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# Experimental Study of Amplification and Nonlinear Compression of Superradiance Microwave Pulses by Quasy-Stationary Electron Beams

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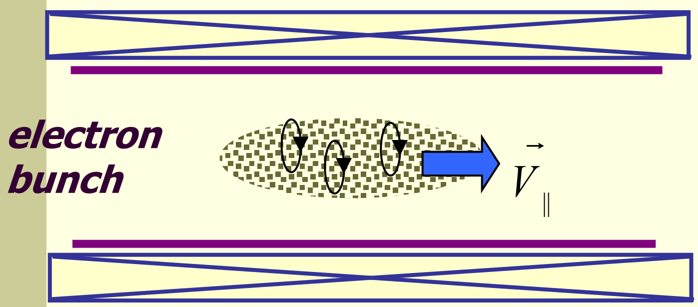
# *Superradiance - coherent short pulse radiation of extended electron bunches*

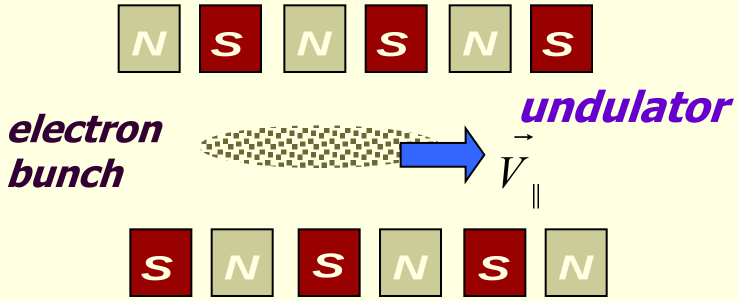
$$\lambda << L_{bunch} \leq L_{cooperative}$$

*Cooperative length is the distance that a wave propagates along electron beam for the time of instability growth up.*

