Overview of Photon-induced Nuclear Reaction Research at the HIGS Facility

Y. K. Wu

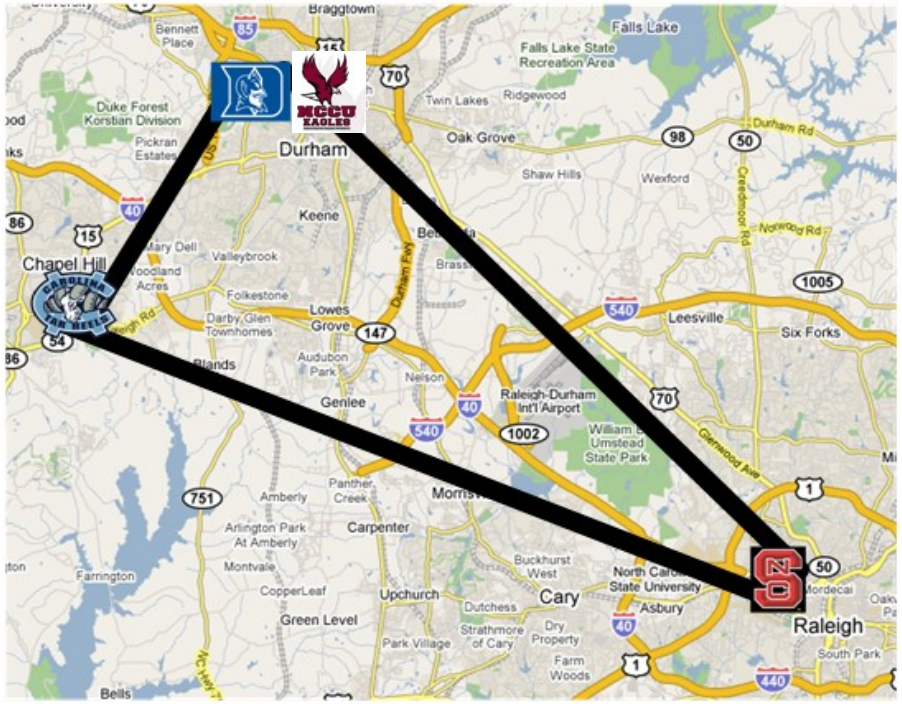
TUNL and Duke University

March 2, 2022

Work supported by U.S. DOE Grant: DE-FG02-97ER41033

Triangle Universities Nuclear Laboratory (TUNL)

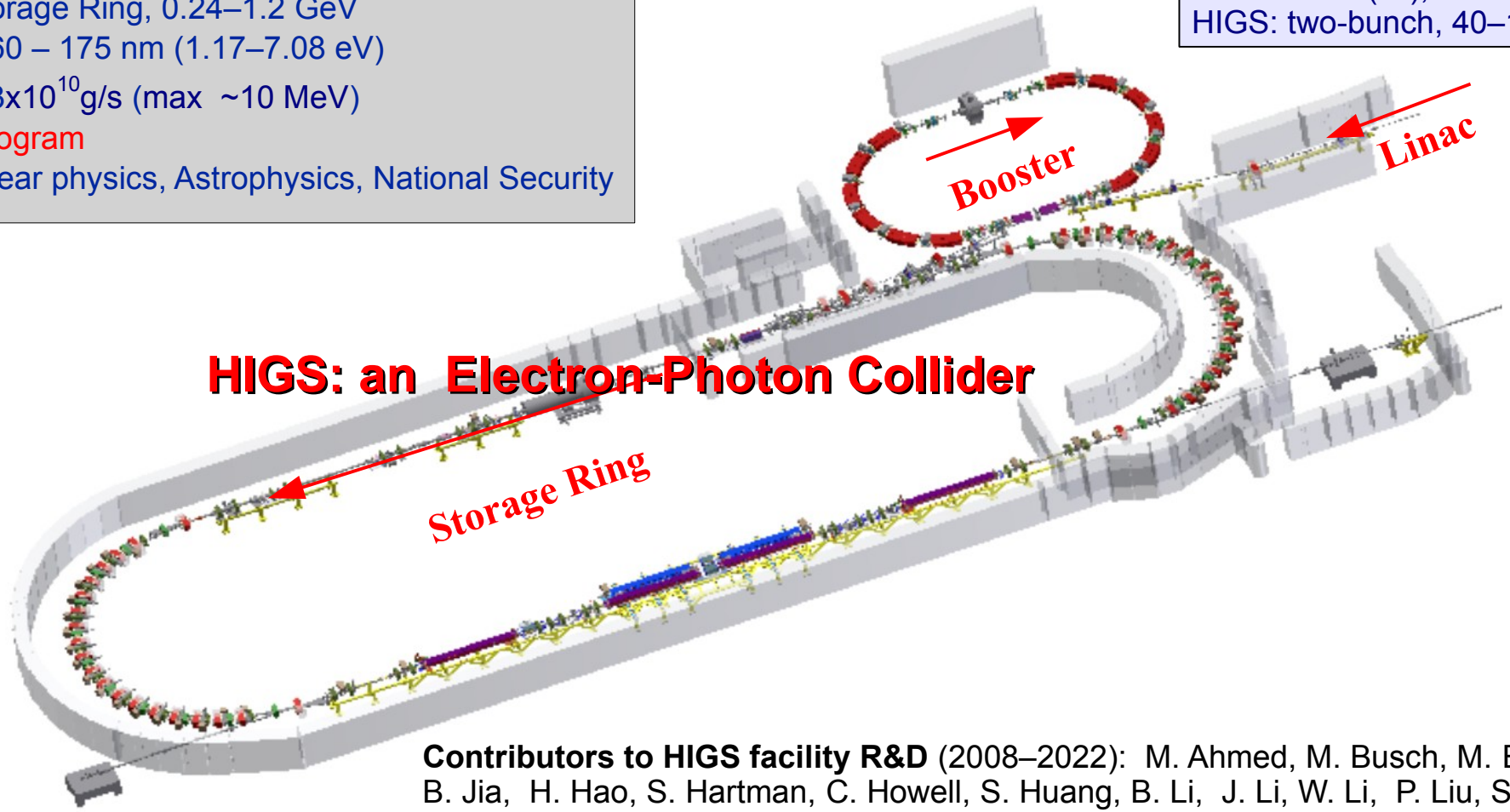
- High Intensity Gamma-ray Source (HIγS) is operated by the Triangle Universities Nuclear Laboratory (TUNL), one of four U.S. Department of Energy (DOE) Centers of Excellence in Nuclear Physics
- TUNL consists of 4 universities in the Research Triangle Area in North Carolina: Duke University and NC Central University in Durham, NC State University in Raleigh, and The University of NC in Chapel Hill
- HIγS is located on the campus of Duke University



HIGS/TUNL: Accelerator Facility

Facility/Project: High Intensity Gamma-ray Source (HIGS)
Institution: TUNL
Country: US
Energy (MeV): 1–120
Accelerator: Storage Ring, 0.24–1.2 GeV
Laser: FEL, 1060 – 175 nm (1.17–7.08 eV)
Total flux: 10^7–3×10^{10} g/s (max ~10 MeV)
Status: User Program
Research: Nuclear physics, Astrophysics, National Security

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)

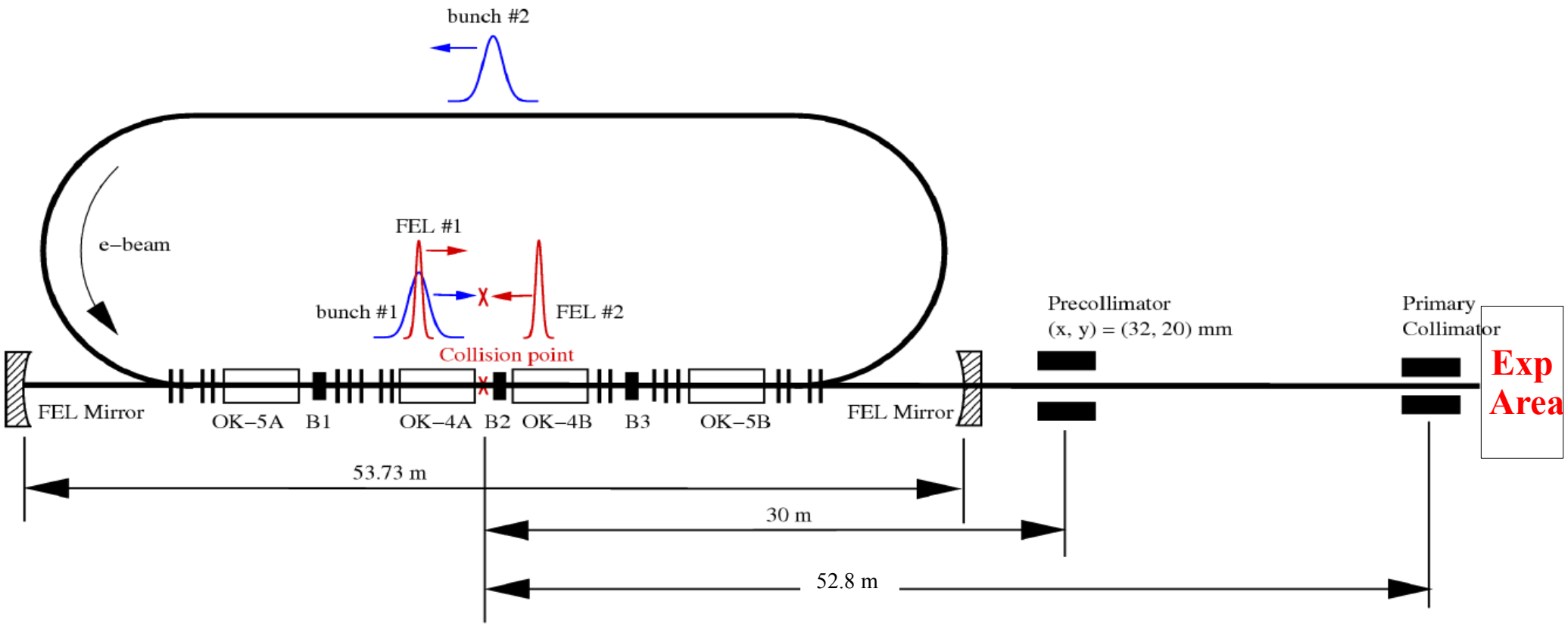


HIGS: an Electron-Photon Collider

Contributors to HIGS facility R&D (2008–2022): M. Ahmed, M. Busch, M. Emamian, J. Faircloth, B. Jia, H. Hao, S. Hartman, C. Howell, S. Huang, B. Li, J. Li, W. Li, P. Liu, S. Mikhailov, M. Pentico, V. Popov, W. Tornow, C. Sun, G. Swift, B. Thomas, P. Wang, P. Wallace, W. Wu, Y.K. Wu, W. Xu, J. Yan

