HIGS - A High-intensity, Mono-energetic, and Tunable Source of Polarized Gamma-rays

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Acknowledgment:

M. Busch, M. Emanian, J. Faircloth, S. Hartman, S. Huang, J. Li, S. Mikhailov, V. Popov, G. Swift, C. Sun, P. Wang, P. Wallace, W. Z. Wu, C. Howell (TUNL and DFELL)

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DOE DE-FG02-01ER41175 and AFOSR MFELFA9550-04-01-0086

Outline

High Intensity Gamma-ray Source at Duke University

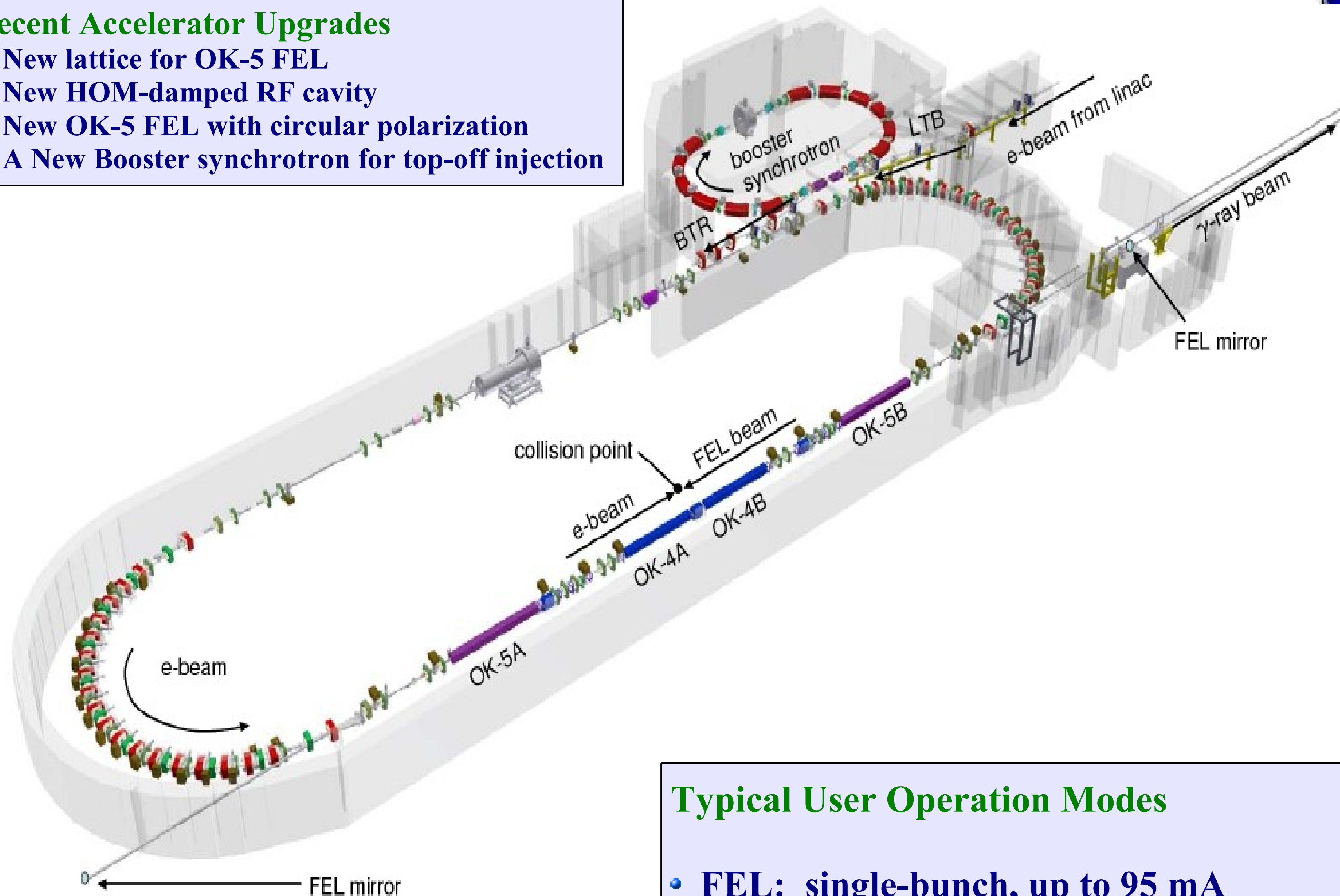
- Accelerator Facility Overview
- Operation Principle of High Intensity Gamma-ray Source (HIGS)
- HIGS Operation Modes
- HIGS Performance Summary: Energy range and Flux rate
- High Flux Operation (> 10^{10} γ/s, total flux around 10 MeV)
- Optics-free Helicity Switch

Research Programs at HIGS

- Nuclear Physics Research Programs
- Astrophysics
- Industrial and Medical Applications

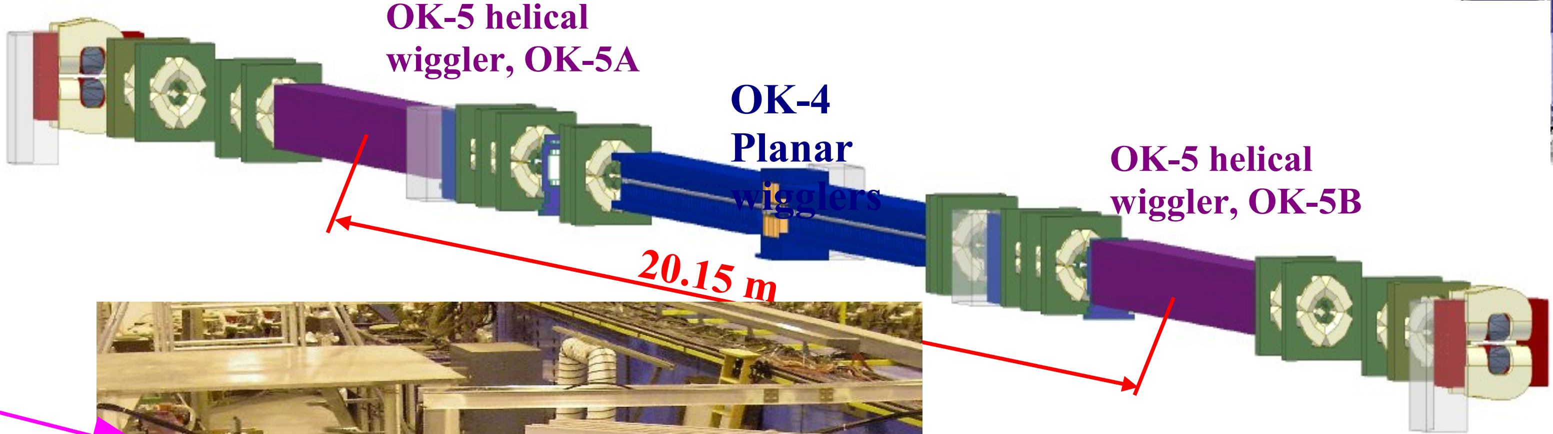
Layout of the Duke FEL Lab Accelerator Facility

Recent Accelerator Upgrades
- New lattice for OK-5 FEL
- New HOM-damped RF cavity
- New OK-5 FEL with circular polarization
- A New Booster synchrotron for top-off injection

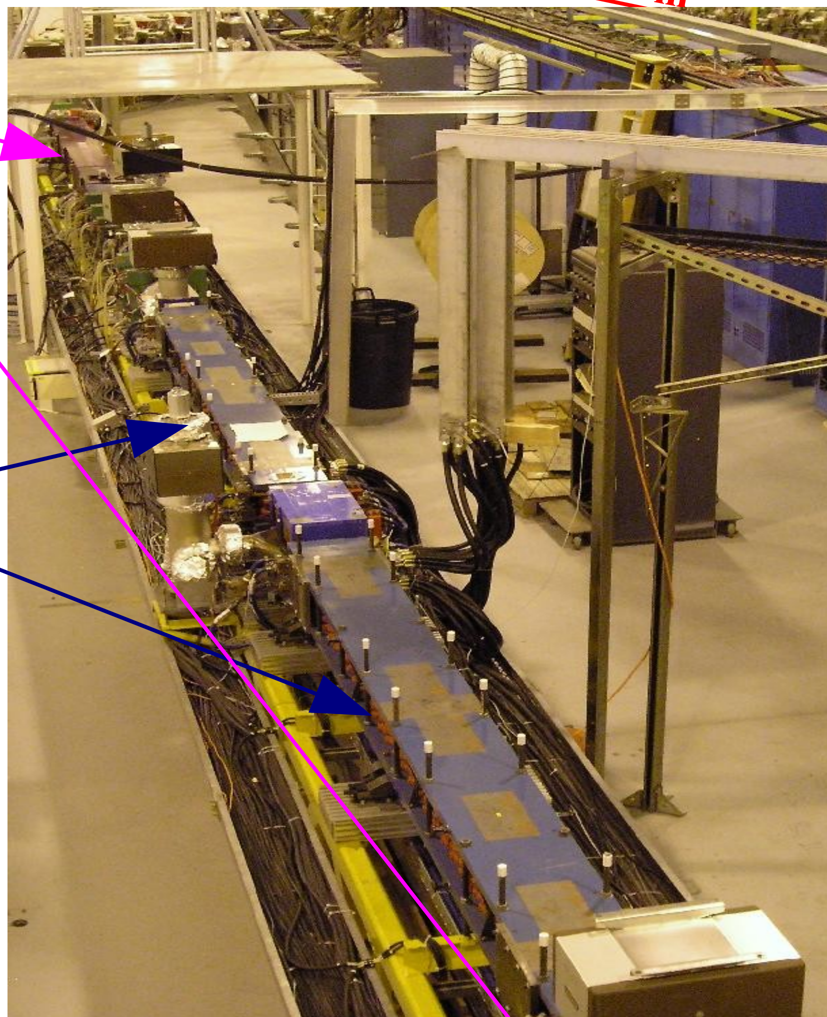


Typical User Operation Modes
- FEL: single-bunch, up to 95 mA
- HIGS: two-bunch, typical 80 - 110 mA

OK-5 and OK-4 FELs (Since Aug. 2005)



OK-5 wigglers



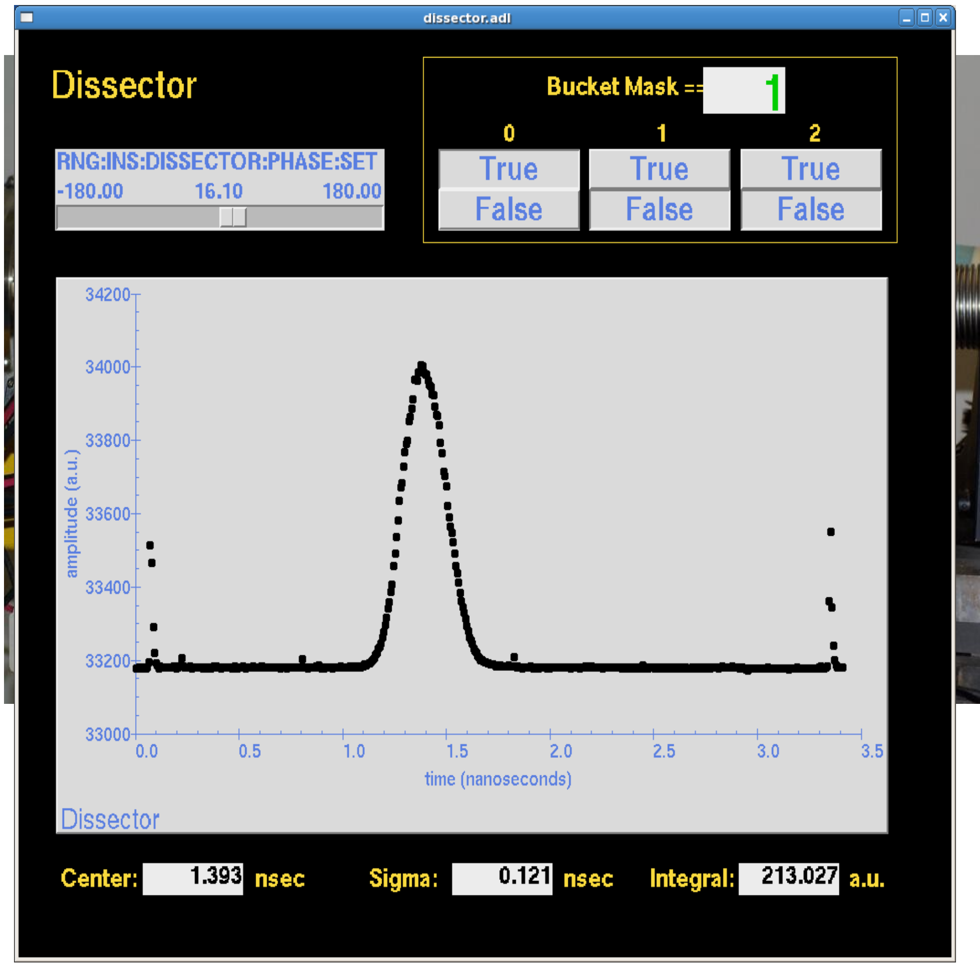
OK-4 wigglers

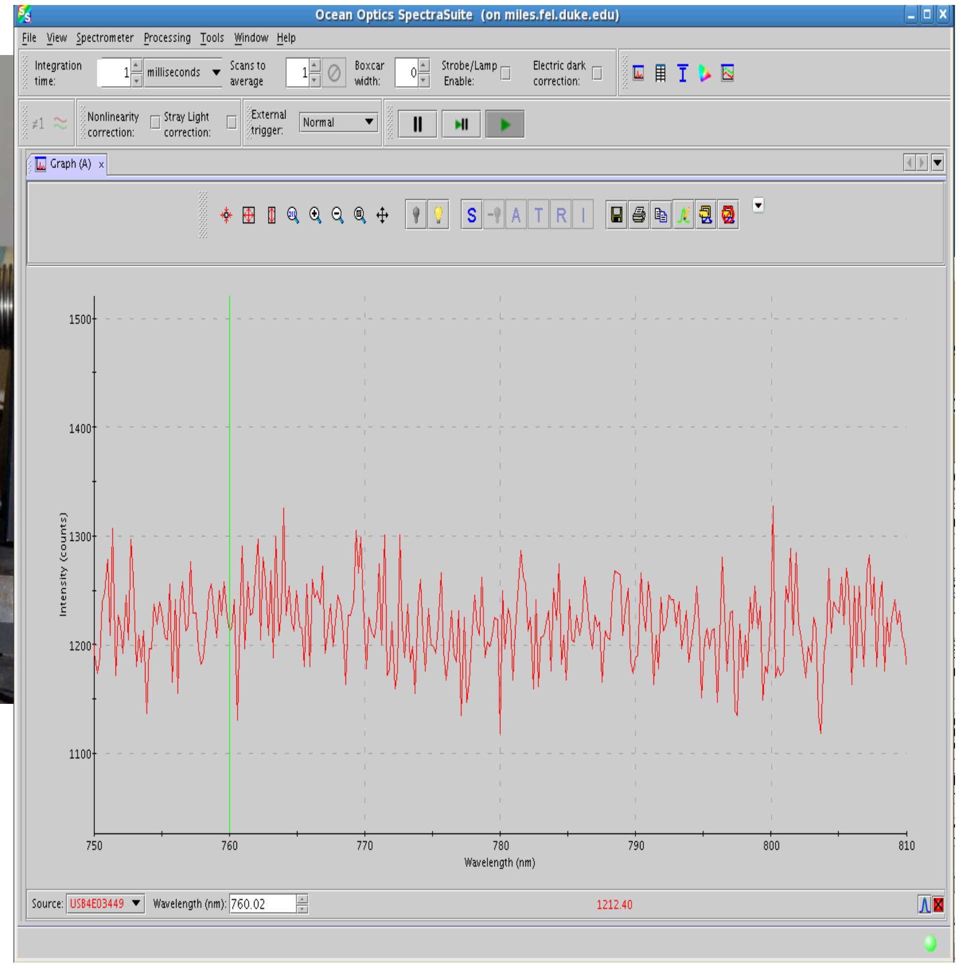
SRFEL Operation: increasing e-beam energy spread

