THz Pulse Generation by Laser Plasma Accelerators

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May 6-10, 2019

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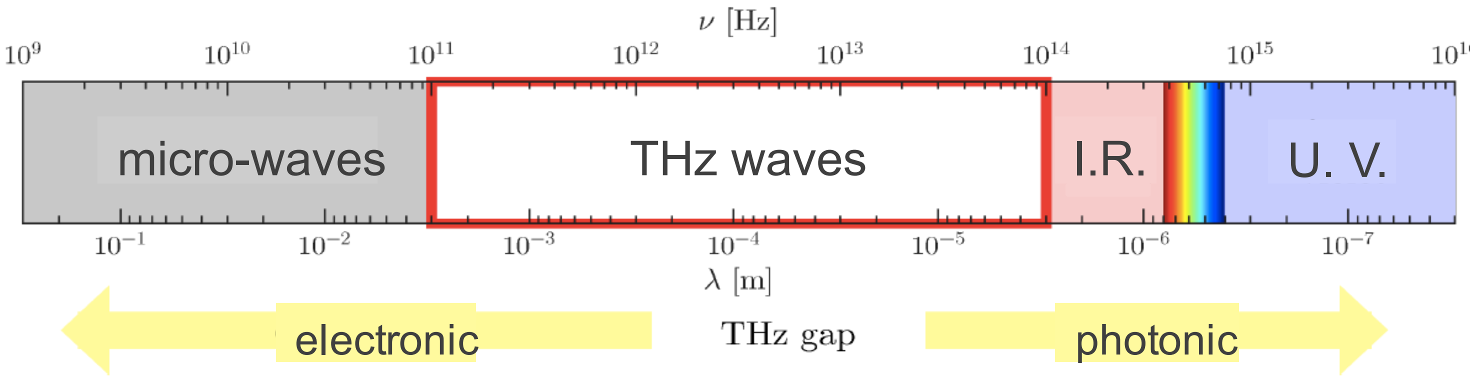
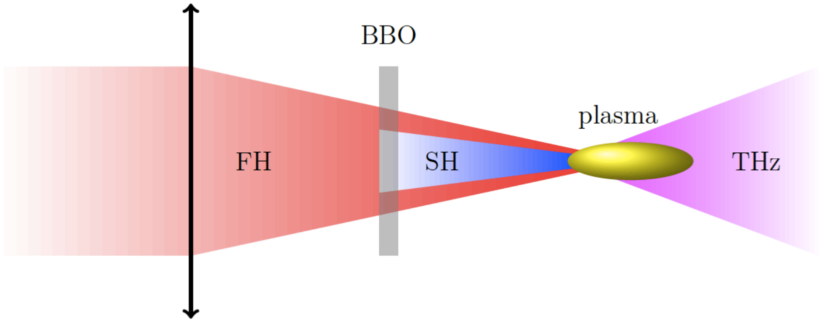
THz frequencies

- Terahertz lies between optical and micro-waves spectra



- For moderately intense laser pulses:



- Applications:
  - Security
  - Remote sensing
  - Molecular dynamic
  - Biology
  - Etc…

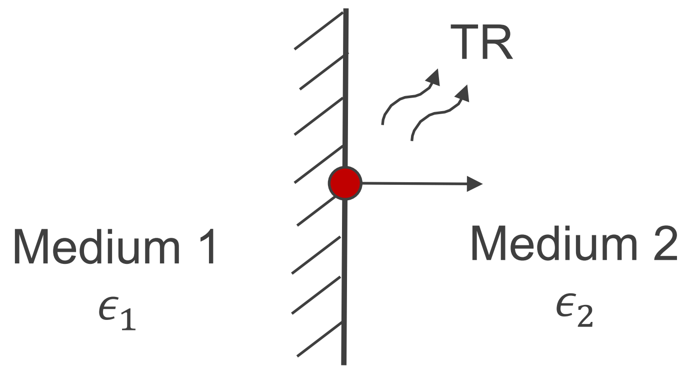
Outline

1. Principle and main features of Coherent Transition Radiation (CTR)
2. Terahertz (THz) emission at the plasma-vacuum interface
3. How to evaluate the CTR contribution in PIC simulations ?
4. Find an optimum for THz generated by CTR

Principle of Transition Radiation

- Transition Radiation (TR) = Emission from a charged particle crossing an interface

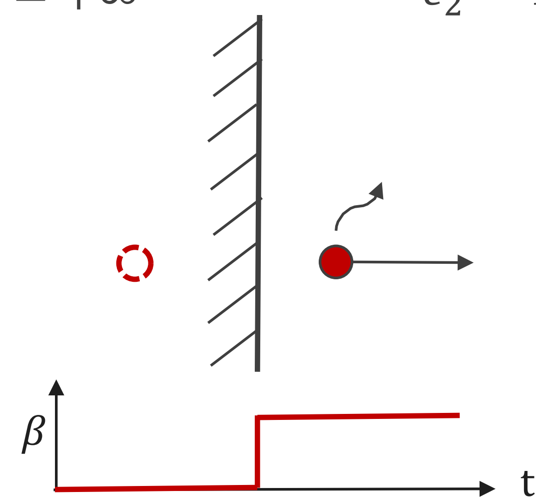
Ginzburg and Frank JETP **16**, 15 (1945)



- The passage of the charged particle results in a transient polarization current emitting radiation

Transition Radiation by 1 electron

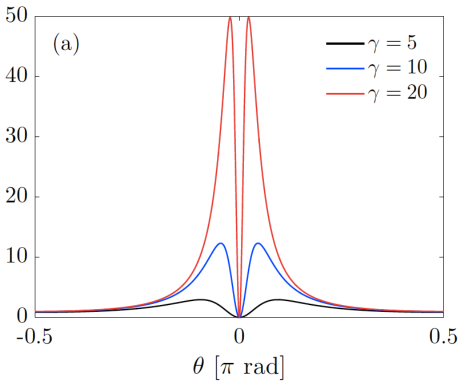
- Perfect conductor-vacuum interface: $|\epsilon_1| = +\infty$ / $\epsilon_2 = 1$



$$\beta(t) = \beta_0 H(t - t_0)$$
$$\dot{\beta}(t) = \beta_0 \delta(t - t_0)$$

- TR energy (W_e) per solid angle unit ($d\Omega$) per frequency angle unit ($d\omega$):

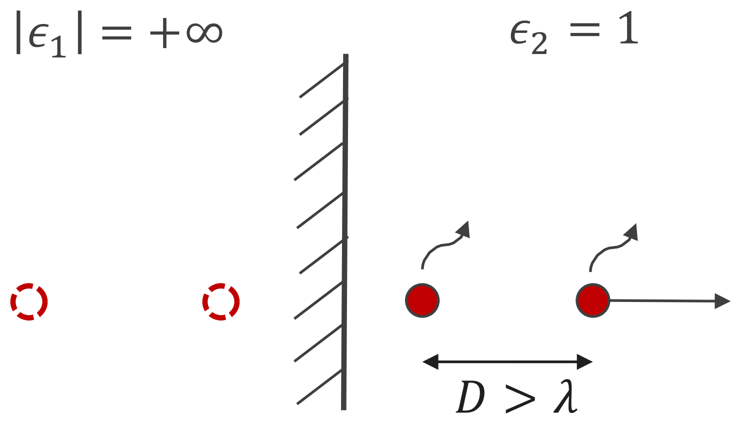
$$\frac{d^2 W_e}{d\Omega d\omega} = \frac{e^2}{\pi^2 c} \times \frac{\beta^2 sin^2\theta}{(1 - \beta^2 cos^2\theta)^2}$$



$$\theta_{max} = 1/\gamma$$

Incoherent Transition Radiation by 2 electrons

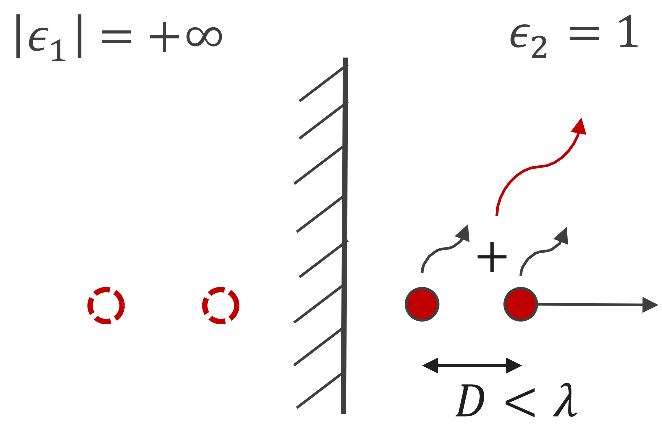
- Perfect conductor-vacuum interface: $|\epsilon_1| = +\infty$ / $\epsilon_2 = 1$



