Tapered Flying RF Undulator

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OUTLINE

1. Two concepts of the tapered RF undulators:

    High-Q cavity;

    High-power traveling structure.

2. Regime of non-resonant trapping in FEL.

3. First simulations of XFEL based on the tapered flying RF undulator.

4. XFELO with self-modulated Q-factor resonator and built-in tapered undulator.

5. Suplemented research in Euclid Techlabs:

    Diamond refractive X-ray lens;

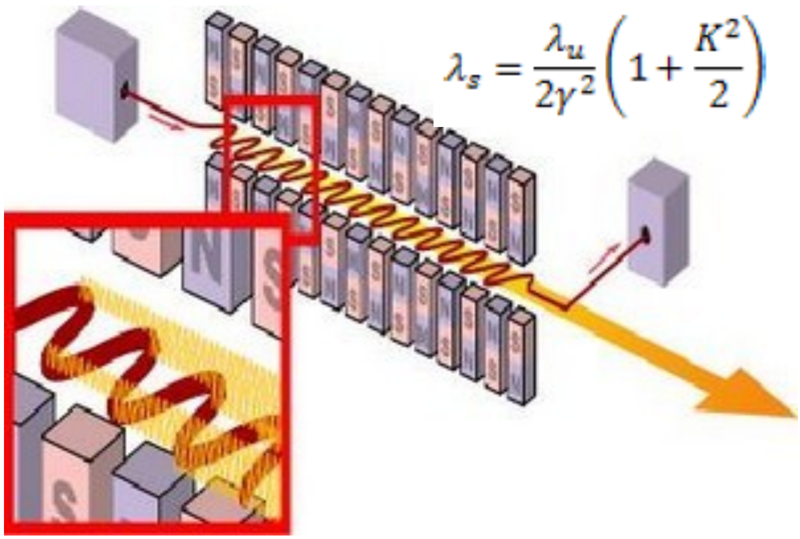
    X-ray CRLs;

    Laser cutting and polishing technique;

    Synthesis of X-ray phase correctors.

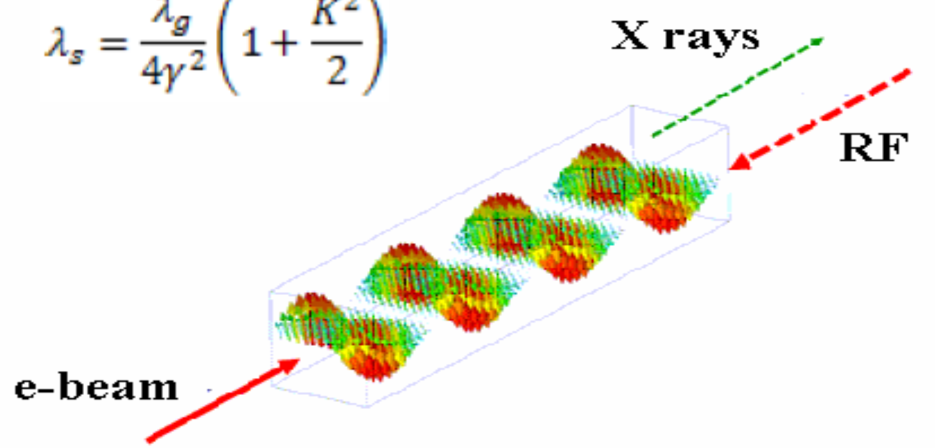
6. Conclusion

Static and Radiofrequency Undulators



$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$\lambda_s = \frac{\lambda_g}{4\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



Permanent Magnet Undulator

•Small aperture and period (~cm);
•Polarization not adjustable;
•Undulator period and other parameters cannot be changed;
•Permanent magnet damage by radiation;
• High cost.

RF Undulator

• $\sqrt{2}$ less energy of electron beam
•Smaller undulator periods possible
•Larger apertures possible
•Fast dynamic control possible for
- Polarization
- Undulator parameter *K*
•No magnets damaged by radiation

RF UNDULATOR CONCEPTS

1. RF undulator based on storing of RF power in a high-Q resonator

Disadvantages: standing wave field structure produces complicated radiation spectrum;

multi-megawatt RF source serves short (~1 m) section;

RF breakdown and pulse heating alert.

Advantages: high peak field (~100 MV/m, *K*~1) is achievable;

field structure does not much depend on amplitude and phase of a RF pulse.

2. RF undulator based on high-power short RF pulse co-propagating with electrons (electrons wiggle in field of the -1st harmonics of the periodic waveguide)

Disadvantages: field structure is more sensible to RF amplitude and phase;

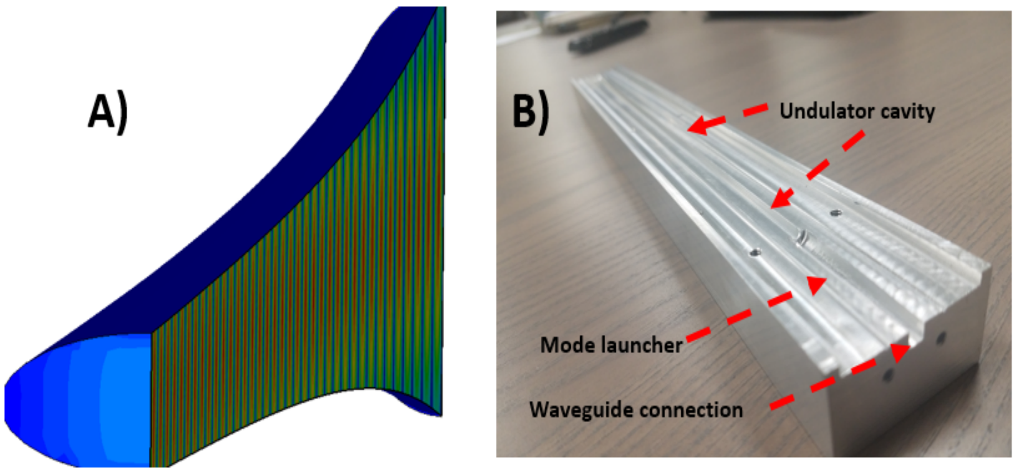
High power RF source is necessary (~1 GW in Ka-band).

Advantages: short RF pulse (~10 ns) can serve long (~10 m) undulator section;

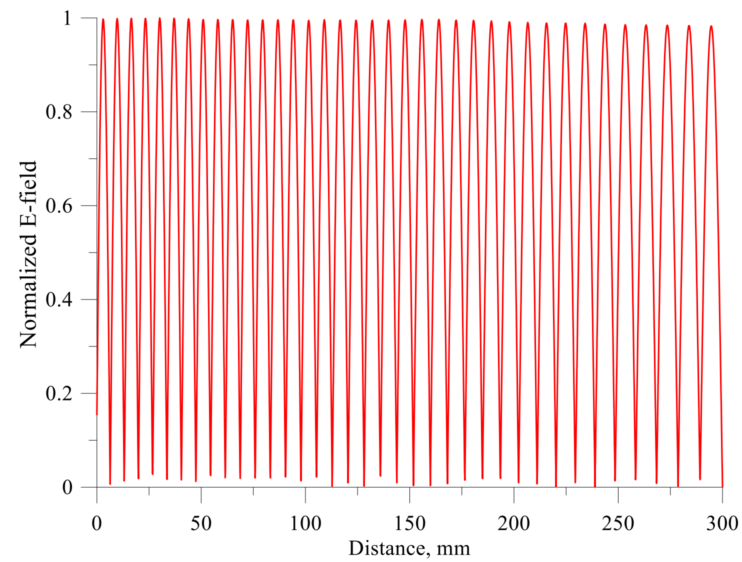
short pulse length allows ~1 GV/m fields;

transverse self-focusing might be provided.

