FRIB

Magnetic Shield in FRIB

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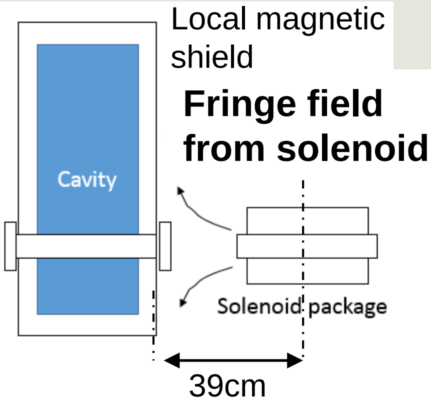
Story of FRIB Magnetic Shielding

Solved the coupled issue between magnetic shield and solenoid package design



Magnetic Shield Design Constraints

- Local magnetic shield (given)
  - Remnant field inside shield: < 15mG (given)
  - Exposed temperature ?,
- Solenoid nearby cavities (Interface is already fixed, shield surface at 39cm from a 50cm solenoid)
  - Allowed solenoid fringe field strength on the magnetic outer surface ?

(1) Experiment

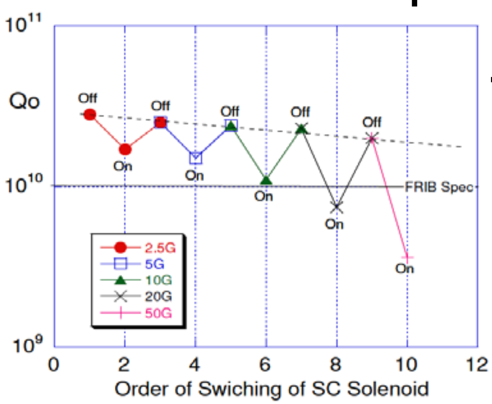
- Proof of local magnetic shield design concept

(2) Experiment Results

- Local magnetic shield is exposed 25 – 30K
- Allowed magnetic field strength inside shield when cavity quenched : 1G (Q_O of 0.53 HWR at 2K drops <10% by the flux trap)

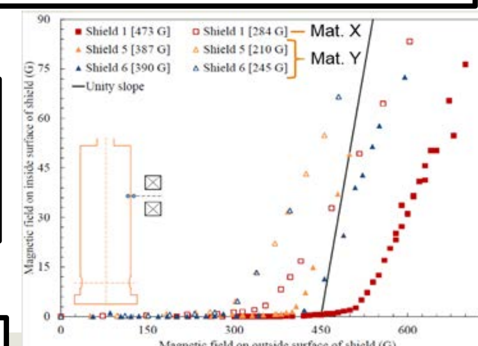
(3) Experiments of Temperature Dependence of Permeability (μ) and Field Penetration

- PC-permalloy μ ~ 10000 at 20K@500mG
- The fringe field strength on the shield surface must be smaller than the fringe field of 300G to suppress the penetration field into the shield < 1G



Solenoid Package Design

- Fringe field strength < 300G on the shield surface 39cm away from the 50cm solenoid center



Magnetic Shield Design

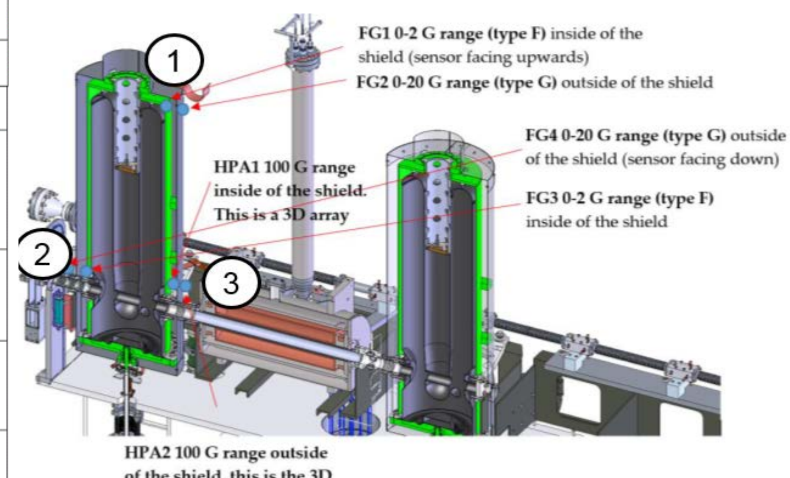
- μ = 9000, 1mm (QWRs) and 2.2mm (HWRs) thick
- Inside remnant field <15mG

