

The Triangle Universities Nuclear Laboratory (TUNL)

Reyco Henning

U. Of North Carolina at Chapel Hill

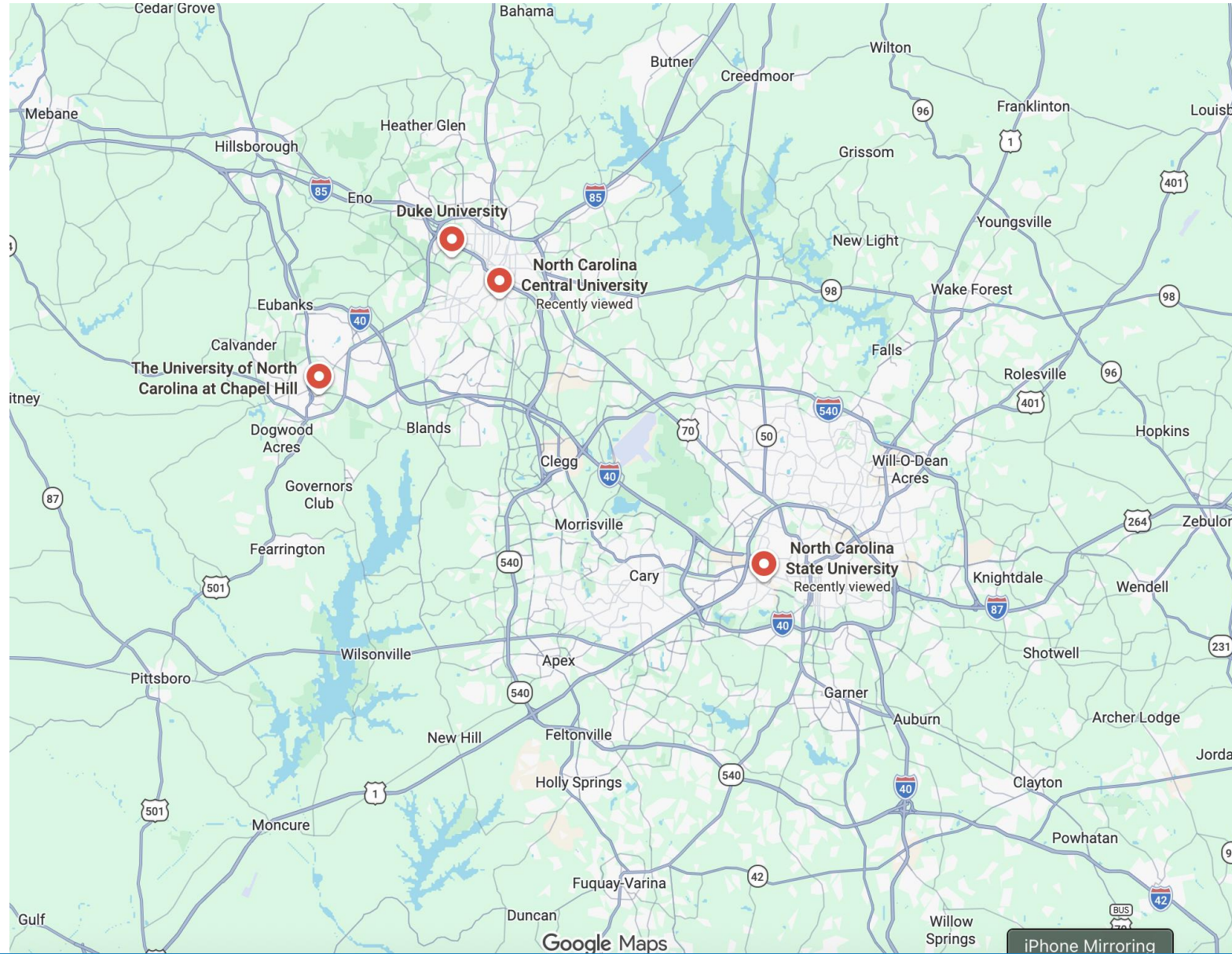
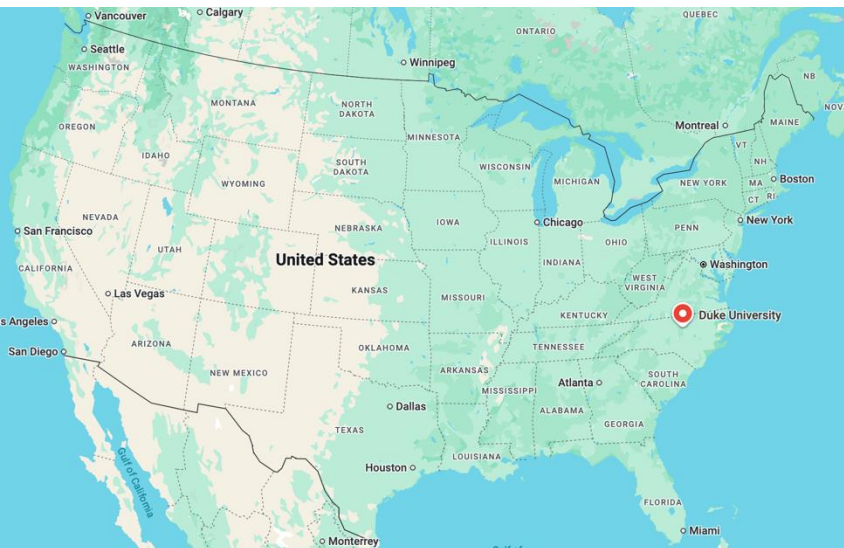
Triangle Universities Nuclear Laboratory

rehenning@unc.edu

tunl.duke.edu



- On campus of Duke University in Durham NC
- Operated by Consortium of NCCU, NCSU, UNC, and Duke
- Primarily Funded by DOE NP/HENP
- NSF REU Program
- 20 faculty, 21 research scientists and postdocs, 15 staff, about 40 graduate students and about 25 undergraduates
- Trains ~8% of NP PhDs in the USA
- NC has second most NP Faculty



Strong Interactions Studies at TUNL

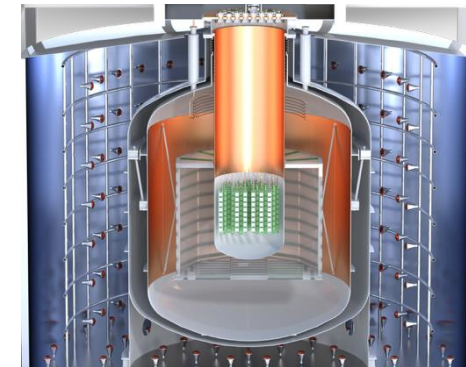
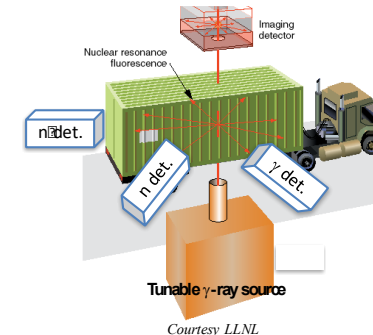
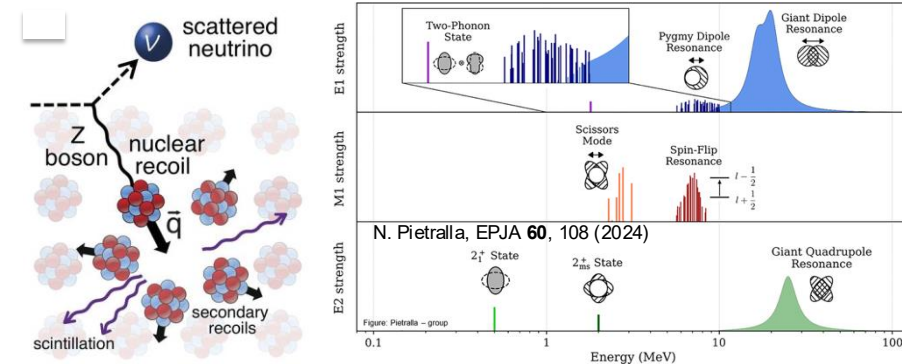
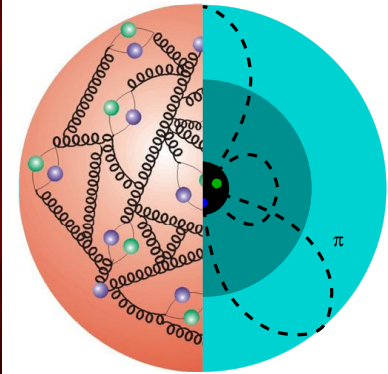
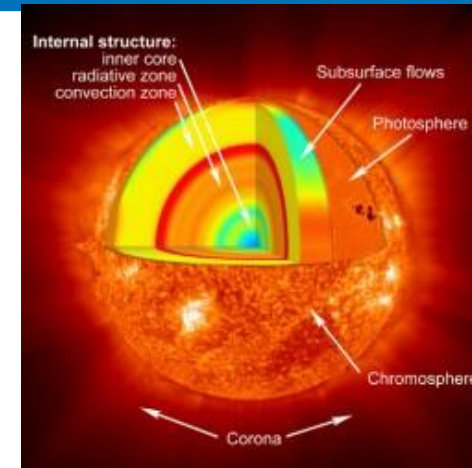
1. Mechanisms by which the strong nuclear force is generated by QCD – HIGS LE QCD program
2. Nuclear reactions that power explosive nucleosynthesis – HIGS, LENA and the tandem lab
3. Origin of Nuclear Structure -- HIGS, LENA and the tandem lab
4. Nucleon tomography and origin of the nucleon spin – JLab
5. Proton Charge-radius Puzzle - JLab

Weak Interactions Studies at TUNL

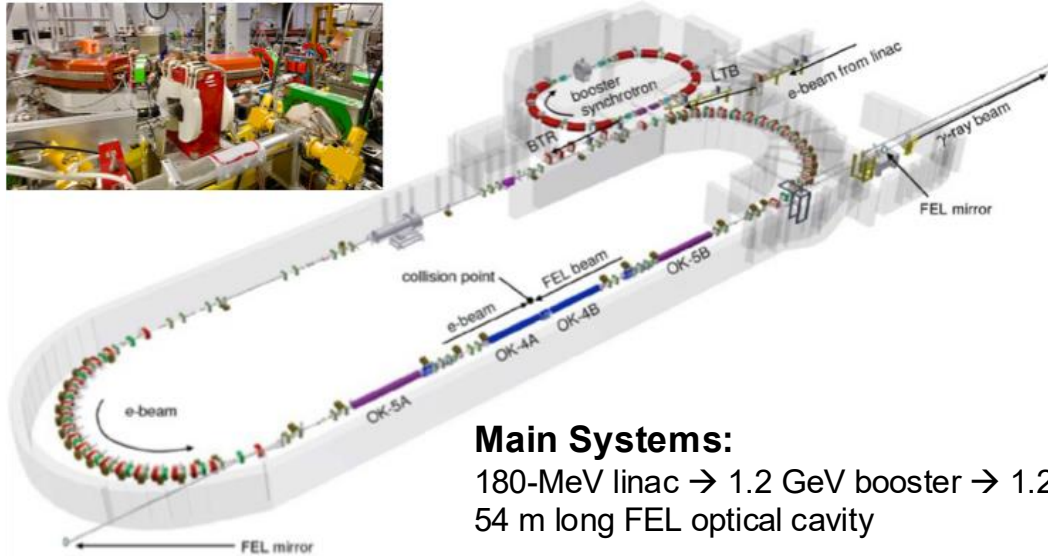
1. Search for Lepton Number Violation via Neutrinoless Double-beta Decay – LEGEND (ORNL) Precision test of Time-Reversal Violation – NAB LANL
2. Precision measurements of electron-quark quark-quark weak interactions – SOLID (JLab)
3. Neutrino-nucleus scattering – COHERENT (ORNL)

Applied Research at TUNL

1. Gamma, neutron and neutrino-induced fission studies
2. Nuclear Data (light nuclei)
3. NNSA/DHS Applications
4. External users: LANL, LLNL, ...



High Intensity Gamma-ray Source (HIGS)



Main Systems:

180-MeV linac → 1.2 GeV booster → 1.2 GeV storage ring

54 m long FEL optical cavity

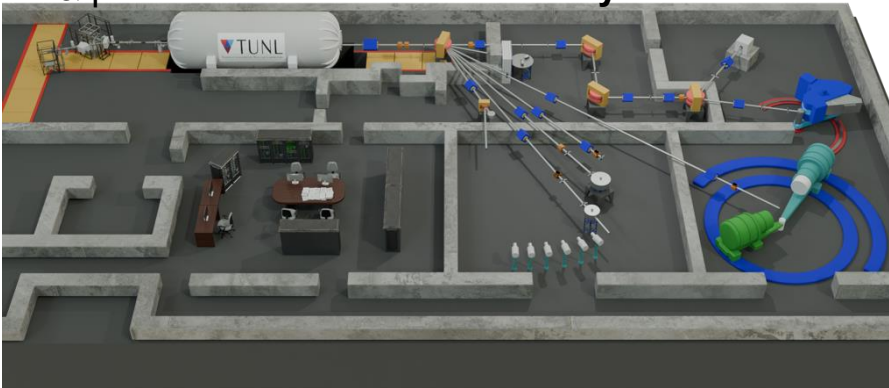
Features that enable basic and applied research

- Most intense Compton gamma-ray source in the world;
- Wide beam energy range: 1 to 100 MeV
- Selectable beam energy spread (by collimation)
- High beam intensity on target ($>10^7$ g/s @ $DE/E = 5\%$)
- $>95\%$ beam polarization (linear and circular)

The Tandem Laboratory

HVE Corp.: **Model FN**
 $TV_{\max} = 10$ MV
 dc & pulsed beams

Light-ion beams: p, d, ^3He , ^4He
Medium-mass ions: from SNIC
Secondary beams: n

