An X-Ray FEL Oscillator: Promises and Challenges

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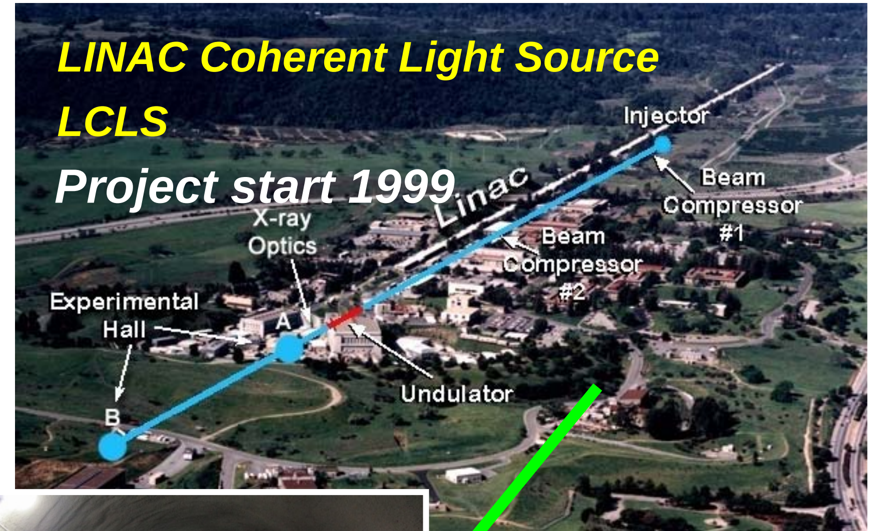
Argonne National Laboratory

December 21, 2009

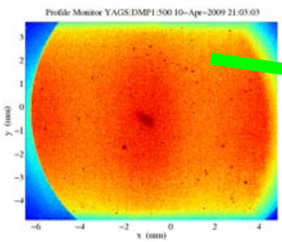
KEK

Tsukuba, Japan

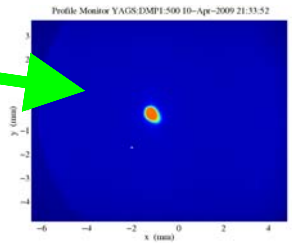
Era of Hard X-Ray (λ 1 Å) FEL has Arrived



I=500 A



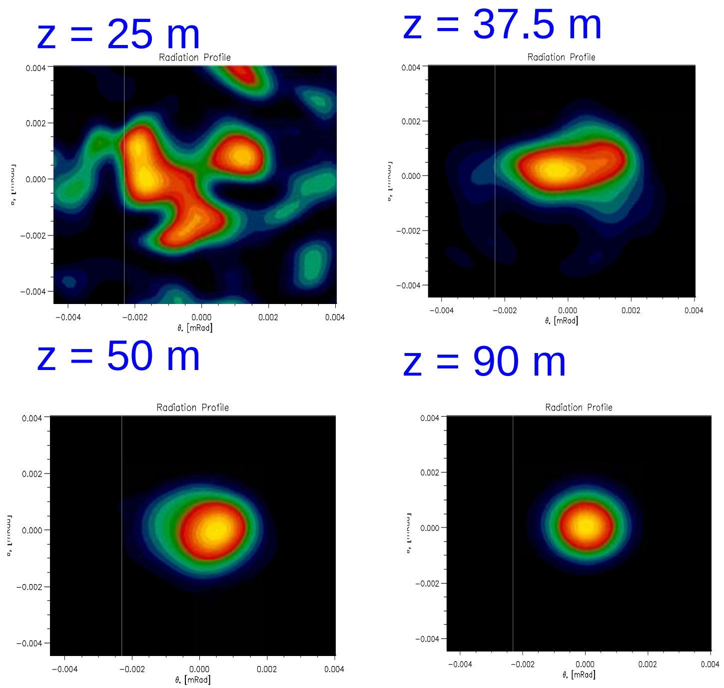
I=3000A

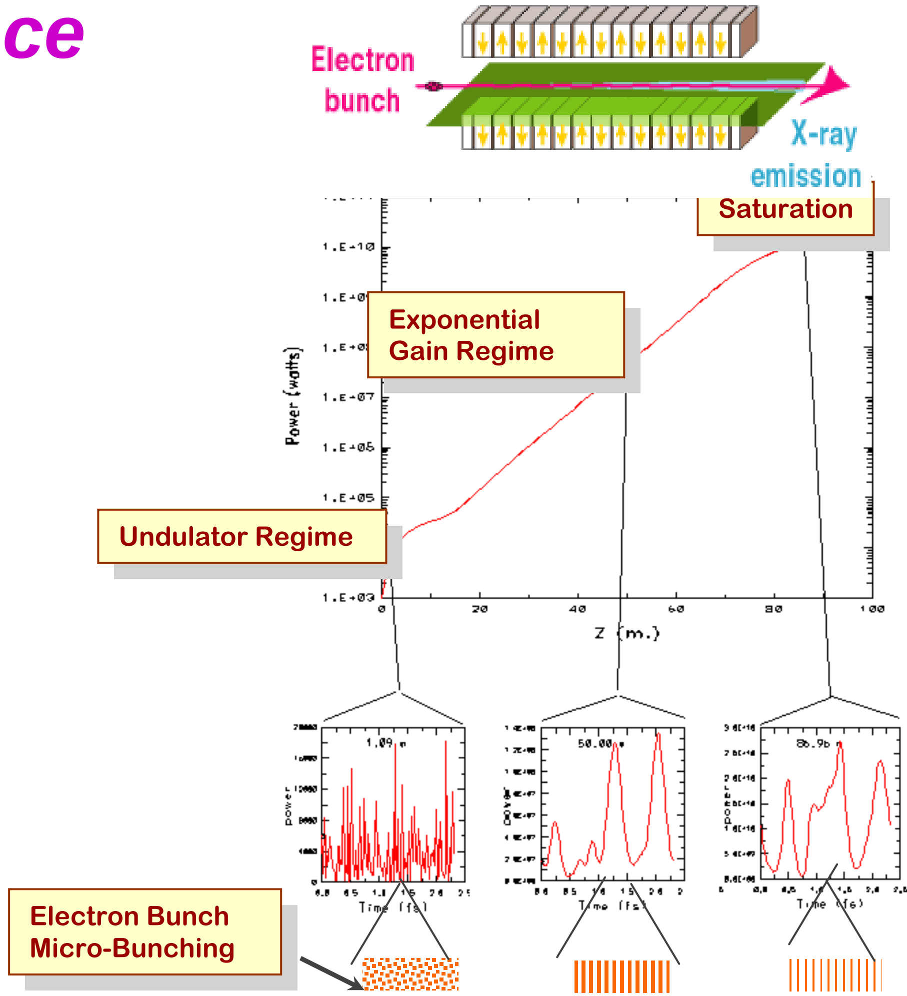


April 10, 2009
User experiment
September, 2009

LCLS: Single-pass, high-gain FEL amplifying initial noise → High transverse coherence but marginal temporal coherence

