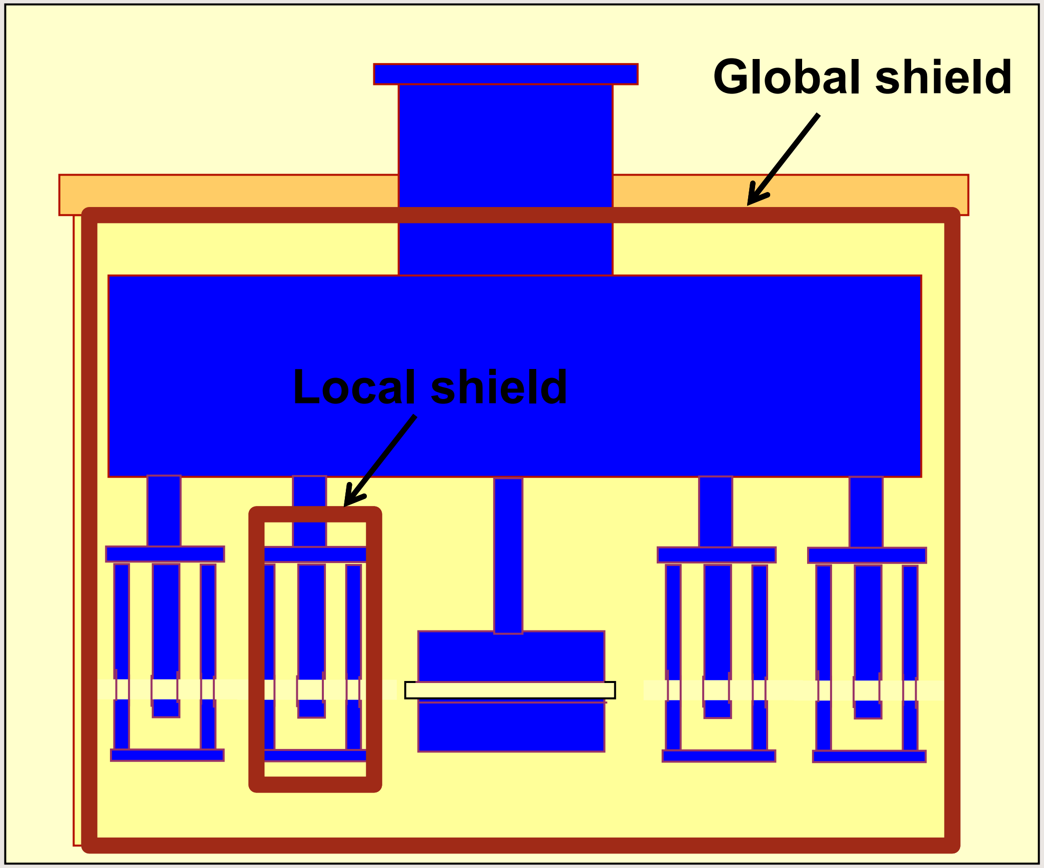
- Residual field will be 100% trapped in the superconductor
- Vortices will have normal cores which increase surface resistance by R_{mag}
- R_{mag} is inversely proportional to H_{c2} so that sputtered Nb cavities are less sensitive due to high H_{c2}
- A reasonable goal is to have $R_{mag} \leq 3n\Omega$ - must have B<3μT at 100MHz and B<1μT at 1GHz

Motivation for low background field

- For large linacs (ie FRIB, Project-X, ADS…) cryogenic load is a cost driver
- It is becoming the norm that low beta cavities for long linacs are choosing to operate at 2K to reduce the medium field Q-slope
- At this temperature for low frequency cavities (f<400Hz) $R_{BCS}< 1n\Omega$ and with new developments $R_s< 5n\Omega$ at the operating gradient
- This means that in order that R_m does not dominate the residual resistance values of $R_m< 1n\Omega$ can be considered – in this case B < 1μT for low beta cavities and B < 0.3μT for high beta cavities – these are challenging numbers – needs careful design

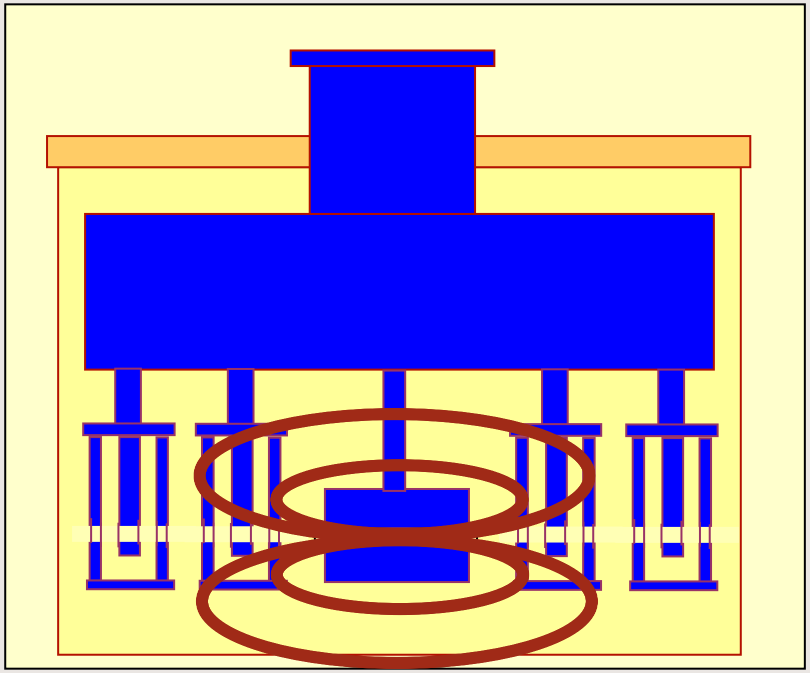
Magnetic Issues I – external field

- Passive or active shielding must be added to the cryomodule to reduce the background magnetic field during cavity cooldown
    - Shielding can be global - typically at the wall of the vacuum vessel
    - Shielding can be local - typically a cold service special mu-metal (CRYOPERM, A4K) placed locally around the cavity



Magnetic Issues II – Internal field

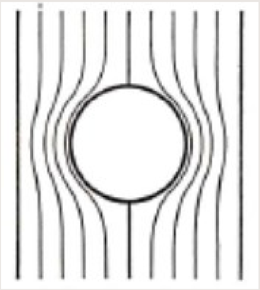
- Solenoid if strong enough can drive the cavity normal
- Solenoid can magnetically pollute the environment
    - Components, including mu metal shield, that are in the environment that can be magnetized will be magnetized by the field from the solenoid
- Solenoid produces a field when at zero current through pinned flux
    - problem if cavities warm above transition
- Solenoid can degrade cavity performance during quench through trapped flux in the quench heat zone



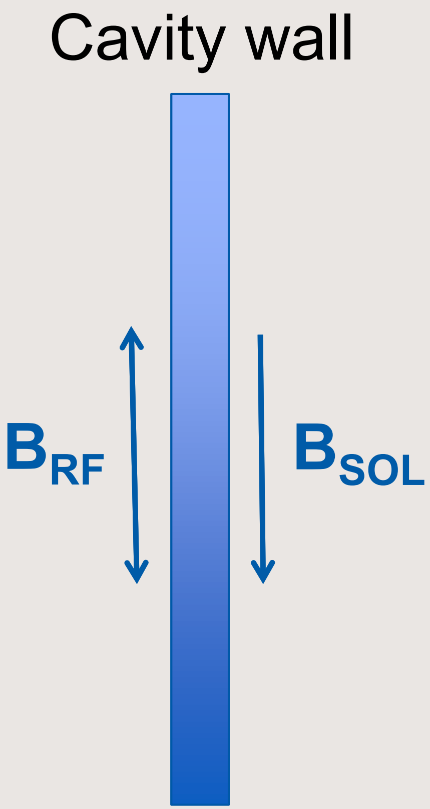
Solenoid field at cavity wall

- Procedurally the solenoid is only turned on after the cavity is cold

- As long as the field at the cavity B_{SOL} is much less than H_{c1} (~160mT) then the outer wall of the cavity will act as a Meissner shield and stop the flux from penetrating to the rf side

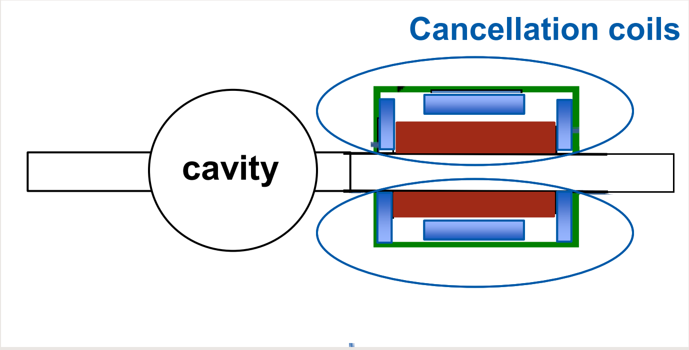


- Solenoid can be designed with bucking coils or return yokes to reduce the fringe field at the cavity

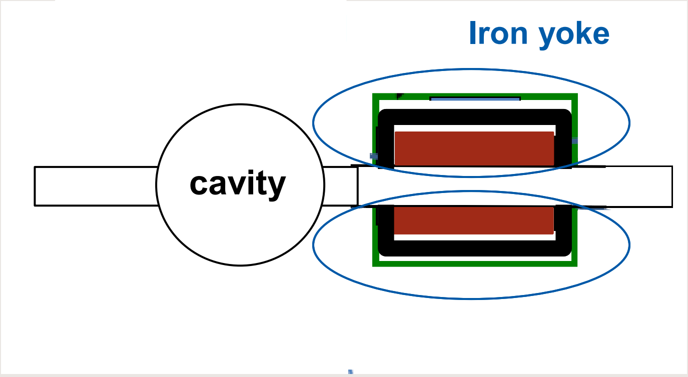


Reducing solenoid fringe field

- the solenoid can be designed with active compensation and bucking coils usually in series with the main coil but cancelling the fringe field
  - No remnant field but complicates solenoid design ($)



- The solenoid can also be outfitted with an iron yoke
  - Simplifies solenoid but risk of remnant field



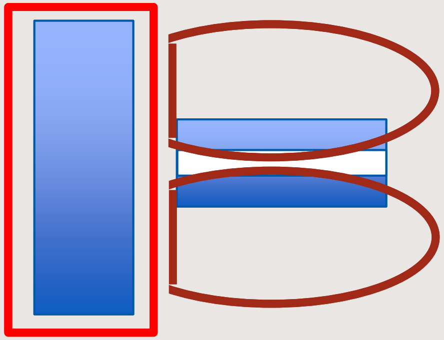
- Another option is to add isolating shields

Magnetic Pollution from Solenoid

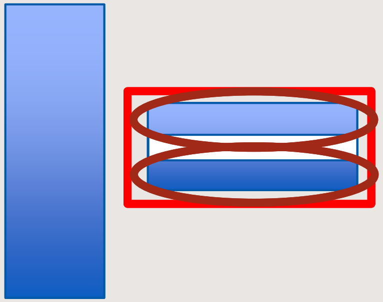
Possible cures:

- Choose materials that are not easily magnetized
  - 316LN ss – although this can become susceptible to magnetization after welding or cold working
  - Pay attention to hardware – bolts, nuts, especially near high H zones

- Isolate the cavity from the environment
  - Add cold mu metal around the cavity
  - Adds to expense and complication of assembly