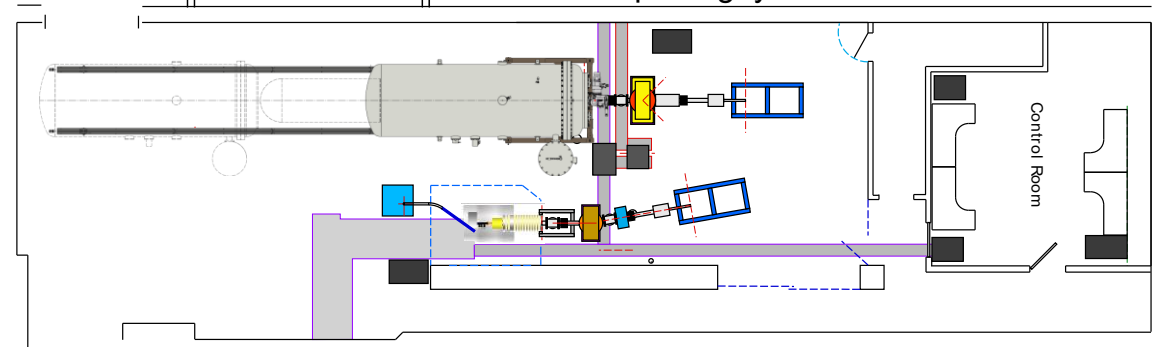


Laboratory for Experimental Nuclear Astrophysics (LENA)

230-kV ECR accelerator:
 ~ 20 mA DC H^+
 Slow pulsing (10% duty cycle)

2-MV HVEE Singletron:

DC beam current at 250 kV: 0.5 mA (H), 0.4 mA (He)
 DC beam current at 1 - 2 MV: 2 mA (H and He)
 Beam pulsing: yes



Facility/Project: HIGS

Gamma Energy (MeV): 1–100

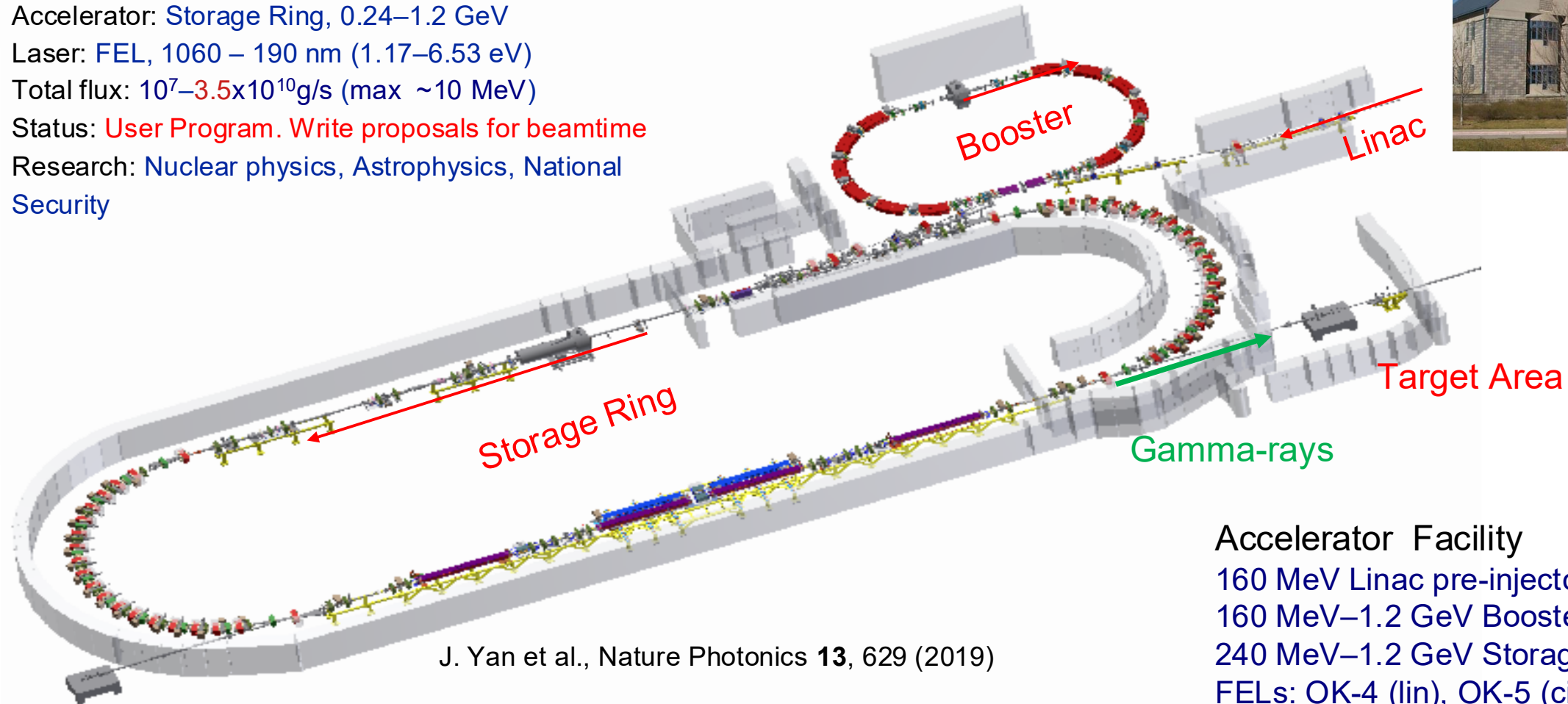
Accelerator: Storage Ring, 0.24–1.2 GeV

Laser: FEL, 1060 – 190 nm (1.17–6.53 eV)

Total flux: 10^7 – 3.5×10^{10} g/s (max ~10 MeV)

Status: **User Program. Write proposals for beamtime**

Research: Nuclear physics, Astrophysics, National Security



J. Yan et al., Nature Photonics **13**, 629 (2019)

Accelerator Facility

160 MeV Linac pre-injector

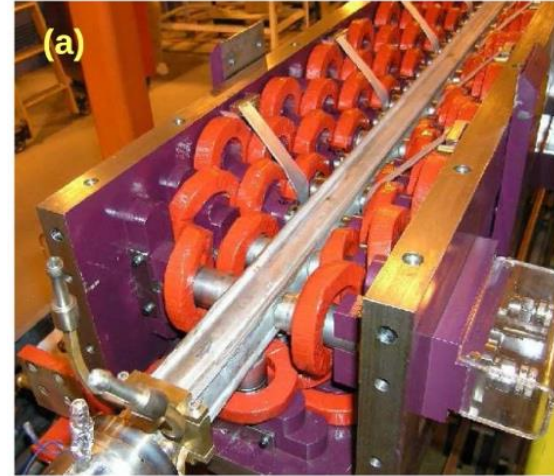
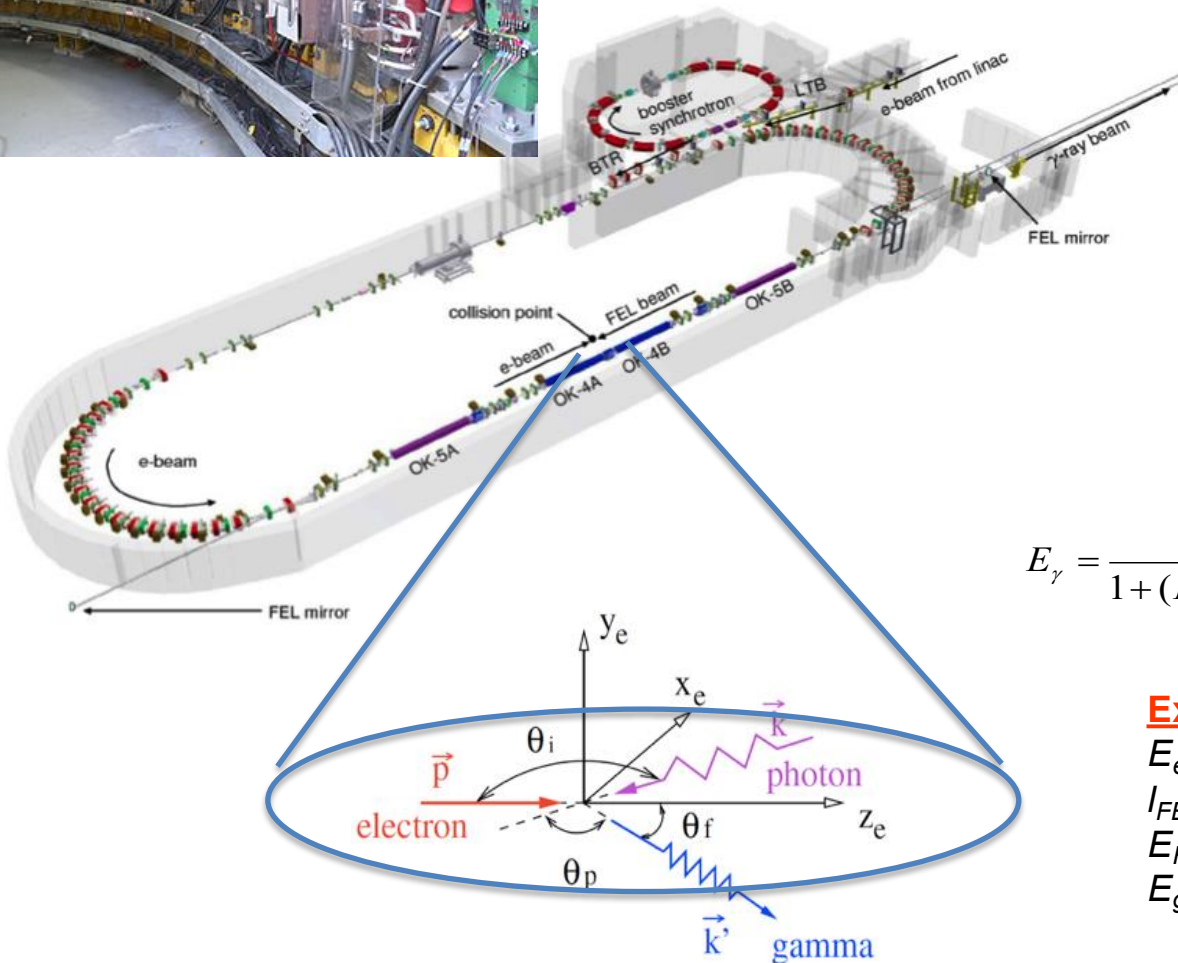
160 MeV–1.2 GeV Booster injector

240 MeV–1.2 GeV Storage ring

FELs: OK-4 (lin), OK-5 (cir)

HIGS: two-bunch, 40–120 mA (typ)

HIGS: an Electron-Photon Collider



$$E_\gamma = \frac{(2\gamma)^2 E_{FEL}}{1 + (E_{FEL} / m_e c^2)(1 + \cos(\theta))}$$

Example:

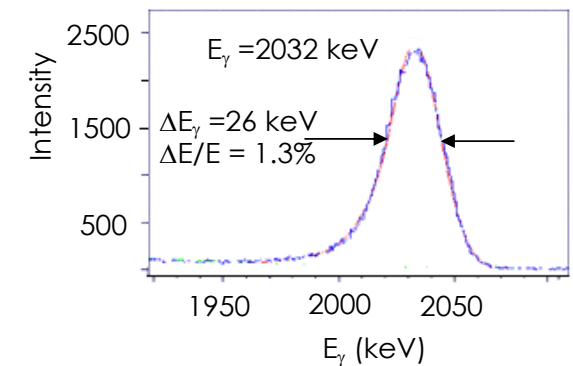
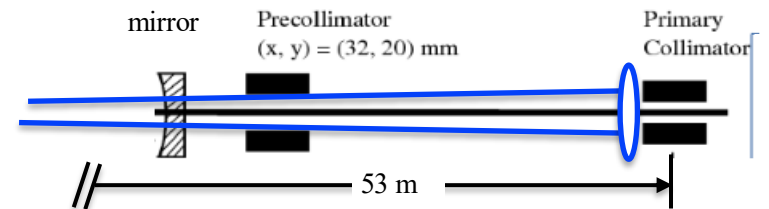
$$E_e = 800 \text{ MeV} \rightarrow \gamma = 1566$$

