X-Ray FEL Oscillator

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3WM08: Accelartor R&D

March 19, 2008

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X-Ray FEL Oscillator (X-FELO)

- **A fully coherent source of x-rays in the spectral range 5-20 keV:**
  - 10^9 photons/pulse, rep rates at least 1 MHz , limited by thermal loading
  - Peak SB ~ SASE from high-gain FEL
  - Average SB~ at least 10 times European XFEL
  - Not tunable
- **Key components:**
  - A continuous sequence of ultra-low emittance, multi-GeV electron bunches → ERL
  - Low-loss x-ray optical cavity using high reflectivity crystals
- **ERL bunches have low intensity and are not suitable for *high-gain* XFEL but OK for X-FEL *oscillator***

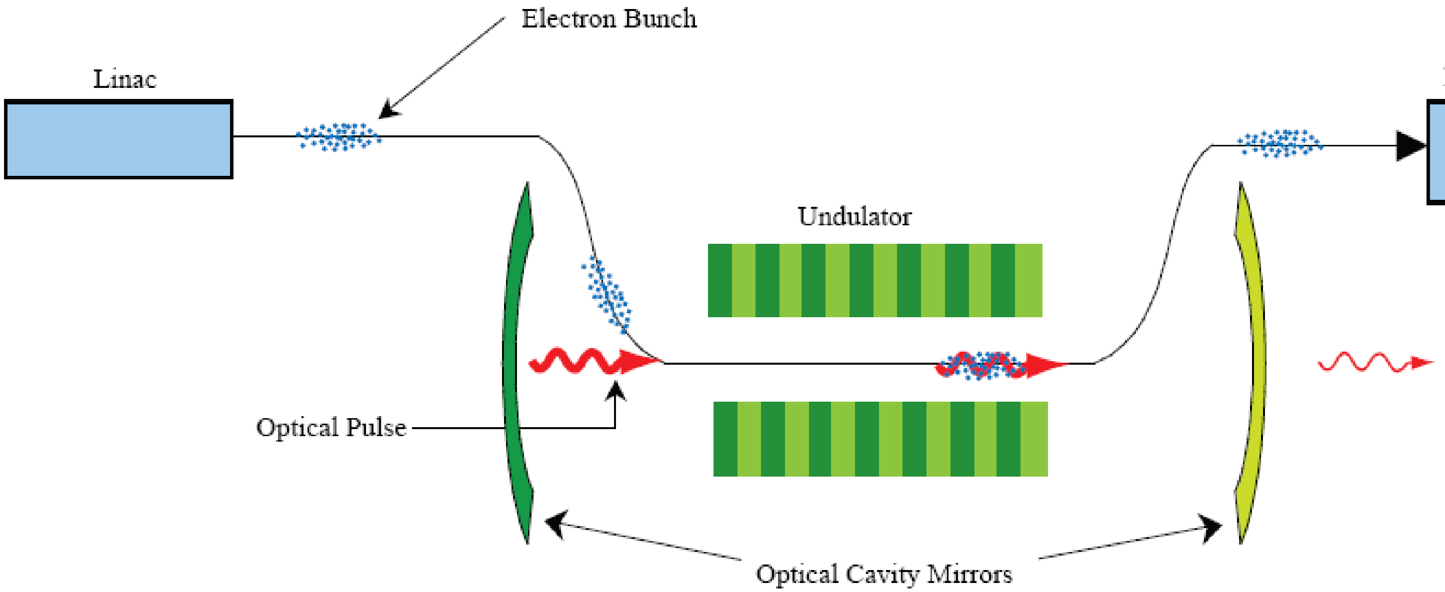
X-Ray Cavity with Crystals

- **X-ray FEL Oscillator (XFEL-O) using Bragg reflector was first proposed by R. Colella and A. Luccio at a BNL workshop in 1984 (The same meeting where high-gain SASE was proposed by Bonifacio, Pellegrini, and Narducci).**

- **However, accelerators producing electron beams with required qualities were not known at that time**

- **More recently, use of X-ray cavities have been studied for improving the performance of high-gain FEL:**
  - Electron out-coupling scheme by B. Adams and G. Materlik (1996)
  - Regenerative amplifier using LCLS beam (Z. Huang and R. Ruth, PRL, 2006)

