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1-Å FEL Oscillator with ERL Beams

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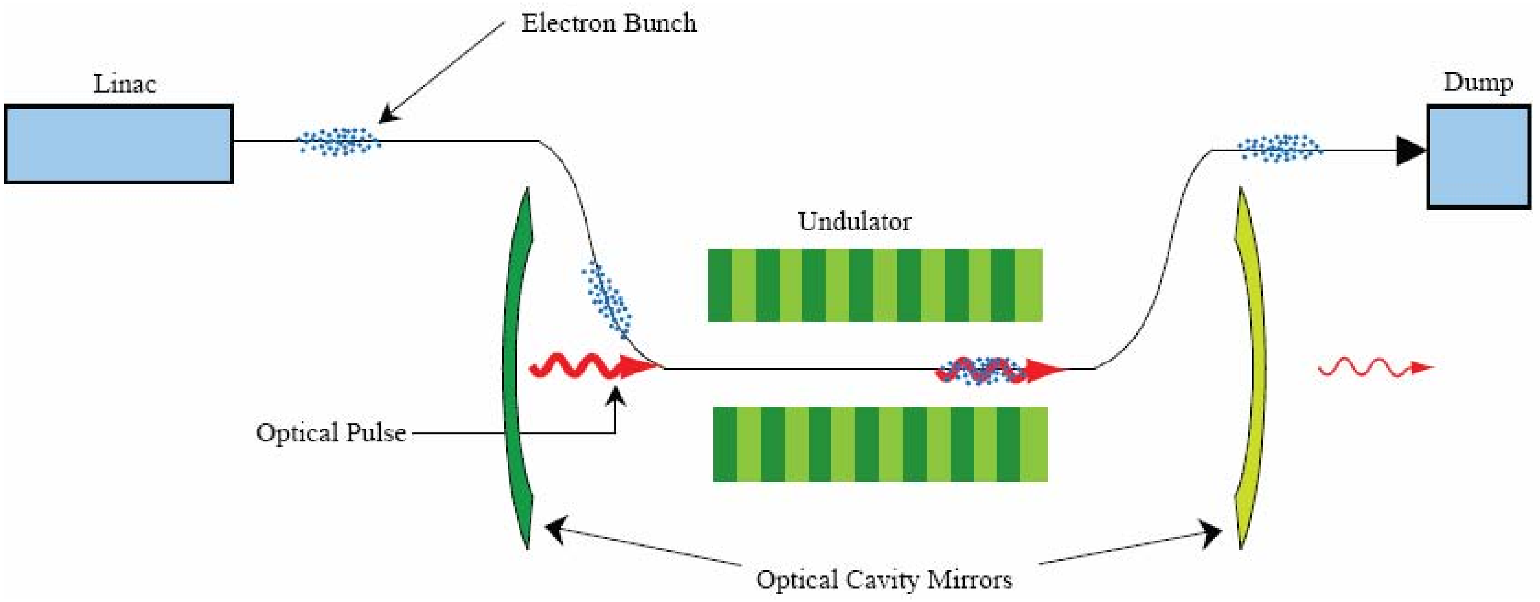
FELs for λ<1-Å Wavelengths

- **High-gain FEL amplifier, SASE or HGHG, as an option for for future light source providing an enormous jump in peak brightness, became realistic due to advance in gun-linac technology**
  - I_P~ several kA, ε_x^n~ 1 mm-mr beams
  - LCLS, European X-FEL, SCSS, Fermi, Arc-en-Ciel,..
- **Electron beams from guns for another option for FLS, the ERLs, promise to be extreme low-emittance, high average power**
  - I_P~ 4-12 A, ε_x^n~ 0.1 mm-mr
  - Rep rates upto 1.3 Gz
- **We discuss an X-ray FEL *Oscillator* (XFEL-O) for λ <1-Å based on high energy ERL beams**
  - High peak as well as average brightness & narrow bandwidth

