# Radiation Effects in Linear Accelerator Operations for Non Destructive Testing, Security, Industrial and Medical Applications

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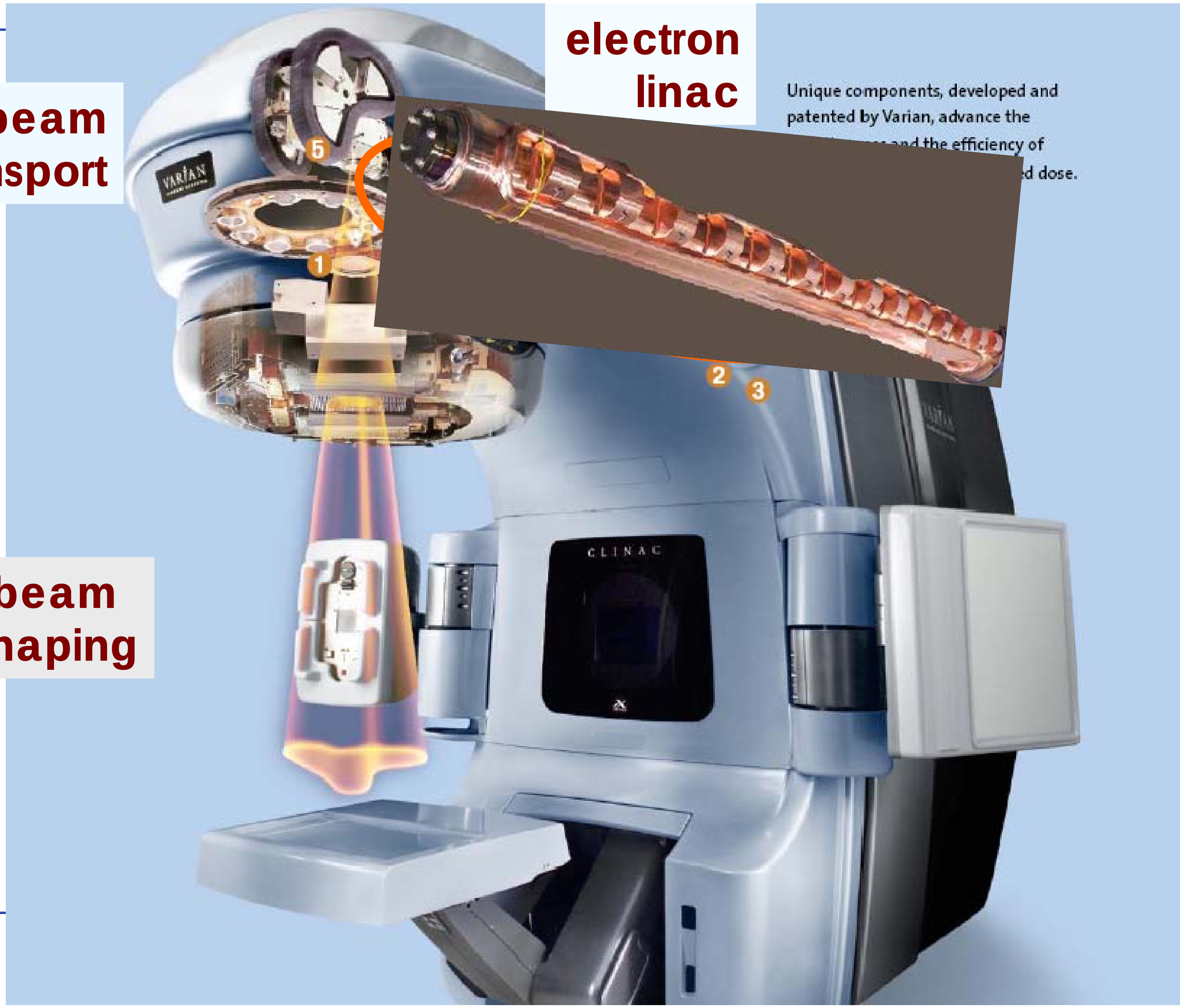
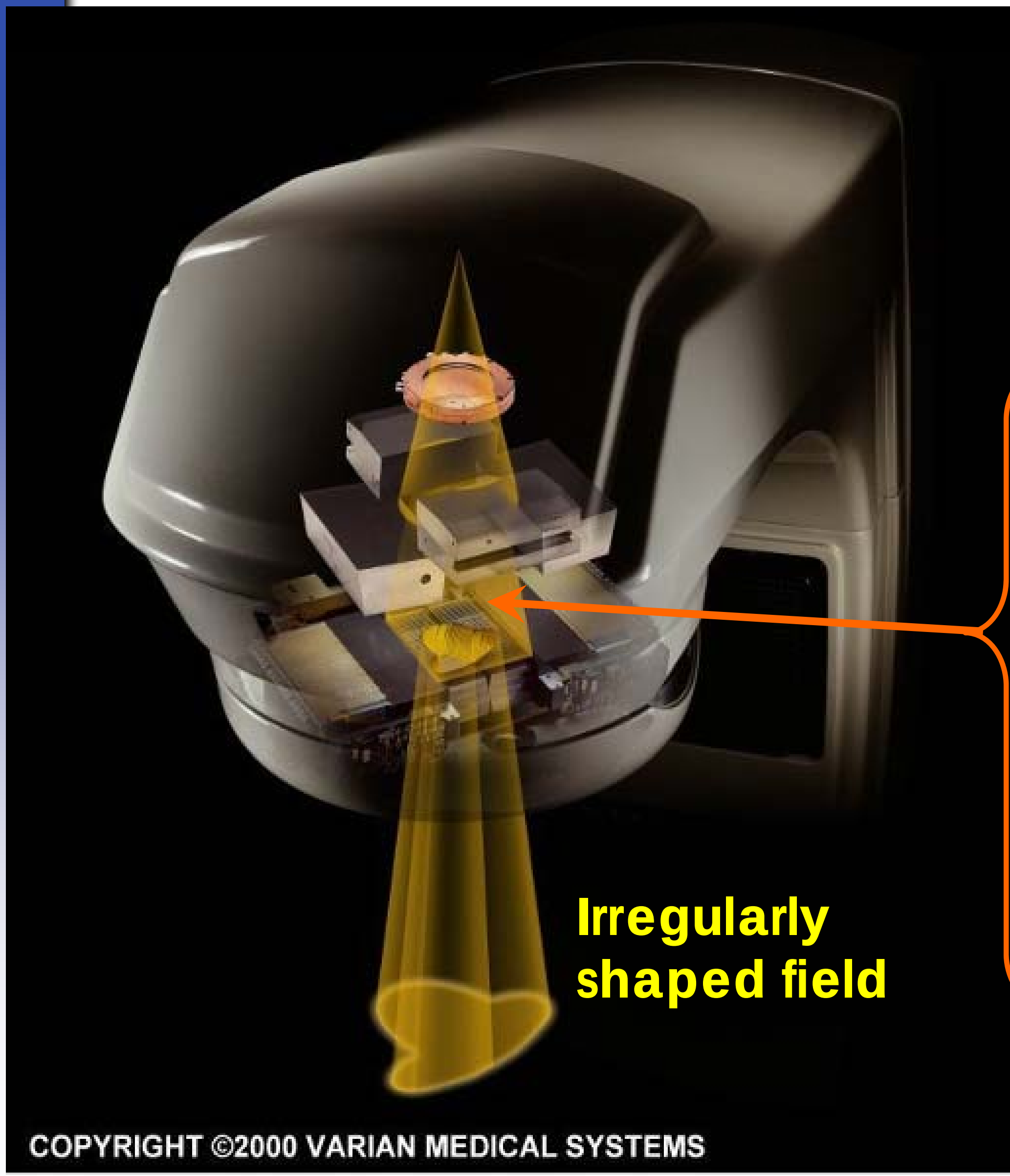
# Outline for Today

- Varian Medical Systems who we are and what do we do?
- More Sophisticated Treatments Require more computer control  - More CPUs, FPGAs, SRAM and DRAM
- Susceptibility of X-rays and Neutrons
- Testing is Critical
- What does a User Need