Operation Principle of HIGS

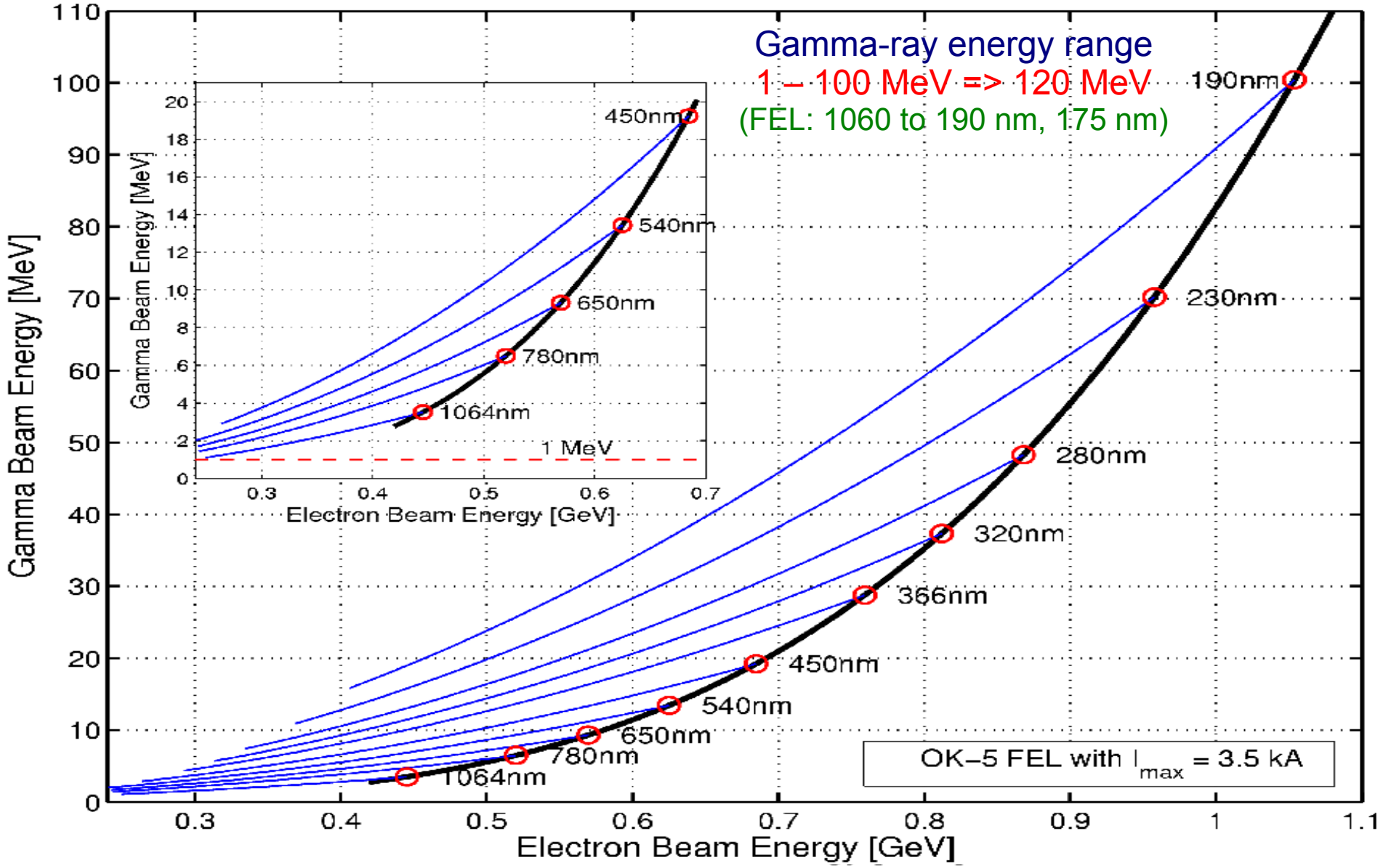
Two electron bunches + two FEL pulses



https://www.youtube.com/watch?v=JoIXGPNGEOc

V.N. Litvinenko *et al.* PRL v.78, n. 24, p. 4569 (1997)

Gamma Energy Tuning Range with OK-5 FEL (3.5 kA)



