Development of powerful long-pulse THz-band FEL driven by linear induction accelerator

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Motivation: powerful long-pulse FELs for potential applications

- *Aim of our work*: ***Development of* powerful narrow-band source *operating from* sub-THz *to* THz band *for* actual applications**

  - ***THz accelerators***
  - ***Pumping systems for Compton FELs***

  ⟹ *compact X-ray sources (XFELs)*

  ***requires narrow-band sources** with*

  - *operating frequencies* from ~ **0.3 THz** to **1 THz** *and higher*
  - *output power* of ~ **sub-GW** to **GW level**

- *Key problems in the FEL development, include*:

- **accelerator and electron-optical system, *which provide formation of* driving beam *able to operate* at sub-THz to THz frequencies**
  (having high oscillation frequency and acceptable spread of parameters)

- **electrodynamic system: high-selective resonator**
  ***responsible for narrow-band (single-mode) operation* in strongly oversized oscillator**

Outline

✓ **Design parameters of sub-THz/THz FEL**
based on linac LIU **(BINP RAS, Novosibirsk) 2 - 20 MeV / 2 kA / 200 ns**

✓ **Result of simulations and "cold" tests of components**

- electron-optical and magnetic system (***helical undulators***)
- electrodynamic system based on ***advanced Bragg resonators***

✓ **Resent proof-of-principal W-band FEM experiments**
at linac LIU-3000 **(JINR, Dubna) 0.8 MeV / 200 A / 200 ns**

✓ **State of experimental realization at 300 GHz and 600 GHz**

✓ **Summary and Discussions**

Project of powerful long-pulse sub-THz/THz Bragg FEL

P.V.Logachev, G.I.Kuznetsov, A.A.Korepanov, e.a.

- **family of Linear Induction Accelerators «LIU» (BINP RAS, Novosibirsk)**

electron energy	2 MeV →	5 MeV →	20 MeV
beam current		1 - 2 kA	
pulse duration		200 ns	
undulator period		3 - 6 cm	
operating frequency	250 GHz →	1 THz →	10 THz
output power		~ 100 MW	
electron efficiency	3 - 5%	1 - 2%	0.1 - 0.2%

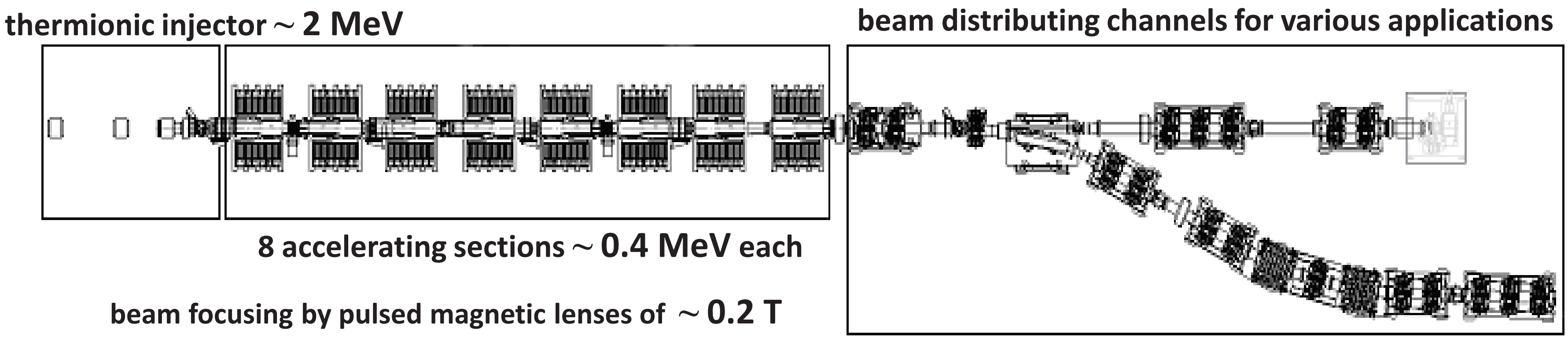
Doppler up-conversion $\sim\gamma^2$

operating velocity $v_\perp \sim \gamma^{-1}$

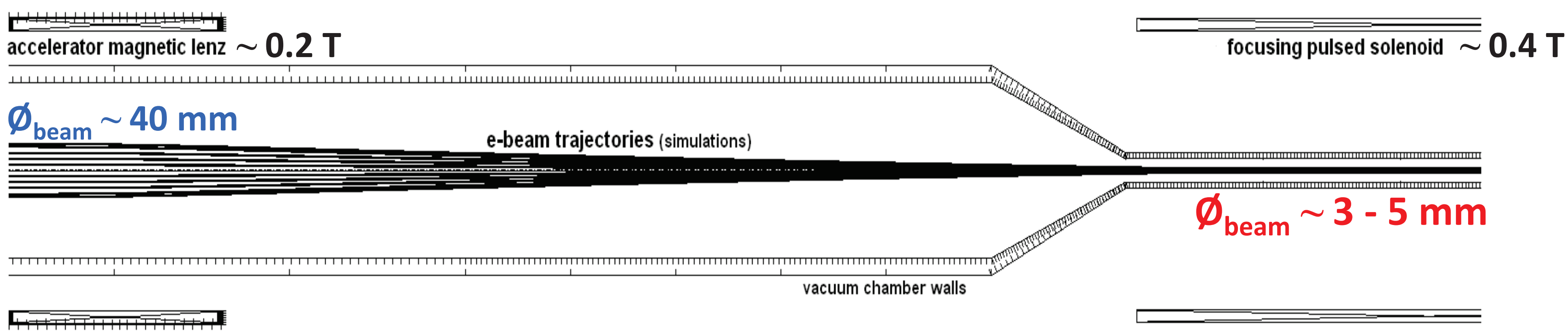
electron bunching parameter $\mu \sim \gamma^{-2}$

