Coherent Diffraction Radiation of Relativistic Terahertz Pulses from a Laser-Driven Microplasma Waveguide

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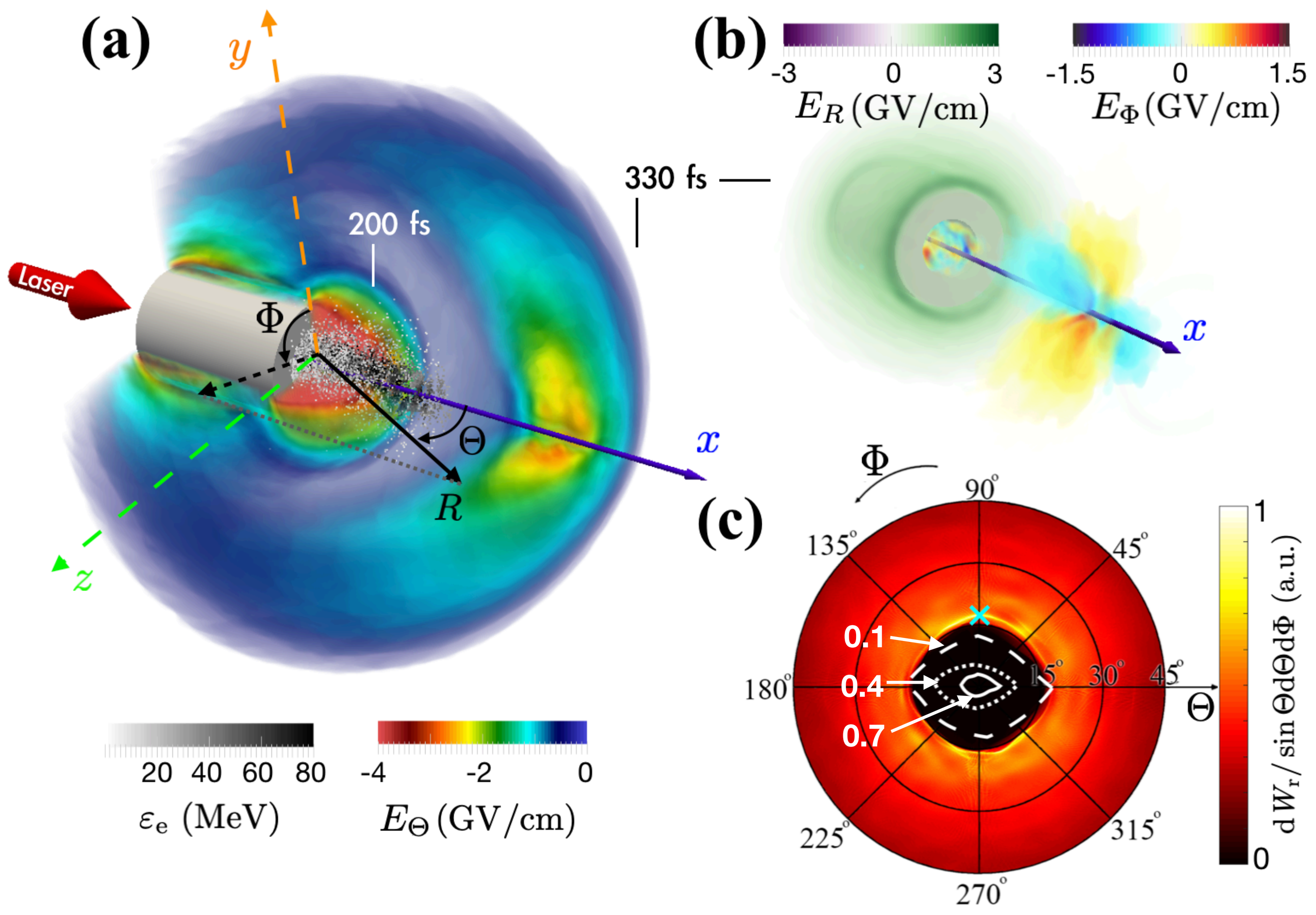
Abstract

