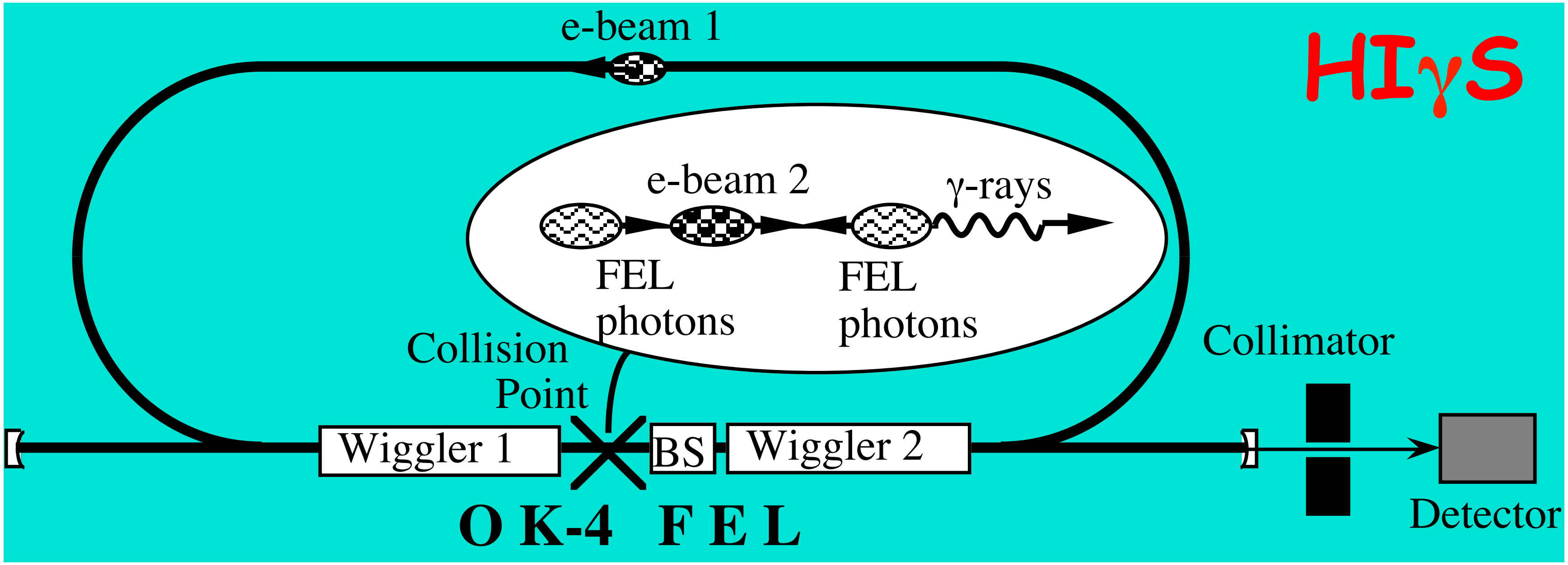
Compton Scheme & Prospects

Vladimir N. Litvinenko

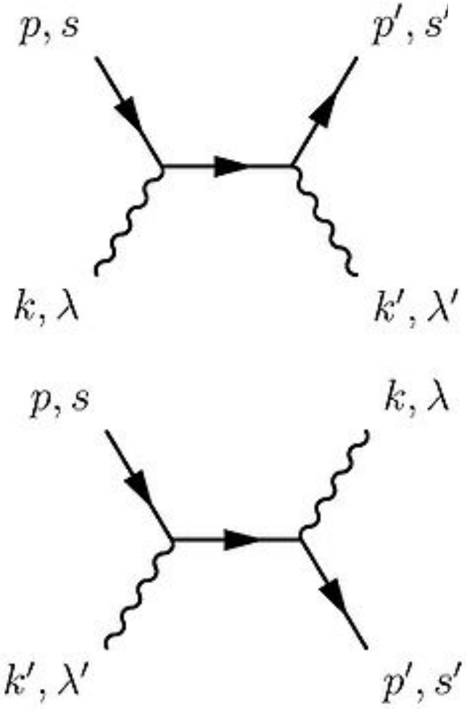
BNL

Schematic of a storage ring FEL γ-ray Source



$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1 + r + \gamma^2\theta^2\right)}; \quad r = \frac{4\gamma E_{ph}}{mc^2}; \quad E_{ph} = \frac{2\gamma^2 hc}{\lambda_w\left(1 + K_w^2/2\right)}; \quad \gamma = \frac{E_e}{mc^2};$$

Gamma-ray Production in a Storage Ring Free Electron Laser, V.N. Litvinenko et. al., PRL, **78**, 24 (1997) 4569



$$s = (p+k)^2 = (p'+k')^2 = m^2 + 2pk = m^2 + 2p'k';$$

$$t = (p-p')^2 = (k-k')^2 = 2(m^2 - pp') = -2kk'; \qquad s+t+u = 2m^2;$$

$$u = (p-k')^2 = (p'-k)^2 = m^2 - 2pk' = m^2 - 2p'k;$$

$$\boxed{x = \frac{s-m^2}{m^2}; \quad y = \frac{m^2-u}{m^2}.}$$

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

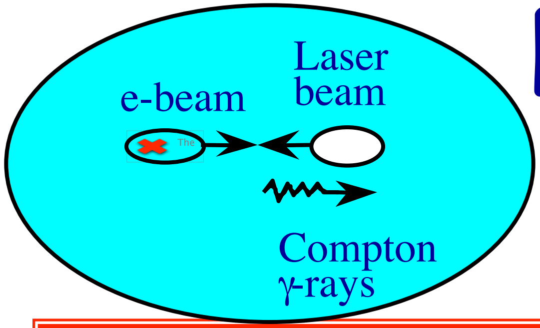
$$x \ll 1$$

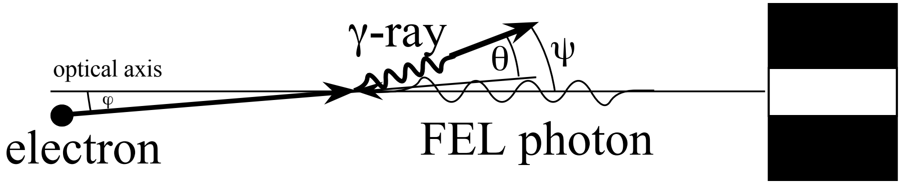
$$\overline{\sigma}_{tot} \cong \frac{8\pi r_e^2}{3}(1-x);$$

$$x \gg 1$$

$$\overline{\sigma}_{tot} \cong \frac{2\pi r_e^2}{x}\left(\ln x + \frac{1}{2} \right).$$

Distribution of γ-rays



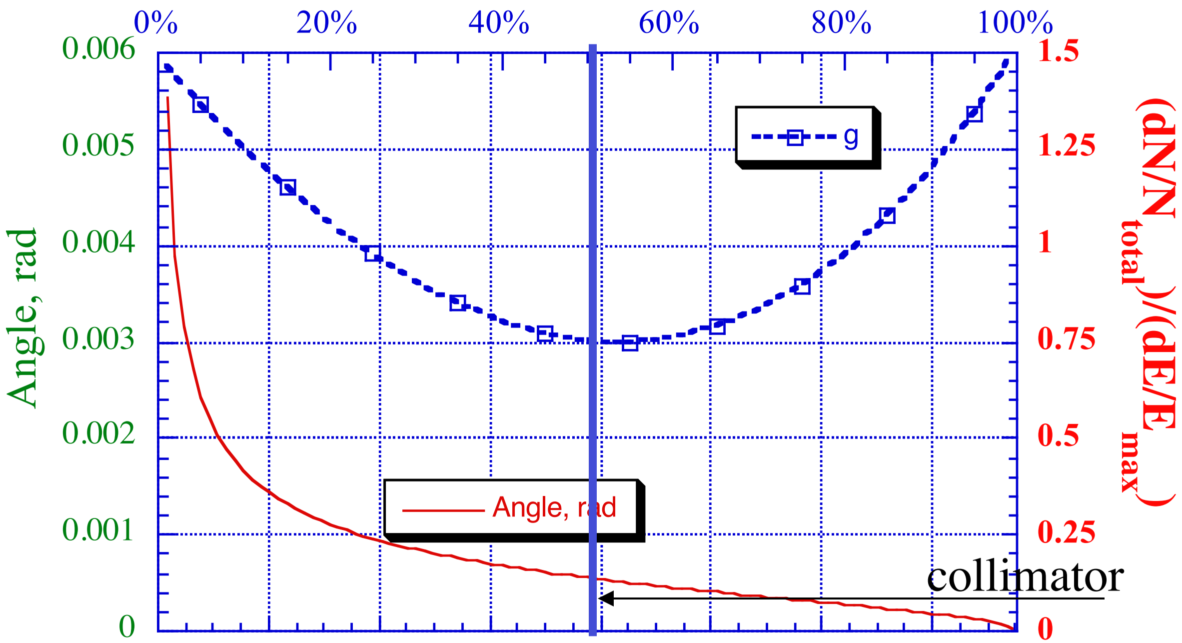


$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1+2x+\gamma^2\theta^2\right)};$$

$$x = \frac{4\gamma E_{ph}}{mc^2};$$

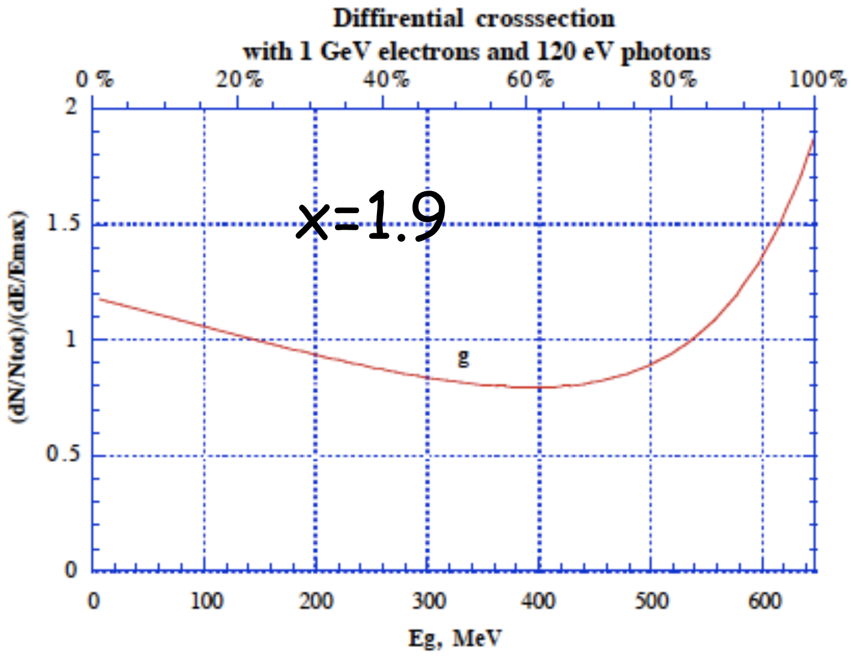
For 20 (25) MeV γ-rays

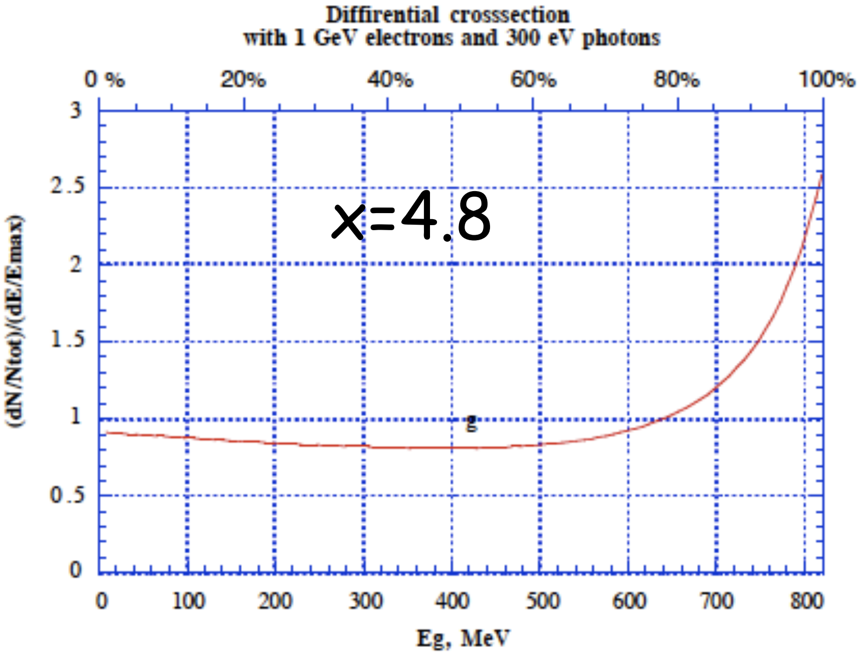
Energy of electrons GeV	Laser λ, μm
3.26 (3.64)	10 (CO_2)
0.93 (1.04)	0.8 (?)
0.66 (0.74)	0.4 (FEL)