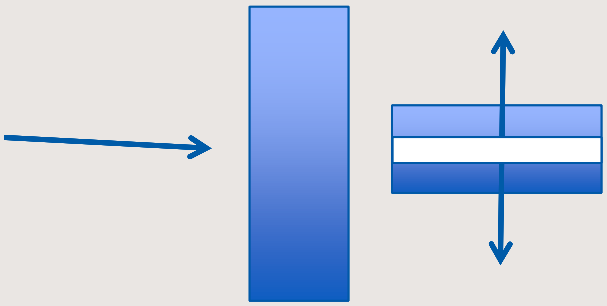


- Isolate the solenoid from the environment
  - Add an iron return core
  - Add a shield around the magnet

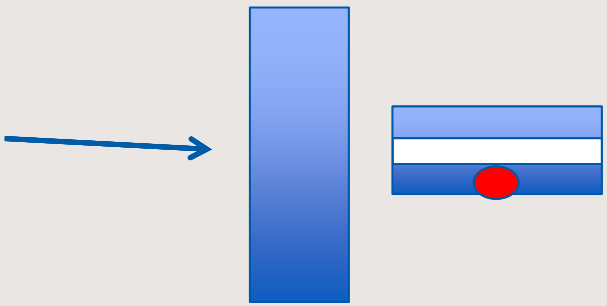


Minimalist approach

•Start unpolluted and use the solenoid to erase magnet memory by employing a degaussing cycle before every warm-up

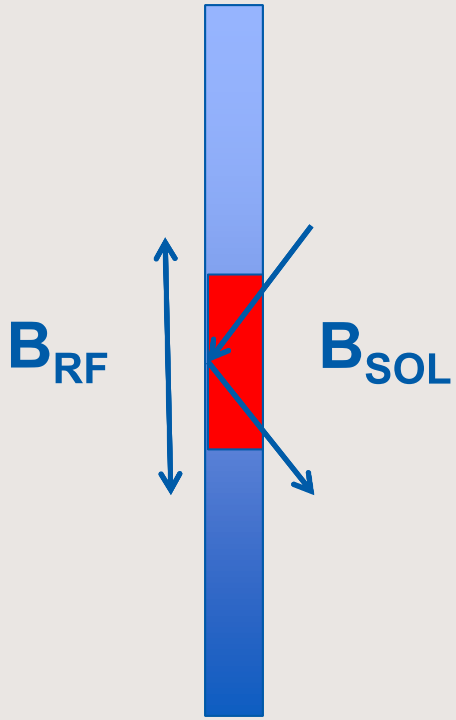


•To combat frozen flux add a heater to the solenoid to allow heating above transition to quench the flux if required



Q-drop from Quench

- During a quench the stored energy in the cavity will be dissipated at the quench location and depending on the energy content, the wall thickness and the thermal conductivity the outer wall can be heated to produce a `normal' hole in the superconducting wall
- The normal hole will soon cool but the flux will be trapped lowering the surface resistance in the hot zone thus lowering the cavity Q



$$Q = \frac{V^2}{\frac{R}{Q}\left(P_{cav} + P_q\right)} \qquad P_q = \frac{1}{2} A_q H_q{}^2 R_q$$

March 2013 – Workshop at MSU

FRIB

Welcome to the Workshop on Magnetic Shielding for Cryomodules

SRF Development Manager

Kenji Saito

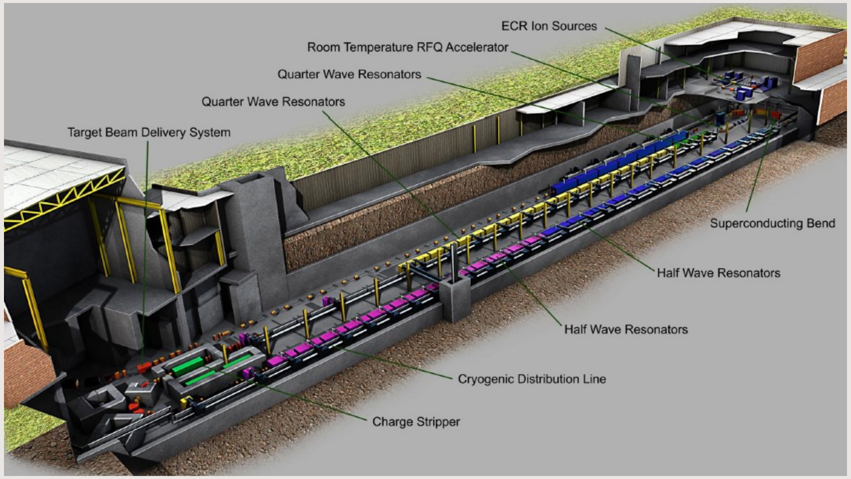
Workshop on Magnetic Shielding for Cryomodules, 6 March 2013

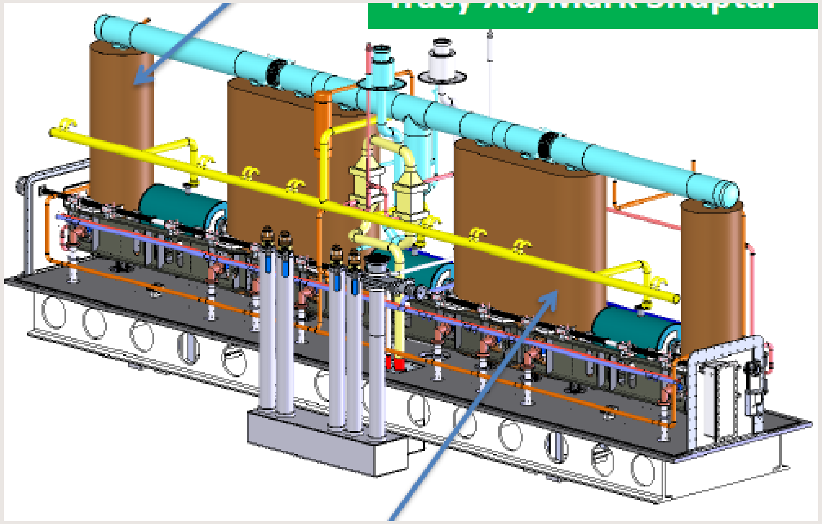
MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

Workshop General

- Two day workshop
- 11 external attendees from TRIUMF, CEA, FNAL, INFN-LNL, KEK, Amuneal, plus FRIB participants
- Topics include
  - Degaussing studies
  - Global vs local shielding
  - Solenoid design issues
  - Q degradation during quench
  - Magnetic shielding materials





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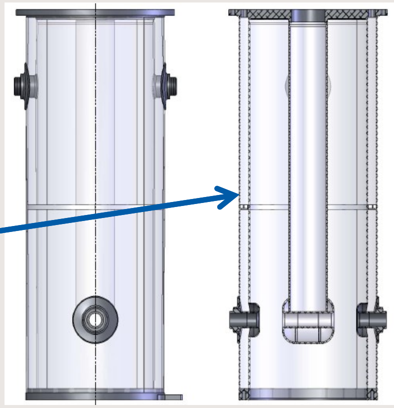
General topics of discussion

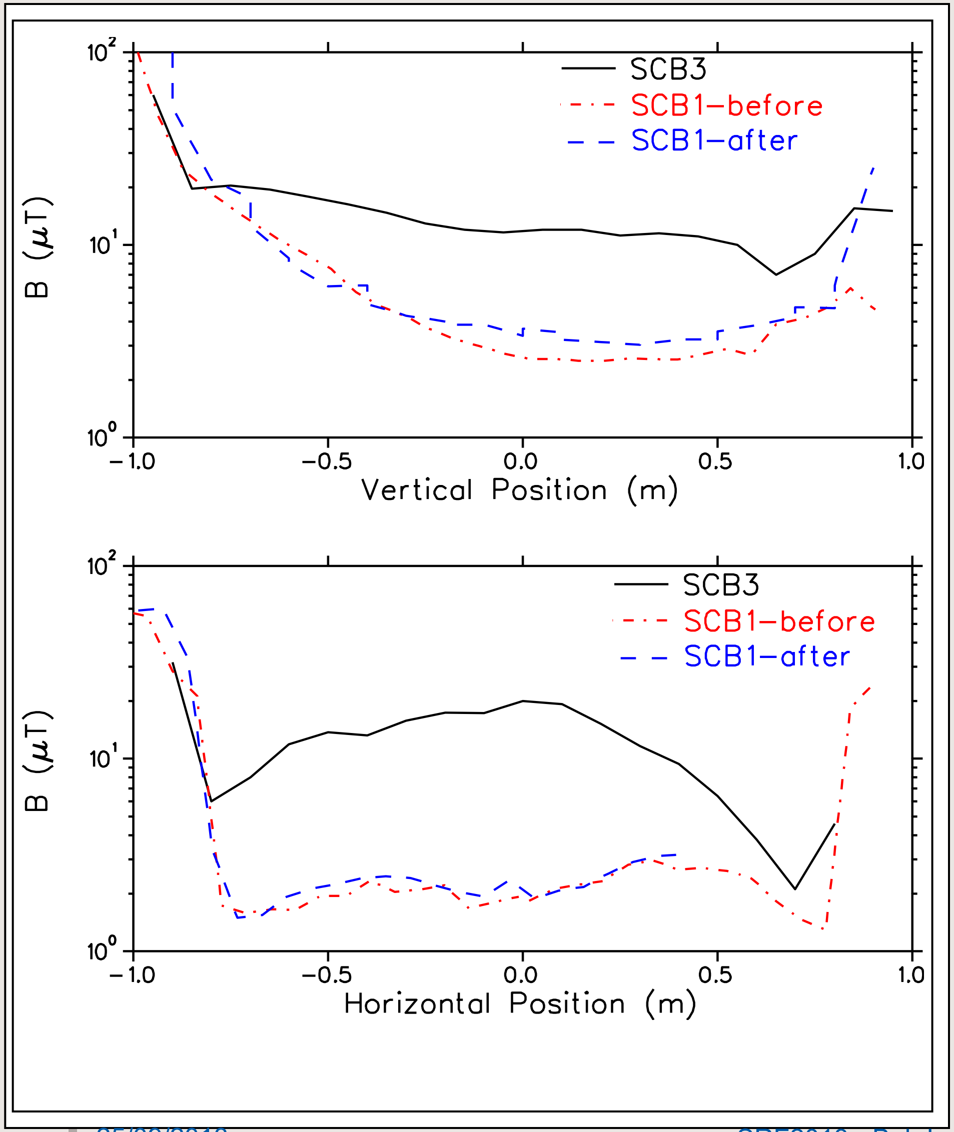
- Degaussing
- Global vs local
- Solenoid design
- Q-degradation due to quench
- Shielding materials

ISAC-II perspective

- In ISAC-II we chose a minimalist strategy – choose non magnetic materials where possible – no shielding between cavity and solenoid – use procedures
- Must do a degaussing of the solenoid before any planned warm-up to erase magnet memory
- During cryogenic events (1-2 per year) of more than a few hours if cavities warm above transition then the solenoid is degaussed and then heated above transition to release frozen flux
  - 30 min to degauss and 30 min to warm to 25K
  - 60 min to cool everything down
- Cavities are insensitive to quench degradation since they have a reactor grade jacket which acts as a Meissner shield