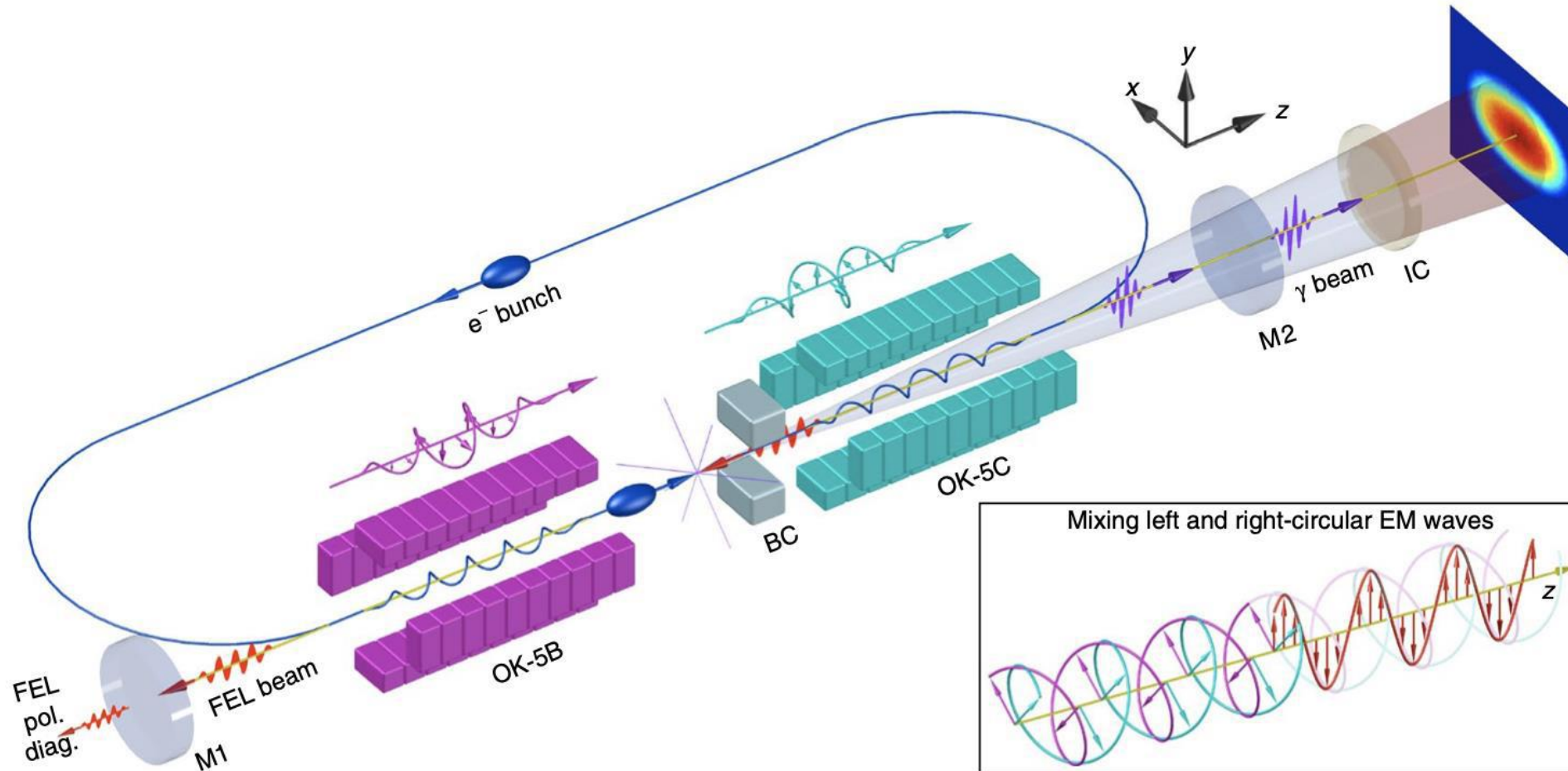
$$I_{FEL} = 193 \text{ nm}$$

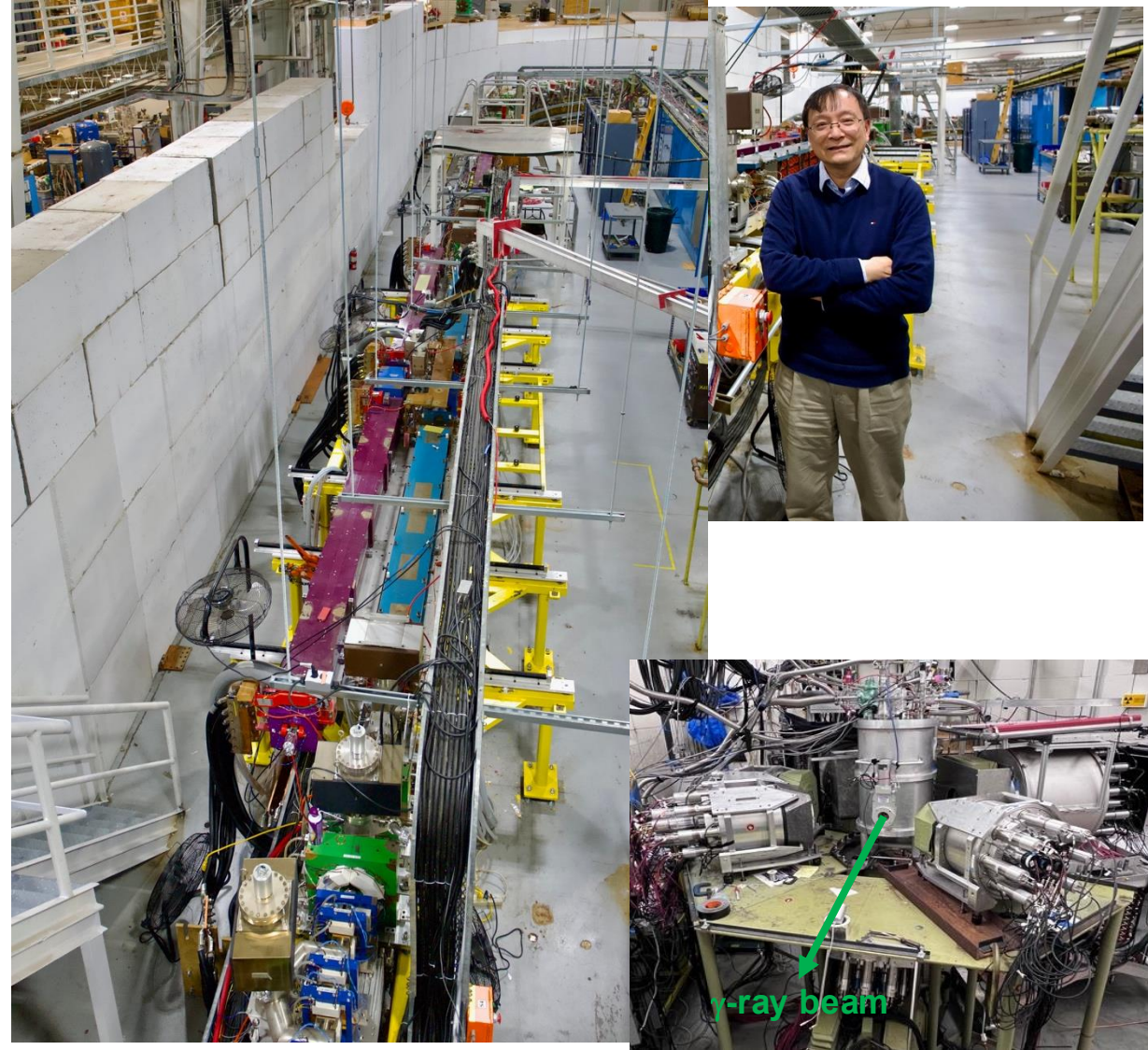
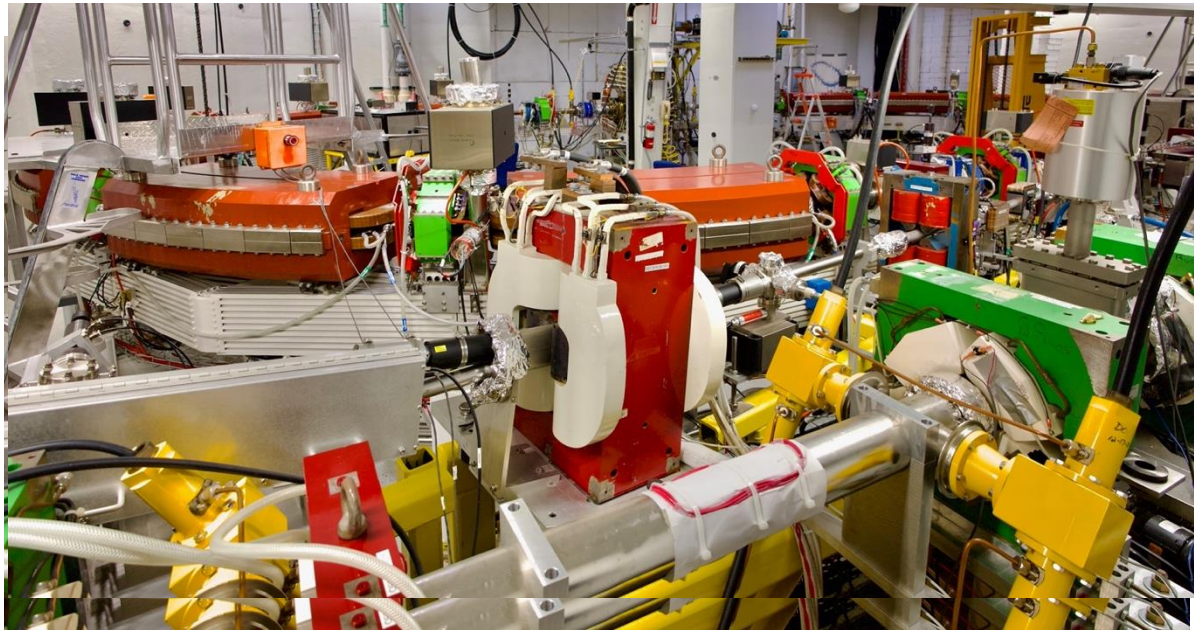
$$E_{FEL} = 6.43 \text{ eV}$$

$$E_g = 63.1 \text{ MeV}$$

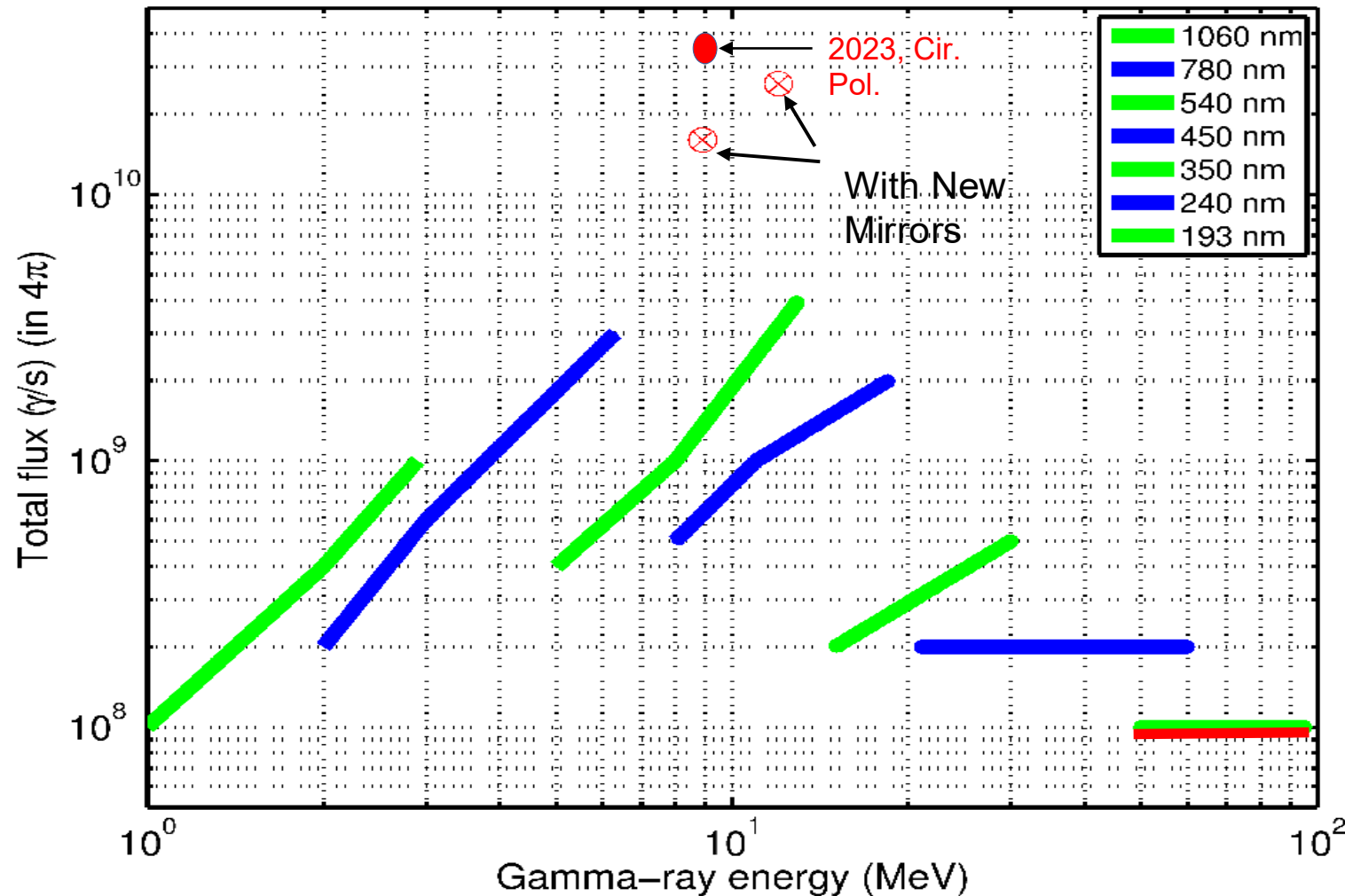
Energy resolution by collimation







HIGS User Flux Capabilities with OK-5 FEL



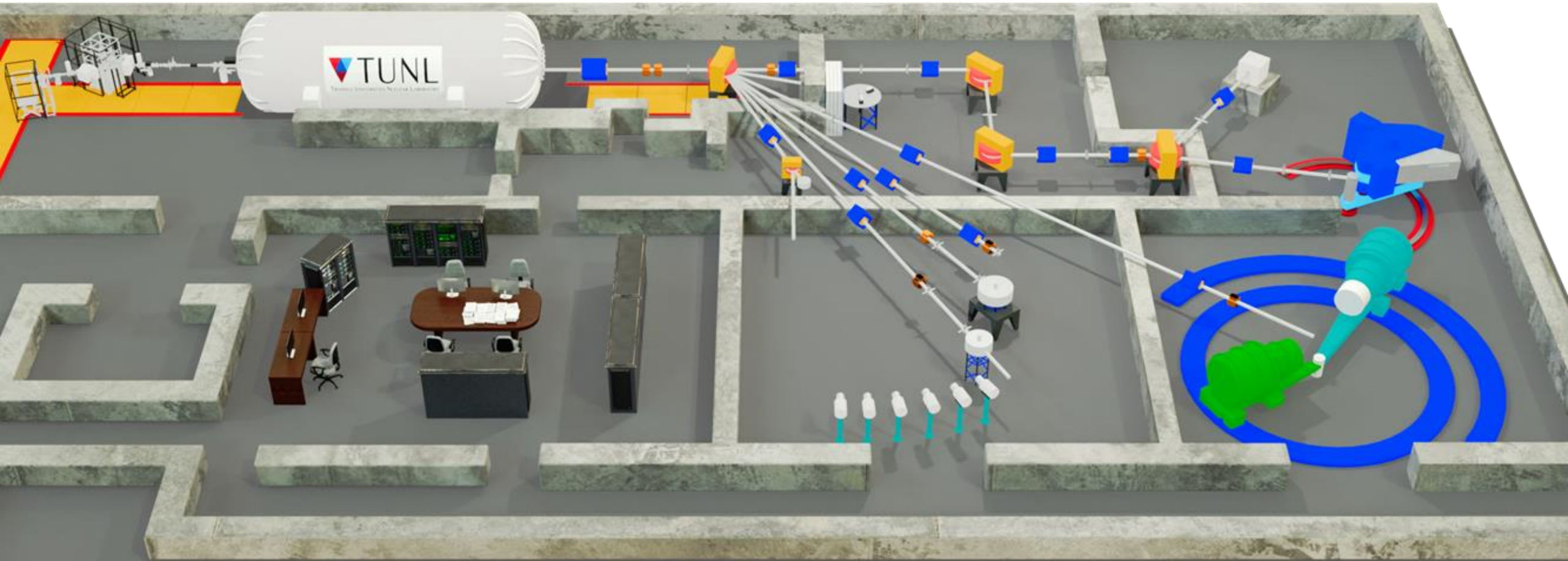
Peak Performance of
HIGS

Total Flux: $\sim 3.5 \times 10^{10}$ g/s,
around 10 MeV ¹

HIGS flux performance table for high-flux, quasi-CW operation, DFELL/TUNL, May 2020 (Version 2.5).

