An X-Ray Free Electron Laser Oscillator: Performance and Feasibility

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Workshop on evolution and control of complexity: Key experiments using sources of hard x-rays

Focus Panel 6: Nonlinear x-ray science and extreme x-ray metrology

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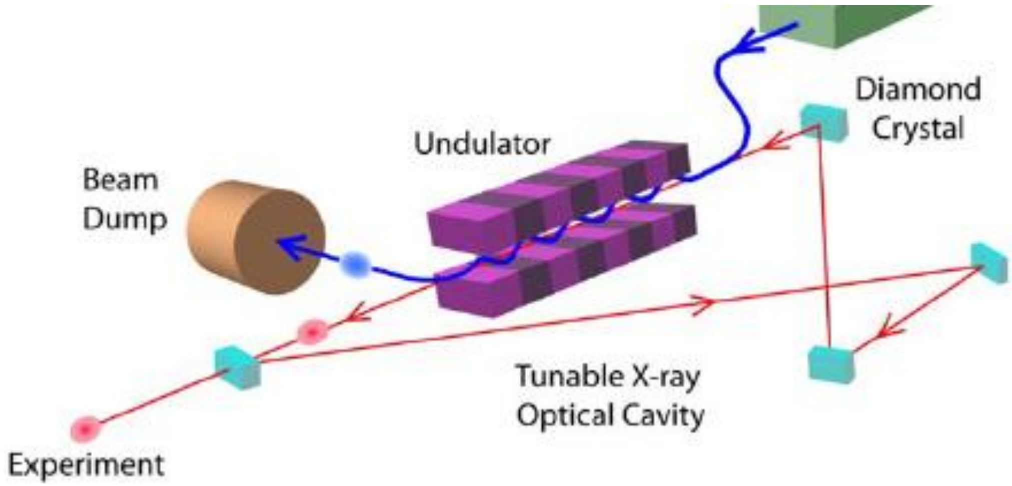
Advanced Photon Source, ANL

X-ray FELs beyond LCLS

- **More facilities**
  - **Higher average brightness (Euro XFEL, SCRF)**
  - **Compact FELs (SPring-8)**
  - **Coherent soft x-rays with harmonic generation**
- **Options with lighter (Q 50 pC) bunches with lower emittance (0.1 mm-mr)**
  - **Atto-second time resolution**
  - **meV spectral resolution**

A hard x-ray FEL oscillator (XFELO) will provide full coherence with ultra-pure spectrum

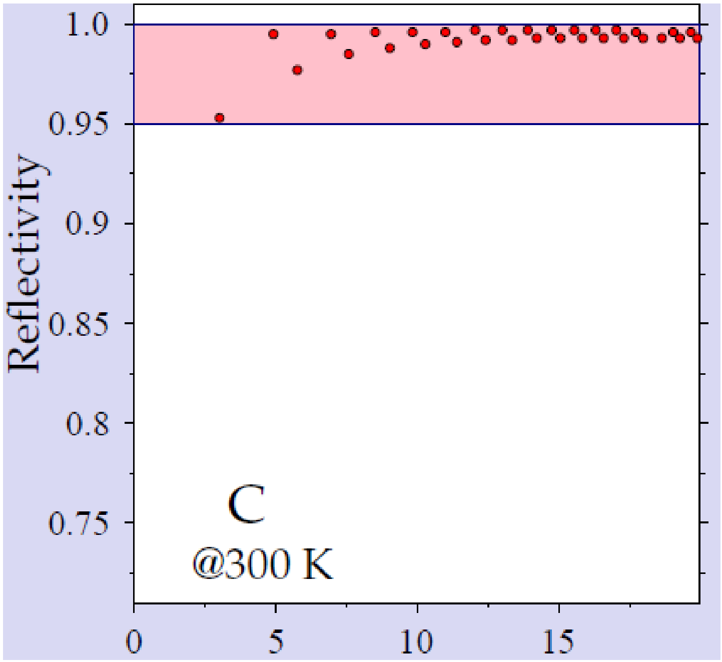


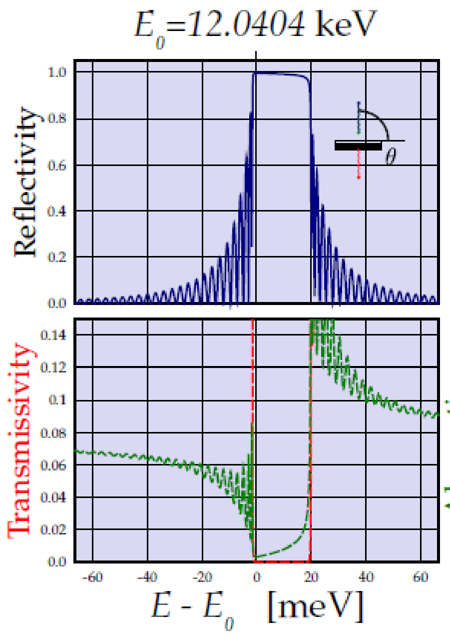
- **An X-ray pulse is stored in a diamond cavity→ multi-pass gain & spectral cleaning**
- **Provide transform limited BW**
  - □ $\Delta\omega/\omega$**~10^{-7}** □$\omega \sim 1$ **meV**
- **Zig-zag path cavity for wavelength tuning**