## Cyclotron SR

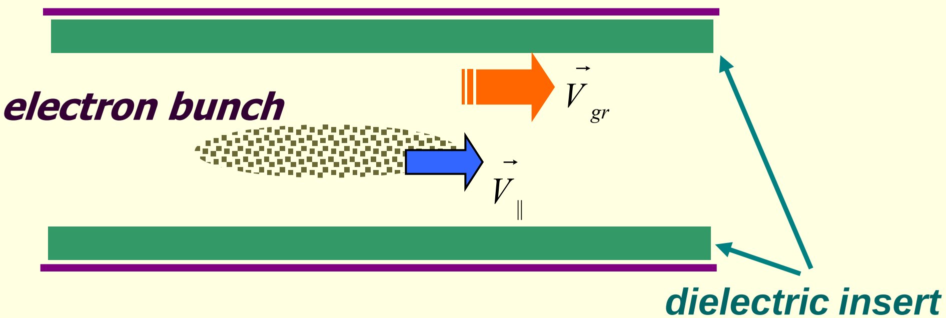



## Bremshstrahlung SR

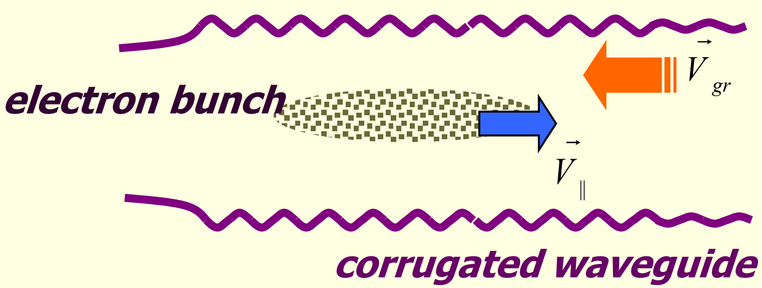



## Cherenkov SR

### Interaction with forward wave

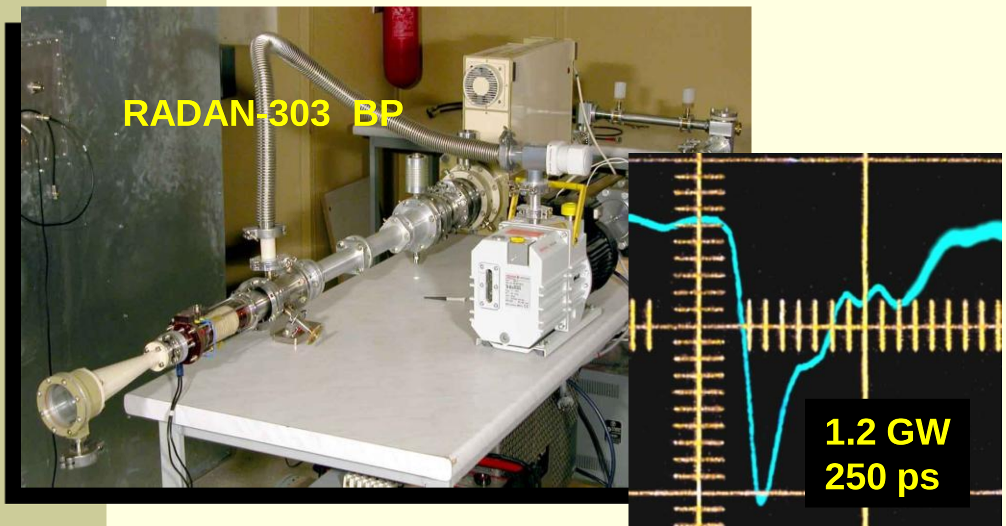



### Interaction with backward wave



# *Generators of ultrashort microwave pulses based on superradiance*

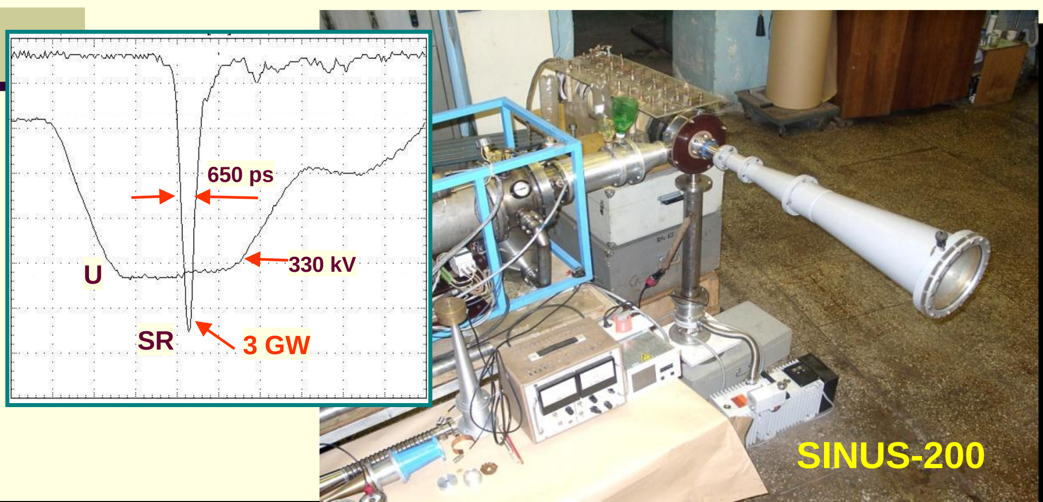
*IEP RAS (Ekaterinburg), IHCE RAS (Tomsk), IAP RAS (N.Novgorod)*




**Ka-BAND**

Electron energy - 300 keV
Electron current - 2.2 kA
Beam power – 0.7 GW
SR pulse duration - 200 ps
Peak power - 1.2 GW
Conversion coefficient - 1.5

*IHCE RAS (Tomsk), IEP RAS (Ekaterinburg)*




**X-BAND**

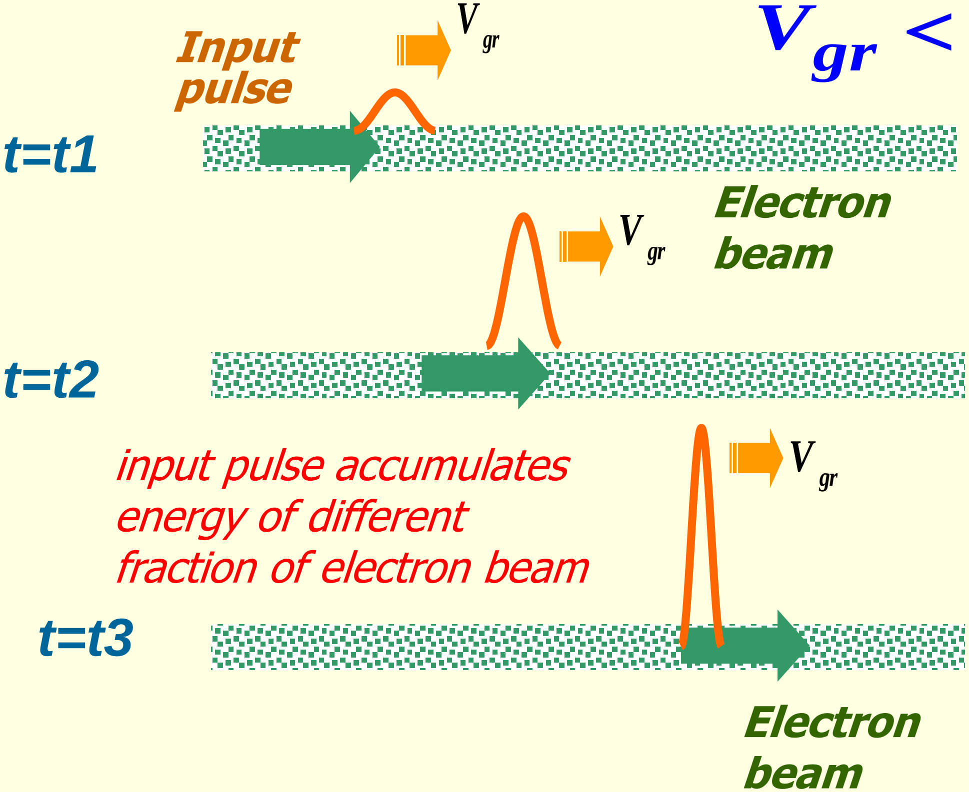
Electron energy - 330 keV
Electron current - 5 kA
Beam power – 1.7 GW
SR pulse duration - 650 ps
Peak power - 3 GW
Conversion coefficient - 1.8

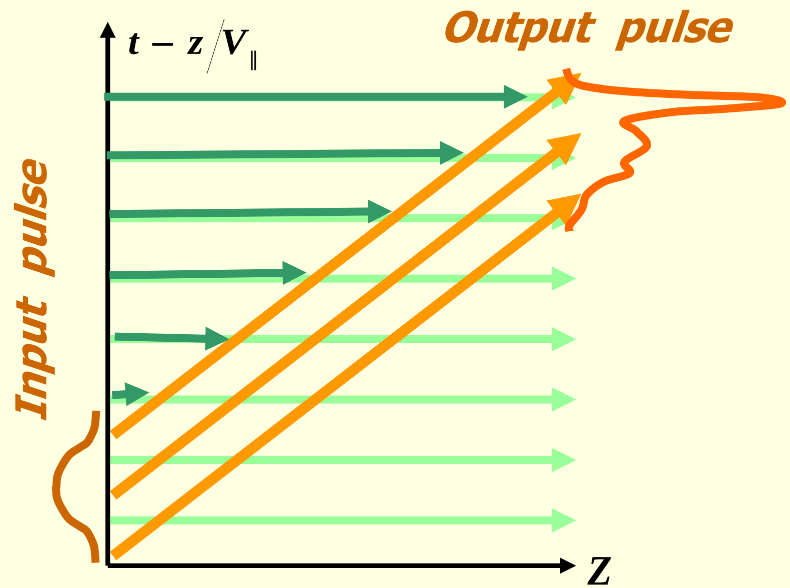
# *Specific of short pulse amplification caused by difference between wave group velocity and electron translational velocity*

