High-Efficient XFELO Based on Optical Resonator with Self-Modulated Q-Factor

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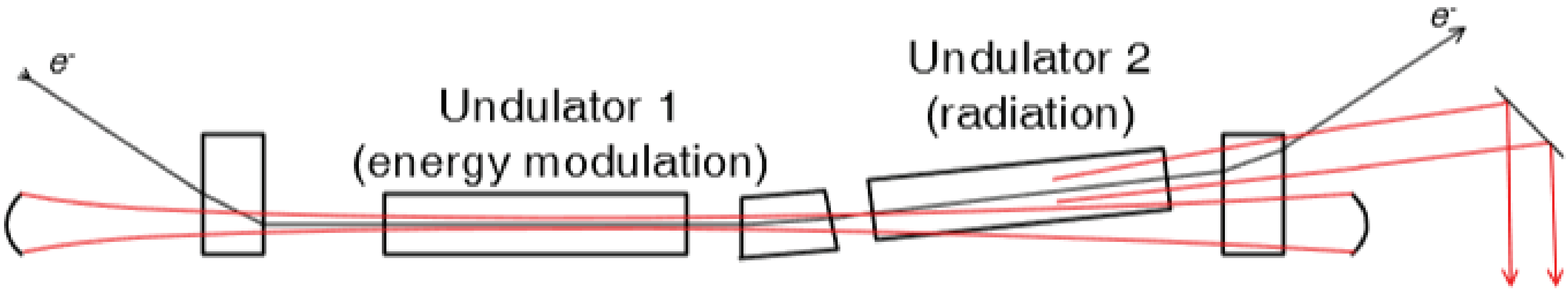
MOTIVATION

Novosibirsk FEL Outcoupling Scheme*



Electron outcoupling scheme with two undulators and bending section between them.

Advantage --- XFELO easily starts.

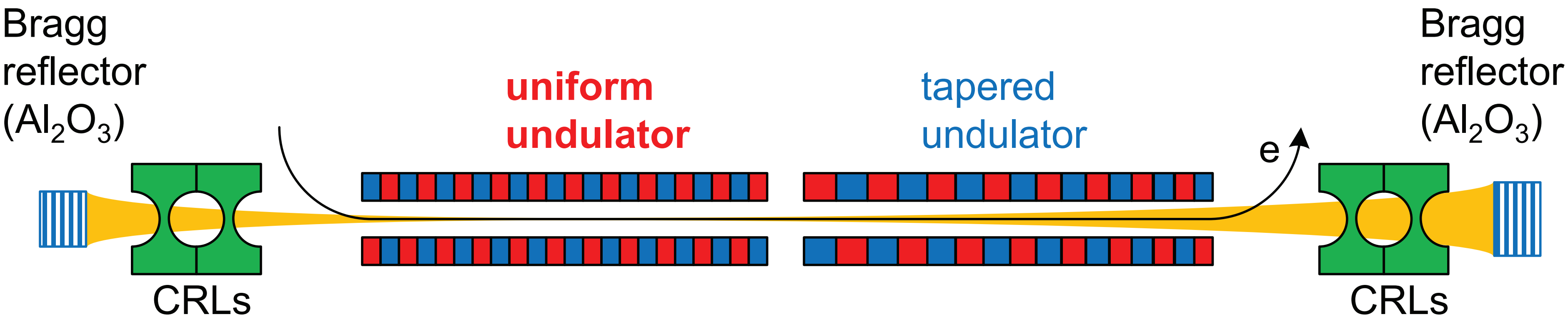
Concerns --- bending magnet spoils e-beam;
X-rays accumulated in the resonator are lost;
high efficiency might be problematic;

*A.N. Matveenko, O.A. Shevchenko, V.G. Tcheskidov, N.A. Vinokurov. ELECTRON OUTCOUPLING SCHEME FOR THE NOVOSIBIRSK FEL , Proceedings of FEL 2007, Novosibirsk, Russia, TUAAU02.