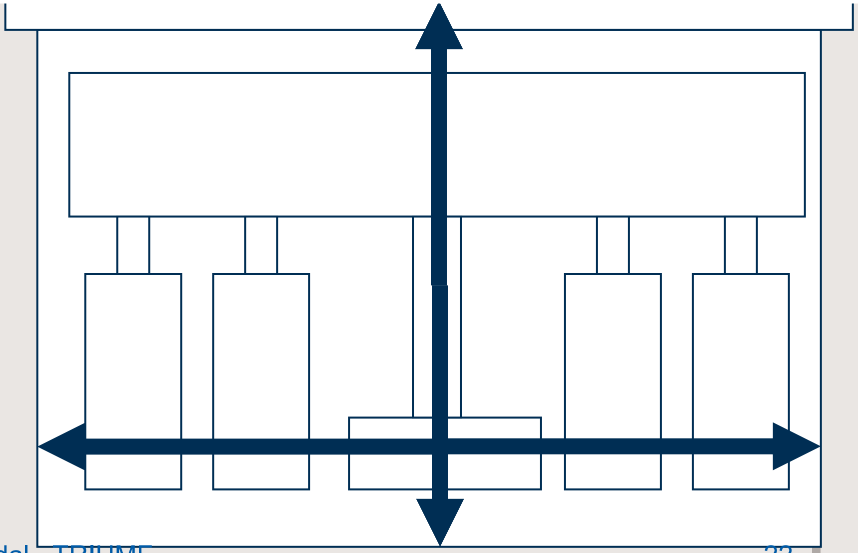
Magnetic Pollution – ISAC-II



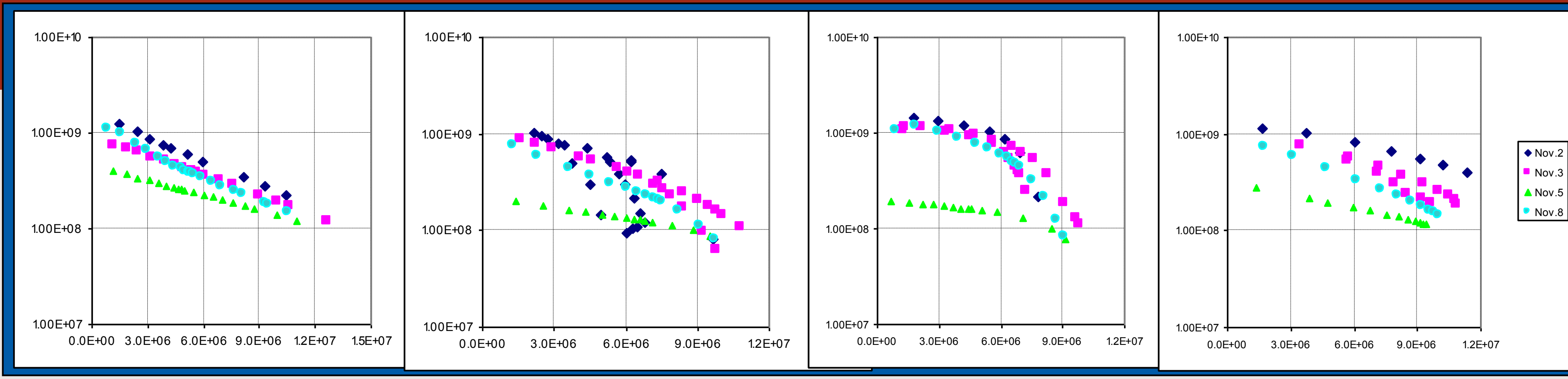
- Mapped the internal magnetic field with a fluxgate magnetometer

1. Measured baseline remnant field
2. Measure remnant field after powering solenoid with no degauss
3. Measure remnant field after powering solenoid and after degauss

Hysteresis cycle required to reduce memory of solenoid

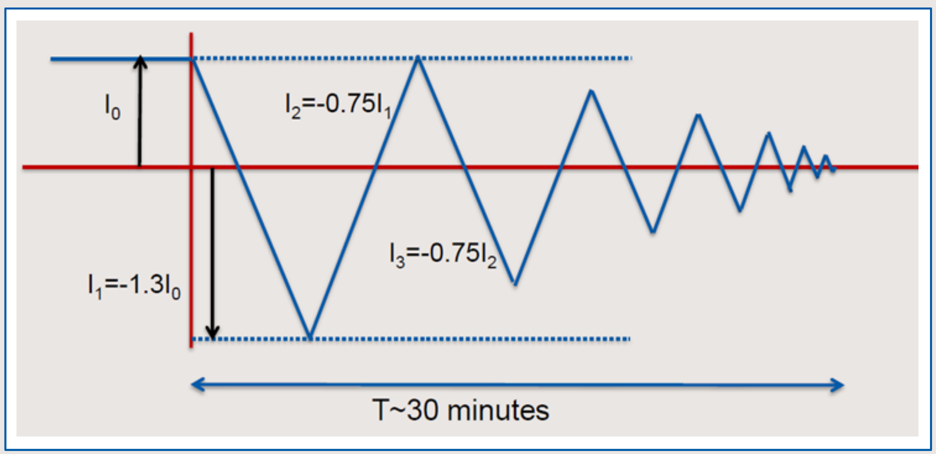


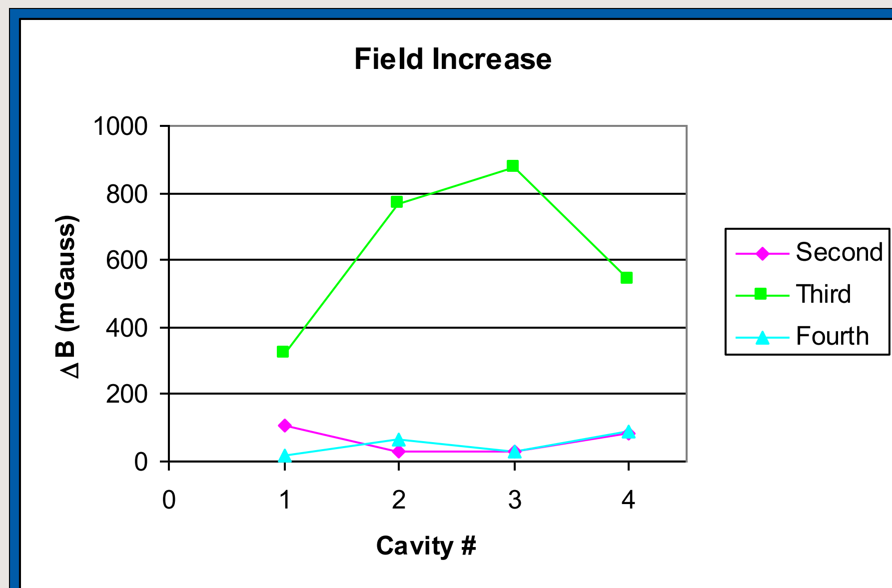
Cavity Q through warming cycles



Cavity #1 Cavity #2 Cavity #3 Cavity #4

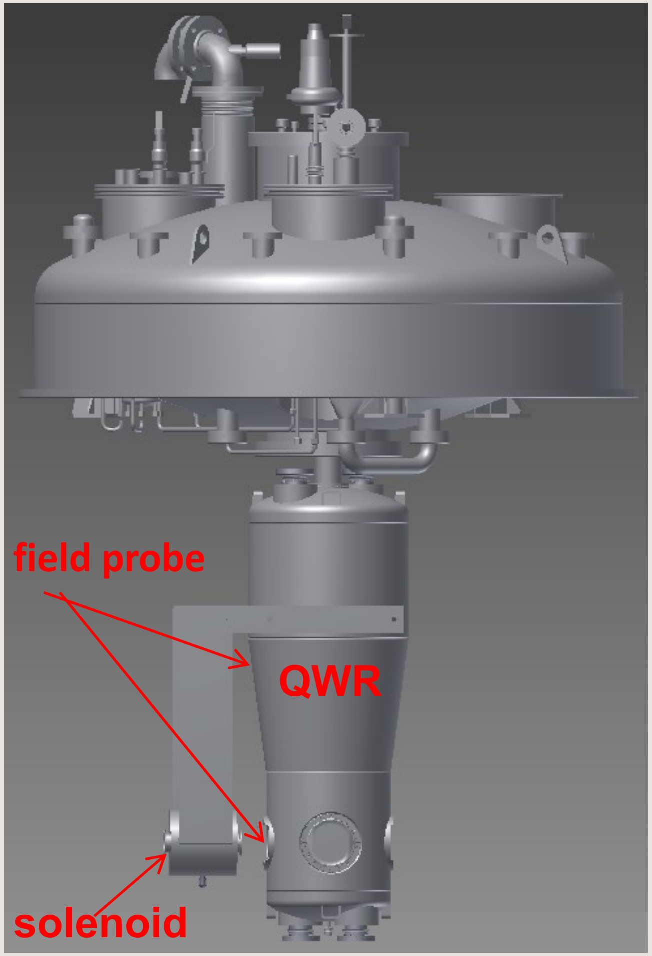
When Solenoid not hysteresis cycled – trapped flux gives large field near solenoid



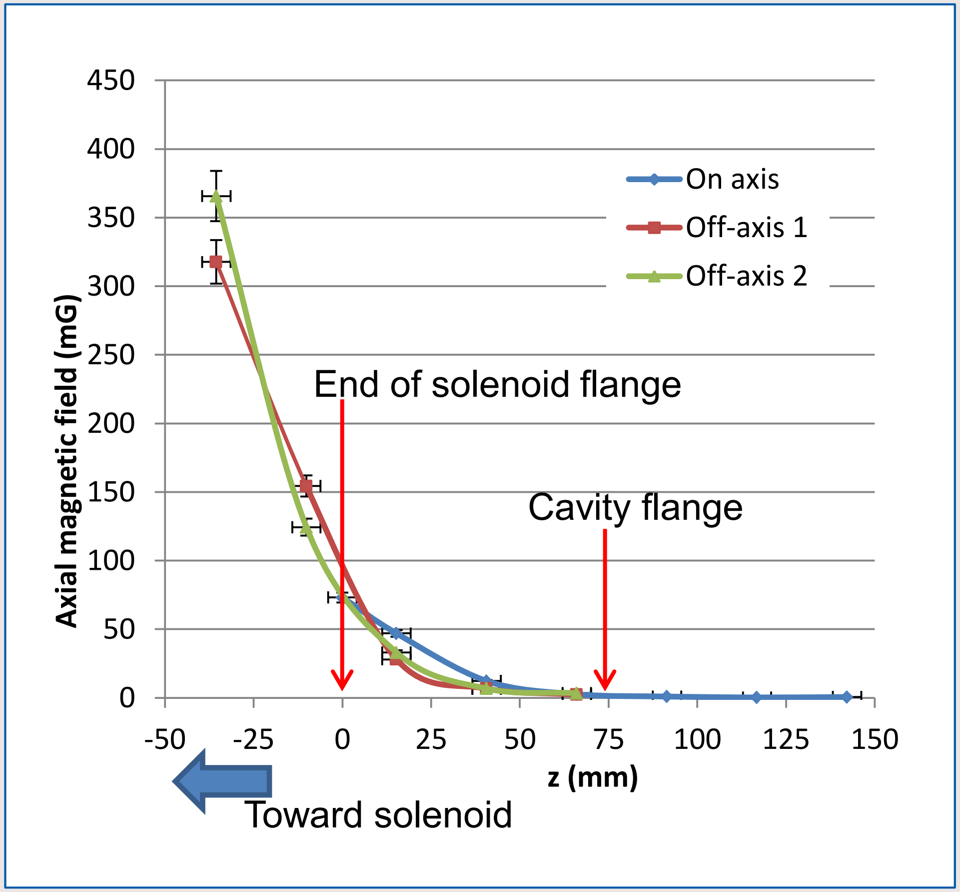


$$\Delta B\left(mGauss\right) = \frac{\Delta R_{mag}\left(n\Omega\right)}{0.3\cdot\sqrt{f\left(GHz\right)}}$$