x<<1

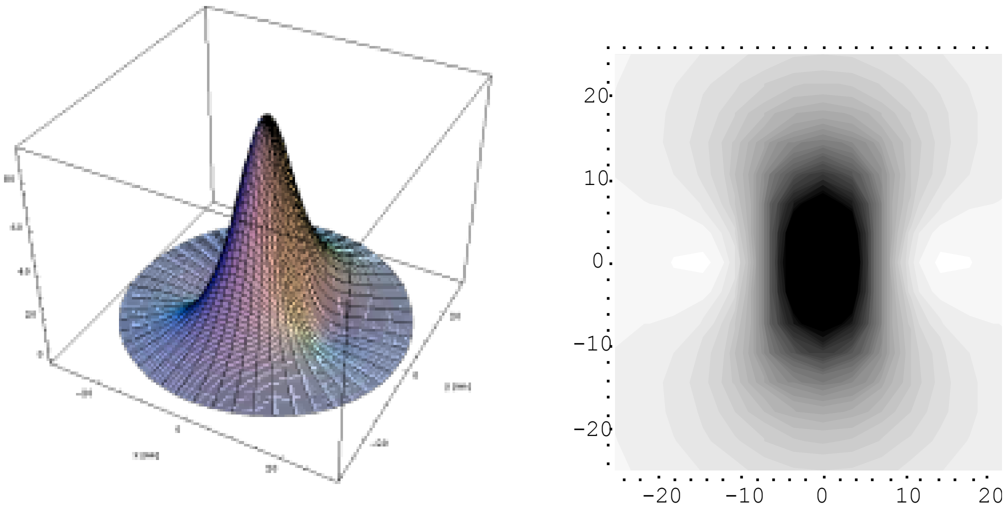
At large recoil R>1





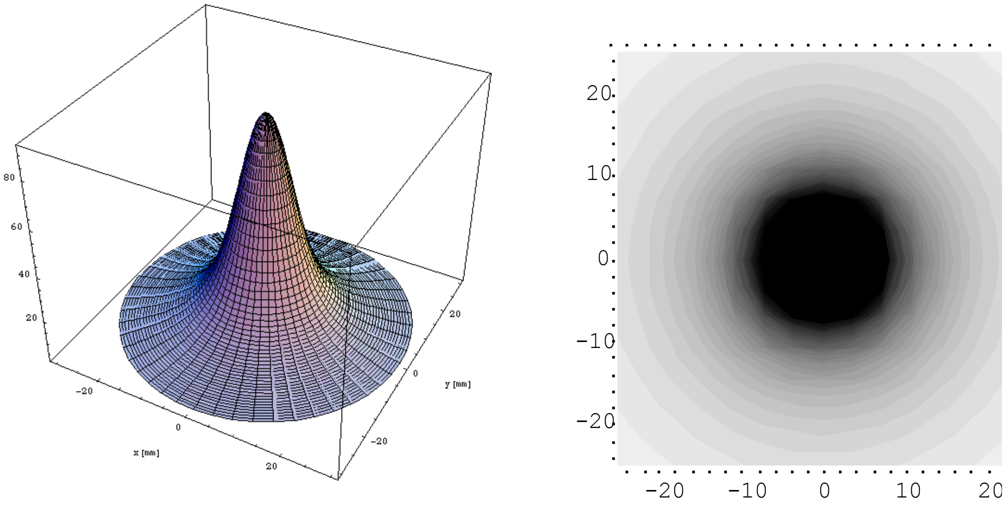
While cross-section is reduced, the spectrum peaks at the Compton edge

Linear polarization



(a)

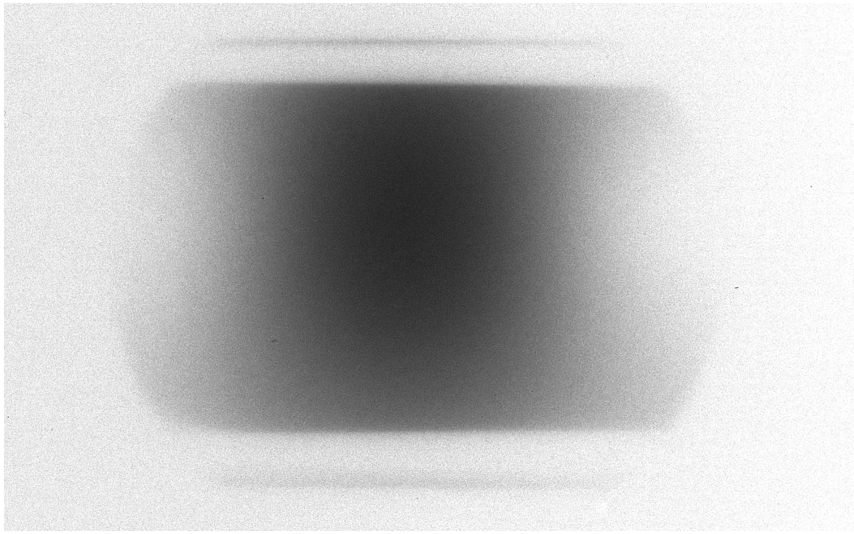
Circular polarization



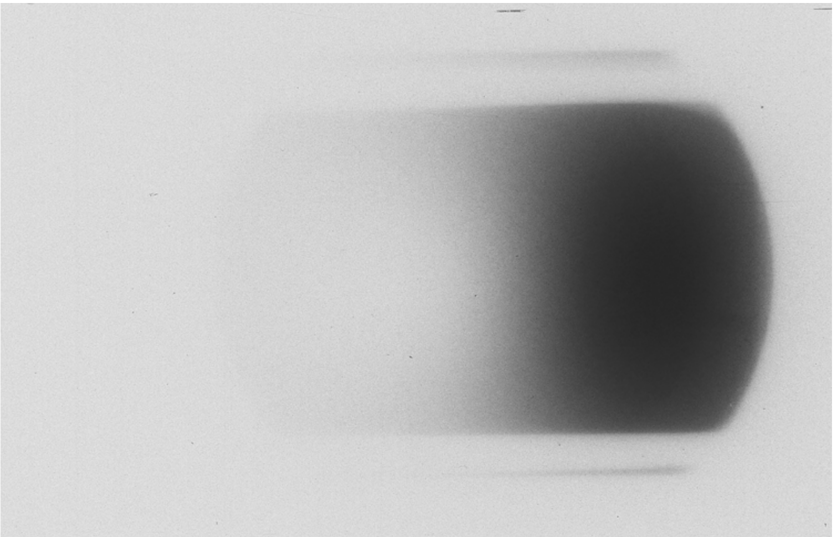
Photograph of the OK-4 DSR γ-ray beam profile

(Spatial distribution: 30 m from Collision Point)

E_e = 600 MeV, E_{ph} = 3.44 e V (λ = 362 nm) and E_g = 18.3 Me V

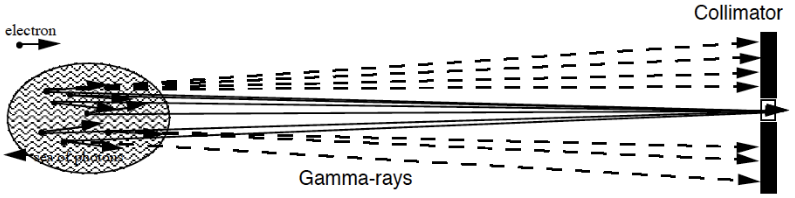


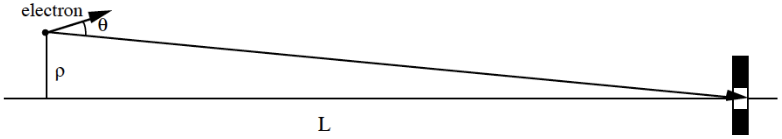
The electron beam is on the axis of OK-4



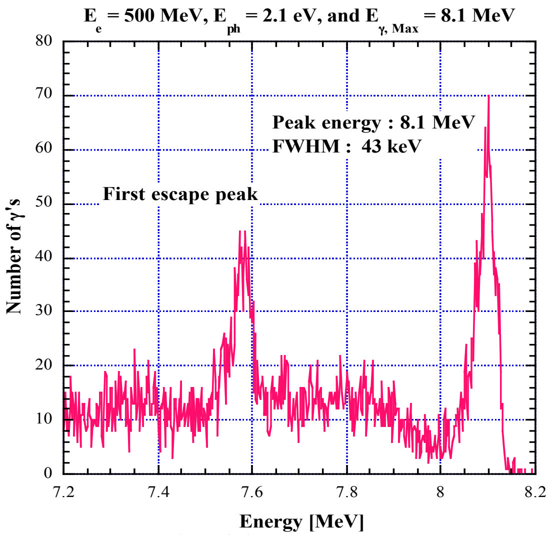
The angle of the e- beam in collision point is +0.25 mrad

Mono-energetic beam

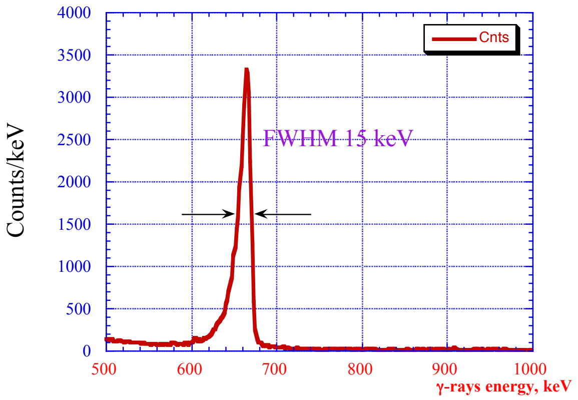




$$\frac{\Delta\omega'}{\omega'} \cong \left\{1-\frac{2\gamma^2\hbar\omega}{\left(1+(\gamma\theta_f)^2\right)\mathbf{E}+2\gamma^2\hbar\omega}\right\}\frac{\Delta\omega}{\omega}-\frac{\theta^2{}_i}{4}$$



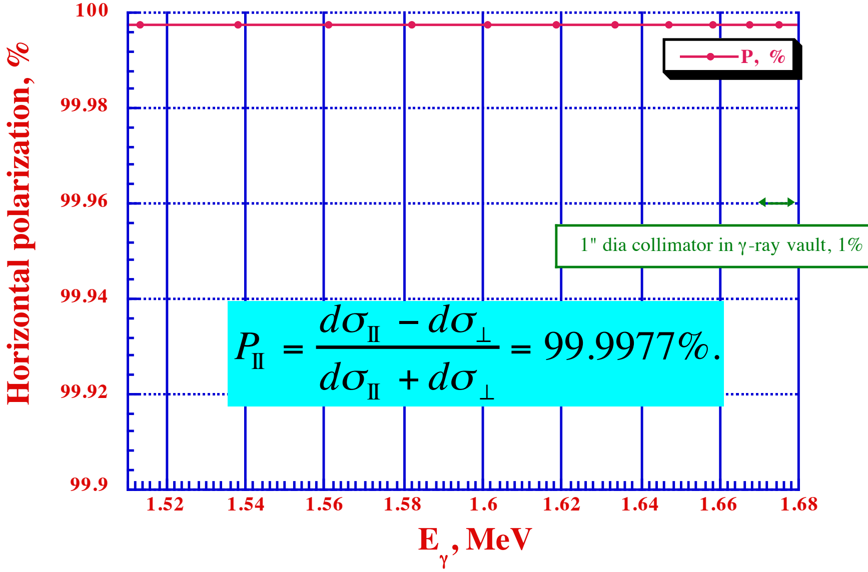
First 670 keV γ-rays
from the OK-4 FEL lasing at 2.1 µm.
The energy of the Duke storage ring is 274 MeV.



