Optics-Free X-ray FEL Oscillator

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PAC'11 New York March 29 2011

Outline

1. Motivation.
2. Basic idea and operation schema
3. Feed back requirements
4. Lasing simulations
5. Conclusions

There is a need for an X-ray Optics-Free FEL Oscillators

1. While SASE (Self-Amplified Spontaneous Emission) FELs demonstrated the capability of providing very high gain and short pulses of radiation and scalability to the X-ray range, the spectra of SASE FELs remains rather wide (~0.5%-1%) compared with typical short wavelengths FEL-oscillators (0.01% - 0.0003% in OK-4 FEL).

2. Absence of good optics in VUV and X-ray ranges makes traditional oscillator schemes with very high average and peak spectral brightness either very complex or, strictly speaking, impossible

Basic ideas and feedback requirements

1. The information in the form of the energy modulation imprinted into the feed-back beam is preserved after the pass from the OFFELO exit to its entrance.

The electrons **must** stay correlated at the scale of FEL wavelength:

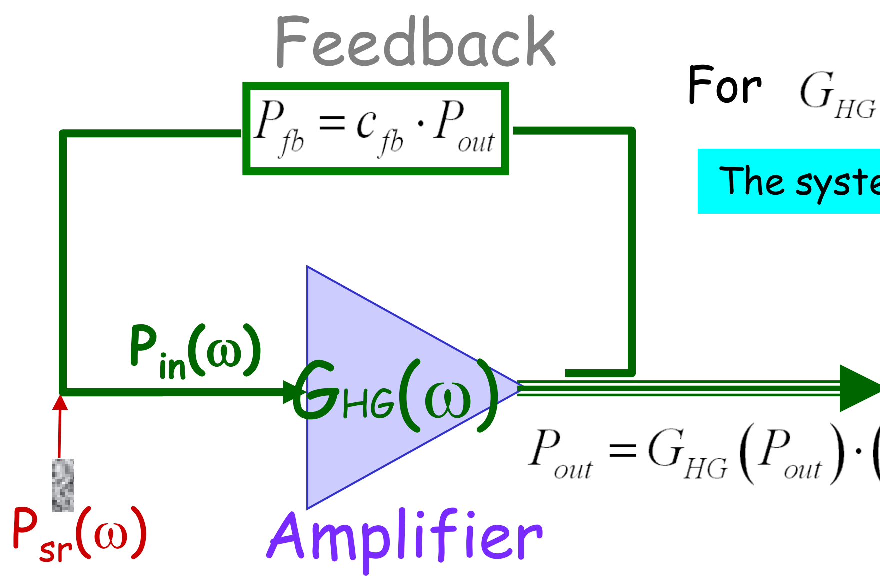
$$\delta S_{turn} = c(\tau_{exit} - \tau_{input}) < \lambda_{FEL}$$

2. The spectral density of the power generated by the feedback e-beam is significantly larger than that of the spontaneous radiation from the amplifier-beam.

When

$$c_{fb} \cdot P_{out} >> P_{sr}$$

The coherent input from the feedback will saturate the gain of the main FEL and suppress SASE noise.

