

HTS for Magnets in High Radiation Environments

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5th Forum on New Material: Session FK-7

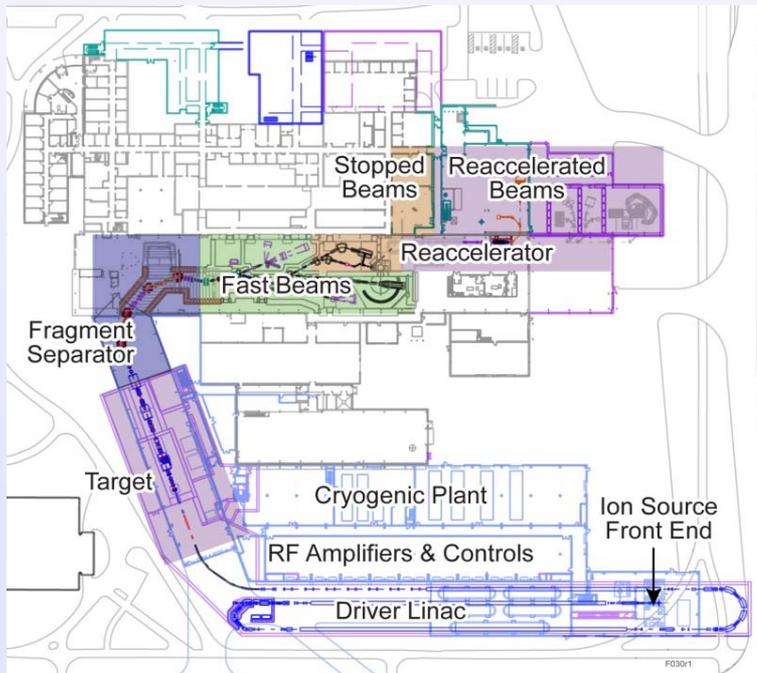
Overview

- **Motivation**
 - Magnets will be subjected to the unprecedented level of radiations in FRIB
- **Samples**
 - YBCO from SuperPower and American Superconductor
- **Radiation Facility**
 - 200 MeV Linac at BNL
- **Experimental Results**
 - Radiation damage – Really? – Some interesting results
- **Impact on the Project**
- **Future Studies**
- **Summary**

FRIB Facility Concept

Superconducting Magnet Division

- MSU (Michigan, US) is the location of the proposed Facility for Rare Isotope Beams (FRIB)
- FRIB will create rare isotopes for research in intensities not available anywhere today
- Uses existing components of NSCL - **Fast start of FRIB science**
- Driver linac with energy of ≥ 200 MeV/amu for all ions, $P_{\text{beam}} = 400$ kW (high beam power)
- Rare isotope production via projectile fragmentation and in-flight fission
- Fast, stopped, and reaccelerated beams

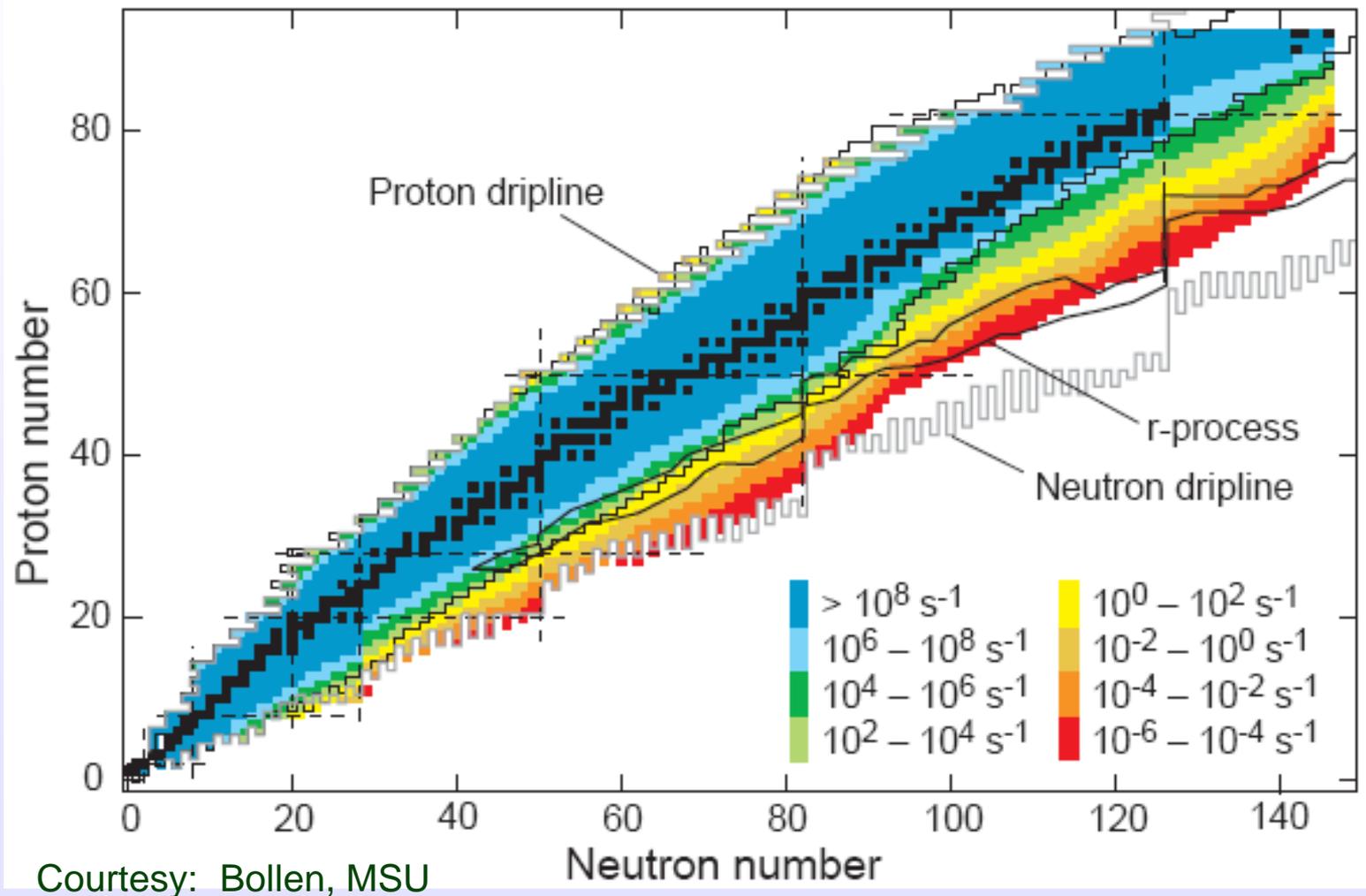


Courtesy: Wilson, MSU



Nuclear Landscape and FRIB Beams

FRIB will create rare short lived isotopes in very large quantities

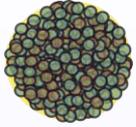


Gain factors
of 10-10000
over
operational
facilities

Black
Rectangles:
Stable
Nuclei

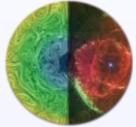
Courtesy: Bollen, MSU

FRIB science



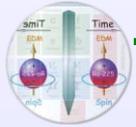
Properties of nucleonic matter

- Classical domain of nuclear science
- Many-body quantum problem – mesoscopic science



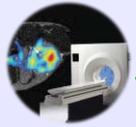
Nuclear processes in the universe

- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, Equation of State (EOS) of asymmetric nuclear matter



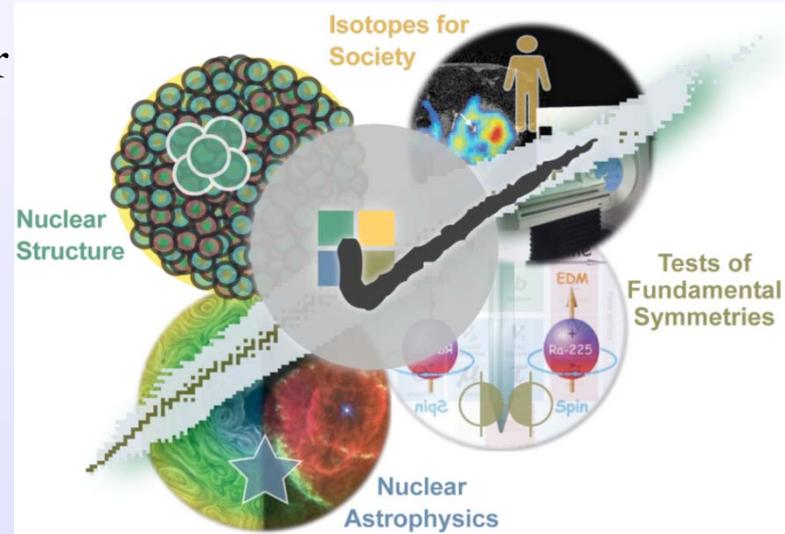
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei



Societal applications and benefits

- Bio-medicine, energy, material sciences, national security

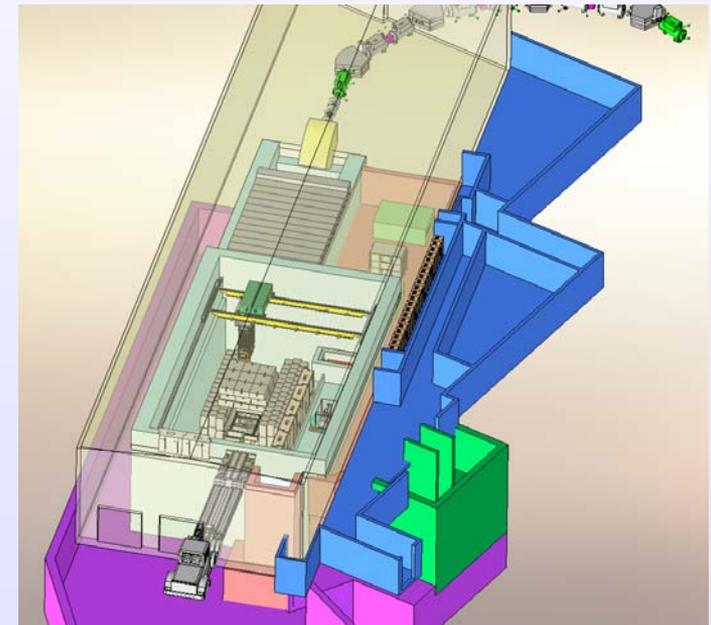
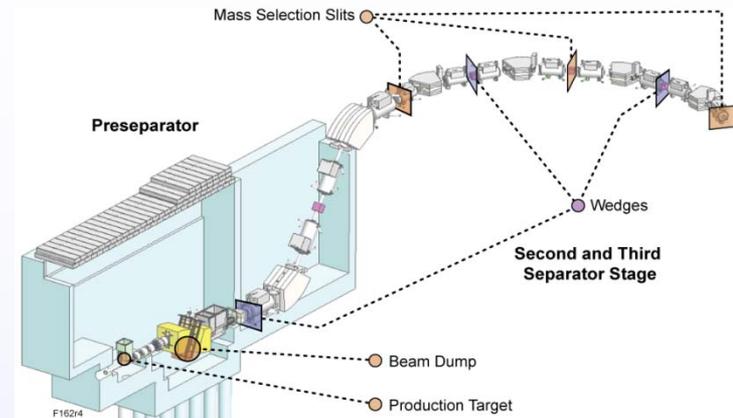