Principles of an FEL Oscillator

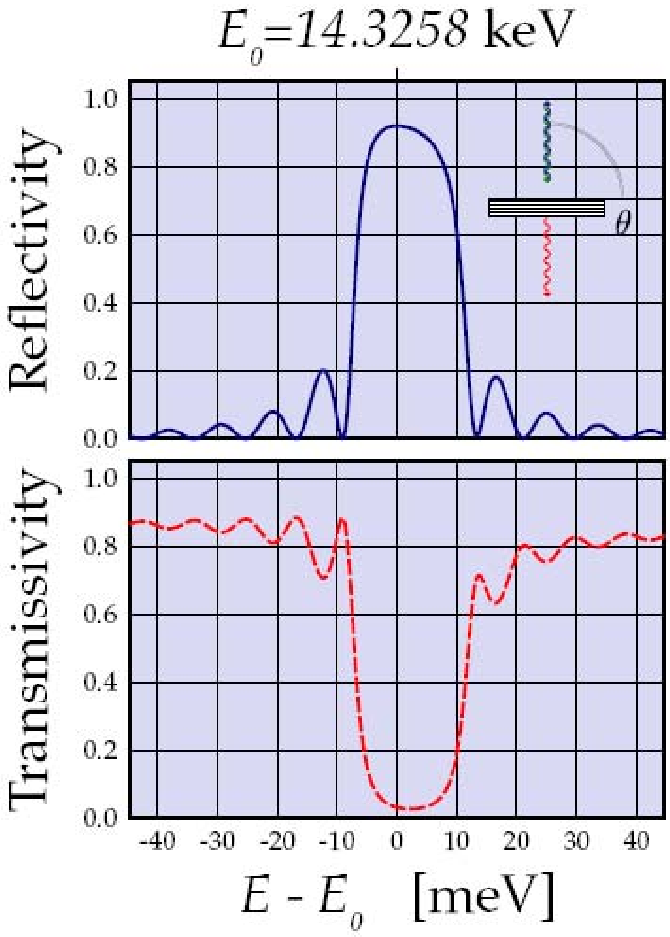


- **Small signal gain g= $\Delta P_{intra}/P_{intra}$**
  - Start-up: $(1+g_0)\ R_1\ R_2 > 1$ (R_1& R_2 : mirror reflectivity)
  - Saturation: $(1+g_{sat})\ R_1\ R_2 = 1$
- **Synchronism**
  - Spacing between electron bunches=2L/n (L: length of the cavity)

