Radiation Challenges in the FCC-hh Magnets and Highlights from RESMM Workshops

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Fermilab

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Outline

- Sources of Backgrounds and Radiation Loads
- Protecting Collider Components against Radiation
- Operational and Lifetime Radiation Loads
- Synchrotron Radiation at FCC-hh
- FCC-hh vs HL-LHC
- Overview of RESMM Workshops

Sources of Detector Backgrounds and Radiation Loads to Magnets in Colliders

Collision debris from IP are the major source (>99%) in IRs. The multi-stage collimation system takes care of beam losses in the machine from the majority of other sources. Still the following processes contribute to backgrounds and radiation loads:

1. **Beam-gas:** products of beam-gas interactions in straight sections and arcs upstream of the experiments and after the cleaning insertions
2. **Tertiary beam halo** escaping the collimation systems ("collimation tails")
3. **Cross-talk between experiments at different IPs**
4. **"Kicker prefire"**: any remnants of a mis-steered beam uncaptured in the beam dump system
5. **FCC-hh:** synchrotron photons

Collider Magnet Protecting Components

- **IP Collision Debris:**
  - 0.95 kW LHC, 4.76 kW HL-LHC and 43.2 kW FCC on each side of IP
  - Inner triplet (IT): front absorber (TAS, L~20m), large-aperture quads with tungsten inner absorbers, absorbers in interconnect regions
  - Neutral beam dump (TAN, L~147m) and Single-Diffraction collimators in dispersion suppression regions (TCL, L~149 and 190m)
- **Beam Loss:**

L is a distance from IP1/IP5 in LHC and HL-LHC

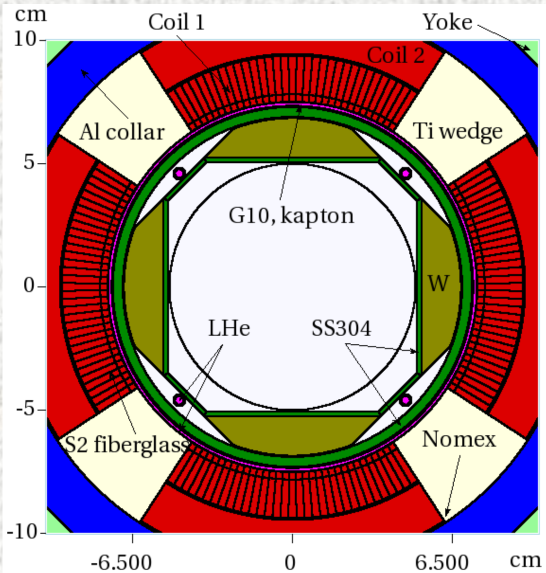
  - Energy stored in each beam: ~0.3 GJ LHC and >8 GJ FCC
  - Betatron and momentum multi-stage collimation systems (L=1/4 C)
  - Beam abort system (L=1/8 and 3/8 Circumference)
  - Tungsten tertiary collimators (TCT, L~150m) and TAS (L~20m)
  - FCC-hh: intercepting synchrotron photons at elevated temperature

Protecting SC Magnets: Design Constraints

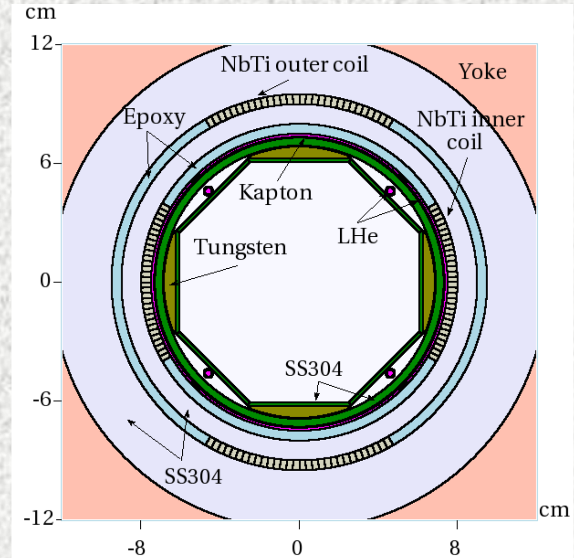
- **Quench stability**: peak power density in the innermost cable; keep < 40 mW/cm^3 and < 13 mW/cm^3 in Nb_3Sn and NbTi, respectively; *primary criterion at LHC*
- **Dynamic heat loads**: cryo plant capacity and operational cost; keep below 10-15 W/m in cold mass; *FCC-hh additionally: 30 W/m/aperture in dipole beam screen*
- **Radiation damage**: peak dose on the innermost coil layer over system lifetime (3000 fb^{-1} at HL-LHC and FCC): keep below 25-35 MGy in insulation and a fraction of DPA in coil inorganic materials; *primary criterion at HL-LHC and FCC*

