Intense Emission of Smith-Purcell Radiation at the Fundamental Frequency from a Grating Equipped with Sidewalls

J. T. Donohue

Centre d'Etudes Nucléaires de Bordeaux-Gradignan, Université
Bordeaux 1, CNRS/IN2P3, BP 120, 33175 Gradignan, France

J. Gardelle, P. Modin

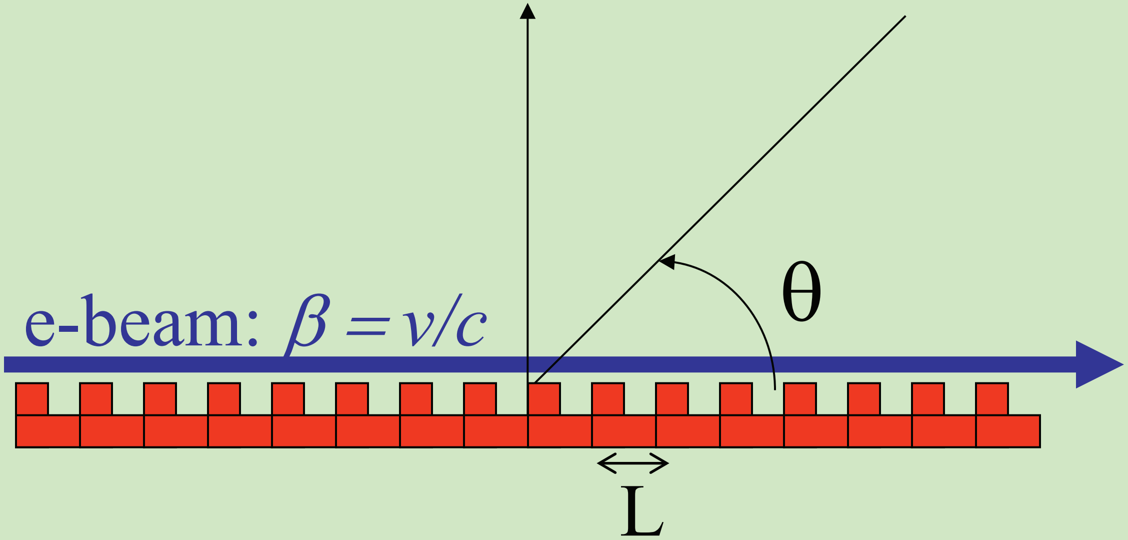
CEA/Centre d'Etudes Scientifiques et Techniques d'Aquitaine
BP 2, 33114 Le Barp, France

SUMMARY

1. Coherent Smith-Purcell radiation (CSP)
2. Model of Andrews, Brau and collaborators (A&B)
3. 2D Experiment at CESTA (wide, flat, and intense beam, 2nd harmonic)
4. 3D Theory for a grating with sidewalls
5. 3D Experiment at CESTA (high power on the fundamental)

SMITH-PURCELL RADIATION

S. J. Smith and E. M. Purcell, Phys. Rev. **92**, 1069 (1953)



Incoherent Smith-Purcell radiation (*first observed in 1953*):

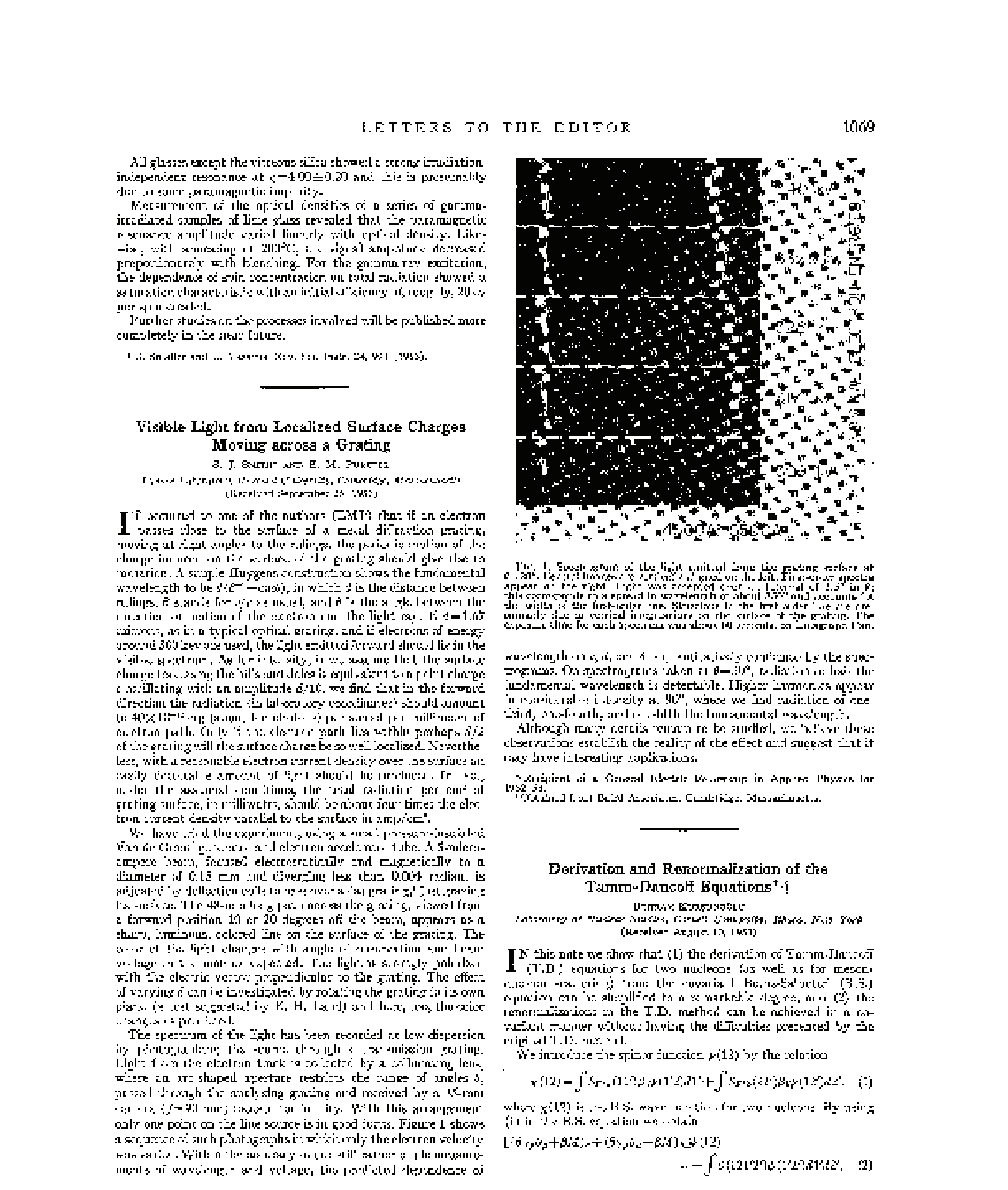
- Diffraction grating
- The observed wavelengths satisfy the following relation:

$$\lambda = \frac{L}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$

Where: L is the grating period

n is the order of diffraction

β is the normalized beam velocity



LETTERS TO THE EDITOR 1069

Visible Light from Localized Surface Charges Moving across a Grating

S. J. SMITH AND E. M. PURCELL

Derivation and Renormalization of the Tamm-Dancoff Equations

S. J. Smith &

E. M. Purcell

Phys. Rev. **92**
1069 (1953)