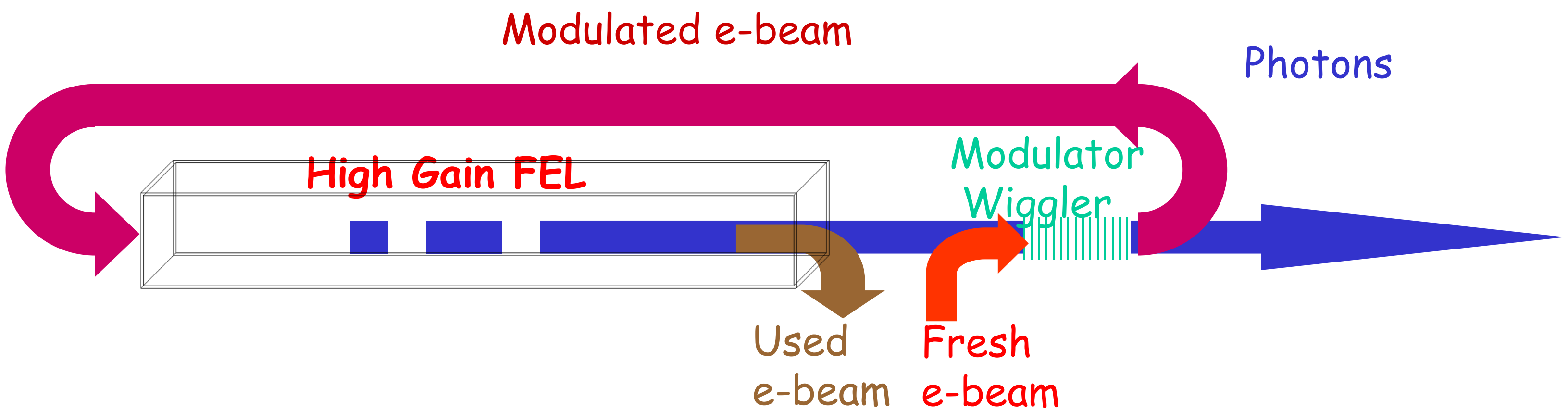


$$P_{out} = G_{HG}(P_{out}) \cdot (c_{fb} \cdot P_{out} + P_{sr}).$$

For $G_{HG}(0) \cdot c_{fb} > 1$

The system oscillates

The simplest schema of optics free FELO #1



- For low energy beam (and rather long wavelength) the same beam can be used in feed back system and in High Gain FEL.
- It is conceivable to modulate the beam using a short wiggler, turn it around, and to amplify the modulation and the resulting optical power in a high gain amplifier

One of the example: HG Ring FEL Suggested by N.A. Vinokurov in 1995 , Nucl. Instr. and Meth. A 375 (1996) 264
then in 2004.

High-gain ring FEL as a master oscillator for X-ray generation

Nikolay A. Vinokurov*, Oleg A. Shevchenko

Nuclear Instruments and Methods in Physics Research A 528 (2004) 491–496

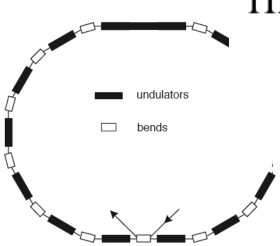


Fig. 1. Scheme of the ring FEL.

Table 2
Soft X-ray ring FEL parameters

Energy (GeV)	0.485
Peak current (kA)	0.3
Relative energy spread (%)	0.05
Normalized rms emittance (μm)	5
Undulator period (m)	0.03
Undulator deflection parameter (K)	2
Radiation wavelength (Å)	500
Undulator section length (m)	12
Undulator first and last section length (m)	5
Bend angle (deg)	60
Bend length (m)	10
Bend $\int \gamma_x \, ds$	3.1
Bend $\int \gamma_y \, ds$	6.22
Distance between first and last undulator ends (m)	2

Turn around feed back lattice requirements

$$\left|\delta S_{turn}\right| \le \lambdabar_{FEL};$$

$$\delta S_{turn} = \delta S_{turn}(\delta E) + \delta S_{turn}(\varepsilon_{x,y}) + \delta S_{HO}(\delta E, \varepsilon) + \delta S_{random};$$

1. Energy spread and compaction factors

$$\delta S_{turn}(\delta E) = L \cdot \left\{ R_{56}\left(\frac{\delta E}{E}\right) + R_{566}\left(\frac{\delta E}{E}\right)^2 + R_{5666}\left(\frac{\delta E}{E}\right)^3 + \dots \right\};$$

$$\Rightarrow \left|R_{56}(0,L)\right| < 10^{-8}; \left\|R_{566}(0,L)\right\| < 10^{-4}; \left\|R_{5666}(0,L)\right\| < 1 \dots$$

-> second order isochronous system is needed

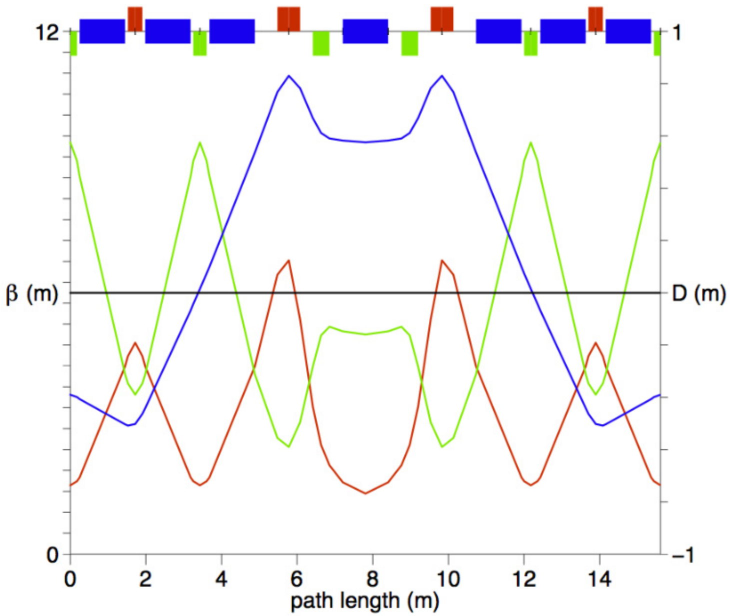
2. Emittance effects:

Linear term comes from symplectic conditions: zeroing both matrix elements R16 and R26 (η=0 and η'=0) automatically zero R51 and R52

It is not a problem to make the turn achromatic.