HL-LHC 150-mm Coil ID Inner Triplet with 6 to 16mm Thick Tungsten Inserts

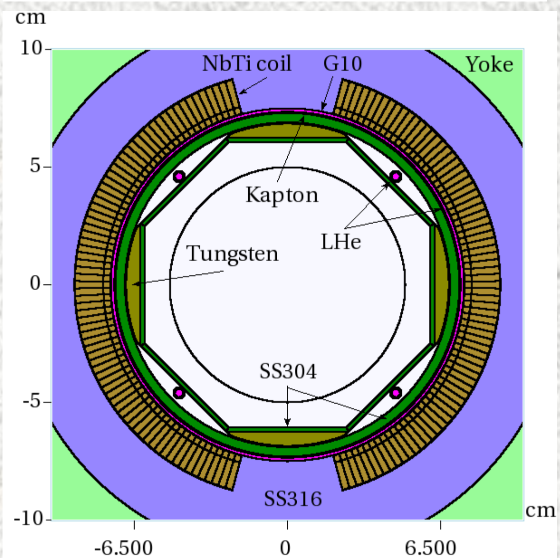
Q1



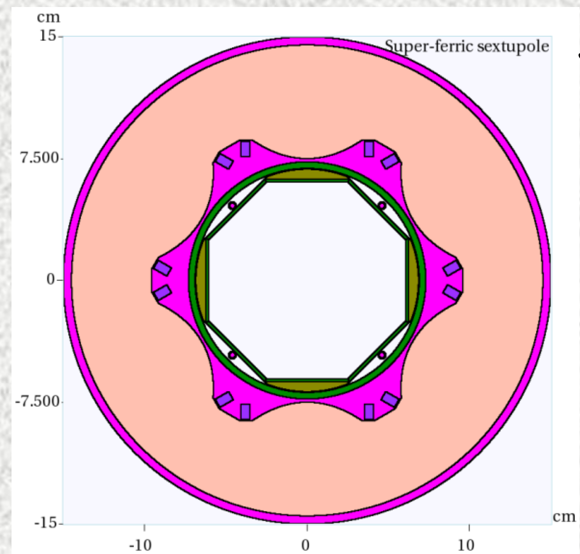
MCBX3



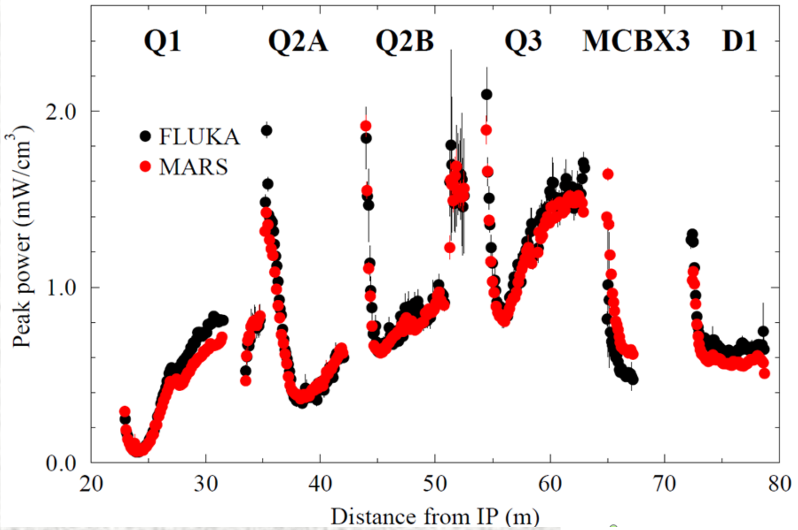
D1



Sextupole



Operational Radiation Loads



HL-LHC: The peak value in the quadrupoles, 2 mW/cm^3, is 20 times less than the assumed quench limit of 40 mW/cm^3 in Nb_3Sn coils

FCC-hh: Same approach with thicker tungsten absorbers

HL-LHC: Integral power dissipation (W) in IT

Component	FLUKA				MARS	
	10 cm gap in ICs		50 cm gap in ICs		50 cm gap in ICs	
	Magnet cold mass	Beam screen	Magnet cold mass	Beam screen	Magnet cold mass	Beam screen
Q1A+Q1B	100	170	100	170	95	170
Q2A+orbit corrector	95	60	100	65	100	65
Q2B+orbit corrector	115	80	120	80	115	80
Q3A+Q3B	140	80	140	80	135	75
Corrector package	55	55	60	55	60	65
D1	90	60	90	60	90	55
Interconnects	20	140	20	105	15	85
Total	615	645	630	615	615	600

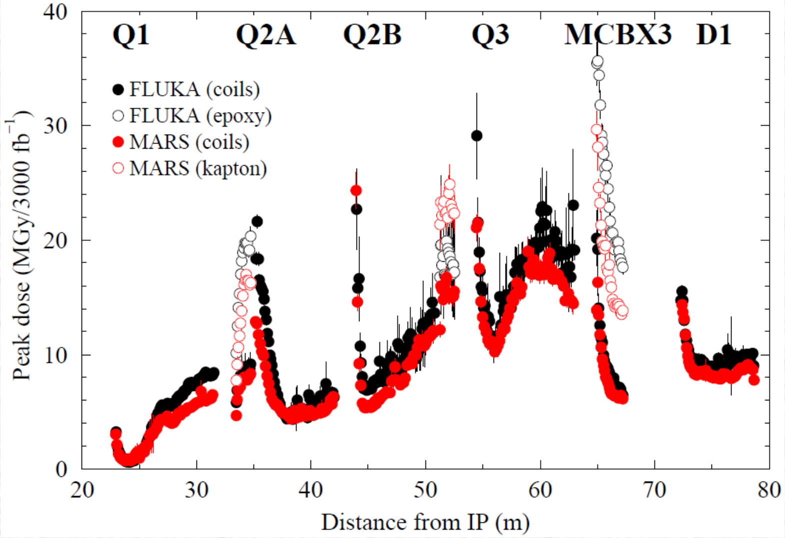
Challenging at FCC-hh

Dynamic Heat Loads on Each Side of IP (kW)

	HL-LHC	FCC
½ Detector w/shield	0.385	0.77
TAS	0.615	5.75
Collider	3.76*	36.68
Total	4.76	43.20

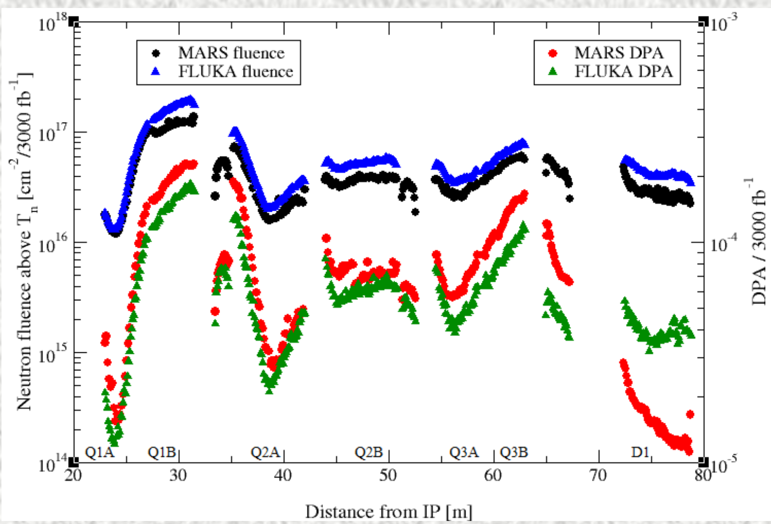
* IT(cold mass)+IT(W/screen)+rest = 0.63 + 0.61 + 2.52 = 3.76 kW

Lifetime Radiation Loads



<u>HL-LHC:</u> The peak dose in <u>insulation</u> per 3000 fb^{-1} integrated luminosity is at the design limit; ***more R&D work on rad-resistant materials and absorbers is needed to provide safety margin.***