ANL - Test with SC Cavity in Cryostat

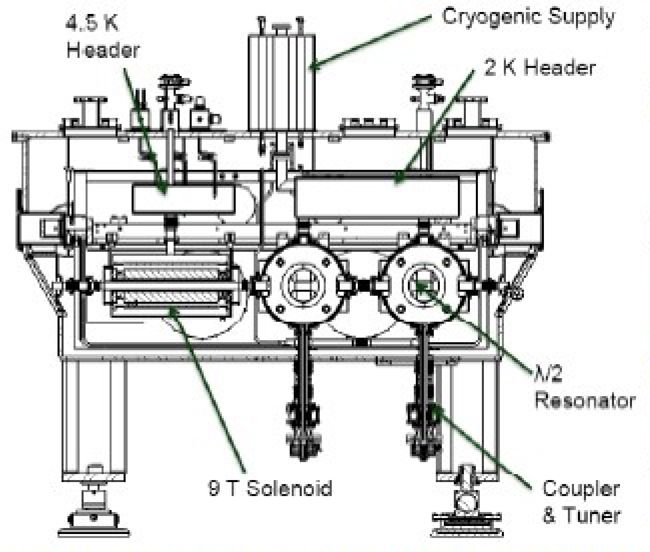


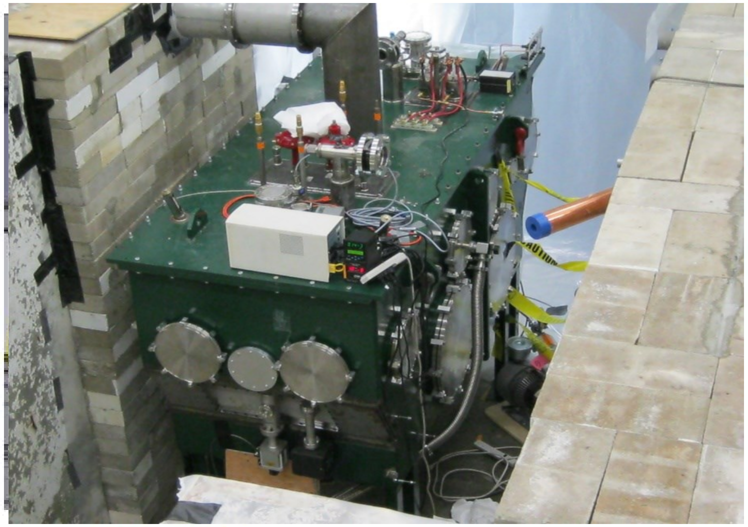
Solenoid was operated up to 6 T then Degaussed – residual magnetic fields at the cavity flange are successfully reduced .



FRIB experience

- TDCM was constructed to study (among other things) the interaction of the solenoid with the cavities and environment
- Initial tests showed too high background field resulting in reduced Q in installed cavities
- Prompted further investigation

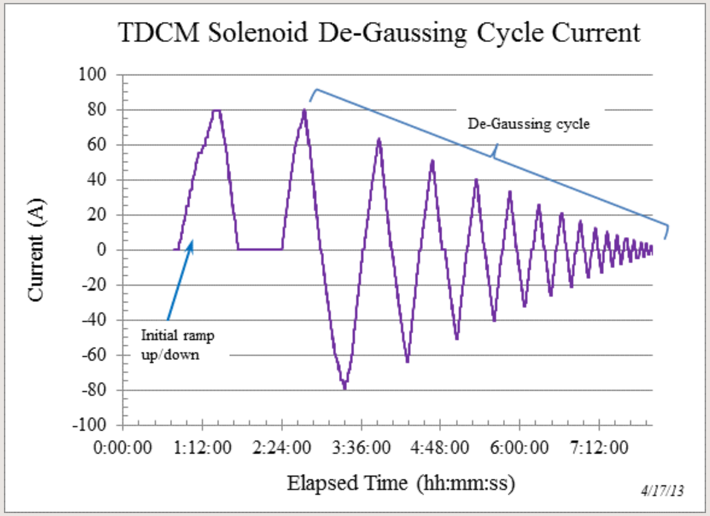




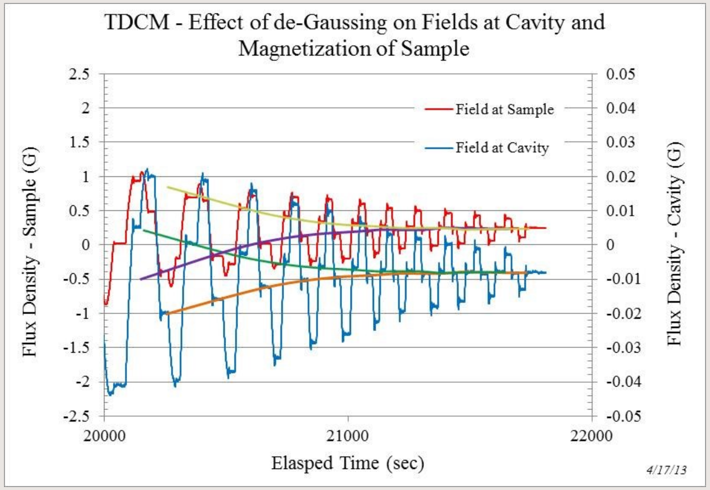
FRIB Degaussing Studies

- Current of TDCM solenoid main coil during degaussing cycle. Current ramped in bipolar fashion, at ±I, ±0.8I, ±0.64I, etc.

- Degaussing cycle including using the steering coils and a thermal cycle, appears to effectively eliminate the effects of solenoid/steering operation.



Condition	Sensor at Cavity (mG)	Sensor in SS Sample (mG)	Comment
Warm	-9	60	
Cold	-11	60	
After Solenoid/Steering Op	-18	1460	Magnetized
After Solenoid DG cycle	-18	210	Degaussed but not perfect
After Thermal cycle 25K	-18	52	Degaussed by thermal cycle up to 25K
After Steering DG cycle	-16	36	Degaussed perfectly
Warm @ 220K	-11	35	

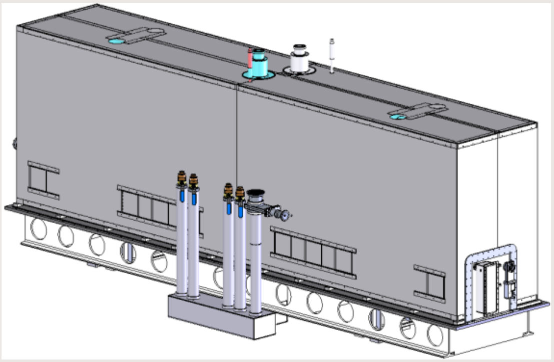


General topics of discussion

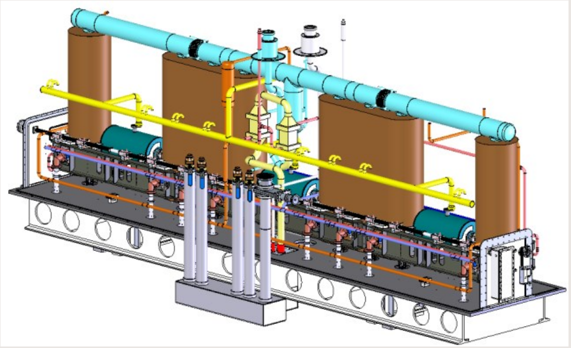
- Degaussing
- Global vs local
- Solenoid design
- Q-degradation due to quench
- Shielding materials

Global vs Local FRIB

- Global vs local for FRIB
  - FRIB spec. $H_{res} < 1.5$ μT
- Simulations performed to estimate remnant field for global and local options
  - Global scheme would require 3mm single layer while cold local shield would require only 1mm single layer
- Further consideration
  - Global shield can not help mitigate fringe field effects from solenoid



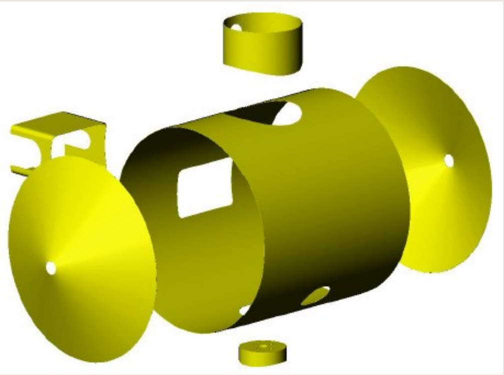
Global shielding

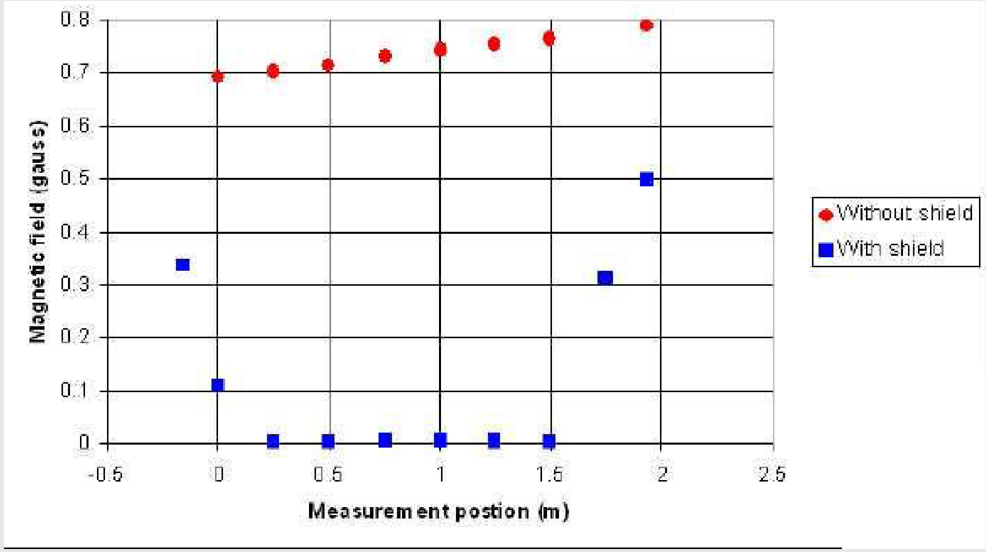


Local shielding

FRIB's conclusion: Local shielding can be cheaper, easier to handle/assemble, and relaxes requirements on screening magnetizable components before assembly.