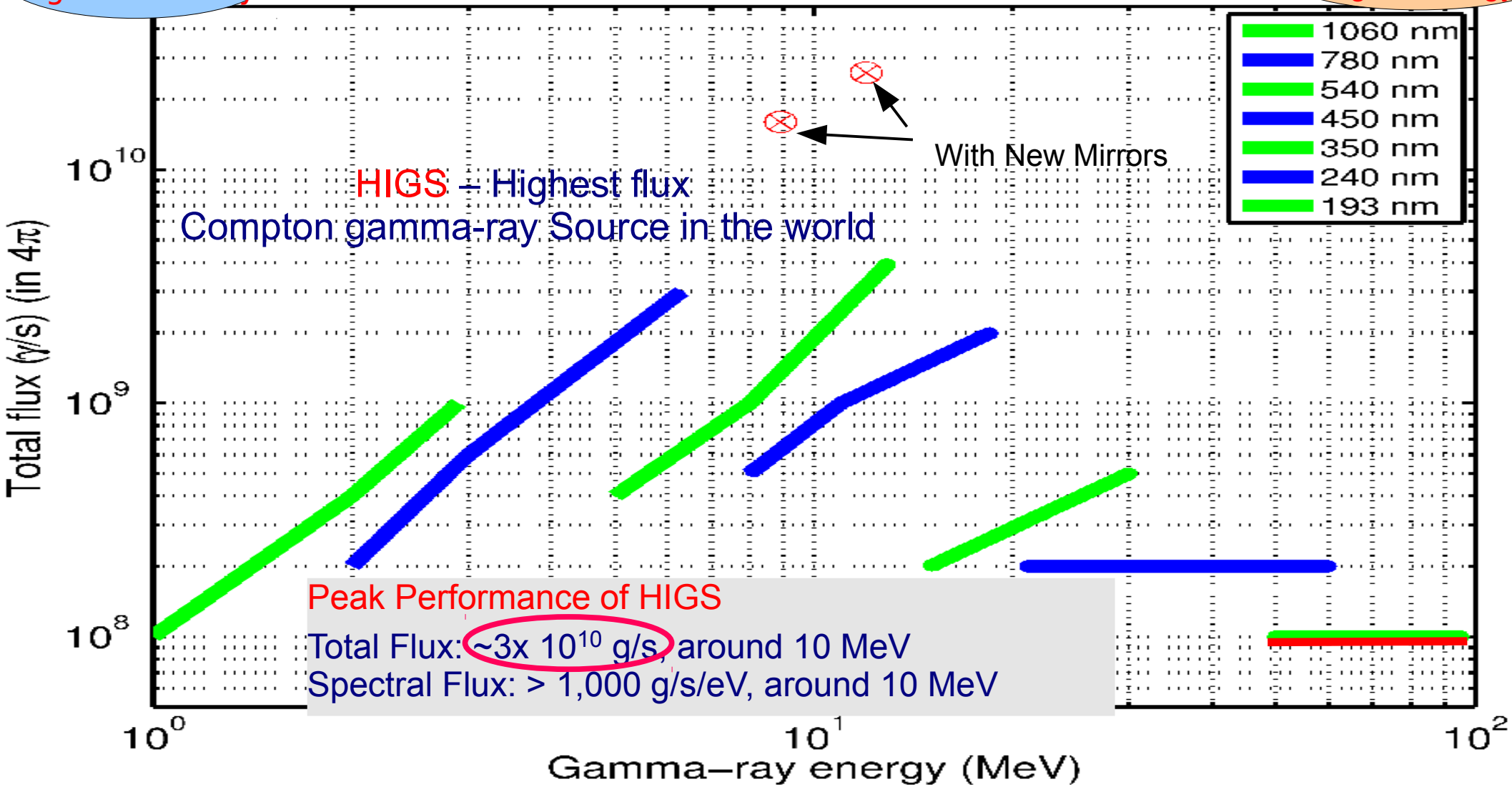
HIGS Flux Summary

TUNL

Development: Higher Intensity

HIGS User Flux Capabilities with OK-5 FEL

Development: Higher Energy

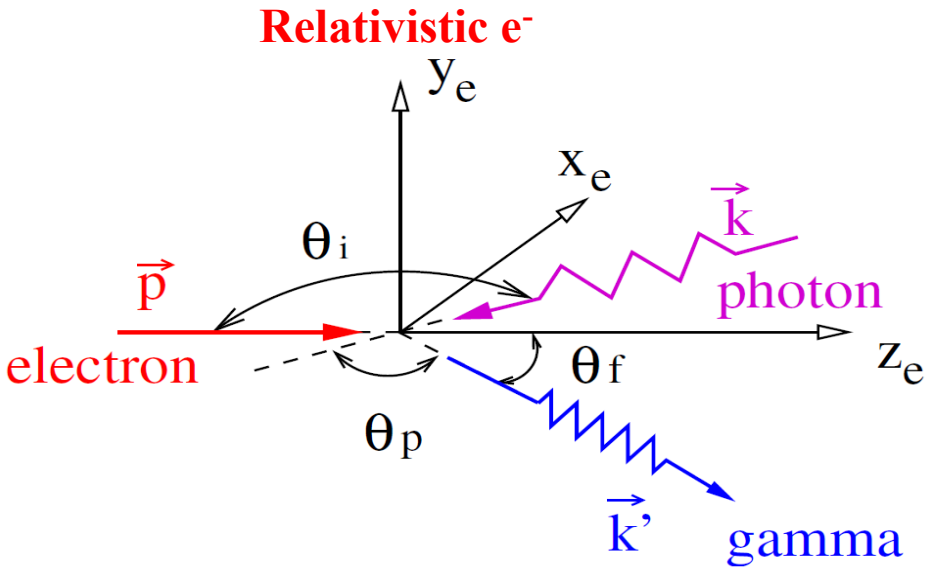


Peak Performance of HIGS

Total Flux: ~3x 10^{10} g/s, around 10 MeV

Spectral Flux: > 1,000 g/s/eV, around 10 MeV

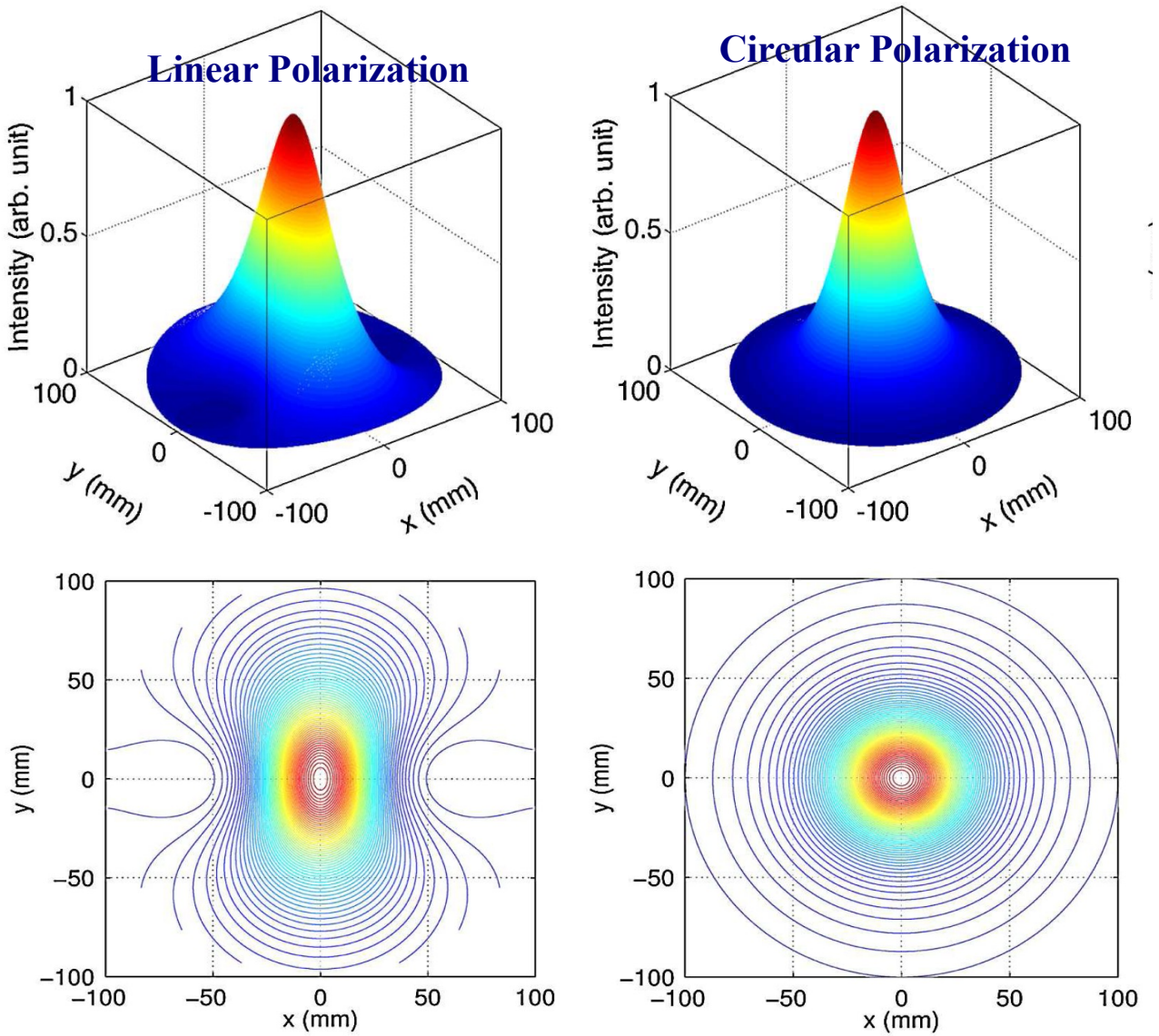
Photon Energy



$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$

Head-on Collision:

$$E_\gamma^{max} \approx (\gamma(1+\beta))^2 \hbar\omega \approx 4\gamma^2 \hbar\omega$$



C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)

Zoomed Out View of Research at HIγS

HIγS operates about 1600 hours/year for nuclear physics research

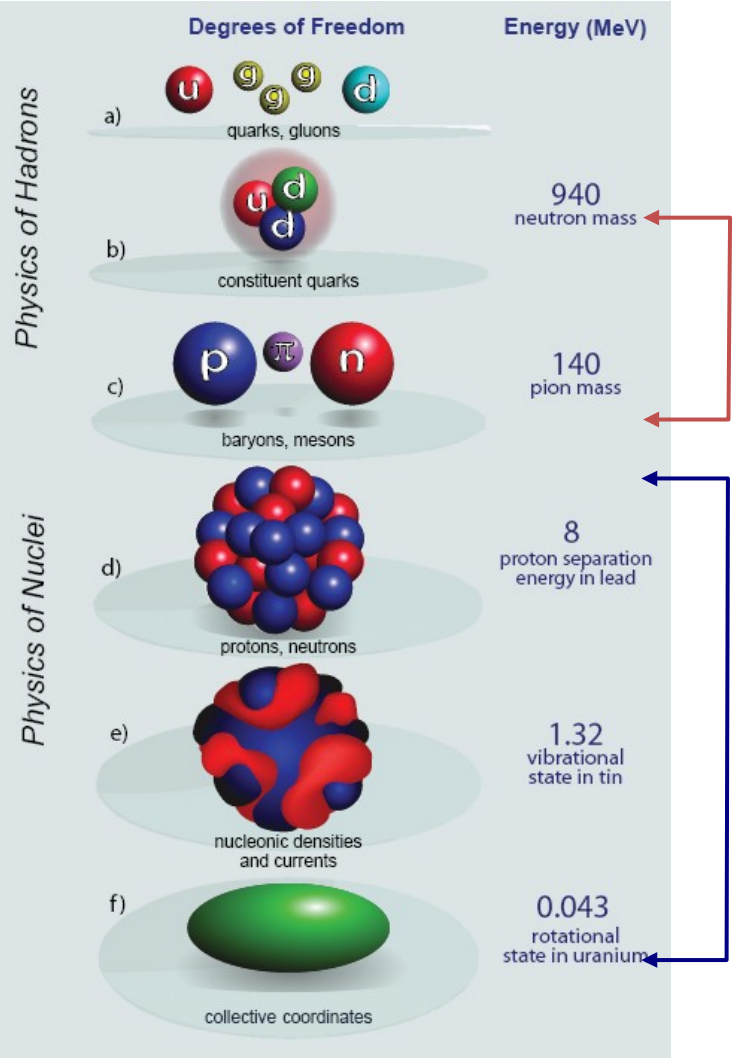


Figure from 2007 USA Nuclear Science LRP

Low-Energy QCD:

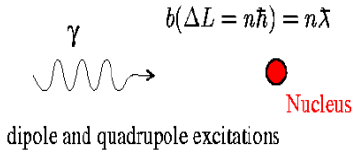
Nucleons

Compton Scattering: nucleon electric and magnetic polarizabilities
nucleon spin polarizabilities

Few-nucleon Systems

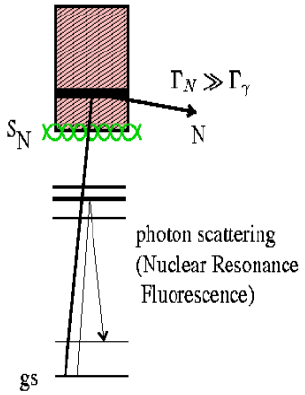
Photodisintegration of ^{2}H, ^{3}He and ^{3}H (cross sections, target-beam helicity dependent cross sections, polarization transfer)