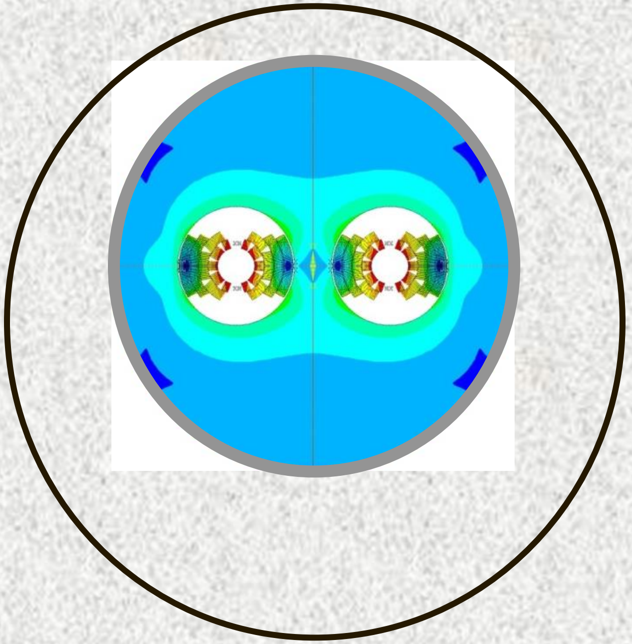
<u>FCC-hh:</u> Brought to the HL-LHC levels with 20-mm W-absorber for Phase I (see talk by M. Besana). ***Further R&D on materials and absorbers.***

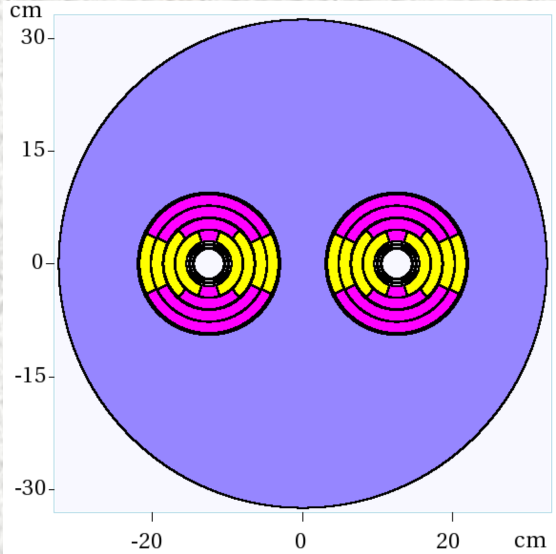


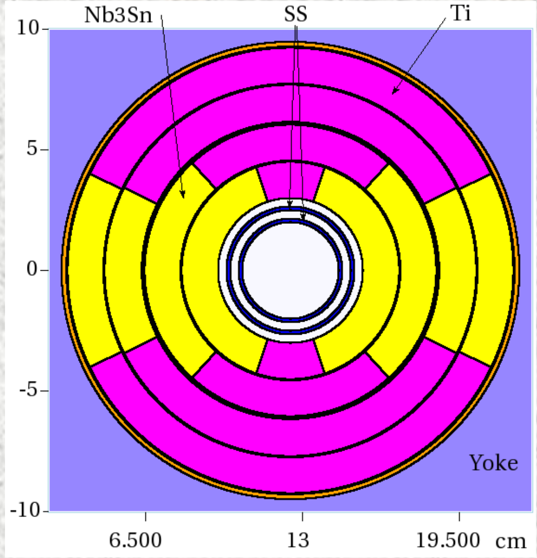
<u>HL-LHC:</u> The peak in the Q1B inner coil is about 2×10^{-4} DPA per 3000 fb^{-1} integrated luminosity, should be acceptable for the <u>superconductors and copper stabilizer</u> provided periodic annealing during the collider shutdowns.

In the quadrupole coils, the peak fluence is ~2×10^{17} cm^{-2} which is substantially lower than the 3×10^{18} cm^{-2} limit used for the Nb_3Sn superconductor, with further R&D for FCC-hh

SyncRad Modeling in FCC-hh Arcs (1)



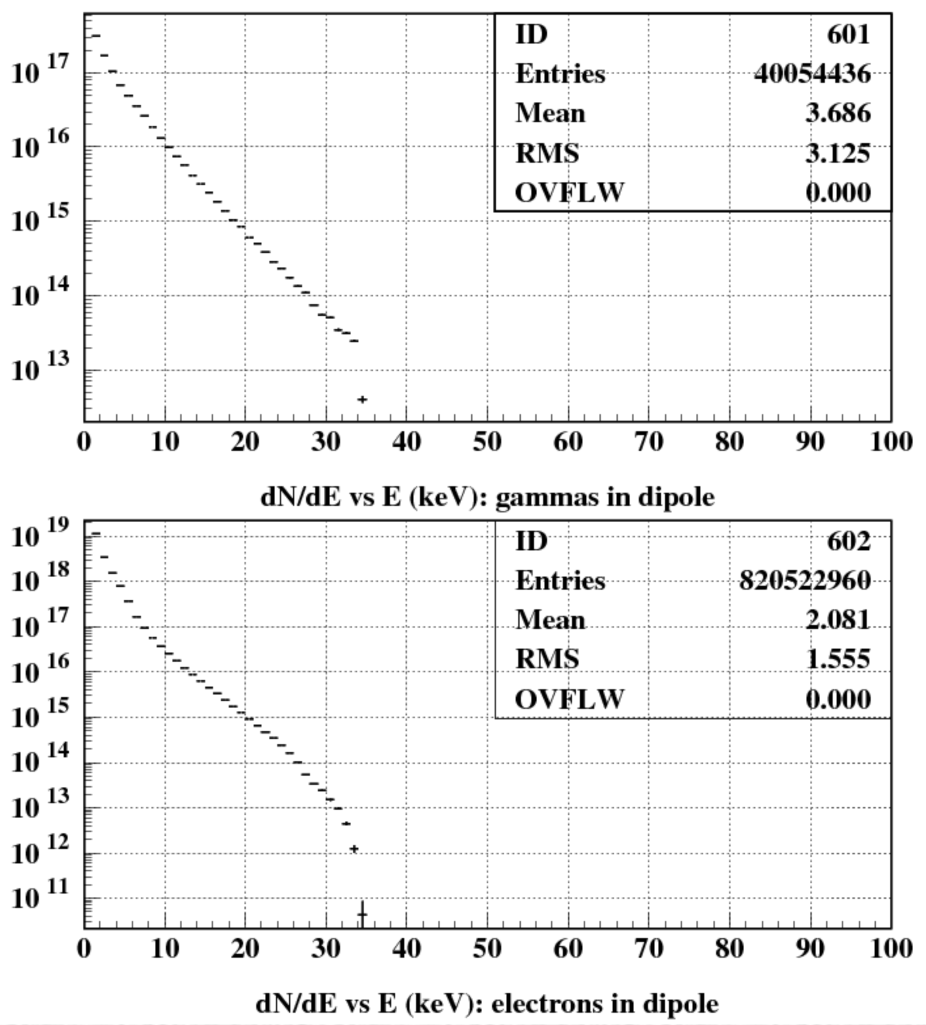




MARS15 model

16-T dual-aperture Nb_3Sn dipole with Ti-collar, in 1-m diameter cryostat envelope (A. Zlobin)