FRIB

Successful Local Magnetic Shield Validation with ReA6-1 CM Bunker Test

- **ReA6-1 CM includes two 0.85QWRs and one 50cm** solenoid package between the cavities at one end side.
- **Local magnetic shield (A4K) validated by the ReA6-1**
  - Meets FRIB remnant field (2.5 mG) < 15 mG.
  - Very small field (162 mG) around cavity short area under 8T solenoid package operation, can expect no Q-drop at cavity quench.
  - Might not need degaussing process.
  - Confirmed local magnetic shield benefit.

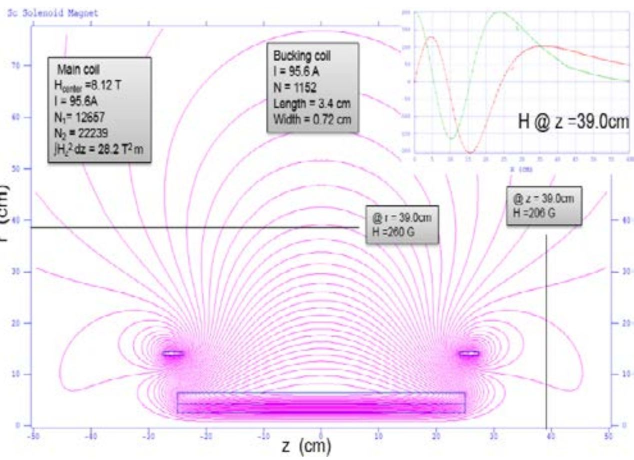
Process	Fluxgates (mG)				Hall probes (mG) at beam port facing solenoid (low sensitivity at small fields) ③							
	Top of cavity		Bottom of cavity		In				Out			
	In ①	Out	In ②	Out	X	Y	Z	Mag.	X	Y	Z	Mag.
After cool down (shield T=24.5 K)	2.5	8.1	3.0	209.3	-850	-370	240	958	0	1000	1000	1414
During solenoid operation	-161.6 ±1.2	-361.2 ±2.1	1659.5 ±20.7	872.0 ±20.2	-6253 ±979	-3000 ±2438	-11350 ±1382	13596 ±2246	-55000 ±2800	-29900 ±2524	-91100 ±860	110849 ±1459
After solenoid operation	30.7 ±0.6	27.6 ±1.2	15.9 ±1.2	290.9 ±0.3	770 ±800	4317 ±833	3133 ±289	5434 ±835	5400 ±2800	-1967 ±1701	7733 ±1097	9906 ±1999
After full degauss	4.2 ±0.7	8.7 ±1.1	0.5 ±1.7	207.6 ±1.6	103 ±907	4133 ±1828	2667 ±2060	5058 ±2519	1933 ±2483	-4000 ±3378	-2767 ±3402	6719 ±1588
After CM warm-up	0 ±0.1	-5 ±0.1	0.6 ±0.1	205 ±0.1	16708 ±83	13845 ±67	7278 ±51	22887	-22061 ±90	-1836 ±62	-5217 ±74	22744



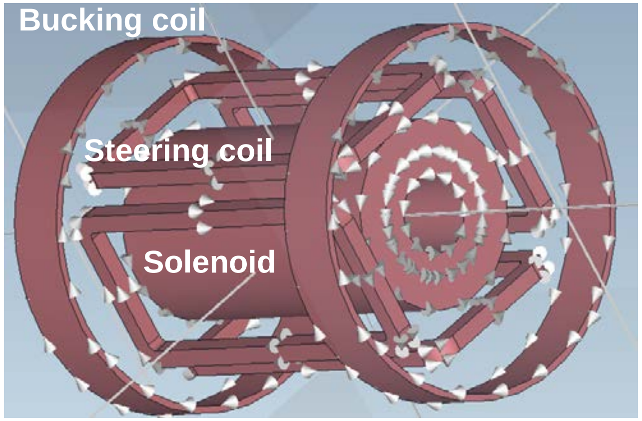
Superconducting Solenoid Package Design
Use bucking coil, Iron York free, Fringe field < 300G at the magnetic shield surface

