An X-Ray FEL Oscillators
(for Record-High Spectral Purity & Brightness)

Kwang-Je Kim

APS Users Monthly Operations Meeting

October 28, 2009

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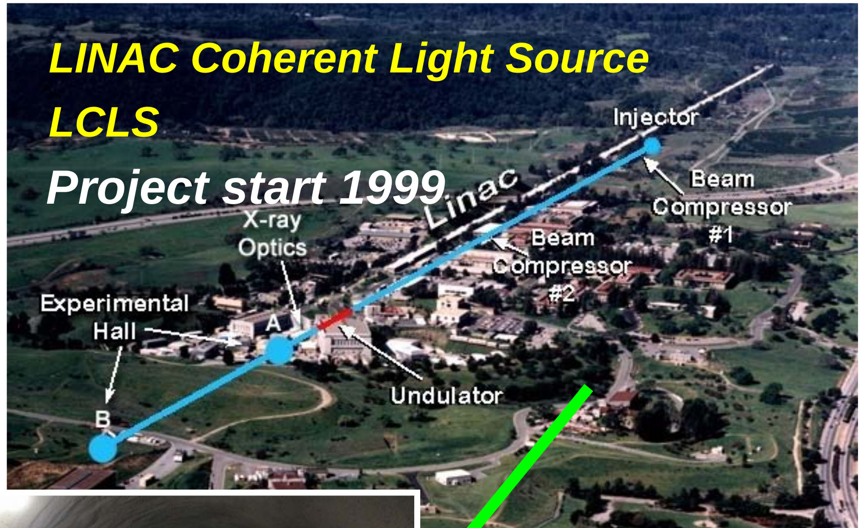
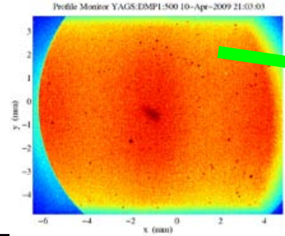
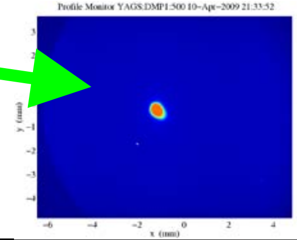
Era of Hard X-Ray ($\lambda \cong 1$ Å) FEL has Arrived