Van de Graaff, 300 kV

5 µA

L=1.67 µm

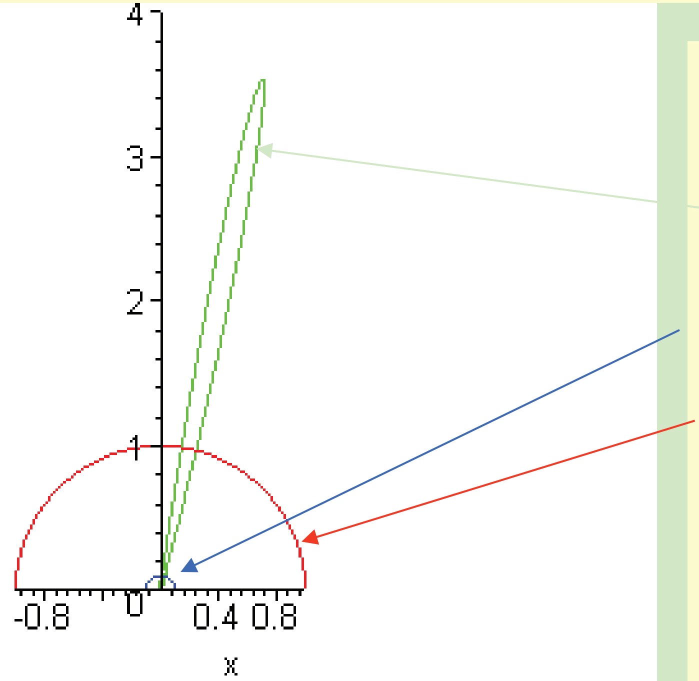
λ: 440-550 nm

θ: 0-20°

COHERENT SMITH-PURCELL RADIATION (CSP)

CSP Radiation has two senses:

- Intra-bunch: bunch size $<< \lambda$, Intensity $\propto N_e^{\,2} \;\; \forall \theta$
- Inter-bunch (time interval T between successive bunches = $n\lambda_{SP}/c$), n integer) $\Rightarrow$ Intensity is enhanced at certain angles



Radiation patterns for

Inter-bunch coherent —

Incoherent S-P —

Intra-bunch coherent —

SMITH-PURCELL RADIATION SINCE 2004

Dispersion relation proposed by Andrews and Brau for 2D lamellar gratings:

H. L. Andrews and C. A. Brau, Phys. Rev. ST Accel. Beams **7**, 070701 (2004).

Evanescent **Floquet** wave above grating, uniform plasma, velocity = v.

$$B_z(x,y,t)=\sum_p B_p \exp\left(i(k+pK)x-\alpha_p y-\omega t\right)$$

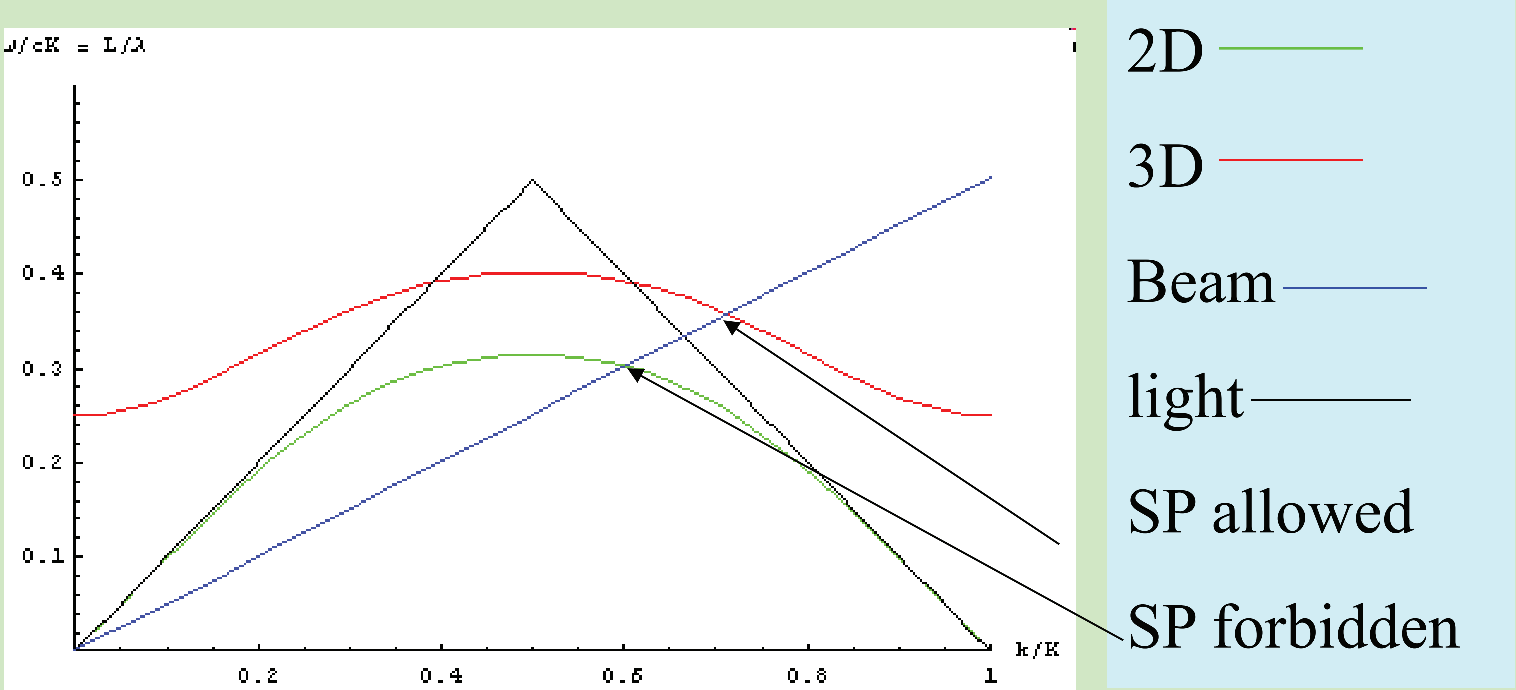
$$(k+pK)^2-\alpha_p{}^2=(\omega/c)^2 \quad 0<k<K=2\pi/L$$

They established the 2D dispersion relation between k and ω.

