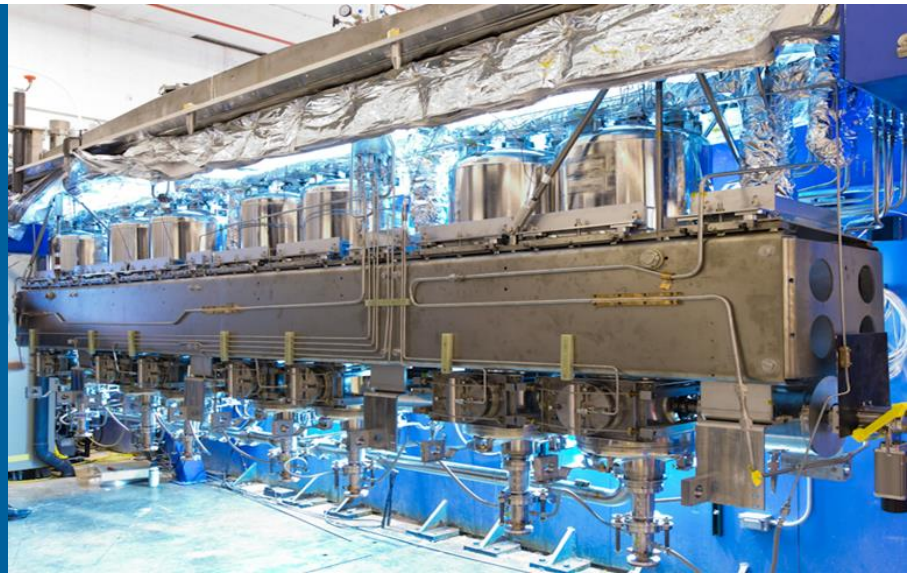
28TH LINEAR ACCELERATOR CONFERENCE (LINAC16)

Argonne NATIONAL LABORATORY

INTEGRATION OF SUPERCONDUCTING SOLENOIDS IN LONG CRYOMODULES



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OUTLINE

- Introduction
- Superconducting (SC) Solenoids in ‘Low-beta’ Cavity Cryomodules
- Experimental Study with SC Solenoids at ANL
  - Alignment inside the Cryomodule
  - Impact of Stray Magnetic Fields on the SRF Cavity
- Summary

INTRODUCTION

- **Superconducting (SC) Solenoid in Low-beta Cavity Cryomodule**
  - Ion linacs in the low-beta regime require use of focusing elements between every ~1-4 cavities to minimize emittance growth and beam loss
  - Using SC solenoids, multiple cavities can be packed into one cryomodule: a cost-effective way to build and maintain long linacs
  - SC solenoid with fields up to ~10 T are well established, however, important issues need to be addressed for applications in real cryomodules:
    - **Alignment after cooldown**
    - **The impact of stray magnetic fields on the SRF cavity**
  - We present experimental studies at ANL using
    - 9 T SC solenoids in the **ATLAS Intensity Upgrade Cryomodule,**
    - 6 T SC solenoids with integrated dipole steering coils in the **Proton Improvement Plan 2 Half-Wave Resonator (PIP-II HWR) Cryomodule** for Fermilab

      (THPLR027: Z.A. Conway, "Progress Towards a 2.0 K Half-Wave Resonator Cryomodule for Fermilab's PIP-II Project")

SC SOLENOIDS IN CRYOMODULES

Currently operational/ under commissioning relatively lower intensity ion accelerators (beam current < ~1 mA)

ATLAS Energy Upgrade Cryomodule:
A 9 T Solenoid with
7x β=0.15 109 MHz QWRs

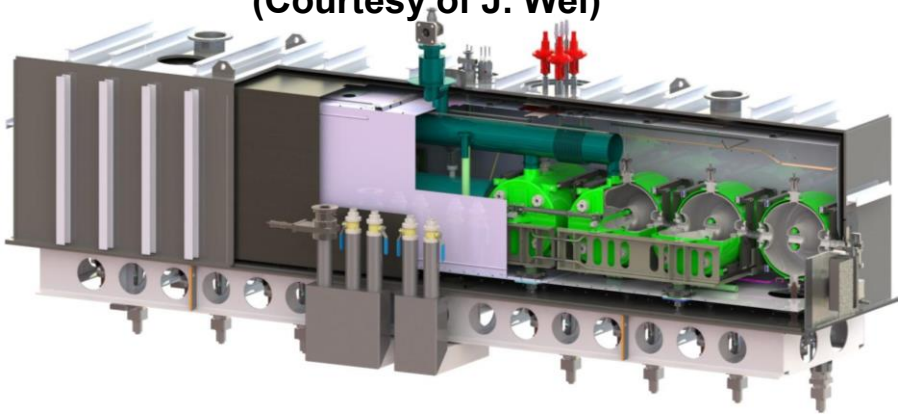
ISAC-II SSC I Cryomodule:
A 9 T Solenoid with
6x β=0.11 106 MHz QWRs
(Courtesy of R.E. Laxdal)

HIE-ISOLDE High Beta Cryomodule:
A 8 T Solenoid with
5x β=0.10 101 MHz QWRs
(Courtesy of W. Venturini Delsolaro)

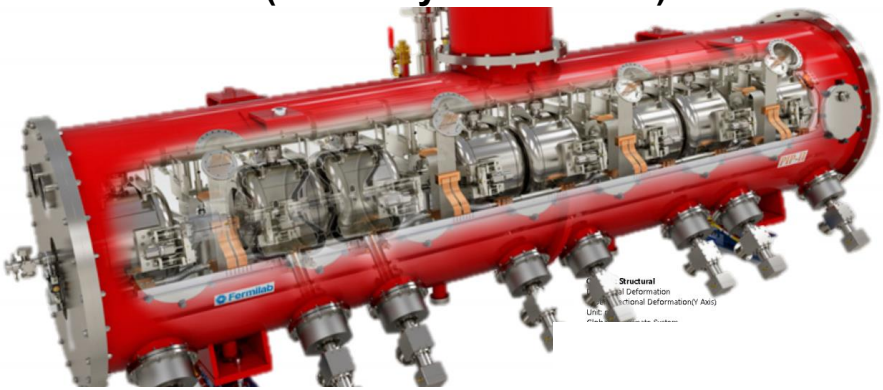
SC SOLENOIDS IN CRYOMODULES (continued)