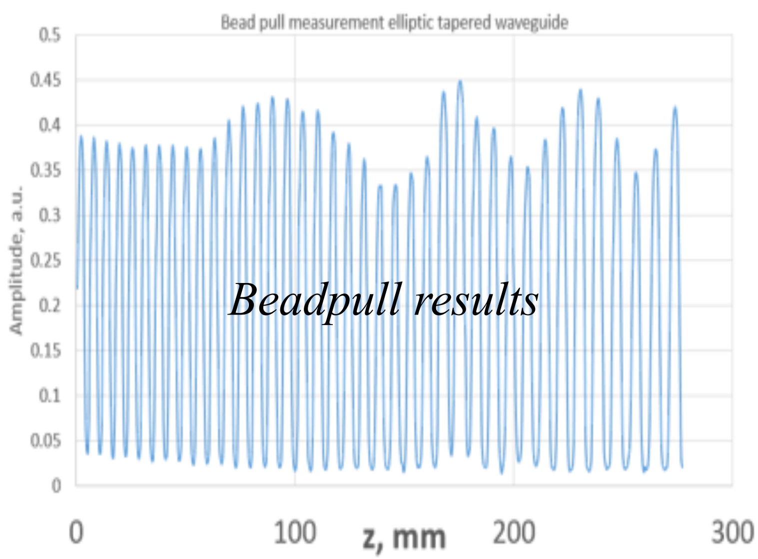
Strongly Tapered Standing Wave RF Undulator

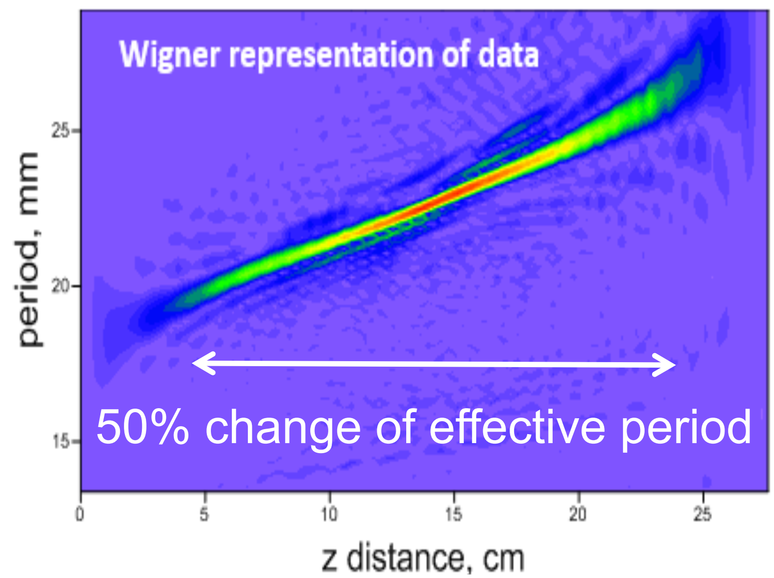


Elliptical TE_{11} tapered undulator.

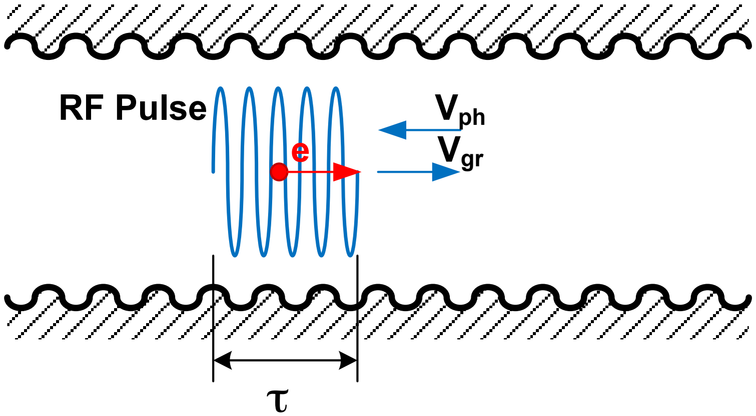


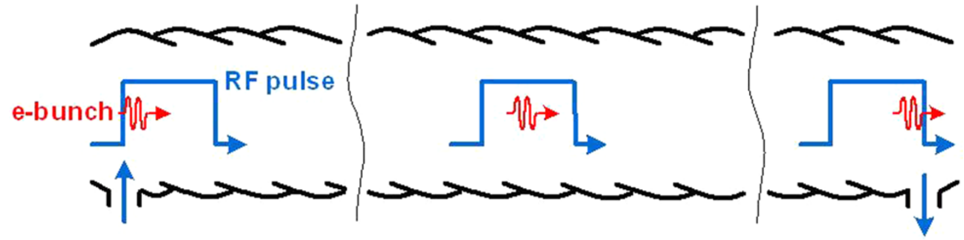
Field structure (calculation).





A Flying RF Undulator Concept





$$\lambda_u = 2\pi/(|h_{-1}| + k)$$ - effective period of undulator

$$h_0 > 0, \quad h_{-1} < 0, v_{gr} = \frac{\partial \omega}{\partial h_0} > 0.$$

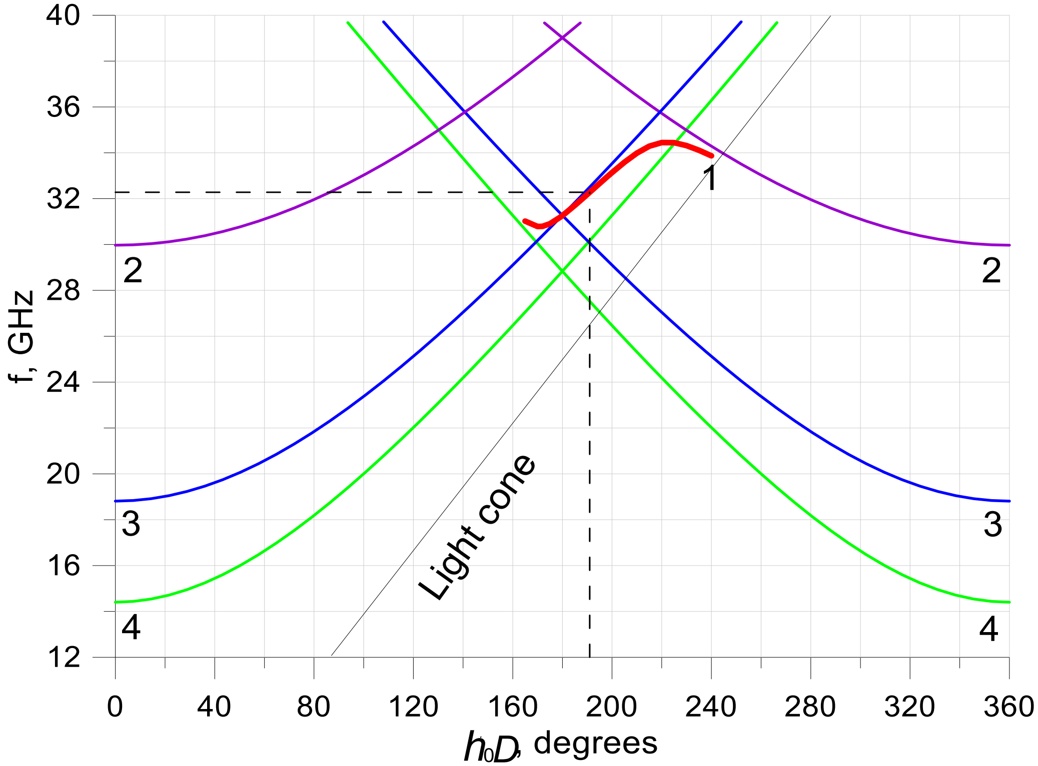
•In a flying undulator the high-power travelling wave (1-10 ns) co-propagates with electrons. Electrons wiggle in a field of the -1st space harmonic which has negative phase velocity.

•The mentioned travelling wave can be excited by already existing BWOs (10-30 GHz, 1 GW, 10 ns) so that undulator parameter can be as high as ~1.

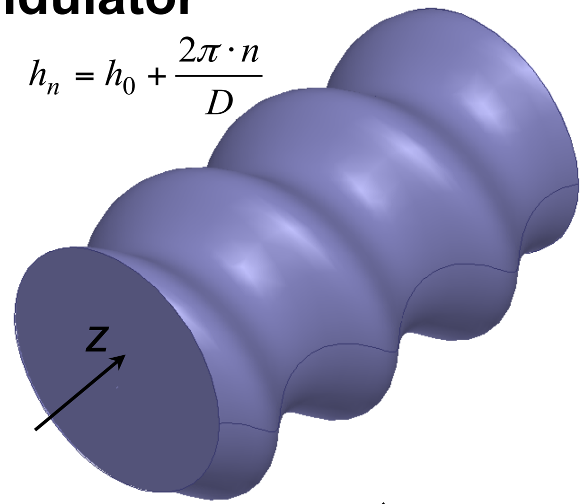
•S.V. Kuzikov, A.V. Savilov, and A.A. Vikharev Appl. Phys. Lett. 105, 033504 (2014).

