Источник жестких гамма-квантов HIγS университета Дюка (США)

О.А. Шевченко

ИЯФ им. Г.И.Будкера СО РАН

Содержание доклада

1. Общая схема установки
2. Основные параметры и режимы работы **HIγS**
3. Работа пользователей

Booster

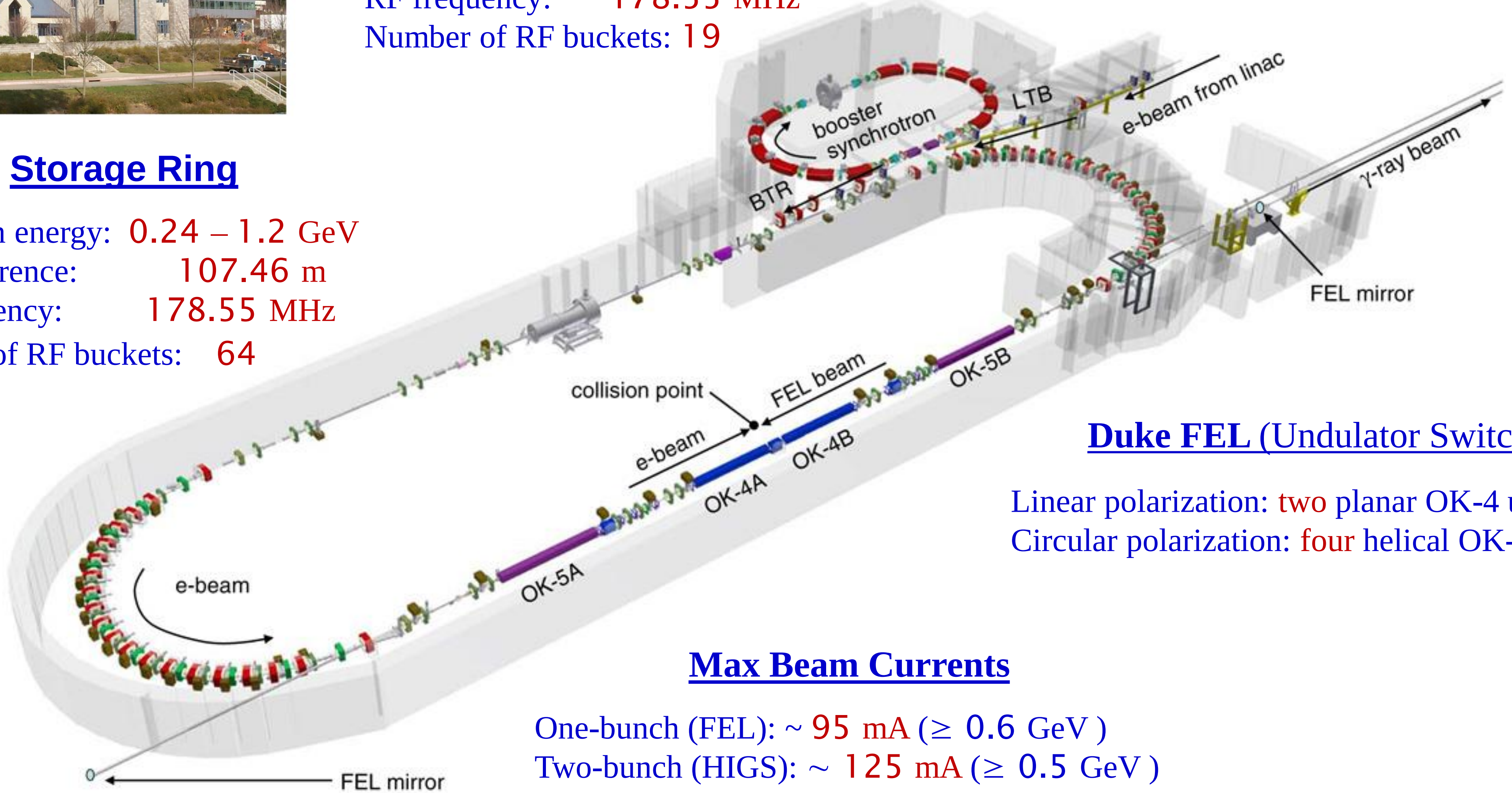
Extraction energy: 0.16–1.2 GeV
Circumference: 31.902 m
RF frequency: 178.55 MHz
Number of RF buckets: 19

Linac

Injection energy: 160 MeV

Storage Ring

Operation energy: 0.24 – 1.2 GeV
Circumference: 107.46 m
RF frequency: 178.55 MHz
Number of RF buckets: 64



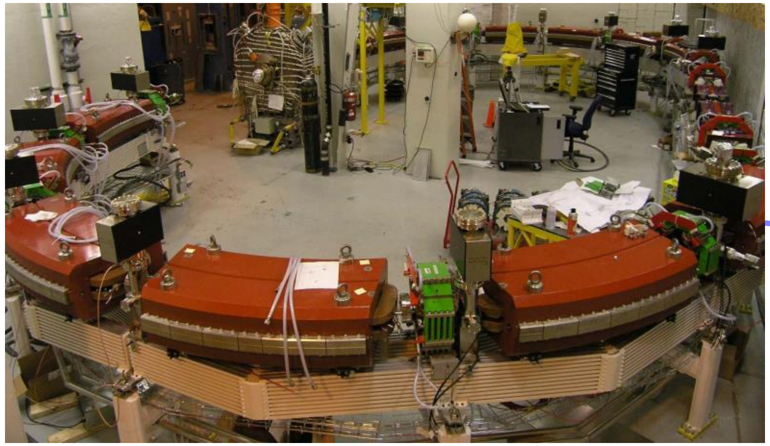
Duke FEL (Undulator Switchyard)

Linear polarization: two planar OK-4 undulators
Circular polarization: four helical OK-5 undulators

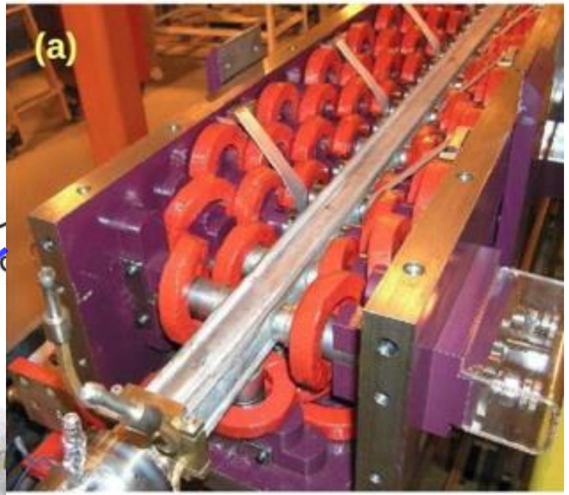
Max Beam Currents

One-bunch (FEL): ~ 95 mA (≥ 0.6 GeV)
Two-bunch (HIGS): ~ 125 mA (≥ 0.5 GeV)