***N.Ginzburg, I.Zotova, A.Sergeev Sov. ZhTF Lett. 1999***

$$K = \frac{P_{out}}{P_{beam}} > 1$$

$$V_{gr} < V_{\parallel}$$




electron characteristics

wave characteristics

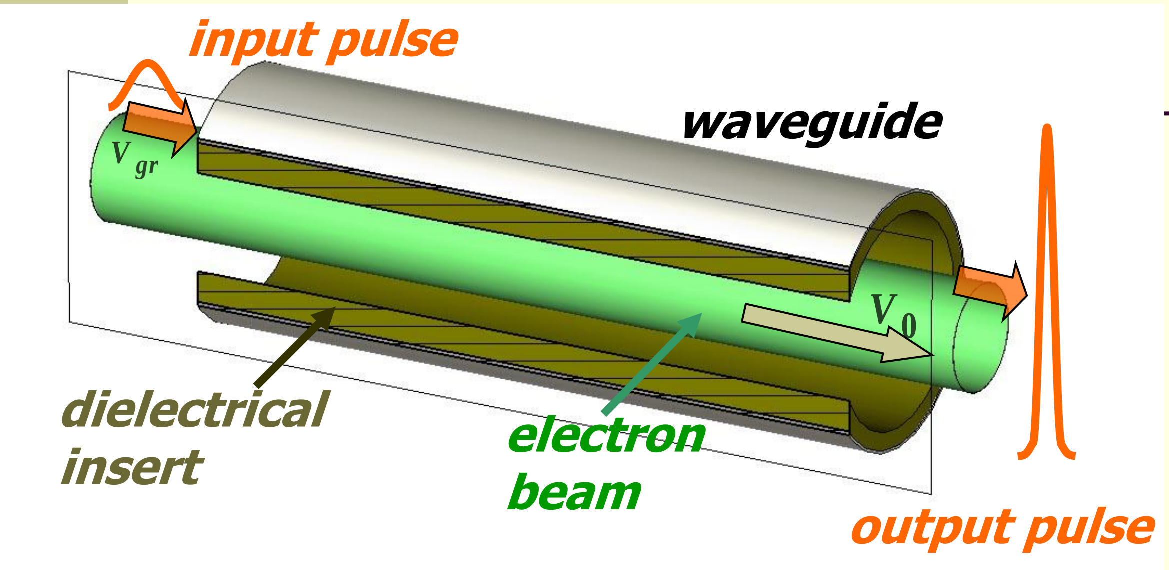
$$T \le T_{coop} = \left(Im\ \Gamma\right)^{-1}\left(1/V_{gr} - 1/V_{\parallel}\right)$$

# OUTLINE

1. Theoretical analysis of Cherenkov amplification of SR pulse propagating along quasi-stationary electron beam in dielectric loaded waveguide

2. The first experimental observation of effect of the nonlinear compression of microwave SR pulses in the process of Cherenkov amplification by quasi-stationary electron beam

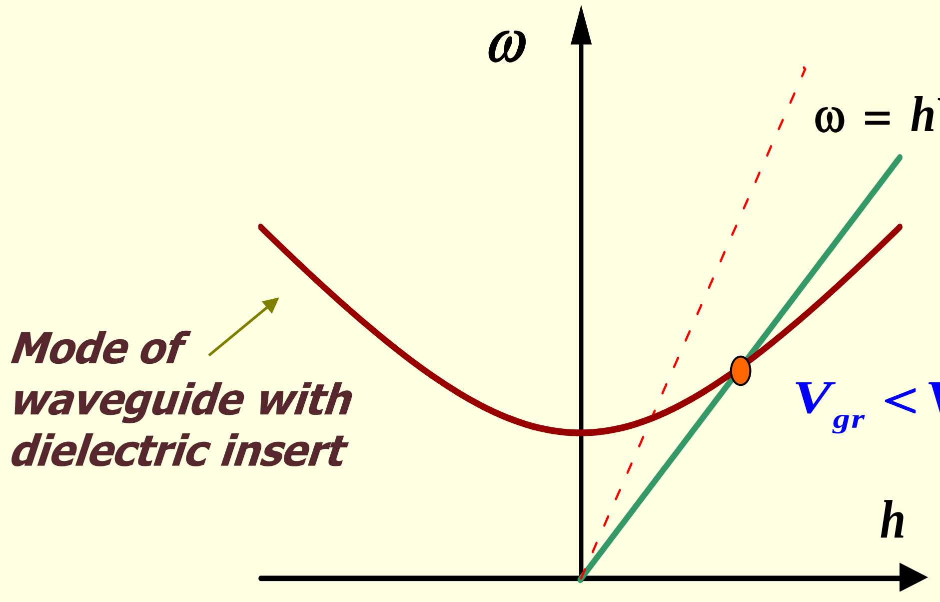
# Basic model




$$\omega \approx h(\omega)V_0$$

**Cherenkov synchronism condition**

**Dispersion diagram**



# Basic equations

$$\left[\frac{\partial}{\partial Z}+\frac{\partial}{\partial \tau}\right]a = \frac{1}{\pi}\int_0^{2\pi}\exp[-i\theta]d\theta_0 ,$$

$$\frac{\partial^2\theta}{\partial Z^2} = \left[1+\nu\frac{\partial\theta}{\partial Z}\right]^{3/2}\mathrm{Re}\left(a\exp[i\theta]\right)$$

$$E_z = \mathrm{Re}\left\{E_z^s(\vec{r}_\perp)A(z,t)\exp(i\omega t - ihz)\right\}$$

$$Z = Cz\omega / V_0$$

$$\tau = (C\omega)^{-1}(t - z/V_0)(1/\beta_{gr} - 1/\beta_0)$$

$$a = eAE_z^s(R_0) / m\omega\gamma_0^3 V_0 C^2$$

$$\nu = 2C\gamma_0^2$$

$$C = \left(\frac{eI_b}{m\omega^2\gamma_0^3}\frac{\left|E_z^s(R_0)\right|^2}{N_s}\right)^{1/3}$$ ***-Pierce parameter***