euclid TECHLABS

Helical Flying TM_{01} - TM_{11} Undulator



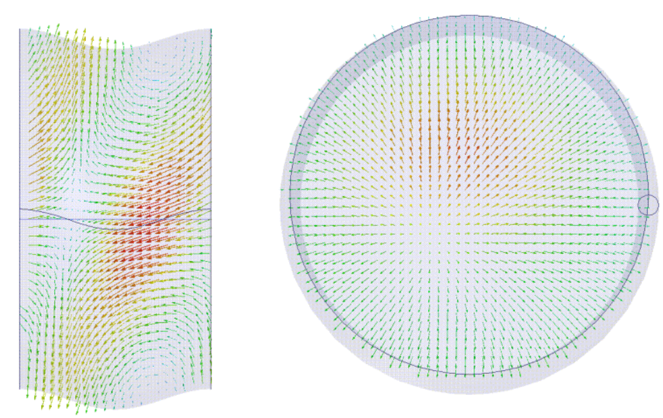
$$h_n = h_0 + \frac{2\pi \cdot n}{D}$$

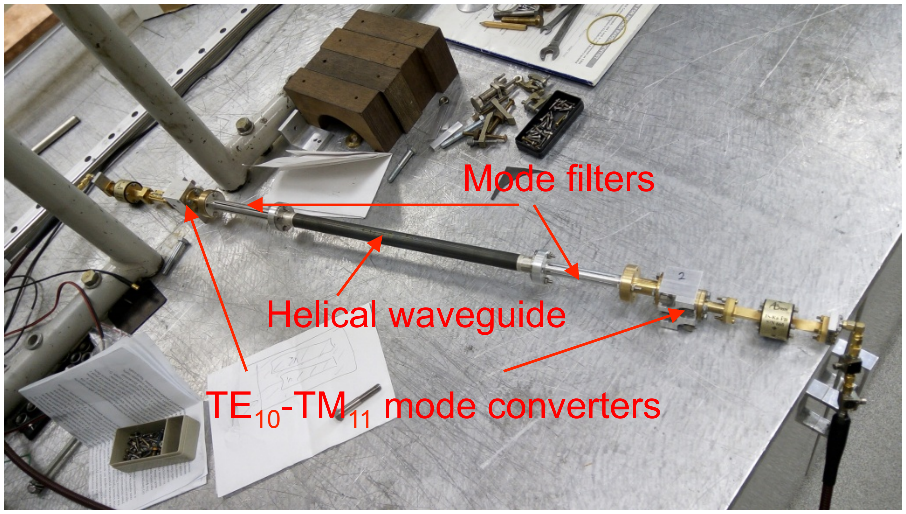


$$r(z,\varphi) = R_0 + a \cdot \sin\left(2\pi z/D + \overline{m}\varphi\right)$$

1 – operating normal wave
2 – partial TM11 mode
3 – partial TM01 mode
4 – TE11

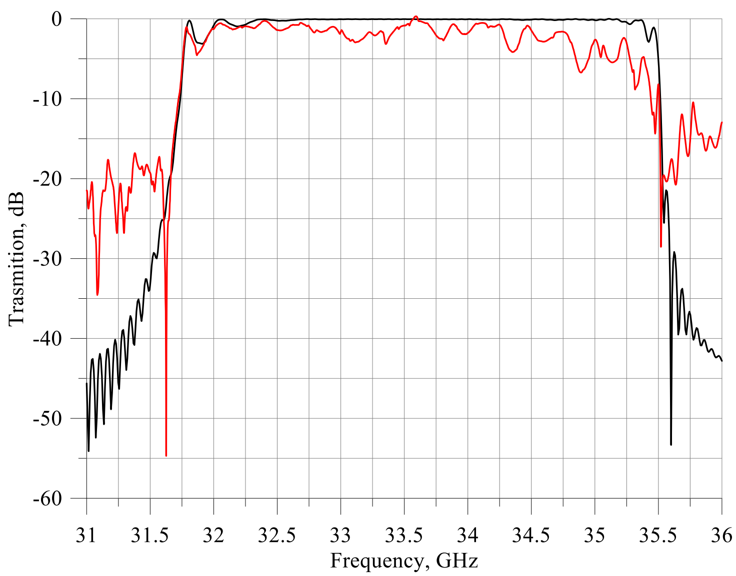
The eigen mode consists of superposition of TM_{01} mode (0^{th} harmonic) and dipole mode (-1^{st} harmonic).



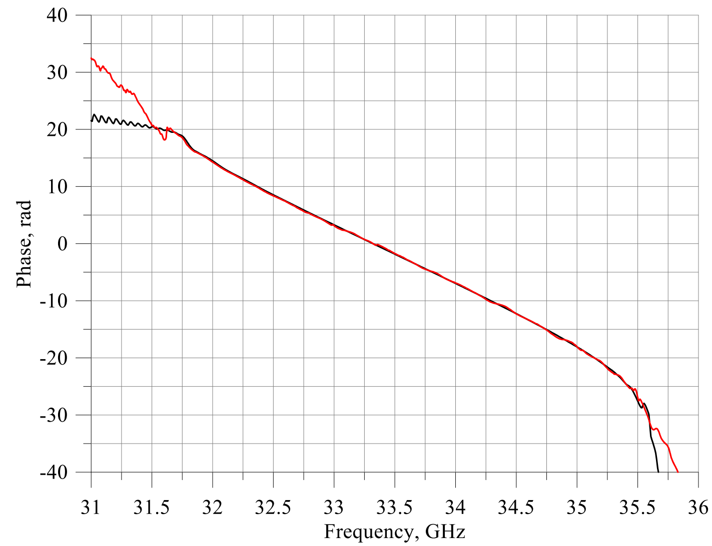


Transmission measurement scheme

Reflection measurement scheme



Transmission of the TM_{01} wave through helical waveguide section: calculation (black), measurement (red).

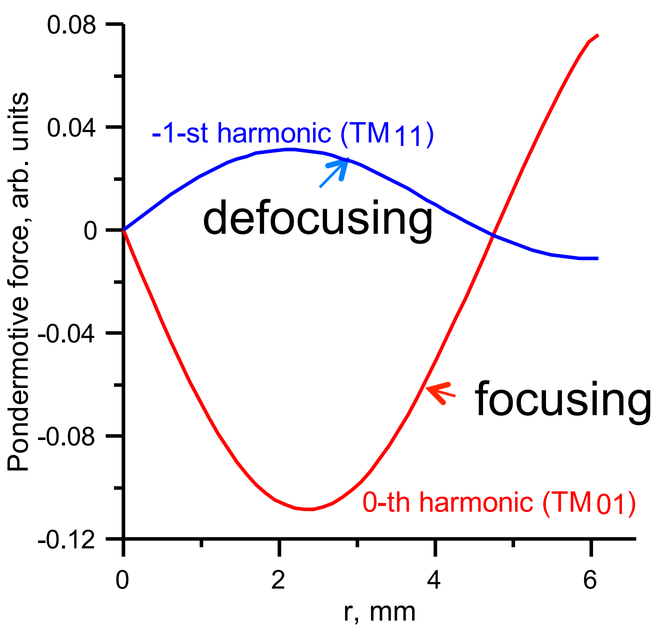


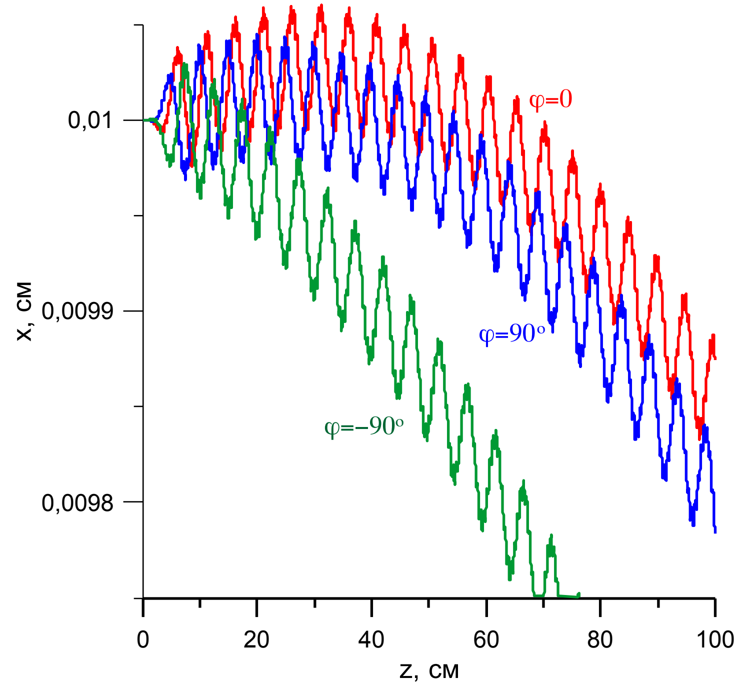
Phase of transmission: calculation (black), measurement (red).