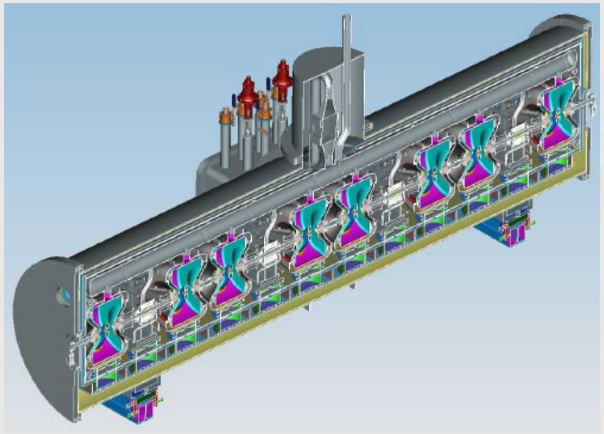
FNAL Test Cryostat and SSR1 325MHz Cryomodule





- Test cryostat - Diameter 1.2m - 1.5mm thick mu metal used
- Field measured at < 1μT everywhere – suppression >70

- SSR1 CM - Specification – ambient field at cavity < 1μT
- Choose single 1.5mm global shield

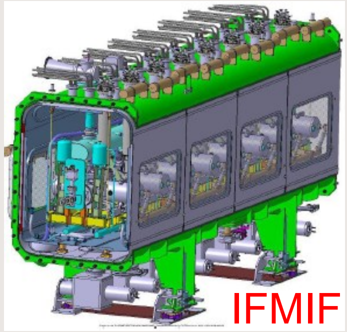


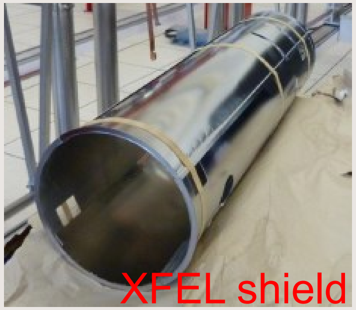
CEA Experience

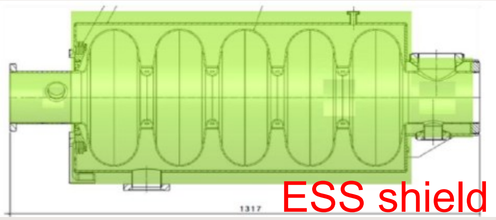
- Involved in several projects

	SPIRAL 2	IFMIF	ESS	XFEL
f(MHZ)	88	175	704	1300
Accelerated particles	Heavy ions	Deuterons	Protons	Electrons
Operating temperature (K)	4,5	4,4	2	2
Target E_{acc} (MV/m)	6,5	4,5	18	23,6
target Q_0	$2{,}2.10^9$	$1{,}4.10^9$	6.10^9	$>10^{10}$
target Bmax (mG)	10	20	14	10

- IFMIF – a single layer of warm mu-metal of 1mm
- Spiral-II – CM1 - 1 single layer of warm 1mm sheet has been measured to give an attenuation of >50
- ESS 1.5mm cold mu metal to save material costs
- XFEL – 1mm cold `CRYOPHY' shield

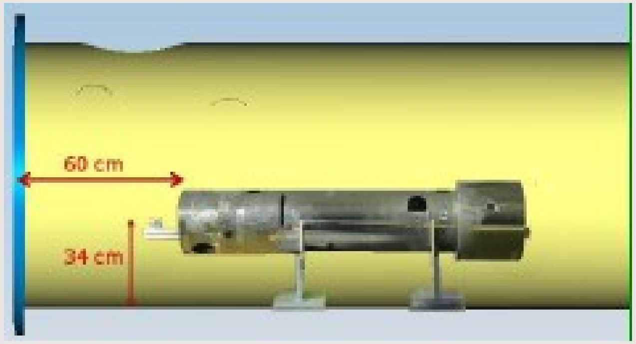


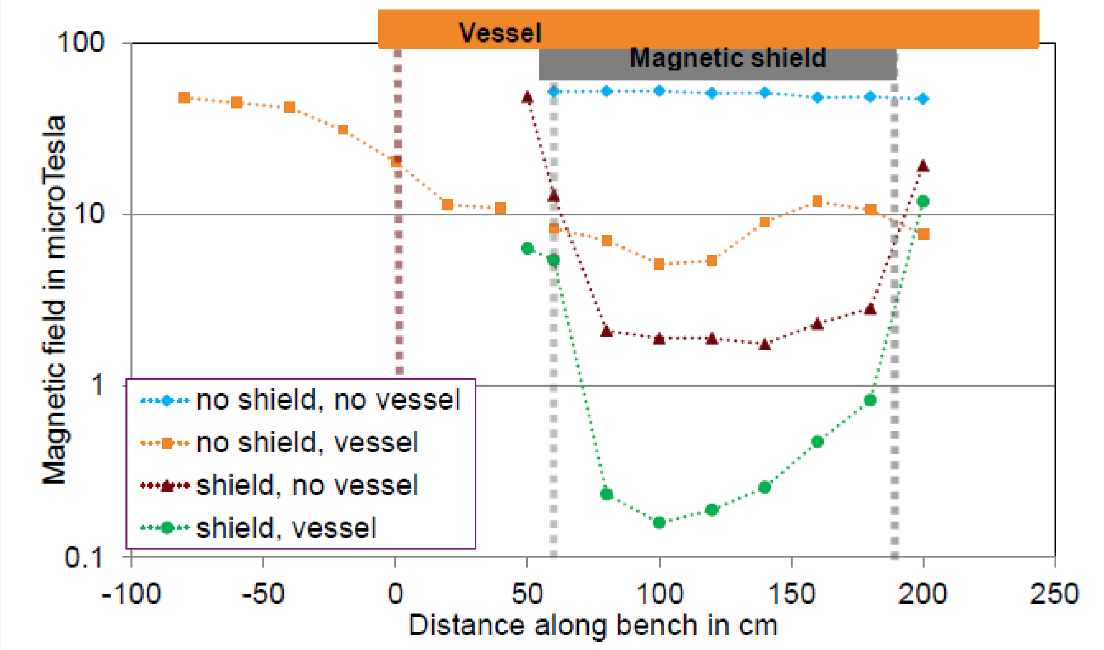




CEA - XFEL

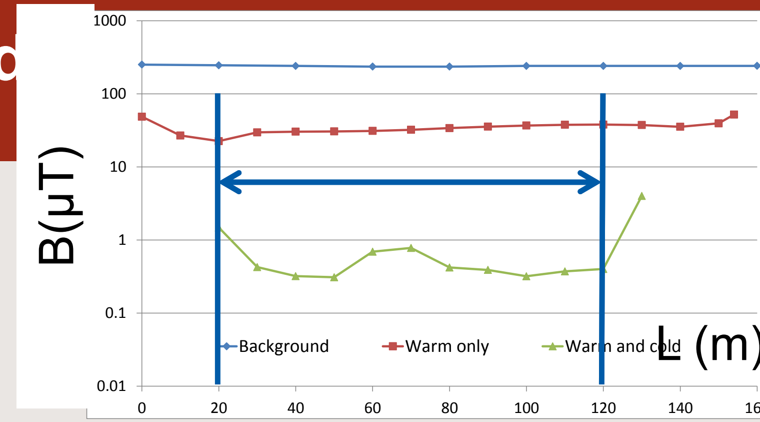
- Measured attenuation of 50µT residual field inside steel CM vessel with and without cold mu-metal
- B is reduced by 5 by vessel alone
- B is reduced by 25 by shield alone
- Total attenuation >100

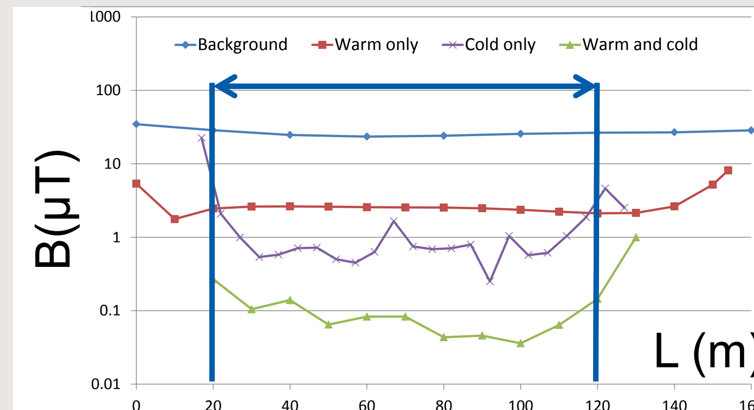


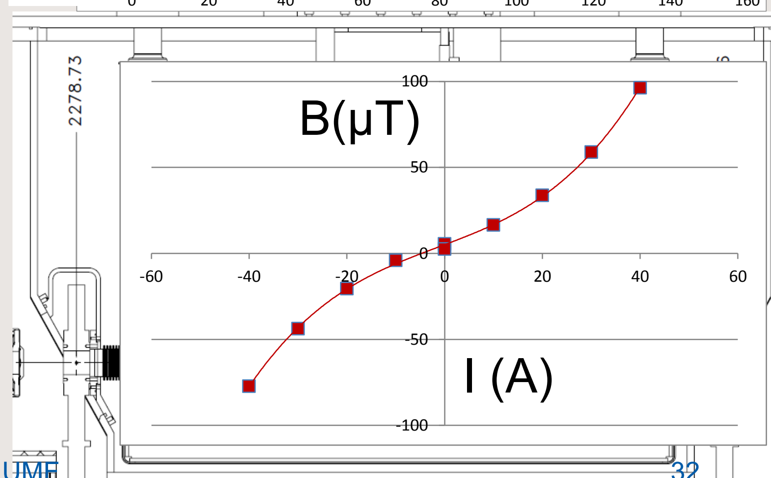


TRIUMF – Varying the background

- For ARIEL the magnetic field suppression was tested with an active background provided by a Helmholtz coil
- Two layers of mu metal – a 1 mm global shield and a 1 mm local shield were used
- The global shield saturated as the background field increased above ambient
- Suppression factors of 10 were achieved by the global shield, while the local shield provided suppression factors of 50-100







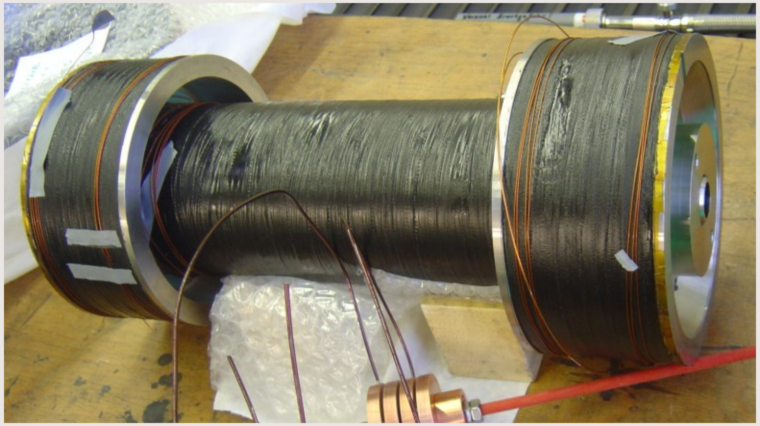
General topics of discussion

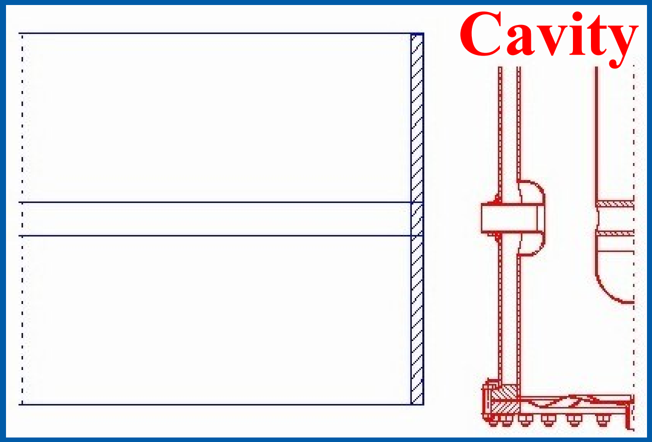
- Degaussing
- Global vs local
- Solenoid design
- Q-degradation due to quench
- Shielding materials

