Relativistic Electron Beam Stimulated Coherent Phenomena mediated by Artificial Structures

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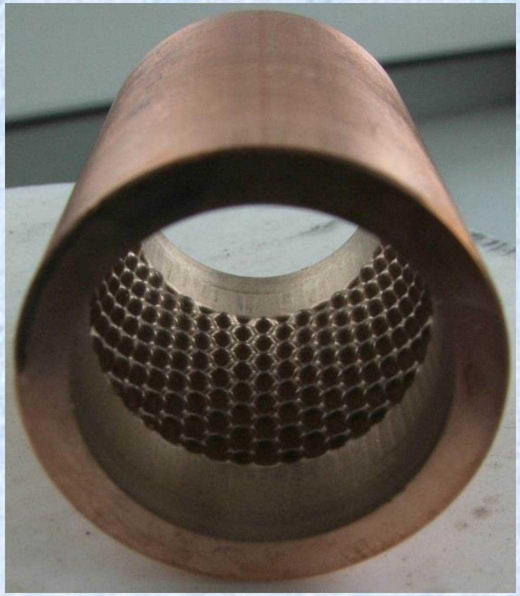
Two-Dimensional Periodic Surface Lattices

- The 2D periodic corrugation of the waveguide surface can be defined as:

$$r = r_0 + r_1 \cos(\bar{k}_z z) \cos(\bar{m} \varphi)$$

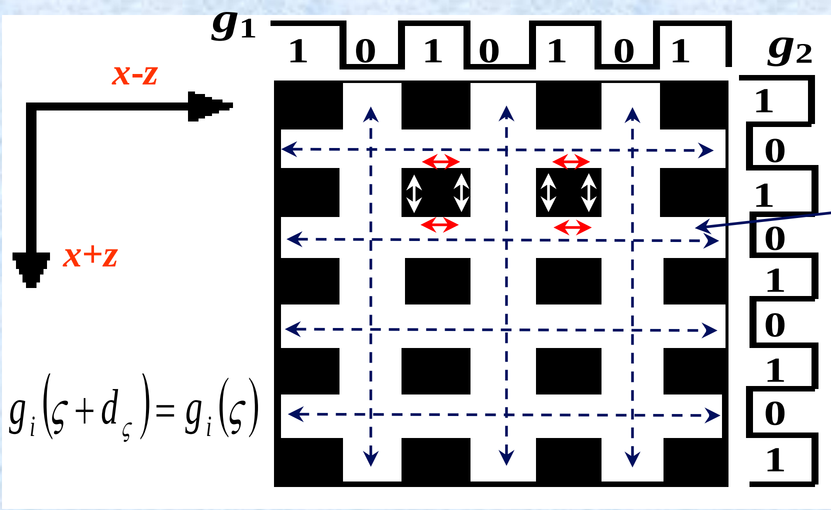
- waveguides' mean diameter 8cm/2cm
- corrugation amplitude 1mm / 0.6mm
- number of azimuthal variations 28/20
- longitudinal period of 8mm/3mm

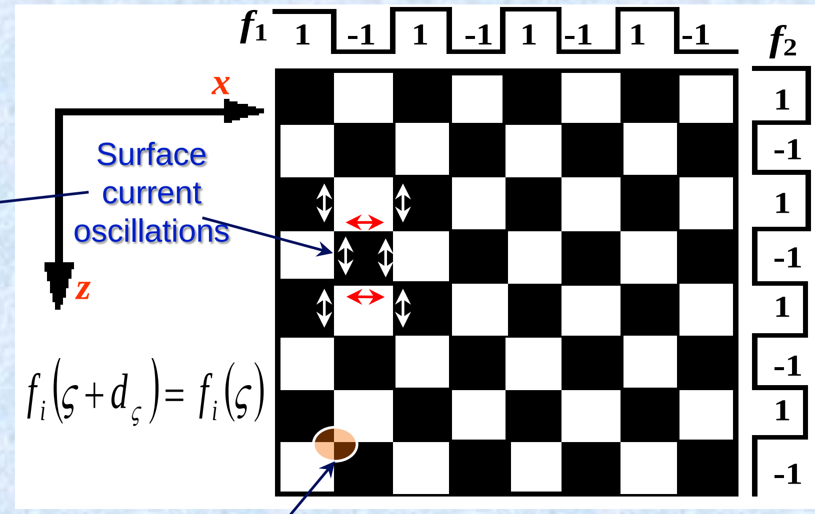


Periodic Surface Lattice operating frequency – 37.5 GHz (8mm)

Periodic Surface Lattice operating frequency~ 95GHz (3.2mm)

Basic model of low-contrast 2D periodic lattice





Mode excitation associated with 2D+1D scattering is observed

Localised singularity point of large resistance for the surface currents

$$\pm\frac{\partial A_\pm}{\partial z} + i\delta A_\pm + i\alpha_1 A_\mp + i\alpha_2 (B_+ + B_-) = 0$$

$$\pm\frac{\partial B_\pm}{\partial x} + i\delta B_\pm + i\alpha_1 B_\mp + i\alpha_2 (A_- + A_+) = 0$$

1D scattering

2D scattering

$$\pm\frac{\partial A_\pm}{\partial z} + i\delta A_\pm + \sigma A_\pm + i\alpha (B_+ + B_-) = 0$$

$$\pm\frac{\partial B_\pm}{\partial x} + i\delta B_\pm + \sigma B_\pm + i\alpha (A_- + A_+) = 0$$

2D scattering

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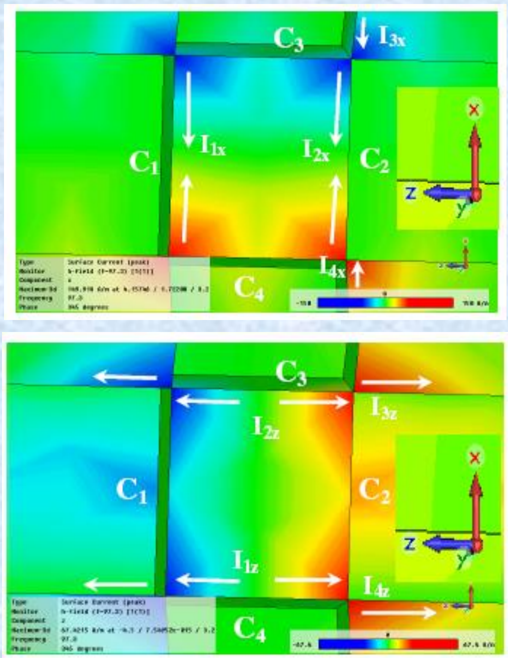
Surface and Volume fields on 2D periodic lattice

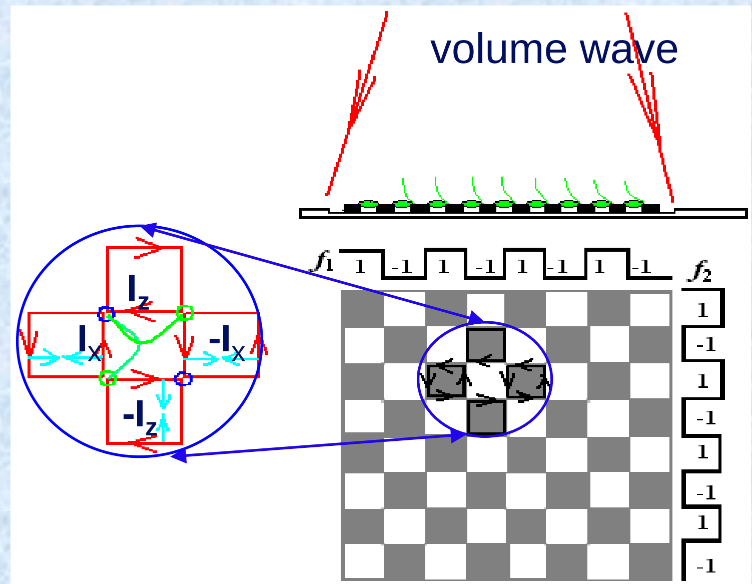
Interaction between the EM fields and the periodic surface lattice:

-1/ surface currents excitation occurs on the lattice fundamental cell boundaries by an incident EM field;

-2/ surface fields excited by the surface currents and at the initial stage, may neither be coherent nor synchronised



Excitation of the surface currents $I_{j(x,z)}$ on the 2D periodic structure observed using CST Microwave Studio.



Schematic representation of 2D periodic structure, incident pump, induced surface currents which are coupled with the surface wave

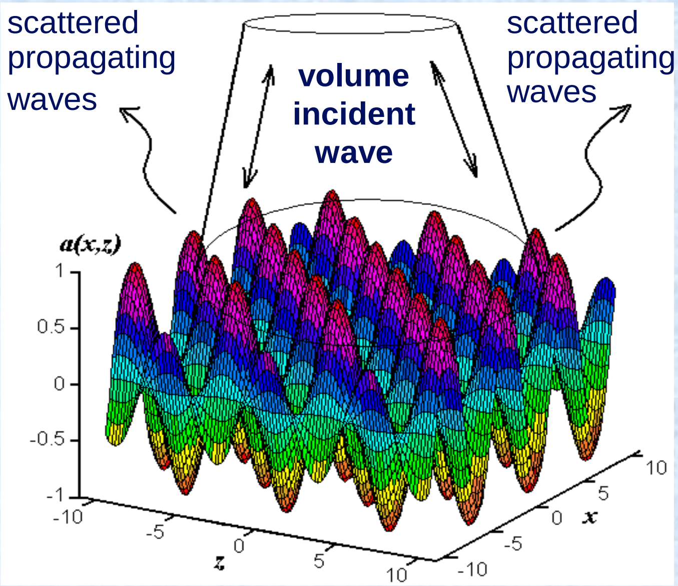
Coupling of surface & volume waves on 2D periodic lattice

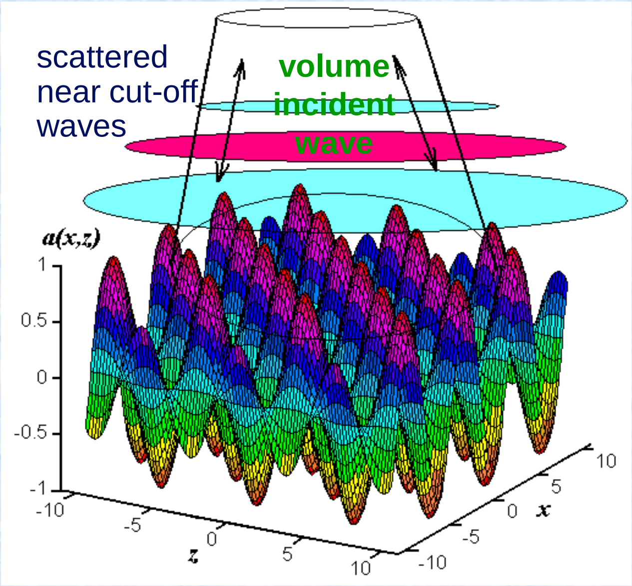
-3/ the surface fields are scattered on the corrugation into propagating waves.

If feedback is provided (by any means) the volume EM fields will accumulate inside the cavity and synchronise the individual scatterers. This leads to coherent and resonant scattering of the surface and volume fields. Some of the EM field will be radiated away from the cavity ensuring high mode selectivity similar to what is observed in Orotrons.