The use of the central cone of the γ-ray beam provides for very high degree of polarization

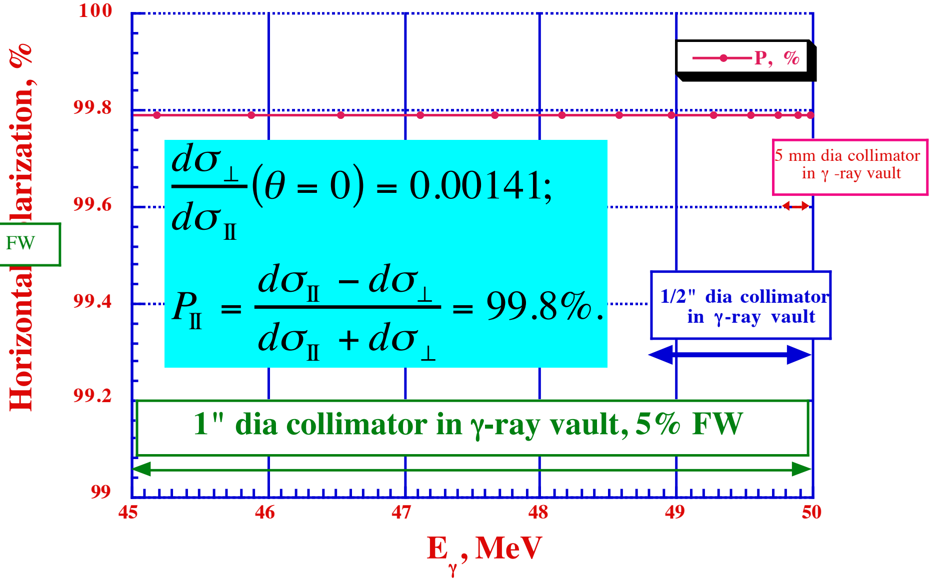
$$\frac{d\sigma_\perp}{d\sigma_{II}}(\theta=0)=\frac{x^2}{(2+x)^2};\quad x=\frac{E_\gamma}{E_e}.$$

Data Polarization @1.68 MeV



$$P_{II}=\frac{d\sigma_{II}-d\sigma_\perp}{d\sigma_{II}+d\sigma_\perp}=99.9977\%.$$

Polarization of HIGS γ-rays
E$_e$=800 MeV, λ$_{FEL}$=227.9 nm



$$\frac{d\sigma_\perp}{d\sigma_{II}}(\theta=0)=0.00141;$$

$$P_{II}=\frac{d\sigma_{II}-d\sigma_\perp}{d\sigma_{II}+d\sigma_\perp}=99.8\%.$$

FEL: E$_{ph}$=1.771 eV; λ=700 nm;
Beam: E$_e$=250 MeV; E$_\gamma$=1.68 MeV.

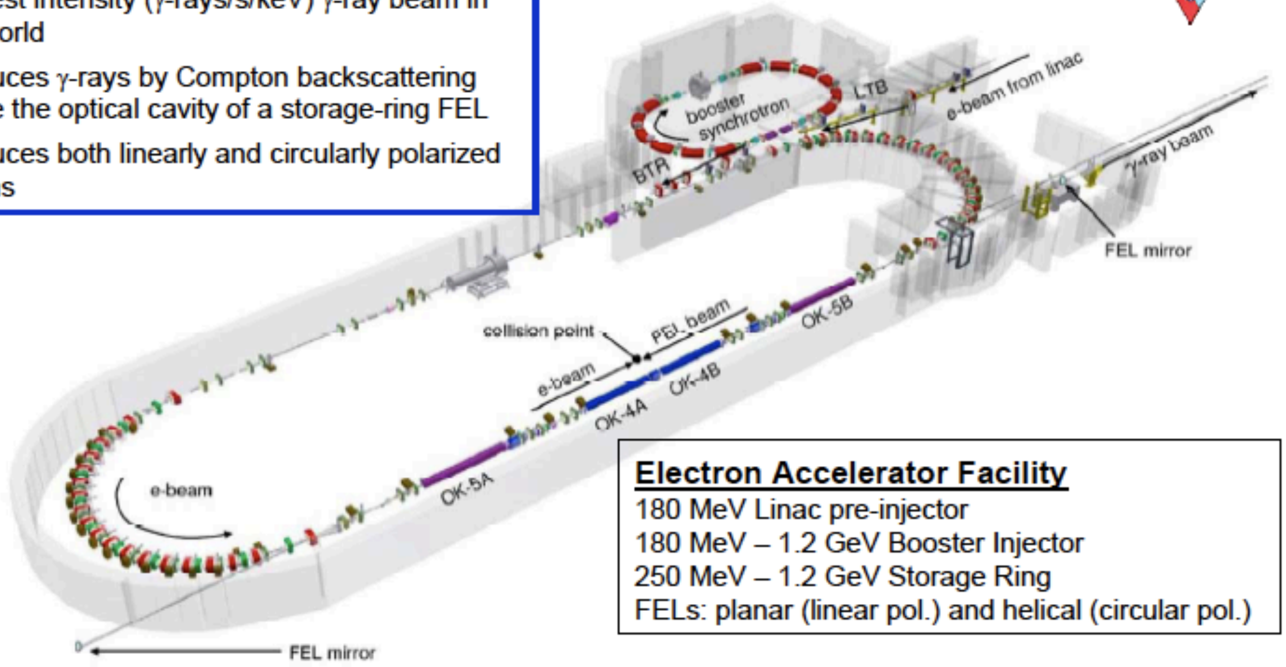
FEL: E$_{ph}$=5.44 eV; λ=227.9 nm;
Beam: E$_e$=800 MeV; E$_\gamma$=50 MeV.

With x~4.8 SAPPHiRE should use polarized electrons!

As August of 2012

High Intensity Gamma-ray Source (HIGS) at TUNL

- Highest intensity (γ-rays/s/keV) γ-ray beam in the world
- Produces γ-rays by Compton backscattering inside the optical cavity of a storage-ring FEL
- Produces both linearly and circularly polarized beams



Electron Accelerator Facility
180 MeV Linac pre-injector
180 MeV – 1.2 GeV Booster Injector
250 MeV – 1.2 GeV Storage Ring
FELs: planar (linear pol.) and helical (circular pol.)

γ-ray beam parameters	Values
Energy	1 – 100 MeV
Linear & circular polarization	> 95%
Intensity with 5% $\Delta E_\gamma/E_\gamma$	> 10^7 γ/s

For more details see:
http://www.tunl.duke.edu/higs/

From: M.W Ahmed et al., HIGS2: The Next Generation Compton g-ray Source

Modes of SR FEL HIγS

- “No-loss” mode
  - γ-rays top energy is less than energy acceptance of the ring (~20 MeV @ Duke)
  - Max γ-ray flux is limited by energy spread growth in the e-beam (~10^{13} γ’/sec, 200 mA, 1 GeV @ Duke)

- Loss mode
  - energy of γ-rays exceeds the acceptance of the ring
  - Max γ-ray flux is limited by the top-off injector capabilities and shielding
  - or by the ramping speed

- SR can do – at most - ~ 1e12-1e13 γ-rays per second in MeV range

Conclusion I (obvious)

- No surprises!

- While being capable of generating MeV scale γ-ray beams with modest intensities, SR FEL sources can not deliver beams necessary for γ-γ **collider!**

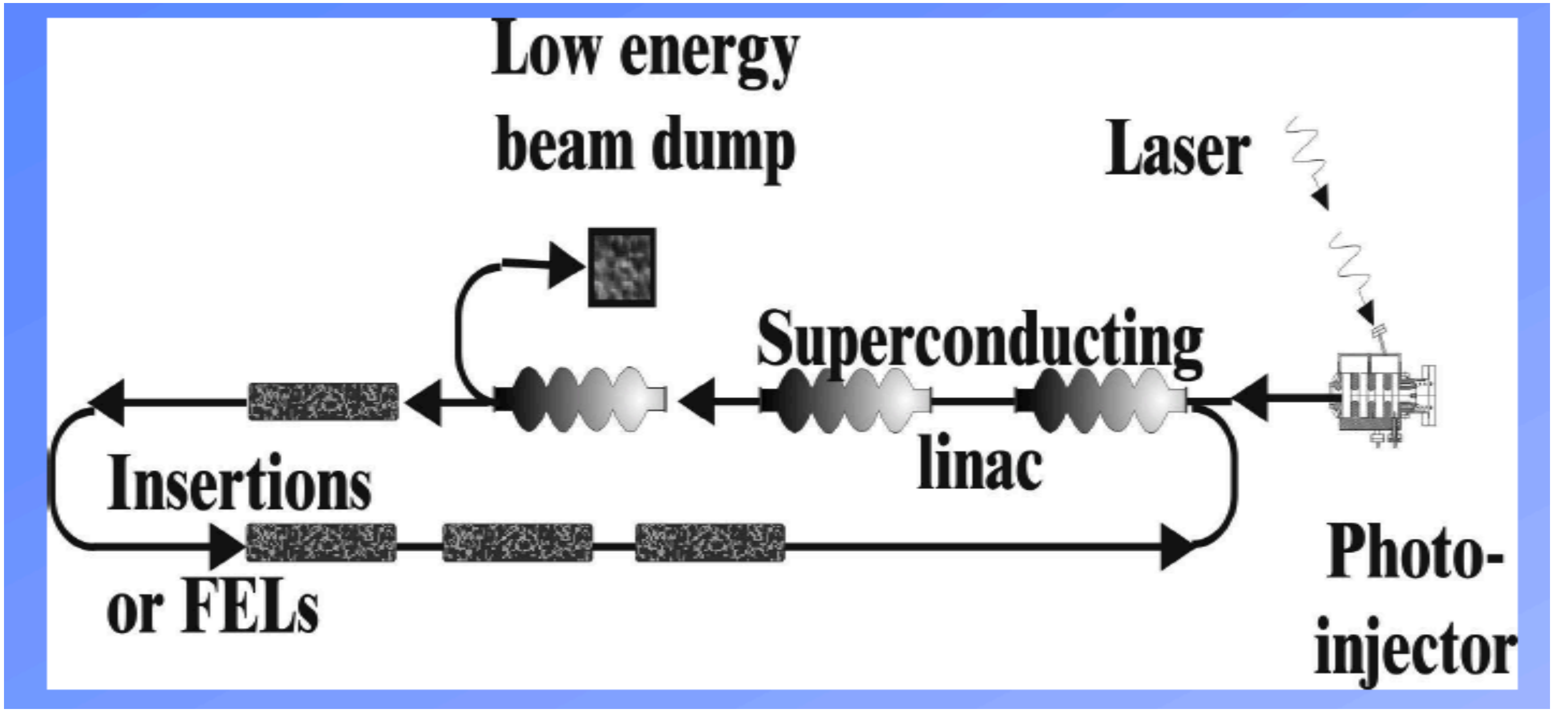
- **Since the entire idea of the γ-γ collider is based converting most of the e-beam energy into γ-ray beam, energy recovery in storage ring is rather useless, especially if one consider the beam losses in the accelerator during the recovery…**

What ERLs can do?