$N_s$ ***-norm of waveguide mode***

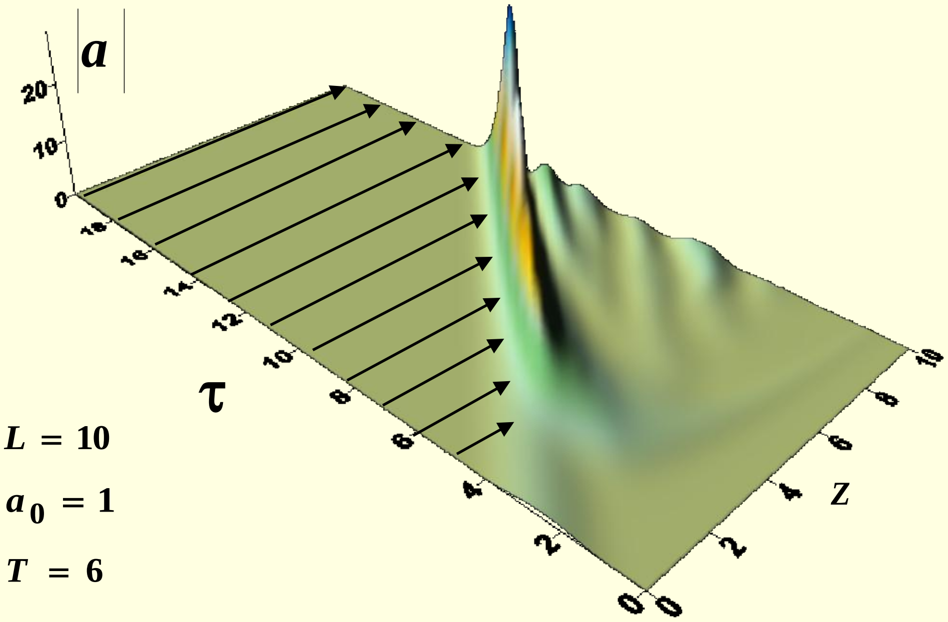
$E_z^s(r)$ ***-transverse structure of operating waveguide mode***

## Boundary condition

$$\theta\big|_{Z=0} = \theta_0 + r\cos(\theta_0 + \varphi(\tau)), \quad \theta_0 \in [0,2\pi], \quad \left.\frac{\partial\theta}{\partial Z}\right|_{Z=0} = 0 .$$