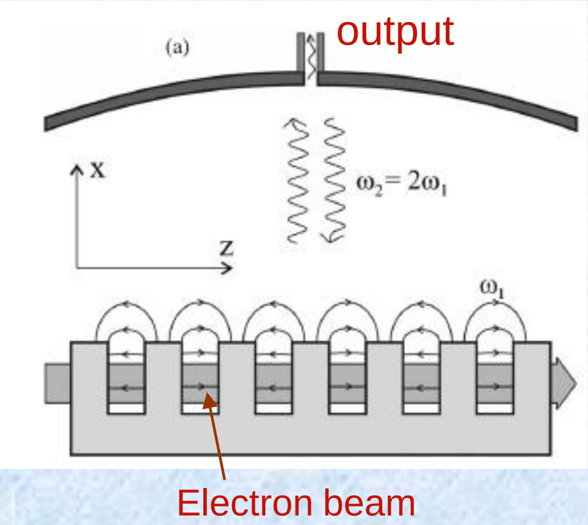
(V.L. Bratman et al., IEEE Transaction on Plasma Science, PS-15(1),p.2,1987;

Yu.A. Grishin et al., Rev. of Sci. Instr., 75(9),p.2926, 2004)





Schematic of Orotron



Planar Orotrons based on 2D PSL

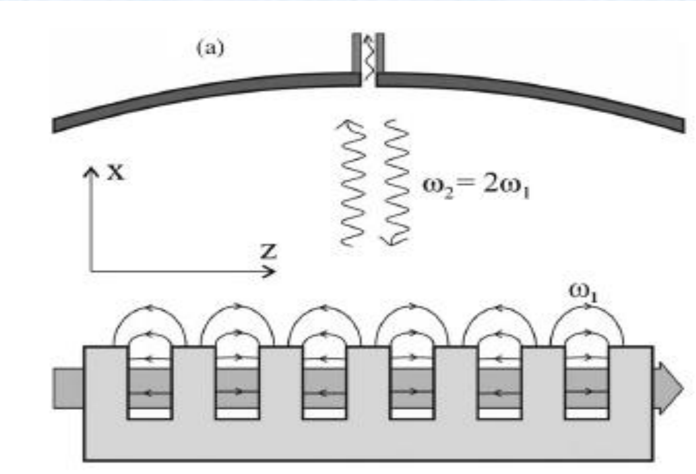
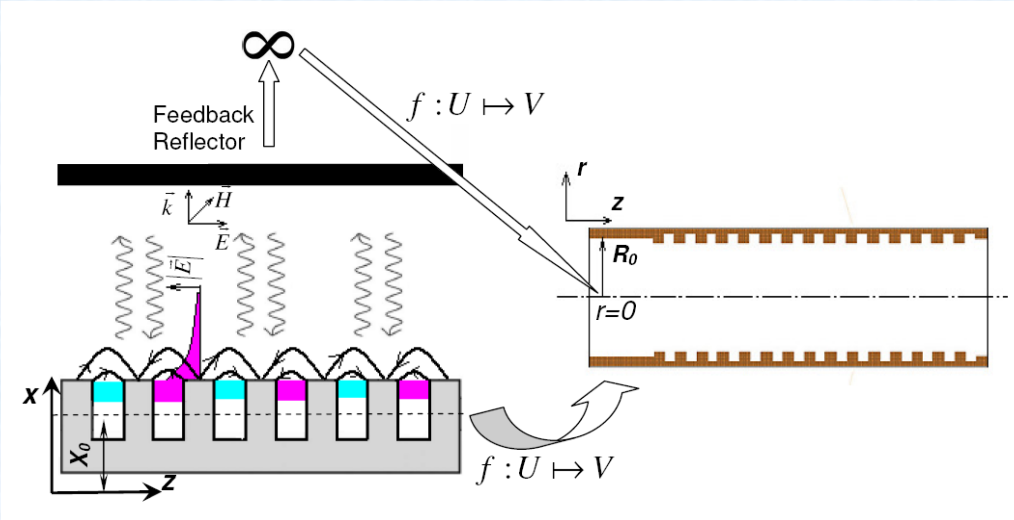


TABLE I
PARAMETERS OF DEVELOPED LOW-VOLTAGE OROTRONS

Structure period (μm)	170	140	120	100	90	82
Frequency (GHz)	90-190	90-300	140-300	260-370	220-355	140-410
Power (mW)	1000-100	500-100	500-50	70-30	100-50	50-200

V.L. Bratman at al., IEEE Trans on Plasma Science, 38(6), p.1466, 2010

New concept: cylindrical 2D PSL



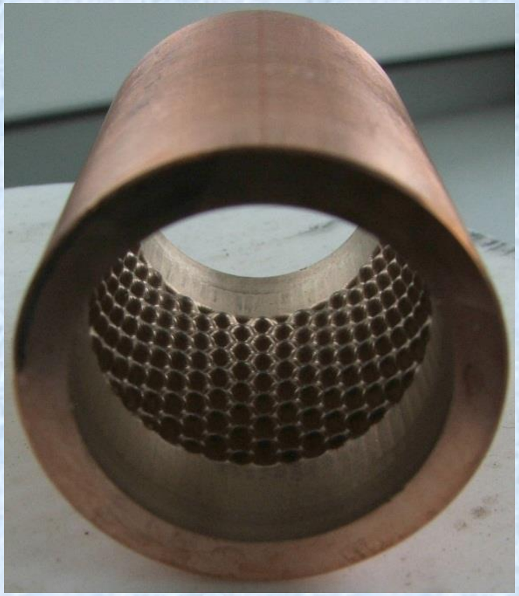
Two-Dimensional Periodic Surface Lattices

- The 2D periodic corrugation of the waveguide surface can be defined as:

$$r = r_0 + r_1 \cos(\bar{k}_z z)\cos(\bar{m}\varphi)$$

Research proposed:

-Cherenkov compact sources of coherent radiation;
-Compact sources of coherent radiation based on standing EM field scattering ;
- Multi-beam accelerating structure.



Periodic Surface Lattice operating frequency – 37.5 GHz

Periodic Surface Lattice operating frequency~ 95GHz

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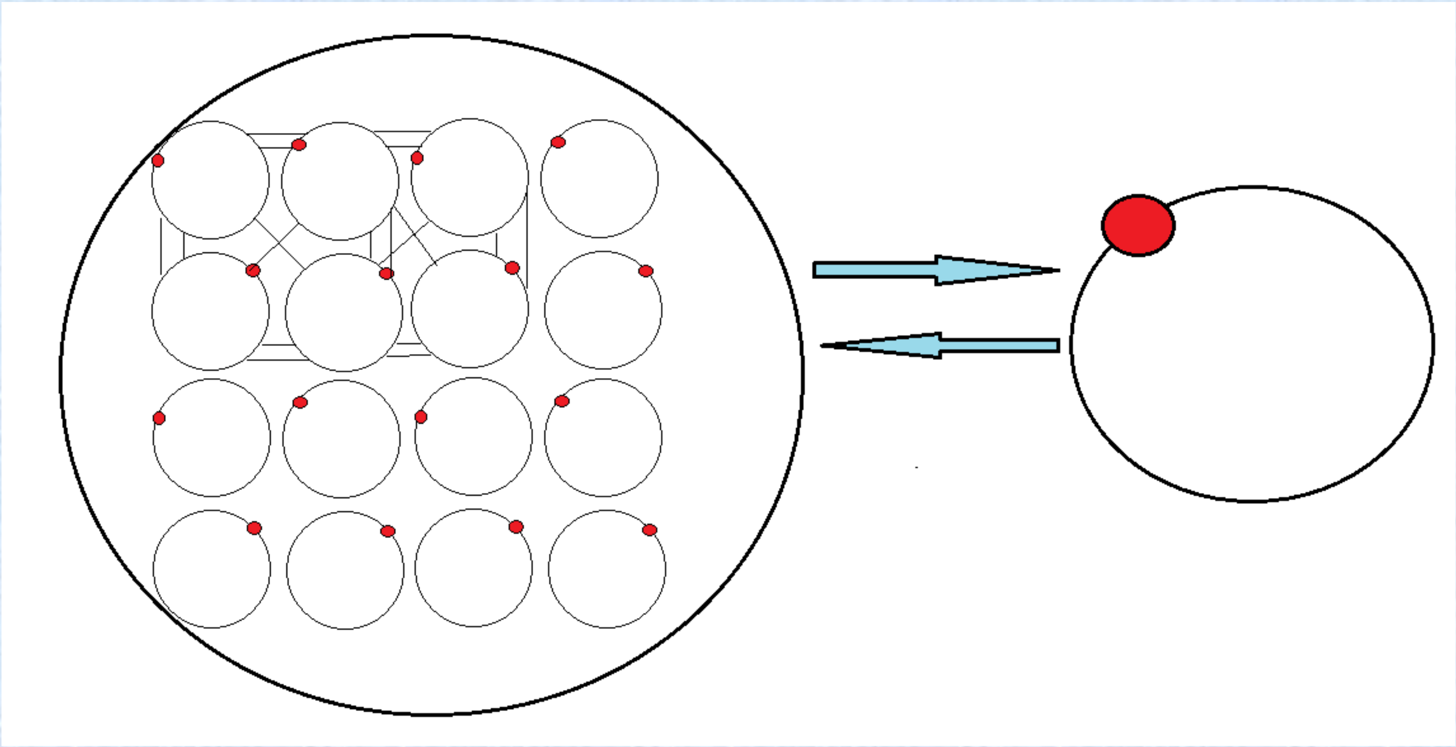
Synchronisation of an ensemble of oscillators distributed over a large surface area

1/ Each single oscillator (defined by a localised surface field) is coupled to the nearest one inductively and via capacitance. Diagonal oscillators are coupled only via capacitance;

2/ All oscillators are coupled to the global oscillator (volume field) individually i.e. without prior knowledge of its neighbour interaction with the global oscillator

3/ Global oscillator affects all oscillators simultaneously



Basic Model of EM field scattering on 2D PSL

– To obtain the effective scattering the Bragg resonance condition has to be met :

$$\vec{k} - \vec{k}_s + \vec{k}_{s'} = 0$$

– The periodic structures are low contrast i.e. either the corrugations on the surface of the conductors are shallow with respect to the wavelength $a_1 < \lambda/4$, or variation of the refractive index is small in comparison with its unperturbed value.