Principles of an FEL Oscillator



- **Small signal gain G= $\Delta P_{opt}/P_{opt}$**
  - Start-up: $(1+G_0)\ R_1\ R_2 > 1$ (R_1& R_2 : mirror reflectivity)
  - Saturation: $(1+G_{sat})\ R_1\ R_2 = 1$
- **Synchronism**
  - Spacing between electron bunches=2L/n (L: length of the cavity)

Feedback-Enhanced x-rays

- **X-ray FEL Oscillator (XFEL-O) using Bragg reflector was first proposed by Colella and Lucio at a BNL workshop in 1984.**

- **(This was also when high-gain FEL and SASE was proposal by Bonifacio, Narducci and Pelegrini , independently from Saldin's earlier work)**

- **Feedback-enhanced x-rays using electron beams optimized for high-gain amplifiers have been studied recently:**
  - Electron outcoupling scheme by Adams and Materlik (1996)
  - Regenerative amplifier using LCLS beam (Huang and Ruth, 2006)

Main Issues for ERL-based XFEL-O

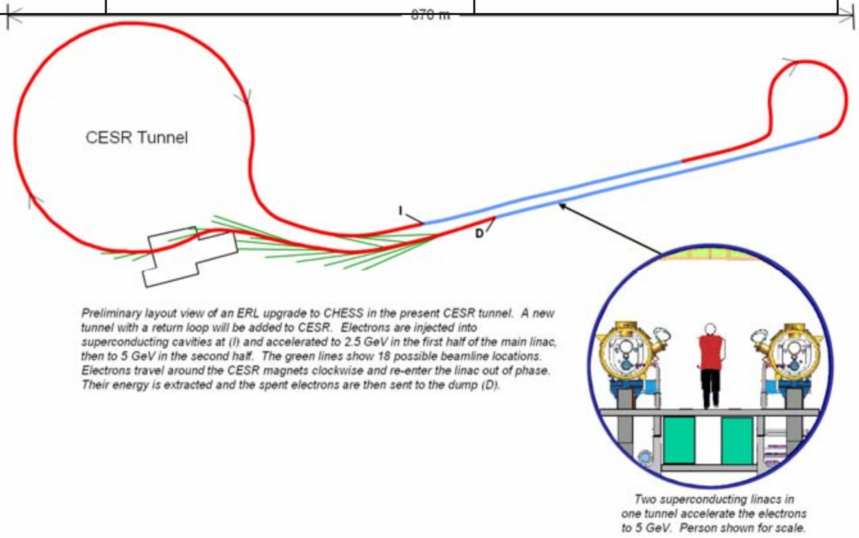
- **Electron beams of suitable characteristics**
  - Production and recirculation of high quality beams
- **FEL dynamics**
  - Sufficient initial gain
  - Coupling of spontaneous emission to coherent mode
  - Beam degradation consistent with recirculation path
- **High reflectivity optical cavity**
  - Crystals in backscattering configuration
  - Focusing elements
  - Outcoupling schemes

Cornell 5 GeV ERL Parameter scaled to 7 GeV APS II: G. Hoffstaetter, FLS 2006 Workshop, DESY

	APS Now	High Flux	High Coherence	Ultrashort Pulse
Average Current (mA)	100	100	25	1
Repetition rate (MHz)	0.3 ~ 352	1300	1300	1
Bunch charge (pC)	0.3 ~ 60	0.077	19 (60)**	1
Emittance (nm)	3.1 x 0.025	0.022 x 0.022	0.006 x 0.006	0.37 x 0.37
Rms bunch length (ps)	20 ~ 70	2	2	0.1
Rms momentum spread (%)	0.1	0.02	0.02	0.3

With gun optimization, the charge can be increased to 60 pC

> **I.V. Bazarov & C.K. Sinclair, PRSTAB,8, 0342002 (2005)**



Preliminary layout view of an ERL upgrade to CHESS in the present CESR tunnel. A new tunnel with a return loop will be added to CESR. Electrons are injected into superconducting cavities at (I) and accelerated to 2.5 GeV in the first half of the main linac, then to 5 GeV in the second half. The green lines show 18 possible beamline locations. Electrons travel around the CESR magnets clockwise and re-enter the linac out of phase. Their energy is extracted and the spent electrons are then sent to the dump (D).

Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.

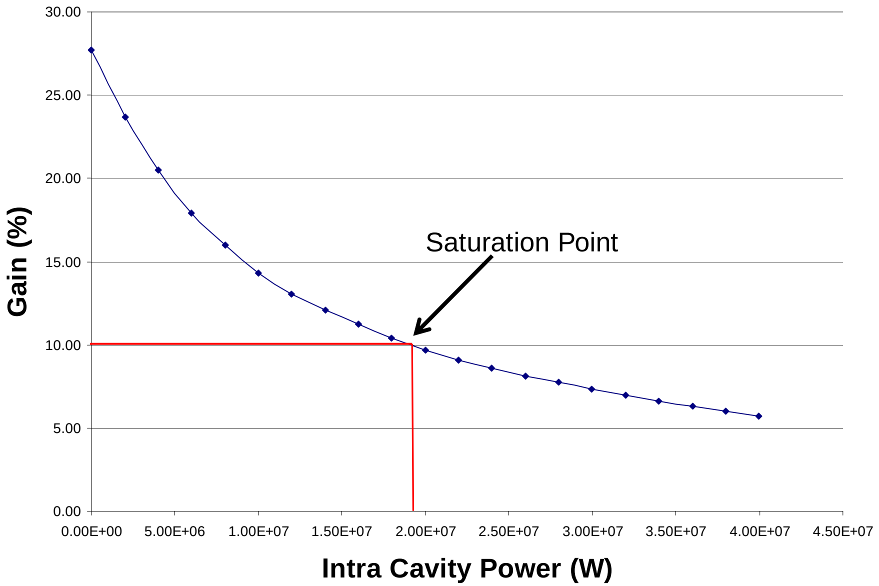
FEL Beam Dynamics

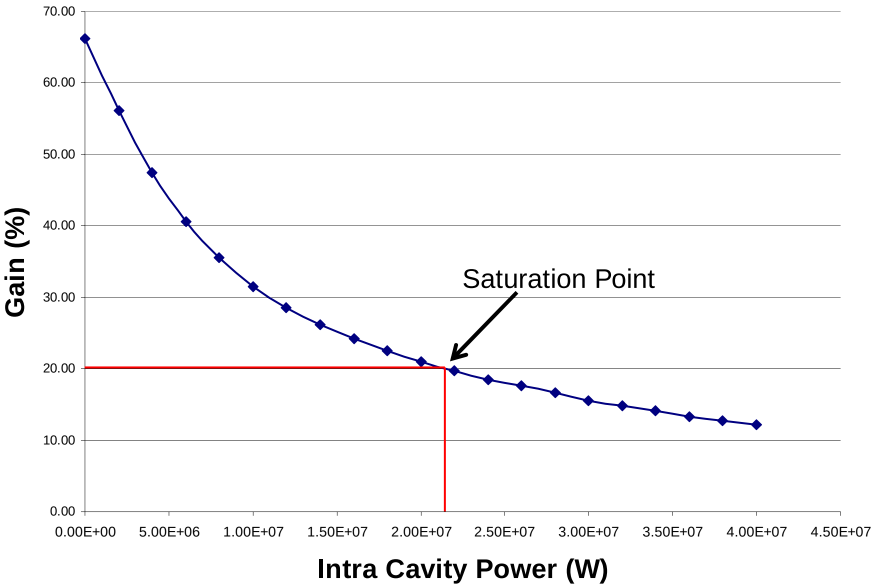
- **Gain calculations**
  - Analytic formula for low signal gain including diffraction and electron beam profile
  - Steady state GENISIS simulation for general intra-cavity power to determine saturation power
- **Time-dependent oscillator simulation by GENO**
  - Extend OPC by adding mirror bandwidth (Reiche)
  - Necessary to establish the growth from spontaneous emission
- **Reduce the CPU time by**
  - Modeling a short window (25 fs)
  - Tracking a single frequency component for radiation wavefront since other components are outside the crystal bandpass
  - About 2 hr for one pass

