Argonne NATIONAL LABORATORY

... for a brighter future

1-Å FEL Oscillator with ERL Beams

Frontiers in FEL Physics and Related Topics
September 8-14

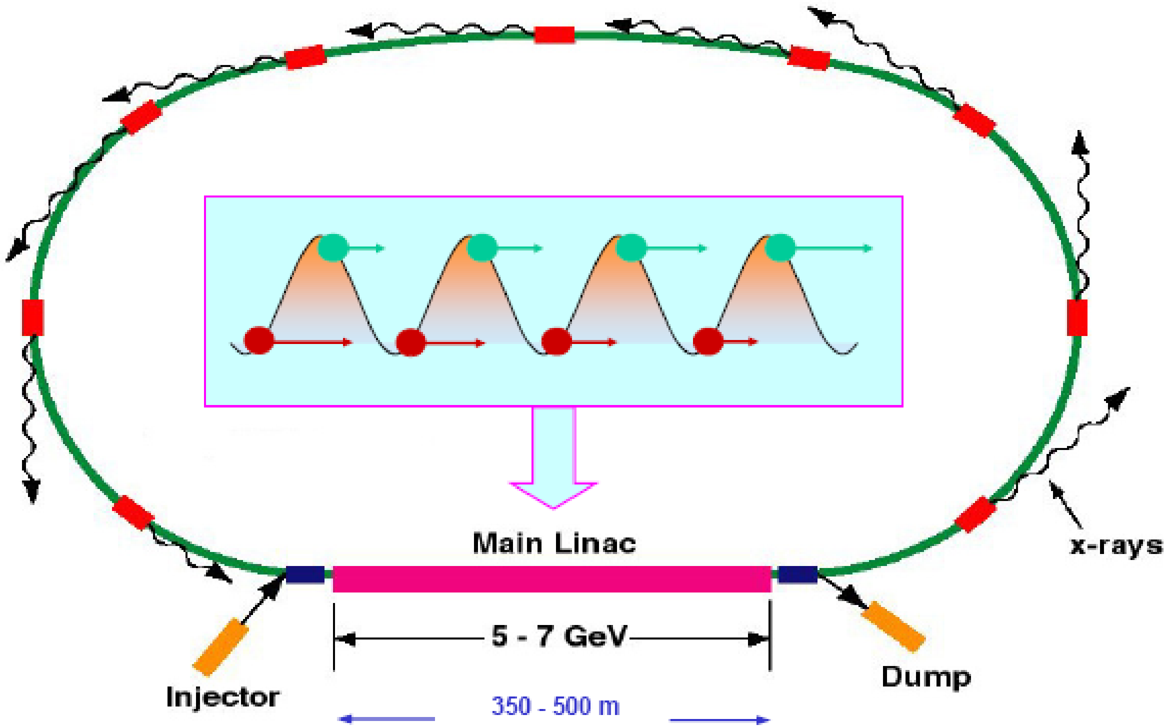
Elba Island-La Biodola, Tuscany, Italy

Kwang-Je Kim, ANL
Sven Reiche, UCLA
Yuri Shvyd'ko, ANL

FELs for λ<1-Å Wavelengths

- **High-gain FEL amplifier, SASE or seeded HG, will provide an enormous jump in *peak* brightness, became realistic due to advances in gun-linac technology**
  - I_P~ several kA, ε_x^n~ 1 mm-mr beams
- **HGFEL is a promising option for future light source (FLS)**
  - LCLS, European X-FEL, SCSS, Fermi, Arc-en-Ciel,..
- **Electron beams for another option for FLS, the Energy Recovery Linacs (ERLs), promise to be extreme low-emittance and high *average* brightness**
  - ε_x^n~ 0.1 mm-mr, I_P~ 4-12 A, I_{AV} up to 100 mA
  - Cornell, MARS, 4GLS, KEK-JAERI, APS,..
- **ERLs have so far been regarded only as a spontaneous emission source**
- **We show that an X-ray FEL *Oscillator* (XFEL-O) for λ <1-Å based on high energy ERL beams is feasible**

Energy Recovery Linac
(Courtesy of Sol Gruner)

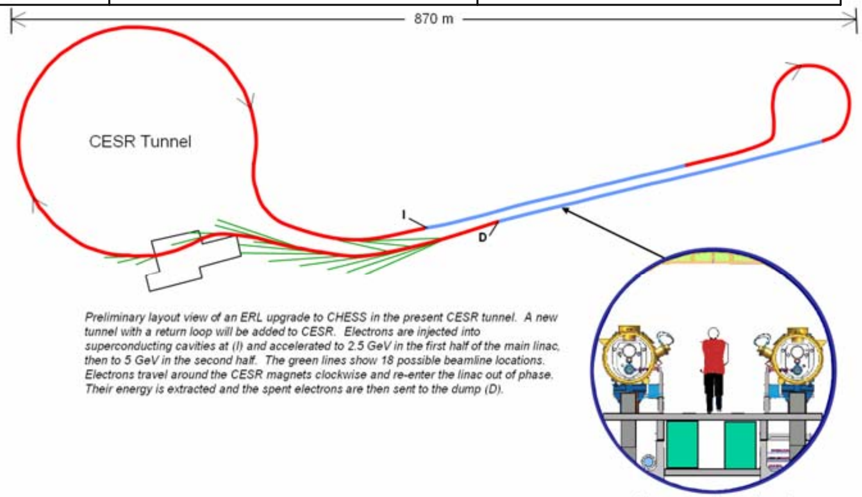


Invented by M. Tigner (1965)

Cornell 5-GeV ERL Parameter Scaled to 7-GeV for 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)