- Destructive interferences ➡ Incoherent radiation

Coherent Transition Radiation by 2 electrons

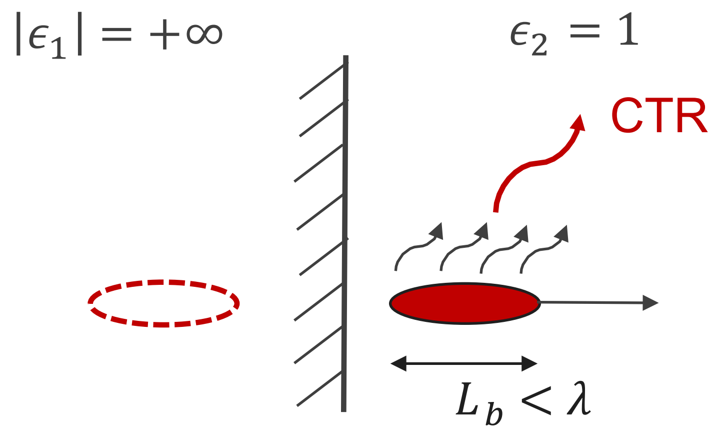
- Perfect conductor-vacuum interface: $|\epsilon_1| = +\infty$ / $\epsilon_2 = 1$



- Constructive interferences ➡ Coherent radiation

Coherent Transition Radiation of an e^- beam

- Perfect conductor-vacuum interface: $|\epsilon_1| = +\infty$ / $\epsilon_2 = 1$



- TR energy (W_e) per solid angle unit ($d\Omega$) per angular frequency unit ($d\omega$):

$$\frac{d^2W}{d\Omega d\omega} = \frac{e^2}{\pi^2 c}\left[N_e \int d^3\boldsymbol{p}\, g(\boldsymbol{p}) E^2 + N_e(N_e - 1)\left|\int d^3\boldsymbol{p}\, g(\boldsymbol{p}) E\mathcal{F}\right|^2\right]$$

Coherent Transition Radiation of an e^- beam

- TR energy (W_e) per solid angle unit ($d\Omega$) per frequency angle unit ($d\omega$):

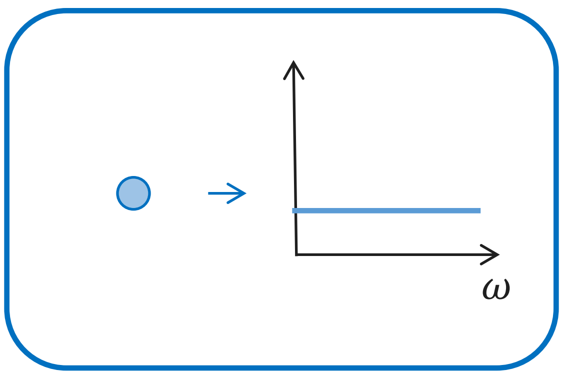
$$\frac{d^2W}{d\Omega d\omega} = \frac{e^2}{\pi^2 c}\left[N_e \int d^3\boldsymbol{p}\, g(\boldsymbol{p}) E^2 + N_e(N_e - 1)\left|\int d^3\boldsymbol{p}\, g(\boldsymbol{p}) \mathcal{F}(\omega, \boldsymbol{p}) E\right|^2\right]$$

Incoherent Transition Radiation (ITR) $\propto N_e$

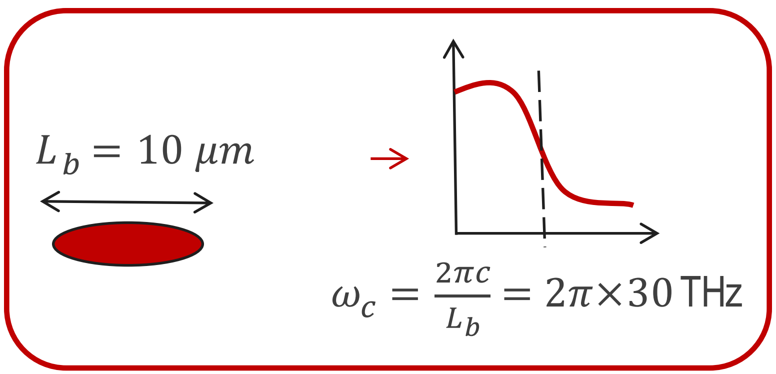
Coherent Transition Radiation (CTR) $\propto N_e^2$

- Spatial form factor: Coherence for radiated wavelength $\lambda > L_b$
  or frequency $\omega < \omega_c = 2\pi c / L_b$

Point-like e^-



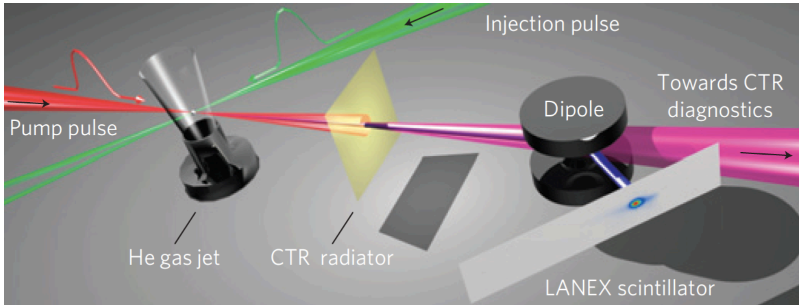
e^- beam



CTR for bunch diagnostic and THz source

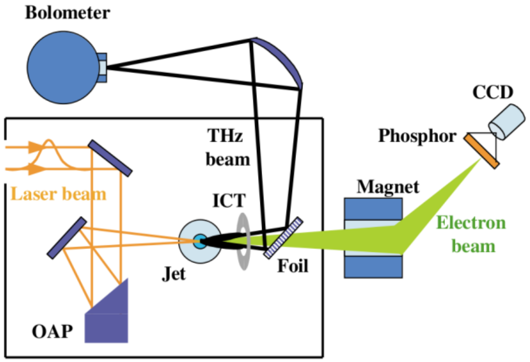
Bunch diagnostic:

e^- beam duration (rms) = 1.5 fs

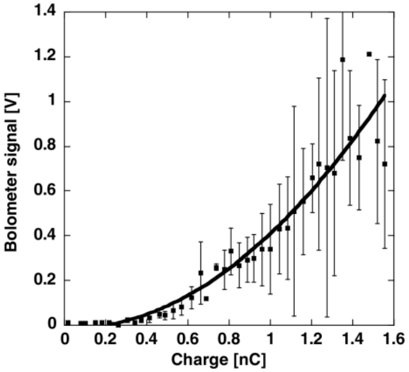


Lundh *et al*. Nat. Phys. **7**, 219 (2011)

THz source:



$P \leq 8$ TW



Leemans *et al*. Phys. Rev. Lett. **91**, 074802 (2003)
Schroeder *et al*. Phys. Rev. E **69**, 016501 (2004)