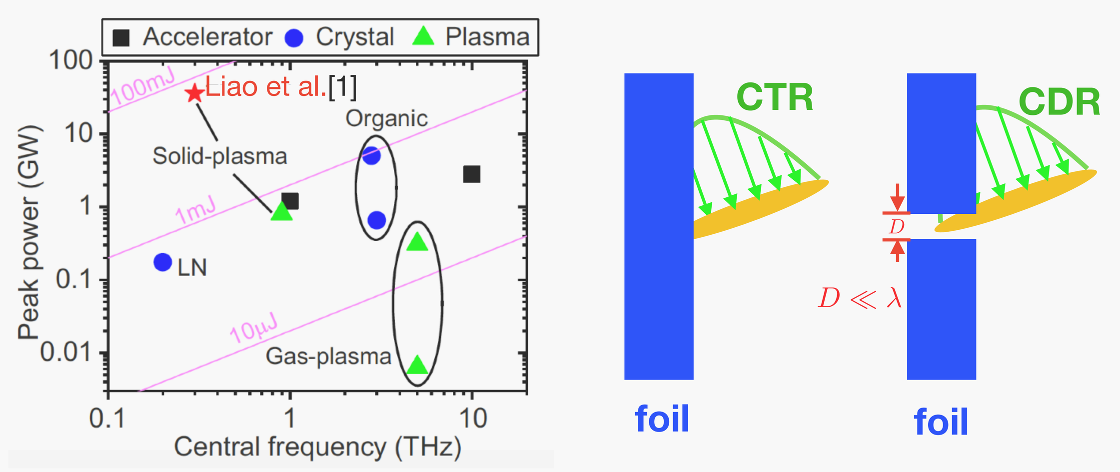
We propose a method to generate isolated relativistic terahertz (THz) pulses using a high-power laser irradiating a microplasma waveguide (MPW). When the laser pulse enters the MPW, high-charge electron bunches are produced and accelerated to ~100 MeV by the transverse magnetic modes (TMM). A substantial part of the electron energy is transferred to THz emission through coherent diffraction radiation as the electron bunches exit the MPW. We demonstrate this process with three-dimensional particle-in-cell simulations. The frequency of the radiation is determined by the incident laser duration, and the radiated energy is found to be strongly correlated to the charge of the electron bunches, which can be controlled by the laser intensity and microengineering of the MPW target. Our simulations indicate that 100 mJ level relativistic-intense THz pulses with tunable frequency can be generated at existing laser facilities, and the overall efficiency reaches 1%.



Sketch: a laser pulse is focused on the entrance of MPW (white cylinder), which produces electron beams up to 100 MeV (black-white dots). THz pulses is generated by CDR as the beam exits the MPW. The THz radiation is radially polarised: E_Θ (a) contains most of the energy; $E_R \& E_\Phi$ (b) are almost negligible. The angular distribution of THz energy (colour) and the contour of the electron beam density (white lines) are shown in (c).

Motivation

• Coherent Transition/Diffraction Radiation & High-field THz pulse



$$\Phi(\vec{r},t) = \int d^3r' \frac{\rho(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\Big|_{\rm ret}$$

$$\vec{A}(\vec{r},t) = \frac{1}{c}\int d^3r' \frac{\vec{j}(\vec{r}',t')}{|\vec{r}-\vec{r}'|}\Big|_{\rm ret}$$