Transversal Focusing of Electron Bunch

Electrons see focusing 0-th harmonic, TM01 (or quadropole TE_{21}), and weak defocusing -1-st harmonic (TM11):

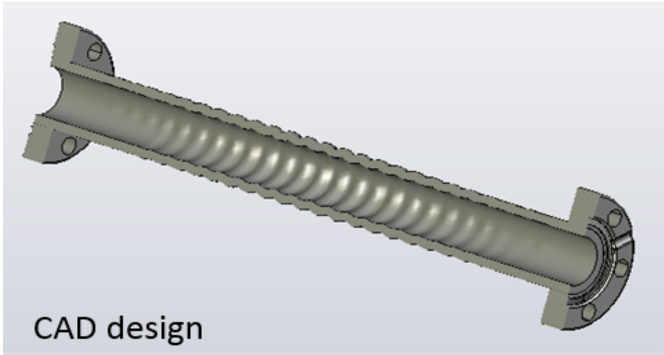
$\vec{F}_M = -\frac{e^2}{4m\omega^2}\nabla\left|\vec{E}\right|^2$ - Pondermotive Miller's force



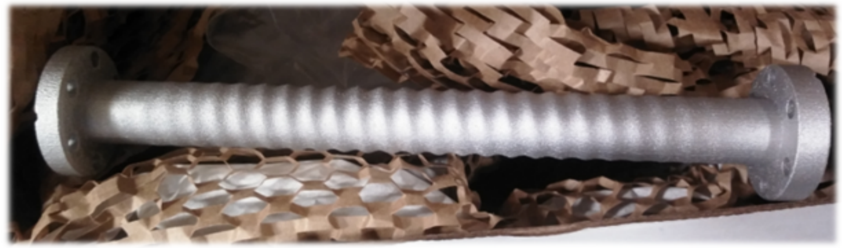


Simulation of particle dynamics with transversal motion taken into account

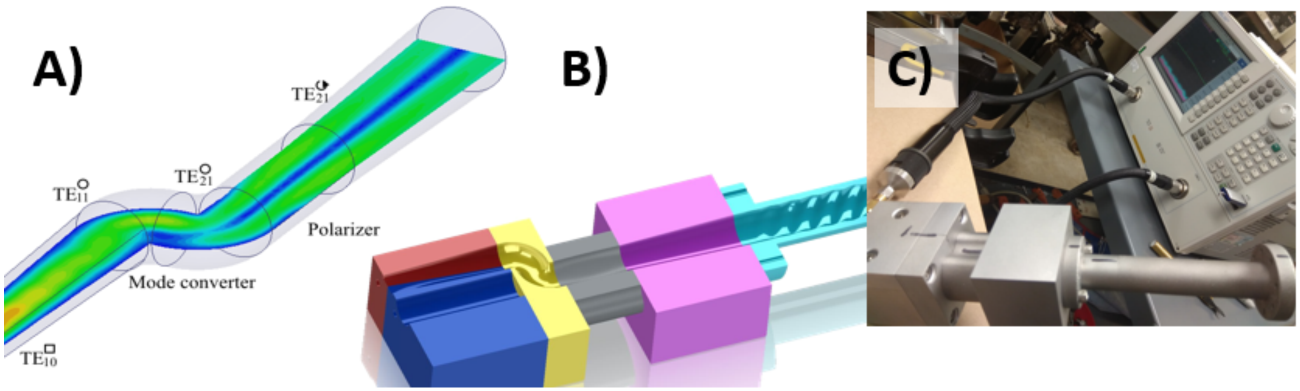
Ka-Band Tapered (15%) Helical RF Undulator



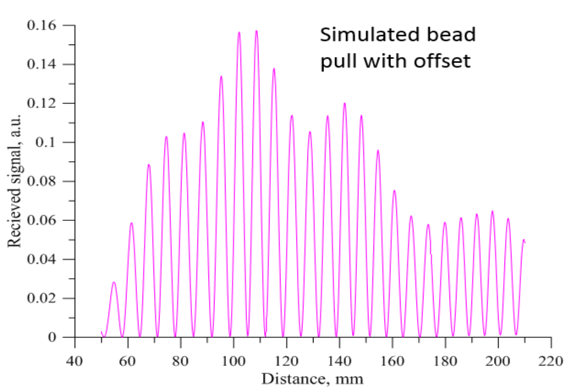
CAD design

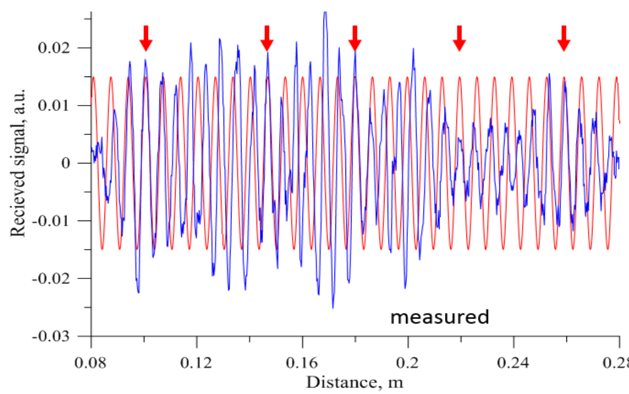


DMLS printed from Aluminum



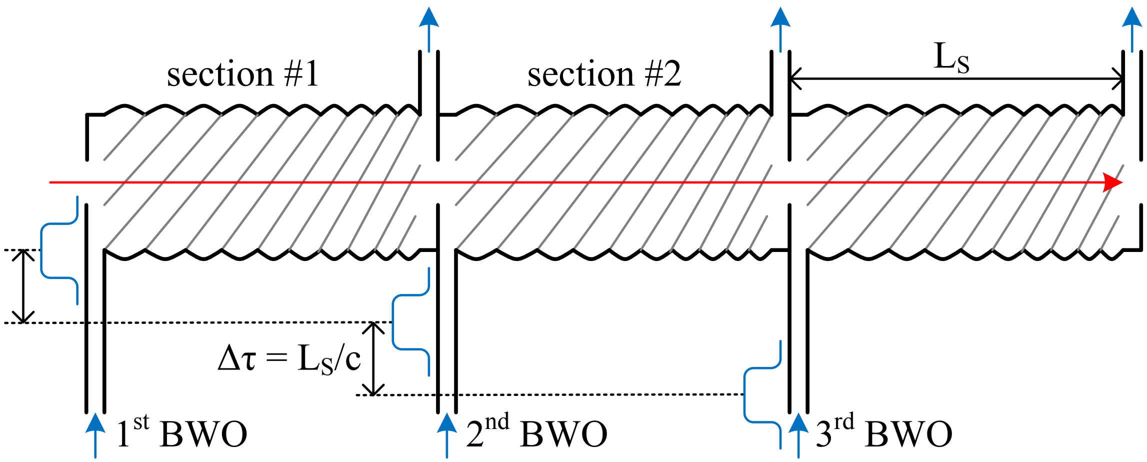
Cold test mode launcher from a standard rectangular waveguide TE_{10} mode into circularly polarized TE_{21} mode.

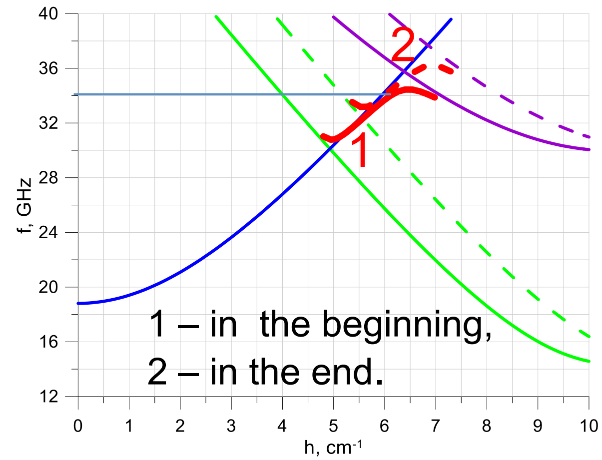




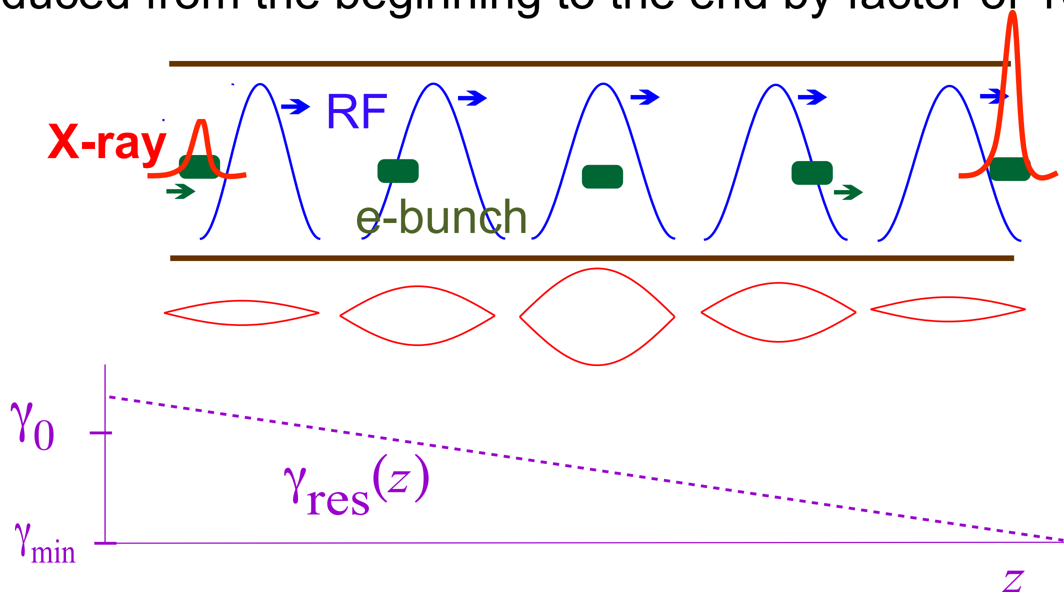
TE_{11}-TE_{21}-TM_{11} undulator field balance. *Left: simulation with 0.5 mm bead offset from centerline. Right: Bead pull measurement (blue) and constant period sine function (red).*

