ERL requirements for X-ray Optics-Free FEL oscillator

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** 10 years old idea: X-OFFELO was introduced in July 2002 at ICFA workshop in Chia Laguna, Sardinia and later at FEL 2005 as FEL prize talk.*

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Dedication

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

MIRRORS

Pushing the FEL oscillator power will require – at some moment- removing the optics and relying on the e-beam

Content

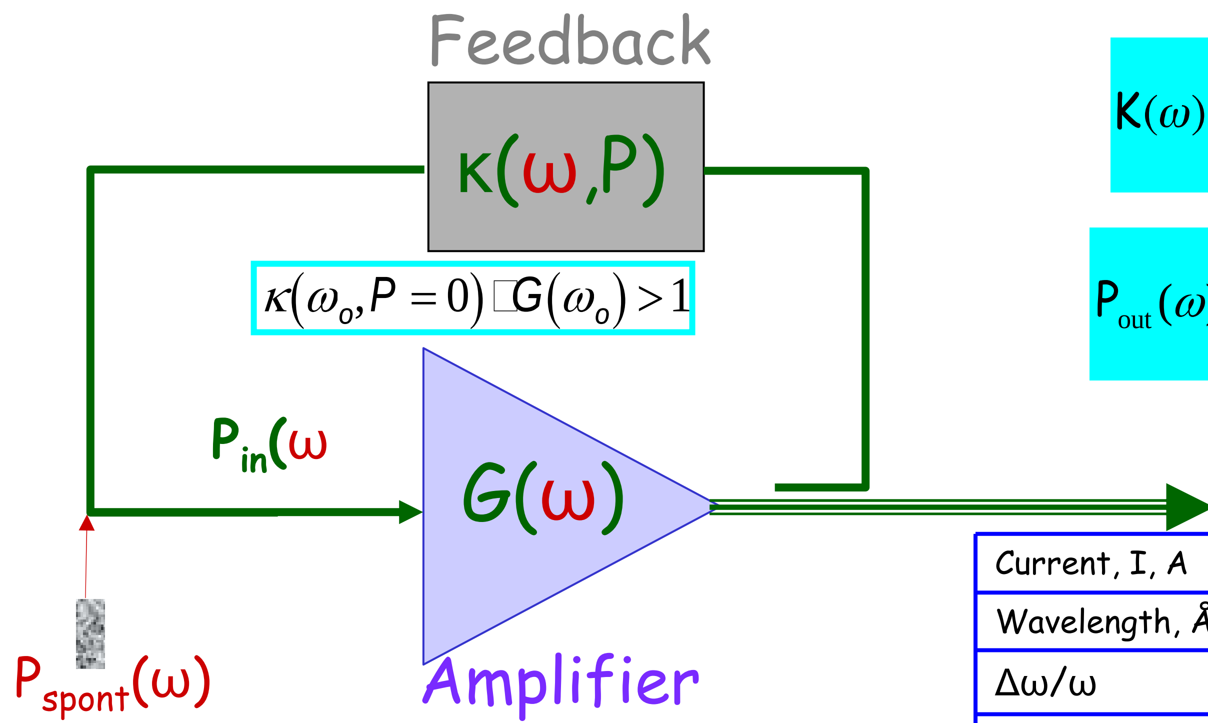
- What is OFFELO?
- Main challenges
- Problems we addressed
- Simulations & results
- Conclusions/Plans

Oscillator

$K(\omega) = G(\omega)\,\kappa(\omega,P)$

$$K(\omega) \approx K(\omega_o)\cdot\left(1 - \frac{(\omega-\omega_o)^2}{\Delta\omega^2}\right)$$

$$P_{out}(\omega) \approx P_{out}(\omega_o)\left(1 - \frac{(\omega-\omega_o)^2}{\delta\omega^2}\right)$$



$P_{out}(\omega) = G(\omega)\cdot P_{in}(\omega)$

Current, I, A	~ 100 A
Wavelength, Å	~ 1
$\Delta\omega/\omega$	~ 10^{-3}
Ko	~ 1.2
$\delta\omega/\omega$ **Correlations length**	**~ 3 10^{-8}** **~ 3 mm !!!**

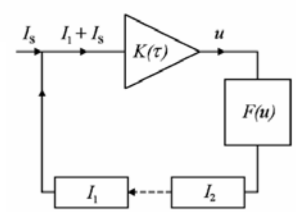
Detailed analysis of the lasing linewidth of saturated oscillator is in:

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

$$\frac{\delta\omega}{\omega} \sim \frac{e\omega}{I}\left(\frac{\Delta\omega}{\omega}\right)^2 |K(\omega)|^2$$



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Electron-beam out-coupling

© N.A.Vinokurov, 1985

On Mutual Coherency of Spontaneous Radiation from Two Undulators Separated by Achromatic Bend

G. N. Kulipanov, V. N. Litvinenko, A. S. Sokolov, and N. A. Vinokurov

Observation of Mutual Coherency of Spontaneous Radiation from Two Undulators Separated by Achromatic Bend

N. G. Gavrilov, G. N. Kulipanov, V. N. Litvinenko, I. V. Pinaev, V. M. Popik, I. G. Silvestrov, A. N. Skrinsky, A. S. Sokolov, N. A. Vinokurov, and P. D. Vobly

INTRODUCTION

In 1985 N. Vinokurov proposed "electron beam out-coupling" to solve the problem of mirror damage in high-power FEL's [1]. The proposed apparatus (see Fig. 1) is comprised of an FEL oscillator (1), an achromatic bend (2), and an additional long undulator (3). An electron bunch achieves a density modulation in the FEL oscillator, passes the achromatic bend, and radiates coherently in the additional undulator ("radiator"). In this system, the output power is comparable with the intracavity power.

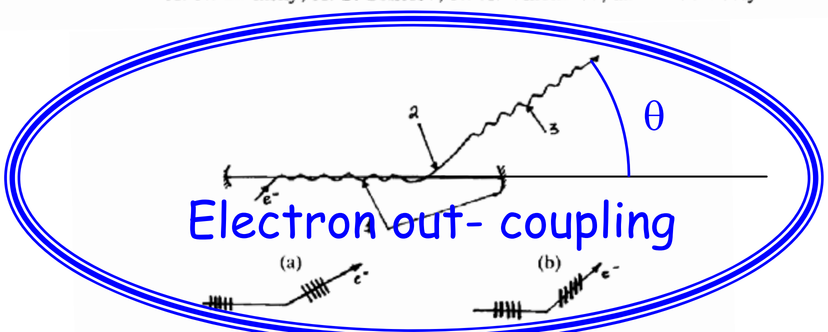

Fig. 1. "Electron beam outcoupling" schematic—1-FEL oscillator; 2-achromatic bend; 3-additional undulator ("radiator"); 4-density modulation after achromatic (a) and simple bends (b).

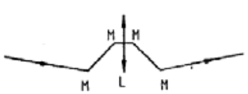

Fig. 2. The layout of the achromatic bend: *M*-bending magnets and *L*-lens.

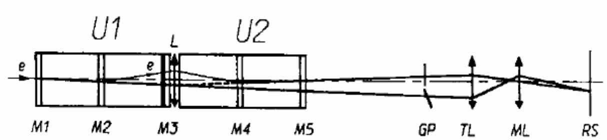

Fig. 3. Layout of magnetic and optical system—M1–M5—steering coils; *L*—quadrupole lens; U1 and U2—undulators; TL and ML—optical lenses, RS—observation screen, GP-glass plates.

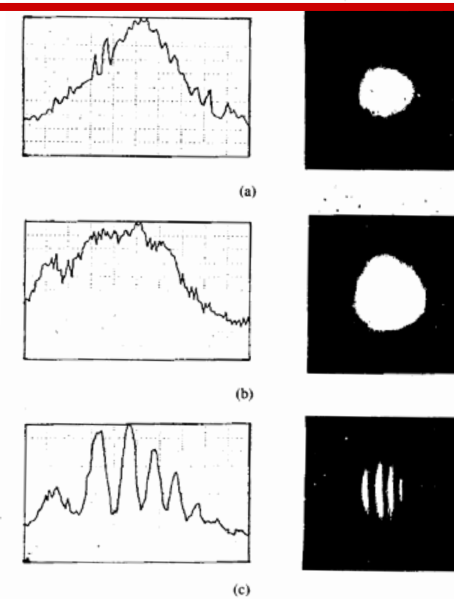

Fig. 4. Interference pictures measured by CCD-array (left-hand side) and photographs (right-hand side). (a) with the conventional bend, but with the time delay compensation; (b) with the achromatic bend, but without the time delay compensation; (c) with the achromatic bend and with the time delay compensation.

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OFFELO #1
High Gain Ring FEL oscillator

Suggested by N.A. Vinokurov in 1995 , Nucl. Instr. and Meth. A 375 (1996) 264

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

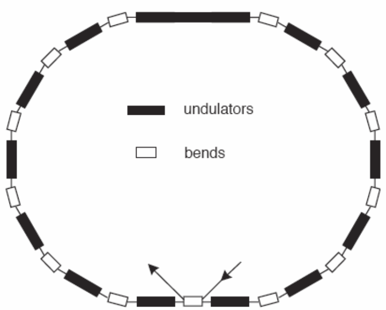


Fig. 1. Scheme of the ring FEL.

$$c\langle \Delta t\rangle = \frac{\varepsilon_x}{2}\int_0^L \gamma_x \, ds + \frac{\varepsilon_y}{2}\int_0^L \gamma_y \, ds$$

Multiple wigglers separated
By second order achromatic
bends

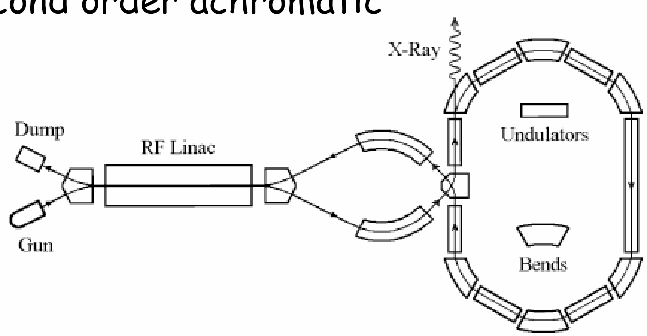


Fig. 7. Possible layout of ring FEL with energy recovery linac.