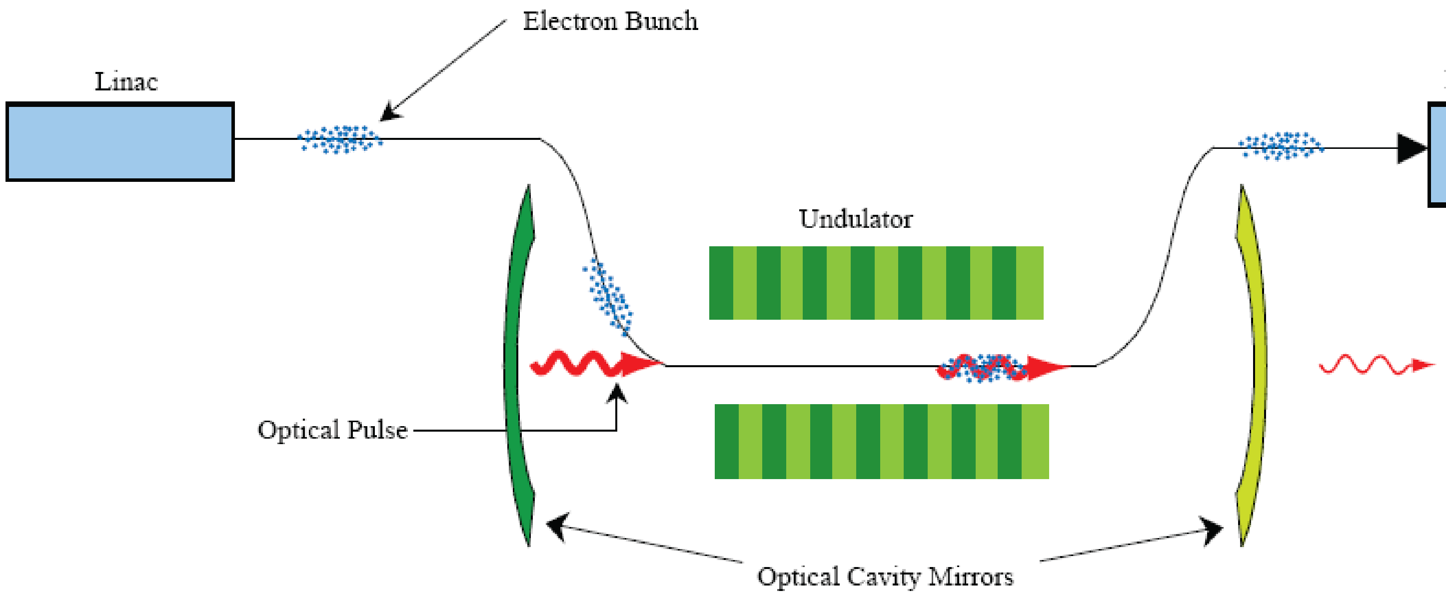
Preliminary layout view of an ERL upgrade to CHESS in the present CESR tunnel. A new tunnel with a return loop will be added to CESR. Electrons are injected into superconducting cavities at (I) and accelerated to 2.5 GeV in the first half of the main linac, then to 5 GeV in the second half. The green 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.

Feedback-Enhanced X-Ray Sources

- **X-ray FEL Oscillator (XFEL-O) using Bragg reflector was first proposed by R. Colella and A. Lucio at a BNL workshop in 1984.**
- **This was also the time when a high-gain FEL(SASE) was proposed by R. Bonifacio, C. Pelegrini, and L. M. Narducci (the "ρ-paper".)**
- **Feedback-enhanced x-ray sources using electron beams optimized for high-gain amplifiers have been studied recently:**
  - Electron out-coupling scheme by B. Adams and G. Materlik (1996)
  - Regenerative amplifier using LCLS beam (Z. Huang and R. Ruth, 2006)
- **We study XFEL-O using the beam parameters of Cornell ERL Coherent Mode scaled to 7 GeV**

Principles of an FEL Oscillator



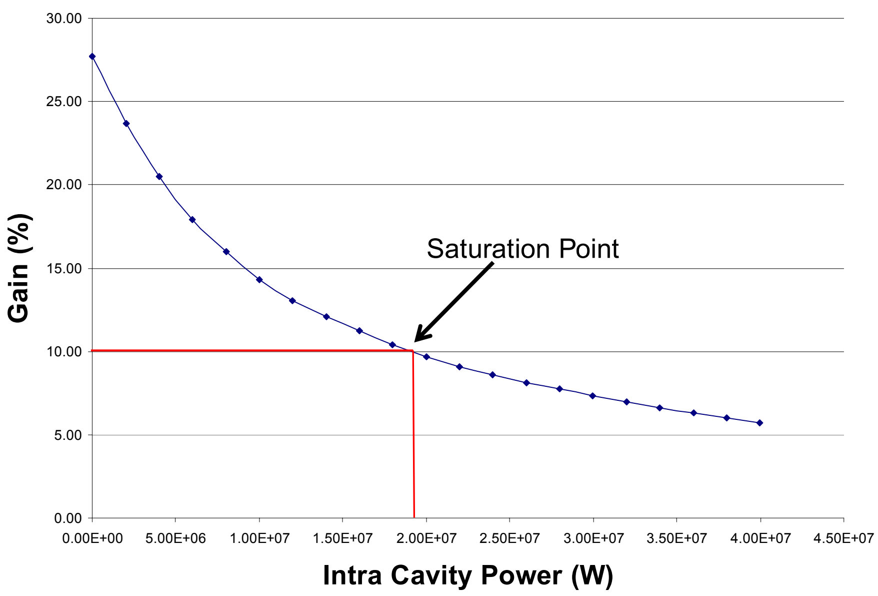
- **Small signal gain G= $\Delta P_{intra}/P_{intra}$**
  - Start-up: $(1+G_0)\ R_1\ R_2 > 1$ (R_1 & R_2 : mirror reflectivity)
  - Saturation: $(1+G_{sat})\ R_1\ R_2 = 1$
- **Synchronism**
  - Spacing between electron bunches=2L/n (L: length of the cavity)