HIGS Flux Performance Projection		Total Flux [g/s] CW Operation Two-Bunch (*)	Collimated Flux ($\Delta E_\gamma / E_\gamma = 5\%$ FWHM) (#), (@)	FEL λ [nm]	Comment Linear Pol. with OK-4 Circular Pol with OK-5
No-loss Mode: $E_\gamma < \sim 16$ MeV					
$E_\gamma = 1 - 2$ MeV	($E_e = 237 - 336$ MeV)	$1 \times 10^8 - 4 \times 10^8$	$6 \times 10^6 - 2.4 \times 10^7$	1064	Linear and Circular (a), (b)
$E_\gamma = 2 - 2.9$ MeV	($E_e = 336 - 405$ MeV)	$4 \times 10^8 - 1 \times 10^9$	$2.4 \times 10^7 - 6 \times 10^7$	1064	Linear and Circular (a), (b)
$E_\gamma = 2 - 3$ MeV	($E_e = 288 - 353$ MeV)	$2 \times 10^8 - 6 \times 10^8$	$1.2 \times 10^7 - 3.6 \times 10^7$	780	Linear and Circular (a), (b)
$E_\gamma = 3 - 5.4$ MeV	($E_e = 353 - 474$ MeV)	$6 \times 10^8 - 2 \times 10^9$	$3.6 \times 10^7 - 1.2 \times 10^8$	780	Linear (a), (b)
$E_\gamma = 3 - 6.3$ MeV	($E_e = 353 - 512$ MeV)	$6 \times 10^8 - 3 \times 10^9$	$3.6 \times 10^7 - 1.8 \times 10^8$	780	Circular (a), (b)
$E_\gamma = 5 - 8$ MeV	($E_e = 380 - 481$ MeV)	$4 \times 10^8 - 1 \times 10^9$	$2.4 \times 10^7 - 6 \times 10^7$	540	Linear and Circular (a), (b)
$E_\gamma = 8 - 11$ MeV	($E_e = 481 - 565$ MeV)	$1 \times 10^9 - 2 \times 10^9$	$6 \times 10^7 - 1.2 \times 10^8$	540	Linear (a), (b)
$E_\gamma = 8 - 13$ MeV	($E_e = 481 - 615$ MeV)	$1 \times 10^9 - 4 \times 10^9$	$6 \times 10^7 - 2.4 \times 10^8$	540	Circular (a), (b)
$E_\gamma = 8 - 11$ MeV	($E_e = 439 - 516$ MeV)	$5 \times 10^8 - 1 \times 10^9$	$3 \times 10^7 - 6 \times 10^7$	450	Linear and Circular (a), (b)
$E_\gamma = 11 - 16$ MeV	($E_e = 516 - 624$ MeV)	$1 \times 10^9 - 2 \times 10^9$	$6 \times 10^7 - 1.2 \times 10^8$	450	Linear (a), (b)
$E_\gamma = 11 - 18.5$ MeV	($E_e = 516 - 671$ MeV)	$1 \times 10^9 - 2 \times 10^9$	$6 \times 10^7 - 1.2 \times 10^8$	450	Circular (a)
$E_\gamma = 15 - 25$ MeV	($E_e = 533 - 691$ MeV)	$2 \times 10^8 - 3 \times 10^8$	$1.2 \times 10^7 - 1.8 \times 10^7$	350	Linear (a)
$E_\gamma = 15 - 30$ MeV	($E_e = 533 - 758$ MeV)	$3 \times 10^8 - 5 \times 10^8$	$1.8 \times 10^7 - 3 \times 10^7$	350	Circular (a)
Loss Mode: $E_\gamma > \sim 16$ MeV					
$E_\gamma = 21 - 65$ MeV	($E_e = 526 - 940$ MeV)	$\sim 2 \times 10^8$	$\sim 1.2 \times 10^7$	240	Circular (c)
$E_\gamma = 21 - 54$ MeV	($E_e = 526 - 854$ MeV)	$\sim 2 \times 10^8$	$\sim 1.2 \times 10^7$	240	Linear (c)
$E_\gamma = 50 - 110$ MeV	($E_e = 738 - 1,114$ MeV)	$0.2 - 1 \times 10^8$	$\sim 1.5 - 6 \times 10^6$	193	Circular (c)
$E_\gamma = 50 - 85$ MeV	($E_e = 738 - 973$ MeV)	$0.4 - 0.8 \times 10^8$	$\sim 3 - 5 \times 10^6$	193	Linear (c), (d)

<https://tunl.duke.edu/sites/tunl.duke.edu/files/documents/HIGSBeamParameters.pdf>



High Voltage Engineering Corp.: Model FN
 $TV_{\max} = 10 \text{ MV}$

Light-ion beams: p, d, ^3He , ^4He
Medium-mass ions: from SNIC
Secondary beams: n

New Injector for the Tandem Accelerator

- TORVIS H/He ion source
 - 75 kV source deck
 - 100 μA H-
 - 20 μA He-
- SNICS-II ion source
 - Heavy ion beams from solid targets
 - 1-300 μA , depending on ion
 - 90-degree magnet for implantation
- Beam pulsing
 - ~ 2 ns FWHM
 - Significantly increased beam current
 - Target beam current: 25-30% of source



Pulsed Neutron Production

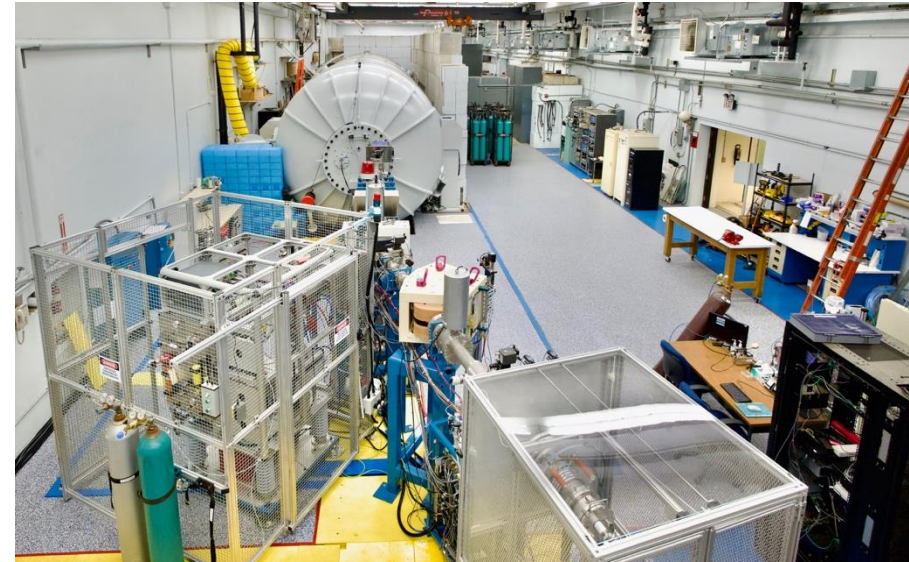
Charged beams on gas/solid targets:

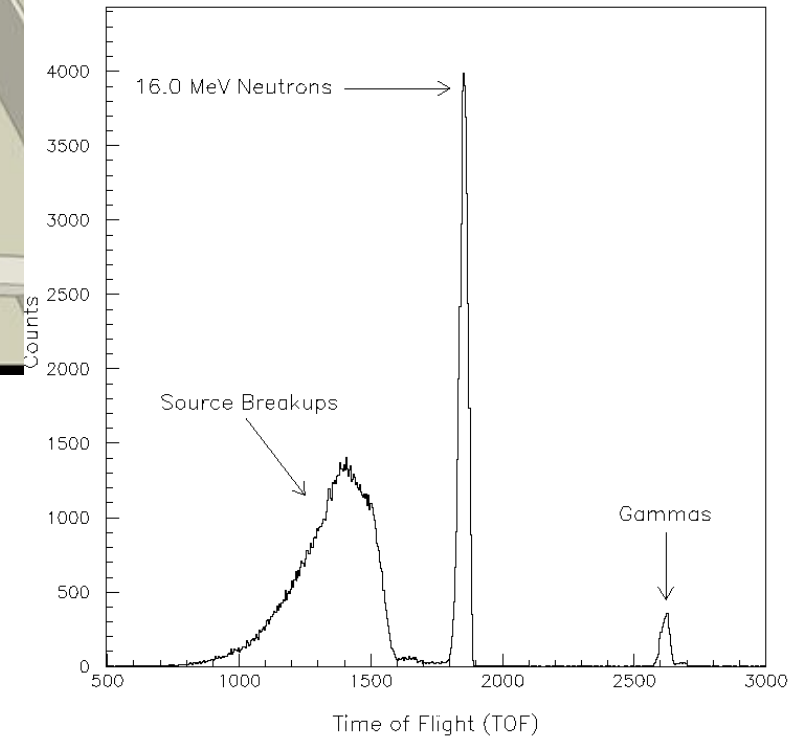
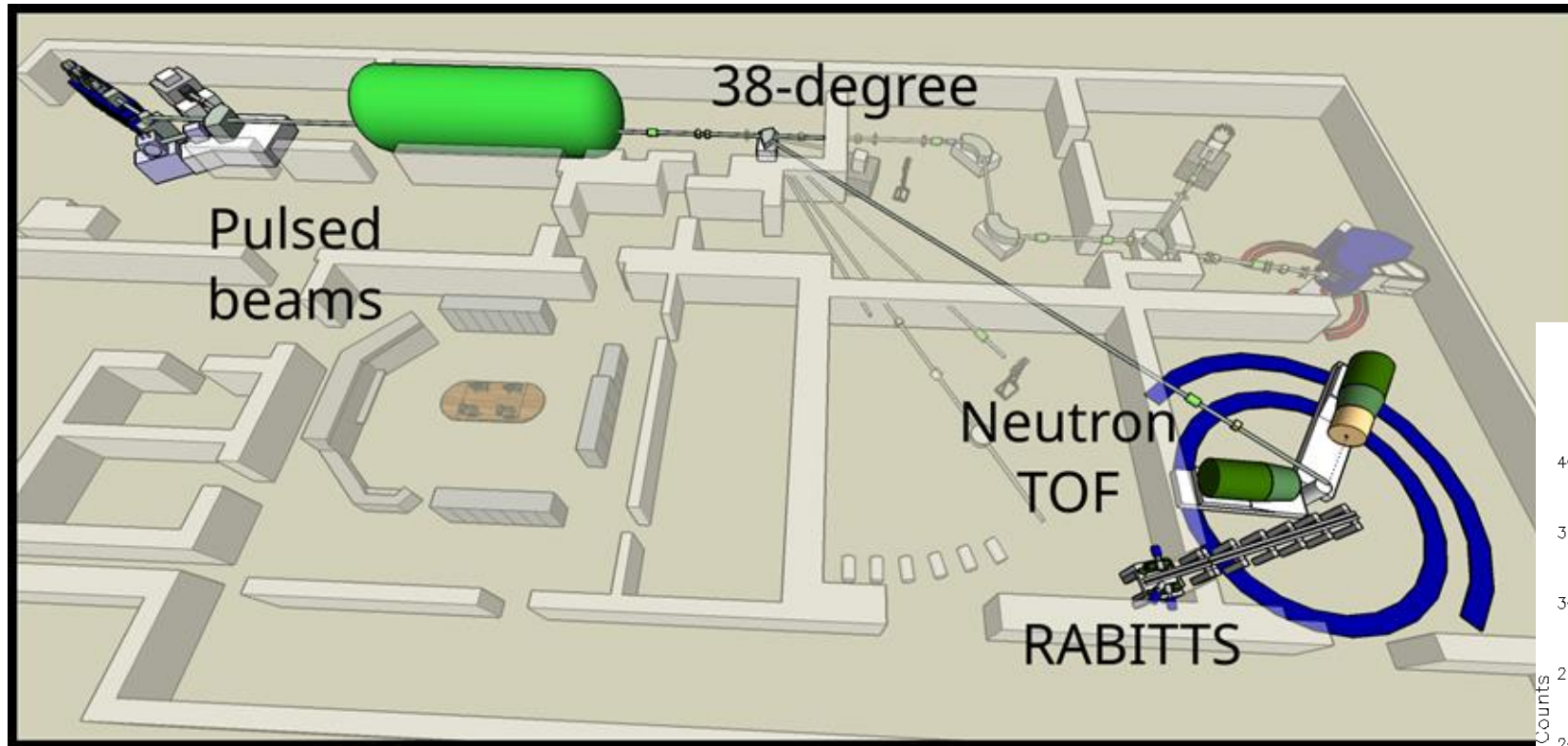