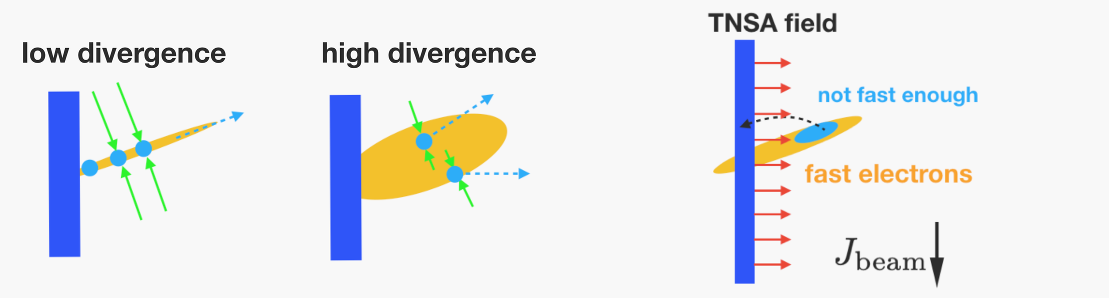
$$\vec{E} = -\nabla\Phi - \frac{\partial \vec{A}}{\partial t}$$

$E_{\rm rad} \sim 1/r$

• Electron Sources [2]

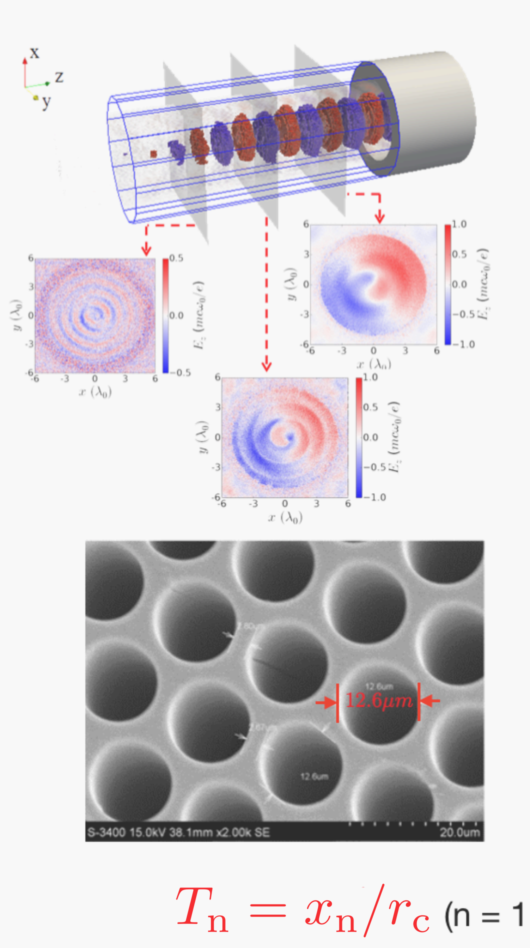
✓**High beam charge** ✓**Well-collimated** ✓**Sufficiently-high Energy**

$P_{\rm rad} \propto J^2_{\rm beam} \propto N^2_{\rm e}$

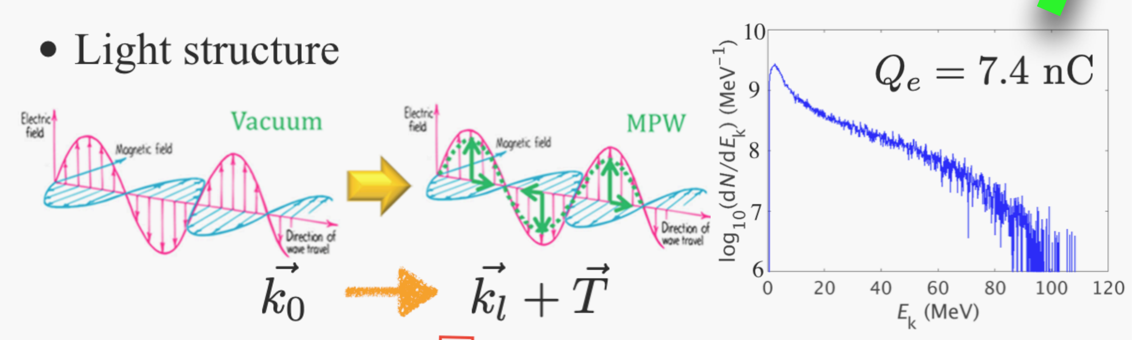


Electron sources:	Charge	Beam duration	Energy	Energy spread	Divergence
Conventional accelerators	1-10nC	0.1-1ps	up to 50GeV	<0.1%	~μrad
LWFA	1-100pC	~10fs	multi-GeVs	~1%	~0.1mrad
SM−LWFA	1-10nC	~laser FWHM	~10MeV	100 %	~100mrad
Laser-solid interaction	nC-μC	~laser FWHM	~1MeV	100 %	~40 deg
TMM acceleration	~10nC	~laser FWHM	~100MeVs	100 %	10-100mrad