Table 1
X-ray ring FEL parameters

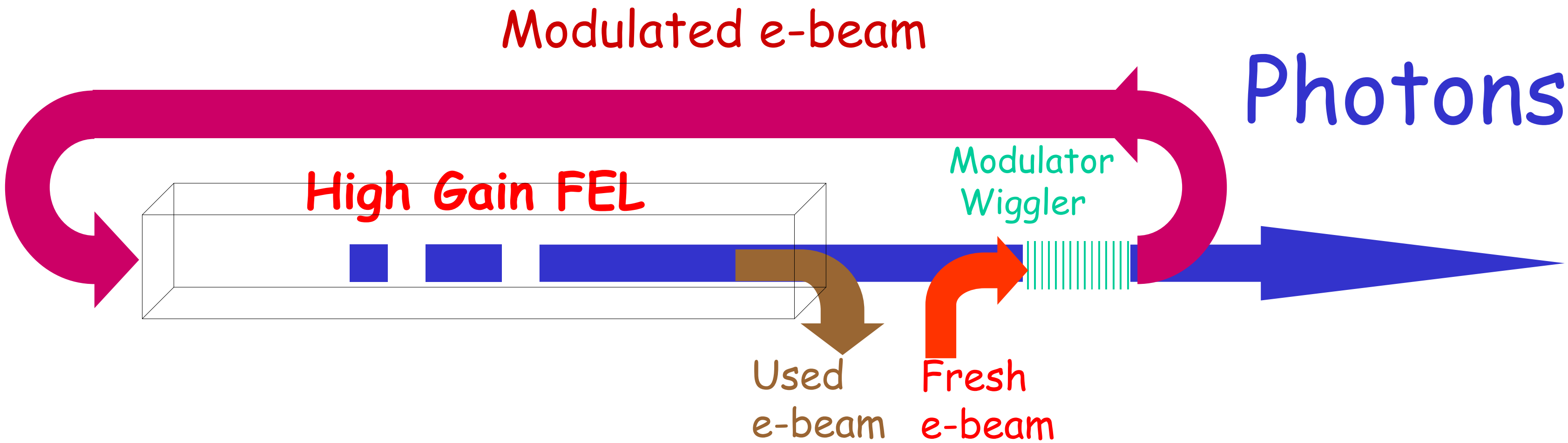
Energy GeV	14.35
Peak current (kA)	2
Relative energy spread (%)	0.008
Normalized rms emittance (μm)	1.2
Undulator period (m)	0.03
Undulator deflection parameter K	3.71
Radiation wavelength (Å)	1.5
Undulator section length (m)	18
Undulator first and last section length (m)	18
Bend angle (deg)	30
Bend length (m)	6
Bend $\int \gamma_x \, ds$	0.864
Bend $\int \gamma_y \, ds$	1.245
Distance between first and last undulator ends (m)	2

Table 2
Soft X-ray ring FEL parameters

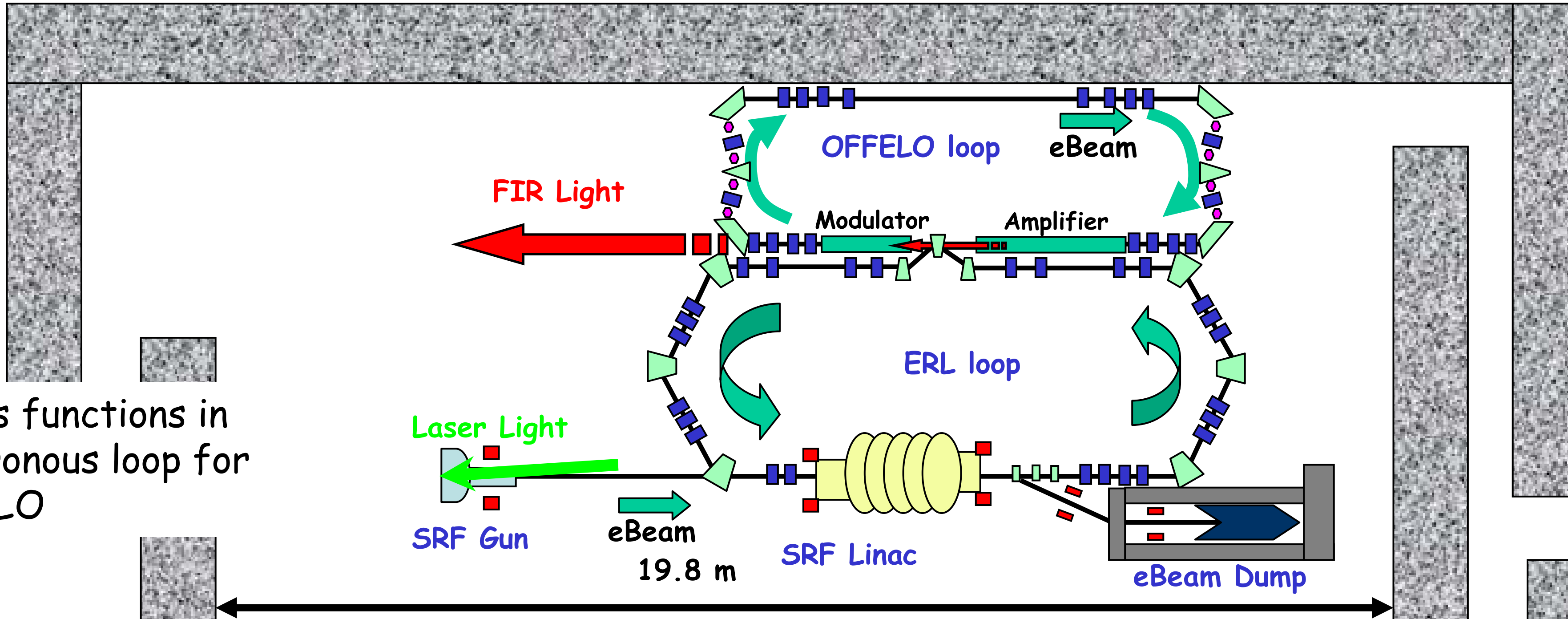
Energy (GeV)	0.485
Peak current (kA)	0.3
Relative energy spread (%)	0.05
Normalized rms emittance (μm)	5
Undulator period (m)	0.03
Undulator deflection parameter (K)	2
Radiation wavelength (Å)	500
Undulator section length (m)	12
Undulator first and last section length (m)	5
Bend angle (deg)	60
Bend length (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

Ring FEL - low energy

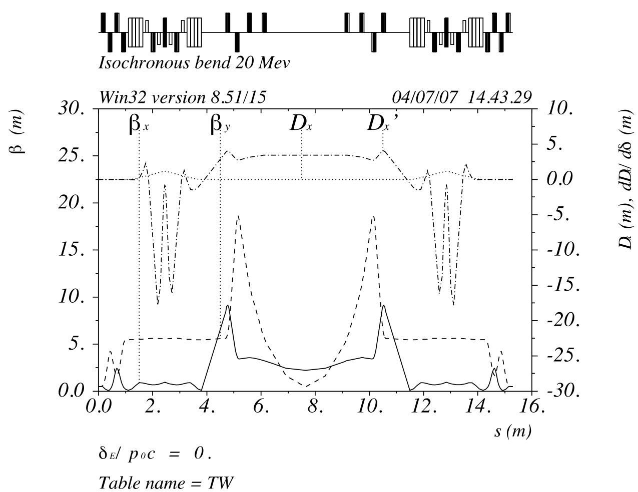
- For a low energy beams (and rather long wavelength) it is conceivable to modulate the beam using a short wiggler, turn it around, and to amplify the modulation and the resulting optical power in a high gain amplifier



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

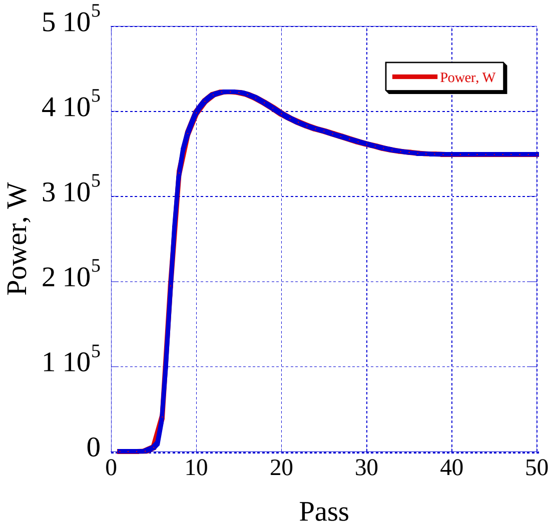


Optics functions in isochronous loop for OFFELO



	(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

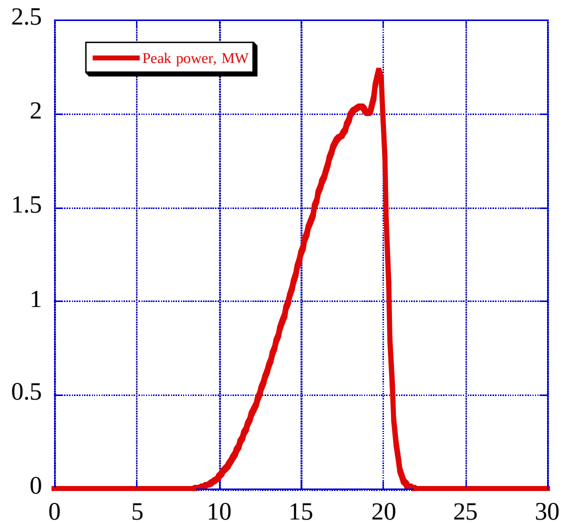
FEL simulation results for OFFELO at BNL R&D ERL GENISIS simulations



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.