Nuclear Structure and Nuclear Astrophysics



Many-body strongly interacting systems

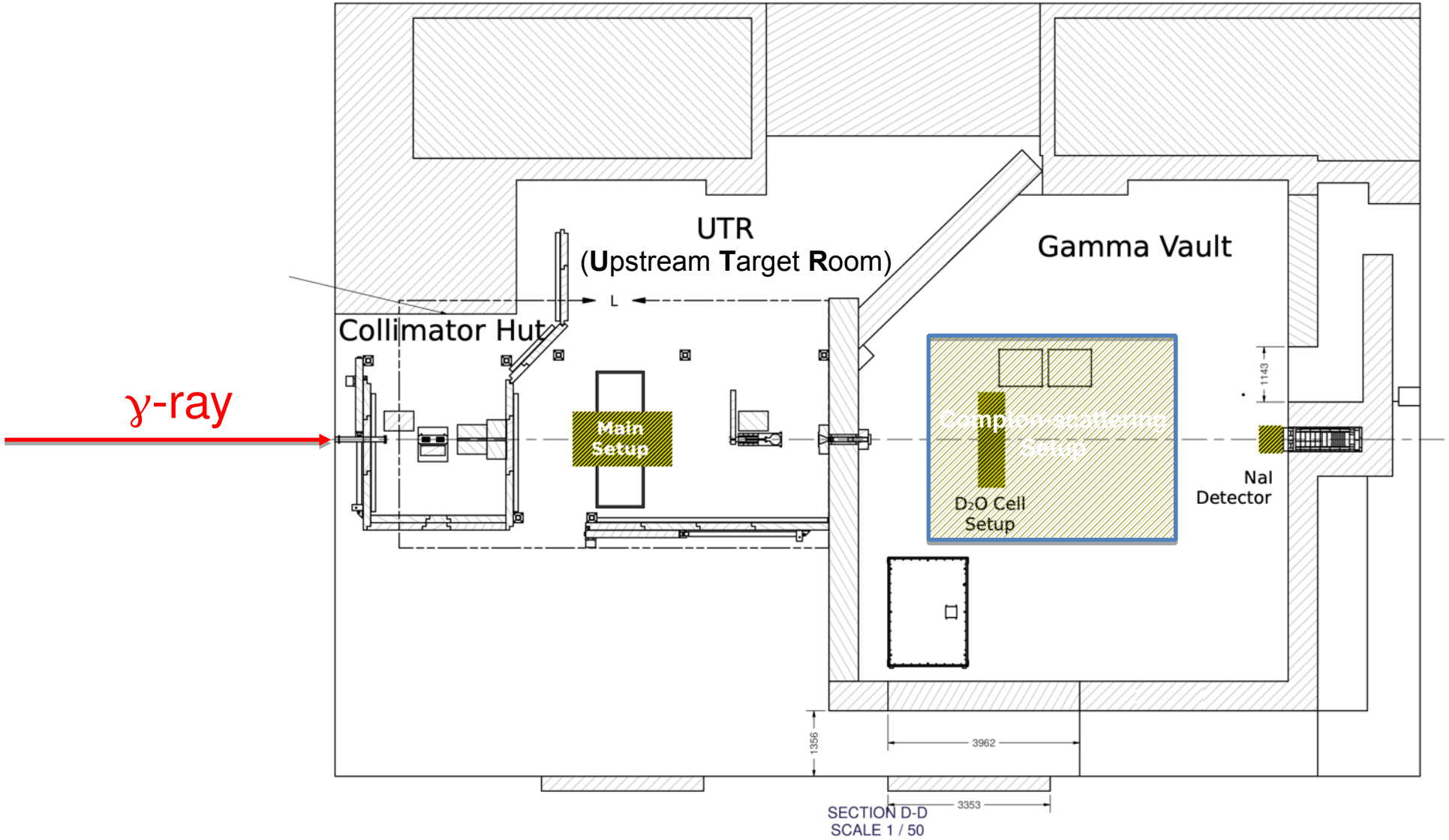
NRF, (γ,γ')
(γ,n), (γ,p), (γ,α) and (γ, fission) reactions



Applied Research:

- Nuclear Security
- Medical Isotope R&D
- Particle Detector R&D

Target Room Layout at HIγS



HIγS Users: Nuclear Structure and Nuclear Astrophysics

TUNL

TUNL groups:

(a) M. Ahmed, NCCU
(b) C. Howell, W. Tornow, Y. Wu, Duke Univ.
(c) A. Ayangeakaa, A. Champagne, C. Iliadis, R. Janssens, H. Karwowski, UNC

External Researchers from 32 institutions: 11 USA + 21 international

Clover-Share Collaboration:

17 institutions = 7 USA + 10 international

A. Clover-Share Collaboration

1) **ANL:** M.P. Carpenter, F.G. Kondev, S. Zhu
2) **Diakonie-Klinikum, Germany & Inst. Nucl. Res., Hungary:** P. Mohr
3) **Helmholtz-Zentrum Dresden-Rossendorf:** R. Schwengner
4) **GSI:** D. Savran, D. Löher
5) **James Madison Univ.:** A. Banu, J.A. Gallant, T.M.-R. Chu
6) **LLNL:** J. Silano, A.P. Tonchev
7) **Miss. State Univ.:** B.P. Crider
8) **NSCL/MSU:** A. Gade, D. Weisshaar, M. Spieker
9) **TU Darmstadt:** J. Isaak, T. Beck, J. Kleemann, N. Pietralla, O. Papst, V. Werner
10) **U.S. Naval Academy:** A.D. Ayangeaka, D.J. Hartley
11) **U. Kentucky:** E.E. Peters, S.A. Yates
12) **Univ. Köln:** J. Wilhelmy, A. Zilges, M. Müscher
13) **Univ. Libre de Bruxelles:** S. Goriely
14) **Univ. of Oslo:** A.C. Larsen
15) **Univ. West Scotland:** M. Scheck
16) **Univ. Witwatersrand:** L. Pellegri, H. Jivan, E. Sideras-Haddad, P. Adsley
17) **Univ. Zululand:** T. Khumalo

B. Other

1) **ANL:** T. Lauritsen
2) **C.S.N.S.M, Orsay:** A. Korichi
3) **ELI-NP and IFNN-HH, Romania:** C. Matei, D. Lattuada, D.L. Balabanski, G.L. Guardo, A. Oberstedt, N. Tsoneva, C.A. Ur
4) **INFN, Catania:** A. Di Pietro, P. Figuera, R.G. Pizzone, A. Tumino, M. La Cognata, L. Lamia, S. Romano
5) **Joint Res. Center, EC, Belgium:** A. Göök, S. Oberstedt, G. Sibbens
6) **LBNL:** A.O. Macchiavelli, I.Y. Lee
7) **MTA Atomki:** G.G. Kiss
8) **NSCL/MSU:** D. Weisshaar
9) **ORNL:** K.A. Chipps, S.D. Pain
10) **Ohio Univ.:** C.R. Brune, Z. Meisel, A. Voinov
11) **Sheffield Hallam Univ.:** R. Smith
12) **SKKU, S. Korea:** K.Y. Chae, M. Kim, K. Ku
13) **Texas A&M Univ.:** J. Bishop
14) **TU Darmstadt:** M. Peck, J. Enders, A-L. Katzenmieier, T. Aumann, N. Pietralla, V. Werner
15) **Univ. Birmingham:** M. Freer, C. Wheldon, Tz. Kokalova
16) **Univ. Conn.:** M. Gai
17) **Univ. Kentucky:** S. Yates
18) **Univ. Mainz:** K. Eberhardt,
19) **Univ. Warsaw:** C. Mazzocchi, W. Dominik
20) **Univ. York:** C.Aa. Diget, B. Fulton, A.M. Laird, M. Williams

HIγS Research: Nuclear Structure, Fission and Astrophysics

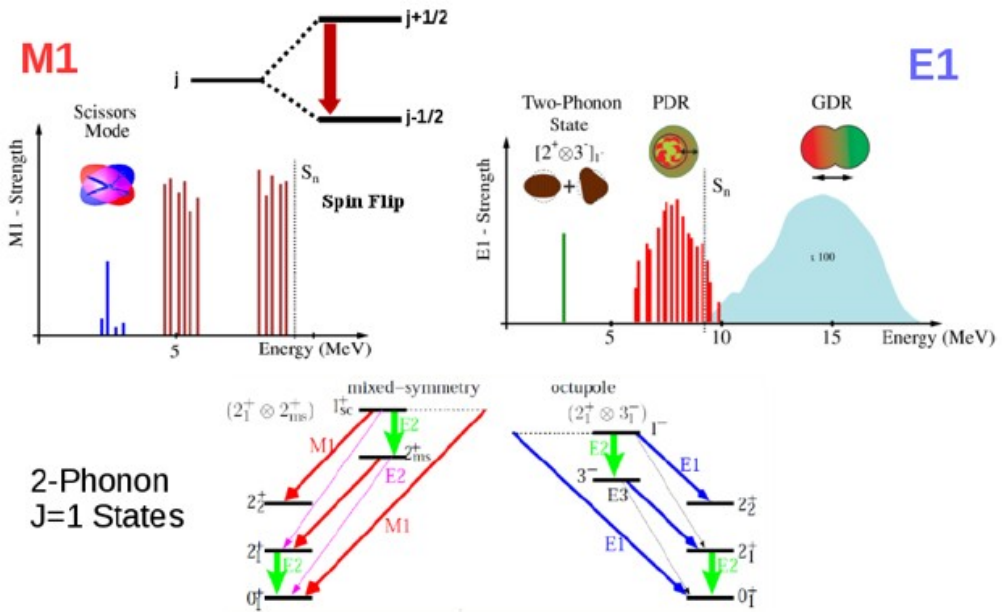
TUNL

A. Nuclear Structure and Many-Body Reactions

A.1. NRF (γ,γ'), (γ,n), (γ,α)
- Collective excitations, e.g., PDR, multiple phonon exchange
- Dipole strength (M1 and E1)
- Structure near the ground state (shapes, coexistence, effective int.)