Courtesy: Bollen, MSU

Production Target Facility and Fragment Separator

High radiation and high power densities pose several technical challenges

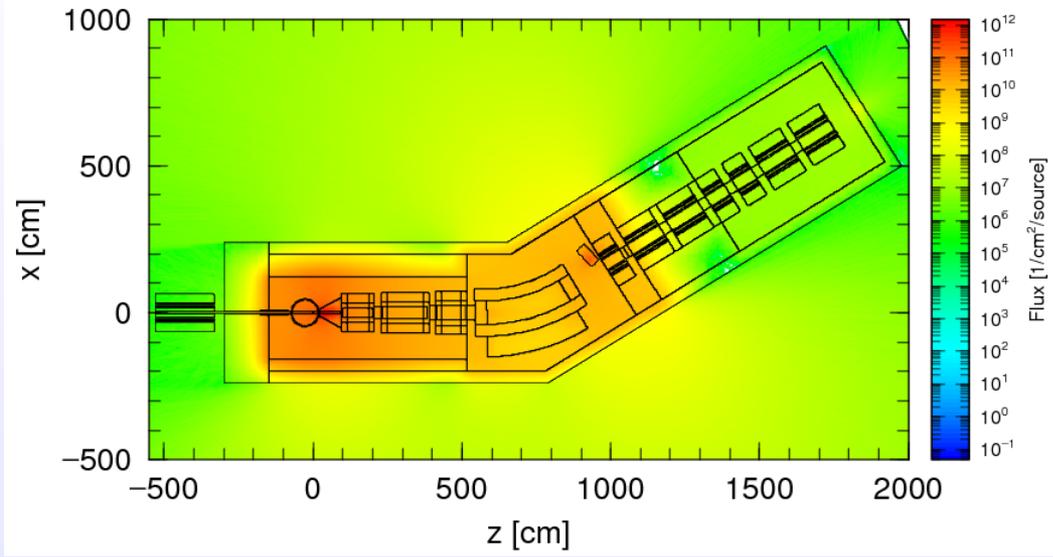
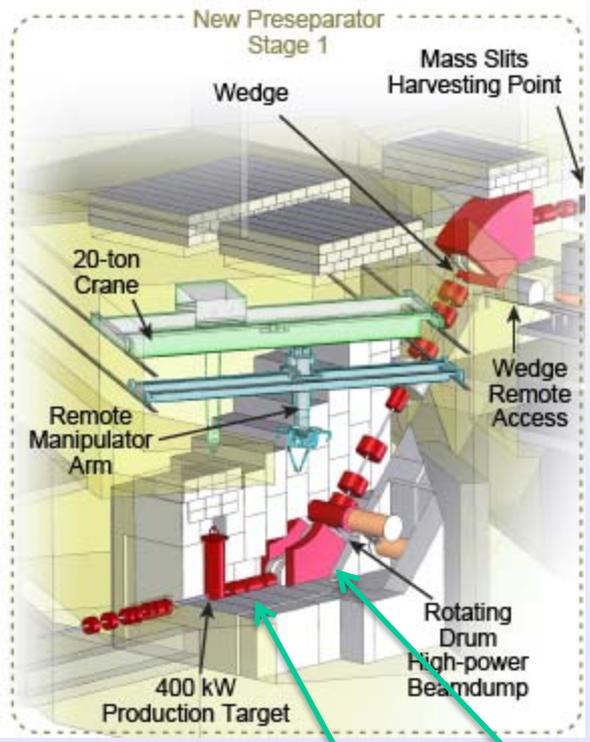
- Self-contained target building to keep most-activated and contaminated components in one spot
 - Remote-handling to maximize efficiency
- High-power targets for light and heavy primary beams
 - R&D on multi slice graphite target promising approach
- **Fragment separator to separate primary beam and select rare isotope beam**
 - **R&D on radiation resistant magnets**
- High-power beam dump to intercept unreacted primary beam
 - R&D on rotating water-filled drum concept and alternatives



Courtesy: Bollen, Zeller, MSU

Radiation and Heat Loads in Fragment Separator Magnets

400 kW beam hits the production target. Quadrupoles following that in Fragment Separator are exposed to unprecedented level of radiation (~20 MGy/year) and heat loads (~10 kW/m, 15 kW in first quad itself).



Neutron fluence on first quad:

$$2.5 \times 10^{15} \text{ n/cm}^2 \text{ per year}$$

Radiation resistant
Pre-separator quads and dipole

Courtesy: Zeller, MSU

Technical Requirements

High fields and large apertures require superconducting magnets.

Magnets in the fragment separator target area that survive the high-radiation environment

- **Require that magnets live at least 10 years at full power**
- **Require refrigeration loads that can be handled by the cryoplant**
- **Require magnets that facilitate easy replacement**

Reduced operational costs

- **No down time for magnet replacement**
- **Higher acceptance reduces experimental times**
- **Robust and resistant to beam-induced quenches**

Courtesy: Zeller (MSU)

HTS Magnets in Fragment Separator

Superconducting Magnet Division

- Use of HTS magnets rather than conventional NbTi Low Temperature Superconducting magnets in Fragment Separator region is highly attractive.
- First generation (1G) HTS would allow operation at ~30 K and second generation (2G) HTS at ~50 K instead of ~4K with conventional NbTi. Removing these large heat loads at higher temperature rather than at 4 K is over an order of magnitude more efficient.
- Moreover, HTS coils can tolerate a large local and global increase in temperature, so are resistant to beam-induced heating, as well.
- Also in HTS magnets, the temperature need not be controlled precisely. It can be relaxed by over an order of magnitude as compared to that in low temperature superconducting magnets. This simplifies the cryogenic system, reduces cost, while making the magnet operation more robust.
- The question is can HTS tolerate these unprecedented level of radiation?
- This R&D may also have a significant impact on other future proposals.

Radiation Facility at BNL

Radiation Damage Studies at BLIP



Figure 2. The BLIP facility.

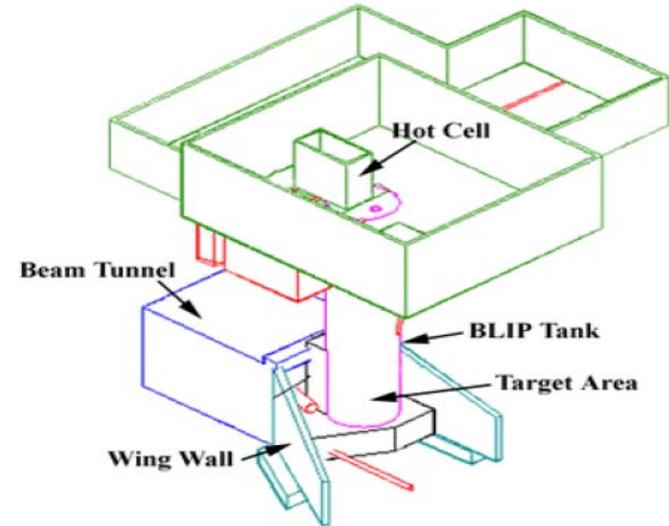
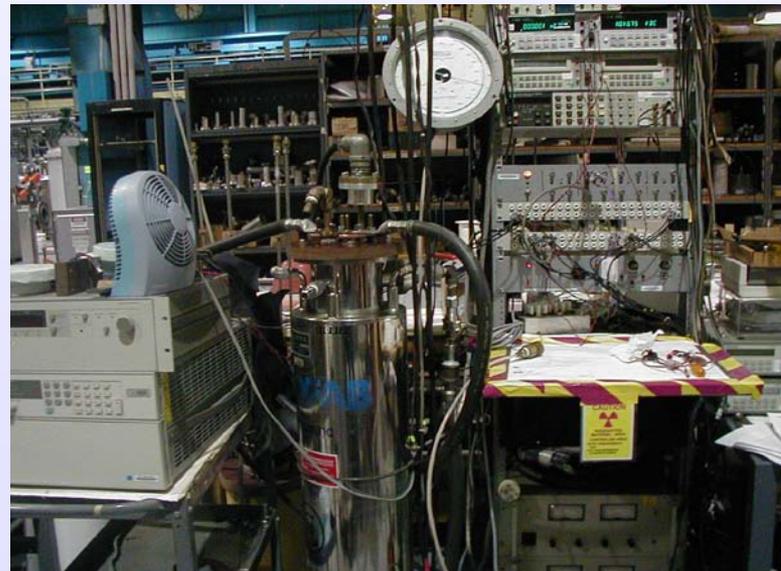
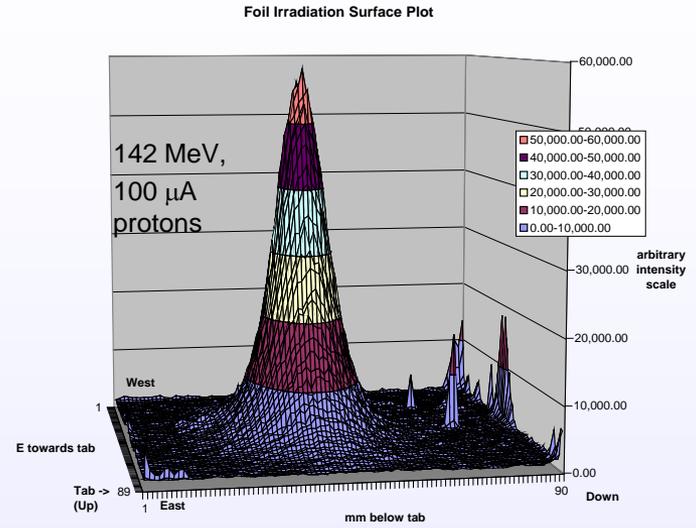
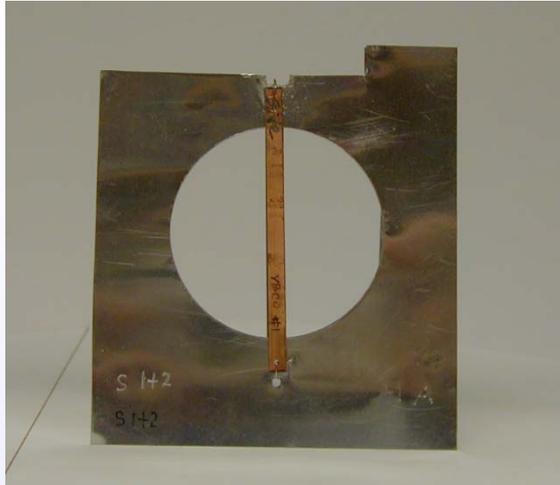


Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 μA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

Key Steps in Radiation Damage Experiment



HTS Samples Examined

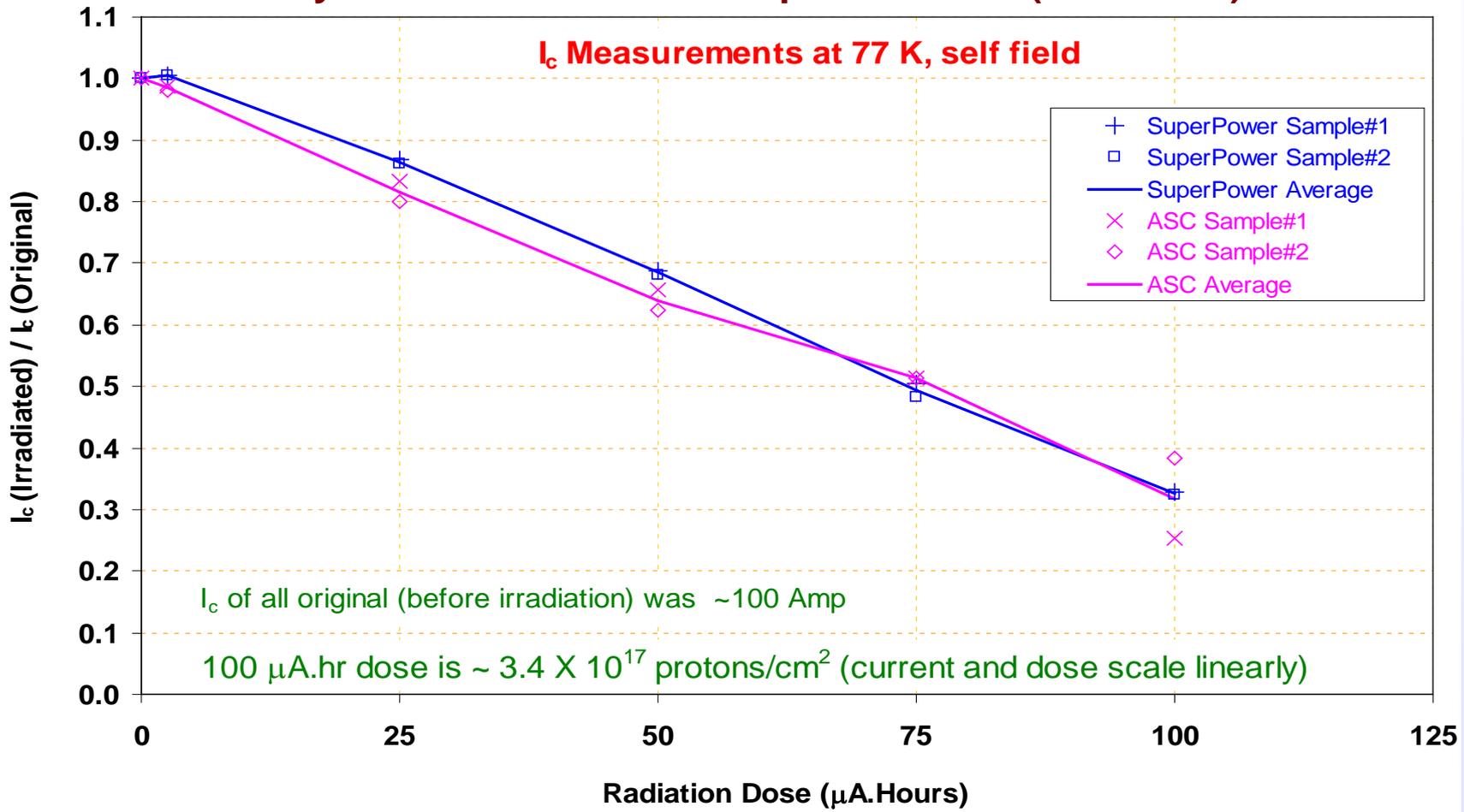
- Samples of YBCO (from SuperPower and ASC), Bi2223 (from ASC and Sumitomo) and Bi 2212 (from Oxford) were irradiated.
- **This presentation will discuss the test results of YBCO only.**
- Twenty samples were irradiated – 2 each at five doses (10^{16} , 10^{17} , 2×10^{17} , 3×10^{17} and 4×10^{17} protons/cm²) from both vendors.
- 10^{17} protons/cm² (25 μ A-hrs integrated dose) is equivalent to over 15 years of FRIB operation (the goal is 10 years).