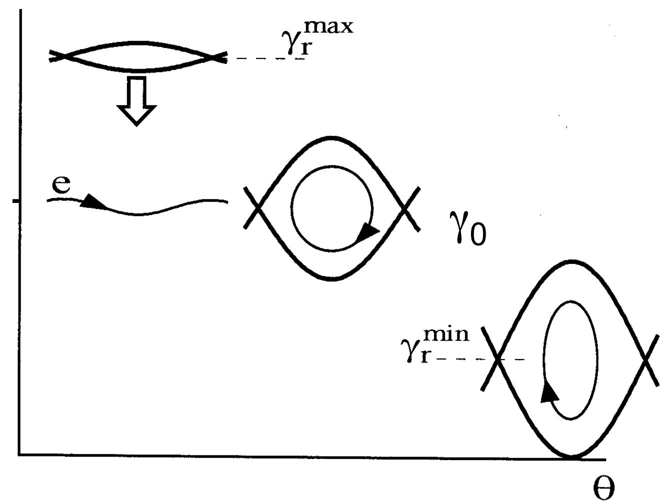
Non-Resonant Trapping with Tapered Flying RF Undulator





Sketch of XFEL amplifier consisted of helical sections wherein undulator period is gently reduced from the beginning to the end by factor of 10-50%.

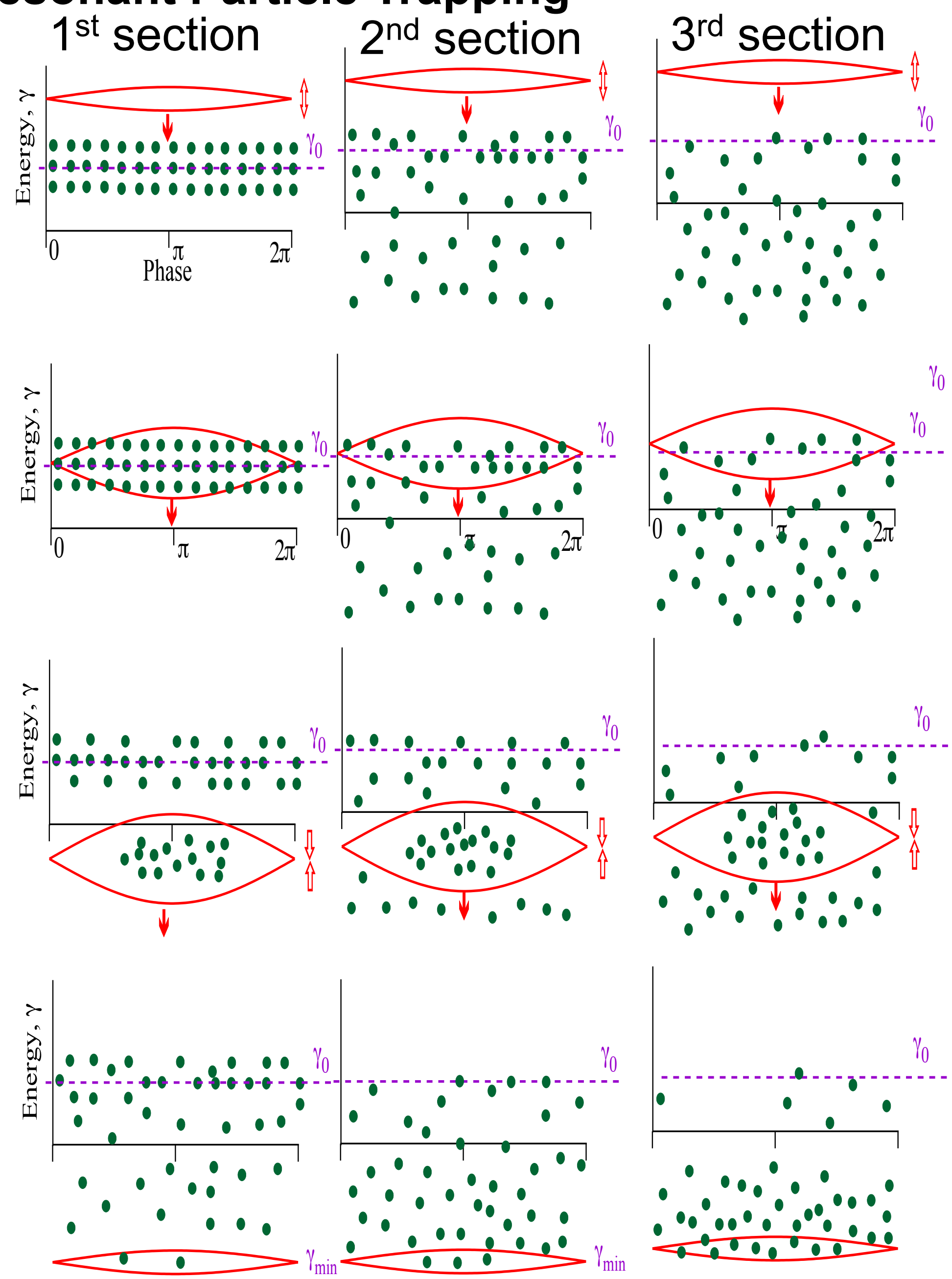




Interaction of trapped electrons with combination wave (forward X-ray + backward RF) in frame of a single helical undulator section.

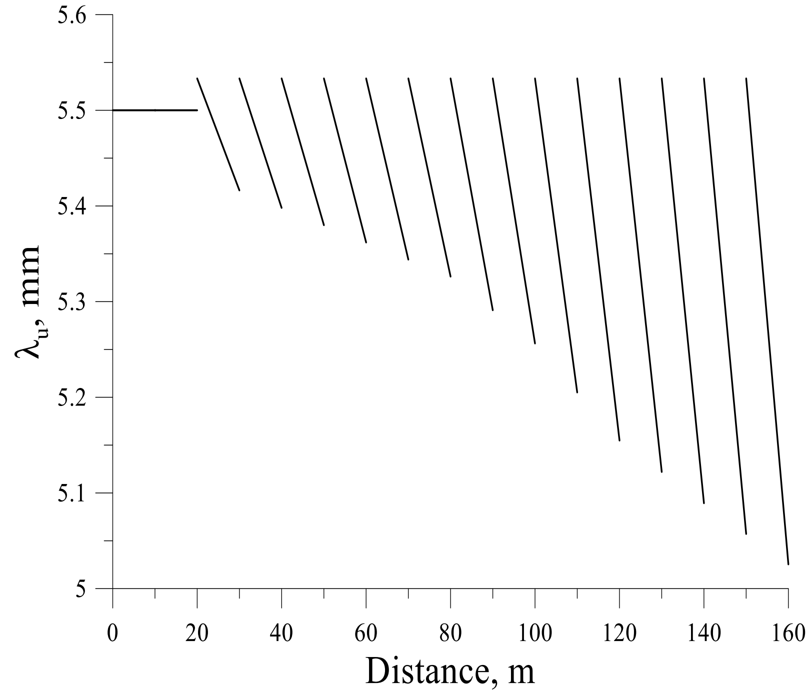
Sketch of Non-Resonant Particle Trapping

- In the beginning of each section the resonant condition is satisfied for high energetic electrons only, then period changes so that in the center most electrons can be in resonance with combination wave, in the end the capturing "eye" goes down to low energetic resonance.
- The non-resonant trapping allows using BWOs instead of more expansive and less powerful klystrons, because no need to lock phase of RF sources.
- Efficiency could be high even taking into account large energy spread.
- The particular shape of *K*(z) is not much important.