We established the 3D dispersion relation among *k*, *ω* , and *q*, the transverse wave-number.

J. T. Donohue and J. Gardelle, Phys. Rev. ST Accel. Beams **14**, 060709 (2011).

See alsq B. D. McVey *et al*, IEEE Trans. Microwave Theory Tech. **42**, 995 (1994).



$$\omega_{3D}(k,q) = \sqrt{(\omega_{2D}(k))^2 + (cq)^2}$$

$$\omega_{3D}(k) = \sqrt{(\omega_{2D}(k))^2 + \left(\frac{c\pi}{W}\right)^2}$$

W = width between sidewalls

2D :

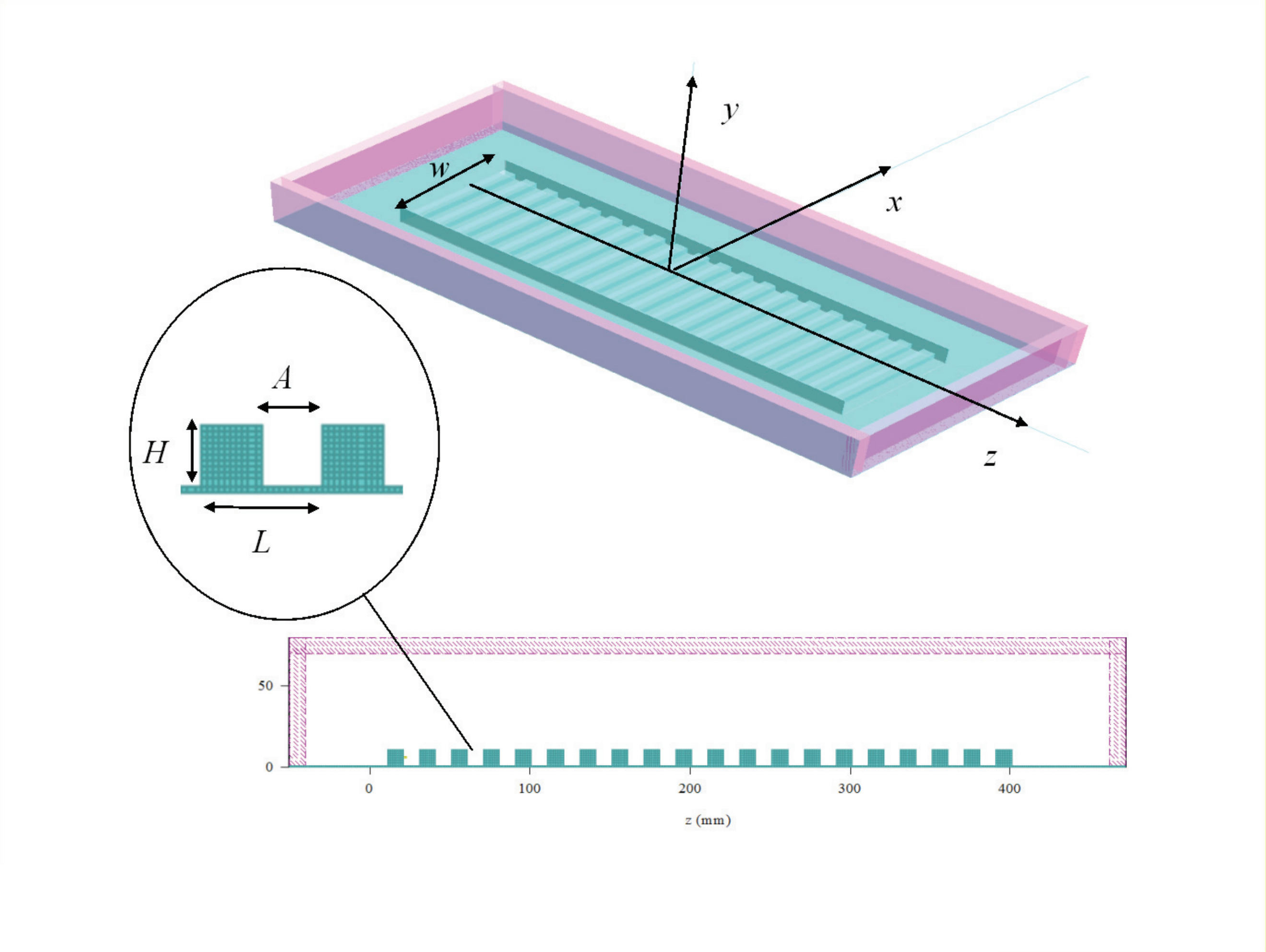
only Harmonics can be radiated

3D :

may radiate Fundamental

Typically

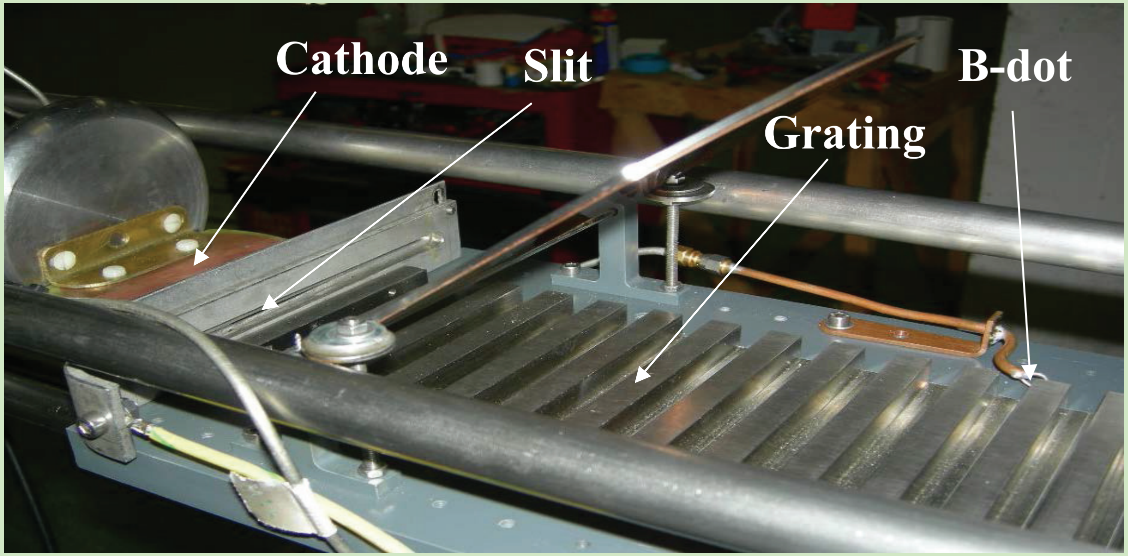
$\text{Bunching}_{\text{Fundamental}} \gg \text{Bunching}_{\text{Harmonic}}$