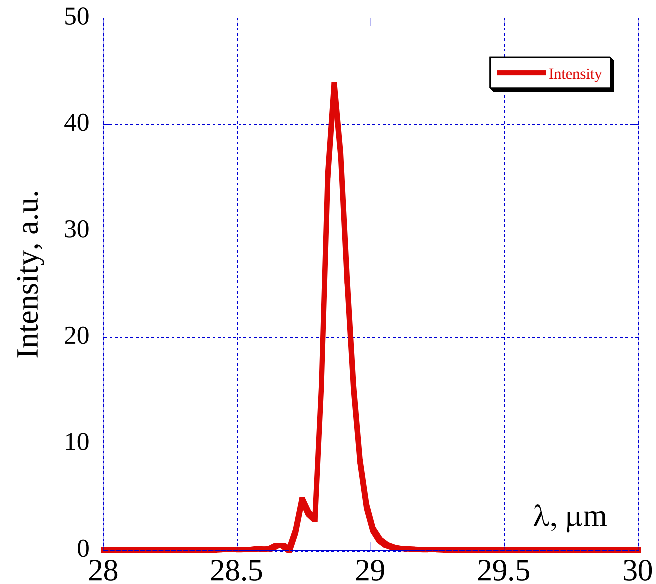
Peak power reaches 2 MW

The central wavelength 29μm and FWHM 0.35%.



Optical pulse

Close to the Fourier limited spectrum



Spectrum

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High Gain Ring FEL oscillator - cont.

A.N. Matveenko et al. / Proceedings of the 2004 FEL Conference, 629-632

ISOCHRONOUS BEND FOR HIGH GAIN RING FEL

A.N. Matveenko, O.A. Shevchenko, N.A. Vinokurov

[*] The debunching due to quantum fluctuations was pointed out by V. N. Litvinenko.

EFFECT OF QUANTUM FLUCTUATIONS OF SYNCHROTRON RADIATION

$$\sigma_{c\Delta t}^2 = \frac{55}{24\sqrt{3}} \frac{r_0^2}{\alpha} \gamma^5 \int_0^L R_{56}^2(0,s) \cdot h^3(s) \cdot ds$$

$h(s)$ is the orbit curvature.

Three-bend isochronous achromat (positive, negative, positive bends)

$$R_{56}(0,s) = \frac{h^2 s^3}{6}$$

$$\sigma_{c\Delta t}^2 = \frac{55}{24\sqrt{3}} \frac{r_0^2}{\alpha} \gamma^5 \frac{\alpha_0^7}{126} \quad \Rightarrow \quad \sigma_{c\Delta t} \sim 60\ \mathring{A}$$

Plus 2nd order aberrations

$$c\Delta t^{(2)} = T_{5ij} x_i x_j \quad \Rightarrow \quad \sigma_{c\Delta t} \sim 80\ \mathring{A} \approx \frac{\lambda}{2\pi}$$

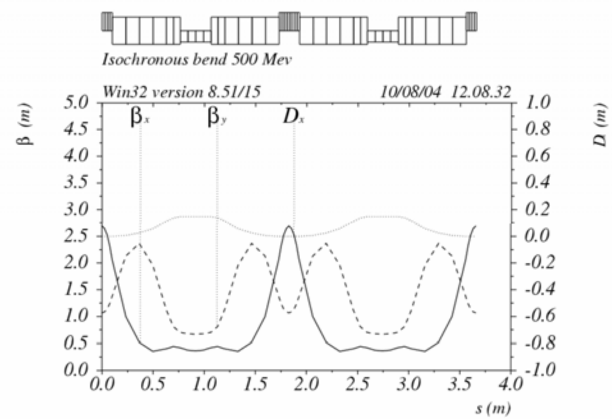

Figure 2. Linear lattice functions β_x, β_y, and D_x of the isochronous bend of the 500 Å ring FEL.

CONCLUSION

The feasibility of the magnetic system for the ring FEL at the soft X-ray band is shown. Quantum fluctuations of synchrotron radiation and second order aberrations in the lattice are taken into account. The collective effects including CSR have to be considered yet.

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Preserving the phase correlations

$$H = -\frac{(1+K_o(s))}{c}\left\{p_o^2c^2 + 2E_o\delta E + \delta E^2 + P_x^2 + P_y^2\right\} - \frac{e}{c}A_s + \frac{\delta E}{v_o}$$

$$\{x,P_x\},\ \{y,P_y\},\ \{\tau=(t_o(s)-t),\delta E\}$$

$$\frac{d\tau}{ds} = -\frac{\partial H}{\partial(\delta E)};\quad \frac{dt_o}{ds} = \frac{1}{v_o}$$

$$\tau_{exit} - \tau_{input} = M_5(x,P_x,y,P_y,\delta E)$$

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

$$|\delta S_{turn}| \ll \lambda_{FEL};$$

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

$$Example:\ L = 100\,m;\quad \lambda = 10^{-10}\,m;\ \ \varepsilon = 10^{-10}\,m\cdot rad;\ \ \sigma_E = 0.01\%$$

1. Energy spread and compaction factors

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

$$\Rightarrow\quad |\alpha_c| = |R_{56}(0,L)| < 10^{-8};\ \|R_{566}(0,L)\| < 10^{-4};\ \|R_{5666}(0,L)\| < 1\ldots$$

-> second order isochronous system

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$\lambda_{FEL} \sim 1Å$

2. Emittance effects

Linear term: comes from symplectic conditions

$$M^T S M = S;$$

$$S = \begin{bmatrix}\sigma & 0 & 0\\ 0 & \sigma & 0\\ 0 & 0 & \sigma\end{bmatrix}; \quad \sigma = \begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix}$$

$$\Rightarrow \quad \delta S_{turn}(\varepsilon_{x,y}) = [\eta \quad \eta'] \begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix} \begin{bmatrix}x\\ x'\end{bmatrix} + f(\varepsilon) + O(\varepsilon^2)$$

$$|\eta| < 10^{-5} m \Big/ \sqrt{\beta[m]}; \quad |\eta'| < 10^{-5}\sqrt{\beta[m]};$$

It is not a problem to make the turn achromatic with $\eta=0$ and $\eta'=0$
It is a bit more complicated to make the condition energy independent.
An elegant solution - sextupoles combined with quadrupoles with $K_2=K_1/2\eta$:

$$x'' = -\frac{K_1 x + K_2 \cdot \left((x+\eta\cdot\delta)^2 - y^2\right)}{1+\delta} = -K_1 \cdot x + O(x^2, y^2)$$

$$y'' = \frac{K_1 y + 2K_2 y \cdot (\eta\cdot\delta + x)}{1+\delta} = K_1 \cdot y + O(xy)$$

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

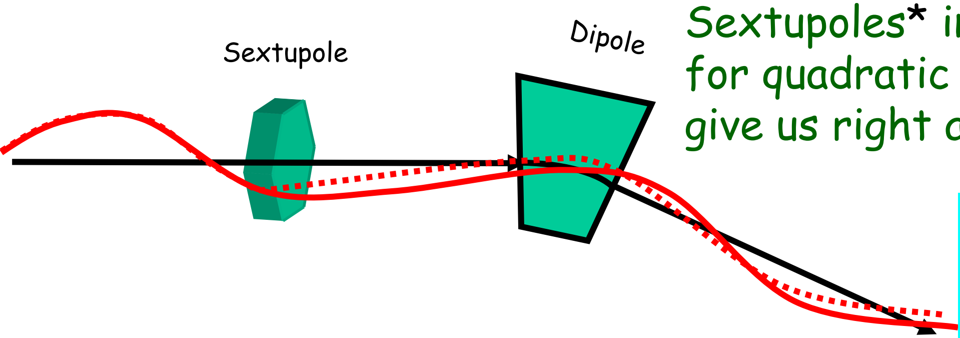
Solution is a second order achromat (N cell with phase advance 2πM, M/N is not integer, etc.) with second order geometrical aberration cancellation

2. Emittance effects

Quadratic term

$$\delta S_2 \propto \int_o^L \frac{x'^2 + y'^2}{2} ds$$

$$x = a_x\sqrt{\beta_x(s)}\cos\left(\psi_x(s)+\varphi_x\right) + \eta(s)\frac{\delta E}{E_o};\ \ y = a_y\sqrt{\beta_y(s)}\cos\left(\psi_y(s)+\varphi_y\right).$$



Sextupoles* in the arcs are required to compensate for quadratic effect sextupole kick + symplectic conditions give us right away:

$$\Delta x'_{sext} = K_2 l \cdot \left(x^2 - y^2\right) \ \Rightarrow\ \delta S = -\eta(s)\cdot \Delta x'_{sext} = -\eta(s) K_2 l \cdot \left(x^2 - y^2\right)$$

$$\frac{1}{2}\int_o^L \left(x'^2 + y'^2\right)ds - \sum_n \eta(s_n)(K_2 l)_n \cdot \left(x^2(s_n) - y^2(s_n)\right)ds \Rightarrow 0$$

Sextupoles located in dispersion area give a kick ~ x^2-y^2 which affect the length of trajectory. Two sextupoles placed 90° apart the phase of vertical betatron oscillations are sufficient to compensate for quadratic term with arbitrary phase of the oscillation

Four sextupoles located in the arcs where dispersion are sufficient to satisfy the cancellation of the quadratic term in the non-isochronism caused by the emittances. Fortunately, the second order achromat compensates the chromaticity and the quadratic term simultaneously. *In short it is the consequence of Hamiltonian term*:

$$h \propto -g(s)\cdot\delta\cdot\left(\frac{x^2 - y^2}{2}\right) \quad C_x\cdot\delta\cdot\frac{a_x^2}{2} + C_y\cdot\delta\cdot\frac{a_y^2}{2}$$

•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

$\lambda_{FEL} \sim 1Å$

- 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

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

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

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

It looks as the toughest requirement for the scheme to be feasible

$$\sqrt{\langle R^2_{56}(s,L)\rangle} < 2.25 \cdot 10^{-5} m \cdot E_e^{-3/2}[GeV] \cdot B^{-1}[T]$$

