ANS AccApp'21

14th International Topical Meeting on Nuclear Applications of Accelerators

Developing Madison Accelerator Laboratory as a Unique Nuclear Research User Facility at James Madison University

- Scottie Pendleton, Ph.D. -Laboratory Manager, Madison Accelerator Lab
- Prof. Adriana Banu – Scientific Coordinator, MAL

Madison Accelerator Laboratory (LAB)

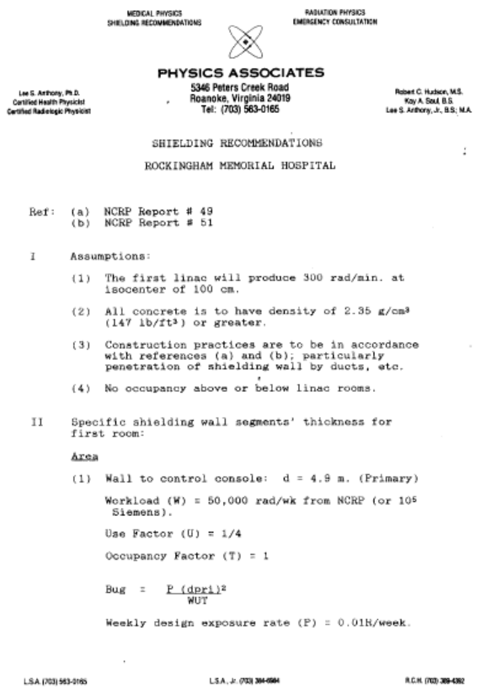
- History/Facilities
- Beam Production and Characteristics
- Nuclear Astrophysics Applications
- Photon Activation Experiments
- Collaborations

MAL Background

- James Madison University is an R2 university located in Harrisonburg, VA
- Dept. of Physics and Astronomy is an undergraduate-only department

MAL History

- 1989 - Rockingham Memorial Hospital Cancer Center built at 100 E Grace St.
  - Concrete shielding poured for two vaults based on calculations for two Siemens 15 MeV linacs



MEDICAL PHYSICS
SHIELDING RECOMMENDATIONS

RADIATION PHYSICS
EMERGENCY CONSULTATION

PHYSICS ASSOCIATES
5346 Peters Creek Road
Roanoke, Virginia 24019
Tel: (703) 563-0165

Lee S. Anthony, Ph.D.
Certified Health Physicist
Certified Radiologic Physicist

Robert C. Hudson, M.S.
Kay A. Saul, B.S.
Lee S. Anthony, Jr., B.S.; M.A.

SHIELDING RECOMMENDATIONS

ROCKINGHAM MEMORIAL HOSPITAL

Ref: (a) NCRP Report # 49
(b) NCRP Report # 51

I Assumptions:

(1) The first linac will produce 300 rad/min. at isocenter of 100 cm.

(2) All concrete is to have density of 2.35 g/cm^3 (147 lb/ft^3) or greater.

(3) Construction practices are to be in accordance with references (a) and (b); particularly penetration of shielding wall by ducts, etc.

(4) No occupancy above or below linac rooms.

II Specific shielding wall segments' thickness for first room:

<u>Area</u>

(1) Wall to control console: d = 4.9 m. (Primary)

Workload (W) = 50,000 rad/wk from NCRP (or 10^5 Siemens).

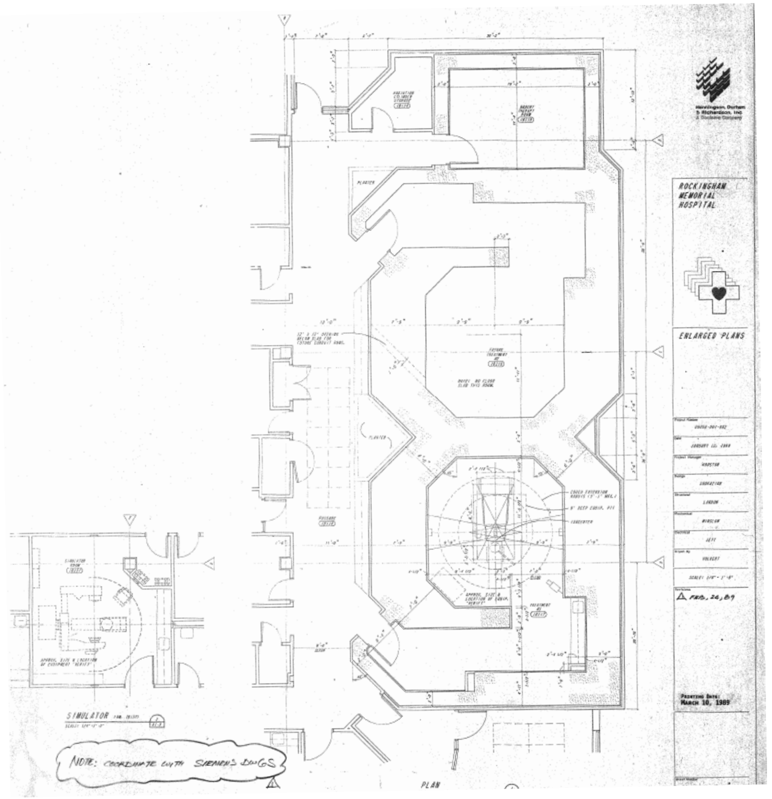
Use Factor (U) = 1/4

Occupancy Factor (T) = 1

$$Bug = \frac{P\,(dpri)^2}{WUT}$$

Weekly design exposure rate (P) = 0.01R/week.

L.S.A. (703) 563-0165 L.S.A., Jr. (703) 384-6984 R.C.H. (703) 389-4392



MAL History

- 1989 - Rockingham Memorial Hospital Cancer Center built at 100 E Grace St.
- 1998 – Current Siemens Mevatron MD2 and Nucletron Simulix purchased, installed, and commissioned at RMH Cancer Center
    - Patient treatment commences

MAL History

- 1989 - Rockingham Memorial Hospital Cancer Center built at 100 E Grace St.
- 1998 – Current Siemens Mevatron MD2 and Nucletron Simulix purchased, installed, and commissioned at RMH Cancer Center
- 2010 – RMH sells building to JMU and moves offsite, bequeathing facility and linac to JMU Department of Physics and Astronomy
  - Facilitated a priori by former physics AUH Steve Whisnant and Prof. Adriana Banu

MAL Facilities

- 2017 – JMU renovates Madison Hall and moves in
- 2018 – MAL is licensed for operations by the Virginia Department of Health

MAL Facilities

- Linac: Siemens Mevatron MD2 15 MeV (mfg. 1998)
  - Shielded vault with area monitoring
  - Suite of HPGe detectors with low-BG shields
  - Vacuum chamber
  - Charged particle detectors
  - NIM, VME, and standalone digital DAQ systems