Microplasma Waveguide [3]



• Light structure



TM mode: $E_{\rm longitudinal} \propto T E_0$ ← Accel. field

TE mode: $B_{\rm longitudinal} \propto T B_0$

• Light propagation

$v_{\rm ph} = (1 + \frac{T^2}{2k_0^2})c, \quad v_{\rm ph} v_{\rm g} = c^2$ ← Dephasing

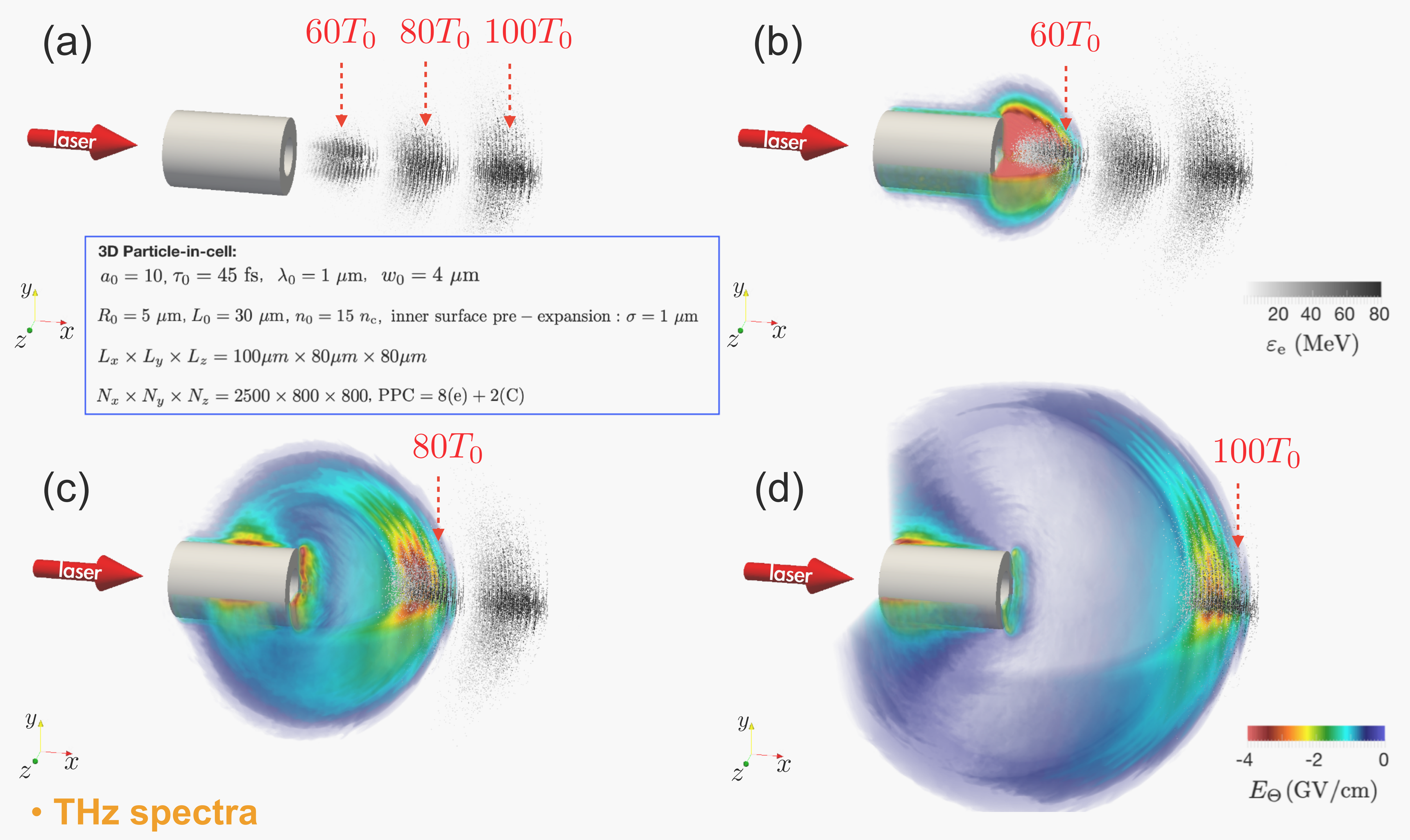
• Light pressure

$P_{\rm T} = (T^2/k_0^2)(I_0/c)$ ← Production of e-beam