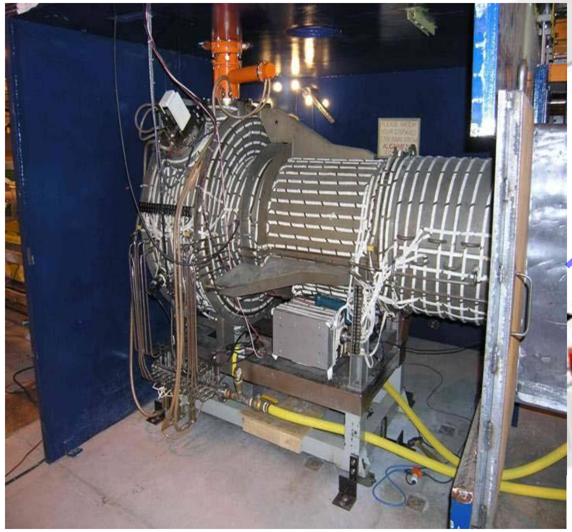
Бустер



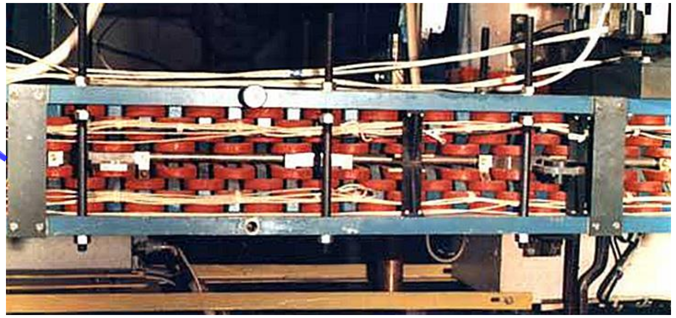
Спиральные ондуляторы ОК-5



ВЧ резонатор с подавлением высших мод

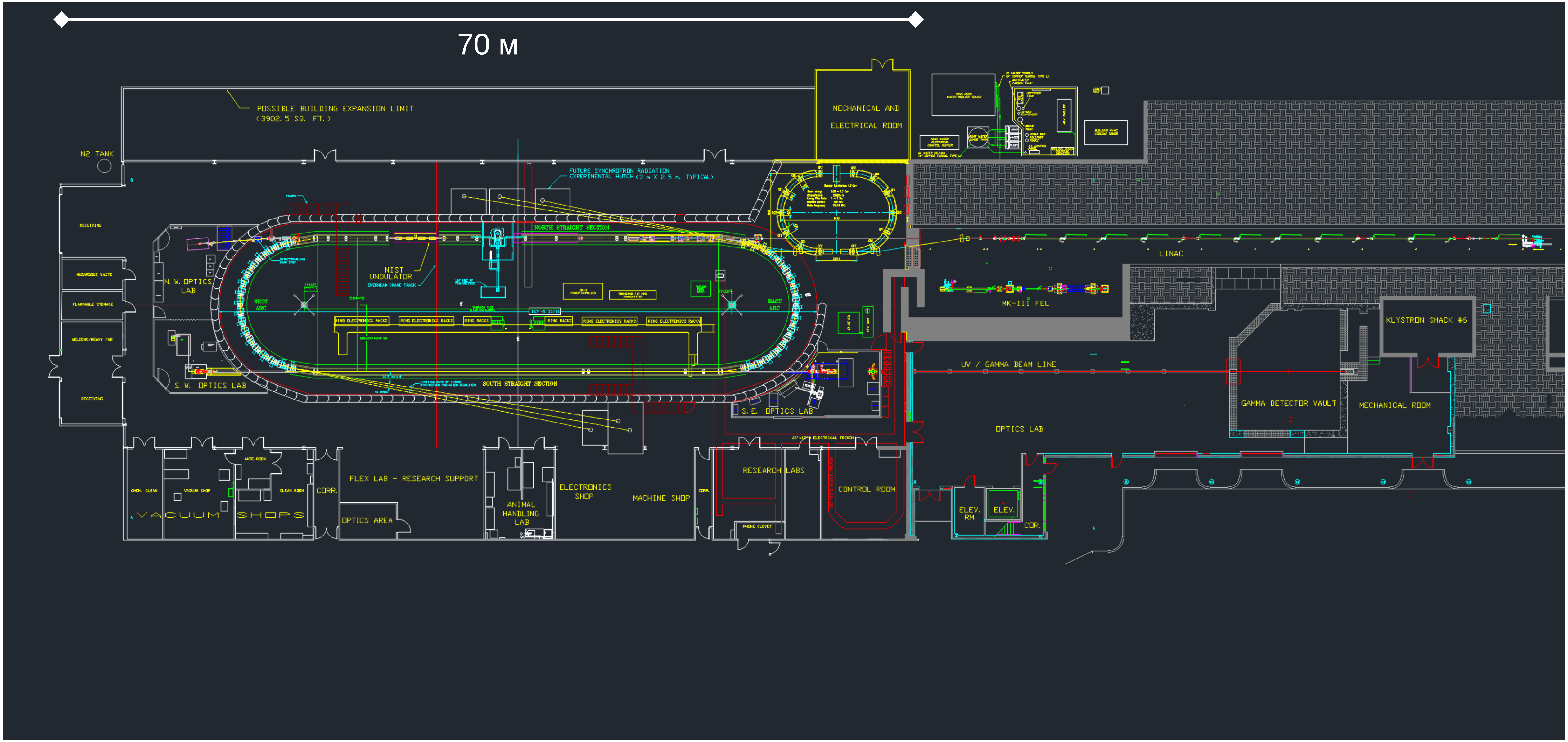


Плоские ондуляторы ОК-4

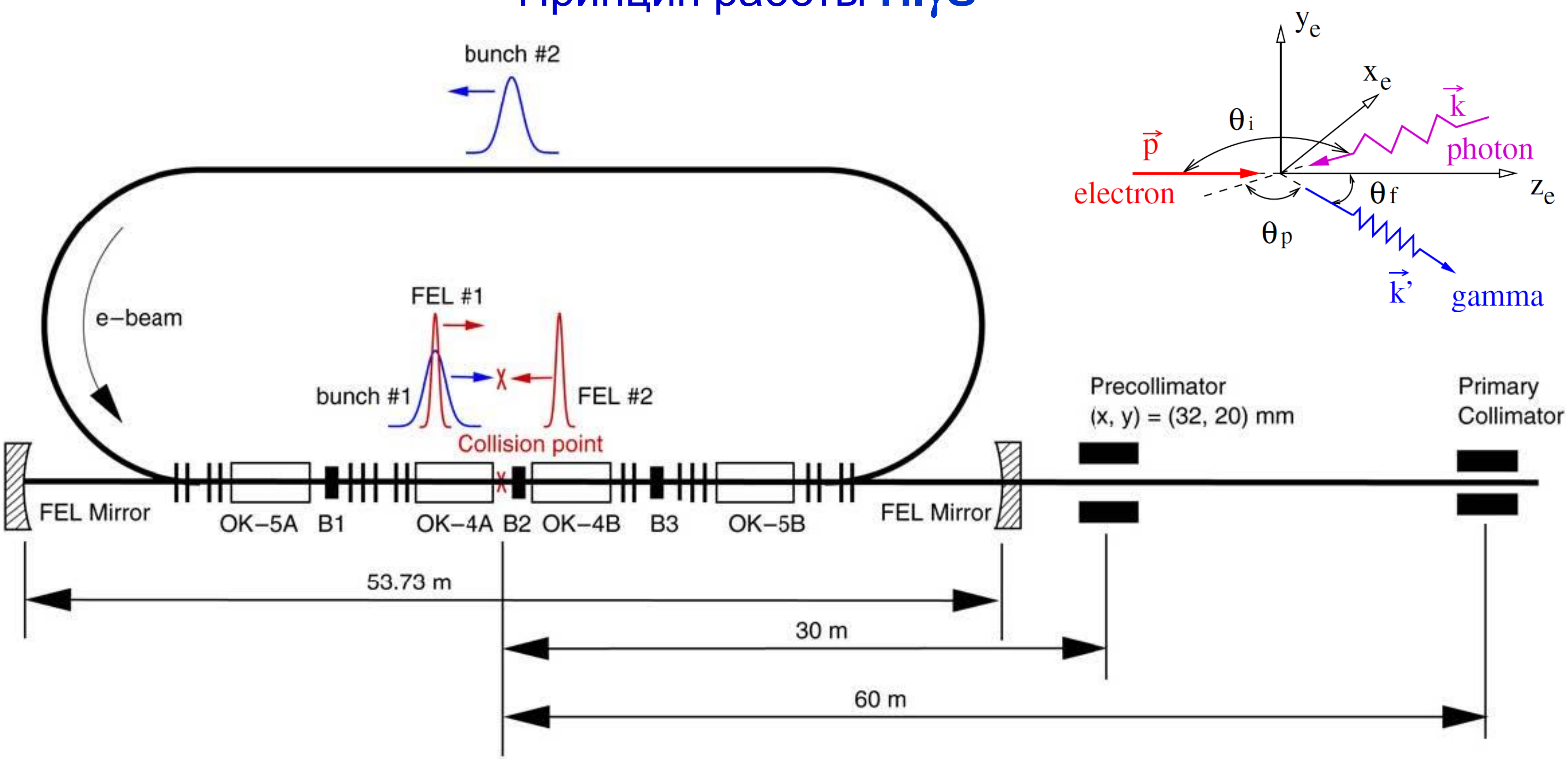


Сделано в ИЯФ!