Saturation: As circulating power increases the gain drops and reach steady state when gain=loss

E=7GeV, λ=1Å
Q=19 pC (Ip=3.8A), N_u=3000
Mirror reflectivity=90%
Saturation power=19 MW

E=7GeV, λ=1Å
Q=40 pC (Ip=8 A), N_u=3000
Mirror reflectivity=80%
Saturation power=21MW





Saturation in about 100-200 passes

Examples of Steady State Calculation

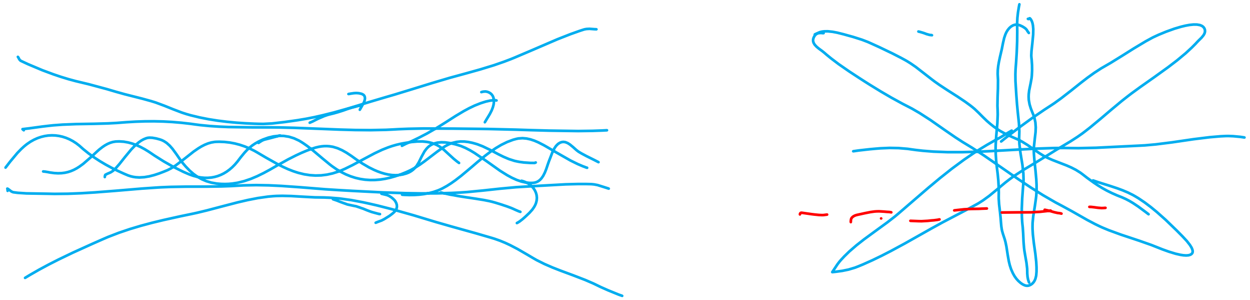
σ_τ=2 ps, σ_γ=1.37, ε_{xn}=0.82 10^{-7}m

$Z_R=\beta^*$=10~12 m

λ(Å)	E(GeV)	Q (pC)	K	λ_U(cm)	N_U	G_0 (%)	R_T (%)	P_{sat} (MW)
1	7	19	1.414	1.88	3000	28	90	19
1	7	60	1.414	1.88	3000	~100	83	21
0.84	7.55	19	1.414	1.88	3000	28	90	20
0.84	10	19	2	2.2	2800	45	83	18

Results of GENO Simulation

- **Constant electron focusing (β_{ave}=5.6 m)**
  - Steady state gain is ~40% for low charge case (19 pC)
  - Exponential growth did not occur-- probably coupling of spontaneous emission to coherent mode is too small



- **No focusing, beam waist at the undulator center (β*~10 m) and mode Rayleigh length ~ β***
  - Smaller gain, but a good coupling to the coherent mode
  - High charge case (60 pC): exponential gain and saturation observed
  - With 19 pC, growth is not strong—factor 6 over spontaneous after 40 passes (as of 6 AM this morning!)
  - Further optimization of electron and mode parameters will be necessary

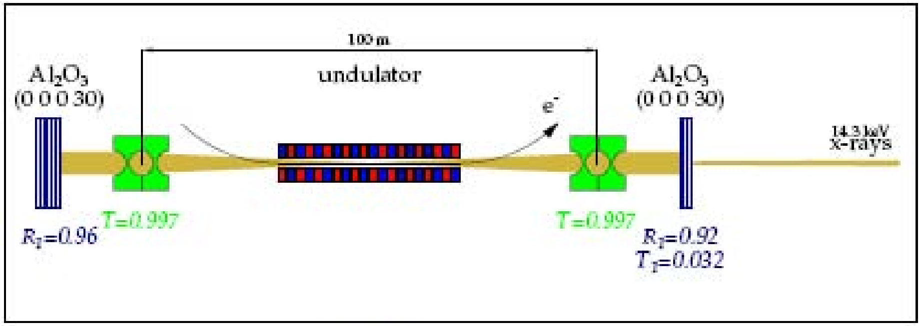
Desired Optics for the X-FEL Oscillator (Y. Shvyd'ko)