Under construction/planned high intensity ion accelerators (beam current > ~1 mA)

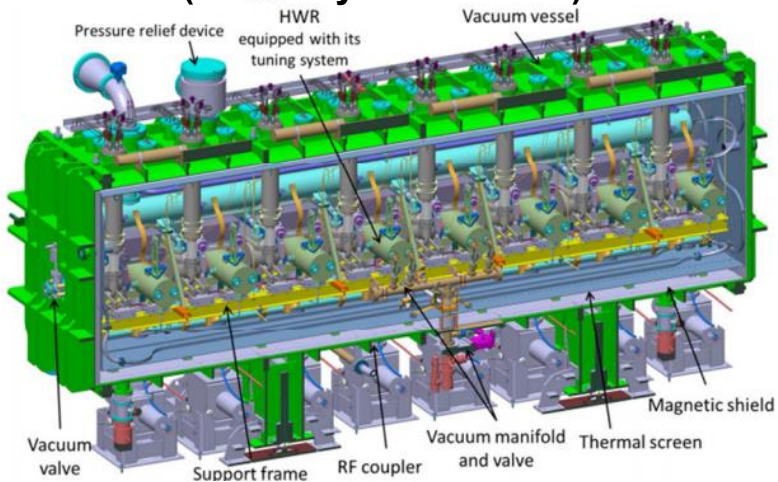
FRIB HWR Cryomodule:
A Solenoid with 8x β=0.53 322 MHz SSRs
(Courtesy of J. Wei)



PIP-II SSR1 Cryomodule:
4x Solenoids with 8x β=0.22 325 MHz SSRs
(Courtesy of L. Ristori)



IFMIF LIPAc Cryomodule :
8x Solenoids with 8x β=0.11 175 MHz HWRs
(Courtesy of H. Dzitko)



IMP ADS HWR010 Cryomodule :
6x Solenoids with 6x β=0.1 162 MHz HWRs
(Courtesy of Y. He)

ALIGNMENT REQUIREMENTS

- Alignment is necessary to suppress emittance growth and reduce beam loss

Alignment Tolerances

Coordinate	ATLAS Intensity Upgrade Cryomodule* (7 QWRs + 4 Solenoids)	PIP-II HWR Cryomodule (8 HWRs + 8 Solenoids)
X/Y	±0.25 mm RMS	±0.25 mm RMS
Z	±1 mm RMS	±0.5 mm RMS
Pitch/Yaw/Roll	±0.1° RMS	±0.1° RMS

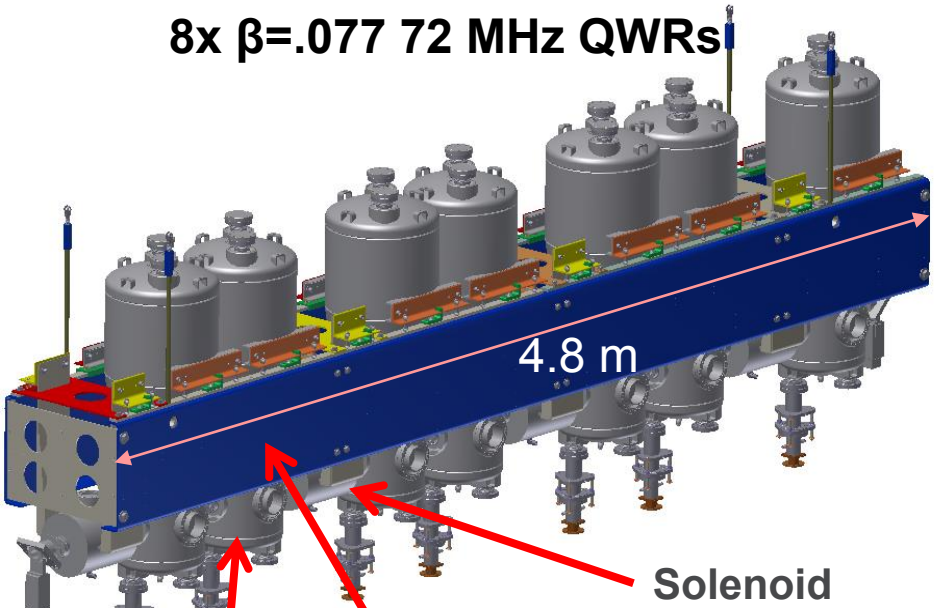
* These are for solenoids; Cavities have 4 times looser transverse/angular tolerances

- The other high intensity ion linacs require similar tolerances:

	Alignment Tolerances	Ion Species	Beam Energy and Current
FRIB	±1 mm	p to U	200 MeV/u, 0.7 mA (U)
IFMIF	±1 mm	p or d	9 MeV, 125 mA (d)

KINEMATIC MOUNT

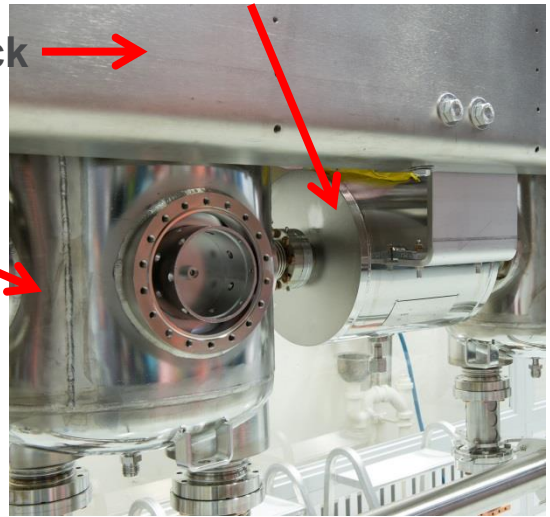
ATLAS Intensity Upgrade Cryomodule:
4x 9 T Solenoids with
8x β=.077 72 MHz QWRs



