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DEVELOPING AN IMPROVED PULSED MODE OPERATION FOR DUKE STORAGE RING BASED FEL*

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Abstract

The Duke FEL and High Intensity Gamma-ray Source (HIGS) facility is operated with an e-beam from 0.24 to 1.2 GeV and a photon beam from 190 to 1060 nm. Currently, the energy range of the gamma-ray beam is from 1 MeV to about 100 MeV, with the maximum total gamma-ray flux about $3E10$ gammas per second around 10 MeV. The FEL is typically operated in quasi-CW mode. Some HIGS user experiments can benefit tremendously from a pulsed mode of FEL operation. For that purpose, a fast steering magnet was developed years ago [1] to modulate the FEL gain. This allows a build-up of a high peak power FEL pulse from a well-damped electron beam. However, the use of this gain modulator at low e-beam energies can dramatically limit e-beam current due to beam instability and poor injection. It also suffers from the problem of a significantly reduced e-beam lifetime. To overcome these shortcomings, we developed and successfully tested an RF frequency modulation technique to pulse the FEL beam. In this paper, we will describe this development, and report our preliminary results of this improved pulsed FEL operation.

DUKE FEL/HIGS FACILITY

The Duke storage ring is designed as a dedicated FEL driver and a host of several FEL wigglers in a thirty-four meter long FEL straight section. The main parameters of the Duke accelerators and FEL's are listed in Table 1.

A planar optical-klystron FEL, the OK-4 FEL, consists of two planar wigglers sandwiching a buncher magnet.

Table 1: Parameters of Duke Accelerators and FELs

Accelerators	Storage ring	Booster injector
Operation energy [GeV]	0.24-1.2	0.16-1.2
Maximum current [mA]	125	15
Circumference [m]	107.46	31.902
Revolution frequency [MHz]	2.79	9.397
RF frequency [MHz]	178.55	
FELs	OK-4	OK-5
Polarization	Horizont.	Circular
No. of wigglers	2	4
No. of regular periods	33	30
Wiggler periods [cm]	10	12
Maximum peak field [kG]	5.36	3.17
Maximum K_w	5.00	3.53
Maximum current [kA]	3.0	3.5
FEL wavelength [nm]	190 - 1064	

A circular optical-klystron FEL employs up four OK-5 helical wigglers, two of them in the middle of the straight section are switchable with two planer OK-4 wigglers. In 2005, operating with two OK-4 and two OK-5 wigglers simultaneously, we demonstrated lasing of the world's first distributed optical klystron FEL, the DOK-1 FEL, with a record FEL gain for storage ring based FELs [2].

DEVELOPMENT OF RF FREQUENCY SWITCH (Q-SWITCH)

Typically, in all the wiggler configurations and polarizations, the Duke FEL is operated in a quasi CW mode. For some user experiments, a pulsed FEL may become exceptionally beneficial. This allows users to additionally reduce the noise background by two to three orders of magnitude using time discrimination synchronized with FEL macro-pulses. To enable a pulsed mode of FEL operation, a fast steering magnet (so called FEL gain modulator) was developed [1]. It decouples the e-beam from the FEL beam in the interaction region for most of time, but periodically allows a brief overlap of the electron and FEL beams. This enables a pulsed mode of FEL operation with a high peak power in the FEL macro-pulses. The low-energy regime is the most commonly demanded for the nuclear physics experiments using a pulsed beam. The production of gamma ray beams of high intensity requires also high beam currents.

(RF drive with modulation)



(Reference CW)

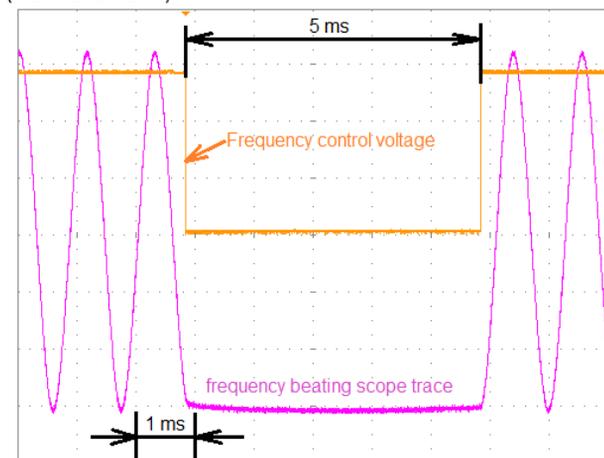


Figure 1: Fast switch of the RF frequency as demonstrated by the transition in time of the beating between the RF drive signal and a CW reference signal.

2: Photon Sources and Electron Accelerators

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The use of gain modulator in such a regime is constrained due to beam instability and poor injection. To facilitate a high intensity gamma production in a pulsed mode, especially at low e-beam and gamma energies, an RF frequency modulation technique (an RF frequency switch, or Q-switch) to pulse the FEL was developed and successfully tested.