# Medical Accelerators for Photons or Electrons



# Multi-Leaf Collimator (MLC)




Millennium MLC: SomaVision™ and VARiS®

## Fine beam collimation

**Because tumors don't have corners**

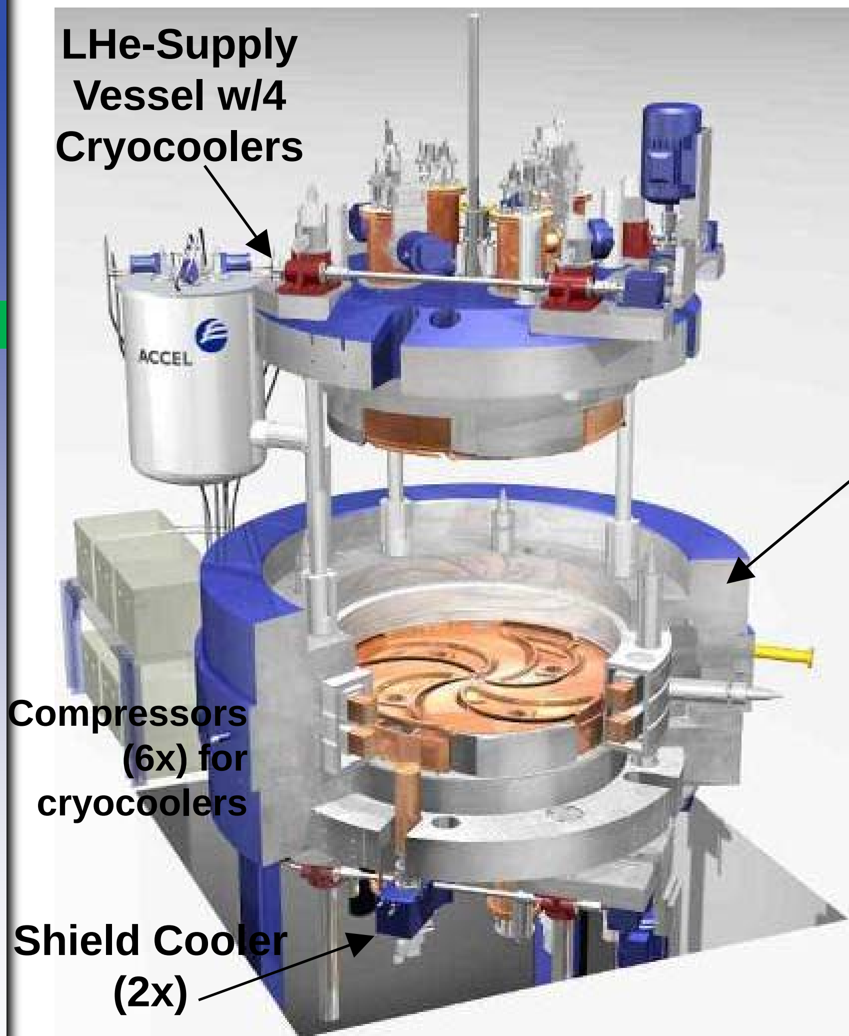

Millennium MLC: MLC-120

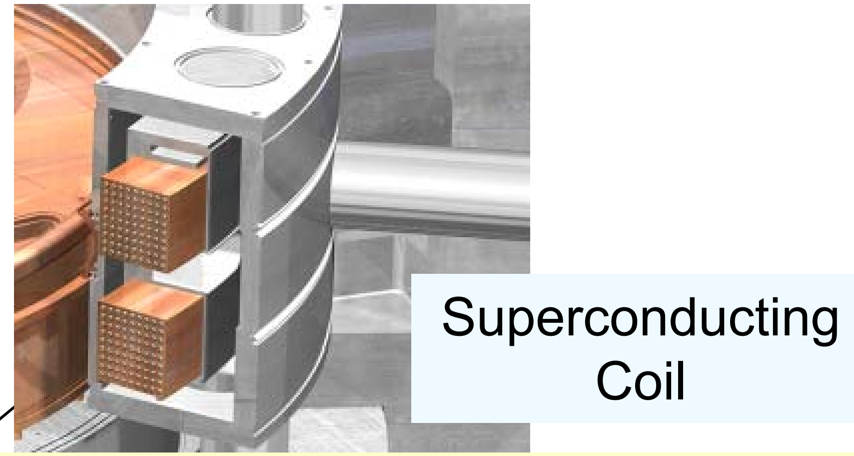
**120 tungsten "leaves"**

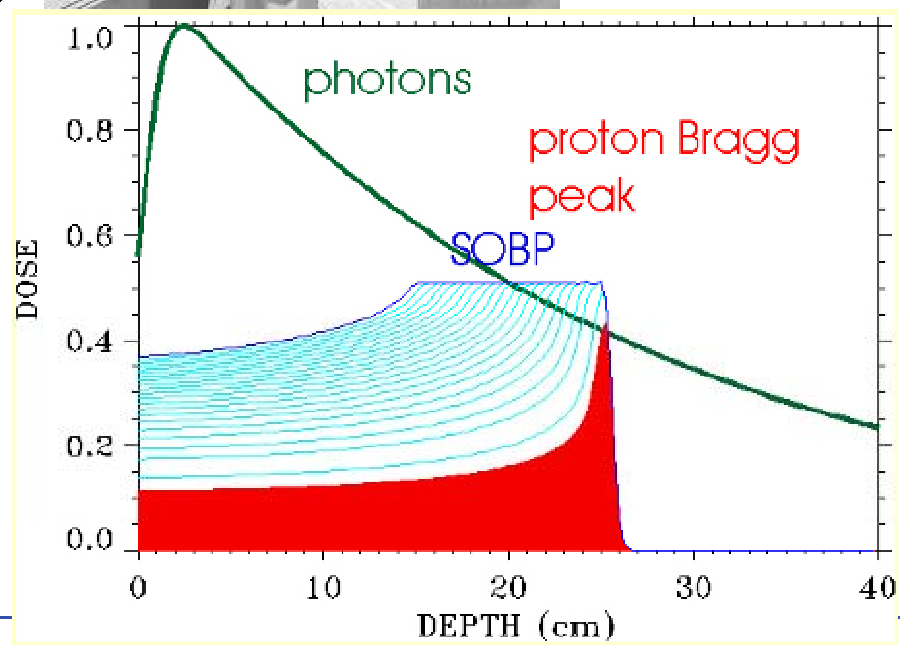
# Medical Accelerators for Proton Therapy

## VMS 250 MeV Isochronous Superconducting Proton Cyclotron

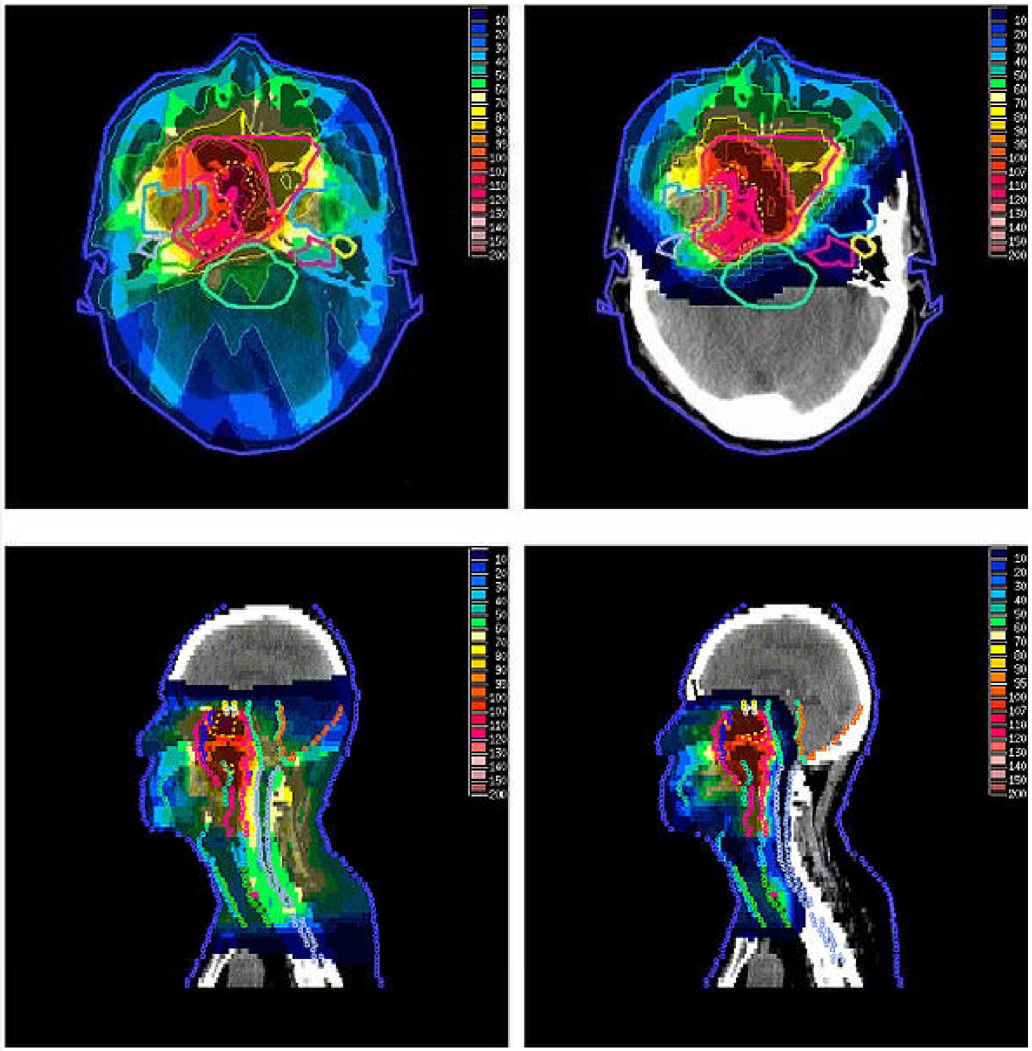
(USA FDA 510 k pending)



# Advantages of Proton Treatment - Healthy Tissue and Critical Structures Spared (USA FDA 510 k pending)



Taheri-Kadkhoda et al.
Radiation Oncology 2008 3:4
doi:10.1186/1748-717X-3-4

Irradiation of nasopharyngeal carcinoma by photon(X-ray) therapy (left) and proton therapy (right).

# Homeland Security Cargo Screening
## A Growing need for accelerators

### Mobile Platforms
Smiths Detection
Rapiscan Systems
L3

2-6.0 MeV
0.2 -3.5 cGy/min
350+ mm Steel

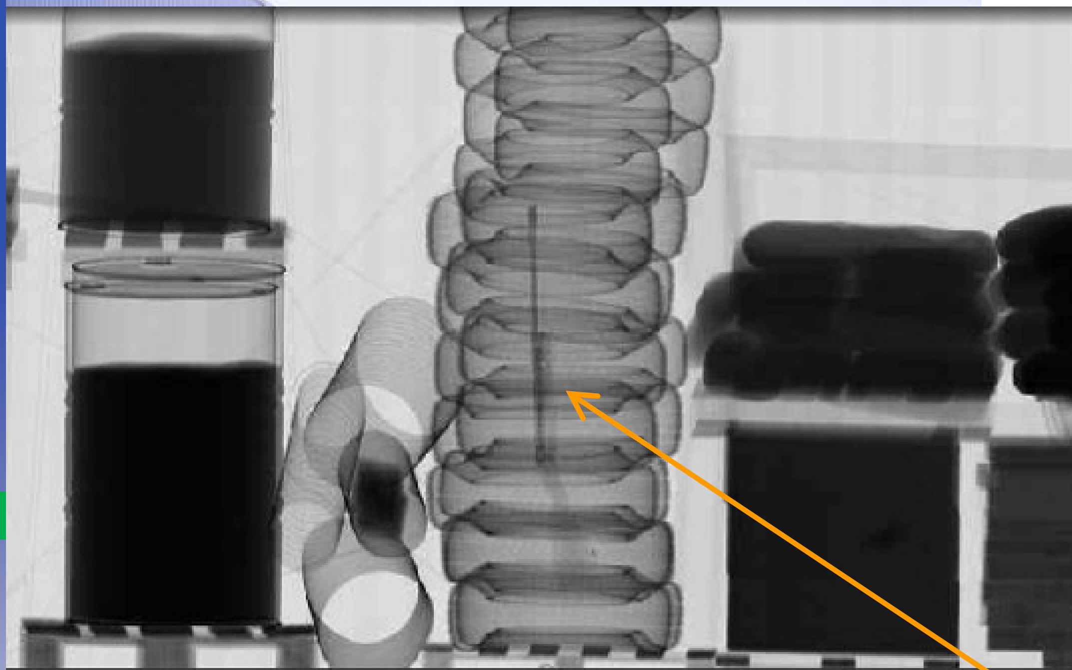
### Gantry Systems
Smiths Detection
Rapiscan Systems
L3
Varian