SyncRad Modeling in FCC-hh Arcs (2)



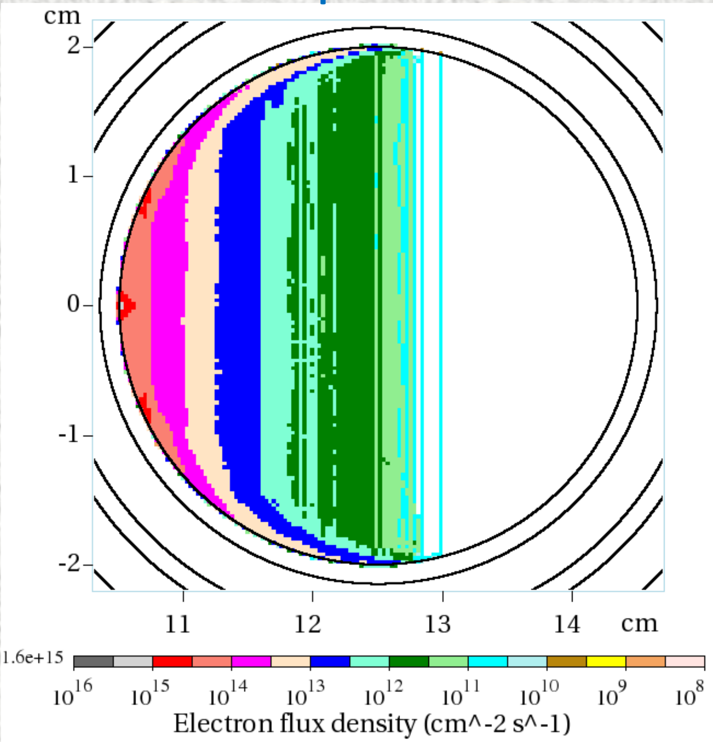
Photon E_c = 4.3 keV. MARS15-calculated spectra in a 1.5-mm SS beampipe of a 16-T dipole span to 35 keV for both photons and electrons.

These result in <u>heat load of ~30 W/m per aperture for 0.5A 50-TeV proton beams.</u>