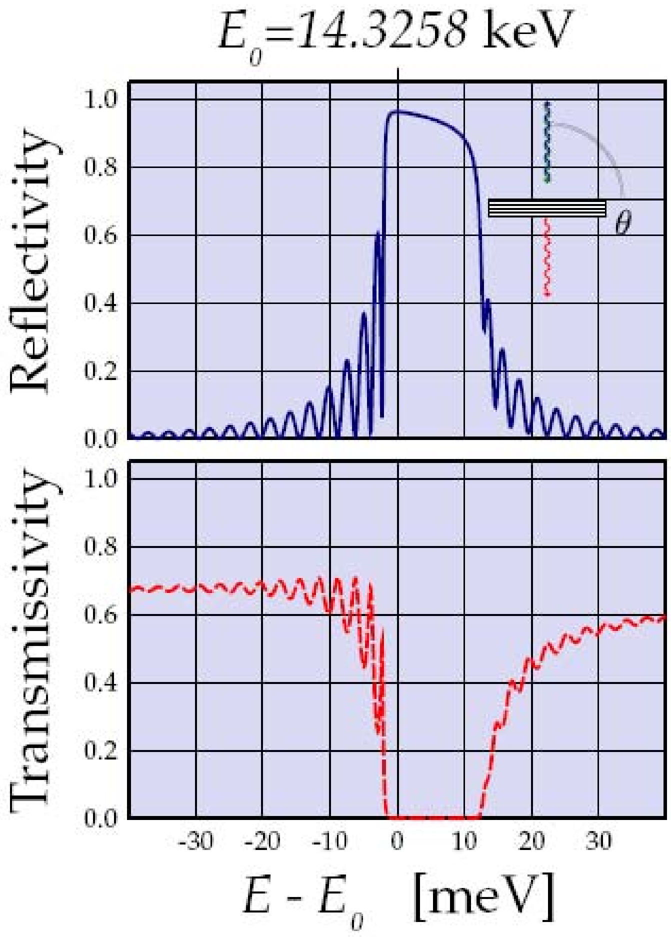
X-ray Optical Cavity

- **Choose low Z, high Debye temperature crystals**
  - C (diamond), BeO, SiC, α-AL_2O_3 (sapphire)
  - Operate T=30K for high-reflectivity, high thermal conductivity, low sensitivity of interplanar spacing on T
  - Avoid exact backscattering in case of C to prevent loss from multiple diffraction
- **Crystal quality issue**
  - Choose a small (d <0.2 mm) high quality single crystal from a bulk sample
- **Focusing elements to adjust mode profile**
  - Bending of crystal may destroy reflectivity
  - Parabolic Compound Refracitive Lenses (CRLs)
  - Grazing incidence mirror when Bragg mirrors are not in exact backscattering