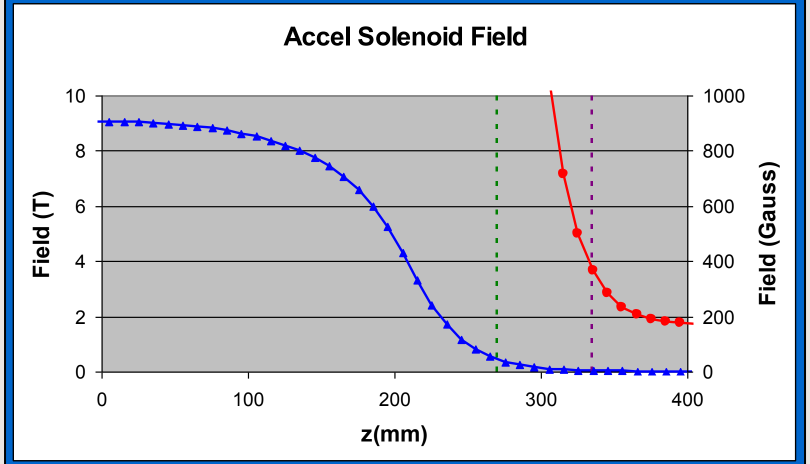
ISAC-II Bucking coils

- Focussing in the SC Linac is provided by superconducting solenoids (B≤9T)
- End fringe fields controlled with active `bucking' coils (B_{cavity}≤30mT)

Prototype Solenoid at Accel

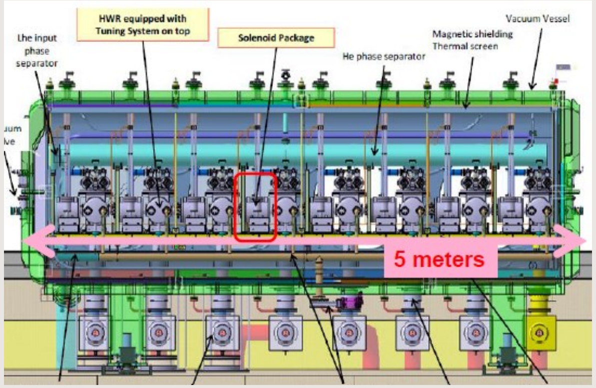


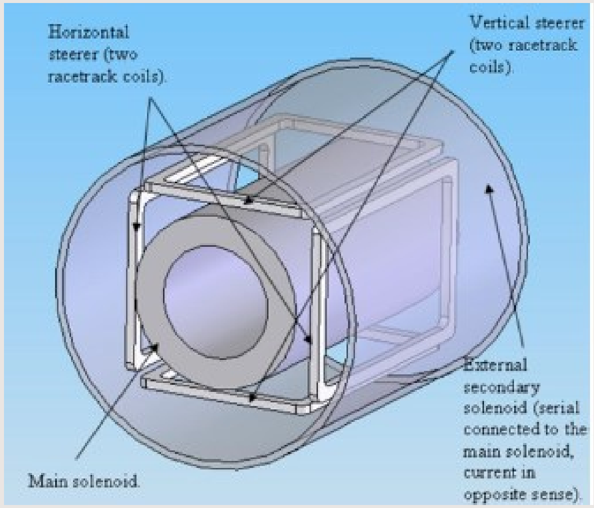




CEA experience – IFMIF solenoids

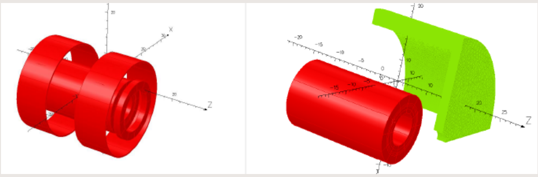
- IFMIF prototype cryomodule has 8 HWR and 8 solenoids
- Solenoid includes BPM, steerers
- Specification for fringe field <20mT at the cavity
  - Iron shield abandoned due to concerns about remnant field during cooldown
  - Compensating (external solenoid) coil chosen (in series with main coil)

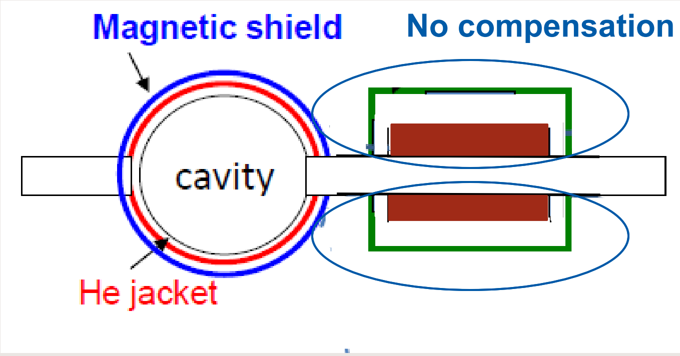


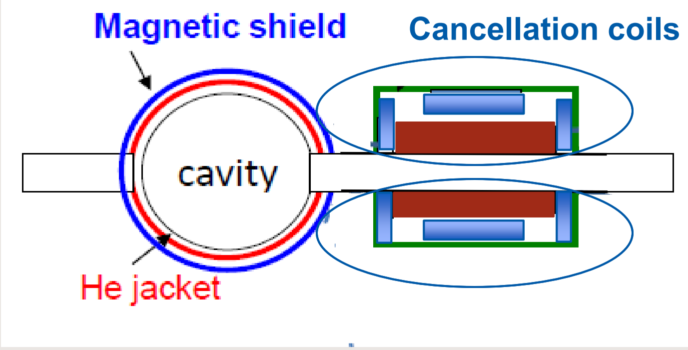


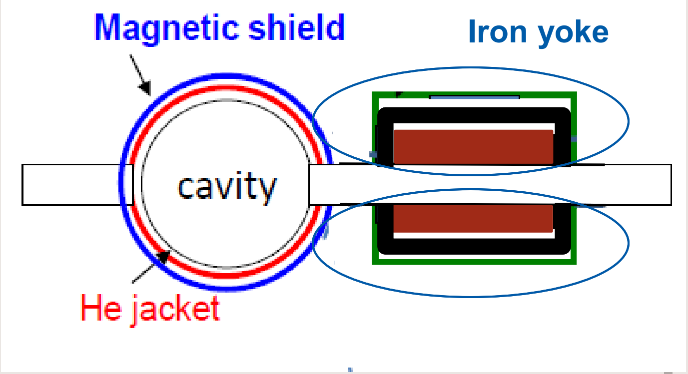
FRIB - solenoids

- FRIB has modeled solenoid and cavity geometry assuming a local shield around cavity
- Specification is to keep the field at the shield < 65 mT to avoid saturation
- Three cases
  - No compensation B~100mT
  - Active compensation B < 8mT
  - Passive compensation (iron yoke) B < 15mT

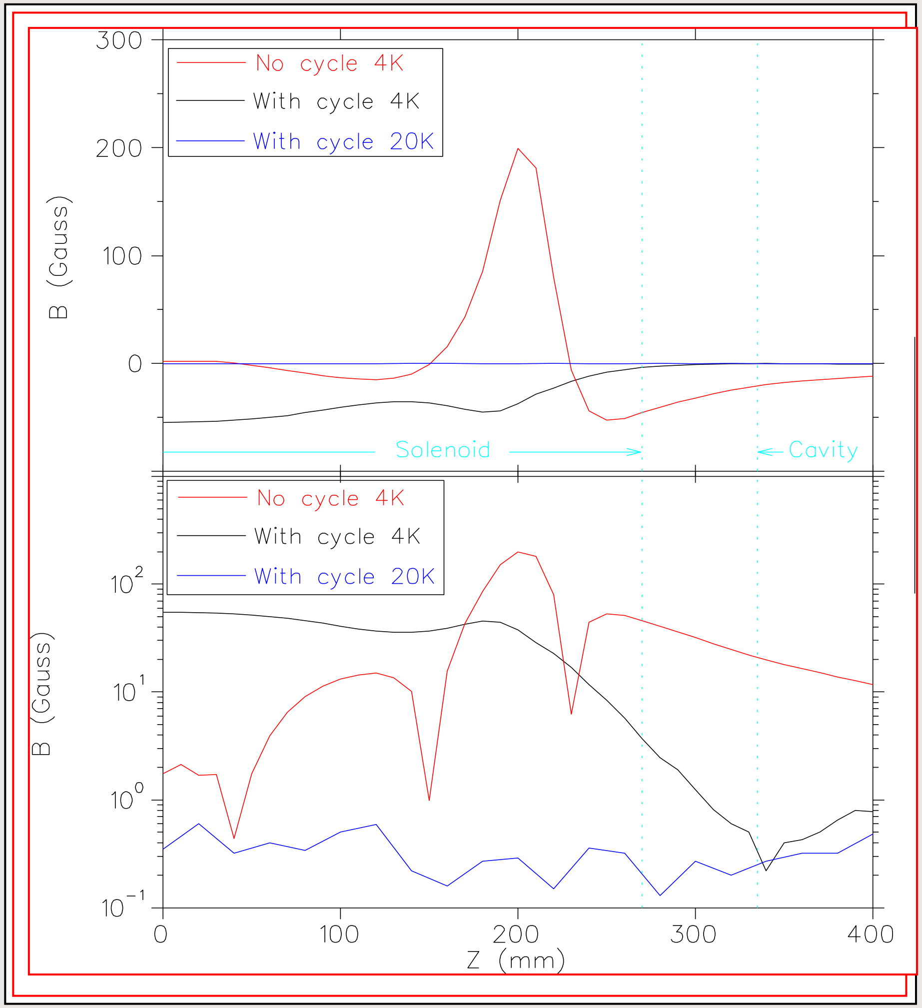








Frozen Flux



Mapping data for ISAC-II Solenoid

- Solenoid is brought to 9 T and

a) Ramped to zero with no cycle at 4K

b) Taken to zero through hysteresis cycle at 4K

c) Ramped to zero and warmed to 20K

Frozen flux in solenoid produces a large (20G) field in cavity region when no hysteresis cycle is used. Cycling the magnet does reduce the field at the cavity but only warming the solenoid can eliminate the field.

General topics of discussion

- Degaussing
- Global vs local
- Solenoid design
- Q-degradation due to quench
- Shielding materials

Study at FNAL on Quenches with solenoid background field

- This was studied in three separate cavity tests at FNAL – two with an elliptical cavity (1.3GHz and 650MHz) and one with a spoke cavity –

Modeling Quench Propagation in Superconducting Cavity Using COMSOL – FNAL Note TD-11-019
I. Terechkine

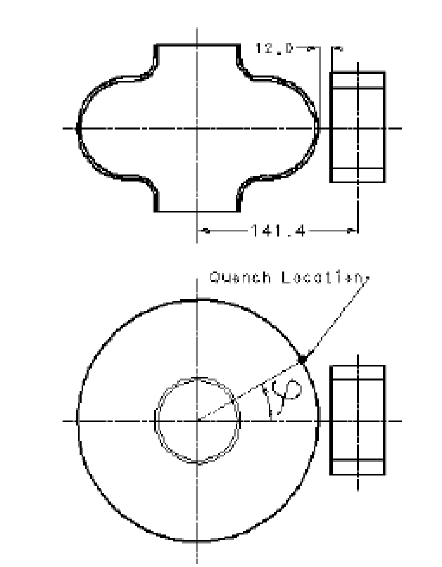
Superconducting Cavity Quenching in the Presence of Magnetic Field – FNAL Note TD-11-020
T. Khabiboulline, J. Ozelis, D. Sergatskov, I. Terechkine

