PERFORMANCE OF HIGH INTENSITY γ-RAYS SOURCE DRIVEN BY THE DUKE STORAGE RING FEL

V.N.Litvinenko for HIγS Collaboration, FEL Laboratory, Department of Physics, Duke University, Durham, NC USA

Abstract

In this paper we report the status of the High Intensity γ-ray Source facility (HIγS) based on intra-cavity Compton back-scattering inside the OK-4/Duke storage ring FEL (SR FEL). The HIγS is generating beams of γ-rays with tuneable energy from 1.8 MeV to 58 MeV and total average flux up to $5 \cdot 10^8$ γ-rays per second. The γ-ray beam is mono-chromatized by on-axis collimator to energy spread as low as 0.2% RMS. The HIγS facility generated in excess of 2,000 hours of the γ-ray beam time for nuclear physics user program. We discuss the incoming up-grades of the facility in next five years including the installation of the OK-5 FEL with controllable polarisation and the full-energy booster-injector.

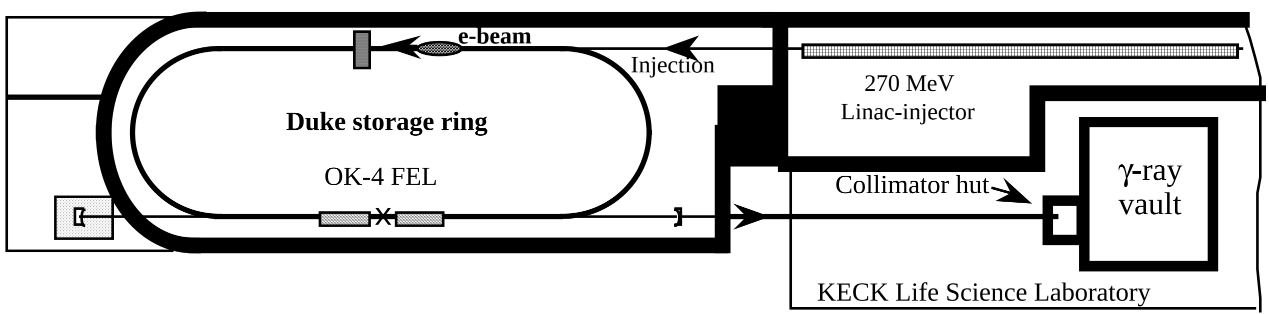

Fig.1 Schematic layout of the HIγS facility. The electron beam is injected from 270 MeV linac and is ramped in the Duke storage ring up-to operational energy. The OK-4 FEL has an optical cavity length equal to the half of the ring circumference. The OK-4 FEL has the field-free collision point (x) in the center of the optical cavity for generation of γ-rays. Generated γ-rays propagate through vacuum beam-line to the collimator hut, located 60-m downstream from the collision point. The collimated γ-ray beam propagates in air to the 100 m^2 γ-ray vault, dedicated for the nuclear physics experiments. Both the collimator hut and the γ-ray vault are shielded by 0.6 m thick concrete walls.

1 INTRODUCTION

The present layout of the HIγS facility is shown in Fig.1. The HIγS facility is based on back-scattering of the FEL photons inside of optical cavity of the OK-4/Duke storage ring free-electron laser, as illustrated in Fig 2 [1]. The HIγS facility is located at Duke Free Electron Laser laboratory and is integrated into the Duke storage ring facility. The main parameters of the HIγS facility (the energy, the flux and the attainable energy resolution of γ-ray beams) are defined by parameters of the electron and FEL beams of the Duke storage ring. Presently, the HIγS facility produces the linearly polarized γ-rays with energies from 1.8 MeV to 58 MeV, total fluxes up to $5\ 10^8$ γ's per second and energy resolution as low as 0.46% FWHM (0.2% RMS). Routinely, it generated γ-rays with 2-to-42 MeV range and1% FWHM energy resolution.