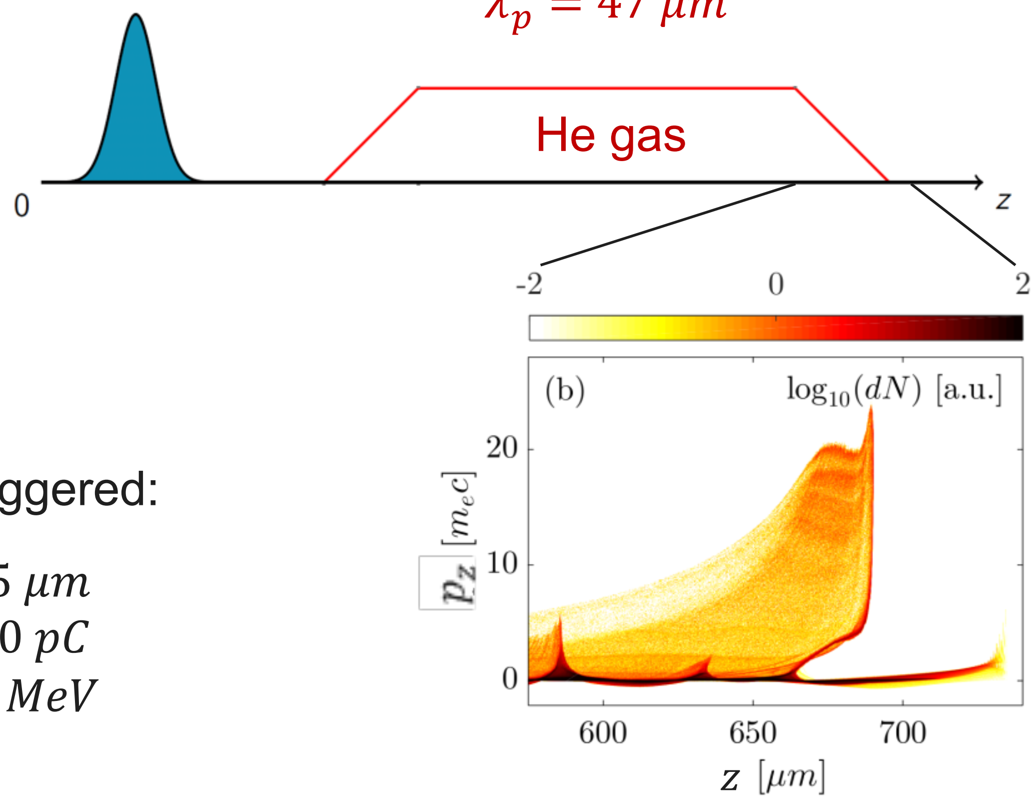
Example of THz generation with PIC code

- Simulation with the PIC code CALDER-CIRC (quasi-3D)

- Laser-plasma parameters:

Laser
$E_0 = 3.7\ J$
$\lambda_0 = 1\ \mu m$
$w_0 = 20\ \mu m$
$\tau_0 = 35$ fs
$P_0 = 100$ TW
$a_0 = 4$

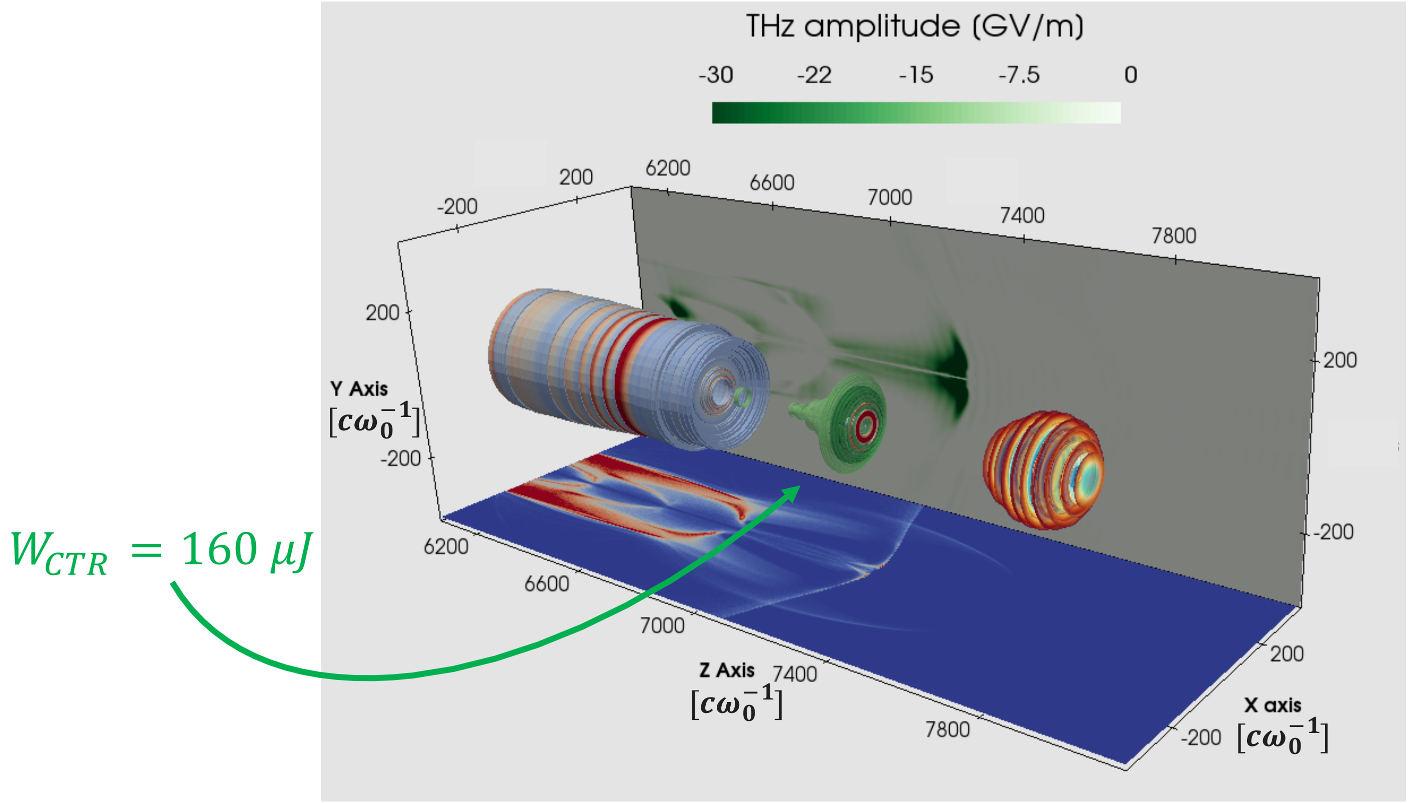
$n_e = 4.8\times 10^{17} cm^{-3}$
$\lambda_p = 47\ \mu m$



- Nonlinear plasma wave is triggered:

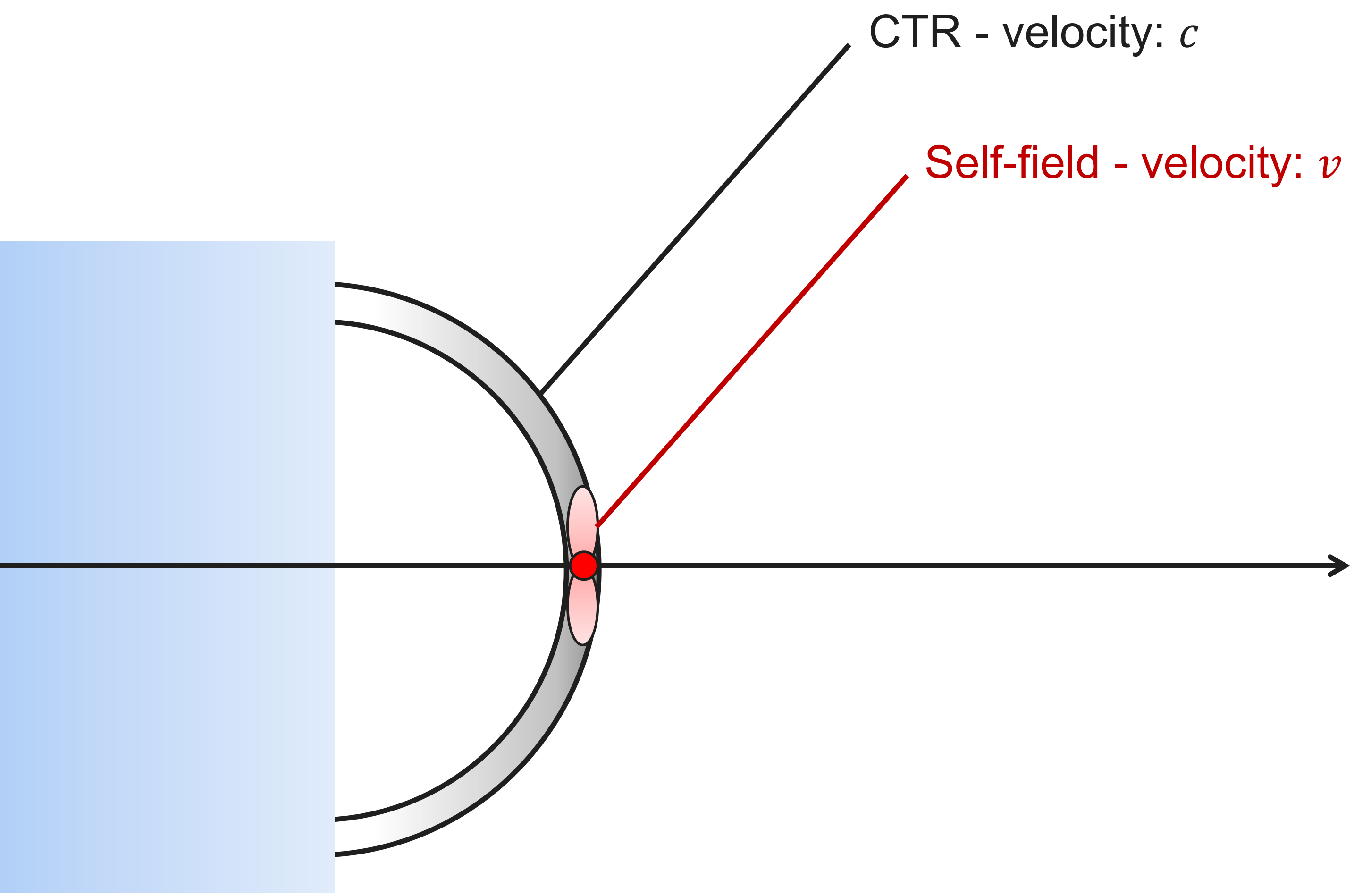
$$L_b \sim 1.5\ \mu m$$
$$Q \sim 150\ pC$$
$$E \sim 10\ MeV$$

CTR at plasma exit



- Low-frequency field of about 30 GV/m amplitude propagates with the electron bunch
- What is the contribution of the particle self-field ?

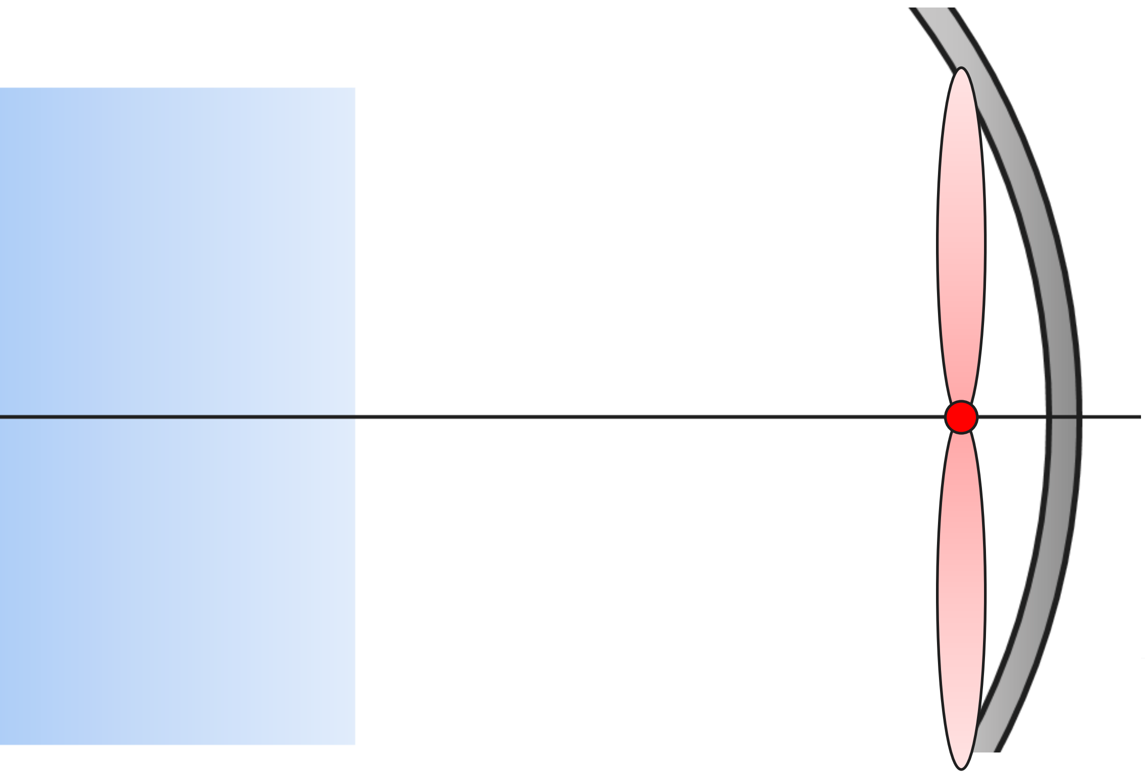
- Particle field lags behind the radiated field:

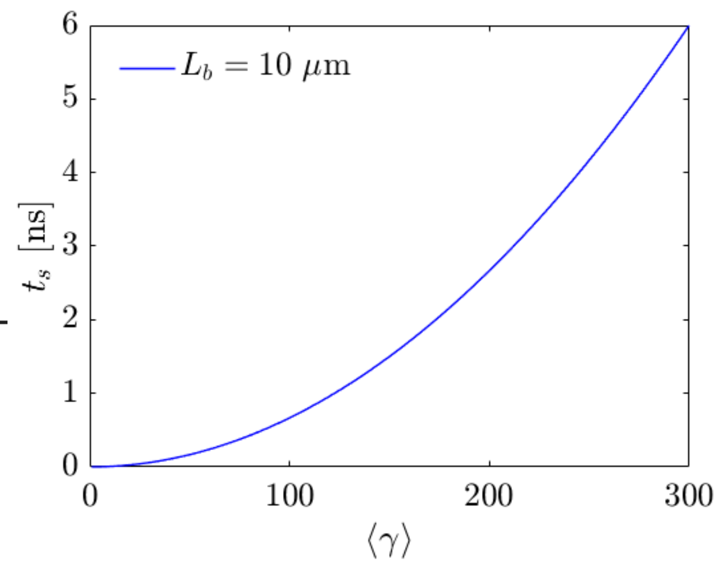


"Separation" phase

- Particle field lags behind the radiated field:

$$ct - vt < c\tau = c\frac{L}{v} = \frac{L}{\beta} \to ct \approx 2\gamma^2 L$$



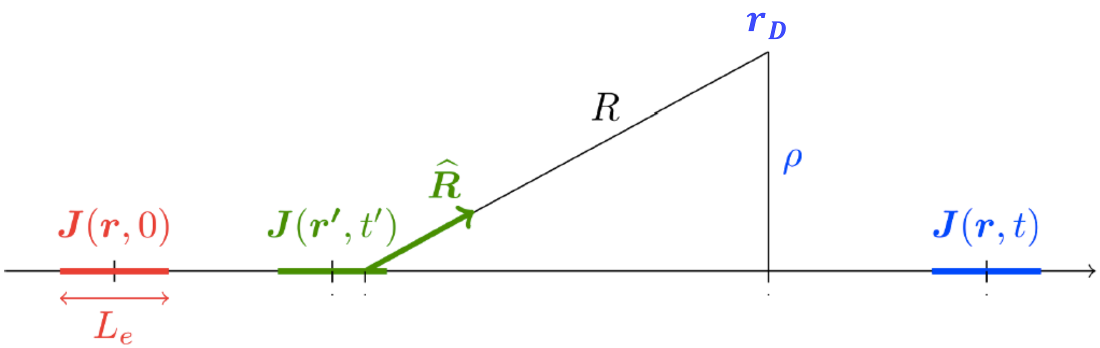


Biot-Savart model

- Make use of the generalized Biot-Savart law:

$$\boldsymbol{B}(\boldsymbol{r},t) = \int dr' \left\{ \frac{[\boldsymbol{J}(\boldsymbol{r}',t')]}{cR^2} + \frac{1}{c^2 R}\left[\frac{\partial \boldsymbol{J}(\boldsymbol{r}',t')}{\partial t'}\right] \right\} \frac{\boldsymbol{R}}{R}$$

with $R \equiv |\boldsymbol{r_D} - \boldsymbol{r}'|$ and $t' = t - \frac{R}{c}$ the retarded time.



- Perfect conductor-vacuum interface:

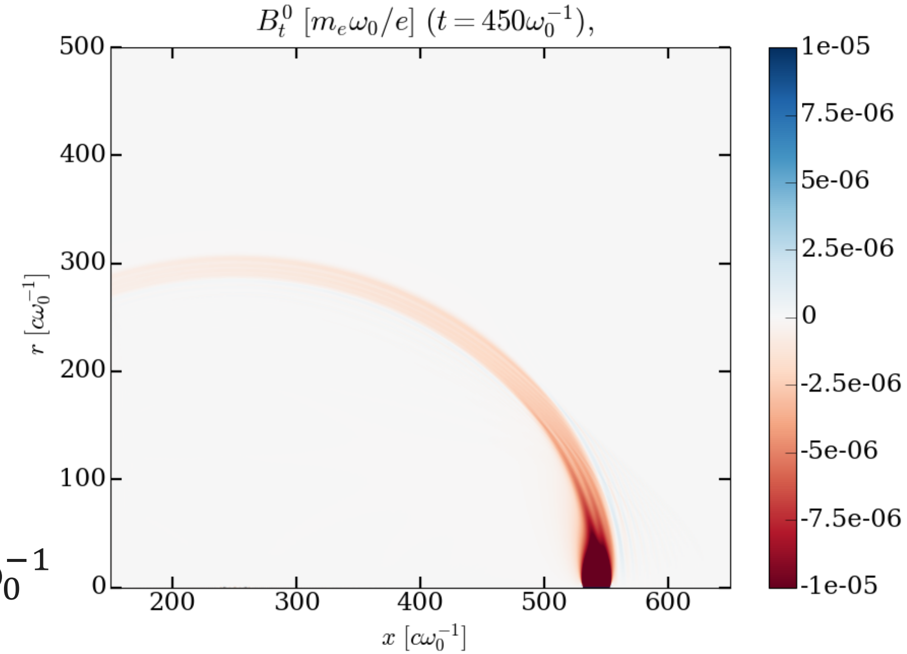
$$\boldsymbol{J} = J_0 H(x)\delta(y)\delta(z)F(x - vt)\boldsymbol{e_x}$$

Sharp transition (Heaviside)

Propagating e^- beam

Input:
$\gamma = 5$
$L = 20\ c\omega_0^{-1}$
$2\gamma^2 L = 1000\ c\omega_0^{-1}$