Transverse mode

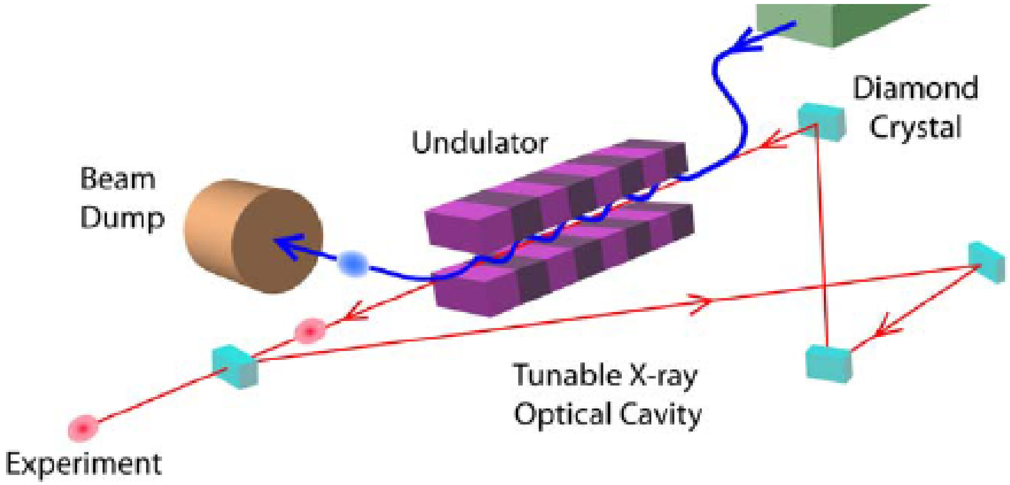




With the LCLS demonstration of e-beam modulation @ Å-scale, further FEL capabilities can be explored

- SASE
  - Ultrafast (down to atto-second ?) regime
- Seeded harmonic amplifier
  - High harmonics (e.g., via echo-assisted technique) for coherent soft x-rays
- Oscillator
  - Ultrahigh spectral purity and high average brightness for hard x-rays

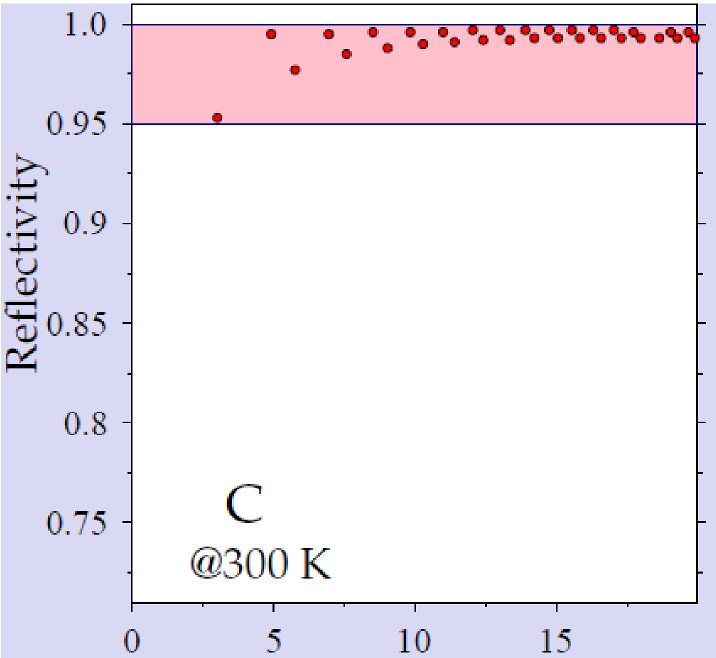
Hard X-Ray FEL Oscillator



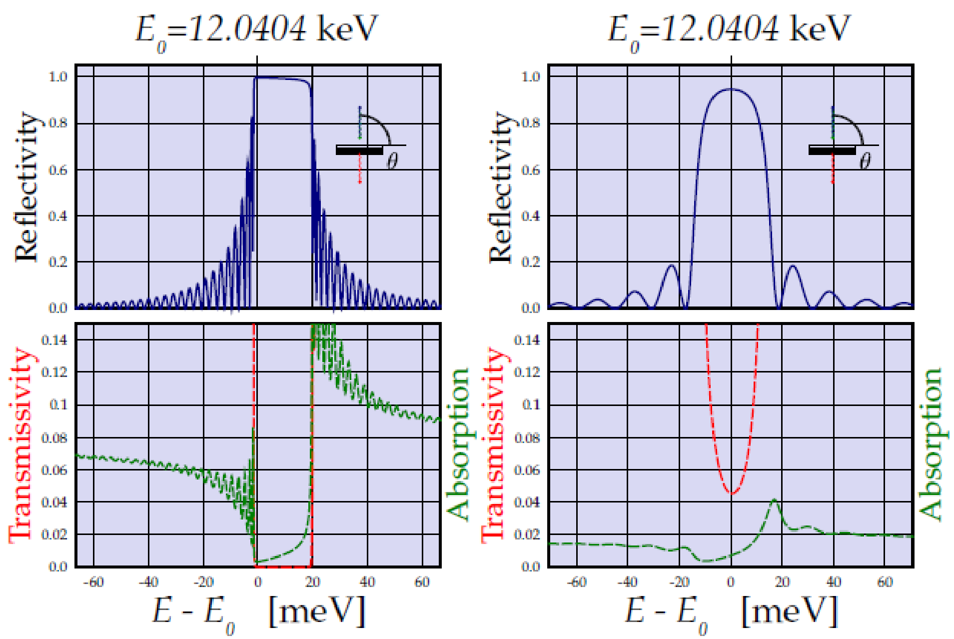
- **Store an X-ray pulse in a Bragg cavity→ multi-pass gain & spectral cleaning**
- **Provide meV bandwidth**
- **MeV pulse repetition rate→ high average brightness**
- **Zig-zag path cavity for wavelength tuning**

Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (KJK, S. Reiche, Y. Shvyd'ko, PRL 100, 244802 (2008)

Diamond backscattering : High reflectivity and narrow bandwidth



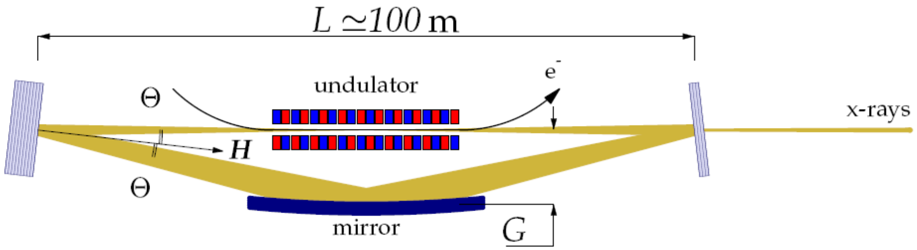
Photon energy (keV)