0.6-30 MeV

$\sim 4 \times 10^4 \text{ n.s}^{-1}.\text{cm}^{-2}$ at 1m

Energy from TOF, 1ns timing

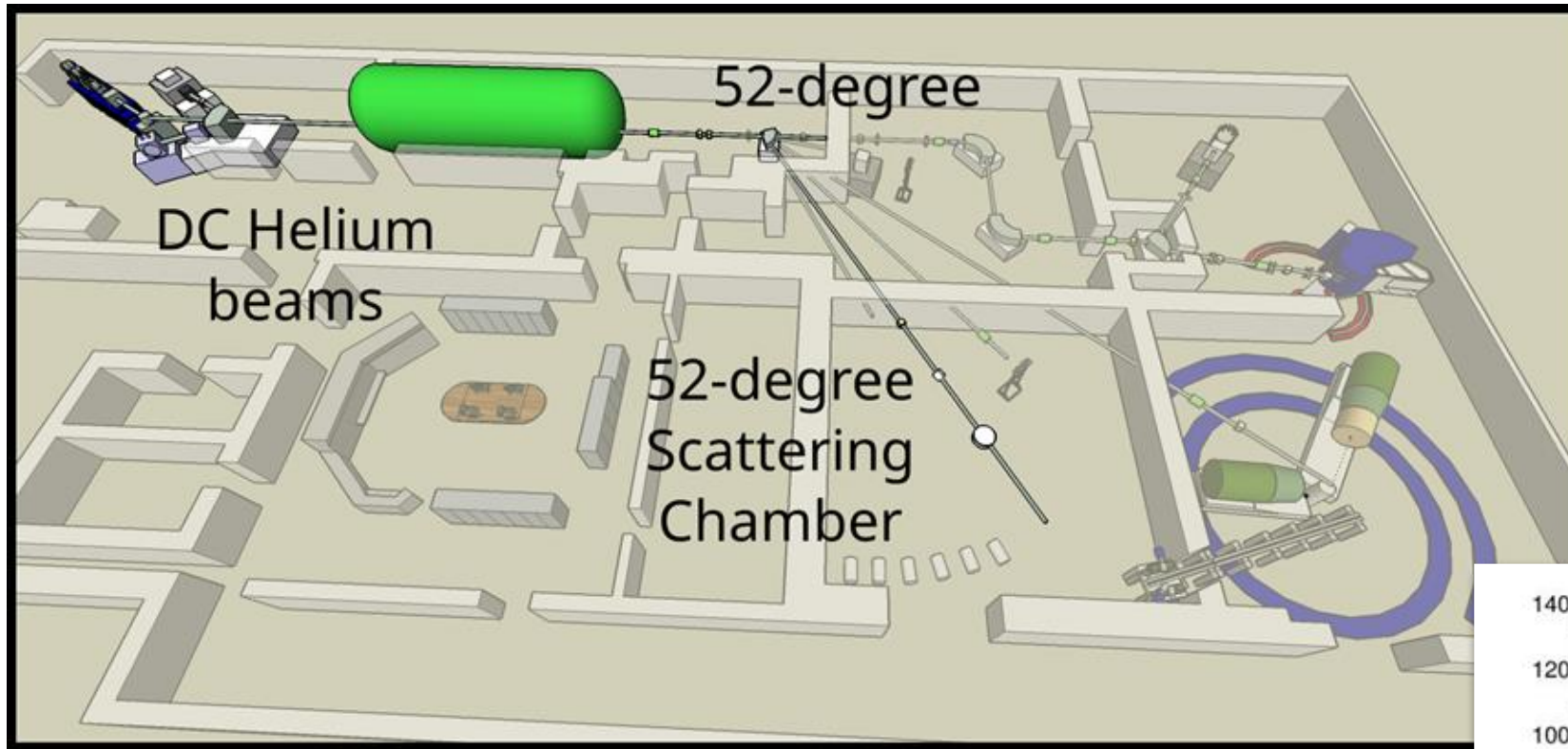




- Measurements of neutron induced cross sections
- RABITTS System

Haselschwardt, PRL, 131 (2023) 052502
Ramirez, PRC 107 (2023) 054608

Finch, NIM A, 1025 (2022) 166127
Tornow, PRC, 103, (2021) 044612
Finch, PRC, 103 (2021) 044609

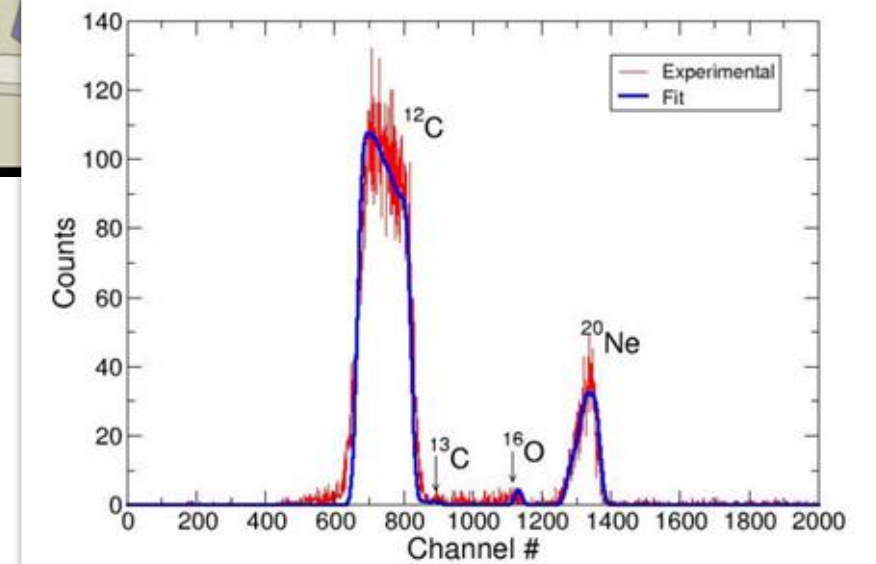


- Used primarily for RBS
- Nuclear reaction cross section measurements
- Supports LENA and Spectrograph programs
- Detector R&D: JLab deuteron charge radius expt.

Cooper, Nucl. Inst. Meth. A, 1056 (2023) 168654

Portillo, Physical Review C, 107 (2023) 035809

Frost-Schenk, MNRAS, 514 (2022) 2650



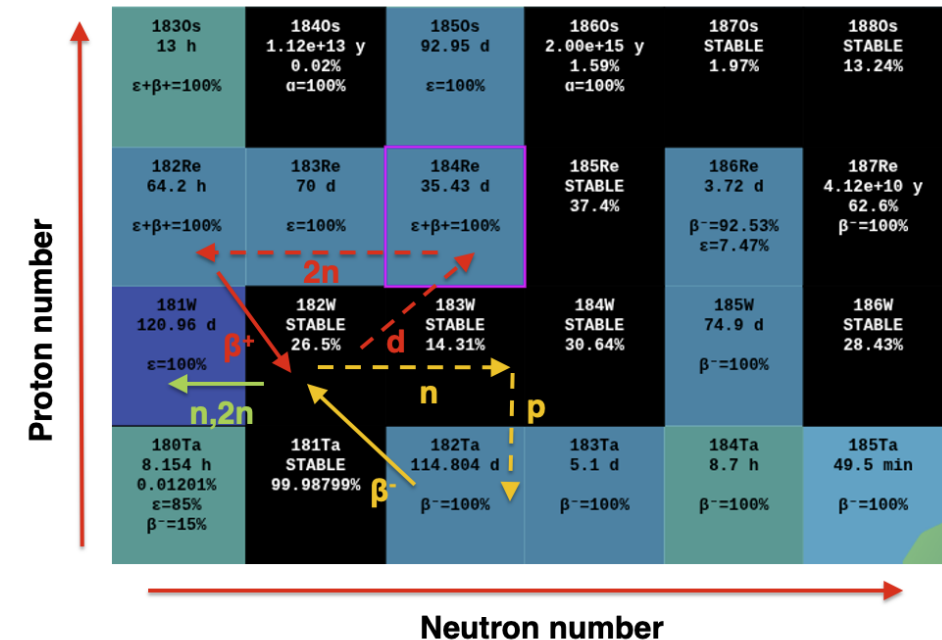
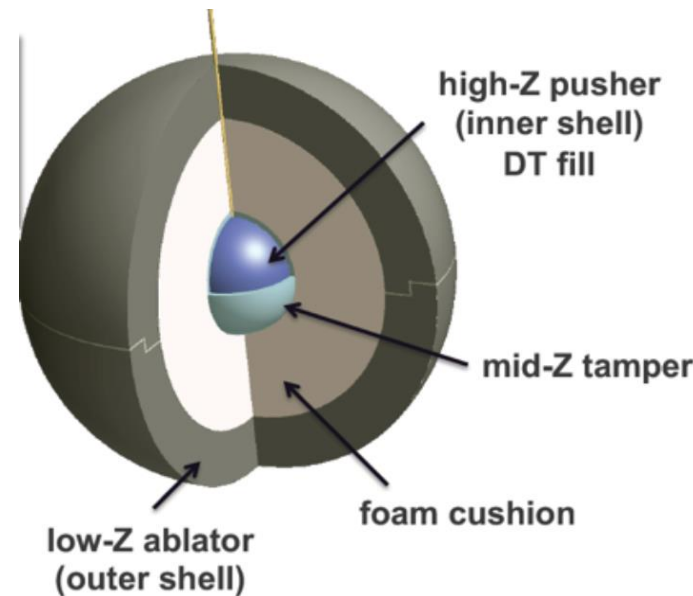
Application Example: Collaboration with Los Alamos National Laboratory (LANL)

Motivation:

- To improve the fusion output at NIF: supporting LANL's double-shell target
- Tungsten inner shell will trap radiation to induce a more complete burn
- Solid debris is collected and activation products measure the “mix” between DT fuel and shell
- Reaction cross-sections measured at TUNL/Tandem: $W(p,n)$, $W(d,n)$ and $W(d,2n)$, $W(n,2n)$

Enabled by:

- High intensity pulsed mono-energetic neutron beam
- Affordable beamtime costs
- Low-background counting facility with HPGeS



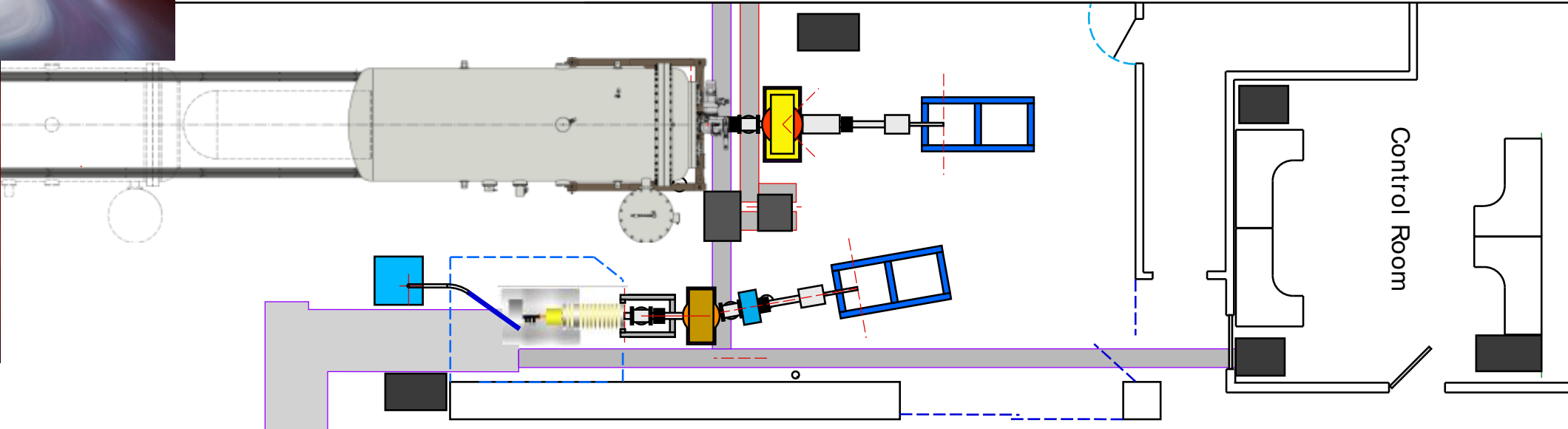
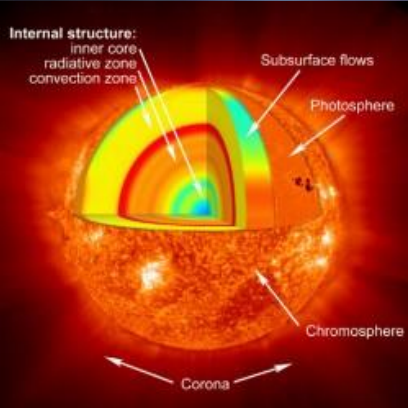
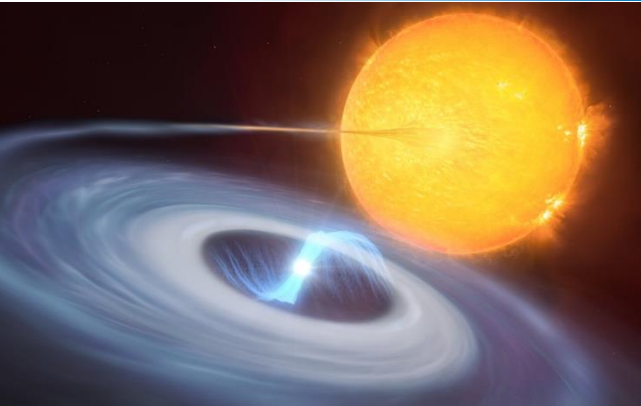
2-MV HVEE Singletron:

DC beam current at 250 kV: 0.5 mA (H), 0.4 mA (He)

DC beam current at 1 - 2 MV: 2 mA (H and He)

Pulse frequency: 0.125, 0.25, 0.5, 1, 2, 4 MHz

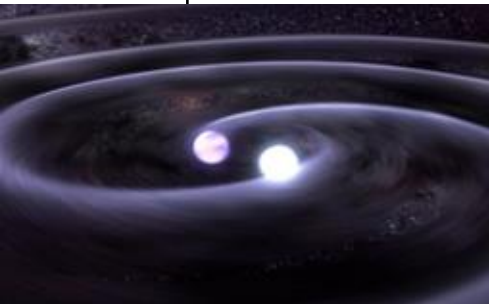
Pulse width: 2 – 20 ns

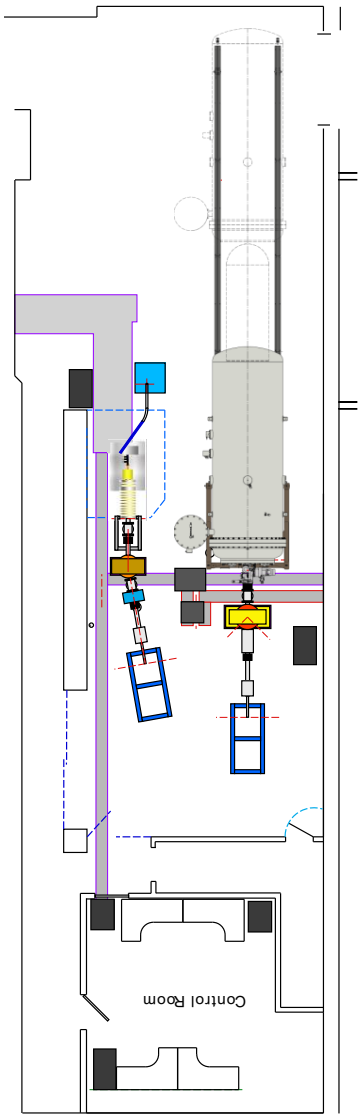


230-kV ECR accelerator:

~ 20 mA DC H⁺

Slow pulsing (10% duty cycle)

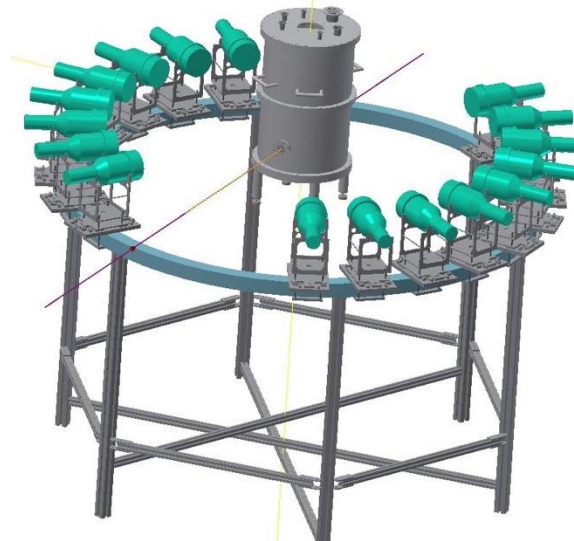
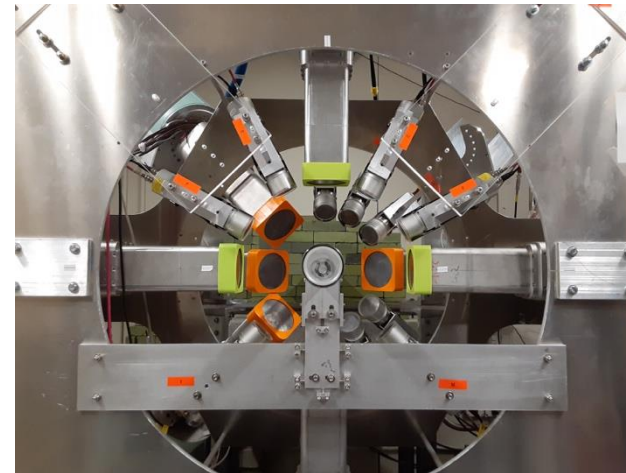




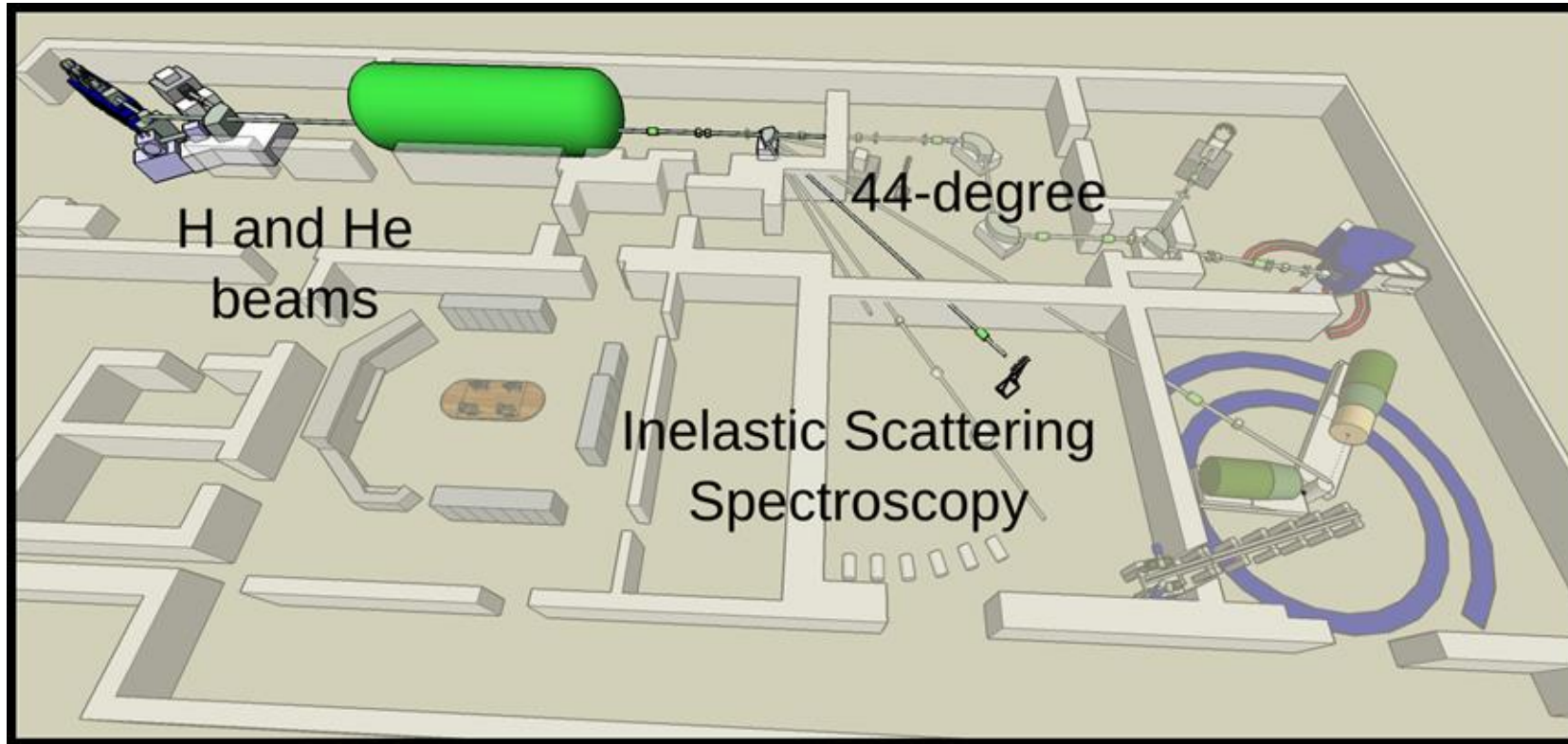
Cleanroom at UNC



Detector Systems

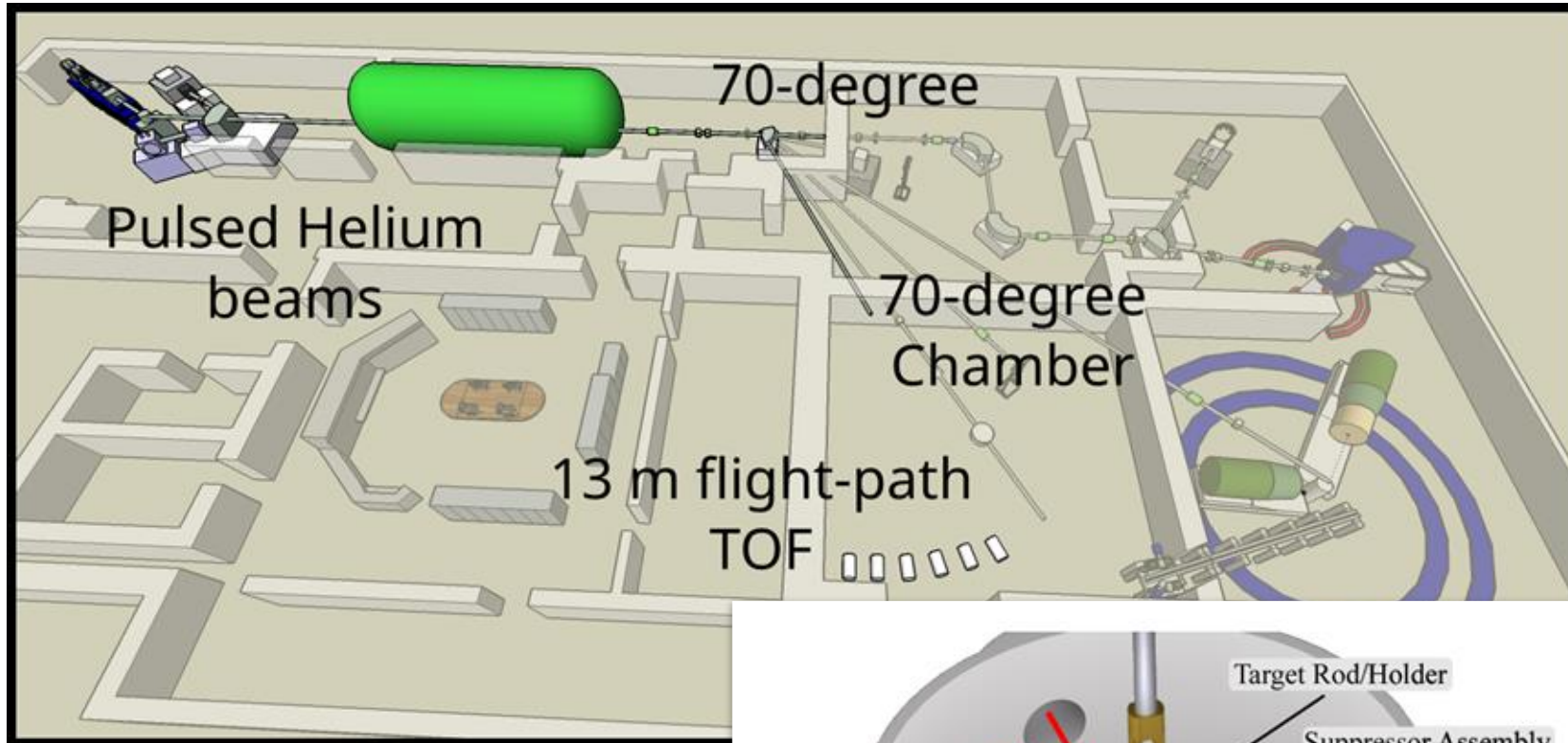


- TUNL has a variety of accelerators and sources for ions, neutrons and gamma-ray beams
- Large local community with expertise in experimental nuclear physics
- New projects/collaborators welcome.
- Please contact me if interested: rhenning@unc.edu



A.D. Ayangaekaa
R.J.V. Janssens

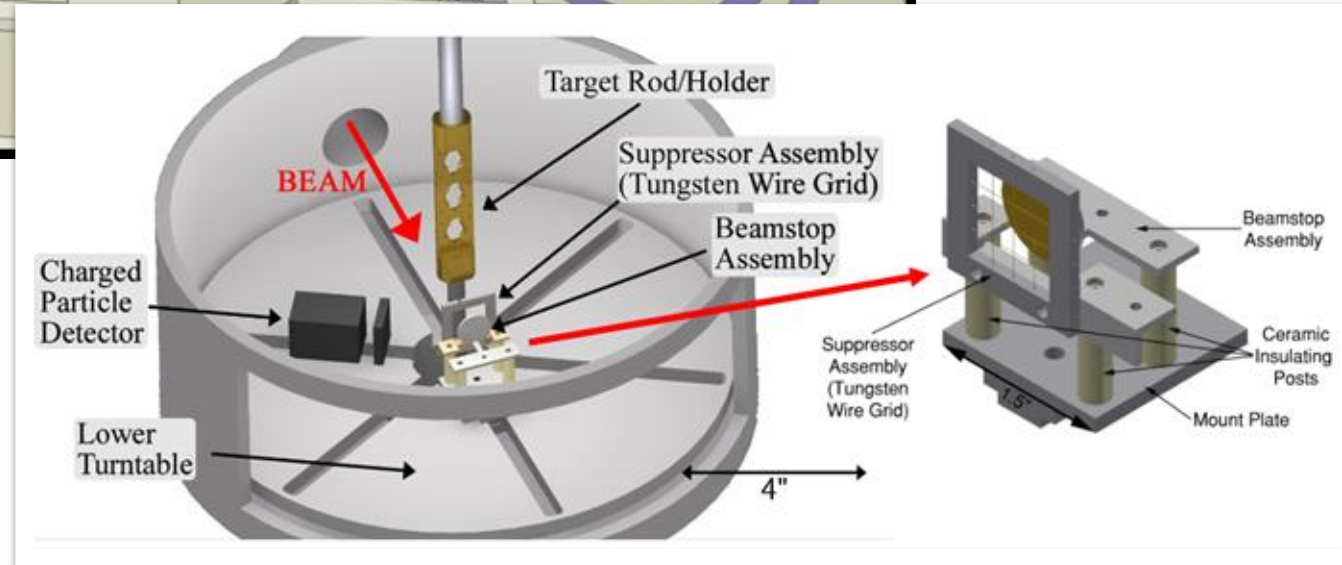
- γ -ray spectroscopy from inelastic scattering
- New project: "Multimessenger Investigation of Nuclear Structure at the Tandem Facility at TUNL"

