A study of two color optical breakdown of gas by investigation of irradiated terahertz pulses properties

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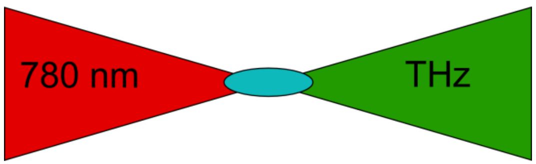
Outline

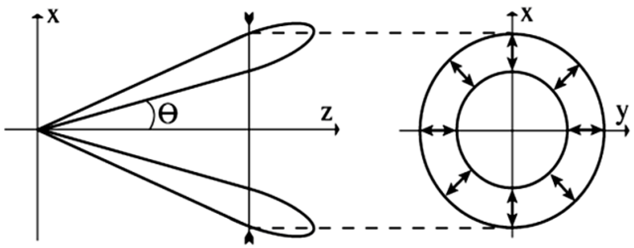
- Background for THz generated with laser-plasma methods
- Importance of optical breakdown in THz generation studies
- Some features of numerical scheme and modeling
- Some general notes for breakdown with single fs pulse
- Bichromatic breakdown
  - THz source features
  - Varying parameters
  - THz radiation pattern

Background: THz generation from gas plasma



~10^{-s} of pJ

First observations in 1994 by H. Hamster, A. Sullivan, S. Gordon, R. W. Falcone, PRE 49 671 (1994)



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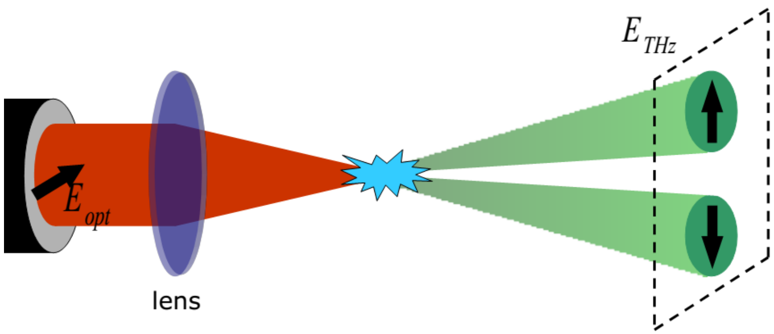

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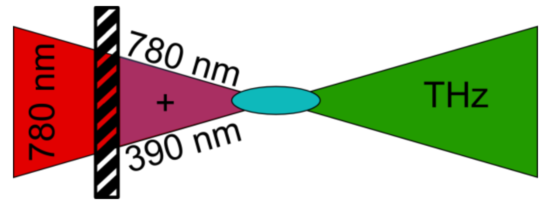

~1 uJ

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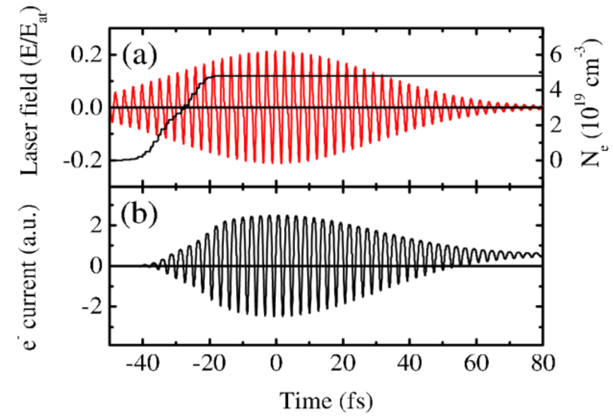

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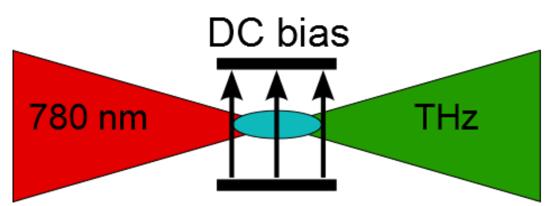


~0.1 uJ

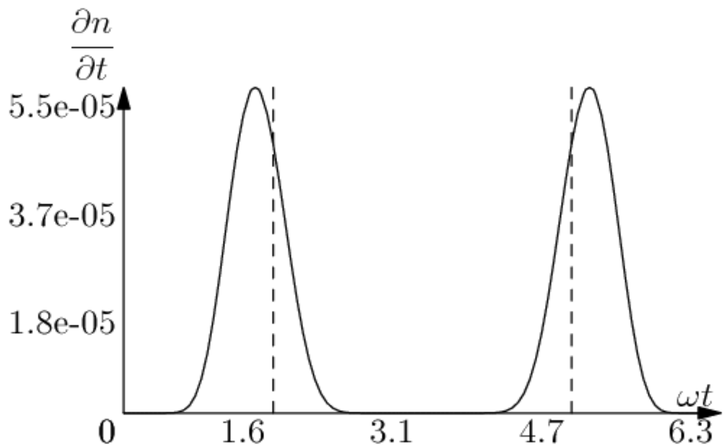
A. Houard. Y. Liu, B. Prade, V. T. Tikhonchuk, A. Mysyrowicz, PRL **100**, 255006 (2008)

Closer look at two color scheme : broken symmetry and phase matching

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \frac{e}{m}\mathbf{E}\frac{\partial f}{\partial \mathbf{v}} = \mathrm{w}(|\mathbf{E}|)$$

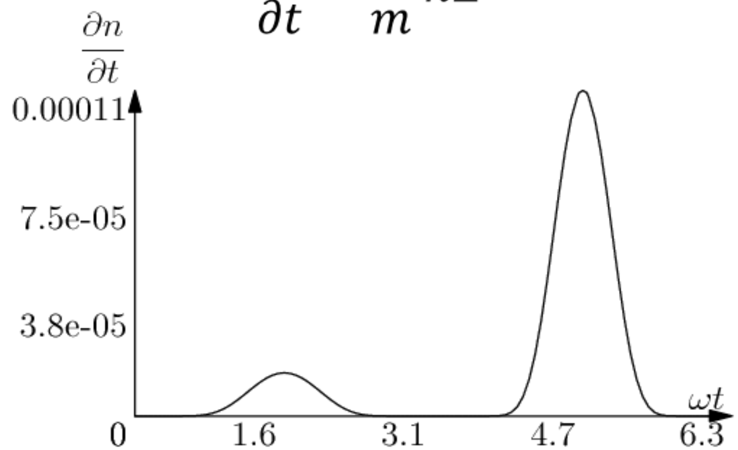
$$\frac{\partial n}{\partial t} = \mathrm{w}(|\mathbf{E}|)$$

$$\frac{\partial \mathbf{j}}{\partial t} = \frac{e^2}{m} n\mathbf{E}$$



$$E_{opt} = E_\omega \sin(\omega t) + E_{2\omega} \sin(2\omega t)$$

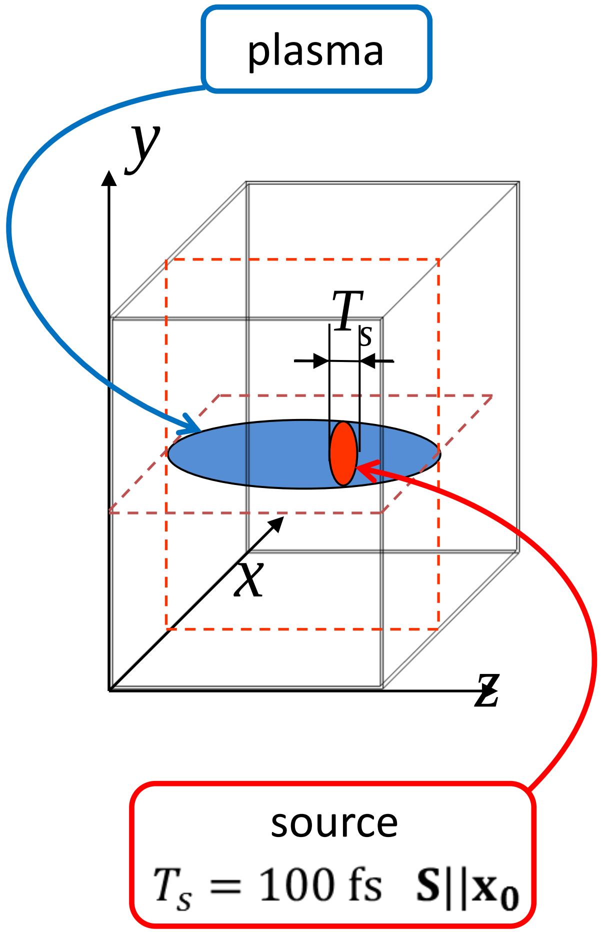
Both E_ω, n_ω and $E_{2\omega}, n_{2\omega}$ harmonics are phase matched.
Residual current is efficiently generated