It is a bit more complicated to make the condition energy independent.
An elegant solution - sextupoles combined with quadrupoles with $K_2 = K_1/2\eta$:

Turn around lattice, based on isochronous cell lattice



The isochronous cell with tune advance 0.95 and 0.525 in horizontal and vertical planes correspondingly.
Similar lattices that is used for eRHIC or LeHC design (talk this morning TUOAN3)

The sextupoles are installed in the middle of quadruples

$$\int_0^L O(x^2, y^2, xy, \eta^2) \Rightarrow 0$$

Solution is a second order achromat (N cell with phase advance 2πM, M/N is not integer, etc.) with second order geometrical aberration cancellation

- This scheme is similar to that proposed by Zolotarev and Zholetz. (PRE 71, 1993, p. 4146) for optical cooling beam-line and tested using COSY INFINITY. It is also implemented for the ring FEL: A.N. Matveenko et al. / Proceedings 2004 FEL Conference, 629-632

Synchrotron radiation

- Turning around strongly modulated high energy beam does not work.
- Why? Synchrotron radiation quantum fluctuation will smooth out micro-bunching structure of the beam.
  - Energy of the radiated quanta $\varepsilon_c[keV] = 0.665 \cdot B[T] \cdot E_e^2[GeV]$
  - Number of radiated quanta per turn $N_c \cong 2\pi\alpha\gamma \cong 89.7 \cdot E[GeV]$
    - Radiation is random -> the path time will vary
    - The lattice should be designed to minimize the random effects

$$(\delta S_{rand})^2 \approx N_c \left(\frac{\varepsilon_c}{E_e}\right)^2 \left\langle R^2{}_{56}(s,L) \right\rangle$$

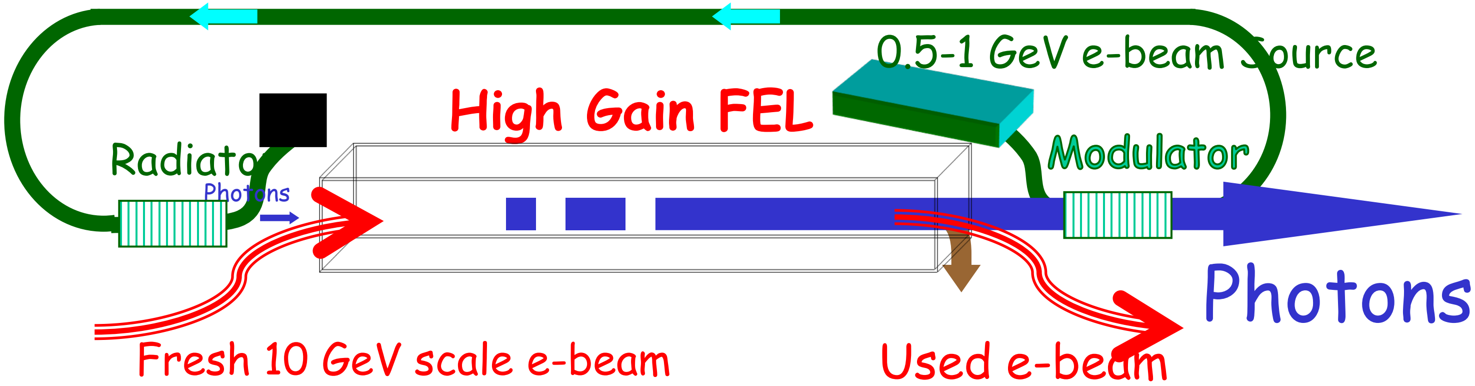
$R_{56}(s,L)$ is the *longtudinal dispersion* from azimuth s to L

$$\Rightarrow \quad \sqrt{\left\langle R^2{}_{56}(s,L) \right\rangle} < \sqrt{\frac{2}{N_c}} \frac{E_e}{\varepsilon_c} \lambda\!\!\!^{-}$$

For $\lambda\!\!\!^{-}{}_{FEL} \sim 1\mathring{A}$ ⟹ $\left\langle R_{56}^2(s,L) \right\rangle < 2.25 \cdot 10^{-5}\, m \cdot E_e^{-3/2}[GeV] \cdot B^{-1}[T]$

- Solution to reduce the synchrotron radiation fluctuation effects => low energy beam and low bending field for feed back loop

Next of possible schemes for X-ray OFFELO #2.



X-ray FEL fed by a high-energy, 10 GeV scale, CW ERL.