Resonant coupling of surface and volume fields

- The field inside is a superposition of partial surface and volume fields :

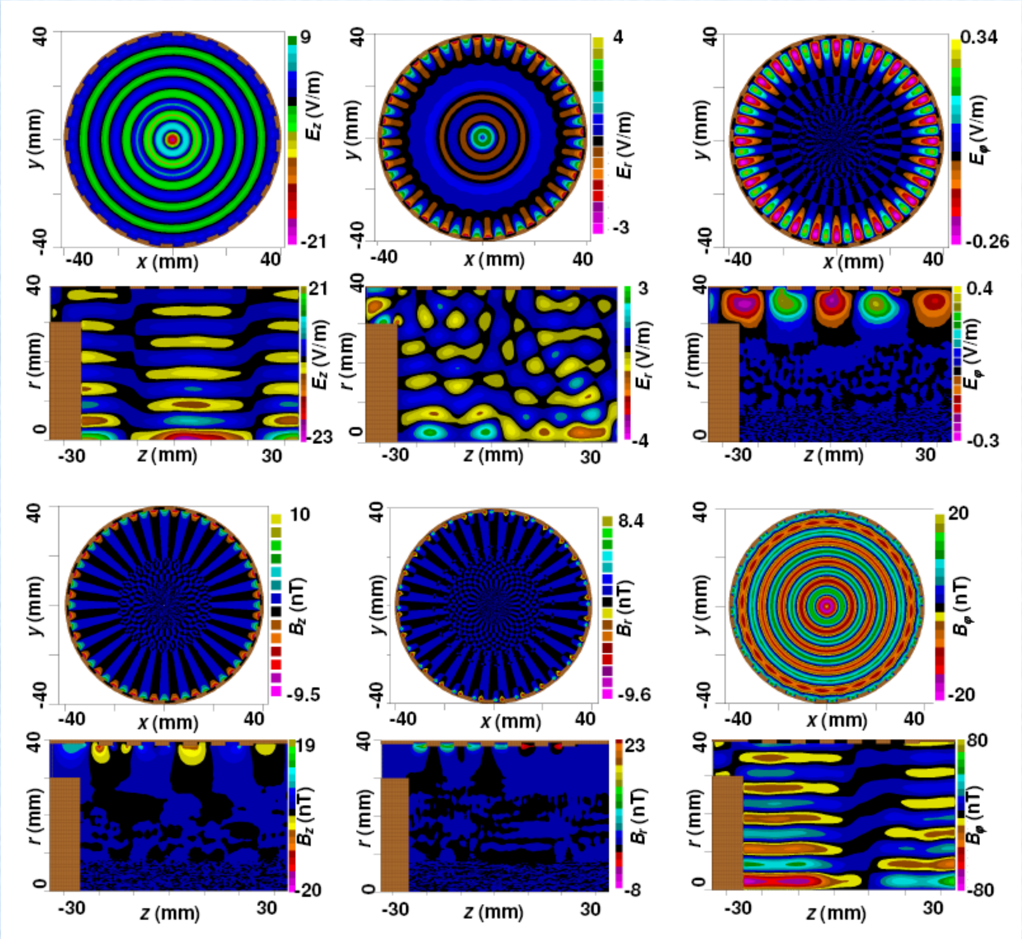
$$\vec{E} = \vec{E}_{surf} + \vec{E}_{vol}$$

-The field coupling takes place if the Bragg resonance conditions are satisfied

$$\vec{k} = \vec{k}_s - \vec{k}_v \Rightarrow \overline{m} = m_s + m_v$$

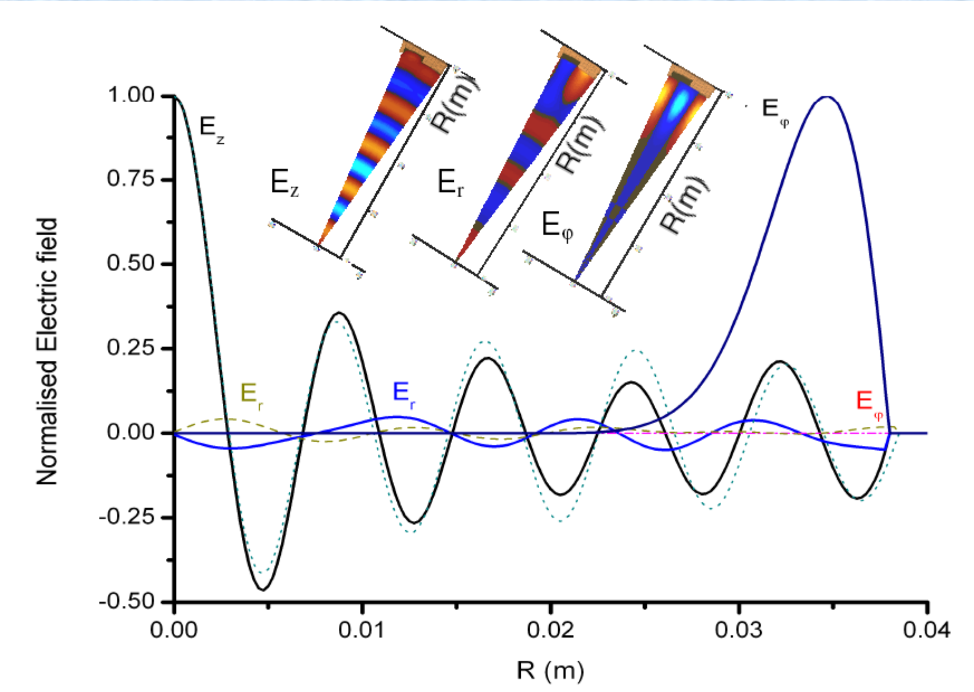
$$\vec{k} = \vec{k}_s - \vec{k}_v \Rightarrow \vec{k}_z = \vec{k}_{zs} - \vec{k}_{zv}$$

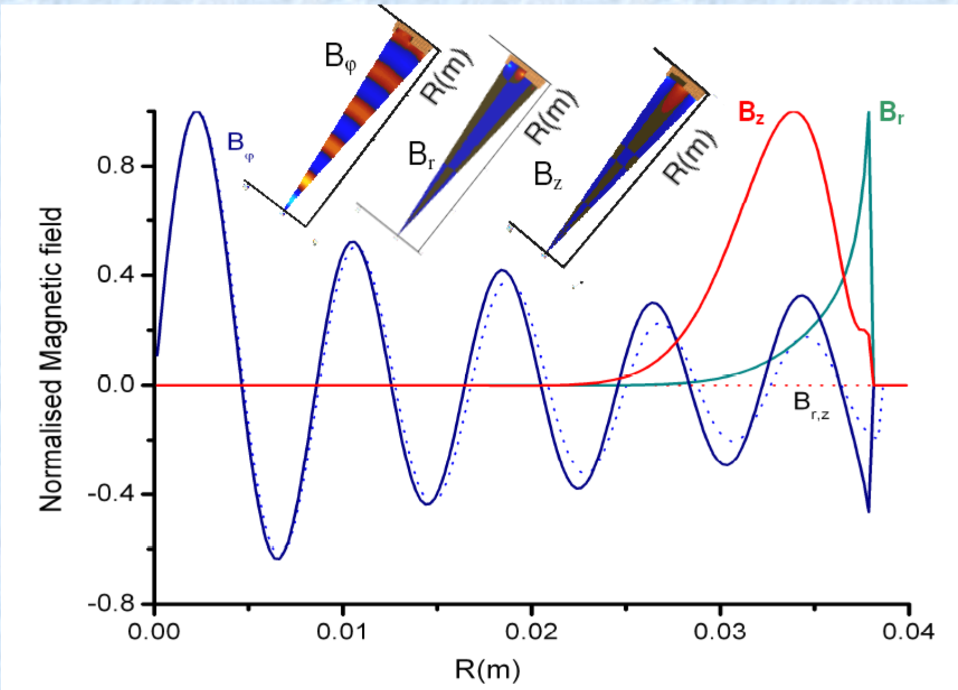
Eigenmode = $HE_{28,1} + TM_{0,10}$



Surface and volume fields observed inside cylindrical 2D periodic lattice

The transverse structures of the fields excited inside periodic surface structure. The inserts are the contour plots of the electric and magnetic field components excited by the pump wave inside the cylindrical 2D periodic lattice.

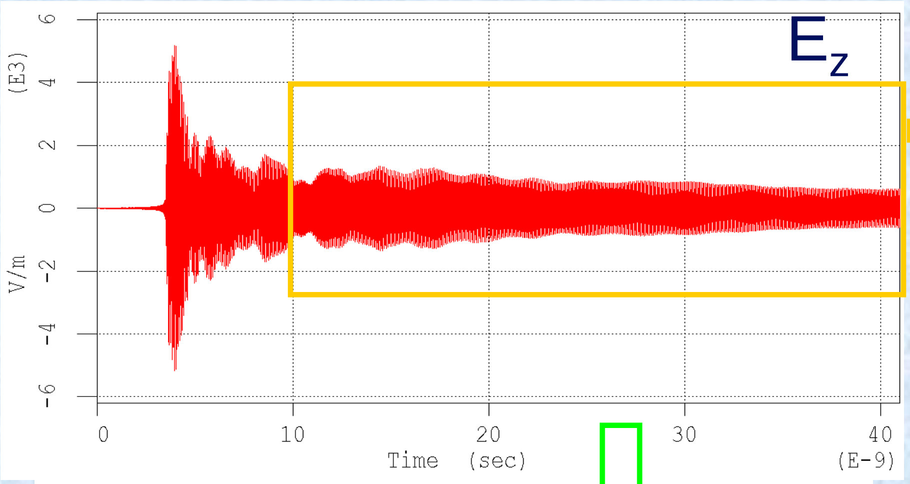




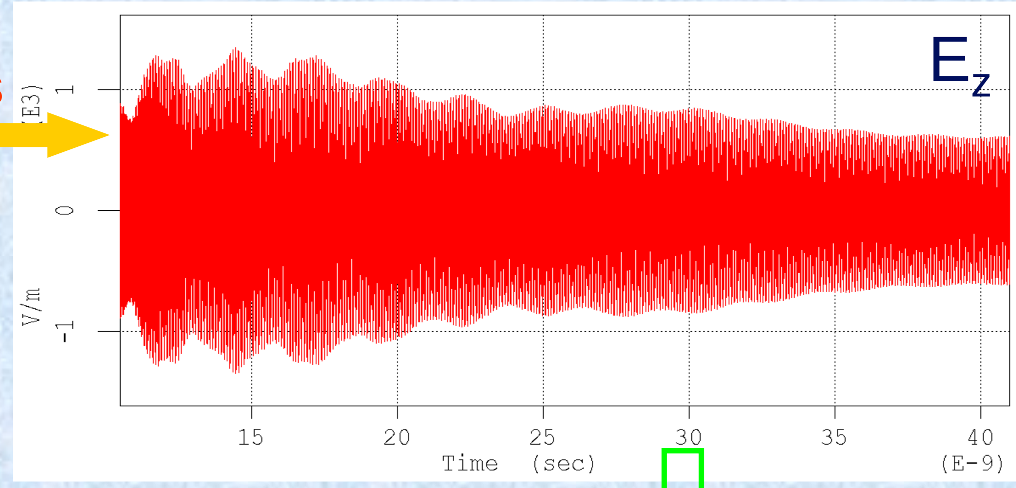
Excitation of the W-band cylindrical surface field cavity by broadband TEM pulse

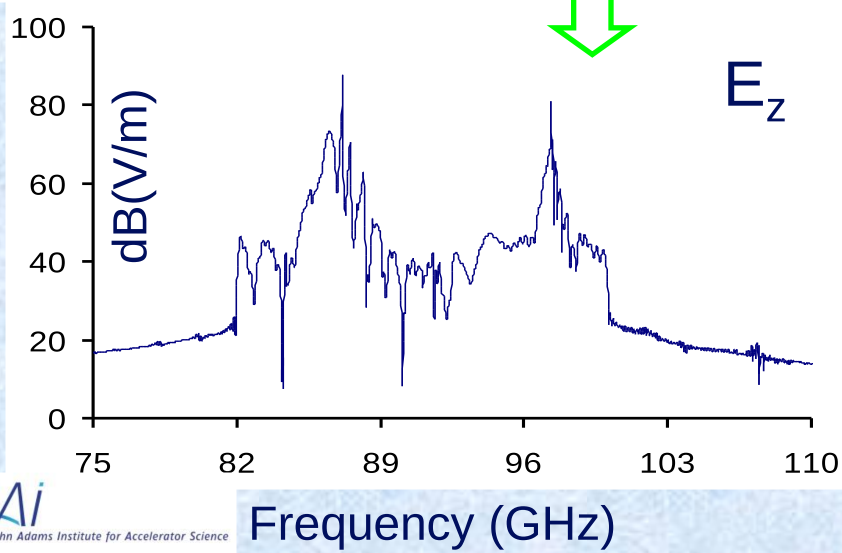
Time dependence of the E_z field component associated with the pump pulse (t $\in$[0,7ns]) and cavity decaying field (t $\in$[7ns,41ns])