I=500 A



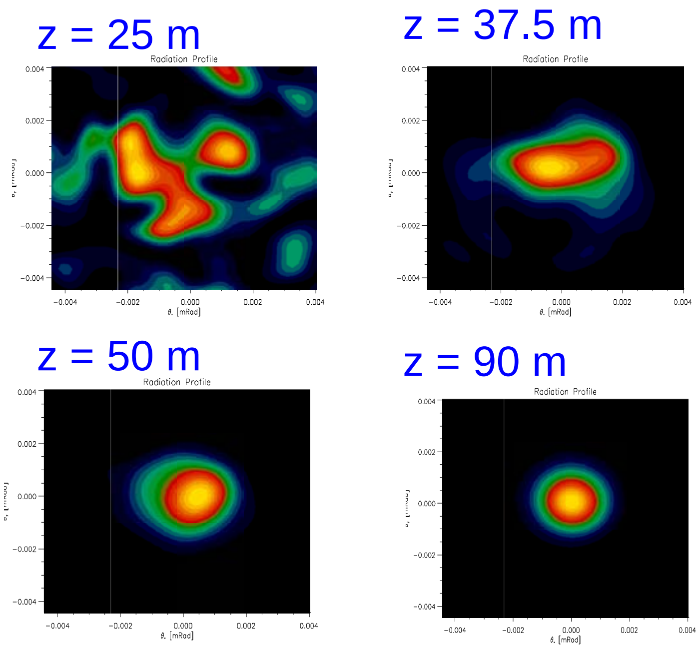
I=3000A

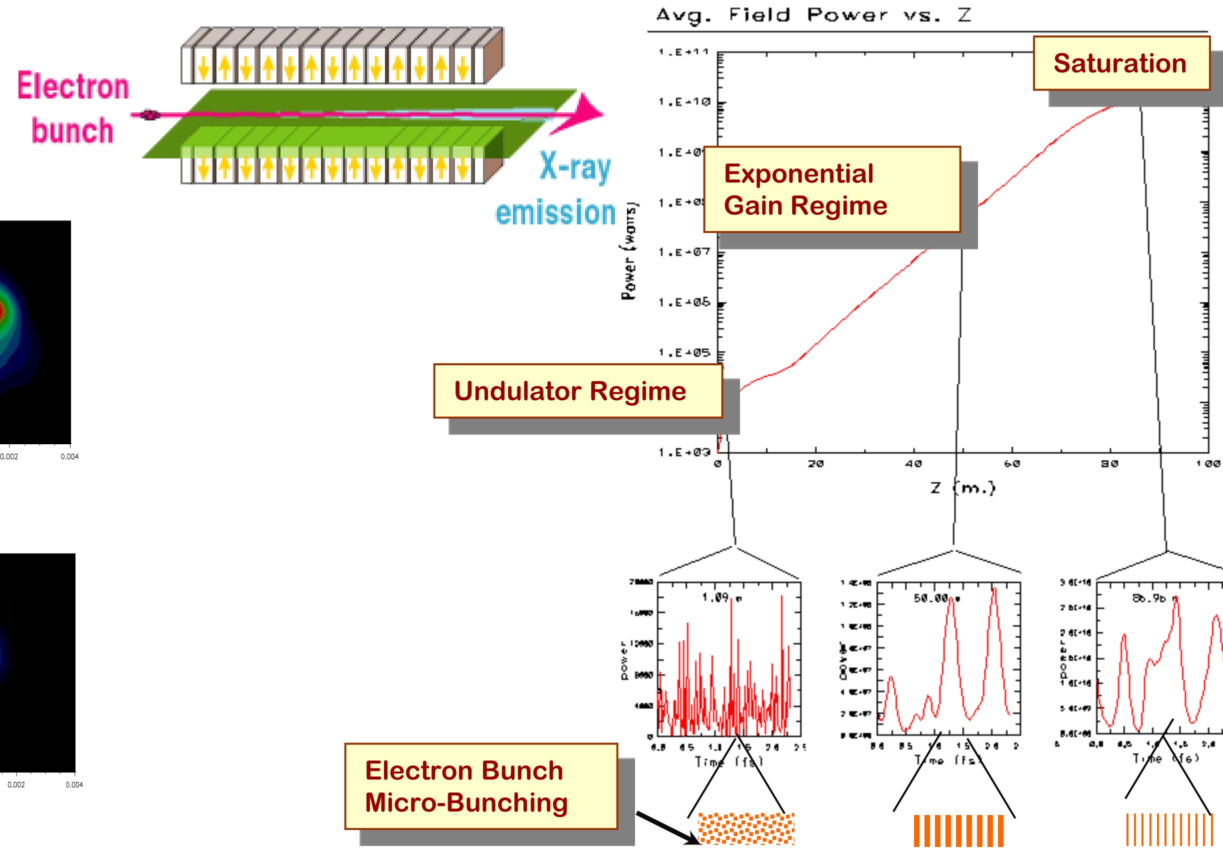


April 10, 2009
User experiment
September, 2009

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

Transverse mode

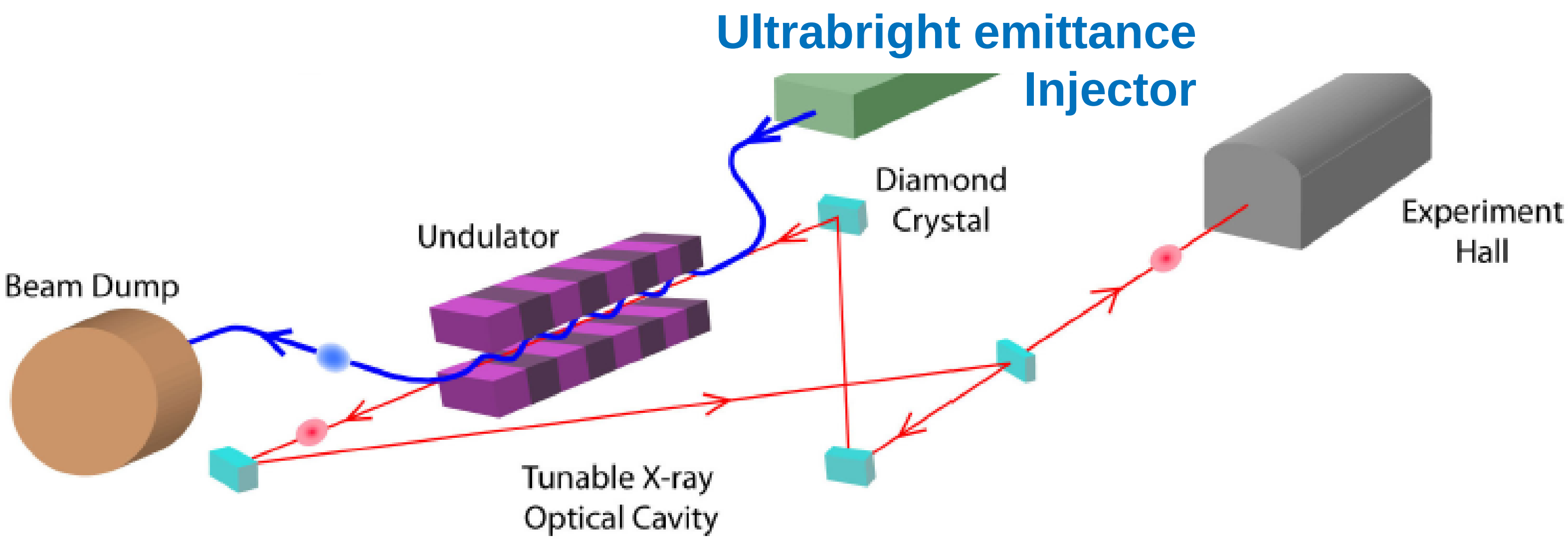




LCLS demonstrates FEL principles work @ Å-scale. It is now time to develop optimized FEL schemes for Future Light Sources