- **Reflectivity R_1 x R_2 >90-80%**
  - "Pure" diamond or sapphire
- **Transmissivity T ~5%**
  - Thin crystal, accompanying diffraction in near BS
- **Focusing elements**
  - Curving crystal can affect reflectivity even for R~50m
  - Grazing incidence mirrors or compound reflective lenses
- **Heat loading is OK to 1 MHz, may be up to 100Mz**
  - Cooling AL2O3 to 40 degree

Options for XFEL-O Cavities *(Y. Shvyd'ko)*

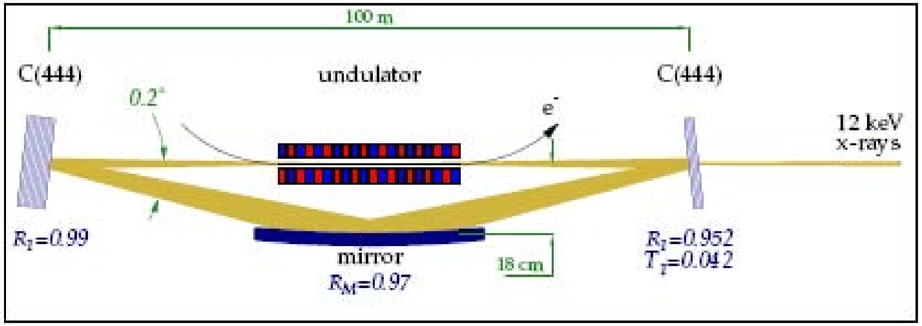
$Al_2O_3xAl_2O_3$ @14.3 keV

R_T=0.87, G_{sat}=15%, T=3%



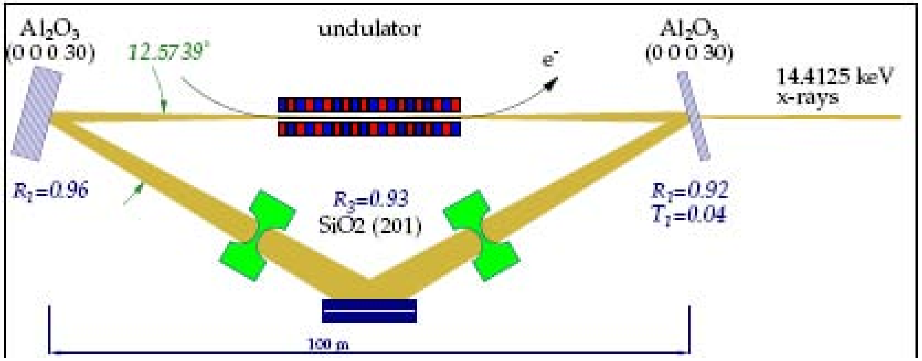
CxCxmirror @12.4 keV

RT=0.91, G_{sat}=10%, T=4%



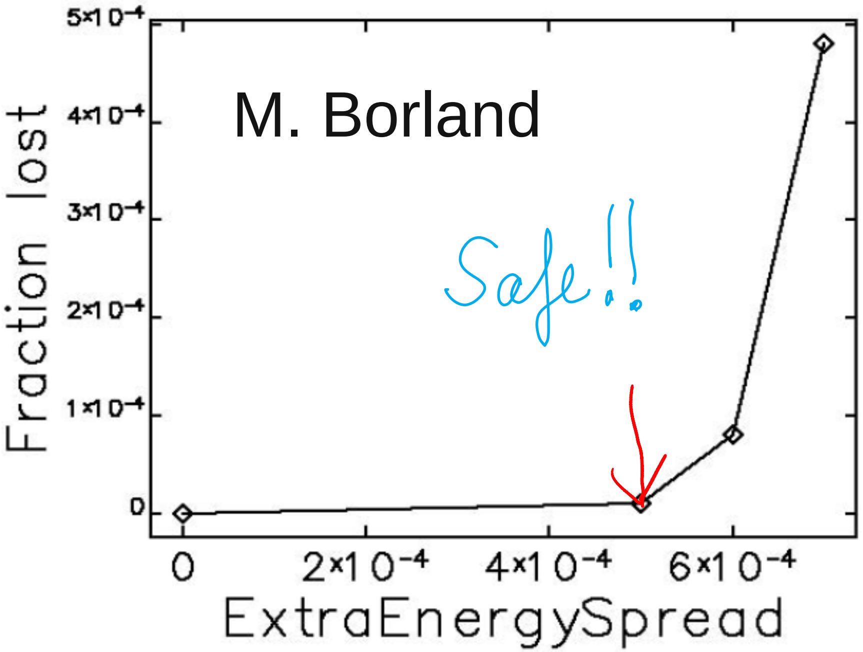
$Al_2O_3xAl_2O_3xSiO_2$@ 14.4125 keV

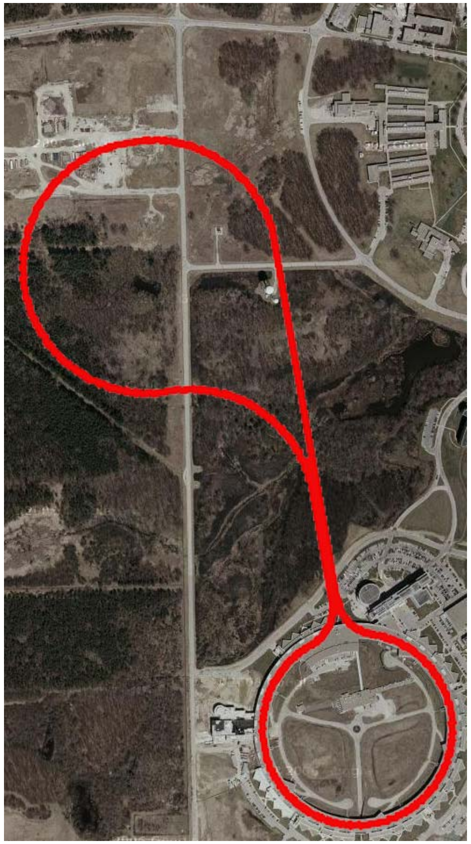
RT=0.82, G_{sat}=22 %, T=4%



Energy Acceptance of the Recirculation-Pass for APS-ERL

- **Genesis simulation shows that the rms energy spead increases from 0.02% to 0.05% after the FEL interaction**
- **The ERL return pass can accommodate 0.05% energy spread**





Photon Performance of XFEL-O

- **Wavelength: 1-Å or shorter, ε_γ=12.4 keV or higher**
- **Full transverse coherence**
- **Full temporal coherence in 1 ps duration**
  - $\Delta\nu/\nu=0.3\ 10^{-6}$; $h\Delta\nu=4$ meV