3-6 MeV
0.3-8 cGy/min
350 mm+ Steel

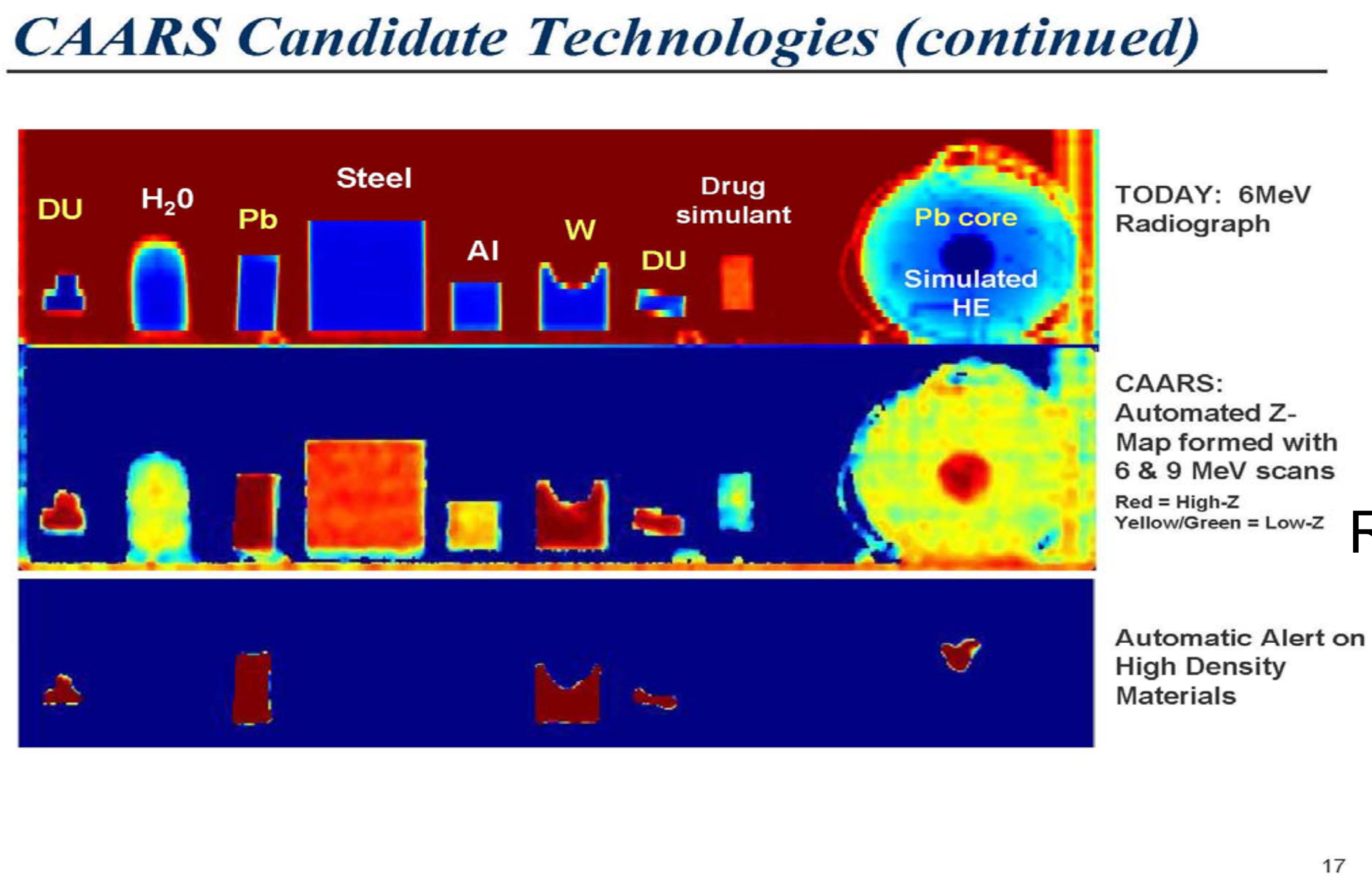
### Fixed Sites
Smiths Detection
Rapiscan Systems
L3
IHI
MHI

6- 9 MeV
10-30 cGy/min
400+ mm in Steel

# X-ray Systems



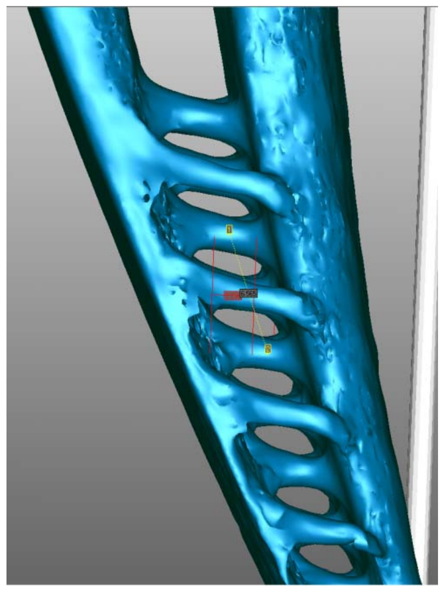
# Dual Energy X-ray Systems for Contraband Detection




Klystron Driven Dual Energy Linac
E= 6-9 MeV
Rep Rate 400 Hz

# Accelerators for NDT

- Mega-Voltage Computed Tomography (CT)
- Digital Radiography

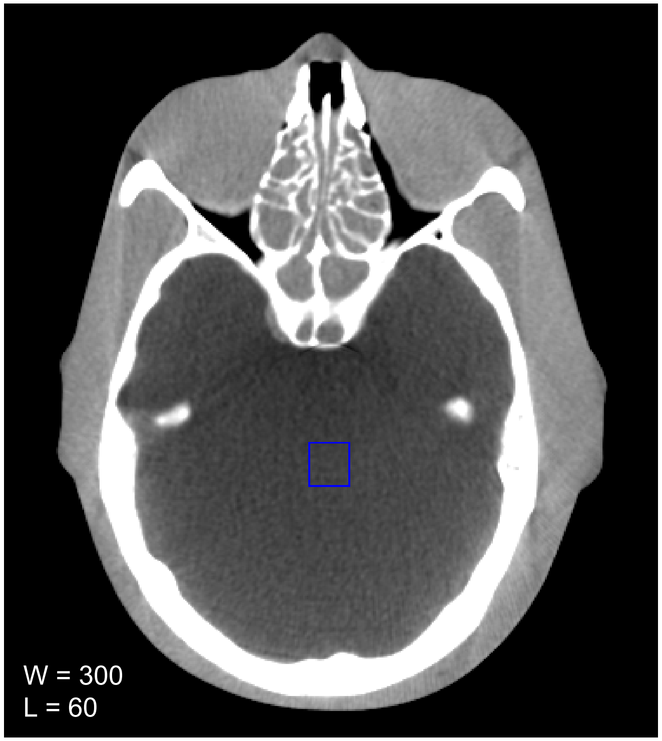


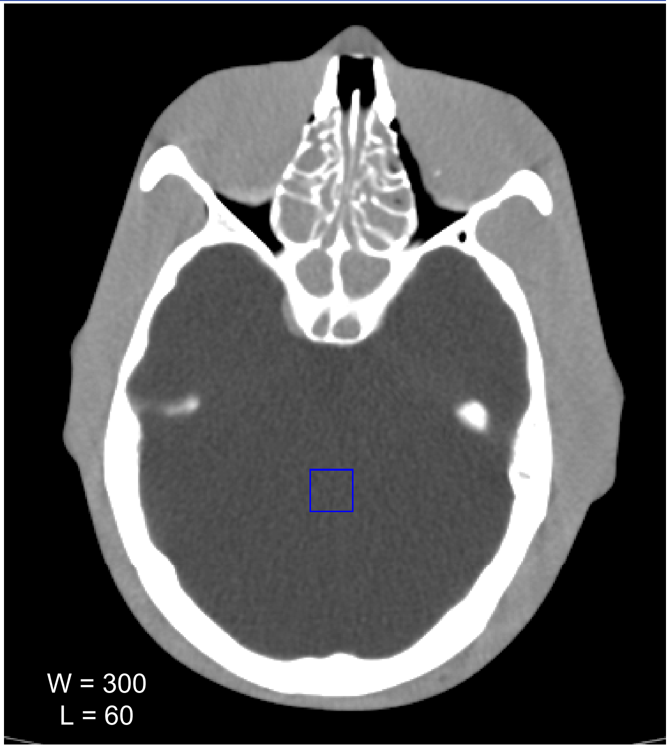

X-band 1 MV

# Amorphous silicon devices

- Device physics
  - a-Si has significant atomic disorder vs. crystalline silicon (c-Si)
  - Film contains ~ 10% atomic hydrogen → a-Si:H
  - Conduction is by trap and release transport
  - Has poor electron drift mobility ($\mu_d$)
    - a-Si $\mu_d$ ~ 1 $cm^2$/Vsec and <<< for holes
    - c-Si $\mu_d$ ~ 1,500 $cm^2$/Vsec
  - P-i-n photodiode fabricated with:
    - 1 µm intrinsic i-layer between 10 nm p+ and n+ layers
    - Has an optical band gap ~ 1.8 eV
    - Spectral quantum conversion efficiency ~ 80% for light 500–600 nm
  - Thin film transistors (TFT) fabricated as N-channel devices with:
    - 100K to 4M ohm on-resistance
    - $10^{15}$ ohm off-resistance
- Radiation tolerance
  - a-Si > 1 M rad gamma ray dose from random defect structure and self annealing at room temp
  - c-Si ~ 10 K rad gamma ray dose

# Strip Detector MDCT Comparison



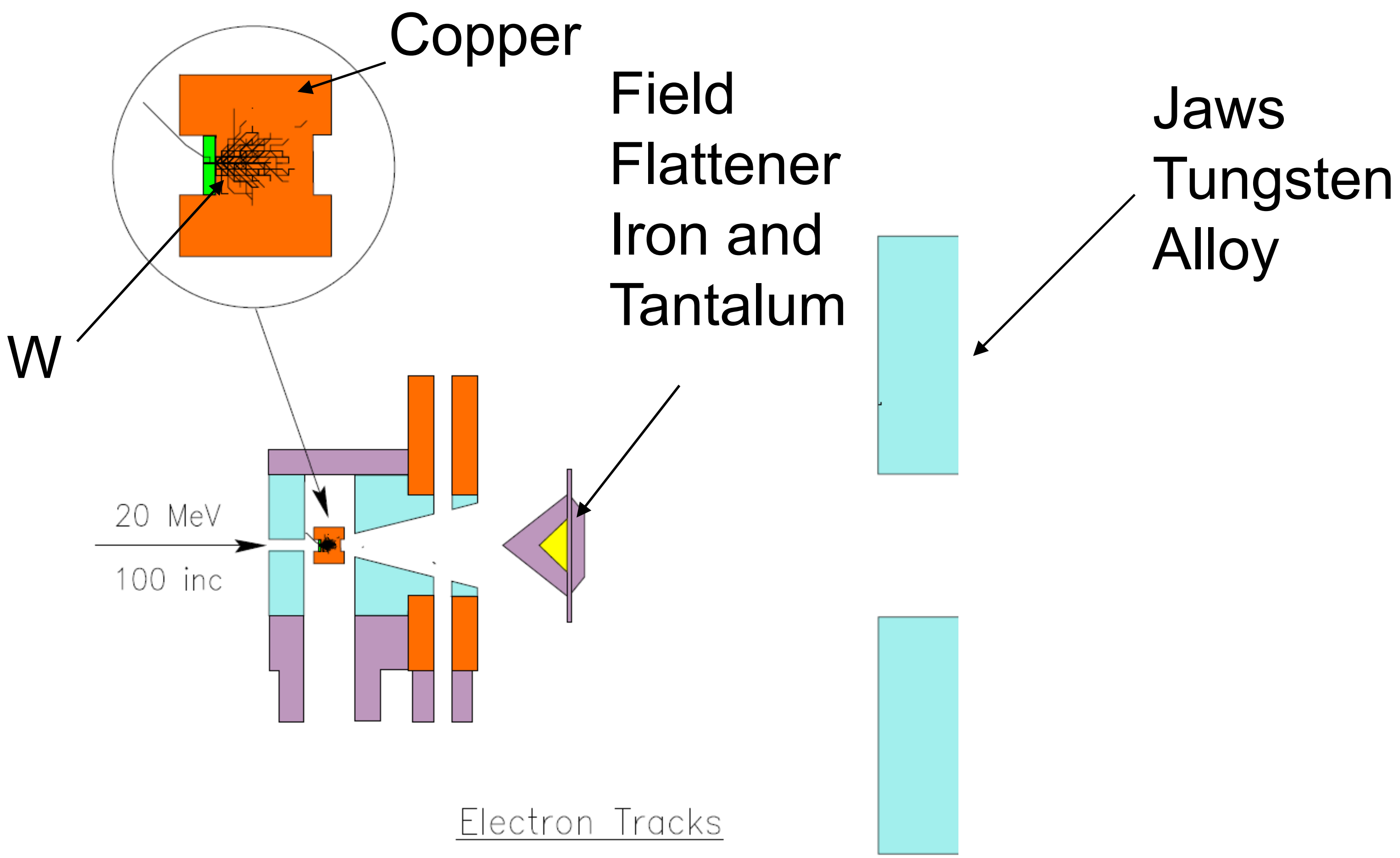

*FP MDCT 64-row*
Tech: 120 kV, 375 mAs, 1. 5 sec
3 mm slice, 25 cm FOV
ROI = 2 HU, noise = 0.51 %