Beam Diagnostics

Live Spectrum Monitor

Live bunch length monitors





SRFEL Operation: increasing e-beam energy spread

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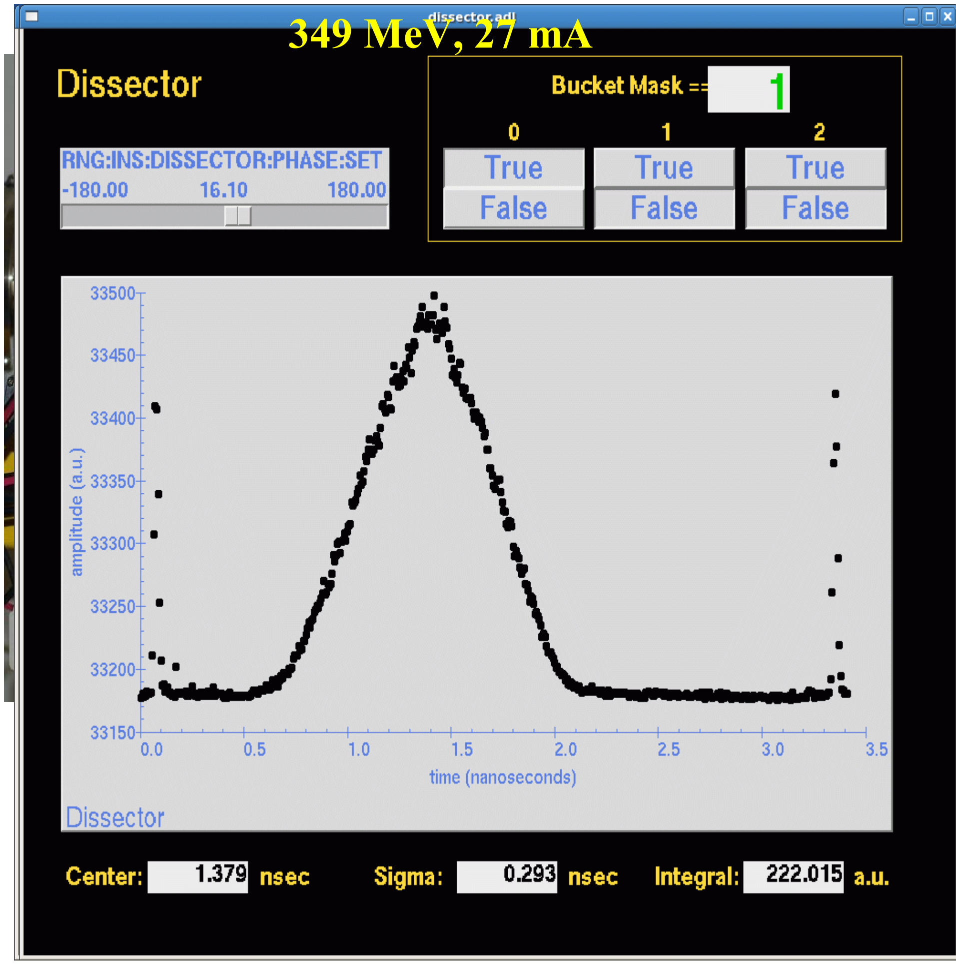
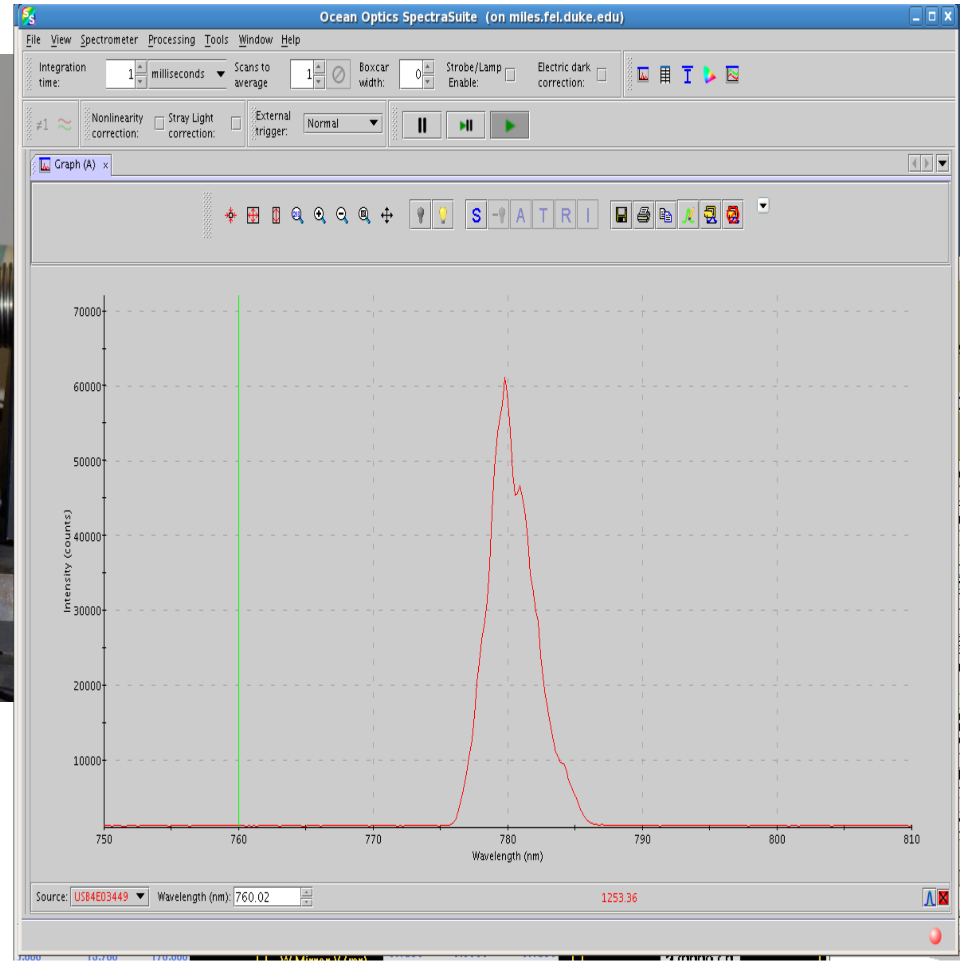
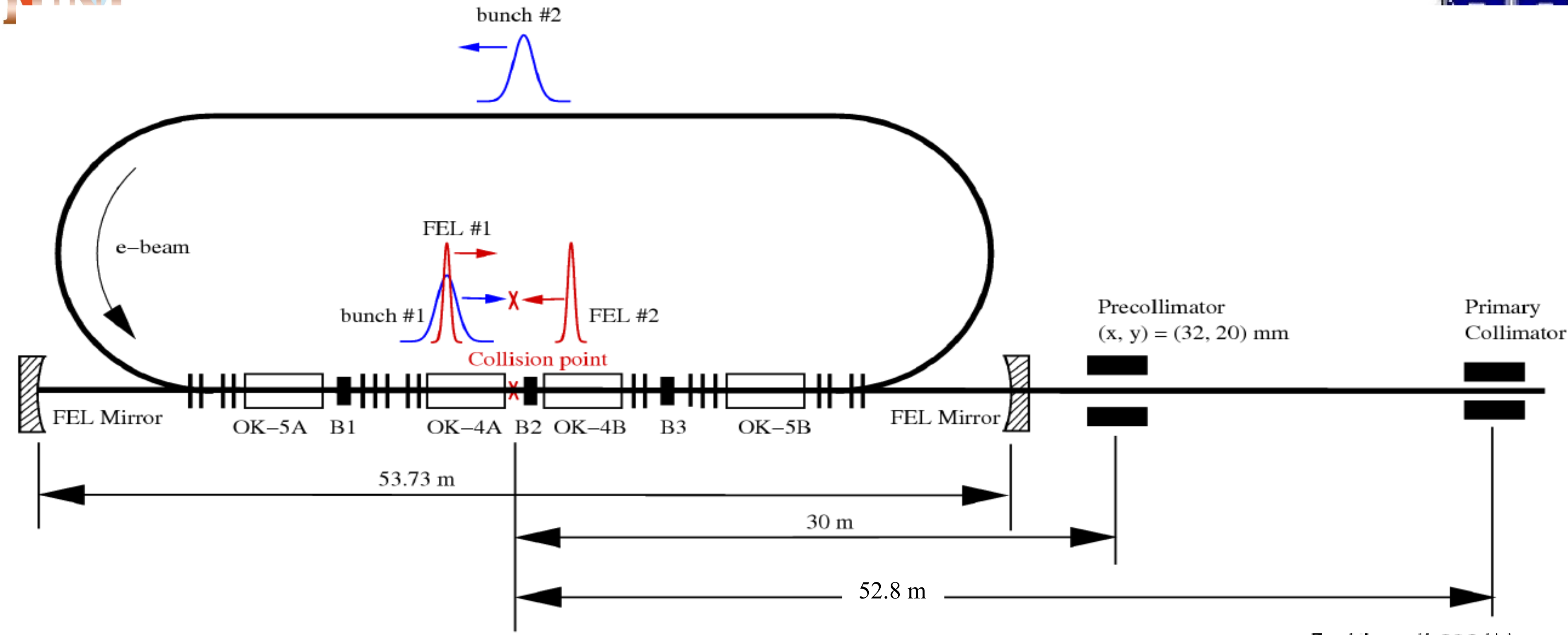
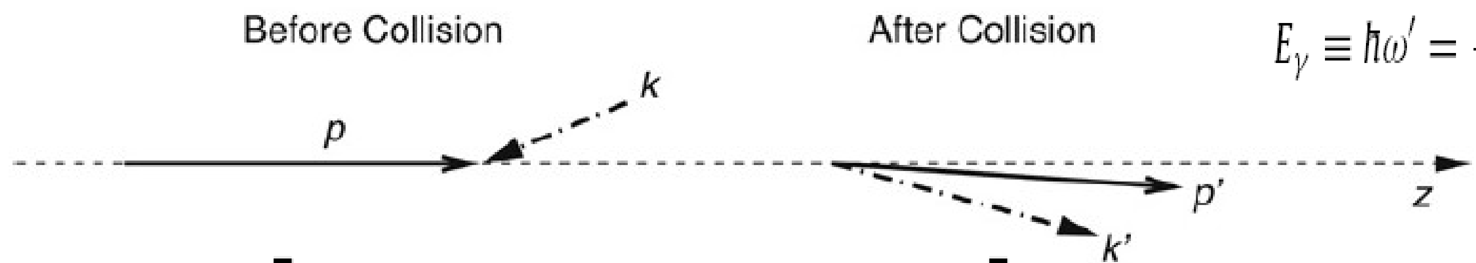