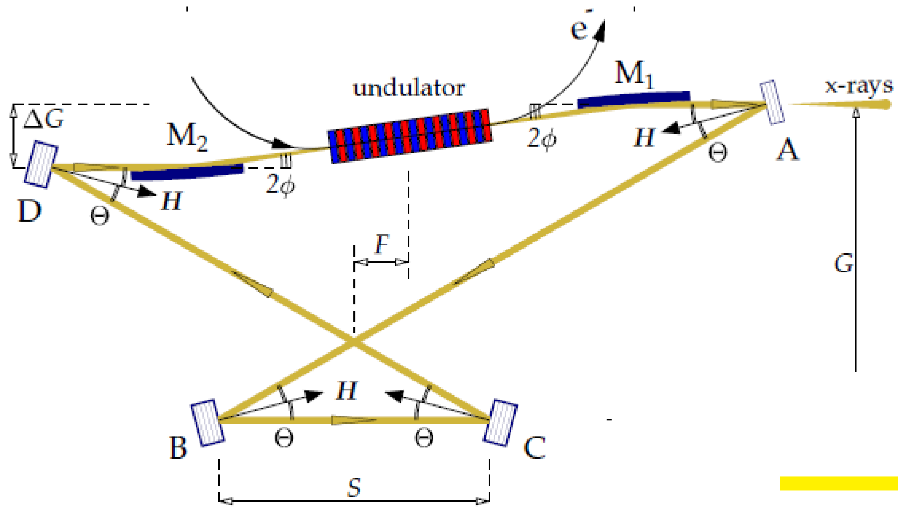


Courtesy of Yuri Shvyd'ko

Tunable X-ray Cavity

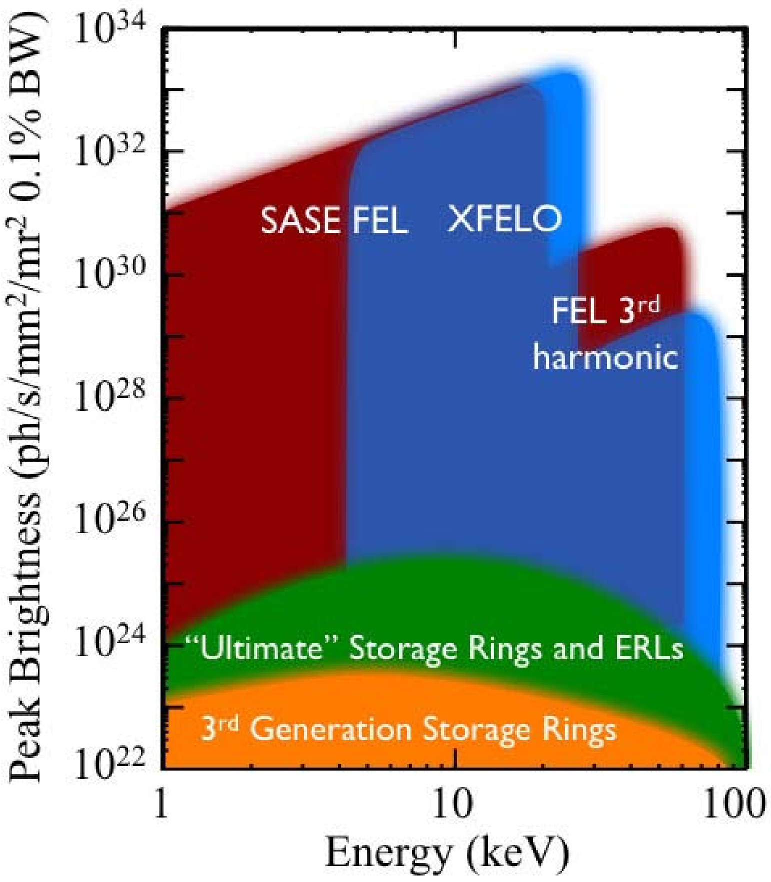
- **Two crystal scheme**
  - **a *very* limited tuning since θ must be kept small**
- **A tunable four crystal scheme**
  - **Any interesting spectral region can be covered by one chosen crystal material**
  - **Simplify the crystal choice →Diamond as highest reflectivity & best mechanical and thermal properties**

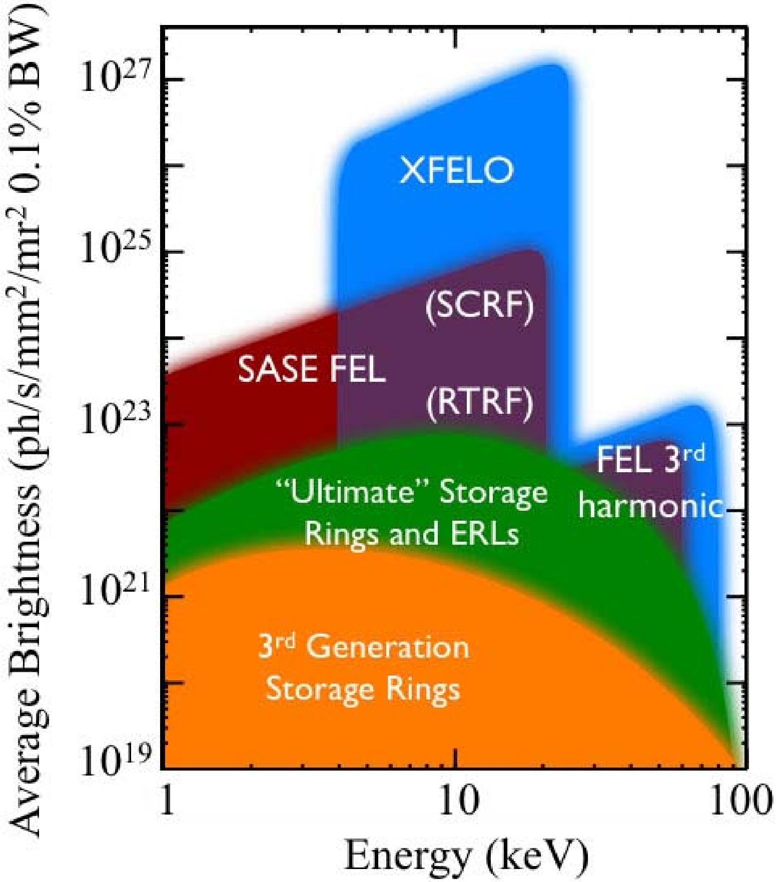




R. M.J.Cotterill, APL, 403,133 (1968)
KJK & Y. Shvyd'ko, PRSTAB (2009)

Brightness of Hard X-Ray Sources





XFELO Parameters

- **Electron beam:**
  - Energy 7 GeV
  - Bunch charge ~ 25-50 pC → *low intensity*
  - Bunch length (rms) 1 (0.1 ps) → Peak current 20 (100) A
  - Normalized rms emittance < 0.2 (0.3) mm-mr, energy spread (rms) ~ 2 10^{-4}
  - Constant bunch rep rate @ ~1 MHz
- **Undulator:**
  - L_u= 60 (20) m, λ_u ~2.0 cm, K=1.0 – 1.5
- **Optical cavity:**
  - 2- or 4- diamond crystals and focusing mirrors
  - Total round trip reflectivity > 85 (50) %
- **XFELO output:**
  - 5 keV ω 25 keV
  - Bandwidth: $\Delta\omega/\omega$ ~ 1 (5) 10^{-7} , pulse length (rms) = 500 (80) fs
  - # photons/pulse ~ 1 10^9

Blue color indicates short-pulse mode for relaxed tolerances

XFELO will revolutionize the hard x-ray techniques developed at storage-ring-based light sources and find new applications in areas complementary to SASE

- **Inelastic x-ray scattering**
- **Mössbauer spectroscopy**
  - **10^3/pulse, 10^9/sec Mössbauer photons (14.4 keV, 5 neV BW)**
- **Bulk-sensitive Fermi surface study with HAXPES**
- **Time-resolved methods (0.1 -1 ps)**
- **X-ray imaging with near atomic resolution (~1 nm)**
  - **Smaller focal spot with the absence of chromatic aberration**
- **X-ray photon correlation spectroscopy**
  - **10^{15} photons/sec is a game changer, better time structure than LCLS, t-coherence is a huge advantage (Alec Sandy)**

XFELO Modeling

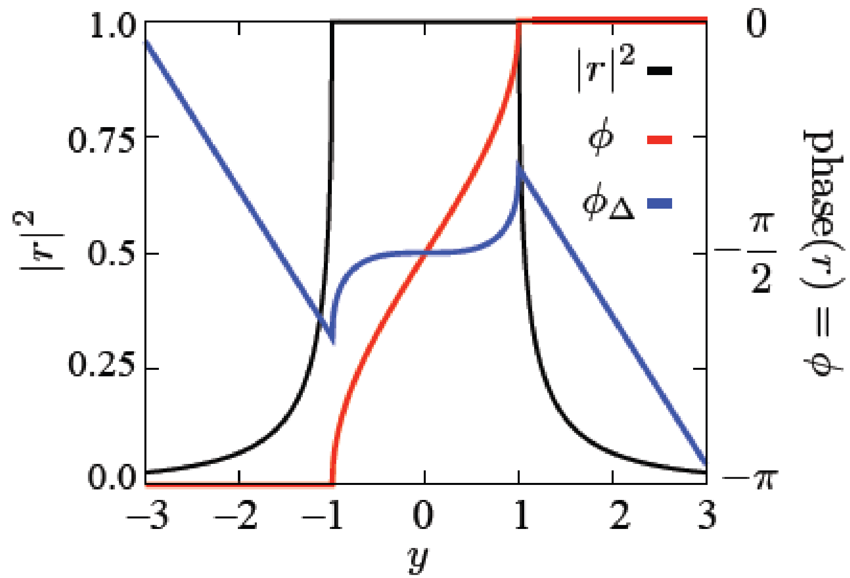
- Analytical (KJK, R. Lindberg)
  - Gain calculation, super-mode theory for evolution in optical cavity
- GENESIS (S. Reiche)
  - (x,y) asymmetric, single wavefront→slow:1 month computing from noise to saturation
- Reduced 1-D FEL code (R. Lindberg)
  - Transverse dependence integrated out assuming Gaussian mode
  - Fast and reasonable agreement with GINGER and GENSIS
- GINGER (W. Fawley, R. Lindberg,Y. Shvyd'ko,..)
  - (x,y) symmetric→much faster than GENESIS
  - Implemented a correct crystal response