electron efficiency $\eta \sim N^{-1}$

induction linac LIU-5 5 MeV / 2 kA / 200 ns

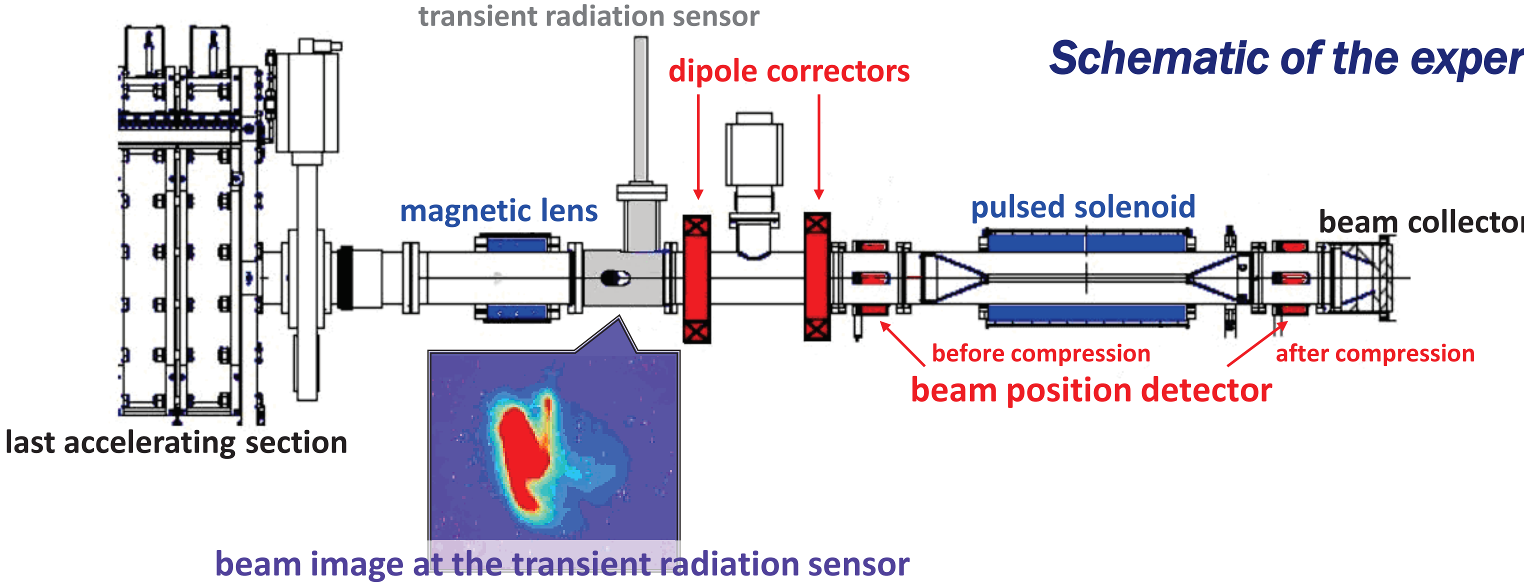


scheme of beam injection into the FEL interaction space



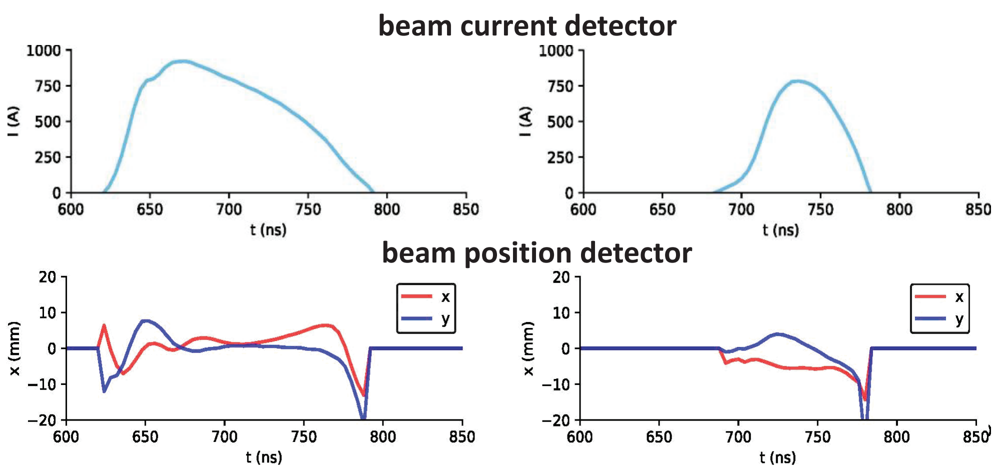
Experiments on beam compression at BINP

Schematic of the experiment

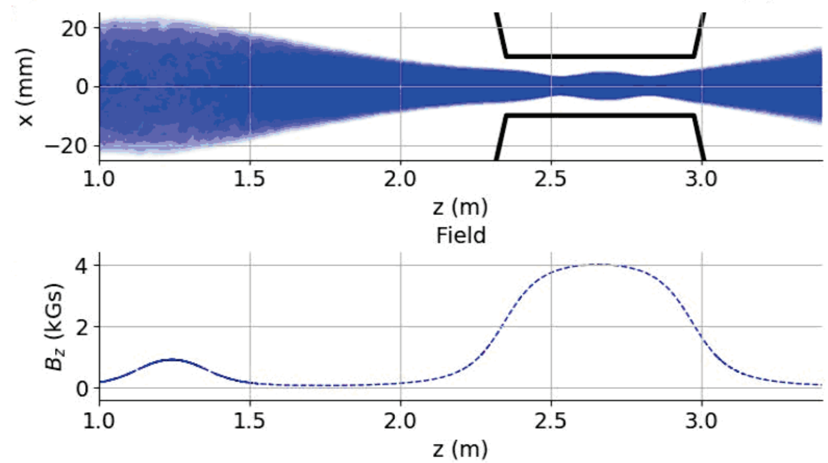


Results of the experiment

before compression *after compression*



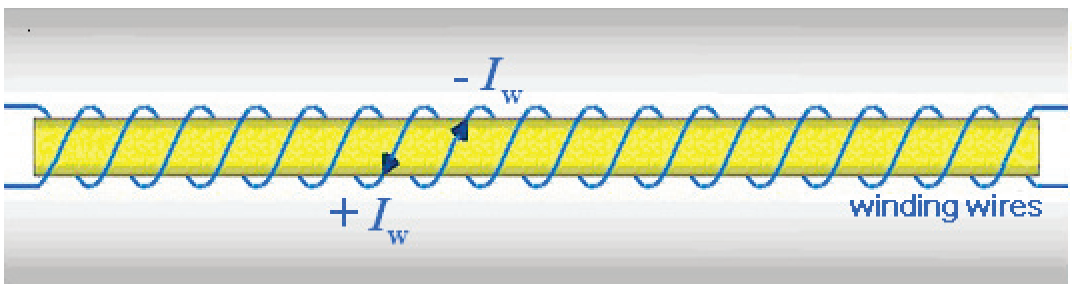
Simulations of beam compression

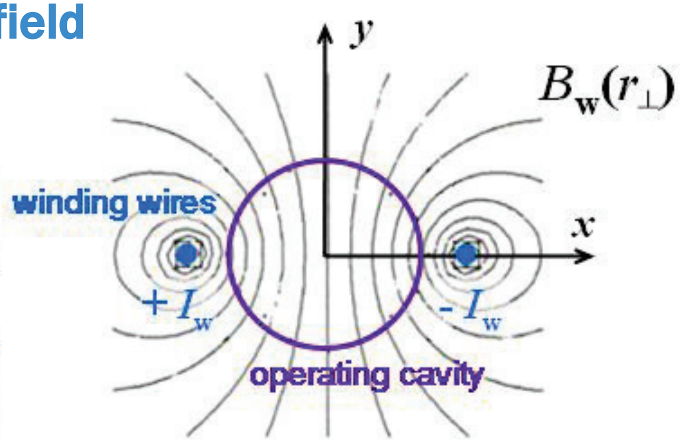


parameters of the undulators	$d_u = 3$ cm	$d_u = 6$ cm	$d_u = 10$ cm
FEL operating frequency f	1.1 THz	0.6 THz	0.3 THz
length of input/output section L_{in} / L_{out}	18 cm / 9 cm	36 cm / 18 cm	60 cm / 30 cm
diameter of the regular section D_u	14 mm	28 mm	48 mm
length of the regular section L_{reg}	60 cm	90 cm	120 cm

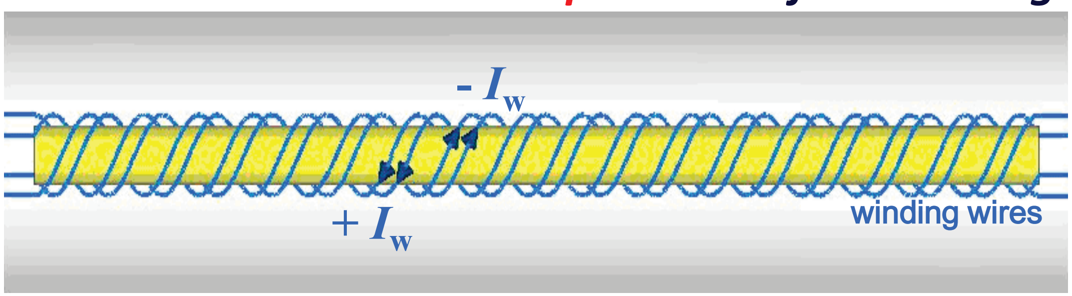
➤ Optimization of transverse structure of undulator field