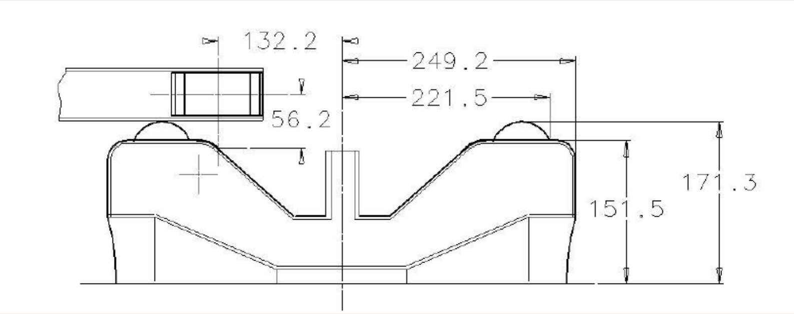
SSR1 CAVITY QUENCHING IN THE PRESENCE OF MAGNETIC FIELD – FNAL Note TD-12-007
T. Khabiboulline, D. Sergatskov, I. Terechkine

*thanks to Yuri Terechkine for pointing out these notes

FNAL study

- **Study 1:** A 1.3GHz cavity with a known quench location was installed in the VTA with a solenoid installed in the bath near the quench location – the cavity was quenched at various solenoid field strengths and the cavity Q was measured
- **Study 2:** A 325MHz spoke cavity was placed near a solenoid and resistive heaters were placed at various locations to initiate quenches with a pulse of heat from the bath side – the Q of the cavity was measured as a function of the solenoid field and the position of the quench

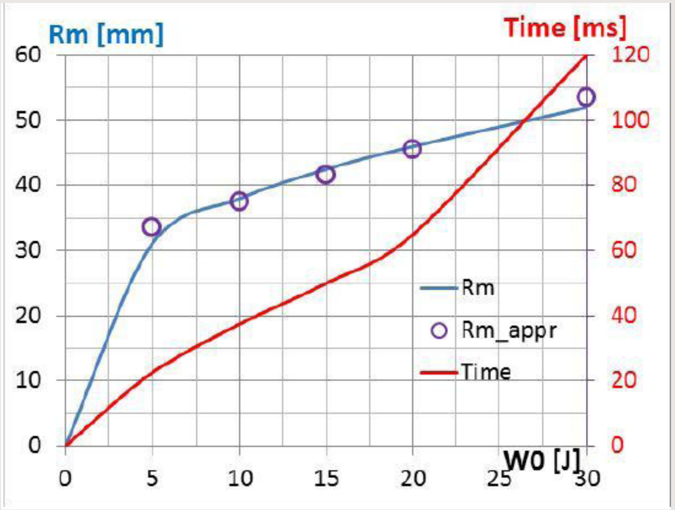


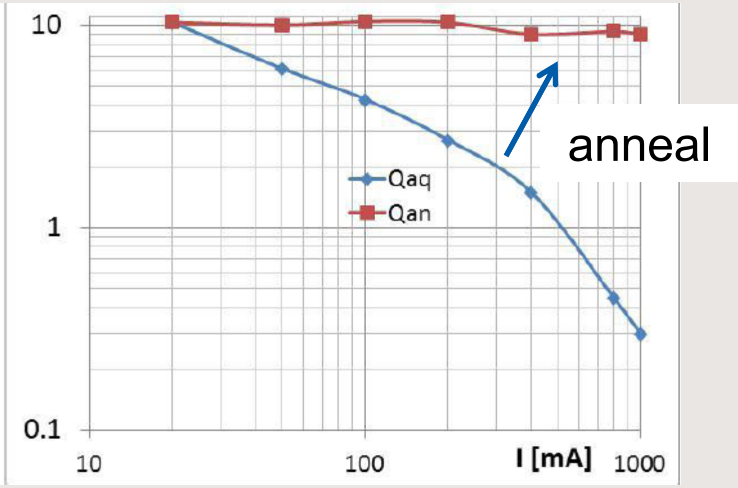


FNAL study conclusions

- A model was developed linking the reduction in Q and the fringe field from the magnet based on an estimation of the size of the `normal opening' during the quench

- A procedure for `annealing' the quench zone trapped flux was developed by repeated quenching of the zone in the presence of no field – the `normal opening' was created several times to release the trapped flux



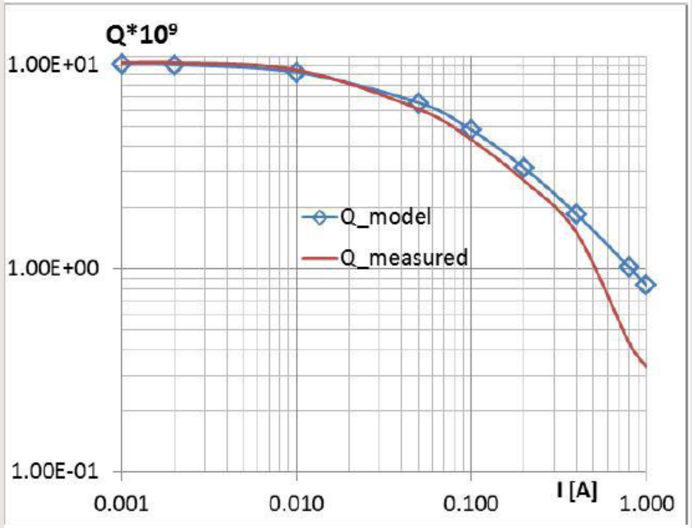


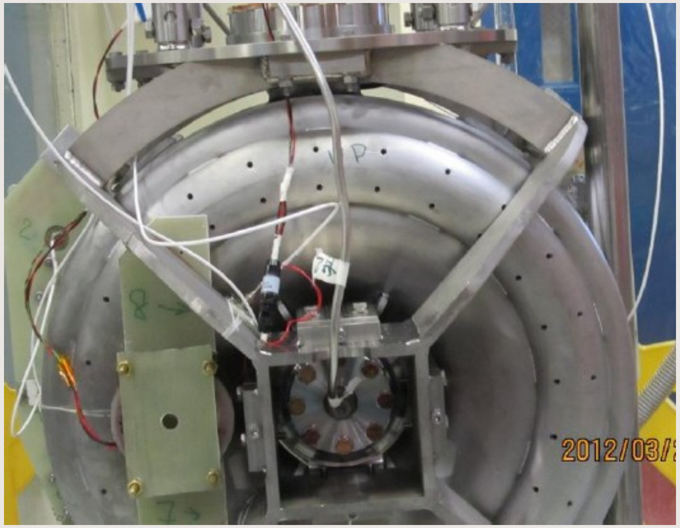
FNAL conclusions

•A model is developed that can fit the results and can be extended to other geometries

•A quench can trap fringe field flux and reduce the Q – the negative effects can be reduced by repeated quenching in zero-field

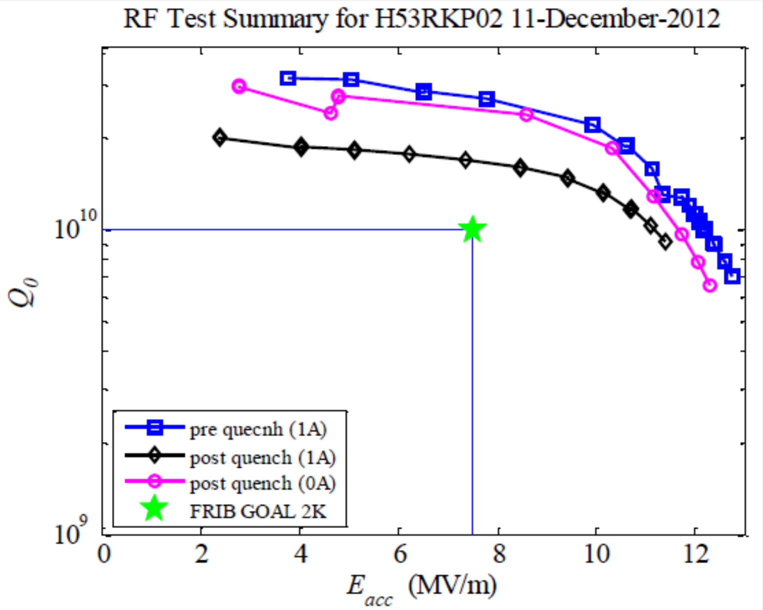
•Using the trapped flux criterion FNAL decided not to use iron yoke in the solenoid

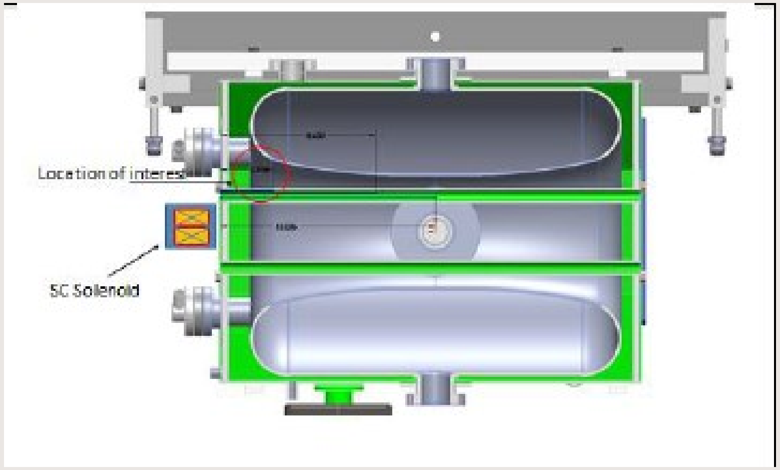


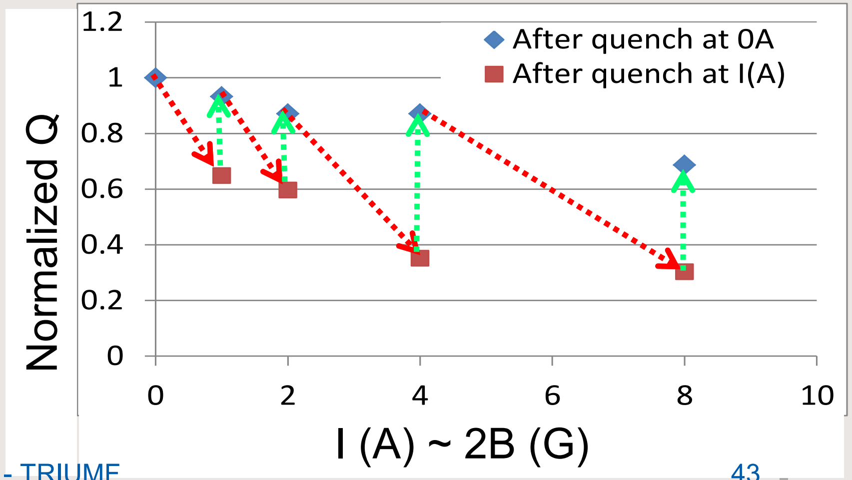


FRIB – Quench studies with solenoid

- A solenoid is positioned in the high field region of a cavity with a known quench location
- The cavity is quenched in the presence of the solenoid field (B (G) ~ I(A)/2)
- The quality factor of the cavity is monitored as a function of solenoid current
- Each time the cavity is also quenched with the solenoid off to release the trapped flux and restore the Q (no degauss step between cycles)