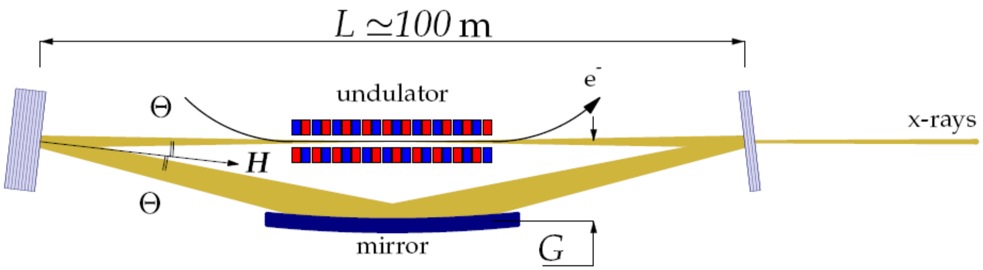
- **SASE**
- **Seeded harmoniuc amplifier**
  - **Soft X-rays**
- **Oscillator**

(Hard) X-Ray FEL Oscillator

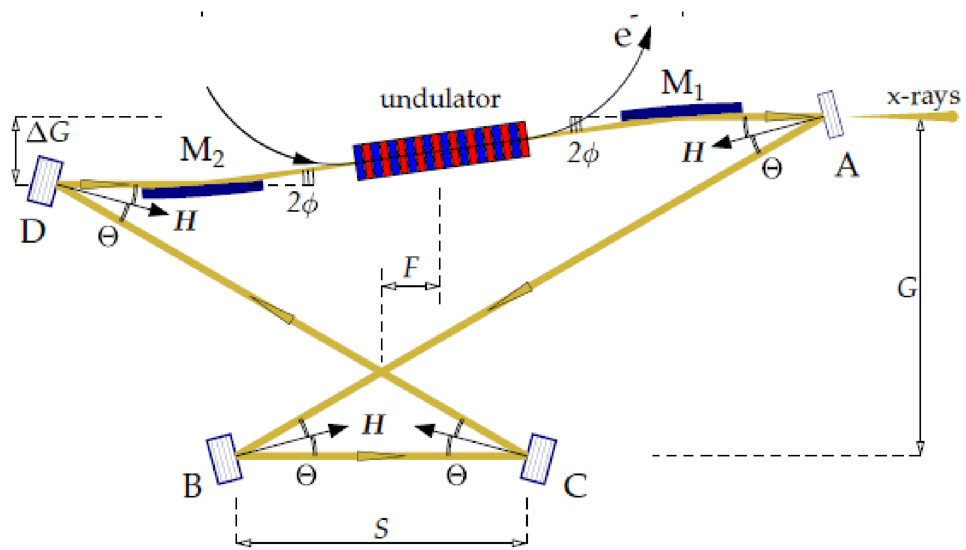


- **An X-ray pulse is stored in a diamond cavity→ multi-pass gain & spectral cleaning**
- **Provide transform limited BW→1×10^{-7} - 5×10^{-7} for σ_t=1-0.1ps @ λ ~1 Å**
- **Zig-zag path cavity allows wavelength tuning**
- **Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (K-J. Kim, S. Reiche, Y. Shvyd'ko, PRL 100, 244802 (2008)**