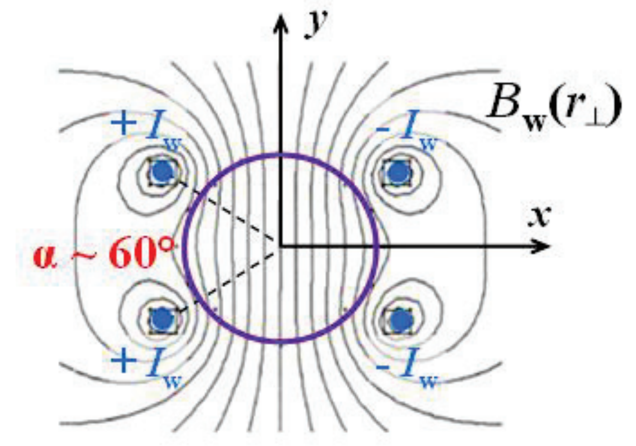
helical undulator with bifilar winding





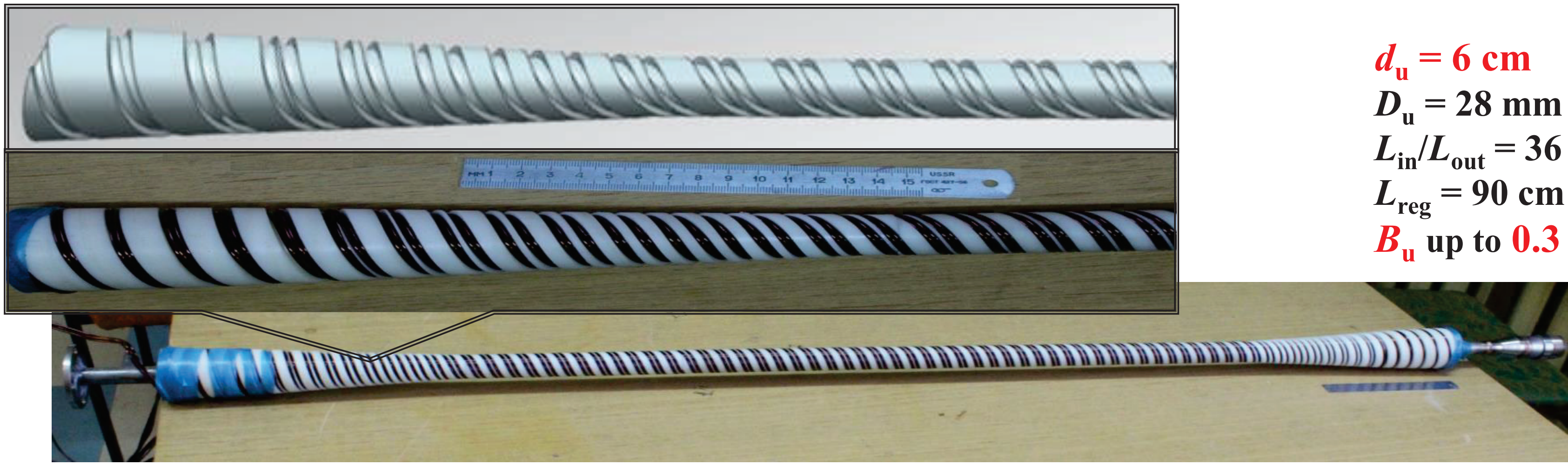
helical undulator with «improved» bifilar winding





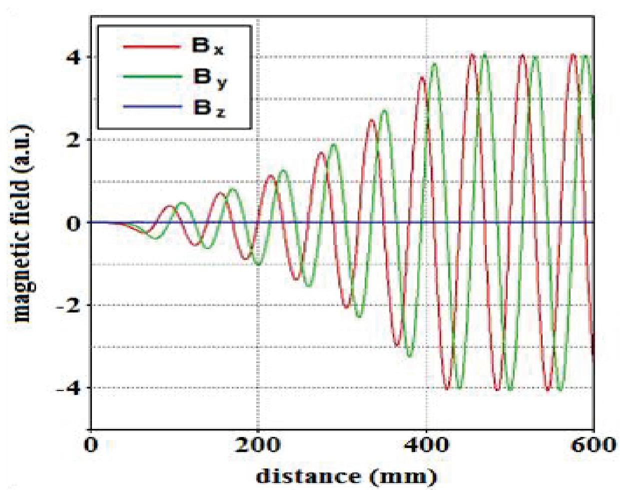
Optimization of up-tapered entrance section *by combination of two methods*:

- increasing distance of the wires from axis (using conical section)
- converging opposite current wires to each other

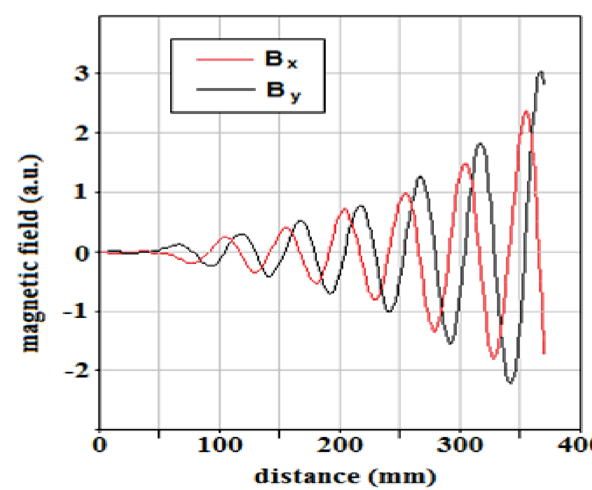


d_u = 6 cm
D_u = 28 mm
L_{in}/L_{out} = 36 cm
L_{reg} = 90 cm
B_u up to 0.3 T

3D simulations (CST "Microwave Studio")



«cold» magnetic measurements



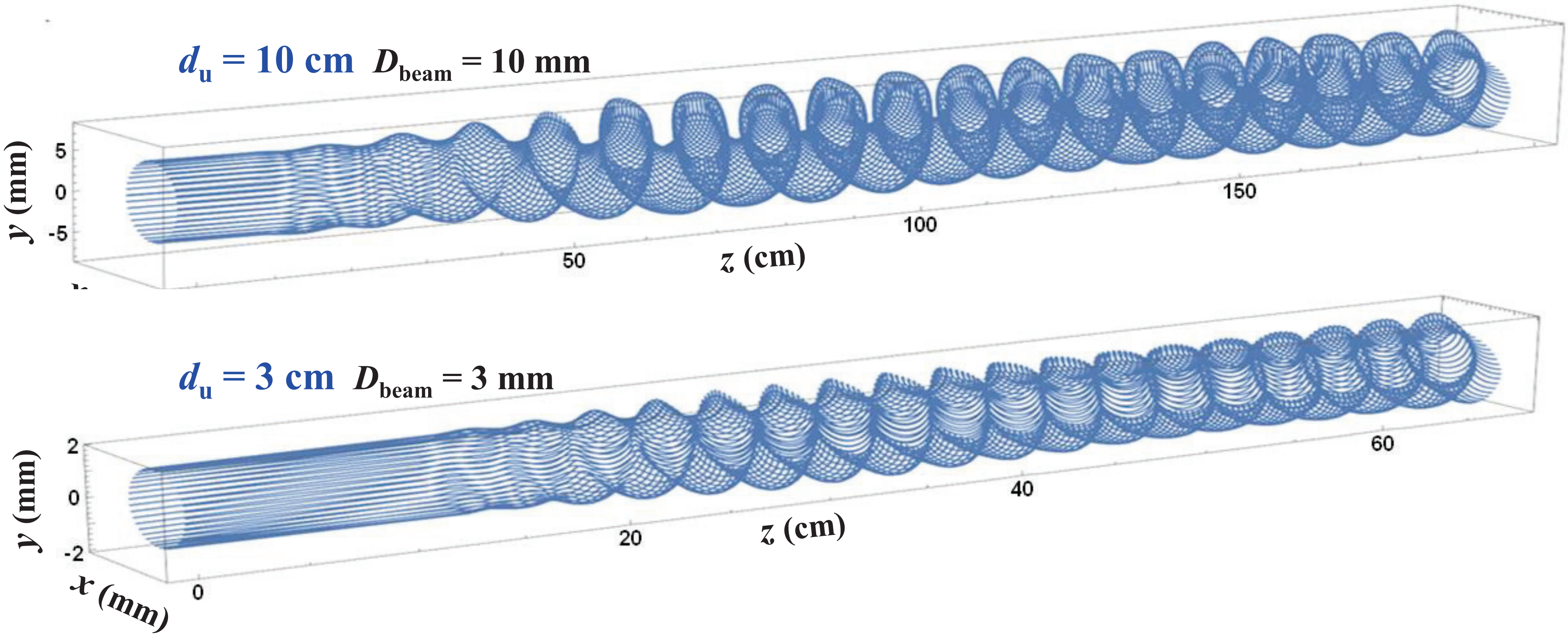
Simulations of beam dynamics in «improved» helical undulator