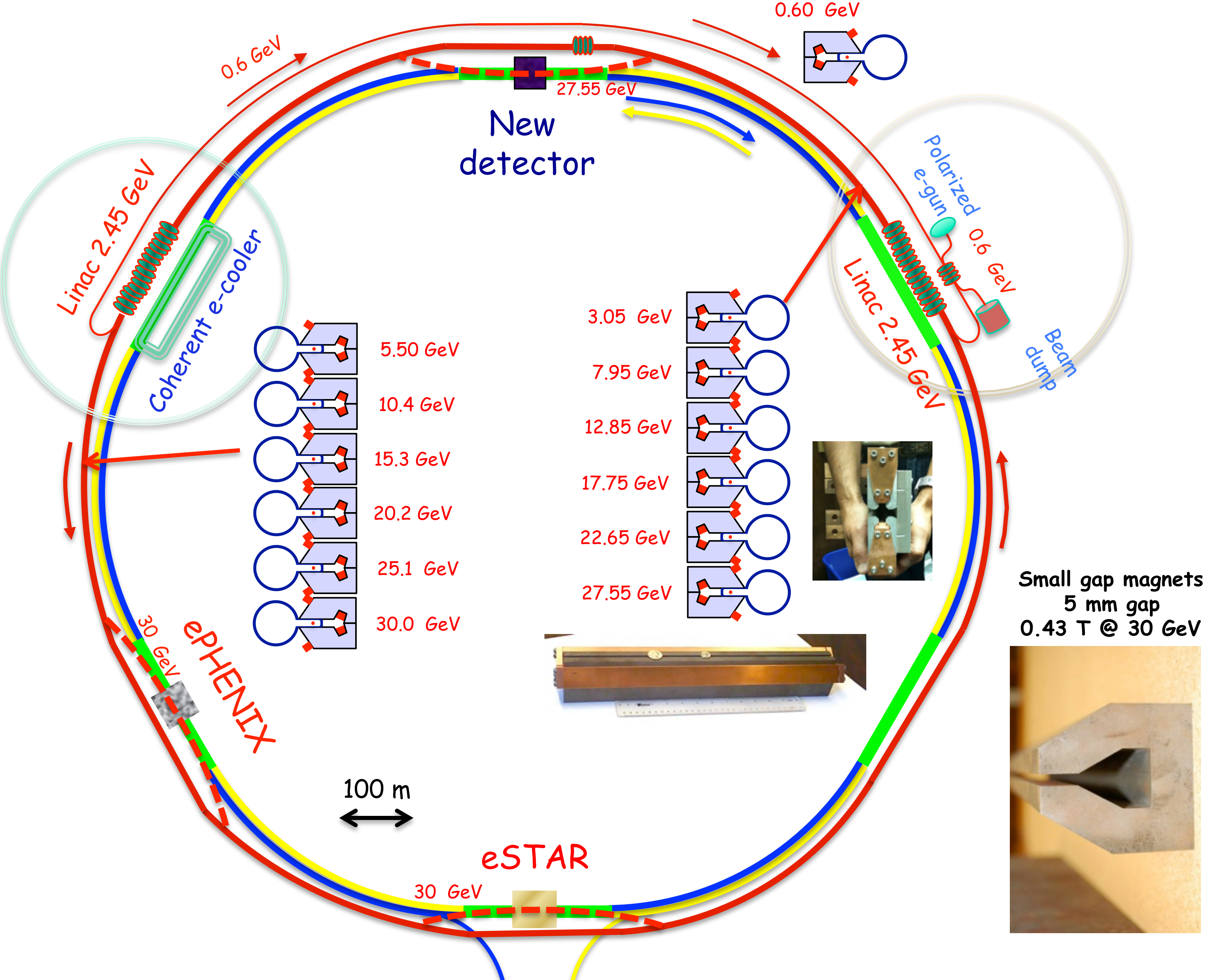
IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 36, NO. 4, AUGUST 2008

Potential Uses of ERL-Based γ-Ray Sources

Vladimir N. Litvinenko, Ilan Ben-Zvi, *Senior Member, IEEE*, Dmitry Kayran, Igor Pogorelsky, Eduard Pozdeyev, Thomas Roser, *Senior Member, IEEE*, and Vitaly Yakimenko

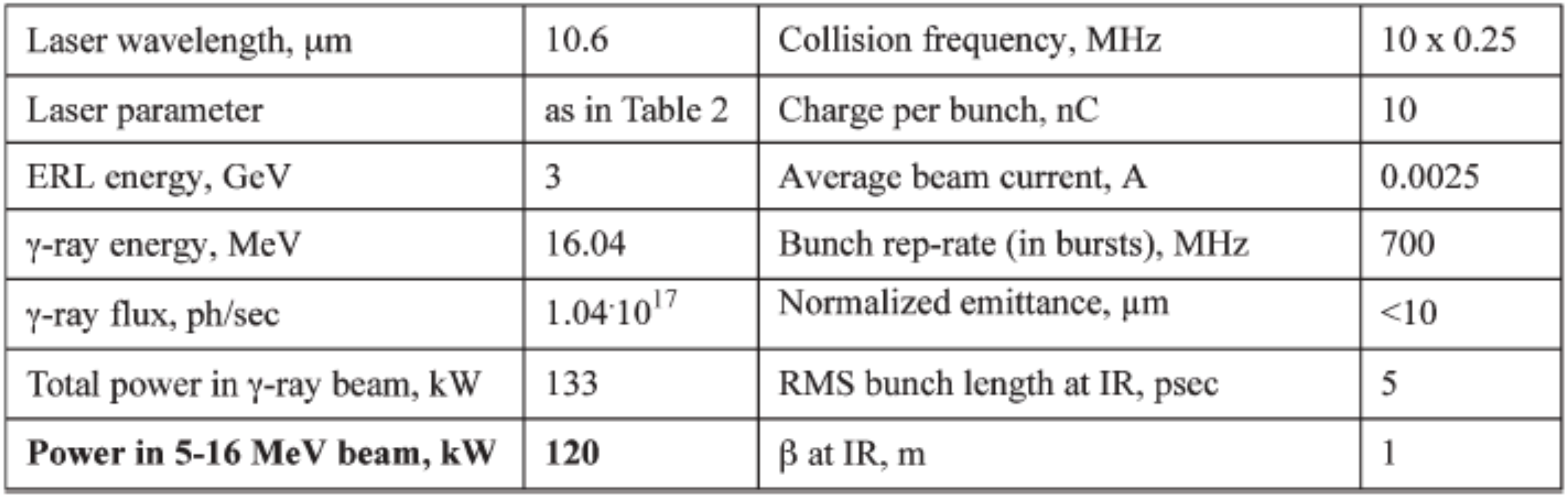


eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 250^*$ GeV or heavy ions $E_A \leq 100^*$ GeV/u



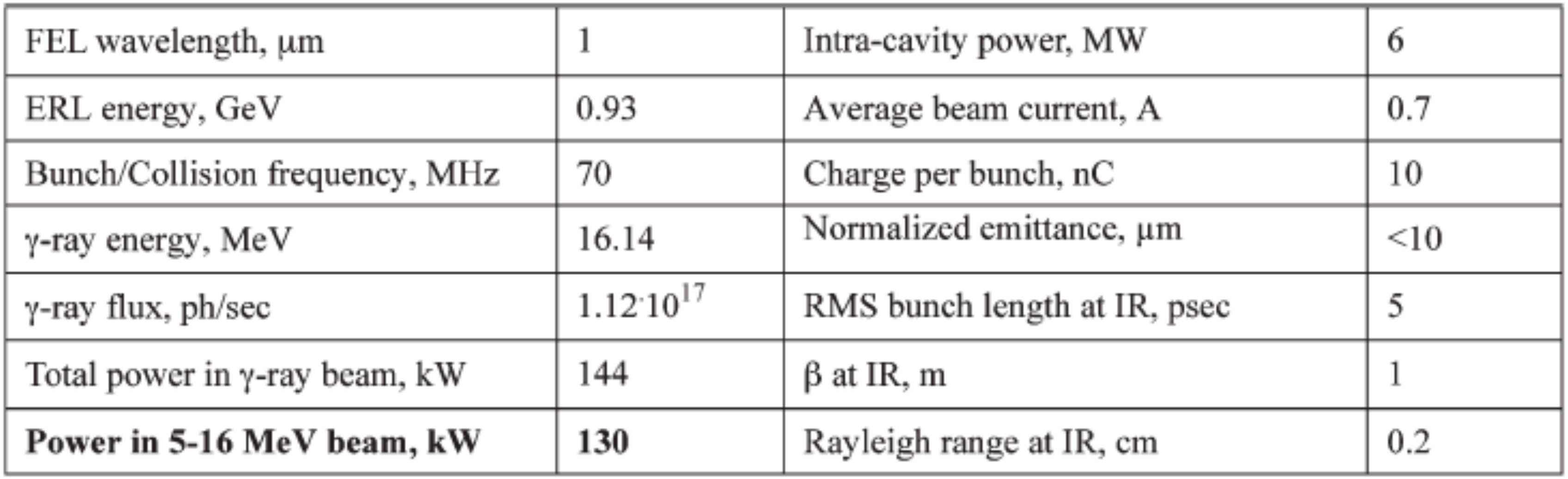
Small gap magnets
5 mm gap
0.43 T @ 30 GeV

TABLE III
γ-RAY SOURCE—THE CO_2 LASER OPTION



Laser wavelength, μm	10.6	Collision frequency, MHz	10 x 0.25
Laser parameter	as in Table 2	Charge per bunch, nC	10
ERL energy, GeV	3	Average beam current, A	0.0025
γ-ray energy, MeV	16.04	Bunch rep-rate (in bursts), MHz	700
γ-ray flux, ph/sec	$1.04 \cdot 10^{17}$	Normalized emittance, μm	<10
Total power in γ-ray beam, kW	133	RMS bunch length at IR, psec	5
Power in 5-16 MeV beam, kW	**120**	β at IR, m	1