Gain Calculation

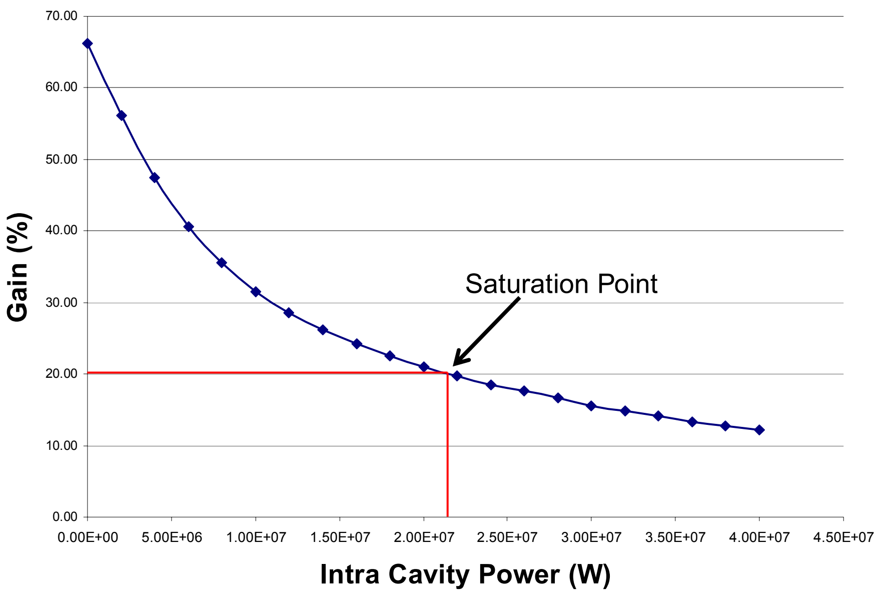
- **Analytic formula for low signal including diffraction and electron beam profile**
  - Sufficiently simple for Mathematica evaluation if electron beam is not focused and distributions are Gaussian
  - Similarily simple but approximate formula for matched electron beam in constant focusing
- **Steady state GENISIS simulation for general intra-cavity power to determine saturation power (Sven Reiche)**

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



Examples of Steady-State Calculation

Electrons are not focused but matched to the optical mode determined by cavity configuration (see later)

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	40	1.414	1.88	3000	66	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

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 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***

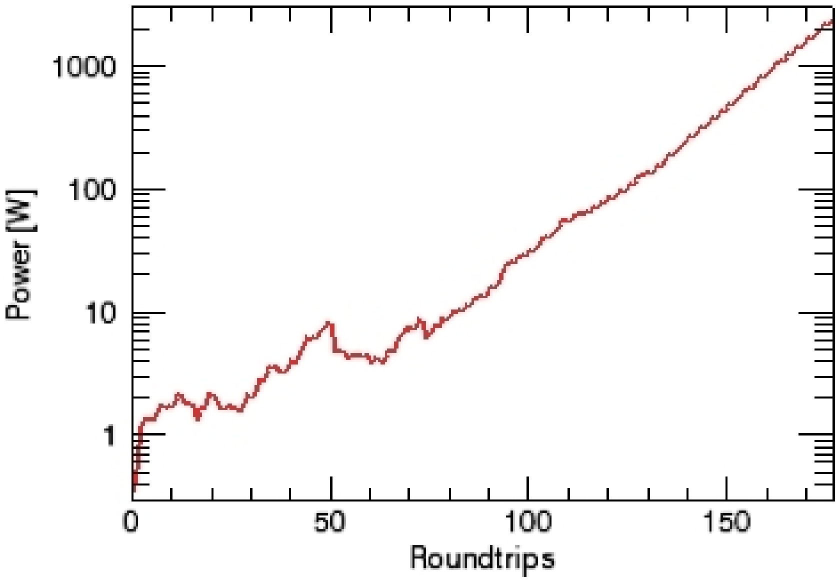
Electron Beam Profile

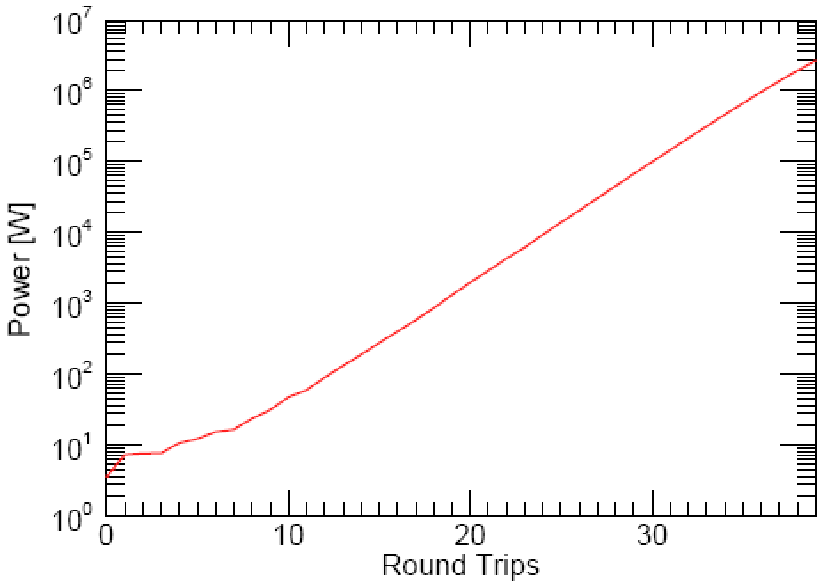
- **Constant cross section with a constant focusing (β_{ave}=5.6 m)**
  - Highest gain (~40% for low charge case (19 pC))
  - However, coupling of spontaneous emission to coherent mode is strongly suppressed due to poor overlap between e-beam and mode phase space distribution