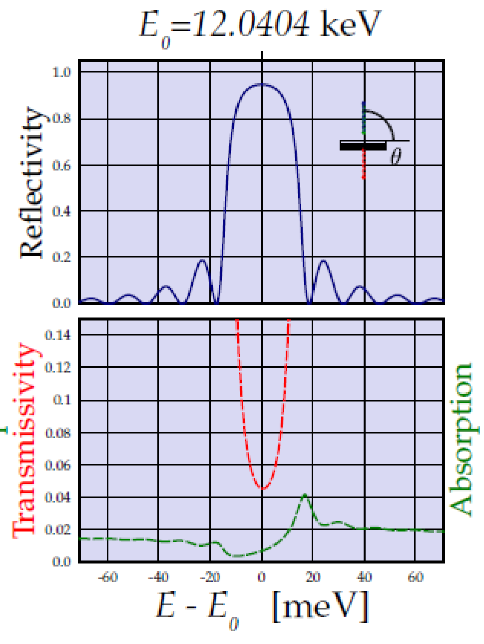
Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (KJK, S. Reiche, Y. Shvyd'ko, PRL 100, 244802 (2008)

High reflectivity and narrow bandwidth with near backscattering from diamond crystals

Courtesy of Yuri Shvyd'ko







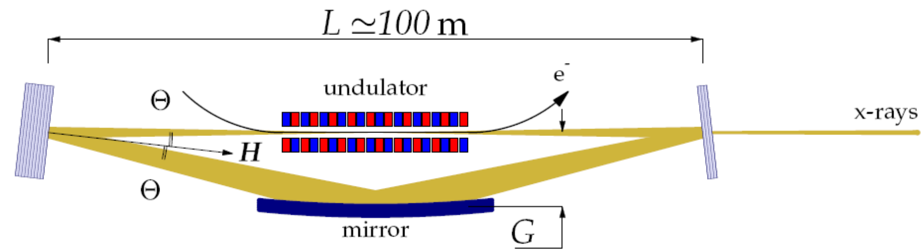
Representative parameters

- **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) ~ 2⑨$10^{-4}$
  - Constant bunch rep rate @ ~1 MHz
- **Undulator:**
  - L_u= 60 (30) 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**

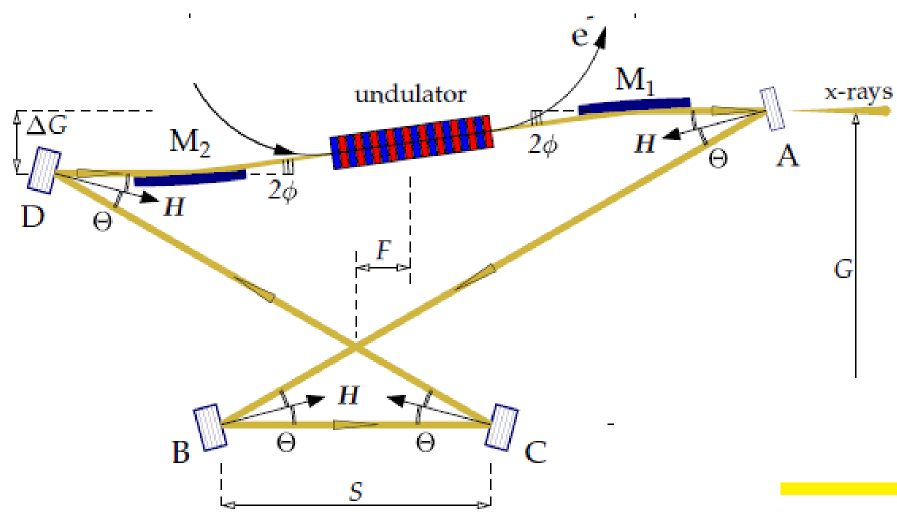
Blue color in the above indicates short-pulse mode for relaxed tolerances

Tunable X-ray Cavity

- **Two crystal scheme is not tunable**



- **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)

XFELO will dramatically improve hard x-ray techniques developed at 3rd generation light sources and find new applications in areas complementary to SASE

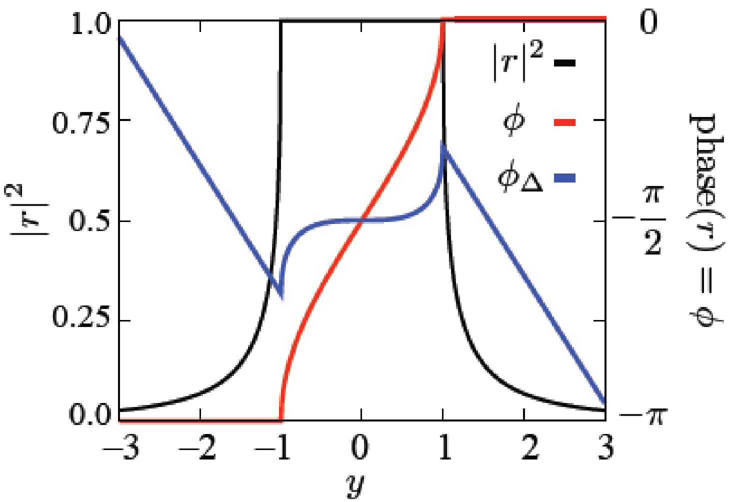
- **High resolution spectroscopy**
  - **Inelastic x-ray scattering**
- **Mössbauer spectroscopy**
  - **10^3/pulse, 10^9/sec Moessbauer γs (14.4 keV, 5 neV BW)**
- **X-ray photoemission spectroscopy**
  - **Bulk-sensitive Fermi surface study with HX-TR-AR PES**
- **X-ray imaging with near atomic resolution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

Is the phase change across the Darwin bandwidth harmful for XFELO operation?