Duke storage ring RF system utilizes a high stability commercial synthesizer HP 4400B as the master oscillator HP [3,4]. An additional SAW oscillator filter is used to eliminate a digital phase and frequency noise of the master oscillator. However, to enable a fast RF frequency jump, the SAW filter has to be bypassed. Under that condition, the RF system allows us to realize a fast frequency jump within tens of microseconds (Fig. 1). Detuning RF frequency to $\Delta f/f \approx 10^{-5}$ is sufficient to fully stop lasing for low gain FEL configurations.

“NATURAL” RELAXATION FEL OSCILLATIONS

We will first describe the “natural” pulsing of the storage ring FEL without any external drive. Such a regime of FEL generation with a sporadic quasi-periodical FEL pulsing was experimentally discovered and theoretically explained in the late 1980’s at the storage ring based low gain FEL’s, such as ACO, OK-4, Super-ACO [5,6].

At Duke HIGS/FEL facility, with two OK-4 and four OK-5 wigglers installed in the FEL straight section, we can have a variety of FEL configurations with different polarizations operated in a large range of gains. For practical gamma production, HIGS usually utilizes low FEL gain configurations. To produce highest intensity of gamma-ray in low-to-medium energy range (2-10 MeV), we typically use a very high reflectivity mirrors of 540-1060nm, and operate with a single wiggler OK-5A, OK-5B, or OK-4A.

High gain FEL configurations, such as OK-5B&C and OK4-A&B, with two OK-5 or two OK-4 wigglers in the middle of the FEL straight section, are usually employed for production of the high energy gamma ray beams of 30-100 MeV, using low reflectivity, high loss VUV mirrors of 250nm and 190 nm.

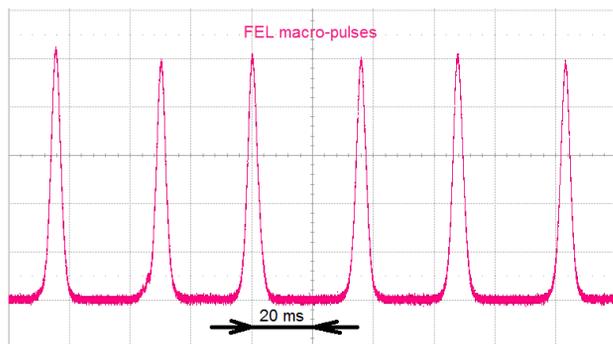


Figure 2: A scope trace of a “natural” FEL relaxation pulsing with a low gain OK-5A FEL, lasing at 705nm, with $E_e = 350$ MeV, mirror round trip loss of $\sim 0.16\%$.

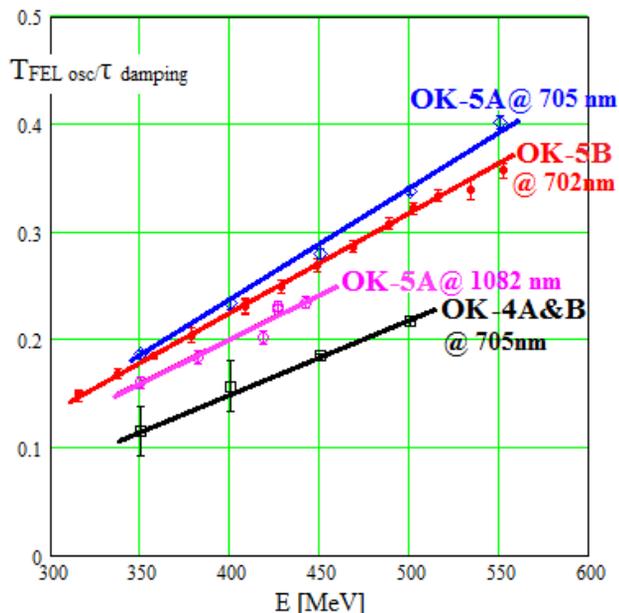


Figure 3: Period of the “natural” FEL relaxation pulsing normalized by the energy damping time vs. the e-beam energy, measured for different FEL configurations.

Fig. 2 shows an example of a “natural” FEL pulsing for OK-5A FEL. It is acquired at a specific detune of the RF frequency from exact FEL resonance, at which the FEL macro-pulses are relatively periodical and rather stable in magnitude. We shall notice, that this condition is met only in an extremely narrow frequency bandwidth of $\Delta f/f \sim 10^{-8}$. A typical range of period of the “natural” relaxation FEL pulsing is ~ 10 -40 ms, depending on the e-beam energy and FEL gain. Dependency of the relaxation pulsing period on the e-beam energy and FEL configuration is shown in Fig.3. The period of the pulsing is expressed as a portion of the synchrotron radiation damping time. As one can see, the “natural” FEL pulsing does not require to cool the e-beam for a full radiation damping, as the FEL macro-pulse builds up only after ~ 10 -30% of the damping time.

FEL power in this pulsing regime is at maximum, practically the same as that in a CW FEL operation in a very small bandwidth around the FEL resonance. Thus, the peak FEL power in the macro-pulses is much higher than the CW or in the quasi CW-operation.