Measurement of Radiation Damage at 77K in Self-field

- Critical current (I_c) of samples was measured before and after irradiation at 77 K, self field. I_c of all samples before radiation was ~ 100 A.
- The ratio of critical current before and after irradiation indicates relative radiation damage.
- **Critical temperature** is also compared before and after irradiation.

Relative Change in I_c due to Irradiation of SuperPower and ASC Samples

Radiation Damage Studies on YBCO by 142 MeV Protons by G. Greene and W. Sampson at BNL (2007-2008)

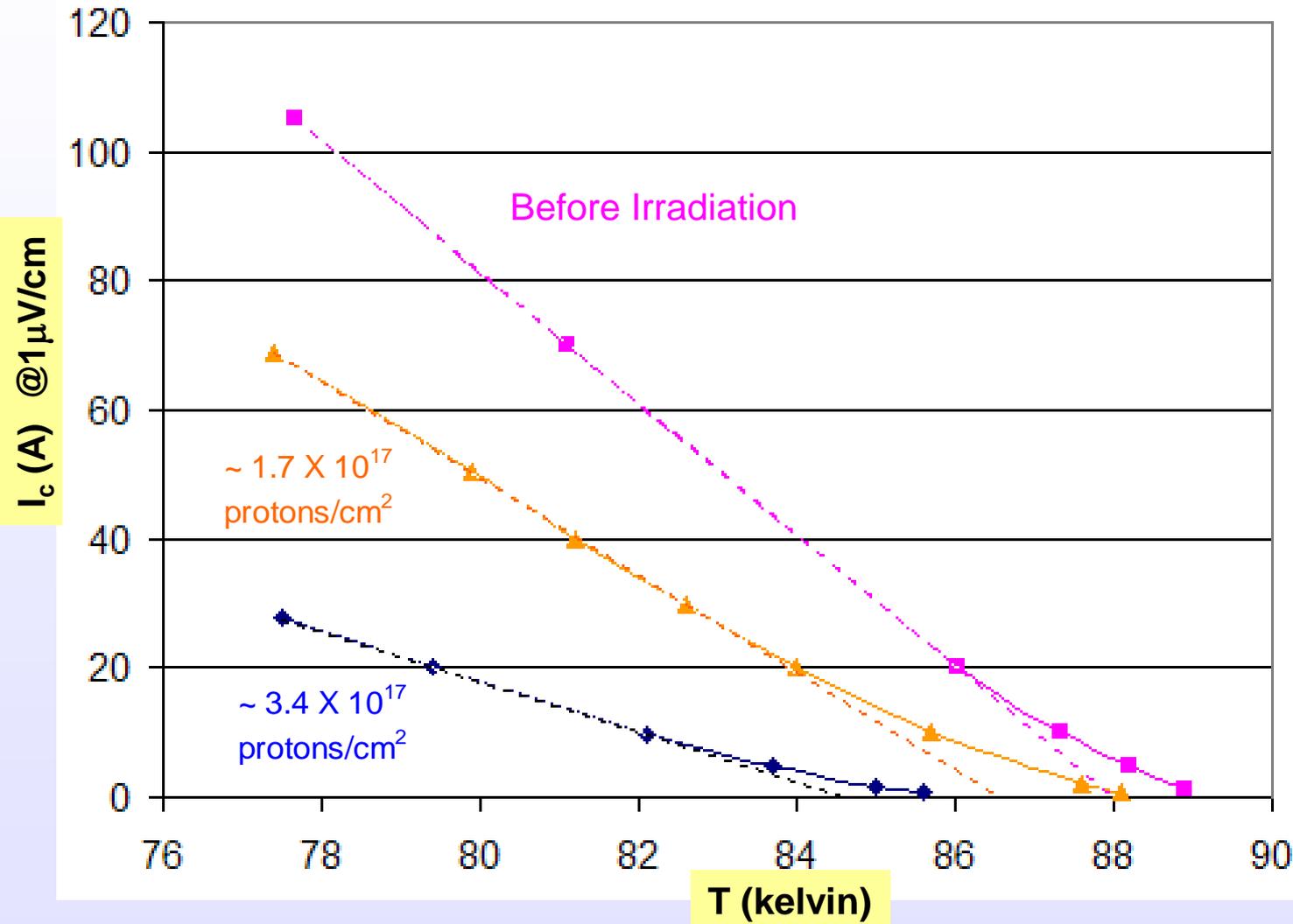


Ramesh Gupta, BNL 3/2008

SuperPower and ASC samples show very similar radiation damage at 77 K, self field

Change in Critical Temperature (T_c) of YBCO Due to Large Irradiation

I_c ($1\mu\text{V}/\text{cm}$) as a function of temperature



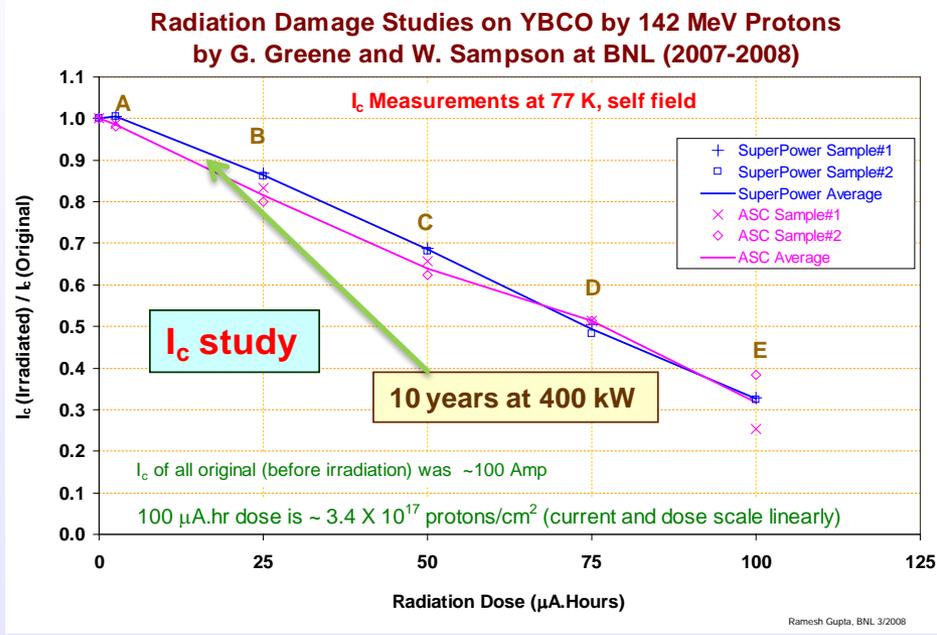
- Radiation has an impact on the T_c of YBCO, in addition to that on the I_c .
- However, the change in T_c is only a few degrees, even at very high doses.

Impact of Irradiation on Magnet

- The maximum radiation dose was 3.4×10^{17} protons/sec (100 μ A.hr) with an energy of 142 MeV. Displacement per atom (dpa) per proton is $\sim 9.6 \times 10^{-20}$. (Al Zeller)
- **This gives ~ 0.033 dpa at 100 μ A.hr for the maximum dose.**

Based on 77 K self field studies:

- Reduction in I_c performance of YBCO (from both vendors) is $< 10\%$ after 10 years of FRIB operation (as per Al Zeller, MSU).
- This is pretty acceptable.
- Drop in I_c at maximum dose (of theoretical interest) is $\sim 70\%$.



It appears that YBCO is at least as much radiation tolerant as Nb₃Sn is (Al Zeller, MSU).

Annealing from Radiation Damage After ~2 Years of Room Temperature Storage

- The samples have been kept at room temperature for about 2 years after initial irradiation.
- We have seen appreciable recovery in lost performance (annealing), particularly when the loss in I_c was large because of high irradiation.

Critical current before and after 100 μ A-hours of irradiation (77 K, self-field)

SuperPower

- Pre-rad:
 $I_c=101A$, $n=39$
- Post-rad (<1 year of irradiation):
 $I_c=32.6A$, $n=23$
- Post-rad (>2 years):
 $I_c=37.7A$, $n=24.4$

ASC

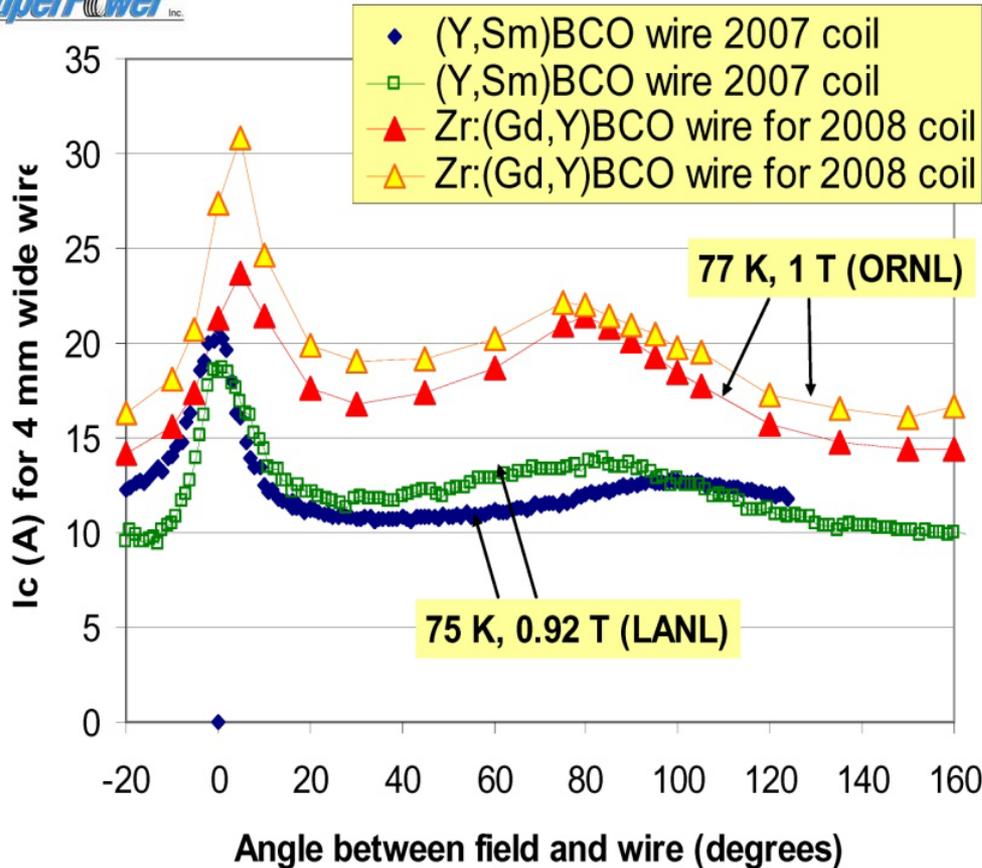
- Pre-rad:
 $I_c=105.3A$, $n=38$
- Post-rad (<1 year of irradiation):
 $I_c=40.9A$, $n=24$
- Post-rad (>2 years):
 $I_c=43.7A$, $n=23.337.7A$

Recovery in I_c : ~16% in case of SuperPower and ~7% in case of ASC.
Smaller recovery for lower doses.