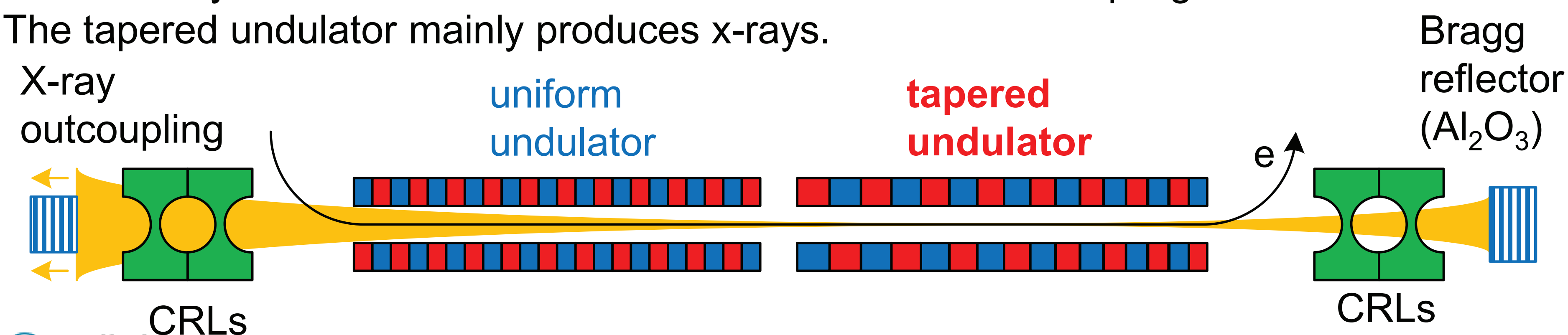
CONCEPT

XFELO Based on Optical Resonator with Self-Modulated Q-Factor

- At start condition Q-factor obtains maximum possible value due to proper optics. The uniform undulator leads the XFELO.



- At steady-state condition Q-factor is reduced due to outcoupling. The tapered undulator mainly produces x-rays.



Working Condition

The two-undulator concept works well only if power generated by a given bunch in the tapered undulator is much greater than power loss due to outcoupling (in this case X-ray field structure can be considered as fully controlled by the tapered undulator).

This conditions means that Pierce parameter must be as large as to satisfy:

$$exp(L_{tu}/L_{gain}) >> P_{out}$$

where P_{out} – normalized power loss per single wave passage in the resonator, L_{tu} – length of the tapered undulator, $L_{gain}=\lambda_u/4\pi\rho$ - gain length, ρ - Pierce parameter, $\rho \propto (K_u I / \gamma_0^3)^{1/3}$

The above equations show that high-current bunches of small cross-section sizes are preferable.

Such bunches are being produced by laser-plasma accelerators. Large energy spread can be mitigated by trapping regime in the tapered undulator.

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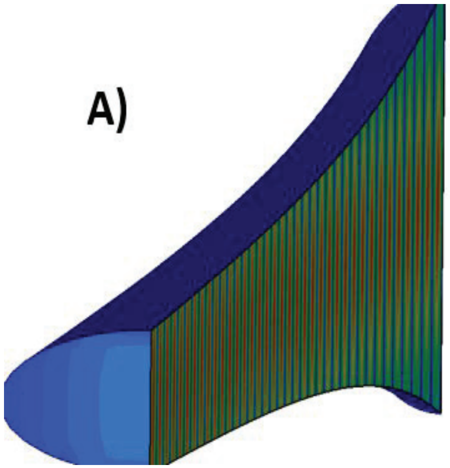
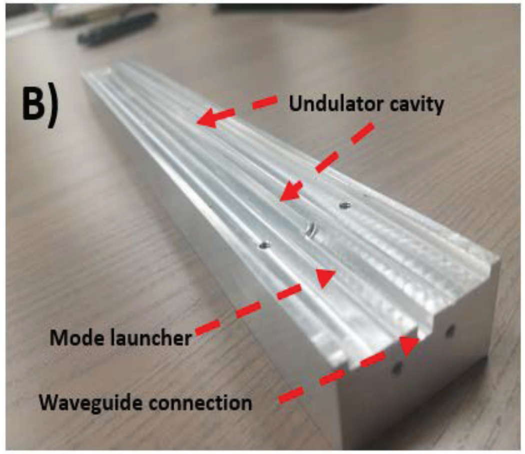
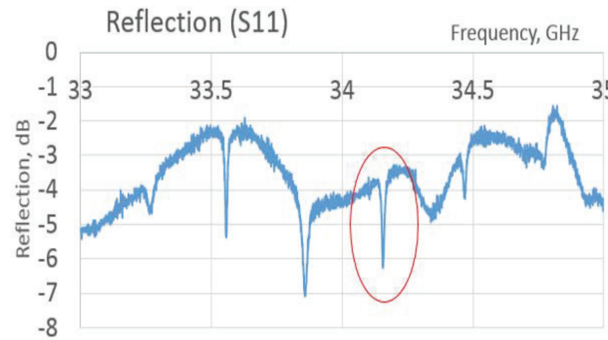
RESEARCH @ EUCLID