Madison Accelerator Laboratory
Physics and Astronomy • James Madison University

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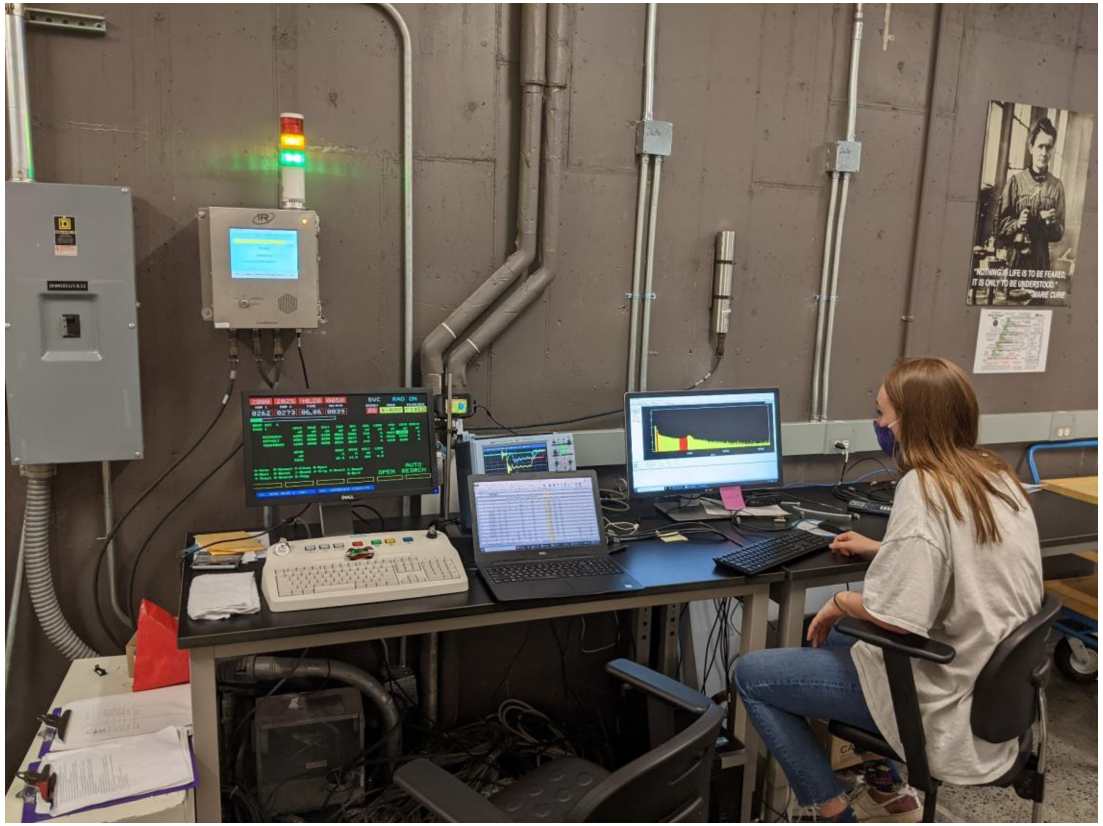
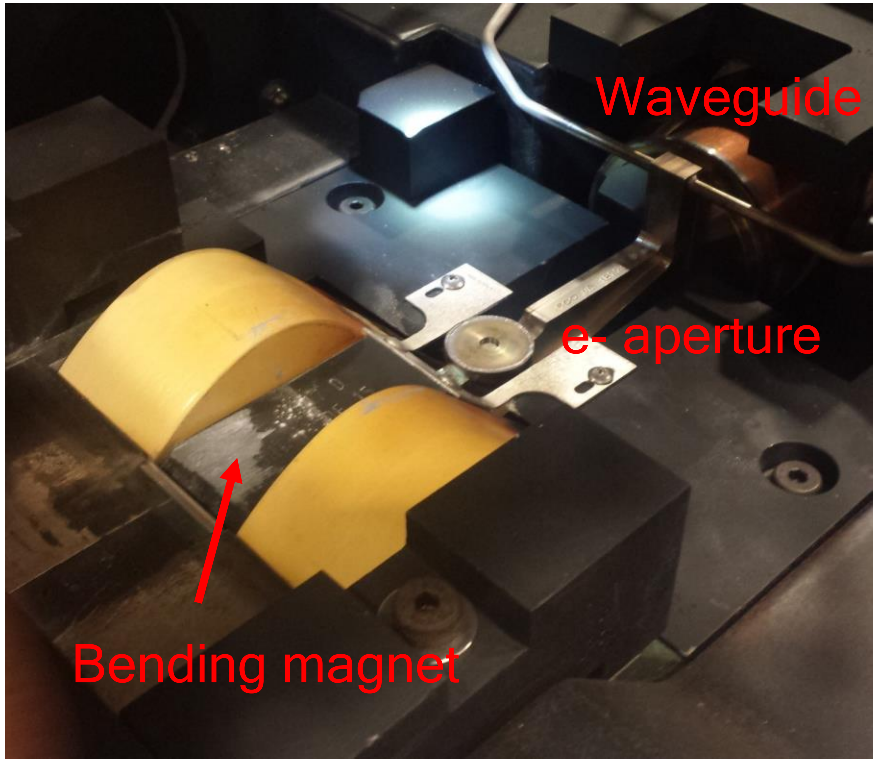
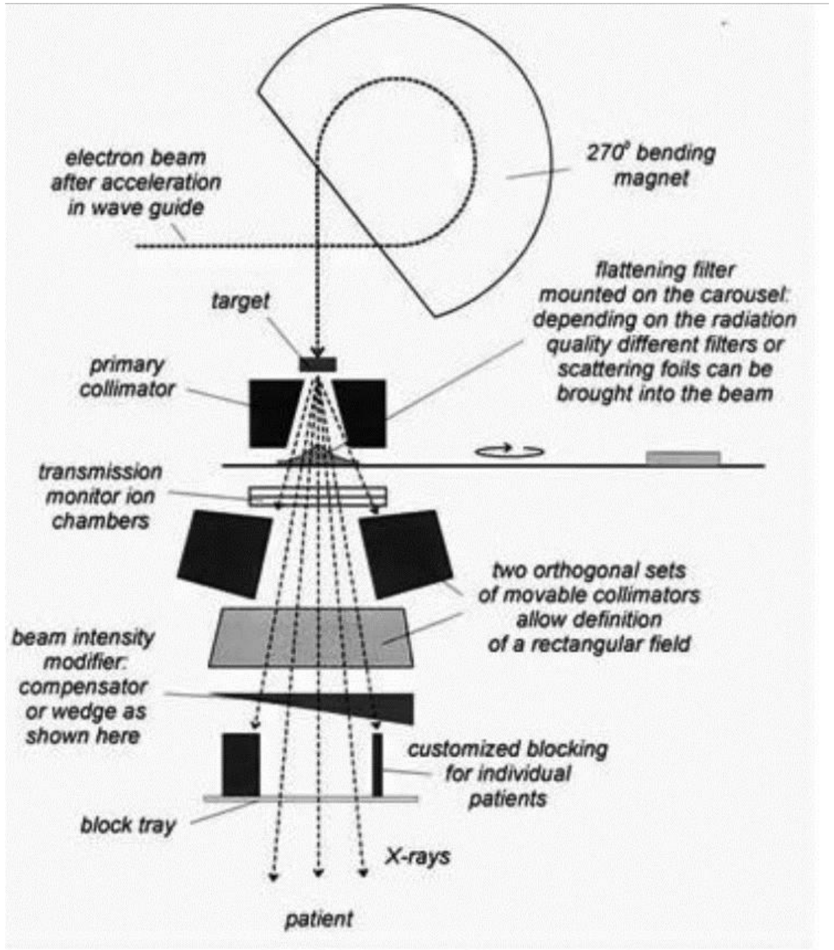
MAL Linac

- Magnetron-based electron accelerator
  - Beam current: 0.1-10 mA avg, 0.15-1.5 A peak
- Electron energy range tunable from 4-15 MeV
- Photon production via bremsstrahlung irradiator
  - 6 MeV and 15 MeV standard modes, photon flux ~ 10^7 γ/s
- Standalone unit operable by single individual, extremely low overhead and footprint



MAL Linac Head

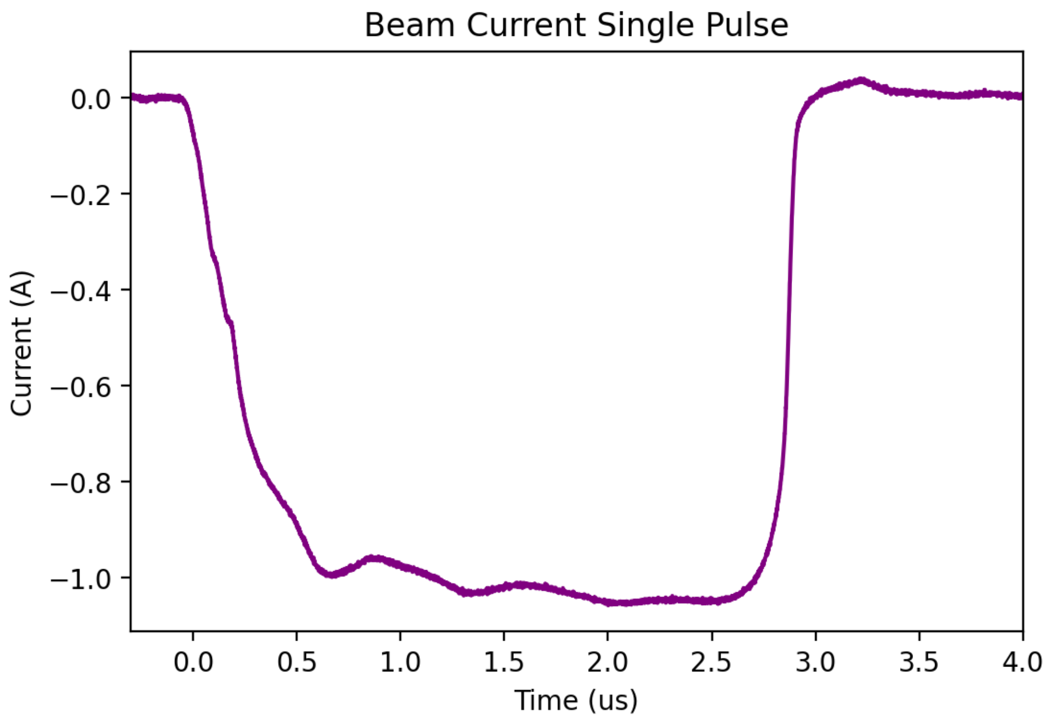


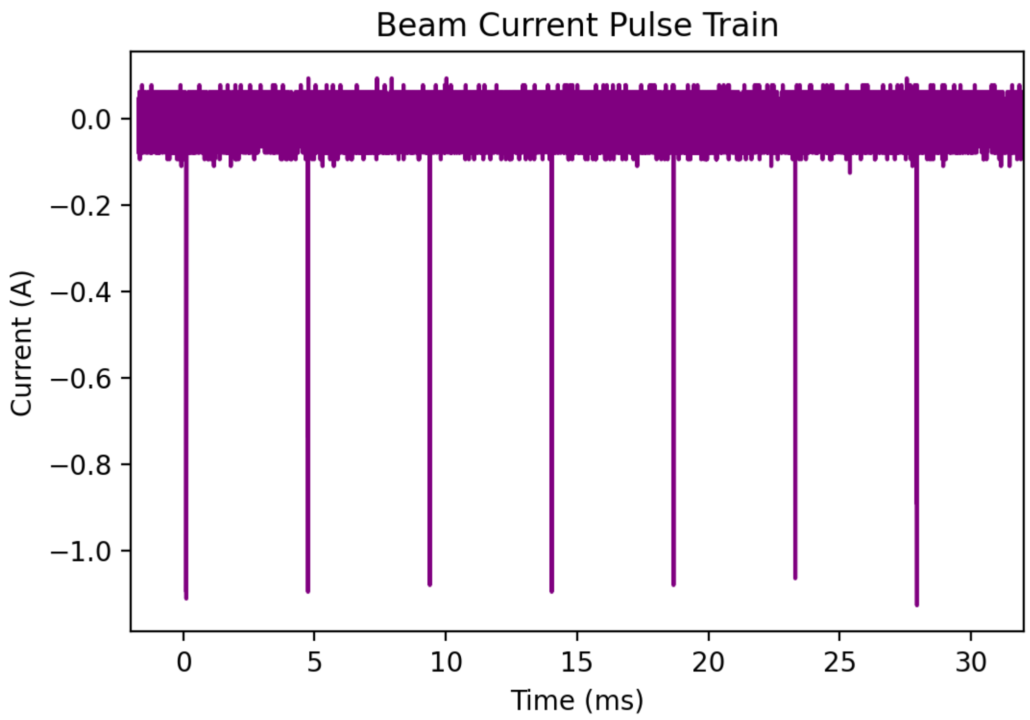


C. J. Karzmark and R. J. Morton, A Primer On Theory And Operation of Linear Accelerators in Radiation Therapy, Madison, WI: Medical Physics Publishing, 1998.