Energy spectra in 1.5-mm SS beampipe

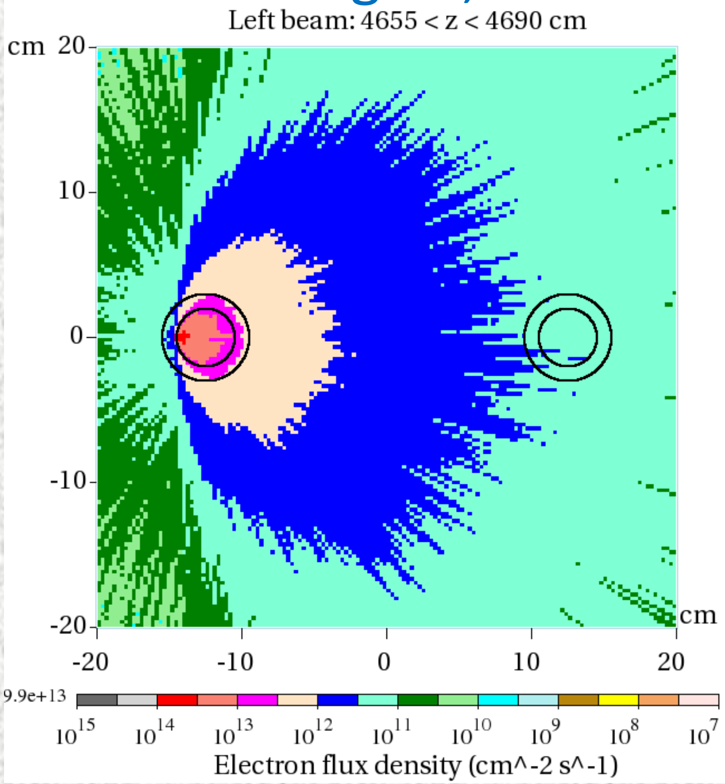
30 W/m Electron Fluxes in Each Aperture

Dipole



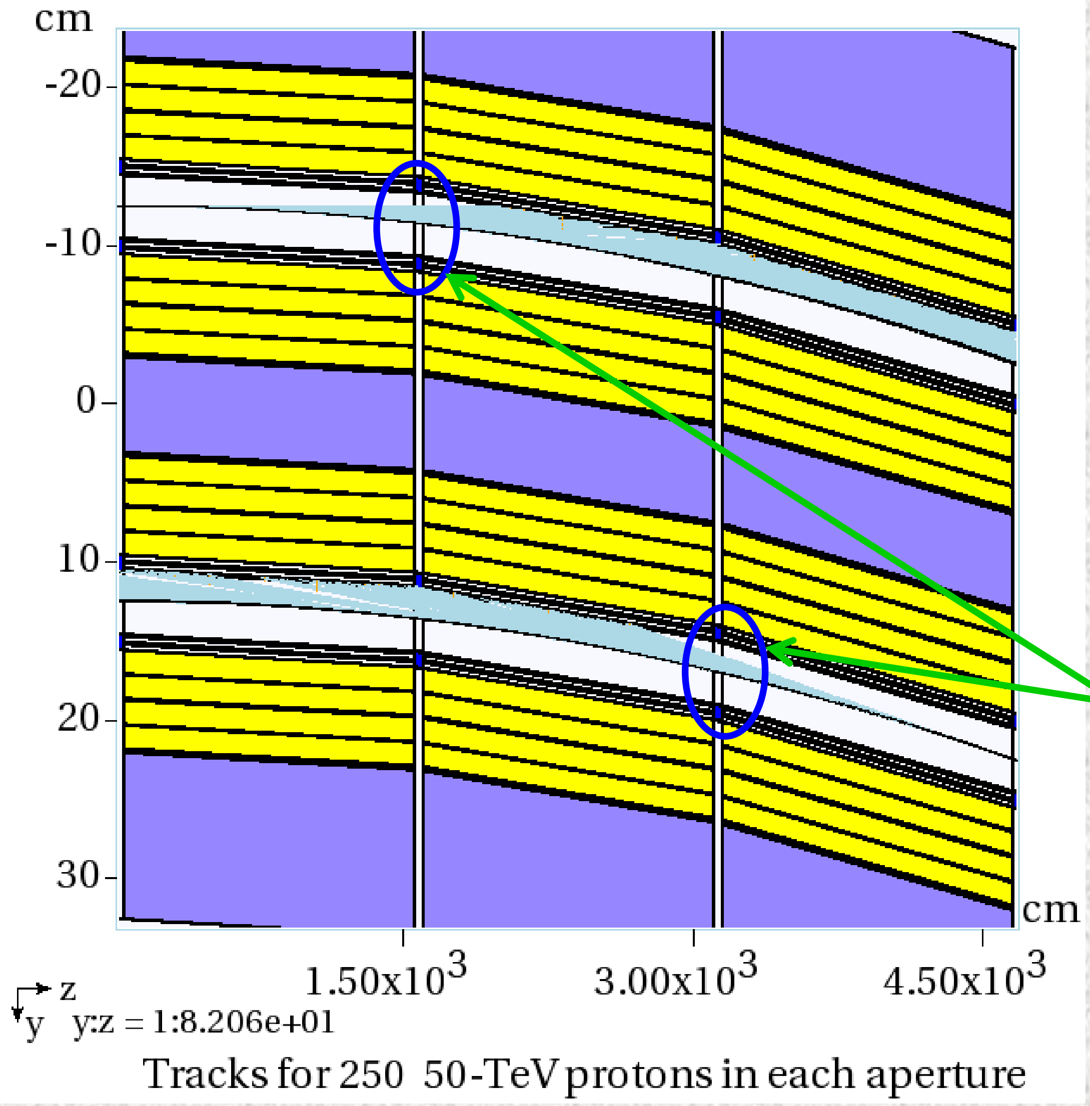
If one does nothing, this heat load is deposited in the beam screen. Fluxes are contained in the outward half of the aperture

Interconnect region, left beam



Fluxes are spread around, resulting in radiation loads to components in the region

Dealing with 30 W/m in FCC-hh Arcs



1. **Synchrotron radiation slit** on the outward of the dipole beam screen with minimal impact on the impedance

2. Starting from the first dipole in the arc cell after a "drift", a steady-state synchrotron radiation level is reached in the second dipole ⟶ **photon absorbers in each interconnect region, designed to mitigate their impact on impedance**

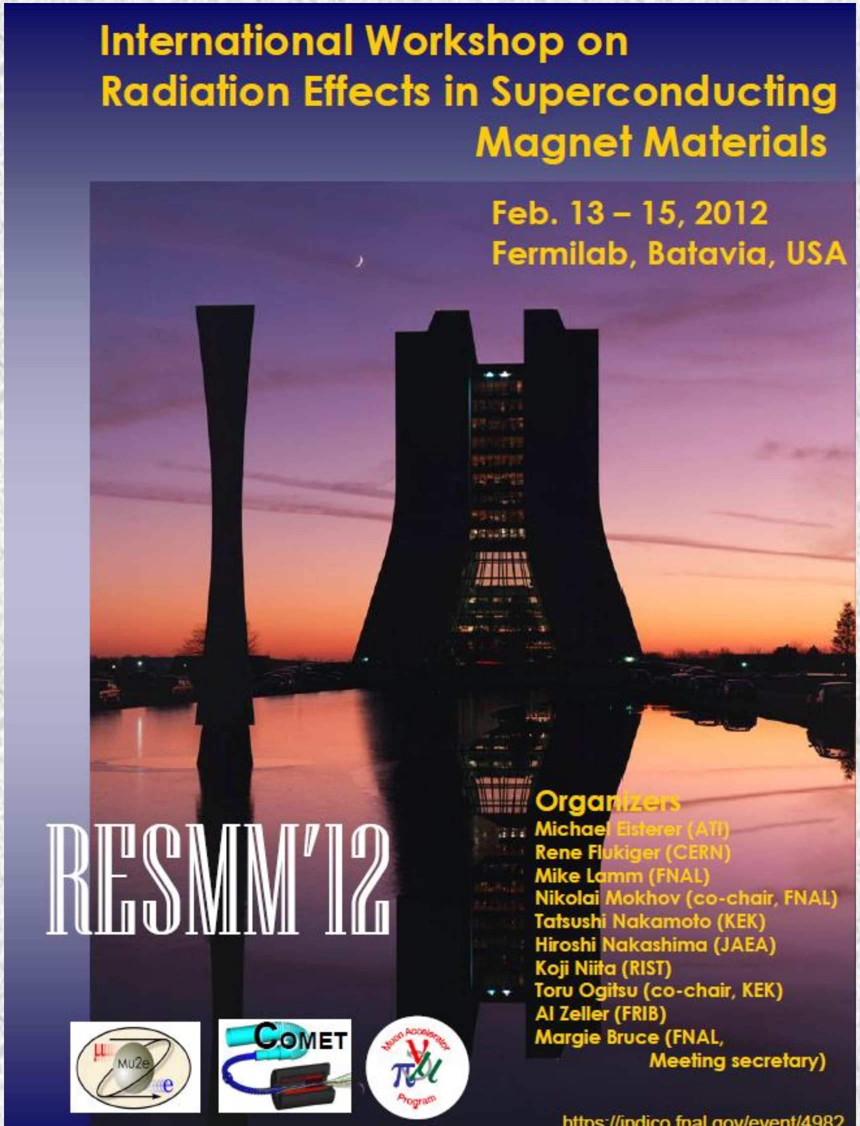
3. In both cases, **heat is removed at 60-80 K (He gas or liquid N2)**