70 м
Free Electron
Laser Laboratory


70 м
POSSIBLE BUILDING EXPANSION LIMIT
(3902.5 SQ. FT.)
N2 TANK
MECHANICAL AND
ELECTRICAL ROOM
FUTURE SYNCHROTRON RADIATION
EXPERIMENTAL HUTCH (3 m X 2.5 m TYPICAL)
NORTH STRAIGHT SECTION
NIST
UNDULATOR
N. W. OPTICS
LAB
WEST
ARC
EAST
ARC
S. W. OPTICS LAB
SOUTH STRAIGHT SECTION
LINAC
MK-III FEL
KLYSTRON SHACK #6
UV / GAMMA BEAM LINE
GAMMA DETECTOR VAULT
MECHANICAL ROOM
S. E. OPTICS LAB
OPTICS LAB
RESEARCH LABS
CONTROL ROOM
ELEV. RM.
ELEV.
COR.
FLEX LAB - RESEARCH SUPPORT
OPTICS AREA
CORR.
VACUUM SHOPS
ANIMAL
HANDLING
LAB
ELECTRONICS
SHOP
MACHINE SHOP
RECEIVING
HAZARDOUS WASTE
FLAMMABLE STORAGE
WELDING/HEAVY FAB

Принцип работы HIγS



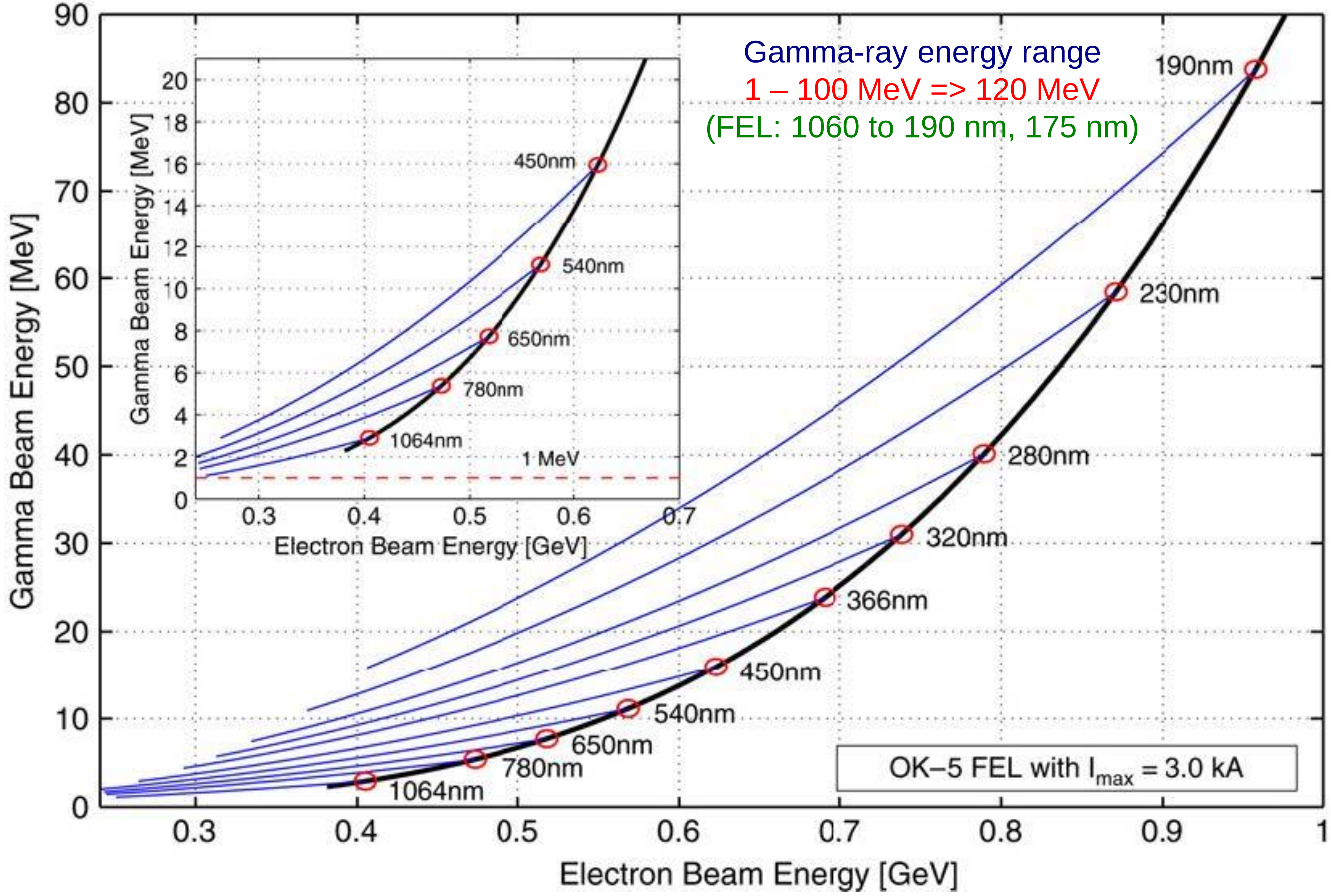
$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\varepsilon_e}(1-\cos\theta_{ph})}$$

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

Режимы работы HIγS

1. **Непрерывный (quasi-CW) режим с большим потоком (high-flux):**
   - микроимпульсы с длительностью доли наносекунды и частотой повторения 5.5796 МГц
   - характерный энергетический разброс (FWHM): 4 – 10% (определяется коллиматором)
   - используются два симметричных электронных сгустка
2. **Непрерывный (quasi-CW) режим с высоким разрешением (high-resolution):**
   - микроимпульсы с длительностью доли наносекунды и частотой повторения 2.7898 МГц
   - характерный энергетический разброс (FWHM): 0.8 – 1.5%
   - поток гамма-квантов меньше в 50-100 раз по сравнению с 1-м режимом
   - используются два электронных сгустка с разным зарядом
3. **Импульсный (pulsed) режим:**
   - макроимпульсы с длительностью 0.5 – 3 мс и частотой повторения от 2 до 50 Гц