Beam Characteristics

- Pulsed 3 us beam at 200±10 Hz





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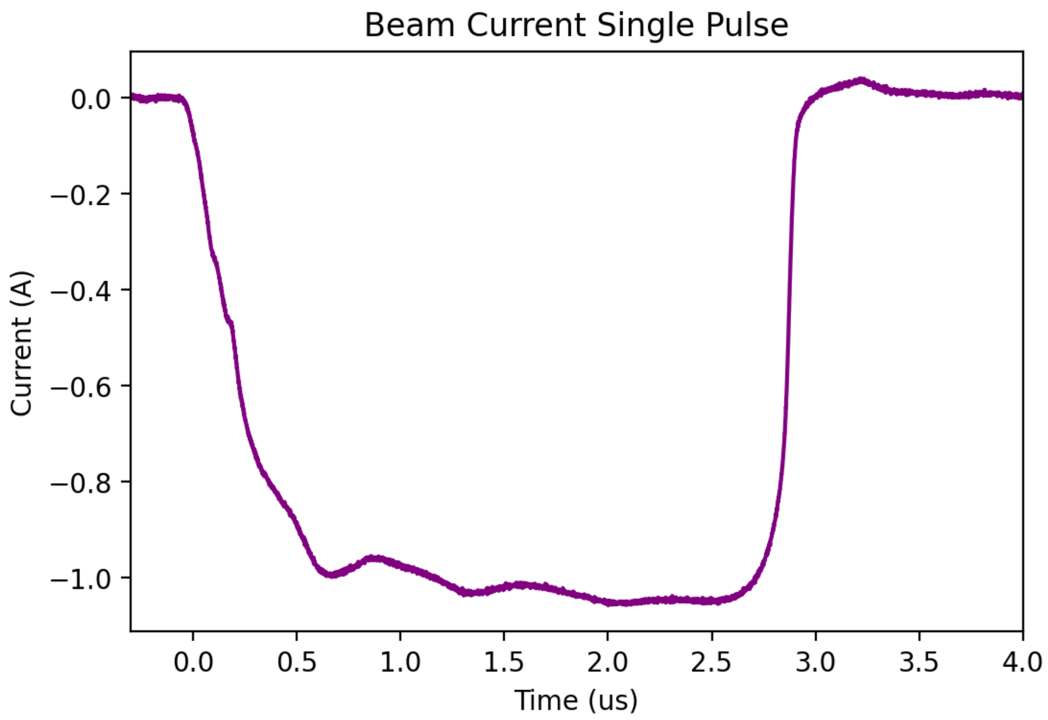
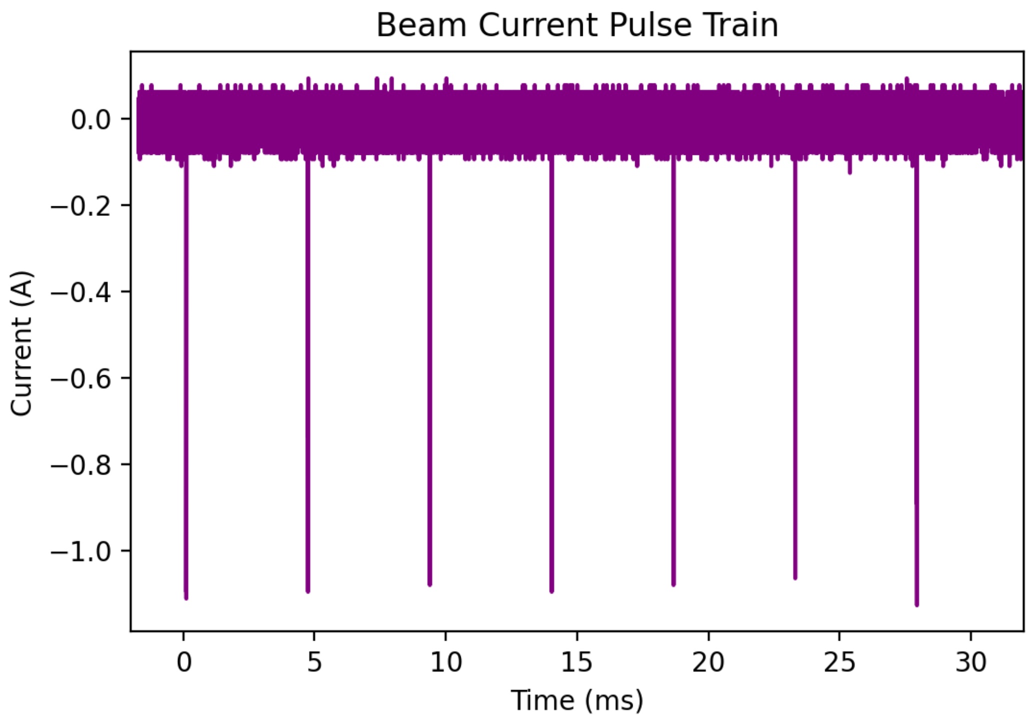


- ~1 A peak pulse height
- ~2.5 uC total pulse charge

Beam Characteristics

- Pulsed 3 us beam at 200±10 Hz
  - ~0.06% duty cycle
  - ~Time-averaged beam current of ~5 mA
  - 200 Hz PRF adjustable to maintain constant output

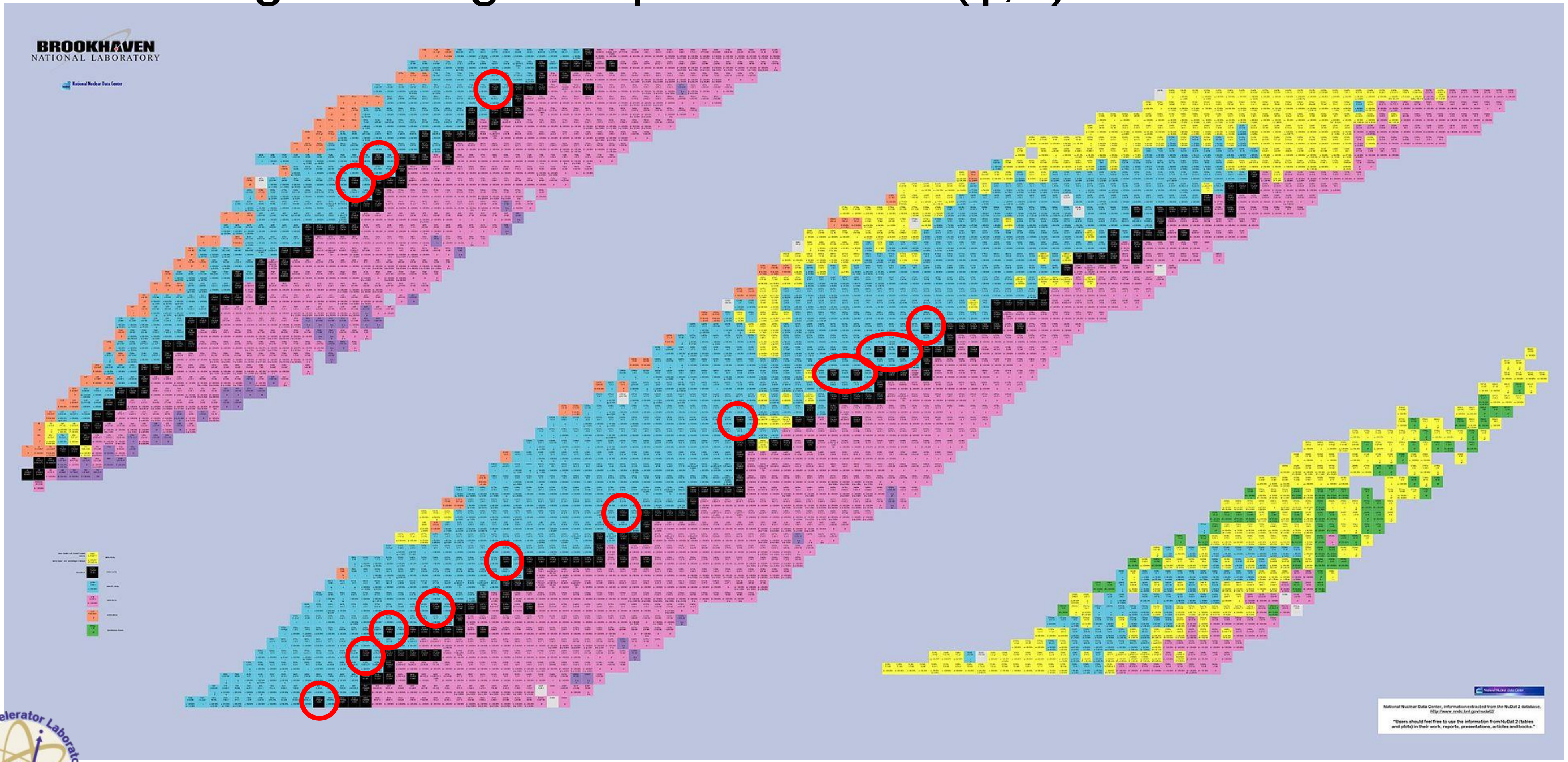


Beam Characteristics

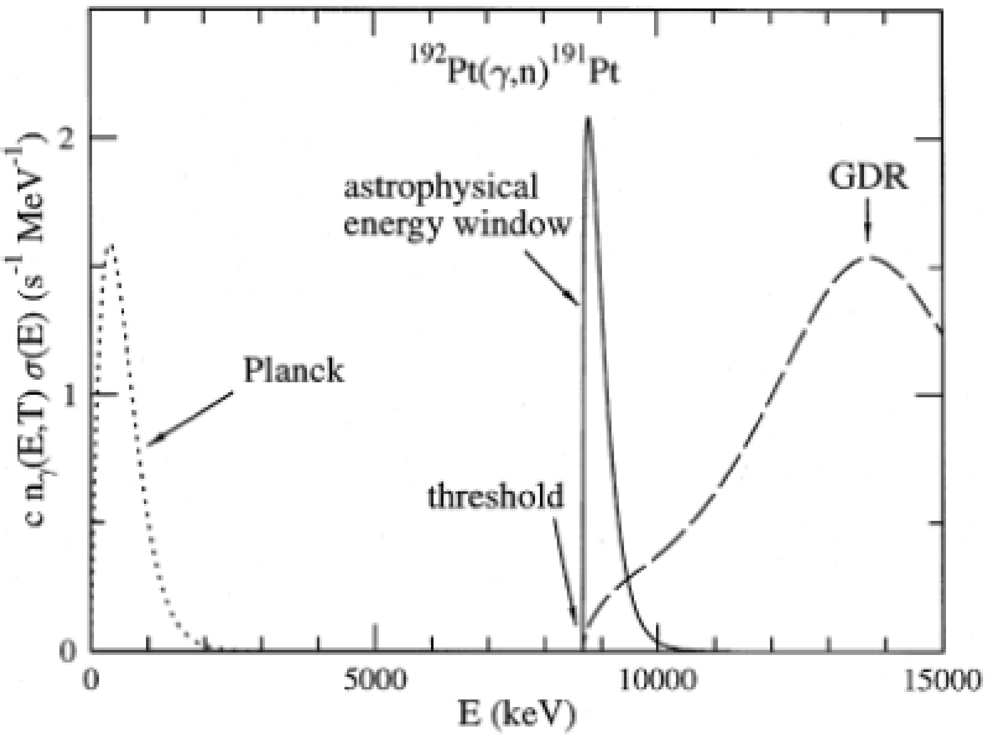
- Bremstrahlung flux: ~10^6-10^8 γ/s average
  - Estimated ~10^7 γ/s via ^{197}Au activation, tunable to 10x in either direction
- More precise flux measurements based on ^{11}B(γ, γ') scattering underway