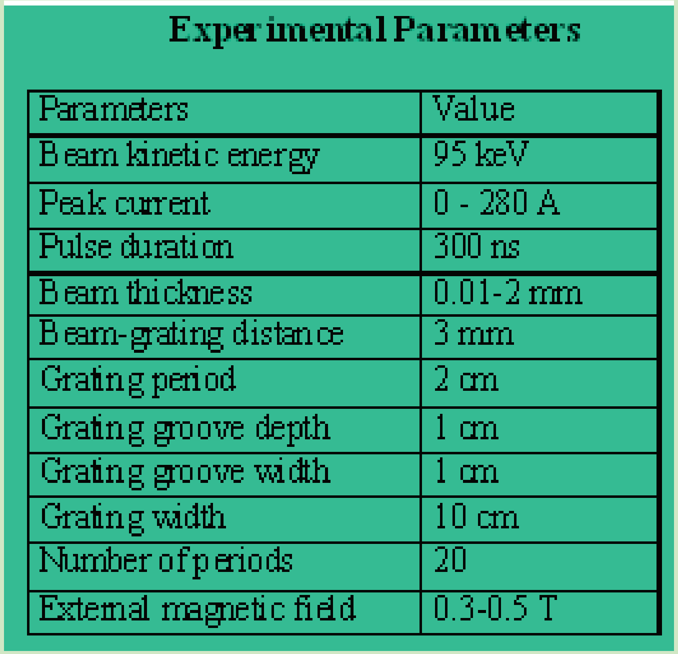


Geometry of our grating with sidewalls:

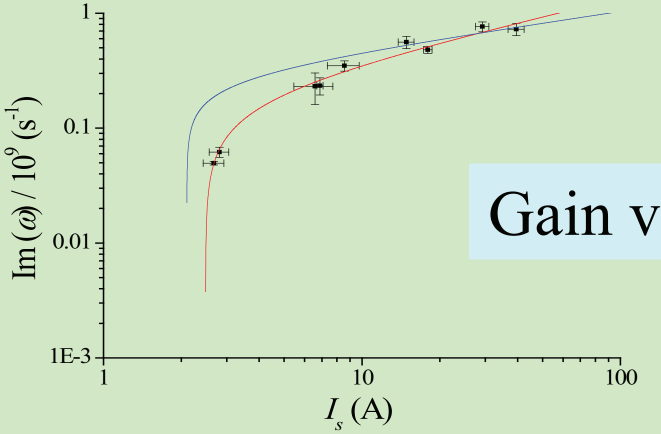
$L = 2$ cm, $A = H = 1$ cm, $w = 4$ cm

THE 2D EXPERIMENT AT CEA/CESTA FEL 2010




Experimental Parameters

Parameters	Value
Beam kinetic energy	95 keV
Peak current	0 - 280 A
Pulse duration	300 ns
Beam thickness	0.01-2 mm
Beam-grating distance	3 mm
Grating period	2 cm
Grating groove depth	1 cm
Grating groove width	1 cm
Grating width	10 cm
Number of periods	20
External magnetic field	0.3-0.5 T