A.2. Compton Scattering (linearly polarized beam) from Nuclei
- IVGQR -> Asymmetry term in the nuclear EOS

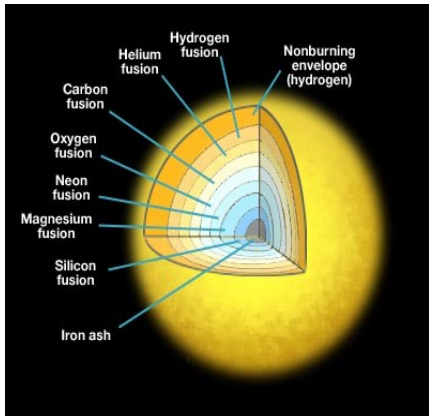
A.3. Photon-Induced Fission
- Fission Product Yields **(activation)**
- Cross sections **(fission chamber and prompt neutron detection)**



B. Nuclear Astrophysics

B.1. NRF (γ,γ')
- Dipole strength function (M1 and E1)
- Identification & properties of states near/at particle threshold

B.2. (γ,n), (γ,p) and (γ,α) reaction measurements
- Cross sections near reaction threshold
- Resonance studies



The mass and size of the final iron core is critically dependent on the $^{12}C(\alpha,g)^{16}O$ reaction rate

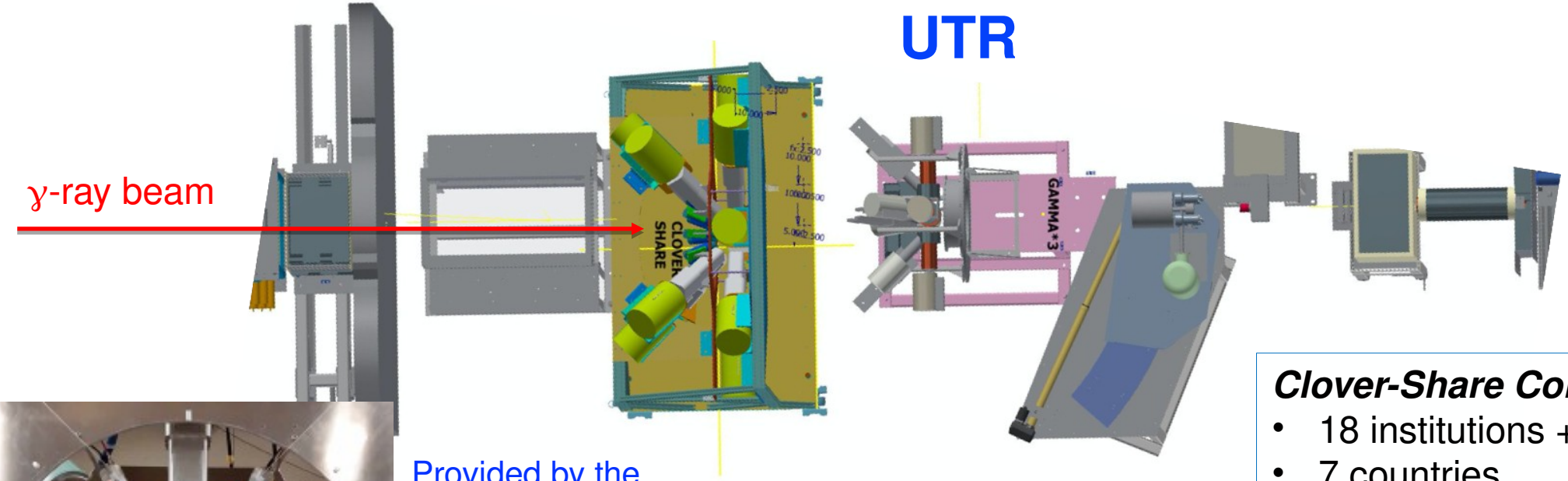
$\alpha + \alpha + \alpha \rightarrow {}^{12}C + \gamma$

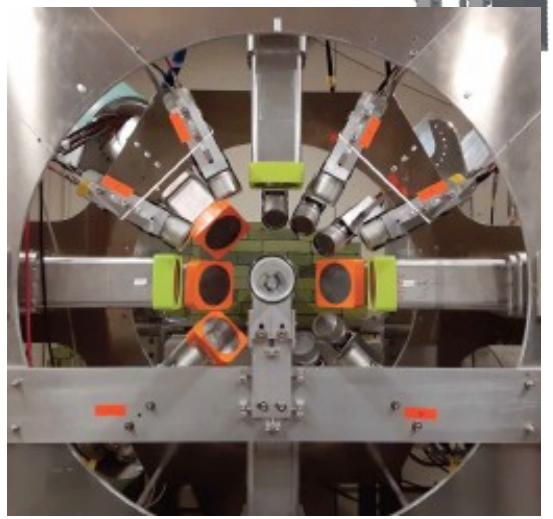
^{12}C production during helium burning

$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

converts ^{12}C to ^{16}O => determines $^{12}C/^{16}O$

Nuclear Structure and Astrophysics: Clover-share Array





Provided by the Clover Share Consortium, the US Naval Academy, the US Army Research Lab, and TUNL

- 8 HPGe clover detectors
- Up to 12 CeBr scintillation detectors

Clover-Share Collaboration

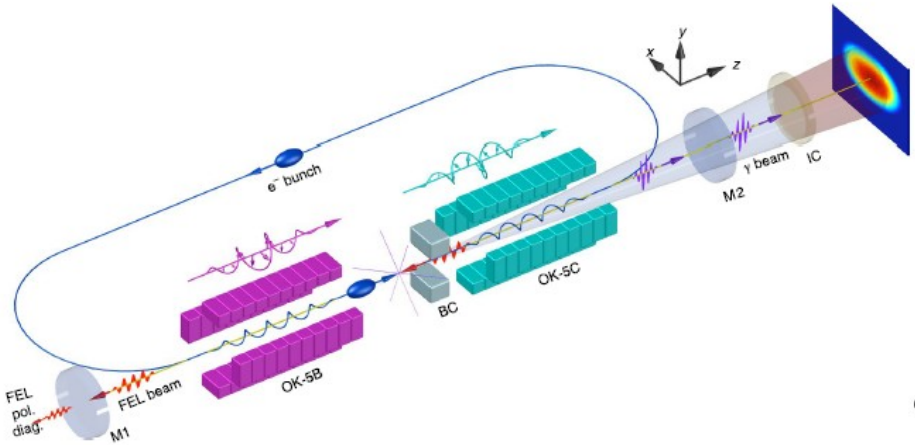
- 18 institutions + TUNL
- 7 countries

Argonne National Lab (USA)	Technische Universität Darmstadt (Germany)
Diakonie-Klinikum Schw¨abisch Hall (Germany)	U.S. Naval Academy (USA)
GSI Helmholtz Centre (Germany)	Univ. of Kentucky (USA)
Helmholtz-Zentrum Dresden-Rossendorf (Germany)	Univ. of Köln (Germany)
Inst. for Nuclear Research (Hungary)	Univ. Libre de Bruxelles (Belgium)
James Madison Univ. (USA)	Univ. of Oslo (Norway)
Lawrence Livermore National Lab (USA)	Univ. of the West Scotland (Scotland)
Mississippi State Univ. (USA)	Univ. of Witwatersrand (South Africa)
NSCL/Michigan State Univ. (USA)	Univ. of Zululand (South Africa)

Nuclear Resonance Florescence (NRF) with linearly polarized photon beam

TUNL

HIγS @ TUNL

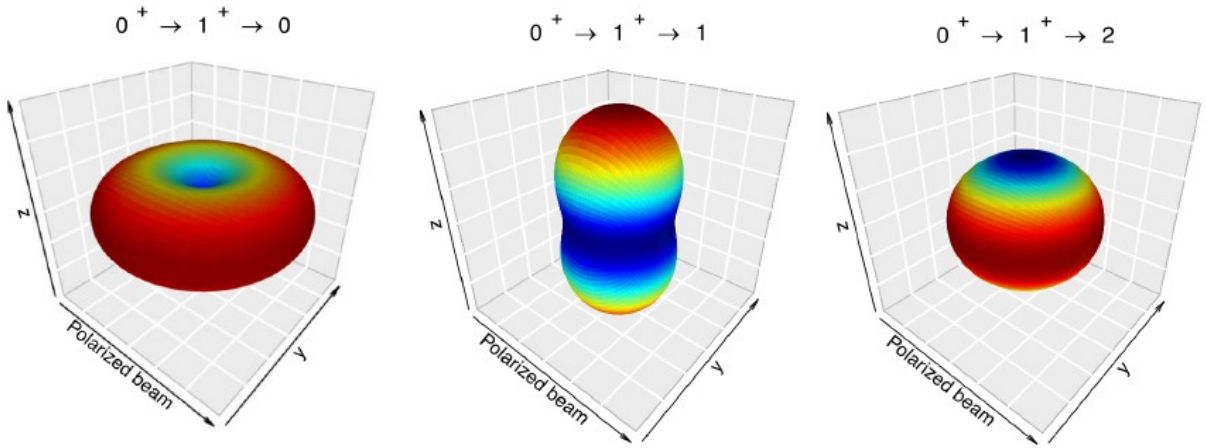


- Highly intense ($\approx 10^8 \gamma s^{-1}$)
- Quasi-monochromatic (FWHM $\approx 100 - 300\,\mathrm{keV}$)
- Polarized ($> 99\%$)
- Bunched ($5.58\,\mathrm{MHz}$)

H. R. Weller *et al.*, *Research opportunities at the upgraded HIγS facility*, Prog. Part. Nucl. Phys. **62**, 257 (2009)

NRF with linearly polarized γ-rays:
spins, parities, branching ratios, and γ-ray multipolarity

- EM excitation from ground state like Coulomb Excitation plus polarization information.
- Decay of high-lying states like neutron capture, but variable energy.