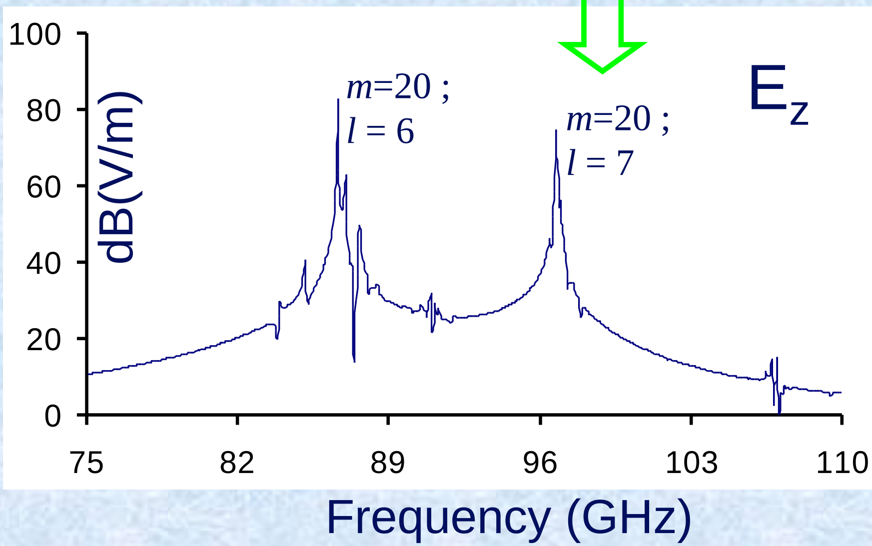
Time dependence of the E_z field component associated with the cavity decaying field (t $\in$[7ns,41ns])



10ns







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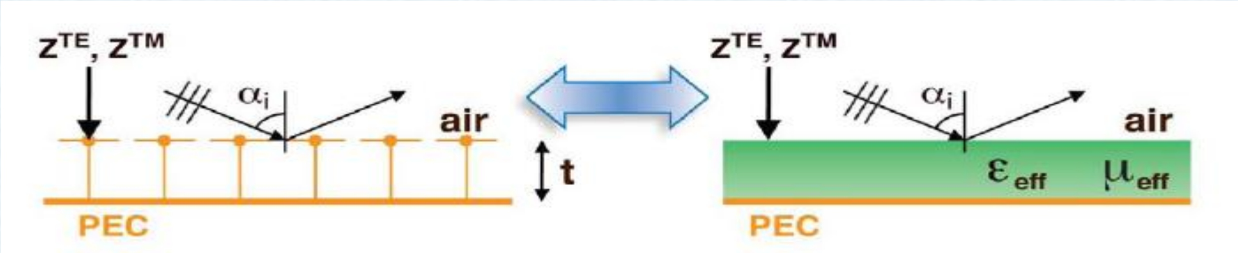
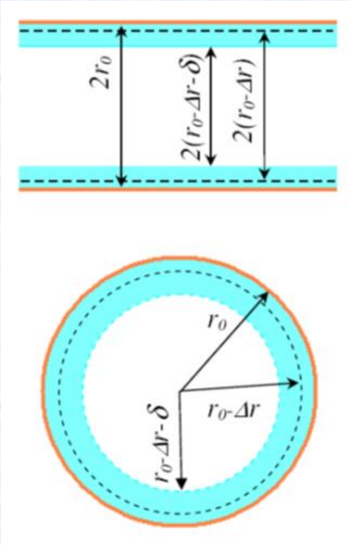
Periodic surface lattice as "effective dielectric"

The set of discrete scatterers is substituted with continues dielectric



E. Lier et al.,Nature Materials,10, pp. 216–222 (2011)



Benefits

1/ No complex or compound materials required

2/ Simple temperature and stress management

3/ Simple dissipation of surface charges into bulk material

4/ Simple machining

5/ Unique electromagnetic and electron beam dispersive properties

Substitution of 2D periodic surface lattice with effective dielectric

$$(E_z;H_z)=\left(\frac{\partial^2}{\partial z^2}+k^2\varepsilon\mu\right)(\Psi_e;\Psi_h)$$

$$\omega/c=\sqrt{(k_\perp)^2+k_z^2}$$

Inside dielectric

$$\kappa_s^2=k^2n^2-\bar{k}_z^2$$

n is the refractive index

$$\Psi_e=C_1F_e(\kappa_s r)\sin(\bar{m}\varphi)\sin(\bar{k}z) \qquad F_e(\kappa_s r)=J_{\bar{m}}(\kappa_s r)N_{\bar{m}}(\kappa_s r_+)-J_{\bar{m}}(\kappa_s r_+)N_{\bar{m}}(\kappa_s r)$$

$$\Psi_h=C_2F_h(\kappa_s r)\cos(\bar{m}\varphi)\cos(\bar{k}z) \qquad F_h(\kappa_s r)=J_{\bar{m}}(\kappa_s r)N'_{\bar{m}}(\kappa_s r_+)-J'_{\bar{m}}(\kappa_s r_+)N_{\bar{m}}(\kappa_s r)$$

Outside dielectric

$$p_s^2=\bar{k}_z^2-k^2$$

$$\Psi_e=C_3\hat{F}_e(p_s r)\sin(\bar{m}\varphi)\sin(\bar{k}z)$$

$$\Psi_h=C_4\hat{F}_h(p_s r)\cos(\bar{m}\varphi)\cos(\bar{k}z) \qquad \hat{F}_e(p_s r)=\hat{F}_h(p_s r)=I_{\bar{m}}(p_s r)$$

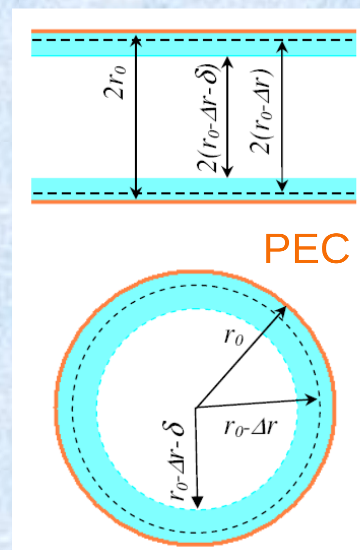
Dispersion relation

$$\begin{cases}\kappa_s^2+p_s^2=k^2(n^2-1)\\ p_s^4\kappa_s^4r_d^4\left(n^2f_e-\hat{f}_e\right)\left(f_h-\hat{f}_h\right)=\bar{m}^2\bar{k}_z^2k^2\left(n^2-1\right)^2\end{cases}$$

$$\hat{f}_e=\hat{f}_h=\hat{f}=-I'_{\bar{m}}(y)/\left(yI_{\bar{m}}(y)\right) \qquad y=p_s r_d$$

$$f_e=\frac{1}{x_d}\frac{J'_{\bar{m}}(x_d)N_{\bar{m}}(x_+)-J_{\bar{m}}(x_+)N'_{\bar{m}}(x_d)}{J_{\bar{m}}(x_d)N_{\bar{m}}(x_+)-J_{\bar{m}}(x_+)N_{\bar{m}}(x_d)}$$

$$f_h=\frac{1}{x_d}\frac{J'_{\bar{m}}(x_d)N'_{\bar{m}}(x_+)-J'_{\bar{m}}(x_+)N'_{\bar{m}}(x_d)}{J_{\bar{m}}(x_d)N'_{\bar{m}}(x_+)-J'_{\bar{m}}(x_+)N_{\bar{m}}(x_d)} \qquad x_{d,+}=\kappa_s r_{d,+}$$



Matching partial fields at the boundary of the dielectric its thickness can be found

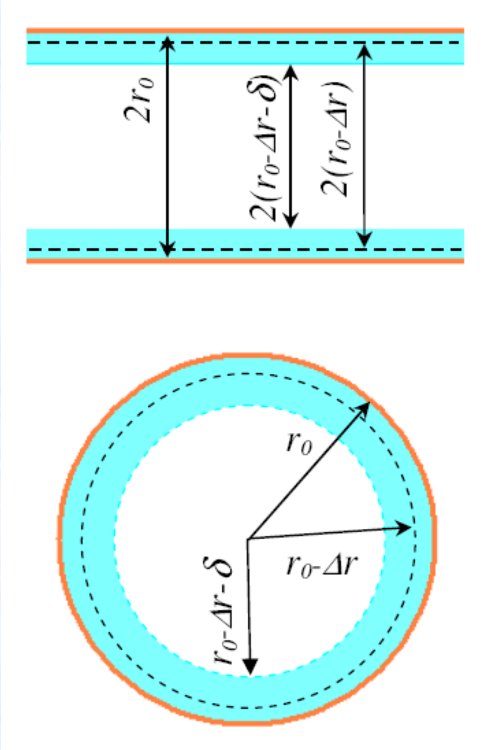
$$p_s\frac{I_{\bar{m}}(p_s r_d)}{I'_{\bar{m}}(p_s r_d)}=k_{\perp v}\frac{J_0(k_{\perp v}r_d)}{J'_0(k_{\perp v}r_d)}$$

$$\delta\cong\frac{p_s^2}{\left(k_{\perp v}^2-p_s^2\right)}\frac{r_-}{\left(p_s r_- -\bar{m}\right)}$$

$$n=\sqrt{1+\frac{\bar{k}_z^2}{k^2}}$$

$k\geq k_{\text{cut-off}}$

Design of Cherenkov maser based on 2D periodic surface lattice



$$U_e(kV) \approx 511(kV) \times \left(\sqrt{\lambda^2/(\lambda^2-d_z^2)}-1\right)$$

$$\delta \cong \frac{p_s^2}{\left(k_{\perp v}^2 - p_s^2\right)} \frac{r_-}{\left(p_s r_- - \overline{m}\right)}$$

(a) $k_{\perp v}^2 - p_s^2 > 0$ while $p_s r_0 - \overline{m} < 0$ or

(b) $k_{\perp v}^2 - p_s^2 < 0$, while $p_s r_0 - \overline{m} > 0$.

$$k_{\perp v} = \omega / c, \quad p_s = \sqrt{\overline{k}_z^2 - (\omega/c)^2}$$

$$d_z = \frac{\lambda}{a}\sqrt{a^2-1} \quad \text{and} \quad a^2 = \left(\frac{U(kV)}{511}+1\right)^2 > 1$$

If U>212kV

(a) $$\frac{2\pi r_0}{\lambda a} < \overline{m}$$

If U<212kV

(b) $$\frac{2\pi r_0}{\lambda a} > \overline{m}$$

High-power THz and X-ray sources of coherent radiation based on 2D PSL

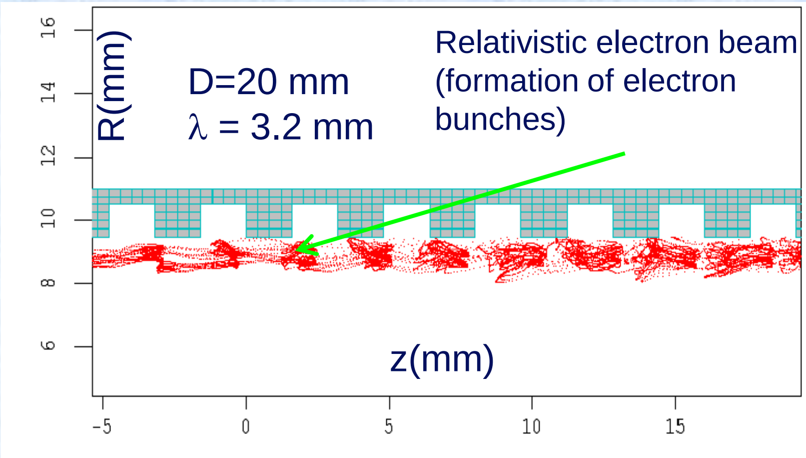
1. Cherenkov type radiators
2. Radiators based on electron scattering of standing EM wave (Kapitza-Dirac effect, FEL type oscillators)