Tunable X-ray Cavity

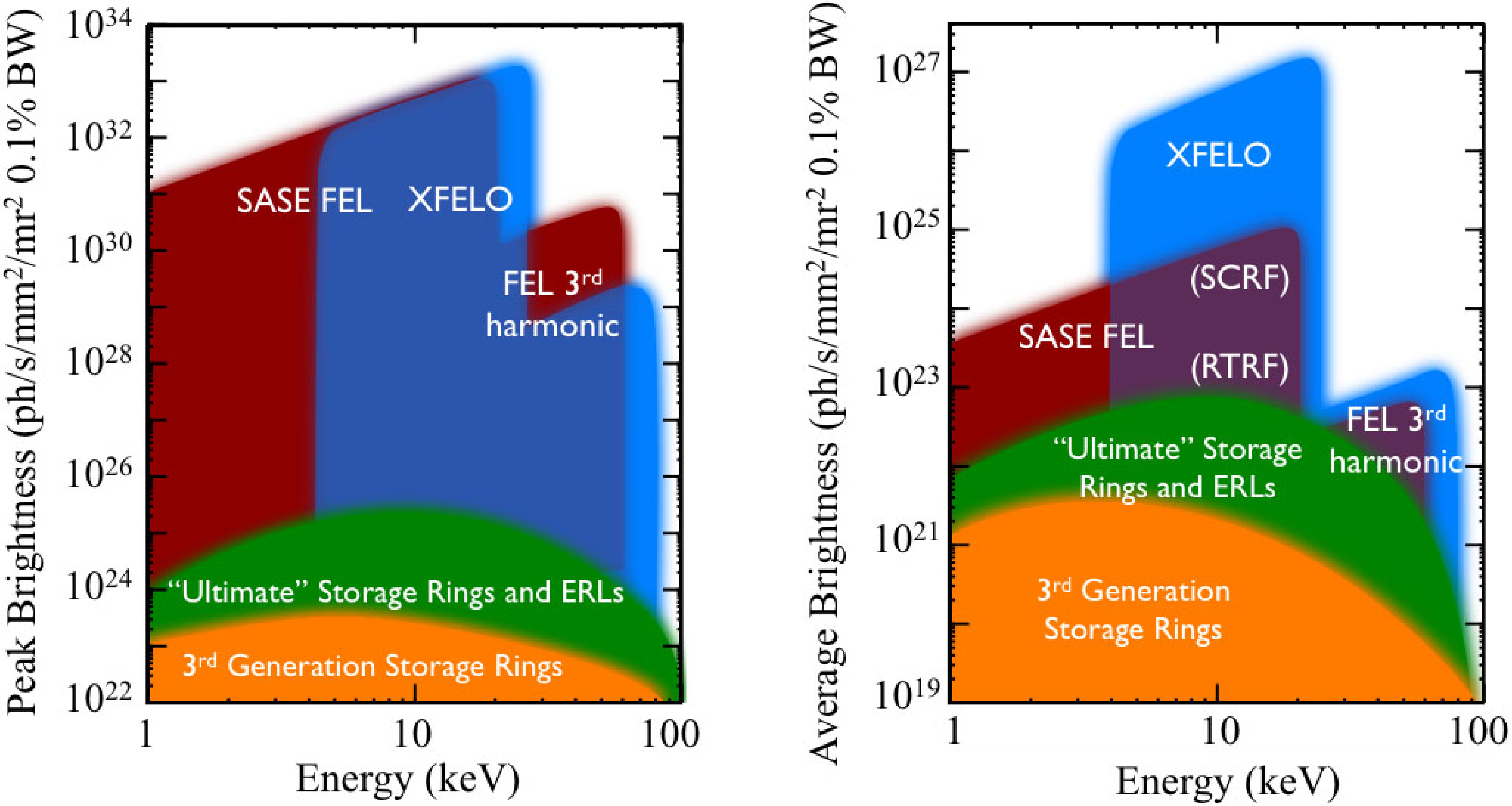


- **Two crystal scheme has a *very* limited tuning since θ must be kept small**
- **A four crystal scheme is tunable**
- **Any interesting spectral region can be covered by one chosen crystal material**
- **Simplify the crystal choice →Diamond as highest reflectivity & best mechanical and thermal properties**



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

Brightness of Hard X-Ray Sources



Major Parameters

- **Electron beam:**
  - Energy ♦ 7 GeV
  - Normalized rms emittance < 0.2 (0.3) mm-mr, energy spread (rms) < 2⑨$10^{-4}$
  - Bunch charge ~ 25-50 pC → *low intensity*
  - Bunch length (rms) ♎ 1 (0.1 ps) → Peak current 20 (100) A
  - A constant bunch rep rate @ ~1 MHz
- **Undulator:**
  - Lu= 60 (30) m, λ_u ~2.0 cm, K=1.0 – 1.5
- **Optical cavity:**
  - 2- or 4- diamond crystals and focusing mirrors
  - Round trip reflectivity should be > 85 (50) %
- **XFELO output:**
  - 5 keV ♎ ⅋ω ♎ 25 keV
  - Bandwidth: Δω/ω ~ 1 (5) ⯑ 10^{-7} , pulse length (rms) = 500 (80) fs
  - # photons/pulse ~ 1⯑10^{9}

Blue color in the above indicates short-pulse mode for relaxed tolerances

XFELO Will Revolutionize the Techniques Developed at 3rd Gen Light Sources and Find New Applications in Areas Complementary to SASE

- **High resolution spectroscopy**
  - **Inelastic x-ray scattering**
- **Moessbauer spectroscopy**
  - **10^3/pulse, 10^9/sec Moessbauer γs (14.4 keV, 5 neV BW)**
- **X-ray photoemission spectroscopy**
  - **Bulk-sensitive Fermi surface study with HX-TR-AR PES**
- **X-ray imaging with near atomic resolution (~1 nm)**
  - **Smaller focal spot with the absence of chromatic aberration**

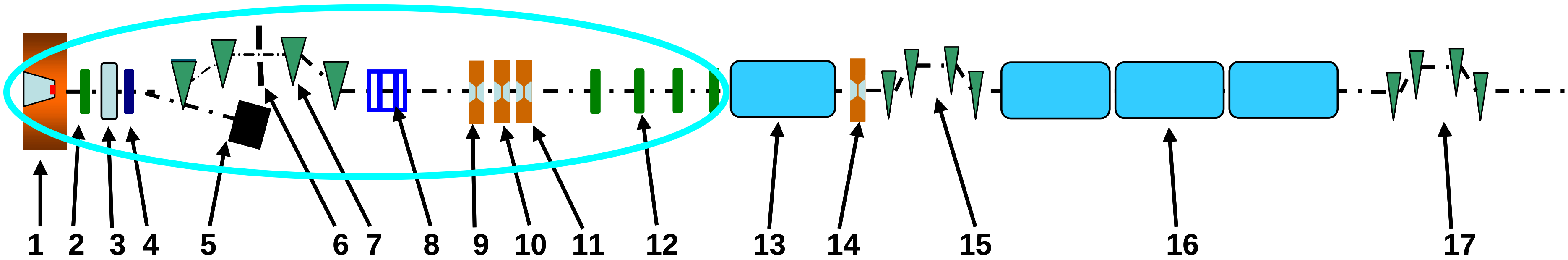
Technology R&D for XFELO

- **Injector**
  - Low-intensity, ultralow emittance, CW Injector

- **X-ray optics**
  - High quality diamond crystals in a small volume (1-2) mm^2 (40-100) μm
  - Highly reflectivity and low phase distortion of grazing incidence focusing mirror
  - Stability
- ***Advances in these R&Ds will benefit general accelerator and synchrotron radiation comunity***