- **10^9 photons (~ 1 μJ) /pulse**
  - Peak spectral brightness~LCLS
- **Rep rate: 1 MHz or higher, limited by crystal heat load, 100MHz?**
  - Average brightness 10^{27} (→10^{29}) #photons/(mm-mr)^2(0.1%BW)
  - 10^3-10^5 times higher than ERL based undulator source

Science Drivers for XFEL-O

- **Inelastic x-ray scattering (IXS) and nuclear resonant scattering (NRS) are flux limited experiments! *Need more spectral flux in a meV bandwidth!* .**
- **Undulators at storage rings generate radiation with ≈ 100−200 eV bandwidth. Only ≈ 10^{-5} is used, the rest is filtered out by meV-monochromators.**

Presently @ APS: ≈ 5 × 10^9 photons/s/meV (14.4 keV)

- **XFEL-O is a perfect x-ray source for:**
  - high-energy-resolution spectroscopy (meV IXS, neV NRS, etc.), and
  - imaging requiring large coherent volumes.
  - Expected with XFEL-O ≈ 10^{15} photons/s/meV (14.4 keV) with 10^7 Hz repetition rate.

Concluding Remarks

- **XFEL-O appears to be feasible with beams expected from future ERLs**
- **It is a promising and powerful addition to ERL capabilities**
- **Application areas: nuclear resonance scattering, coherent imaging, inelastic scattering,…**
- **This is initial exploration with much room for further optimization.**