RESMM Workshops: Focus & Topics

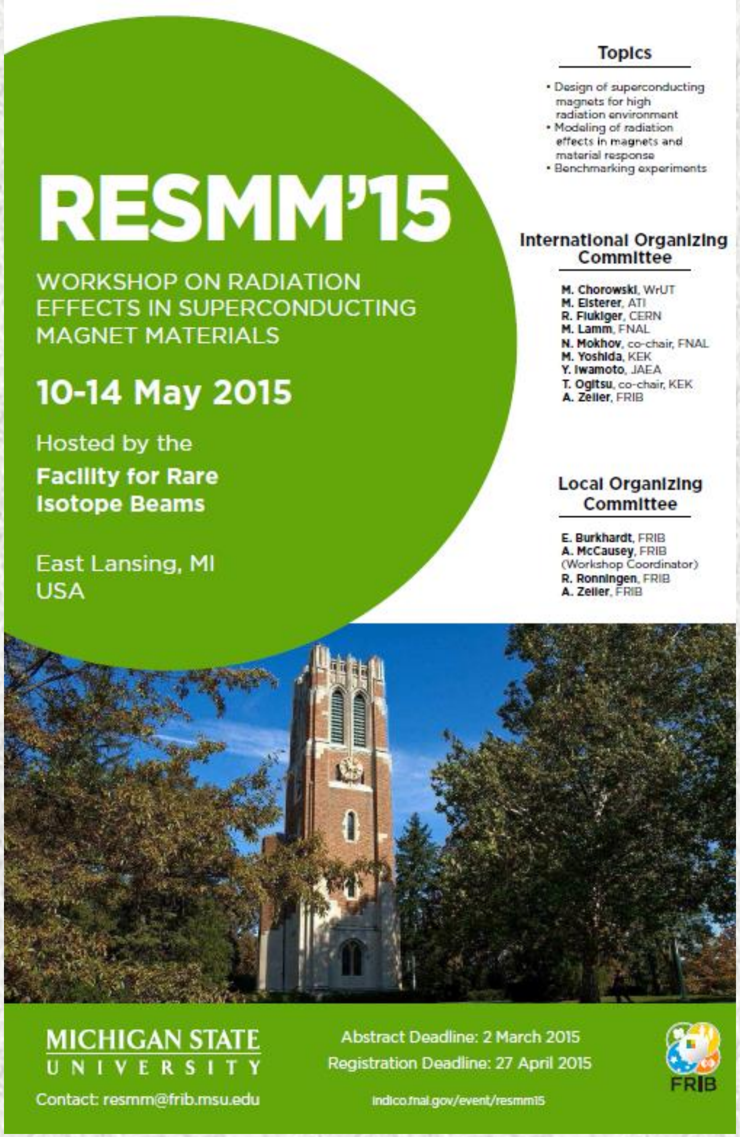
The series of annual workshops on "Radiation Effects in Superconducting Magnet Materials (RESMM)" has started at Fermilab in 2012. It focused on establishing radiation damage limits and design of large superconducting systems, for the Mu2e and Comet experiments as well as for HL-LHC, ITER, FRIB and muon collider magnets, covering three major topics:

- Design of superconducting magnets for high radiation environment
- Modeling of radiation effects in magnets and material response
- Benchmarking experiments

RESMM Workshops 2012 & 2013



RESMM Workshops 2014 & 2015



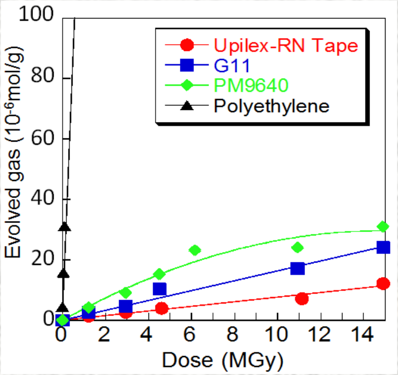
RESMM Workshops: Sessions

The workshops are organized in five major sessions:

1. Superconducting Magnets in High Radiation Environment
2. Radiation Effects in Magnets
3. Modeling Radiation Effects in Magnets and Material Response
4. Irradiation Tests and Benchmarking Experiments
5. Summary, Discussion, Plans and Action Items

Superconducting Magnets in High Radiation Environment

- Uncertainties with radiation damage limits for Nb_3Sn
- The choice of copper vs. aluminum stabilizer
- Concerning the DPA damage, aluminum can be completely repaired with a room temperature annealing, while copper is restored only to ~90%
- The effect of DPA damage has to be understood within the particular magnet application by determining the allowable changes in resistivity, heat capacity and struct. properties between planned annealing cycles
- The programmatic implications of these annealing cycles must be weighed against other design issues such as dynamic heat removal, conductor stability against mechanical disturbances, absorbed dose during the magnet lifetime, as well as fabrication and operation costs
- Advanced insulation materials with very low H_2 yield:



Rad. Loads in J-PARC SCFM System

Computed using MARS

1 w/m, 4000 hr/year

Coil (~30kGy/y)

- GFRP (~10^7Gy)
- Polyimide (~10^7Gy)

Plastic Collar (~10kGy/y)

- Glass Filled Phenol (~10^7Gy)