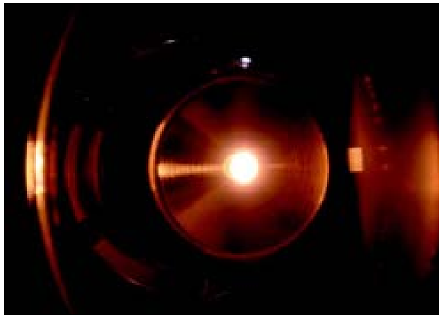
Injector for XFELO: A Novel Approach

- Current paradigm of injector design: laser driven rf photocathode
- For low intensity & ultra-low emittance → thermionic cathode inside VHF band cavity (~ 100 MHz)
- Inspired by the SCSS/Spring-8 success of pulsed DC gun (T. Shintake, K. Togawa,..)

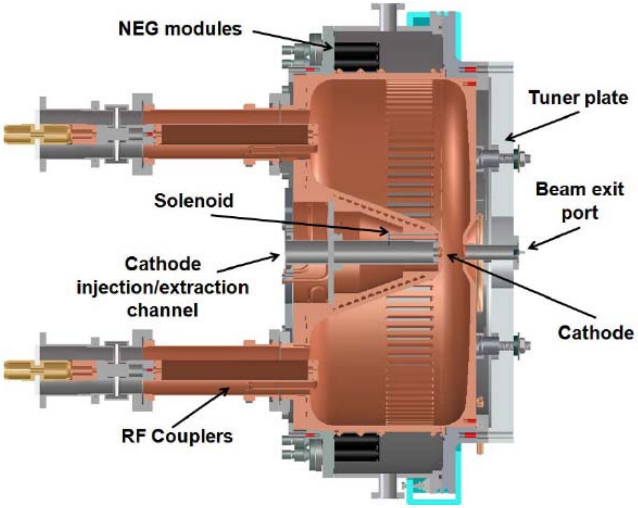


Injector R&D

- **Small diameter CeB6 thermionic cathode**
  - 0.5 mm (3 mm for RIKEN/SPring-8)
- **100 MHz, 1 MV RF cavity**
  - Peak accelerating field=20 MV/m is slightly below 1.8⑨Kilpatrick limit (1.76)
  - Similar to LBNL 187 MHz cavity but with thermionic cathode and without vacuum holes
- **Laser-induced cathode-heating may obviate the deflecting cavity/slits and back bombardment problem**