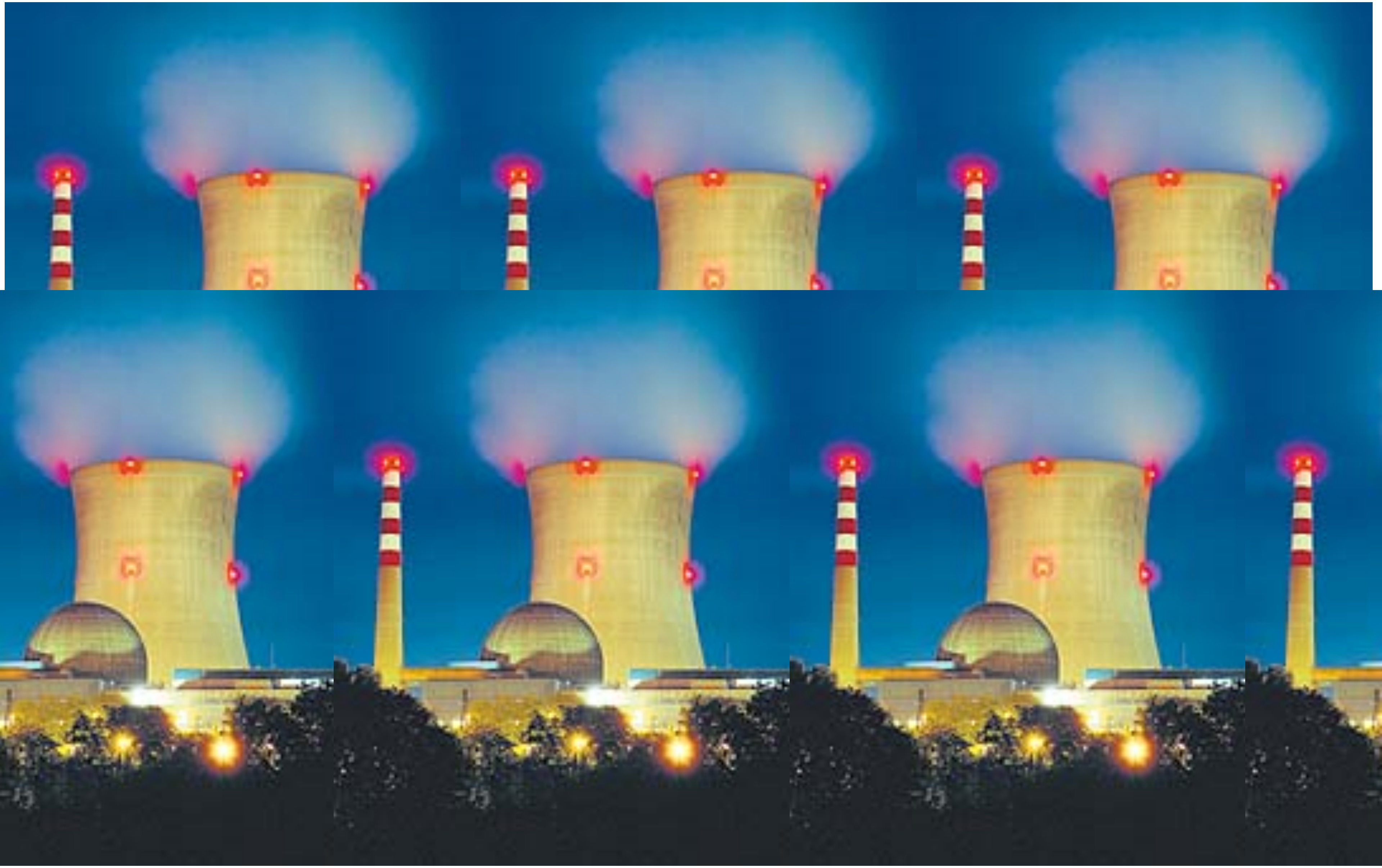
TABLE IV
γ-RAY SOURCE—THE FEL OPTION



FEL wavelength, μm	1	Intra-cavity power, MW	6
ERL energy, GeV	0.93	Average beam current, A	0.7
Bunch/Collision frequency, MHz	70	Charge per bunch, nC	10
γ-ray energy, MeV	16.14	Normalized emittance, μm	<10
γ-ray flux, ph/sec	$1.12 \cdot 10^{17}$	RMS bunch length at IR, psec	5
Total power in γ-ray beam, kW	144	β at IR, m	1
Power in 5-16 MeV beam, kW	**130**	Rayleigh range at IR, cm	0.2

Conclusion II (obvious)

- While being capable of generating sub-MW class γ-ray beams, ERLs as the main e-beam driver do not bring any advantages to the γ-γ collider scheme.
- But ERLs can be very useful for generating a needed FEL beam, whose intra-cavity power then can be utilized: an example of MW intra-cavity CW power is ERL prototype at JLab
- **Since the entire idea of the γ-γ collider is based converting most of the e-beam energy into γ-ray beam, energy recovery of the e-beam either in ERL or in storage ring is rather useless, especially if one consider the beam losses in the accelerator during the recovery**
- Hence, a linac (just straight or RL) with 50 MW scale e-beam dump is most likely the only viable solution for SAPPHiRE



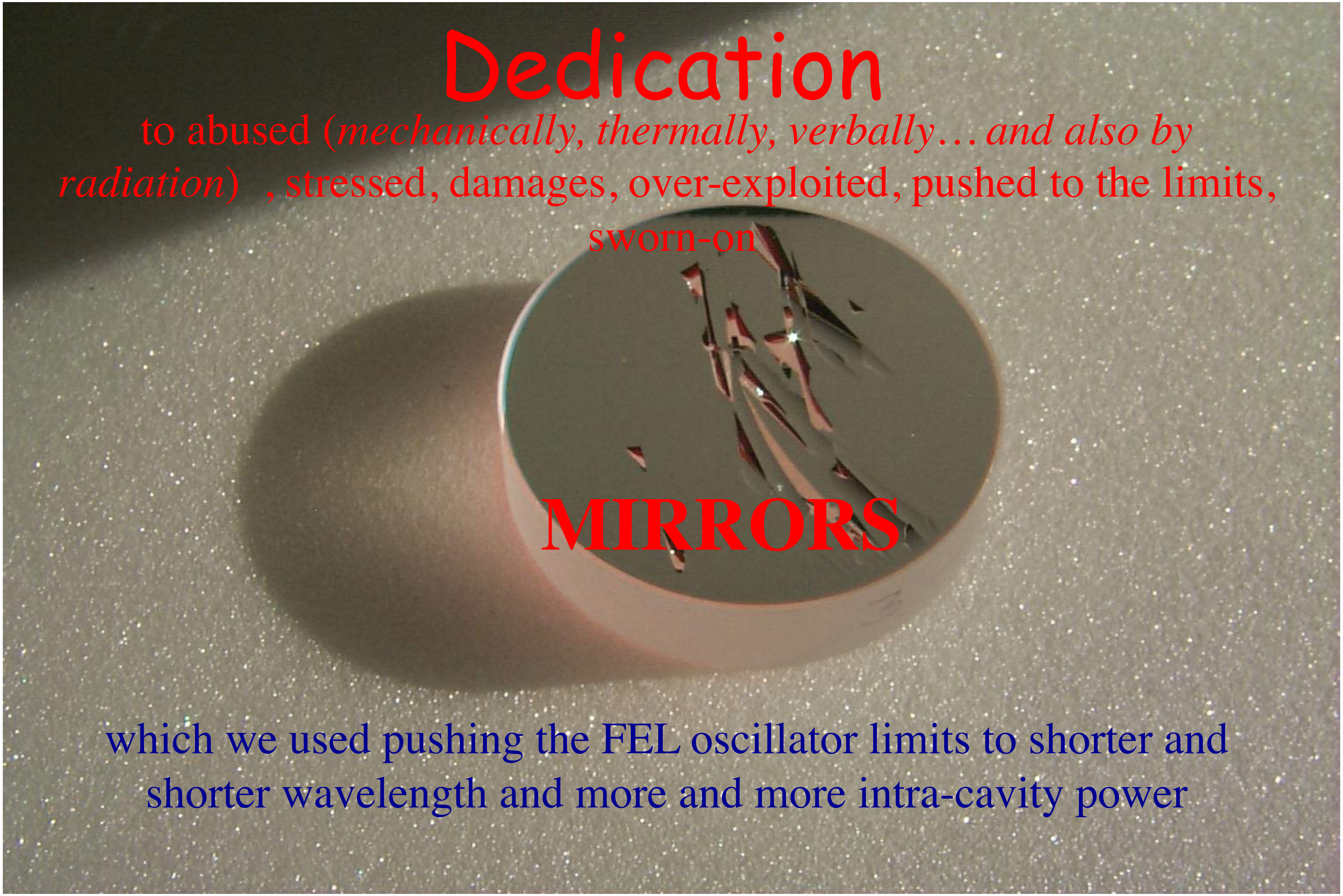
What ERL can be useful for?

An ERL driven FEL

SAPPHiRE can use MW scale intra-cavity power

Note: FELs do not have neither peak not average laser power damage threshold

Dedication



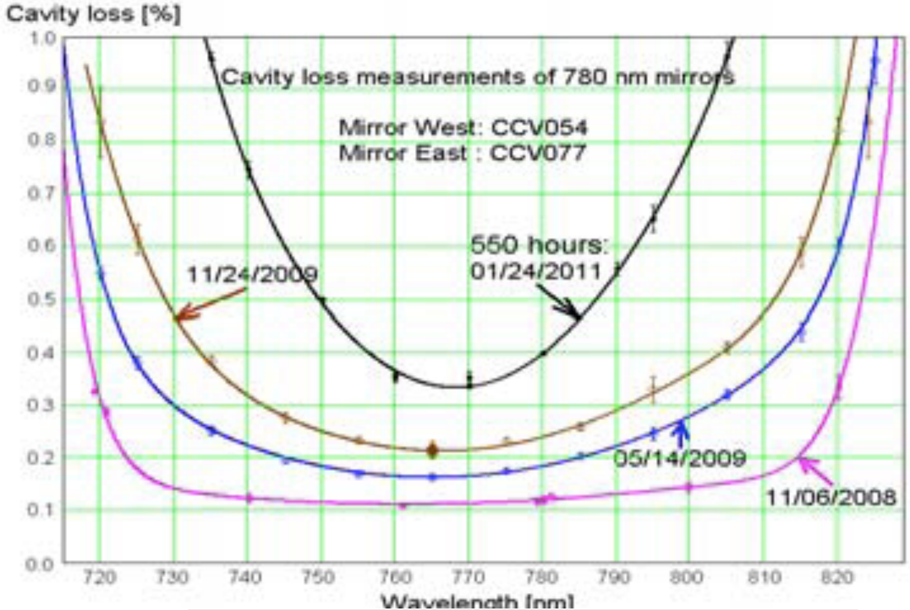
to abused (*mechanically, thermally, verbally… and also by radiation*) , stressed, damages, over-exploited, pushed to the limits, sworn-on

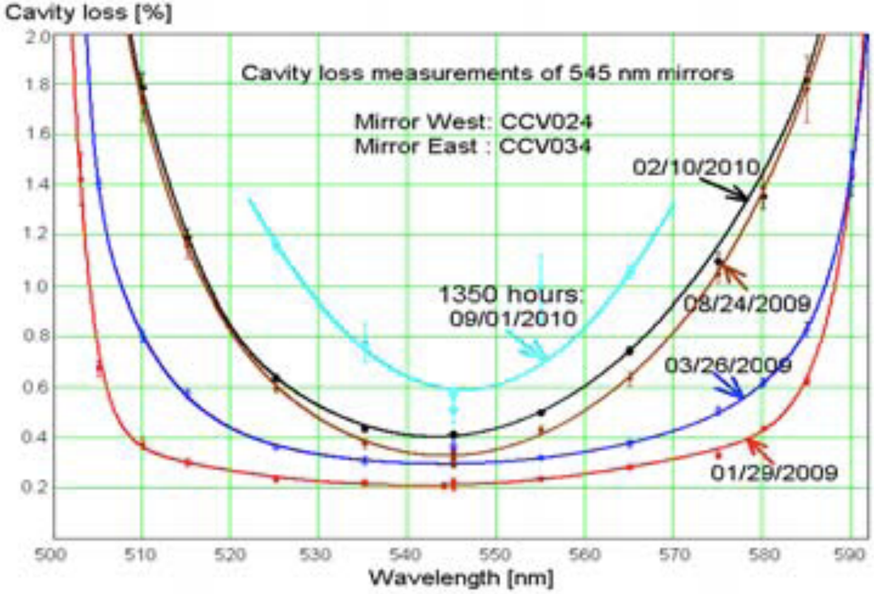
MIRRORS

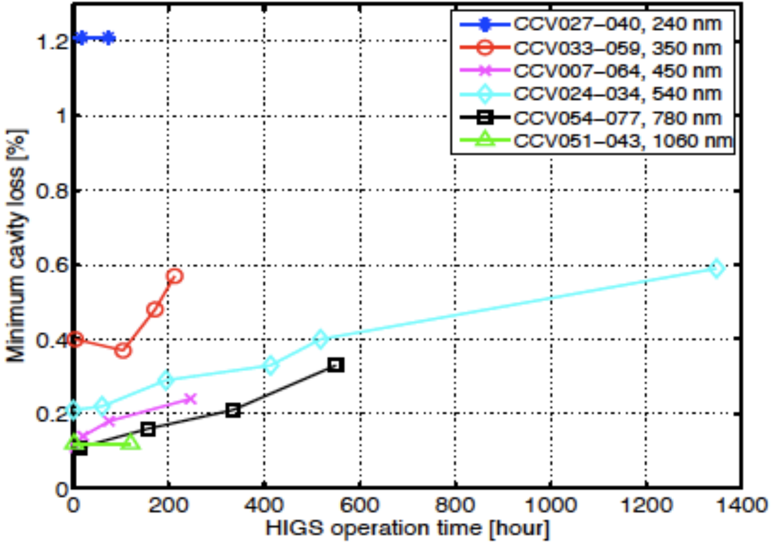
which we used pushing the FEL oscillator limits to shorter and shorter wavelength and more and more intra-cavity power

From 2011 TUNL progress report

Cause of the mirror degradation is VUV and soft-X-ray spontaneous radiation from FEL wigglers, bunchers, bending magnets ..