Super Insulator

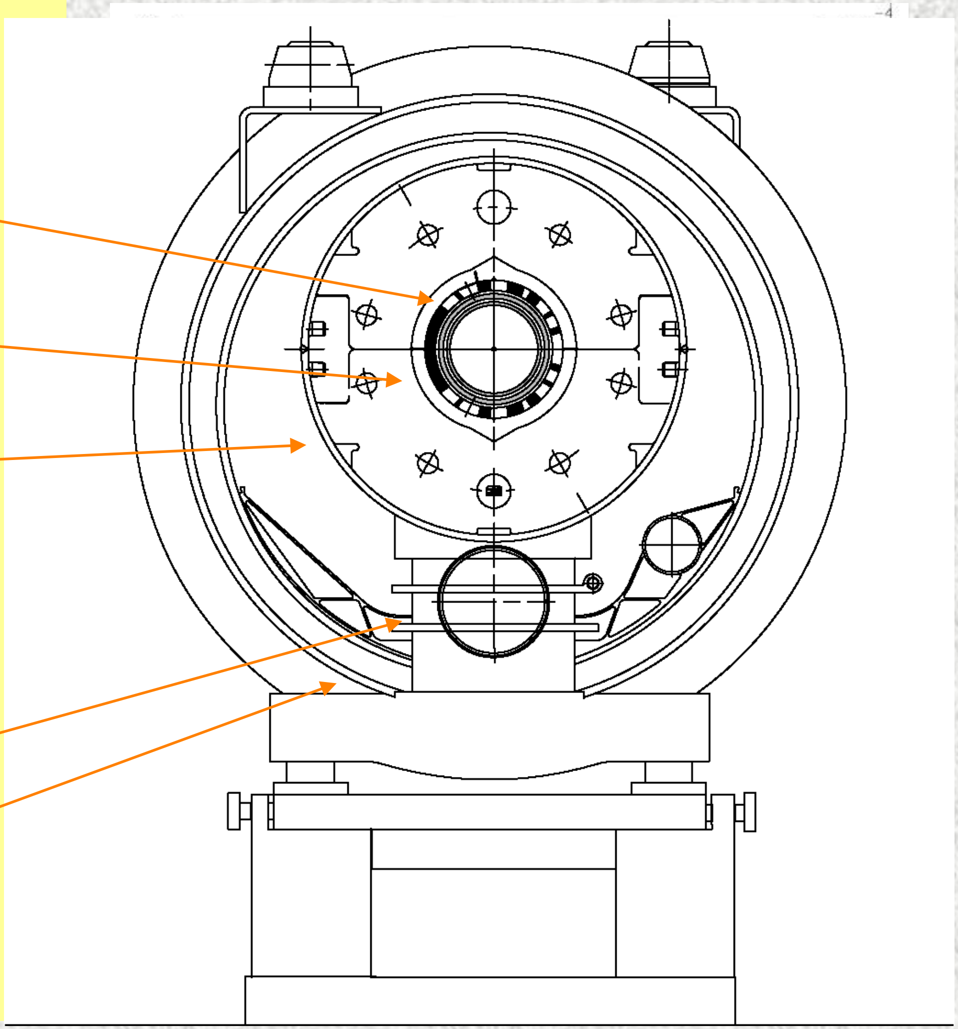
- Body (~200Gy/y)
  - Polyester (10^5~10^6Gy)
- End (~30kGy/y)
  - Polyimide (~10^7Gy)

Support Post (~200Gy/y)

- GFRP (10^7Gy)

O-ring (~200Gy/y)

- EPDM (~10^6 Gy)



Modeling Radiation Effects in Magnets and Material Response (1)

Substantial progress on Monte-Carlo codes used in this field and understanding of damage phenomena recently made with attention to reliability of simulation tools in four classes:

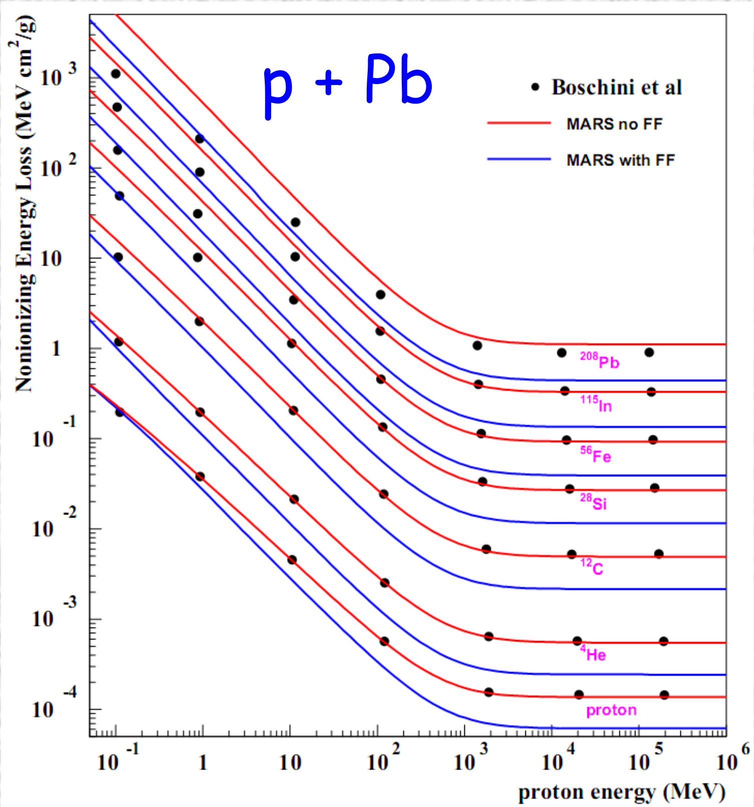
1. Modeling of particle production focusing on those causing the deleterious radiation effects in the magnets
2. Quench, integrity and lifetime: power density and integrated dose in critical components, e.g., SC coils, organic materials etc.
3. Radiation damage to superconducting, stabilizing and insulating materials: DPA, H2/He gas production, particle flux and dose; **linking these to changes in material properties**
4. ES&H aspects: shielding, nuclide production, residual dose, impact on environment

Modeling Radiation Effects in Magnets and Material Response (2)

In majority of cases integral values on particle yields, energy deposition and radiation field can be predicted with accuracy of < 10-20%. However, uncertainties of a factor of 2 or more still remain for differential values in some phase space regions as well as for values of DPA. Data needs to achieve better accuracy identified for the above four classes:

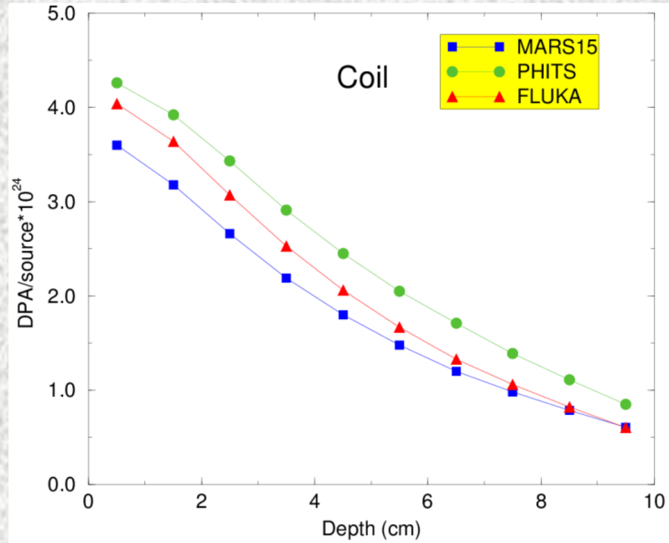
1. Low-E pion/kaon/pbar spectra at E_p=2-7 GeV; neutrons in fragmentation region; light fragment yields; nuclide yields for difficult cases; more ion and photon induced reactions.
2. Energy deposition profiles in fine-segmented setups with combination of low-Z and high-Z composite materials for hadron, heavy ions, electron and low-energy neutron dominated cases.
3. Annealed vs non-annealed defects, especially at cryo temperatures.
4. More reliable data on radiation penetration through composite setups and on radioactivation.