Nuclear Astrophysics at MAL

- Understanding the origin of p-nuclei via (γ,n) reactions



Photoneutron Reaction Rates



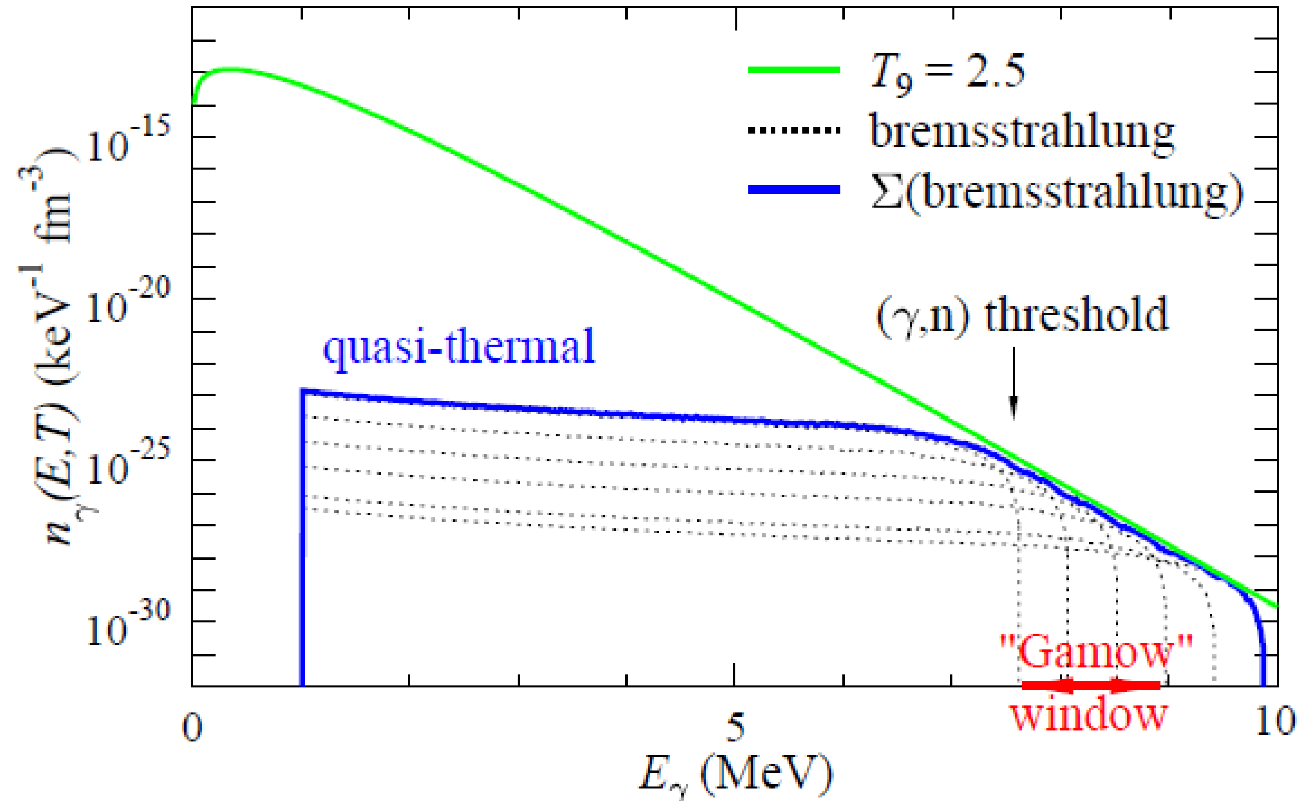
The reaction rate for a photodisintegration reaction

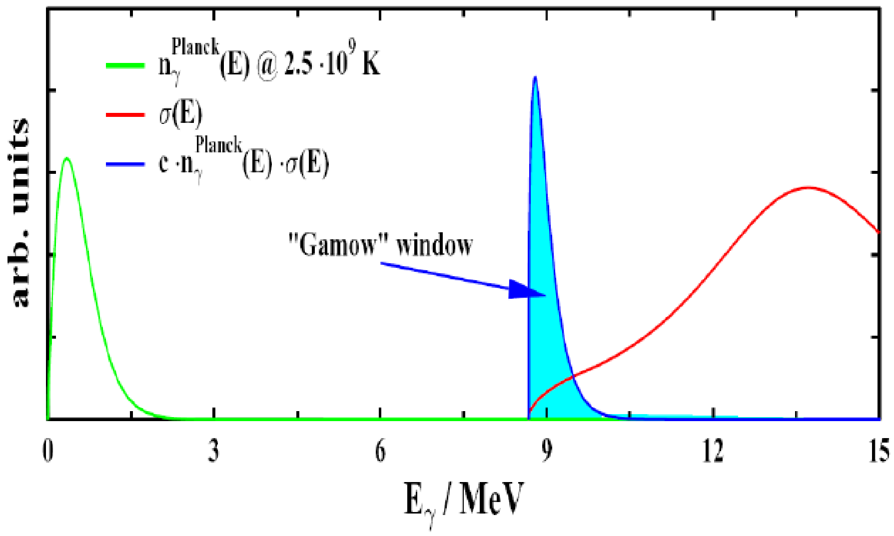
$$\lambda(T) = \int_0^\infty c n_\lambda^{Planck}(E,T)\sigma(E)\,dE$$

$$n_\gamma^{Planck}(E,T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{\hbar c}\right)^3 \frac{E^2}{\exp(E/kT)-1}$$

P. Mohr et al. (Phys. Lett. B 488, (2000))

"Superposition Method"

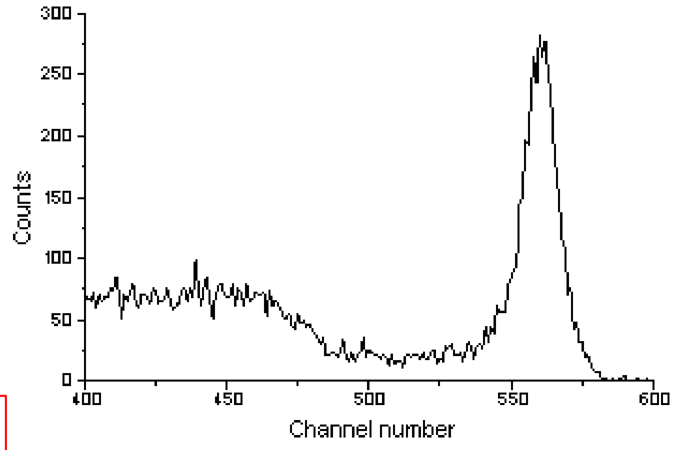




$$c n_\gamma^{Planck}(E,T) \approx \sum_i a_i(T) \Phi_\gamma^{brems}(E, E_{\max,i})$$

D. Galaviz et al. (Nucl. Phys. A 758, 521c (2005))

$$\gamma + {}^{A}X \rightarrow {}^{A-1}X^{*} + n$$



$$A_{\gamma} = N_{T}\varepsilon_{\gamma} I_{\gamma}\, p \frac{t_{life}}{t_{real}} \frac{\left(1 - e^{-\lambda t_{irr}}\right)}{\lambda t_{irr}} e^{-\lambda t_{cool}} \left(1 - e^{-\lambda t_{meas}}\right) I_{\sigma(\lambda,n)}$$

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

$A_{\gamma} \Rightarrow$ Number of counts in the decay lines of ${}^{A-1}X$

$\varepsilon_{\gamma} \Rightarrow$ Absolute detector efficiency

$t_{irr} \Rightarrow$ Duration of the irradiation

$t_{cool} \Rightarrow$ Time between the end of the irradiation and the beginning of the measurement