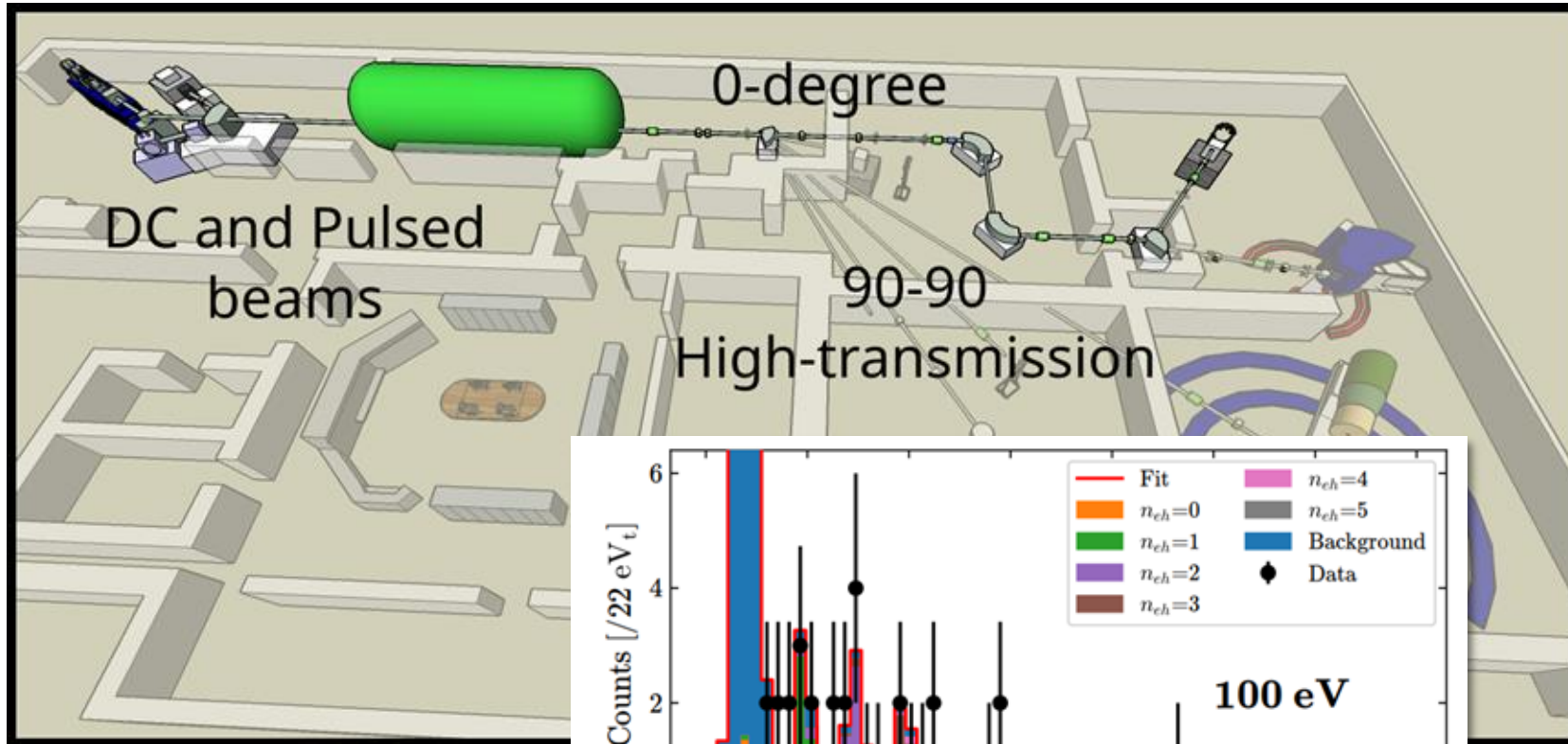


P. Barbeau
C.R. Howell
A.R. Young

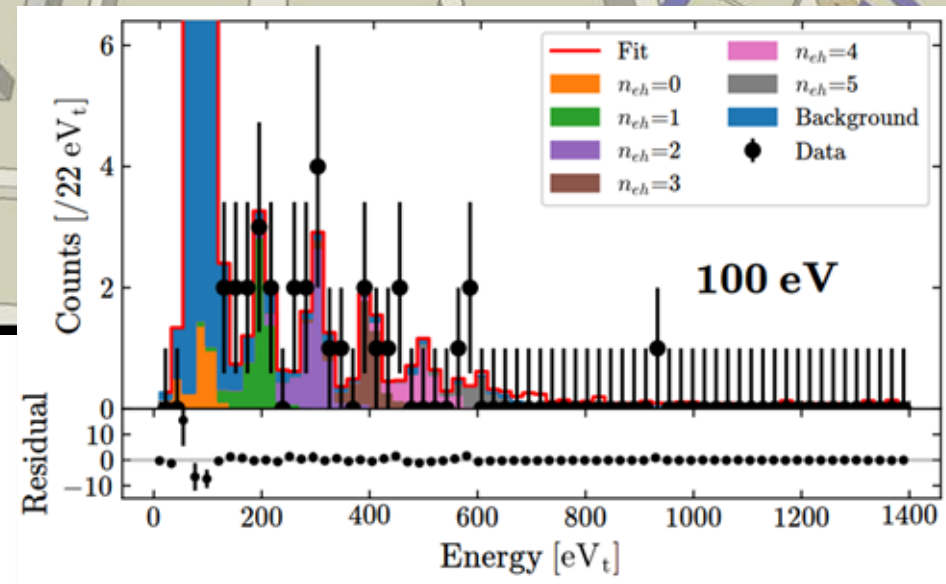
- 2-proton exchange cross section measurements
- ($^3\text{He}, n$)
- $0\nu\beta\beta$ decay studies

Manuscripts in preparation





P.S. Barbeau
D. Markoff



LUX/LZ, COSINE,
ANAIS, SuperCDMS,
NEWSG,
COHERENT,
CHANDLER, CNEC,
among others

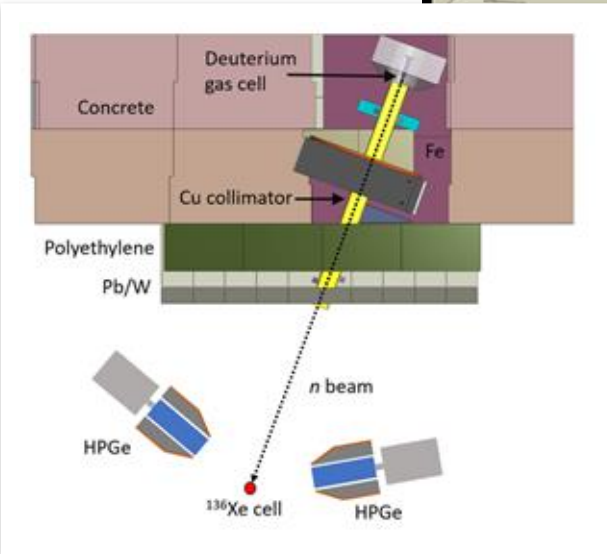
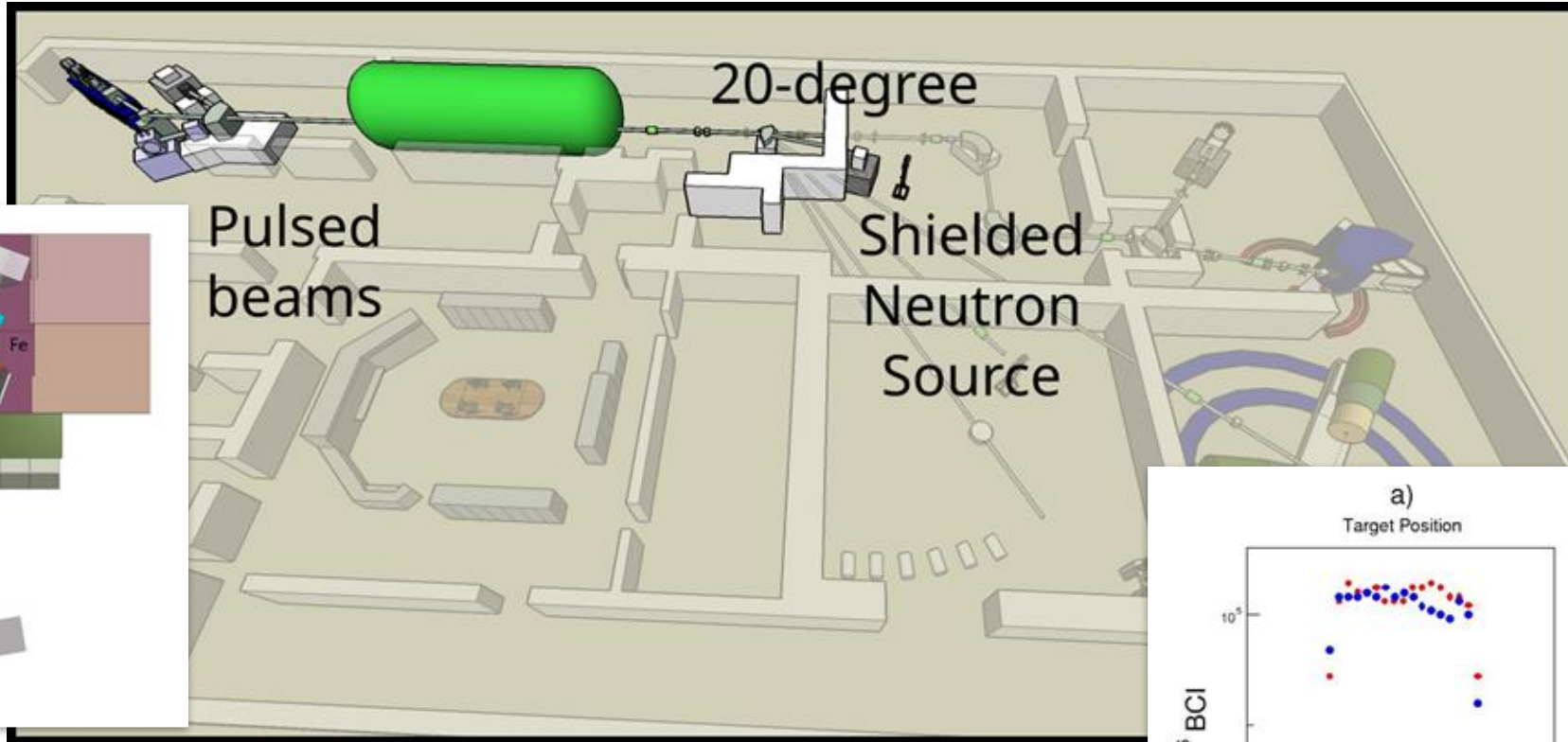
Detector development for:

- neutrinos
- dark matter
- nuclear security

Albakry, Physical Review Letters, 131 (2023) 091801
Akimov, J. Inst. 17 (2022) P10034

Balogh, Physical Review D, 105 (2022) 052004
Awe, J. Inst. 16 (2021) P02035

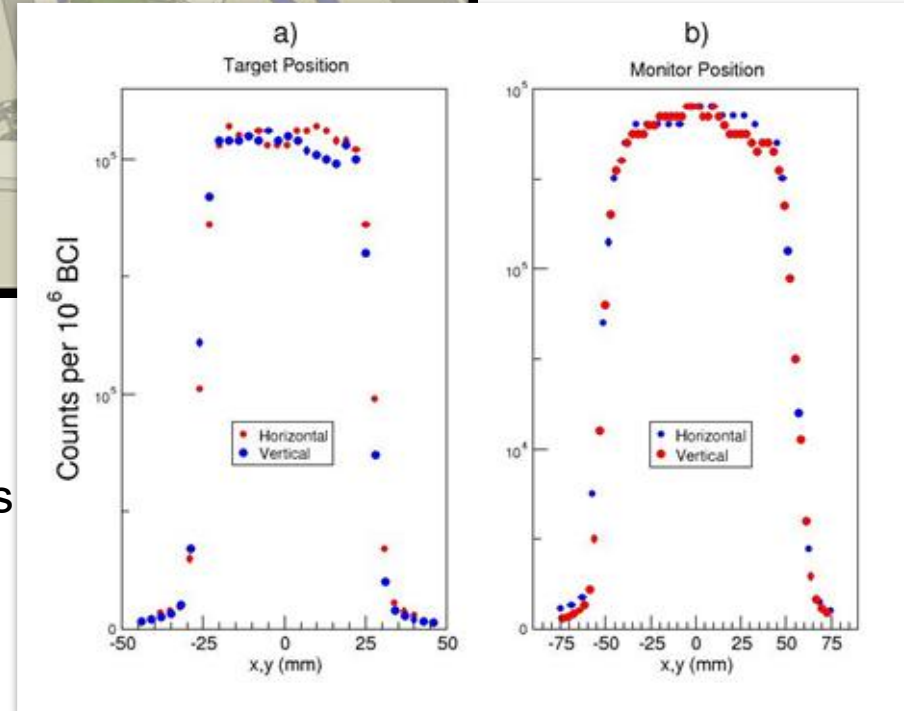
P.S. Barbeau
C.R. Howell
W. Tornow



- Measurements of neutron induced cross sections
- Monoenergetic neutron beam via the $^2\text{H}(d,n)^3\text{He}$ reaction
- 4 - 18 MeV neutrons at 10^4 n/s/cm² using 800 nA pulsed deuterons

Malone, PLB, 835 (2022) 137557

Malone, PRC, 101 (2020) 034002



Angular Differential Cross Section Measurements:

- Provides data for benchmarking Chiral Effective Field Theory (χ EFT) Calculations;
- Compton scattering is connected to QCD via χ EFT and Lattice QCD (LQCD):
[measured $d\sigma(\theta)/d\Omega$] $\rightarrow$ [analyze with χ EFT] $\rightarrow$ [α_n, β_n] $\leftarrow$ [LQCD]
- An objective of the TUNL program is to reduce uncertainty in α_n and β_n with the intent of putting the precision of neutron measurements on par with those for the proton.

$$\left. \begin{array}{ll} \alpha_{E1}^{(p)} = 11.5 \pm 0.4 \text{ (3.5\%)} & \beta_{M1}^{(p)} = 2.31 \pm 0.29 \text{ (13\%)} \\ \alpha_{E1}^{(n)} = 11.8 \pm 1.1 \text{ (9.3\%)} & \beta_{M1}^{(n)} = 3.7 \pm 1.1 \text{ (32\%)} \end{array} \right\} \begin{array}{l} \text{PDG(2024)} \\ \text{in units of} \\ 10^{-4} \text{ fm}^3 \end{array}$$

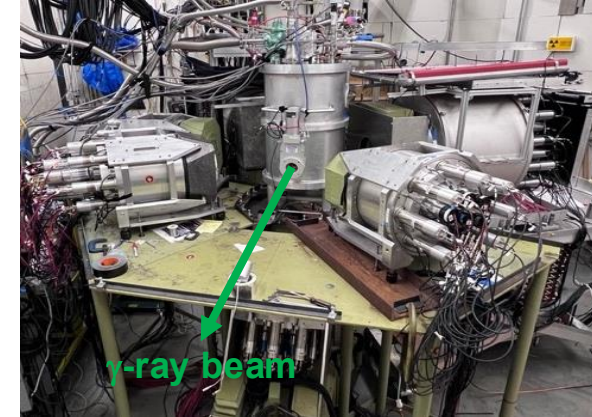
What enables this research:

- High intensity mono-energetic γ -ray beam at HIGS, $E_{\gamma} = 60 - 100$ MeV;
- Cryogenic liquid targets;
- Gamma-ray detection with high efficiency and adequate energy resolution
- Strong synergy of experiment and theory in experiment design and data analysis