5 MeV / 2 kA

$B_u \sim 0.25$ T

$B_0 \sim 0.4$ T

reversed guide field regime



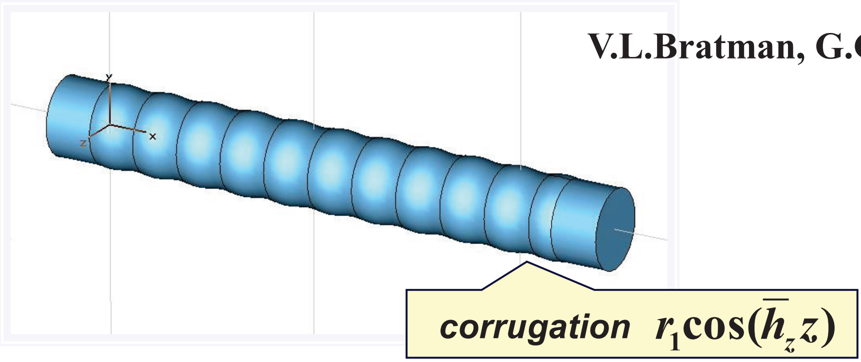
formation of helical electron beam for driving FEL-oscillator $\beta_\perp \sim 0.1$ $\dfrac{r_{cycl}}{R_{bounce|}} \leq 2-2.5\%$

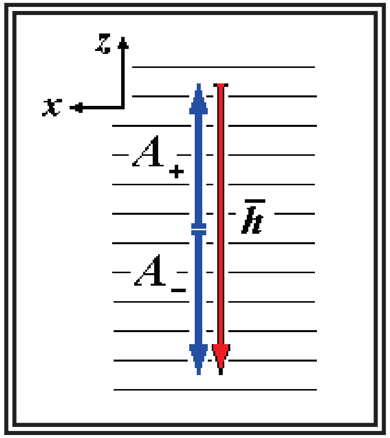
How to provide narrow-band (single-mode) operating regime in strongly oversized FEL-oscillator?

➢ **Development of high-selective oversized resonator**

«conventional» microwave Bragg resonators

V.L.Bratman, G.G.Denisov, N.S.Ginzburg, N.F.Kovalev, M.I.Petelin (1980)





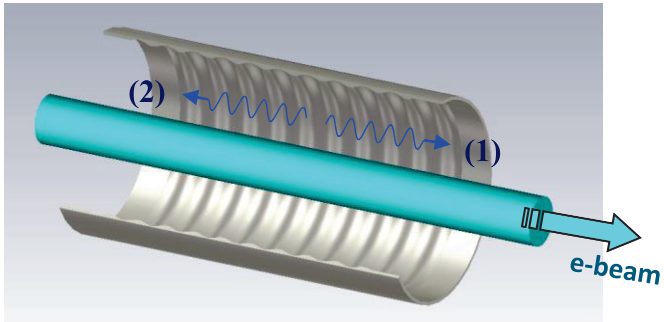
provides coupling of two counter propagating partial waves $A_+ e^{-ih_+ z} \oplus A_- e^{ih_- z}$

under the Bragg resonance condition $h_+ + h_- = \bar{h}$

- «+» ***possess good compatibility with intense electron beam transportation***
- «+» ***provide mode selection over longitudinal coordinate***
- «-» ***lose selectivity over transverse coordinate in oversized cavity***

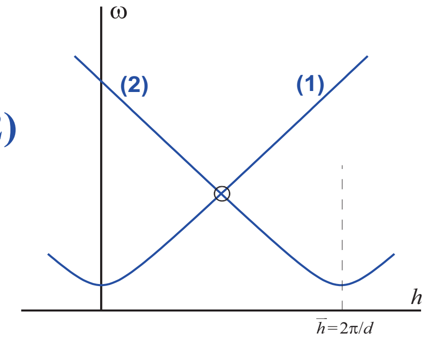
Bragg resonators of different types

«conventional» microwave Bragg resonators



coupling of *propagating waves* (1) and (2)

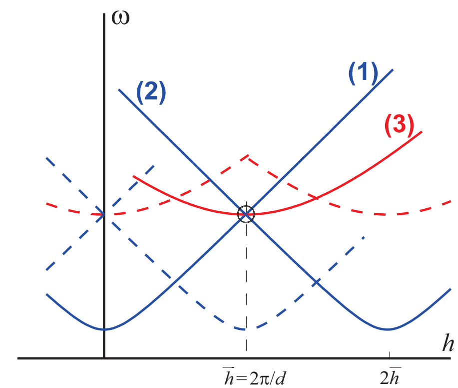
$$\bar{h} \approx 2h_{conv} \quad d \approx \lambda/2$$

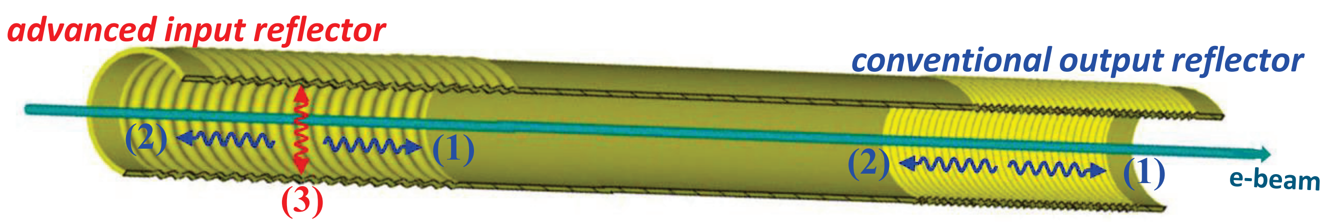


«advanced» Bragg resonators

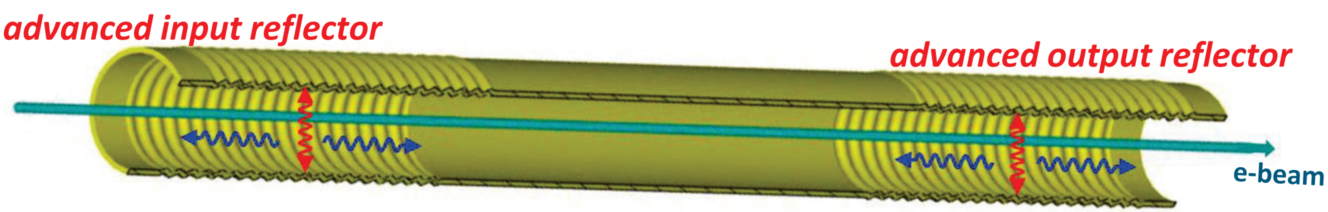
coupling of *propagating* (1, 2) and *cutoff* (3) ***waves***

$$\bar{h} \approx h_{adv} \quad d \approx \lambda$$





Ø/λ ~ 5 - 7



Ø/λ ≥ 10

Advanced vs Conventional Bragg resonators

✓ **decrease in corrugation period** $d_{adv} \approx 2d_{conv}$

- ***beneficial from technological point of view***

✓ **waves coupling coefficients increase** ***for near cutoff waves*** $h_{\pm} \to 0$

$$\alpha = \frac{r_1}{2R_0} \frac{-\kappa_+^2 \kappa_-^2 R_0^2 + m_+ m_- \left(h_+ h_- + k_0^2\right)}{\sqrt{h_+ h_-} \sqrt{\left(\kappa_+^2 R_0^2 - m_+^2\right)\left(\kappa_-^2 R_0^2 - m_-^2\right)}} \qquad \mathbf{TE} \leftrightarrow \mathbf{TE}$$

$$\alpha = \frac{r_1}{2R_0} \frac{\omega\left(h_+ + h_-\right)}{c\sqrt{h_+ h_-}} \frac{m_H}{\sqrt{\kappa_H^2 R_0^2 - m_H^2}} \qquad \mathbf{TE} \leftrightarrow \mathbf{TM}$$