$t_{meas} \Rightarrow$ Duration of the measurement

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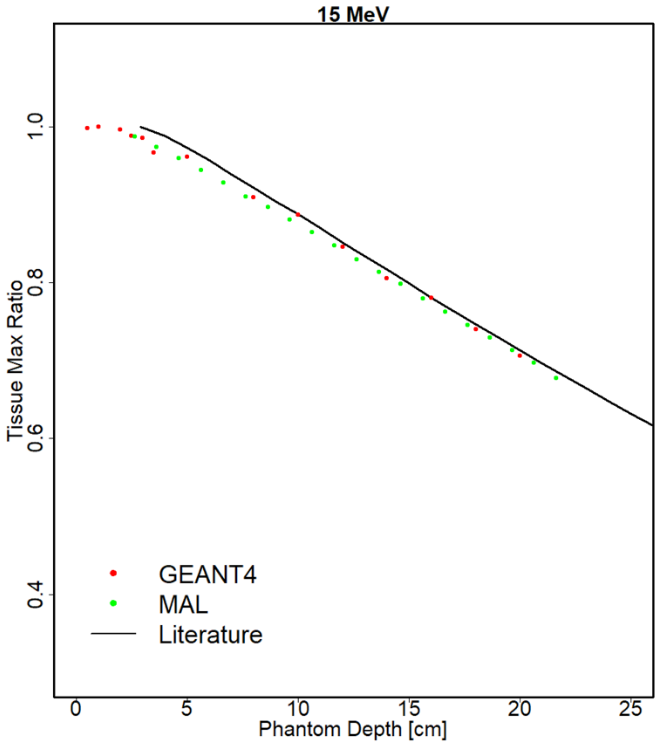
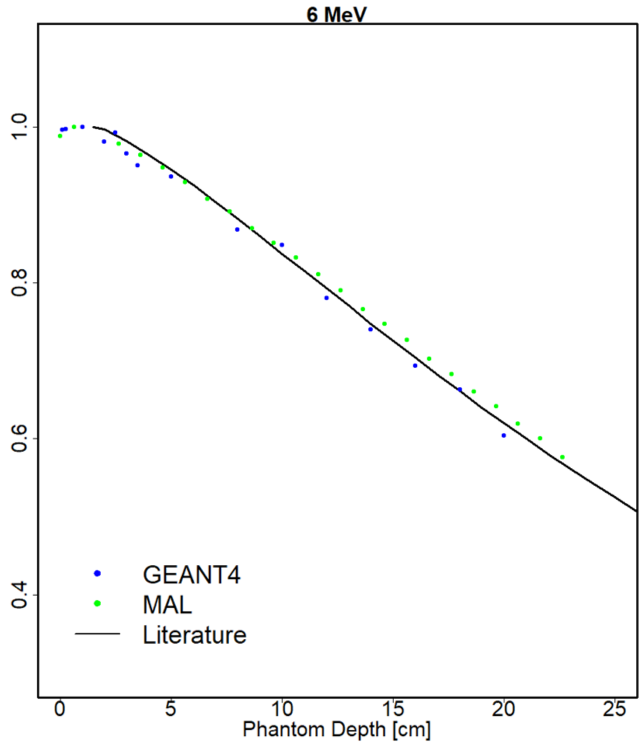
Energy Measurements

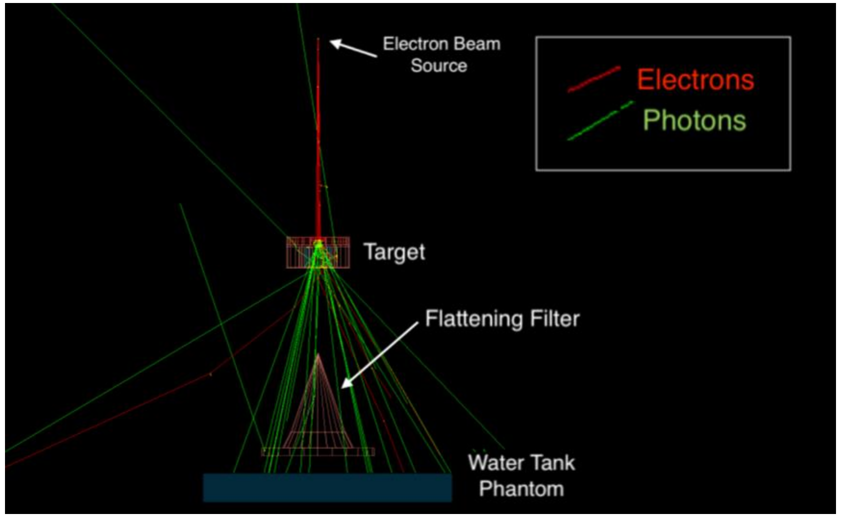
- Electron energy and bremsstrahlung endpoint energy tunable from 4-16 MeV
- Not easily measureable, however!
  - Water tank method fine for determining whether on-spec (6 or 15 MeV)

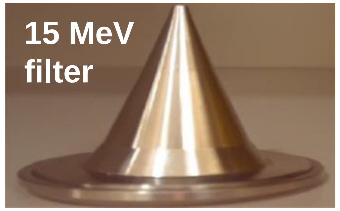


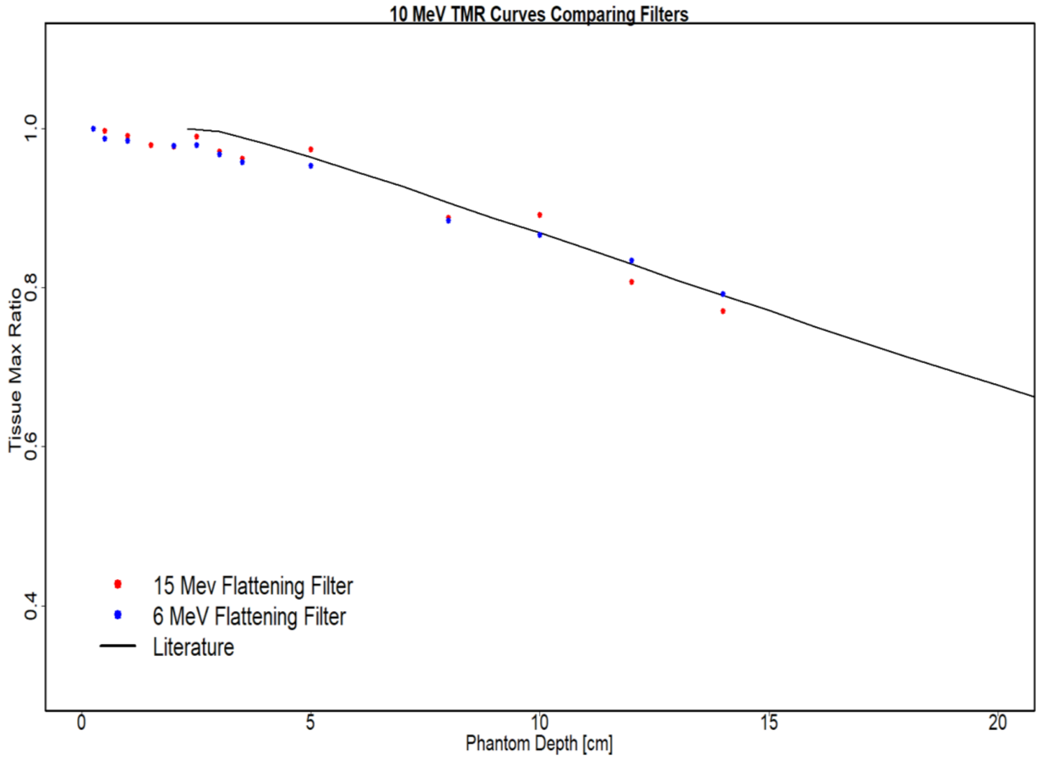


Energy Measurements

- Electron energy and bremsstrahlung endpoint energy tunable from 4-16 MeV
- Not easily measureable, however!
  - Water tank method fine insufficient for intermediate energies due to dependence of energy distribution on flattening filter design



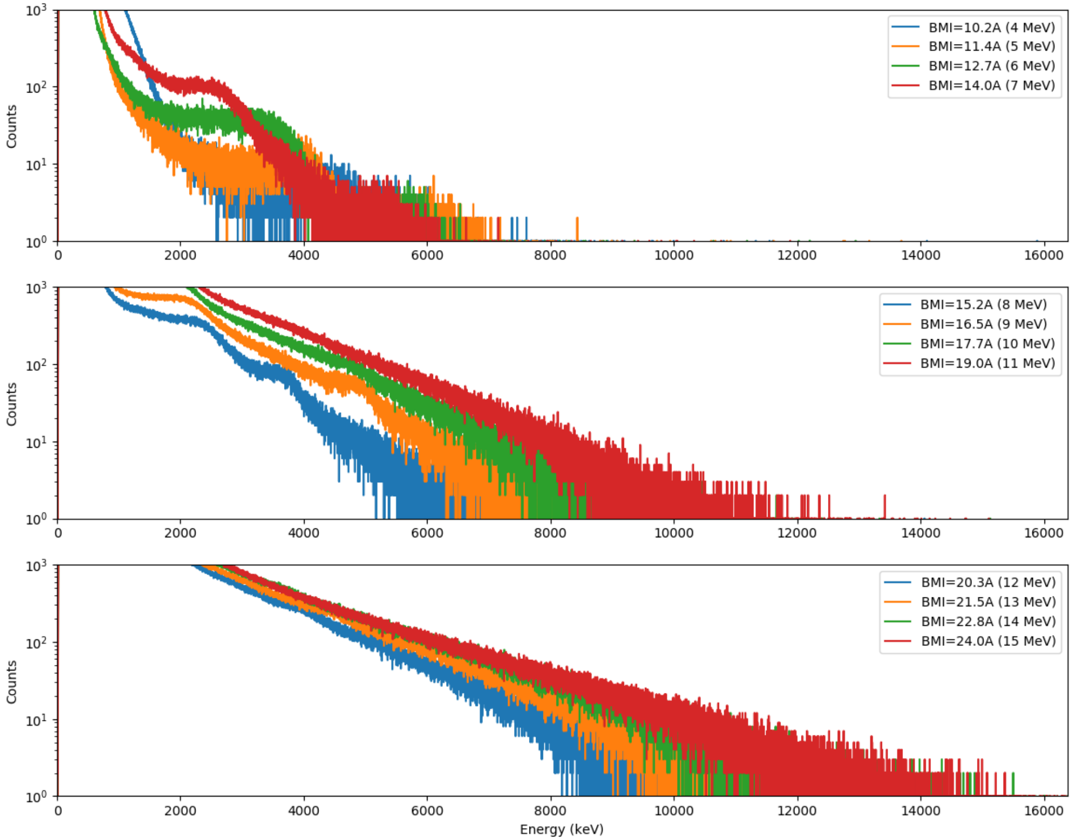


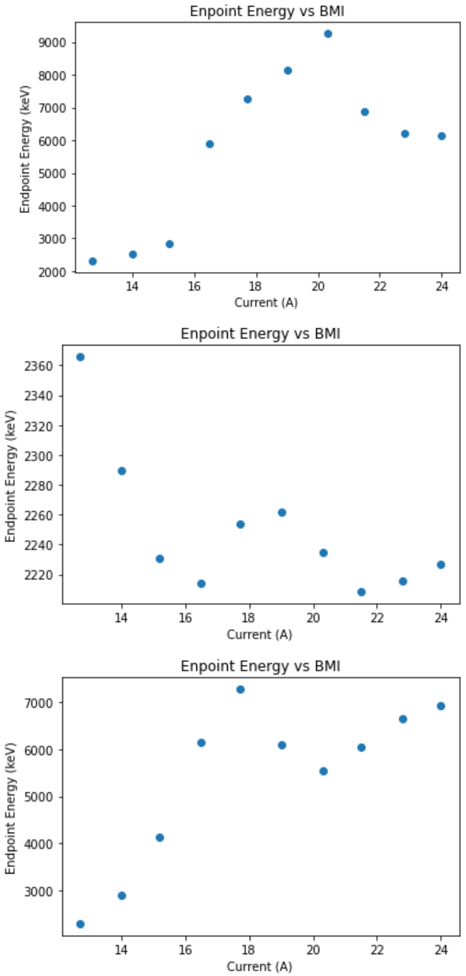


Energy Measurements

- Direct HPGe/NaI spectra not reproducible

Direct spectrum measurement attempted using large array NaI on loan from Duke University