Strongly Tapered RF Undulators R&D at Euclid



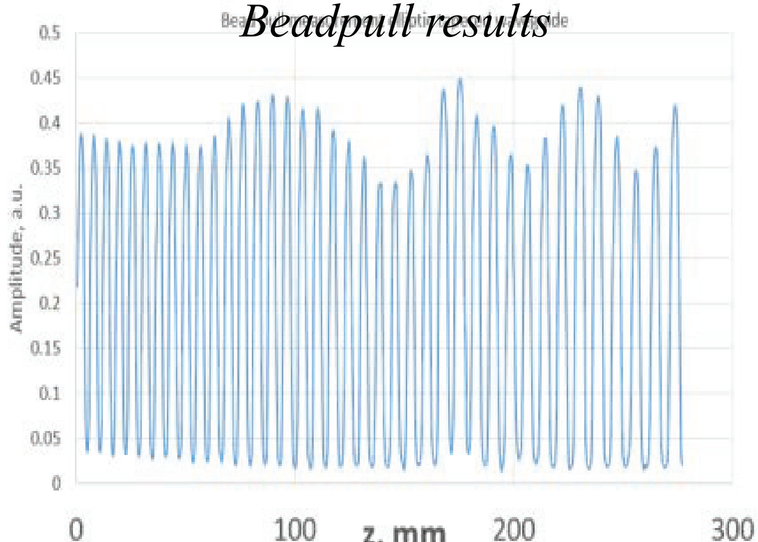


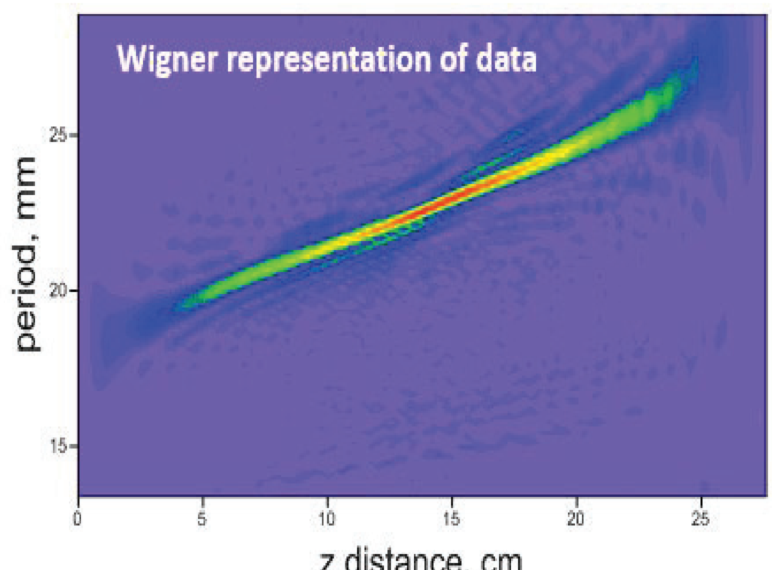
Elliptical TE_{11} tapered undulator.



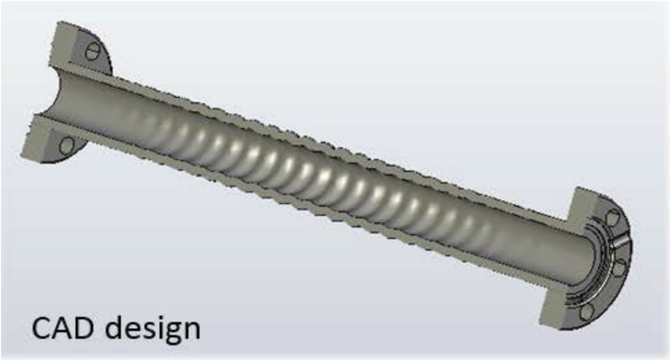
Reflection (S_{11}) measured. Working mode at just above 34 GHz.