Диапазон перестройки энергии гамма-квантов



HIGS Flux Summary

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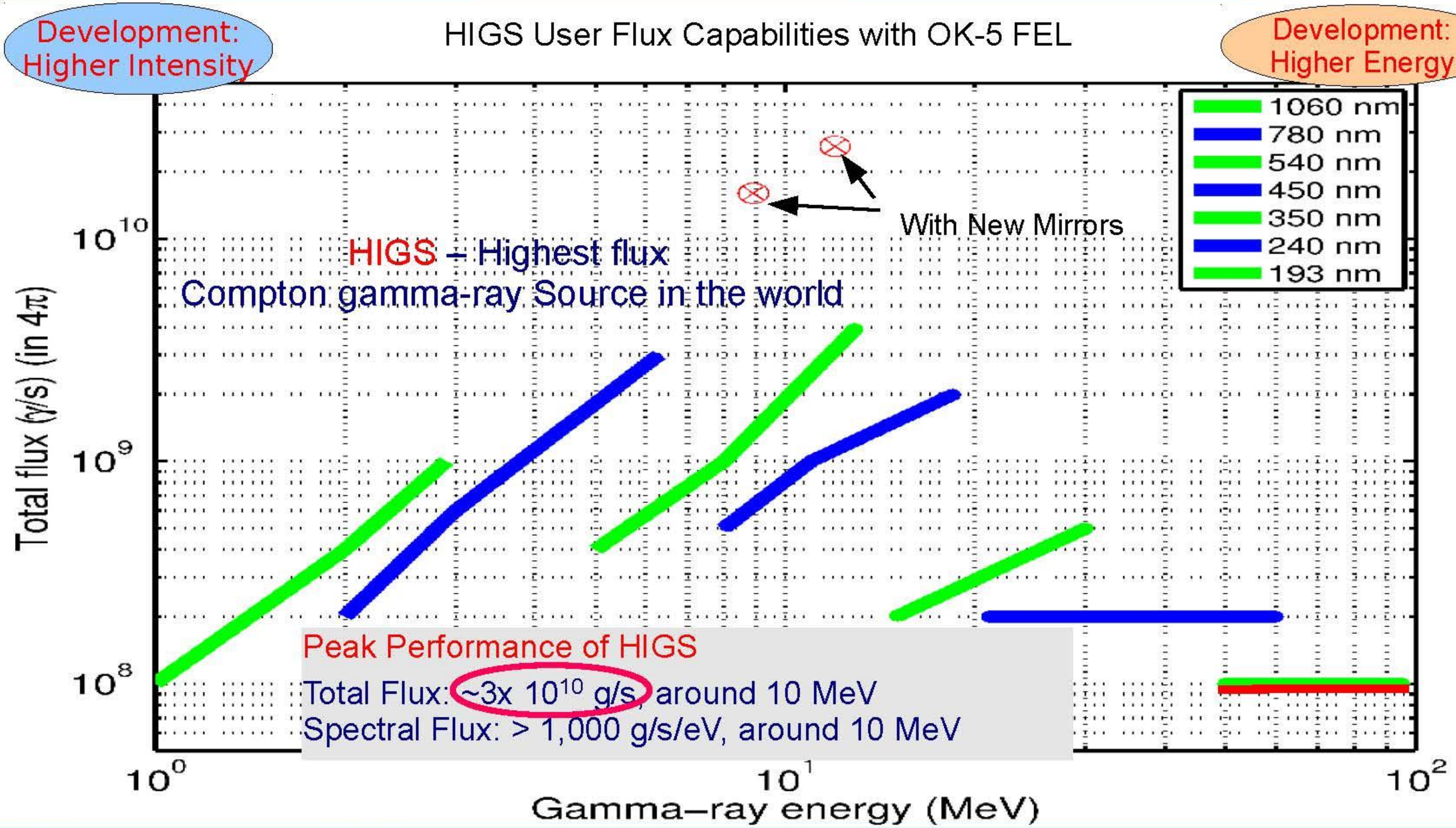
Development: Higher Intensity

Development: Higher Energy



Duke University · NC Central University · NC State University · The University of North Carolina at Chapel Hill

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(C) Y. K. Wu, Overview of Photon-induced Nuclear Reaction Research at the HIGS Facility

HIGS Flux Performance Projection		Total Flux [g/s] CW Operation Two-Bunch	Collimated Flux ($\Delta E_g/E_g$ = 5% FWHM)	FEL λ [nm]	Comment Linear Pol. with OK-4 Circular Pol with OK-5
No-loss Mode: E_g < ~16 MeV					
E_g = 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
E_g = 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
E_g = 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
E_g = 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
E_g = 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
E_g = 5 – 8 MeV	(E_e = 380 – 481MeV)	$4 \times 10^8 - 1 \times 10^9$	$2.4 \times 10^7 - 6 \times 10^7$	540	Linear and Circular
E_g = 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
E_g = 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
E_g = 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
E_g = 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
E_g = 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
E_g = 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
E_g = 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
Loss Mode: E_g > ~16 MeV					
E_g = 21 – 65 MeV	(E_e = 526 – 940 MeV)	$\sim 2 \times 10^8$	$\sim 1.2 \times 10^7$	240	Circular
E_g = 21 – 54 MeV	(E_e = 526 – 854 MeV)	$\sim 2 \times 10^8$	$\sim 1.2 \times 10^7$	240	Linear
E_g = 50 – 110 MeV	(E_e = 738 – 1,114 MeV)	$0.2 - 1 \times 10^8$	$\sim 1.5 - 6 \times 10^6$	193	Circular
E_g = 50 – 85 MeV	(E_e = 738 – 973 MeV)	$0.4 - 0.8 \times 10^8$	$\sim 3 - 5 \times 10^6$	193	Linear

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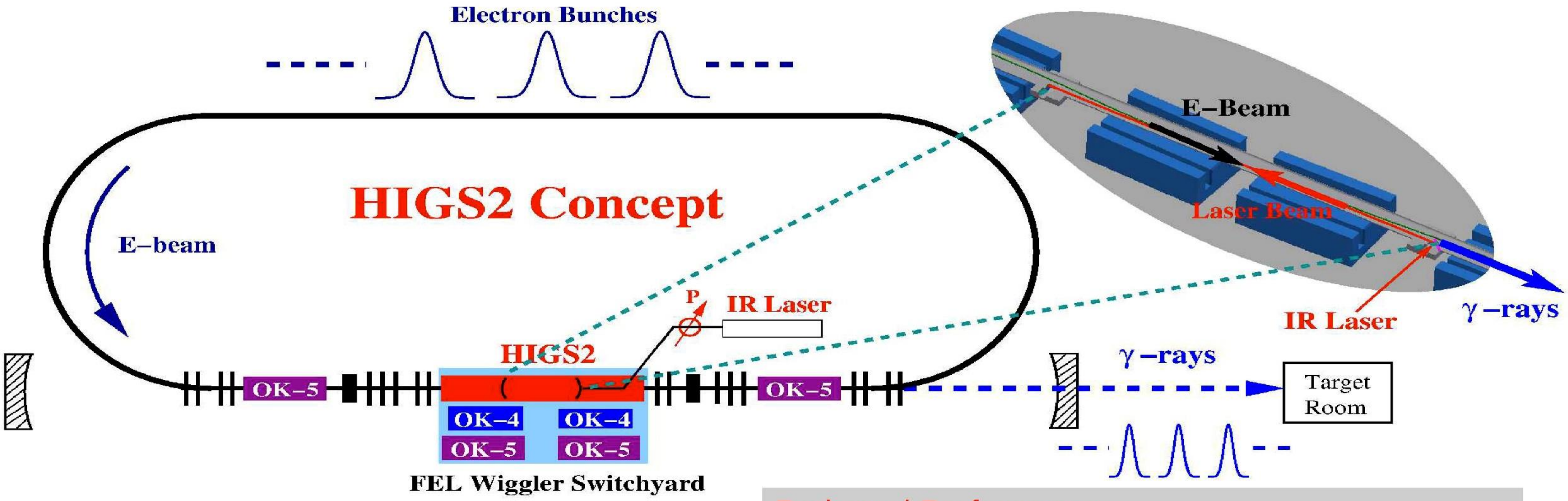
HIGS2: Next-Generation Gamma-ray Source



Research Programs

- Nuclear Structure
- Nuclear Astrophysics
- Hadronic Parity Violation

Status: Seeking funding

Projected Performance

- 2–3 orders of higher flux than HIGS (2–8 MeV)
- 1064 nm FP cavity: 2 – 12 MeV
- Total Flux: 10^{10} – 2×10^{12} g/s
- Pol: Linear, or Circular (rapid switch)
- High-res capability: 0.6% (FWHM)

28

(C) **Y. K. Wu**, Present and Future Compton Gamma-ray Sources

Основные направления работ пользователей

1. **Квантовая хромодинамика в пределе низких энергий:**
    - комптоновское рассеяние на нуклонах, измерение поляризуемости
    - фоторасщепление простых ядер (^{2}H, ^{3}H, ^{3}He)
2. **Структура ядер и ядерная астрофизика:**
    - ядерная резонансная флюоресценция (Ba, Sr, Zr, Mo)
    - измерение сечений ядерных реакций
    - исследование формирования кислорода в звездах (отношение C/O)
3. **Прикладные исследования**:
    - ядерная безопасность
    - исследование изотопов для медицины
    - детекторы частиц