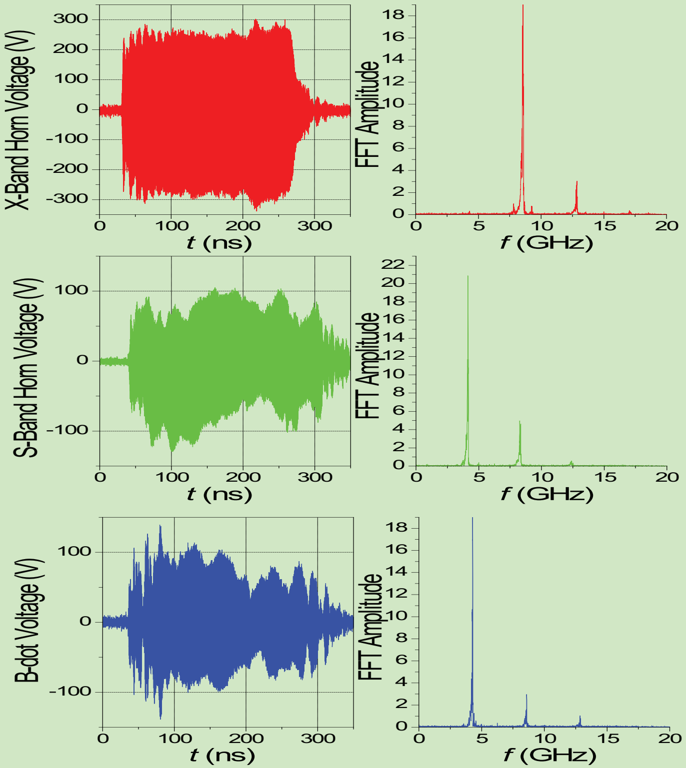
Gain v. current

Efficiency

= 0.1 %

2-D EXPERIMENTAL RESULTS

Wave forms on a
12 GHz BW oscilloscope

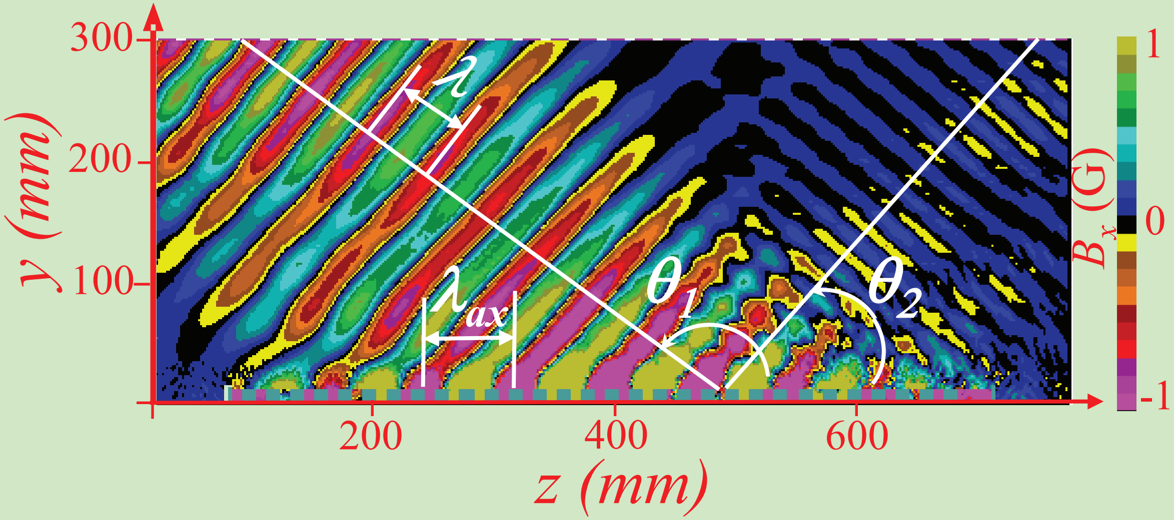


Time signals and their FFTs:
X-band horn placed outside vacuum chamber.
Magnetic field (parallel to groove) as measured with the B-dot probe at a groove end.
S-band horn to detect evanescent wave.

MAGIC 3D SIMULATION

Contours of B_x in the median *y-z* plane at fixed time

The fundamental is radiated at θ_1 (140 °)
The 2nd harmonic is radiated at θ_2 (60 °)



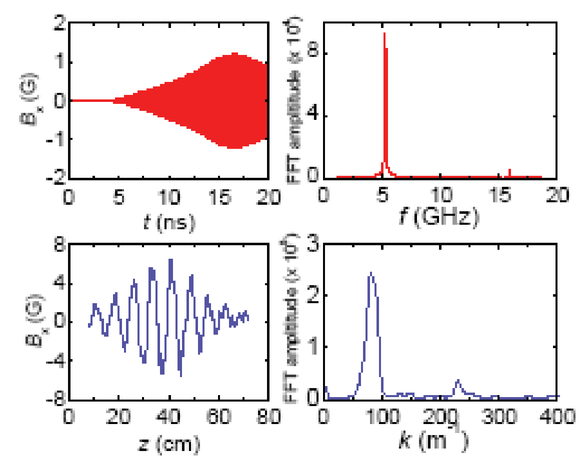
3D simulation with « free-space » on boundaries.
Reflections are tolerable.

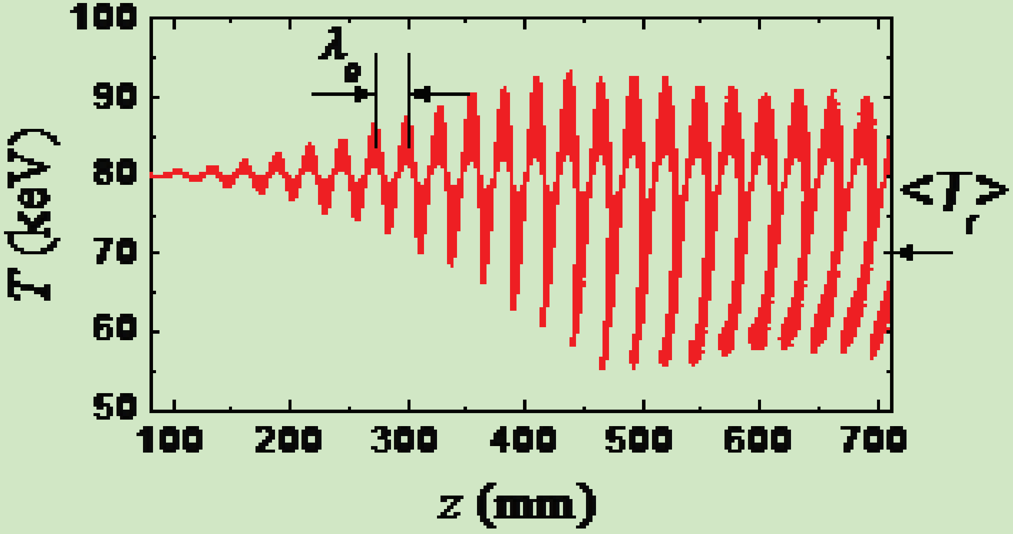
J.T. Donohue , J. Gardelle, "Simulation of a Smith-Purcell free-electron laser with sidewalls: Copious emission at the fundamental frequency ", Appl. Phys. Lett. **99,** 161112 (2011).

MAGIC 3D SIMULATION

$f = 5.2$ GHz $\lambda = 5.8$ cm
$k = 230\ \mathrm{m}^{-1}$ $\lambda_0 = 2.8$ cm
$k\text{-}K = -84\ \mathrm{m}^{-1}$ $\lambda_{-1} = 7.6$ cm

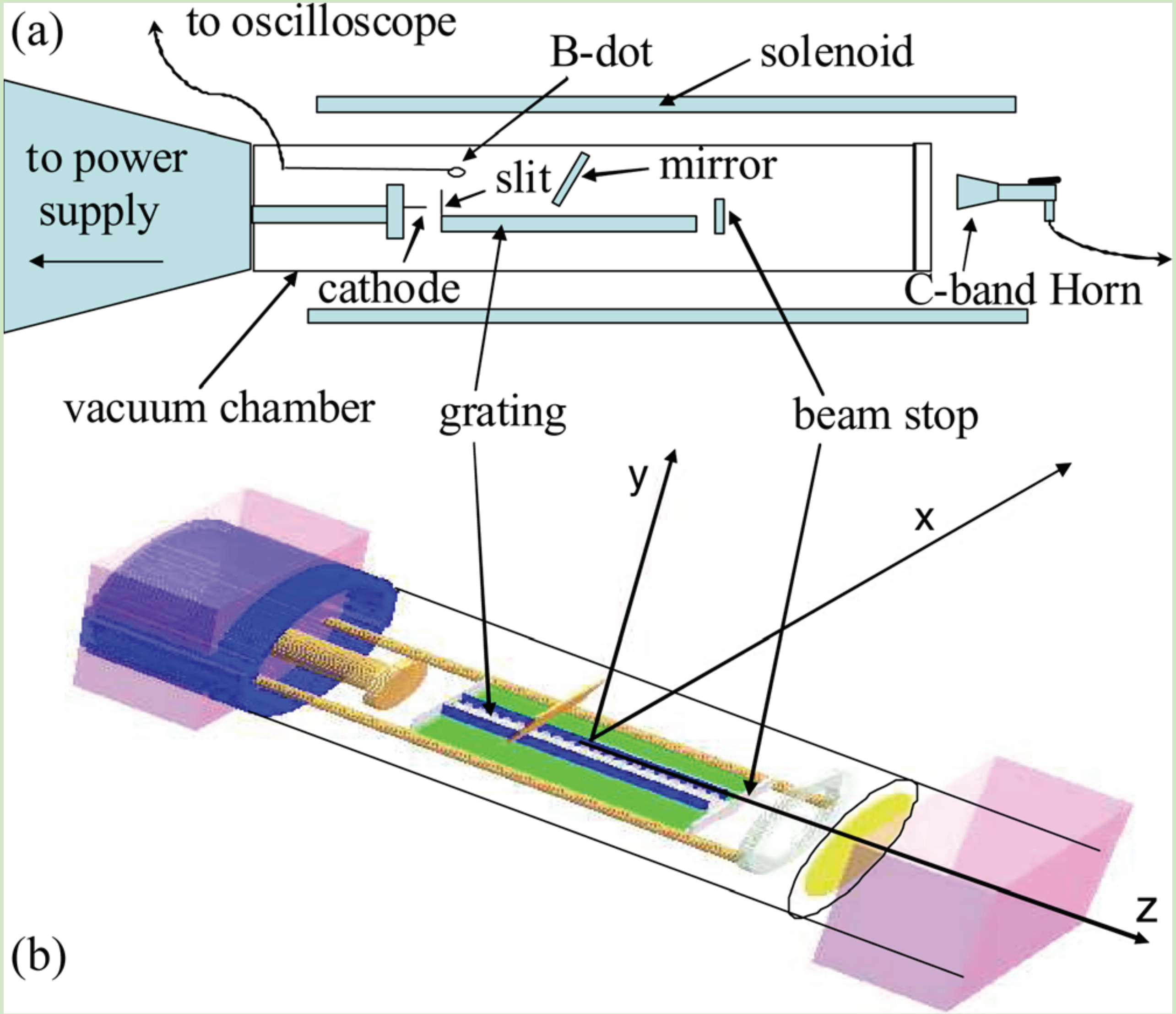
Mean energy loss 10 keV at 5 A:
50 kW emitted on fundamental
CSP efficacité = 12.5%