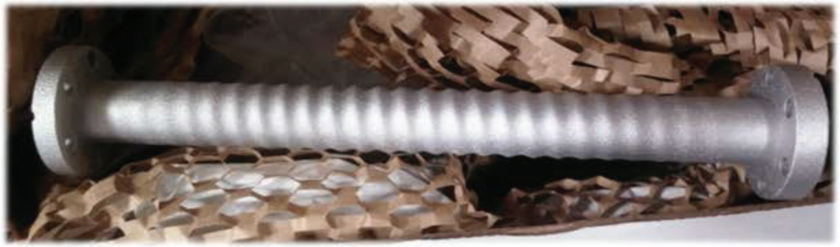
Beadpull results

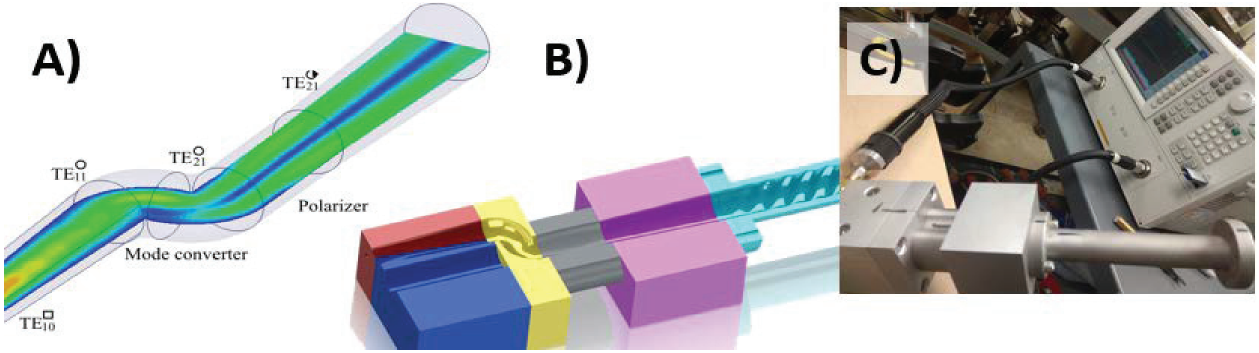




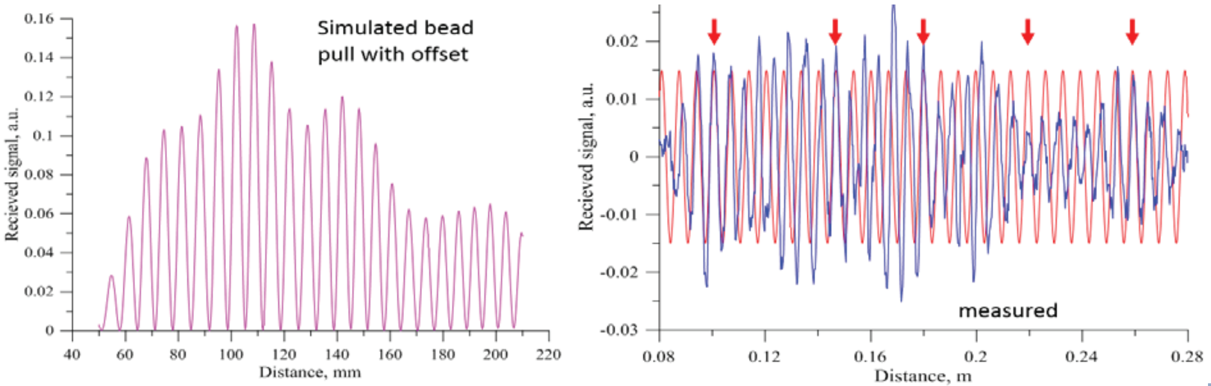
Strongly Tapered Helical RF Undulator





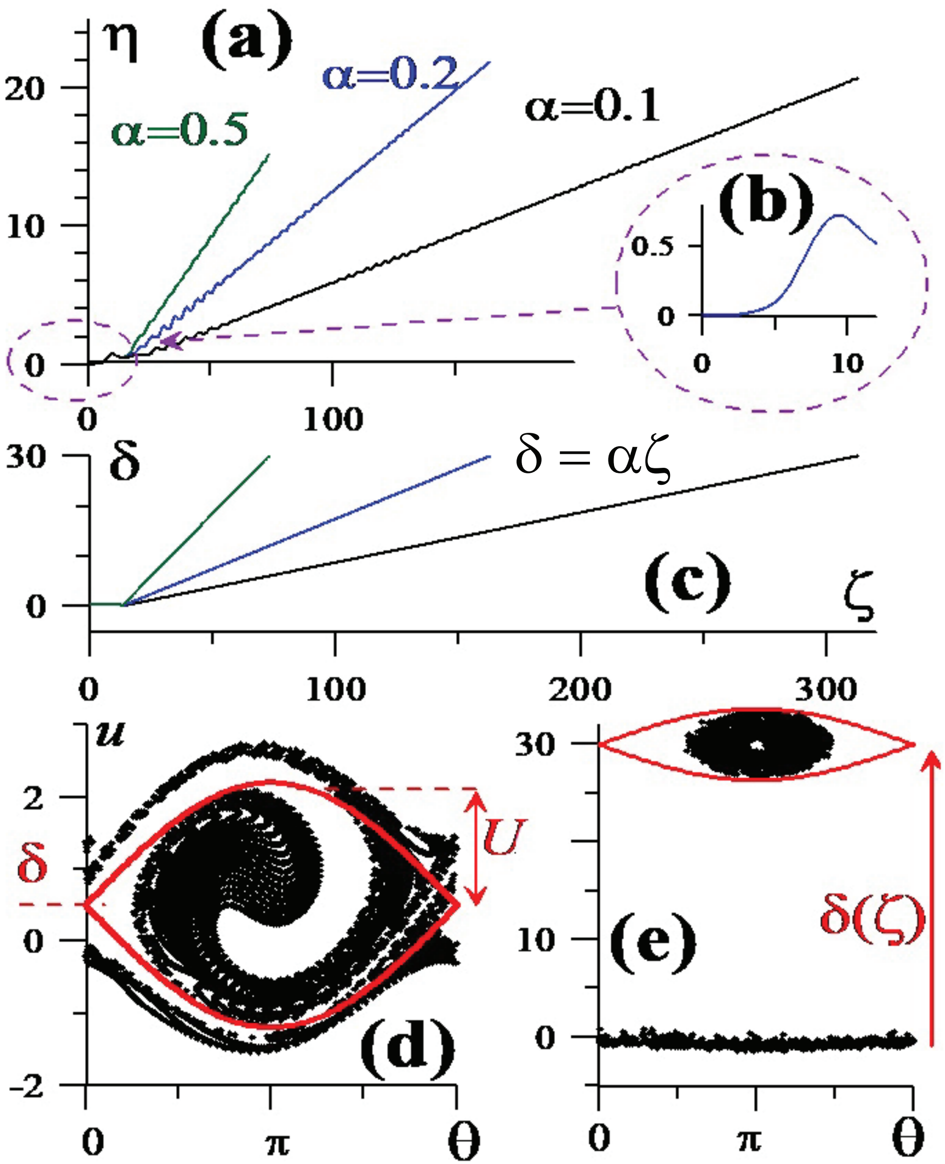


Cold test mode launcher from a standard rectangular waveguide TE_{10} mode into circularly polarized TE_{21} mode.



TE_{11}-TE_{21}-TM_{11} undulator field balance. *Left: simulation with 0.5mm bead offset from centerline. Right: Bead pull measurement (blue) and constant period sine function (red).*

Simulation of Trapping Regime in Strongly Tapered Undulator



Regime of trapping in the case of a relatively small energy spread, *S*=2.

(a) and (c): normalized efficiency and mismatch versus the axial coordinate at three different rates a of the profiling of the mismatch.

(b) : evolution of the efficiency in the regular section.

(d) and (e): positions of the bucket and electrons on the phase plane at the end of the regular section (d) and at the end of the interaction (e), in the case of α=0.2.

The normalized electron efficiency is related with the wave amplitude by the energy conservation law:

$$\eta = \langle u - u_0 \rangle = \frac{1}{2}\left[|a|^2 - |a_0|^2 \right]$$

Equations and Calculation Model

$$\frac{du}{d\zeta} = Ref(\zeta)aexp(i\theta) \qquad \frac{d\theta}{d\zeta} = u - \delta(\zeta) \qquad \frac{da}{d\zeta} = \left\langle f * \exp(-i\theta) \right\rangle$$

$u = (\gamma_0 - \gamma)/\gamma_0\rho$ - is electron energy change,

$\zeta = z / L_{gain}$ - is a normalized axial coordinate,

$\theta = \omega t - (2\pi / \lambda_u + k_{||})z$ - is a resonant electron phase with respect to the wave,