Use lower energy e-beam with very low charge (few pC), peak current (few A) and emittance (ε_n~10 nm) for the feed-back

The feed-back-beam is energy-modulated and carries-on the modulation to the entrance of the FEL

The energy modulation is transferred into the density modulation only at radiator there the beam radiates coherently.

This radiation is further amplified in the HGFEL, which completes the close loop of the oscillator.

Loop is closed

Low energy beam is much easy to turn around but how low one can go?

Parameters used for simulations

Low energy beam is much easy to turn around but how low one can go?

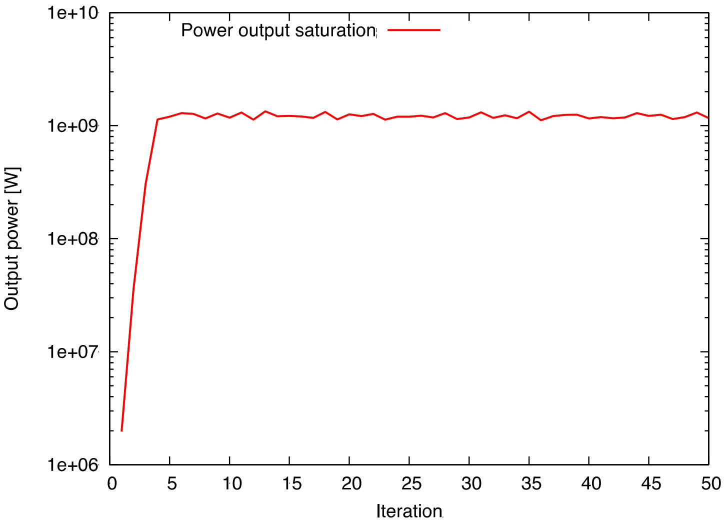
Feed back electrons has to be synchronized with FEL wave length → Modulator period scaled with Energy and K

Parameters	High energy beam	Low energy beam
Electron energy (GeV)	13.6	1
Energy deviation dE/E	1e-4	1e-5
Peak current (A)	3000	15
Normalized emittance (mm-mrad)	1.5	0.015
Undulator period [mm]	30	0.636*
Undulator Length [m]	60	
Number of undulator period		120/800
Undulator parameter K	2.616	0.1
Radiation wavelength [nm]	1.66	1.66
Average beta function (FEL) [m]	18	
R56 of the feed back transport		0

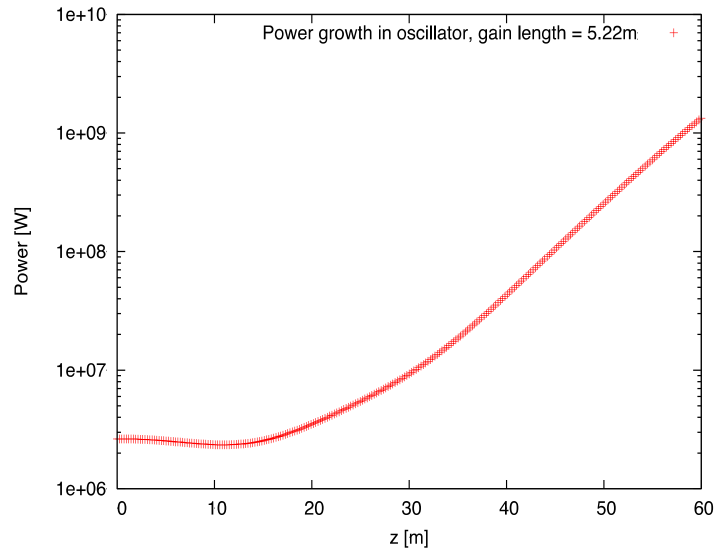
* The micro-wigglers are used as temporary tool, which will be replaced by interaction with high harmonics of a high-K wiggler with next stage of simulation

X-ray OFFELO Simulation results

Genesis 2.0 in combination with additional homegrown program used to simulate the processes in the OFFELO. *