Operation Principle of HIGS





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

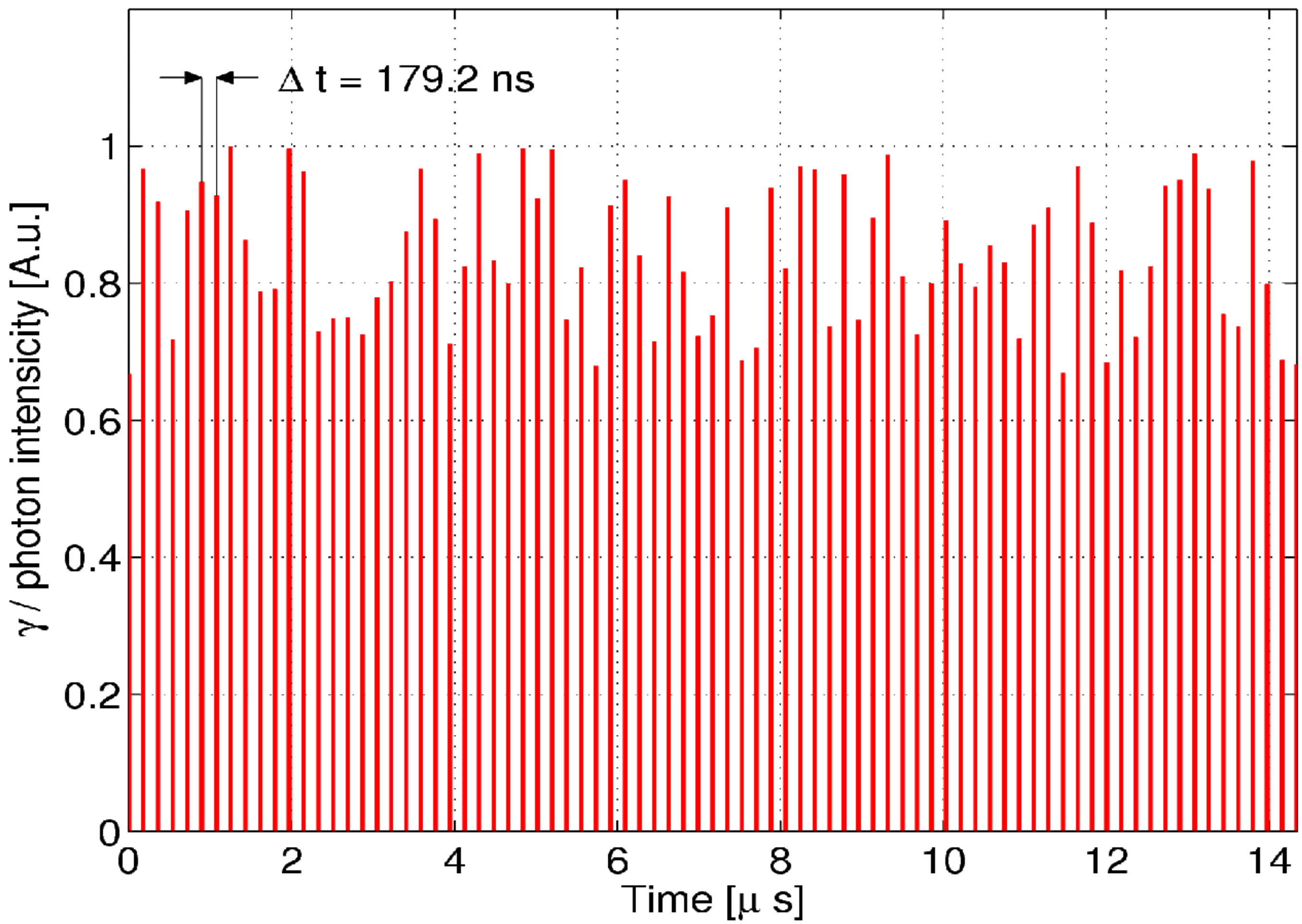
$$d\sigma = 8\pi r_e^2 \frac{dy}{x^2}\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2 + \left(\frac{1}{x}-\frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)\right]$$

$$x = \frac{2\gamma\hbar\omega(1-\beta\cos\theta_i)}{mc^2}, \qquad y = \frac{2\gamma\hbar\omega'(1-\beta\cos\theta_f)}{mc^2}$$

Operation Modes of HIGS

Operation Modes of HIGS

- Qusi-CW operation vs Pulsed
- High-flux vs high energy resolution



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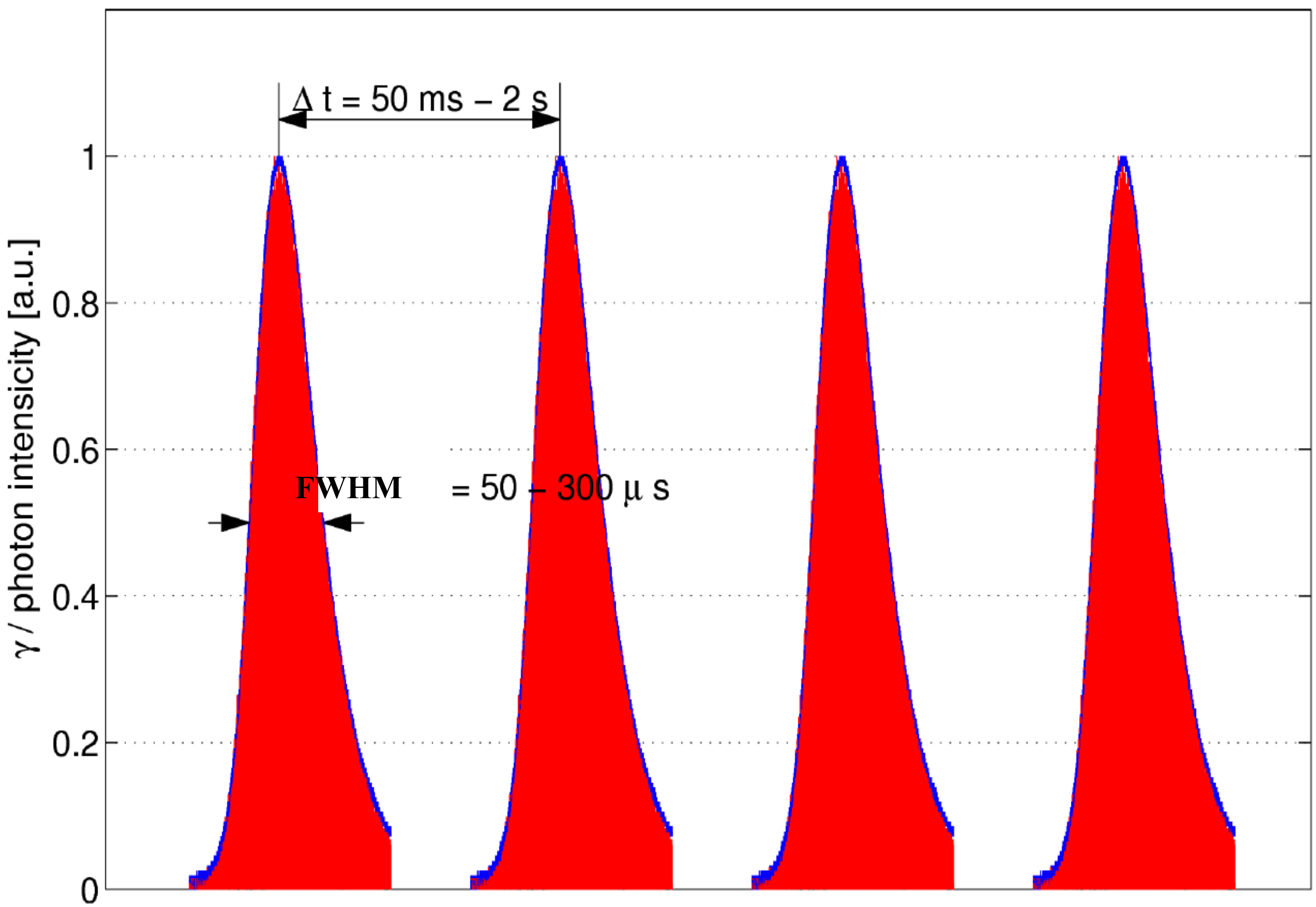
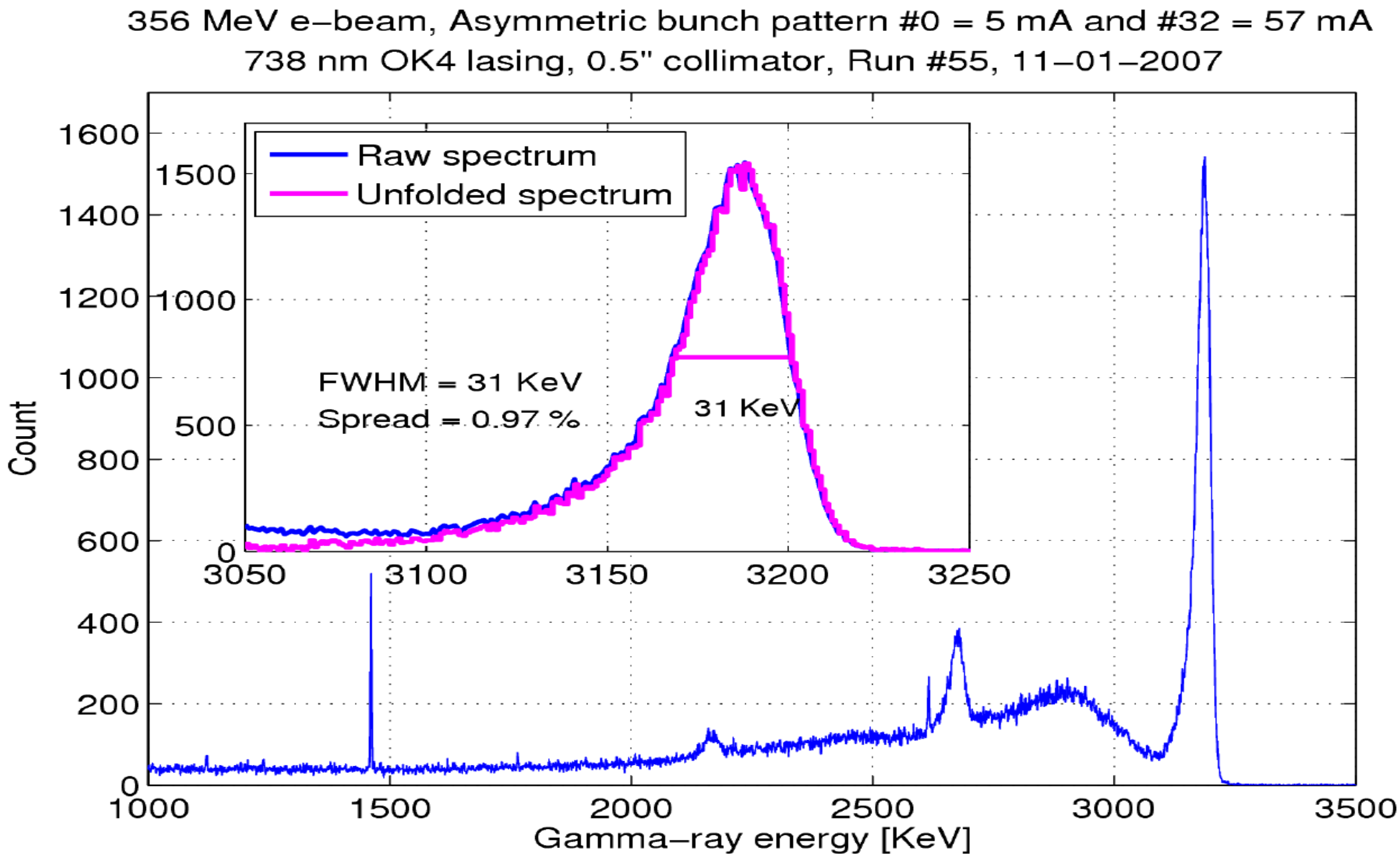


High Energy-Resolution Operation

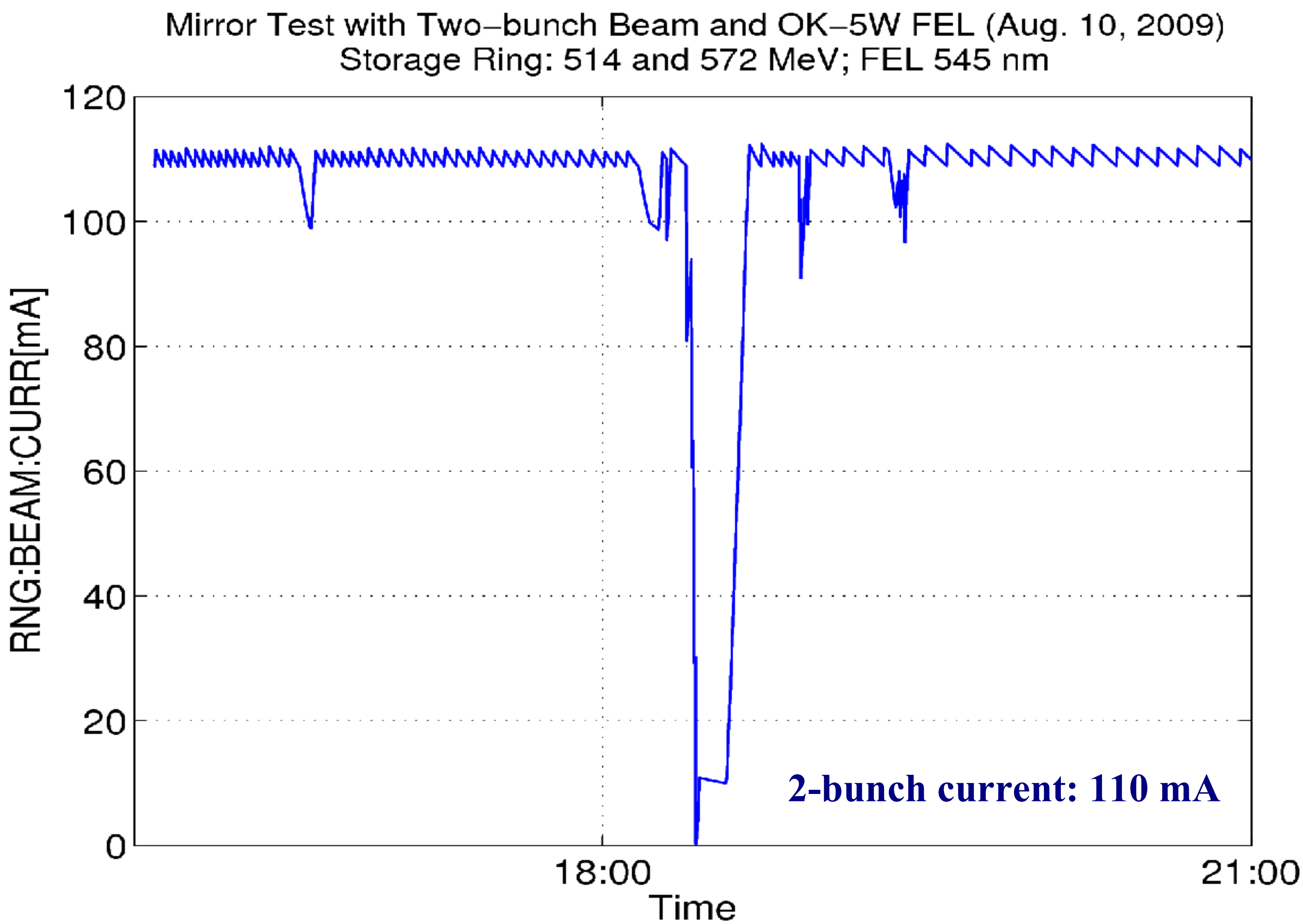
Asymmetric Bunch Pattern: one large (lasing) and one small (non-lasing)