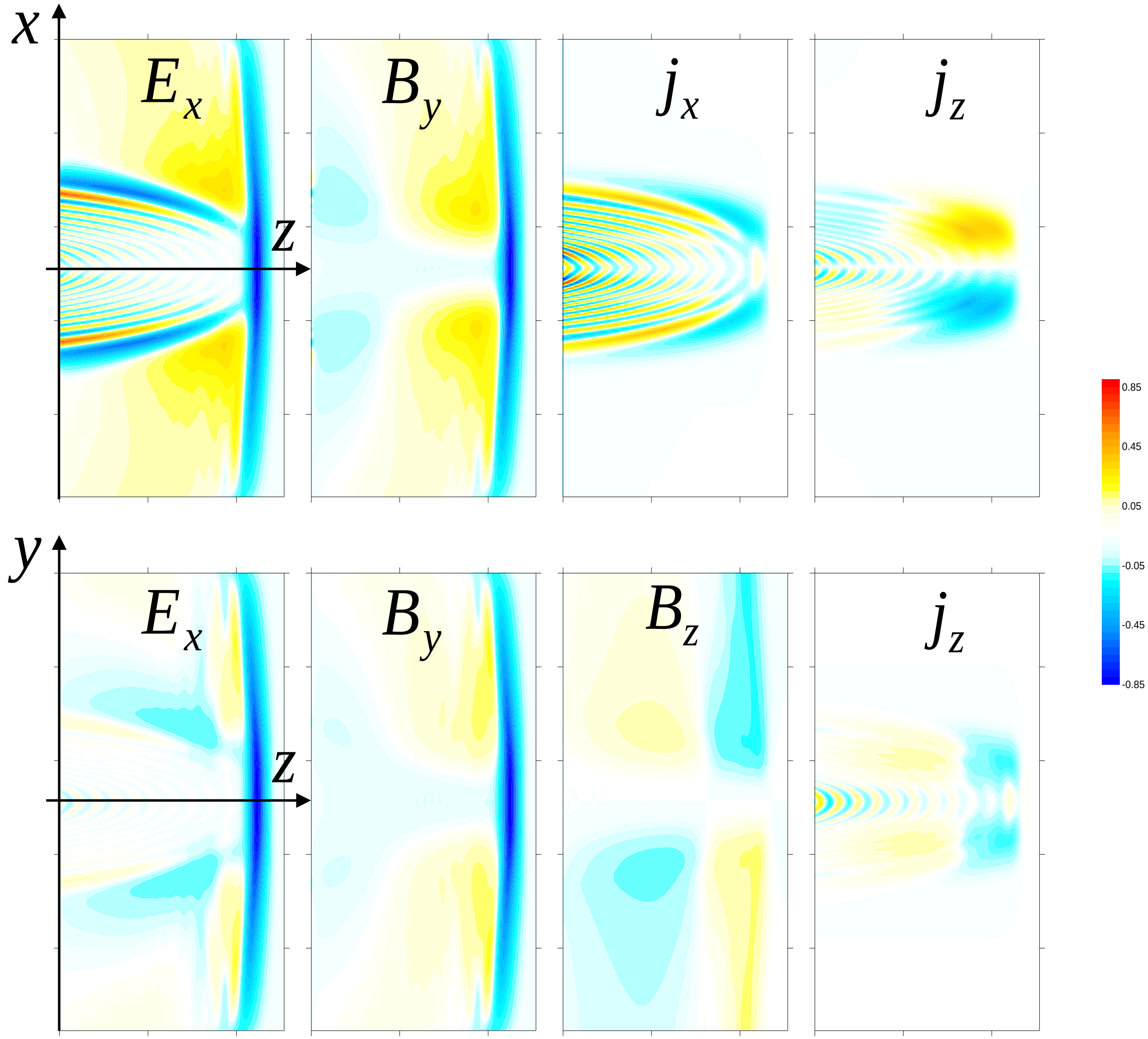


$$E_{opt} = E_\omega \sin(\omega t) + E_{2\omega} \cos(2\omega t)$$

No phase matching for both E_ω, n_ω and $E_{2\omega}, n_{2\omega}$ harmonics.
Residual current is not generated at all

THz radiation : model problem

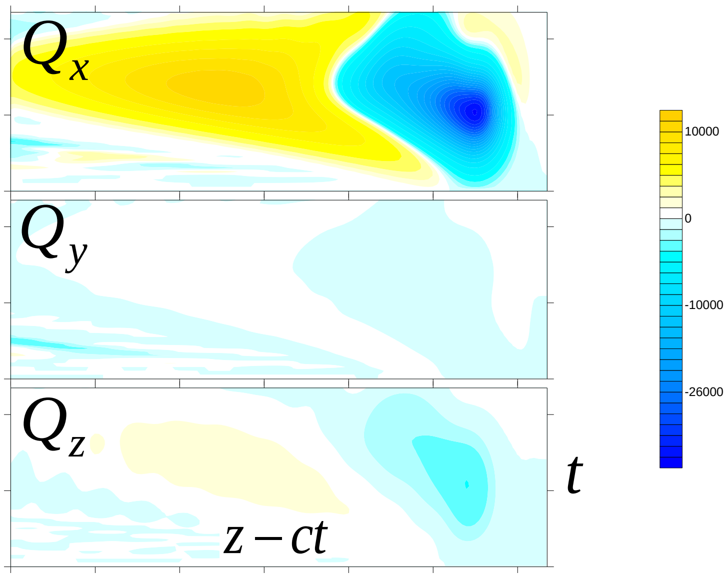




$$\mathrm{rot}\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}$$

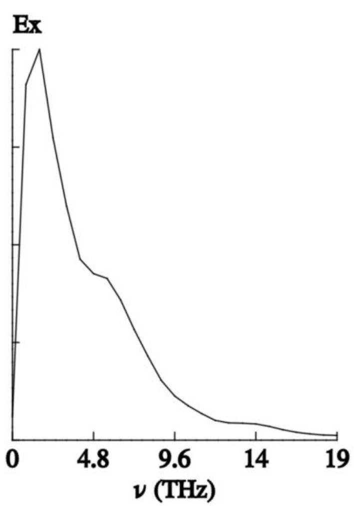
$$\mathrm{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \qquad \frac{\partial \mathbf{j}}{\partial t} = \frac{e^2}{m} n_i (\mathbf{E} + \mathbf{S})$$