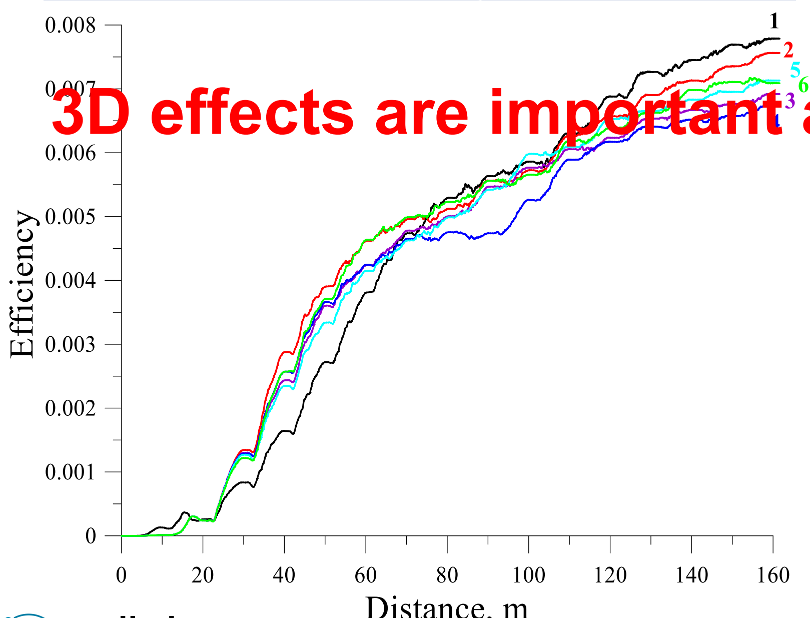


First 1D theory simulations of 2 nm FEL

Parameters:	
Bunch energy	600 MeV
X-ray wavelength	2 nm
Charge	100 pC
Bunch length	0.17 ps
Bunch diameter	30 μm
Energy spread	0.1%
Section length	10 m
Number of sections	16
K_{max}	0.25



Effective undulator period.



3D effects are important and must be taken into account!

Efficiency of lasing along FEL for in-phase undulator sections (black curve#1) and for 5 different sets with randomly distributed phases (curves 2-6).

Summary

1. **High efficiency (~10%) is achievable in presence of the considerable energy spread, but *3D effects must be taken into account*.**

2. **The higher necessary efficiency the stronger tapering is required in last sections.**

•Tapering of *K*-parameter is not convenient in RF undulator (if one tries to vary an amplitude of RF wave, it will automatically change period).

•The magnitude of *K*-tapering is limited.

•Variations of *K* lead to variations of electron-wave interaction strength.

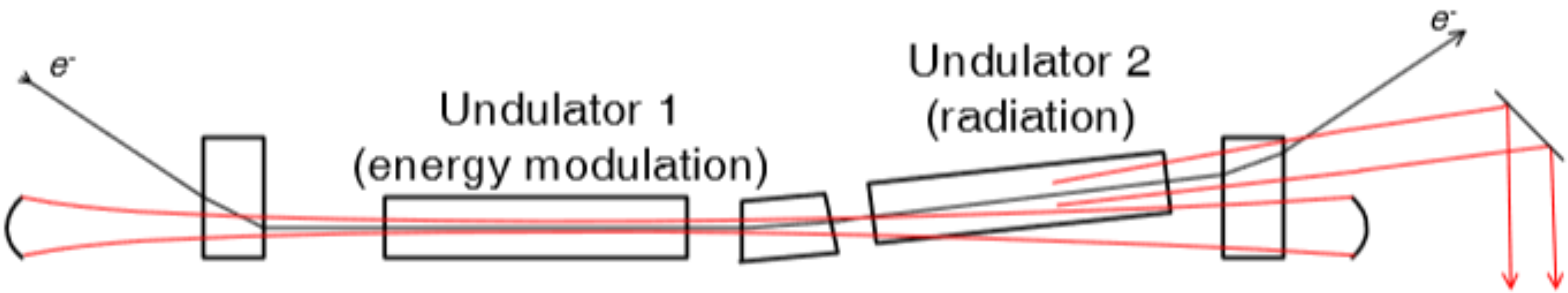
•Tapering of the undulator period is inevitable.

3. **Tapering is not efficient until X-ray wave amplitude is low.**

•Non-resonant trapping regimes assume rather long FEL (but price per meter is less!).

•Short, compact, high current bunches produced by laser-plasma accelerators is appealing even taking into account large energy spread (~10%).

A NEW XFELO WITH SELF-MODULATED Q-FACTOR



Electron out-coupling scheme with two undulators and bending section between them (Novosibirsk)*.

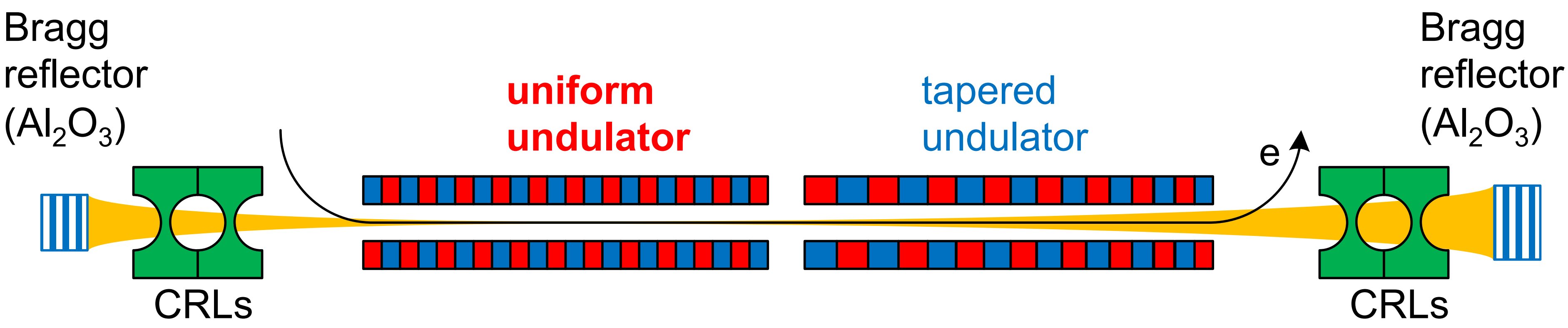
Advantage --- XFELO easily starts.

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

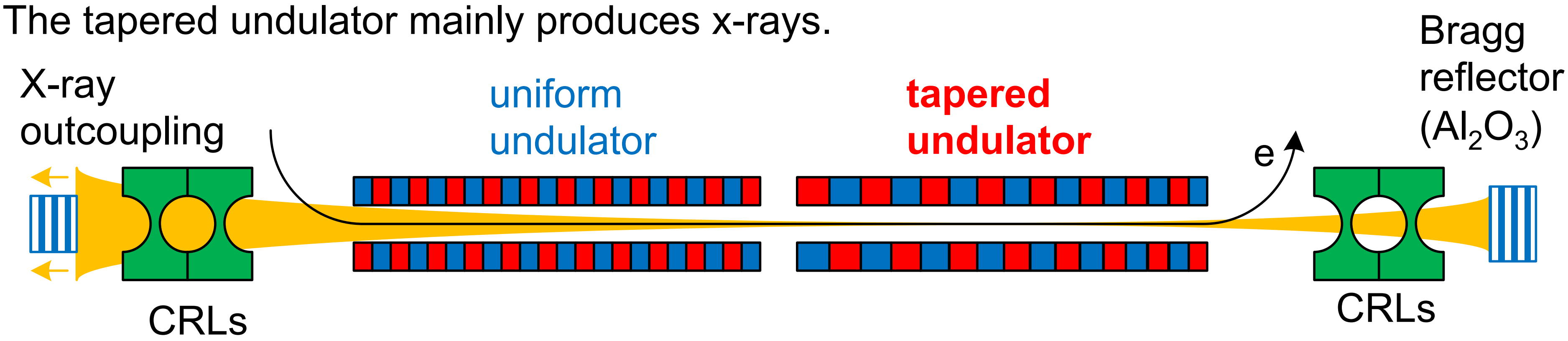
*A.N. Matveenko, O.A. Shevchenko, V.G. Tcheskidov, N.A. Vinokurov. ELECTRON OUTCOUPLING SCHEME FOR THE NOVOSIBIRSK FEL , Proceedings of FEL 2007, Novosibirsk, Russia, TUAAU02.

XFELO Optical Resonator with Self-Modulated Q-Factor

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



1) 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 the amplification 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).