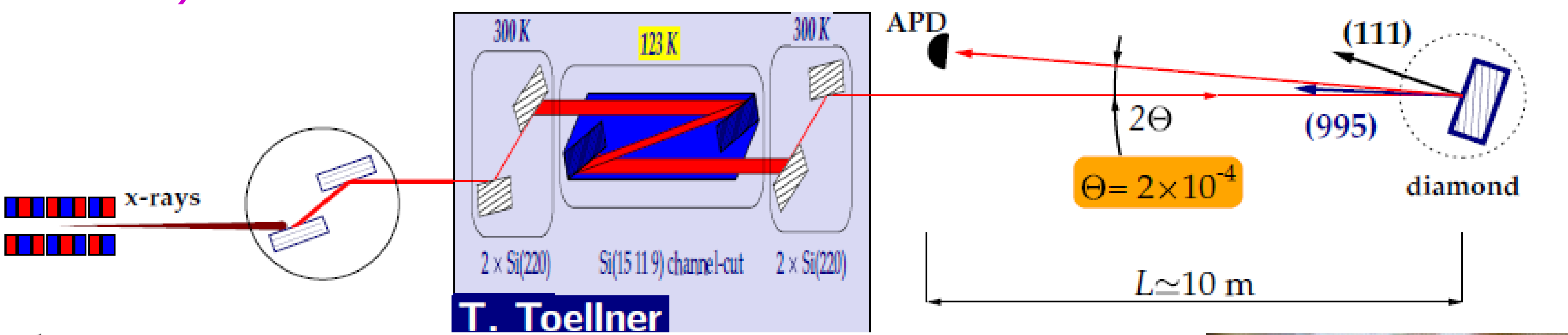
RIKEN/Spring-8 cathode

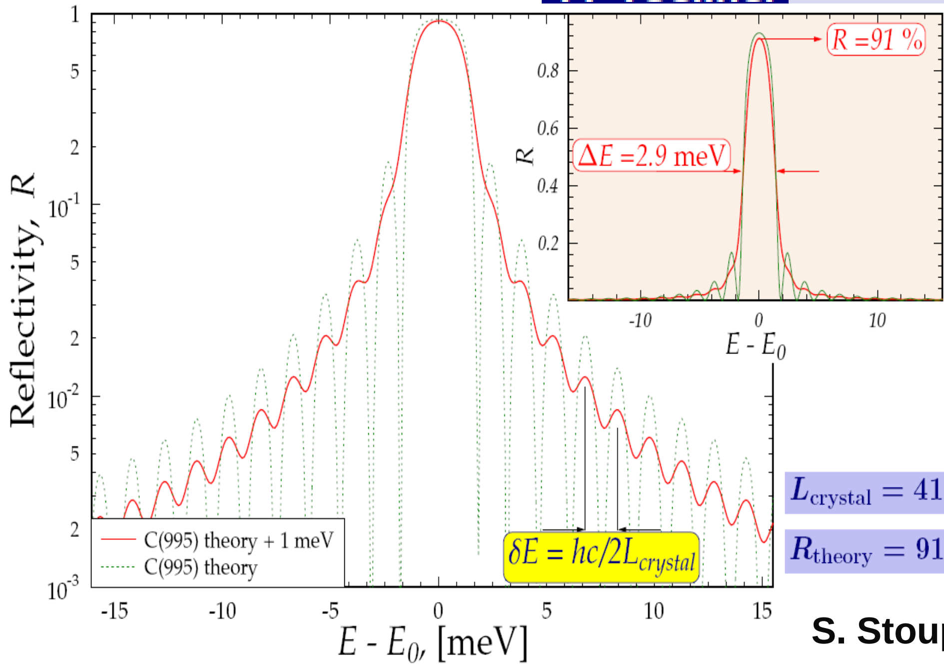


LBNL 187 MHz cavity
Courtesy: F. Sannibale

Reflectivity and Spectral Width Measurement at APS Sector 30 in good agreement with Theory

March, 2009





C(995)

E_H=23.765 keV

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

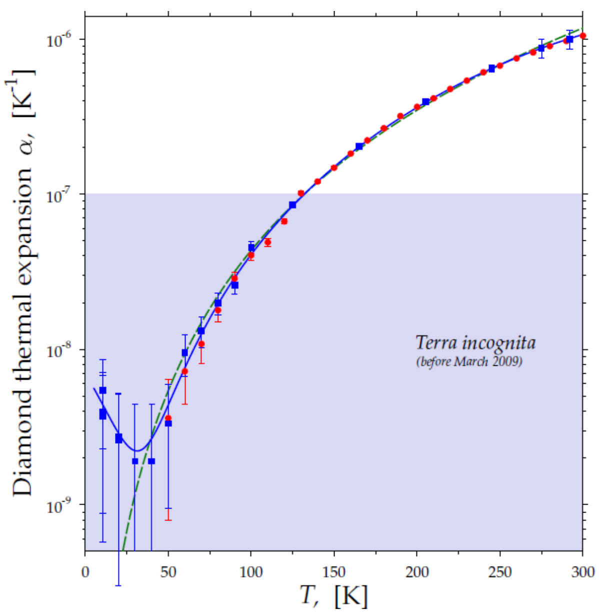
$R_{\text{theory}} = 91\%$

S. Stoupin, Y. Shvyd'ko, A. Cunsolo, A. Said, S. Huang

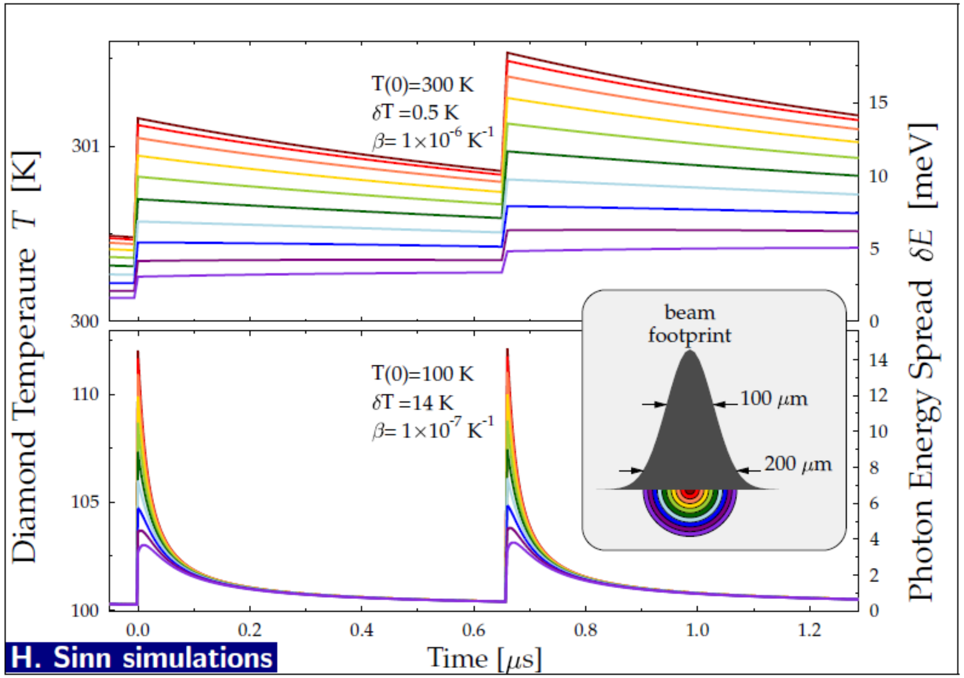
Heat Load Problem?