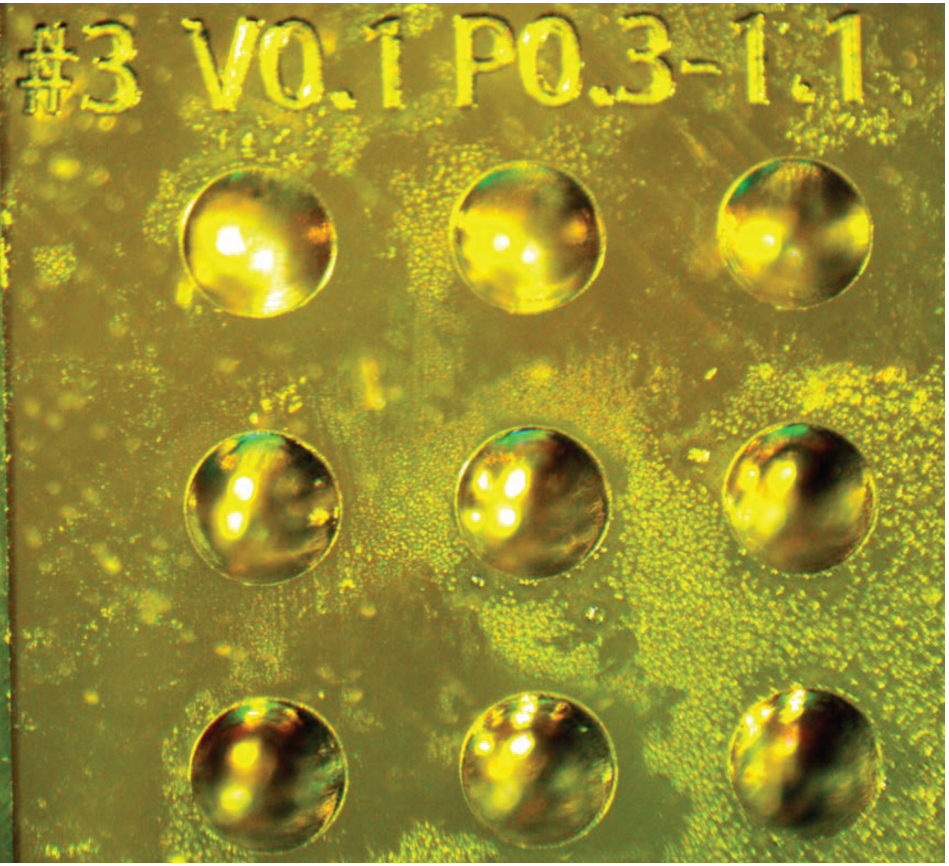
a - is a normalized wave amplitude, $a(0) = a_0$

$\delta = (\gamma_0 - \gamma_{res})/\gamma_0\rho$ - is a normalized mismatch of the electron-wave resonance,

$f(\zeta)$ - describes profiling of the system.

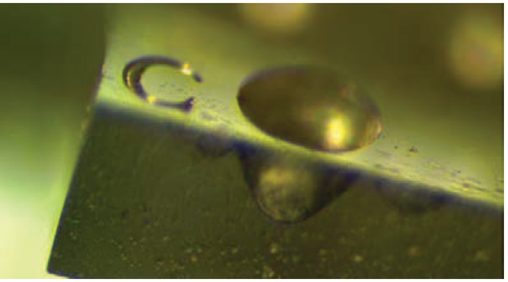
$u(0) = u_0 \in [-S/2, S/2]$, where *S* – is an amplitude of energy spread.

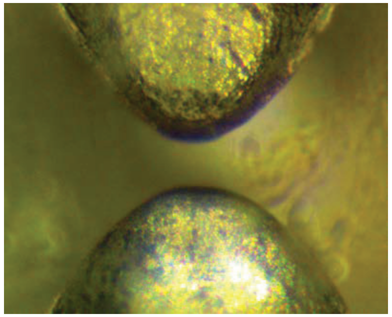
Diamond Refractive Lens

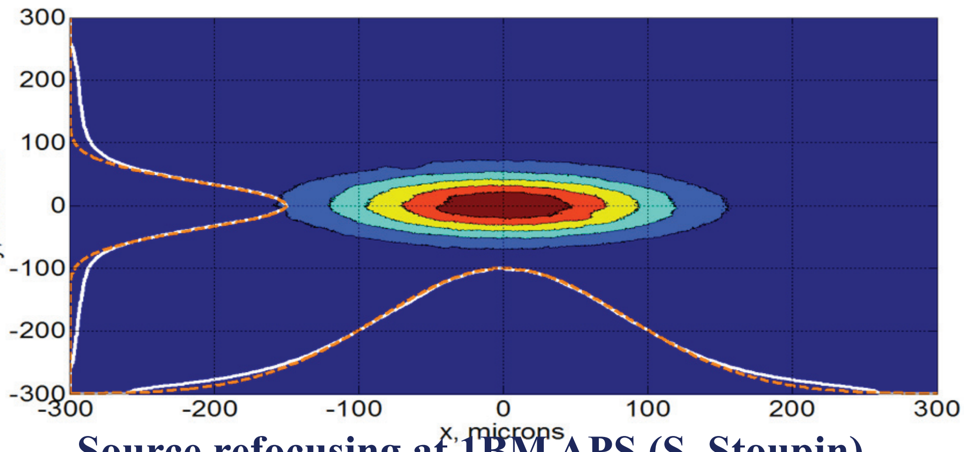


- Why?
  - High [peak/average] heat load / thermal stability
  - Single crystal possible vs polycrystalline beryllium
  - Radiation damage
- How?
  - fs-laser ablation of diamond
  - post-polishing