Study of Radiation Damage at 77K in Applied Field

Measurement of HTS Critical Current (I_c) at 77K at Several Applied Fields

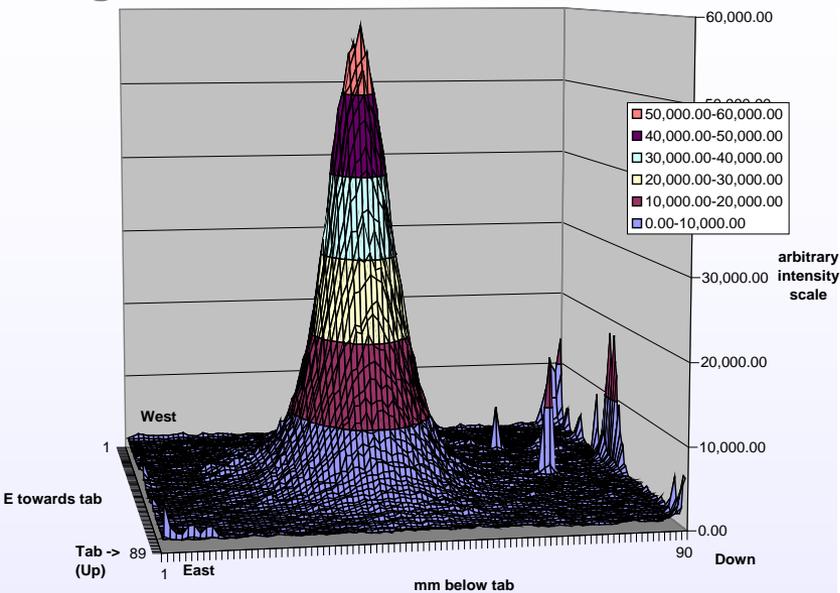
SuperPower Inc.



- Critical current of HTS depends not only on the magnitude of the field, but on the direction as well.
- The presence of doping (or nano-dots) or other defects can modify this behavior.
- The goal of this study is to determine the impact of radiation on I_c as a function of angle at the field and temperature of interest.

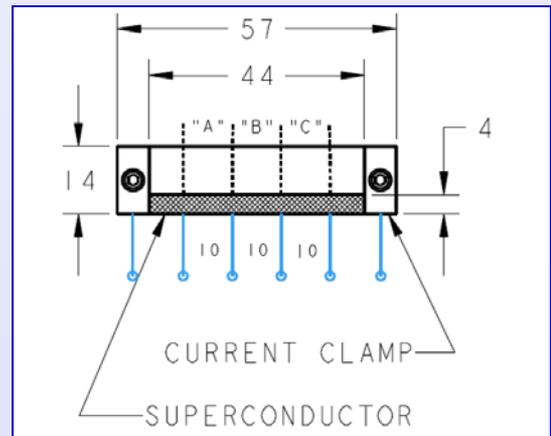
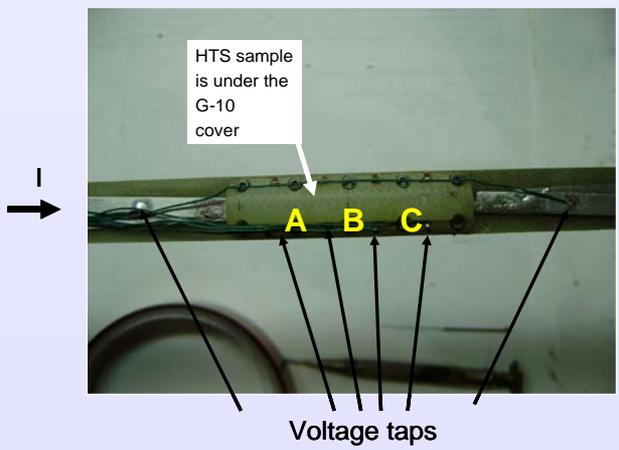
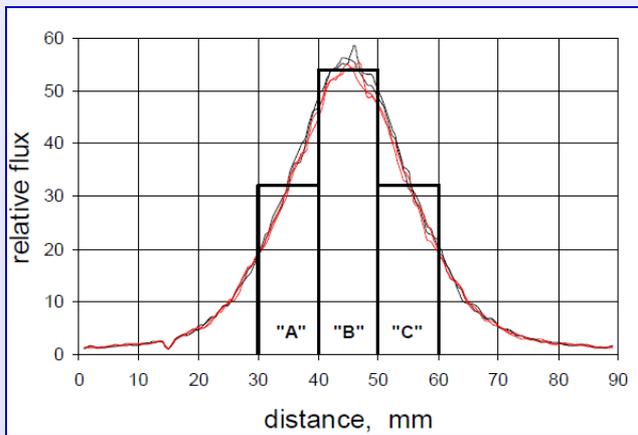
Courtesy:
D. Hazelton, SuperPower, Inc.

Details of Irradiation on Sample

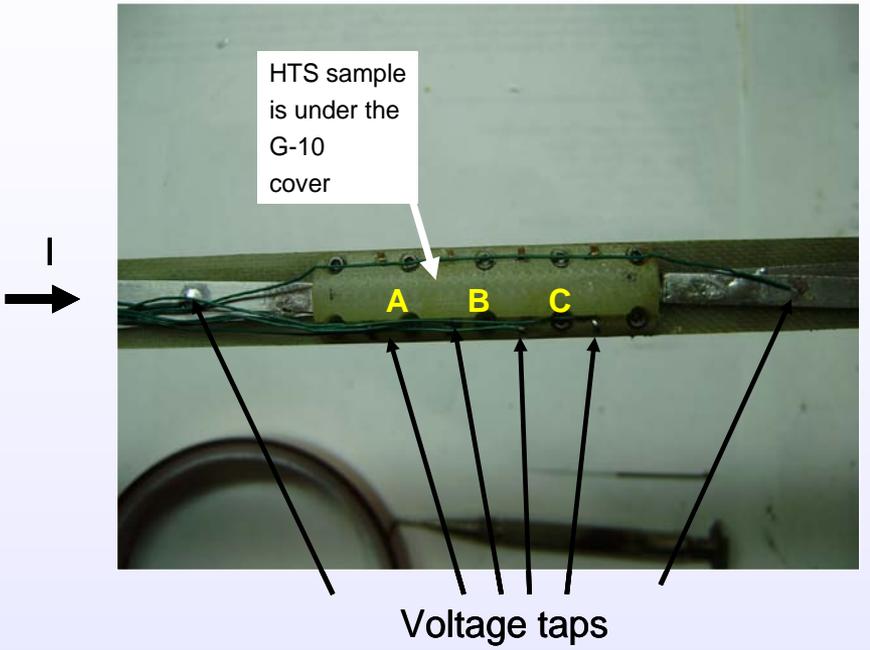


Gaussian distribution

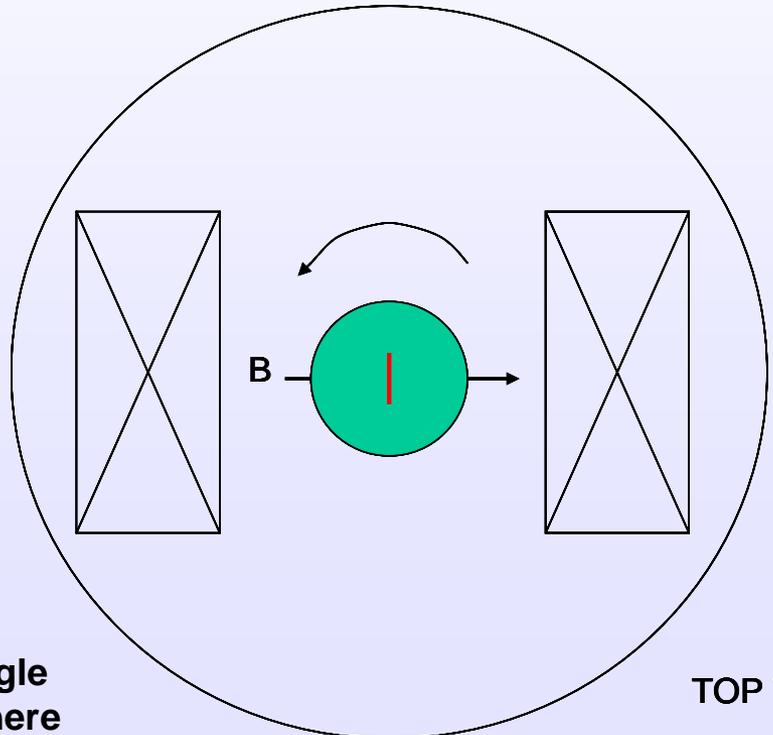
- Each sample was irradiated with 42 μA , 142 MeV proton beam from BLIP.
- Five doses were chosen: 2.5, 25, 50, 75 and 50 $\mu\text{A-hrs}$ or 10^{16} , 10^{17} , 2×10^{17} , 3×10^{17} and 4×10^{17} protons/cm².
- I_c measurements on samples are carried out in three sections (10 mm each), with middle section “B” having a uniformity of $\sim \pm 7\%$, but larger variation on two sides “A” and “C” : $\sim \pm 40\%$.



**Measured Angular Dependence in ASC Samples
at 77K (liquid nitrogen) in Various Applied Field**

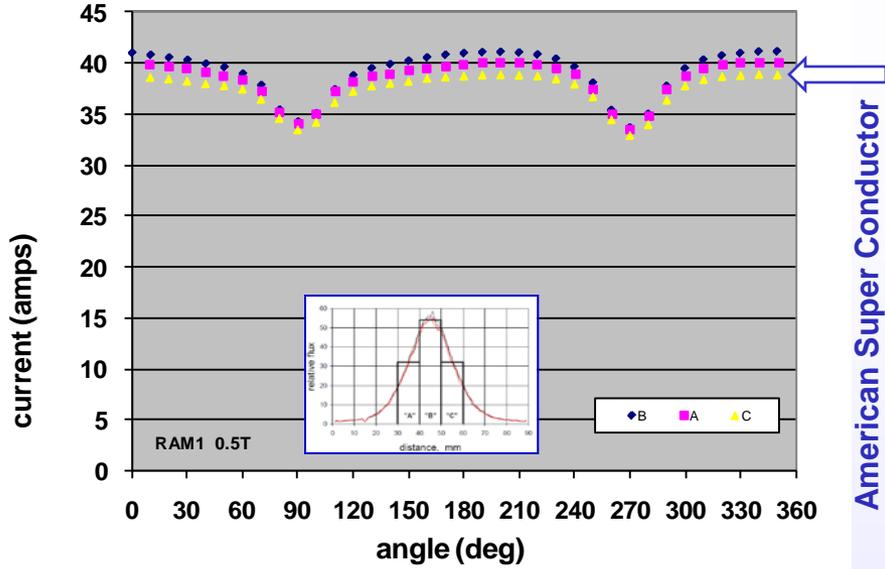


Field is measured with respect to c-axis (see below on right)

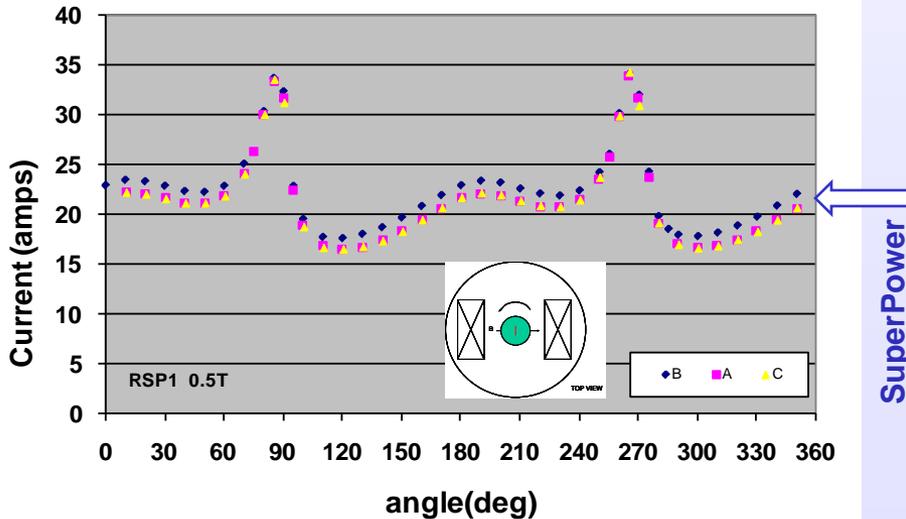


Impact of 142 MeV Proton Irradiation on 2G Samples from ASC and SuperPower @77K in 0.5T Applied Field