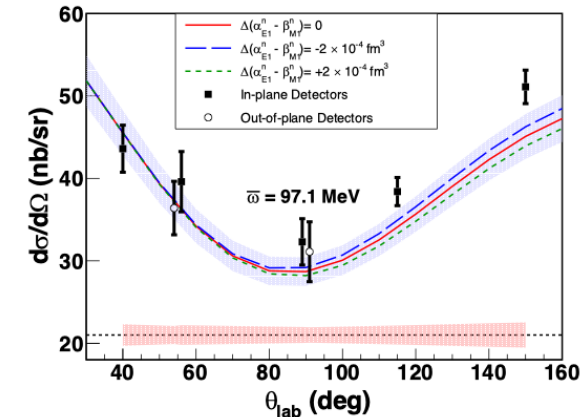
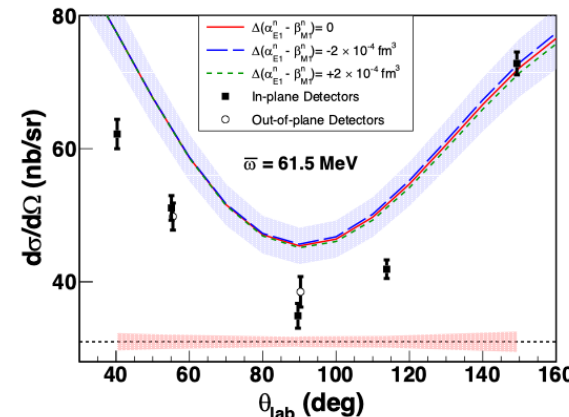
Recent Accomplishment:

- **Performed the first cross-section measurement of Compton scattering measurements on ^3He ;**
- Reported in J. Zhou, E. Mancil *et al.*, Phys. Rev. Lett. (2026), accepted;
- Measurements at $E_{\gamma} = 61.5$ and 97.1 MeV

Experiment setup for Compton scattering from ^3He : Cryogenic liquid target surrounded by heavily shielded large NaI detectors



Plots of angular differential cross sections for Compton scattering from ^3He at $E_{\gamma} = 61.5$ and 97.1 MeV. The points are the TUNL data and the bands are χ EFT calculations. Figure adapted from J. Zhou, E. Mancil *et al.*, PRL (2026)





R. Longland
J. Kelley
A.E. Champagne
A. Psaltis

A. Laird (York)
C. Barton (York)
A. Chen (McMaster)

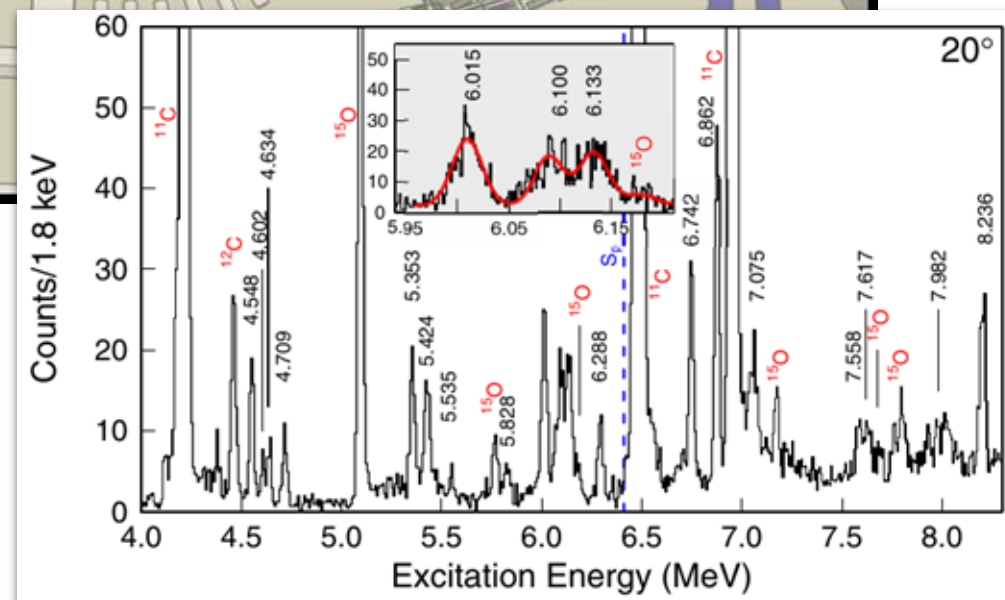
- Nuclear astrophysics program
- High-resolution charged-particle spectroscopy

Portillo, PRC, 107 (2023) 035809

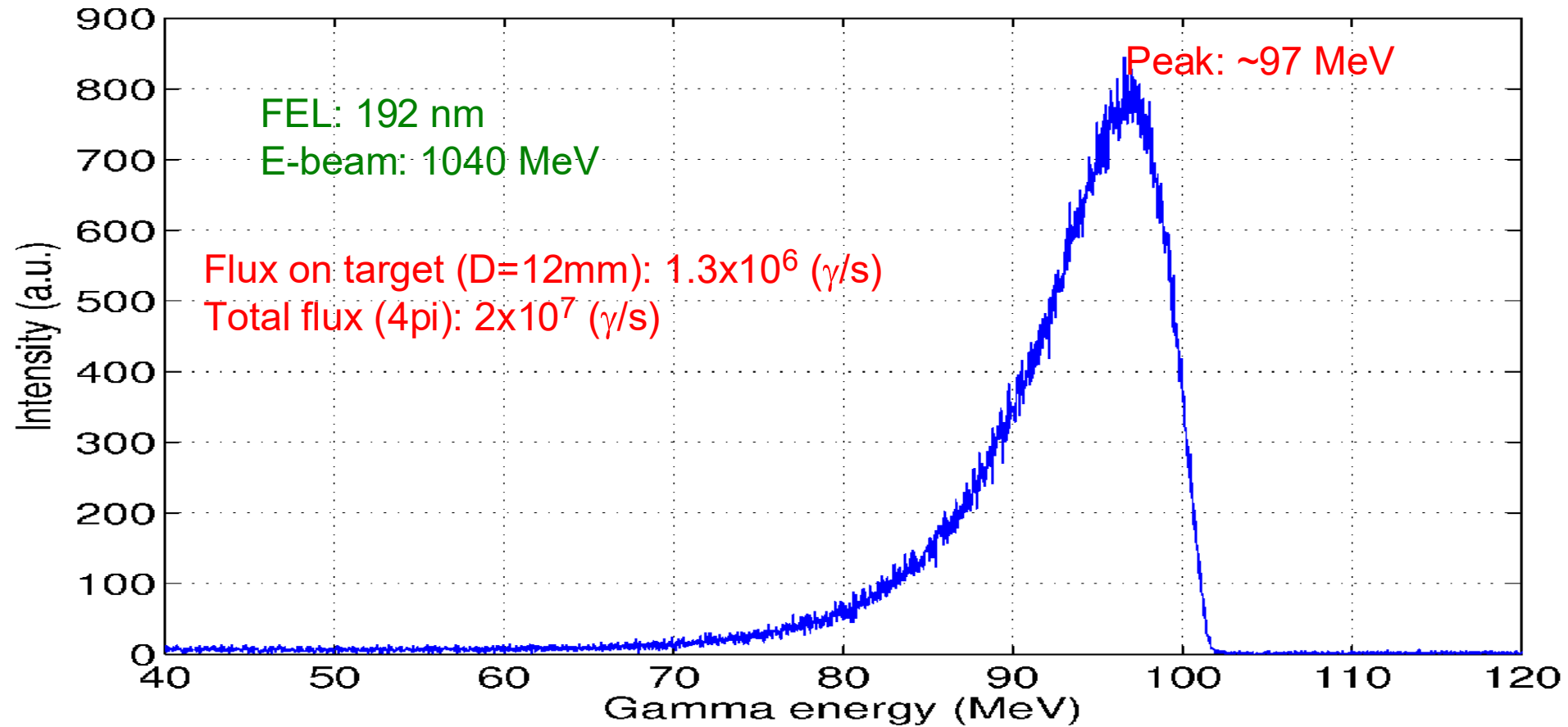
Marshall, PRC, 107 (2023) 035806

Frost-Schenk, MNRAS, 514 (2022) 2650

Marshall, PRC, 104 (2021) L032801



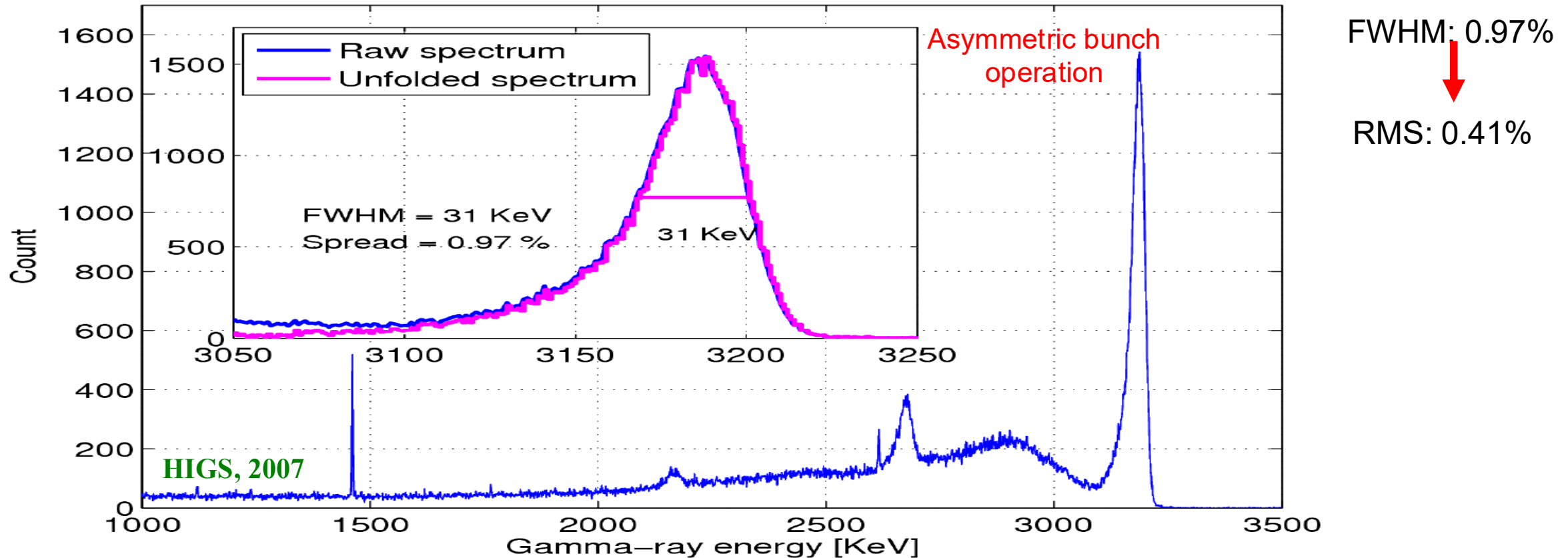
HIGS Circularly Polarized Gamma-ray Beam on 2010-09-29
 λ (OK-5 FEL) = 192 nm; SR Energy = 1040 MeV; Collimation D = 12 mm



Research area: nucleons structure

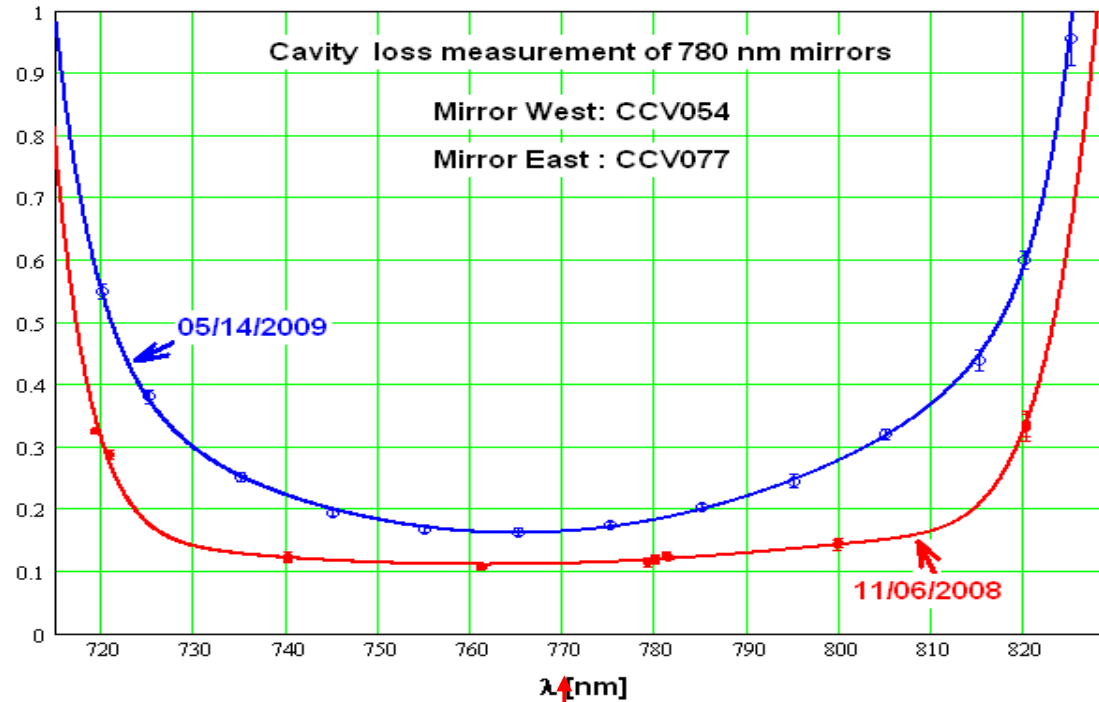
- Electric and magnetic polarizabilities
- Spin polarizabilities

356 MeV e-beam, Asymmetric bunch pattern #0 = 5 mA and #32 = 57 mA
738 nm OK4 lasing, 0.5" collimator, Run #55, 11-01-2007



- Gamma beam energy resolution in high-flux operation:
- Typically 3 – 5% (FWHM), or larger, selected by collimation

Cavity loss [%]



761 nm, Loss ~ 0.00107

Average FEL intracavity power:

1 to 2 kW in visible wavelengths

780 nm Mirrors

Minimal round-trip loss: $\sim 0.107\%$

Effective: $R \sim 99.95\%$

Kicker firing