Diamond CRL

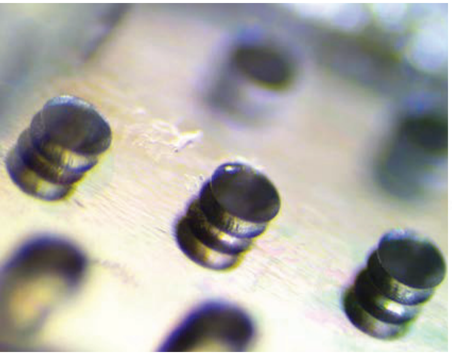


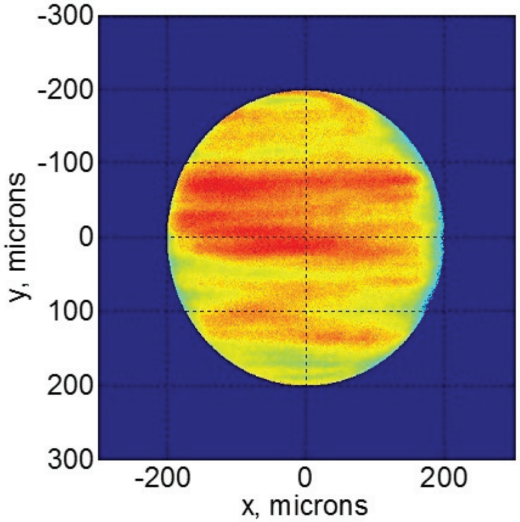


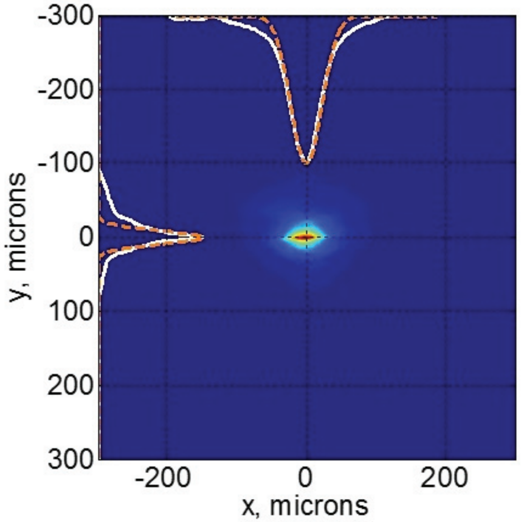


Source refocusing at 1BM APS (S. Stoupin)