- The complex reflectivity for near normal incidence x-rays

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

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

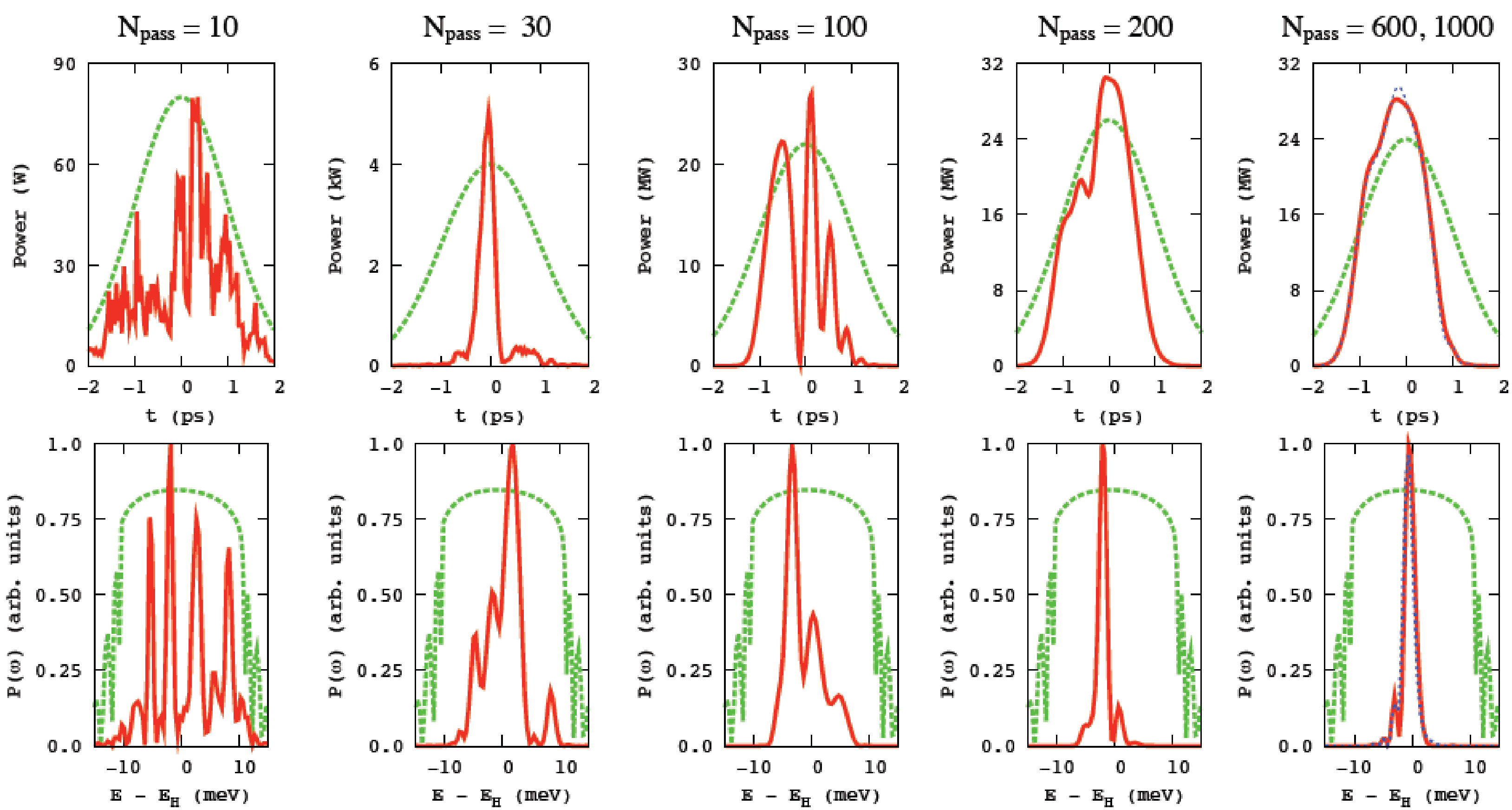


- XFELO works near y~0.
  The angular spread effect is small
- **The ω-dependent phase shift**