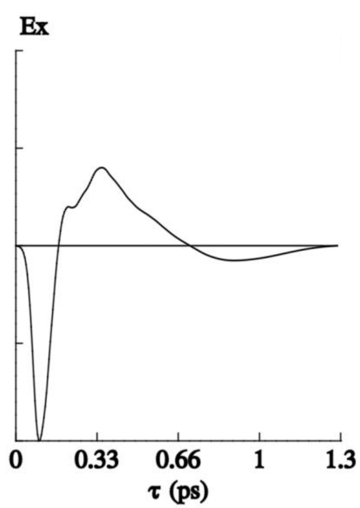
THz radiation : waveform

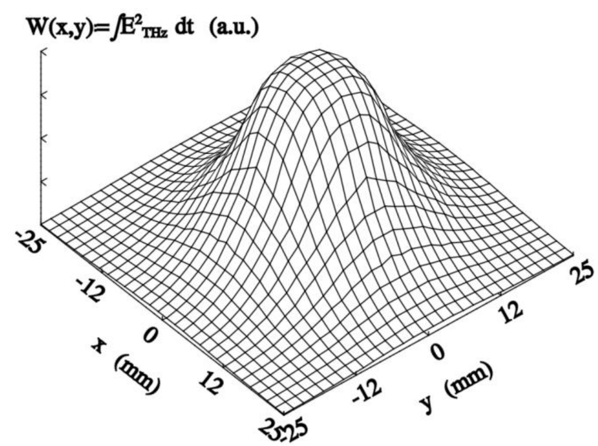


$$\mathbf{E}(\omega, R) = \frac{ik_0 \exp(ik_0 R)}{cR} \left[\mathbf{n}, \left[\mathbf{n}, \int e^{-ik_0 \mathbf{rn}} \mathbf{j}(\mathbf{r}, \omega) d^3\mathbf{r} \right] \right]$$

$$\mathbf{Q}(t, z) = \iint \mathbf{j}(\mathbf{r}, t) dx dy$$

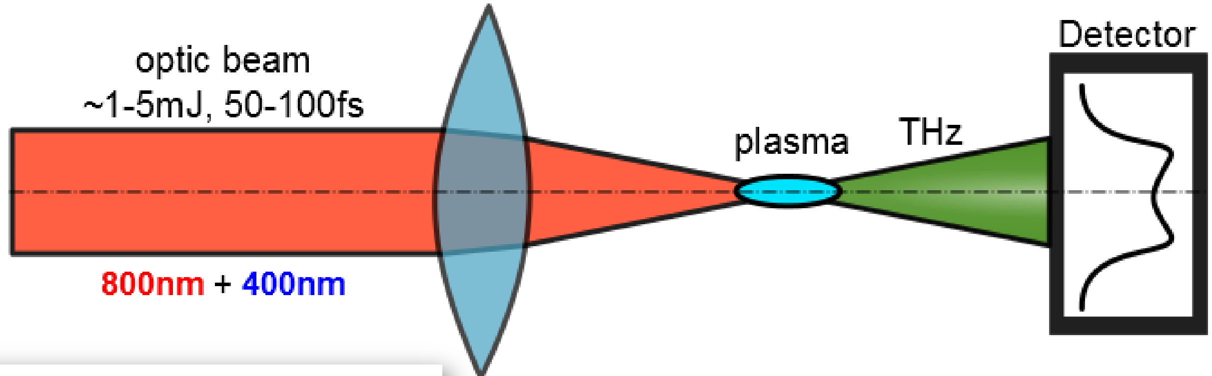


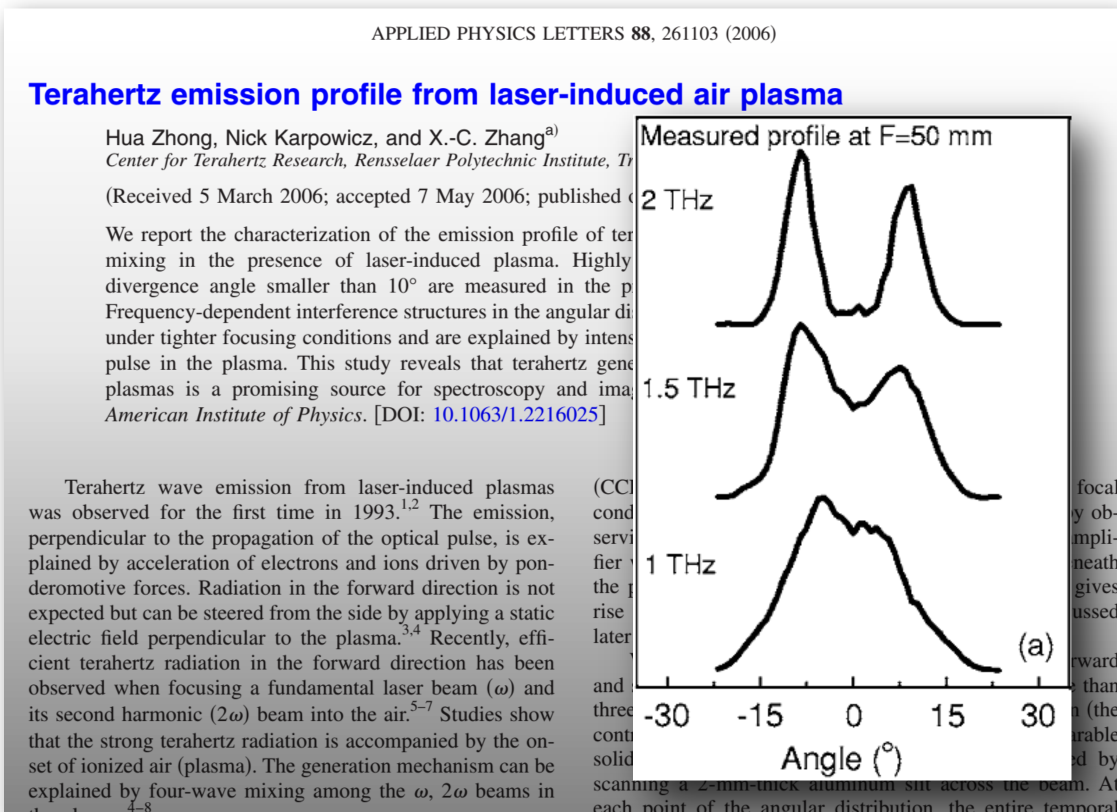




THz radiation : spatial properties : experimental observations

In experiment THz radiation pattern obtained with notch on the axis





APPLIED PHYSICS LETTERS **88**, 261103 (2006)

Terahertz emission profile from laser-induced air plasma

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We report the characterization of the emission profile of ter
mixing in the presence of laser-induced plasma. Highly
divergence angle smaller than 10° are measured in the p
Frequency-dependent interference structures in the angular di
under tighter focusing conditions and are explained by intens
pulse in the plasma. This study reveals that terahertz gene
plasmas is a promising source for spectroscopy and ima
American Institute of Physics. [DOI: 10.1063/1.2216025]

Terahertz wave emission from laser-induced plasmas was observed for the first time in 1993.[1,2] The emission, perpendicular to the propagation of the optical pulse, is explained by acceleration of electrons and ions driven by ponderomotive forces. Radiation in the forward direction is not expected but can be steered from the side by applying a static electric field perpendicular to the plasma.[3,4] Recently, efficient terahertz radiation in the forward direction has been observed when focusing a fundamental laser beam (ω) and its second harmonic (2ω) beam into the air.[5–7] Studies show that the strong terahertz radiation is accompanied by the onset of ionized air (plasma). The generation mechanism can be explained by four-wave mixing among the ω, 2ω beams in the plasma.[4–8]

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scanning a 2-mm-thick aluminum slit across the beam. At
each point of the angular distribution, the entire temporal

Lens focal length

Notch in THz radiation pattern

Back to nonlinear light propagation

The most interesting features of THz radiation are expected to be explained by strongly nonlinear evolution of fs pulse during breakdown of air.