Superconducting
Magnet Division

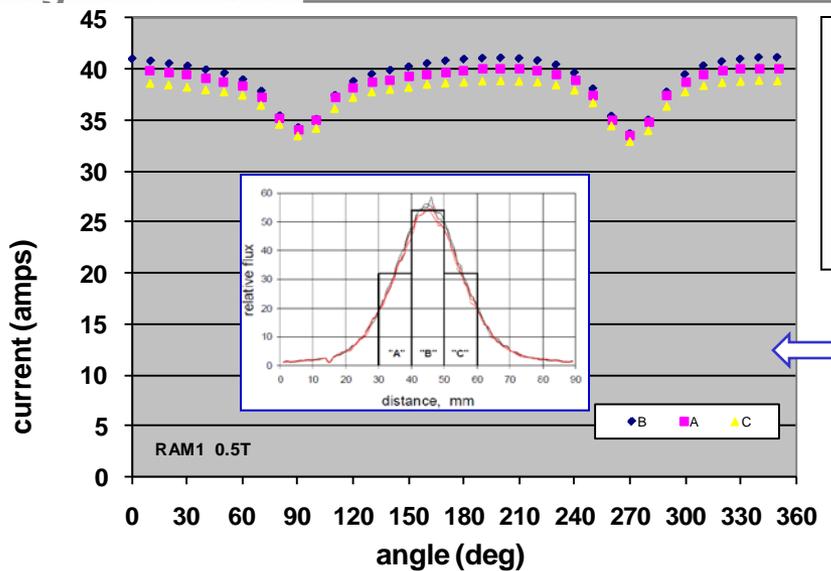


Very Low Radiation: 10^{16} protons/cm²



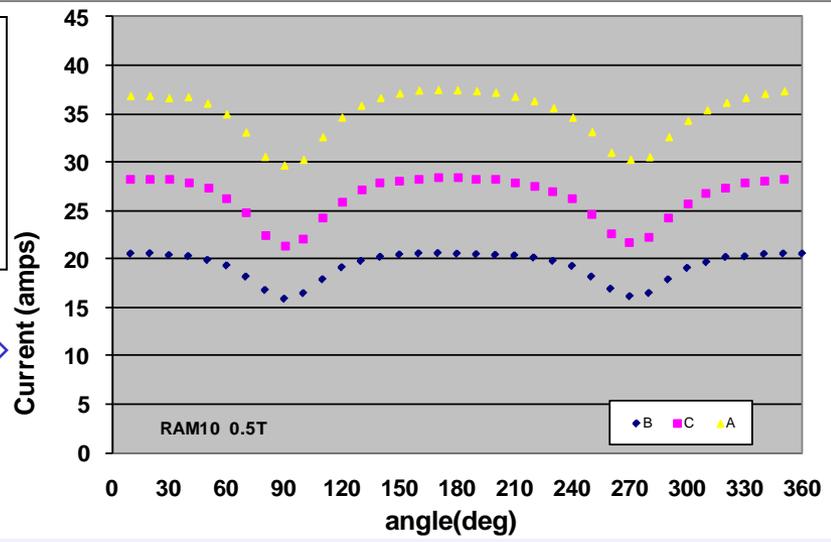
- Recall: The samples from ASC and SuperPower had similar critical current (~100 A) and showed very similar radiation damage at 77 K in self-field.
- However, the two behaved very differently in the presence of applied field. Anisotropy in this ASC sample (not their standard product) was small and is opposite to what usually is the case (critical current higher in a plane parallel to tape, i.e., ab-plane or at 90 degree).
- This difference in anisotropy in the samples from two vendors (ASC and SuperPower) was retained after small exposure.

Impact of 142 MeV Proton Irradiation on 2G Samples from ASC and SuperPower @77K in 0.5T Applied Field

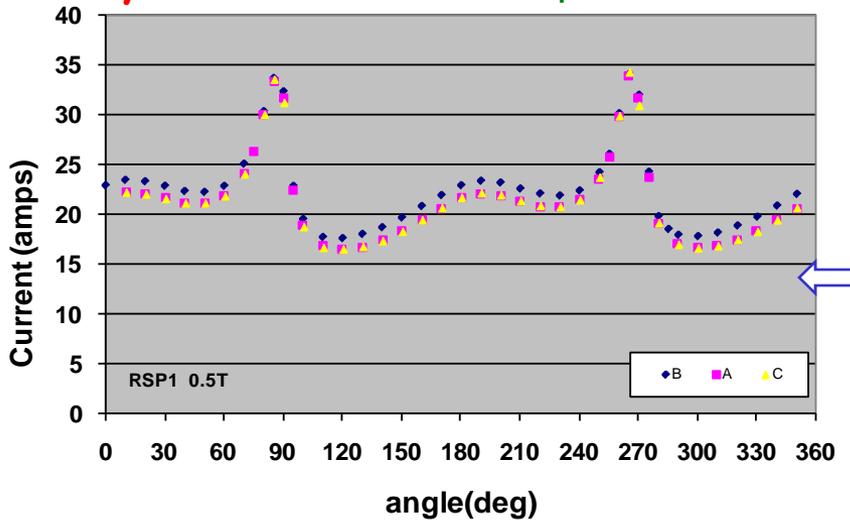


Very different behavior. Details follows...

ASC

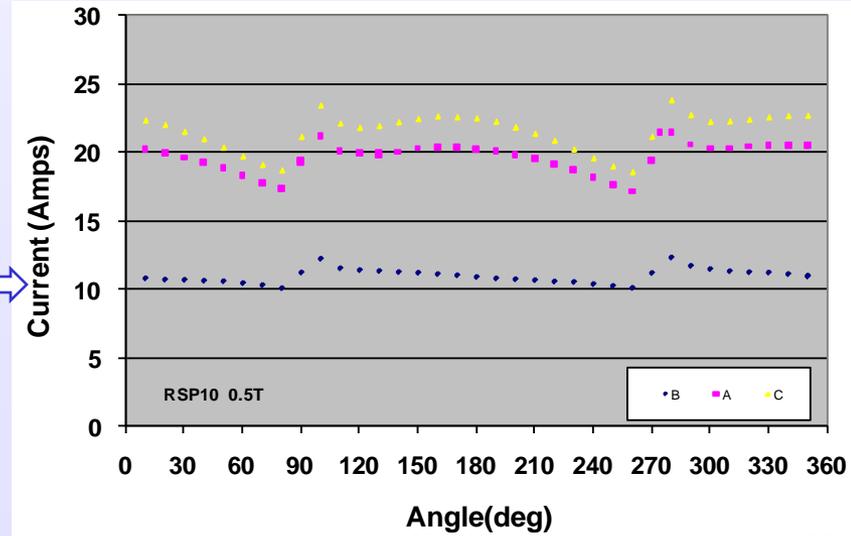


Very Low Radiation 10^{16} protons/cm²



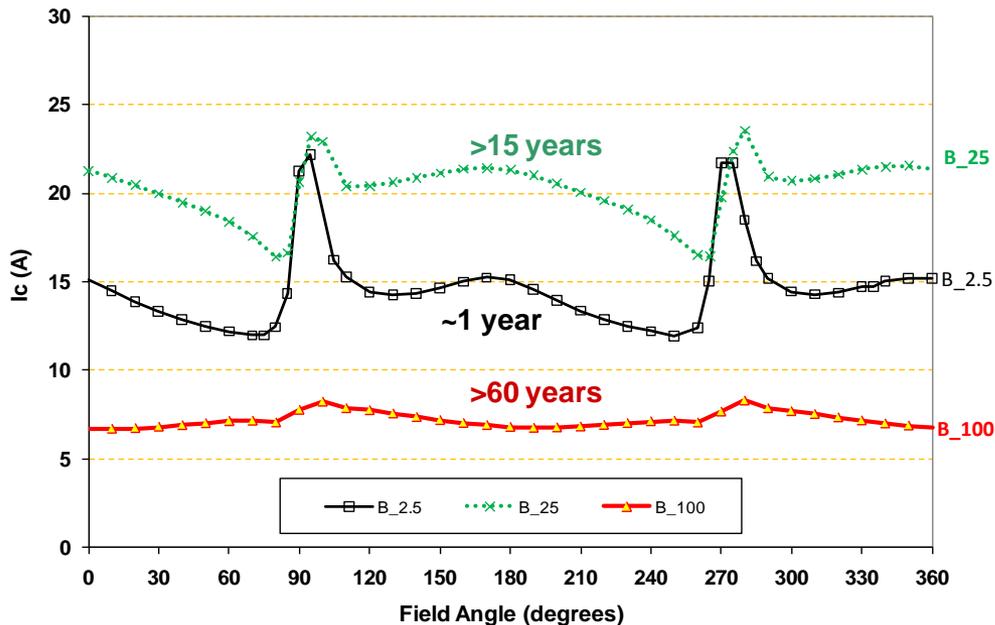
SuperPower

Very High Radiation 4×10^{17} protons/cm²



Impact of Various Doses in 2G Samples from SuperPower @77K in 1 T Applied Field

Ic Measurements of SuperPower Samples at 77 K in background field of 1 T

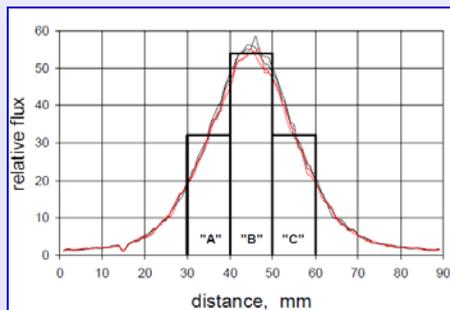


No. of years are estimated based on calculations at MSU

B_25 denotes 25 μ A-hrs integrated dose at location B (center position).

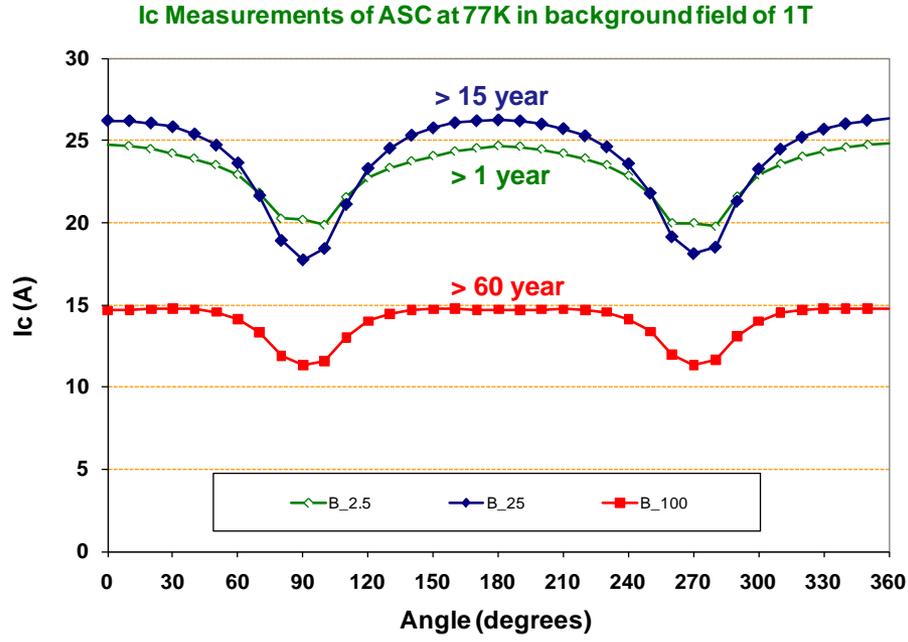
B_2.5 denotes 2.5 μ A-hrs and

B_100 denotes 100 μ A-hrs.