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

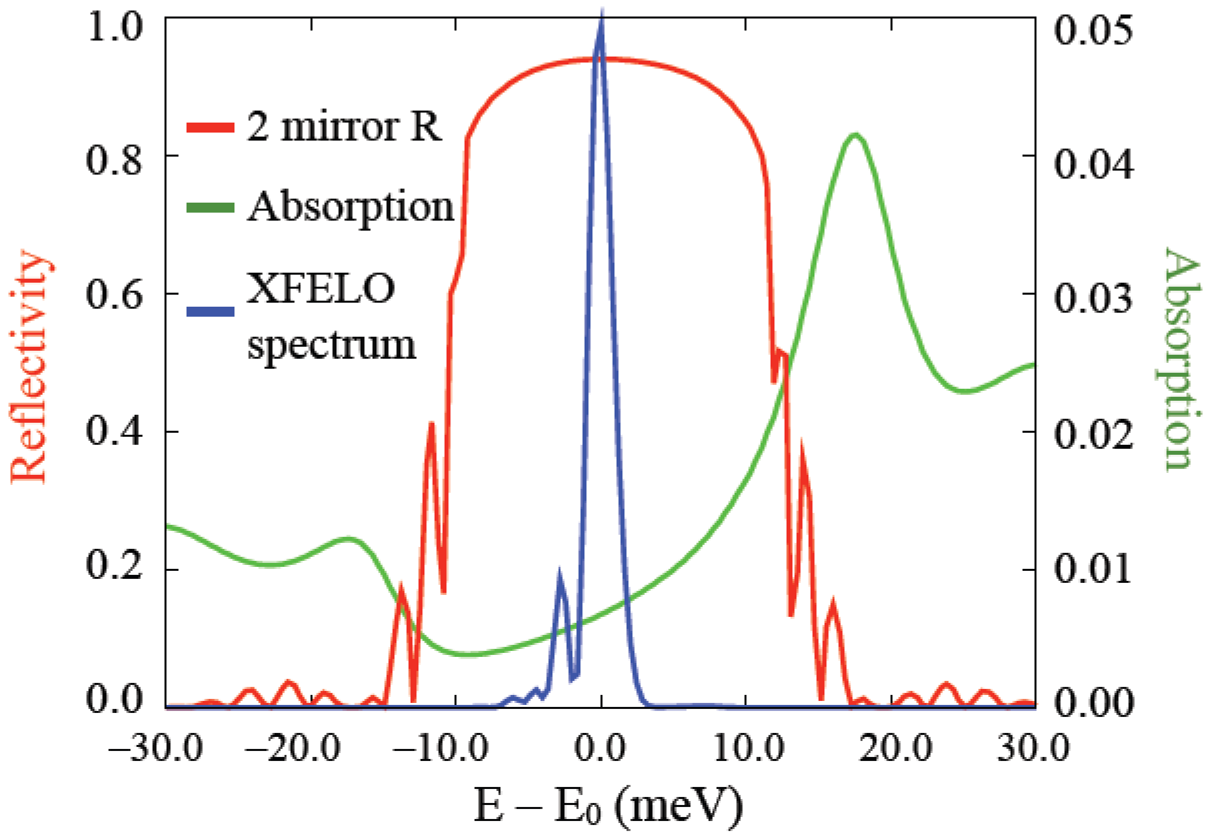
can be corrected by cavity length adjustment

Filtering by crystals expedite and stabilize the approach to the ultra-narrow spectrum. Spectrum saturation takes much longer than intensity saturation



The XFELO spectrum after 500 passes with GINGER (W. Fawley)

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

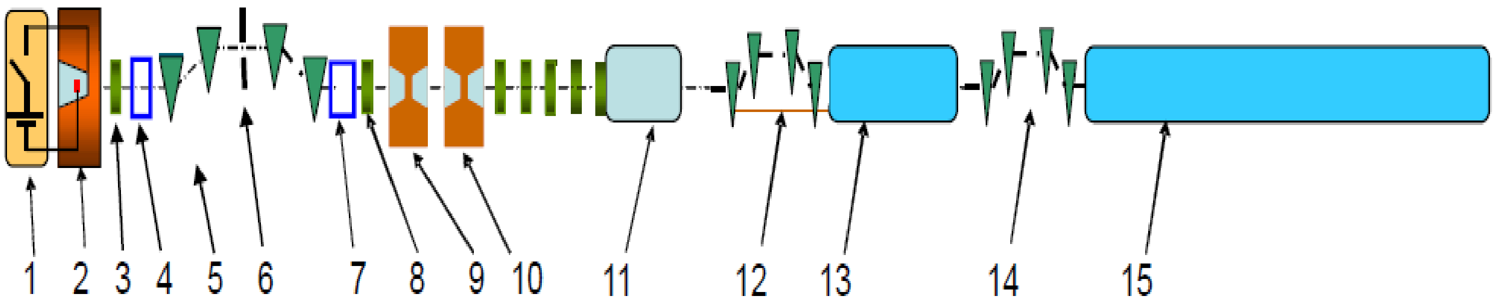


Technology Development for XFELO

- **Electron injector**
- **Diamond crystal**
  - **Reflectivity**
  - **Heat load dynamics**
- **Grazing incidence mirrors**
- **Stability of optical elements**

Electron guns for XFELO can be built

- The LCLS gun has already demonstrated low emittance with low charge
- The RF photo-cathode gun being developed at LBNL can be configured for XFELO application
- Cornell and KEK/JAEA are developing ERL guns satisfying the XFELO requirement
- A thermionic-cathode based injector appears also feasible by modifying the RIKEN/Spring-8 pulsed DC