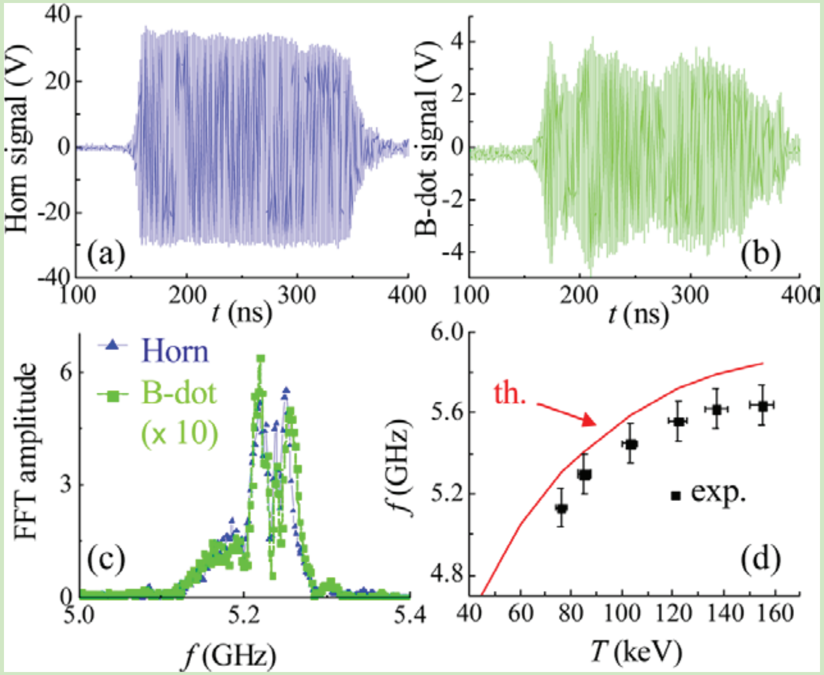
Simulation predicts high efficiency for the Fundamental

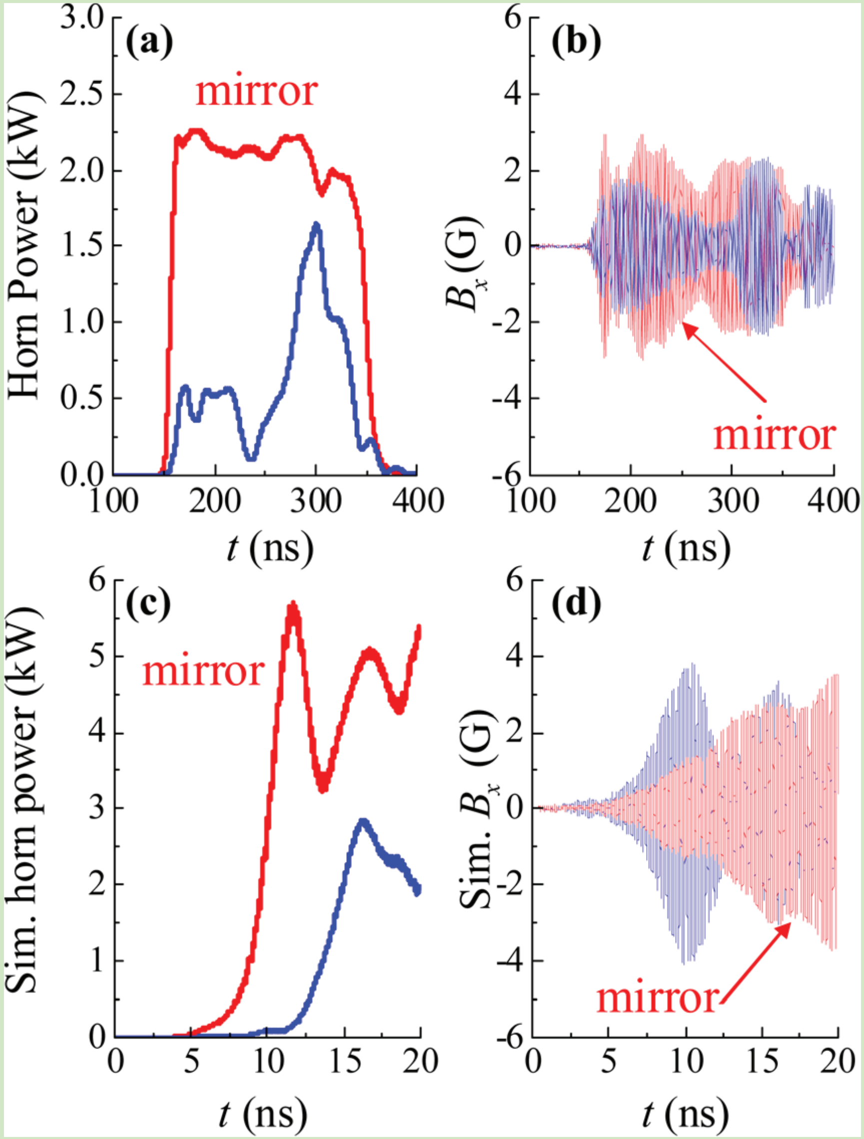
3-D CESTA Experiment: Set-up and Simulation volume