Zoomed Out View of Research at HIγS

HIγS operates about 1600 hours/year for nuclear physics research

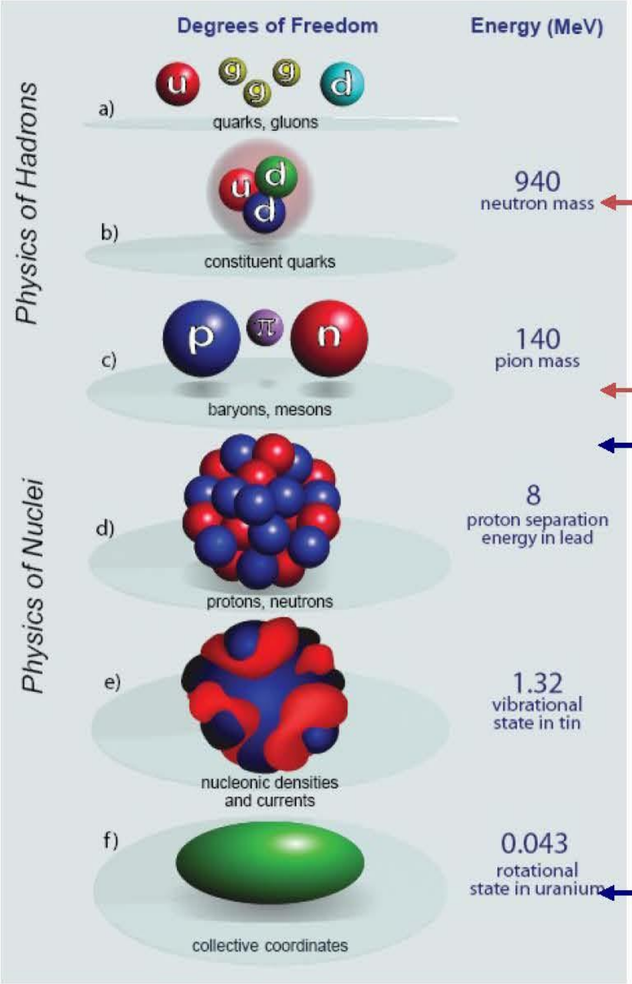


Figure from 2007 USA Nuclear Science LRP

Low-Energy QCD:

Nucleons

Compton Scattering: nucleon electric and magnetic polarizabilities nucleon spin polarizabilities

Few-nucleon Systems

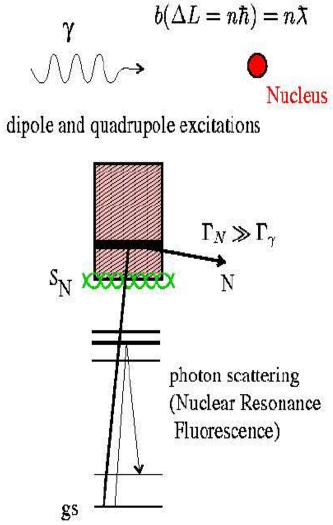
Photodisintegration of ^{2}H, ^{3}He and ^{3}H (cross sections, target-beam helicity dependent cross sections, polarization transfer)

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

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

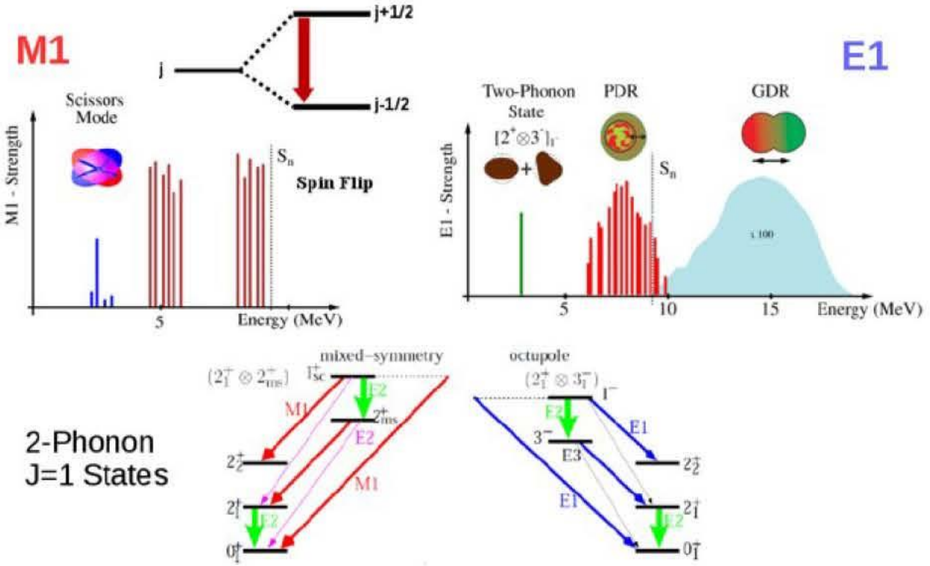
TUNL

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

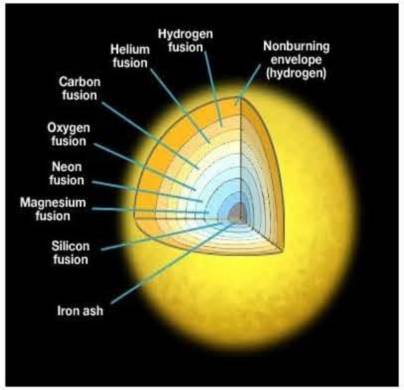
A.3. Photon-Induced Fission
- Fission Product Yields **(activation)**
- Cross sections **(fission chamber and prompt neutron detection)**



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 $^{12}C/^{16}O$

Duke University · NC Central University · NC State University · The University of North Carolina at Chapel Hill

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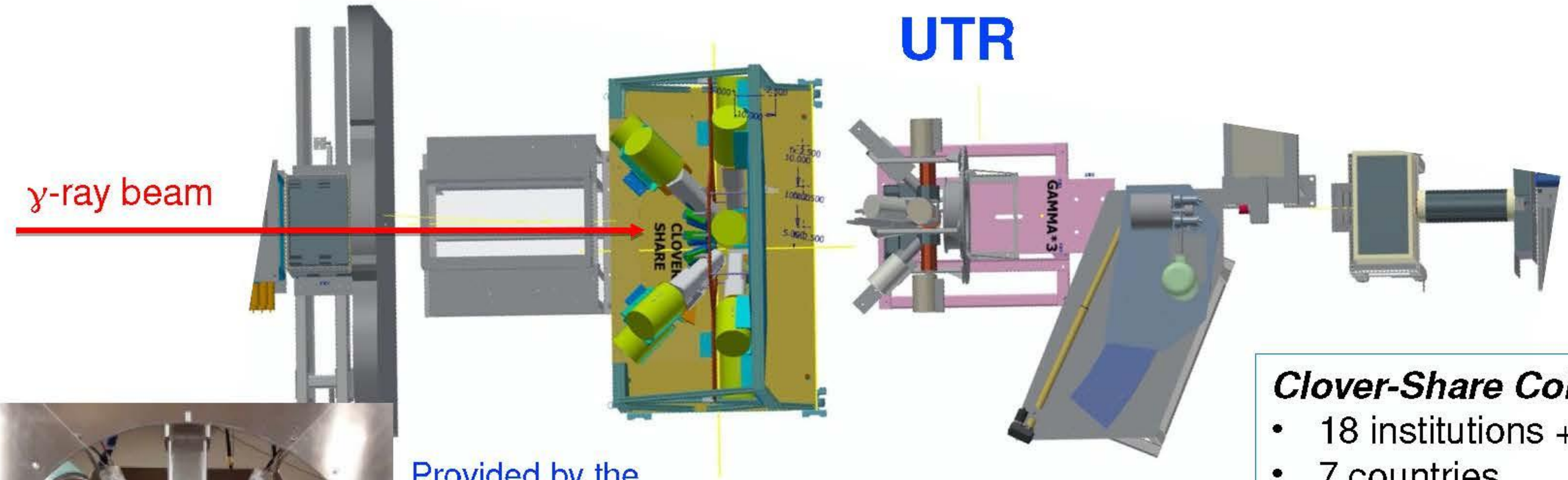
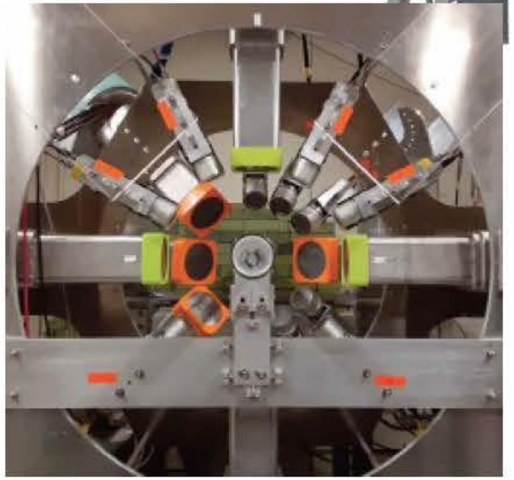