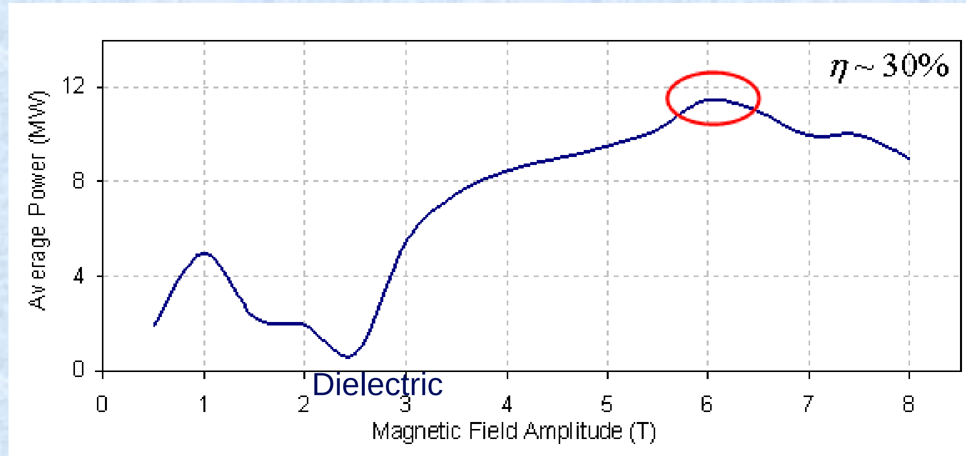
96GHz Cherenkov Maser based on 2D PSL

(1st type radiators)

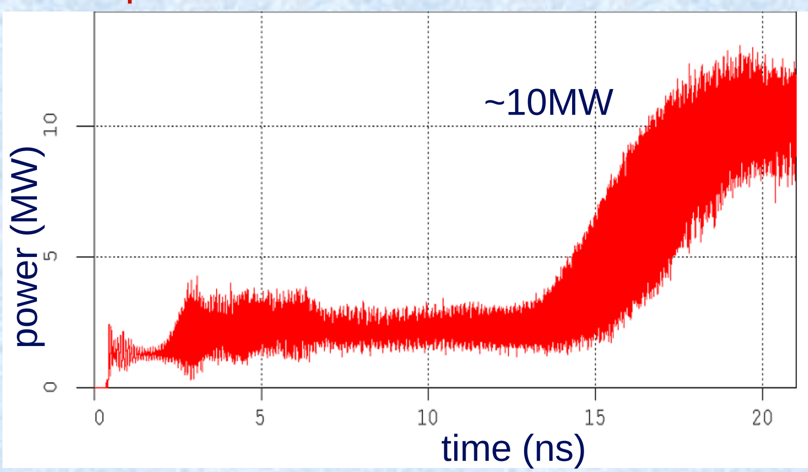
Nonlinear interaction between relativistic electrons and EM radiation result in electron bunch formation in EM field decelerating phase

Electron Beam 300kV, 100A

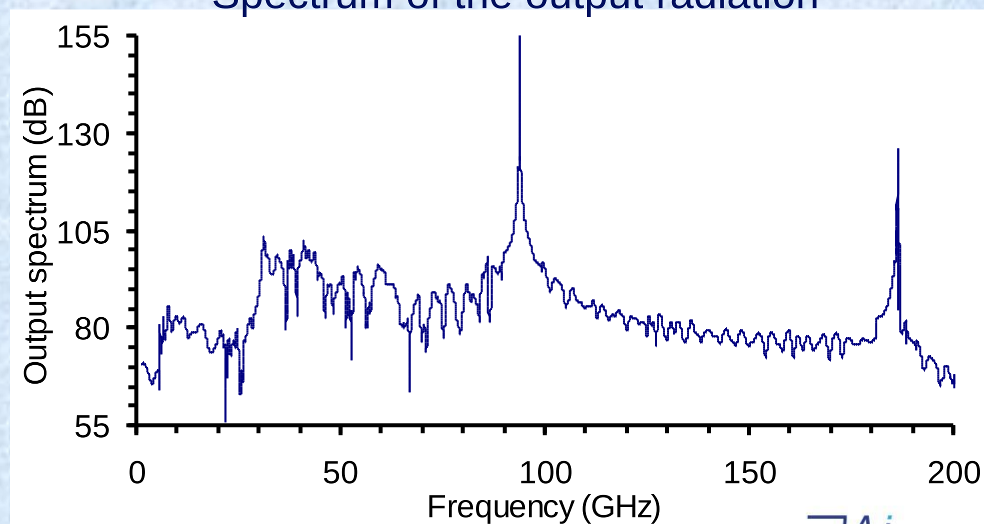




Output power from Cherenkov maser based on 2D periodic lattice



Spectrum of the output radiation



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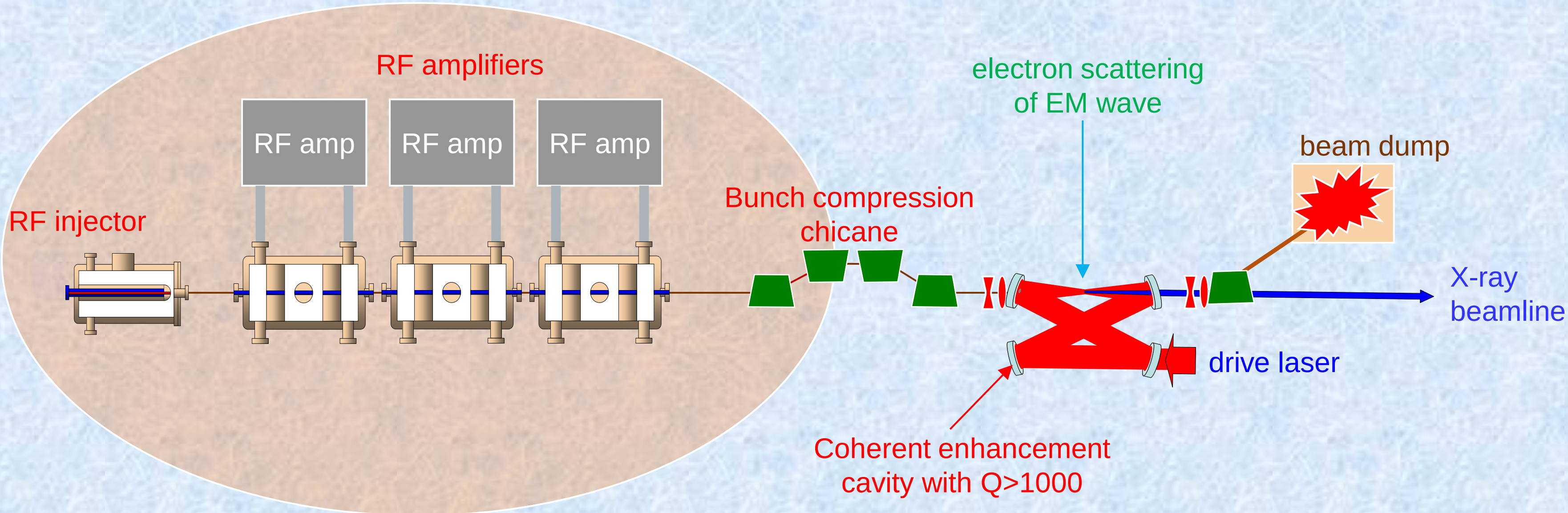
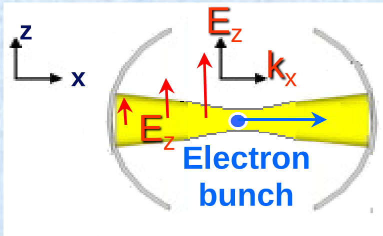
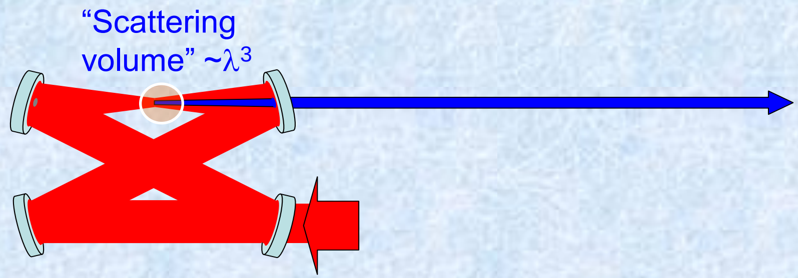
Compact Light Sources