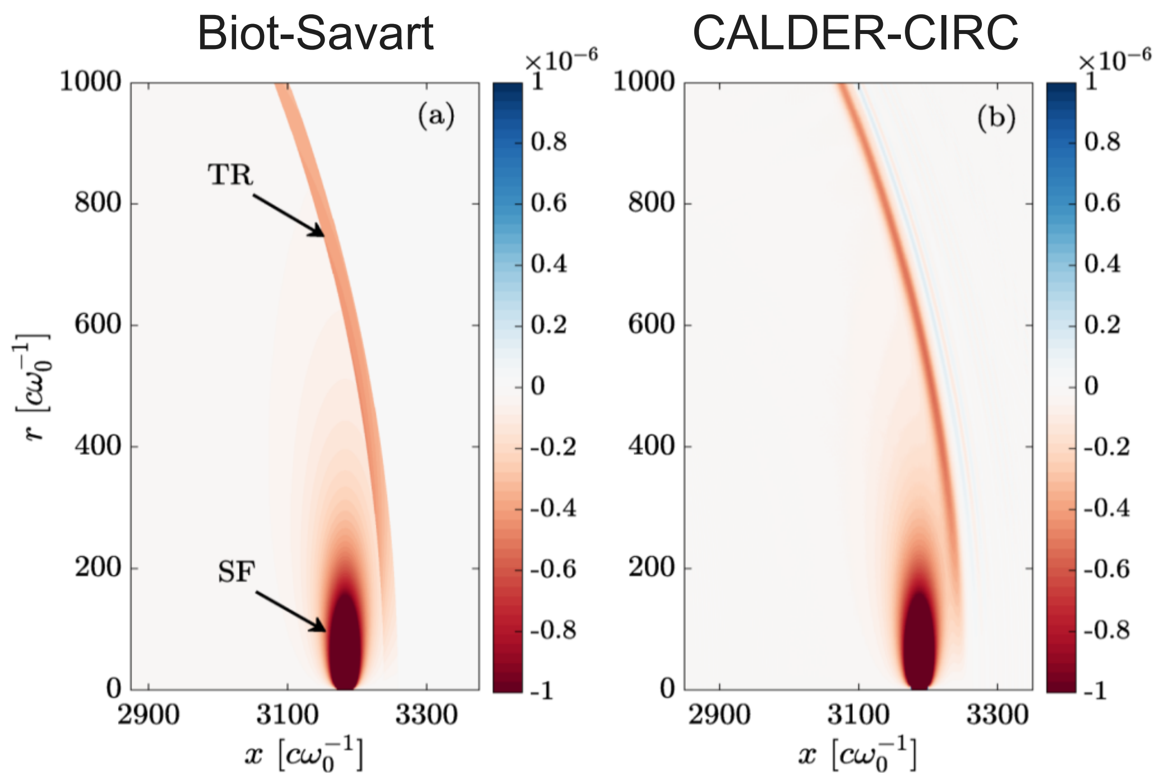
Transition in $x = 150\ c\omega_0^{-1}$



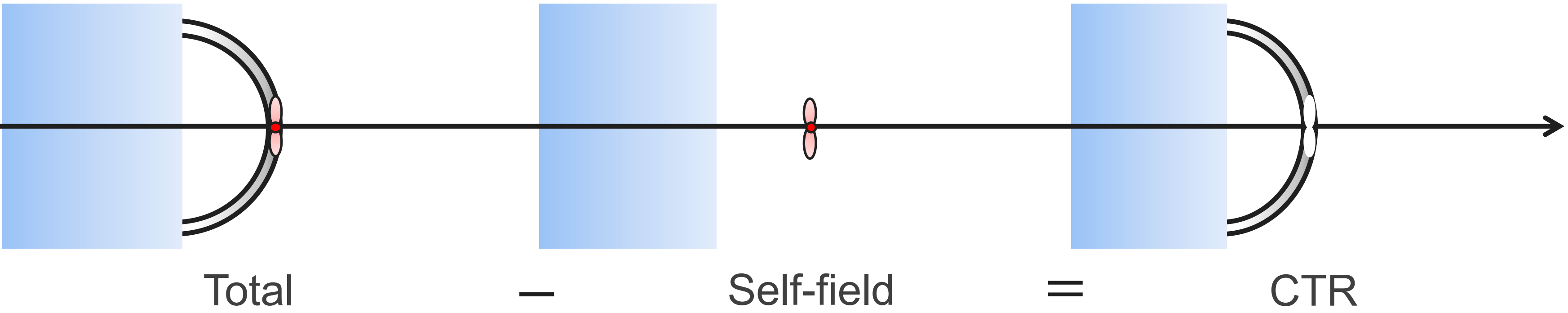
Biot-Savart vs CALDER-CIRC

- Model validation:

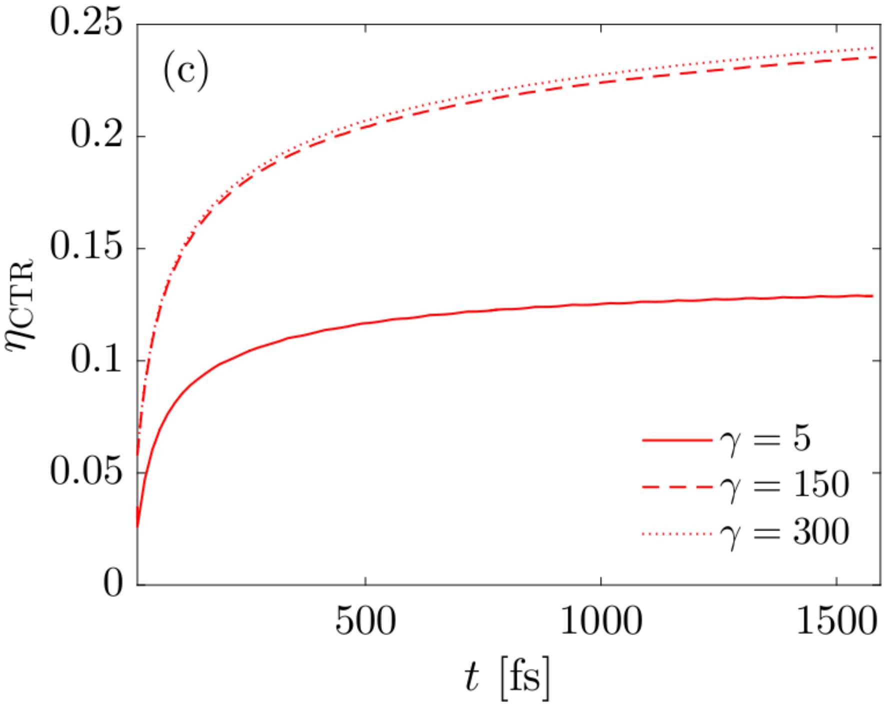
Input:
$\gamma = 5$
$L = 20\ c\omega_0^{-1}$
$2\gamma^2 L = 1000\ c\omega_0^{-1}$



CTR energy contribution



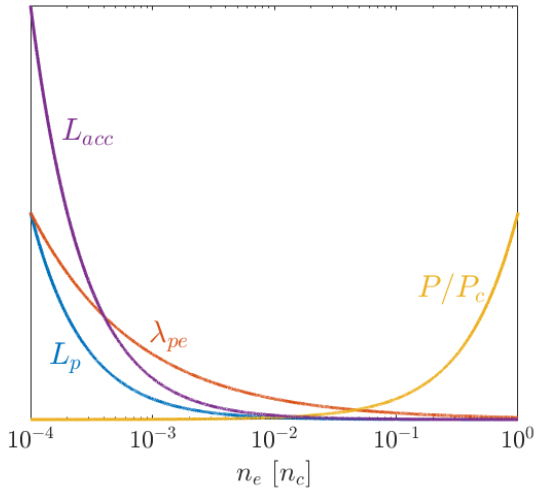
- Weak dependance on γ
- CTR contribution $\sim 25\%$



From underdense to near-critical density

- Similar laser parameters ($E_0 = 3.7$ J, $\lambda_0 = 1\mu m, \tau = 35$ fs, $P_0 = 100$ TW)
- Areal density $n_e L_p = cte$

Simulations #	n_e [10^{18}cm^{-3}]	[n_c]	L_p [μm]	λ_{pe} [μm]	P_c [TW]	$L_{acc.}$
1	0.24	0.00044	16 000	47	39	30 000
2	1.2	0.0022	3 200	21	8	6 000
3	2.4	0.0044	1 600	15	4	3 000
4	4.8	0.0088	800	10	2	1 500
5	9.6	0.0176	400	7.5	1	750
6	24	0.044	160	4.7	0.4	300
7	36	0.11	64	3.0	0.15	120
8	72	0.22	32	2.1	0.07	60
9	144	0.44	16	1.5	0.04	30
10	546	1	7	1	0.02	13



From underdense to near-critical density

- Similar laser parameters ($a_0 = 4, \tau = 35$ fs, $w_0 = 20\ \mu m$)
- Areal density $n_e L_p = cte$

Simulations #	n_e [10^{18}cm^{-3}]	[n_c]	L_p [μm]	λ_{pe} [μm]	P_c [TW]	$L_{acc.}$
1	0.24	0.00044	16 000	47	39	30 000
2	1.2	0.0022	3 200	21	8	6 000
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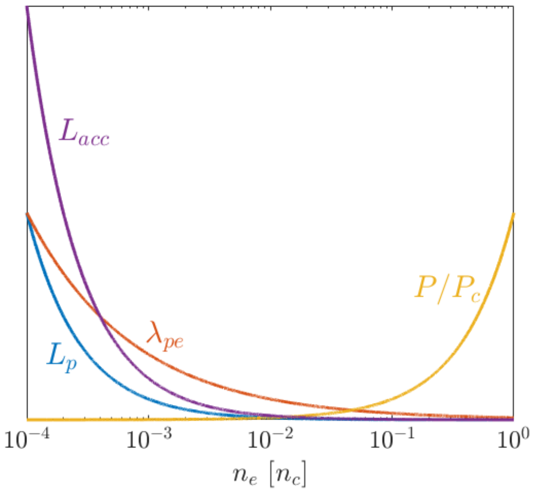