Sapphire Reflectivity @ 14.3 keV



Al2O3(0 0 30); L = 0.07 mm; T = 40 K;
bradix version: January, 2007

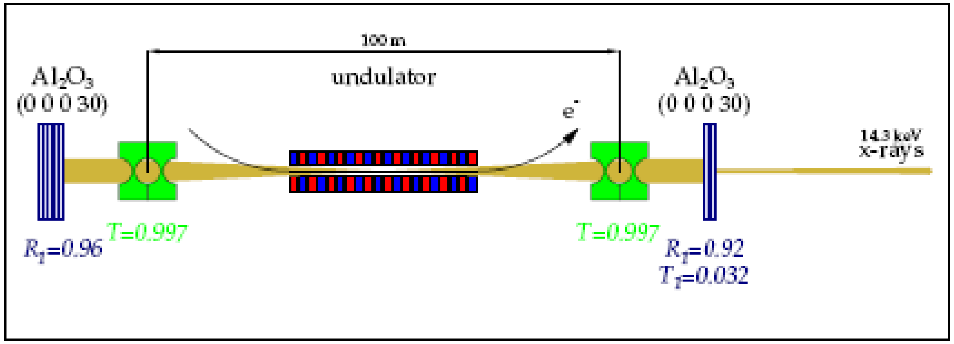


Al2O3(0 0 30); L = 0.2 mm; T = 40 K;
bradix version: January, 2007

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

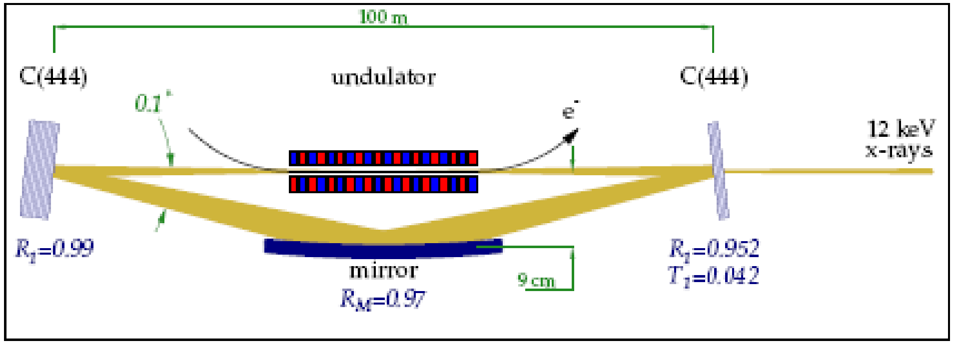
$Al_2O_3 x Al_2O_3$ @14.3 keV

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



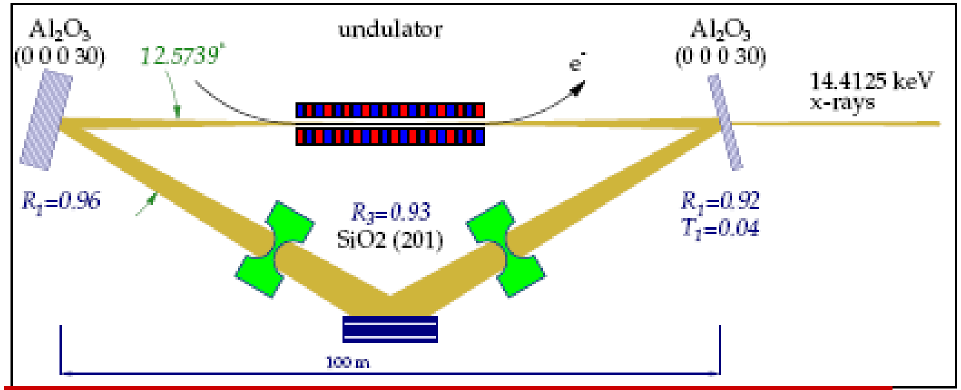
CxCxmirror @12.4 keV

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



$Al_2O_3 x Al_2O_3 x SiO_2$@ 14.4125 keV

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



FEL Performance Study

- **Analytic formula for initial gain including diffraction and electron beam profile**
- **Steady state GENISIS simulation for gain as a function of intra-cavity power to determine saturation power**
- **Simulation of build up from spontaneous emission using modified GENESIS**
- **“Supermode” analysis to determine temporal structure, in particular length of x-ray pulse**

Beam Quality Parameters (ERL High-Coherence Mode)

	Q(pC)	ε_{nx}(10^{-7} m)	$\sigma_{\Delta E}$(MeV)	τ_{el} (ps)
A: Conservative	**19**	**1.64**	**1.4**	**2**
B: Cornell Design*	**19**	**.82**	**1.4**	**2**
C: Optimistic**	**40**	**.82**	**1.4**	**2**

* D.H. Bilderback, C. K. Sinclaire, and S.M. Gruner, Synch. Rad. News, 19-6, 30 (2007)