- **No focusing with beam waist at the undulator center (β^*~10 m) and mode Rayleigh length ~ β^***
  - Smewhat lessgain, but a good coupling to the coherent mode since the electron and radiation phase space shape is similar

Start-up Simulation (Reiche)

1-Å Case, 7 GeV





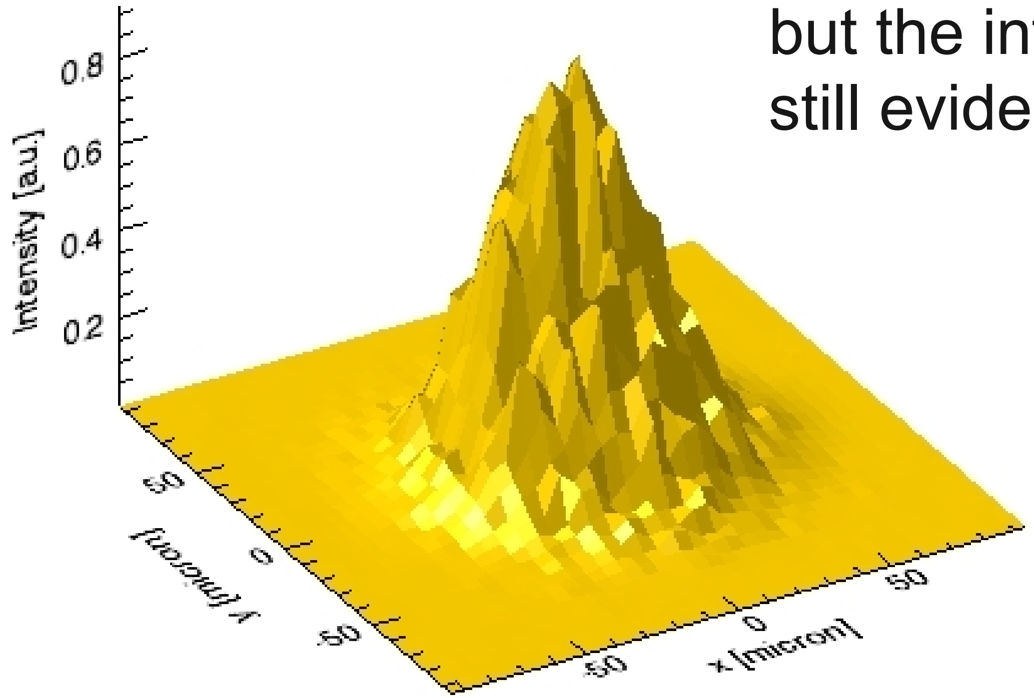
19 pC, mirror loss=10%

Effective net gain~6%

Q=60 pC, mirror loss=20%

Effective net gain ~ 47%

Transverse Profile @128th Pass



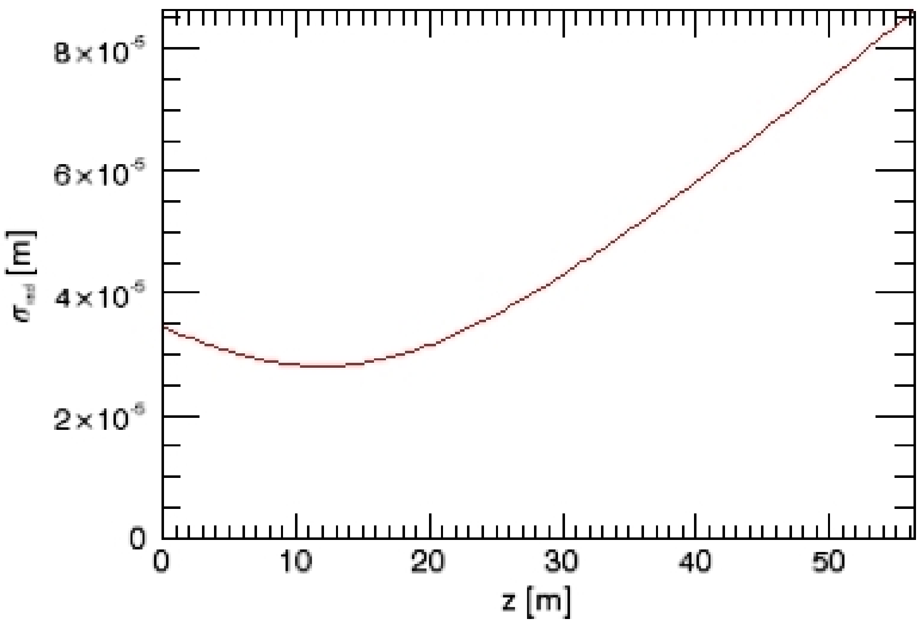
More or less Gaussian but the influence of SE still evident

Evolution of RMS Radius (GENO)