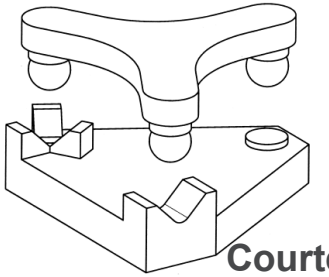
Solenoid

Strongback

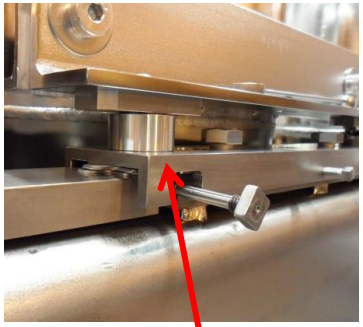
Cavity



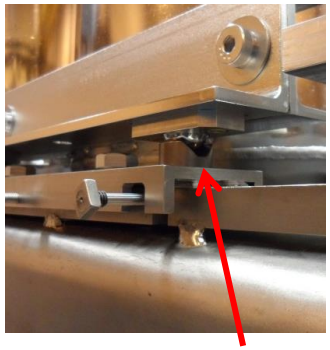
Kelvin Type Kinematic Coupling for Solenoid/Cavity Mount



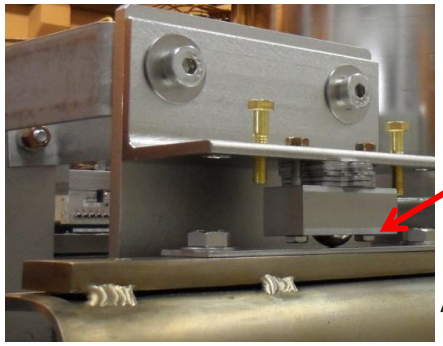
Courtesy of Hale (2001)



Ball in Ring



Ball on Vee



Ball on Flat Surface

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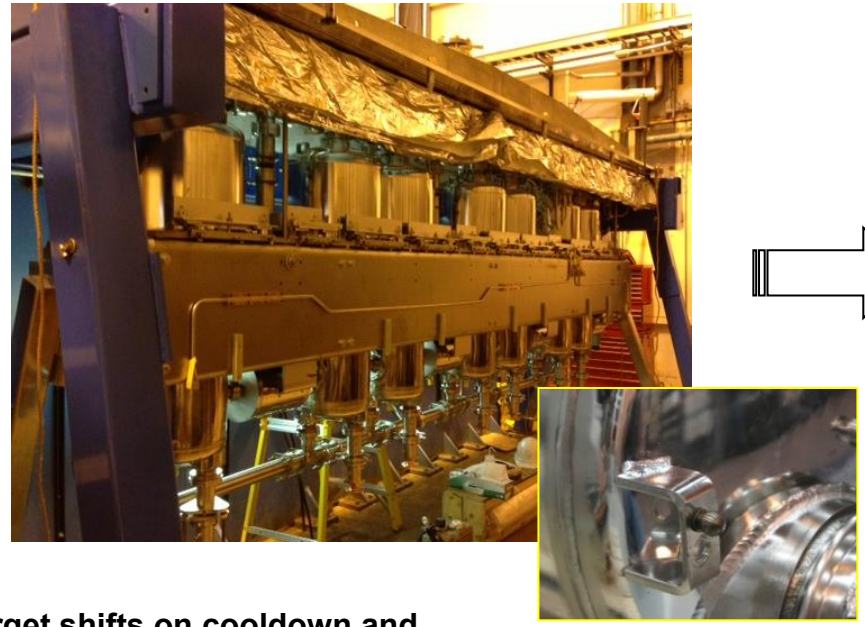
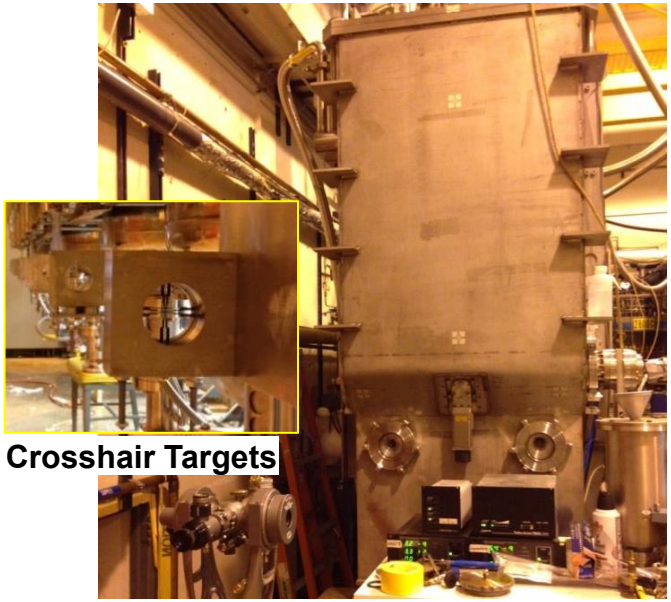
ALIGNMENT RESULTS