$$a\big|_{Z=0} = a_0\sin^2(\pi\tau/T)$$ ***- input signal***

# *Results of simulations*

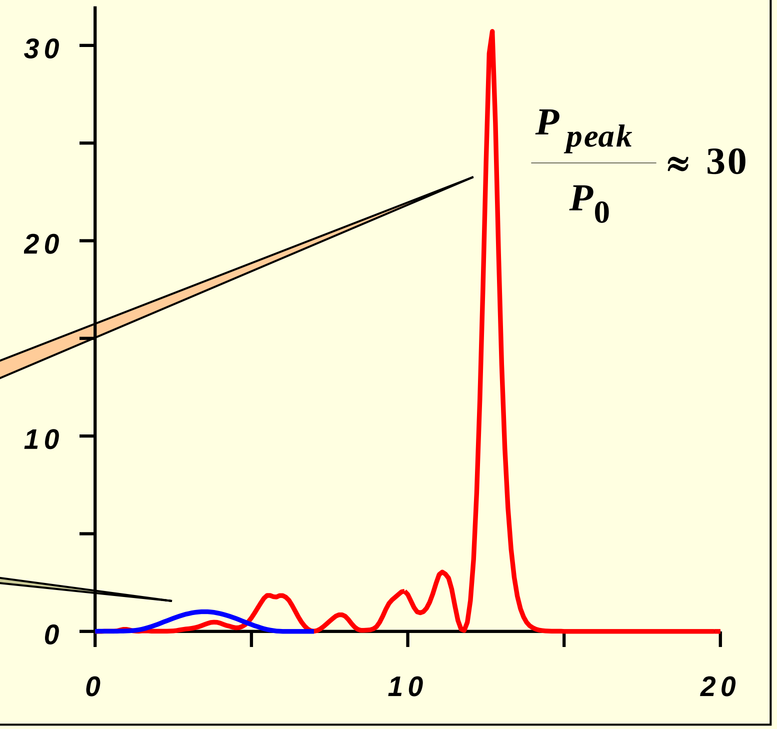



$L = 10$

$a_0 = 1$

$T = 6$

$$K = \frac{P_{peak}}{P_{beam}} \approx 2$$

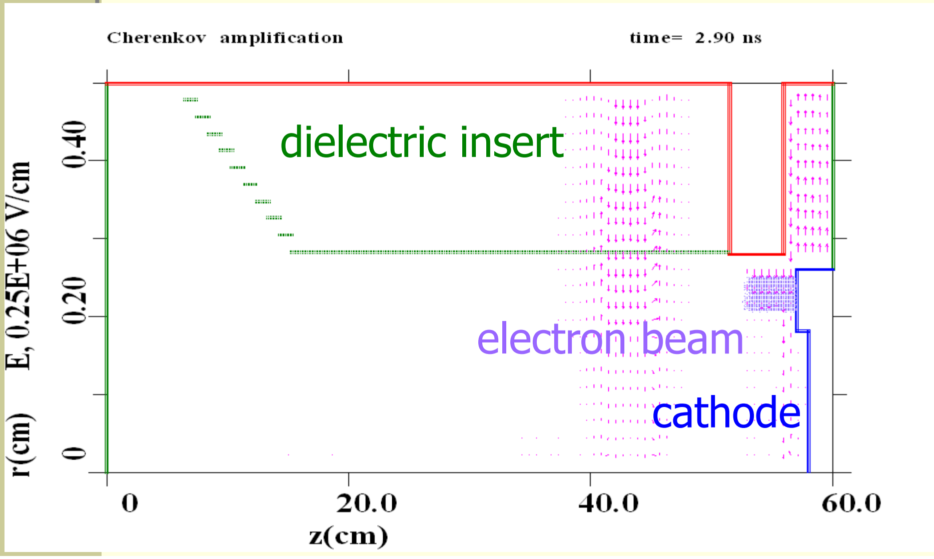



$$\frac{P_{peak}}{P_0} \approx 30$$

Input pulse

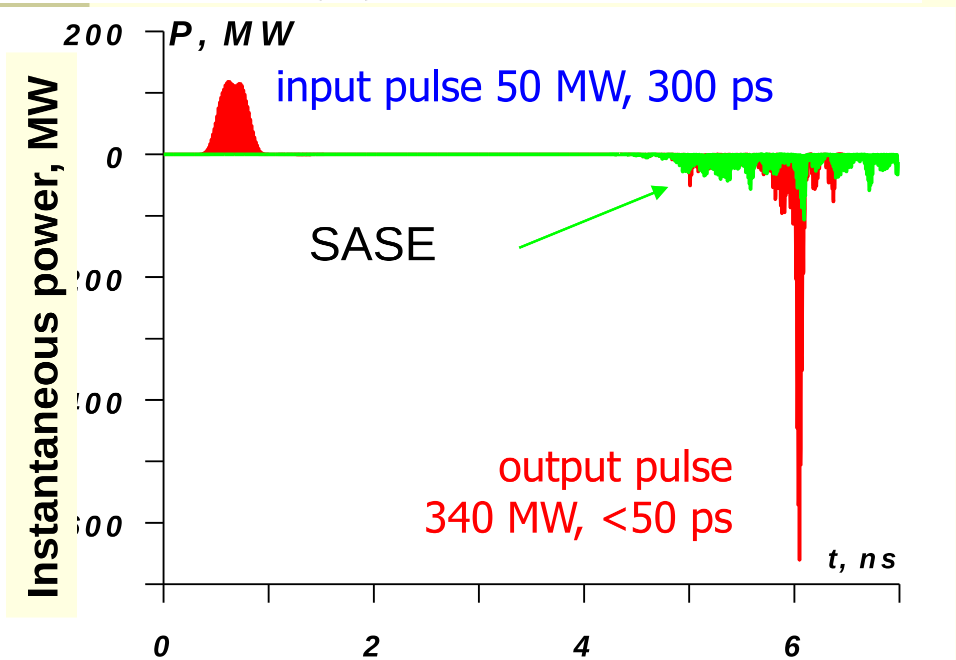
Output pulse

# *2D simulation of Cherenkov amplification of SR pulse based on PIC-code KARAT*




*Slow-wave structure parameters*

| | |
|---|---|
| *Waveguide radius* | *0.45 cm* |
| *Length of dielectric insert* | *35 cm* |
| *Width of dielectric insert* | *0.135 cm* |
| *Dielectric permittivity* | *3.8* |
| *Operating mode* | *$TM_{01}$* |
| *Operating frequency* | *38 GHz* |




*Parameters of electron beam*

| | |
|---|---|
| *Duration* | *3-4 ns* |
| *Electrons energy* | *250 keV* |
| *Electron current* | *800 A* |
| *Beam power* | *200 MW* |
| | |
| *Output peak power* | *340 MW* |
| *Conversion coefficient* | ***1.7*** |

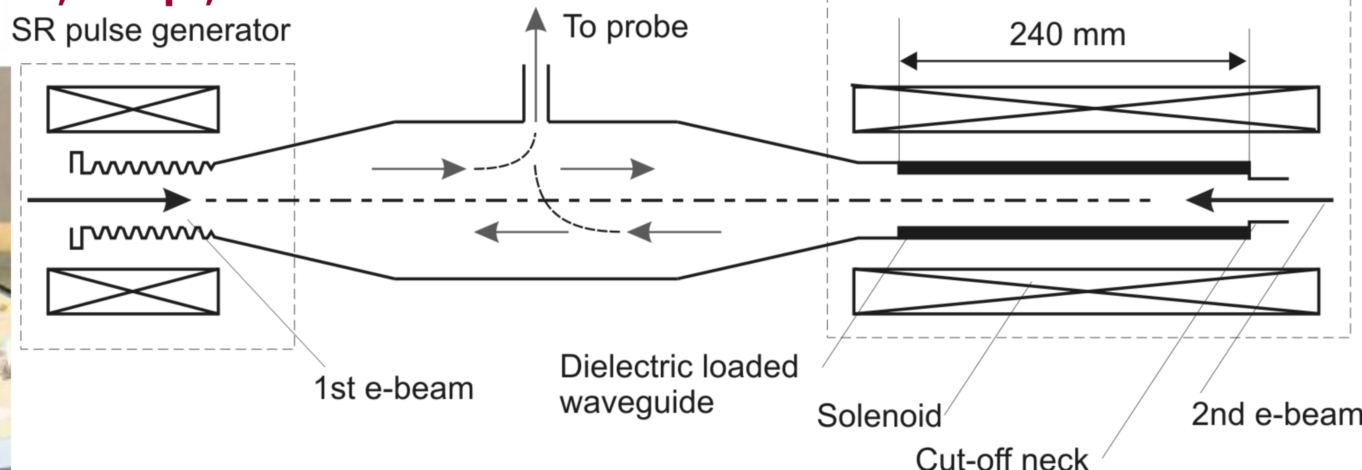
# *Experimental observation of nonlinear compression of microwave SR pulses in the process of amplification by quasi-stationary electron beam*