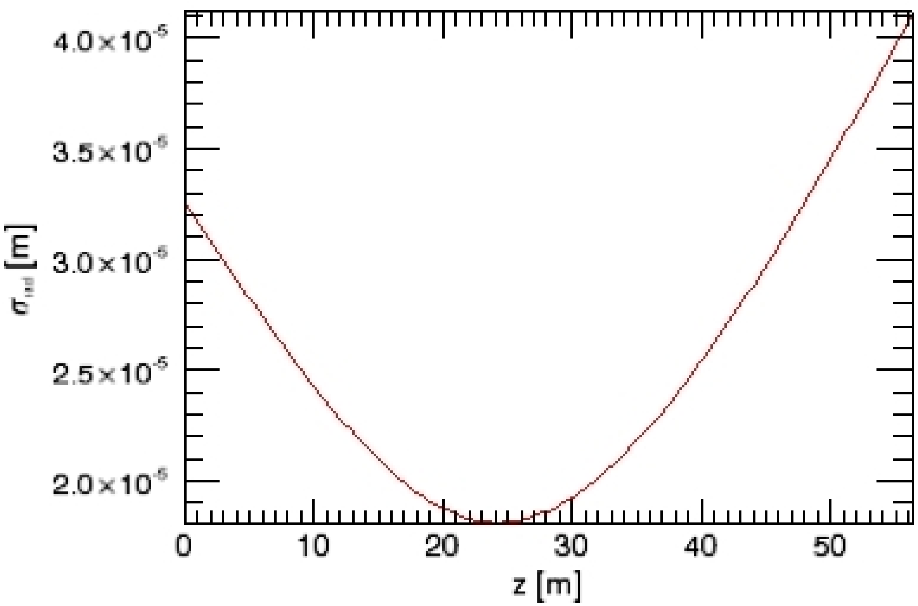
128th pass (P_{intra}~100W)

Z_R=15.3 m

Waist in the front!



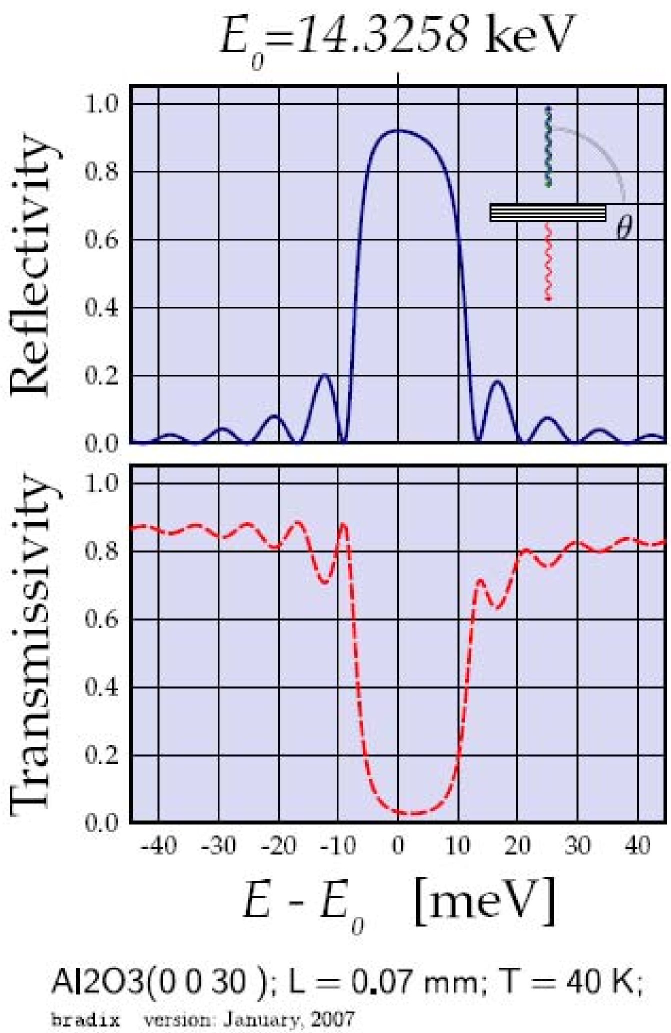
179 th pass (Pintra~100W)
Z_R~10 m and
the waist closer to the center as designed