** I.V. Bazarov and C. Sinclaire, , PRSTAB, 8, 034202(2005)

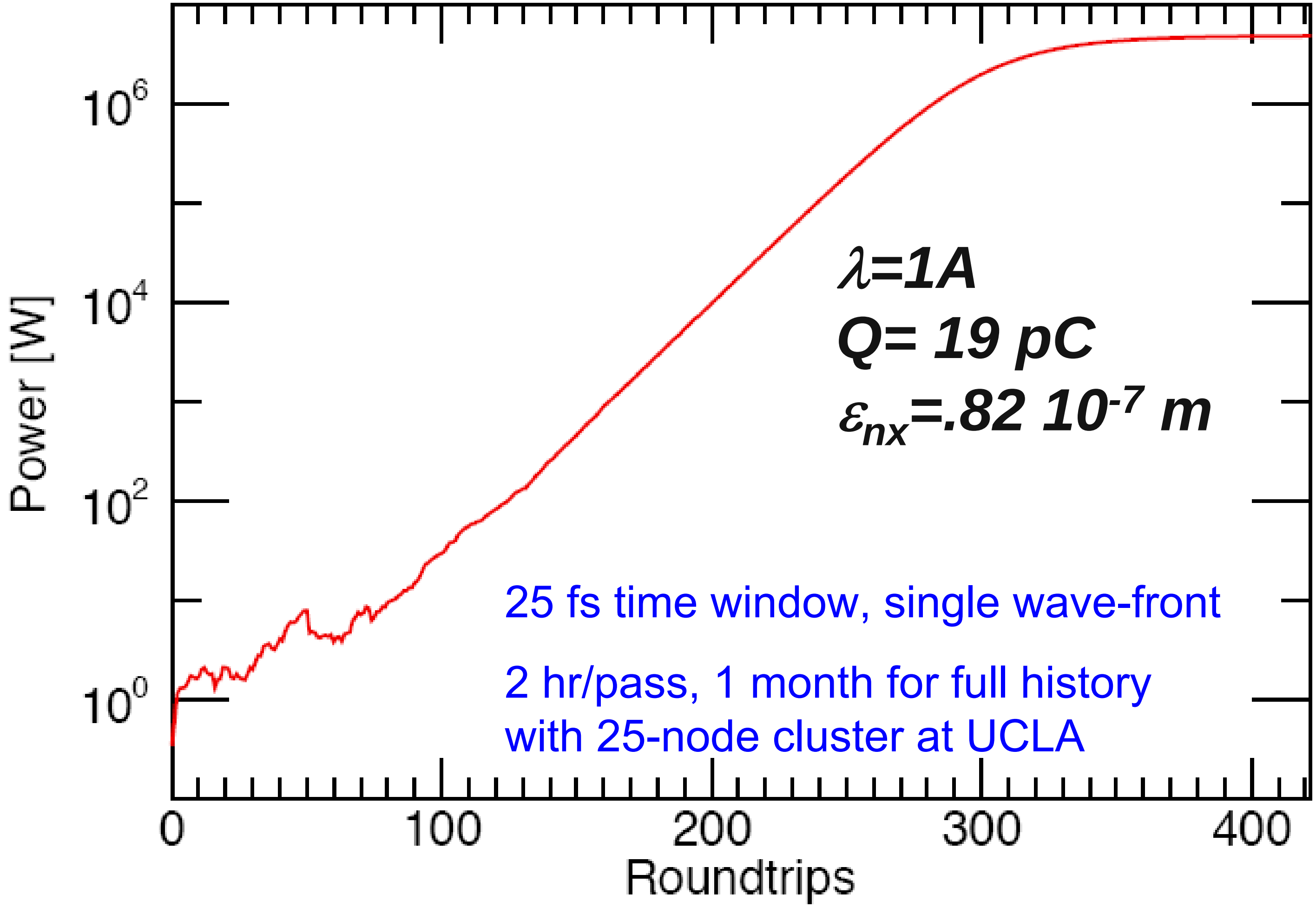
Examples of Steady-State Calculation

Electrons are not focused but matched to the optical mode determined by cavity configuration

($Z_R=\beta^*=10\sim12$ m)

λ(Å)	E (GeV)	Bunch Quality	K	λ_U (cm)	N_U	G_0 (%)	R_T (%)	P_{sat} (MW)
2.48	7	A	2.5	2.26	2600	35	83	10
1	7	B	1.414	1.88	3000	28	90	19
1	7	C	1.414	1.88	3000	66	83	21
0.84	7.55	B	1.414	1.88	3000	28	90	20
0.84	10	B	2	2.2	2800	45	83	18