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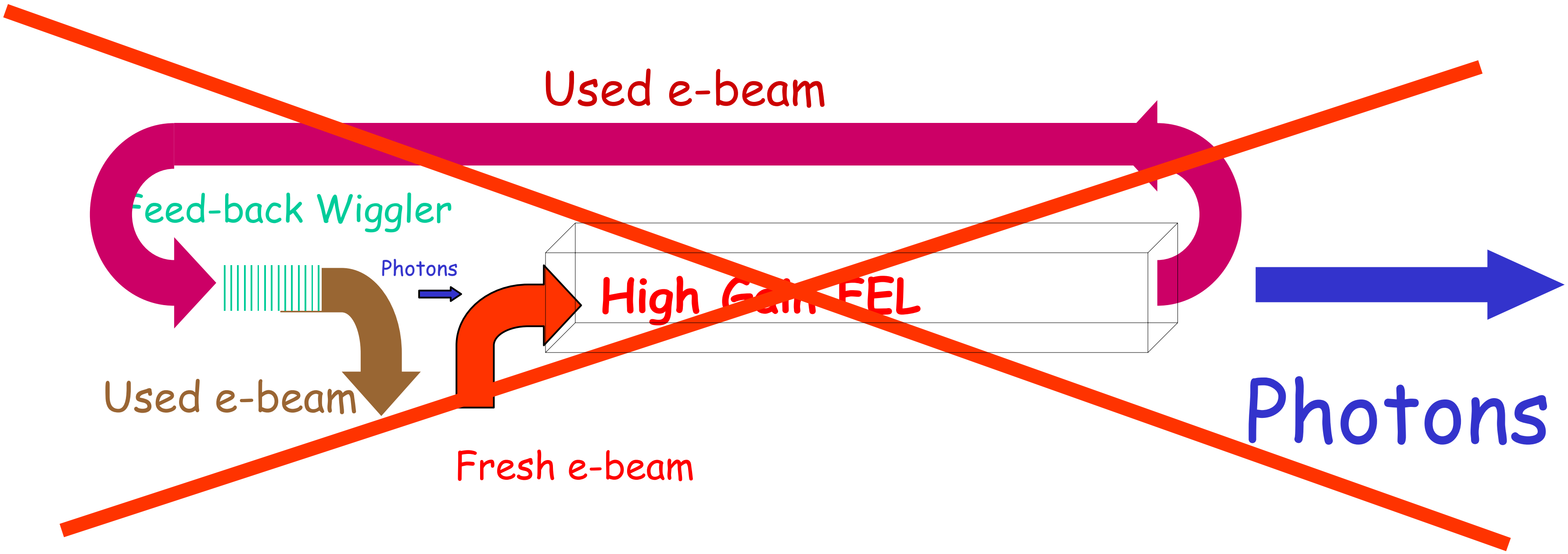
Ultimate Ring FEL

- Turning around strongly modulated beam after high gain amplifier

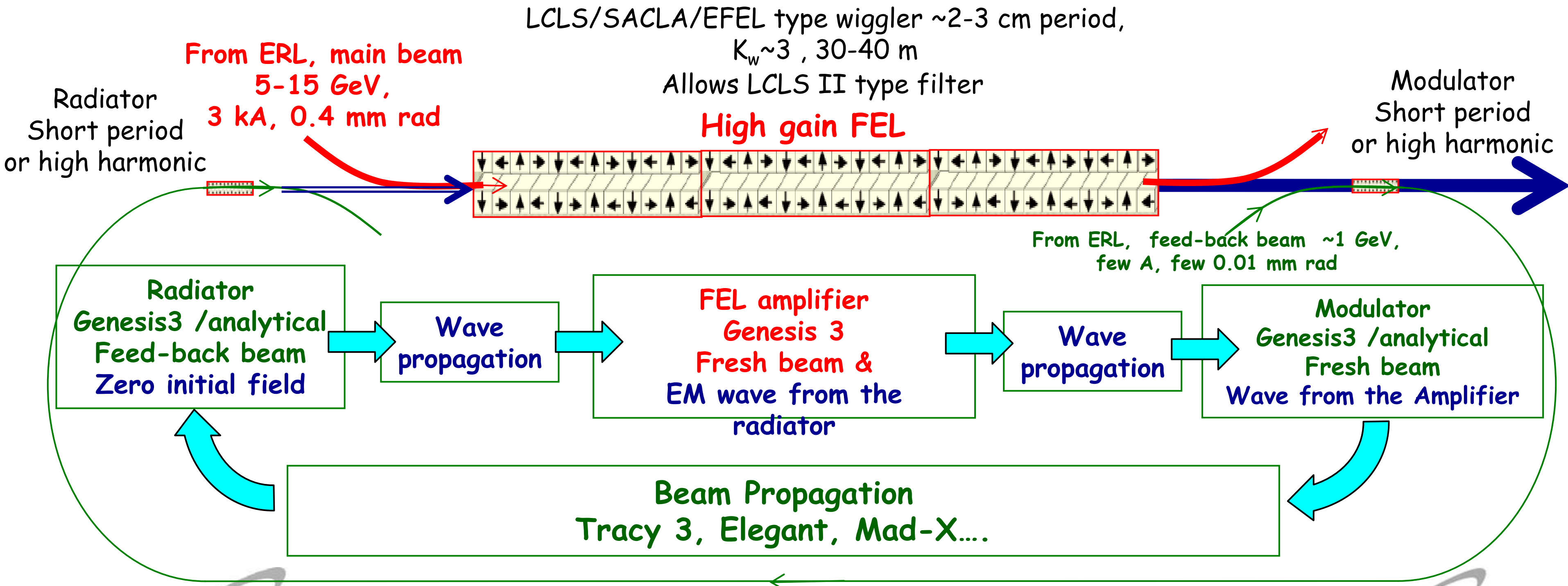
CAN BE TOO TOUGH

beam has high energy and large energy spread



OFFELO

1. High gain amplifier/ main e-beam (from ERL or CW linac)
2. Feed-back is provided by a low-current e-beam
3. Feed-back e-beam picks the energy modulation from the FEL laser beam in modulator, preserves the correlations at 1/10th of the FEL wavelength in the long transport line, radiates coherently in the radiator.
4. The later serves as the input into the high gain FEL & compeates wit the spontaneous radiation



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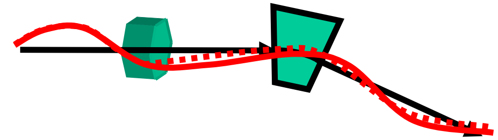
Main challenges



- Preserving correlation between particles at sub-Å level
  - Highly isochronous lattice $\delta S_{turn} = c\,\delta(\tau_{exit} - \tau_{input}) < \lambda_{FEL}$
  - Canceling time-of-flight dependence on transverse motion
  - Fundamental effects of quantum nature of synchrotron radiation

$$\sigma_{ct}[m] \cong 1.61 \cdot 10^{-5} \frac{E[GeV]^{5/2}}{\rho[m]} \sqrt{\left\langle R_{56}^2(s|C) \right\rangle_{mag}}[m] \Rightarrow E < 1 GeV$$

- Collective effects ⇒ Low current, long bunches
- Modulator/Radiator: Using very high harmonics or sub-mm FEL

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Problems we addressed

- We developed a concept of high-order isochronous lattice comprised of a multiple cells with the total integer tunes in both directions
- We created 3km long lattice based on this concept, which preserves correlations at sub-Å scale for 1.5 GeV e-beam, including quantum effects of synchrotron radiation
- We considered the CSR wake-fields for the e-beam and found a solution for compensating the effect
- We included the high order map and random effects resulting from quantum nature of synchrotron radiation into the self-consistent simulation of this FEL oscillator
- We made first attempt of simulating the generation e-beam with required quality for the feed-back….

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Lattice

- Concept*
  - use a periodic isochronous lattice** with N cell and total integer tunes in both directions

$$N\Delta\nu_x = K;\ N\Delta\nu_y = M$$

  - cell tune advances avoiding low order resonances

$$n\Delta\nu_x + m\Delta\nu_y \;\square\; l;\ n,m = 1,2,3,4...$$

  - such lattice is a natural (Brown) achromat and compensating chromaticities automatically kills second order terms in time of flight dependence on x,x',y,y'
  - use additional sectupole (multipole) families to reduce higher order terms (Tracy 3)
  - Example is below: N=11x19=209, $\Delta\nu_x = 18/19; \Delta\nu_y = 5/11$ lowest order resonance - 30

Cell	$\otimes\{_x$	$\otimes\{_y$		$\otimes\{_x$	$2\otimes\{\nu_x$	$3\otimes\{_x$	$2\otimes\{_y$	$\otimes\{_x$- $2\otimes\{_y$	$\otimes\{_x$+2 $\otimes\{_y$	$4\otimes\{_x$	$4\otimes\{_y$	$2\otimes\{_x$- $2\otimes\{_y$	$2\otimes\{_x$+2⊗ $\{_y$	$5\otimes\{_x$	$\otimes\{_x$- $4\otimes\{_y$	⊗{ +4⊗{ $_y$	$3\otimes\{_x$- $2\otimes\{_y$	$3\otimes\{_x$+2⊗{ $_y$
1	0.947	0.455		0.95	1.89	2.84	0.91	0.04	1.86	3.79	1.82	0.99	2.80	4.74	-0.87	2.77	1.93	3.75

*VL, Chromaticity and Isochronous lattices

**D.Trbojevic et al, AIP CONFERENCE PROCEEDINGS, V. 530, (2000) p. 333

Lattice; Proof of existence

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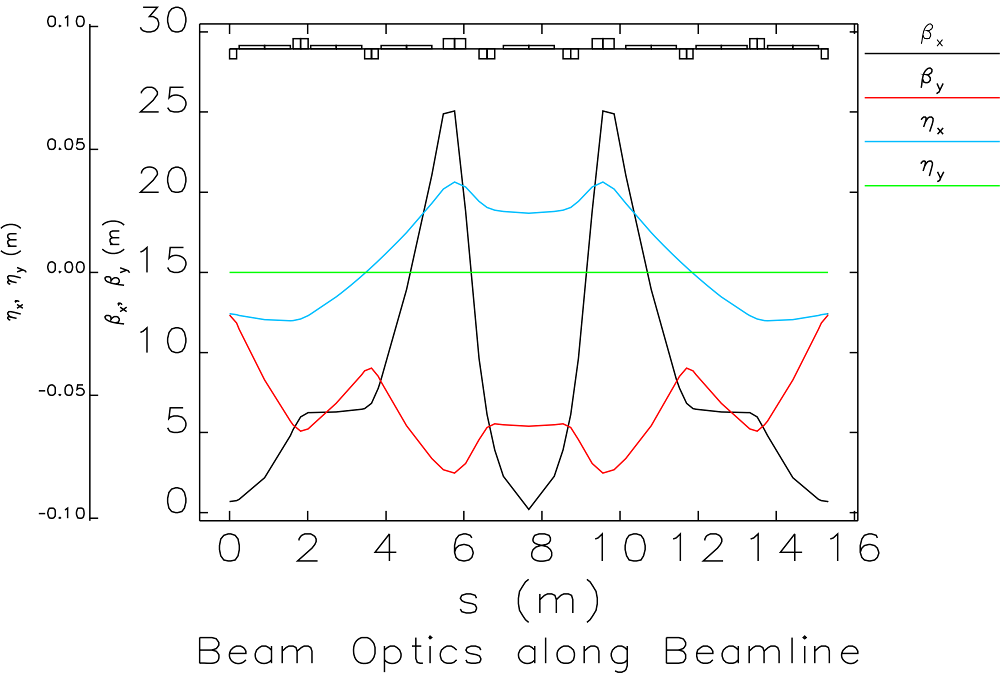
J.Bengtsson

$$\Delta\nu_x = 18/19; \Delta\nu_y = 5/11$$



Radius of curvature= 302.7 m
O, OFW, O1F, O2F are drifts with lengths: O: L = 0.075;
OFW: L = 0.3; O1F: L = 0.35; O2F: L = 0.221;
B2H is the dipole: B2H: L=0.65,ANGLE=0.00214736339583

The quadrupole settings are:
QF2: L = 0.19, K2 = 1.294; QD2: L = 0.175, K2= -1.296;
QF3: L = 0.28, K2 = 1.777; QD3: L = 0.2, K2 = -1.348.