A. Zilges, D.L. Balabanski, J. Isaak, N. Pietralla, *Photonuclear reactions—From basic research to* applications, Prog. Part. Nucl. Phys. 122, 103903 (2022).

C. Iliadis and U. Friman-Gayer, Linear polarization-direction correlations in g-ray scattering experiments, Eur. Phys. J. A 57, 190 (2021).

Nuclear Astrophysics: $^{16}O + \gamma => \alpha + {}^{12}C$

TUNL

nature COMMUNICATIONS

NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-021-26179-x

ARTICLE

https://doi.org/10.1038/s41467-021-26179-x OPEN

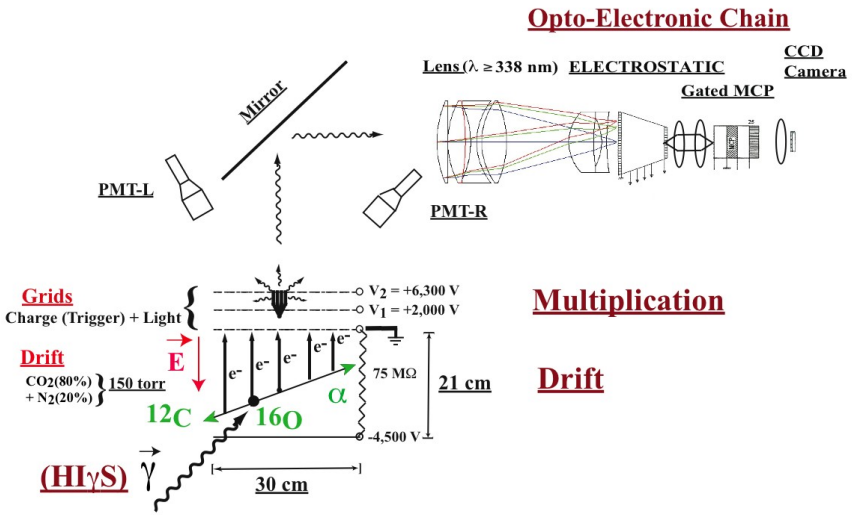
Check for up

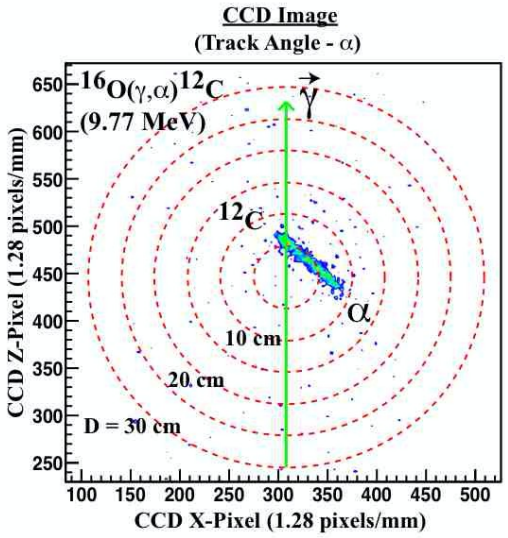
Precision measurements on oxygen formation in stellar helium burning with gamma-ray beams and a Time Projection Chamber

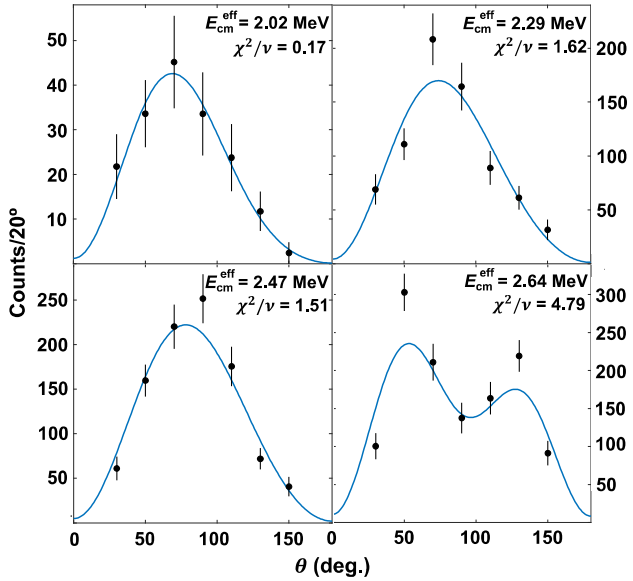
R. Smith[1,2✉], M. Gai[2], S. R. Stern[2], D. K. Schweitzer[2] & M. W. Ahmed[3,4]

The carbon/oxygen (C/O) ratio at the end of stellar helium burning is the single most important nuclear input to stellar evolution theory. However, it is not known with sufficient accuracy, due to large uncertainties in the cross-section for the fusion of helium with ^{12}C to form ^{16}O, denoted as $^{12}C(\alpha,\gamma)^{16}O$. Here we present results based on a method that is significantly different from the experimental efforts of the past four decades. With data measured inside one detector and with vanishingly small background, angular distributions of the $^{12}C(\alpha,\gamma)^{16}O$ reaction were obtained by measuring the inverse $^{16}O(\gamma,\alpha)^{12}C$ reaction with gamma-beams and a Time Projection Chamber (TPC) detector. We agree with current world data for the total reaction cross-section and further evidence the strength of our method with accurate angular distributions measured over the 1^- resonance at $E_{cm} \sim 2.4$ MeV. Our technique promises to yield results that will surpass the quality of the currently available data.

2. The O-TPC Detector System
2.1 The TPC

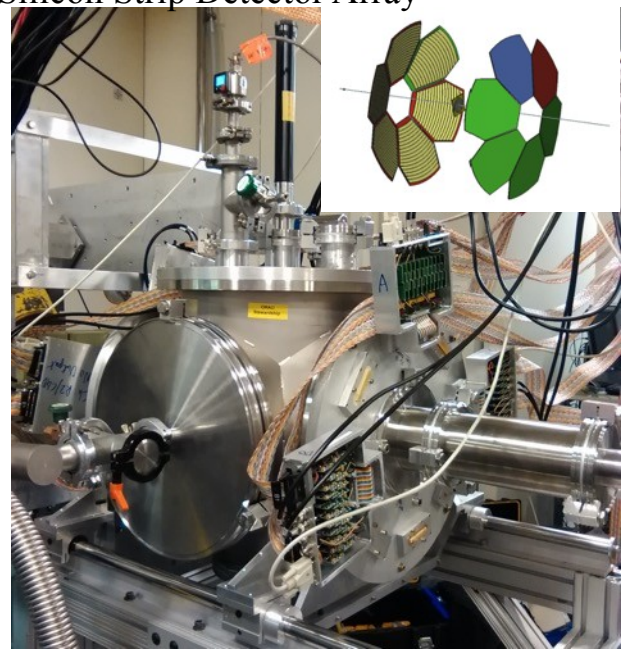




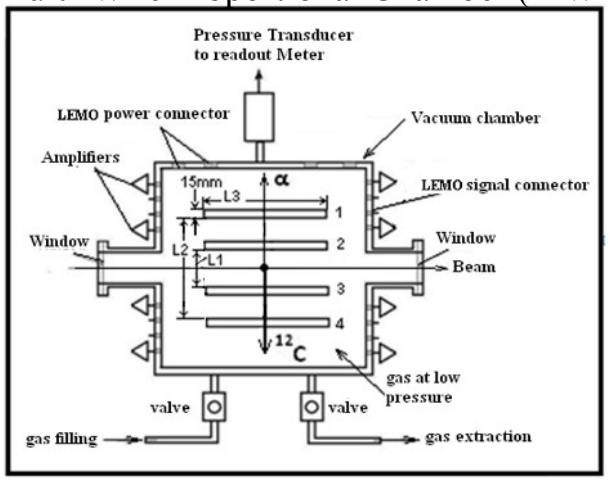


Nuclear Structure and Astrophysics: Other Technologies

Silicon Strip Detector Array



Multi-Wire Proportional Chamber (MWPC)

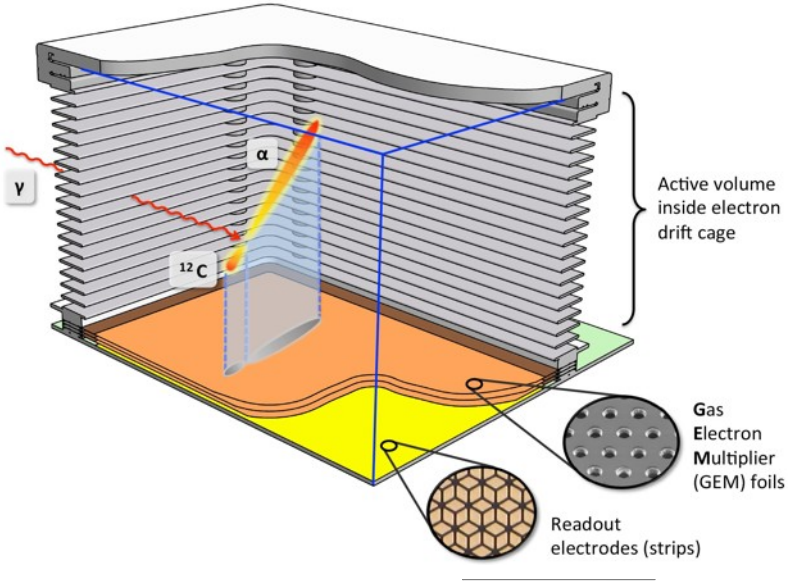


Photon-induced Nuclear Reactions with Emission of Charged Particles

Examples:

- $^{16}O(\gamma, \alpha)$, $^{12}C(\gamma, 3\alpha)$
- $^{9}Be(\gamma, \alpha\alpha)n$
- $^{2}H(\gamma, p)$
- $^{7}Li(\gamma, t)$

Time Projection Chamber (TPC)



Users

- 20 institutions + TUNL
- 10 countries

ANL (USA)	Sheffield Hallam Univ. (UK)
C.S.N.S.M, Orsay (France)	Sungkyunkwan (S. Korea)
ELI-NP and IFNN-HH (Romania)	Texas A&M Univ. (USA)
INFN, Catania (Italy)	TU Darmstadt (Germany)
Joint Res. Center, EC (Belgium)	Univ. Birmingham (UK)
LBNL (USA)	Univ. Connecticut (USA)
MTA Atomki (Hungary)	Univ. of Kentucky (USA)
NSCL/Michigan State Univ. (USA)	Univ. of Mainz (Germany)
ORNL (USA)	Univ. of Warsaw (Poland)
Ohio Univ. (USA)	Univ. of York (UK)

HIγS Users: Low Energy QCD

TUNL groups:

(a) M. Ahmed, B. Crowe, D. Markoff, NCCU
(b) H. Gao, C. Howell, W. Tornow, Y. Wu, Duke Univ.
(c) H. Karwowski, UNC
(d) A. Young, NC State Univ.

External Researchers from 14 institutions: 9 USA + 5 international

A. Compton Scattering Collaboration

1) **GWU:** E. Downie, J. Feldman, H. Griesshammer
2) **James Madison Univ.:** A. Banu and S. Whisant
3) **North Georgia State Univ.:** M. Spraker
4) **Ohio Univ.:** D. Phillips
5) **Univ. Kentucky:** M. Kovash,
6) **Univ. Manchester:** J.A. McGovern
7) **Univ. New Hampshire:** R. Miskimen
8) **Univ. Saskatchewan:** R. Pywell

B. Few-Nucleon Systems

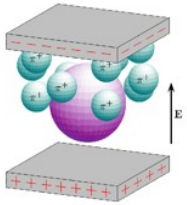
1) **Budker Inst. Nucl. Phys., Russia:** R.N. Lee, A.I. Milstein, V.M. Strakhovenko
2) **Jagiellonian Univ.:** H. Witała
3) **JLab:** D.W. Higinbotham, B. Sawatzky
4) **Univ. Rochester:** C.J. Forrest, W. Shmayda
5) **Univ. Saskatchewan:** R. Pywell,
6) **UVA:** B. Norum and D. Crabb
7) **Vilnius Univ., Lithuania:** A. Deltuva,

TUNL

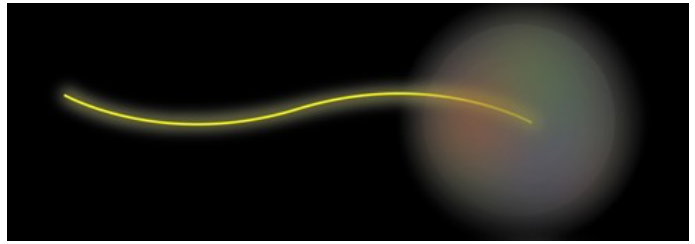
C. Low-Energy QCD

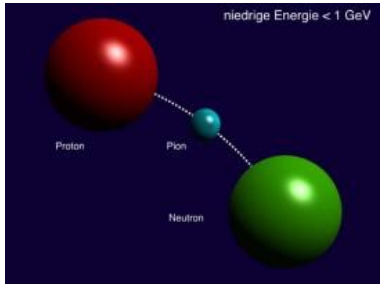
C.1. Compton Scattering from Unpolarized Nuclei:
Proton and Light Nuclei (A < 5)
$d\sigma(\theta)/d\Omega$, Σ_{beam}, Σ_3=>[EFT analysis]=>α^p, β^p, γ^p, α^N, β^N α^n, β^n

α

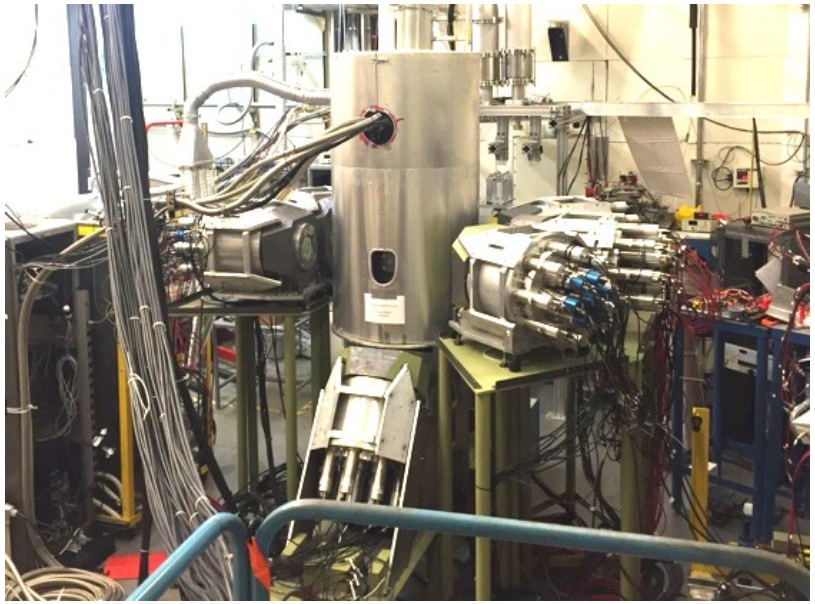


C.2. Polarization transfer in photodisintegration of ^{2}H





C.3. Photodisintegration of Few-Nucleon Systems, e.g., ^{3}He, ^{3}H



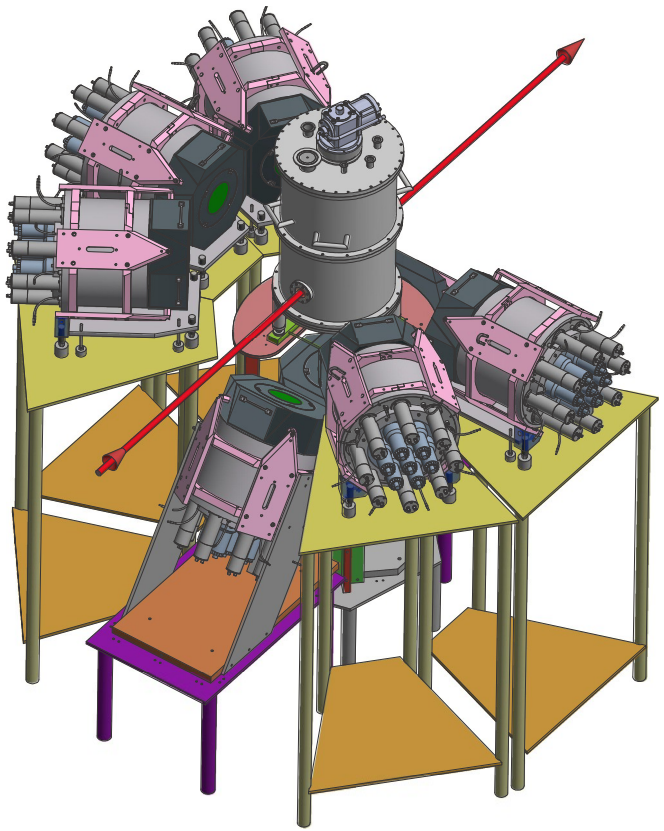
* Picture from: J. Arrington, arXiv:1208.4047v1[nucle-ex]

Recent Compton-scattering results from HIγS

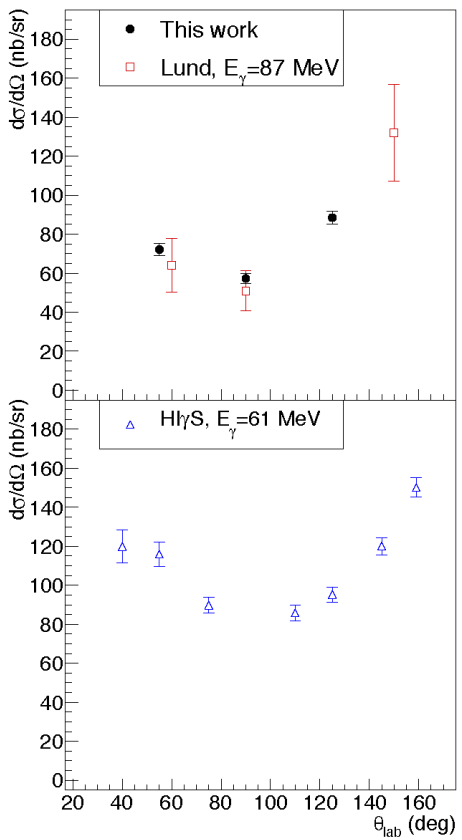
PHYSICAL REVIEW C 101, 034618 (2020)