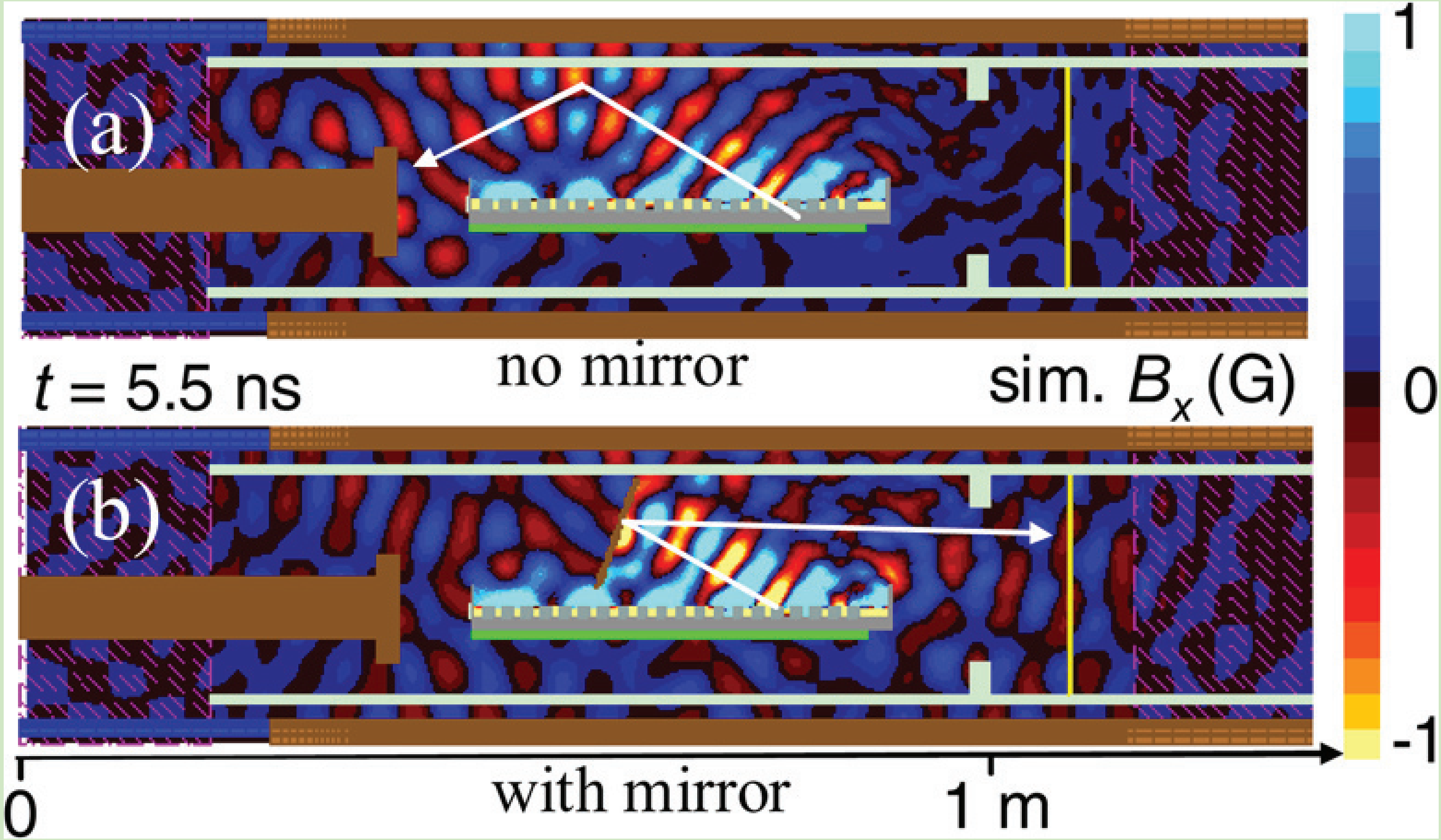
J. Gardelle, P. Modin and J.T. Donohue, "Observation of Copious Emission at the Fundamental Frequency by a Smith-Purcell Free-Electron Laser with Sidewalls", Appl. Phys. Lett. **100,** 131103 (2012),.

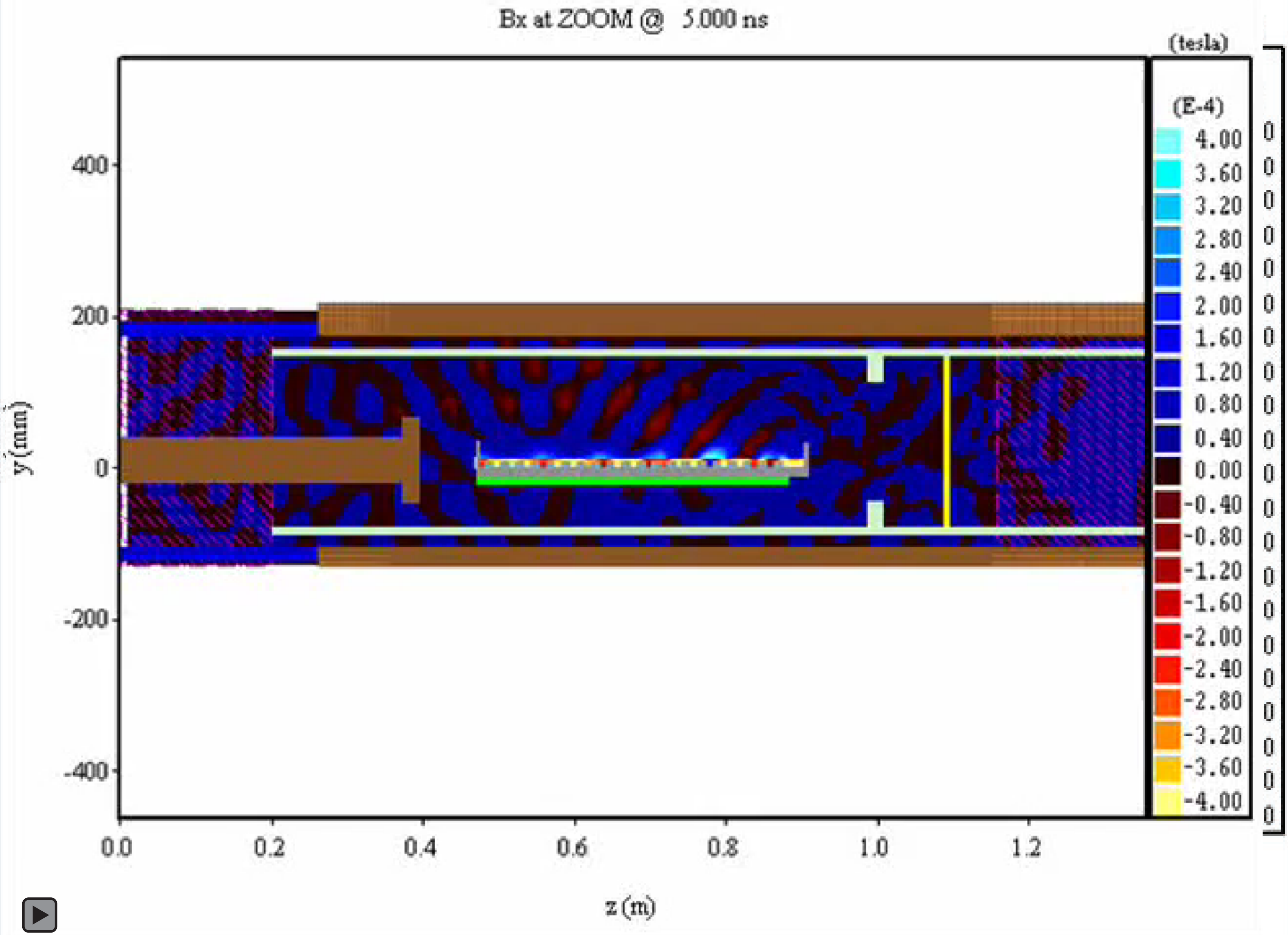
3-D CESTA Experiment: Signals and Power.