*Diagnostic 16-slice scan PB*
Tech: 120 kV, 400 mAs, 1.5 sec
3 mm slice, 25 cm FOV
ROI = 0 HU, noise = 0.44 %

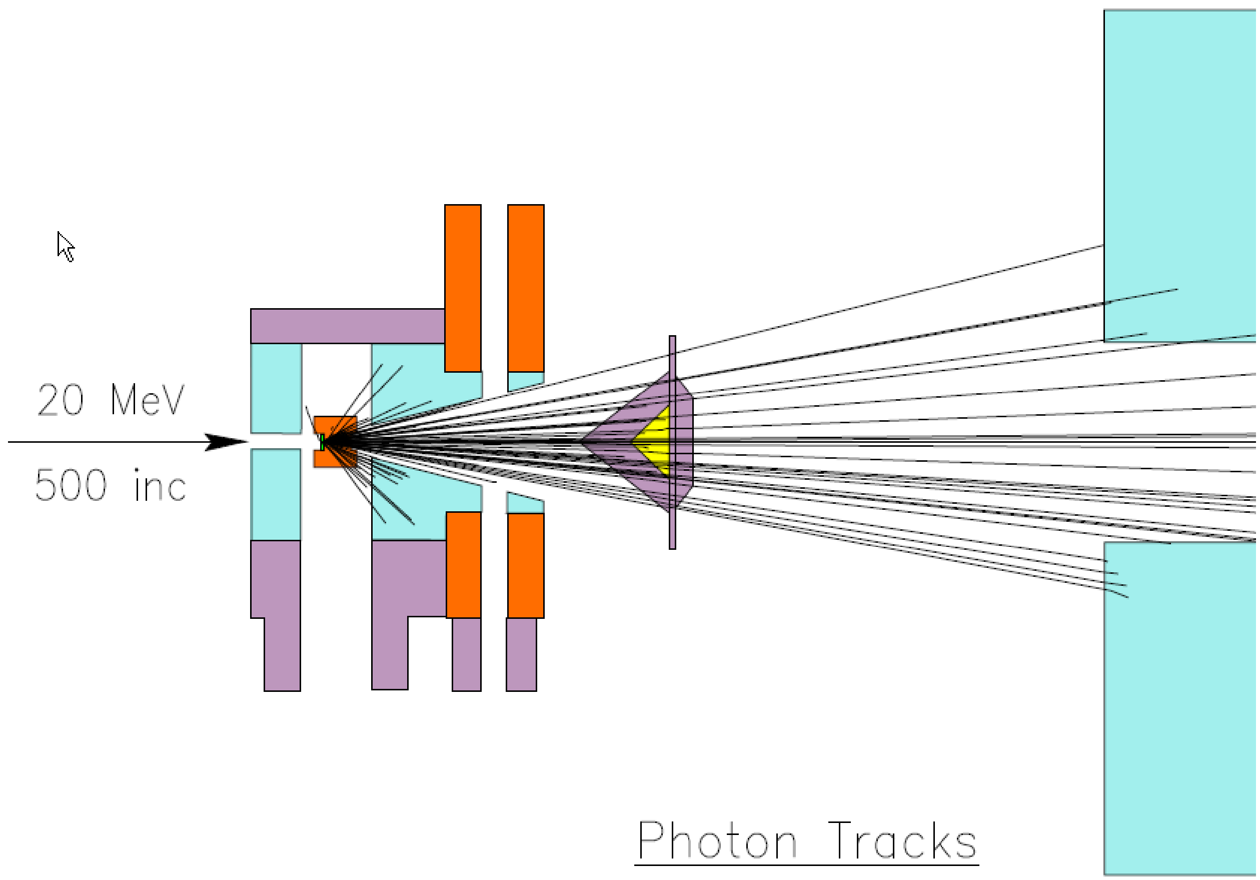
# Neutron Production in Linear Accelerators
# A Brief Primer

- Neutrons arise from ($\gamma$,n) reactions
  - Targets, Collimators, Field Flatteners and MLC
  - Threshold Energy for ($\gamma$,n) Dependent on Materials
    - Be 1.67 MeV
    - W 6.19 MeV
    - Cu is 9.91 MeV
  - Can be made in Electron Mode
    - The probability is small only ~1% of the photon rate