S1: K3L=-87.6, K4L=-2.06E5; K5L=-5.16E9;
S2: K3L= 267. 9, K4L= 3.24E5, K5L=-1.90E9;
S3: K3L=-223.2, K4L= 2.43E5. K5L=-5.33E9;
S4: K3L= 61.9, K4L=-8.35E4, K5L=-3.40 E6;
S5: K3L= 23.3, K4L= 2.48E5, K5L=-4.85E8.

nu: 1.0000000000, 0.0000000000
m_11 - 1: 1.534e-13, -9.093e-14
m_12: -9.059e-13, 2.287e-11
ksi: -1.155e-03, -2.001e-03
R_56: 2.476e-19; R_566: -
1.184e-11
R_5666: 3.445e-12;
R_56666: 7.312e-13

½ BeamLine; S1, QD2,O,B2H,B2H,O,QF2,S2,QF2,O,B2H,B2H, O,QD2,S3,QD2,O,B2H,B2H,OFW,QF3,QF3,S4,O1F,QD3,QD3, S5,O2F,B2H
+ bilateral part

Cell	⊗{$_x$	⊗{$_y$		⊗{$_x$	2⊗{ ν$_x$	3⊗{$_x$	2⊗{$_y$	⊗{$_x$- 2⊗{$_y$	⊗{$_x$+2 ⊗{$_y$	4⊗{$_x$	4⊗{$_y$	2⊗{$_x$- 2⊗{$_y$	2⊗{$_x$+2 ⊗{$_y$	5⊗{$_x$	⊗{$_x$- 4⊗{$_y$	⊗{ +4⊗ {$_y$	3⊗{$_x$- 2⊗{$_y$	3⊗{$_x$+2 ⊗{$_y$
1	0.947	0.455		0.95	1.89	2.84	0.91	0.04	1.86	3.79	1.82	0.99	2.80	4.74	-0.87	2.77	1.93	3.75

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V.N. Litvinenko, FEL 2012, Nara, Japan

Center for Accelerator Science and Education

*VL, Chromaticity and Isochronous lattices

**D.Trbojevic et al, AIP CONFERENCE PROCEEDINGS, V. 530, (2000) p. 333

Beam transport $\Delta\nu_x = 18/19; \Delta\nu_y = 5/11$

- Exercise
  - N= 209; path length – **3221.323 m**
  - lowest regular resonance order – 41

    $$19\Delta\nu_x + 22\Delta\nu_y = 28$$

  - Test beam parameters:
    - relative RMS energy spread 10^{-4};
    - Normalized emittance, x & y – 0.02 μm
  - Fifth order map
  - Synchrotron radiation at 1.5 GeV is OK

    $$\left\langle R_{56}^2(s|C)\right\rangle = 8.06 \cdot 10^{-8}.$$

  - 50% of the modulation at 1 Å is preserved
  - CSR wake – manageable

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J. Bengtsson
Y.Jing

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		1	2	3	4	5	6
		x	x'	y	y'	δ	ct
1	1.7487905669206507e-19	1	0	0	0	0	0
1	2.0673820289257054e-20	0	1	0	0	0	0
1	2.4761280265767074e-19	0	0	0	0	1	0
1	1.0000000000000000e+00	0	0	0	0	0	1
2	-7.5525693400348191e-13	2	0	0	0	0	0
2	9.4684272921669303e-23	1	1	0	0	0	0
2	-7.5497742554840793e-13	0	2	0	0	0	0
2	1.0452067194273214e-12	0	0	2	0	0	0
2	2.4658675101818518e-21	0	0	1	1	0	0
2	1.0459284822532135e-12	0	0	0	2	0	0
2	-2.7175462537259362e-12	1	0	0	0	1	0
2	-4.1906530772670468e-22	0	1	0	0	1	0
2	4.0933549122163592e-12	0	0	0	0	2	0
3	4.2627661981805402e-12	3	0	0	0	0	0
3	-4.7920366859653766e-24	2	1	0	0	0	0
3	4.2769026098856557e-12	1	2	0	0	0	0
3	5.2144677818663399e-24	0	3	0	0	0	0
3	3.7727932849036214e-12	1	0	2	0	0	0
3	-2.1284786277441330e-22	0	1	2	0	0	0
3	-2.0111682438652990e-22	1	0	1	1	0	0
3	-4.2521617243397188e-13	0	1	1	1	0	0
3	4.1028146230153669e-12	1	0	0	2	0	0
3	-4.3815196522505170e-22	0	1	0	2	0	0
3	5.1338910746389662e-12	2	0	0	0	1	0
3	-1.4184367553033096e-23	1	1	0	0	1	0
3	-2.4921081665149797e-12	0	2	0	0	1	0
3	-7.8097237258347493e-12	0	0	2	0	1	0
3	-2.3468817289540312e-22	0	0	1	1	1	0
3	-7.1327970245969211e-12	0	0	0	2	1	0
3	-6.8345476626196068e-12	1	0	0	0	2	0
3	-6.8389553483116789e-18	0	1	0	0	2	0
3	-4.0489736363830835e-16	0	0	0	0	3	0
4	-6.0925615934169556e-13	4	0	0	0	0	0
4	-1.3634583698549667e-12	2	2	0	0	0	0