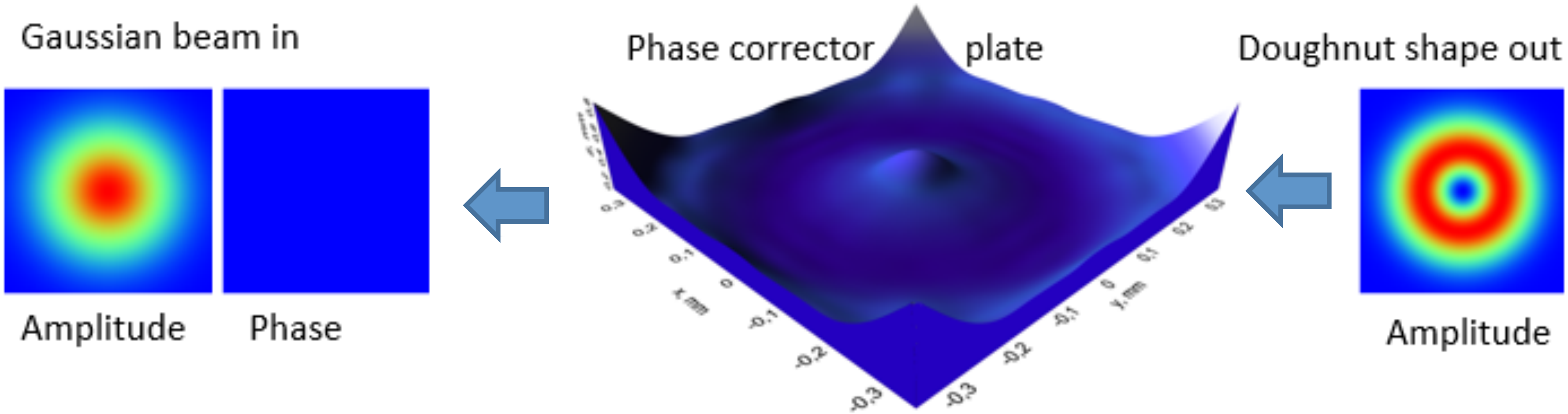
This conditions means that Pierce parameter must be as large as to satisfy:

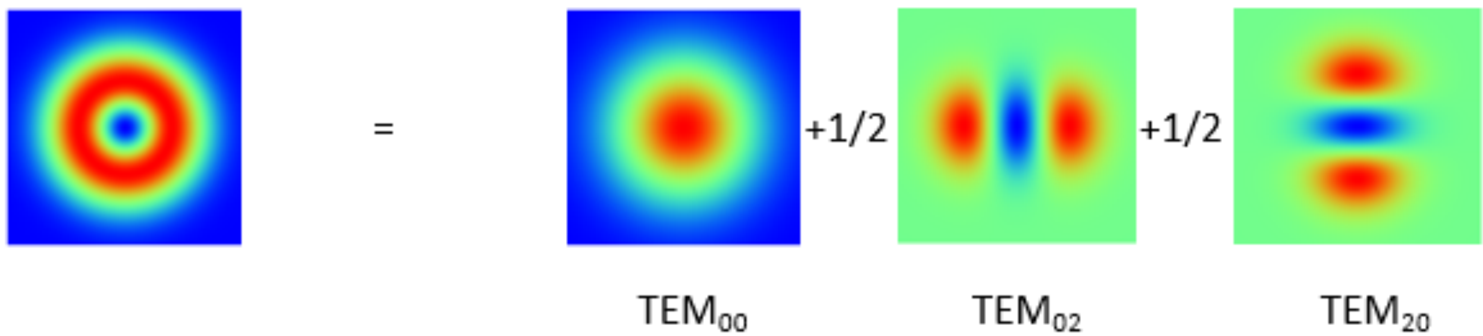
$$exp(L_{tu}/L_{gain}) >> P_{out}$$

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.

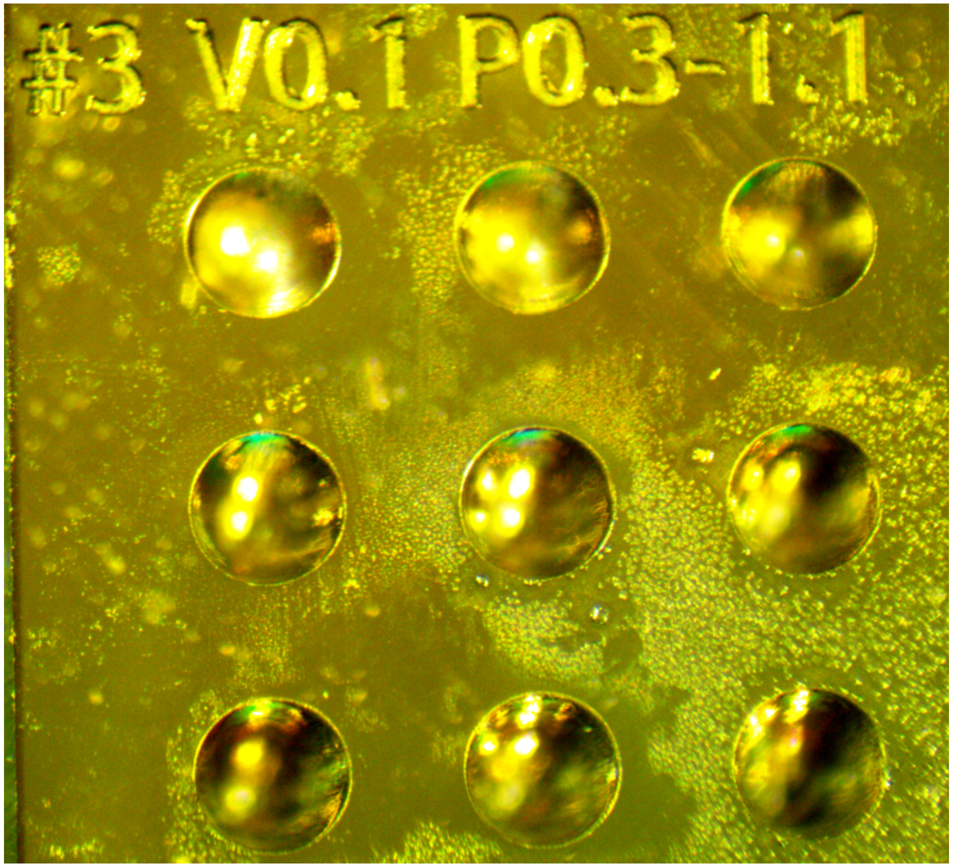




A Gaussian beam is converted into a mix of three free space eigenmodes that combine to form the doughnut shape.

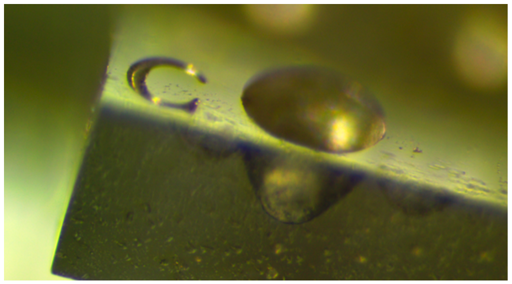
The phase plate is assumed to be made of diamond.

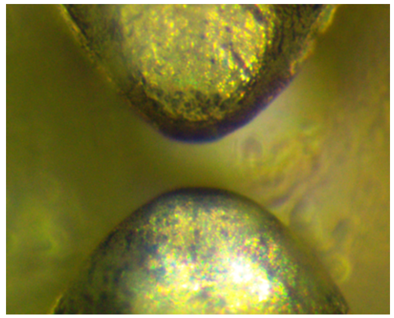
Diamond Refractive Lens

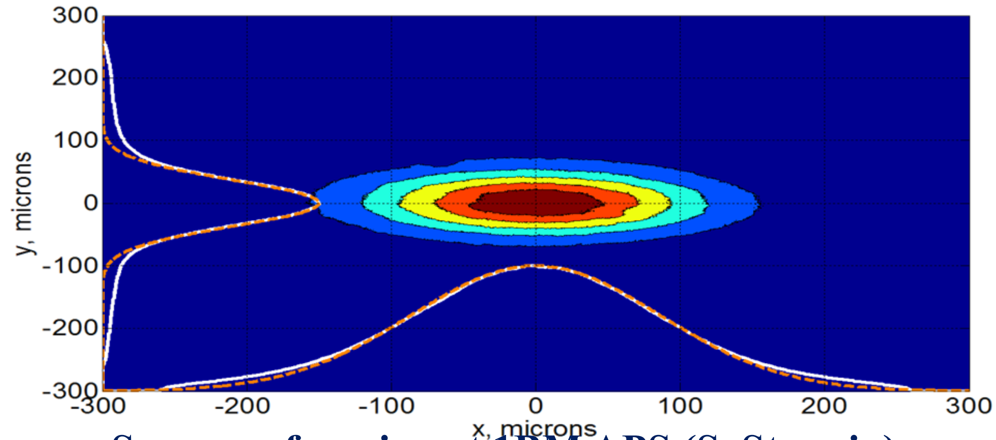


- Why?
  - High [peak/average] heat load / thermal stability
  - Single crystal possible vs polycrystalline beryllium
  - Radiation damage
- How?
  - fs-laser ablation of diamond
  - post-polishing