Improving stability of gamma energy resolution and increase flux

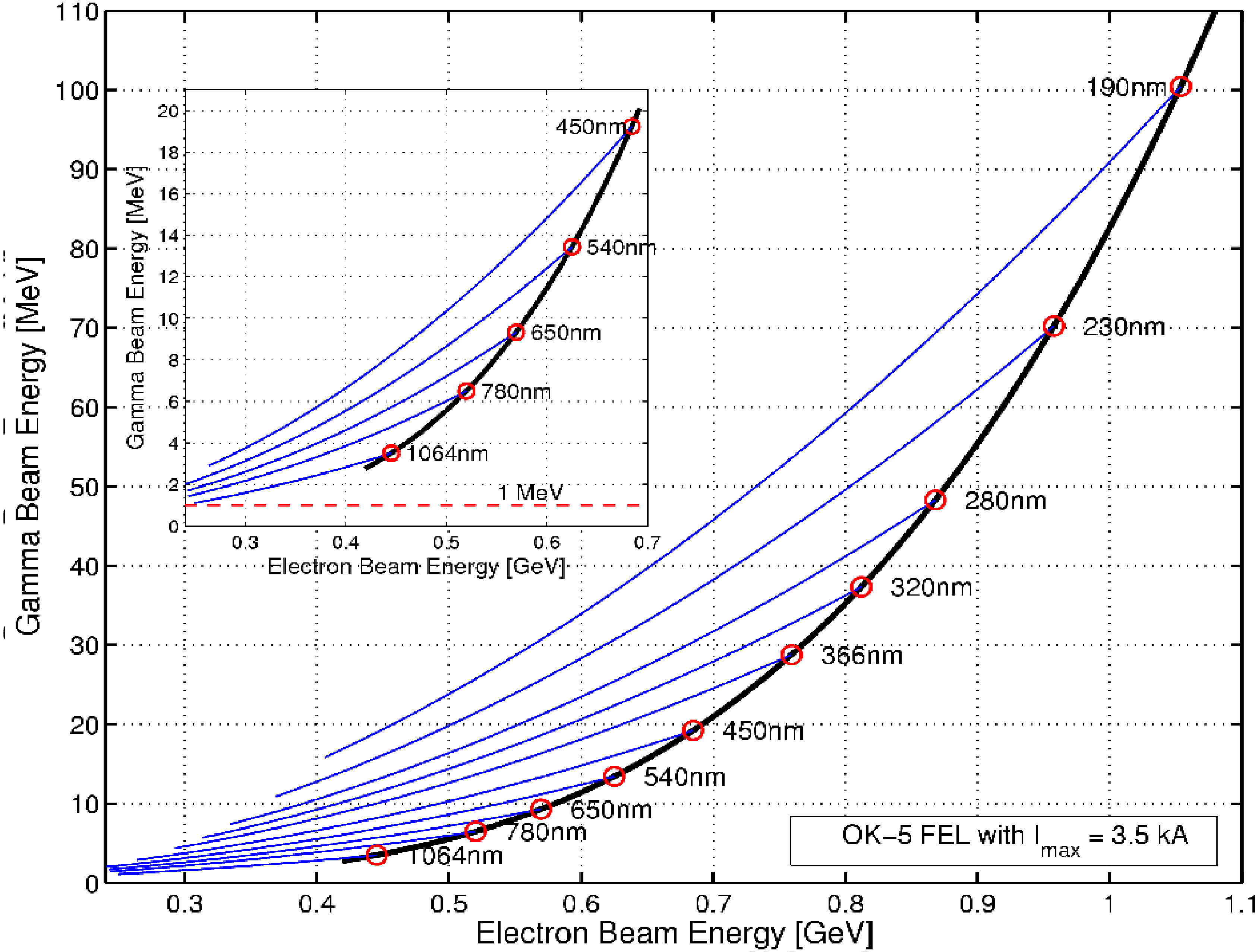
- Develop a reliable way to measure bunch pattern, and
- An automatic injection scheme to maintain charge distribution

HIGS Operaton with Top-off Injection



Maximum single-bunch beam current: ~95 mA with FEL lasing

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



HIGS Capabilities for User Programs in 2010

Parameter	Value		Comments
E-beam Configuration E-beam current [mA]	Symmetric two-bunch beam 50 - 100		High flux configuration
Gamma-ray Energy [MeV]	1 – 100		with mirrors 1064 to 190 nm Available with existing hardware Extending wiggler current to 3.5 kA
(a) No-loss mode	Total flux [γ /s]	Collimated flux ($\Delta E/E \sim 5\%$) [γ /s]	Both Horizontal and Circular Polarizations
1 – 3 MeV[(a)]	$1 \times 10^8 – 1 \times 10^9$	$6 \times 10^6 – 6 \times 10^7$	
3 – 5 MeV	$6 \times 10^8 – 2 \times 10^9$	$3.6 \times 10^7 – 1.2 \times 10^8$	
5 – 13 MeV	$4 \times 10^8 – 4 \times 10^9$	$2.4 \times 10^7 – 2.4 \times 10^8$	
13 – 20 MeV	$1 \times 10^9 – 2 \times 10^9$	$6 \times 10^7 – 1.2 \times 10^8$	
(b) Loss mode	Total flux [γ /s]	Collimated flux ($\Delta E/E \sim 5\%$) [γ /s]	
21 – 54 MeV	$> 2 \times 10^8$ [(b)]	$> 1 \times 10^7$	To extend mirror lifetime, circular polarization is preferred
55 – 65 MeV	$\sim 2 \times 10^8$ [(b)]	$\sim 1 \times 10^7$	240 nm mirrors, summer 2010
66 – 100 MeV	$1 – 2 \times 10^8$ [(b) (c)]	$0.5 – 1 \times 10^7$	190 nm mirrors, 2011

[(a)] With present configuration of OK-5 wigglers separated by 21 m, the circular polarization is about ½ the values here.
[(b)] The flux in loss mode is mainly limited by injection rate.
[(c)] Thermal stability of FEL mirror may limit the maximum amount of current can be used in producing FEL lasing, thus flux.

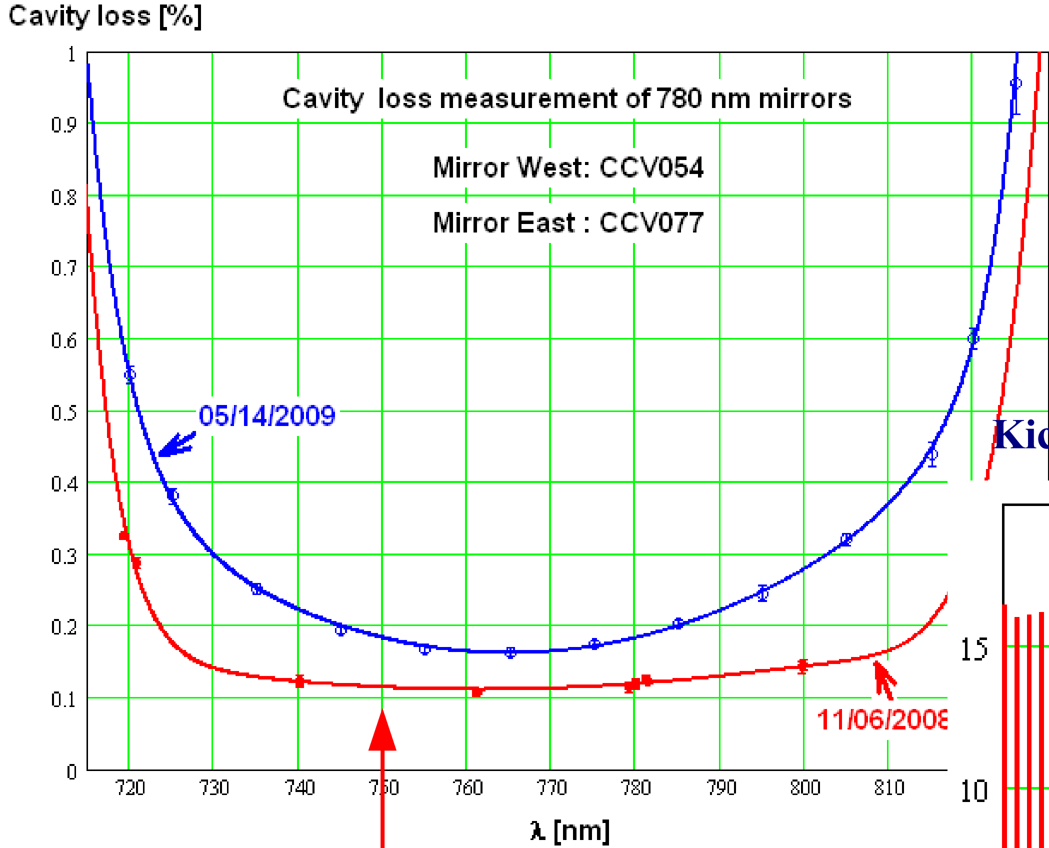
Highest Total Flux (2009): > 10^{10} γ/s @ 9 – 11 MeV

H. R. Weller *et al.*, "Research Opportunities at the Upgraded HIγS Facility," Prog. Part. Nucl. Phys. Vol 62, Issue 1, p. 257-303 (2009).