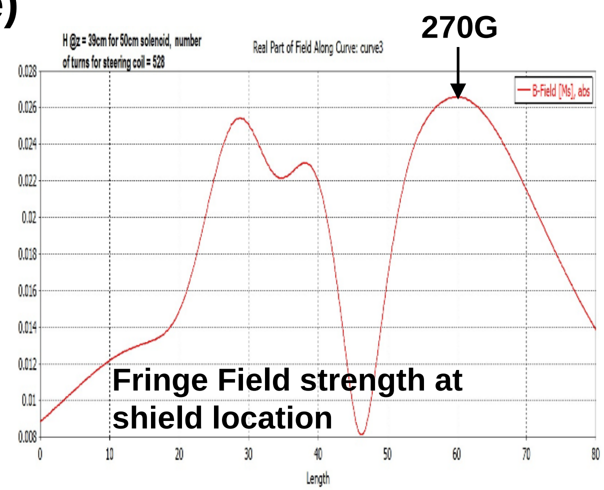
- Iron yoke free solenoid design has been completed with bucking coil
- 3D simulation by CST Studio shows the fringe field of 270G on the magnetic shield
- Fringe field of 100G exposes outside shield around the high RF magnetic area

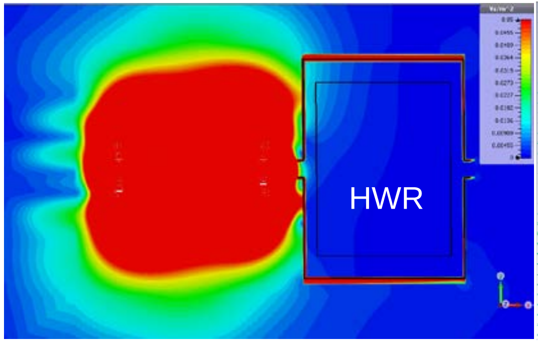
Poisson 2D

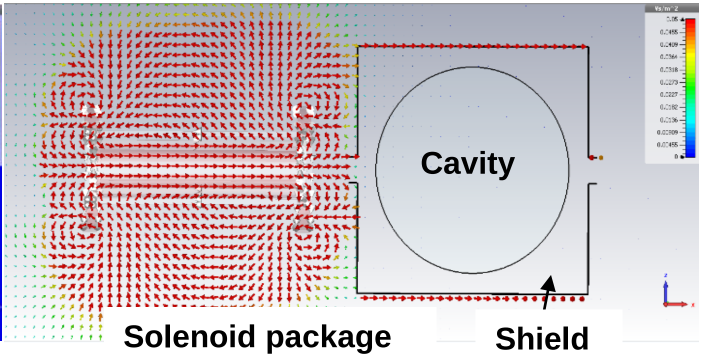


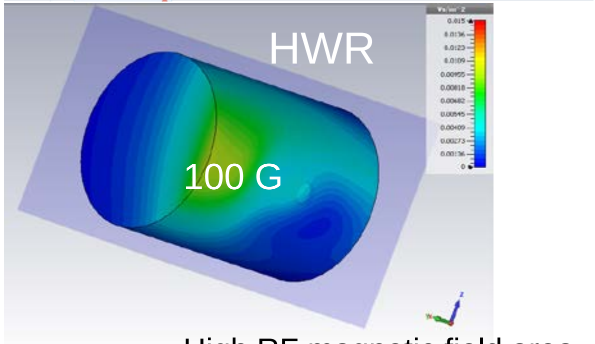
CST Studio 3D (solenoid package)