Room Temperature Fine Alignment



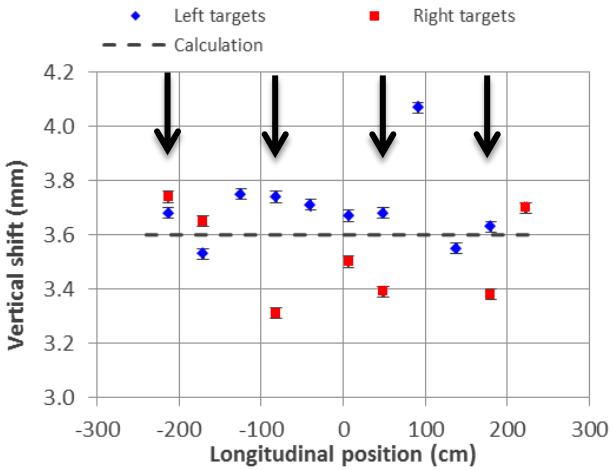
Fiducials on Cavity

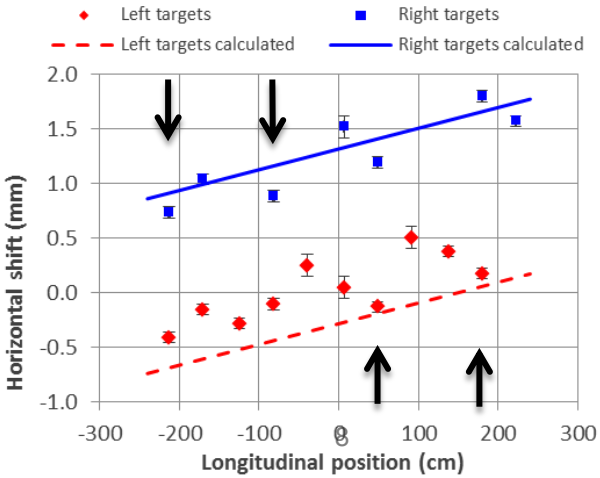
Measurements of Shifts on Cooldown



Crosshair Targets

Target shifts on cooldown and evacuation of insulation vacuum





RMS Alignment Results at Cold
(RMS deviations from the beam axis)

	Solenoids	Cavities
Horizontal*	0.12 mm	0.50 mm
Vertical	0.18 mm	0.28 mm

* The yaw of the whole cavity string is assumed to be compensated by adjusting the cryomodule

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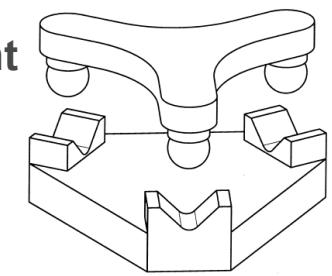
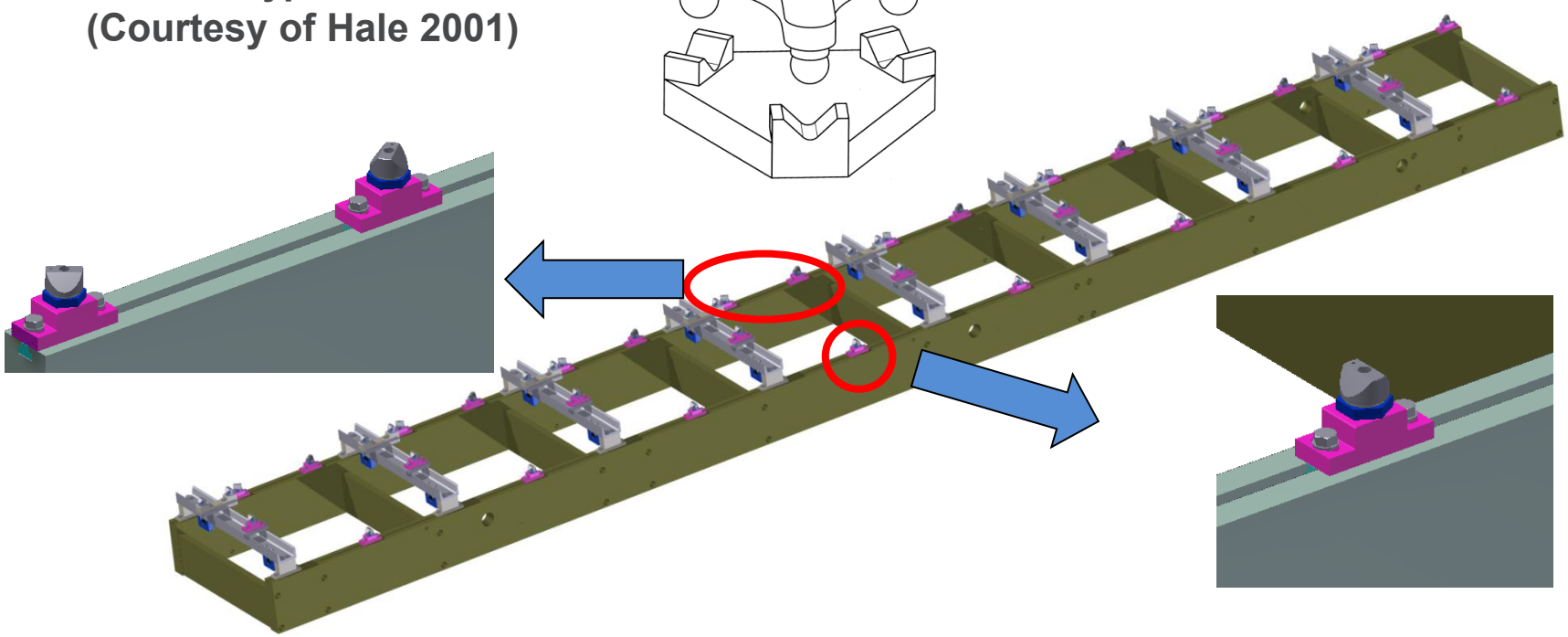
IMPROVEMENTS FOR THE NEXT CRYOMODULE

PIP-II HWR Cryomodule

- Machined stock Ti bars are used for the strongback. Less effort is required for the room temperature alignment with the improved position adjustment system.
- A Maxwell kinematic coupling system is used for cavity and solenoid mounts. The beam axis will not have thermally-induced motion on the kinematic mount plane.
- 4 targets will be attached per each cavity and solenoid. Changes in pitch and yaw can be monitored on cooldown.