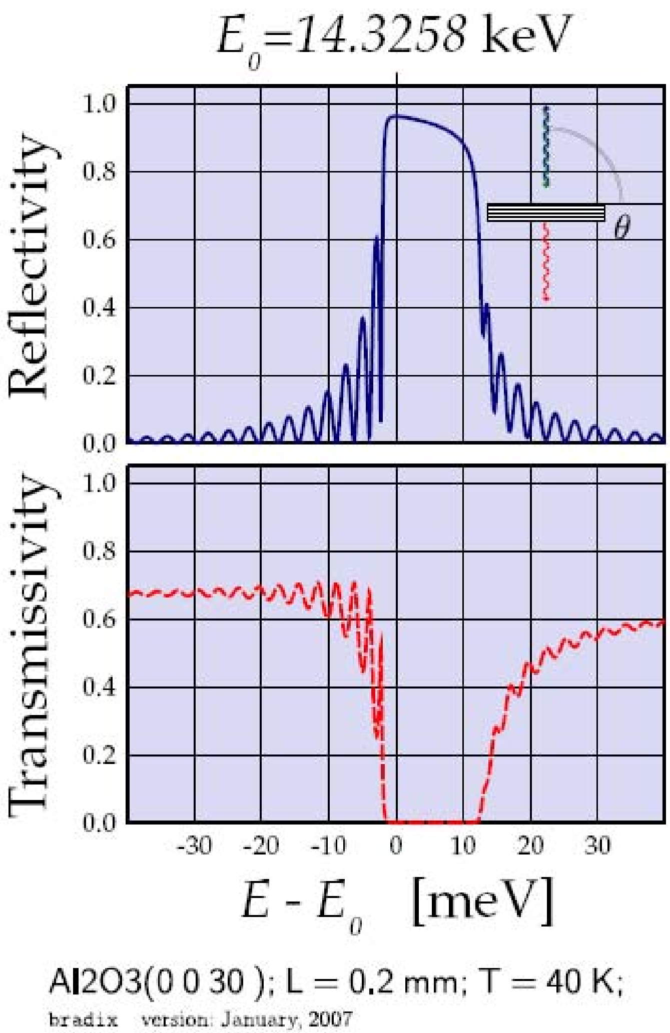


Bragg Mirrors

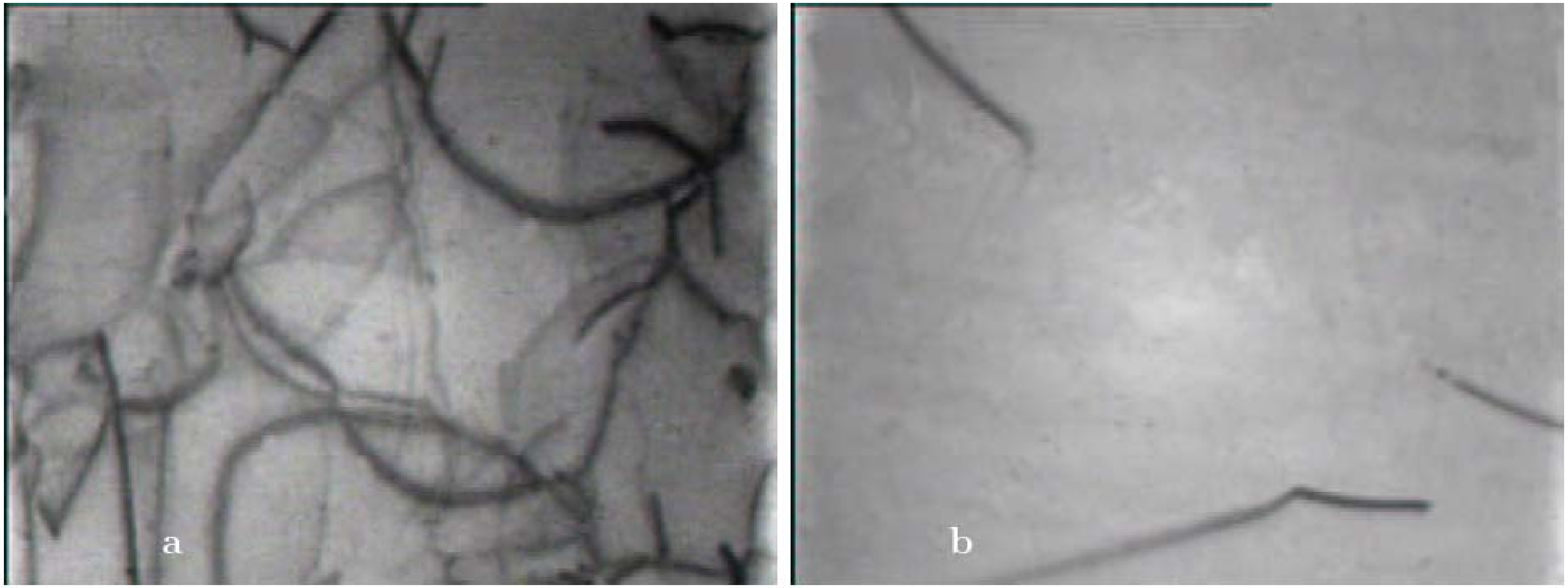
- **Requiring total loss per pass to be 10-20%, the reflectivity of each Bragg mirror should be well over 90%**
- **Possible crystal candidates are**
  - Silicon
    - *Perfect crystals exist but the reflectivity is not sufficient*
  - Diamond
    - *Highest reflectivity & hard (small Debye-Waller reduction)*
    - *Multiple beam diffraction in exact backscattering except (111) and (220) (can use as a coupling mechanism?)*
  - Sapphire
    - *High reflectivity without multiple beam diffraction*
    - *Small thermal expansion coefficient for T<100K and large heat conductivity at T=40K*

Sapphire Reflectivity @ 14.3 keV





Sapphire Crystal Quality



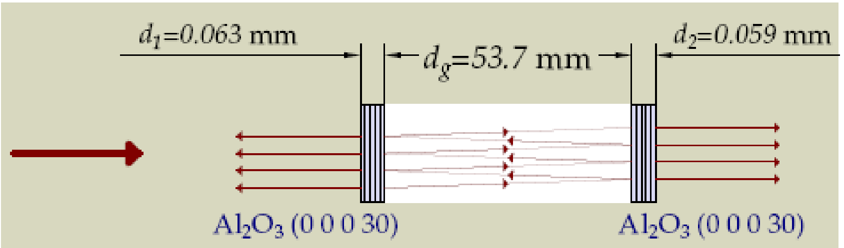
Back-reflection topographs of HEMEX sapphire wafers cut from different boules show different dislocation densities:

(a) $\simeq 10^3$ cm^{-2}, (b) much lower dislocation density.