$$\tau = t - z/c, \quad z = z$$

$$\frac{2}{c}\frac{\partial^2 E}{\partial\tau\partial z} + \Delta_\perp E + \omega_p^2 E = 0$$

$$\frac{\partial n}{\partial \tau} = \mathrm{w}_0 N_0 F^{\alpha} \exp\left(-\frac{1}{F}\right)$$

$$F = \frac{3}{2}\left(\frac{I}{I_H}\right)^{\frac{1}{2}}\frac{|E|}{E_0}$$

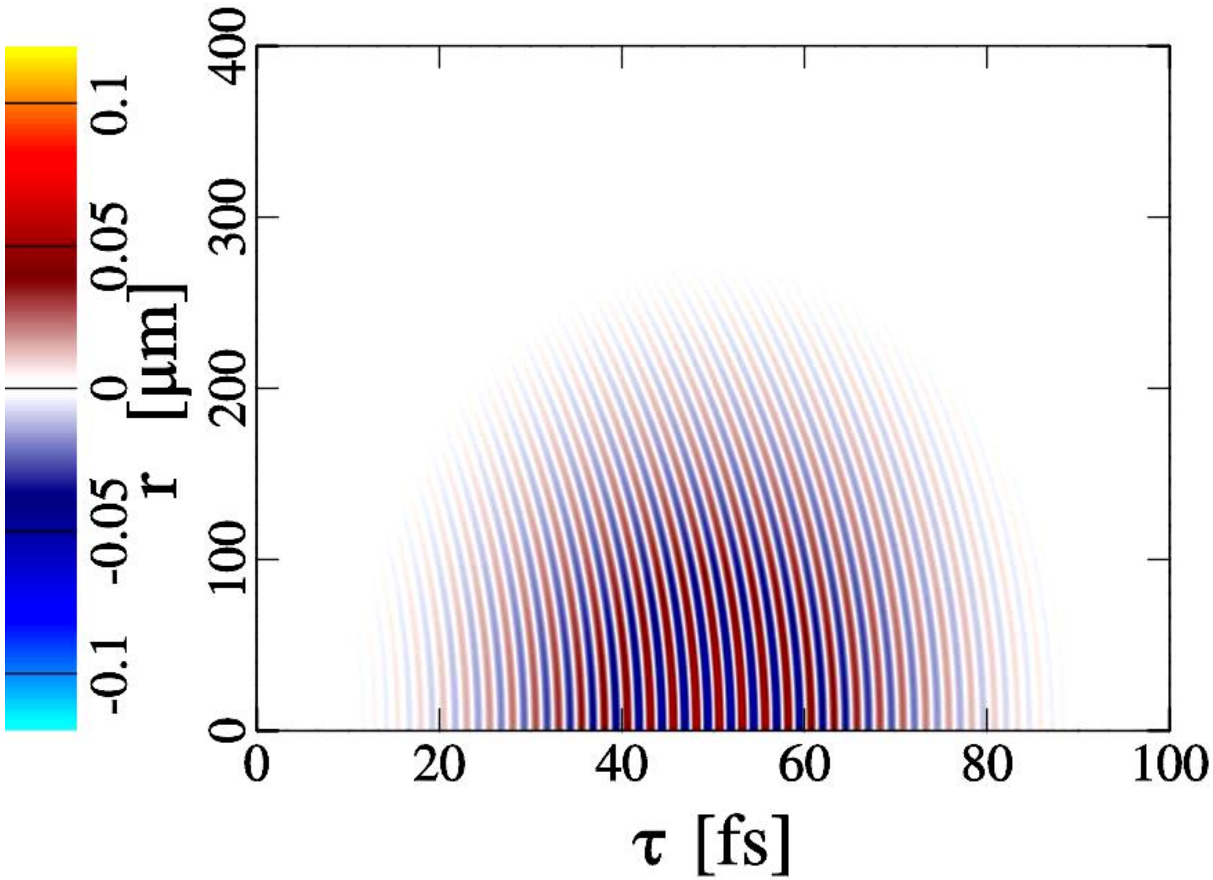
ASSUMPTIONS:

- ☐ Paraxial approximation $\partial^2/\partial z^2 = 0$ in (1)
- ☐ No Kerr effect in (1) (short focal length)
- ☐ Small ionization rate N_0 = const in (2)

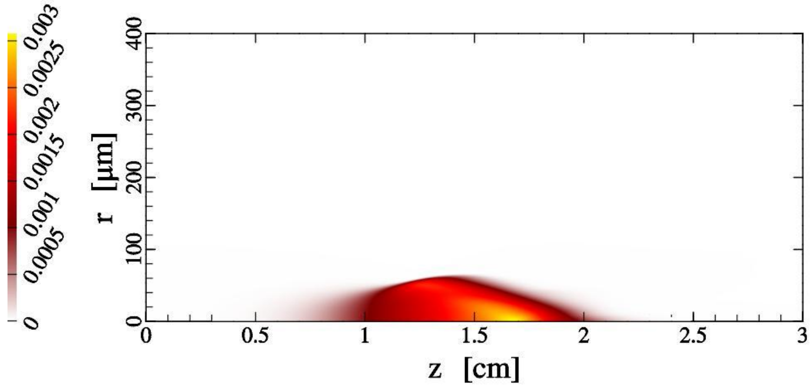
Optical breakdown with quasi-monochromatic pulse

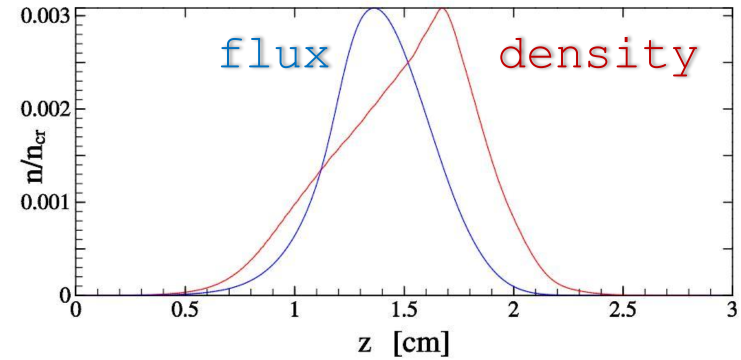
Focal lens length 40 cm.

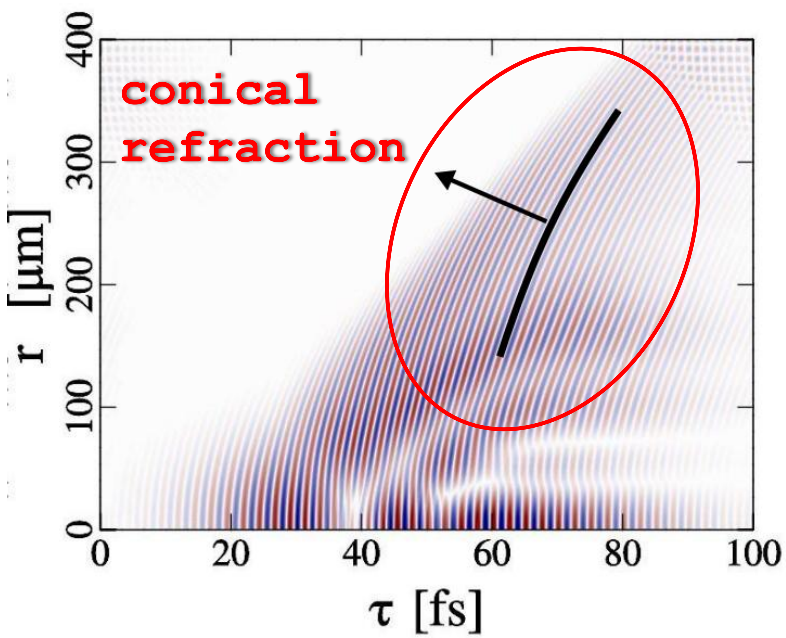
Distance range z ϵ (focal point - 2 cm .. focal point + 1 cm)