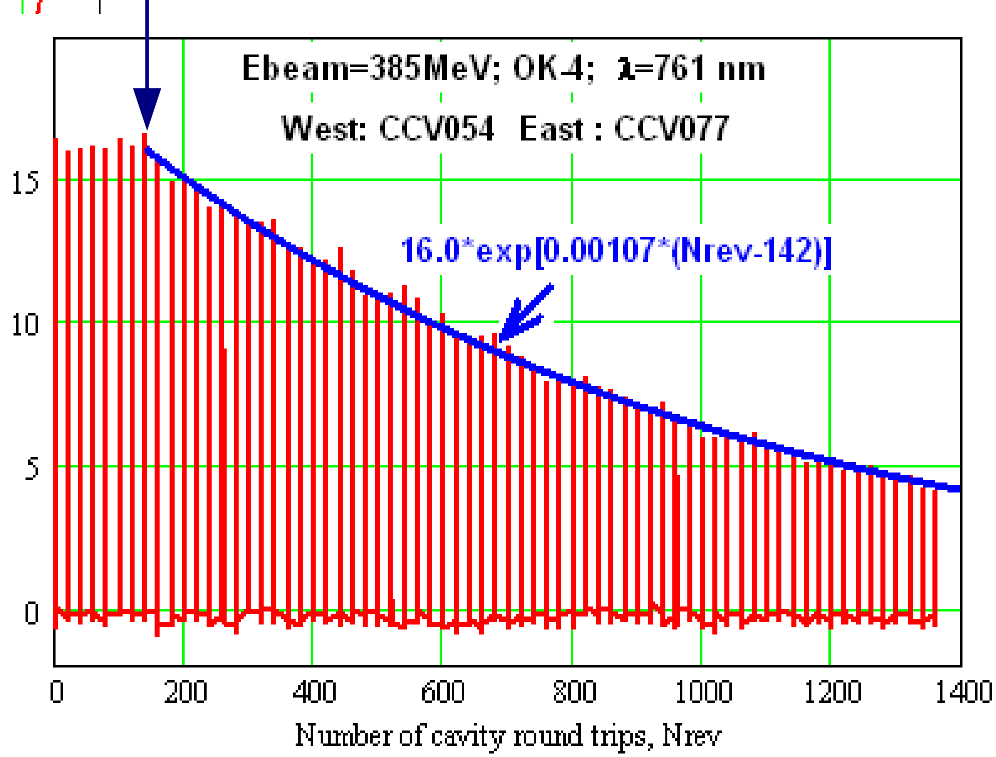
High Finesse, FEL Optical Resonator

780 nm Mirrors
Minimal round-trip loss: ~ 0.107%
Finesse @ Low power ~ 3,000

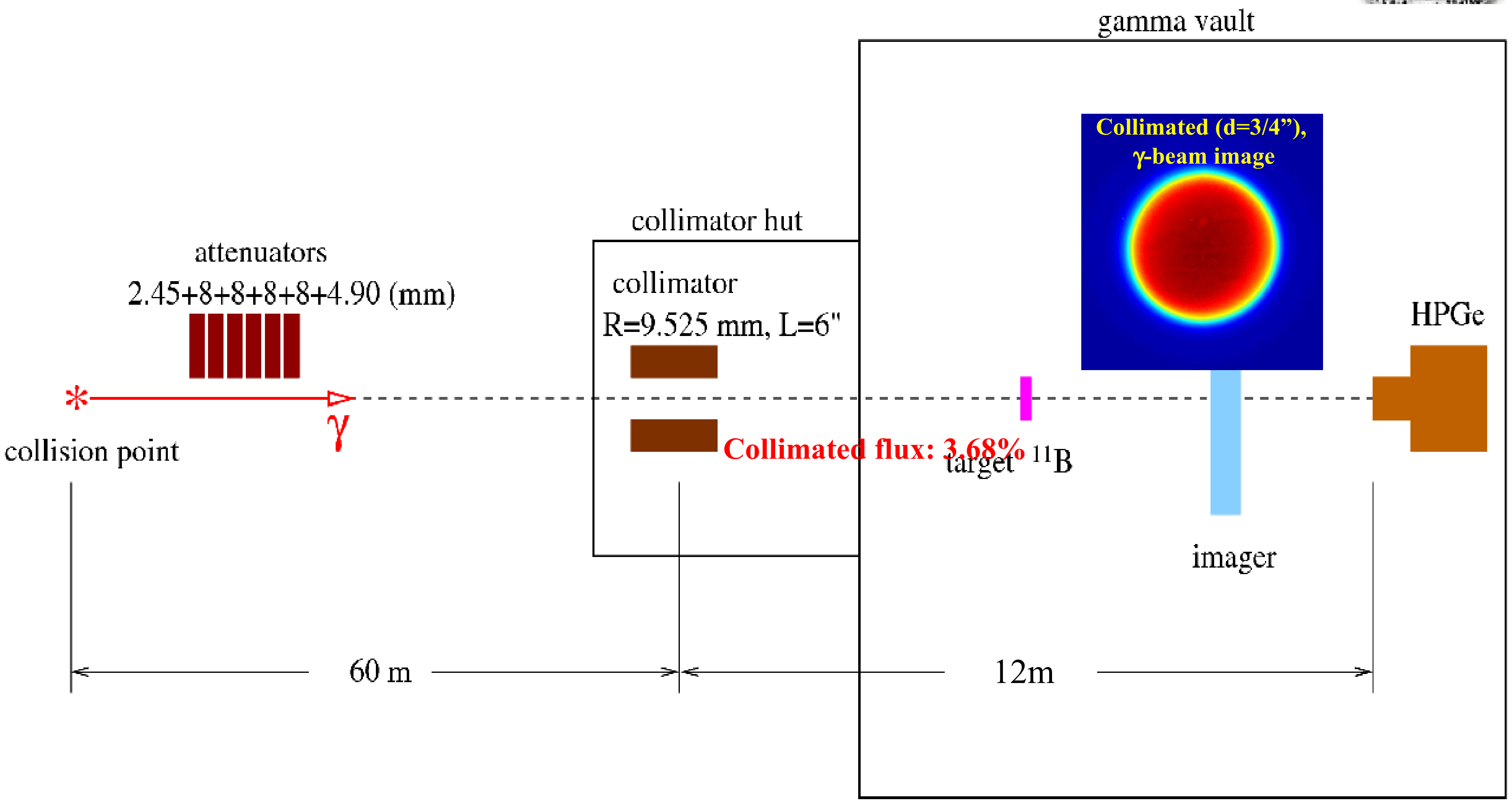
Effective: R ~ 99.95%



761 nm, Loss ~0.00107

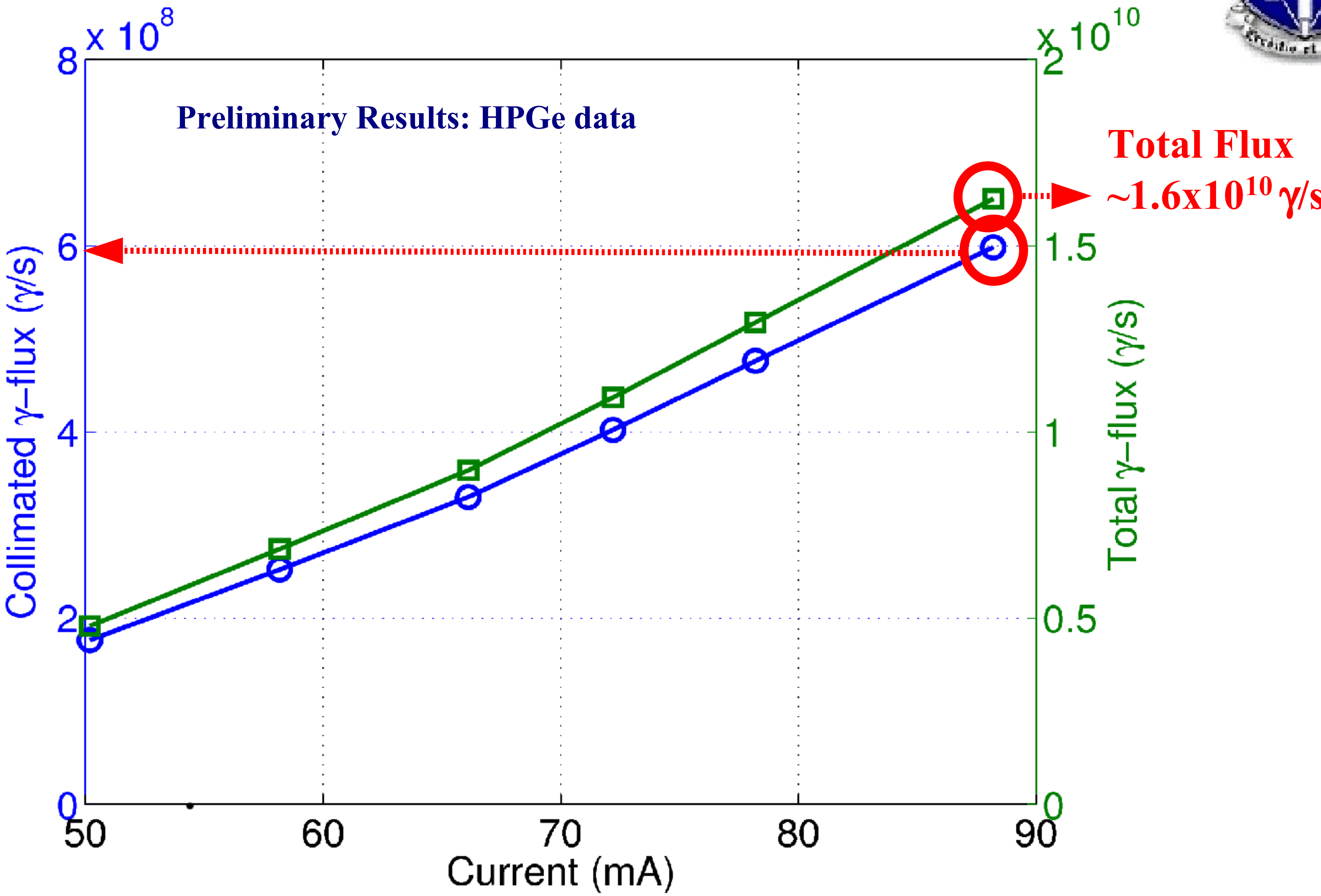


Total Flux and FEL Intracavity Power Measurements



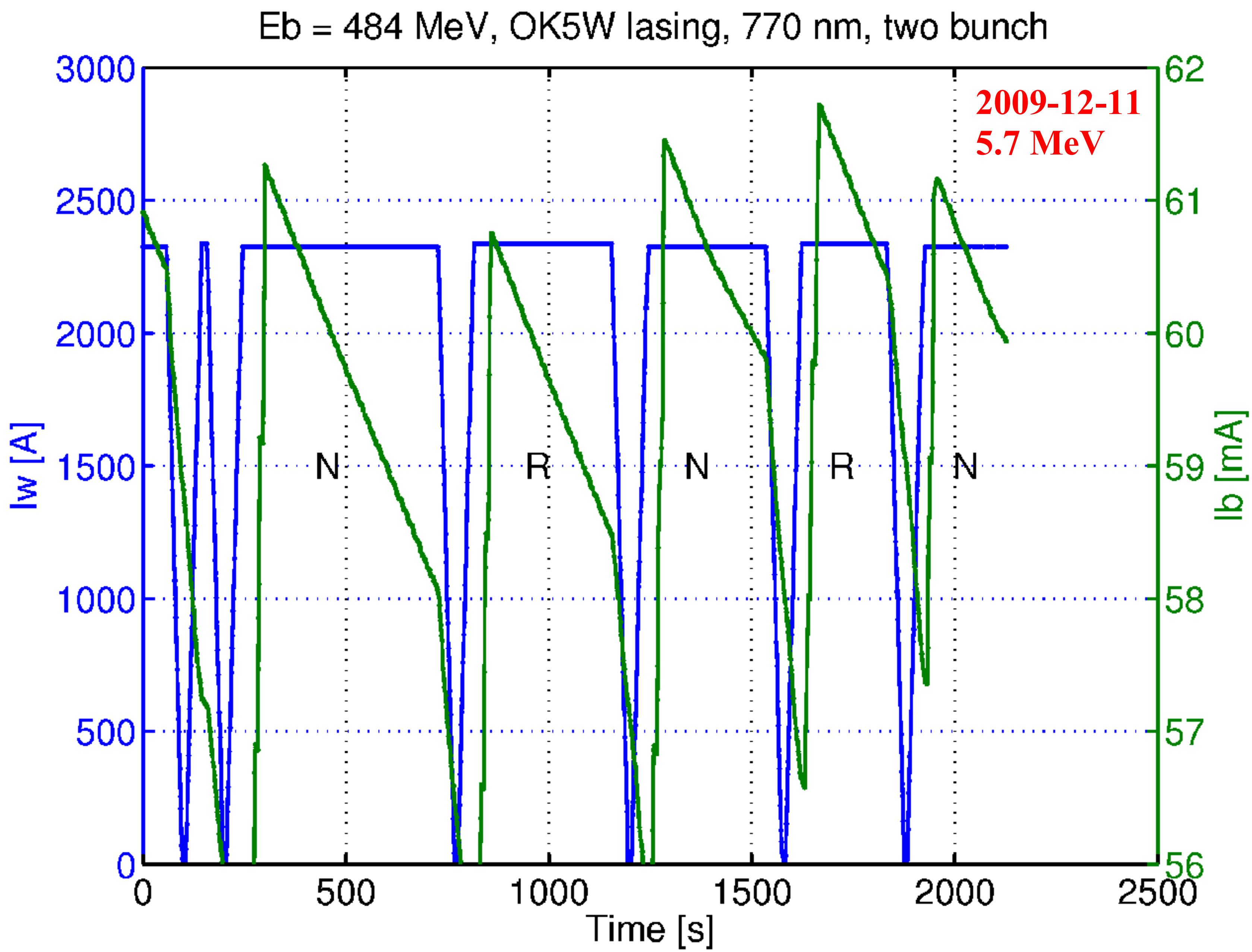
Peak Performance of HIGS Gamma-ray Beam

Ebeam: 514 MeV; FEL beam λ = 545 nm; Collimator: d = 0.75"

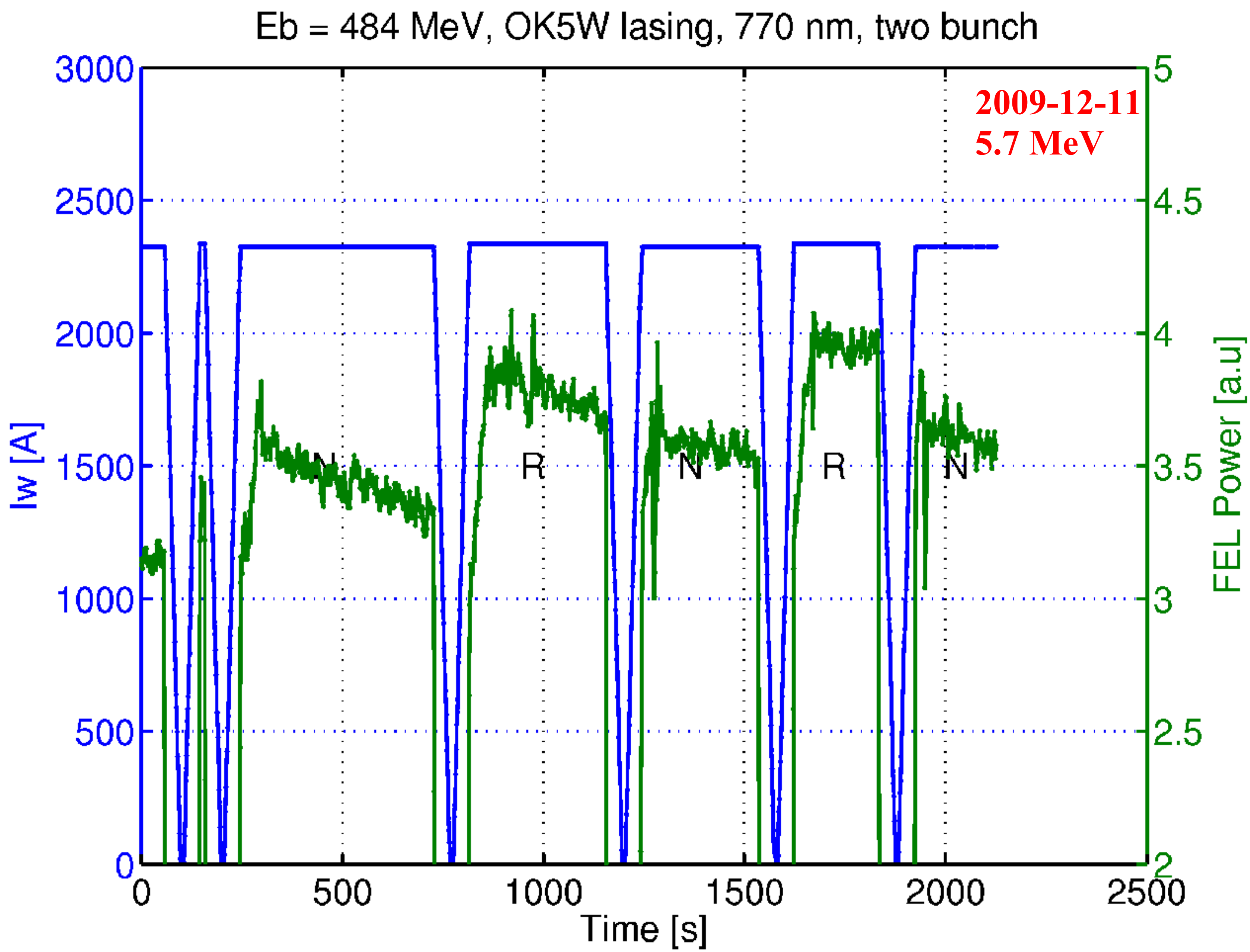


^{11}B data: 8.9 MeV gammas, P_{FEL} = 1.6 kW (+/- 0.2 kW) (two-bunch)