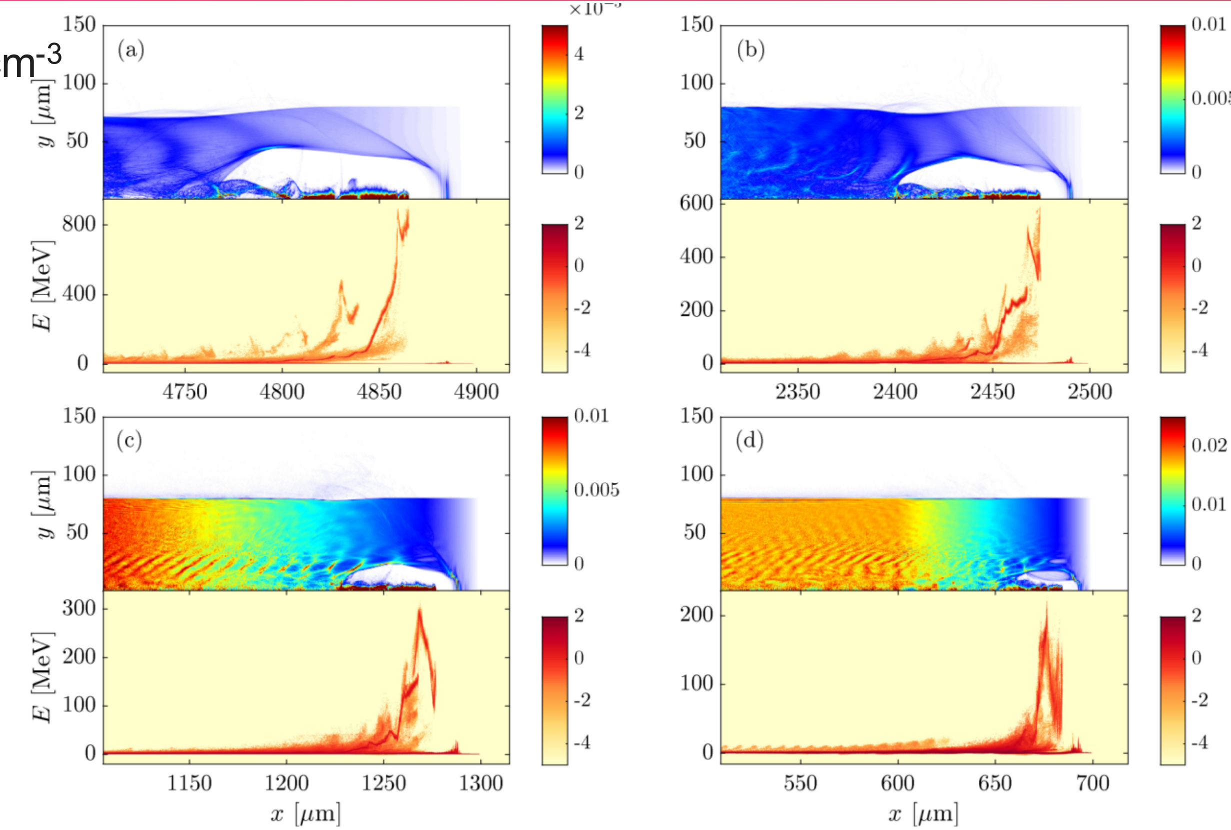
In the blow-out regime

$n_e = 2.5 \times 10^{18}$ cm^{-3}

$Q = 2.6$ nC

$n_e = 5 \times 10^{18}$ cm^{-3}

$Q = 4.8$ nC



$n_e = 10^{19}$ cm^{-3}

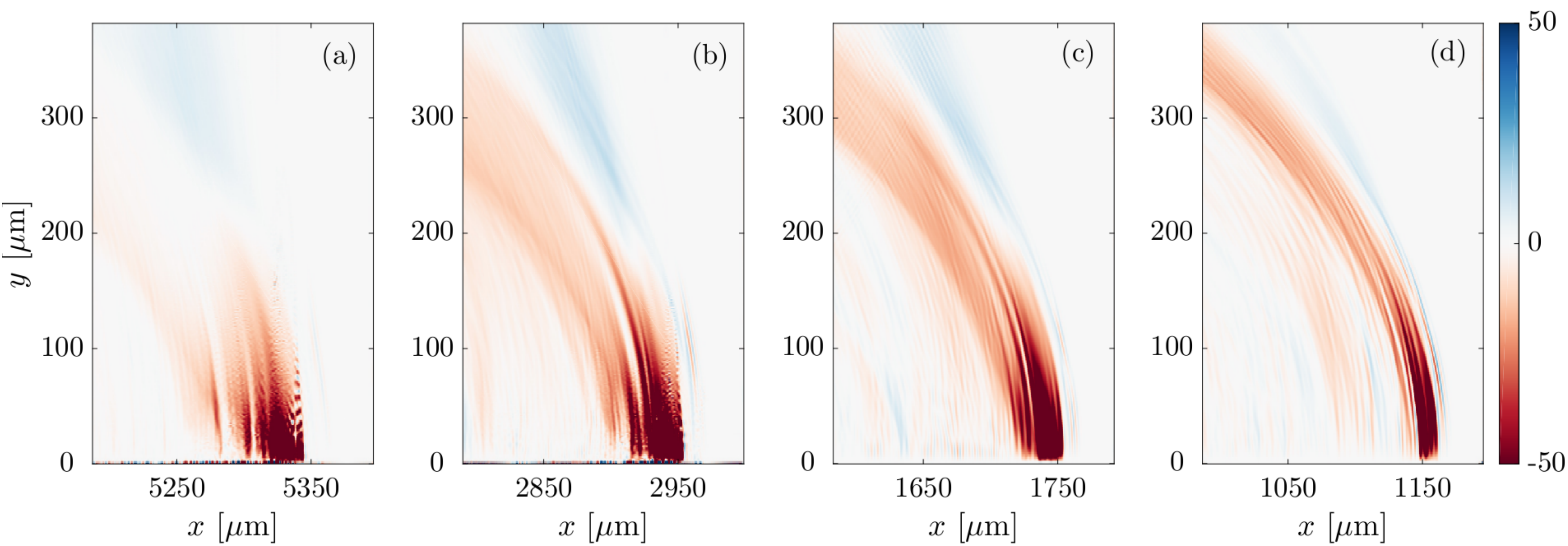
$Q = 6.0$ nC

$n_e = 2 \times 10^{19}$ cm^{-3}

$Q = 3.8$ nC

- Two injection mechanisms: self-injection + density transition
- $n_e \nearrow$ then $Q \nearrow$ up to highly charged blow-out regime
- Bunch length $\searrow$ when $n_e \nearrow$

THz fields 500 μm after the plasma



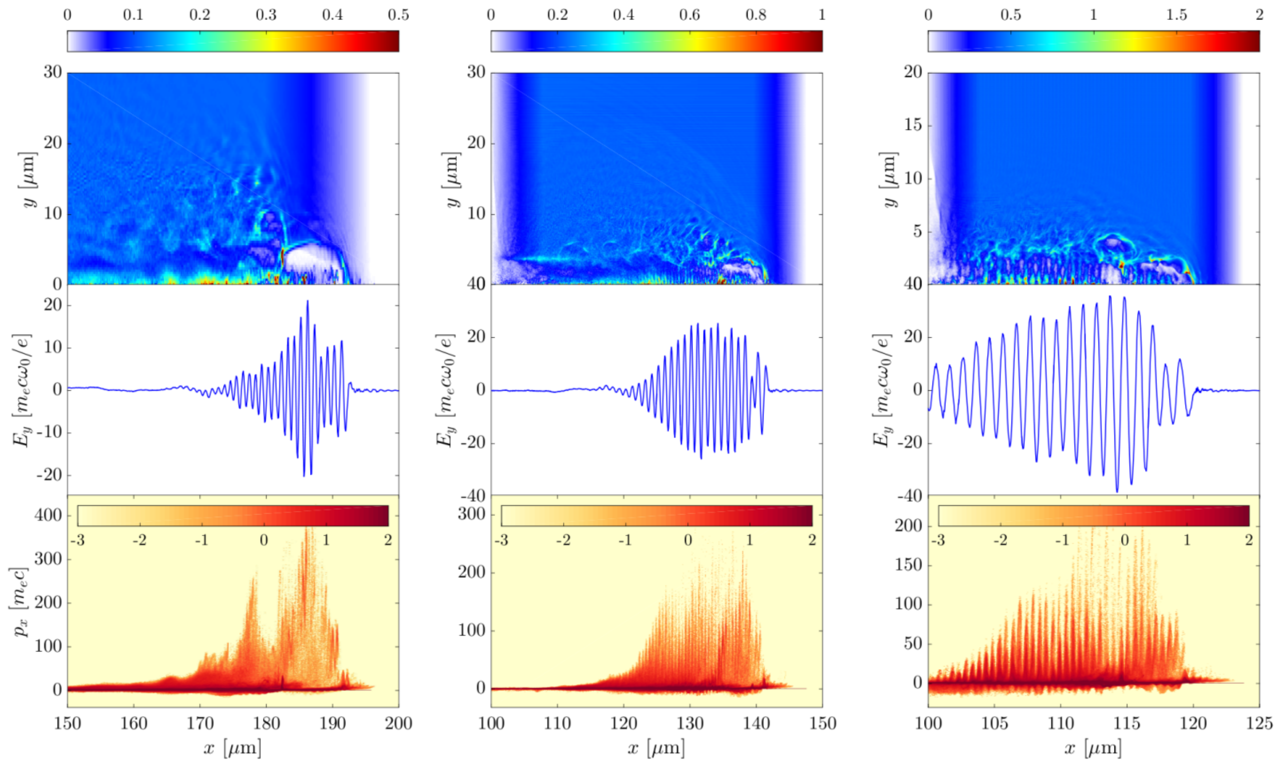
- Radially polarized field filtered in the THz domain
- Field amplitude higher than 50 GV/m
- Pulse duration ~ Beam duration due to coherence effect