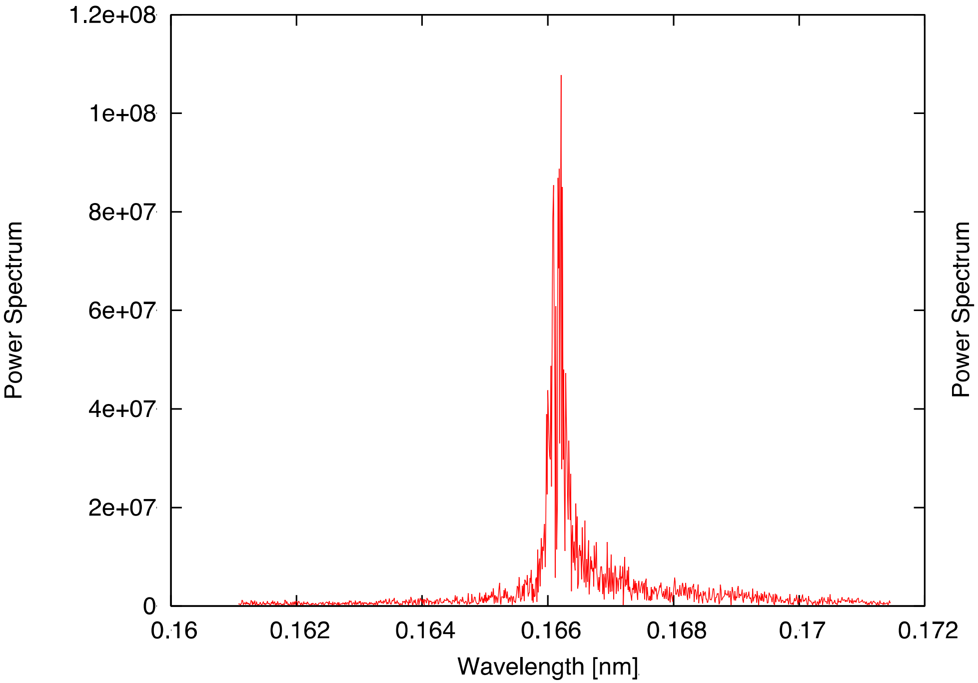
The curve shows the system saturates at 1.3GW because of the nonlinear bunching.



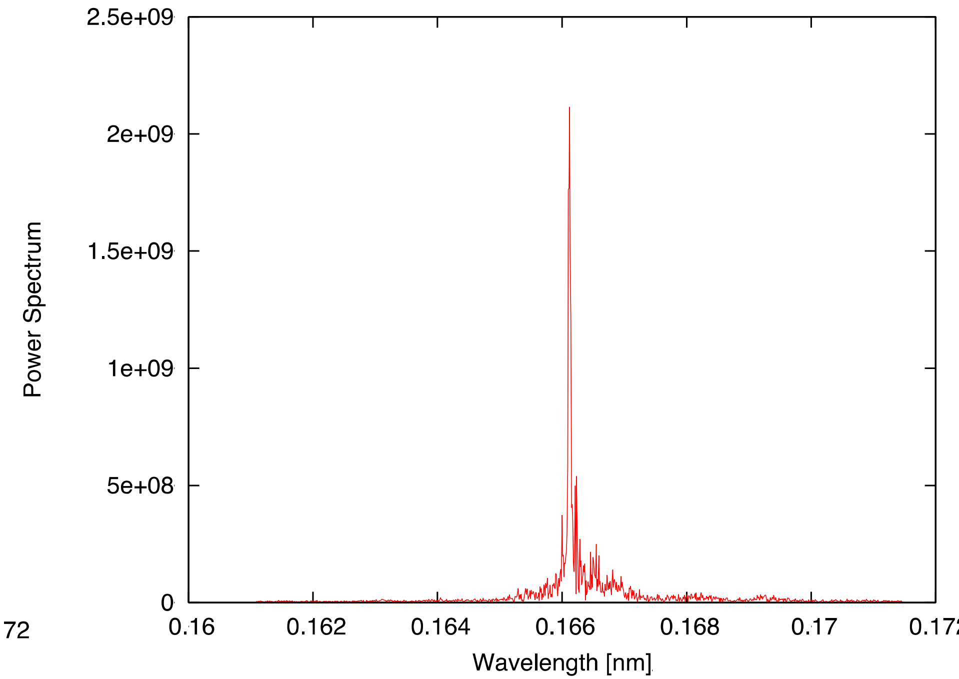
Power in main oscillator in #40 iterations.
3-D Gain length 5.22m

* More about these results see: Y.Hao and V.N.Litvinenko, Proc. of FEL'2010 conference, August 2010, Malmo, Sweden, p. 554