Gain **5.71**$_{theory}$ vs **2.83**$_{exp}$



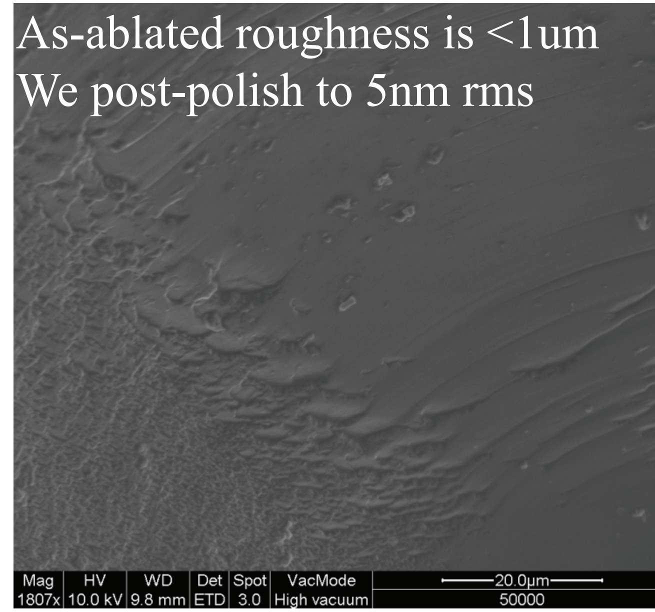


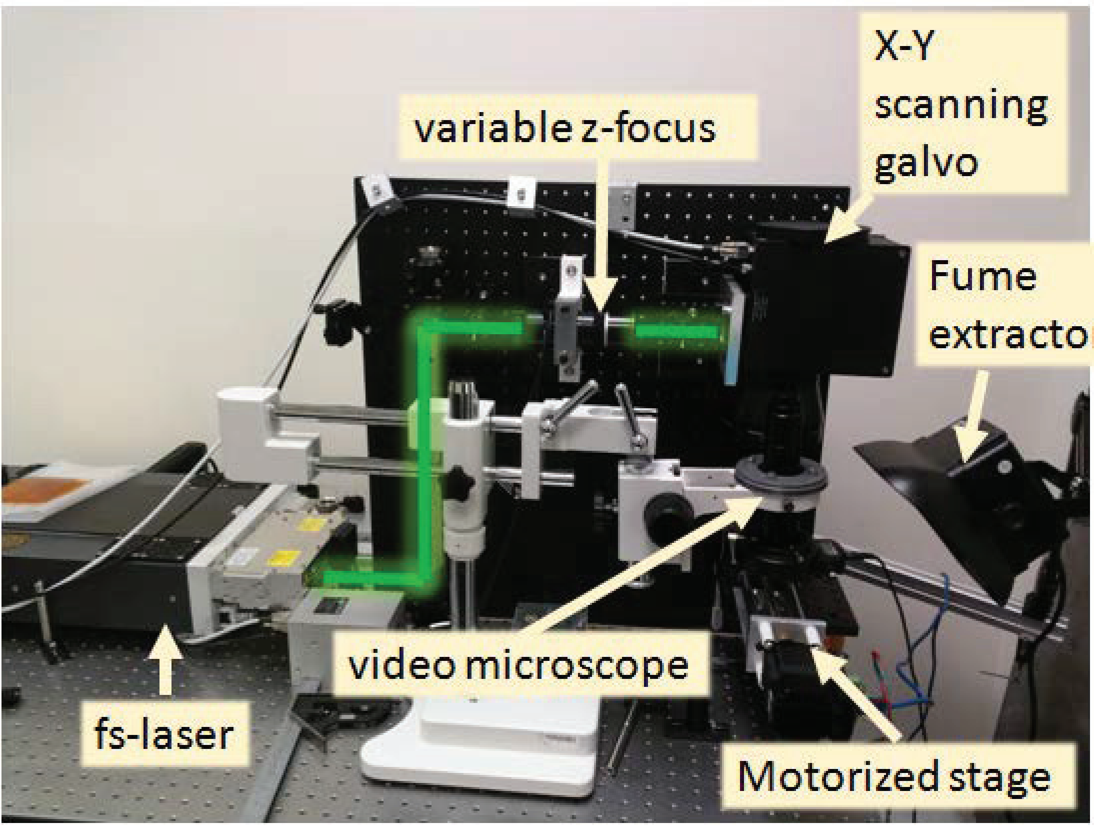


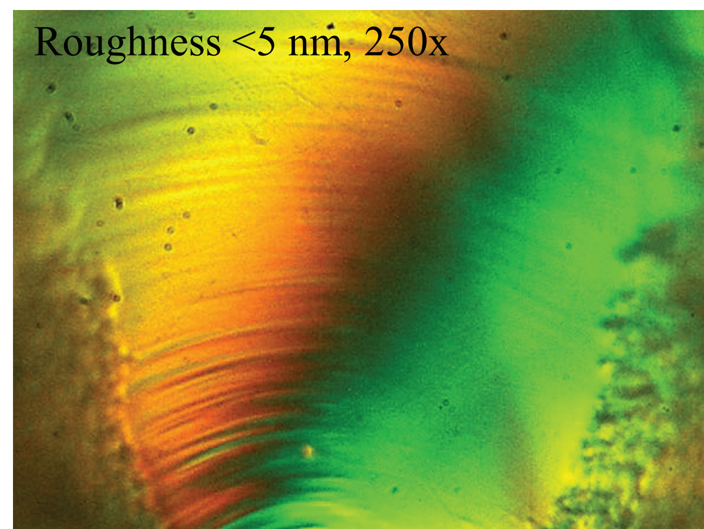
X-ray: **11.85 keV**
ID – Lens **62m**
R = **105 um**
f = **3.36 m** (3 lens)
Pinhole = **400 um**
Focused beam:
24.5 um x 17.6 um
Gain 50-100

CRL test at BIOCAT IIT (O. Antipova) - APS (S. Stoupin)

Femtosecond lens cutter and Polishing development@Euclid







Summary

- Preliminary calculations show that concept of the XFELO with self-modulated Q-factor is appealing:
  - It allows XFELO easy to start up;
  - The concept is also promising to provide high efficiency at steady state condition due to trapping regime.
- Tapered RF undulator and diamond CRL are under investigation at Euclid.

Acknowledgement: Investigation of Tapered RF underlator is funded by US DoE SBIR Grant #DE-SC0017145; Investigation of the single crystal CVD diamond CRL is funded by US SBIR Grant #DE-SC0013129