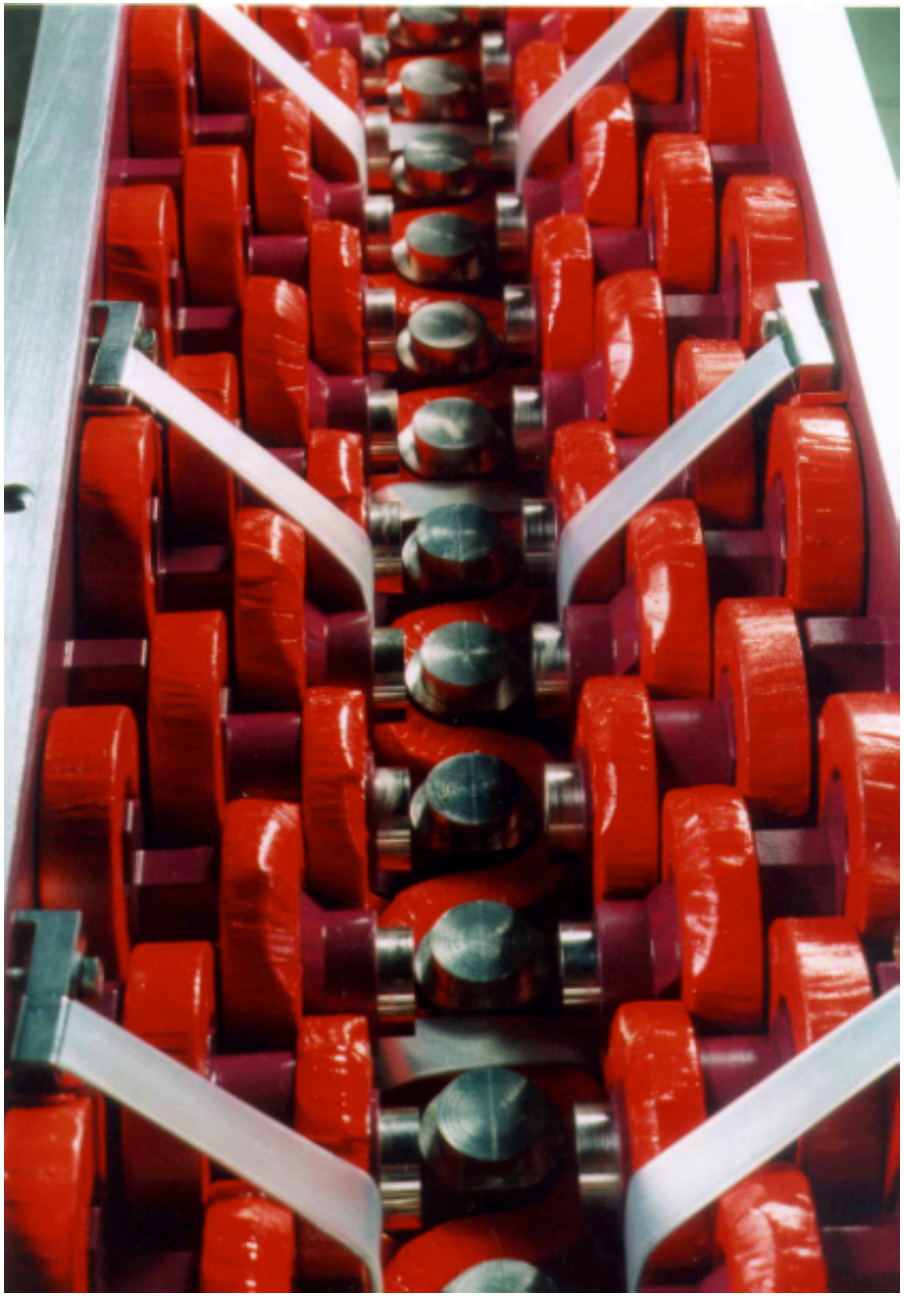
Courtesy S. Mikhailov et al.

Cooking recipe

- BINP OK-4 (1980s): For any UV resistant mirrors (including 350 nm) use HfO top layer on the top of highly reflecting multilayer (AlO is an other possibility)
- Use helical wiggler and helical trajectory of electrons thought the cavity, electrons never should "see" the mirrors within $1/\gamma$ angle
- If possible, use low a_w~1 wiggler to avoid generating VUV harmonics
- It will allow you to have Q ~ 1,000, i.e you would need to generate (and to dissipate) ONLY 1 kW for 1MW of intra-cavity power

Trajectory through FEL optical cavity

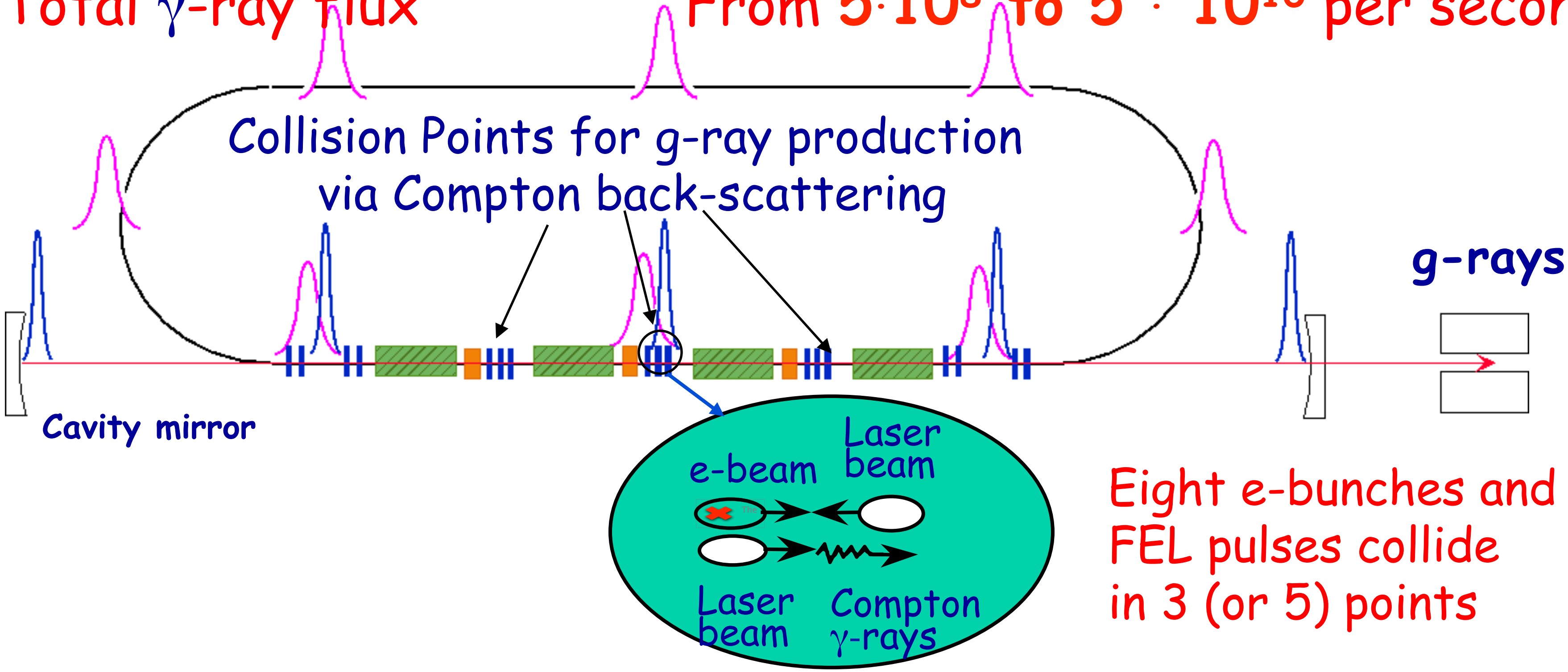
One of four OK-5 EM wigglers with switchable helicity



- Helicity of the wiggler determines the helicity of the FEL photons
- Using combination of helical wigglers with opposite helicities you can have FEL with linear polarization

OK-5/Duke FEL SR γ-ray design

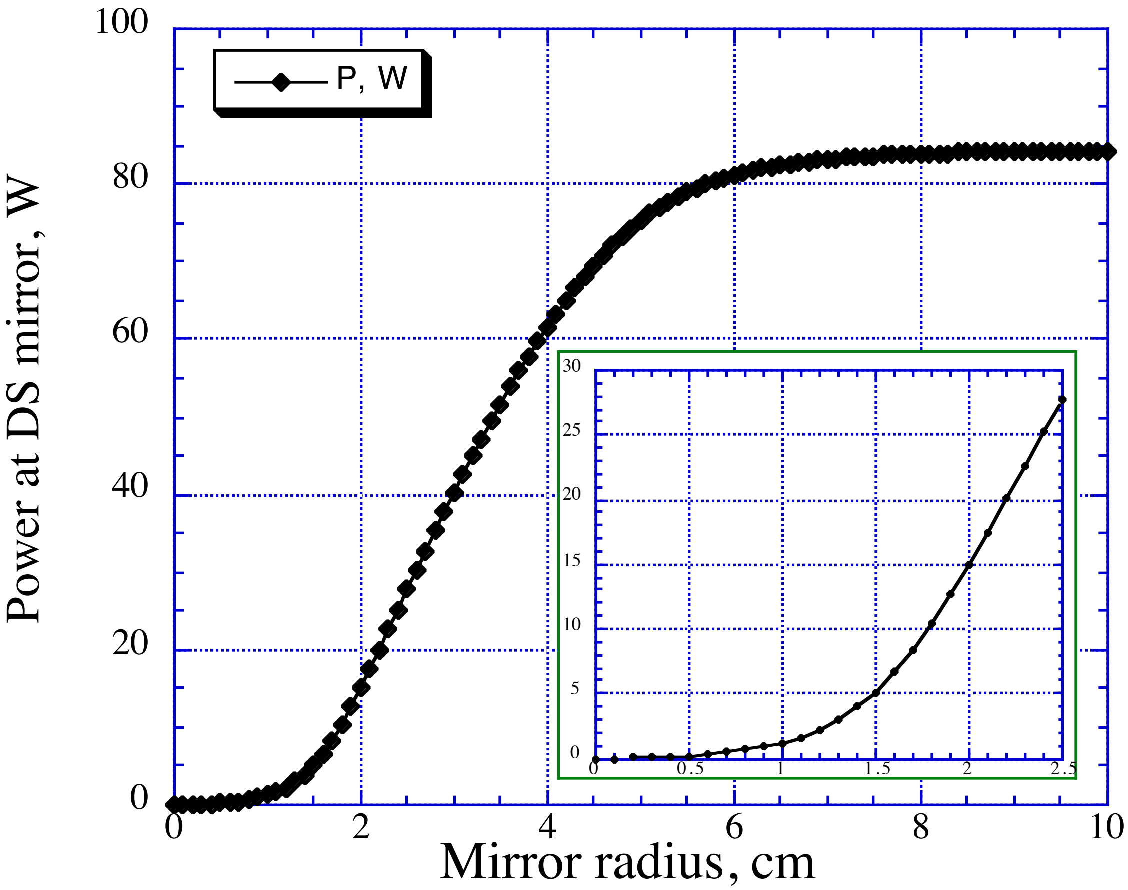
γ-rays energy range:	From 2 MeV to 200 MeV
Polarization	Circular (left or right), Linear x/y
γ-rays energy resolution	From 0.4% to 1%
Total γ-ray flux	From $5 \cdot 10^{8}$ to $5 \cdot 10^{10}$ per second