Maxwell-type Kinematic Mount (Courtesy of Hale 2001)





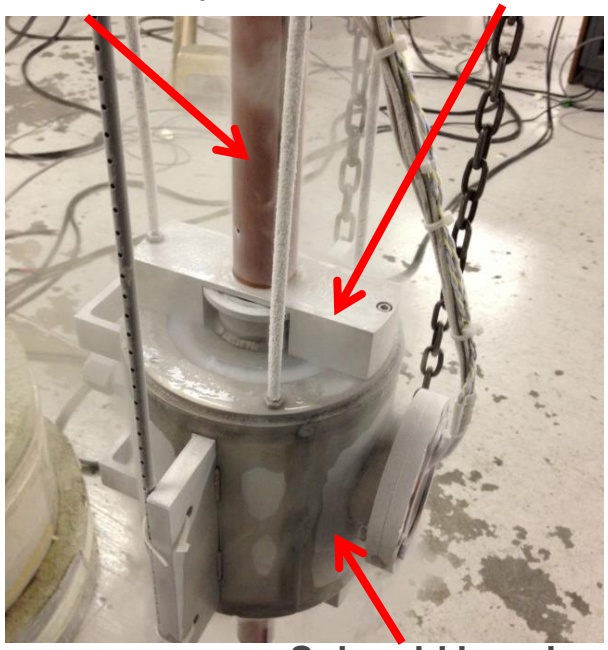
MAGNETIC AXIS OF SOLENOIDS

Measured the magnetic axis referenced to the mechanical axis at cold

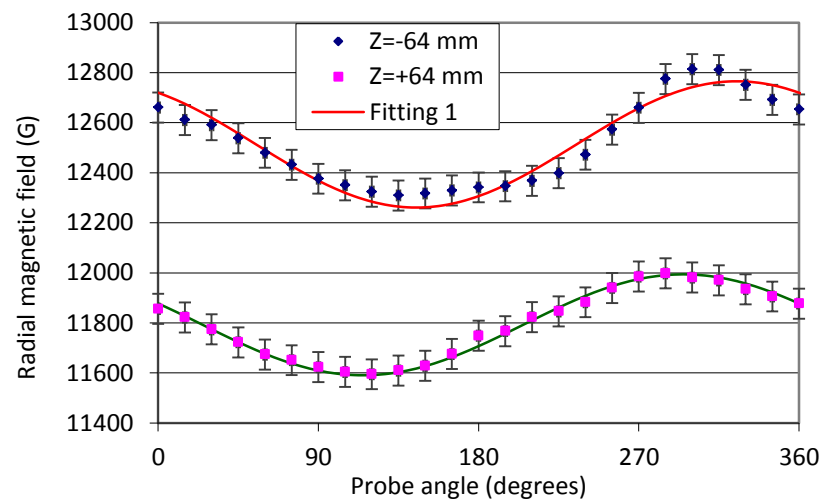
- Angular scan of the radial component of the fringe field
  - $B_r \propto r$ (r: radial coordinate)
  - The fractional oscillation amplitude represents the radial offset and the 'phase' represents angular offset of the magnetic axis

Rotating rod: Bakelite (Hall sensor attached)

Rotation guide: Aluminum



Solenoid housing: Stainless steel 304



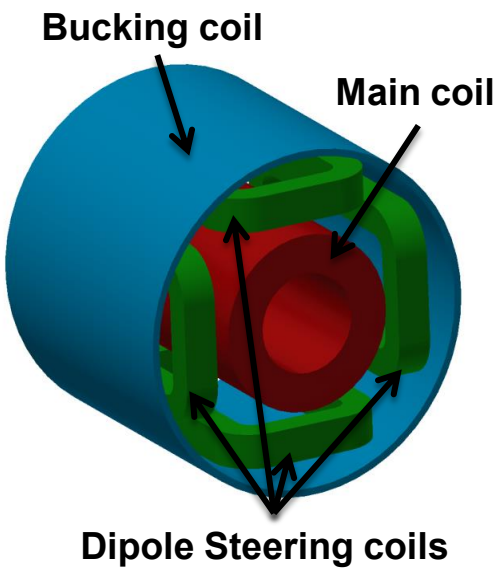
Magnetic Centers at flanges (unit: mm)		
	x	y
Flange 1	-0.30 ± 0.07	0.17 ± 0.04
Flange 2	-0.08 ± 0.02	0.26 ± 0.07

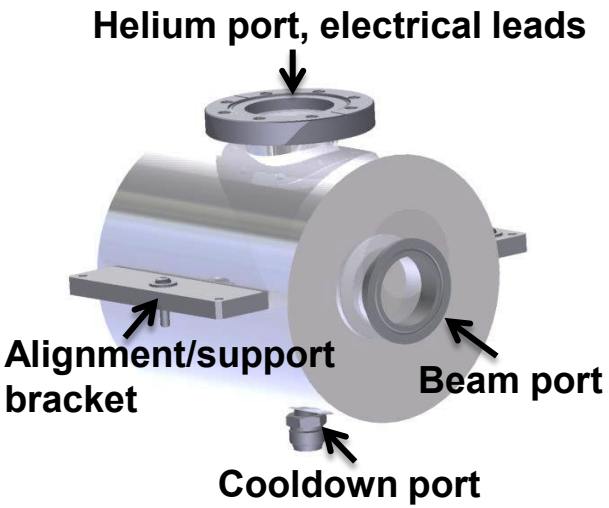
SC SOLENOID WITH INTEGRATED DIPOLE STEERING COILS

- Allows to additionally improve packing efficiency of an accelerator
- 8 Solenoids are assembled in the PIP-II HWR Cryomodule together with 8x β=0.11 162.5 MHz HWRs

Solenoid	Solenoid Field B_S	6 T max
	$\int B_S^2 \cdot dz^{(1)}$	3.6 $T^2 \cdot m$ max
	Current	82 A max
X/Y Steering Coils	Dipole Field B_X	0.2 T max
	$\int B_X \cdot dz^{(2)}$	0.037 T·m max
	Current	50 A max
Bore Diameter of Housing		35 mm

(1) $f_s \approx 0.13\ m$ and
(2) $\Delta\theta \approx 0.1\ rad$ for $\beta = 0.11$ proton