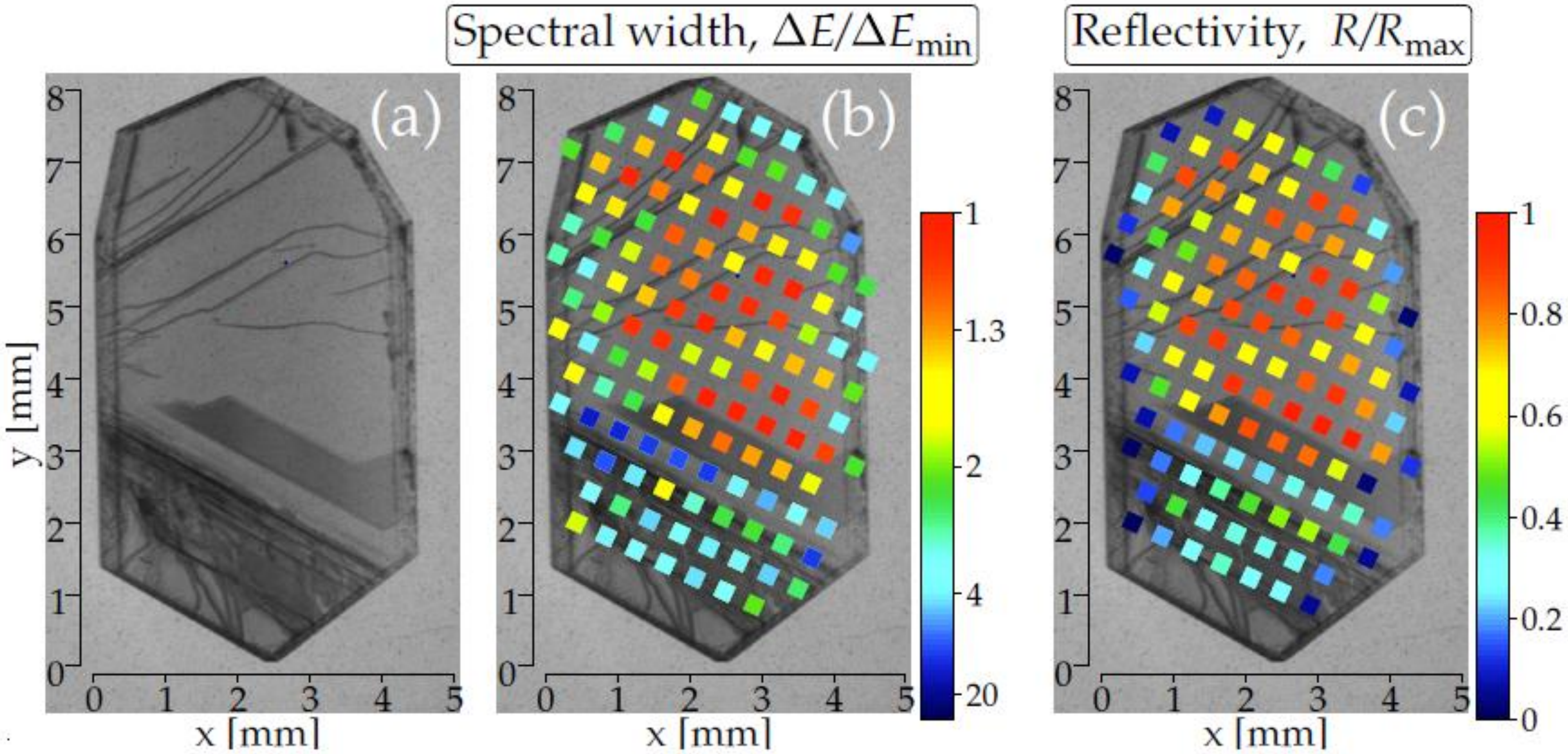


X-Ray Optics R&D for XFELO

- **Diamond crystal**
  - **High-reflectivity**
  - **Head-load dynamics**
  - **Damage issue**
- **Grazing incidence focusing mirror**
  - **Reflectivity and phase front quality**
- **Positional and angular stability**
- ***Advances in these technologies are eagerly sought after by broader synchrotron radiation community***

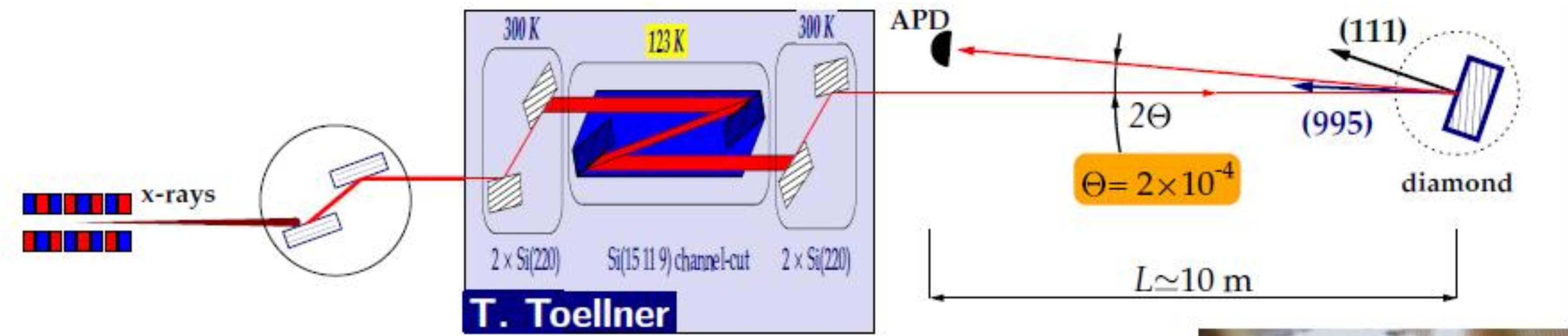
Optical Properties of HPHT Synthetic Diamond Crystals