Provided by the Clover Share Consortium, the US Naval Academy, the US Army Research Lab, and TUNL

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

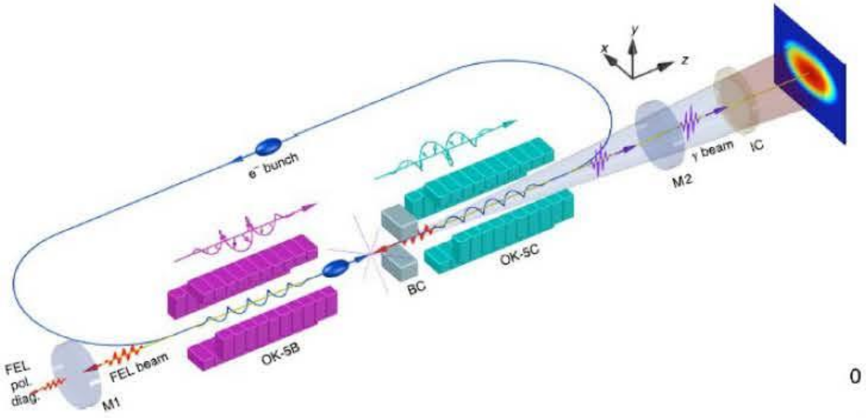
Clover-Share Collaboration
- 18 institutions + TUNL
- 7 countries

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

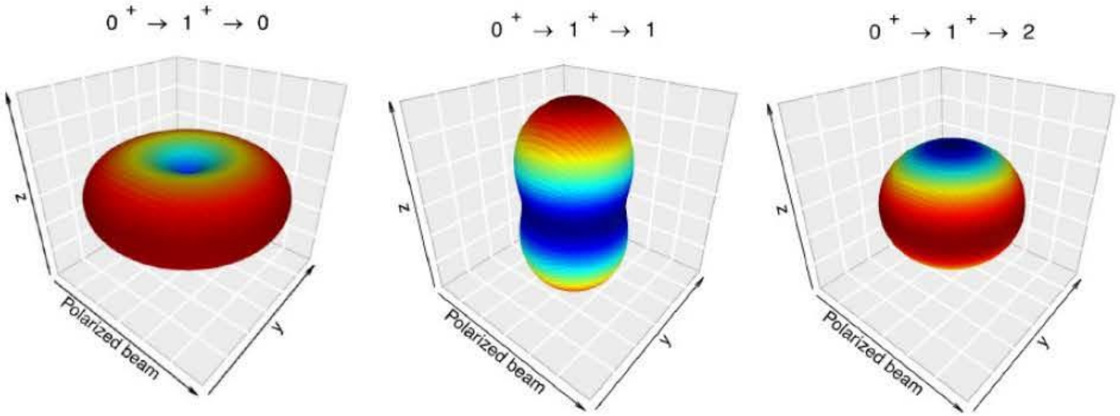


- Highly intense ($\approx 10^8 \gamma s^{-1}$)
- Quasi-monochromatic ($\mathrm{FWHM} \approx 100 - 300\,\mathrm{keV}$)
- Polarized ($> 99\%$)
- Bunched ($5.58\,\mathrm{MHz}$)

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).

nature COMMUNICATIONS

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

ARTICLE

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

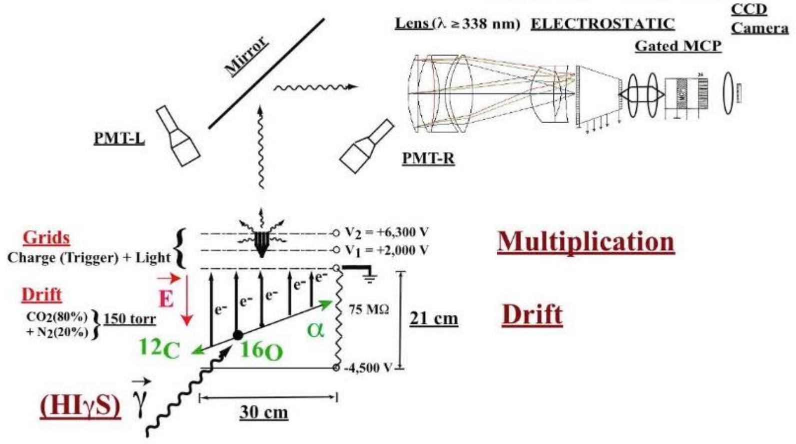
Precision measurements on oxygen formation in stellar helium burning with gamma-ray beams and a Time Projection Chamber

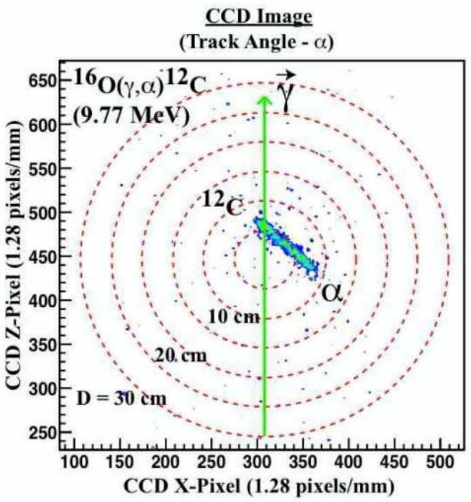
R. Smith [1,2], M. Gai [2], S. R. Stern [2], D. K. Schweitzer [2] & M. W. Ahmed [3,4]

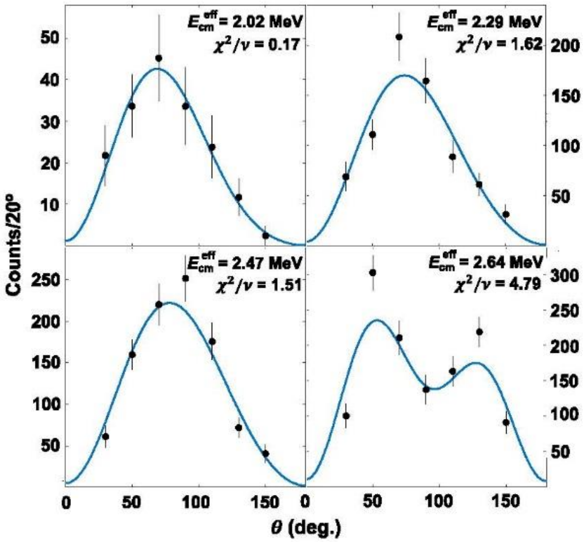
The carbon/oxygen (C/O) ratio at the end of stellar helium burning is the single most important nuclear input to stellar evolution theory. However, it is not known with sufficient accuracy, due to large uncertainties in the cross-section for the fusion of helium with ^{12}C to form ^{16}O, denoted as $^{12}C(\alpha,\gamma)^{16}O$. 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

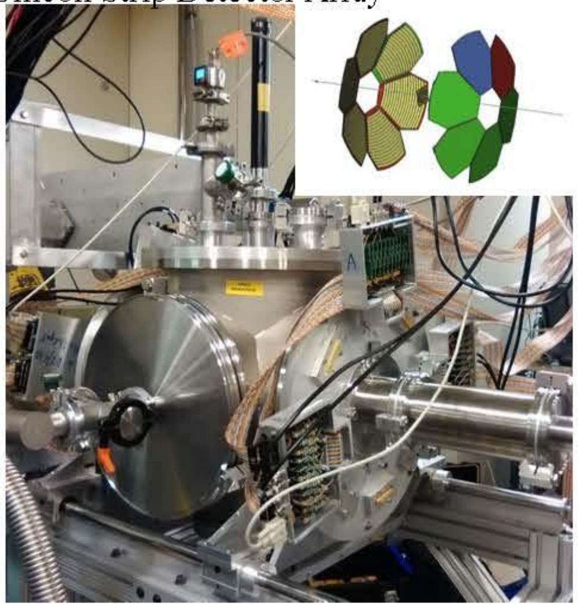






(C) Y. K. Wu, Overview of Photon-induced Nuclear Reaction Research at the HIGS Facility