Collision Points for g-ray production via Compton back-scattering

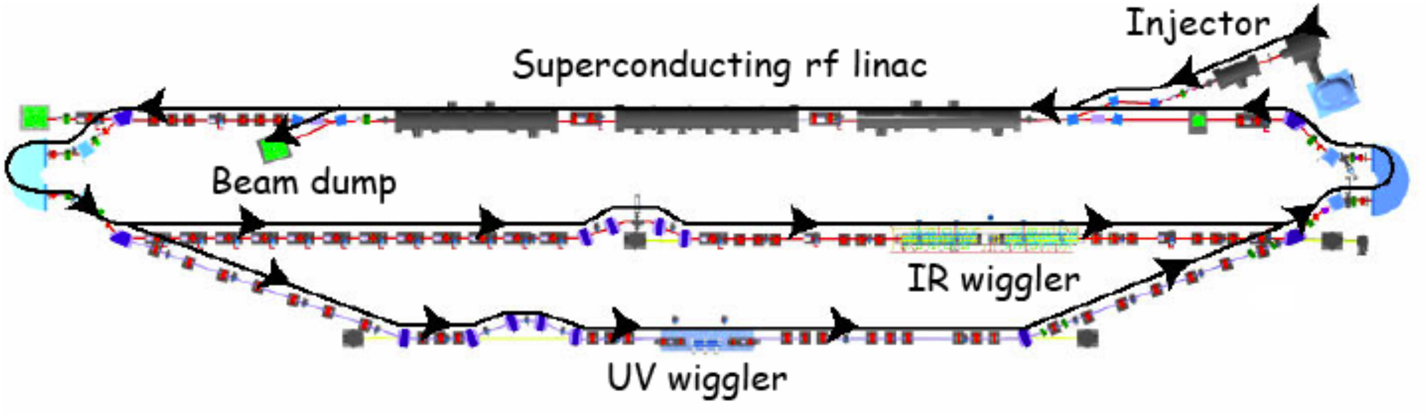
Eight e-bunches and FEL pulses collide in 3 (or 5) points

SR on the mirrors



JLab: 160 MeV ERL

JLab 10kW IR FEL and 1 kW UV FEL

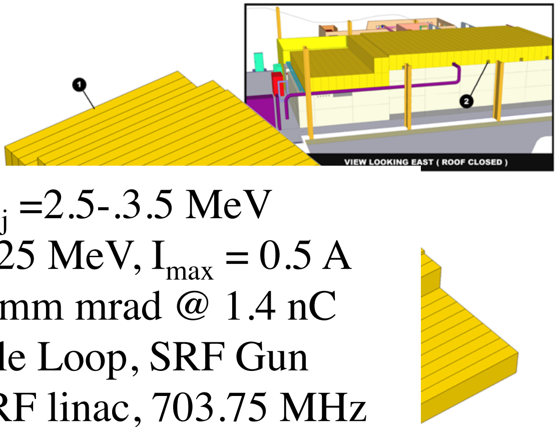


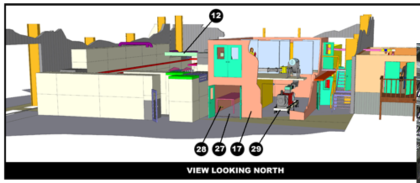
Output Light Parameters	IR	UV
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

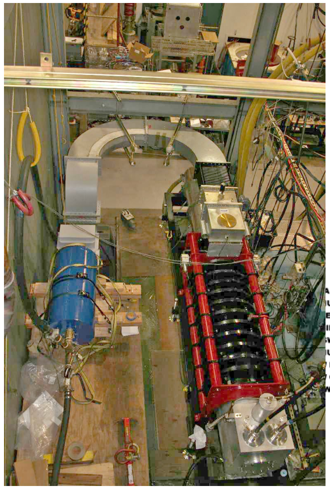
Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

S. Benson et al, *High power lasing in the IR upgrade at Jefferson Lab*, 2004 FEL Conference Proceedings, 229-232.

R&D ERL at BNL







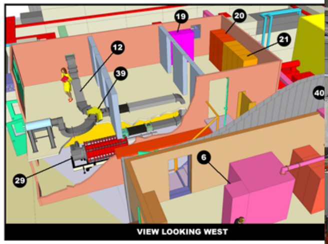
E_{inj} =2.5-.3.5 MeV

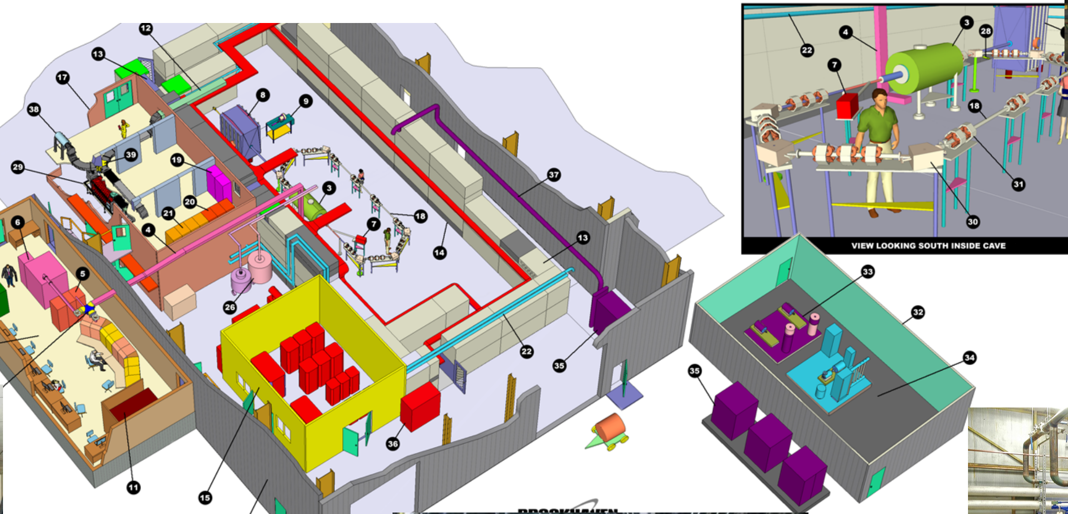
E_{total} = 25 MeV, I_{max} = 0.5 A

ε_n ~ 2 mm mrad @ 1.4 nC

Single Loop, SRF Gun

5 cell SRF linac, 703.75 MHz





Possible ERL driven FEL

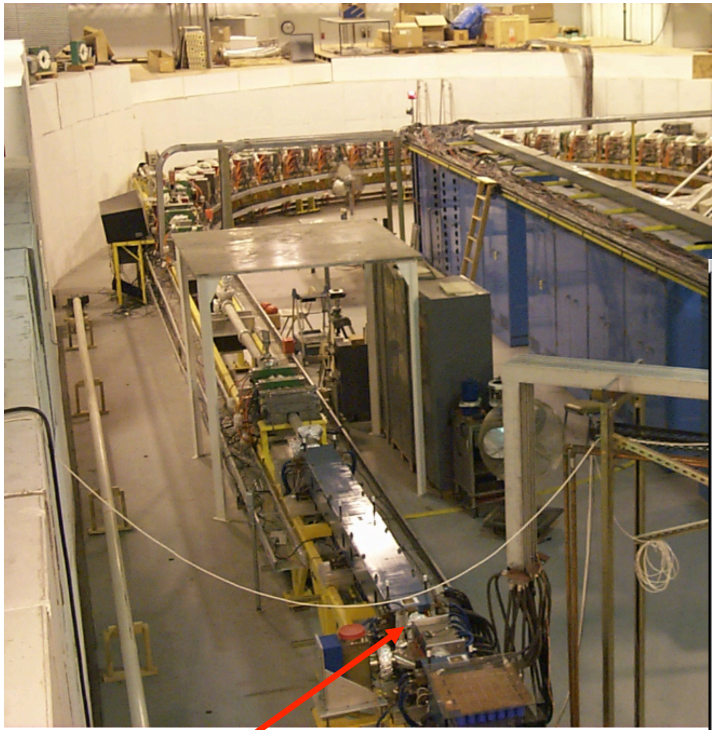
- ERL energy – 150-200 MeV
- Beam current – 5-10 mA
- Wavelength – 300-400 nm (tunable)
- FEL active power – 10 kW (demonstrated at Jlab)
- Optical cavity
  - Q ~ 1,000 (should be rather straightforward)
  - Length – 150 m (3x that at Duke FEL)
  - Energy per laser pulse – 5 J
  - Rep-rate – 2 MHz (10x the collision rate in γ-γ)
  - Intra-cavity power - 10 MW
  - Power loss per mirror – 5 kW (requires active cooling)

Conclusion III

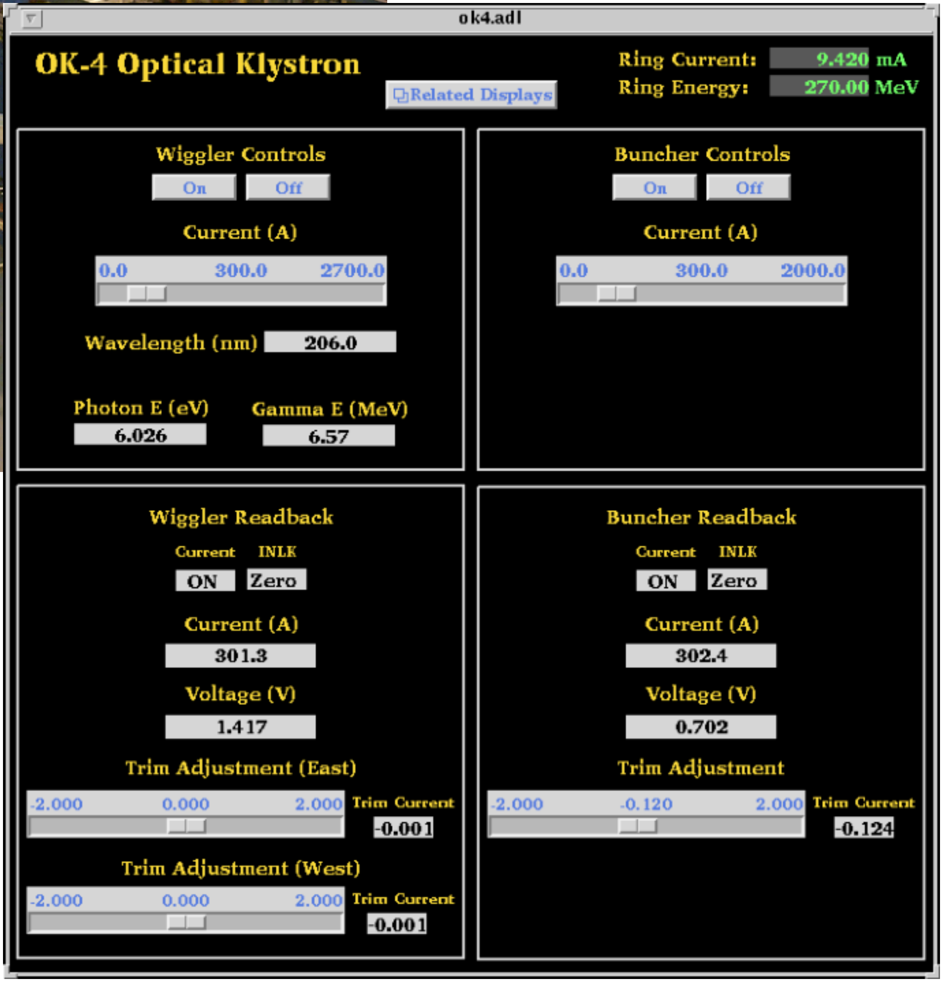
- Being a simple QED process, Compton scattering is both well understood and studied theoretically and experimentally: flux, distribution, polarization – just name it - are in full agreements with analytical formulae and simulations
- As was established by V. Telnov about 30 years ago, we must stay away from the threshold of generating pairs in collisions of Compton γ-ray with laser photons (and especially hadron pairs). This is to prevent depopulation of the γ-ray beam by laser photons
- There is no mysteries about Compton sources. One just need a proper components.
- ERL based FEL seems to be an excellent choice for a laser. Its fully controllable polarization of the laser photons, and it wavelength tunability are very valuable additions for unraveling the physics of the collider.