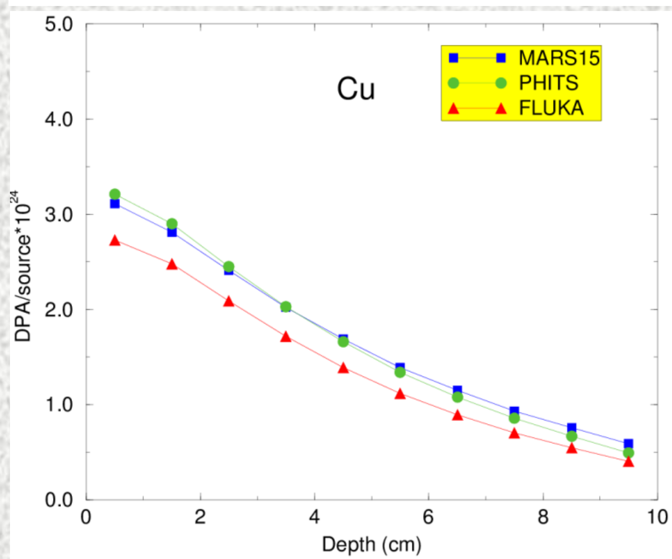
DPA Code Intercomparision

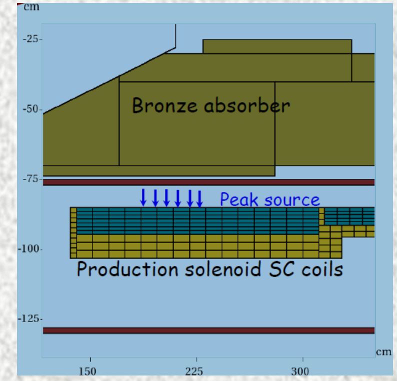


Proton NIEL for lead due the Coulomb scattering

M.J. Boschini et al., “Nuclear and Non-Ionizing Energy-Loss for Coulomb Scattered Particles from Low Energy up to Relativistic Regime in Space Radiation Environment”, arXiv:1011.4822v6 [physics.space-ph] 10 Jan 2011







2013 FLUKA, MARS15 and PHITS intercomparison for Mu2e SC coil hottest spot: 15% agreement

2014 FLUKA and MARS15 HL-LHC studies: typically within 20% for energy deposition and neutron fluxes, and 50% for DPA

Irradiation Tests and Benchmarking

- First direct benchmarking of DPA has been achieved by using the in-situ Transmission Electron Microscopy (TEM) ion irradiation tool at ANL. The method introduces disorders in materials in the well-controlled conditions while performing real time observation of defects. Powerful tool to validate and verify computer models
- Neutron irradiation tests under cryogenic temperature (10~20 K) for Al and Cu performed at KURRI, Japan. The resistivity degradation and recovery by room temperature annealing were measured (M. Yoshida)

- Irradiation tests on insulation materials at Wroclaw, Poland with electron beams under LN2 temperature. Measurements and criteria to qualify materials and certification standards for mechanical, electric, and thermal performances

Results of Neutron Irradiation Tests at KURRI

	Aluminum										Copper					
	Horak	Guinan	Al-5N	Al+CuMg	Al+Y 2011	Al+Y 2012	Al+Y 2013	Al+Y 2014	Al+Ni 2013	Al+Ni 2014	Horak	Guinan	OFHC 2011	OFHC 2012	OFHC 2013	OFHC 2014
RRR	2286	74	3000	450	341, 360	342, 360	-, 368	-, 367	561	566	2280	172	308 (10K)	291 (13K)	285 (13K)	277 (12K)
T_{irr} (K)	4.5	4.2	15	12	12	15	15	14	15	14	4.5	4.2	12	15	15	14
Neutron Source	Reactor	14 MeV	Reactor								Reactor	14 MeV	Reactor			
Φ_{tot} (n/m²) (>0.1MeV)	2×10^{22}	$1\text{-}2 \times 10^{21}$	2.6×10^{20}	2.3×10^{20}	2.6×10^{20}	2.6×10^{20}	2.6×10^{20}	2.7×10^{20}	2.6×10^{20}	2.7×10^{20}	2×10^{22}	$1\text{-}2 \times 10^{21}$	2.6×10^{20}	2.6×10^{20}	2.6×10^{20}	2.7×10^{20}
$\Delta\rho_{irr} / \Phi_{tot}$ $\times 10^{-31} (\Omega m^3)$	1.9	4.1	2.5	2.4	2.6, 2.8	2.7, 2.9	2.5	2.2	2.3	2.3	0.58	2.29	0.93	1.02	0.77	0.73
Recovery by thermal cycle	100 %	100 %	100 %	100 %	100 %	100 %	100 %	TBD	100 %	TBD	90%	80%	82%	92%	95%	TBD

- Degradation rate ($\Delta\rho_{irr} / \Phi_{tot}$) seems to be consistent with the previous reactor neutron irradiation.
  - higher in 14 MeV neutron irradiation.
- Present work shows that difference in RRR (300-3000) of Al doesn't influence the degradation rate or recovery behavior.
- Partial recovery observed in Cu, but would be saturated after multiple irradiation??

Makoto Yoshida (KEK)

Proton Irradiation Tests at FFAG (KURRI)

Main parameters in the FFAG accelerator

# of sectors	12
Energy	2.5 - 100MeV
Repetition rate	30 - 120Hz
Average beam current	1nA
Rf frequency	1.5 - 4.6MHz
Field index	7.5
Closed orbit radius	4.4 - 5.3m

Materials Irradiation Chamber

Irradiation temperatures: 6K – 700 K

In-situ fatigue test

Post irradiation test

- **Positron annihilation lifetime measurements**
- **Electrical resistivity measurement**

Link of Calculated Quantities to Observable Changes

- Link of calculated quantities (DPA, dose, fluence etc.) to observable changes in critical properties of materials in theoretical/modeling studies remains to be a dream
- Promising experiments
  - Low-energy heavy ions at GSI in very clean conditions (although, surface *vs* bulk damage?)
  - Studies at BNL: 200-MeV protons and fast neutrons at BLIP, and 28-MeV protons at TANDEM (BNL)
  - Kurchatov institute experiments
  - Neutrons at Kyoto reactor at room and cryo temperatures
  - Direct DPA measurements with TEM at ANL
  - Measuring gas production
- Promising developments: kinetic Monte-Carlo
- Meanwhile, rely on phenomenology and correlations