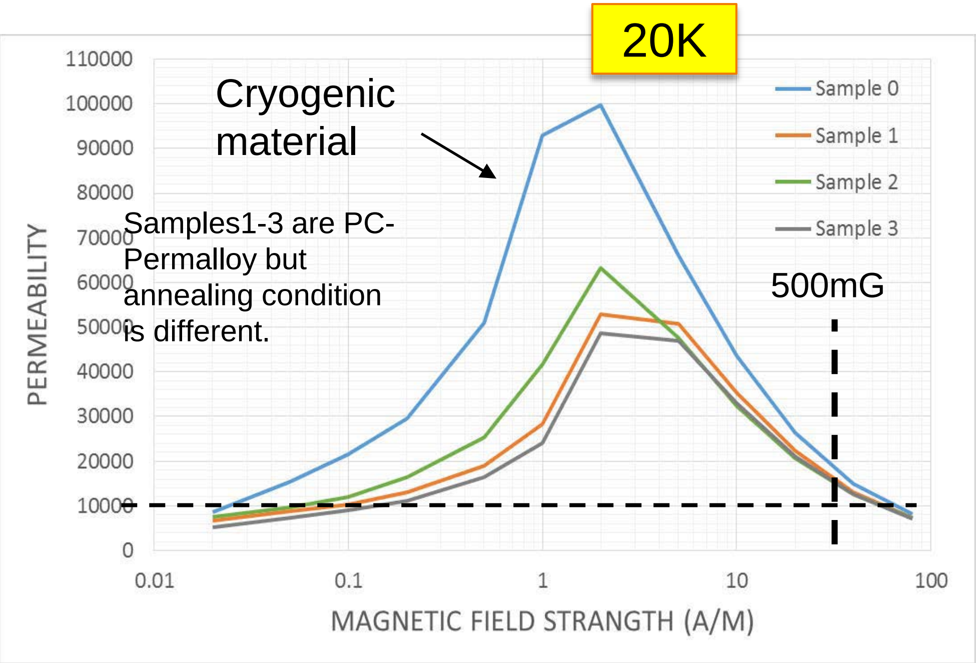


High RF magnetic field area

Conventional Mu-metal for FRIB Cryomodule
Mu-metal was selected for FRIB local magnetic shields for cost-effective way

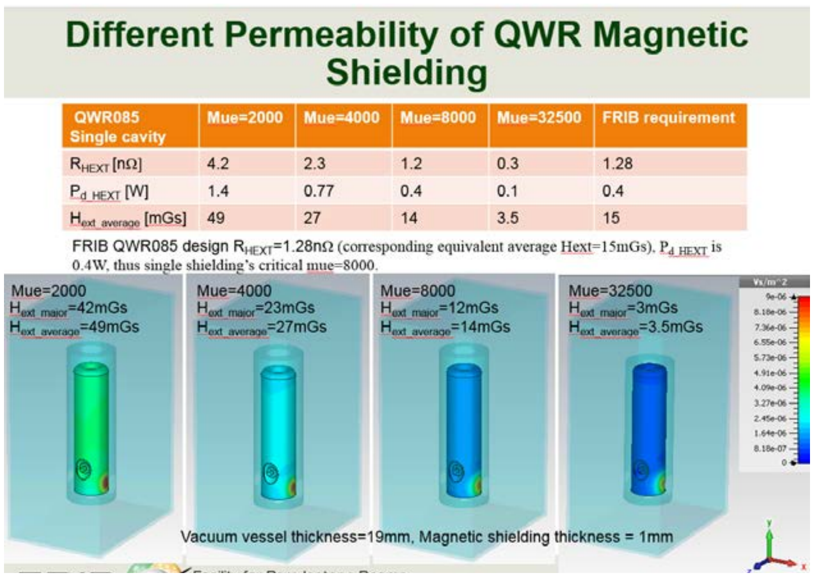
- **Cold performance measurement of Mu-metal**
  - PC - Permalloy (Mu-metal) was measured at 4.2 K in KEK 2014 by M. Masuzawa and K. Tsuchiya, the results showed that $\mu >$ 9000 under 500mG (40 Am).
  - Again PC - Permalloy has been measured at 20K in KEK 2015 by M. Masuzawa and K. Tsuchiya (KEK/MSU collaboration), the results:

    $\mu >$ 10000 under 500mG (40Am).
  - Cryogenic material has little benefit (10-20%) under the these condition.
- **Mu-metal could be acceptable for FRIB spec < 15mG in the shield, if magnetic shield is carefully designed.**



FRIB Magnetic Shield Designs
Example 0.085QWR

- **Magnetic shield design with FRIB QWR cryomodule**
  - This simulation includes the Earth magnetic field (500 mG), vacuum steel vessel, magnetic shield (1 mm thick), and cavity (full simulation). The result shows that μ=8000 meets the FRIB request (< 15 mG inside magnetic shield) for single shield.
  - For the triple shield, if an additional shield is put between the cavity magnetic shield, μ=9000 can meet FRIB specification (< 15mG).