Crystal Phase Shift and Cavity Length Detuning

- **Amplitude reflectivity for near normal incidence x-rays**

$$r(y) = y - i\sqrt{1-y^2} \approx -ie^{iy}$$

$$y = \frac{1}{|\chi_H|}\left[\frac{2(E-E_H)}{E_H} + \chi_0\right]$$

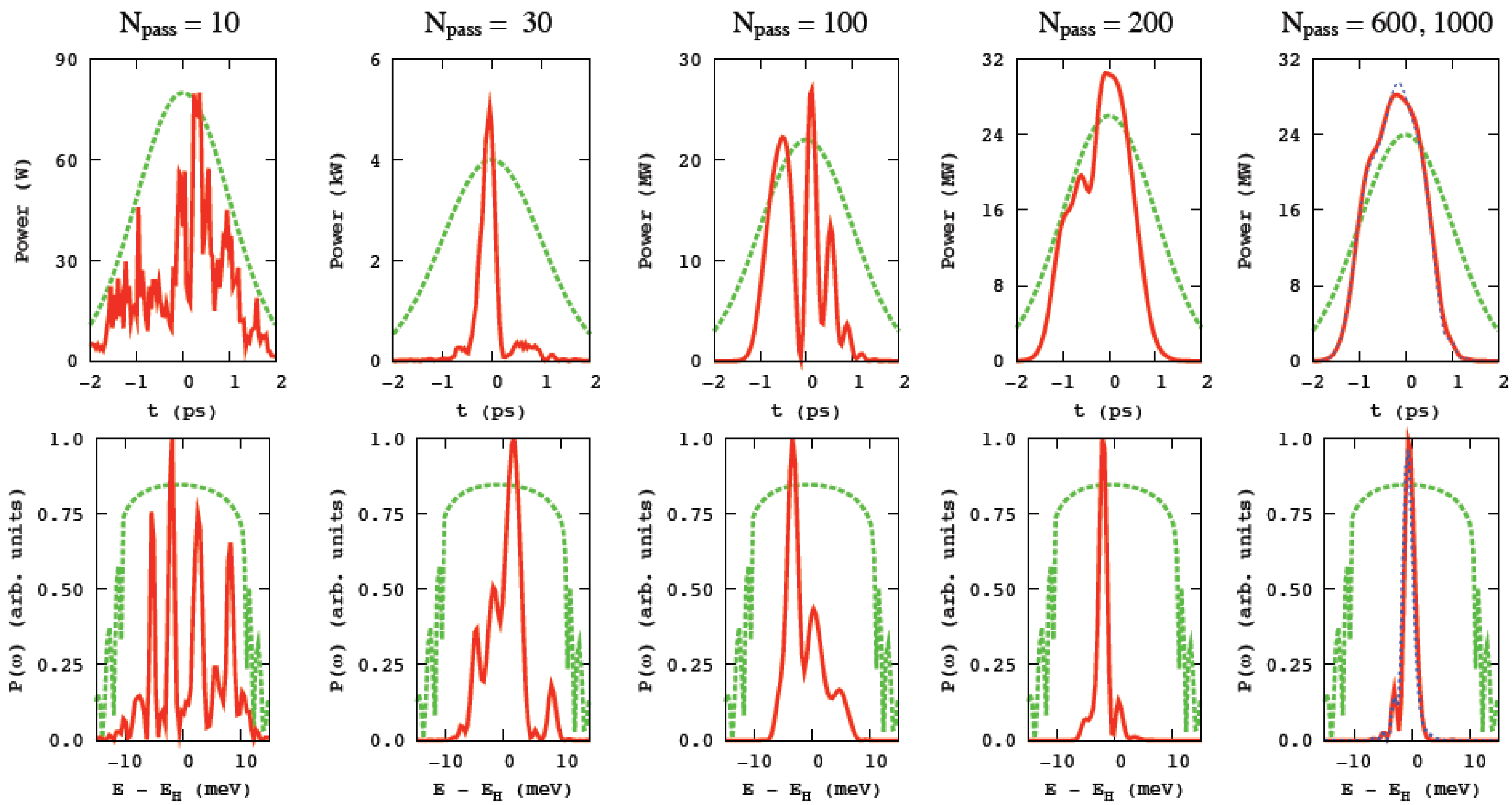


- **XFELO works near y~0. The angular spread effect is small**
- **ω-dependent phase shift**

$$exp(i\omega\tau) \qquad c\tau = \frac{\lambda_H}{2\pi|\chi_H|}$$

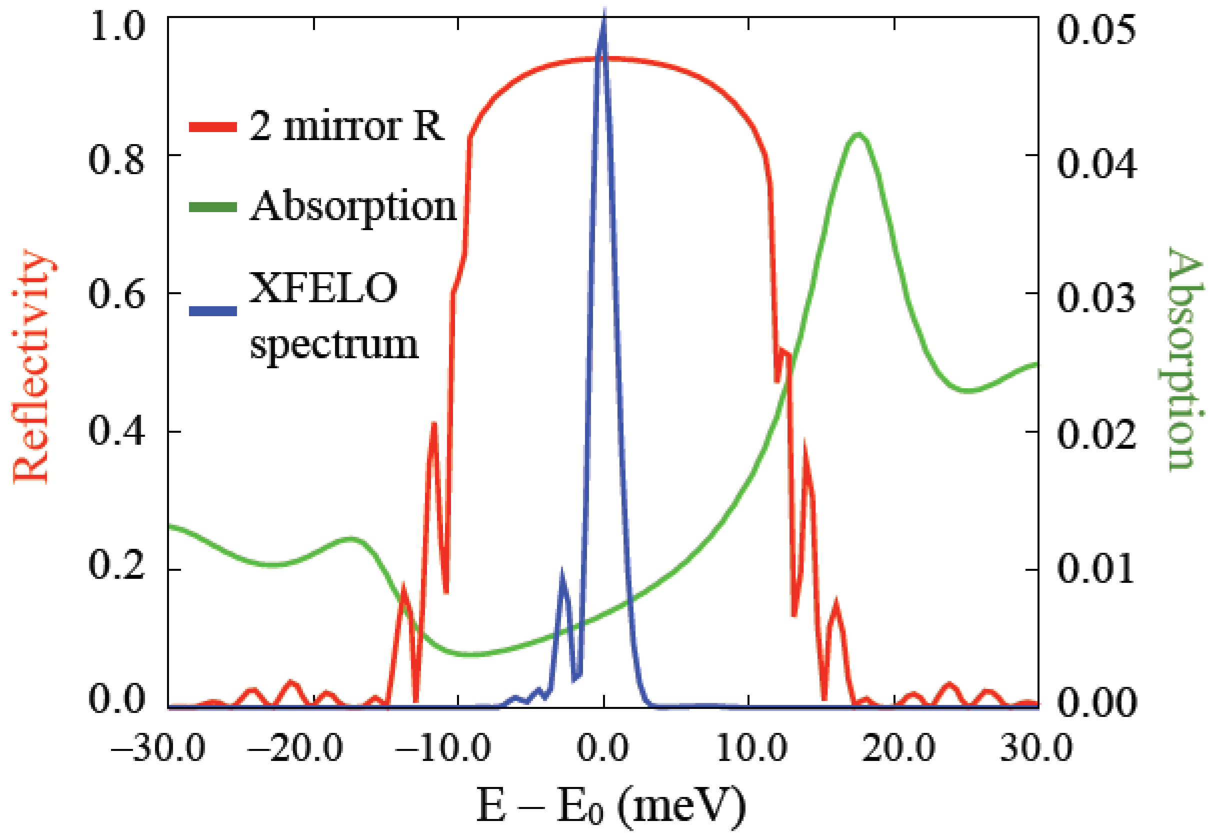
- **can be corrected by cavity length adjustment**