The OK-4 FEL is the heart of the HIγS facility: the electron bunches generate a high power FEL optical beam and Compton back-scatter it to make an intense pencil-like γ-ray beam. The use of intra-cavity collision is responsible for the boost of the γ-ray beam intensity compared to other facilities using external lasers.

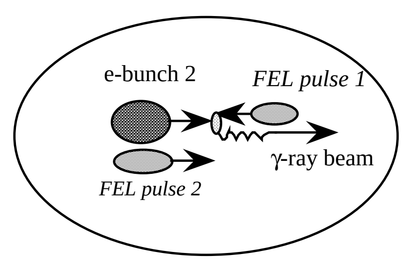

Fig.2. The process of Compton back-scattering in the center of the OK-4 FEL. The Duke storage ring operates with two equally spaced electron bunches, which generate FEL pulses with eV-range photons. The FEL pulse, generated by the first e-bunch, collides head-on with the second e-bunch. The back-scattered photons with ~ $4\gamma^2$ boost in the energy become MeV-range γ-rays.

The use of dedicated storage ring and FEL provides for continuous tunability of the energy of the γ-rays:

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

via the change of the electron beam energy E_e, from 0.25 GeV to 1 GeV or/and via the change of the wiggler parameter K_w in the FEL from 0 to 5. The dependence of the γ-ray's energy on the scattering angle provides for monochromatization of the γ-rays by a simple collimation around the beam axis (θ = 0). The attainable resolution of the γ-ray energy is determined by the quality of the electron beams. The Duke/OK-4 FEL was designed with a collision point for the Compton backscattered γ-ray production that is free of magnetic fields. The measured parameters of the γ-ray beams are in excellent agreement with our theoretical predictions [2].

2 PRESENT PERFORMANCE OF THE HIγS

High intracavity power of the OK-4 FEL translates into a high average flux of γ-rays. The HIγS generates the highest flux of γ-rays compared with other Compton γ-ray facilities. The HIγS also has the best absolute energy resolution for γ-ray beams. The parameters of the OK-4/Duke FEL and the HIγS are listed in Table I. Additional details can be found in Refs. [1,2]. During 1998-1999, the properties of γ-ray beams from the HIγS facility were carefully analyzed both theoretically and experimentally [2]. These results confirm our predictions and, therefore, make us very confident that we will obtain the beam parameters predicted for the OK-5 FEL.

Table I. Present performance of the HIγS

Operating energy, E_e [GeV]	0.23 -1.1 [a]
Energy acceptance, ΔE, of the ring	20.5 MeV [b]
Multi-bunch beam current [mA]	155
Single bunch beam current [mA]	17 [c]
Emittance at 1 GeV, ε_x and ε_y, [nm rad],	18±1, < 1
Beam size in OK-4, σ_x and σ_y , [mm]	0.27, 0.085
OK-4 FEL	
Tuning range, λ [nm]	193.7 - 730
Tuning range, E_{ph} [eV]	1.7 - 6.4
Electron beam current for FEL [mA]	5-40 [d]
Average lasing power [W]	0.1 – 0.9
Average intracavity power [W]	10 – 90
Linewidth, [δλ/λ]	$1 \cdot 10^{-4}$
Spatial distribution	TEM_{00}
Compton γ–rays source	
Energy of γ-rays, E_γ [MeV]	1.6 – 58 [e]
Energy resolution, FWHM,%	0.5 – 1
Resolution, FWHM, MeV, E_γ=3 MeV	0.016
E_γ=50 MeV	0.4
Total flux, [γ‘s/sec]	10^7 -5 10^8 [e]
Through the collimator, $1\%_{FWHM}$ [e]	3 10^4 -7.5 10^6
$3\%_{FWHM}$ [e]	9 10^4 -2.2 10^7
Flux density, [γ‘s/sec/MeV]	$1 \cdot 10^6$ - 5 10^6
Time Average flux, [γ‘s/sec], E_γ•20 MeV	upto 4 10^8
E_γ > 20 MeV	• 1.5 10^6 [f]
Linear Polarization, %	99.8 - 99.998
Lifetime, e-beam [hr], E_γ • 20 MeV	2-6 (∞ [f])
E_γ > 20 MeV	~ 0.1 [f]
Spatial distribution	Pencil beam, 0.1-1" in diameter