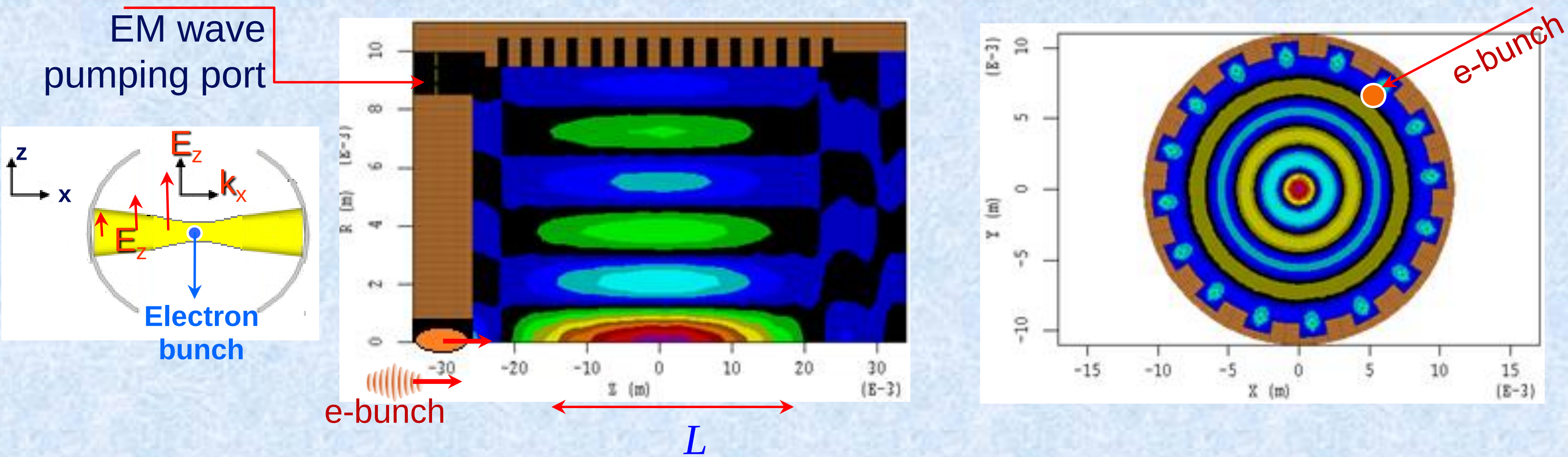
Compact Source of Coherent Radiation

Conventional schema



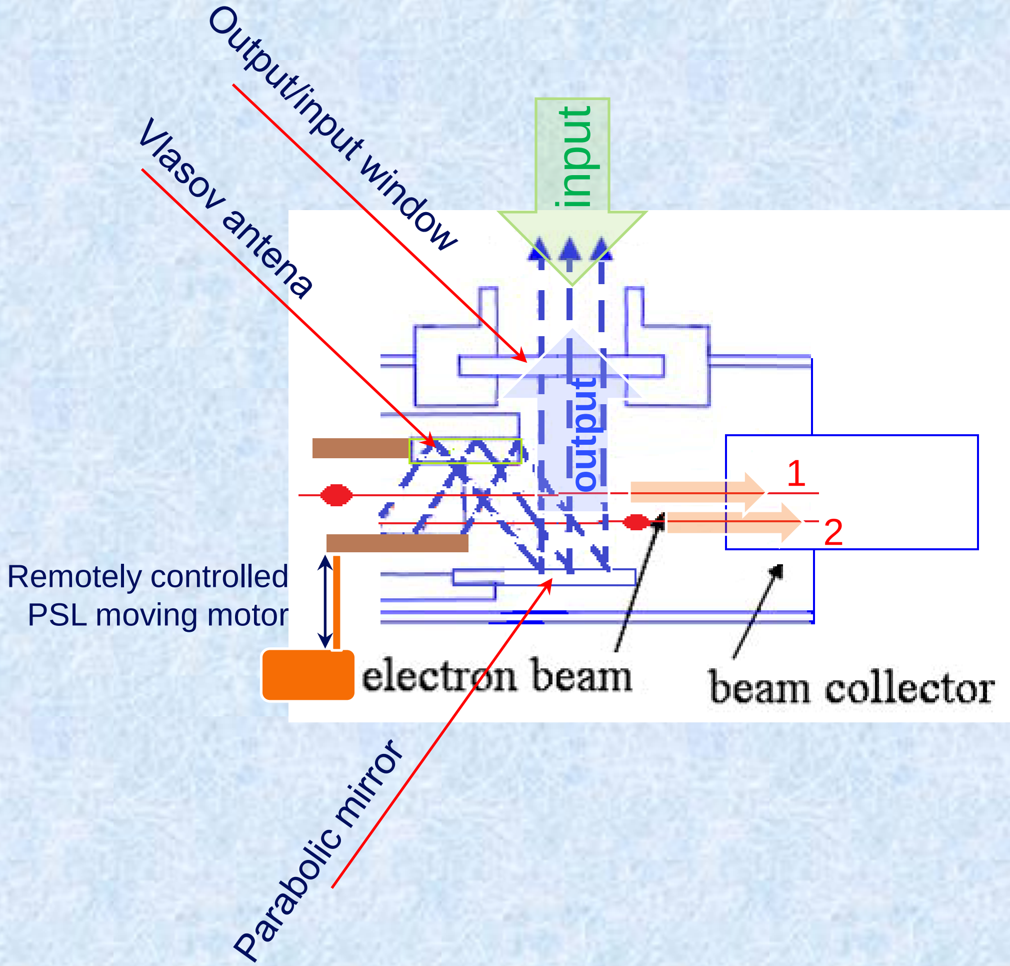


Scattering of the standing EM field with relativistic electron beam



Continuous interaction (scattering) between electron bunch and radiation along long distance $L \gg \lambda$ i.e. "scattering volume" ~ $\lambda^2 L$

Compact Source of Coherent Radiation



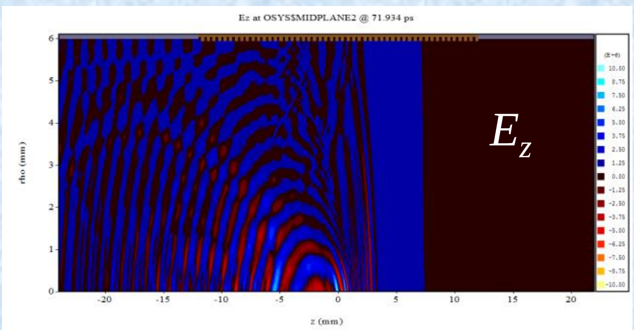
1/ Experiment on standing EM wave scattering by electron bunch
2/ Experiment on direct generation of EM radiation by electron bunch

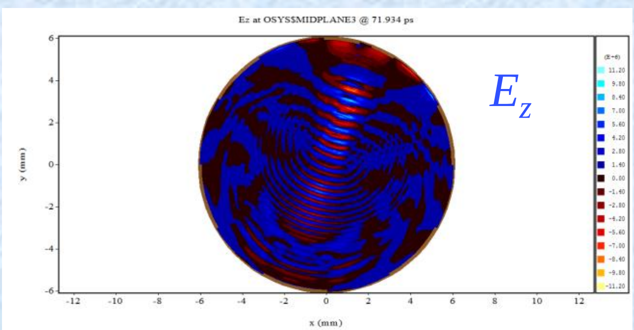
Compact Source of Coherent Radiation

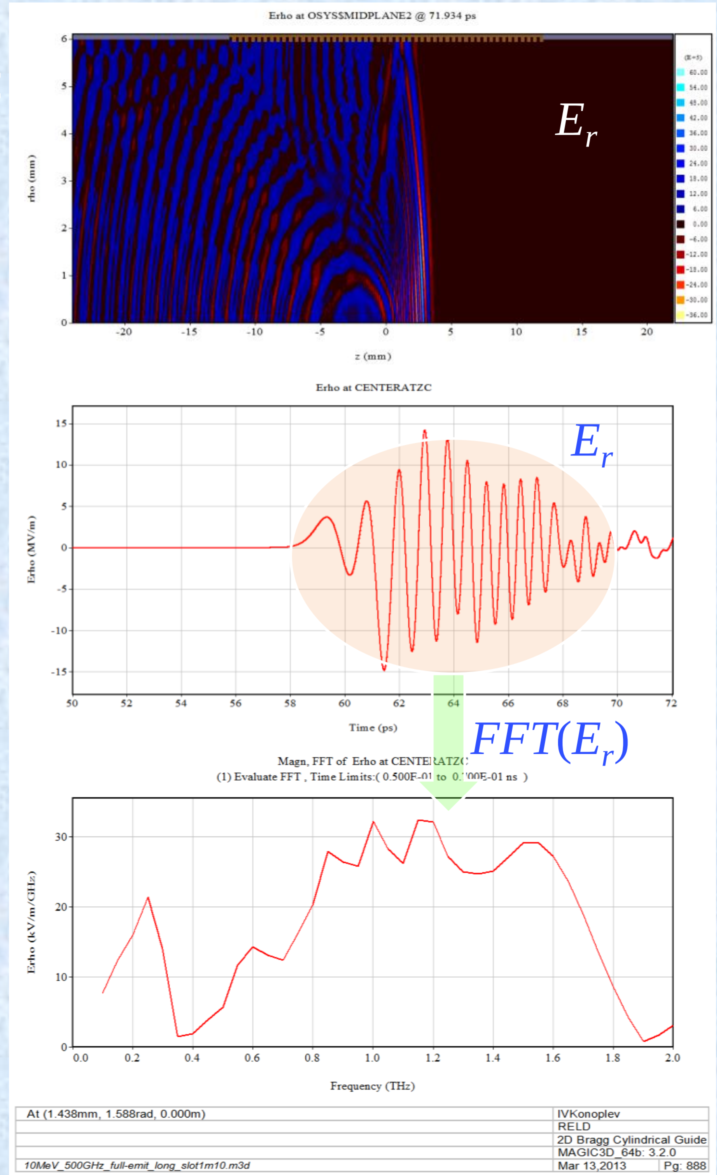
(1st type radiators)

Electron bunch having the following parameters

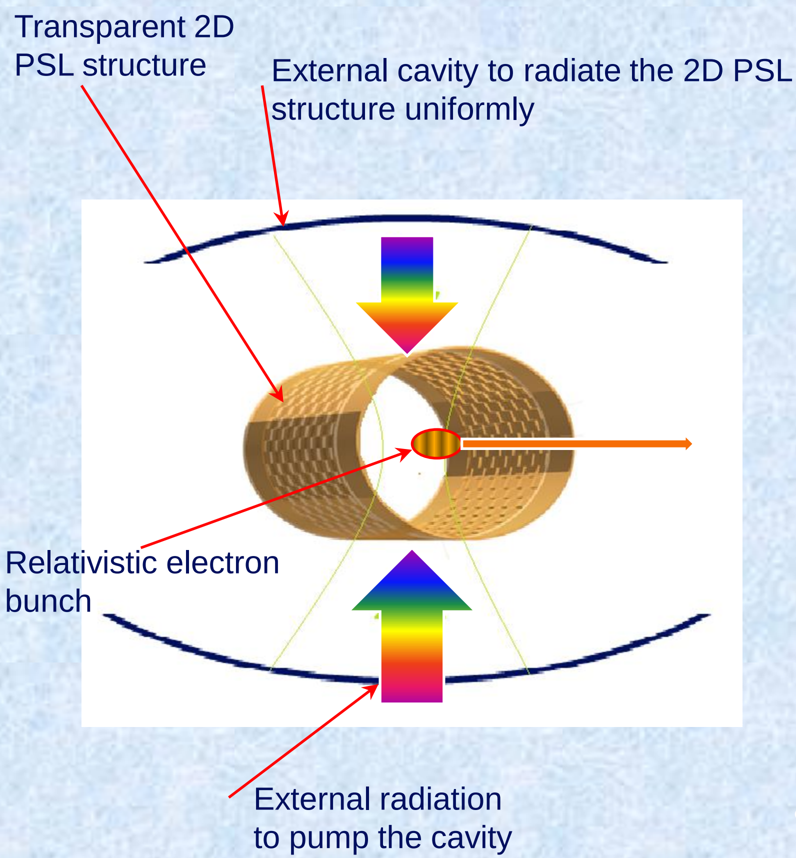
- 0.8nc
- Bunch length 800fs
- Electron energy 8MeV