X-ray OFFELO Time Dependent Results *



After the first iteration
FWHM 2e-3



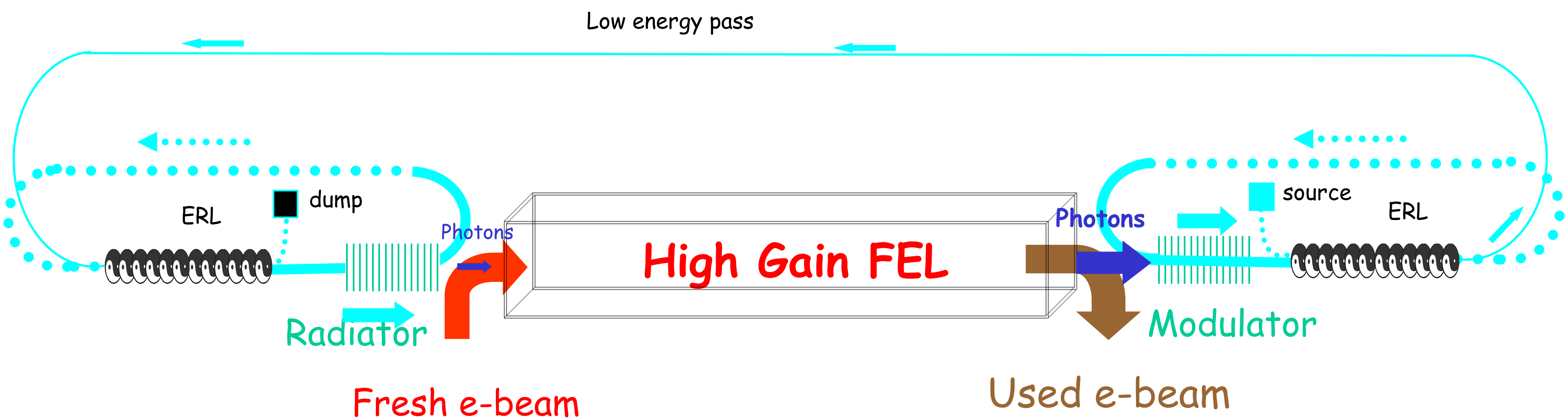
After the 10th iteration
FWHM 3e-4

The preliminary results of the evolution of the OFFELO radiation from the SASE (on the pass #1) with broad-band spectrum to a more typical oscillator like (on the path #10). In tem passes the spectral purity of radiation (i.e. spectral brightness) grew 20-fold.

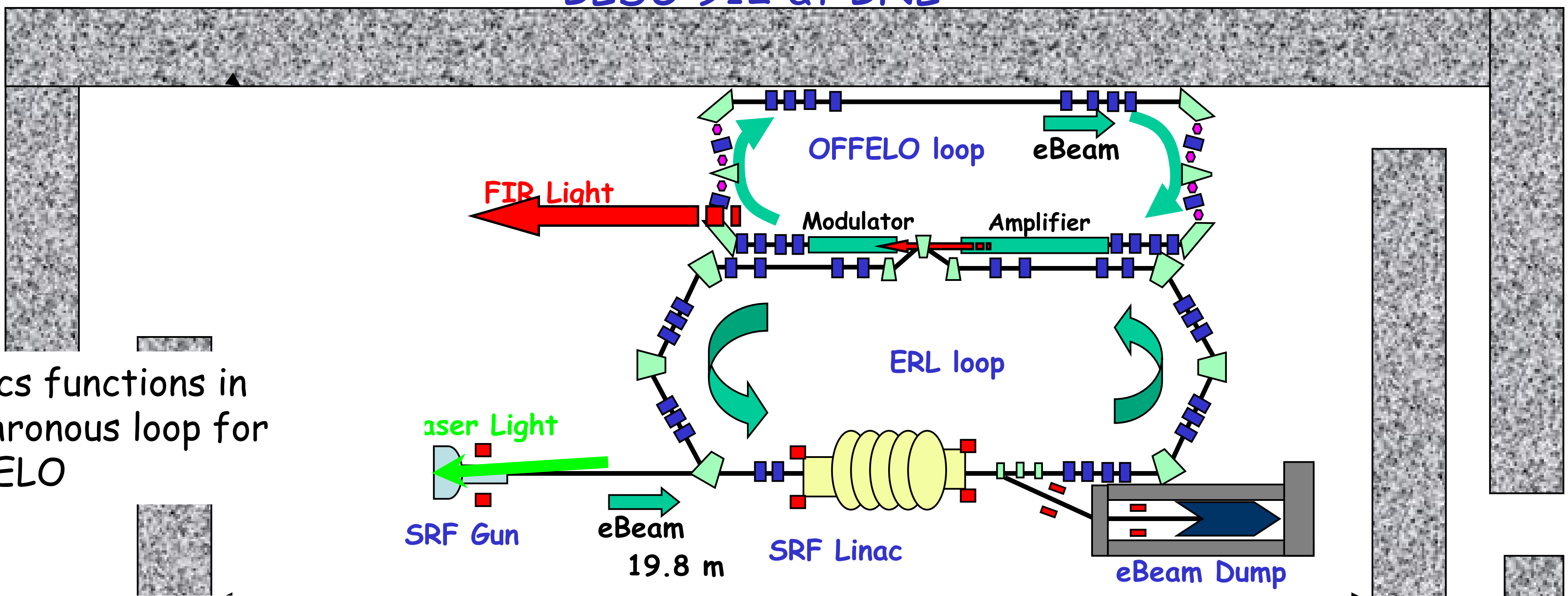
* More about these results see: Y.Hao and V.N.Litvinenko, Proc. of FEL'2010 conference, August 2010, Malmo, Sweden, p. 554