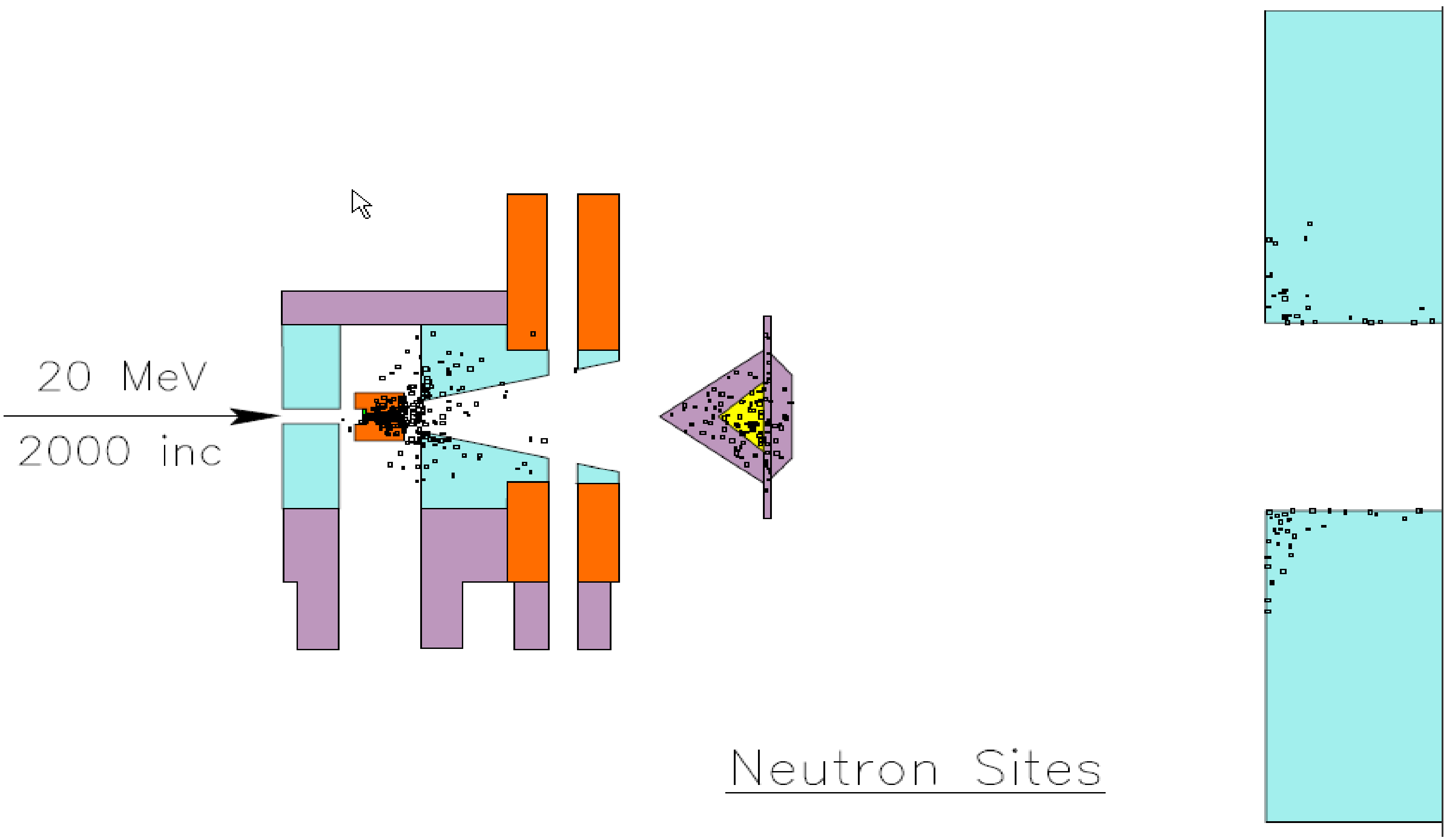
# Electrons in the Target



# Photons Created in the Target



# Photoneutron Production from the Photons and Electrons



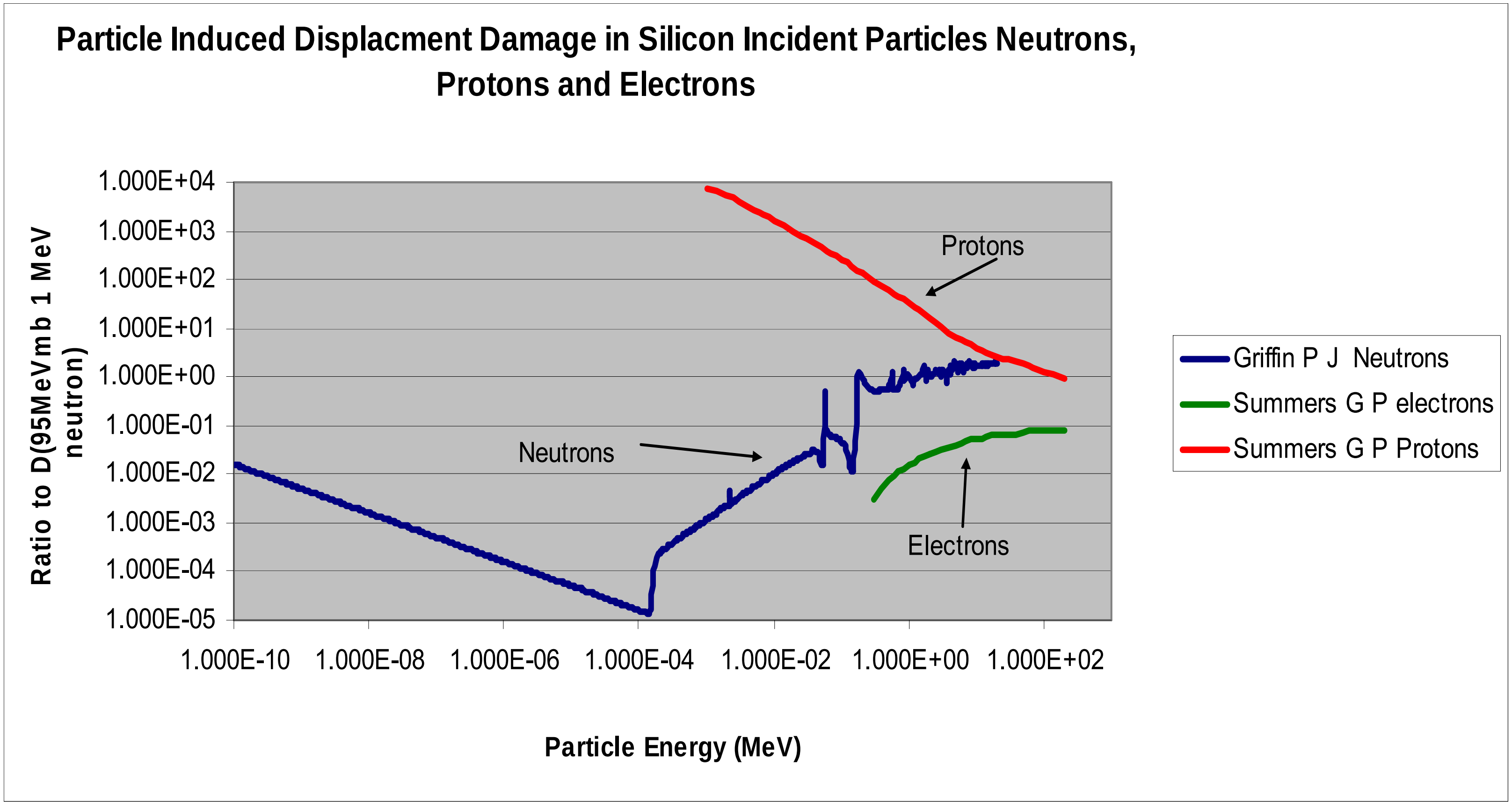
# Why is this a Problem?

- Neutrons Induce Damage in Silicon Devices Two Ways
- First - Fast Neutrons can cause nuclear reactions in the chip leading to bit flips
  - (n, α), (n, p), and (n, d) are the possible nuclear reactions
  - Reaction thresholds are 2.75, 3.99, and 9.69 MeV respectively
- Second - The long term damage related to lattice dislocations, this is a Total Dose Exposure Issue

# Definitions - What is the Damage Process

- SEU – Single Event Upset  (Most Frequent)
  - Passage of a high energy particle through an electronic device that causes a change in the state of the device
  - Need to Reload Data to continue
- SEL - Single Event Latch-up  (Less Frequent)
  - Power on and off - Hard Reset to recover
- SEB or SEGR – Single Event Burnout or Single Event Gate Rupture  (Not Yet Observed on HET)
  - Complete Device Failure

# Comparison of Particle Induced Damage in Silicon relative to the damage of a 1 MeV Neutron



# IGBT Failure Due to a Neutron Induced SEB

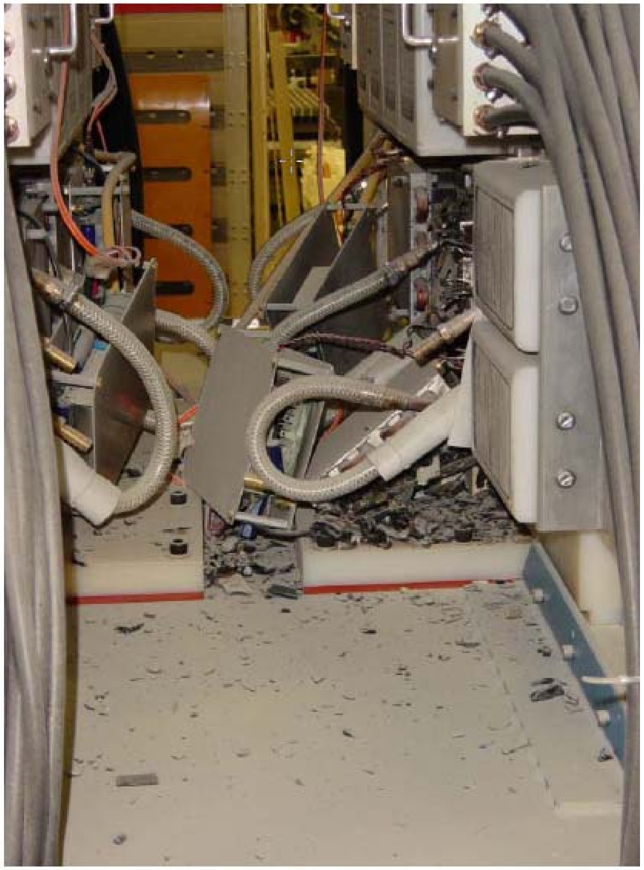


Figure 1: Example of IGBT failure during recent acceptance tests.

- IGBT Switch Failure from Cosmic Ray Neutron
- SEB on the Klystron Modulator for the SNS Accelerator Facility at Oak Ridge National Laboratory

# Neutron Spectra from Cosmic Rays at sea level and Mauna Kea

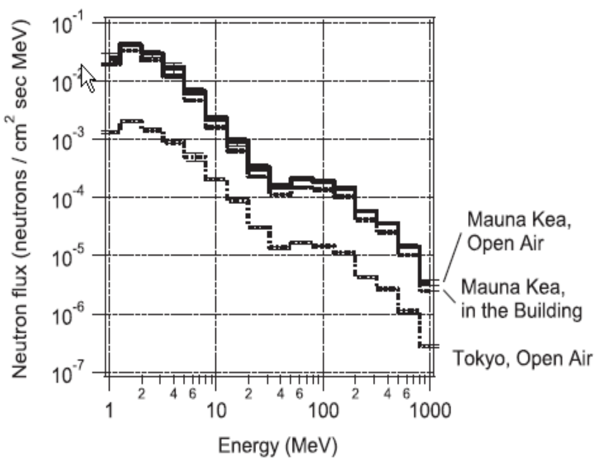



Fig. 3: Neutron energy spectra measured by Bonner multisphere spectrometer measured at the open air area and in the building of Subaru Telescope, and open air area of Tokyo.

of 10 cm for main detector. The main detector is

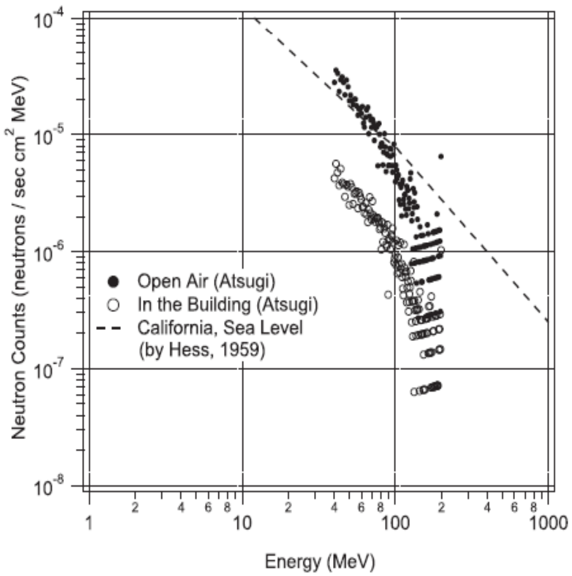



Fig. 4: Neutron energy spectra preliminary measured by scintillator spectrometer at Atsugi (Japan). Solid circles and open circles are measured at open air area and in the building, respectively. Dotted line indicates the spectrum reported by Hess et al. (1959) [1]

# VMS at 15 MeV,18 MeV, and 20 MeV

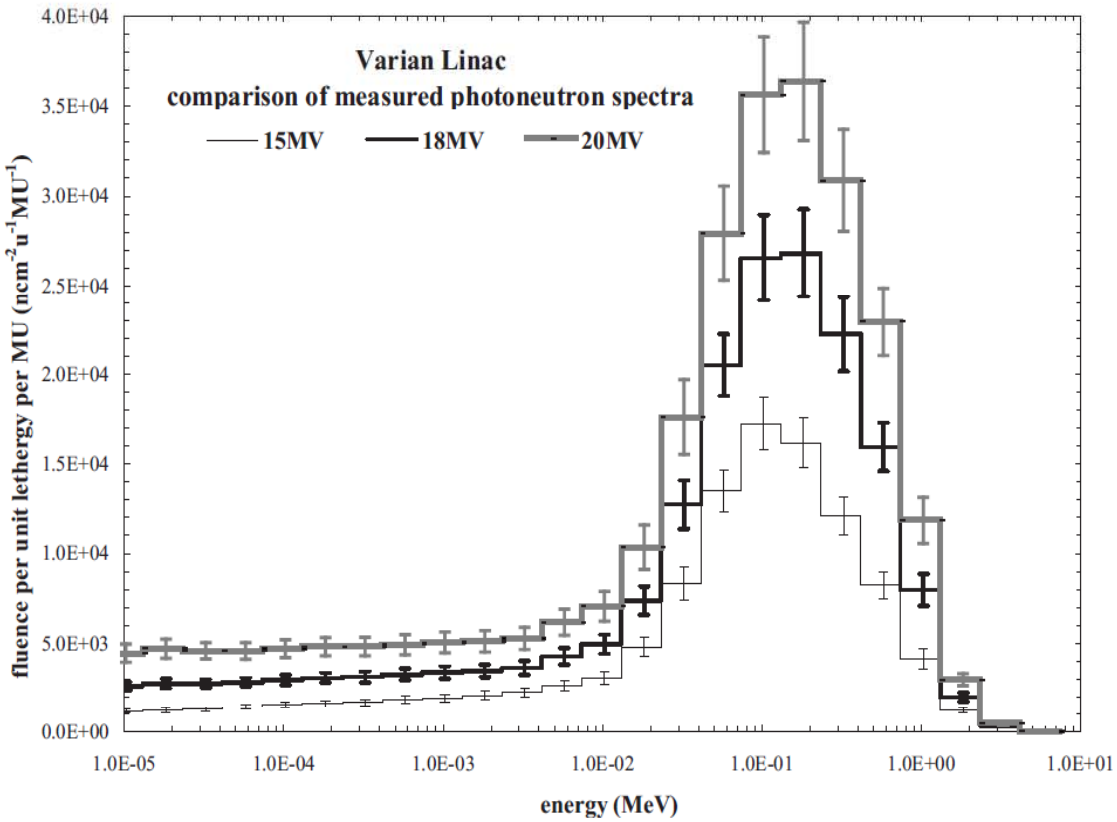



FIG. 7. Measured photoneutron spectra for Varian 21EX linacs with nominal photon beam energies of 15, 18, and 20 MV and the upper and lower jaws and MLC closed.