- Note: A remarkable increase in I_c caused by irradiation from 142 MeV protons.
- 25 indicates 25 μ A-hrs integrated dose (10^{17} protons/cm²) which is equivalent to >15 years of FRIB operation.
- The desired goal was to allow less than 10% damage in 10 years of operation.
- These measurements imply that this HTS from SuperPower tape is acceptable.
- In fact, rather than causing any damage in performance, the radiation seems to improve it based on the measurements at 77K, in 1 T applied field at all field angles.
- Anisotropy is significantly reduced at very high doses.

**Impact of Various Doses in 2G Samples from
ASC @77K in 1 T Applied Field**

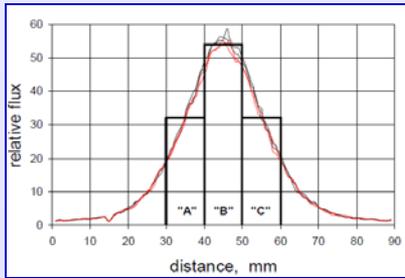


No. of years are estimated based on calculations at MSU

B_25 denotes 25 μ A-hrs integrated dose at location B (center position).

B_2.5 denotes 2.5 μ A-hrs and

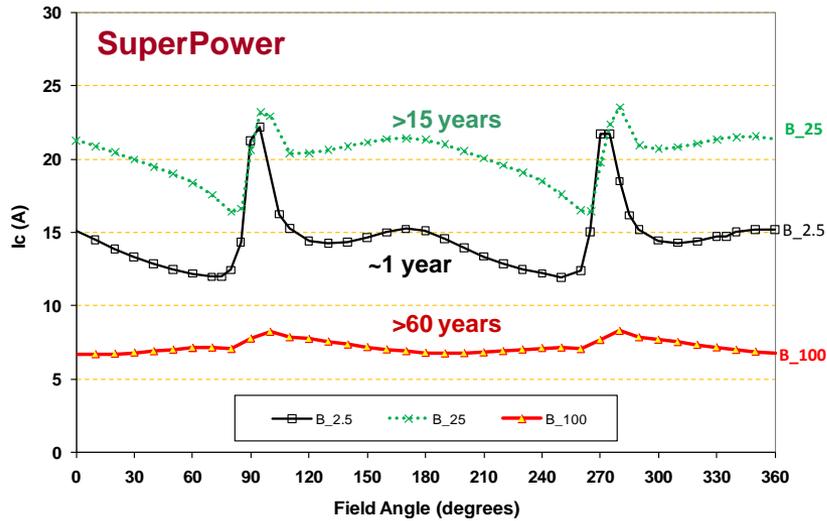
B_100 denotes 100 μ A-hrs.



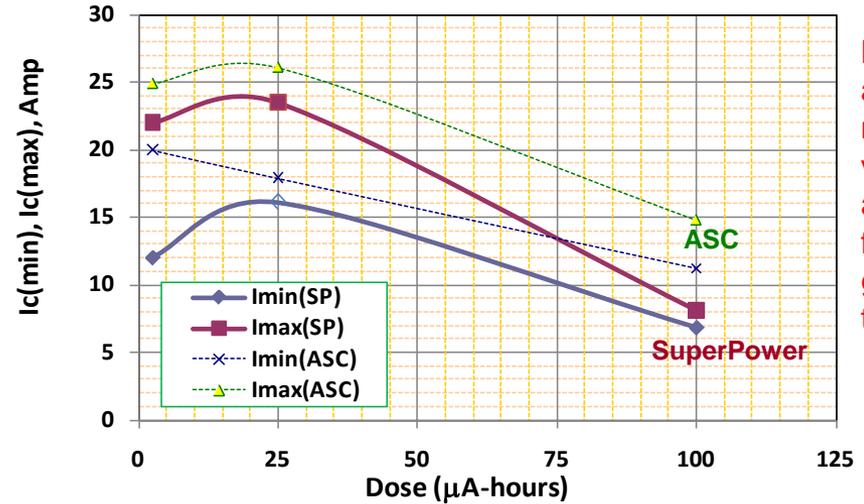
- Note: A remarkable change in I_c caused by irradiation from 142 MeV protons.
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- The desired goal was to allow less than 10% damage in 10 years of operation.
- These measurements imply that this HTS from ASC is acceptable for FRIB.
- Initially there is an increase in the maximum value of I_c and decrease in the minimum based on the measurements at 77K, in 1 T applied field at all field angles.
- Anisotropy is increased initially but then reduced at very high doses.

Comparison of 2G from SuperPower and ASC @77K in 1 T Applied Field from 142 MeV Proton irradiation

Ic Measurements of SuperPower Samples at 77 K in background field of 1 T

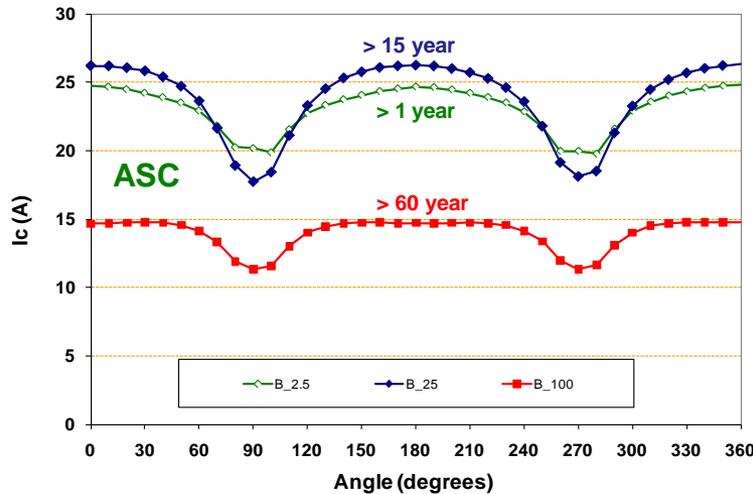


Ic Measurements of SuperPower and ASC at 77K in field of 1T



Minimum and maximum values of I_c are obtained from the graphs on the right

Ic Measurements of ASC at 77K in background field of 1T



- Initially there is an increase in the maximum value of I_c in both samples (see maximum value of each curve).
- In case of SuperPower, both minimum and maximum value increases.
- In ASC, anisotropy initially increases.
- However, after a very large irradiation, samples from both SuperPower and ASC become more isotropic and there is less damage in ASC samples than in SuperPower samples.

Previous Work on Radiation Damage

- Similar work has been performed previously and increase in critical current has been observed.
- The work presented here shows a significant increase when YBCO was irradiated with proton beam – a level previously never observed before.
- Examples of some previous work will be shown in next few slides (not intended for an exhaustive reference list).

Previous Studies Bi2223

Budhani, et al.: 800 MeV proton irradiation on Bi2223

Studies of flux pinning by proton-induced fission tracks in multifilamentary tapes of $(\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}/\text{Ag}$ superconductors

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(Received 29 April 1997; accepted for publication 10 June 1997)

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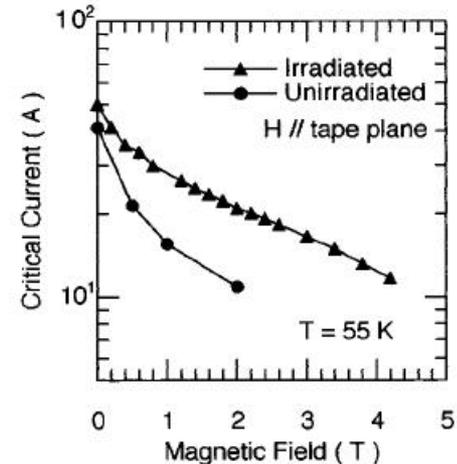


FIG. 6. Critical current at 55 K of the unirradiated (open circles) and irradiated ($B_\phi = 1$ T) (open triangle) tapes at 55 K for the field aligned parallel to the plane of the tape.

Previous Studies Bi2212

Ballarino, et al.: Neutron irradiation on Bi2212

Effect of fast neutron irradiation on current transport properties of HTS materials

A. Ballarino*, A.N. Bruchanov**, V.S. Kruglov**, S.T. Latushkin**,
A.N. Lubimov**, A.I. Ryazanov**, S.V. Shavkin**, T.M. Taylor*,
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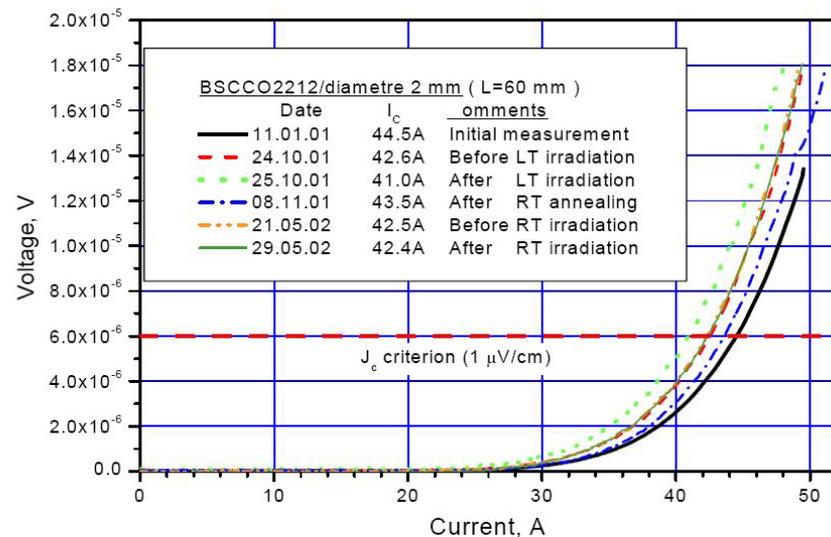


Figure 2. Voltage-current characteristics of sample D2 (bulk material).

EUCAS2003

Previous Studies YBCO

Chudy, et al.: Neutron irradiation on YBCO

Influence of Neutron Irradiation on YBCO Coated Conductors

M. Chudy, M. Eisterer, H.W. Weber

Atominstut, Vienna University of Technology, Vienna, Austria

Introduction

High temperature superconductors (HTS) may be applied for the magnets in next generation fusion devices (e.g. DEMO). These magnets may operate in the temperature range of liquid nitrogen or slightly below, which could save energy spent for cooling and also replace expensive and scarce helium as a coolant. Apart from the special requirements on the mechanical properties, the conductors will be exposed to radiation. Therefore, the influence of neutron irradiation on coated conductors was examined. The development of coated conductors has rapidly advanced in the last few years. The critical current density (J_c) improved by approximately 30% every 2 years. The following generation of coated conductors has, apart from other improvements, usually more pinning centres, which are much more effective. Irradiation by fast neutrons is a useful tool to introduce effective pinning centres into a superconductor, but too many pinning centres and the introduced disorder may cause degradation of the superconducting properties [1].

Transport measurements

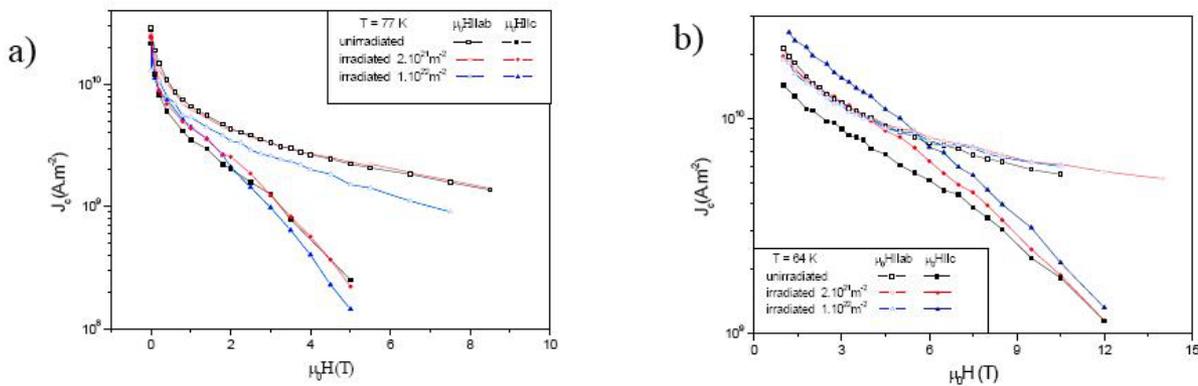


Figure 3: Transport measurements for the main field orientations prior to and after irradiation a) 77 K, b) 64 K.