POSSIBLE IMPACTS ON THE CAVITY DUE TO STRAY MAGNETIC FIELDS

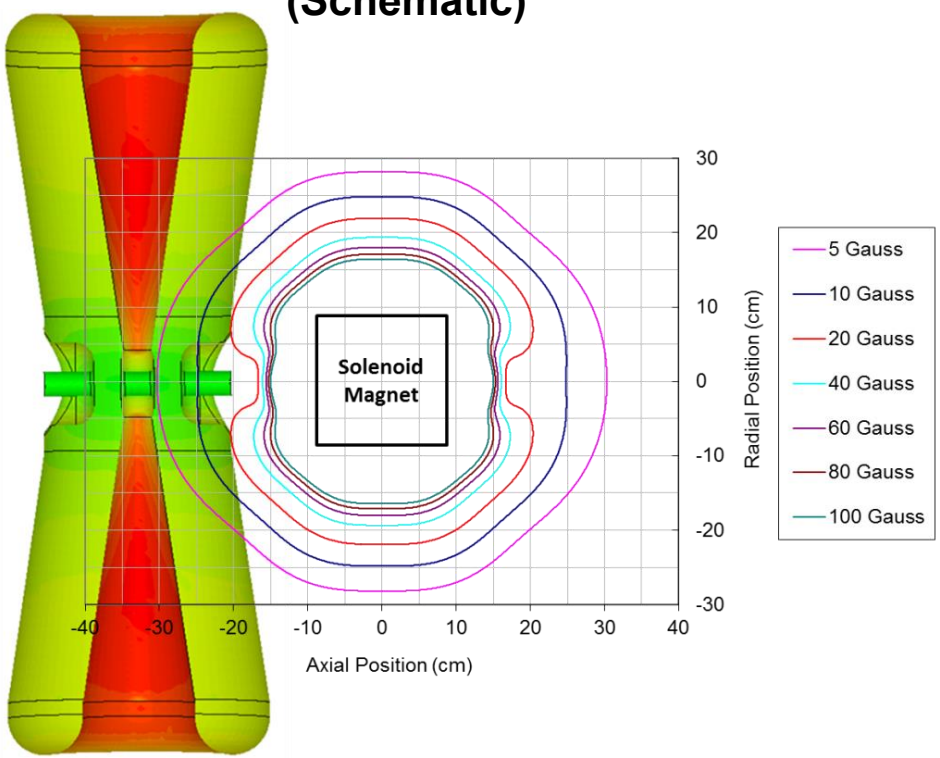
- **High Stray Magnetic Field on the Cavity Niobium Surface**
  - Increase RF losses and reduces thermal breakdown (quench) threshold of the cavity
  - Solution: Use return (bucking) coils to minimize stray field
- **Magnetization of Materials in the Vicinity of the Cavity**
  - Materials around the cavity are magnetized by the solenoid field, if not highly non-magnetic
  - The magnetic field generated by such magnetized materials can be trapped on the cavity niobium surface during cooldown; this will leads to increase of the residual resistance ($R_H \approx 1.2\ n\Omega\ @\ H_{ext} = 10\ mG, f = 162\ MHz$)
  - Solution: Degaussing cycles of the solenoid to prevent magnetization
- **Magnetic Flux Trapped due to Cavity Quench**
  - Cavity quench may happen in the presence of the solenoid field
  - Magnetic flux produced by the solenoid can be trapped through the 'normal conducting opening' on the cavity surface, if solenoid field at such location is not negligible
  - At ANL, we measured this effect to see how strong it is in our cavity

SOLENOID FIELD WITH BUCKING COIL

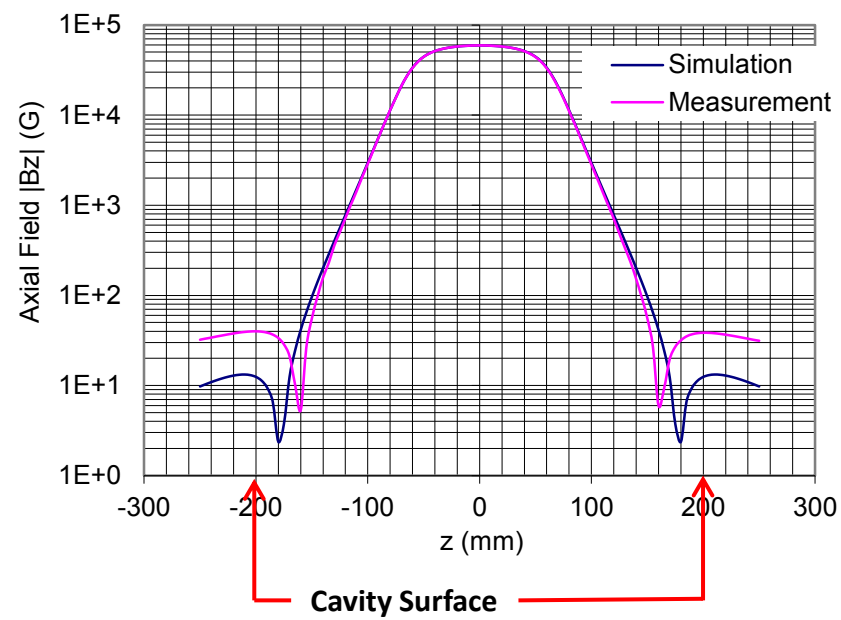
Minimization of the stray field

- Stray field on the cavity niobium surface is much smaller than the critical field of niobium so no measurable change in the cavity quench limit
- Used 304 stainless steel housing; No iron shield or return yoke is used