Compton scattering from ^{4}He at the TUNL HIγS facility

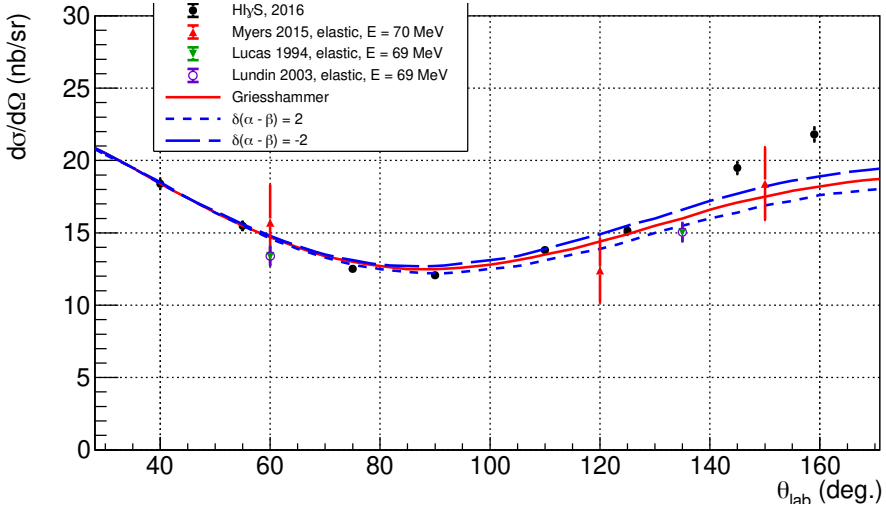
X. Li, M.W. Ahmed, A. Banu, C. Bartram, B. Crowe, E.J. Downie, M. Emamian, G. Feldman, H. Gao, D. Godagama, H.W. Grießhammer, C.R. Howell, H.J. Karwowski, D.P. Kendellen, M.A. Kovash, K.K.H. Leung, D. Markoff, S. Mikhailov, R.E. Pywell, M.H. Sikora, J.A. Silano, R.S. Sosa, M.C. Spraker, G. Swift, P. Wallace, H.R. Weller, C.S. Whisnant, Y.K. Wu, and Z.W. Zhao



^{4}He CS



deuteron CS at E_γ = 65 MeV



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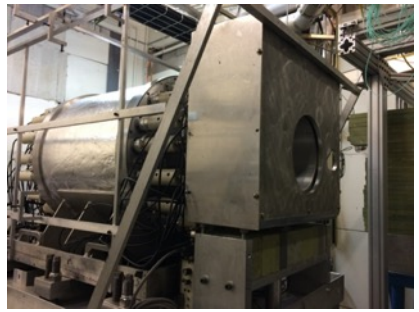


BUNI

HIγS Research Program: 10-year horizon

TUNL

A. Nuclear Structure (E_γ < 20 MeV)

A.1. NRF (γ,γ') - **(linear beam polarization)**; and photon-induced reactions: (γ,n), (γ,α) **(real-time particle detection and activation)**

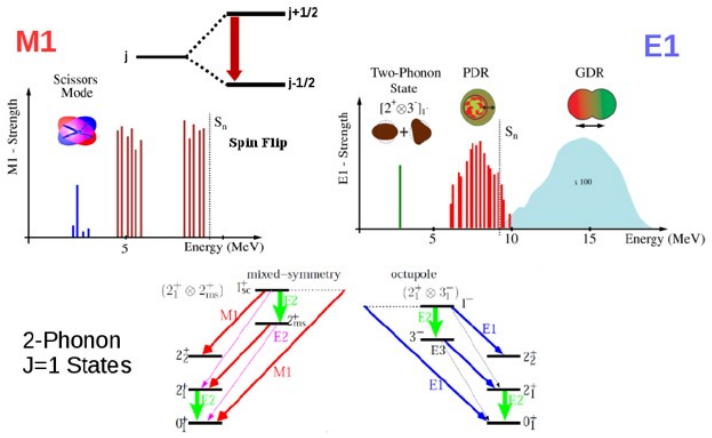
- Collective excitations, e.g., Pygmy Dipole Resonance, multiple phonon exchange
- Dipole strength (M1 and E1)
- Structure near the ground state (shapes, coexistence, effective interactions)

A.2. Compton Scattering **(linearly polarized beam)** from Nuclei (E_γ < 20 MeV)

- Isovector Giant Quadrupole Resonance => Asymmetry term in nuclear Equation of State

A.3. Photon-Induced Fission

- Cumulative Fission Product Yields **(activation)**
- Independent FPYs: kinetic energy distribution, isotope ID, angular distribution **(particle tracking ionization chamber)**
- Prompt and delayed neutron distributions **(fission chamber and fast neutron detection)**



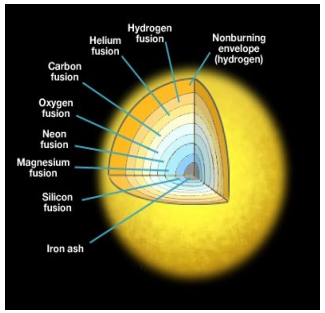
B. Nuclear Astrophysics (E_γ < 20 MeV)

B.1. NRF (γ,γ') - **(linear beam polarization)**;

- Dipole strength function (M1 and E1)
- Identification & properties of states near/at the particle threshold

B.2. (γ,n), (γ,p) and (γ,α) reaction measurements – **(Time project chambers, silicon strip detectors, activation, real-time neutron detection)**

- Cross sections near reaction threshold
- Resonance studies



The mass and size of the final iron core is critically dependent on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

$\alpha + \alpha + \alpha \rightarrow {}^{12}C + \gamma$

^{12}C production during helium burning

$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

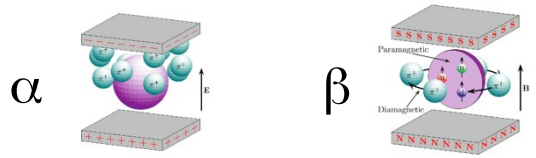
converts ^{12}C to ^{16}O => determines $^{12}C/^{16}O$

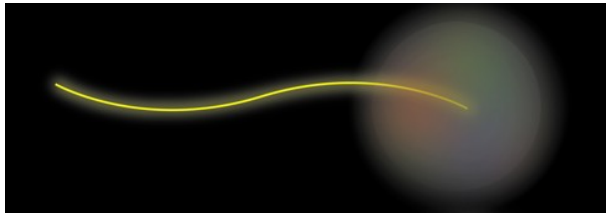
TUNL

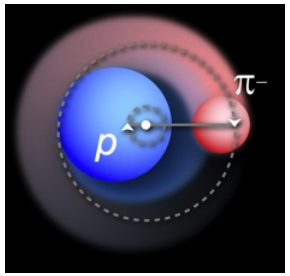
C. Low-Energy QCD (E_γ > 60 MeV) - (circular beam polarization);

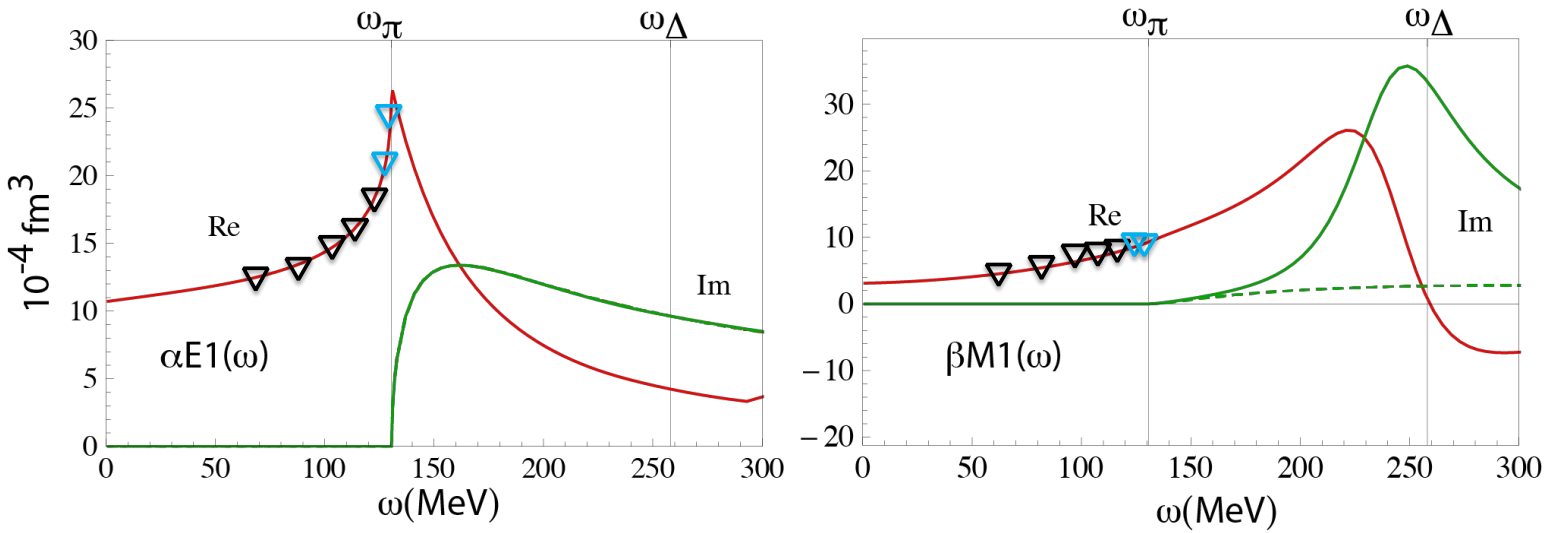
- **Determination of the neutron dipole electric and magnetic polarizabilities: Compton scattering from liquid H,D,^{3}He, and ^{4}He targets**
  - at E_γ = 65 - 120 MeV (**175-nm FEL mirrors**)
  - at E_γ = 130 - 150 MeV (**155-nm mirrors**, R&D planned by TUNL-LZH collaboration)
- **Measurement of proton spin polarizabilities**
  - Double polarization (beam and target) Compton scattering from proton
  - E_γ = 120 – 150 MeV
  - Requires development of scintillating polarized cryogenic target

Dipole EM dipole polarizabilities:









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