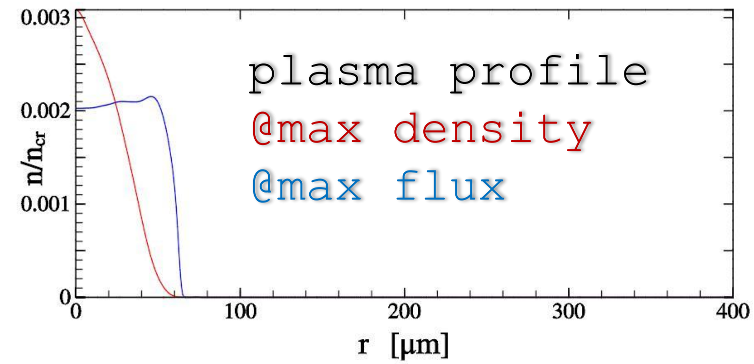


Optical breakdown with quasi-monochromatic pulse

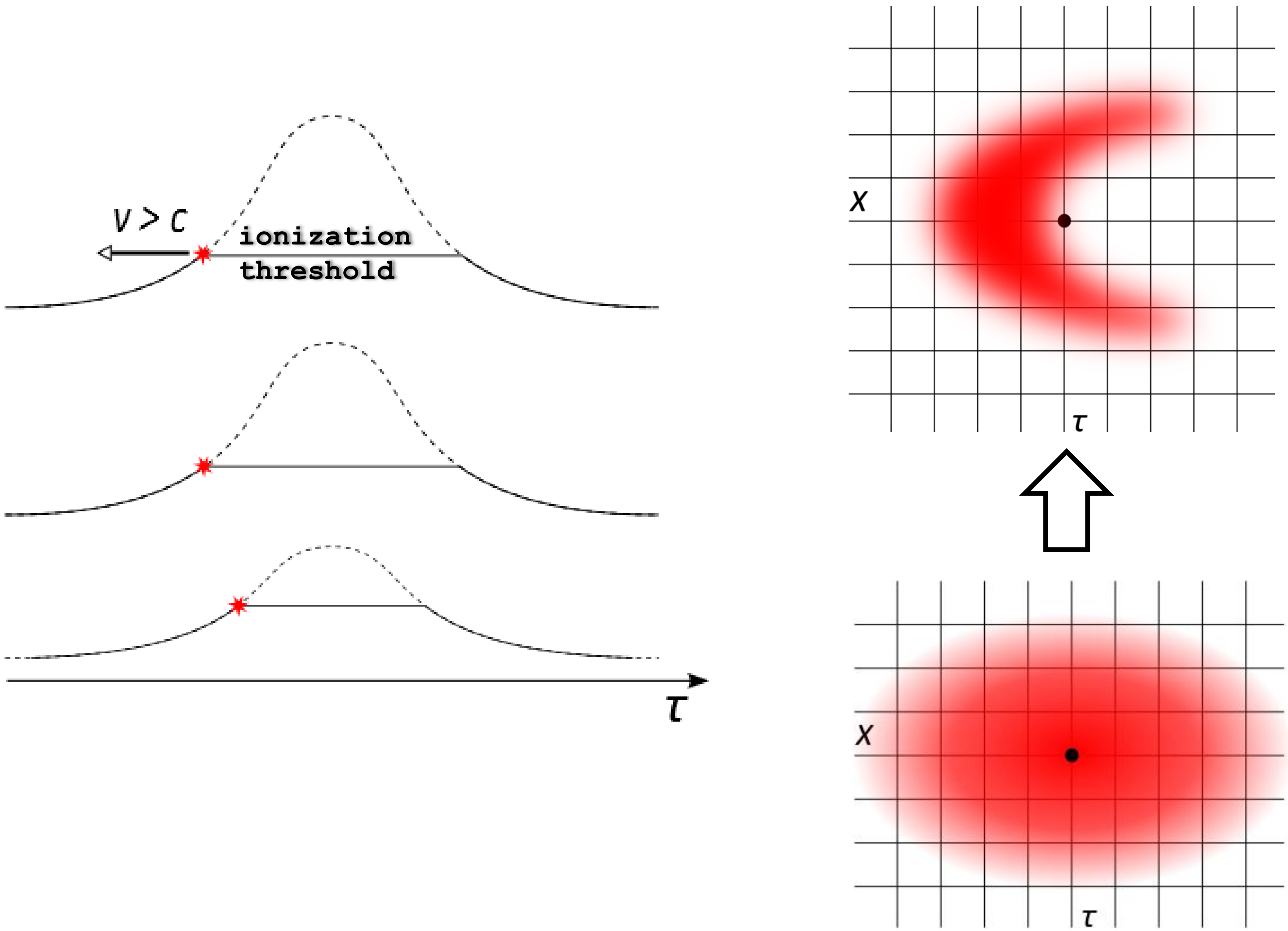




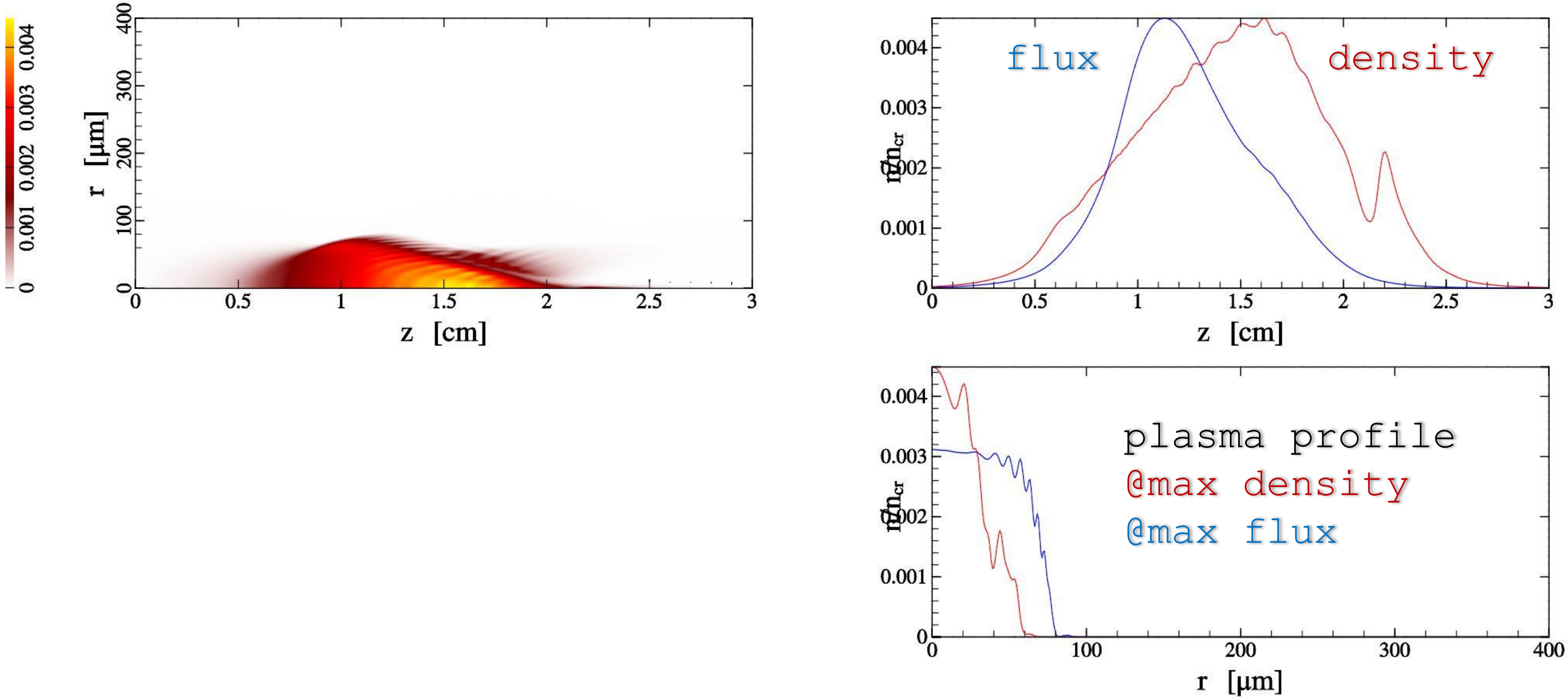




Optical breakdown with quasi-monochromatic pulse: schematic representation

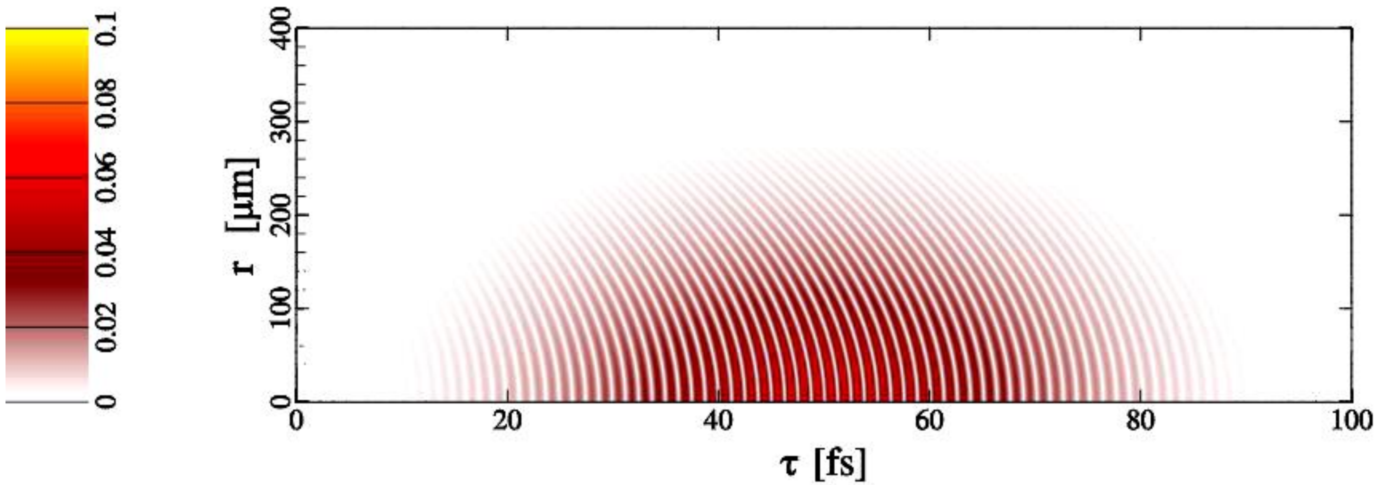


Optical breakdown with bichromatic pulse : plasma channel

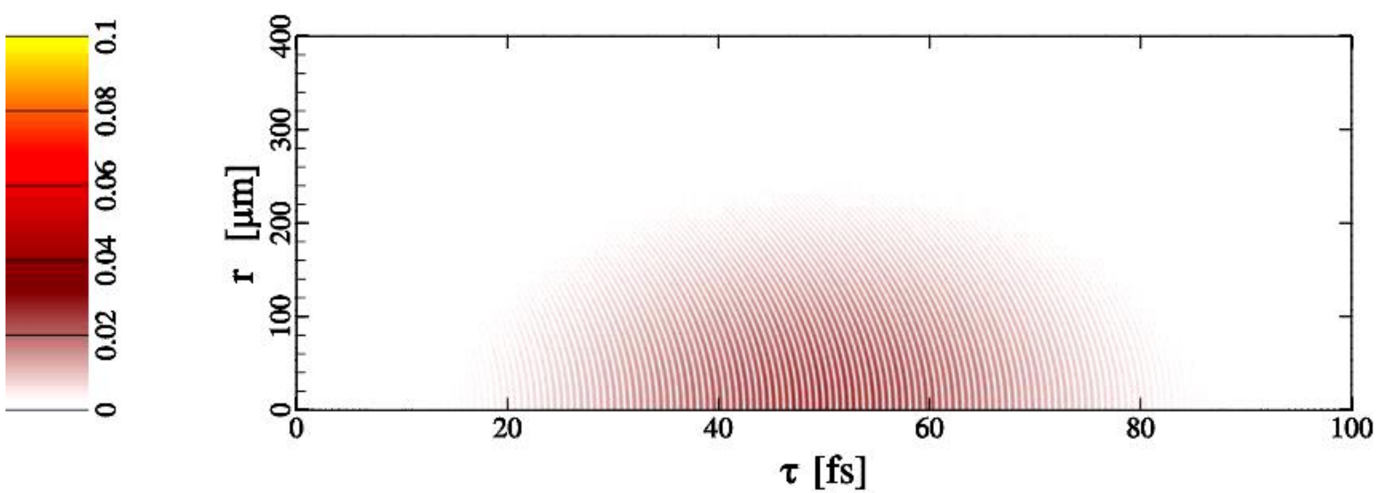


Bichromatic breakdown : refraction of components

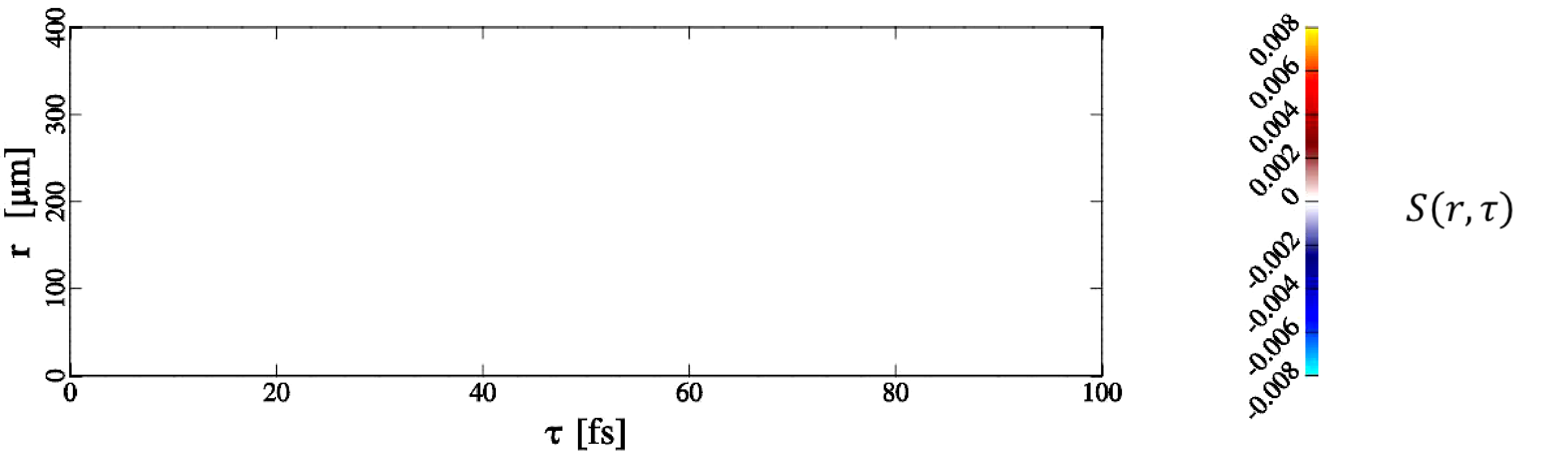
E_{ω}

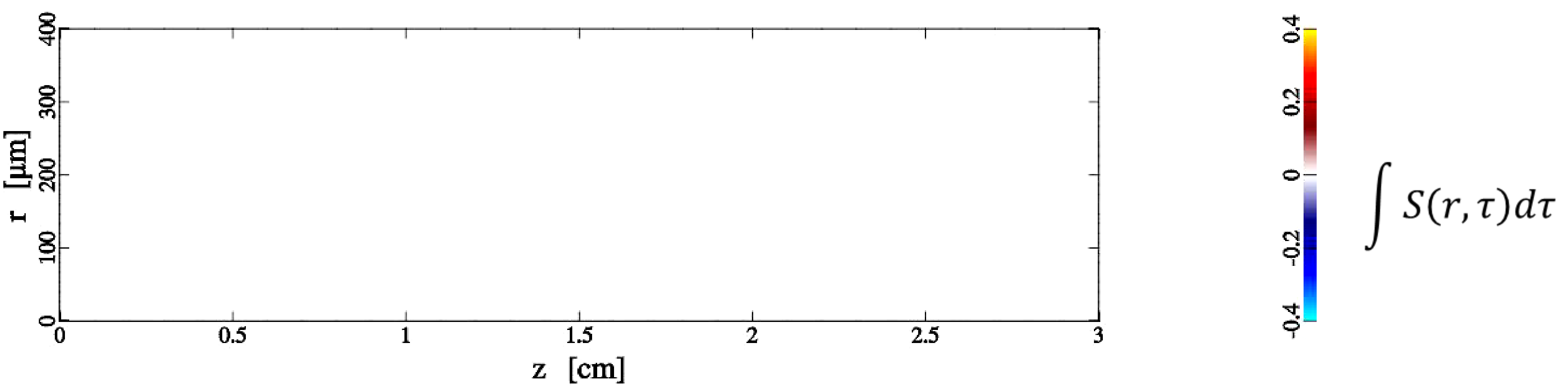


$E_{2\omega}$

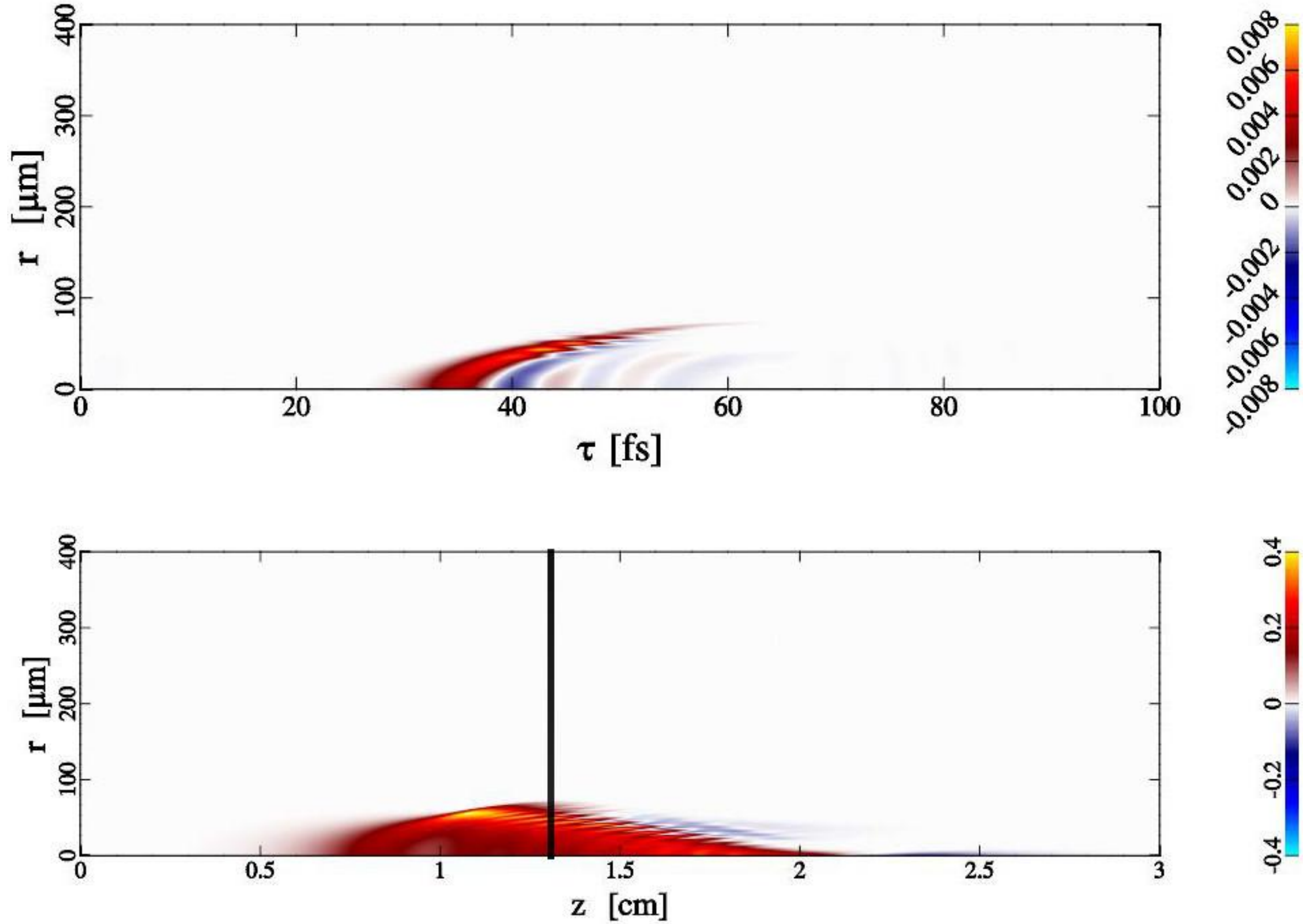


Bichromatic optical breakdown : closer look at THz source