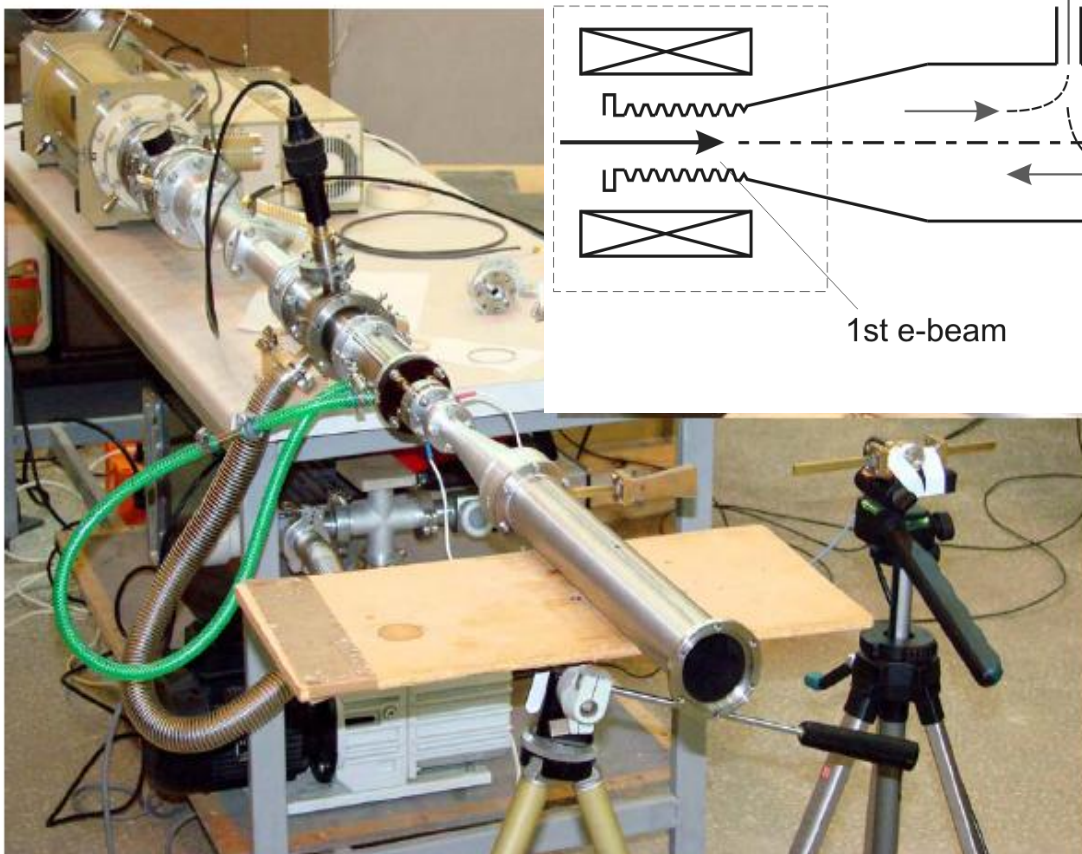
*IAP N.Novgorod, IEP Ekaterinburg*

*JETP Letters 2010, Vol. 91, iss.11, p.620*

## *Principal scheme of experimental set-up*

**37 GHz, 300 ps, 50-200 MW**

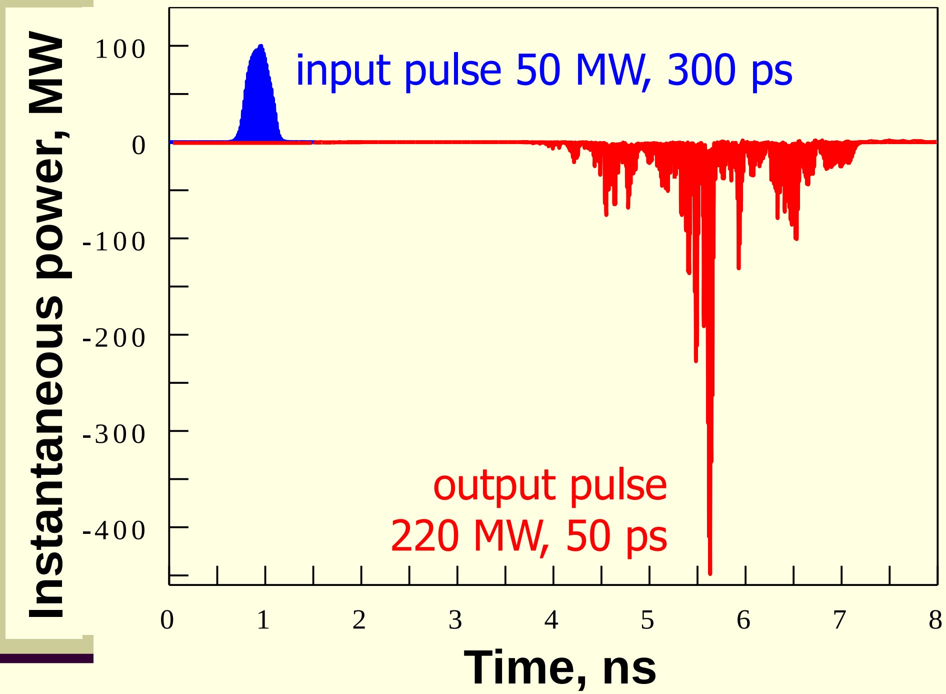


### *Experimental parameters*

| | |
|---|---|
| *Electrons energy* | *300 keV* |
| *Electron current* | *1.2 A* |
| *Operating frequency* | *37 GHz* |
| *Operating mode* | *$TM_{01}$* |

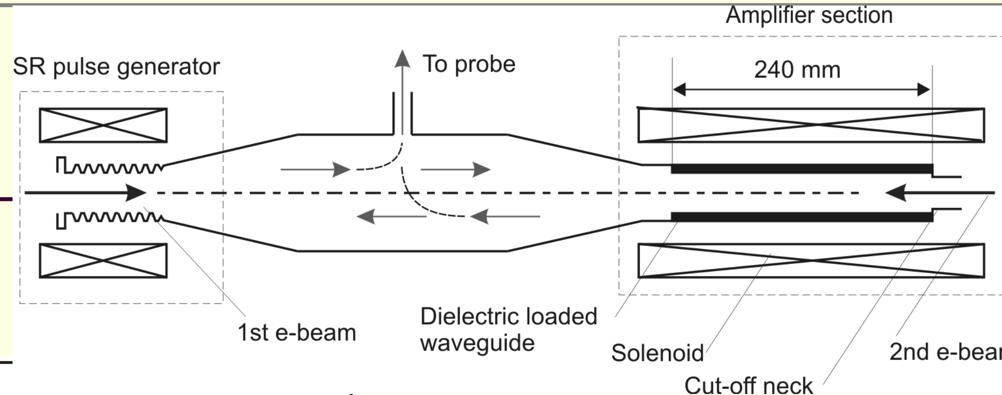
# 2D KARAT simulation of SR pulse amplification under experimental condition



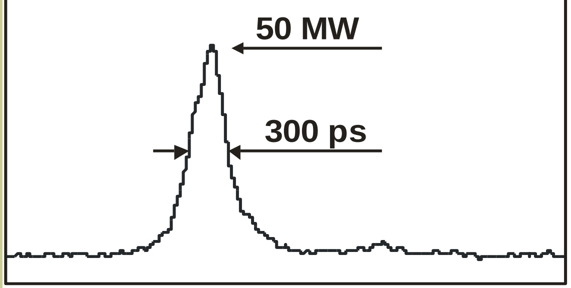

*Parameters of simulations*

| | |
|---|---|
| *Electrons energy* | *300 keV* |
| *Electron current* | *1.2 A* |
| *Waveguide radius* | *0.45* |
| *Length of dielectric insert* | *25 cm* |
| *Width of dielectric insert* | *0.135 cm* |
| *Dielectric permittivity* | *3.8* |
| *Operating frequency* | *38 GHz* |
| *Operating mode* | $TM_{01}$ |