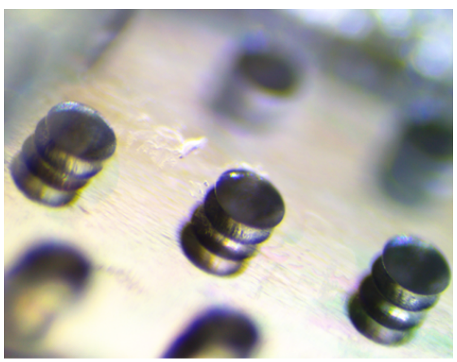
Diamond CRL

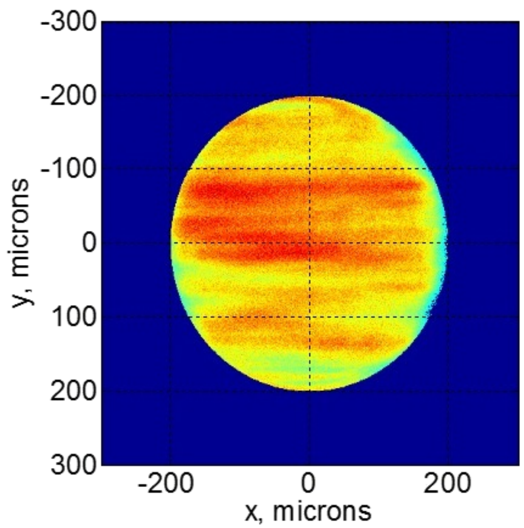


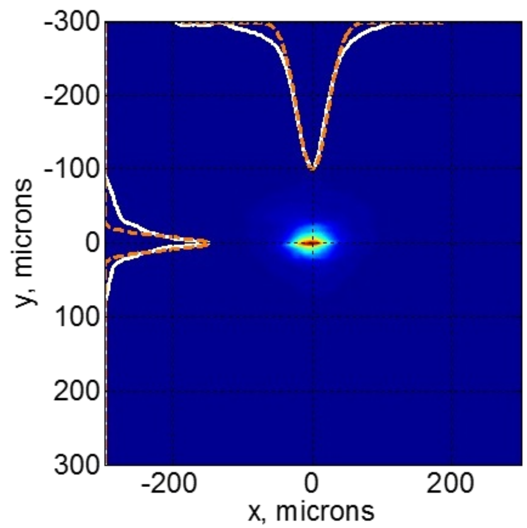




Source refocusing at 1BM APS (S. Stoupin)
Gain **5.71**$_{theory}$ vs **2.83**$_{exp}$



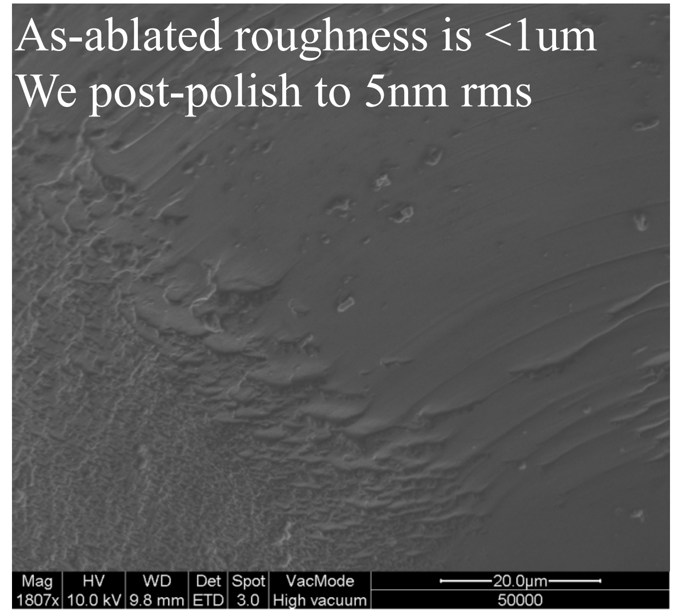


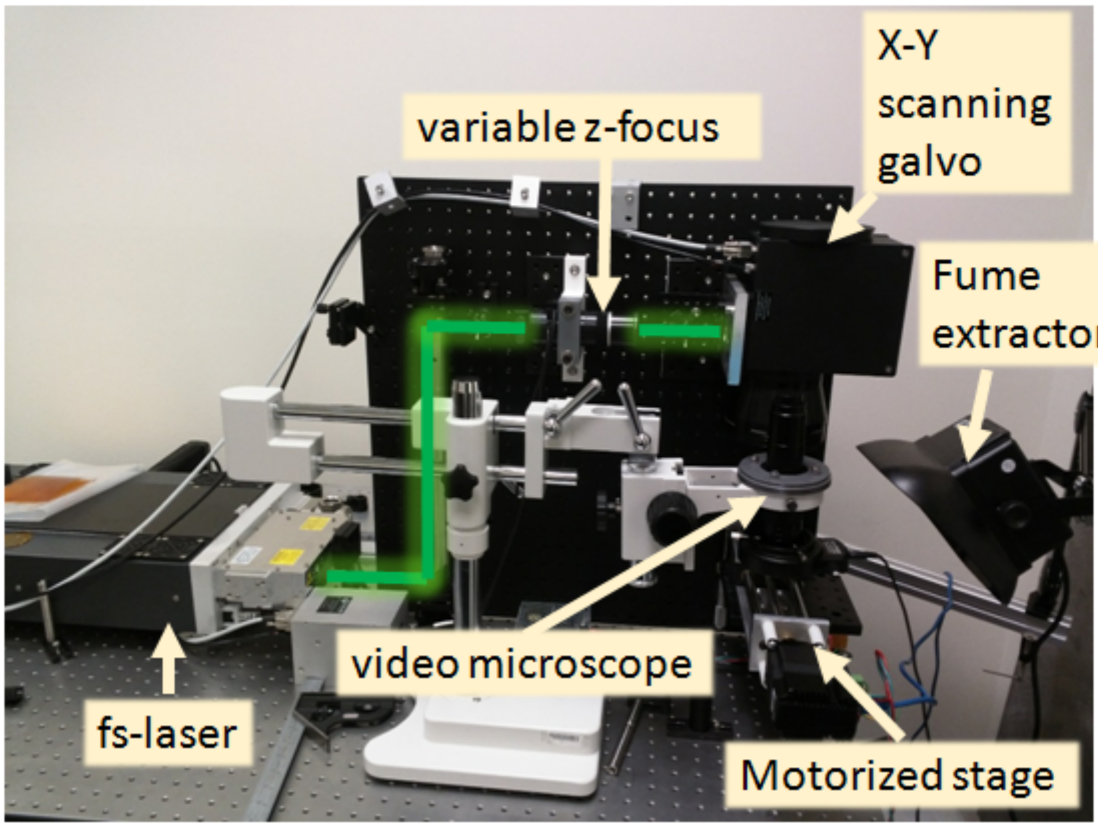


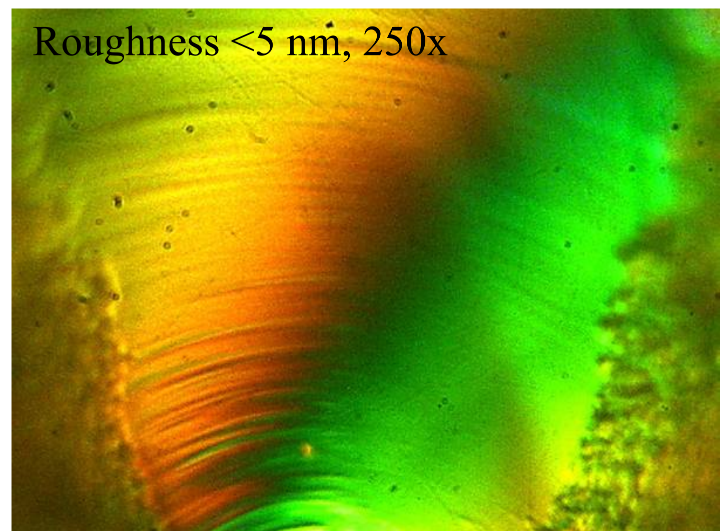
X-ray: **11.85 keV**
ID – Lens **62m**
R = **105 um**
f = **3.36 m** (3 lens)
Pinhole = **400 um**
Focused beam:
24.5 um x 17.6 um
Gain 50-100

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

Femtosecond lens cutter and polishing development@Euclid







Summary

- The tapered flying RF undulator is a cheap and robust solution for a high-efficient XFEL.
- A concept of the XFELO with self-modulated Q-factor allows XFELO easy to start up and to provide high efficiency at steady state condition due to trapping regime.
- Smart diamond CRLs and phase plate converters are under investigation at Euclid.

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