Near-critical densities

Simulations #	n_e [10^{18}cm^{-3}]	[n_c]	L_p [μm]	λ_{pe} [μm]	P_c [TW]	$L_{acc.}$
6	24	0.044	160	4.7	0.4	300
7	36	0.11	64	3.0	0.15	120
8	72	0.22	32	2.1	0.07	60
9	144	0.44	16	1.5	0.04	30
10	546	1	7	1	0.02	13

Laser filamentation when $\lambda_p < w_0$

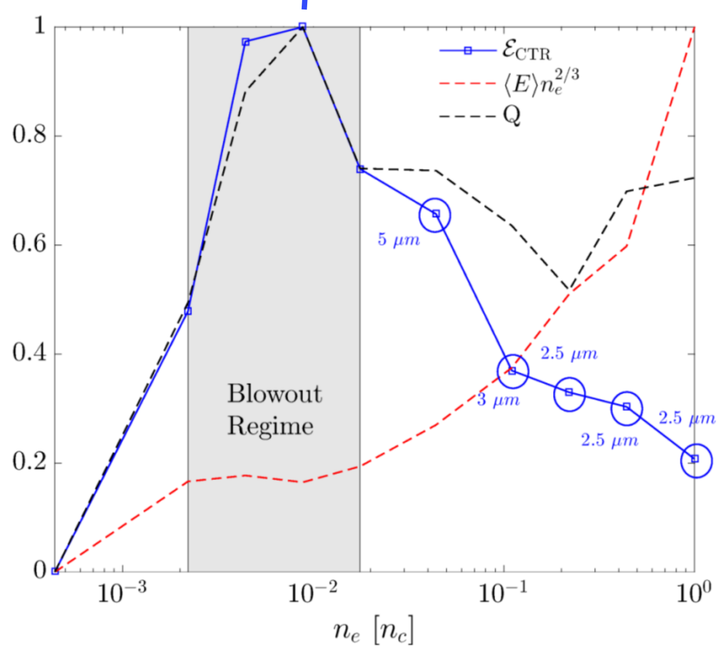
→ decrease w_0

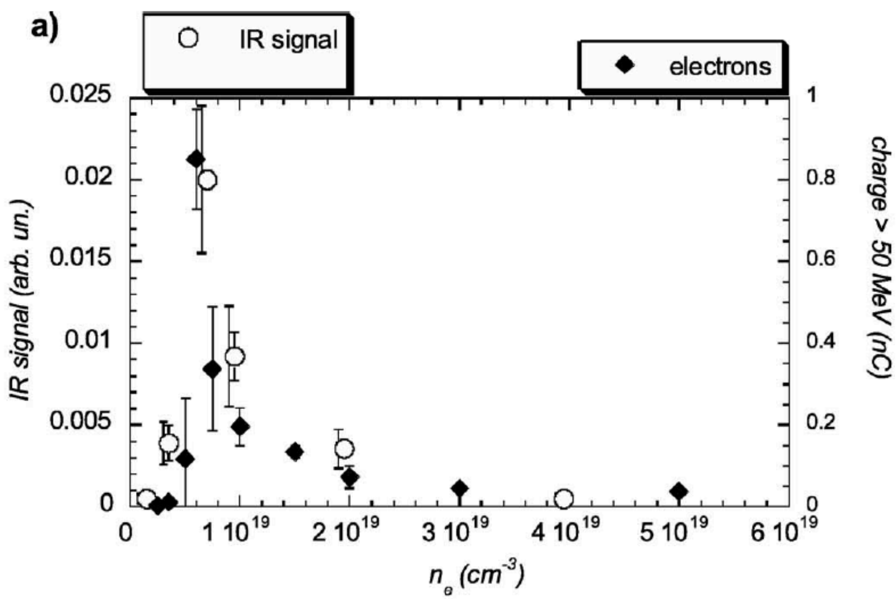


❑ Mixed wakefield + DLA regime with Maxwellian energy distribution

CTR Energy Trend

40 mJ ⟶ Few mJ from CTR contribution





Faure *et al*. Phys. Plasma **13**, 067606 (2006)

- CTR optimum in the blow-out regime
- Correlation between CTR energy and e^- beam charge
- CTR seems robust over a wide range of laser-plasma parameters

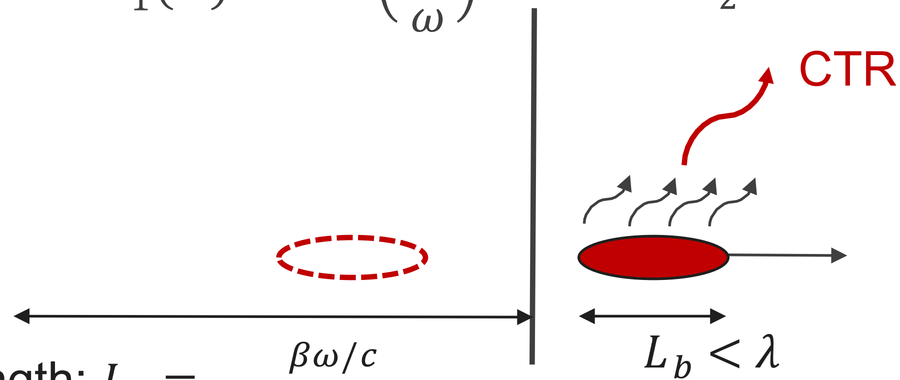
Key points

- LWFA in the highly charged blow-out regime are suitable for THz emission by CTR
- Tuning the density profile allows to modulate the emitted spectrum
- CTR contribution in PIC simulations is about 25% (need radiation processing tool)
- As a result, few mJ THz pulses are achievable

APPENDIX

- Plasma-vacuum interface: $\epsilon_1 = \epsilon(\omega)$ / $\epsilon_2 = 1$

$$\epsilon_1(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \qquad \epsilon_2 = 1$$



Photon formation length: $L_f = \frac{\beta\omega/c}{1-\sqrt{\epsilon(\omega)}\cos\theta} \approx \gamma c/\omega_p$

- Frequency dependent radiated field:

$$E \rightarrow E(\omega) = \frac{\beta^2 sin^2\theta cos^2\theta}{(1-\beta^2 cos^2\theta)^2} \times \frac{[\epsilon(\omega)-1]\left[1-\beta^2-\beta\sqrt{\epsilon(\omega)-sin^2}\right]}{\left[\epsilon(\omega)cos^2\theta+\sqrt{\epsilon(\omega)-sin^2\theta}\right)\right]\left[1-\beta\sqrt{\epsilon(\omega)-sin^2\theta}\right]}$$