EUCAS 2009

Future Plans on Radiation Studies

- Perform 77 K, in-field radiation damage studies on the remaining samples (samples with integrated dose of 50 and 75 μA -hours).
- Perform radiation damage studies at 40 K – 50 K up to 2 T (or more).
- There is also a plan to extend this study to 4 K and at high fields.
- Irradiate the current production from ASC and SuperPower. Both have a different in-field behavior (pre-irradiation) than those used in this study.
- The in-field radiation damage response of new samples may, in detail, be different from the samples examined here even if the FRIB requirement of >10 years of safe magnet operation is met.

First Generation HTS Magnet R&D

- 25 coils were successfully built and tested with ~5 km of Bi2213 (1G) HTS
- Several HTS magnet structures were successfully built and tested over a wide temperature range (4K-80 K).
- Large energy deposition experiment were carried out to demonstrate that HTS can operate robustly under such hostile environment.
- The first generation R&D has now been completed and this forms the basis of the next demo magnet for FRIB.

Second generation magnet design responds to

- Higher gradient requirements (~15 T/meter instead of ~10 T/meter)
- Shorter magnetic length (first quad 0.6 meter instead of 1 meter)
- Discontinuation of manufacturing of 1st generation HTS (a corporate decision because 2nd generation HTS is projected to be cheaper)
- 2nd generation HTS also allows a more efficient removal of large heat loads at ~50 K rather than ~30 K in magnets with the 1st generation

Acknowledgements

- A productive collaboration with Michigan State University (MSU), the site of proposed FRIB, is highly appreciated. In particular, Al Zeller help determined the FRIB equivalent dose of 142 MeV proton beam. R. Ronningen did the transport calculations.
- Number of slides on FRIB presented here were prepared by G. Bollen, C. Wilson and A. Zeller of MSU.
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- We appreciate support of Radiological Control Division and Safety and Health Services Division for their help in dealing with radiation and cryogenic safety issues.
- The design and establishment of FRIB as a DOE Office of Science National User Facility is supported by the Nuclear Physics Program in the DOE Office of Science under Cooperative Agreement DE-SC0000661.

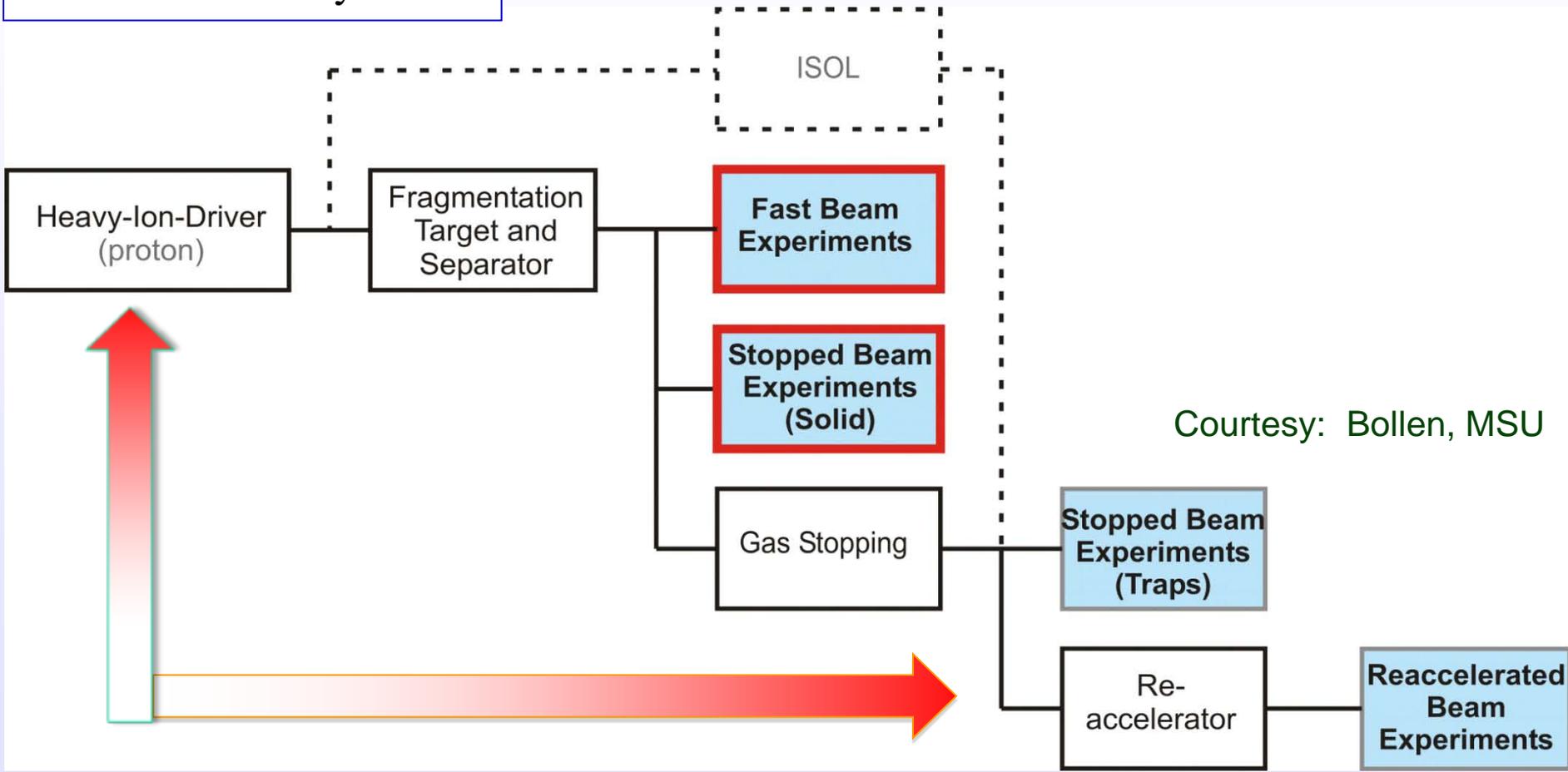
Summary

- A number of measurements have been performed at 77 K to examine the radiation damage of 2G conductors from SuperPower and ASC. These includes measurements in applied field up to 1.25 T.
- Based on these measurements both SuperPower and ASC seem to satisfy the FRIB radiation magnet resistant requirement of 10 years of safe operation despite a very high radiation dose.
- In case of SuperPower, there is an overall improvement in critical current during the intended lifetime.
- In case of ASC there is improvement in the maximum value, but minimum value drops, however, stays within the required limit.
- These points will be reevaluated after the measurements at 40K-50 K.
- Future plans include more testing of existing samples and testing of the radiation damage of the latest 2G HTS from both SuperPower and ASC.

Backup Slides

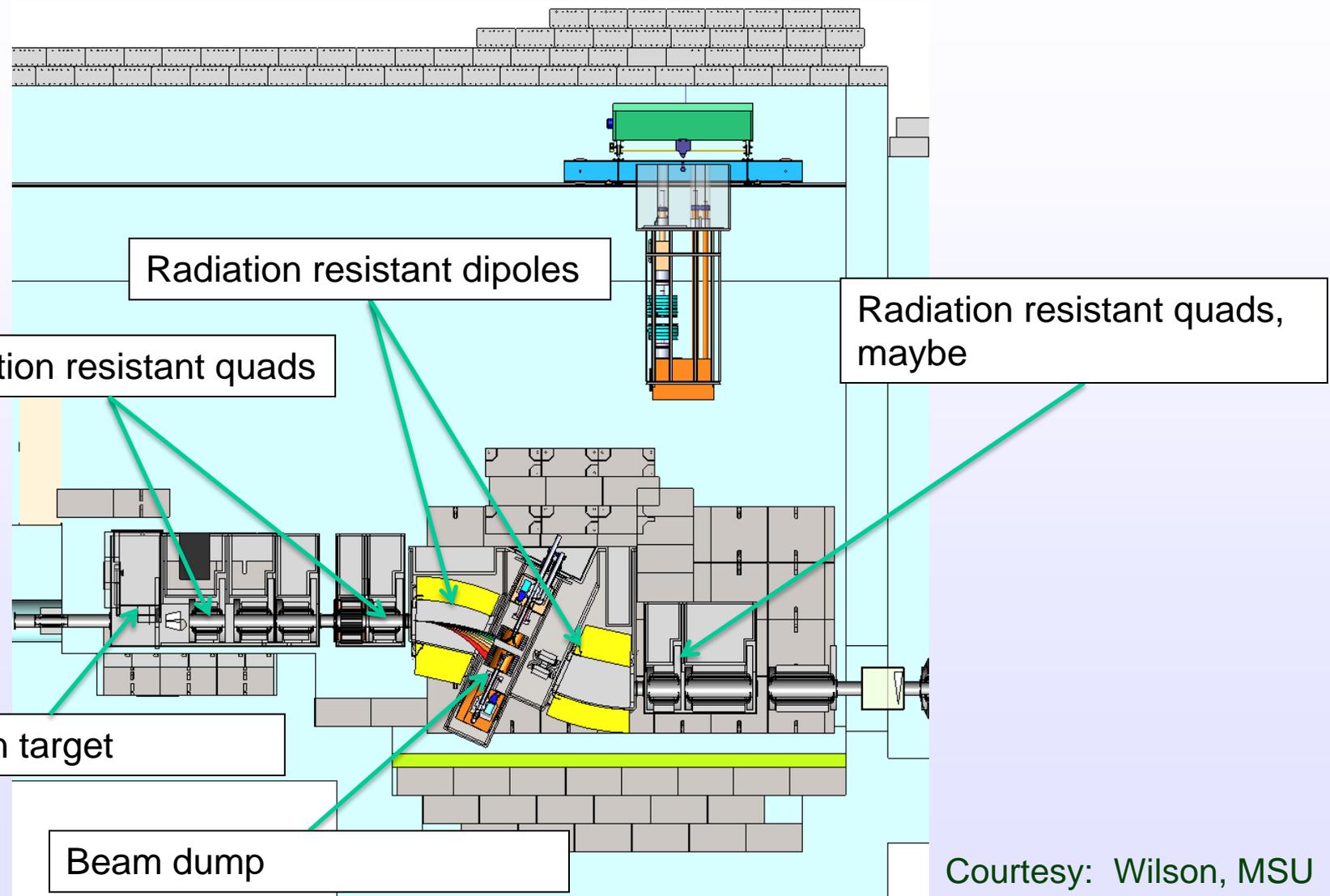
FRIB concept

A heavy-ion driver can also accelerate light ions needed for an ISOL facility



Courtesy: Bollen, MSU

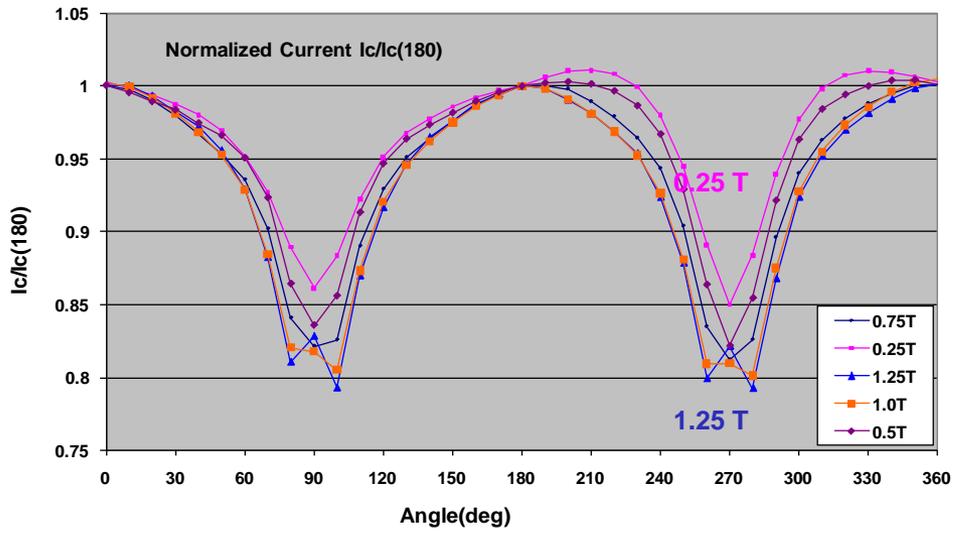
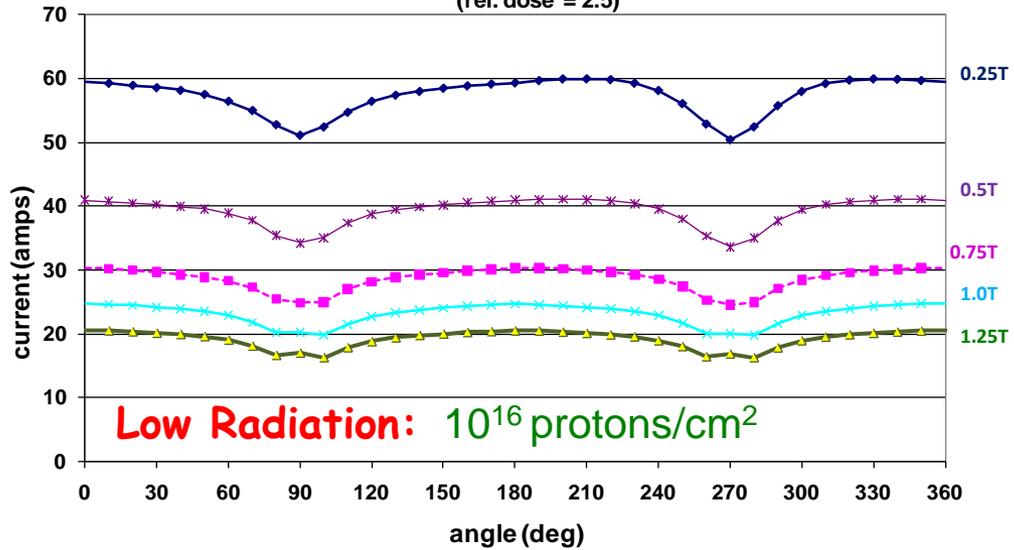
Radiation Resistant Magnets for FRIB Pre-separator