QWR085 Single cavity	Mue=2000	Mue=4000	Mue=8000	Mue=32500	FRIB requirement
R_{HEXT} [nΩ]	4.2	2.3	1.2	0.3	1.28
$P_{d\ HEXT}$ [W]	1.4	0.77	0.4	0.1	0.4
$H_{ext\_average}$ [mGs]	49	27	14	3.5	15

Figure 1: Simulation of magnetic shield for FRIB 0.085QWR magnetic shield, μ=8000 meets FRIB request.

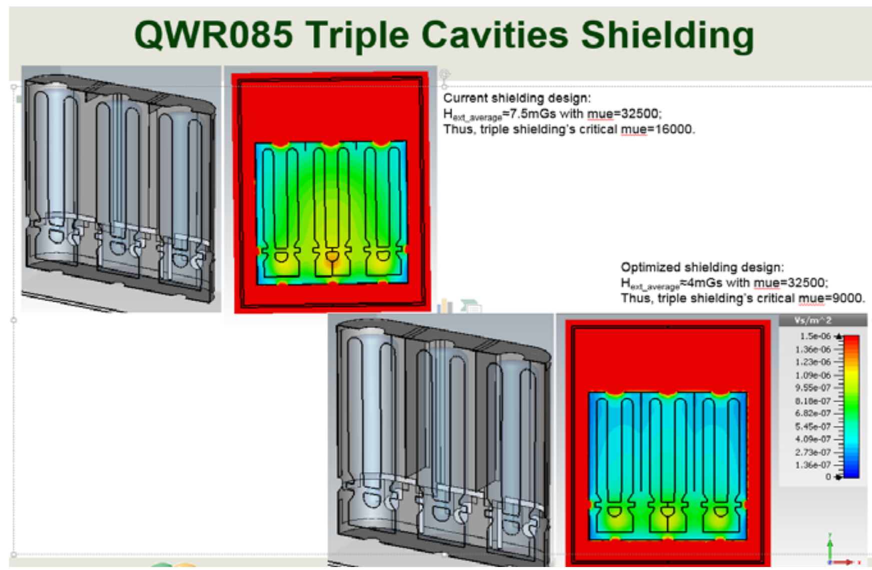


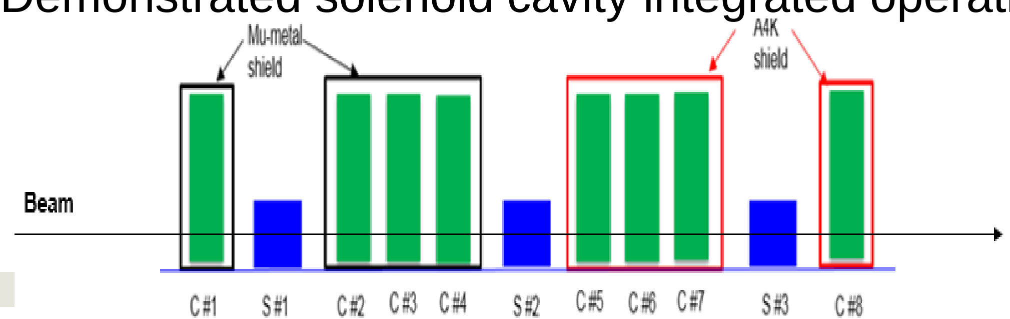
Figure 2: Additional shield between cavity magnet shield reduce the acceptable μ to 9000.