Approach to high spectral purity is expedited by spectral filtering at crystals



Ginger Simulation of XFELO Spectrum After 500 Passes

(*Two Diamond Crystal Cavity, 50 μm and 200μm, R. Lindberg*)



Electron Gun Technologies

- **The LCLS S-band NC RF PC demonstrated ultra-low ε_x**

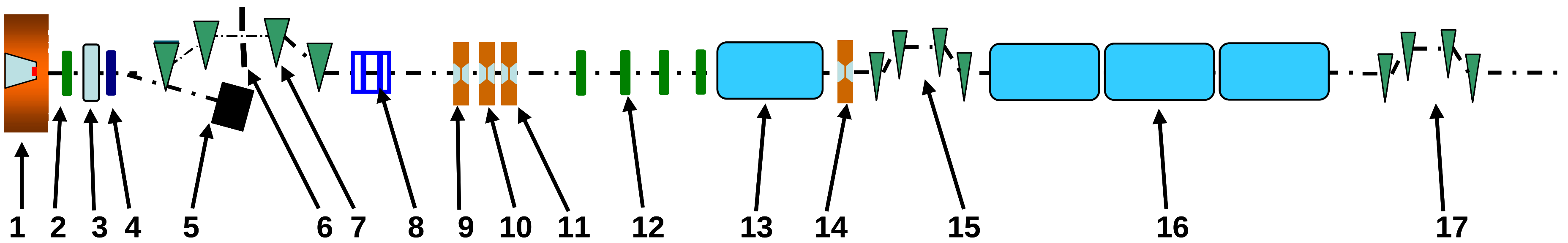
  ε_x=0.14 10^{-6} m, Q=20 pC, f_b=120 Hz
- **The PITZ L-band NC RF PC may be suitable a pulsed XFELO:**

  ε_x=0.3-0.4 10^{-6} m, Q=100 pC, f_b=1 MHz, t_{macro}=800 μs, f_{macro}=10 Hz
- **Cornell DC PC for ERL**

  ε_x=0.2 10^{-6} m, Q=20 pC, f_b=1.3 GHz, CW
  - **Requires 750 kV DC voltage?**
- **SCRF guns (FZD, HZB, Peking U, WIFEL)**
  - **CW but ε_x > 1 10^{-6} m**
- **LBNL 200 MHz, NC RF Gun (CW) (design)**
  - **Could be configured for XFELO requirements**
- **RIKEN/Spring-8 *thermionic*, pulsed DC**
  - **500 kV @ 60 Hz, ε_x=0.6 10^{-6} m with 3 mm diameter**

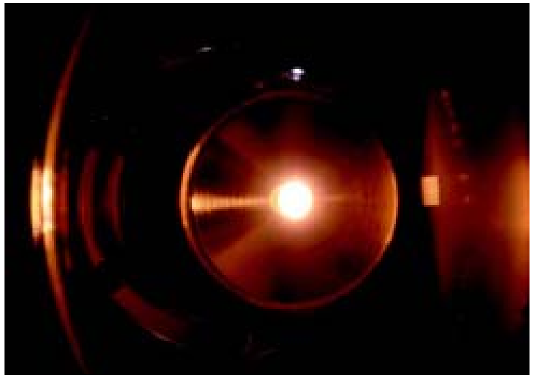
A Novel Injector Concept for XFELO

- **Current paradigm of injector design: *laser driven rf photo-cathode***
- **For low intensity & ultra-low emittance → *thermionic cathode***
- **Inspired by the SCSS/Spring-8 success of pulsed DC gun**
  - **T. Shintake and K. Togawa**
- **Low frequency RF gun-cavity for high, constant repetition rate**
- **Performance**
  - **Normalized rms emittance < 0.2 (0.3) mm-mr**
  - **Bunch length (rms) 1 (0.1 ps)**
  - **Peak current 20 (100) A**
  - **A constant bunch rep rate @ ~1 MHz**

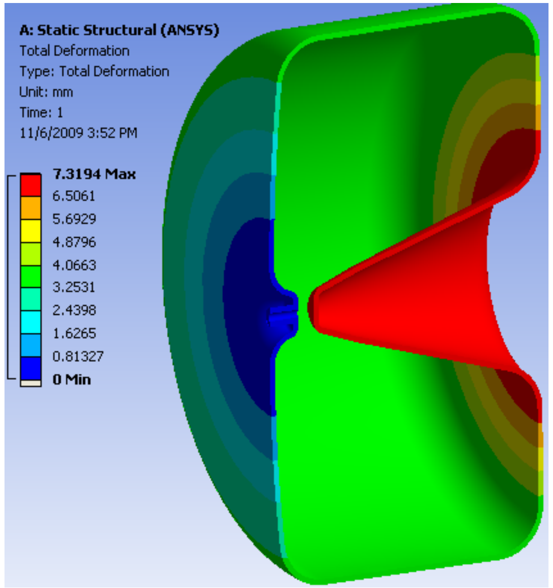


Critical R&D Items for an XFELO Injector

- Small diameter CeB6 thermionic cathode
  - 1 mm (3 mm for RIKEN/SPring-8)
- 100 MHz, 1 MV RF cavity
  - Peak accelerating field=20 MV/m below 1.8 Kilpatrick limit (1.76)
  - Similar to LBNL 187 MHz cavity but without vacuum holes
- Addressing back-bombardment issue
  - Off-centered cathode or a magnet to deflect returning electrons
  - Cathode heating by ns laser pulse with MHz rep rate