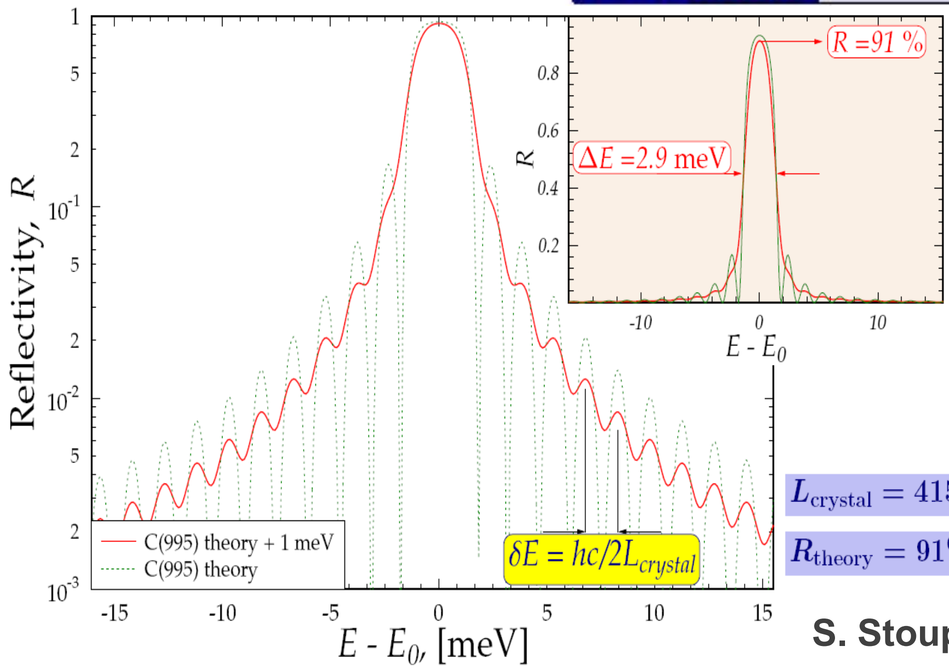
Crystal supplier: Element 6, Sumitomo, TISNUM (Moscow)



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



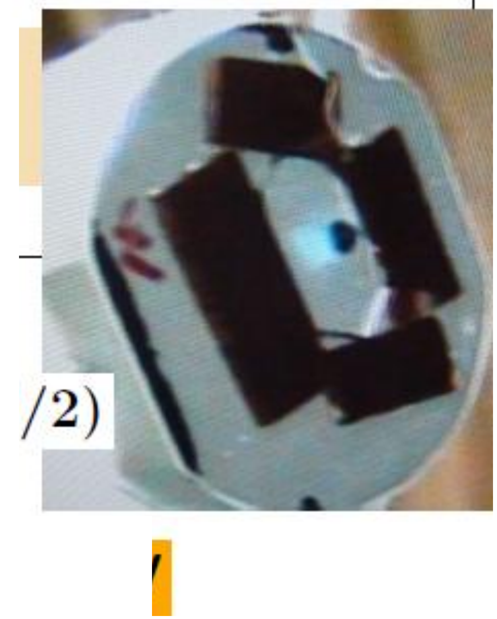


C(995)

E_H=23.765 keV

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

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

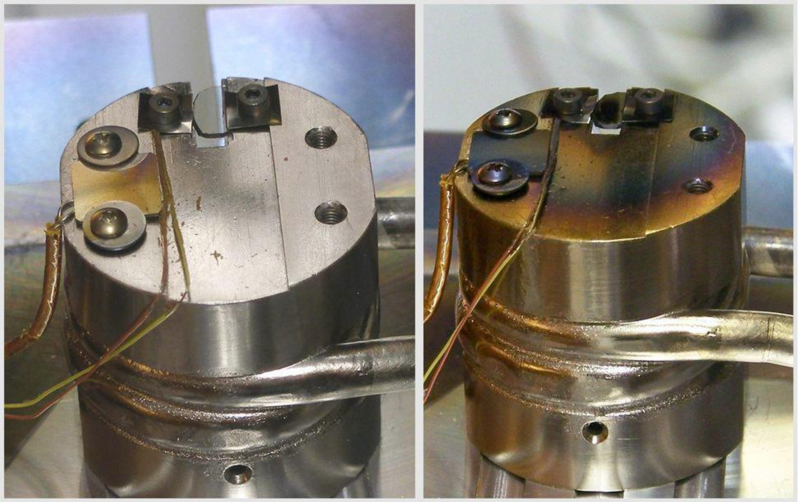


S. Stoupin, Y. Shyv'dko, A. Cunsolo, A. Said, S. Huang

(*Nature Physics 6(2010)196*)

Radiation damage issues

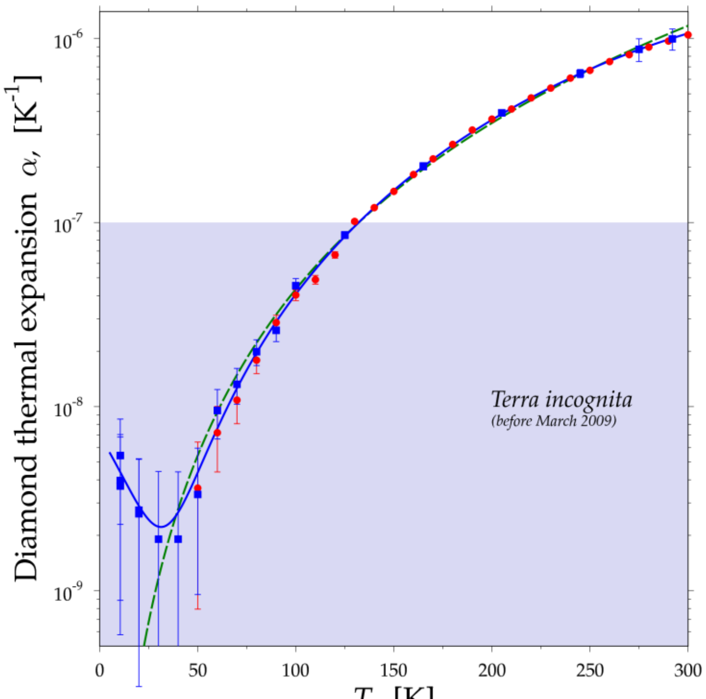
- **Power density on crystals is about 30 times higher than that of the APS undulators**
- **Estimate shows that all atoms will be ionized in 300s *in the absence of recombination* (Robin Santra)**
- **Various recombination processes may prevent an irreversible damage**
- **However, charge build-up at the surface due to photo-emission may lead to structural change at the surface**
- **Possible remedies**
  - **Isotopically pure ^{12}C crystals, cryogenic temperature**
  - **Attaching a thin conducting layer, e.g. graphene**
- **We plan for a thorough theoretical and experimental study**