Bichromatic optical breakdown : closer look at THz source



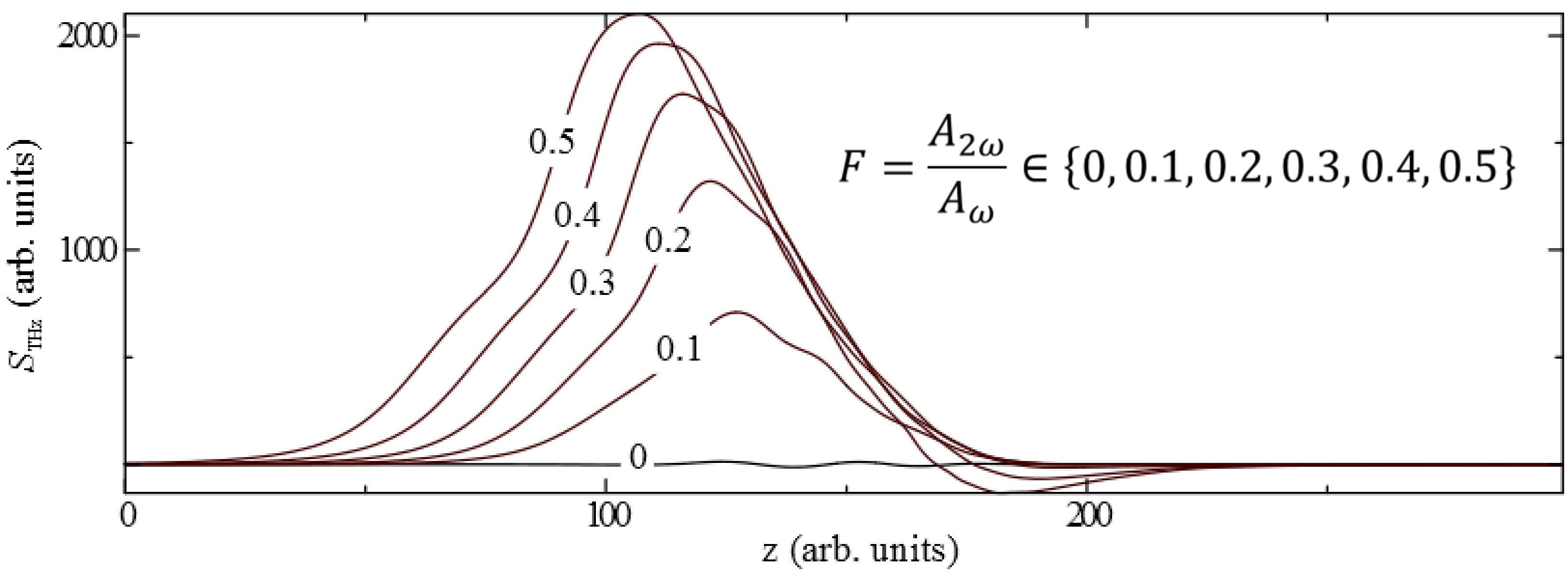
$S(r,\tau)$

$\int S(r,\tau)d\tau$

Bichromatic optical breakdown : varying second harmonic amplitude

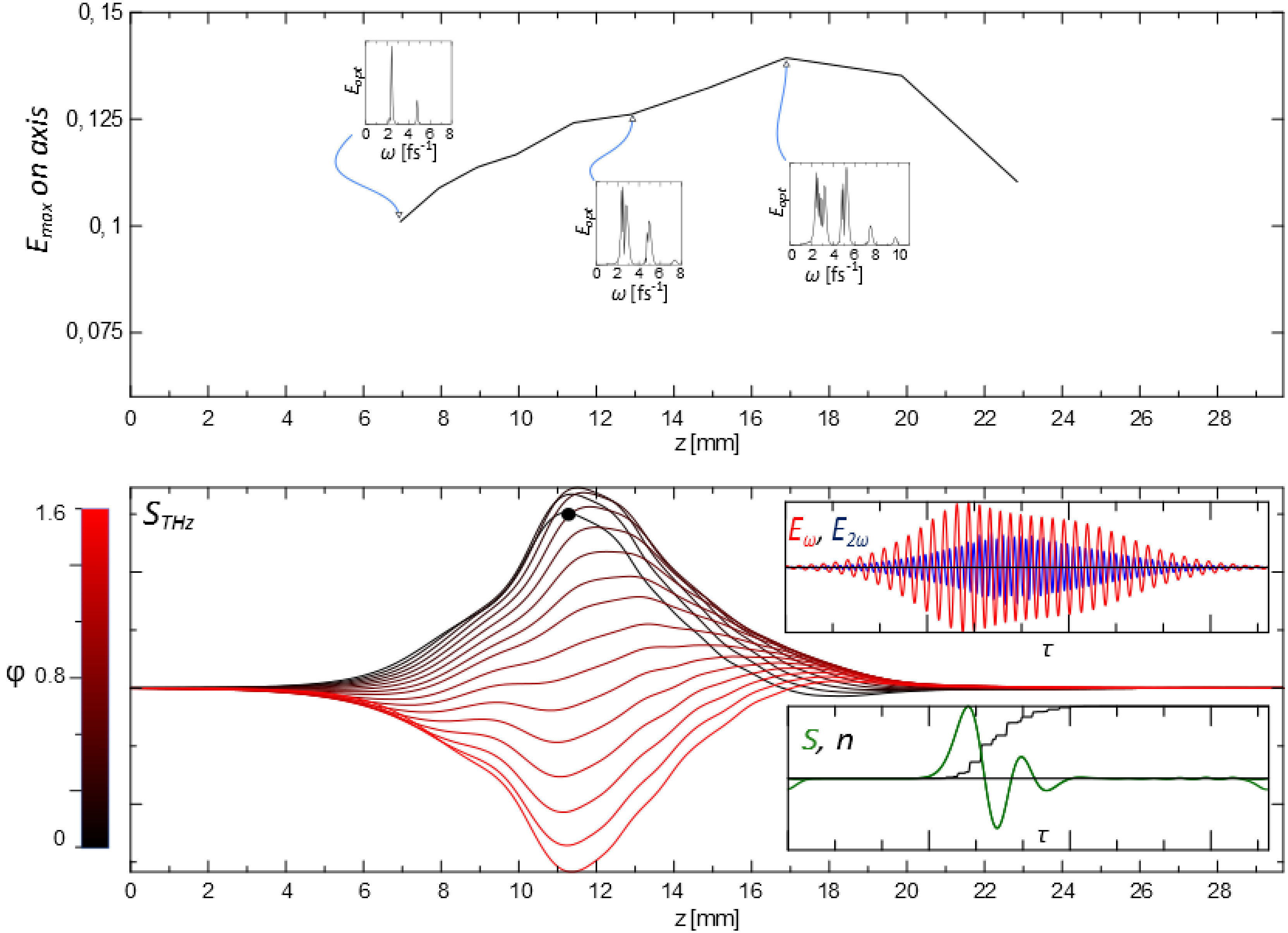
$$E\Big|_{z=0} = A_0 \exp\left(-\frac{\tau^2}{T^2}\right)\exp\left(-\frac{r^2}{R_0^2}\right)\left(\sin(\omega\tau - Cr^2) + F\sin(2\omega\tau - 2Cr^2 + \varphi)\right)$$

Source of residual current along the propagation distance



For every F phase φ was tuned for optimal residual current generation. It was found that optimal phase is the same $\varphi = 0.4$

Bichromatic optical breakdown : optimal phase