Helicity Switch with OK-5 FEL



Helicity Switch with OK-5 FEL



User Research Programs at HIGS Facility

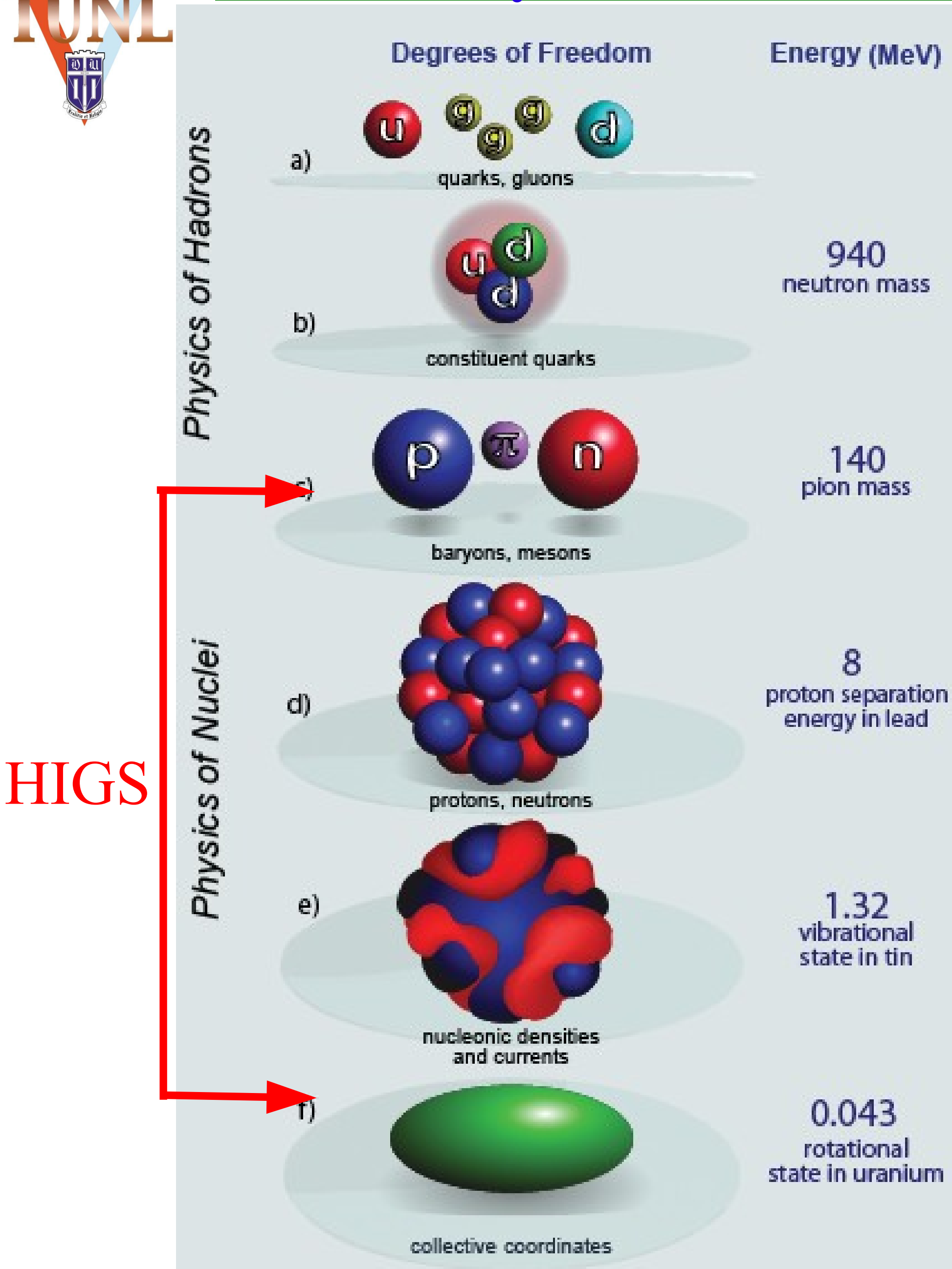
Nuclear Physics Research

Astrophysics Research

Novel Detector Development and Calibration

Industrial and Medical Applications

Nuclear Physics: A Hierarchy of Scales and Energies



Nuclear Structure

Low-energy Electromagnetic Few-Nucleon Physics

Astro-physics

Gerasimov-Drell-Hearn (GDH) Sum Rule

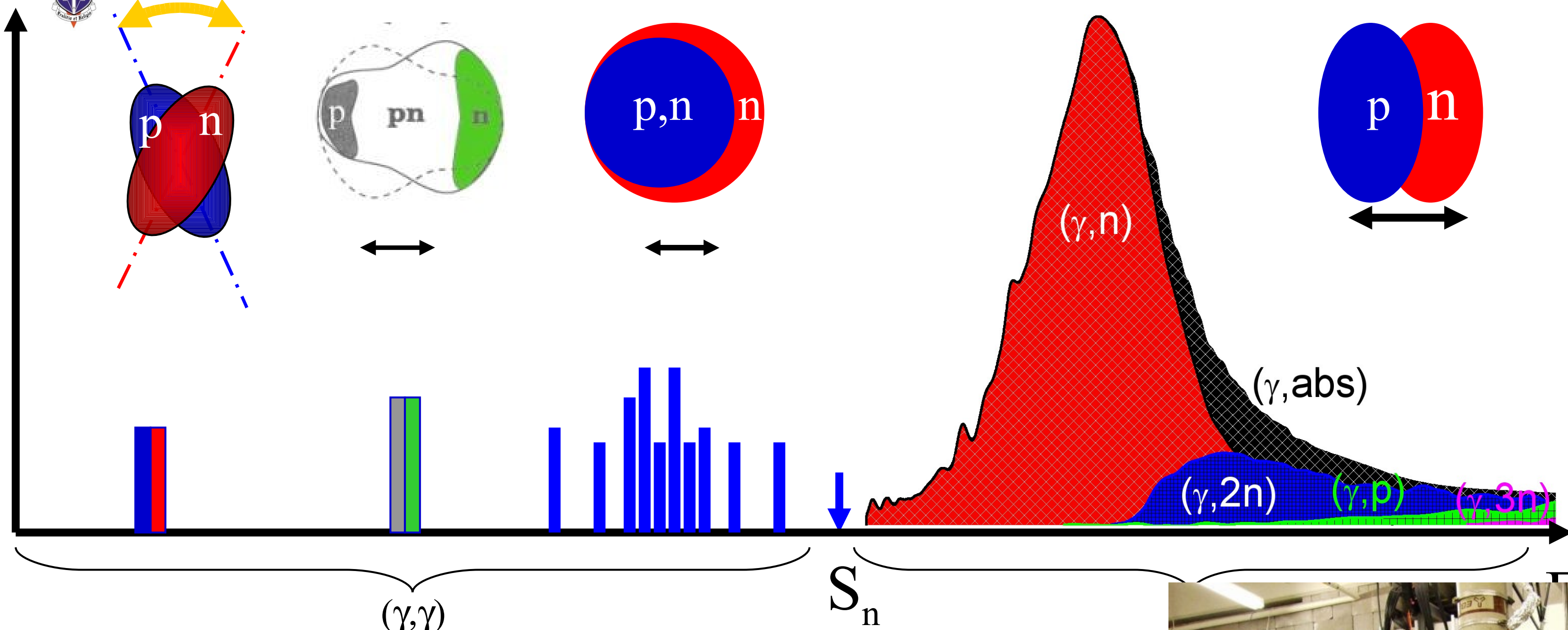
Compton Scattering from Nucleons

Photon-Pion Physics

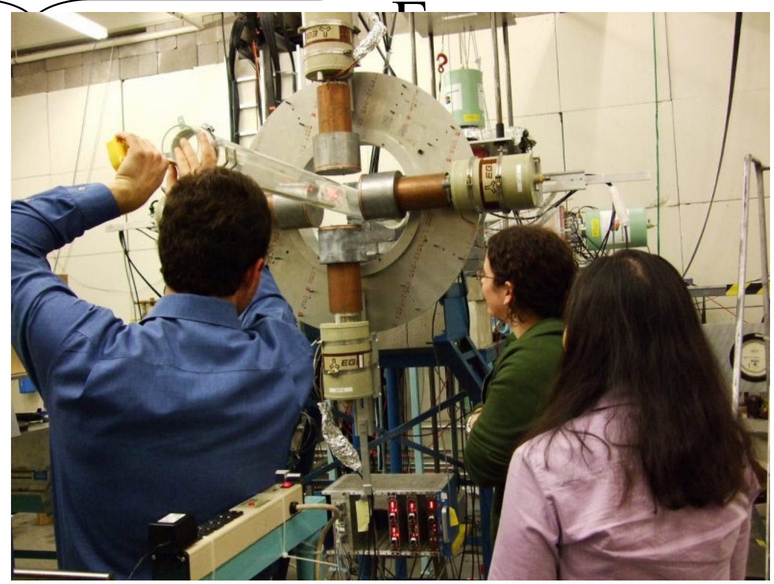
US DoE Division of Nuclear Physics 2007 Long Range Plan
dnp.nscl.msu.edu/nplinks/

H. R. Weller *et al.*, "Research Opportunities at the Upgraded HIγS Facility," Prog. Part. Nucl. Phys. Vol 62, Issue 1, p. 257-303 (2009).

Characteristic Response of Nucleus to EM Radiation



- Giant Dipole Resonance: E_x ~16 MeV, B(E1) ~ 10 W.u.
- Orbital "Scissors" mode: E_x ~ 3 MeV, B(M1) ~ $3\mu_N^2$
- Two Phonon Excitation: E_x ~ 4 MeV, B(E1) ~ 10^{-3} W.u.
- Pygmy Dipole Resonance ?

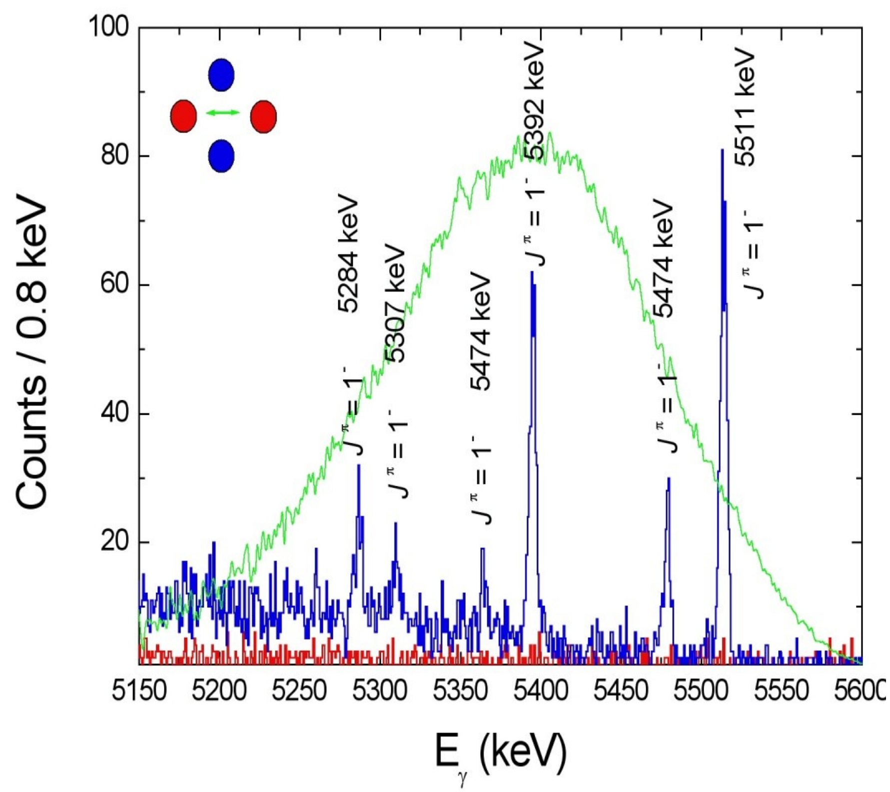


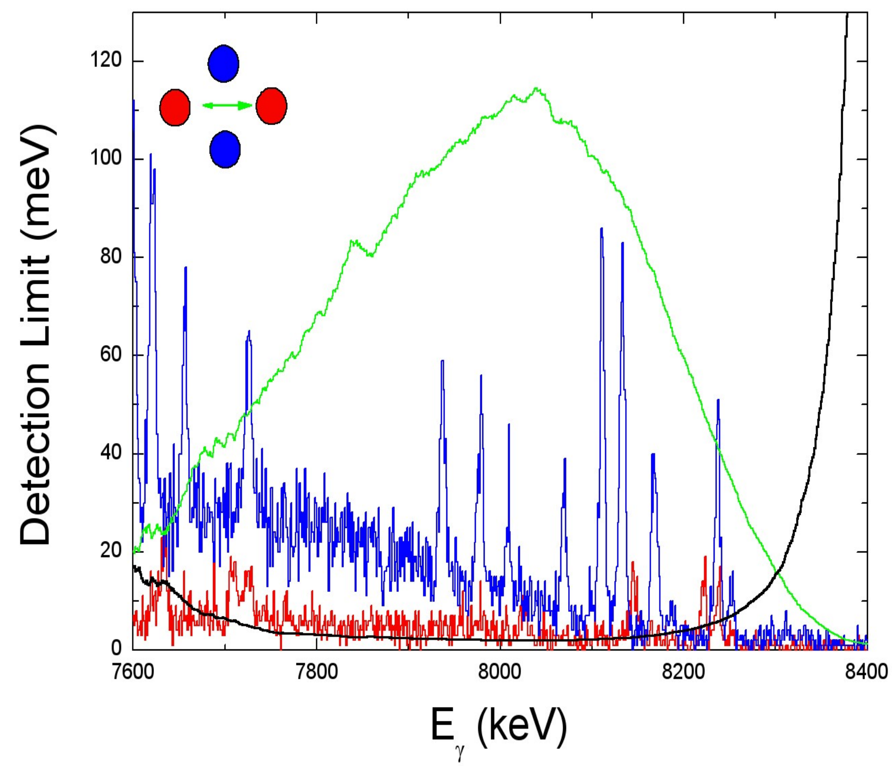
Courtesy of Anton Tonchev, TUNL&Duke U.

Nuclear Resonance Fluorescence Technique

$^{138}Ba(\gamma,\gamma')$ $E_\gamma = 5.40 \pm 0.11$ MeV

$^{90}Zr(\gamma,\gamma')$ $E_\gamma = 8.10 \pm 0.40$ MeV



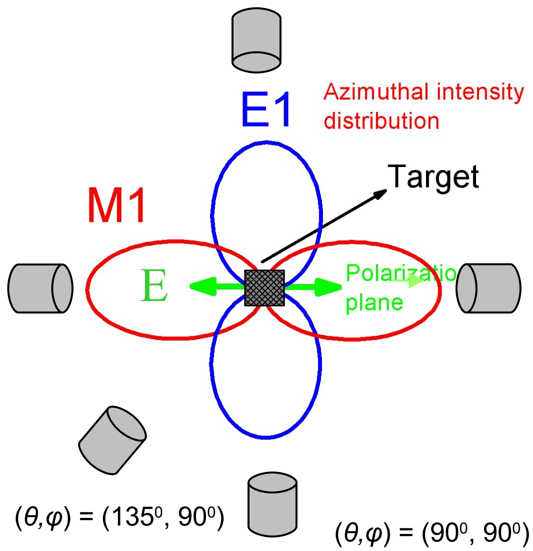


High detection sensitivities: resonance states with $\Gamma_{tot} \geq$ 1meV

Courtesy of Anton Tonchev, TUNL&Duke U.