- **As an intracavity x-ray pulse hit a crystal, r-dependent temperature rise δT → crystal expansion → δE/E = β δT (δL/L=β δT/T) → δE/E<<10^{-7}?**
- **Due to high thermal-diffusivity, Inter-pulse effect can be made small if T< 100K (high heat diffusivity)**
- **Intra-pulse effect δE/E <<10^{-7} if the expansion time scale << pulse duration (~ps). Otherwise δE/E ~5-10 10^{-7}**

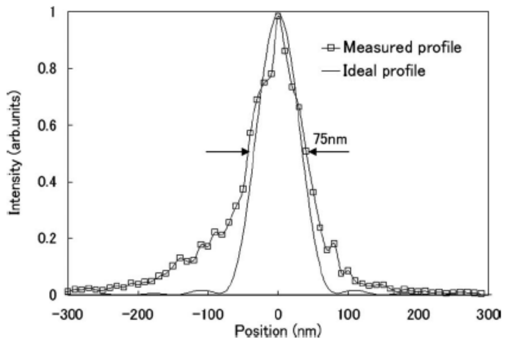
β

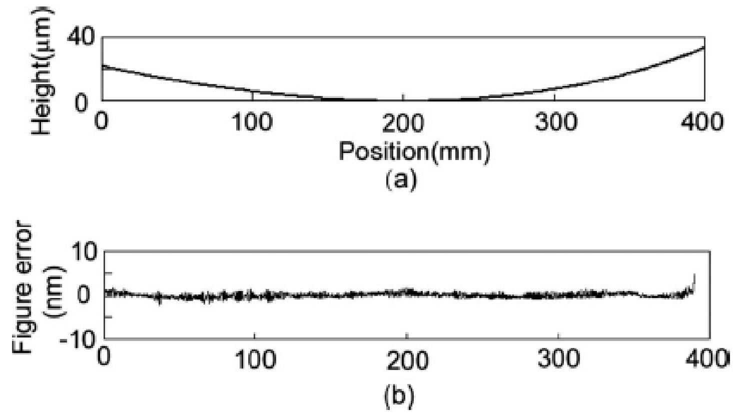


S. Stoupin and Y. Shvyd'ko, March 2009



Grazing Incidence, Curved Mirror





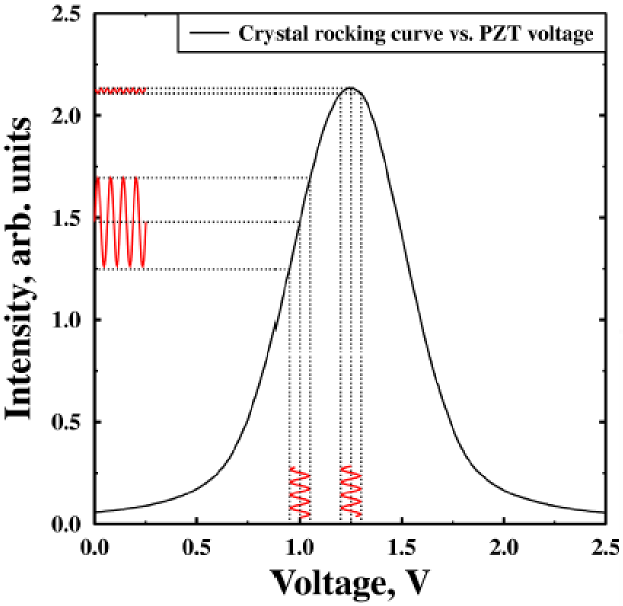
H. Mimura, et. al.