$\lvert I \rvert$	a_I	i_1	i_2	i_3	i_4	i_5	i_6	i_7
1	1.7487905669206507e-19	1	0	0	0	0	0	0
1	2.0673820289257054e-20	0	1	0	0	0	0	0
1	2.4761280265767074e-19	0	0	0	0	1	0	0
1	1.0000000000000000e+00	0	0	0	0	0	1	0
2	-7.5525693400348191e-13	2	0	0	0	0	0	0
2	9.4684272921669303e-23	1	1	0	0	0	0	0
2	-7.5497742554840793e-13	0	2	0	0	0	0	0
2	1.0452067194273214e-12	0	0	2	0	0	0	0
2	2.4658675101818518e-21	0	0	1	1	0	0	0
2	1.0459284822532135e-12	0	0	0	2	0	0	0
2	-2.7175462537259362e-12	1	0	0	0	1	0	0
2	-4.1906530772670468e-22	0	1	0	0	1	0	0
2	4.0933549122163592e-12	0	0	0	0	2	0	0
3	4.2627661981805402e-12	3	0	0	0	0	0	0
3	-4.7920366859653766e-24	2	1	0	0	0	0	0
3	4.2769026098856557e-12	1	2	0	0	0	0	0
3	5.2144677818663399e-24	0	3	0	0	0	0	0
3	3.7727932849036214e-12	1	0	2	0	0	0	0
3	-2.1284786277441330e-22	0	1	2	0	0	0	0
3	-2.0111682438652990e-22	1	0	1	1	0	0	0
3	-4.2521617243397188e-13	0	1	1	1	0	0	0
3	4.1028146230153669e-12	1	0	0	2	0	0	0
3	-4.3815196522505170e-22	0	1	0	2	0	0	0
3	5.1338910746389662e-12	2	0	0	0	1	0	0
3	-1.4184367553033096e-23	1	1	0	0	1	0	0
3	-2.4921081665149797e-12	0	2	0	0	1	0	0
3	-7.8097237258347493e-12	0	0	2	0	1	0	0
3	-2.3468817289540312e-22	0	0	1	1	1	0	0
3	-7.1327970245969211e-12	0	0	0	2	1	0	0
3	-6.8345476626196068e-12	1	0	0	0	2	0	0
3	-6.8389553483116789e-18	0	1	0	0	2	0	0
3	-4.0489736363830835e-16	0	0	0	0	3	0	0
4	-6.0925615934169556e-13	4	0	0	0	0	0	0
4	-1.3634583698549667e-12	2	2	0	0	0	0	0
4	-8.0660563991742595e-25	1	3	0	0	0	0	0
4	-6.6656732473884208e-13	0	4	0	0	0	0	0
4	-3.9521245585897409e-12	2	0	2	0	0	0	0
4	3.0116618763046885e-23	1	1	2	0	0	0	0
4	-3.9758379601763162e-12	0	2	2	0	0	0	0
4	1.5806073430424698e-11	0	0	4	0	0	0	0
4	4.3261915199957297e-23	2	0	1	1	0	0	0
4	-8.6747266393727828e-13	1	1	1	1	0	0	0
4	8.8039577067425866e-23	0	2	1	1	0	0	0
4	6.9755405489696060e-23	0	0	3	1	0	0	0
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4	-1.0046217760097237e-11	0	0	2	2	0	0	0
4	8.9010069560564544e-23	0	0	1	3	0	0	0
4	-2.5883921274274050e-11	0	0	0	4	0	0	0
4	-4.3437147205202525e-12	3	0	0	0	1	0	0
4	4.2900249811345957e-17	2	1	0	0	1	0	0
4	-4.5164910084921710e-12	1	2	0	0	1	0	0
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4	-3.8167550015267932e-12	0	0	0	2	2	0	0
4	-8.7122594198860168e-12	1	0	0	0	3	0	0
4	-2.2933010987969747e-17	0	1	0	0	3	0	0
4	-3.0415524785123360e-12	0	0	0	0	4	0	0
5	-1.2410001011112450e-16	2	1	2	0	0	0	0
5	-3.3739999492765848e-09	1	2	2	0	0	0	0
5	-1.2405409614606939e-16	0	3	2	0	0	0	0
5	2.8620517107562123e-09	1	0	4	0	0	0	0
5	-5.7236422467608124e-17	0	1	4	0	0	0	0
5	-7.2686686085329473e-23	1	0	3	1	0	0	0
5	-8.4949809637270792e-12	0	1	3	1	0	0	0
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5	-2.4181192473119710e-16	3	1	0	0	1	0	0
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5	-2.4261502529089122e-16	1	3	0	0	1	0	0
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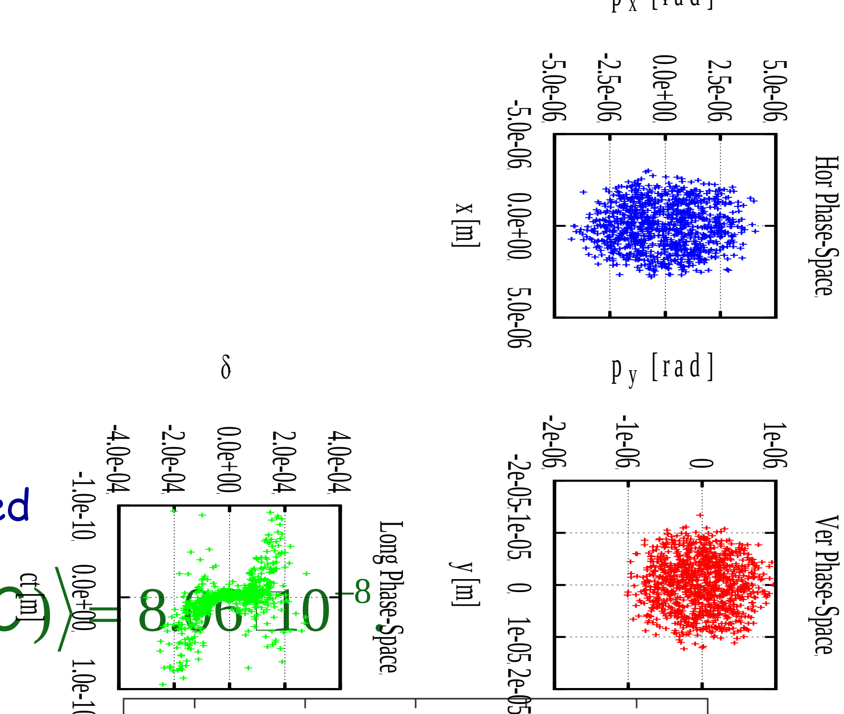
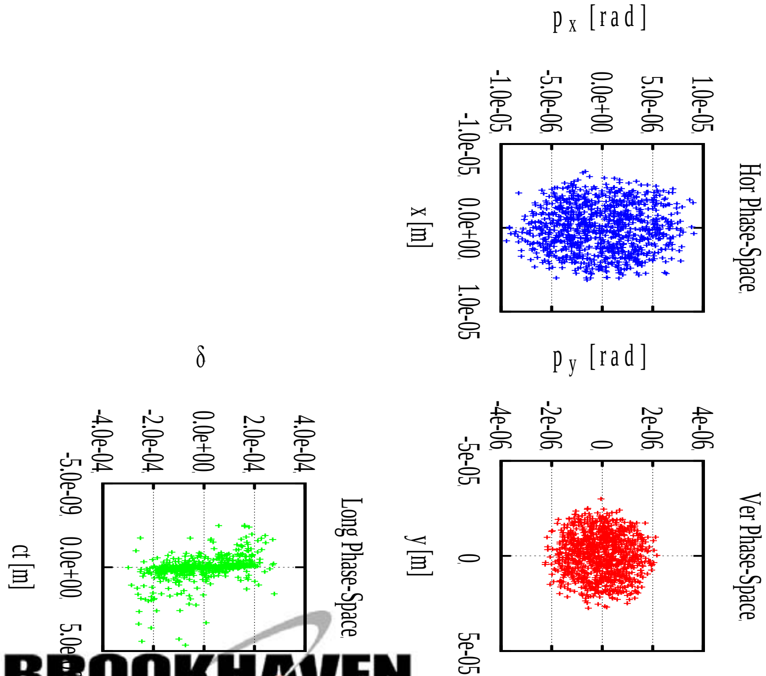
5	-9.2222599378940371e-09	2	0	2	0	1	0	0
5	-2.2345029545597995e-16	1	1	2	0	1	0	0
5	-3.1487558350231196e-09	0	2	2	0	1	0	0
5	2.5703850210375351e-09	0	0	4	0	1	0	0
5	1.5240352078710214e-17	2	0	1	1	1	0	0
5	4.0330697056882054e-12	1	1	1	1	1	0	0
5	5.9647682190174430e-18	0	2	1	1	1	0	0
5	-1.1505196843660681e-15	0	0	3	1	1	0	0
5	5.1539973882010306e-09	0	0	2	2	1	0	0
5	-8.2119624756291215e-10	3	0	0	0	2	0	0
5	-1.6712444366910548e-16	2	1	0	0	2	0	0
5	-4.6923109126702629e-10	1	2	0	0	2	0	0
5	4.8882417168131931e-17	0	3	0	0	2	0	0
5	-8.5010028381148899e-09	1	0	2	0	2	0	0
5	-4.7312732232378398e-18	0	1	2	0	2	0	0
5	2.6810837925306211e-17	1	0	1	1	2	0	0
5	4.2053494098612977e-13	0	1	1	1	2	0	0
5	-8.5100541366479728e-09	1	0	0	2	2	0	0
5	-3.2859174137644429e-18	0	1	0	2	2	0	0
5	-6.8269966923456770e-10	2	0	0	0	3	0	0
5	8.9842723976985677e-17	1	1	0	0	3	0	0
5	-1.1921557671949587e-10	0	2	0	0	3	0	0
5	-2.6206209332726543e-09	0	0	2	0	3	0	0
5	-2.4147117069721751e-17	0	0	1	1	3	0	0
5	-2.6224127716567658e-09	0	0	0	2	3	0	0
5	-2.6847505658376925e-10	1	0	0	0	4	0	0
5	-4.1145305690787728e-17	0	1	0	0	4	0	0
5	-3.7988578983552299e-11	0	0	0	0	5	0	0

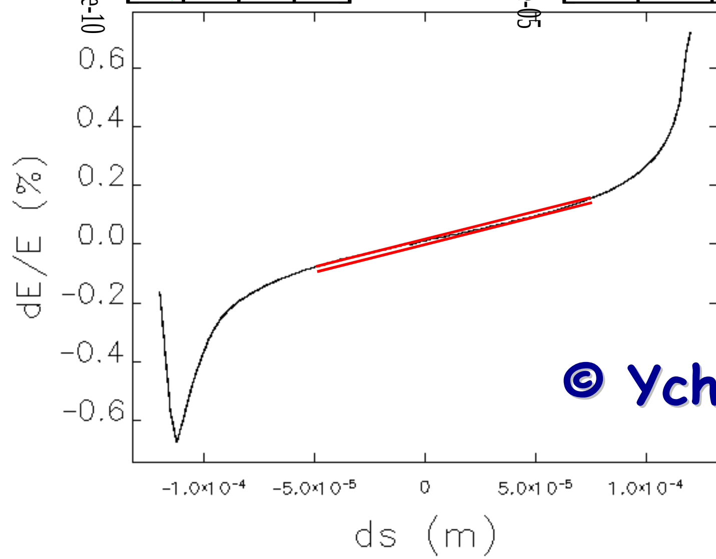
Beam transport

- Exercise $\Delta\nu_x = 18/19; \Delta\nu_y = 5/11$
  - N= 209; path length – 3221.323 m
  - Test beam parameters:
    - relative RMS energy spread 10^{-4};
    - Normalized emittance, x & y – 0.02 µm
  - Synchrotron radiation at 1.5 GeV is OK
  - 50% of the modulation at 1 Å is preserved
  - CSR wake – manageable

$$\langle R_{56}^2(s|C)\rangle = 8.06\cdot 10^{-8}$$







Final longitudinal phase space

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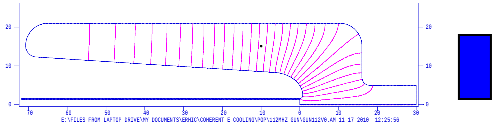
We also explored 300 m path length – much much easier!!!