## How do the Linac Photoneutron Rates compare to Cosmic Ray Fluence Rates at Sea Level?

- Compare the 3 MeV neutron rate for a VMS Clinac at 20X to Cosmic Ray Fluence at Sea Level (Tokyo, JP 35°40’ N SF is 37° 46’ N)
  - Clinac Rate is ~ **2.0 x $10^6$ higher**
- Initial VMS Measurements show a mean neutron energy of about 0.45 MeV
- Monte Carlo Calculations show a neutron spectrum out to ~16 MeV

# Data Comparison of New and Old Data on VMS Systems

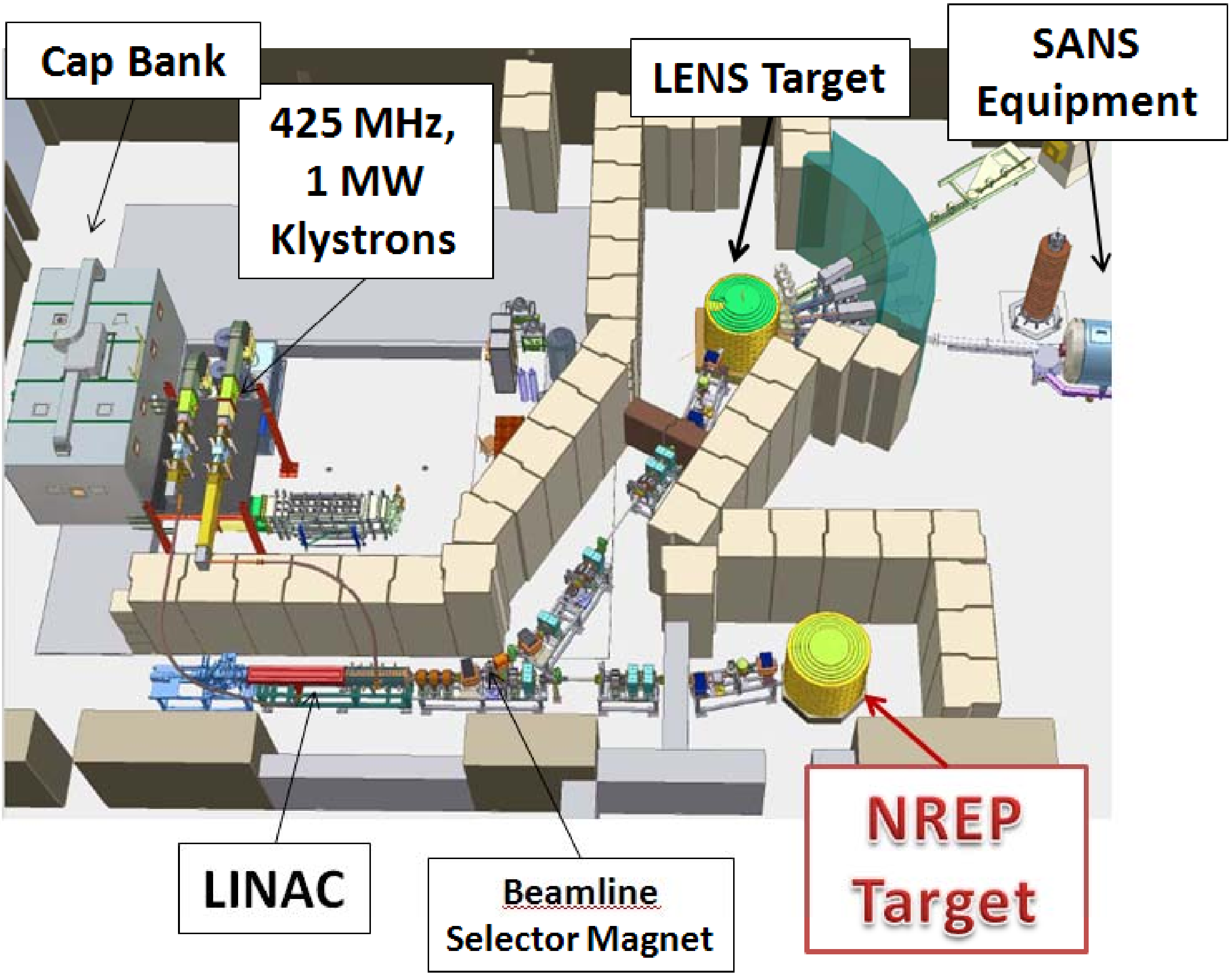
TABLE IV. Measured photoneutron data from the current study and previously reported measured and Monte Carlo calculated data for Varian linacs with 15, 18, and 20 MV photon beam energies.

| | Neutron fluence ($n\ cm^{-2}\ MU^{-1}$) | | | Average energy (MeV) | | |
|---|---|---|---|---|---|---|
| | Kase *et al.*[a] | | Current study | Kase *et al.*[a] | | Current study |
| Energy | Calc. | Meas. | Meas. | Calc. | Meas. | Meas. |
| 15 | $7.6\times10^4$ | $5.3\times10^4$ | $6.67\times10^4$ | 0.3 | 0.19 | 0.23 |
| 18 | $1.4\times10^5$ | $0.8\times10^5$ | $1.18\times10^5$ | 0.36 | 0.42 | 0.24 |
| 20 | $1.5\times10^5$ | $1.1\times10^5$ | $1.69\times10^5$ | 0.36 | 0.29 | 0.24 |

[a]Reference 8.