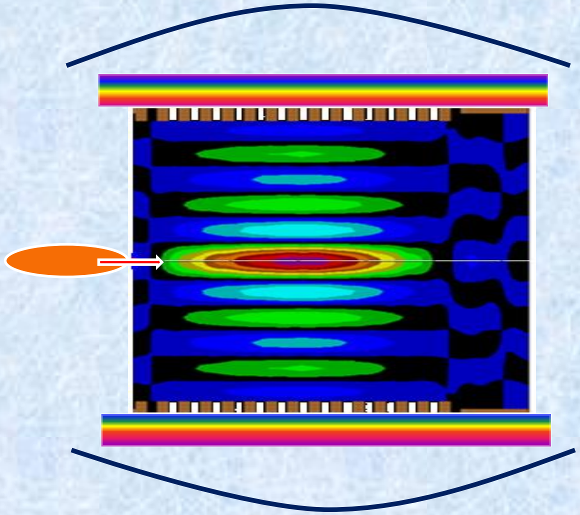




Compact Source of Coherent X-ray based on Standing EM Field Scattering

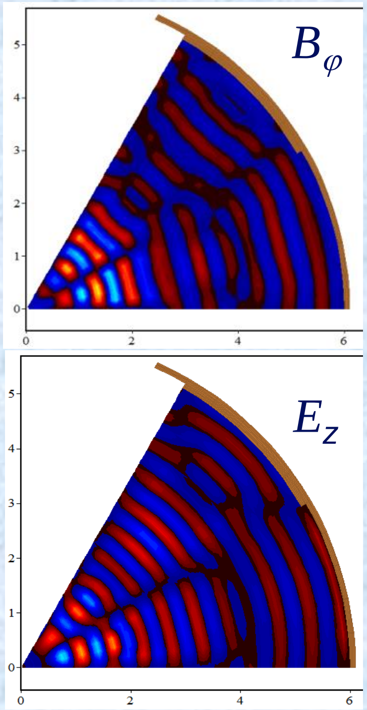


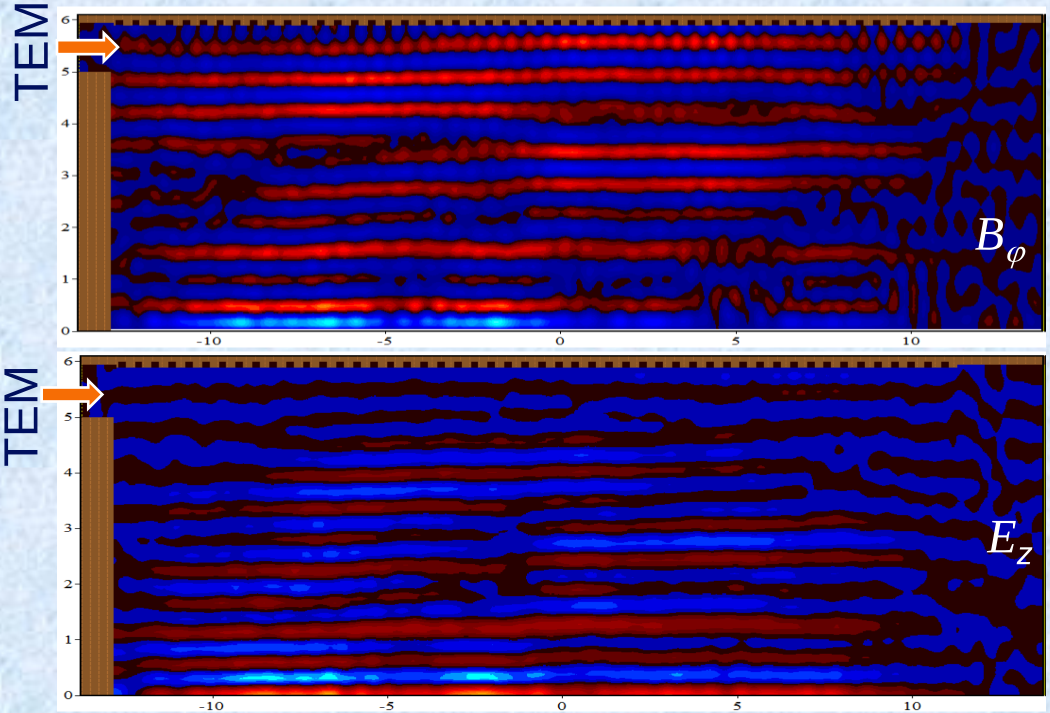
1/ EM field transparent structure is used with 2D periodic surface lattice on the inner side
2/ PSL is pumped by an external source of radiation which can be incoherent
3/ PSL operates as a cavity accumulating the EM energy
4/ Relativistic electron beam is used to observe standing wave scattering



Compact Source of Coherent Radiation based on Standing EM Field Scattering

12 mm diameter 2D PSL is excited via coaxial line termination by short (6ns) broad band pulse with flat frequency spectra in range from 400GHz to 700GHz





Wakefield Acceleration mediated by 2D PSL

Dielectric Wake-Field accelerator

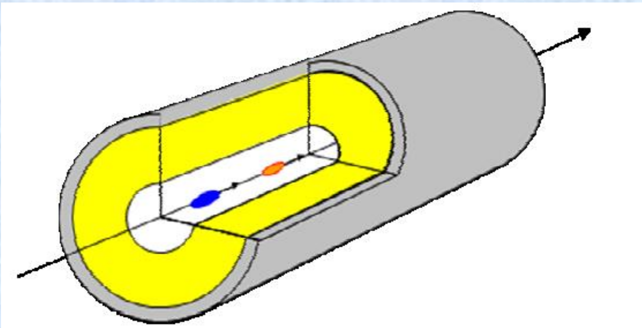


Table 1: Parameters of Cordierite Dielectric Structures

Parameter	Structure 1	Structure 2	Structure 3
Inner Diameter	10 mm	10 mm	5 mm
Outer Diameter	15 mm	15 mm	15 mm
Length	102 mm	23 mm	28 mm
Frequency of monopole mode	14 GHz	14 GHz	10 GHz
Gradient (per nC)	0.5 MV/m	0.5 MV/m	1.0 MV/m

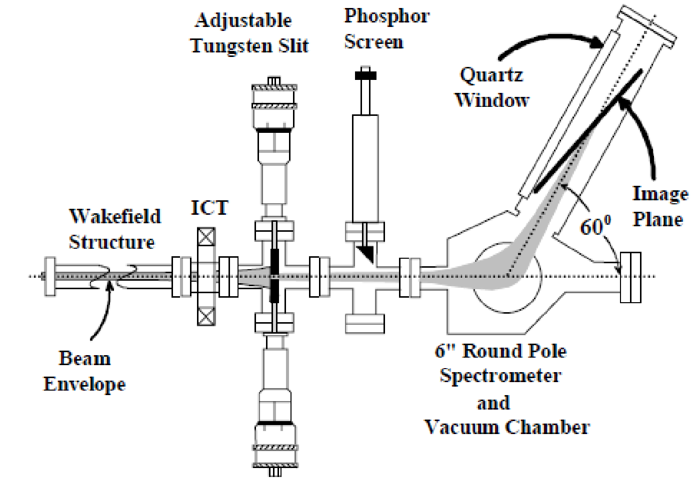
SURVEY OF ADVANCED DIELECTRIC WAKEFIELD ACCELERATORS*

M. E. Conde#, ANL, Argonne, IL 60439, U.S.A.

Proceedings of PAC07, Albuquerque, New Mexico, USA

Measurements of the longitudinal wakefields in a multimode, dielectric wakefield accelerator driven by a train of electron bunches

J. G. Power, M. E. Conde, W. Gai, R. Konecny, and P. Schoessow
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439



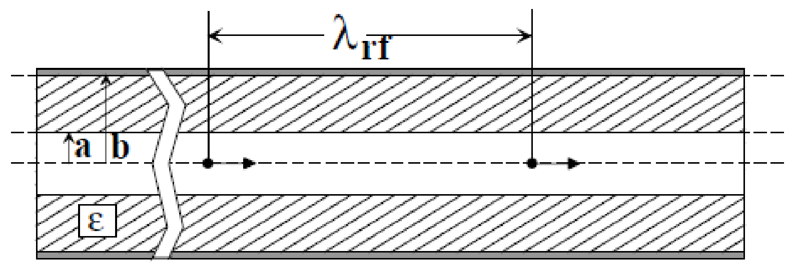


FIG. 1. The multimode waveguide driven by a bunch train (two bunches, separated by λ_{rf}, shown). The thick walled dielectric waveguide has inner radius $a = 0.5$ cm, outer radius $b = 1.44$ cm, length $L = 60$ cm, and dielectric constant $\varepsilon = 38.1$.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 3, 101302 (2000)

Dielectric Wake-Field accelerators based on co-axial structures

Coaxial two-channel high-gradient dielectric wakefield accelerator

G. V. Sotnikov,[1,2,*] T. C. Marshall,[3,2,†] and J. L. Hirshfield[4,2,‡]

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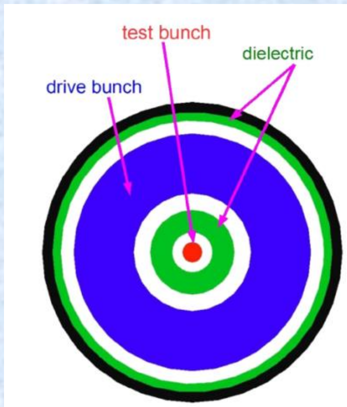


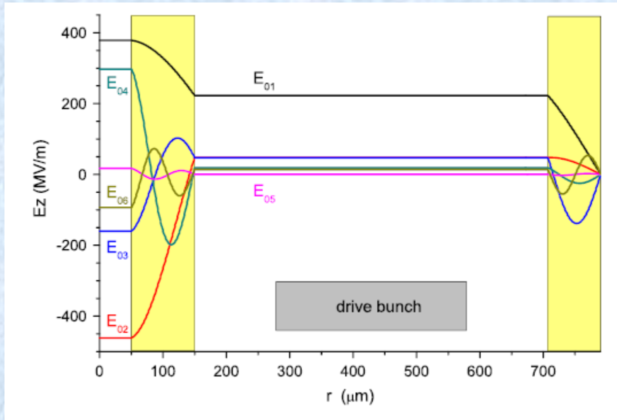


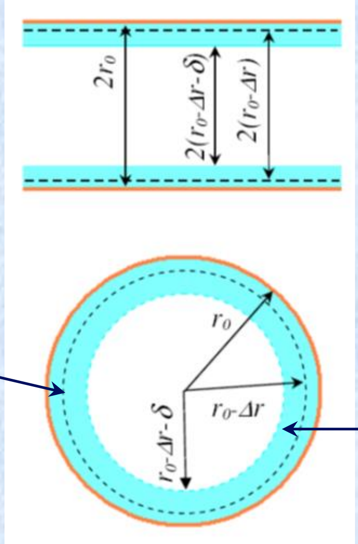
TABLE II. Parameters for a GHz two-channel coaxial wakefield accelerator module using alumina dielectric tubes.

Frequency of the E_{02} design mode	28.092 GHz
External radius of outer coaxial dielectric shell r_4	14.05 mm
Inner radius of outer coaxial dielectric shell r_3	13.51 mm
External radius of inner coaxial dielectric shell r_2	3.18 mm
Accelerating channel radius (inner radius of inner coaxial dielectric shell) r_1	2.0 mm
Relative dielectric constant of dielectric shells ε	9.8
rms bunch length σ_z (Gaussian charge distribution)	1 mm
Outer drive bunch radius (box charge distribution) r_{b2}	10.39 mm
Inner drive bunch radius r_{b1}	6.39 mm
Bunch energy	14 MeV
Bunch charge	50 nC

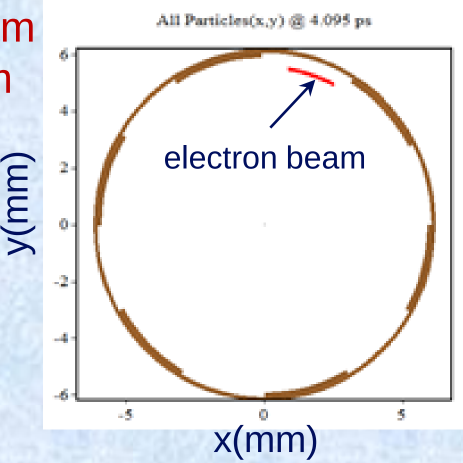
Wake-field Acceleration mediated by 2D PSL operating as artificial dielectric

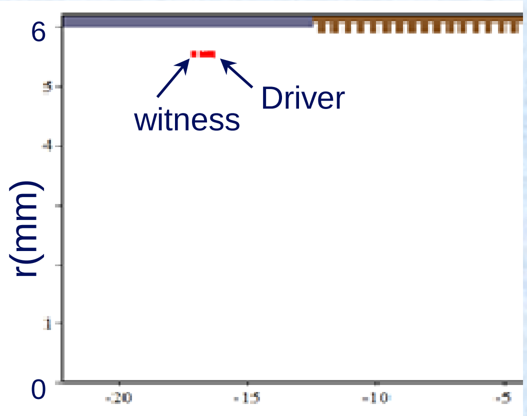
Parameters of the structure:
1/ diameter 1.2 cm;
2/ period of corrugation along z 0.6 mm;
3/ number of azimuthal periods 6;
4/ amplitude of corrugation 0.2 mm
5/ corrugation length 24 mm;
6/ beam thickness 0.1 mm
7/ distance between beam and the structure 0.4 mm