Injector simulations

preliminary

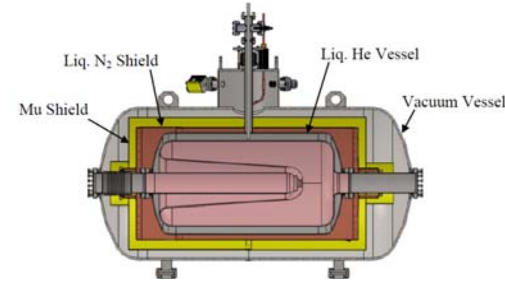
112 MHz SRF Gun

Solenoid



Cathode E peak field 20 MV/m

e^- @ 2.5 MeV

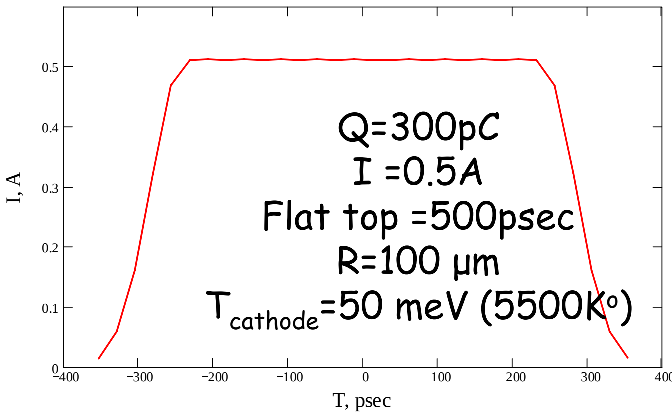


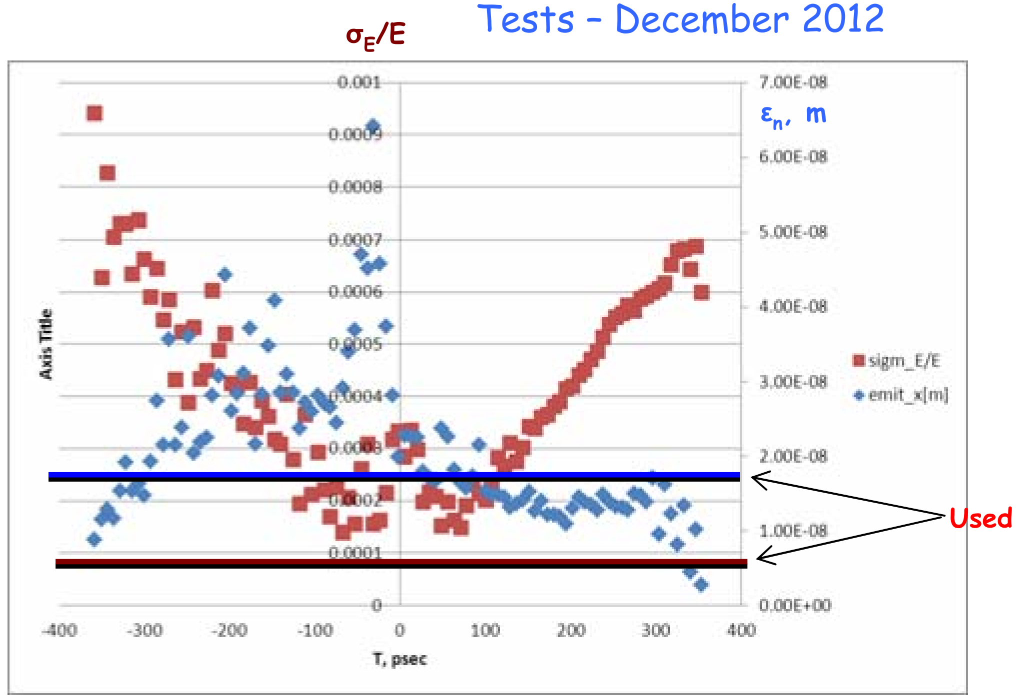
112 MHz SRF Gun

Under construction NIOWAVE

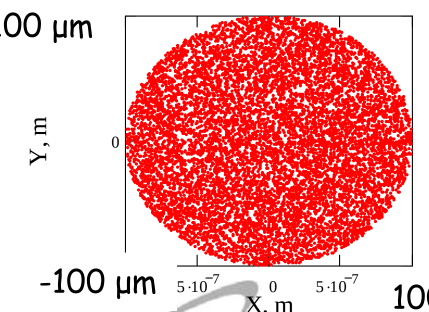
Tests – December 2012

Initial pulse shape





Transverse distribution



Slice emittance and energy spread after acceleration to 2.5 MeV as a result of PARMELA simulation

© Dmitry Kayran

During first 100 psec
Effective charge Qeff=50 pC
Rms energy spread 1.5-3e-4
Rms emittance 15-20 nm rad

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Undulator/Wiggler for Modulator/Radiator

- It is very desirable to use low energy < 1 GeV for feed-back beam to avoid the most fundamental limitation by quantum nature of synchrotron radiation
  - Unless we use accelerator/decelerator scheme (later slide)…
- This results in two potential solutions:
  - Using very high harmonic, N ~ 25; $JJ_N \sim 10^{-3} - 10^{-4}$
  - Using an TEM wiggler with Kw ~10^{-1}

High Harmonic

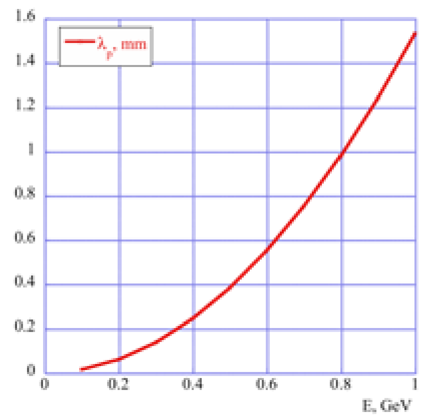
Energy ~ 1.5 GeV
Wiggler period ~ 3 cm
Kw ~ 3

$$\lambda_{FEL} = \frac{\lambda_w}{2\gamma^2(2N-1)}\left(1+\frac{K_w^2}{2}\right)$$

For 1Å FEL it yields
N ~ 25-50
JJ ~ 10^{-3}

FEL driven TEM undulator
Efb ~ 250 MeV, FEL pump- at 0.1 mm

$$\lambda_p = 4\gamma^2\lambda_{FEL}; \quad K_w^2 << 1$$



Well within achievable parameters

$$N_u K^2 \sim 0.3 \cdot \hat{p}[GW]$$

Rep-rate ~ 1 MHz
Pulse length ~ 10 psec
Intra-cavity:
Peak power ~ 1 GW
Energy in pulse ~ 10 mJ
Average power ~10 kW
FEL
Q ~ 10^3
Average power ~ 10 W
N=1;
JJ=0.996;
Kw ~ 0.17

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Feed-Back e-beam

- Energy Modulation of the feed-back e-beam should not be a problem - the FEL power is high and a few wiggler periods will do the job
- For efficient feed-back the spectral intensity of the coherent feed-back radiation should be significantly larger than the spontaneous radiation at one-gain length
- 10A long-bunch with $\varepsilon_n < 0.1$ mm rad can be achieved
  - by using slice emittance of a few-psec, a few pC bunch
  - By the the collimating the beam in current sources
- Flat beam is preferable for the feed-back
- Estimations show that this is feasible.....

- But direct simulations are better – hence, recent results from Yue Hao and Yichao Jing

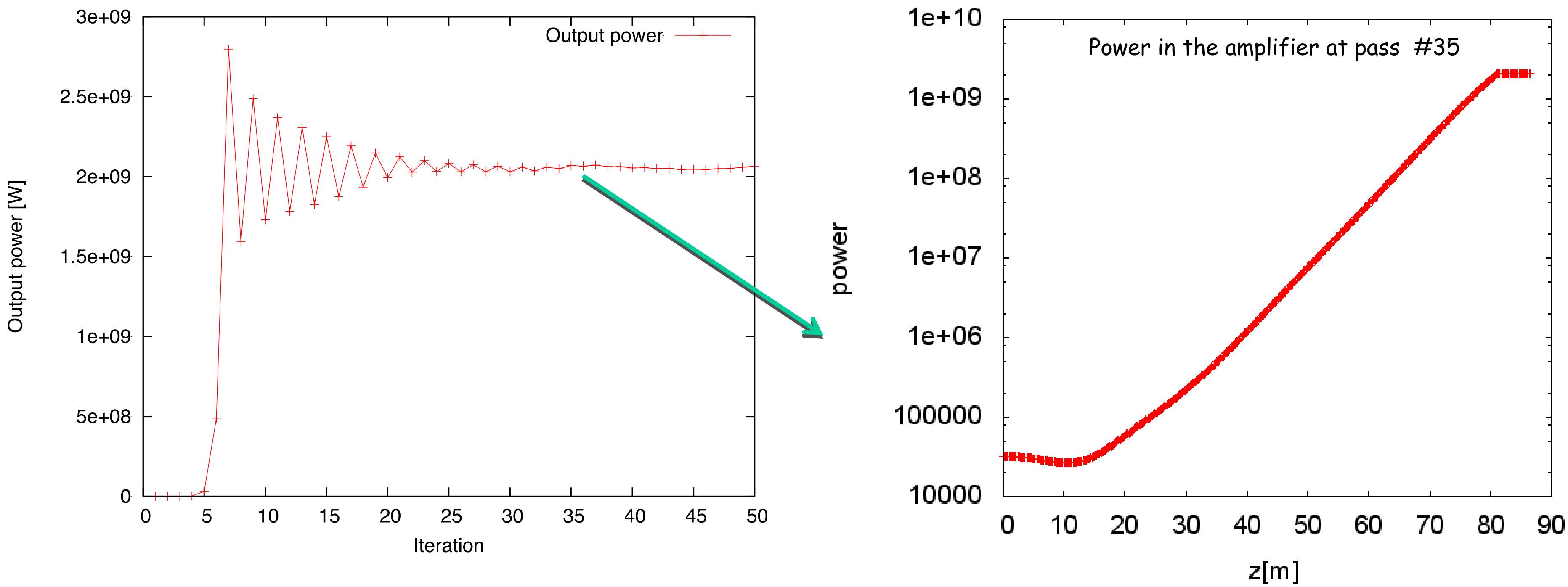
Parameters for High Energy Electron Beam

Parameters of high energy beam	Values
Electron Energy (GeV)	13.6
Energy Deviation dE/E	1e-4
Peak Current (A)	3000
Normalized Emittance (mm-mrad)	1.5
Undulator Period [m]	0.03
Undulator Length [m]	81
Undulator Parameter K	2.616
Radiation Wavelength [10^{-10} m]	1.66
Average beta function [m]	18

Start-up and saturation of OFELLO

The parameter is chosen to avoid nonlinear regime in feed-back system.

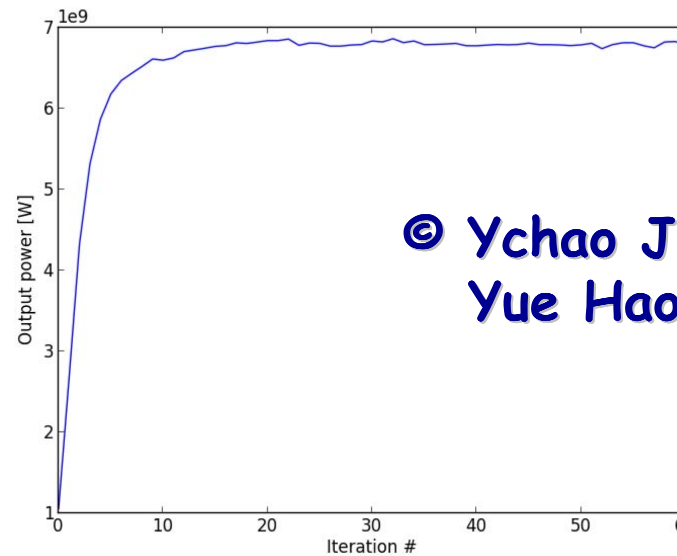
The gain length is 5.45m, calculated from the simulation result.