RIKEN/Spring-8 cathode

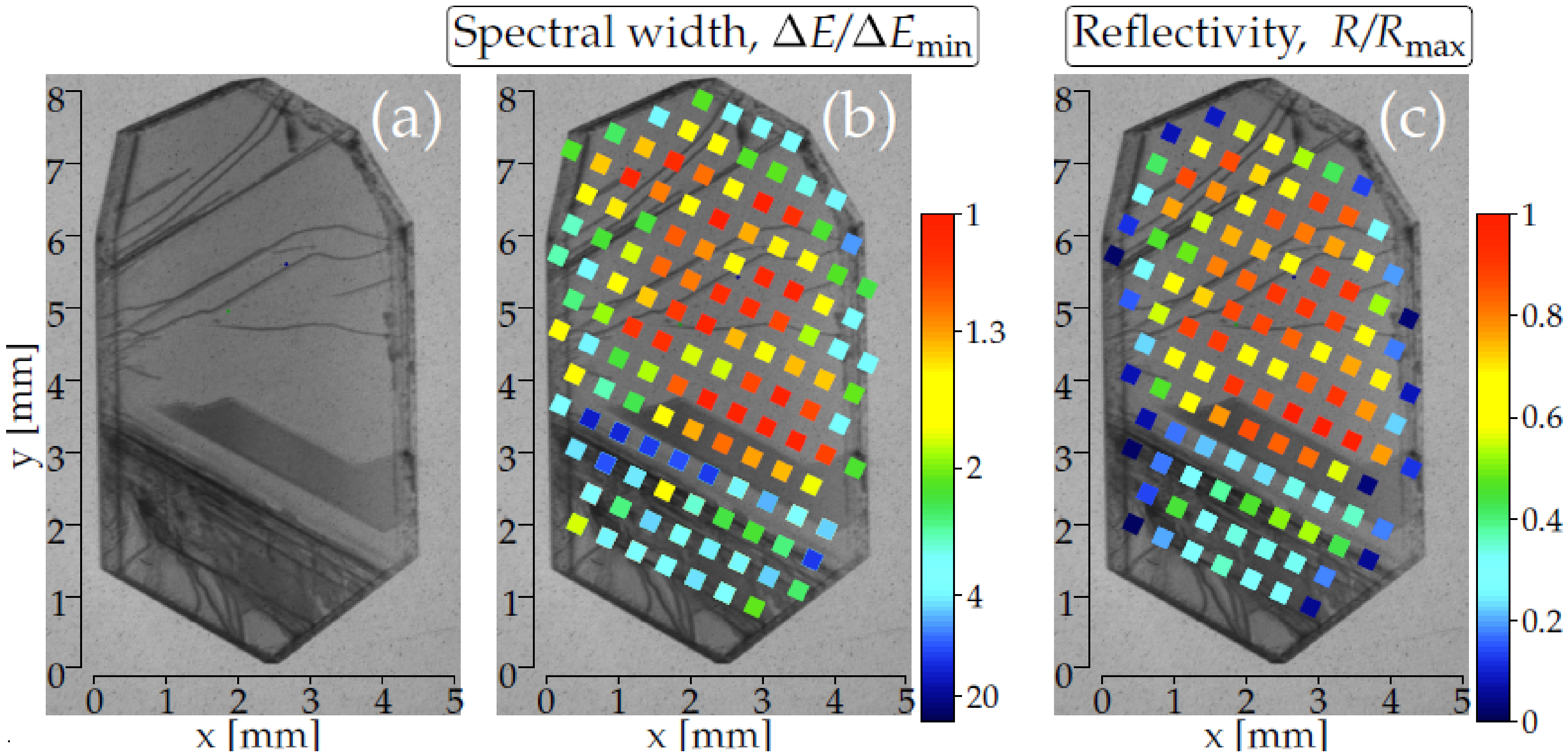


100 MHz cavity shape

Technology R&D for XFELO X-Ray Optics

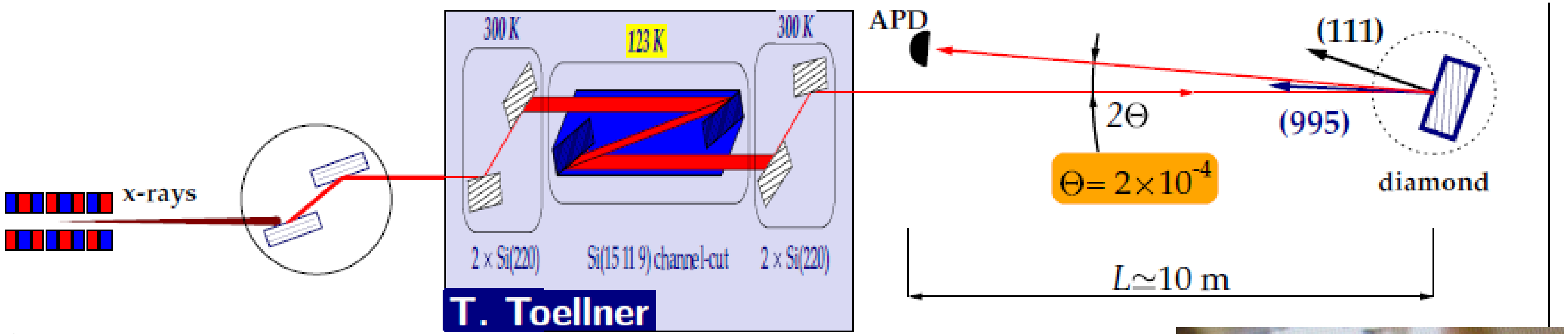
- **High quality diamond crystals**
- **Highly reflectivity and low phase distortion of grazing incidence focusing mirror**
- **Stability**
- ***Advances in these technologies are eagerly sought after by broader synchrotron radiation community***

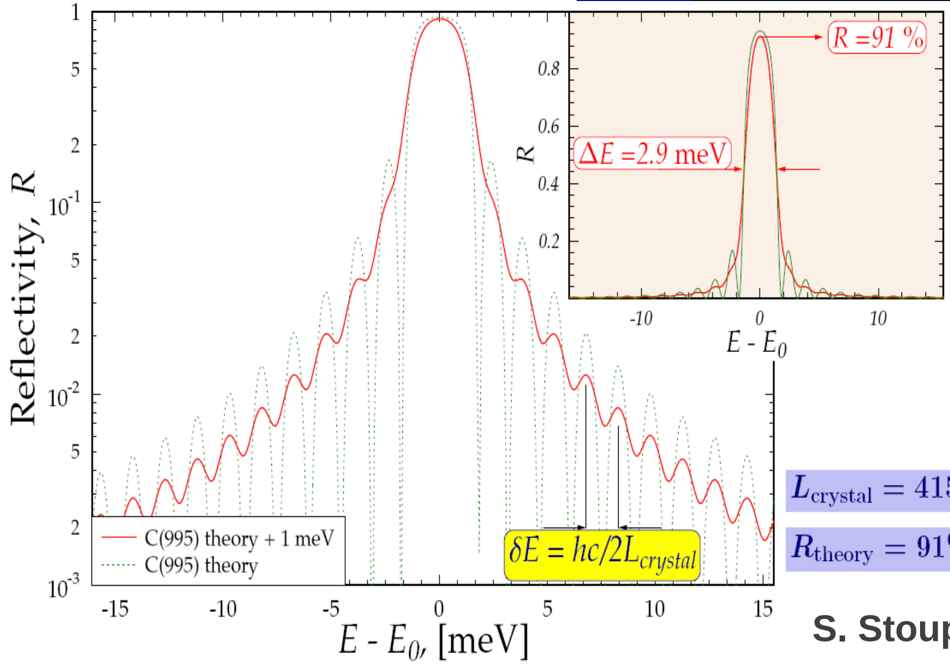
Optical properties of available diamond crystals



Topograpy, R and ΔE data (Sumitomo sample, S. Stoupin & Y. Shvyd'ko)

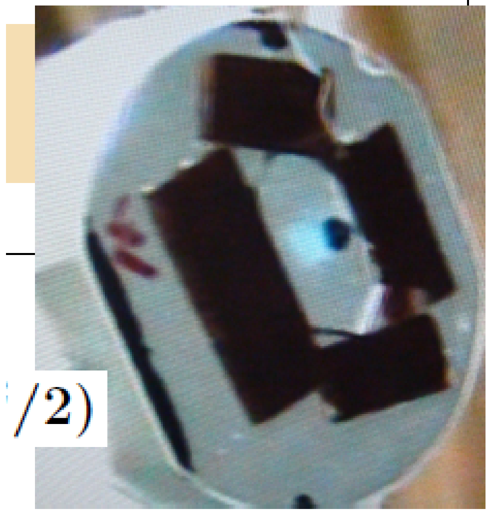
Reflectivity and spectral width measurement at APS sector-30 in good agreement with theory





C(995)