[a] 0.8 GeV is current limit by overheated coils, up-grade in Fall 2001 will increase it to 1.2 GeV; [b] - limited by existing RF system; [c] – limited by HOMs in the existing RF system; [d] HOMs in the existing RF system limit it to ~ 8-10 mA/bunch in the two bunch operation; [e] – the 2-51 MeV energy range is readily available, the 1.8-2 and 51-58 MeV - demonstrations only; [f] - the average flux is limited by short beam life time in the loss mode and slow re-injection and ramping processes; "•" with continuous top-on injection - available only at and below 270 MeV.

The present facility has 270-MeV linac-injector. The low energy of injection is one of the limiting factors for the attainable e-beam currents and, therefore, for higher fluxes of γ-rays. The second limiting factor is the presence of large number of transverse high-order modes (HOMs) in the RF cavity. These modes affect the stability of the e-beam and limit the current in the two-bunch and four-bunch operation used for γ-rays production. The proposed eight-bunch operation, would be impossible with this RF cavity.

The energy of the e-beam is tuned to the energy of operation via slow ramping of the storage ring magnets. The storage ring magnets were not designed for ramping and this process is very slow (~10 mins). In addition, each re-injection required complete magnetization cycle, which is also slow (~5mins) and can't be accelerated.

There are two distinct modes of the HIγS facility operation: *"no-loss"* and *"loss"* modes. In *"no-loss"* mode, the energy lost by an electron for generating a γ-ray is insufficient to kick the electron out-side of the energy acceptance of the Duke storage ring. With current parameters of the OK-4 FEL and the ring, the *"no-loss"* mode is possible for γ-rays energy below 20 MeV. In a matter of few milliseconds, the electron recovers the energy loss and return to the core of electron beam. Therefore, the *"no-loss"* mode does not effect lifetime of the e-beam.

When an electron generates a γ-ray with energy above 20 MeV, it is lost and should be later replaced with the new one. This is the *"loss"* mode, in which the lifetime of the e-beam can as short as few minutes. It means, that after few minutes of the beam time, the lengthy process of normalization, injection and ramping must be repeated. In current state of the facility, this mode of operation could not support high time-average flux. We tested this mode for generating of 50 MeV γ-rays for TUNL experiments for about two weeks. The e-beam lifetime was ~10 minutes, the duration of the run was ~ 5 minutes, while standard cycle was ~ 20 minutes.

We demonstrated the "full energy" injection in the "top-on" mode using the existing linac and operating at 270 MeV. We kept operational current at 40 mA for complete shift (8 hours) while producing the continuous flux of γ-rays. The "top-on" mode did not interrupted the experiment and did not caused any measurable increase in the background.

Currently, the hardware of the Duke storage ring limits the available range of electron beam and γ-ray parameters. Some of these limitations will be overcome by planned up-grades in 2001. There are other limitations specific for the HIγS facility. In the *"no-loss* "mode we are limited by the vertical multi-bunch instability caused by the HOMS of the RF cavity. It currently limits our average flux to ~$5\cdot10^{8}$ γ's per second. In the *"loss* "mode, the absence of full-energy injector limit us to average flux ~ 10^{6} γ's per second.