Silicon Strip Detector Array



Photon-induced Nuclear Reactions with Emission of Charged Particles

Examples:

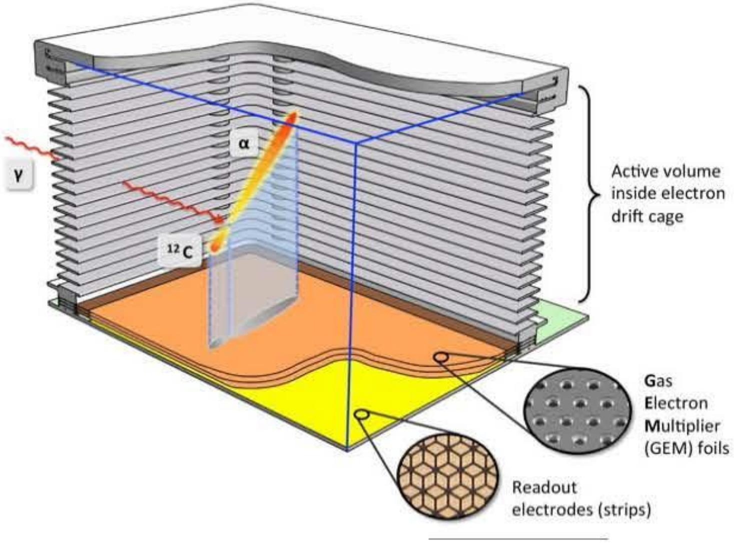
- $^{16}O(\gamma, \alpha)$, $^{12}C(\gamma, 3\alpha)$
- $^{9}Be(\gamma, \alpha\alpha)n$
- $^{2}H(\gamma, p)$
- $^{7}Li(\gamma, t)$

Users

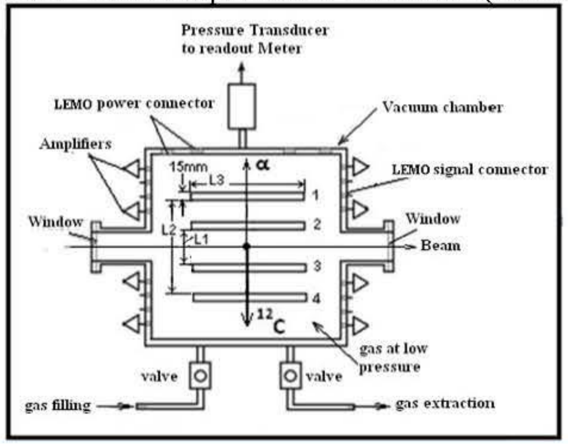
- 20 institutions + TUNL
- 10 countries

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)

Time Projection Chamber (TPC)



Multi-Wire Proportional Chamber (MWPC)



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TUNL

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

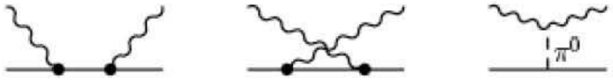
1) **GWU:** E. Downie, J. Feldman, H. Griesshammer
2) **James Madison Univ.:** A. Banu and S. Whisant
3) **North Georgia State Univ.:** M. Spraker
4) **Ohio Univ.:** D. Phillips
5) **Univ. Kentucky:** M. Kovash,
6) **Univ. Manchester:** J.A. McGovern
7) **Univ. New Hampshire:** R. Miskimen
8) **Univ.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

B. Few-Nucleon Systems

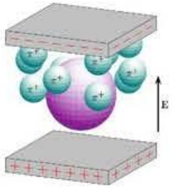
1) **Budker Inst. Nucl. Phys., Russia:** R.N. Lee, A.I. Milstein, V.M. Strakhovenko
2) **Jagiellonian Univ.:** H. Witała
3) **JLab:** D.W. Higinbotham, B. Sawatzky
4) **Univ. Rochester:** C.J. Forrest, W. Shmayda
5) **Univ. Saskatchewan:** R. Pywell,
6) **UVA:** B. Norum and D. Crabb
7) **Vilnius Univ.,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

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

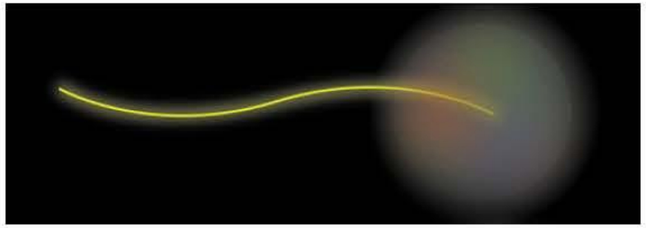


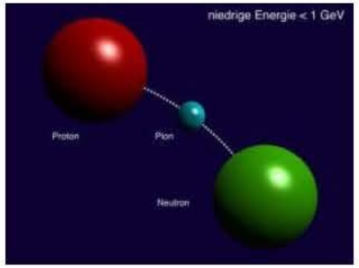
α



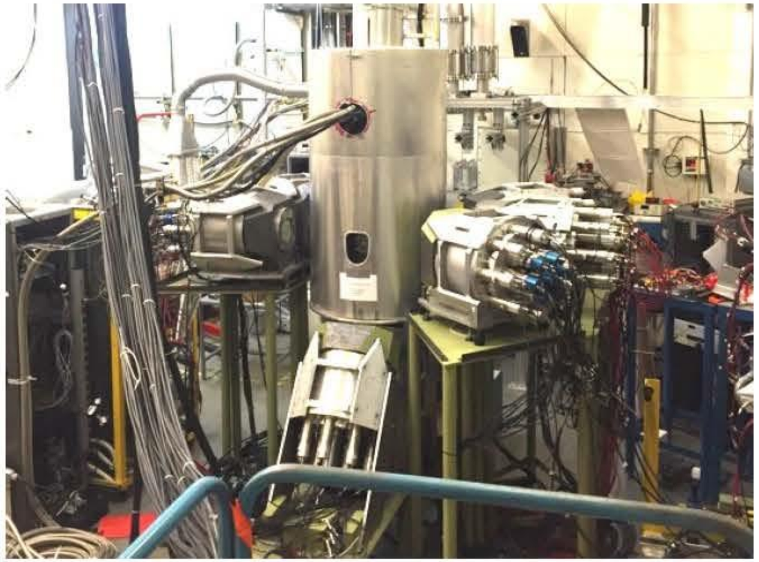
C.2. Polarization transfer in photodisintegration of ^2H

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





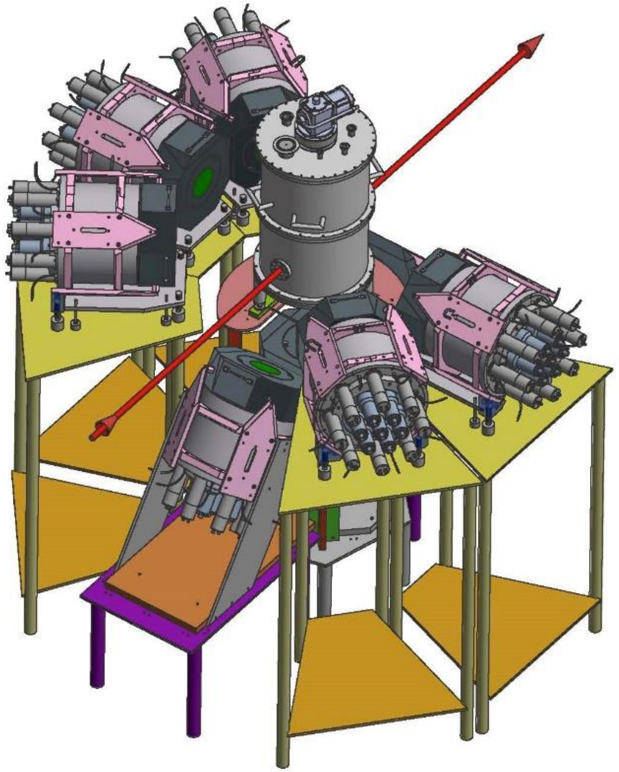
* Picture from: J. Arrington, arXiv:1208.4047v1[nucle-ex]