Certification of Mu-metal Shield and 50cm Solenoid Packages

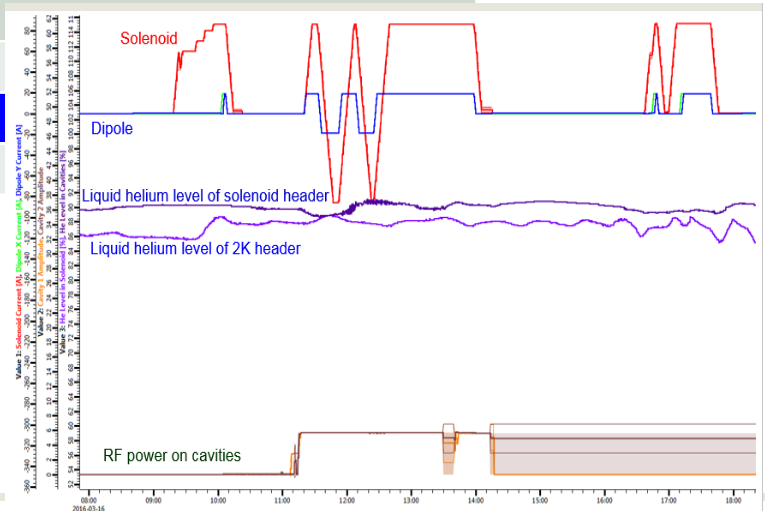
- Certification of mu-metal magnetic local shielding and solenoid packages
  - A4K magnetic shields for 4 cavities and Mu-magnetic shields another 4 cavities with SCM801
  - Compared the cavity 2K dynamic losses: **Any visible Q_O degradation was not observed in Mu-metal shields**

Cavity/ solenoid package	Magnetic shield	2K dynamic heat load at 5.6MV/m, FRIB spec Q_O=1.8E+9, 3.85 W
Cavity #1	Mu-metal	6.2 W (Q_O=1.11E+9), Q_O at VTA also worth (low Q-issue)
Solenoid#1		
Cavity #2	Mu-metal	2.4 W (Q_O=2.9 E+9)
Cavity #3		2.5 W (Q_O=2.8 E+9)
Cavity #4		1.0 W (Q_O=6.9 E+9)
Solenoid#2		
Cavity #5	A4K	2.4 W (Q_O=2.9 E+9)
Cavity #6		2.5 W (Q_O=2.8 E+9)
Cavity #7		2.4 W (Q_O=2.9 E+9)
Solenoid#3		
Cavity #8	A4K	2.6 W (Q_O=2.7 E+9)

- Demonstrated solenoid cavity integrated operation



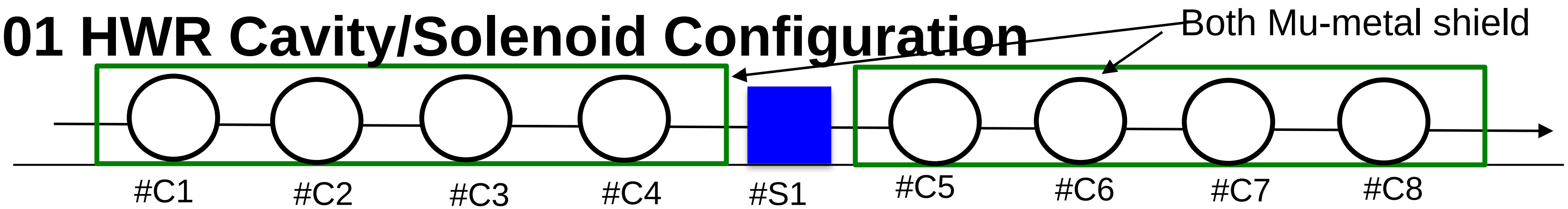
SCM801: A4K shield for 4 cavities and Mu-metal shied for another 4 cavities



50cm solenoid package operation at 8T: Demonstrated robust and stable operation with cavities at 5.6MV/m