Sample area illuminated by x-rays is 2.1 x 1.7 mm^2

Chen, McNally et al., *Phys. Stat. Solidi. (a)* **186 (2001) 365**

Sapphire X-ray Resonator Demonstrated Experimentally



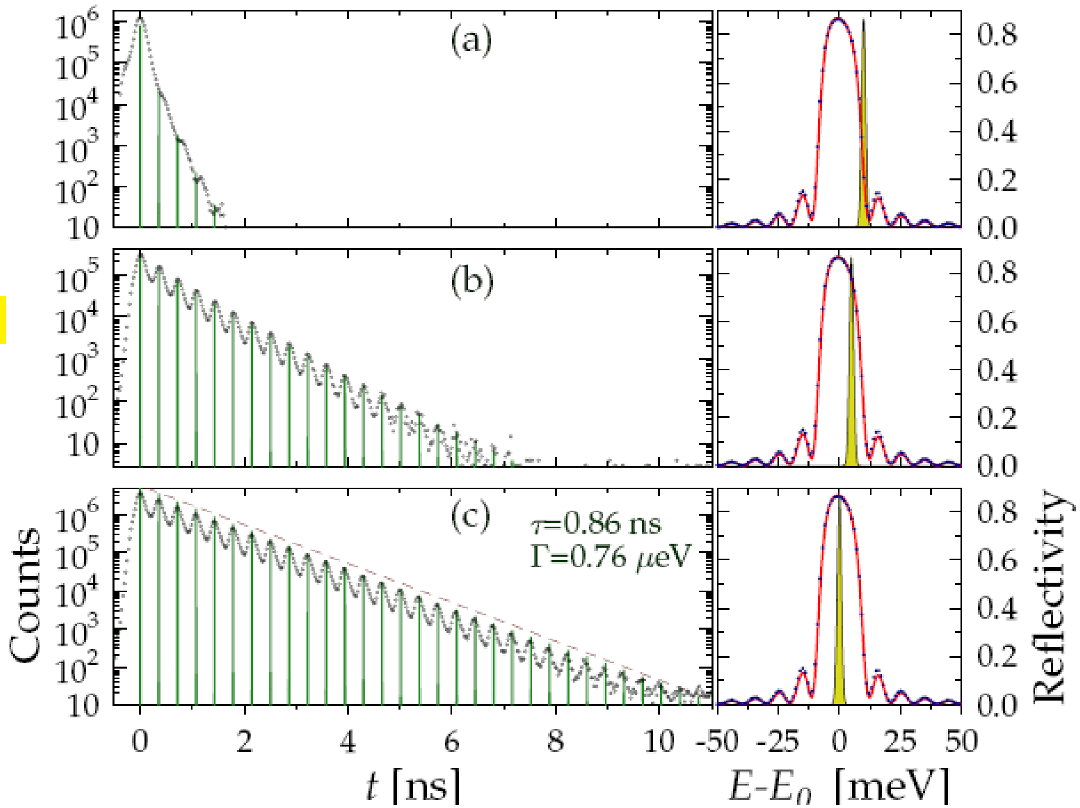
Shvyd'ko, Lerche, Wille et al, *PRL* 90 (2003) 013904

Experiment @ APS, Sector 3

Measured finesse = 15

Measured reflectivyty = 0.82

Expected reflectivyty = 0.86



Focusing Elements

- **Focusing is required to adjust the mode profile**
- **Bending the Bragg mirrors for a desired curvature (~50m)**
- **However, bending may destroy high-reflectivity**
  - P. Suortti et al, J. Appl. Cryst. 19 (1986) 336
- **Possible options:**
  - Grazing-incidence, curved-mirrors for non backscattering configuration
  - Compound refractive lenses of high transmissivity can be constructed (B.Lengeler, C. Schroer, et. Al., JSR 6 (1999) 1153)