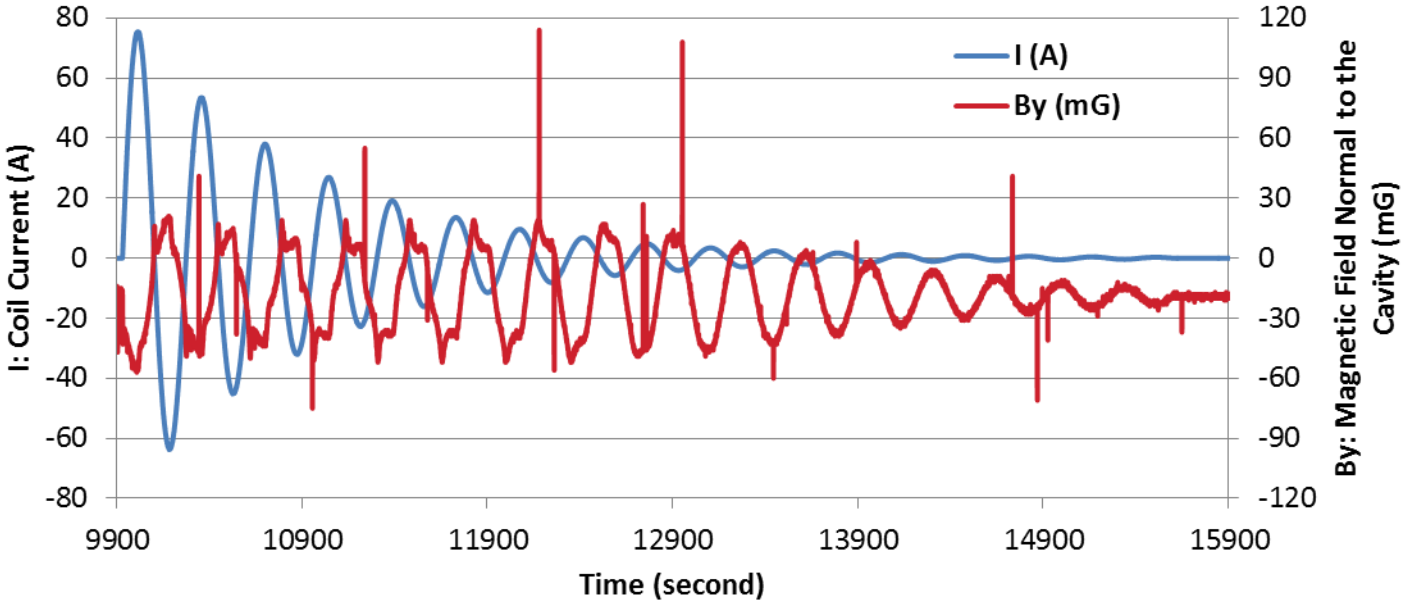
Stray Field Map in PXIE Cryomodule (Schematic)

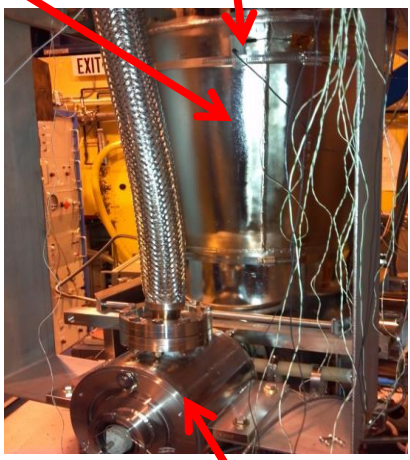


On-axis Field (Simulation and Measurement)

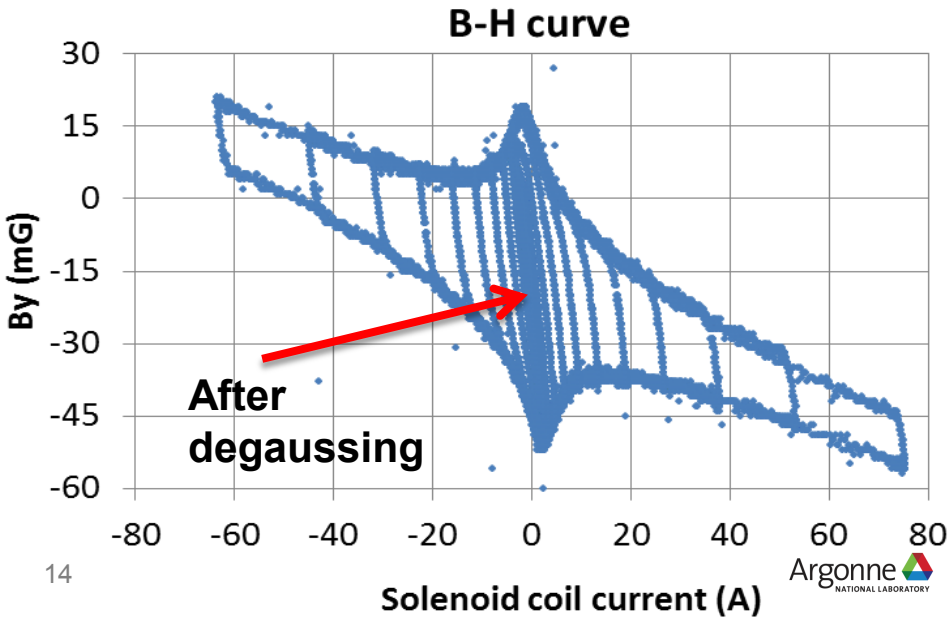


DEGAUSSING





- A strong source of measured magnetization is the superconducting NbTi. This disappears upon warm up. Even though there is small contribution from magnetic materials, magnetization is reduced by degaussing
- A manual survey after opening the cryostat indicated no measureable magnetization after running the degaussing cycle