Evolution from Spontaneous Emission



λ=1A

Q= 19 pC

ε_{nx}=.82 10^{-7} m

25 fs time window, single wave-front

2 hr/pass, 1 month for full history with 25-node cluster at UCLA

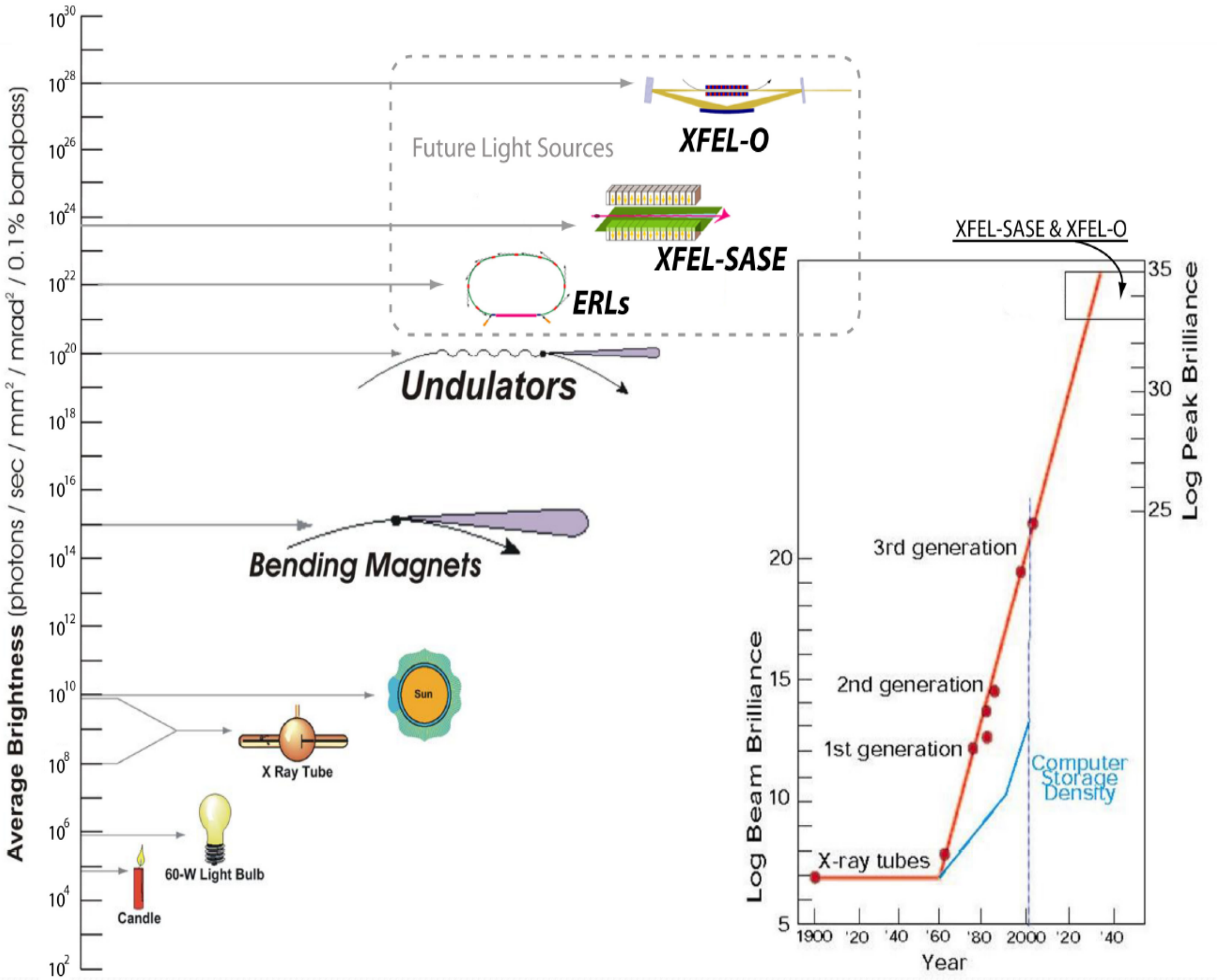
Photon Performance of XFEL-O

- **Photon energies: 5 keV < ε_γ <20 keV**
- **Full transverse coherence**
- **Full temporal coherence**
  - 1 ps duration (rms),
  - **B.W.=2 meV (rms)**
- Adjustable polarization via crossed undulator configuration
- **Not Tunable**
- **10^9 photons (~ 1 μJ) /pulse**
  - Peak spectral brightness~LCLS
- **Minimum rep rate is (1-100) MHz, the maximum could be 100 MHz limited by crystal heat load→ average spectral brightness (10^{26} -10^{28}) ph/(mm-mr)^2(0.1%BW)**

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
  - X-FELO: ≈ 10^{15} photons/ meV
- **Coherent imaging**
- **Measurement of time-resolved, bulk-senstive Fermi surfaces via hard x-ray angle resolved photo-emission spectrsocopy (F. Parmigiani)**

Current and Future X-Ray Sources



Back-Up VGs

Multi-GeV Energy Recovery Linac

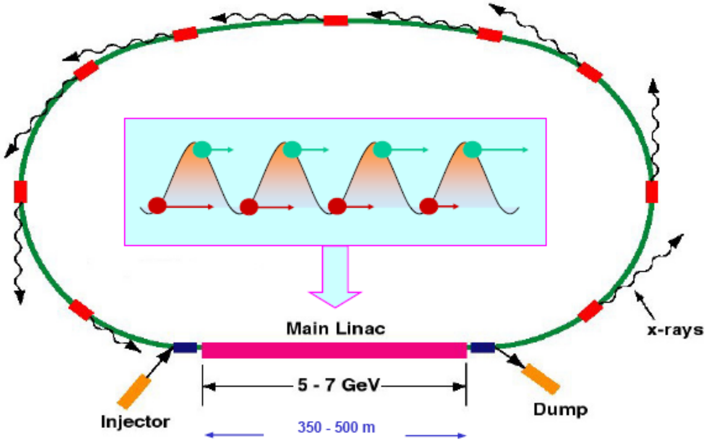
- Invented by M. Tigner in 1965 for HE collider
- Cornell proposal as 4th generation x-ray source
- Electron beam qualities determined by the gun→ higher brightness, shorter bunch length, more flexible bunch format than the ring-based 3rd generation sources
- Under study at JAERI-KEK, APS, Daresbury

Three operating modes:

High-Flux

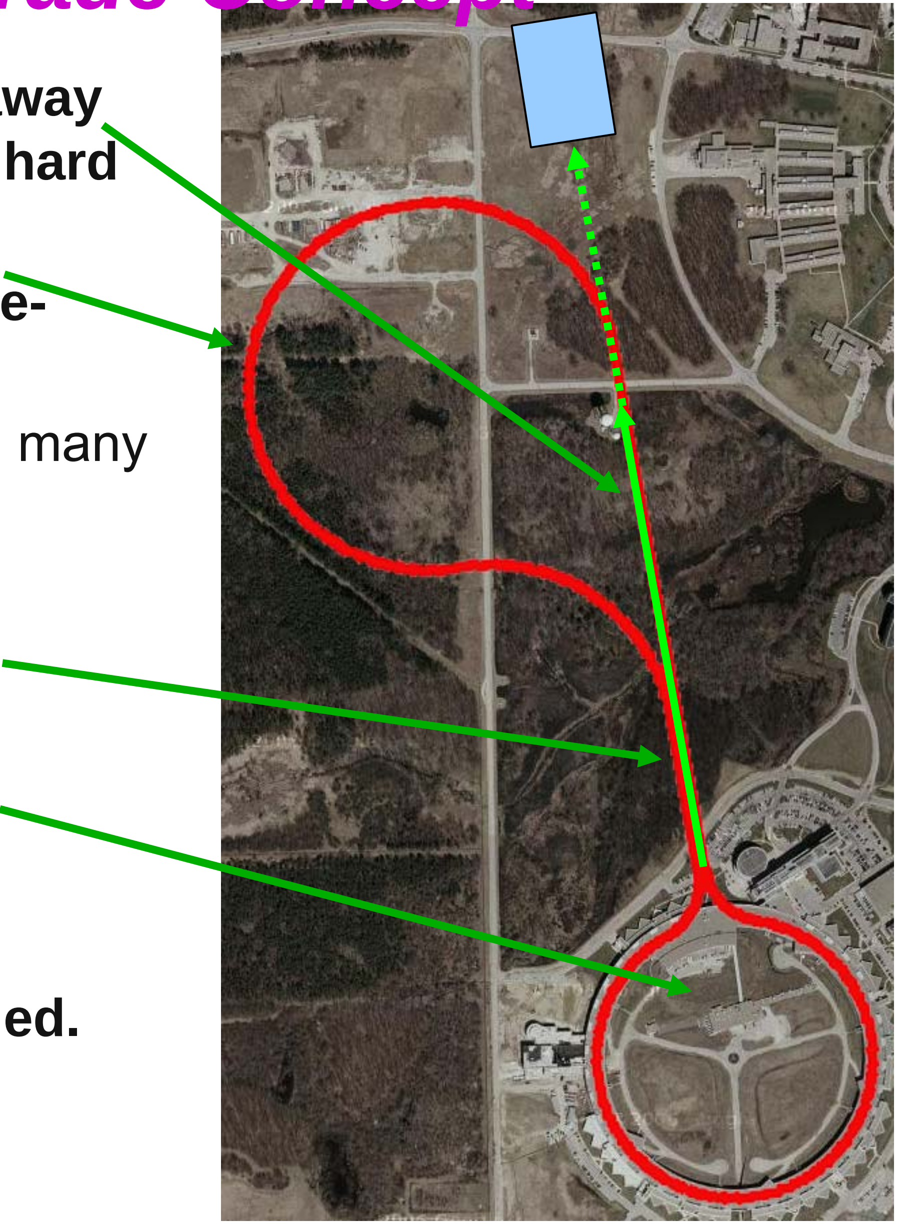
High-Coherence

Ultrafast



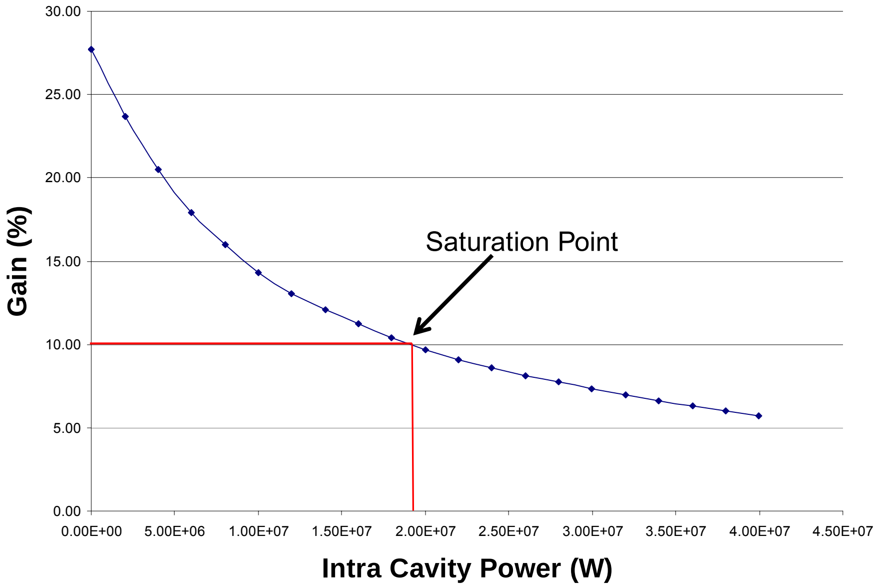
Ultimate APS ERL Upgrade Concept

- **Single-pass 7~8 GeV linac points away from APS to permit straight-ahead hard x-ray short-pulse facility**
- **Beam goes first into new, emittance-preserving turn-around/user arc**
  - Second-stage upgrade would add many new beamlines
- **ERL can benefit from very long undulators**
  - Higher flux and brightness
  - Could add these using somewhat different geometry
- **Ability to store beam unchanged**
- **Existing injector complex unchanged.**

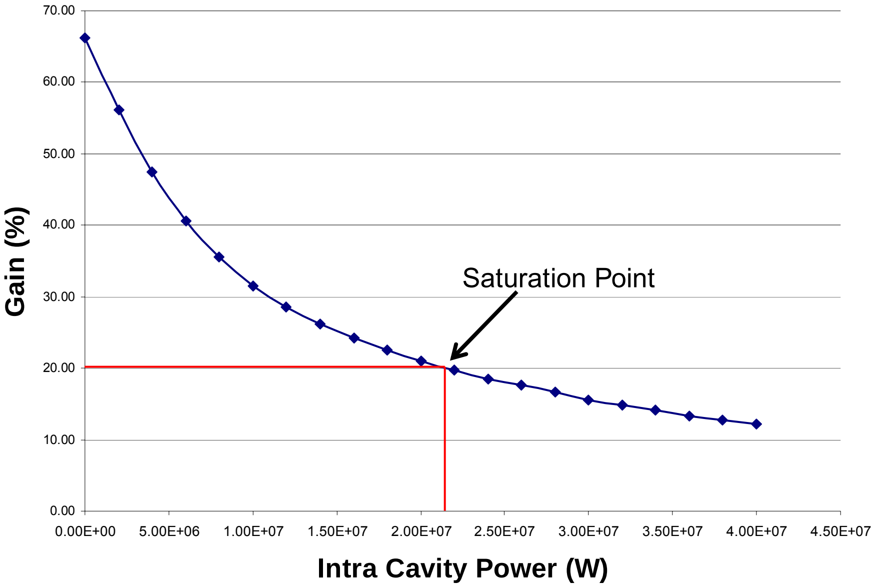


Saturation: As circulating power increases, the gain drops and reaches steady state when gain=loss

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



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



Simulation of Oscillator Start-up

- **Time-dependent oscillator simulation using GENO (GENESIS for Oscillator) written by Sven**
  - Taking into account FEL interaction (GENESIS), optical cavity layout, and mirror bandwidth (Reiche)