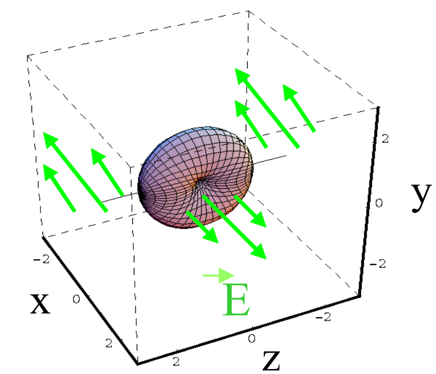
Parity Measurements with a Linearly Polarized Photon Beam

Azimuthal distribution



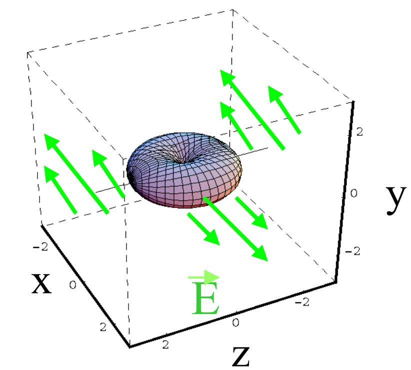
Electric (E1)

$0^+ \rightarrow 1^- \rightarrow 0^+$



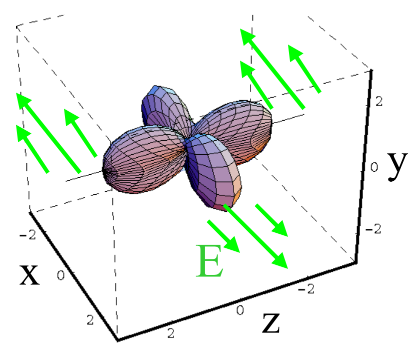
Magnetic (M1)

$0^+ \rightarrow 1^+ \rightarrow 0^+$



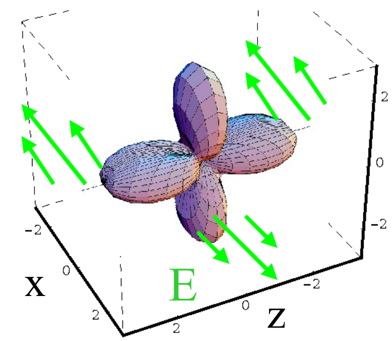
Quadruple (E2)

$0^+ \rightarrow 2^- \rightarrow 0^+$



Quadruple (M2)

$0^+ \rightarrow 2^+ \rightarrow 0^+$



$$\Sigma = \frac{W(90^0,0^0) - W(90^0,90^0)}{W(90^0,0^0) + W(90^0,90^0)} = \pi_1 = \begin{cases} +1 & \text{for } J^\pi = 1^+, 2^+ \\ -1 & \text{for } J^\pi = 1^-, 2^- \end{cases}$$

Experimental Asymmetry of 0.96

A. Tonchev, NIM B 241 (2005) 51474

Courtesy of Anton Tonchev, TUNL&Duke U.

O-TPC at HIGS Collaboration:

The O-TPC at HIγS Collaboration (2009)

UConn :*
M. Gai
T.J. Kading
P.N. Seo (50%)
L. Weissman
A.H. Young
William R. Zimmerman

TUNL, Duke:*
M.W. Ahmad
E.R. Clinton
C.R. Howell
S.S. Henshaw
P.P. Martel
P.N. Seo (50%)
S.C. Stave
C. Sun
H.R. Weller
Y.K. Wu

Yale:**
G.F. Burkhard
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UHartford:
J.E. McDonald

PTB, Braunschweig: ***
B. Bromberger
V. Dangendorf
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GCSU:
R.H. France III
NGCSU:*
R.M. Prior
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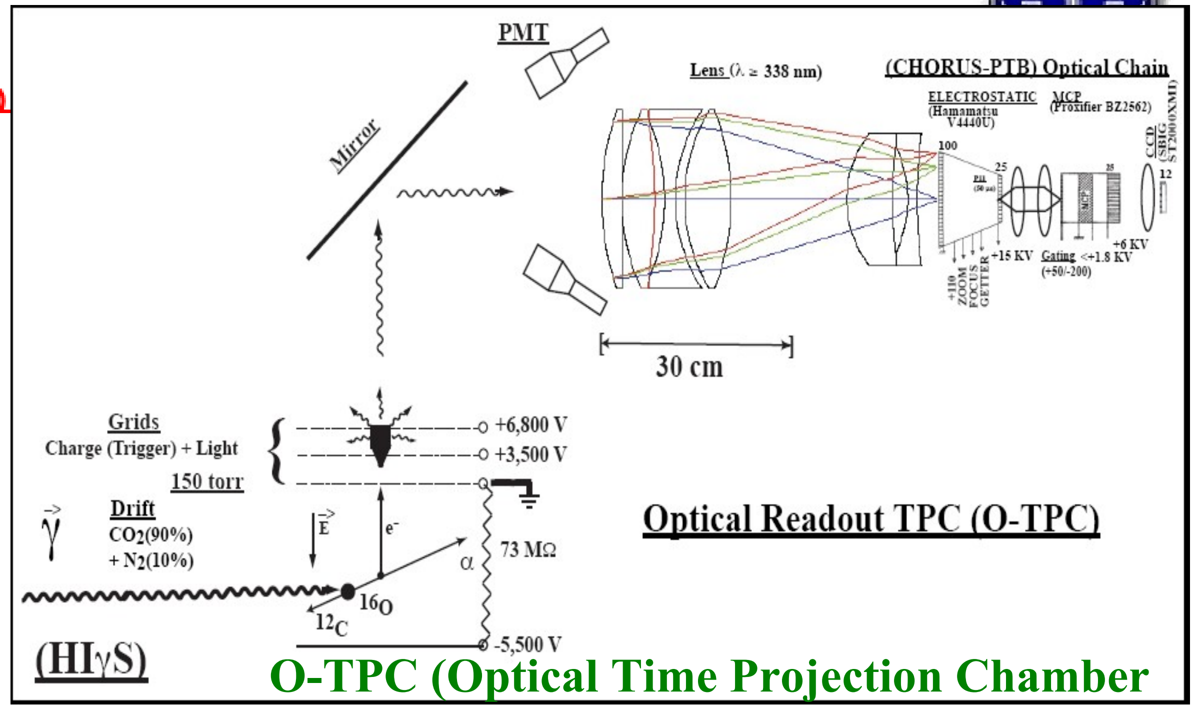
Weizmann, Israel:**
A. Breskin
R. Chechik
M. Klin

UCL, LLN, Belgium:***
Th. Delbar

*   Supported by US Department of Energy

**   Supported by the American Committee on Weizman



O-TPC (Optical Time Projection Chamber


Some collaborators in HIGS target room, April 3, 2008

Courtesy of M. Gai, UConn & Yale

Nuclear Synthesis: Helium Burning Problem

Helium Burning:

$3\alpha \rightarrow {}^{12}C$ Known

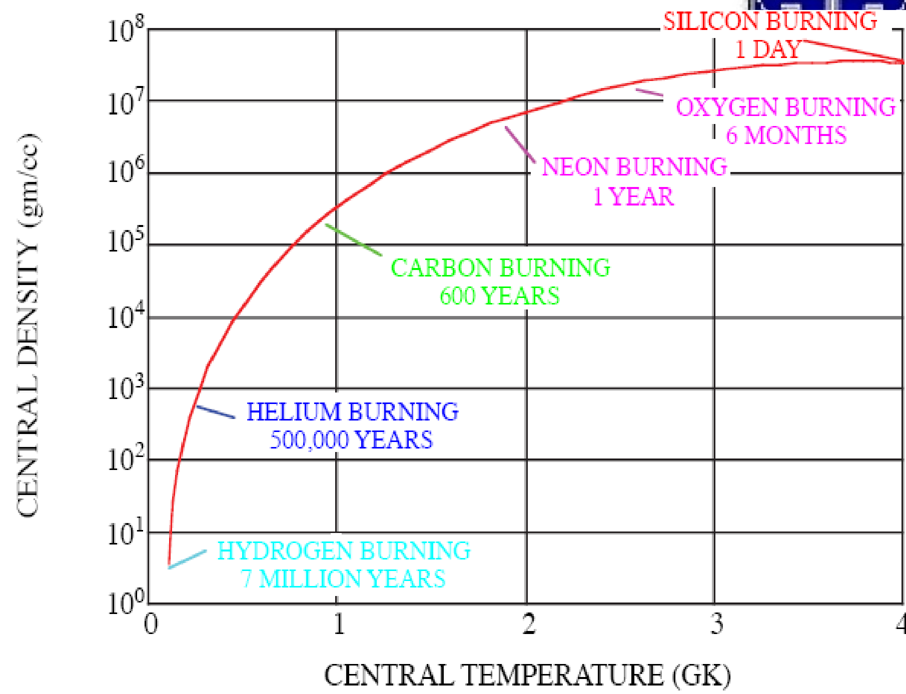
$\alpha + {}^{12}C \rightarrow {}^{16}O$???

C/O = ?

${}^{12}C(\alpha,\gamma){}^{16}O$ (E_{cm} = 300 keV)

$$\sigma(\alpha,\gamma) = S/E \times e^{-2\pi\eta}$$

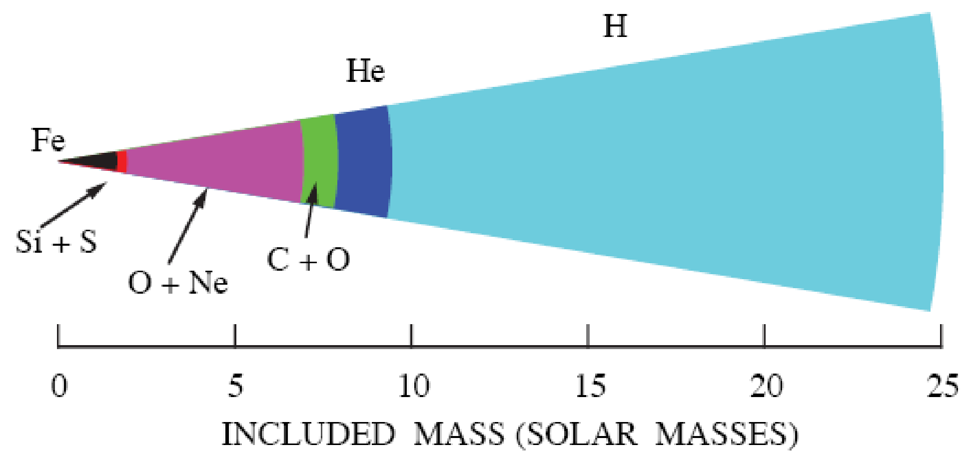
$$(\eta = e^2 Z_1 Z_2/\hbar\upsilon = Z_1 Z_2 \alpha/\beta)$$



Bethe & Brown, 1985 (x10)

At HIGS: reverse reaction

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

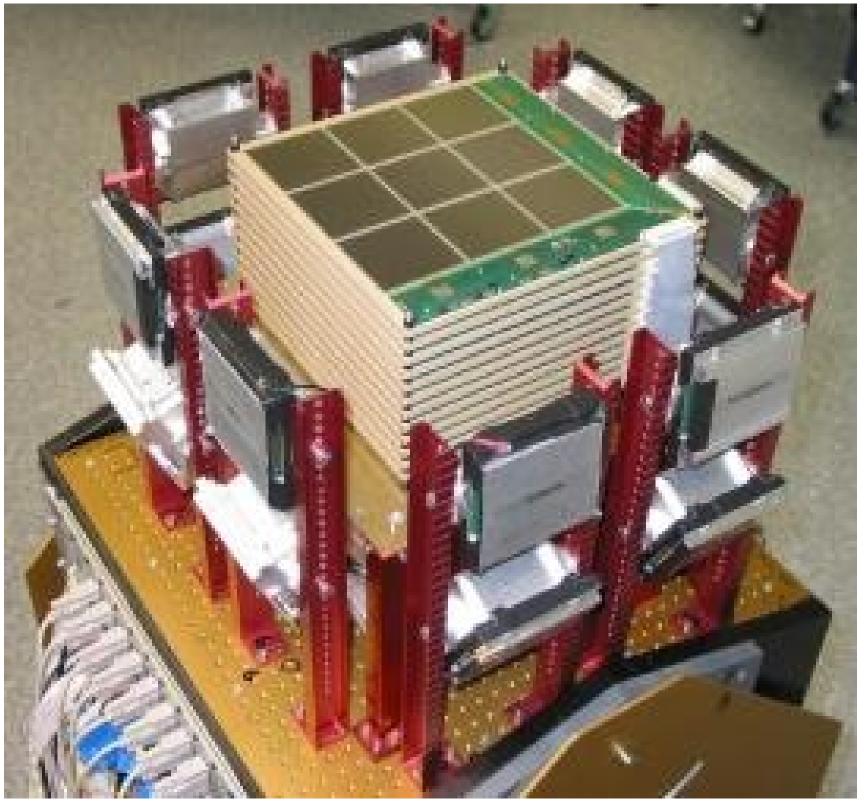


Courtesy of M. Gai, UConn & Yale

Gamma-ray Telescope Calibration

MEGA Project (Max-Planck-Institut für extraterrestrische Physik)

- Medium Energy Gamma-Ray Astronomy Telescope: 400 keV and 50 MeV
- Essential component for next-generation astrophysics satellite observatories
- A tracker: silicon strip detectors + a calorimeter with segmented CsI(Tl) bars



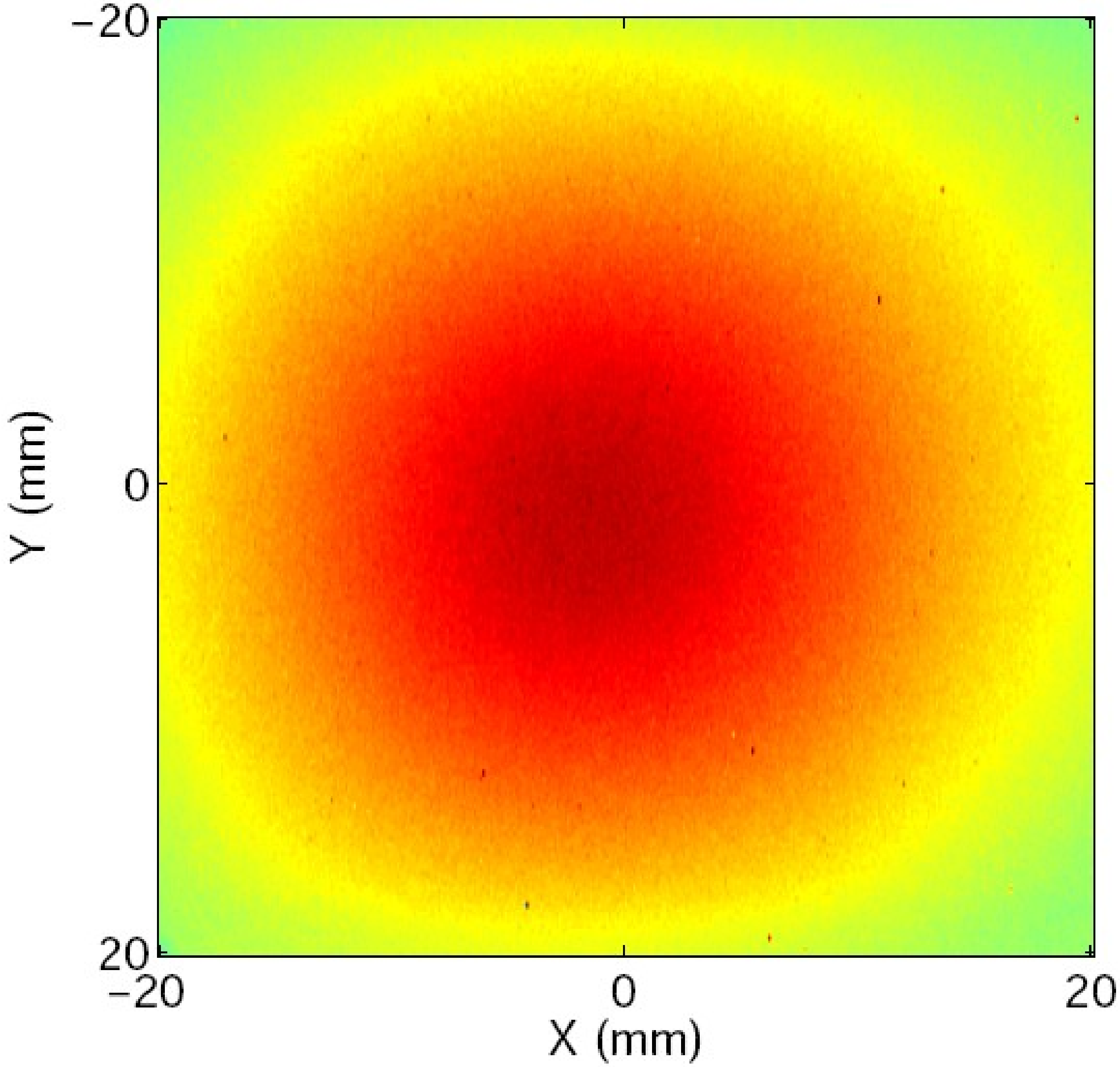
MEGA Prototype detector

calibrated at HIGS (2002-2003)

www.gamma.mpe-garching.mpg.de/MEGA/mega.html
R. Andritschke et al., NewAR 48 (2004) p. 281-285.