Medical Physics, Vol. 36, No. 9, September 2009

# Testing and Indiana University Low Energy Neutron System (LENS)

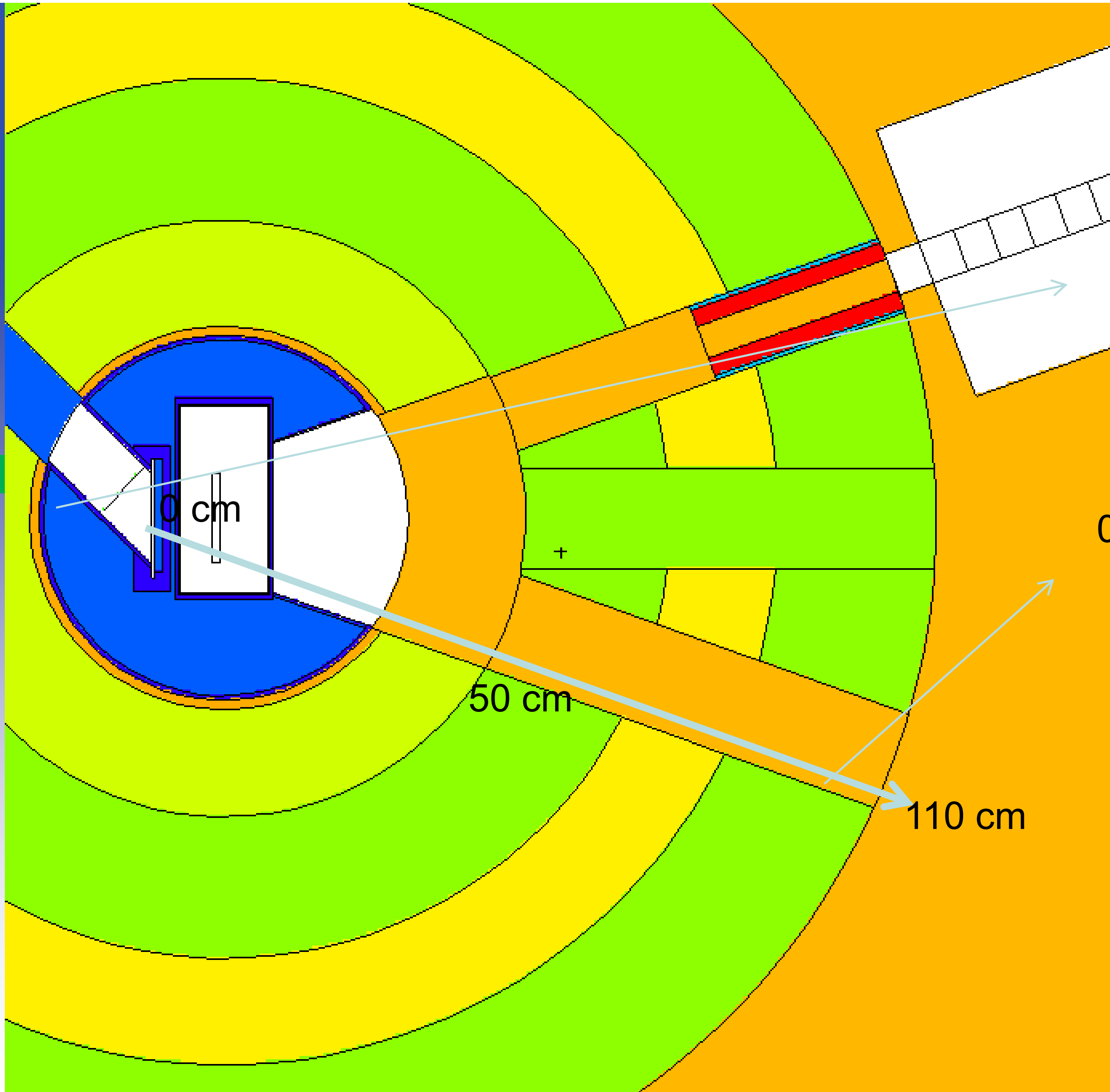


# Reaction Channels Open for particle production

**Open channels for the reaction:**

**p + $^{9}$Be at 13.00 MeV**

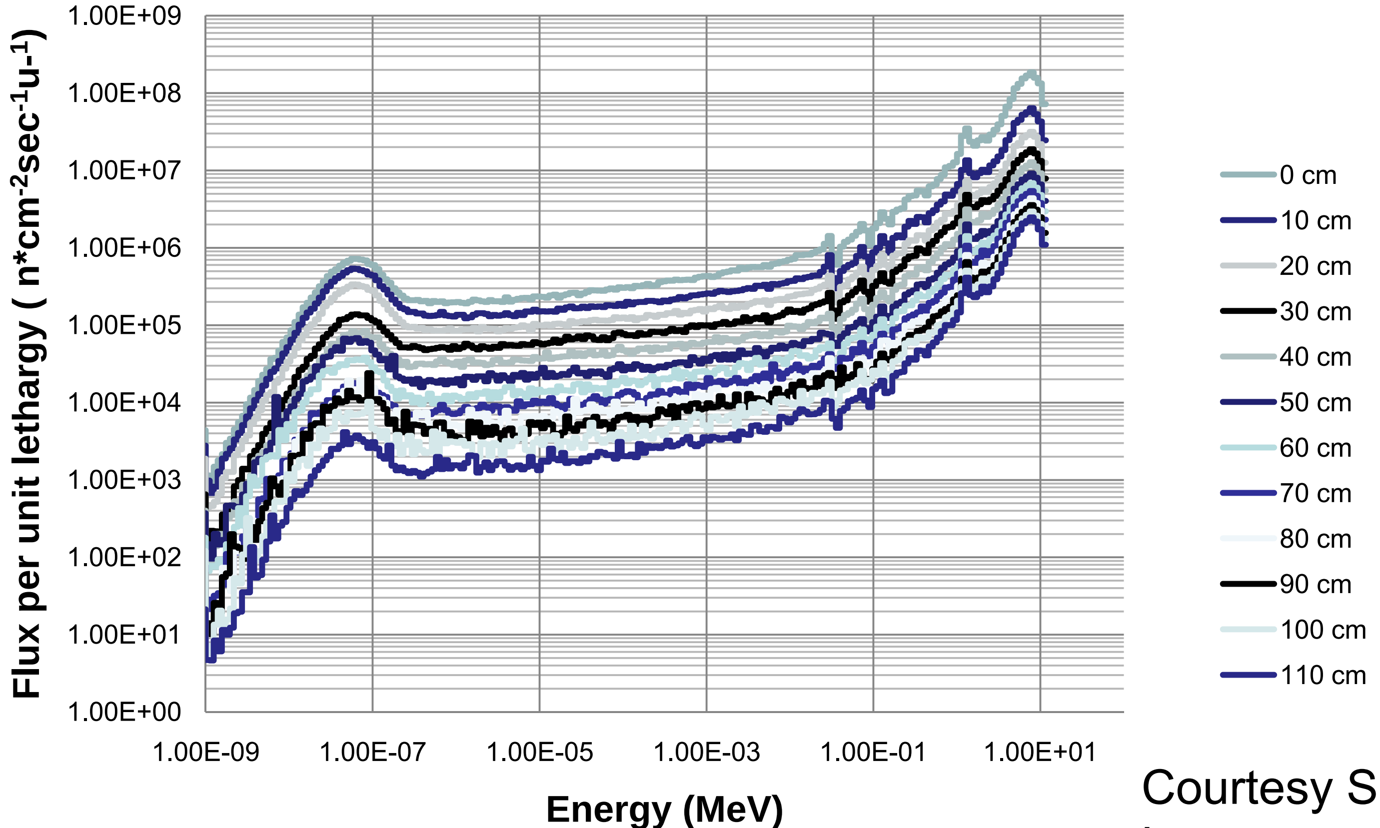
| Reaction Products | *Q*-Value (MeV) | Threshold (MeV) |
|---|---|---|
| $^{10}B + \gamma$ | 6.58585 | 0 |
| $^{6}Li + \alpha$ | 2.12535 | 0 |
| $d + 2\ \alpha$ | 0.65102 | 0 |
| $^{8}Be + d$ | 0.55918 | 0 |
| $^{9}Be + p$ | 0 | 0 |
| $n + p + 2\ \alpha$ | -1.57357 | 1.74955 |
| $^{8}Be + n + p$ | -1.66541 | 1.85166 |
| $^{9}B + n$ | -1.85049 | 2.05743 |
| $^{5}He + p + \alpha$ | -2.46358 | 2.73908 |
| $^{5}Li + n + \alpha$ | -3.53859 | 3.93431 |
| $^{7}Li + {}^{3}He$ | -11.20242 | 12.45517 |



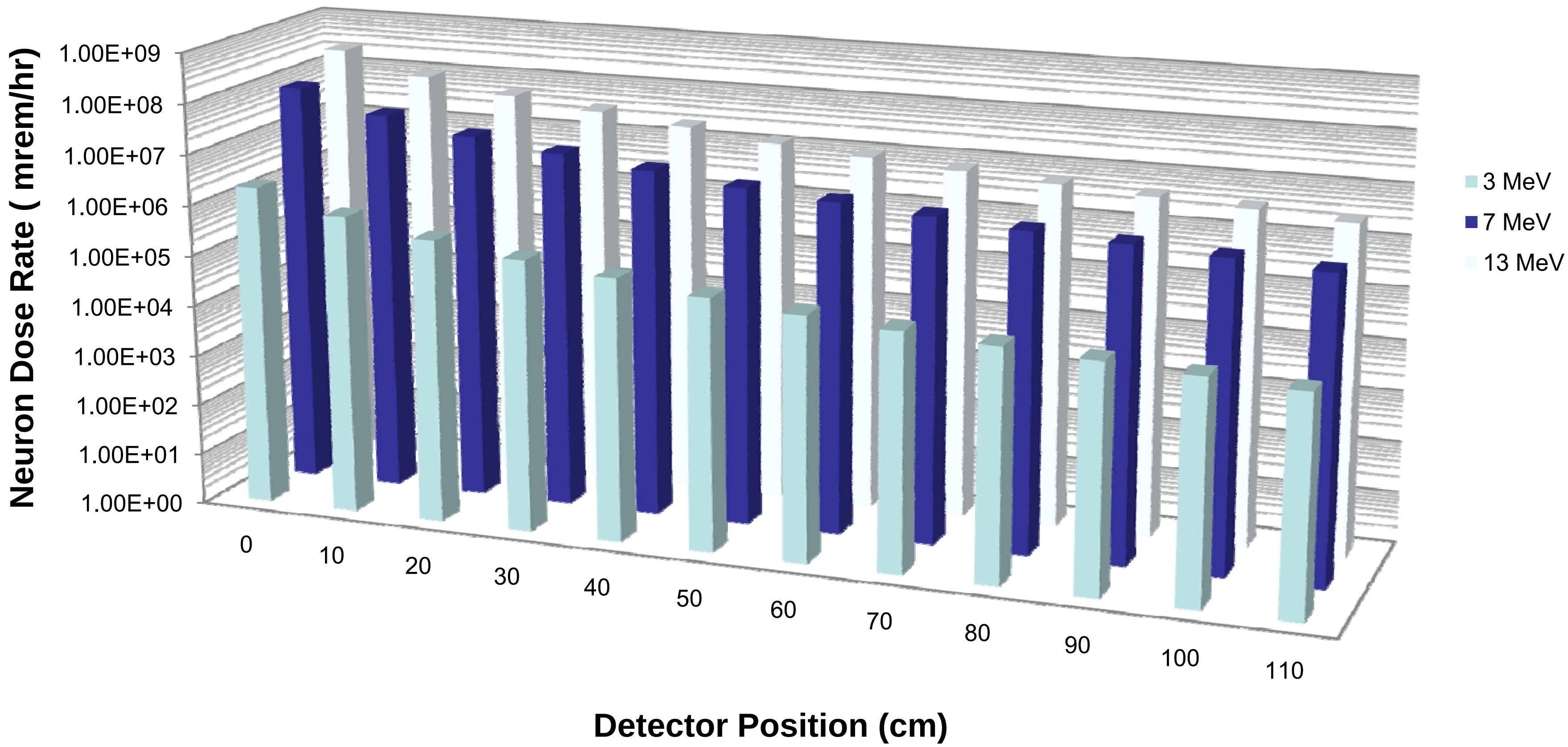

13 MeV 15mA 20Hz
400us proton beam
= 0.12mA , 1.56 Kw

0cm, 10 cm ~ 110 cm
Detector positions

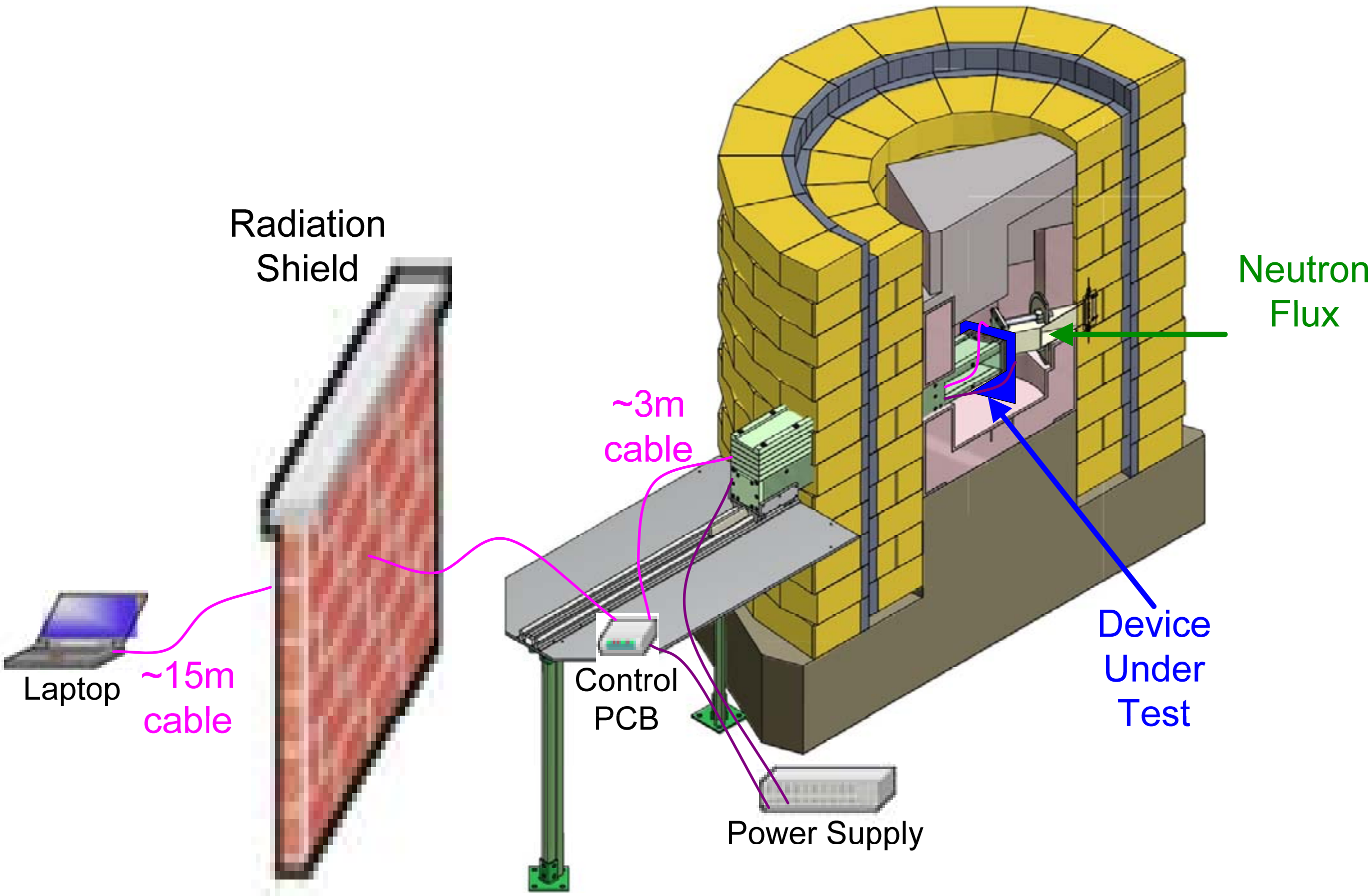
# Neutron Spectrum with 13MeV 15mA 20Hz 400us proton beam