- ***decrease in corrugation depth (or length of corrugated section)***
  lead to increase of starting current for neighboring «parasitic» Bragg zone

✓ **purification of mode spectrum** ***when coupling of propagating and cutoff waves***

density of mode spectrum: $$\frac{\Delta\omega}{\omega} \approx \left(\frac{\lambda}{L_x}\right)^2$$ *for coupling of two paraxial waves*

$$\frac{\Delta\omega}{\omega} \approx \frac{\lambda}{L_x}$$ *for coupling of propagating and cutoff waves*

L_x - transverse size of the system

- ***increase in distance between neighboring Bragg zones***
  (in comparison with the FEM amplification band)

«+» **provide discrimination of parasitic modes** ***and*** **improve selectivity over transverse coordinate**

FEM with advanced Bragg resonator. Modeling experiment at W-band

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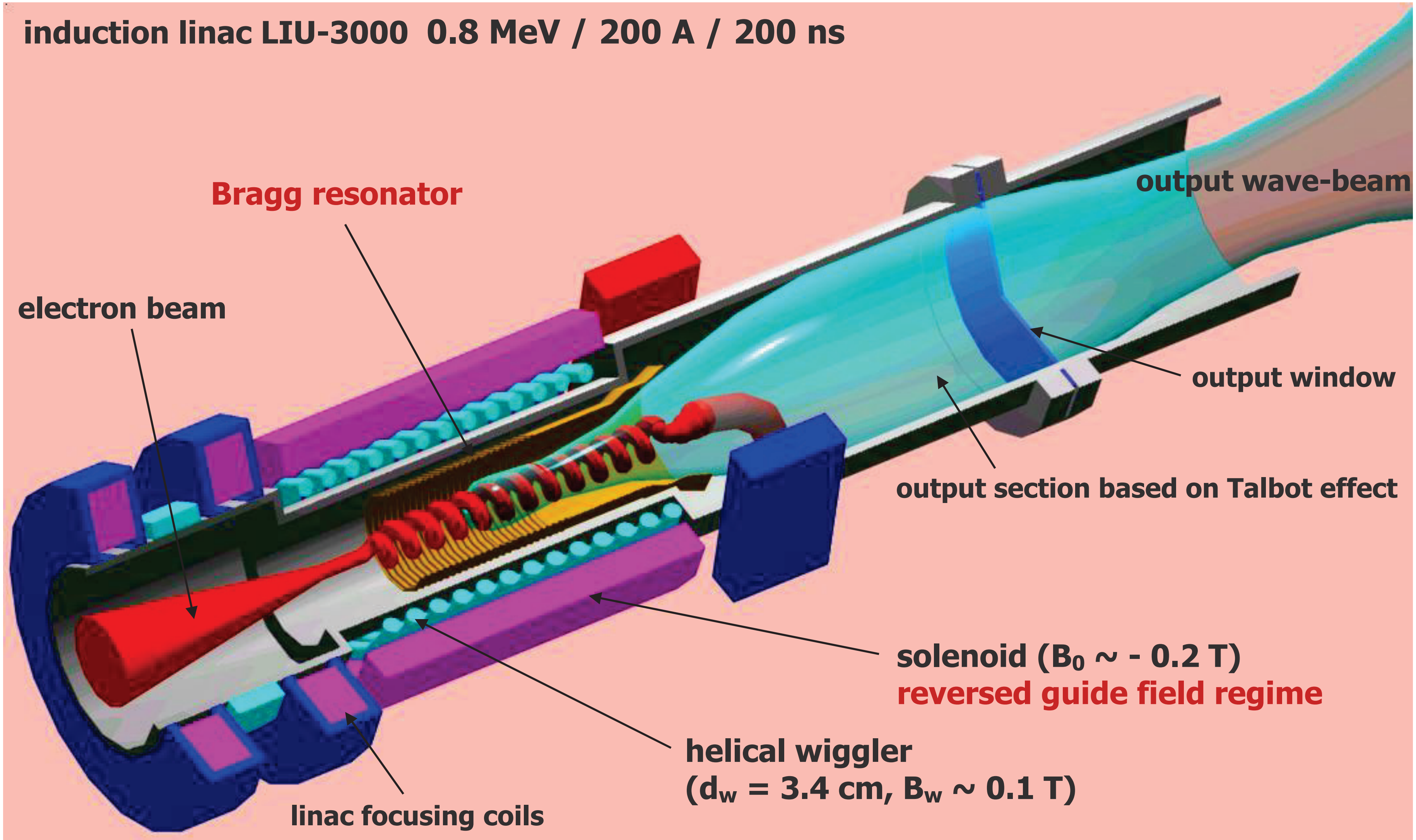
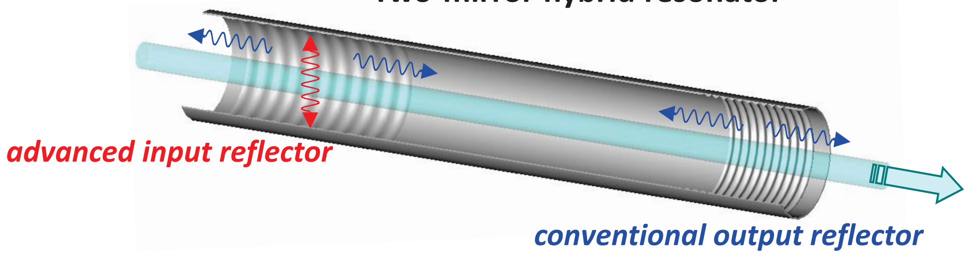
Joint Institute for Nuclear Research, Dubna, Russia



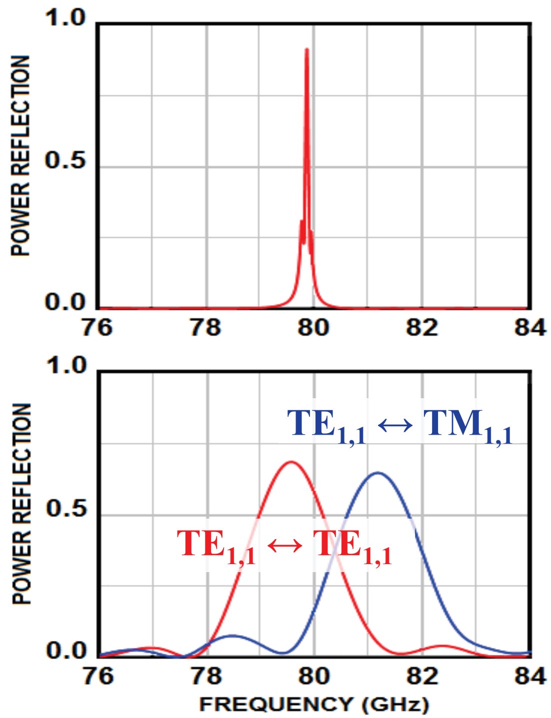
FEM with advanced Bragg resonator. Modeling experiment at W-band

Two-mirror hybrid resonator



cavity oversize Ø/λ ~ 5

3D simulations (code CST «*Microwave Studio*»)