E_H=23.765 keV



$L_{\mathrm{crystal}} = 415\mu\mathrm{m}$

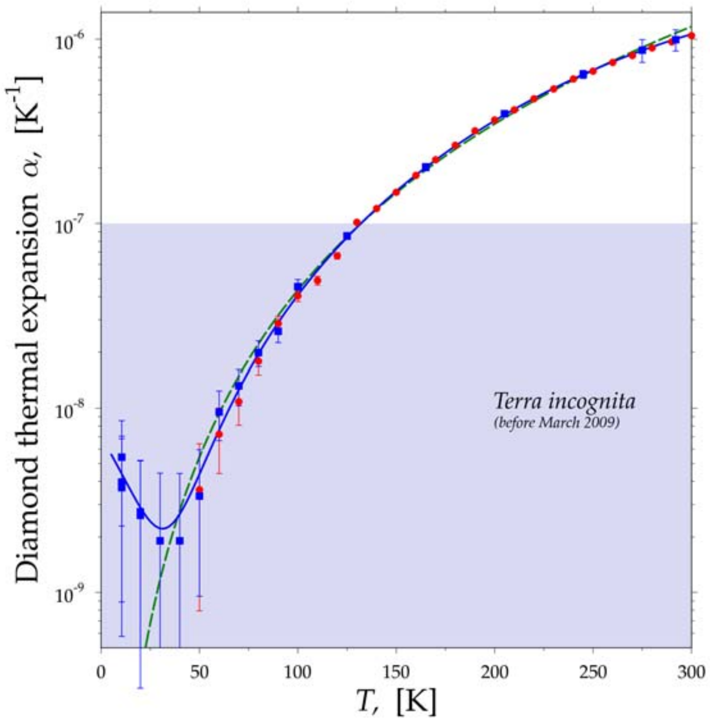
$R_{\mathrm{theory}} = 91\%$

S. Stoupin, Y. Shyv'dko, A. Cunsolo, A. Said, S. Huang

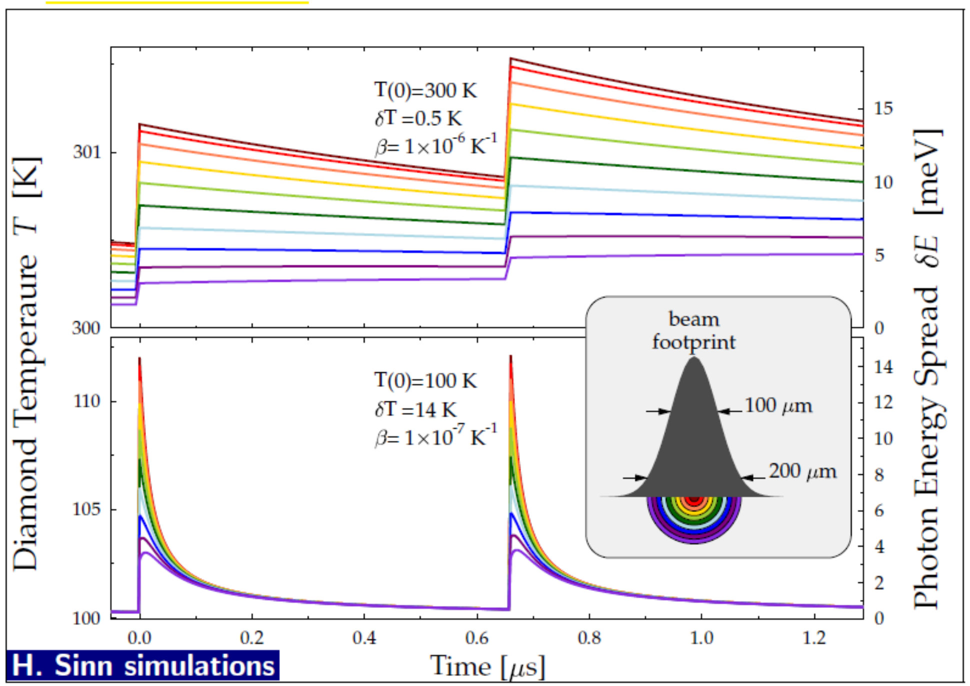
(Nature/Physics)

Heat Loading Issues

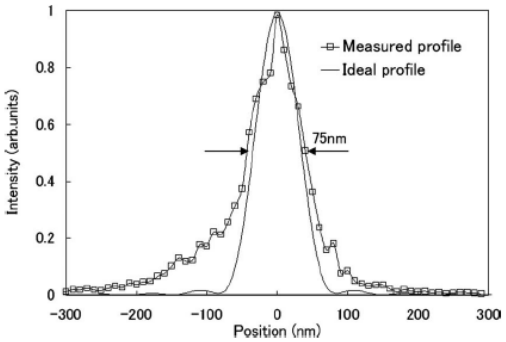
- **As an intracavity x-ray pulse hit crystals, r-dependent temperature rise δT → crystal expansion → $\delta E/E = \beta\, \delta T$ ($\delta L/L=\beta\, \delta T/T$). Is this <$10^{-7}$?**
- **Yes, T< 100K**
  - **Inter-pulse $\delta E/E$ <10^{-7} due to high thermal-diffusivity**
  - **Intra-pulse $\delta E/E$ <10^{-7} due to β <10^{-7} and if the expansion time < pulse duration (~ps)**