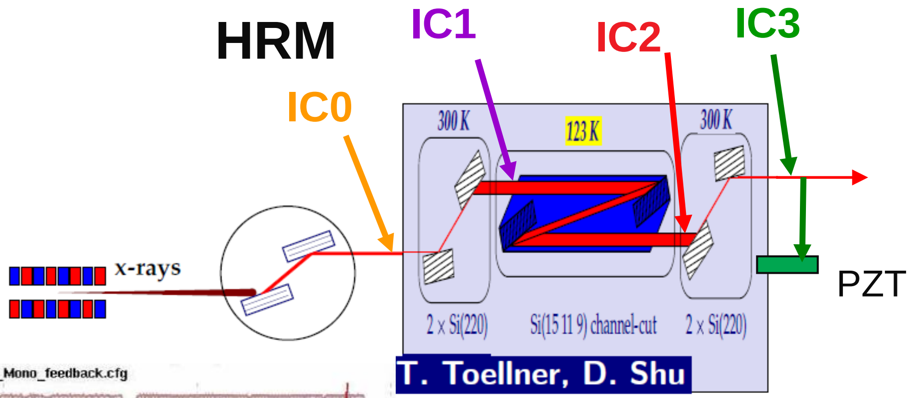
RSI 79, 083104, 2008

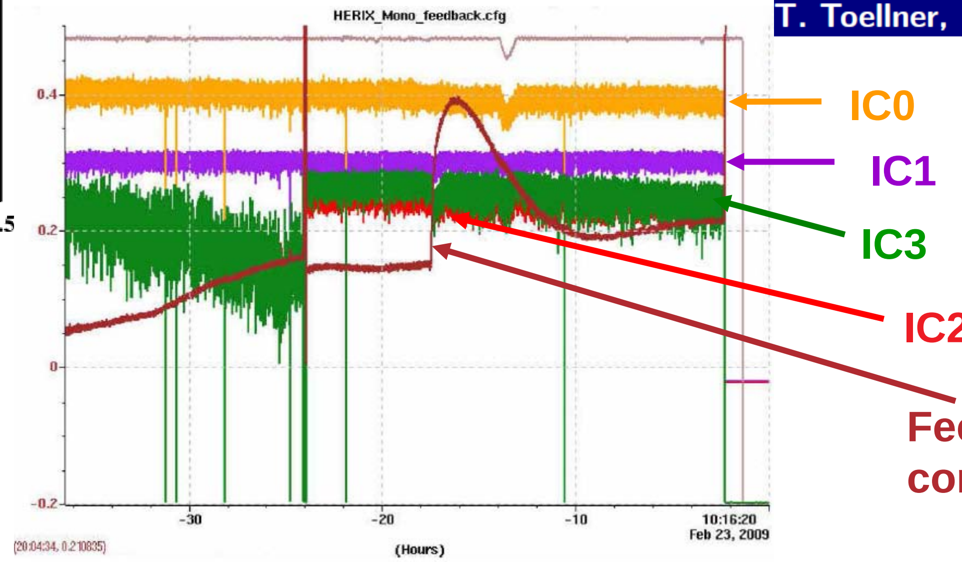
- **JTEC**
  - Developing a technique combining elastic emission machining (EEM, slow) and electrolytic in-process dressing (ELID, fast) to fabricate an “arbitrary” surface, such as ellipsoidal, to <nm height error and 0.25 mrad figure error
  - Such mirrors are sought after by “every body” in SR business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

Null-Detection FB at APS Sector 30

(S. Stoupin, F. Lenkszus, R. Laird, Y. Shvyd'ko, S. Whitcomb,..)

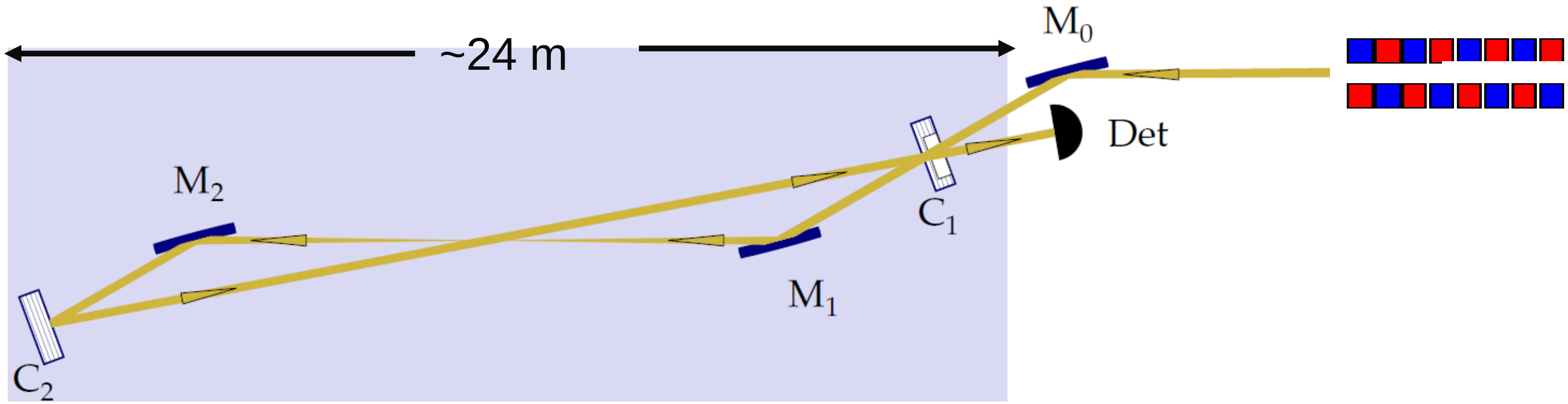






- **The stability of IC3 signal indicates the angular stabilization of the 3rd crystal pair within 50 nrad is achieved (~1 Hz BW)**

Prototype X-Ray Cavity at an APS Beamline



- **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, transverse mode profile**

XFELO Study Group

- **Modeling/Simulation**
  - R. Lindberg, W. Fawley, S. Reiche
- **Injector**
  - A. Nassiri, N. Sereno, M. Borland, G. Waldschmidt, D. Capatina, P. Ostroumov, B. Mustapha, P. Piot, S. Kondrashev, …
- **X-ray Optics:**
  - Y. Shvyd'ko, S. Stoupin, D. Shu, A. Macrander, L. Assoufid, G. Park,..
- ***Institutions interested in collaboration***
  - RIKEN/Spring-8: Injector, X-ray optics
  - DESY: XFELO test at European XFEL ?
  - LBNL: 100 MHz cavity
  - KEK: XFELO at ERL
  - Inst. for Geology and Mineralogy (Novosibiersk) and Tech. Inst. for Superhard & Novel Carbon Materials, Moscow: Diamond