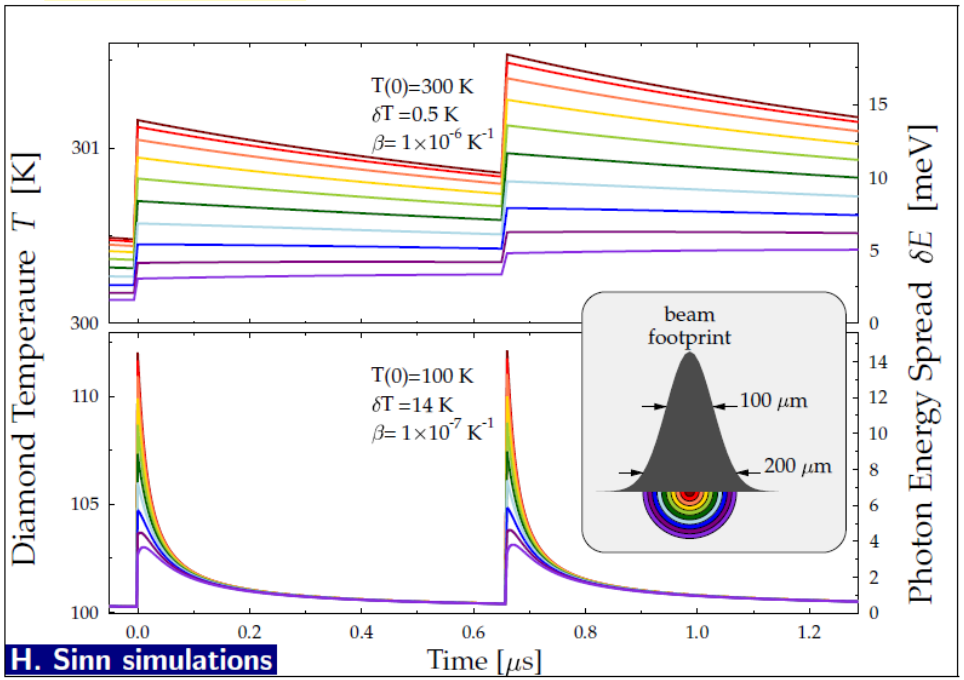
Graphitization of a diamond crystal at an APS HHLM (high heat load monochromator at the APS. The crystal surface became darkened without apparent performance degradation after 1 year of exposure.

Heat Load Dynamics

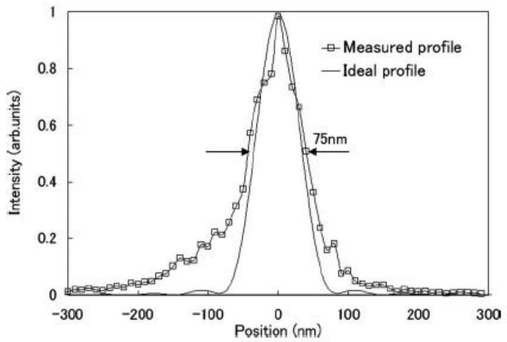
- An r-dependent temperature rise of crystal due to x-ray absorption → expansion → $\delta E/E = \beta\,\delta T$ ($\delta L/L = \beta\,\delta T$). **Is this $<10^{-7}$?**
- Yes, if cooled to a cryogenic temperature: T< 100K
  - Inter-pulse $\delta E/E$ **$<10^{-7}$** due to high thermal-diffusivity
  - Intra-pulse $\delta E/E <10^{-7}$ due to $\beta <10^{-7}$ and if the expansion time < pulse duration (~ps)
- Theories suggest the expansion is slow. We will pursue experimental study using laser heating