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

$Al_2O_3 x Al_2O_3$ @14.3 keV

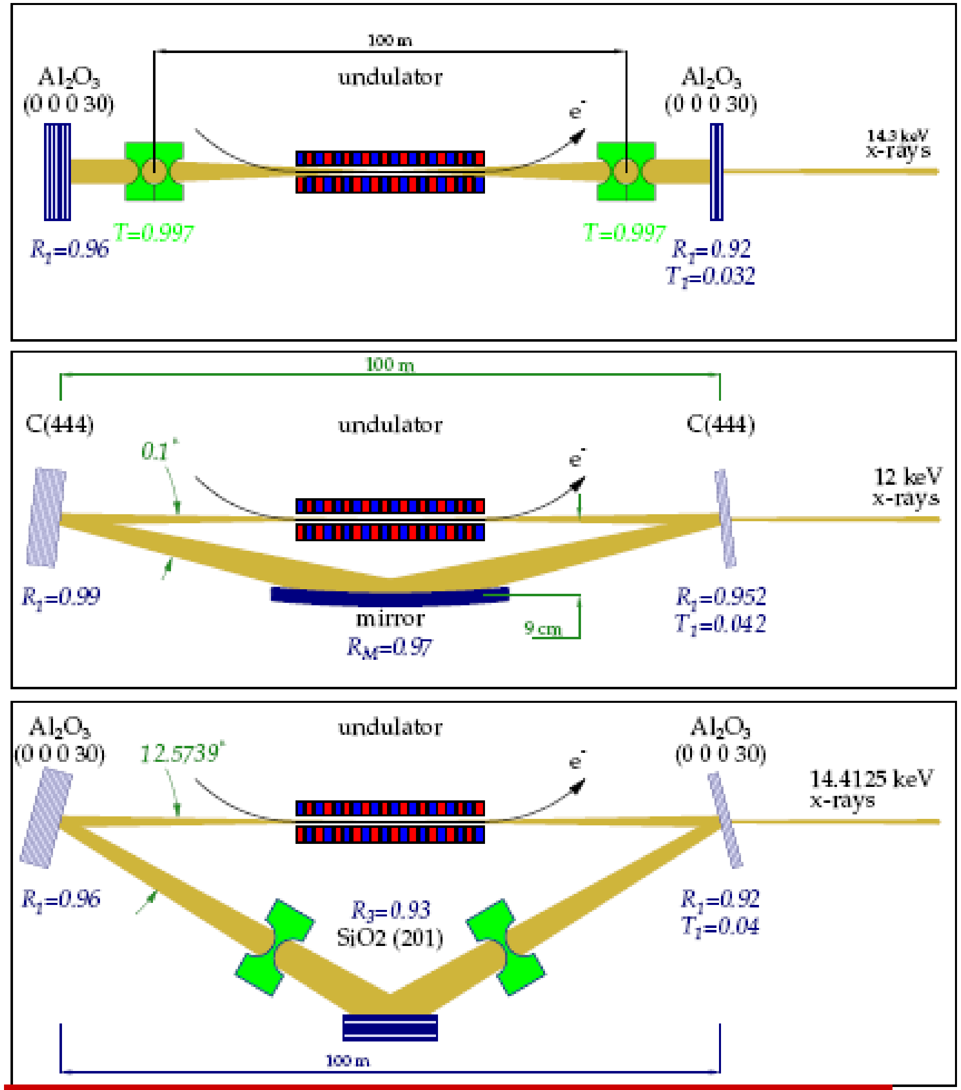
R_T=0.87, G_{sat}=15%, T=3%

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%



Crystal Damage/Heat Loading Issues

- Peak power absorbed P_{peak}< 1 MW

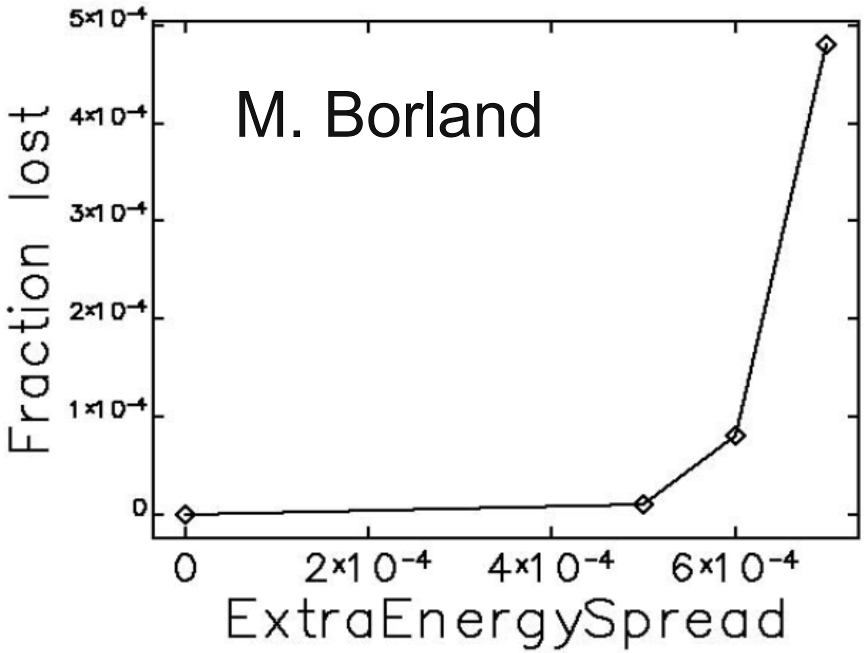
(Compare P_{peak}= 1 GW for X-ray Regen . Huang and Ruth find that this is 100 times smaller than the melting threshold)

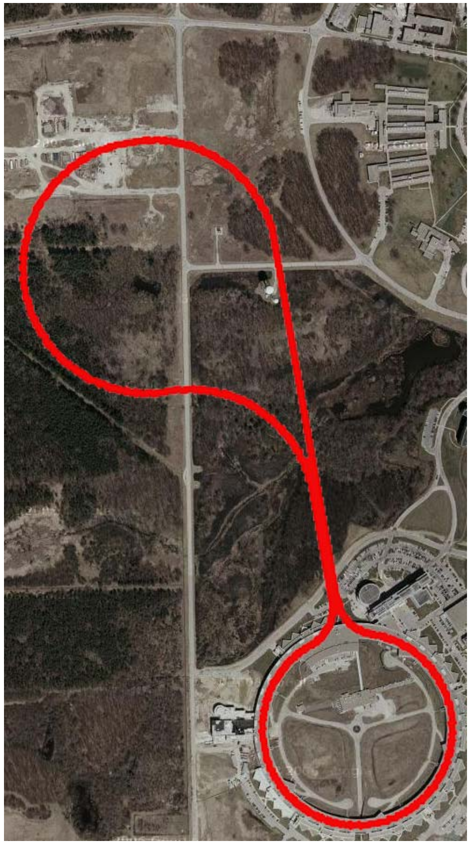
- Thermal loading: P_{av}< 10 W

→Temperature at the hot spot is estimated to be <35º compared to 25º at the side (A. Khounsary)

Energy Acceptance of the Recirculation-Pass for APS-ERL

- **GENESIS simulation shows that the rms energy spread 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 and temporal coherence in 1 ps duration**
  - **$\Delta\nu/\nu=0.3\ 10^{-6}$; $h\Delta\nu$=4 meV**
- **Not Tunable**
- **10^9 photons (~ 1 μJ) /pulse**
  - Peak spectral brightness~LCLS
- **Minimum rep rate is 1 MHz, the maximum could be 100 MHz limited by crystal heat load→ average spectral brightness 10^{27} (→10^{29}) ph/(mm-mr)^2(0.1%BW)**
- **The average brightness is higher by a factor of**
  - **10^5-10^7 than other future light sources considered so far, ERL-based or high-gain FEL-based**
  - **Current APS about 100-1000 less than ERL**

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

- A XFEL-O around 1-Å is feasible with beams expected from future ERLs
- It is a powerful addition to ERL capabilities
- Application areas: nuclear resonance scattering, coherent imaging, inelastic scattering,…
- This study is an initial exploration with much room for further optimization.

Comments by Fulvio Parmigiani during the Workshop

- **Rep rate >1 MHz important for statistics, avoiding Coulomb repulsion, etc**
- **Application to study Fermi surface of bulk materal**