Energy Measurements

- Developing deutron breakup measurements similarly to ELBE facility

- Irradiate deuteron breakup target with γ and measure p energy

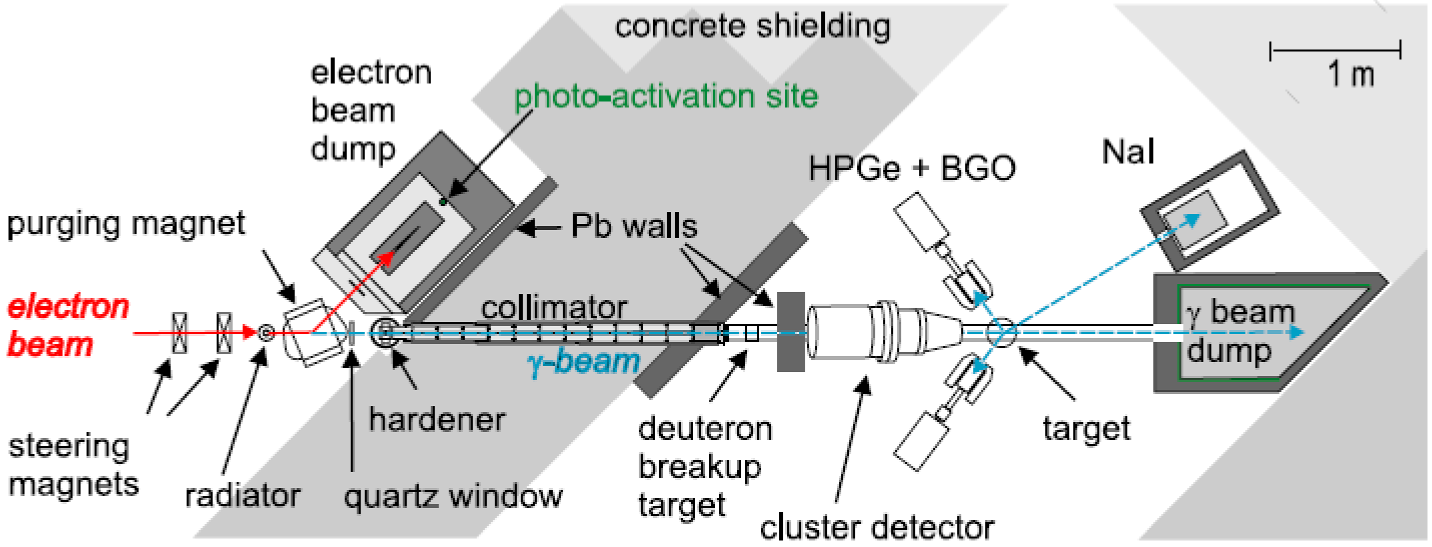
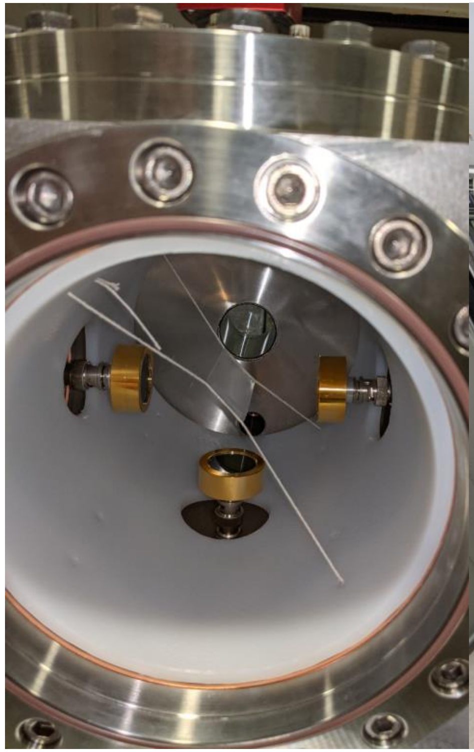


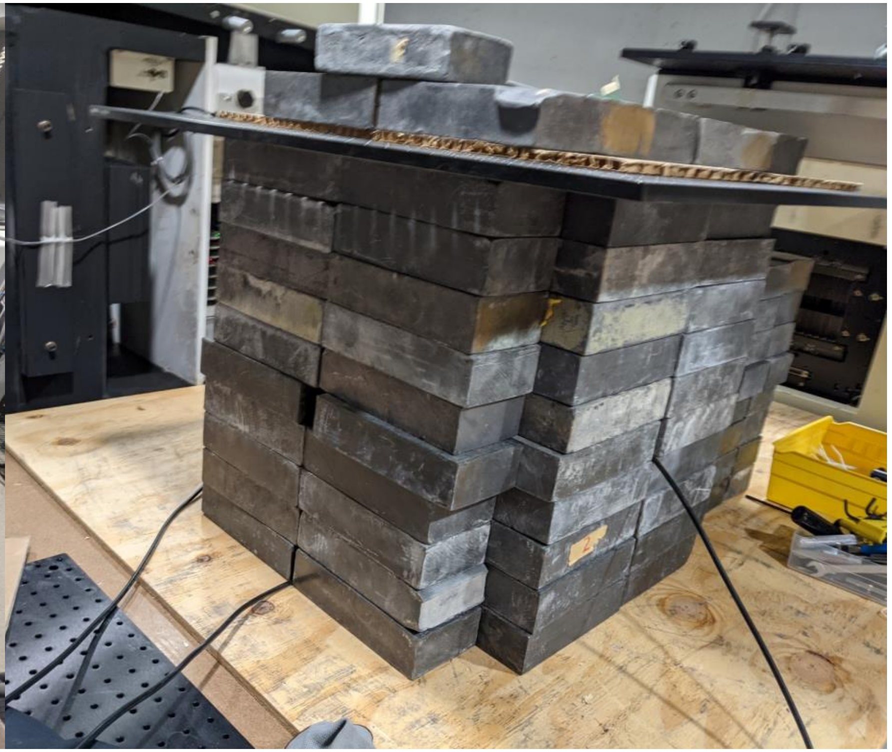
Figure 1. Bremsstrahlung facility and experimental area for photon-scattering and photo-dissociation experiments at the ELBE accelerator.

Wagner et al. (J. Phys. G 31 (2020))

Energy Measurements

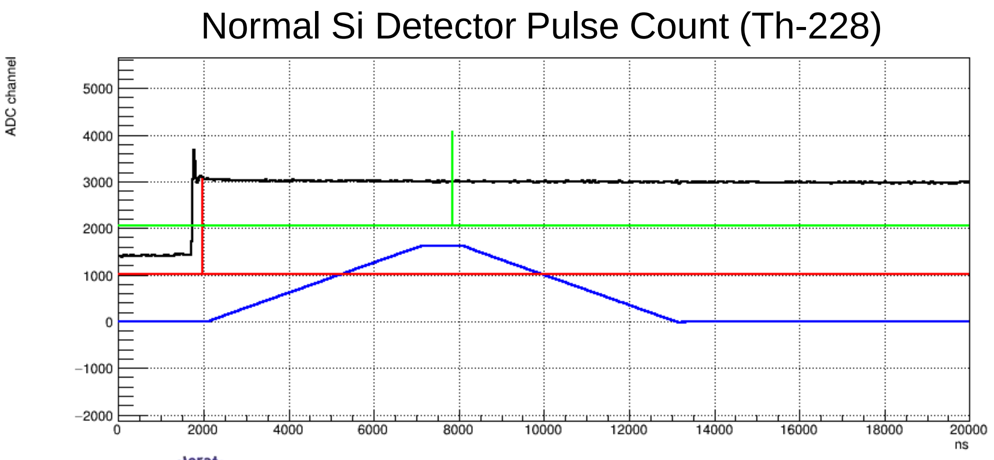
- Have acquired deuteron target and assembling shielded beam line