- **To reduce CPU**
  - Follow a short time-window (25 fs)
  - Track a single frequency component for all radiation wavefronts since other components are outside the crystal bandpass
  - ***Even with these simplifications, one pass takes about 2 hr***

Micro-Temporal Structure

G. Dattoli, et. al (1981), P. Elleaume (1985)

- **Four rms lengths**
  - τ_{el}=electron bunch length, τ_{opt}= optical pulse length, $\tau_M = \omega/2\sigma_{\omega M}$ ($\sigma_{\omega M}$=cavity BW), τ_s=slippage length
  - $\tau_{el} >> \tau_{opt} >> \tau_M >> \tau_s$
- **Fundamental super mode with cavity "detuning" u**
  - $a_n(\zeta) = \exp [n\Lambda - u\zeta/(2\tau_M^2) - \zeta^2/(2\tau_{opt}^2)]$
  - $\zeta = t - z/c$, $\tau_{opt}=(2\tau_{el}\tau_M)^{1/2}/ g^{1/4}$
  - $\Lambda = (g-\alpha)/2 - (u/2\,\tau_M)^2 - 0.5\, g^{1/2}(\tau_M / \tau_{el})$
- **X-FELO**
  - τ_{el}= 2 ps, $\tau_{opt} \sim$ 1 ps, τ_M ~0.1 ps (BW of single crystal 4 meV)
  - τ_s=1 fs
  - u < 20 fs, cavity detuning < 3 μm
- **Tolerance on mirror angle < 8 nr**