Advanced reflector

$TE_{1,1} \leftrightarrow TE_{1,5} \leftrightarrow TE_{1,1}$

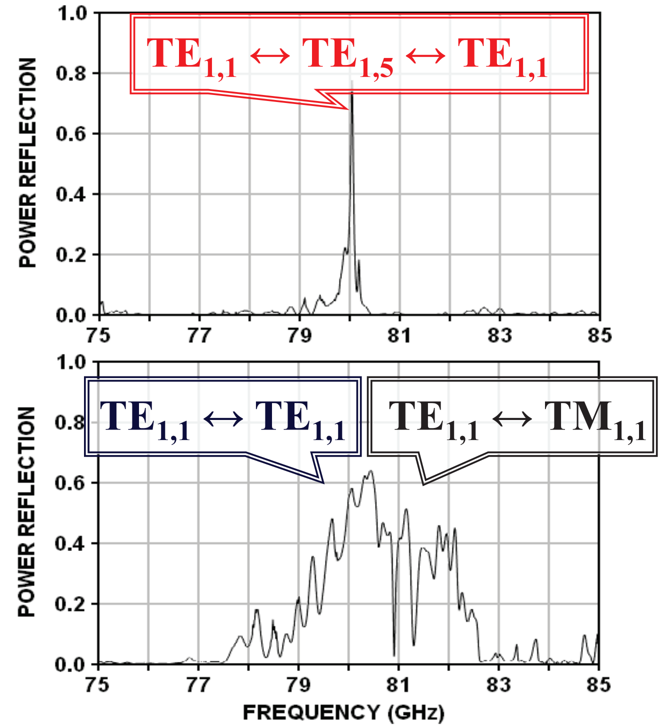
Waveguide diameter 17 mm
Section length 12 cm
Corrugation period 3.7 mm
Corrugation depth 0.15 mm

Conventional reflector

$TE_{1,1} \leftrightarrow TE_{1,1}$

Waveguide diameter 17 mm
Section length 8 cm
Corrugation period 1.8 mm
Corrugation depth 0.2 mm

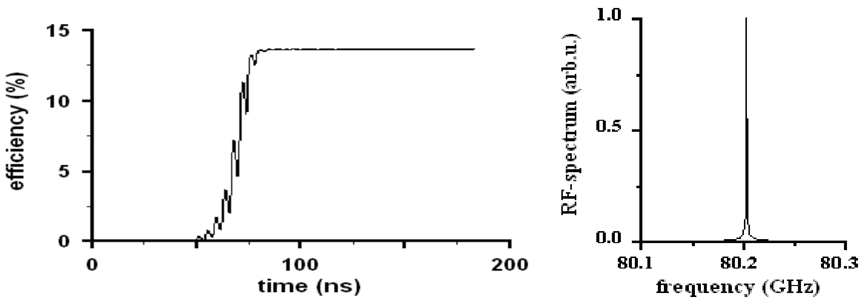
«Cold» tests



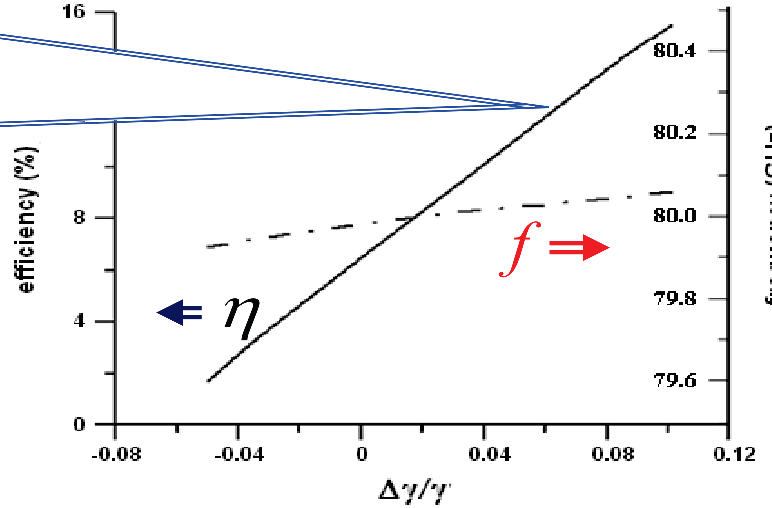
Simulation of W-band FEM with advanced Bragg resonator

quasi-optical coupled waves approach

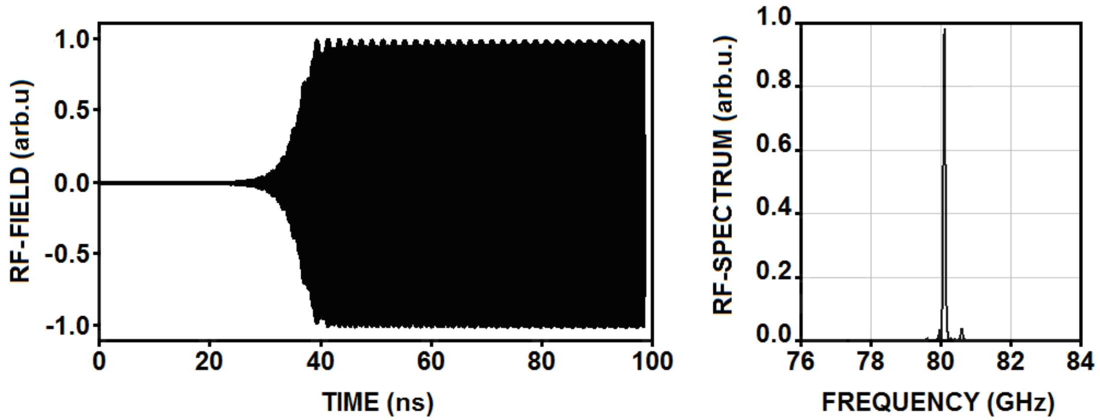
establishment of single-mode oscillation



stabilization of radiation frequency

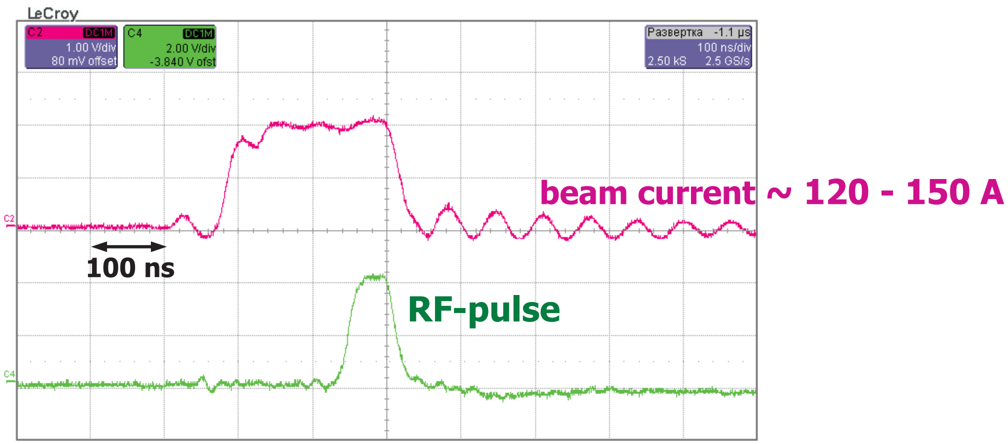


3D simulations (code CST "Studio Suite")