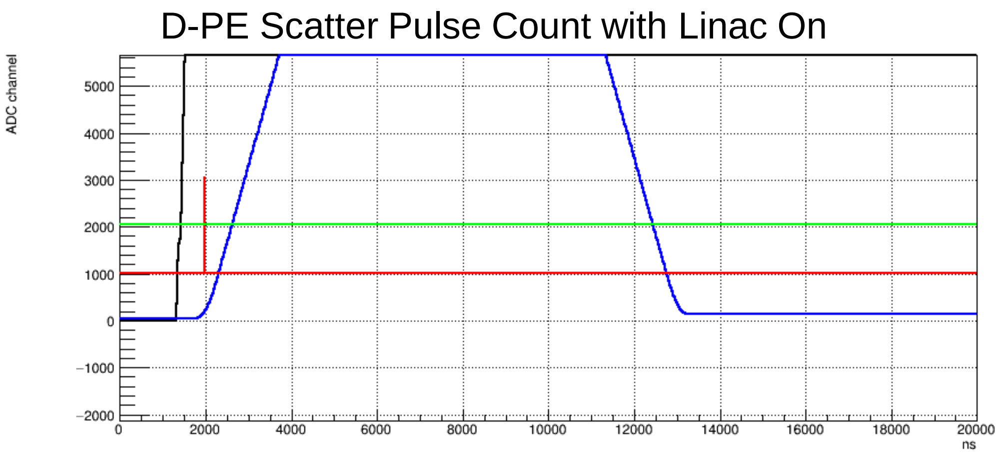




Energy Measurements

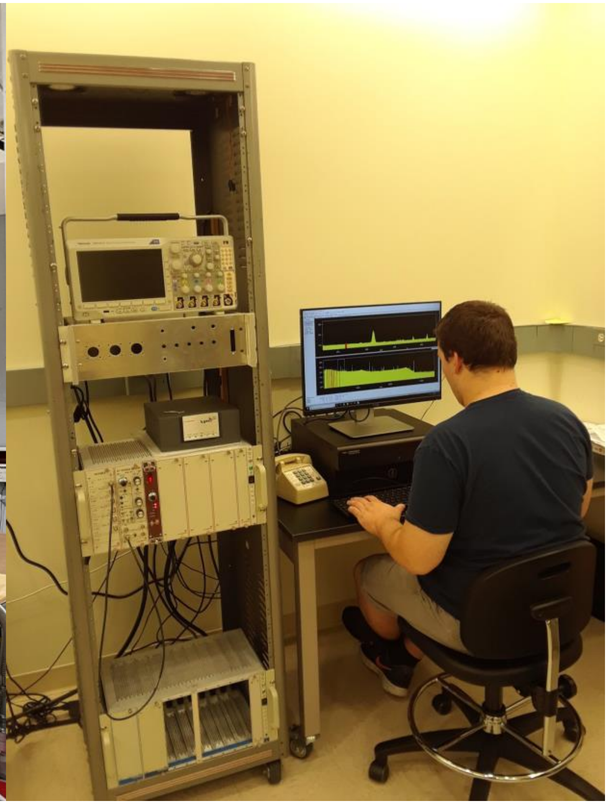
- Pulse structure saturates charged particle detectors
  - Average γ flux at suitable levels for detectors, but peak pulse current creates peak γ flux that saturates detectors
- Solution: reduce peak flux while maintaining sufficient average flux
  - New irradiator (Al or Cu)?





Photon Activation Analysis

- Activate samples with (γ,n) and measure γ decay spectrum



Photon Activation Analysis

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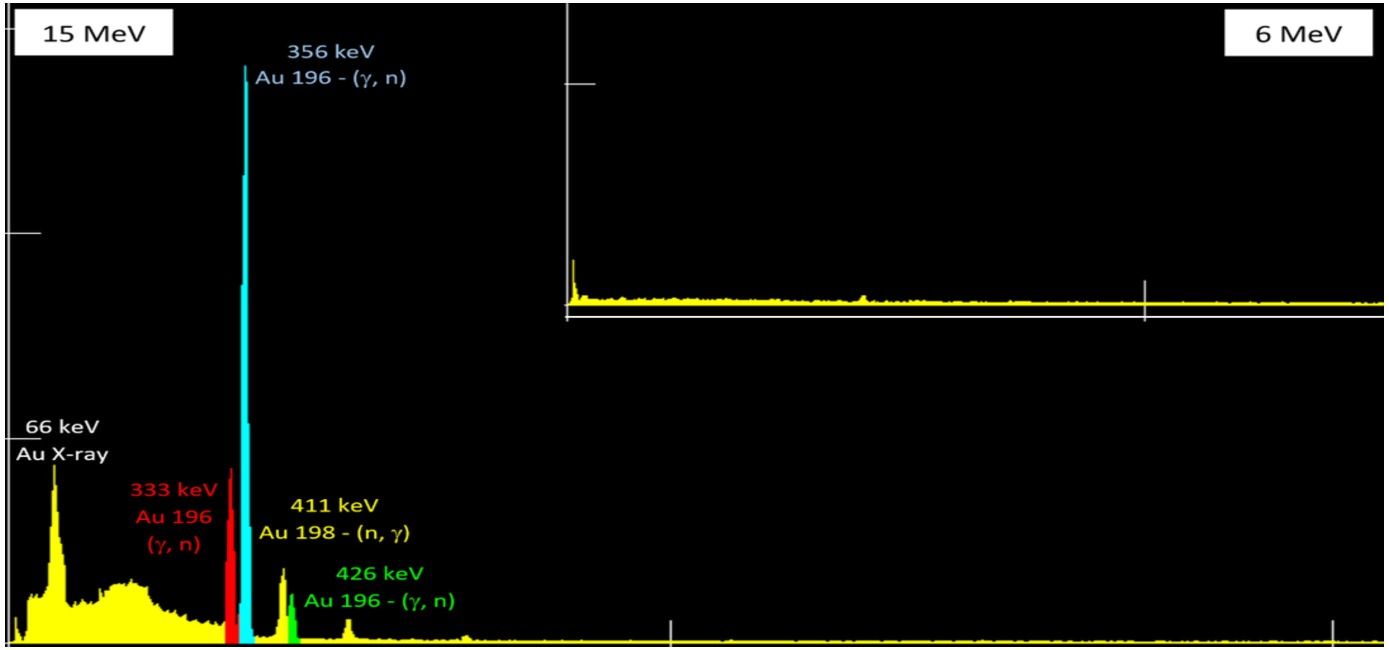


Half-Life Measurements

High-precision measurements of half-lives for ^{69}Ge, ^{73}Se, ^{83}Sr, ^{85m}Sr, and ^{63}Zn radionuclides relevant to the astrophysical *p*-process via photoactivation at the Madison Accelerator Laboratory

T. A. Hain[1] · S. J. Pendleton[1] · J. A. Silano[2] · A. Banu[1]

Received: 3 September 2020 / Accepted: 31 December 2020

Abstract
The ground state half-lives of ^{69}Ge, ^{73}Se, ^{83}Sr, ^{63}Zn, and the half-life of the $1/2^-$ isomer in ^{85}Sr have been measured with high precision using the photoactivation technique at an unconventional bremsstrahlung facility that features a repurposed medical electron linear accelerator. The γ-ray activity was counted over about 6 half-lives with a high-purity germanium detector, enclosed into an ultra low-background lead shield. The measured half-lives are: $T_{1/2}(^{69}\text{Ge}) = 38.82 \pm 0.07$ (stat) ± 0.06 (sys) h; $T_{1/2}(^{73}\text{Se}) = 7.18 \pm 0.02$ (stat) ± 0.004 (sys) h; $T_{1/2}(^{83}\text{Sr}) = 31.87 \pm 1.16$ (stat) ± 0.42 (sys) h; $T_{1/2}(^{85m}\text{Sr}) = 68.24 \pm 0.84$ (stat) ± 0.11 (sys) min; $T_{1/2}(^{63}\text{Zn}) = 38.71 \pm 0.25$ (stat) ± 0.10 (sys) min. These high-precision half-life measurements will contribute to a more accurate determination of corresponding ground-state photoneutron reaction rates, which are part of a broader effort of constraining statistical nuclear models needed to calculate stellar nuclear reaction rates relevant for the astrophysical *p*-process nucleosynthesis.