General topics of discussion

- Degaussing
- Global vs local
- Solenoid design
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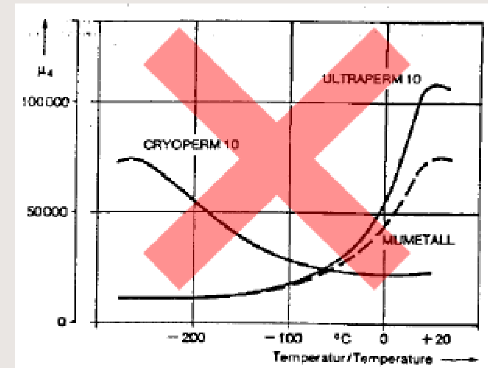
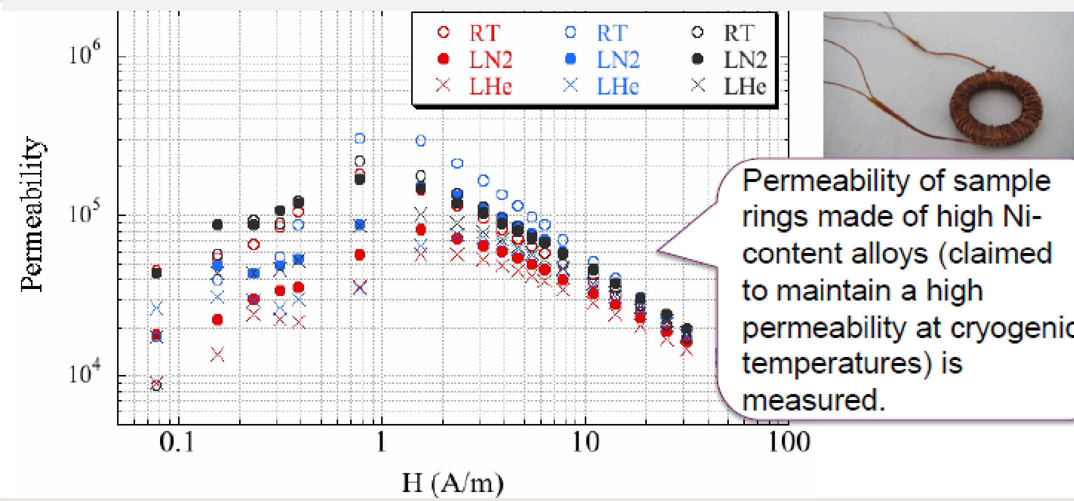
CEA – KEK Collaboration

- Collaboration to study magnetic materials – book curves are not necessarily indicative of real performance
- Cold temperature materials typically used are CRYOPERM ad CRYOPHI

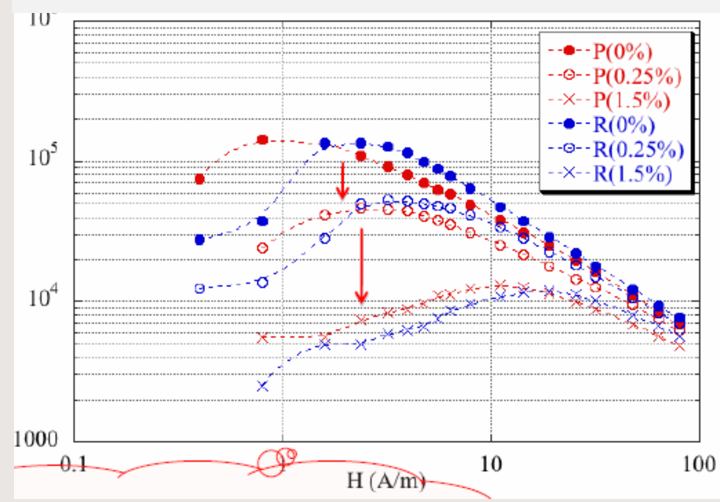


Effect of temperature



Permeability of sample rings made of high Ni-content alloys (claimed to maintain a high permeability at cryogenic temperatures) is measured.

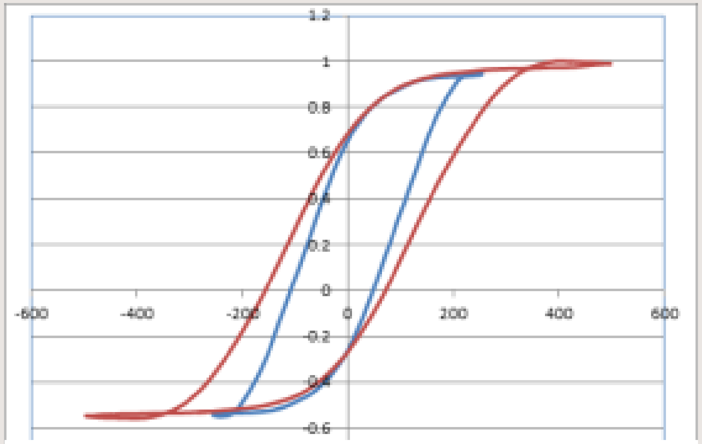
Effect of mechanical strain



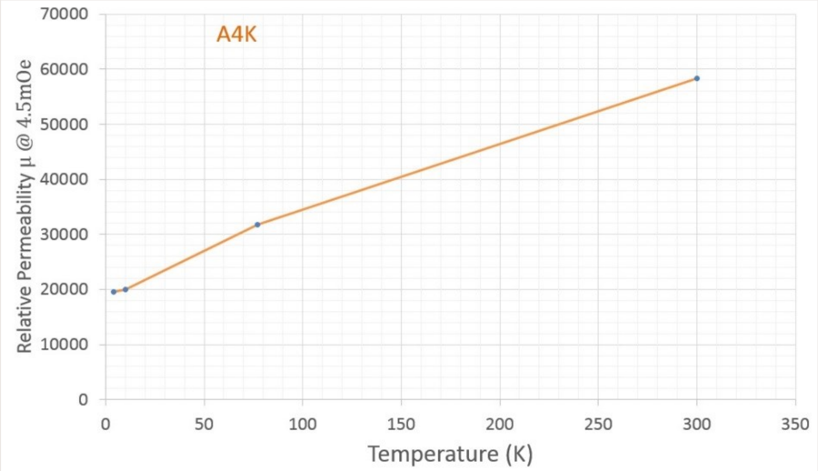
FRIB – magnetic materials investigation

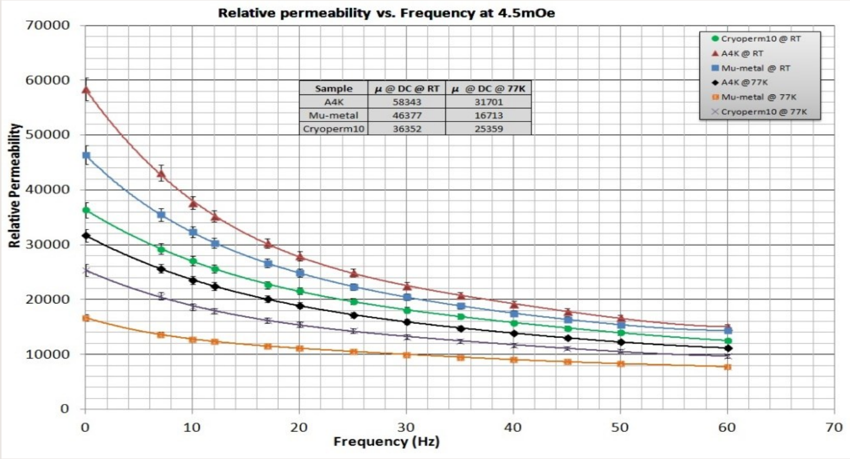
THP046

- Material investigations at room and cryogenic temperature are on-going characterization of shielding effectiveness, magnetization, and de-Gaussing of m-metal, A4K, Cryoperm
  - Test realistic shield designs – saturation, attenuation
  - Measure B-H curves and permeability as function of temperature, frequency, background field



Sample B-H curve

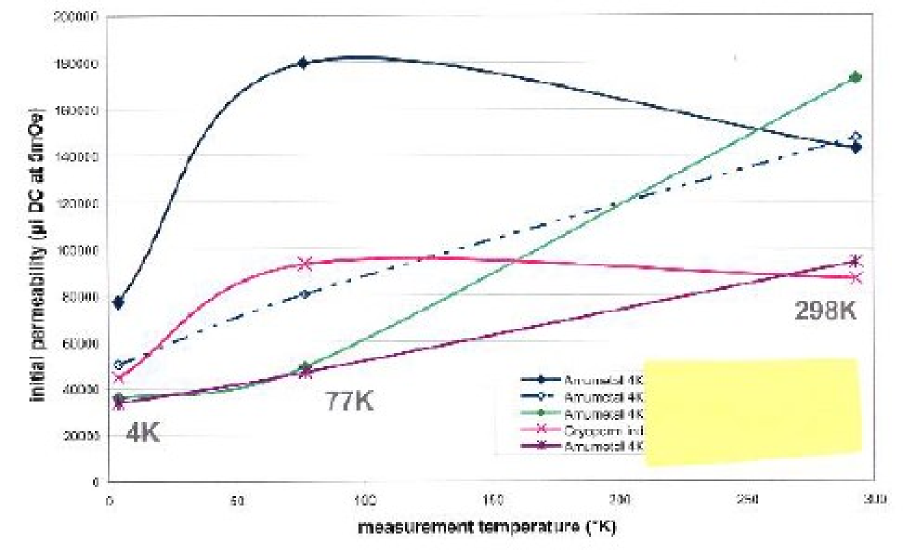


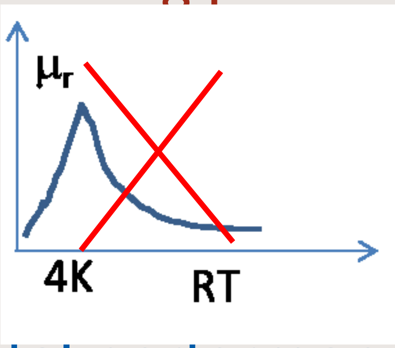


Sample	μ @ DC @ RT	μ @ DC @ 77K
A4K	58343	31701
Mu-metal	46377	16713
Cryoperm10	36352	25359

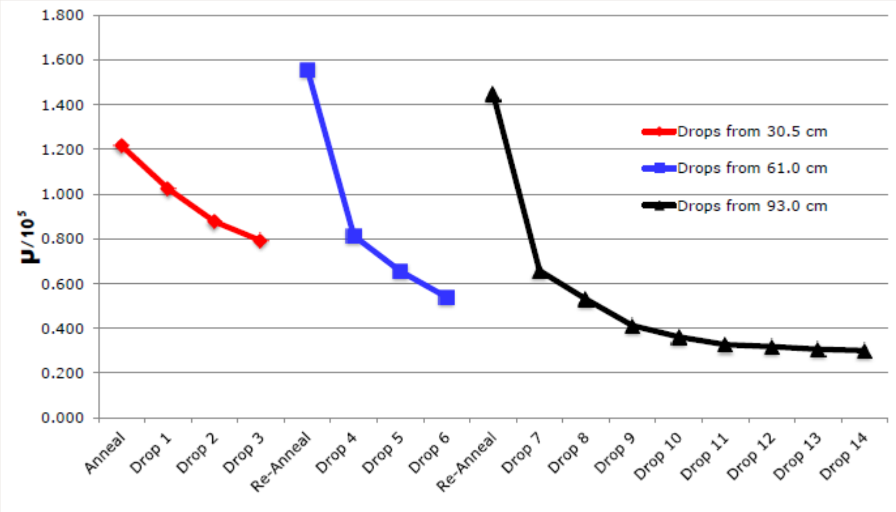
Mu-metal performance and handling

- Actual permeability and temperature performance very sensitive to the heat treatment and the cooling rate - Lessons learned: Do not assume that you always get the catalog performance.





- Mu metal performance also sensitive to handling – be careful



Conclusion

- Many new projects in progress or proposed will use superconducting solenoids in cryomodules

- Due to the interaction of residual and fringe fields with cavity performance it is important to pay attention during design and development – and to imagine mitigation strategies of potentially reduced Q during operation

- As cavity performances continue to improve reducing magnetic pollution will become increasingly more challenging

- Many common issues – people making or planning test facilities

Thanks, Merci

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- Kenji Saito (MSU) and workshop participants
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