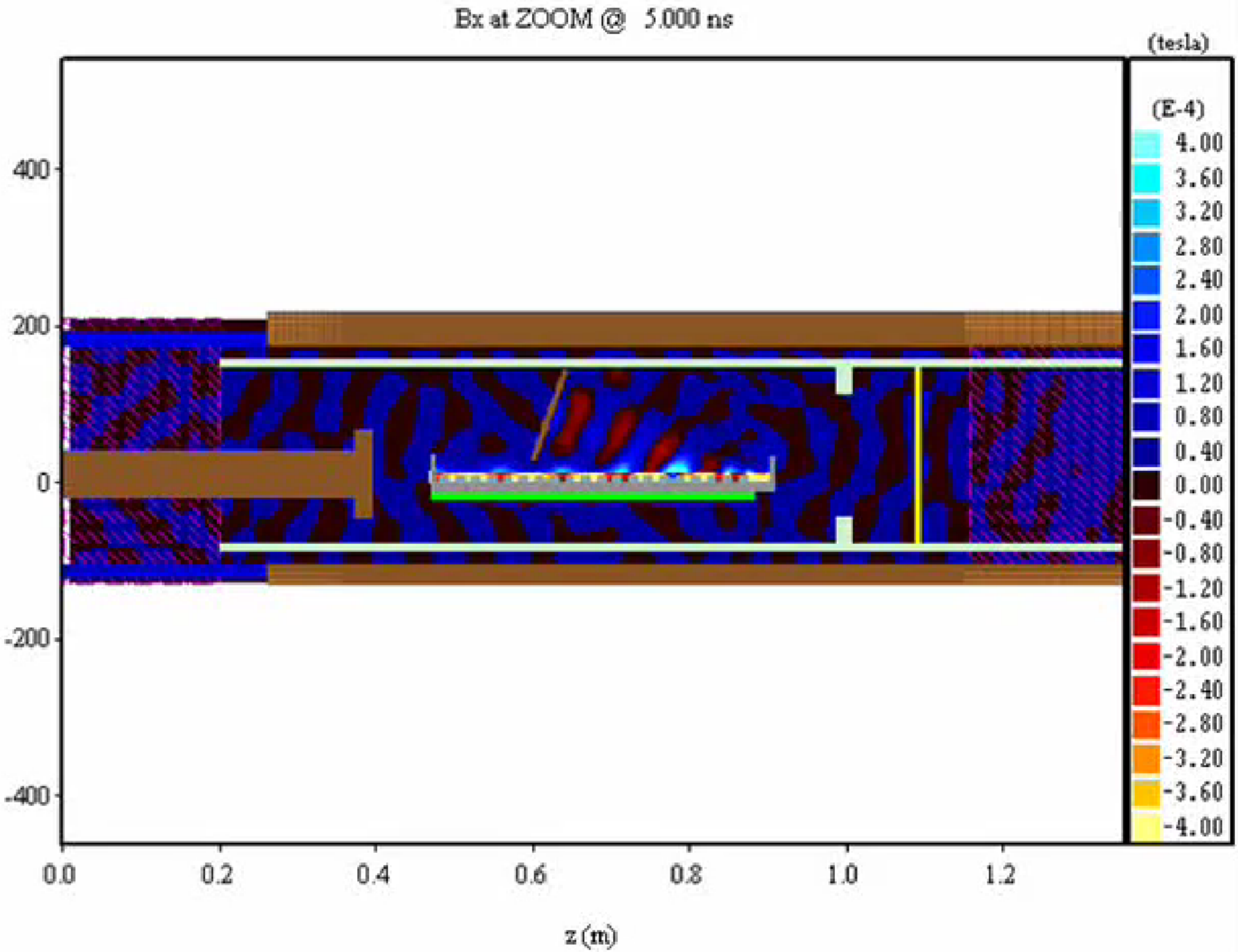




Oscilloscope signals, FFT and energy dependence of *f*.


(a)
t = 5.5 ns
no mirror
sim. B_x (G)
(b)
with mirror
0
1 m
1
0
-1


Bx at ZOOM @ 5.000 ns
(tesla)
(E-4)
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
-0.40
-0.80
-1.20
-1.60
-2.00
-2.40
-2.80
-3.20
-3.60
-4.00
400
200
0
-200
-400
y (mm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
z (m)


Bx at ZOOM @ 5.000 ns
(tesla)
(E-4)
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
-0.40
-0.80
-1.20
-1.60
-2.00
-2.40
-2.80
-3.20
-3.60
-4.00
400
200
0
-200
-400
y (mm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
z (m)

Conclusion

By a proper choice of grating width (between sidewalls), and beam energy, we can produce intense SP radiation at the fundamental frequency of the evanescent wave.