Alternative Feed-back scheme #3 (the most complete so far)

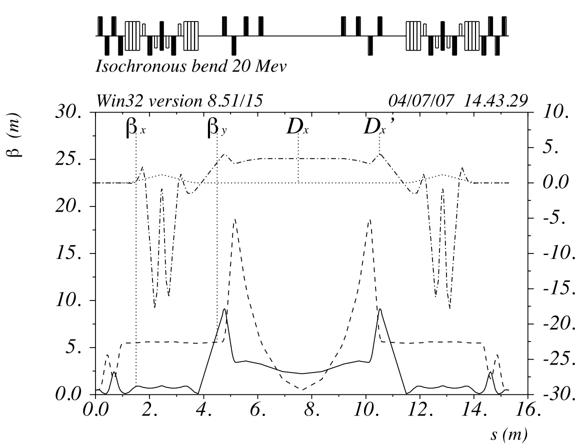
- Use beam with necessary energy for effective energy modulation (i.e. use of a typical wiggler)
- Decelerate the feed-back beam to much lower energy (*let's say ~100 MeV*) where synchrotron radiation is mitigated
- Turn the beam around, accelerate it to radiate in the radiator, decelerate it and dump it



Optics Free FEL based on R&D ERL fitted in accelerator cave in BLDG 912 at BNL



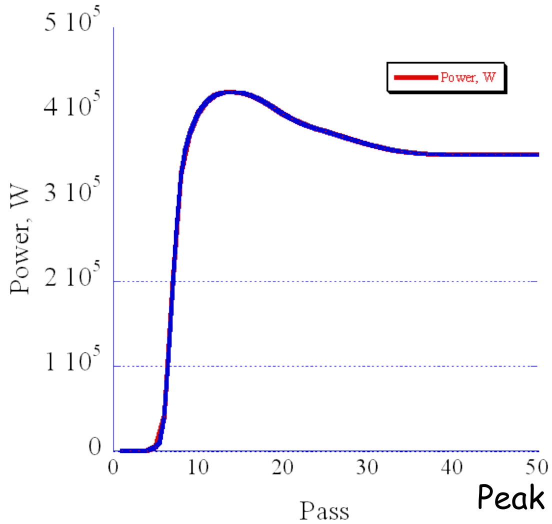
Optics functions in isochronous loop for OFFELO



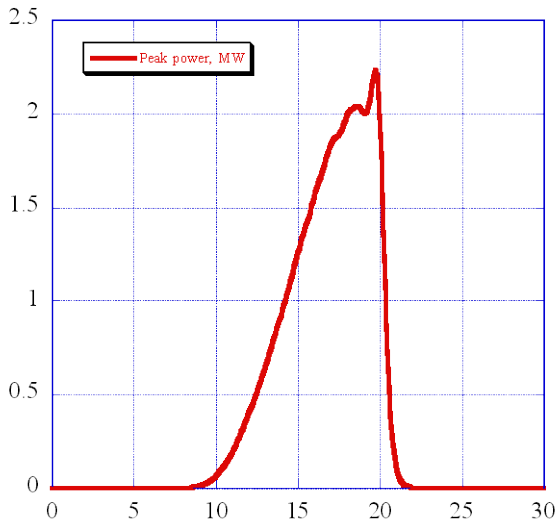
	(PARMELA simulation)		
Charge per bunch, nC	0.7	1.4	5
Numbers of passes	1	1	1
Energy maximum/injection, MeV	20/2.5	20/2.5	20/3.0
Bunch rep-rate, MHz	700	350	9.383
Average current, mA	500	500	50
Injected/ejected beam power, MW	1.0	1.0	0.15
Normalized emittances ex/ey, mm*mrad	1.4/1.4	2.2/2.3	4.8/5.3
Energy spread, dE/E	3.5×10^{-3}	5×10^{-3}	1×10^{-2}
Bunch length, ps	18	21	31

FEL simulation results for OFFELO at BNL R&D ERL GENISIS simulations *

5 cm undulators period and 0.7 nC electron beam at rep. frequency 9.38 MHz the GENESIS simulation gives: wavelength **29 microns**, peak power **2 MW** and average power 400 W. For full current mode operation rep. rate 703.75 MHz we obtain **30 kW** far infrared in CW mode.