Half-Life Measurements

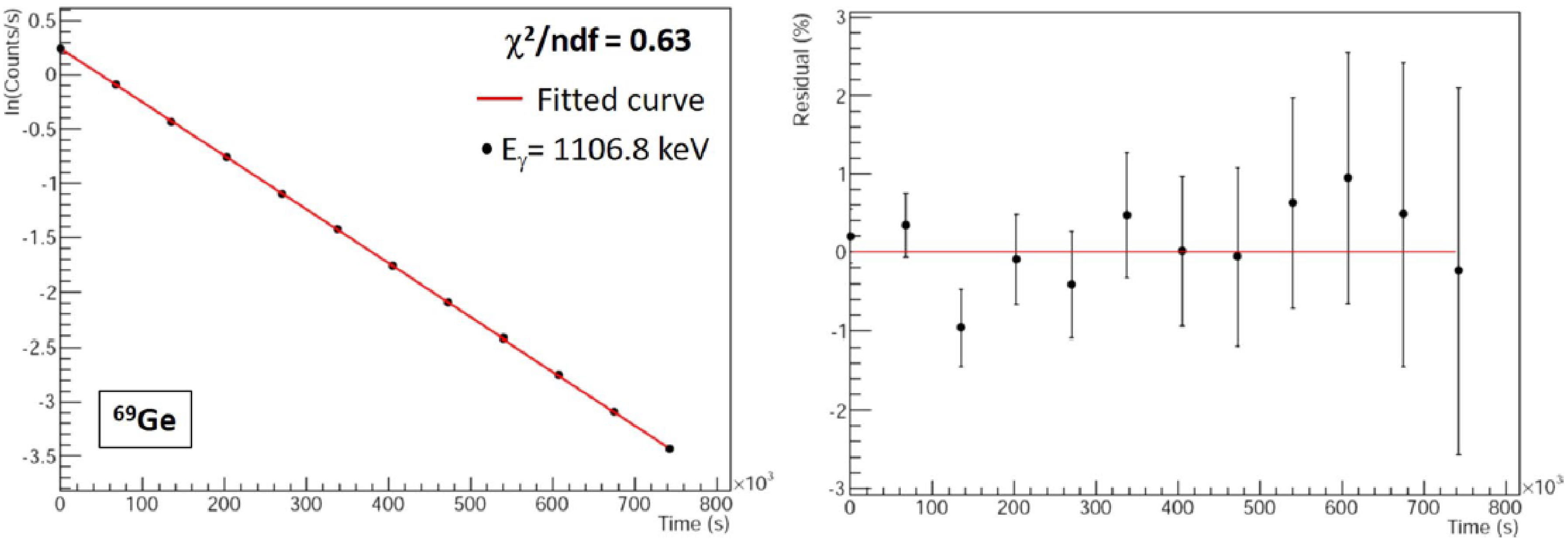
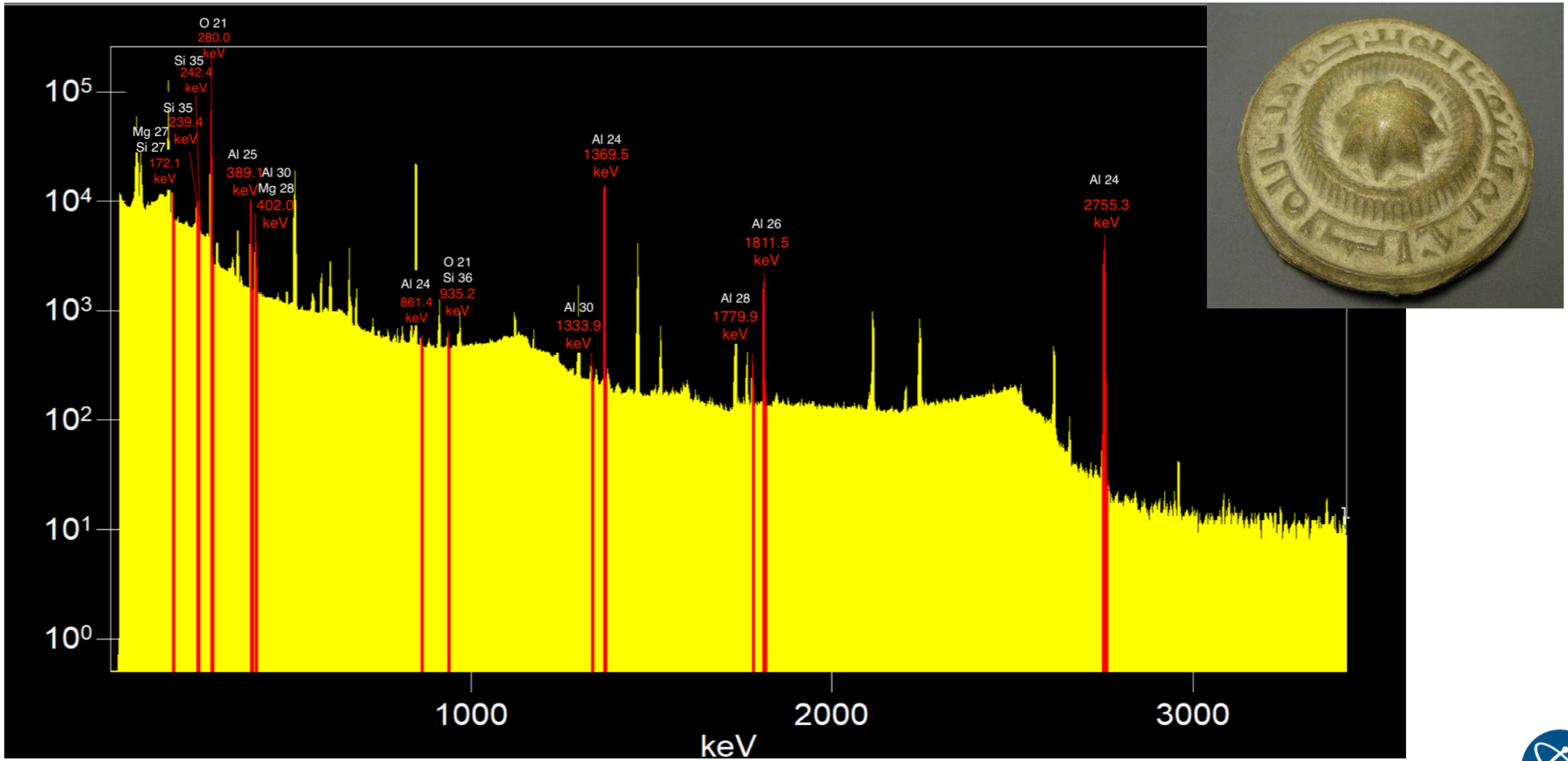


Fig. 3 Decay curve of ^{69}Ge at $E\gamma = 1106.8$ keV (left) and its corresponding % residual between the linear fit and decay data points (right)

Hain et al. (J. Radioanalytical and Nuclear Chemistry 327(3) (2020))

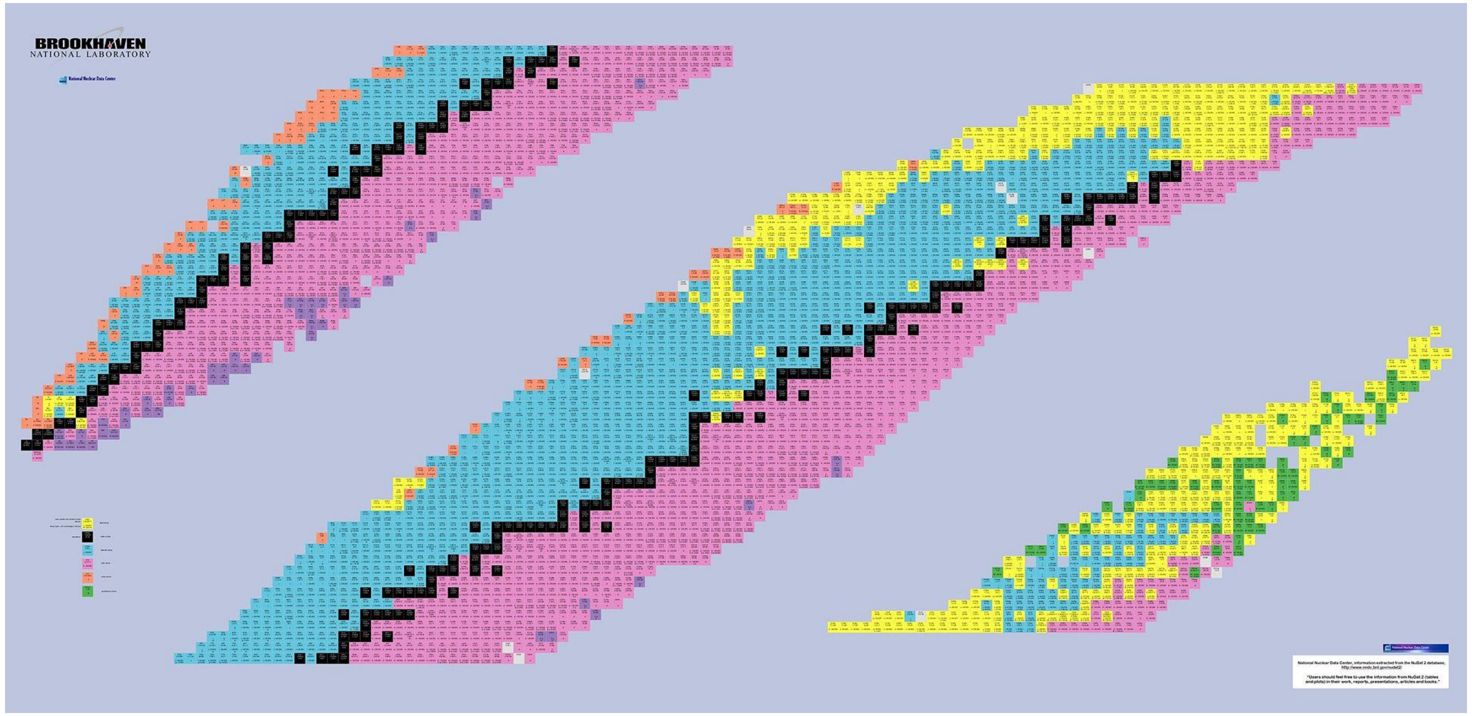
Composition using PAA

- Activate samples with (γ,n) and analyze γ decay spectra
  - Example of an Islamic Prayer Seal, primarily aluminum oxides



Composition using PAA

- Activate samples with (γ,n) and analyze γ decay spectra
- Limited by γ spectrum of target materials with (γ,n) thresholds and available products, availability of standards of target materials



Collaborations

- PAA and other beam experiments possible with low overhead
- May also be used to mimic clinical linac conditions for biomedical experiments

Radiocatalytic performance of oxide-based nanoparticles for targeted therapy and water remediation

M. Molina Higgins (Ph.D)[a], A. Banu (Ph.D)[b], S. Pendleton (Ph.D)[b], J.V. Rojas (Ph.D)[a,*]

[a] *Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University, Richmond, United States*
[b] *Department of Physics and Astronomy, James Madison University, Harrisonburg, VA, United States*

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Metal oxide nanoparticles

ABSTRACT

The radiocatalytic behavior of zinc oxide (ZnO), hafnia (HfO_2), titania (TiO_2), and gold-titania ($Au@TiO_2$) nanomaterials was investigated through the degradation of methylene blue as the organic probe. The dye degradation by X-rays from a medical linear accelerator with endpoint energy of 6 MeV was enhanced in the presence of the oxide-based nanoparticles evidencing their promise as radiosensitizers. An increase in the dye apparent reaction rate constants of ~20% and up to 82% was observed in the presence of oxides-based nanoparticles during exposure to X-rays. This enhancement is attributed to the increased production of reactive species in solution. Gold-titania nanocomposites evidenced one of the highest radiocatalytic activity among the materials under investigation, with an increase in the MB apparent reaction rate constant of 50.3%. Overall, our experiments showed that radiocatalysis with oxides-based nanoparticles is a promising concept worth exploring in applications such as targeted radiation therapy and pollutant removal of water streams.

Radiation Physics and Chemistry 173 (2020) 108871

Collaborations

- PAA and other beam experiments possible with low overhead
- May also be used to mimic clinical linac conditions for biomedical experiments
- Beam time is flexible and easy to accommodate given small footprint and required staff

Conclusion

- We have an active user facility with low overhead and staff requirements for research and teaching
  - Already integrated into education/research curriculum
- In-house measurements successful, especially for nuclear astrophysics and PAA
- Characterization and tenability of beam a work in progress
- Open for more collaborations

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Students: Tyler Hain, Jessica Mayer, Natasha Gallant, Theodore Chu, Drew Balbuena, Evan Witczak, David Purdham, Audrey Lindsay

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