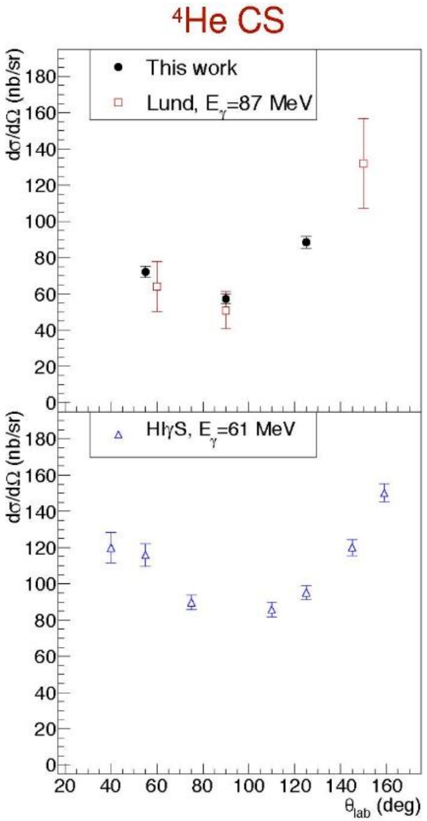


PHYSICAL REVIEW C 101, 034618 (2020)

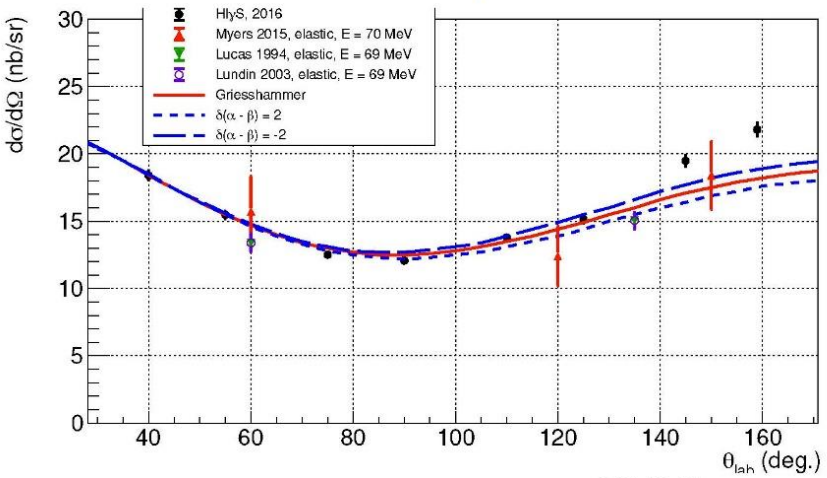
Compton scattering from ^{4}He at the TUNL HIγS facility

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





deuteron CS at E_γ = 65 MeV



DIANA

BUNI

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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)**

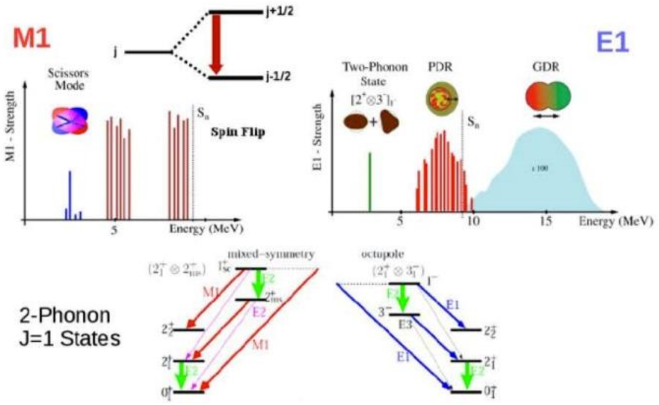
- Collective excitations, e.g., Pygmy Dipole Resonance, multiple phonon exchange
- Dipole strength (M1 and E1)
- Structure near the ground state (shapes, coexistence, effective interactions)

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)**



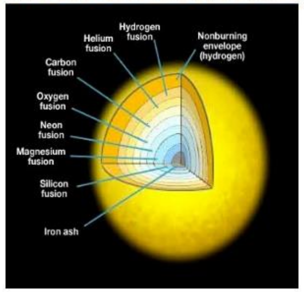
B. Nuclear Astrophysics (E_γ < 20 MeV)

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 $^{12}C/^{16}O$

Duke University | NC Central University | NC State University | The University of North Carolina at Chapel Hill

WANDA2022: Feb. 28 – March 4, 2022 19

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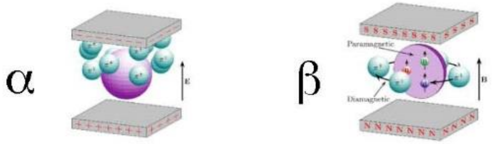
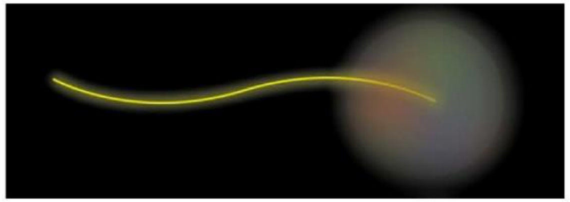
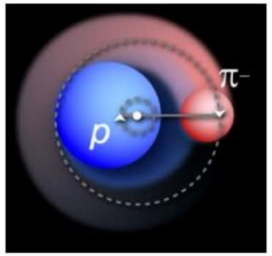
C. **Low-Energy QCD** (E_γ > 60 MeV) - **(circular beam polarization)**;

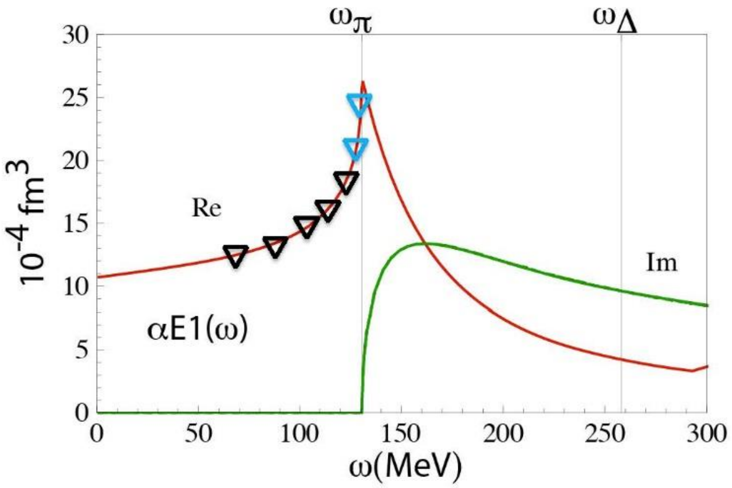
- **Determination of the neutron dipole electric and magnetic polarizabilities: Compton scattering from liquid H,D,^{3}He, and ^{4}He targets**
  - at E_γ = 65 - 120 MeV (**175-nm FEL mirrors)**
  - at E_γ = 130 - 150 MeV (**155-nm mirrors**, R&D planned by TUNL-LZH collaboration)
- **Measurement of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

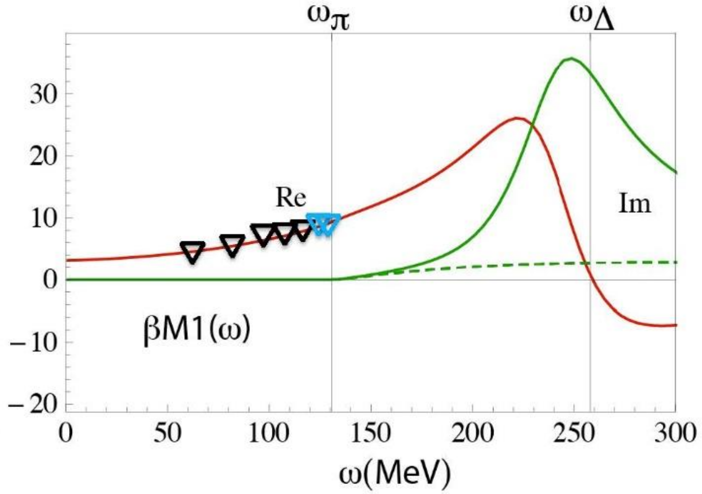
Dipole EM dipole polarizabilities:











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Спасибо за внимание!