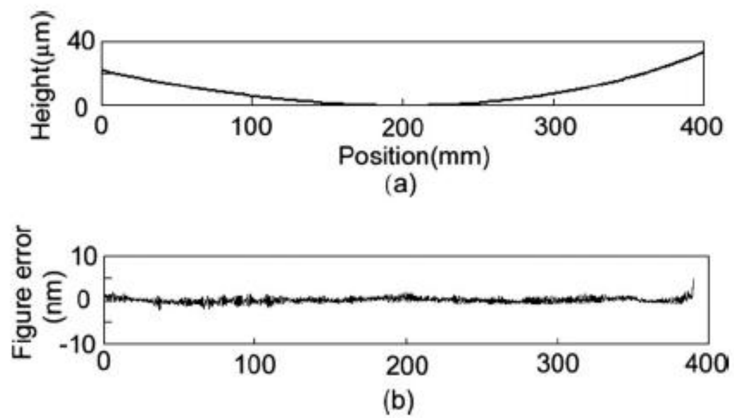


S. Stoupin and Y. Shvyd'ko, PRL



Grazing Incidence, Curved Mirror





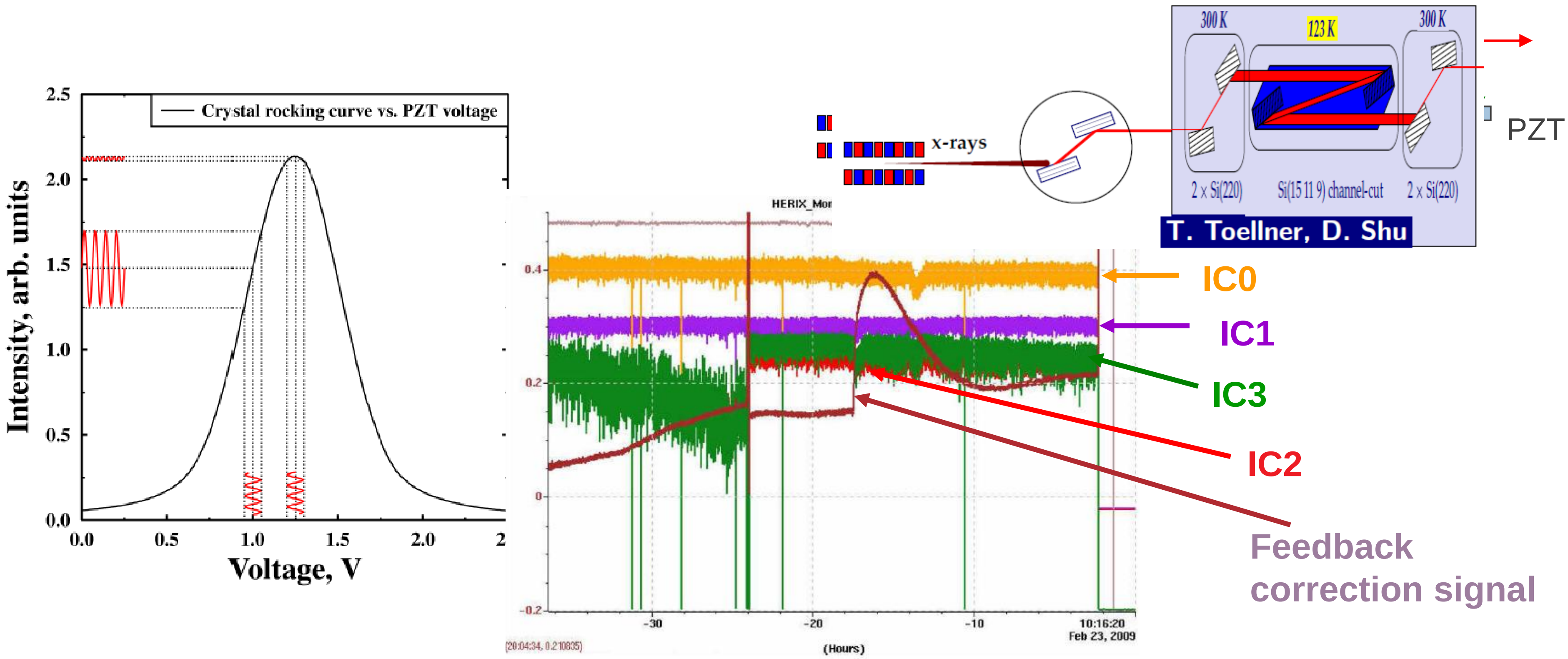
H. Mimura, et. al.

RSI 79, 083104, 2008

- **JTEC**
  - **Developing a technique combining elastic emission machining (EEM, slow) and electrolytic in-process dressing (ELID, fast) to fabricate a smooth surface to <nm height error and 0.25 mrad figure error**
  - **Issue: large ration in the sagital and meridional depths**
  - **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,..)

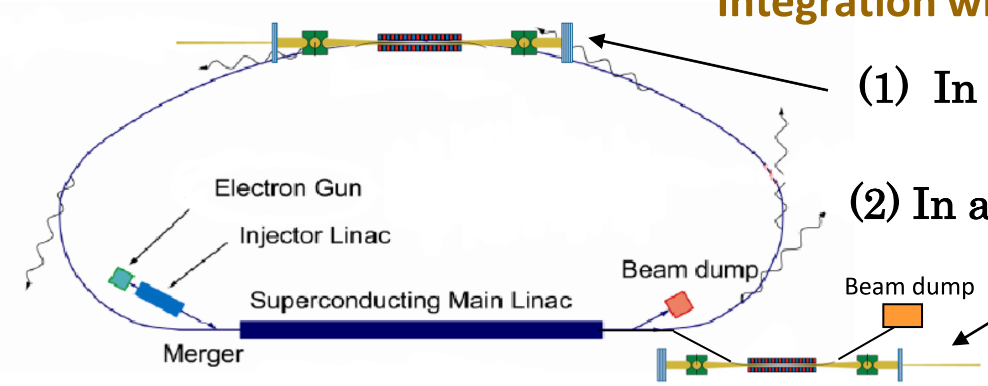


- **The stability of IC3 signal indicates the angular stabilization of the 3rd crystal pair within 50 nrad is achieved (~1 Hz BW)**
- **(S. Stoupin, F. Lenkszus, R. Laird, Y. Shvy'dko, S. Whitcomb,., RSI, 81, 055108, 2010)**

Where can an XFELO be implemented?

- **Euro-XFEL**
  - **The length of the macro-pulse (1 ms) is sufficient for a pulsed XFELO (being studied by J. Rossbach)**
  - **The 14 GeV pulsed SCRF linac could in the future be operated in CW mode at a lower energy (5 GeV?)**
- **Plan for JAEA-KEK ERL includes an XFELO**

Integration with an ERL light source



(1) In a straight section of the loop

(2) In an additional single-ended branch

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

- **A future XFEL facility using recirculation incorporating both ultra-fast SASE and XFELO?**