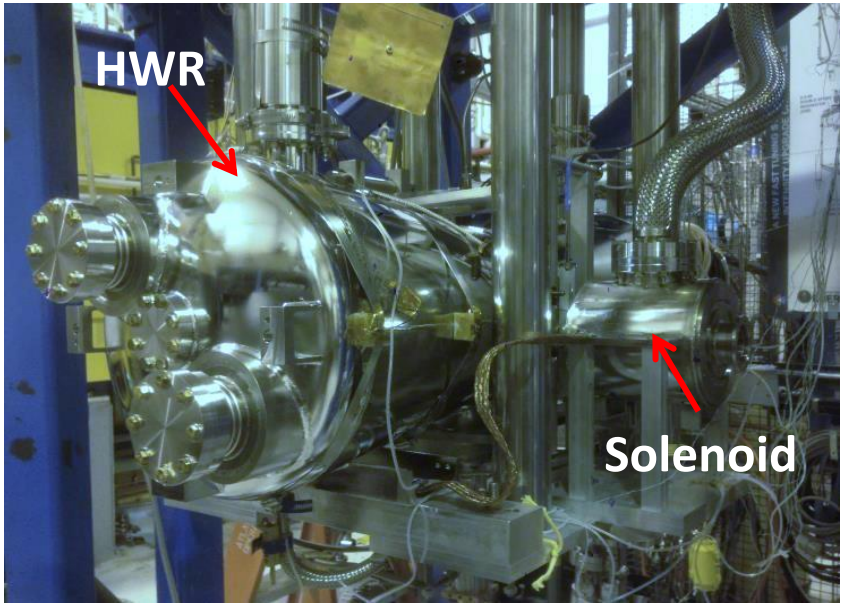


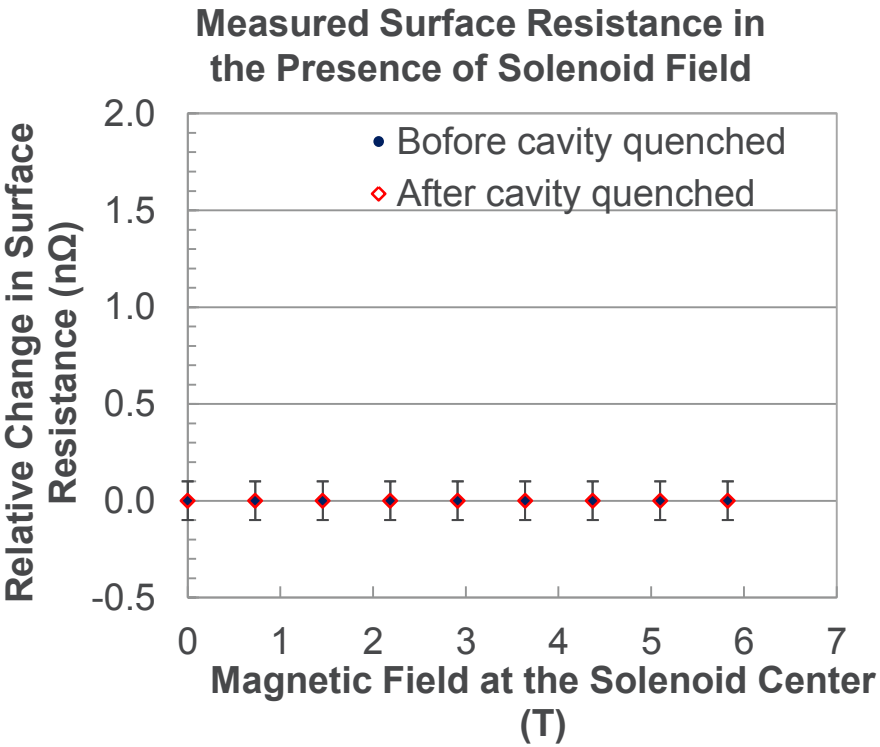
CAVITY QUENCH IN THE PRESENCE OF SOLENOID FIELD

No Measurable Change in Residual Resistance

- For the indicated orientation, no change in RF surface resistance was measured with a sensitivity of ±0.1 nOhm when cavity was quenched and recovered back to the superconducting state in the presence of the solenoid field

PXIE Solenoid Assembled Together with the HWR in a Test Cryostat, Similar to the PXIE HWR Cryomodule

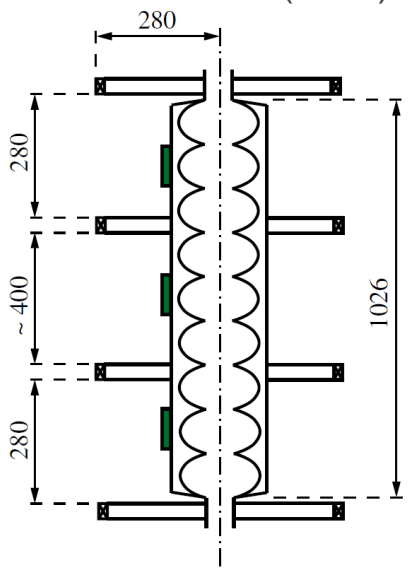


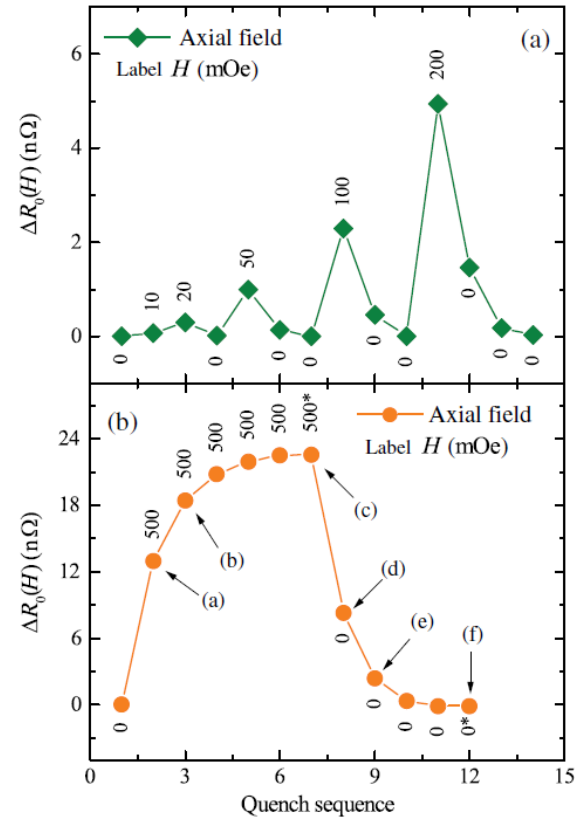


POSSIBLE REASONS FOR Q PRESERVATION

- Other studies show magnetic flux can be trapped through the normal conducting 'opening' when cavity is quenched in the presence of the magnetic field

Courtesy of M. Checchin, "Quench-Induced Degradation of the Quality Factor in Superconducting Resonators (2016)





- The **Q preservation in our cavity** is due to a combination of
  - **Low stray fields**
  - **The favorable location of the quench and normal conducting 'opening'**

SUMMARY AND CONCLUDING REMARK

- Alignments of the SC solenoids
  - Achieved alignments within ±0.25 mm RMS at cold

- The SC Solenoid with the integrated dipole steering coils
  - Stray field is sufficiently low so no measurable changes in the cavity quench limit was found
  - Degaussing successfully demagnetized materials magnetized by the peak solenoid field
  - In our HWR, it is found the Q is preserved when the cavity is quenched in the presence of the solenoid field

- Based on these results, SC solenoids are suitable focusing magnets in a long cryomodule

ACKNOWLEDGEMENTS

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