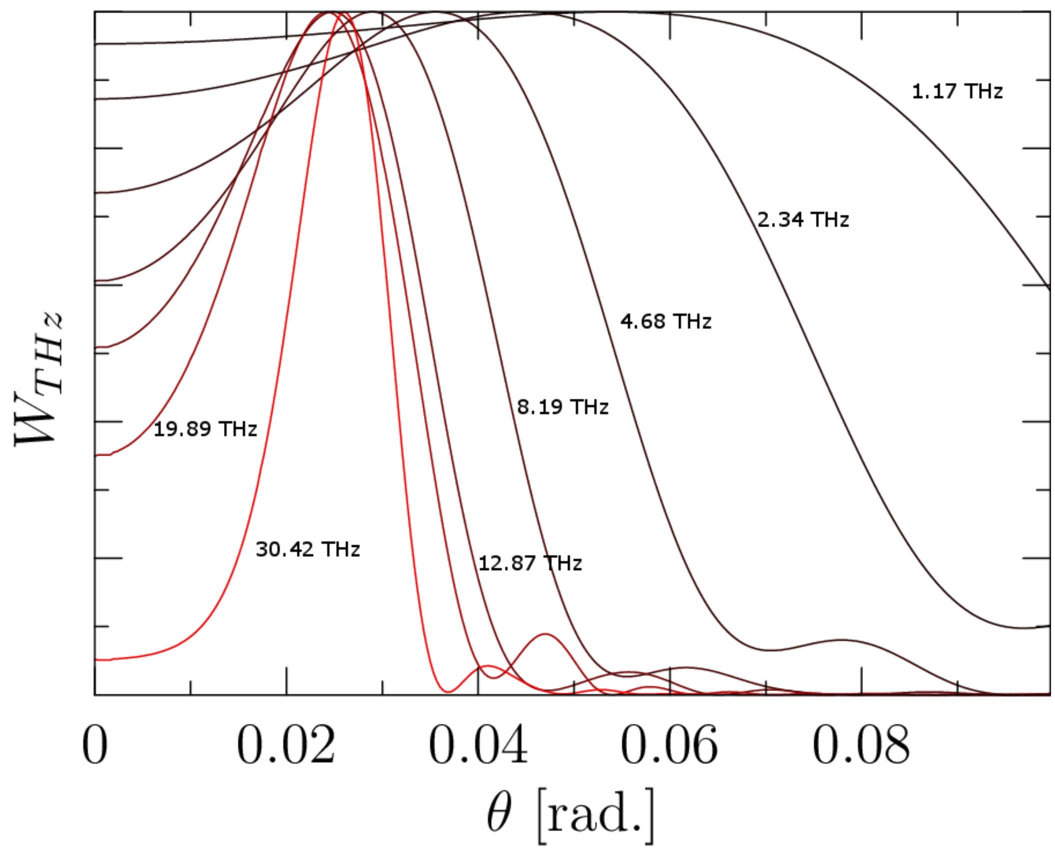


Bichromatic optical breakdown : moving plasma front : THz radiation pattern

Field integrated from plasma string to a far zone:

$$\mathbf{E} \sim \frac{\exp(ik_0R)}{R} \iiint \exp(i\mathbf{nr})\mathbf{j}(\mathbf{r})d^3r$$

⚠ estimation



Some notes about numerical model

Numerical Scheme

$$\frac{\partial^2 E}{\partial\tau\partial z} + \Delta_\perp E + \omega_p^2 E = 0$$

split-step…

$$\frac{\partial^2 E}{\partial\tau\partial z} + \Delta_\perp E = 0$$

Fourier:

$$i\omega\frac{\partial E}{\partial z} + \Delta_\perp E = 0$$

implicit Krank-Nicholson scheme

$$\frac{\partial^2 E}{\partial\tau\partial z} + \omega_p^2 E = 0$$

predictor-corrector scheme

$\Delta_\perp$ operator representing transverse Laplassian in cylindrical coordinates written as Hermitian matrix

Implementation

All **GPU** design (**CUDA**)

$$i\omega\frac{\partial E}{\partial z} + \Delta_\perp E = 0$$

Inverse Laplassian operator is implemented in massive parallel way both by $\boldsymbol{r}$ and $\boldsymbol{\tau}$ directions

$$\frac{\partial n}{\partial\tau} = \mathrm{w}(|\mathbf{E}|)$$

Implemented in GPU way each integration performed by portions in **shared memory**

coalesced read/write

12.000 steps on 512x1024 mesh are done in 5 minutes on below top GeForce gaming card GTX 770.

thnx for attention