stable narrow-band operation under optimal parameters

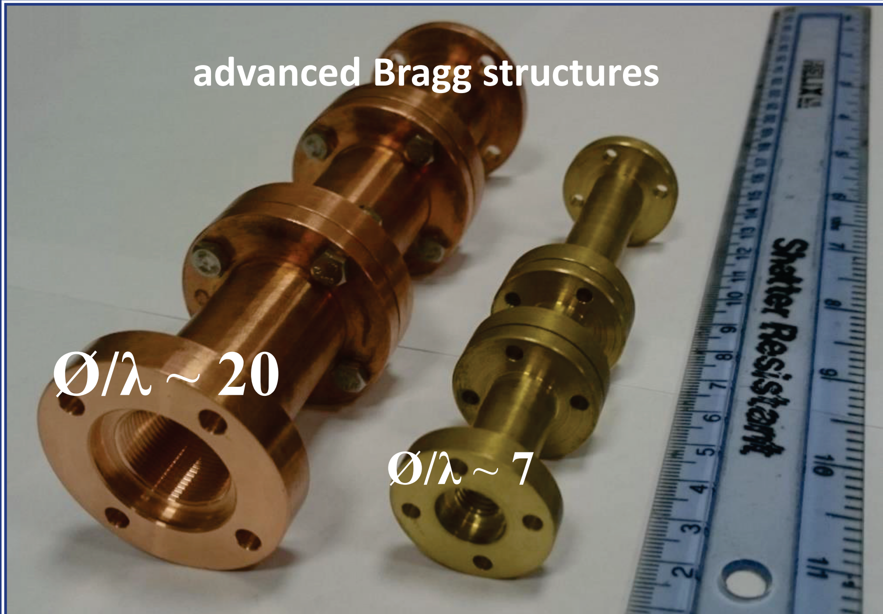
Results of the experiments

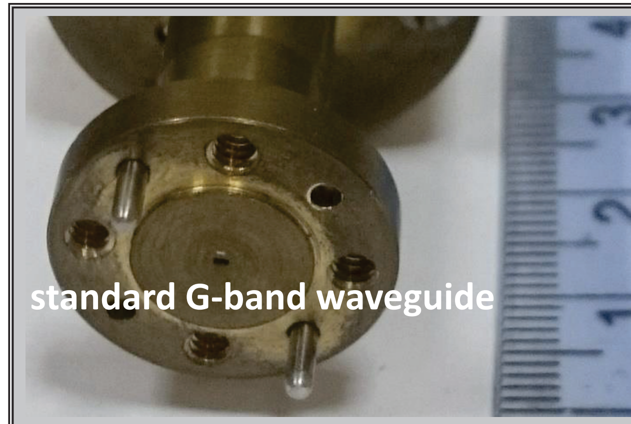


P_{out} ~ 7 MW
efficiency ~ 7%
f ≈ 80 GHz (±0.5 GHz)

- ✓ *oscillation at the fundamental mode of the resonator was obtained at any wiggler fields from the zone of self-excitation synchronism*
- ✓ *oscillation frequency close to cutoff frequency of the trapped wave (with accuracy of electron frequency shift)*

«Cold» tests of advanced Bragg structures at the G-band





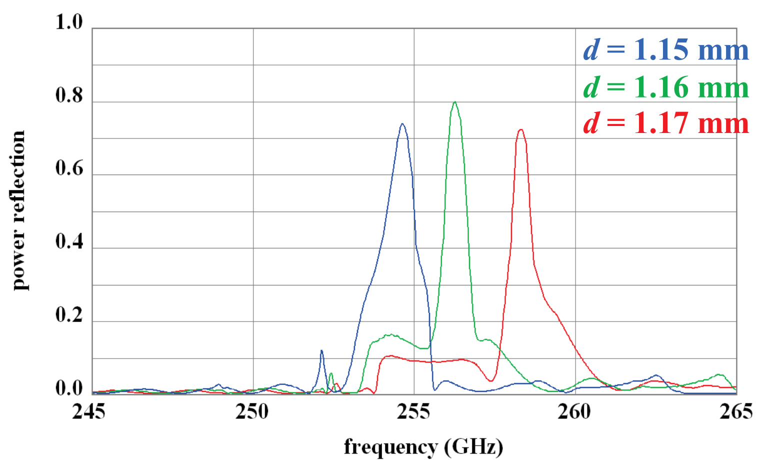
Proof-of-principle studying of Bragg cavity for 300 GHz FEL

Advanced Bragg reflector $TE_{1,1} \leftrightarrow TE_{1,7} \leftrightarrow TE_{1,1}$

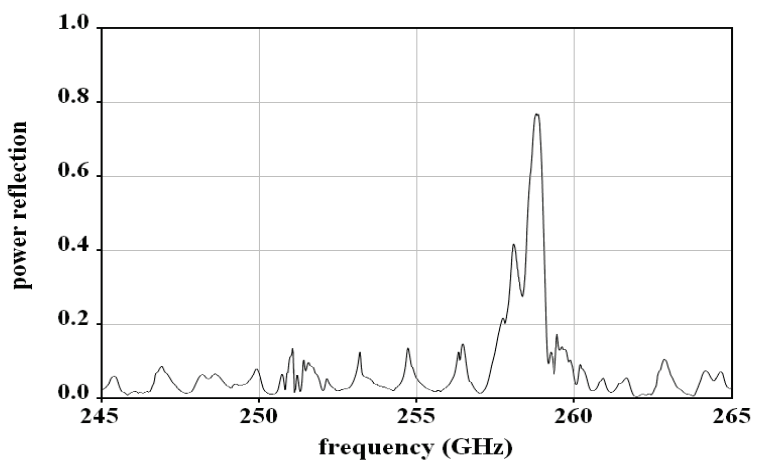
length 5.5 cm
waveguide diameter 8 mm
corrugation period 1.16 mm
corrugation depth 0.2 mm

cavity oversize $Ø/\lambda \sim 7$

3D simulations (code CST «*Microwave Studio*»)



«Cold» tests



Prototype of Bragg cavity for 300 GHz FEL experiment at LIU-5

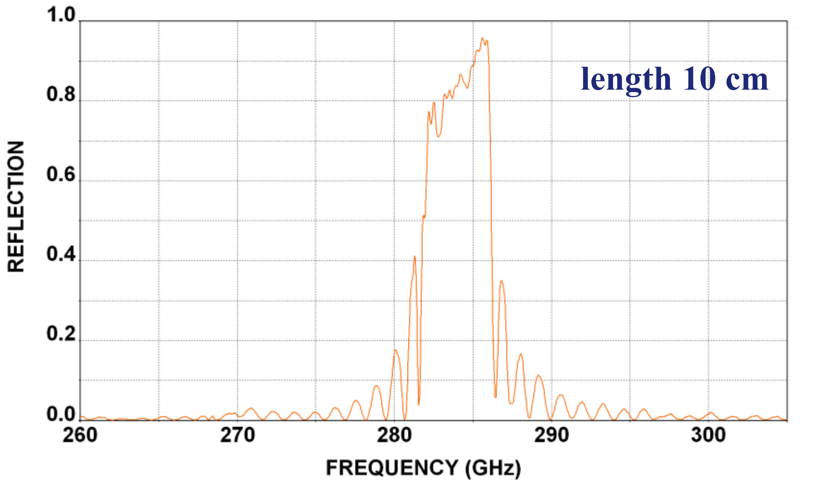
cavity oversize $\text{Ø}/\lambda \sim 20$

$\text{Ø}_{beam} \sim 3 - 5$ mm

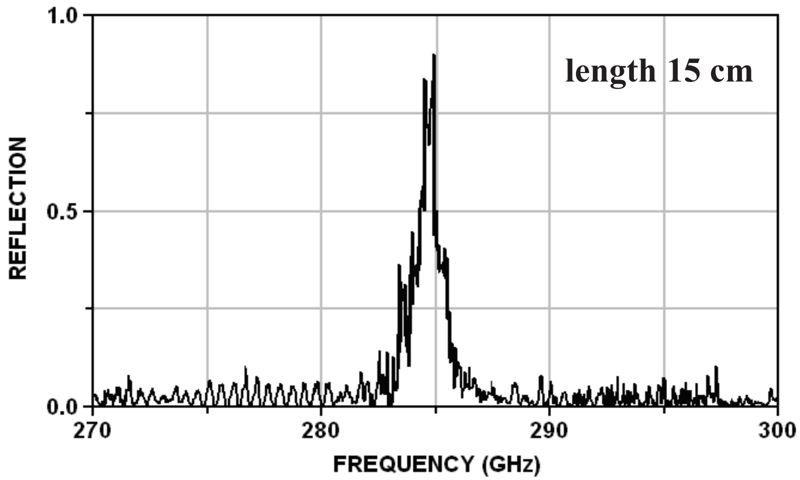
$\text{Ø}_{cavity} \sim 20$ mm

feedback loop $TE_{1,1} \leftrightarrow TE_{1,20} \leftrightarrow TE_{1,1}$
corrugation period 1.05 mm
corrugation depth 0.6 mm