2010: LANL Group used HIGS beams to
Calibrate Gamma Reaction History diagnostic (GRH-6m) and OMEGA Gas Cherenkov Detector (GCD-1) for *National Ignition Facility (NIF)*
(PI: Hans Herrmann, LANL)

Compton Gamma-beam Imaging at HIGS



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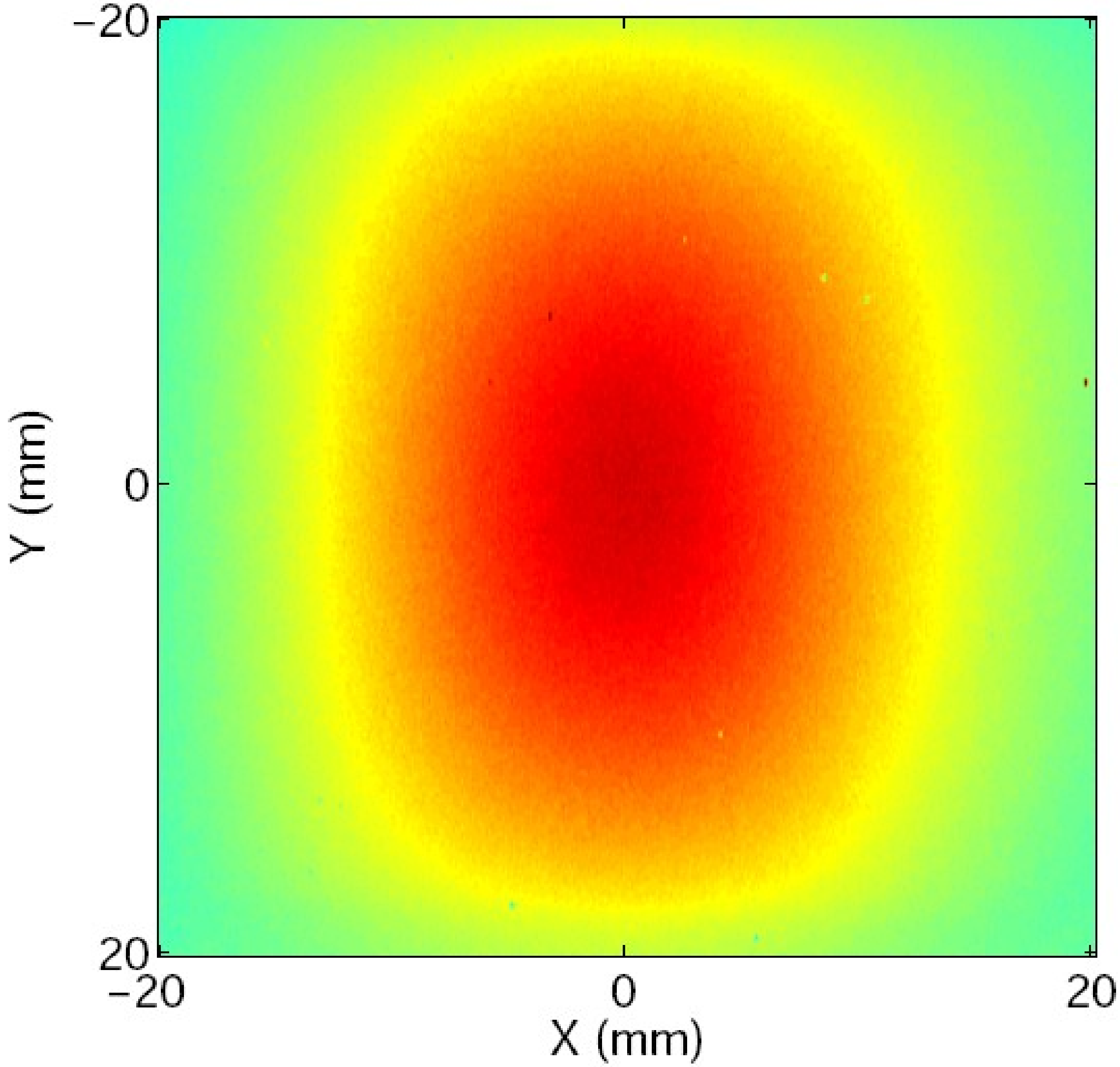
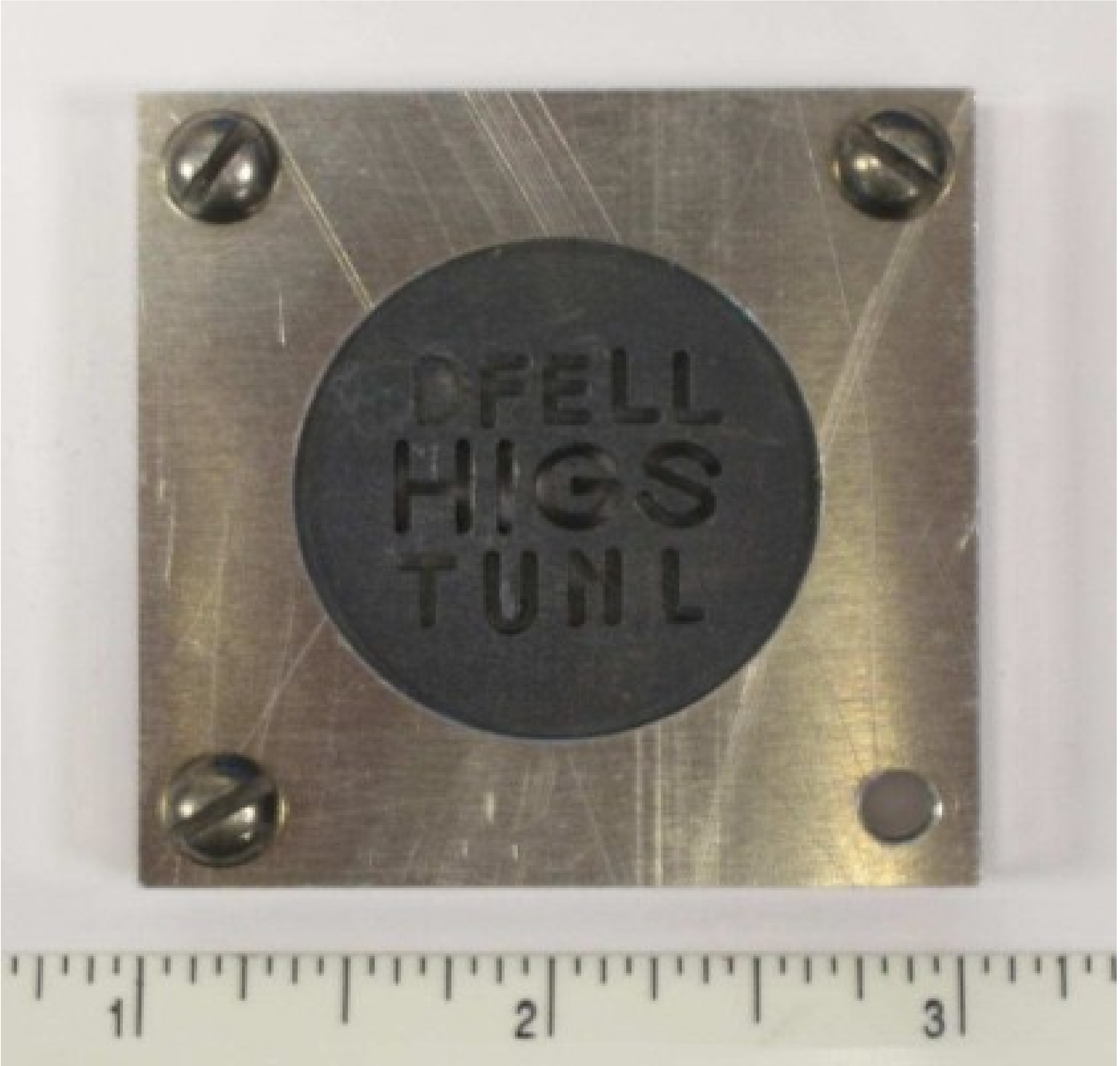
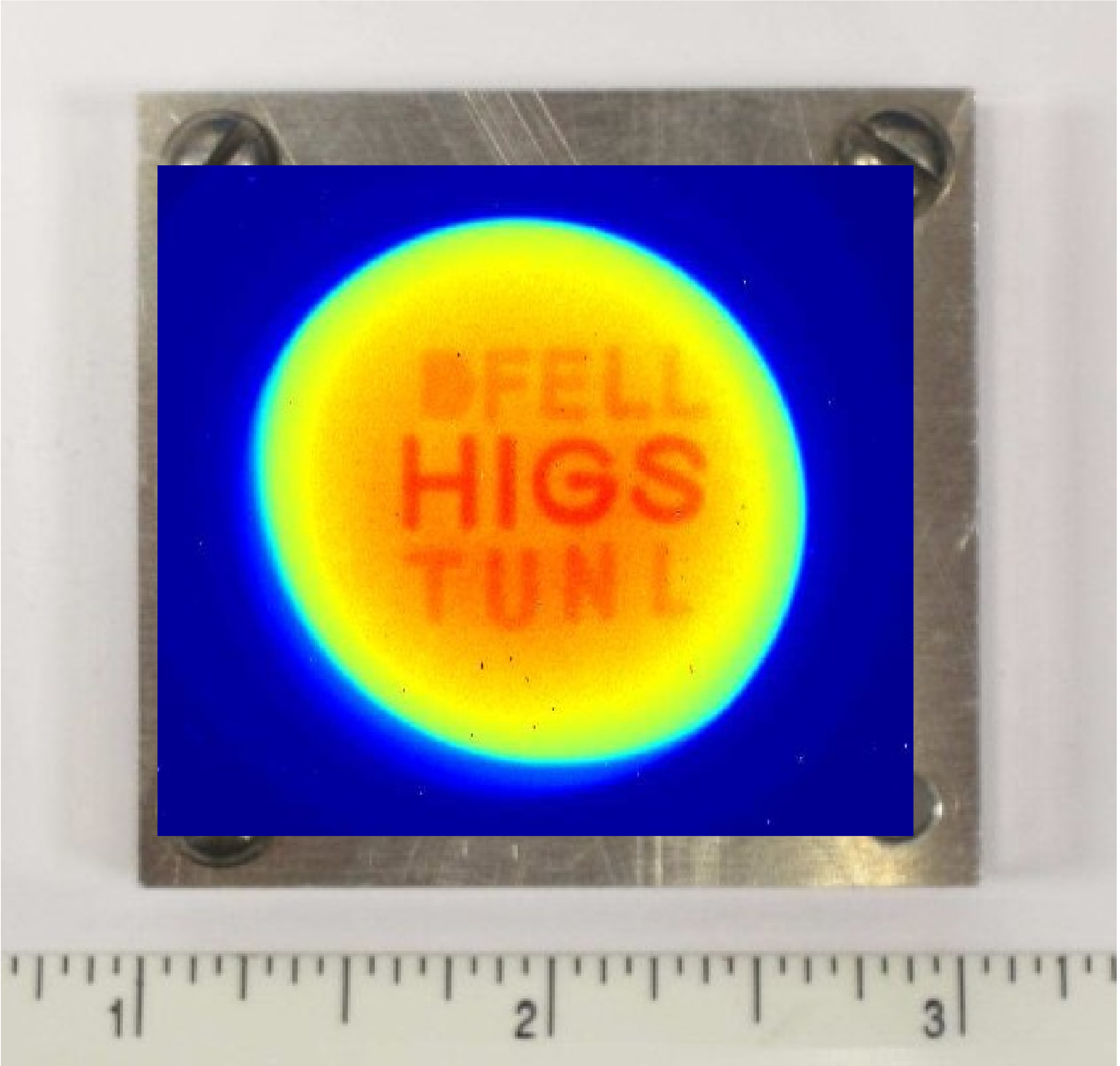


Compton Gamma-beam Radiograph



Compton Gamma-beam Radiograph



Summary

High Intensity Gamma-ray Source (HIGS) in 2010

- Capabilities
  - Energy Tuning: 1 - 100 MeV
  - Maximum Total Flux: ~ 10^{10} γ/s around 10 MeV
  - Maximum Spectrum Flux: : ~ 10^{3} γ/s/eV around 5 - 10 MeV
  - High Energy Resolution: 0.8% (< = 5 MeV)
  - Polarization: linear, and switchable left- and right-circular

Future Development

- Higher Gamma-beam Energy: 100 - 160 MeV for photon-pion physics research
- High Flux Operation 10^{12} γ/s (total flux) 2 – 20 MeV

Thank You