Certification of Mu-metal shield and Solenoid Package with 0.5HWR cryomodule

▪ SCM501 HWR Cavity/Solenoid Configuration



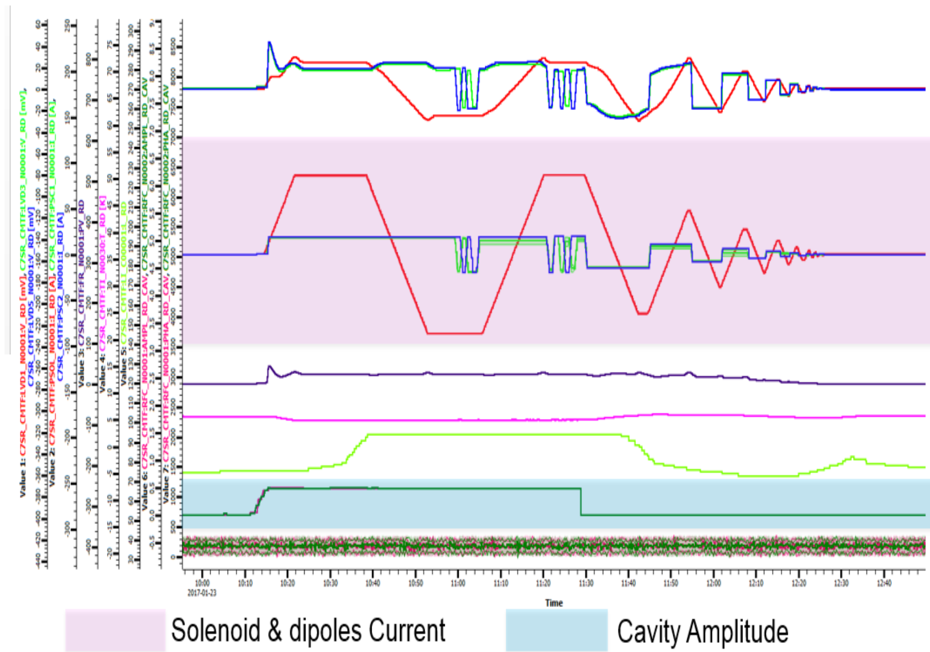
- Eight 0.53HWRs (#C1 - #C8) and one solenoid package (#S1)
- PC-Permalloy (Mu-metal) local magnetic shield

▪ Solenoid package test

- Solenoid and dipoles energized up to 8 T (87A), and 0.064Tm (19A, respectively.
- Integral operation with solenoid package (8T) and cavities (~7.5 MV/m). Solenoid package and cavities are very stable.

▪ Thermal cycle test

- After degaussing the solenoid package, warmed up to 30K and re-cold tested at 2K
- Cavity 2K dynamic loss was'nt changed, no impact with solenoid operation on the cavity performance.
- Not yet know whether the degaussing is needed or not.



Solenoid package bunker test results

Results in the FRIB Production

High Q performance is preserved in FRIB production cryomodules

1) NO Q_O degradation is observed by flux trapping between VTA and bunker test for both A4K and PC-Permalloy magnetic shield

Cavity Type	Shield material	Tested cryomodule	Q_O in VTA 2K	Q_O in CM 2K
0.041QWR	PC-Permalloy	4	$5.7 \pm 0.7 \times 10^9$	$> 2.9 \pm 2.0 \times 10^9$
0.085QWR	A4K	11	$4.0 \pm 1.0 \times 10^9$	$> 3.5 \pm 1.5 \times 10^9$
0.29HER	PC-Permalloy	9	$1.4 \pm 0.2 \times 10^9$	$2.2 \pm 0.7 \times 10^9$
0.53HWR	PC-Permalloy	2	$1.9 \pm 0.3 \times 10^9$	$2.0 \pm 0.6 \times 10^9$

2) Cavities are stably operated at the FRIB operation gradient under 8T solenoid operation.

3) NO Q_O degradation is observed by flux trapping in a thermal cycle (only one test with CSM501):
RT → 2K → degauss → 30K → 2K

4) Not yet confirmed whether the degaussing after the solenoid operation can be saved or not.

PC-Permalloy magnetic shield on a 0.53HWR cryomodule

Summary

- FRIB has carefully designed superconducting solenoid packages and magnetic shields.
- FRIB mainly uses PC – Permalloy with μ ~ 10000 (20K) for the local magnetic shields.
- High Q cavity performance by the local magnetic shield is validated in the FRIB production cryomodules.