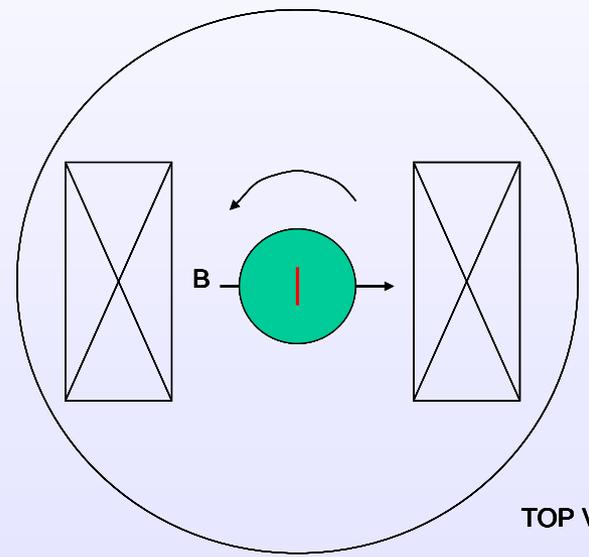
Courtesy: Wilson, MSU

Measured Angular Dependence in ASC Samples at 77K (liquid nitrogen) in Various Applied Field

Angular dependence of ASC Sample on I_c at various magnetic fields (rel. dose = 2.5)



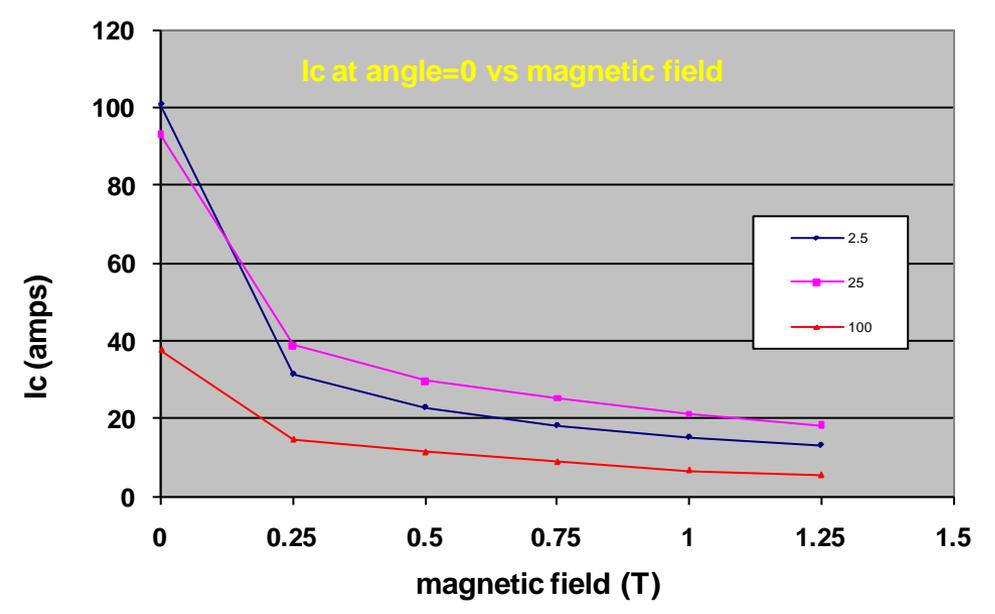
Field is measured with respect to c-axis



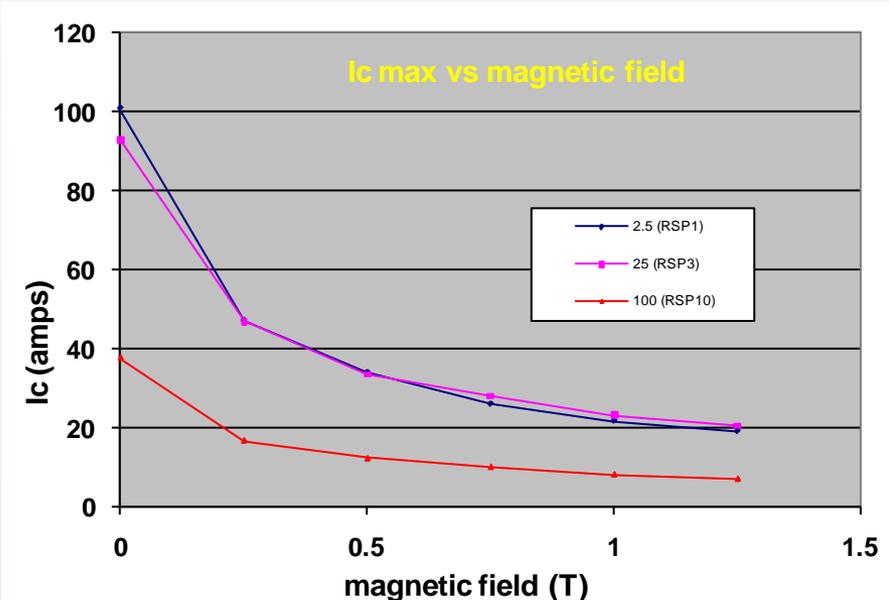
Field angle is zero here

Ic vs B in SuperPower Samples

- As magnetic field increases, Ic decreases for any radiated samples.
- However, rel.dose=25 gives higher Ic than rel.dose=2.5 under magnetic fields.



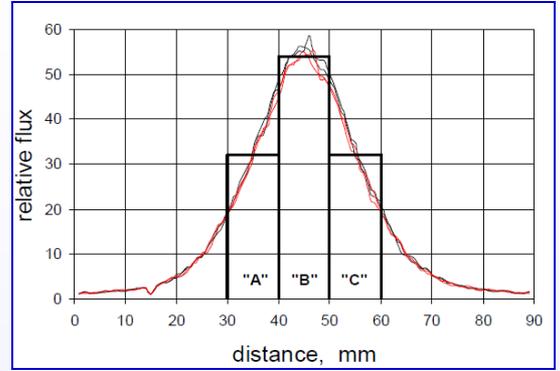
Angle = 0



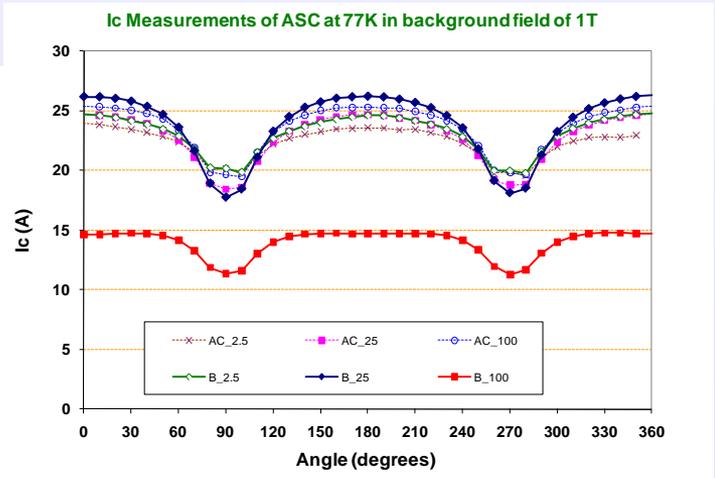
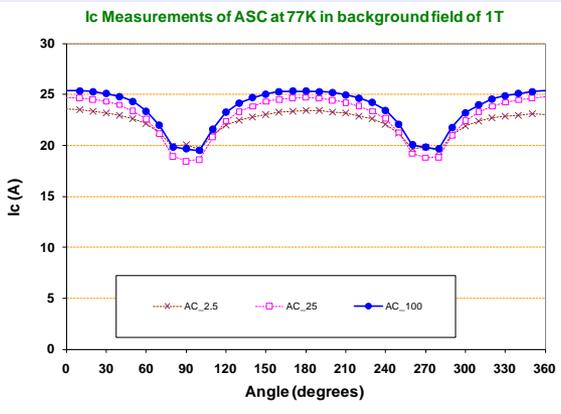
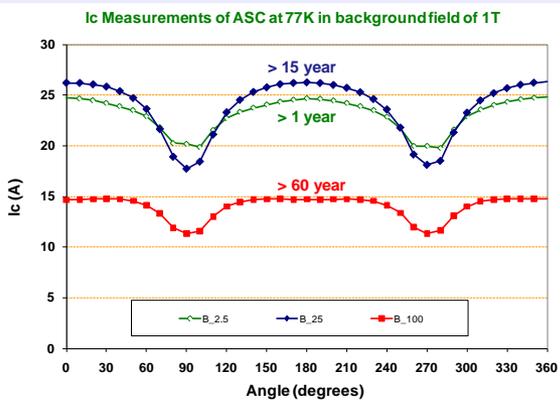
Angle = ~90 (peak)

More Statistics of Radiation Damage in 2G Samples from **ASC**

- I_c measurements were carried out in 3 sections (10 mm each).
- Middle section "B" was preferred for analysis because of higher uniformity in dose across the length ($\sim \pm 7\%$).
- The two sides "A" and "C" have lower integrated dose and hence they can provide additional data for intermediate points.
- However, the dose itself is not so uniform (variation $\sim \pm 40\%$) and therefore these points should be used with caution.
- They can be used to provide an indication of radiation damage at intermediate level.

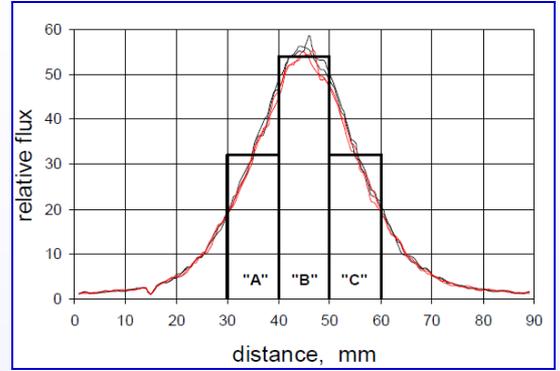


- B_25 denotes 25 $\mu\text{A-hrs}$ integrated dose at location B (center position).
- AC_100 denotes average of dose on side sections A&C when integrated dose in the middle section is 100 $\mu\text{A-hrs}$.



More Statistics of Radiation Damage in 2G Samples from SuperPower

- I_c measurements were carried out in 3 sections (10 mm each).
- Middle section "B" was preferred for analysis because of higher uniformity in dose across the length ($\sim \pm 7\%$).
- The two sides "A" and "C" have lower integrated dose and hence they can provide additional data for intermediate points.
- However, the dose itself is not so uniform (variation $\sim \pm 40\%$) and therefore these points should be used with caution.
- They can be used to provide an indication of radiation damage at intermediate level.



- B_25 denotes 25 μ A-hrs integrated dose at location B (center position).
- AC_100 denotes average of dose on side sections A&C when integrated dose in the middle section is 100 μ A-hrs.