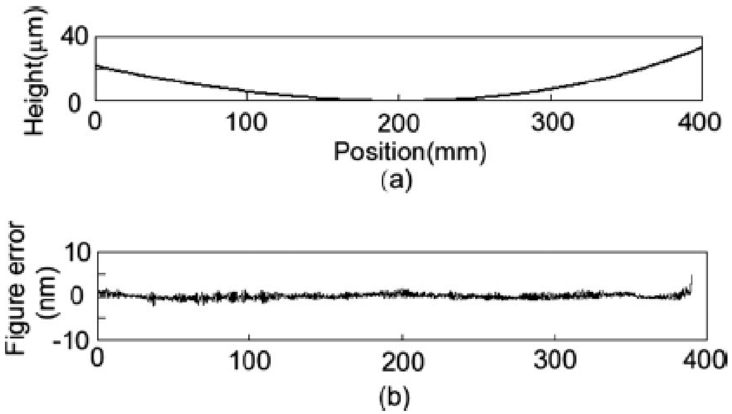


S. Stoupin and Y. Shvyd'ko, PRL



Grazing Incidence, Curved Mirror





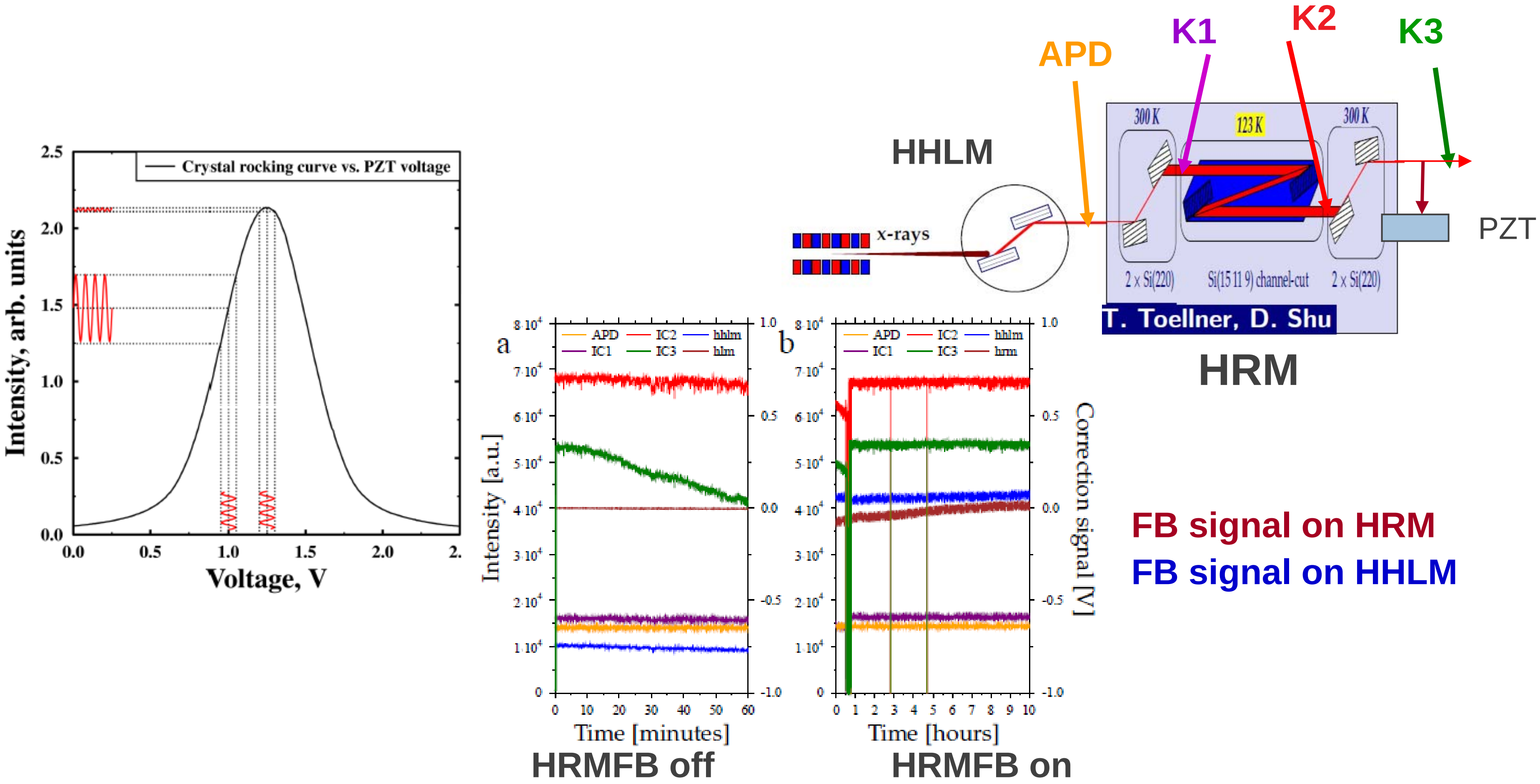
H. Mimura, et. al.

RSI 79, 083104, 2008

- **JTEC**
  - **Developing a technique combining elastic emission machining (EEM, slow) and electrolytic in-process dressing (ELID, fast) to fabricate an "arbitrary" surface, such as ellipsoidal, to <nm height error and 0.25 mrad figure error**
  - **Such mirrors are sought after by "every body" in SR business**
- **Other ways of focusing**
  - **Curved crystal surface, CRL,..**

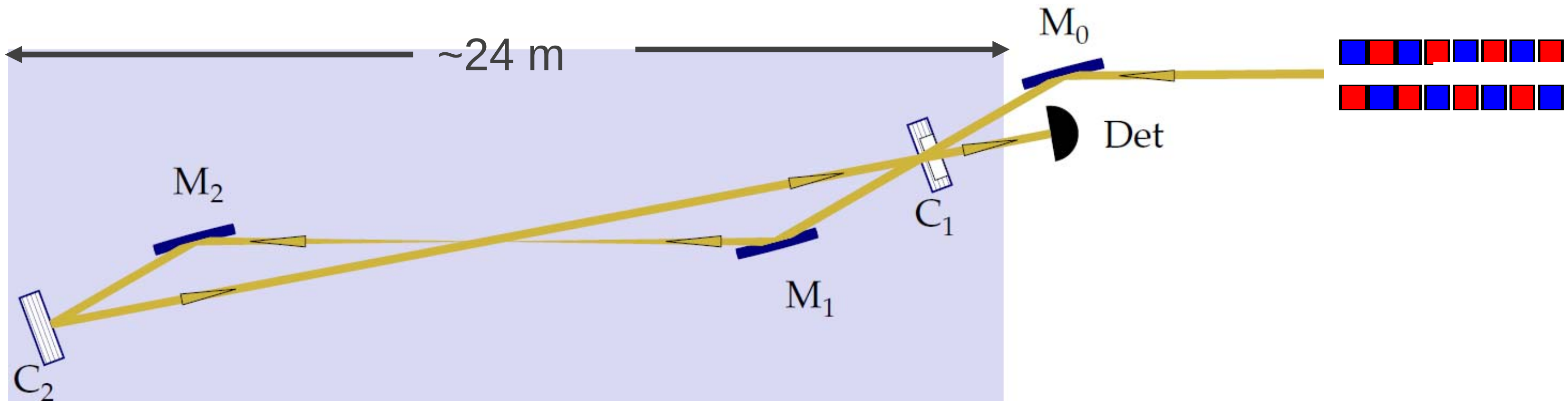
Null-detection FB stabilization at APS Sector 30

(S. Stoupin, F. Lenkszus, R. Laird, Y. Shvy'dko, S. Whitcomb,..)



- **The stability of K3 signal indicates the angular stabilization of the 3rd crystal pair within 13 nrad (rms) is achieved @ 1 Hz BW**

Prototype X-Ray Cavity at the APS

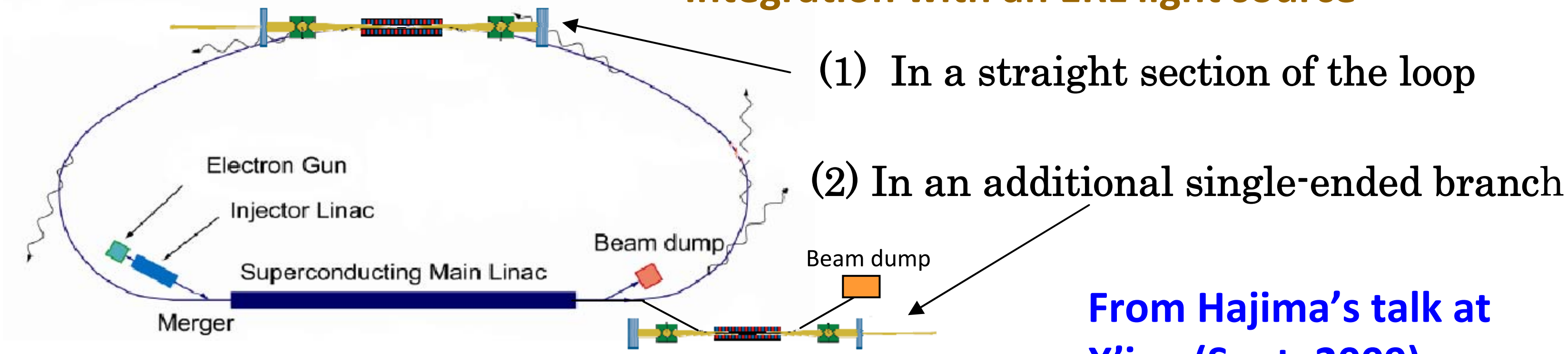


- **About 1/5 model of an XFELO cavity**
- **Adjust the distance M_1-M_2 to control the stability**
- **Adjust the round trip path length to match/mismatch the spacing (46m) between the APS x-ray pulses**
- **Test overall reflectivity, crystal and mirror stabilization, and transverse mode profile**

Accelerator Options

- **Straight SCRF linac is the most versatile but also the most expensive**
  - **Can also accommodate ultrafast SASE**
- **Recirculation will save the cost.**
  - **Energy recovery is not mandatory for a single XFELO due to low average power**
  - **The injector, accelerator, and recirculation passes should be optimized as a single system (See the following talk))**

Integration with an ERL light source



From Hajima's talk at X'ian (Sept. 2009)