3D simulations (code CST «*Microwave Studio*»)



«Cold» tests



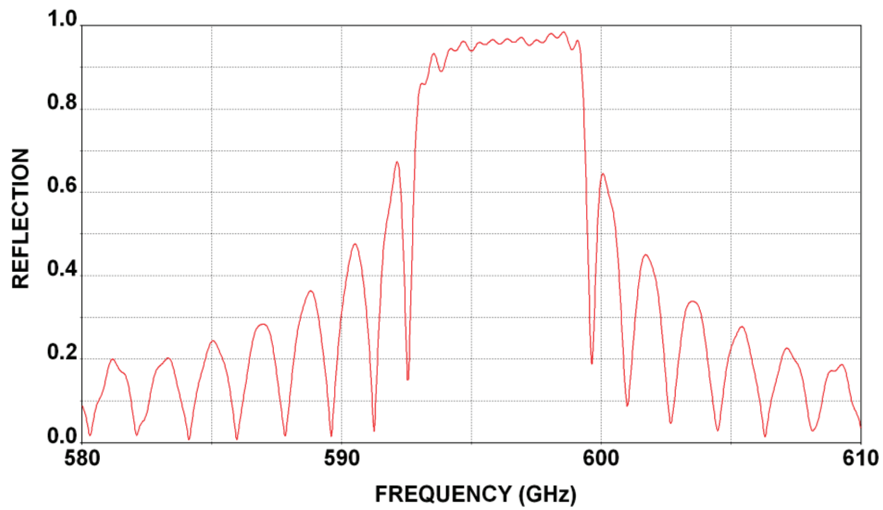
Simulations of advanced Bragg resonator for FEL experiment at LIU-5

600 ГГц *cavity oversize* Ø/λ ~ 40

$Ø_{beam}$ ~ 3 - 5 mm
$Ø_{cavity}$ ~ 20 mm

feedback loop $TE_{1,1} \leftrightarrow TE_{1,40} \leftrightarrow TE_{1,1}$
length 7.5 cm
corrugation period 0.5 mm
corrugation depth 0.6 mm

code CST «Microwave Studio»



Simulations of THz-band FEL

based on 5 MeV / 1 kA / 200 ns electron beam

coupling waves model **(3D quasi-optical approximation)**

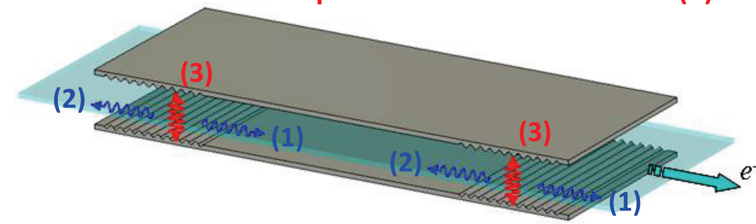
$$
\begin{cases}
\dfrac{\partial A_+}{\partial Z}+\dfrac{\partial A_+}{\partial \tau}+i\dfrac{\partial^2 A_+}{\partial Y^2}=i\alpha\left(F\big|_{Y=0}+F\big|_{Y=B}\right)+\dfrac{1}{\pi}\displaystyle\int_0^{2\pi} e^{-i\theta}d\theta_0 \\
-\dfrac{\partial A_-}{\partial Z}+\dfrac{\partial A_-}{\partial \tau}+i\dfrac{\partial^2 A_-}{\partial Y^2}=i\alpha\left(F\big|_{Y=0}+F\big|_{Y=B}\right) \\
\dfrac{\partial F}{\partial \tau}+\dfrac{iC}{2}\dfrac{\partial^2 F}{\partial Z^2}+\sigma F=i\alpha\left[\left(A_+ + A_-\right)\big|_{Y=0}+\left(A_+ + A_-\right)\big|_{Y=B}\right] \\
\left(\dfrac{\partial}{\partial \tau}+\beta_{\parallel}^{-1}\dfrac{\partial}{\partial Z}\right)^2\theta=\mathrm{Re}\left(A_+ e^{i\theta}\right)
\end{cases}
$$

normalized variables: $\tau = C\omega_s t \quad (X;Z)=Ck_s(x;z) \quad Y=\sqrt{2C}k_s y$

$F=\dfrac{e\mu A_i F_s}{2\sqrt{2}mc^2 k_s \gamma_0^2 C^2}$ quasi-cutoff feedback wave

$A_{\pm}=\dfrac{e\mu A_i A_{s;\pm}}{2mc^2 k_s \gamma_0^2 C^2}$ paraxial forward and backward waves

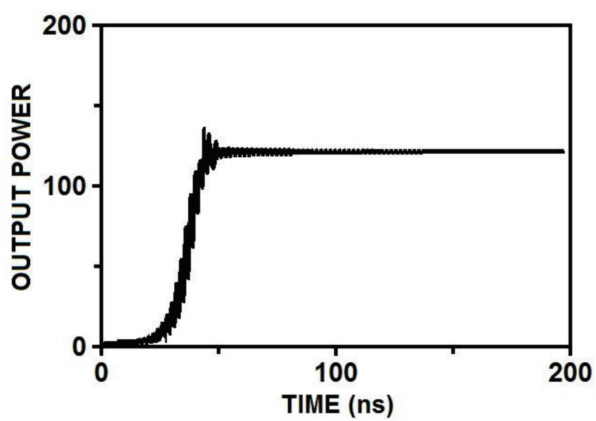
Two-mirror Advanced Bragg resonator

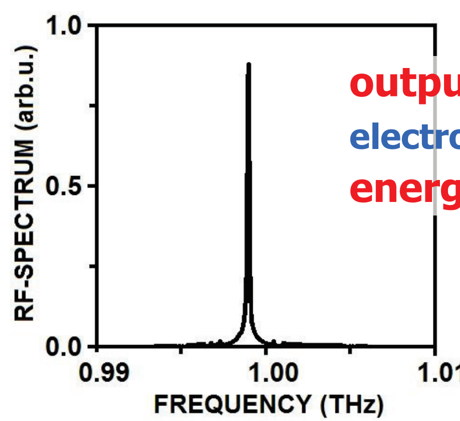


operating frequency **1 THz**
gap **6 mm (20λ)**
regular section **50 - 70 cm**
reflectors up/down-stream **20 cm / 10 cm**
corrugation period/depth **0.3 mm /15 μm**

undulator period **4 cm**
gain (Piers) parameter **~ 2 x 10^{-3}**

establishment of stationary narrow-band oscillation regime





output power ~ 0.1 - 0.2 GW
electron efficiency ~ 2 - 3%
energy content ~ 10 - 20 J

Summary

✓ Conception of **powerful long-pulse FEL-oscillators operating from sub-THz to THz band** has been developed based on linear induction accelerators.

✓ «Key» components of electron-optical and electrodynamic systems for the FEL were elaborated, including:

- **helical undulators of optimized geometry**, *which provide high-quality electron beam formation*;
- **advanced Bragg resonators based on coupling of propagating and quasi-cutoff waves**, *which improve selectivity and allow advance of FEM into short wavelengths*.

→ ***undulator*** *prototype was realized and magnetic measurements corresponds to simulations*

→ *«cold» tests of* ***resonator*** *for FEL prototype* ***at 300 GHz*** (***cavity oversize*** **Ø/λ ~ 20**) *are in good agreement with simulations and, thus, proved high potential of this conception.*

✓ Proof-of-principle FEM experiments were carried at W-band based on linac LIU-3000 0.8 MeV / 200 A / 200 ns (JINR, Dubna). Stable narrow-band generation was demonstrated at **cavity oversize Ø/λ ~ 5** and **multi-MW power**.

✓ Project of **300 GHz** and **600 GHz** FEL based on linac LIU-5 5 MeV / 2 kA / 200 ns (BINP RAS, Novosibirsk) is in progress and aimed to achieve **100-MW level radiation** in the specified frequency bands with the **pulse energy content of ~ 10’s J**.

Thank you!

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