3 FUTURE OF THE HIγS

Table II. Parameters of "Year -2004" HIγS facility

Operating energy, E_e [GeV]	0.27 -1.2
Energy acceptance, ΔE, of the ring	25.8 MeV
Multi-bunch beam current [mA]	160
Single bunch beam current [mA]	20
Emittance at 1 GeV, ε_x and ε_y, [nm rad],	18±1, < 1
Beam size in OK-4, σ_x and σ_y , [mm]	0.27, 0.085
OK-5 FEL	
Tuning range, λ [nm]	100 - 1,000
Tuning range, E_{ph} [eV]	1.2 - 12
Electron beam current for FEL [mA]	8 x 20
Average lasing power [W]	1 – 30
Average intracavity power [W]	100 – 3,000
Linewidth, [δλ/λ]	$1\cdot10^{-4}$
Spatial distribution	TEM_{00}
Compton γ–rays source	
Energy of γ-rays, E_γ [MeV]	1.4 – 206
Energy resolution, FWHM,%	0.5 – 1
Resolution, FWHM, MeV, E_γ=1.5 MeV	0.005
E_γ=150 MeV	1.5
Total flux, [γ's/sec] (a)	$5\ 10^{7}$ -1 10^{11}
Through the collimator, [γ's/sec], $1\%_{FWHM}$	$7\ 10^{5}$ -1.4 10^{9}
$3\%_{FWHM}$	$2\ 10^{6}$ -4.5 10^{9}
Flux density, [γ's/sec/MeV]	$3.5\cdot10^{5}$ - 3 10^{8}
Time Average flux, [γ's/sec]	= Total flux
X or Y, Linear Polarization, %(c)	98.25 - 99.998
Left or Right Circular Polarization, %(c)	98.25 - 99.998
Lifetime, e-beam [hr]	• (d)
Spatial distribution	Pencil beam, 0.1-1" in diameter

(a) The best performance will be in the 10-to-100 MeV range; (b) Lowest flux density of 3.5 10^{4} γ's/sec/MeV will be at γ-ray energies of 206 MeV; (c) Polarization of ~98% is typical γ-ray energies ~ 200 MeV; (d) with the top-off full energy

Number of the Duke storage ring facility improvements is under way. They include the reliability and performance up-grade of the Duke storage ring and the installation of the new OK-5 FEL [3], which will produce FEL and γ-ray radiation with tunable polarization. The choices of polarization includes, but is not limited to, left and right circular, and horizontal and vertical linear polarizations. These up-grades will also provide for higher intensities and higher energies of γ-ray beams. The OK-5 FEL system is designed to operate with 8 electron bunches and has 3 optimized collision points for γ-ray production, which boost the γ-ray flux by a factor of 24 [3]. The full-energy booster-injection (2004) [4] and the new RF system for the Duke storage ring will provided for the full flux and the full γ-ray energy operation of the HIγS facility (see Table II).

4 CONCLUSIONS

The present performance of the OK-4 FEL is rather remarkable and the HIγS facility delivered in excess of 2,000 hours of the γ-ray beam-time. The up-grades will further improve the performance by two orders of magnitude. Meanwhile, we will continue with dozen of experiment in low energy nuclear physics (Eγ<20MeV) [5].

We would like to thank Prof. Berndt Müller and Prof. Glenn Edwards from Duke University for the continuous support of project. We acknowledge the support of by the US Department of Energy, Duke University and MFEL program of Air Force Office of Scientific Research.

5 REFERENCES

[1] V.N.Litvinenko et al., NIM A 375 (1996) 580; SPIE **2521** (1995) 55, Phys. Rev Lett. **78** (1997) 4569
V.N.Litvinenko et al., PAC'97 Vancouver, 1997, p.833

[2] S.H.Park, "Characteristics of the Duke/OK-4 storage ring FEL and γ-ray Source", Thesis, January 2000, Duke University;
S.H.Park et al., "Dependence of energy resolution of Compton backscattered γ-rays on incoming beam parameters in the Duke/OK-4 Storage Ring FEL", Presented at International FEL Conference, August 2000, Durham, NC, (to be published)

[3] V. N. Litvinenko et al., "Predictions and Expected Performance for the VUV OK-5/Duke Storage Ring FEL with Variable Polarization",
O.Shevchenko et al., "The VUV/UV OK-5/Duke Storage Ring FEL with variable polarization", these proceedings

[4] S.F.Mikhailov et al., "Project of Booster Synchrotron for the Duke FEL Storage Ring", these proceedings

[5] DoE Proposal, TUNL and DFELL, September 2000