Dotted line is a Lattice boundary



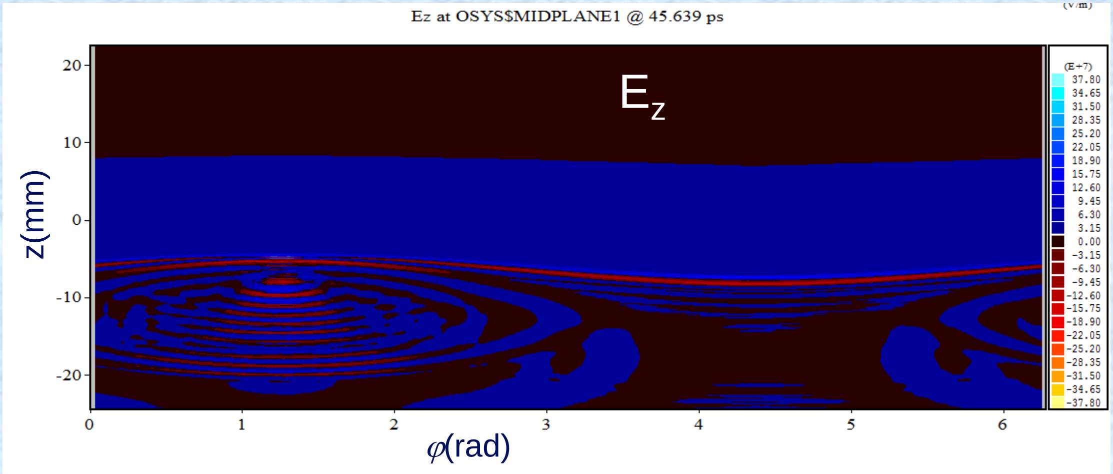
Solid blue is an artificial dielectric

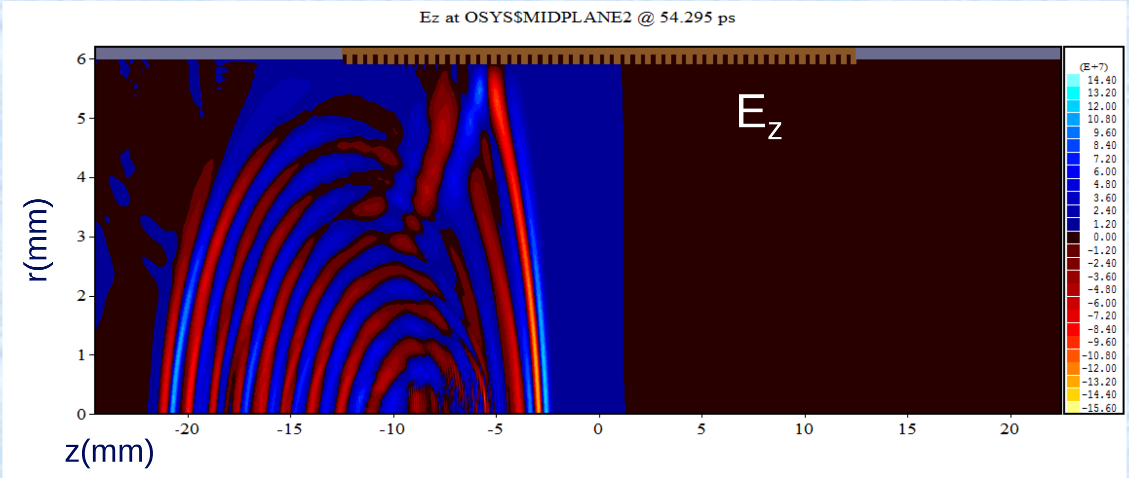




Wake-Field mediated by 2D PSL

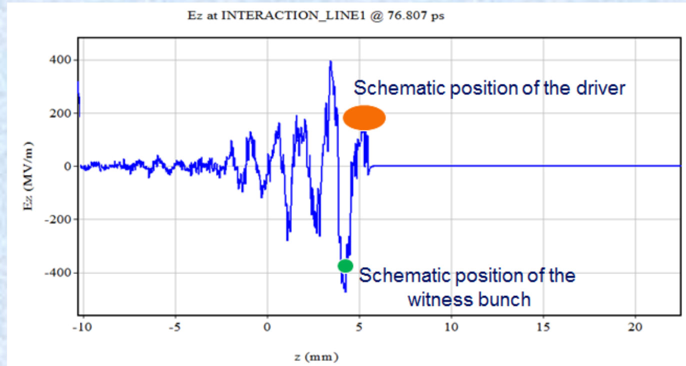
The wakefield field is driven by the electron bunch propagating close to the lattice

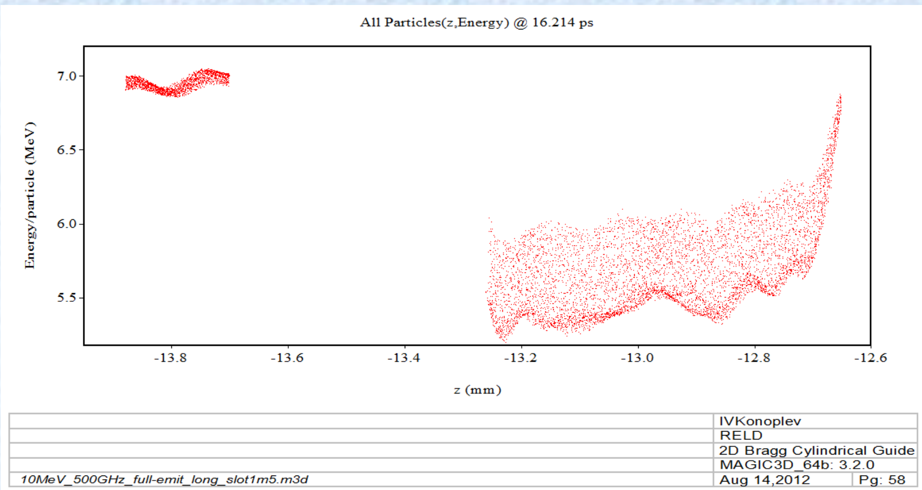


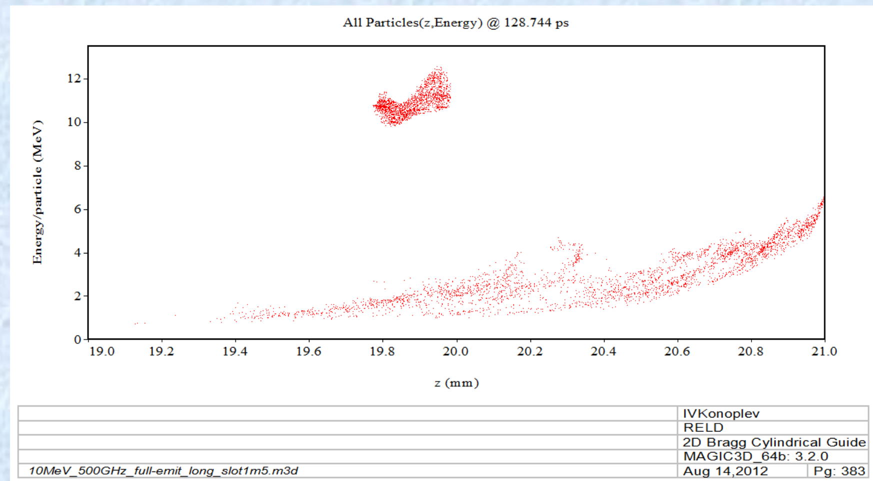


The maximum wakefield field strength observed is 370MV/m

Wake-Field acceleration mediated by PSL







Acceleration of 0.5ps, 0.2nC witness bunch from 7MeV to 12MeV inside 24mm long 2D PSL by 2ps, 7MeV, 20nC driver beam and

Parameters of the structure:

1/ diameter 1.2 cm; 2/ period of corrugation along z 0.6 mm;

3/ number of azimuthal periods 6; 4/ amplitude of corrugation 0.2 mm

5/ corrugation length 24 mm; 6/ beam thickness 0.1 mm

7/ distance between beam and the structure 0.4 mm

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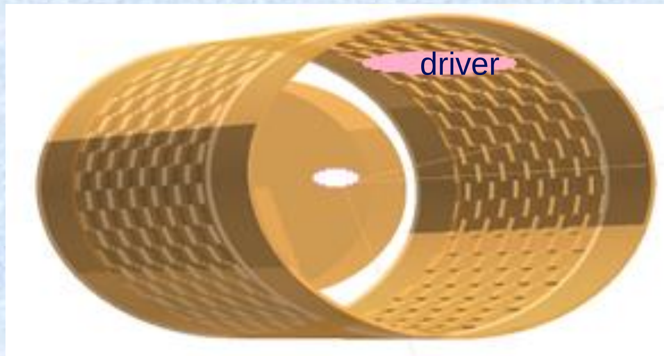
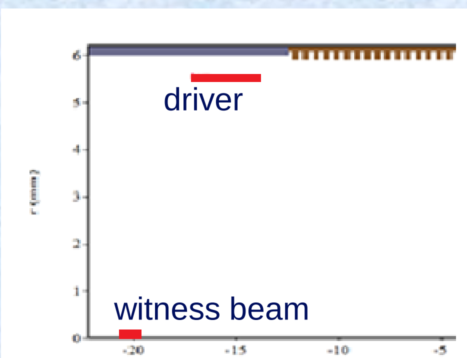
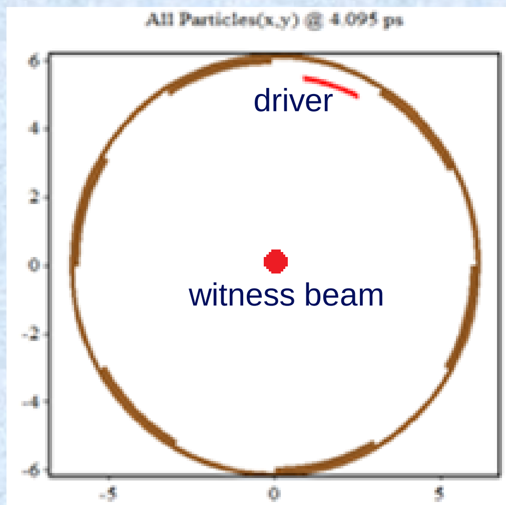
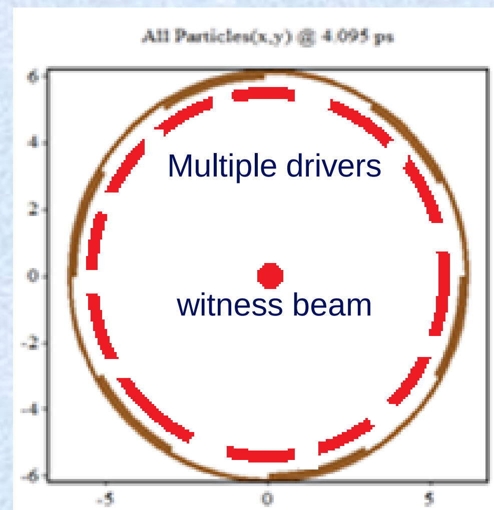
Wakefield Acceleration in a co-axial beam configuration

Schematic diagrams of possible co-axial configurations using single and multiple drivers which will allow wake-field acceleration of witness beam









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Conclusion

- Compact sources of coherent and incoherent radiation based on PSL and driven by electron beams
- High gradient linear accelerators based on Periodic Surface Lattices (PSL)
- Electron beam diagnostics based on and mediated by PSL

Thank you!