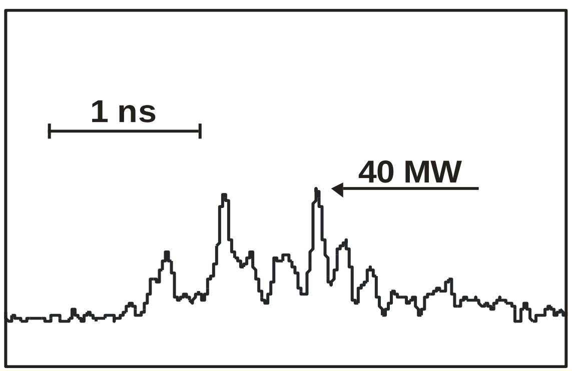
# Experimental results

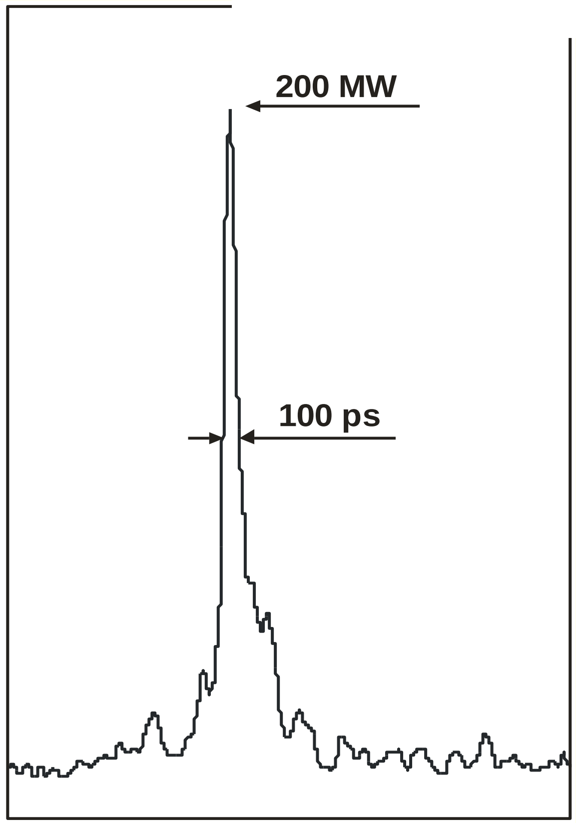



***Input SR pulse***




***SASE***



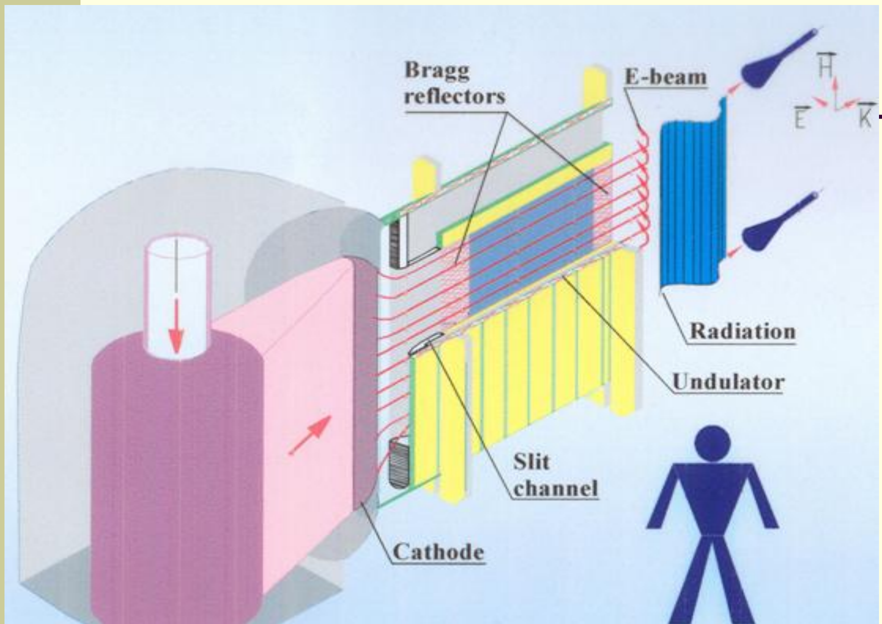




***Amplified pulse***

*Amplification factor~ 4*

*Compression factor~ 3*

# SR pulse amplification by powerful sheet electron beam in planar undulator



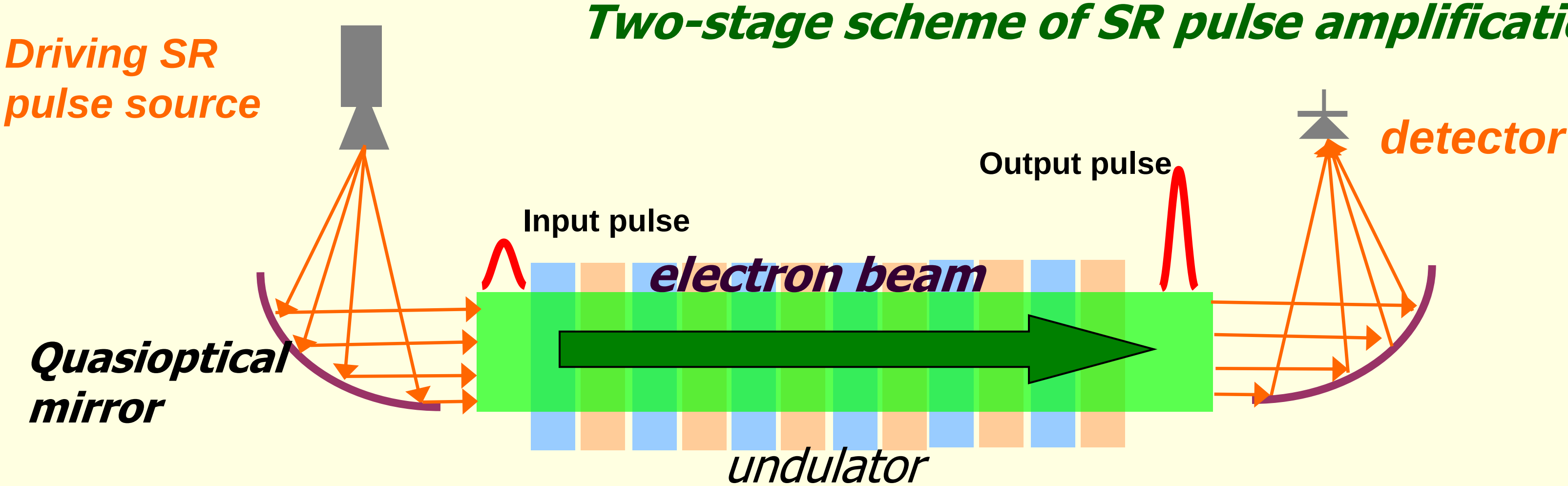

***Budker Institute of Nuclear Physics, Novosibirsk, Russia***

***Accelerator U-2***

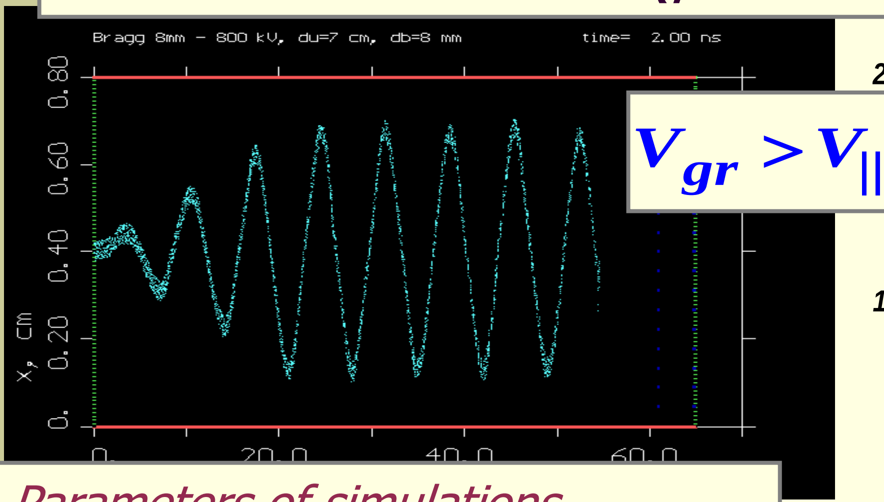
***Beam parameters***

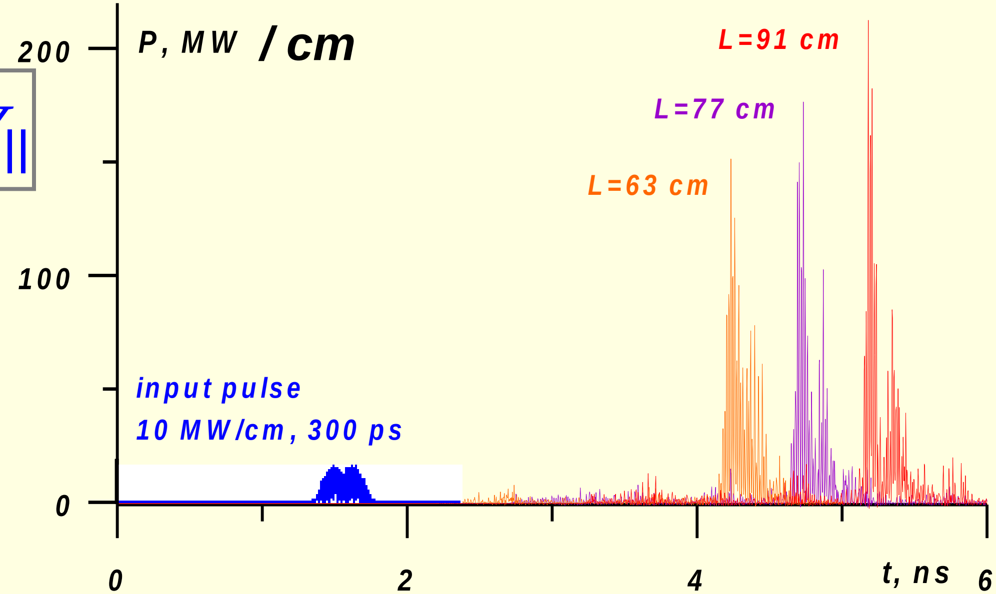
| | |
|---|---|
| *Electron energy* | *1 MeV* |
| *Electron current* | *50 kA* |
| *Beam duration* | *8 ns* |

## *Two-stage scheme of SR pulse amplification*



# 2D simulation of amplification of SR pulse in undulator based on PIC-code KARAT (planar model)




| Parameters of simulations | |
|---|---|
| Waveguide width | 0.8 cm |
| Undulator period | 7 cm |
| Undulator length | 63-100 cm |
| Undulator magnetic field | 2.5 кOe |
| Guiding magnetic field | 12 кOe |

| Beam parameters | |
|---|---|
| Electron energy | 800 keV |
| Current density | 200 A/cm |
| Pitch-factor | 0.17 |
| Beam duration | 4-5 ns |

| | |
|---|---|
| Operating mode | TEM |
| Operating frequency | 38 GHz |

**U-3 accelerator**
**(Budker Institute, Novosibirsk)**
**Beam width 20 cm**
**Peak power of radiation ~ 2 GW**

**U-2 accelerator**
**(Budker Institute, Novosibirsk)**
**Beam width 100 cm**
**Peak power of radiation ~ 10 GW**

# Conclusion

***"Proof of principle" experiments on observation of amplification of superradiance (SR) pulses under propagating along quasi stationary electron beams were performed. According to theoretical analysis amplification of microwave pulses (in 4 times on power) was accompanied by significant shortening of pulse duration.***

***The resulting pulse duration (shorter than 100 ps) is unique for Ka wave band***