Preliminary Simulation Results

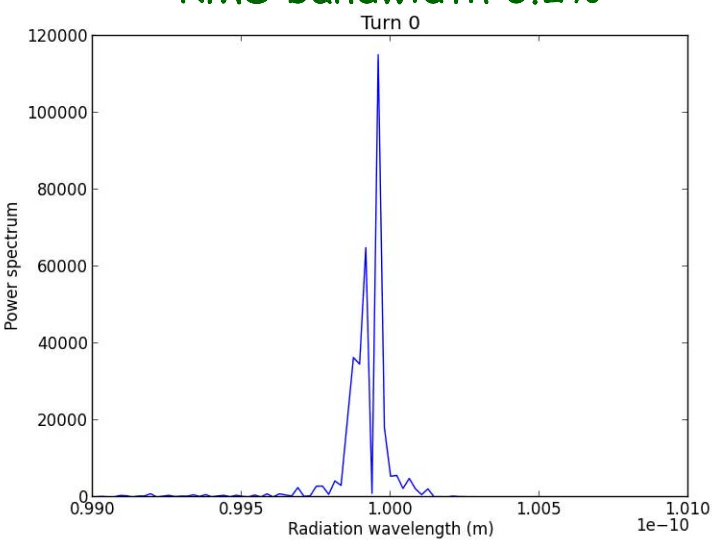
Parameter	HG FEL	Feed-back I	Feed-back II	Units
Wavelength	1	1	1	Å
Energy	10	0.75	1.5	GeV
Wiggler period	3	0.0426	0.01	cm
a_w	1.24	0.1	2.95	
N_w	1600	28	28	
Wiggler length	48	0.01	1	m
Peak current	3000	50	400	
Norm emittance	0.5	0.02	0.02	µm rad
RMS energy spread	$5\ 10^{-5}$ 500	10^{-5} 7.5	10^{-5} 15	KeV

Peak power evolution in OFFELO



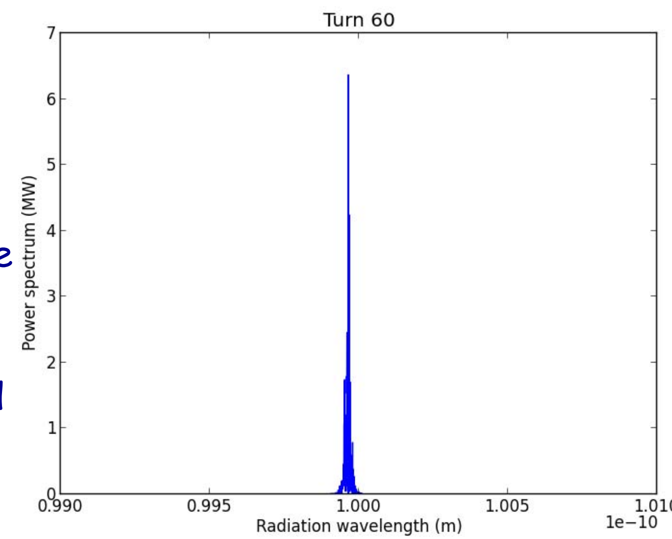
© Ychao Jing
Yue Hao

First pass SASE spectrum
RMS bandwidth 0.2%

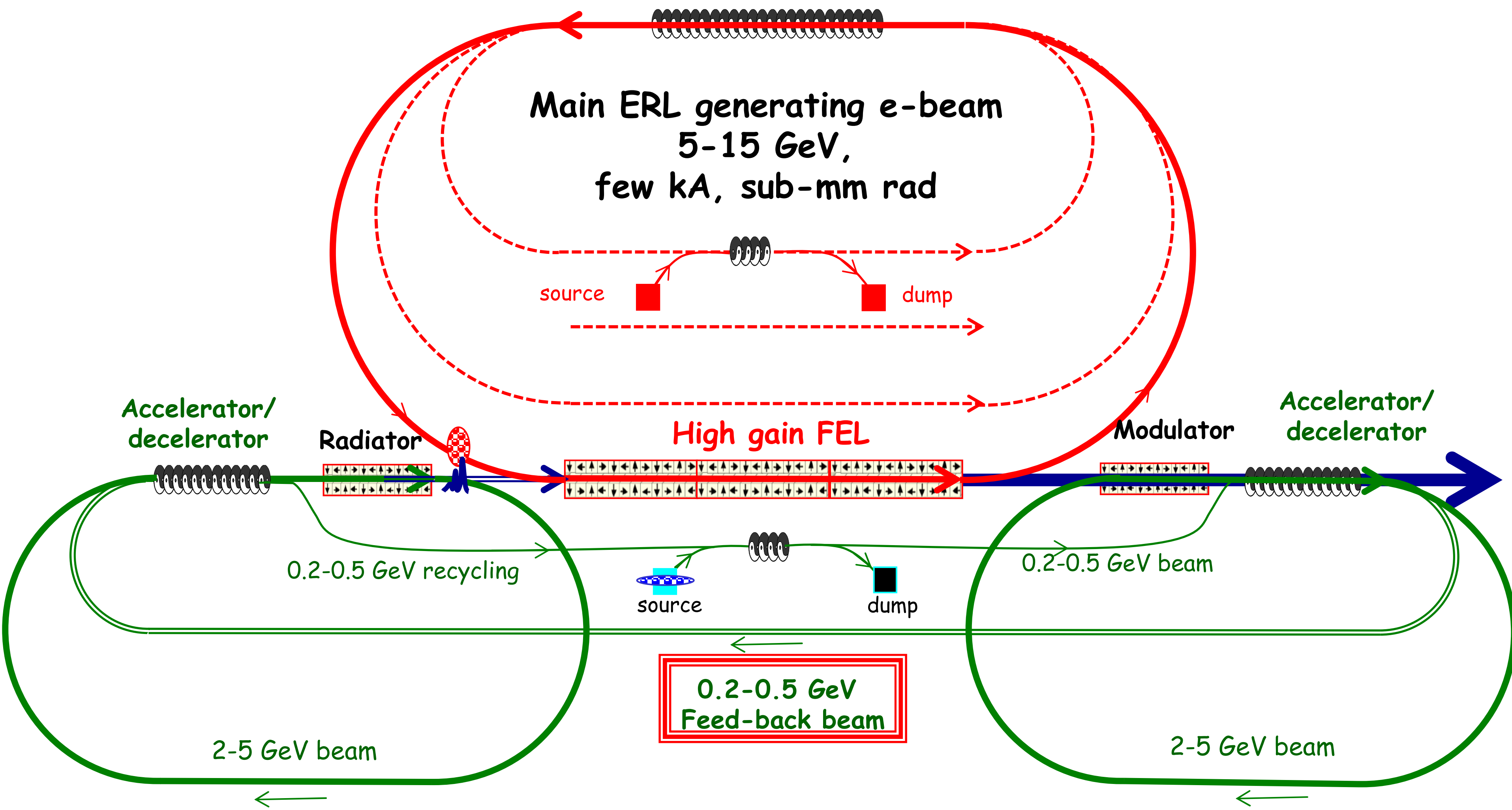


- 20-fold narrowing of the spectrum after 60 passes
- Using LCLS II technique should bring it to 10 ppm level
- System is not optimized & improvements are expected..

Pass #60 - OFFELO spectrum
RMS bandwidth 0.01%



Alternative Feed-back scheme



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

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Conclusions

- FEL oscillator without optics seems to be feasible
  - No show-stoppers had been found
  - An arc lattice can be designed to meet the challenge
- Using intra-cavity power of sub-mm FEL for modulator and the radiator works best for the presented scheme
- It is our understanding (see my talk on Wednesday) ELR can generate beams ~ 10GeV sufficient to drive 1 Å HG FEL amplifier
- E-beam for the feed-back is the main ERL challenge: generating and operating beam with normalized slice emittance ε_n ~ 0.1-0.01 μm rad is a serious challenge
- Possible technical technical improvements:
  - sub-mm FEL for modulator and the radiator
  - the Accelerator/Decelerator the feed-back beam
- Our test-studies of 300-m feed-back beam-line showed very high tolerance to the larger emittance and energy spread

Laundry List

- Sensitivity to the errors, Ripples in the power supplies
- **Locking-in the feed-back using long wavelength laser system**
- Space charge effects in the feed-back loop
- Intra-beam scattering
- Wake-fields
- Optimization of the system
- ………..
- Starting R&D with sun-μm before going to Å scale is worth considering
- Technical details – such as electron-beam mirror, can be studied using existing ATFs

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Back-up slides

Synchrotron Radiation

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

$\alpha_c(s,L)$ is the momentum compaction factor from azimuth s to L

$$\Rightarrow \quad \text{RMS}\,\alpha_c(s,L) < \sqrt{\frac{2}{N_c}\frac{E_e}{\varepsilon_c}\frac{\lambda\!\!\!^{-}}{L}}$$

$$\text{RMS}\,\alpha_c(s,L) < 0.225\cdot 10^{-6}\cdot E_e^{-3/2}[GeV]\cdot B^{-1}[T]$$

It looks as the toughest requirement for the scheme to be feasible

Synchrotron Radiation - cont…

$$\mathrm{RMS}\,\alpha_c(s,L) < 0.225\cdot 10^{-6}\cdot E_e^{-3/2}[GeV]\cdot B^{-1}[T]$$

$$but\ \ for$$

$$E_e = 0.5\,GeV; B = 100\,GS \Rightarrow \ \mathrm{RMS}\,\alpha_c(s,L) < 0.64\cdot 10^{-4}$$

This value is already close to that of the 3rd generation rings:

ESRF: $\alpha_c = 1.99 \cdot 10^{-4}$

APS: $\alpha_c = 2.28 \cdot 10^{-4}$

Spring 8: $\alpha_c = 1.46 \cdot 10^{-4}$

THUS - the arcs should have ~ 100 bending magnets