PULSED FEL OPERATION USING RF FREQUENCY SWITCH

For the practical use of pulsed FEL operation at HIGS, we need to achieve a reasonable reproducibility of the magnitude and the length of the FEL macro-pulses. To provide for such reproducibility, we can force the FEL to operate in the pulsed mode. The period of the forced pulsing, and therefore of the forcing drive, has to be at least twice as long as the period of the “natural” FEL relaxation pulsing ($T_{forced} \geq 2T_{natural}$). If that period is shorter than that ($T_{forced} < 2T_{natural}$), e-beam is not damped sufficiently to build up every FEL macro-pulse. As a

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result, we have a macro-temporal structure with every other macro-pulse fully developed, while those in between the full strength macro-pulses are under-developed, as shown in Fig.4.

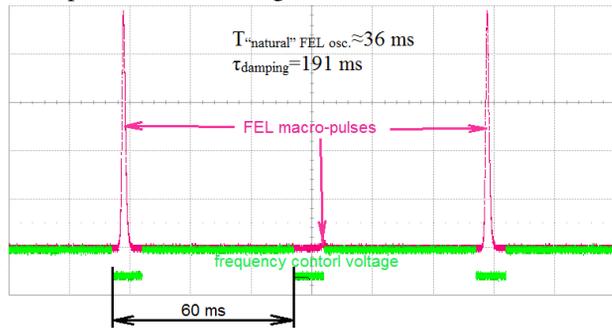


Figure 4: Pulsed FEL operation with a drive period too short to provide for reproducible FEL macro-pulses. OK-5A FEL at 705nm, $E_e = 350\text{MeV}$, mirror round trip losses of $\sim 0.16\%$.

To insure a reasonable stability of the pulsed FEL operation, it is better to set some longer period of pulsing ($T_{\text{forced}} \geq 2.5T_{\text{natural}}$). Under condition that $T_{\text{forced}} \approx 2.5T_{\text{natural}}$, the average FEL power is practically the same as that in a quasi-CW regime, with a very high peak power in the FEL micro-pulses. Fig.5 shows dependency of the shape of the FEL macro-pulses on the period of the pulsing for a fully periodical macro-temporal structure ($T_{\text{forced}} \geq 2T_{\text{natural}}$). With longer period of pulsing, the reproducibility of the FEL macro-pulses is also much better, and the jitter much lower.

The RF frequency drive signal has to switch periodically to a frequency which allows full synchronization of the e-beam and FEL beam for a minimum duration. This duration has to be long enough to allow the FEL to build up fully, reaching saturation. Such a minimum duration depends on the period of the pulsing (see Fig. 5). For low gain wiggler/FEL configuration, such as OK-5A, it was typically ~ 10 ms, as shown in Fig. 4 and Fig. 5, while for the OK4-AB two-wiggler configuration it was ~ 4 -5 ms.

For the HIGS gamma ray users requiring additional noise background reduction, the most important parameter is the ratio of the period of the pulsing and the width of the FEL macro-pulse. As one can see, with an increase of the period, that ratio grows faster than the period itself as the FEL micro-pulses become much shorter (Fig. 5).

The limiting factor to increase the pulsing period is a risk of the e-beam loss. For typical HIGS gamma production we operate with the electron beam currents above the two-bunch current threshold without FEL.

The electron beam is stable due to a significant FEL induced beam stretch. If this stretch is reduced substantially, beam loss can happen.

The other factor which has to be considered with an increase of the pulsing period is that the average FEL power becomes lower than the power of the quasi-CW FEL operation with the same e-beam currents (see Fig. 5).

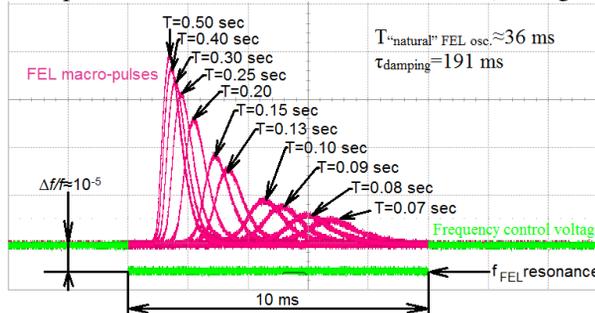


Figure 5: FEL pulsed operation: “stable” fully periodical FEL macro-pulses for different periods of drive. OK-5A FEL at 705nm, $E_e = 350\text{MeV}$, mirror round trip losses of $\sim 0.16\%$.

For synchronization of their acquisition equipment, HIGS users are provided with a trigger by the relative level of FEL macro-pulses, which can be set at 10-70% of level of a typical maximum.

CONCLUSION

An RF frequency detune drive has been developed at DFELL and is ready to be used in a pulsed FEL and HIGS operation. It can provide for high gamma ray beam intensity, with average intensity close to the level of a quasi-CW operation, and therefore, with a very high peak intensity during the pulses.

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