???

Energy of γ-ray beam is continuously tunable from 0.67 to 58 MeV



Collision point



OK-4 Optical Klystron

Ring Current: 9.420 mA
Ring Energy: 270.00 MeV

Wiggler Controls

Current (A): 0.0 300.0 2700.0

Wavelength (nm): 206.0

Photon E (eV): 6.026
Gamma E (MeV): 6.57

Buncher Controls

Current (A): 0.0 300.0 2000.0

Wiggler Readback

Current: ON
INLK: Zero
Current (A): 301.3
Voltage (V): 1.417

Trim Adjustment (East): -2.000 0.000 2.000 Trim Current -0.001

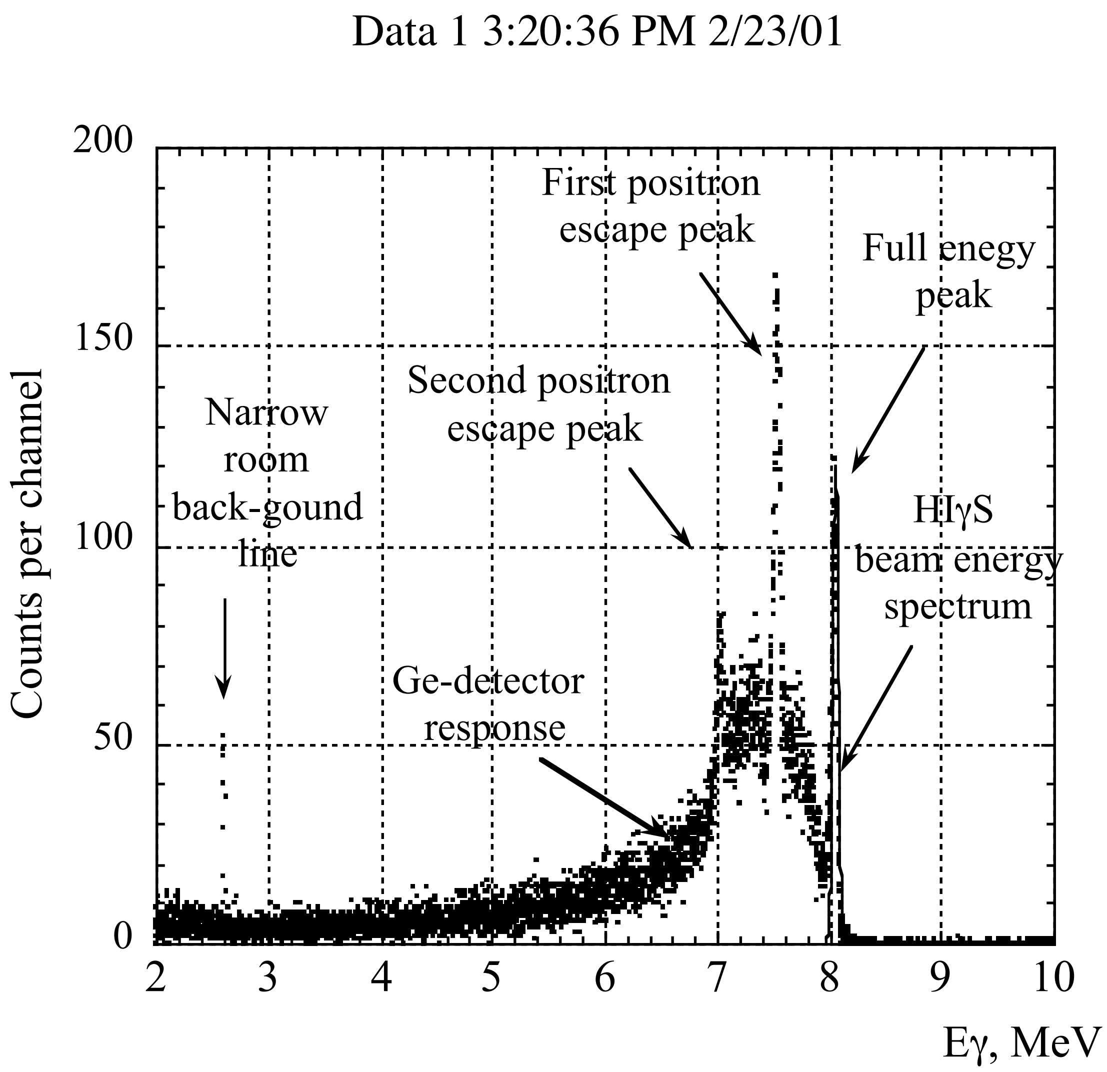
Trim Adjustment (West): -2.000 0.000 2.000 Trim Current -0.001

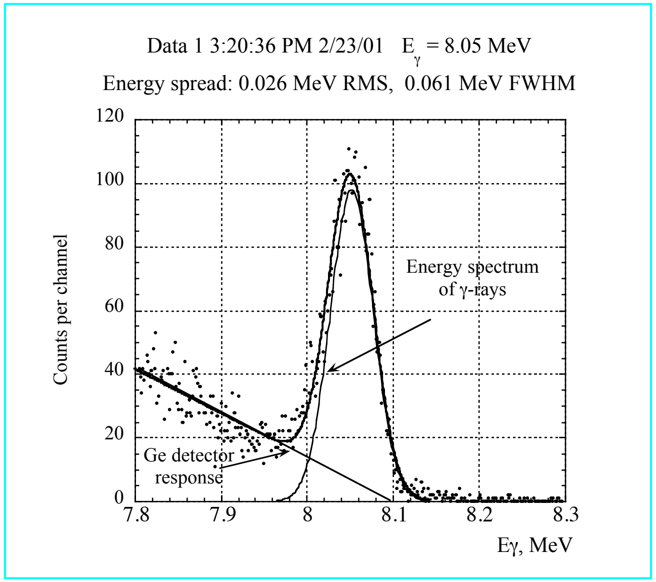
Buncher Readback

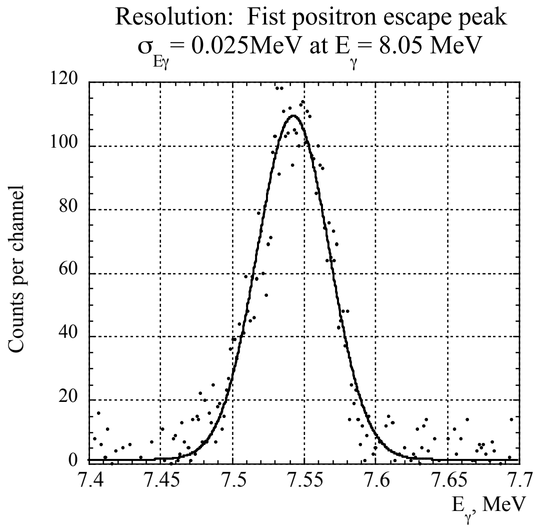
Current: ON
INLK: Zero
Current (A): 302.4
Voltage (V): 0.702

Trim Adjustment: -2.000 -0.120 2.000 Trim Current -0.124

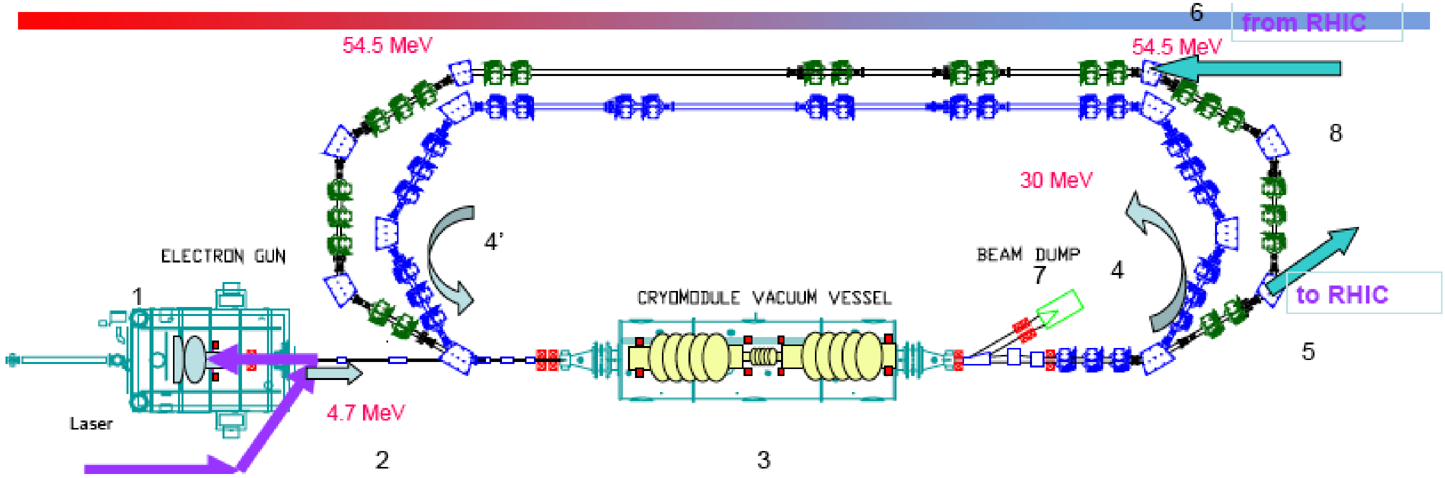
Computer controls of the OK-4 FEL provide for tuning of wavelength (i.e. photon energy and energy of γ-rays), the optical axis and the OK-4 gain (via buncher).

Data 1 3:20:36 PM 2/23/01
Counts per channel
200
150
100
50
0
2
3
4
5
6
7
8
9
10
Eγ, MeV
Narrow room back-gound line
Second positron escape peak
First positron escape peak
Full enegy peak
Ge-detector response
HIγS beam energy spectrum

Data 1 3:20:36 PM 2/23/01 E$_\gamma$ = 8.05 MeV
Energy spread: 0.026 MeV RMS, 0.061 MeV FWHM
Counts per channel
120
100
80
60
40
20
0
7.8
7.9
8
8.1
8.2
8.3
Eγ, MeV
Energy spectrum of γ-rays
Ge detector response

Resolution: Fist positron escape peak
σ$_{E\gamma}$ = 0.025MeV at E$_\gamma$ = 8.05 MeV
Counts per channel
120
100
80
60
40
20
0
7.4
7.45
7.5
7.55
7.6
7.65
7.7
E$_\gamma$, MeV

e-cooler: 2 pass ERL layout



1. SRF Gun
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3rd harmonic cavity

4, 4’. 180° achromatic turns

5, 6. Transport lines to and from RHIC,

7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

54 MeV, 5 nC at 9.4 MHz. RF 703.75 MHz. Gun 5 MeV