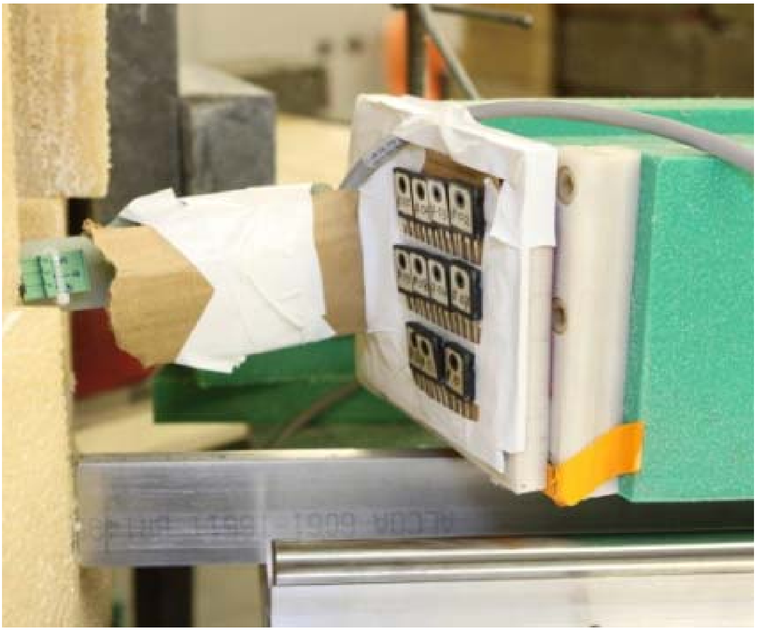

Courtesy Sangjin Lee

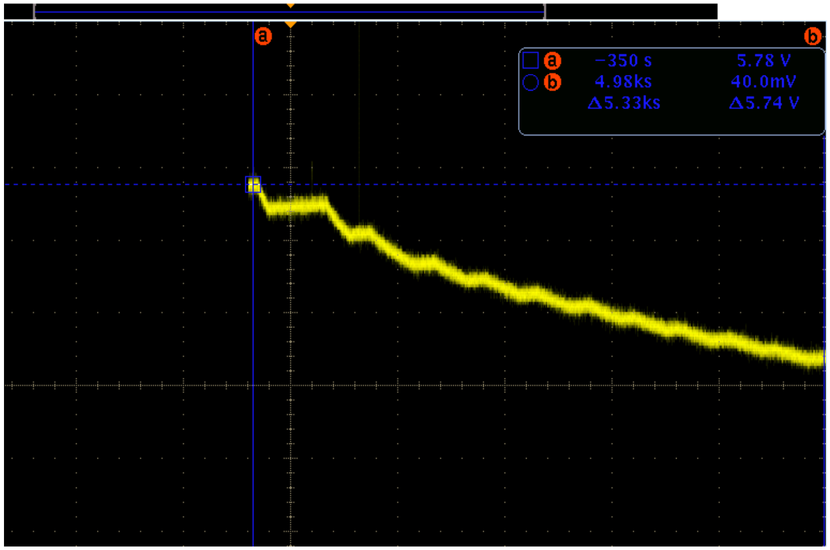

Neuron Dose Rate ( mrem/hr)
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0
10
20
30
40
50
60
70
80
90
100
110
Detector Position (cm)
3 MeV
7 MeV
13 MeV

# Experimental Setup



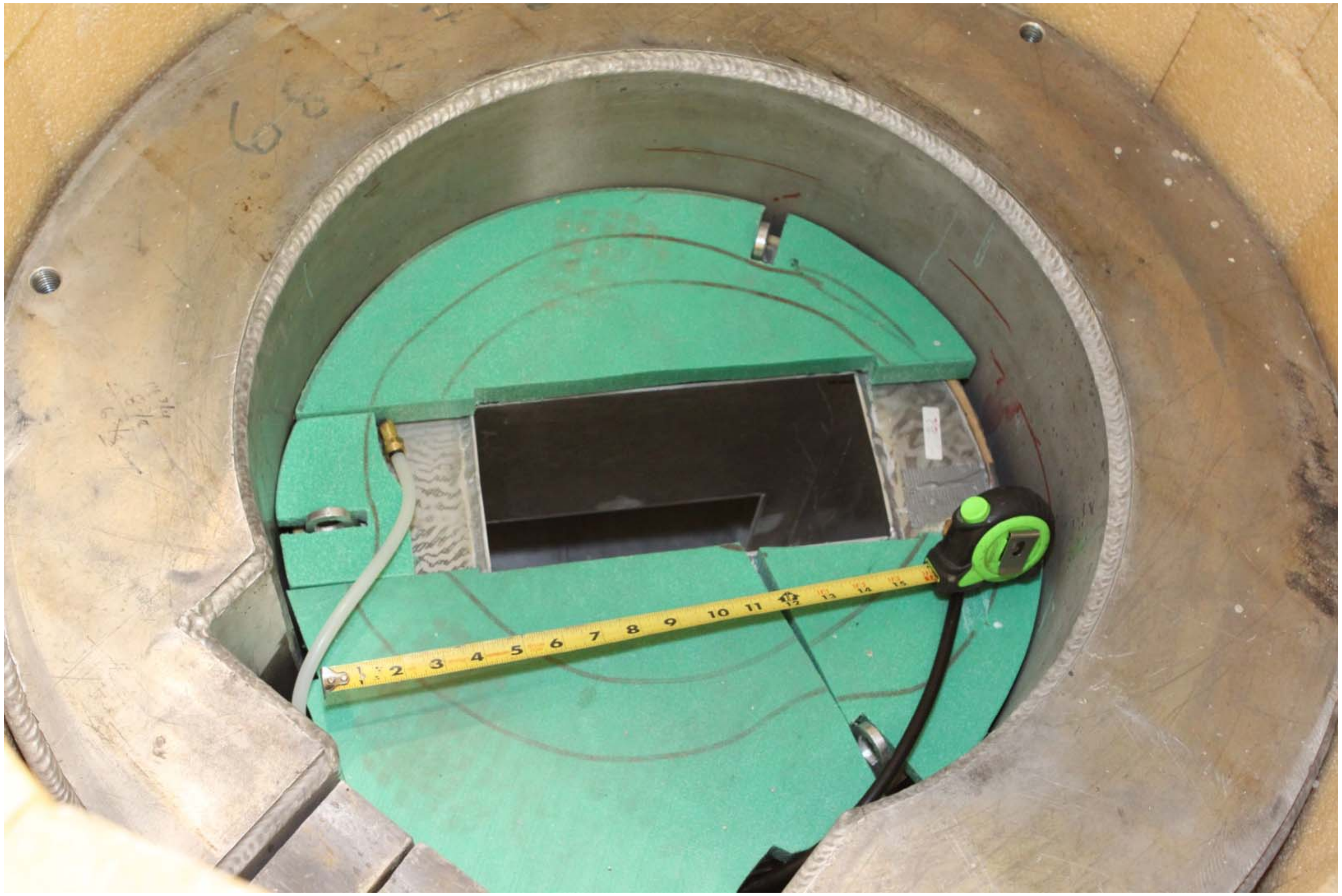
# Testing IGBTs



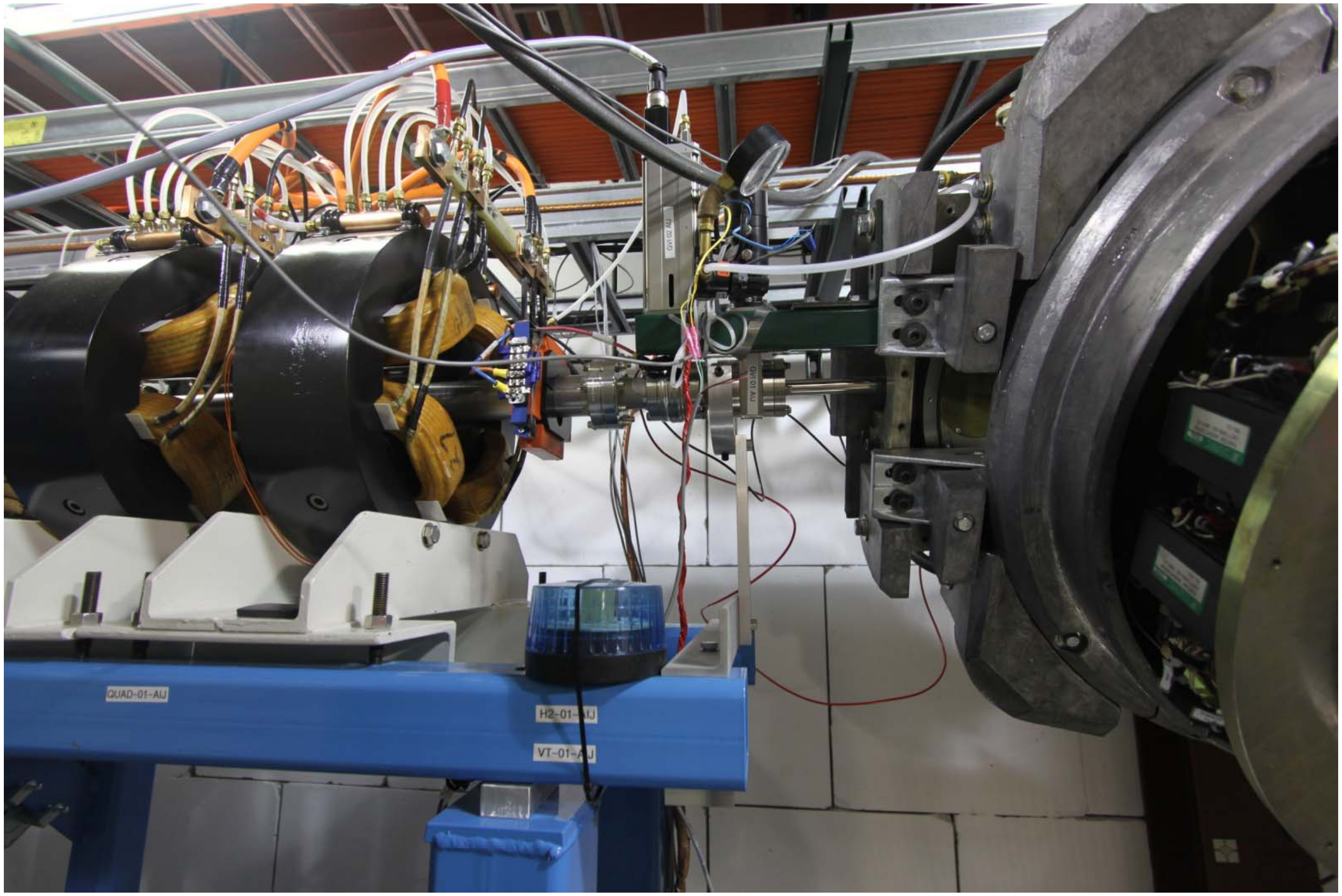


# Placing a Larger Circuit Board is Problematic

# The Inner Chamber could be Larger



# Using the 0° Port on the Match into a Storage Ring



# Recommendations

- Easy Access to test ports fast change out
- High Average beam current and Energy Tailoring
- Connections for Power and Signal Cables
- Calibration of beam energy and particle fluences
- Offer outside groups physics and testing expertise