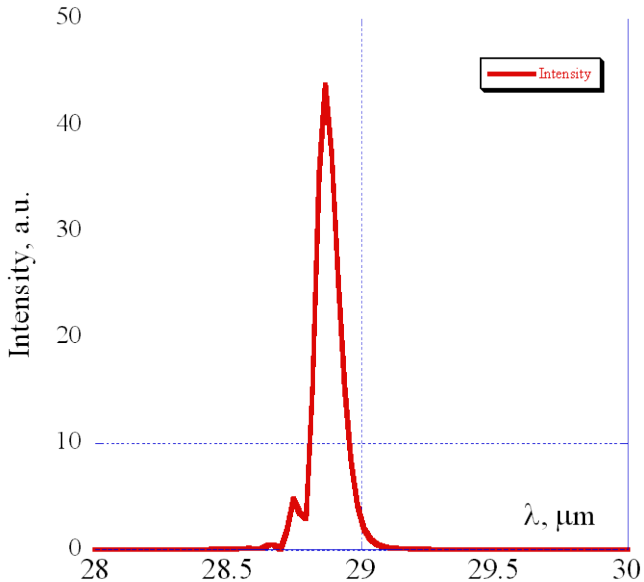
Peak power reaches 2 MW



Optical pulse

Close to the Fourier limited spectrum

The central wavelength 29μm and FWHM 0.35%.



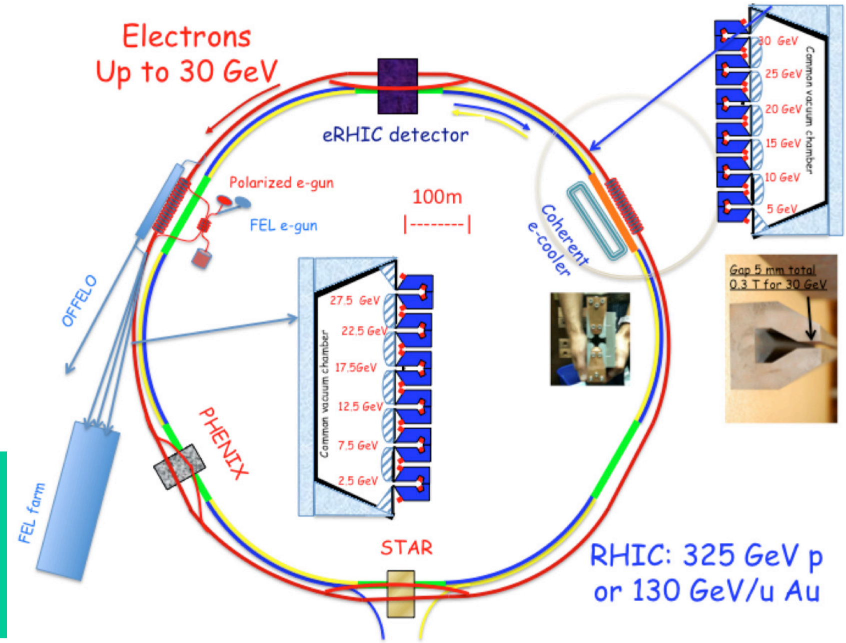
Spectrum

*) Presented at FEL2007

eRHIC based FEL

Electron: 5 Gev to 20 GeV upgradable to 30 GeV

multi-pass ERL: 2 x 200 m SRF linac maximum 4.9 GeV per pass



Top Energy of the ERL (collision energy)	Available Energy for FEL
5 GeV	2.55, 2.96, 3.37, 3.78, 4.18, 4.59, 5.00
10 GeV	3.47, 4.28, 5.10, 5.92, 6.73, 7.55, 8.37, 9.18, 10.00
15 GeV	2.75, 3.98, 5.20, 6.43, 7.65, 8.88, 10.10, 11.33, 12.55, 13.78, 15.00
20 GeV	3.67, 5.30, 6.93, 8.57, 10.20, 11.83, 13.47, 15.10

More about eRHIC design:
today morning talk TUOAN2
and eRHIC uses for FEL application:
Thursday poster THP007

Conclusions

FEL oscillator without optics seems to be scientifically feasible

We tested some of the key assumptions of OFFELO concept in direct 3D-FEL simulations and observed the behavior consistent with our theoretical models.

For different wave length different scheme of OFFELO can be considered. From the simplest for soft X-ray to more sophisticated one for the hard X-ray

The concept is very promising and we plan to continue more detailed and more realistic simulation of such system.

R&D is required to check very important technical details

A long few pC bunch with few A peak current with $\varepsilon_n \sim 0.01$ μm rad is needed.

The simulation supports the theory - needs an experiment

The last remark

- The free electrons – are the pure media which does not care about the wavelength and the intensity of radiation, the heat stress, the absorption, the losses, the reflectivity and by the way do not need "conditioning"
- But it needs "only" delicate preparation and proper transport system design.

Thank you!