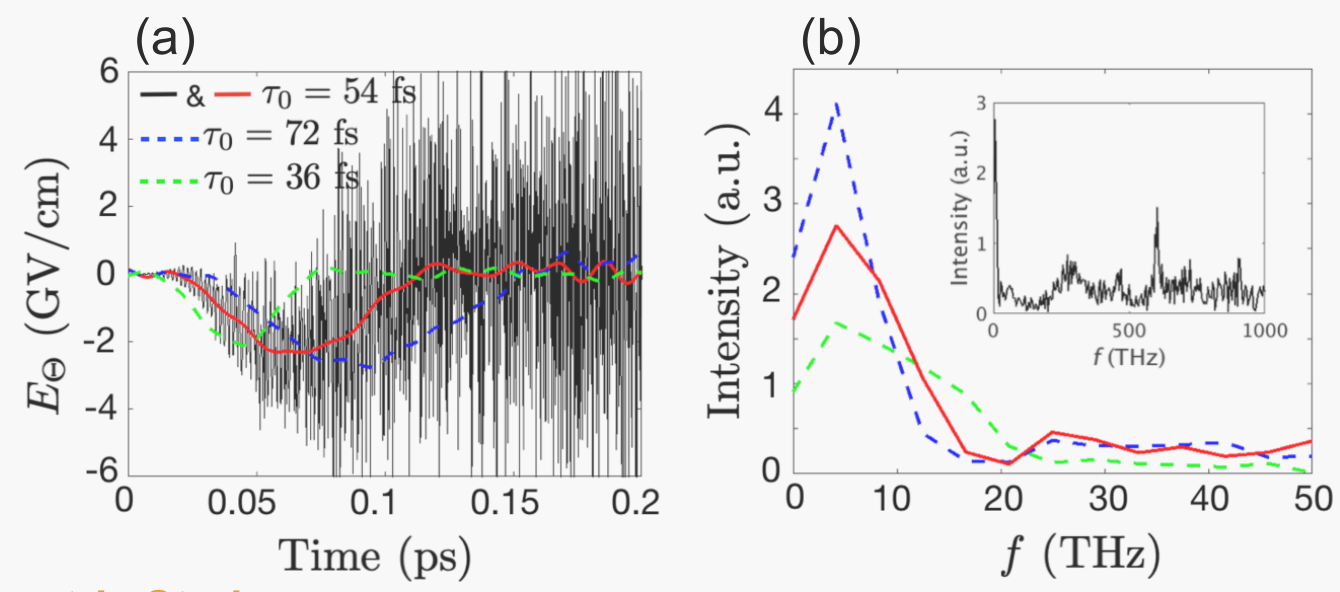
$T_{\rm n} = x_{\rm n}/r_{\rm c}$ (n = 1,2,3,...) → $T_1 = x_1/r_{\rm c}$ $(x_1 \approx 2.4)$

THz emission [4]

• Time evolution



• THz spectra



• Parametric Study

$$Q \approx \frac{x_1 a_m}{2}\frac{mc^3}{e}\tau_0 \propto a_0 \text{ (fixed MPW)}, \propto r_c^{-1} \text{ (fixed laser)} \quad (\Gamma \gg 1)$$

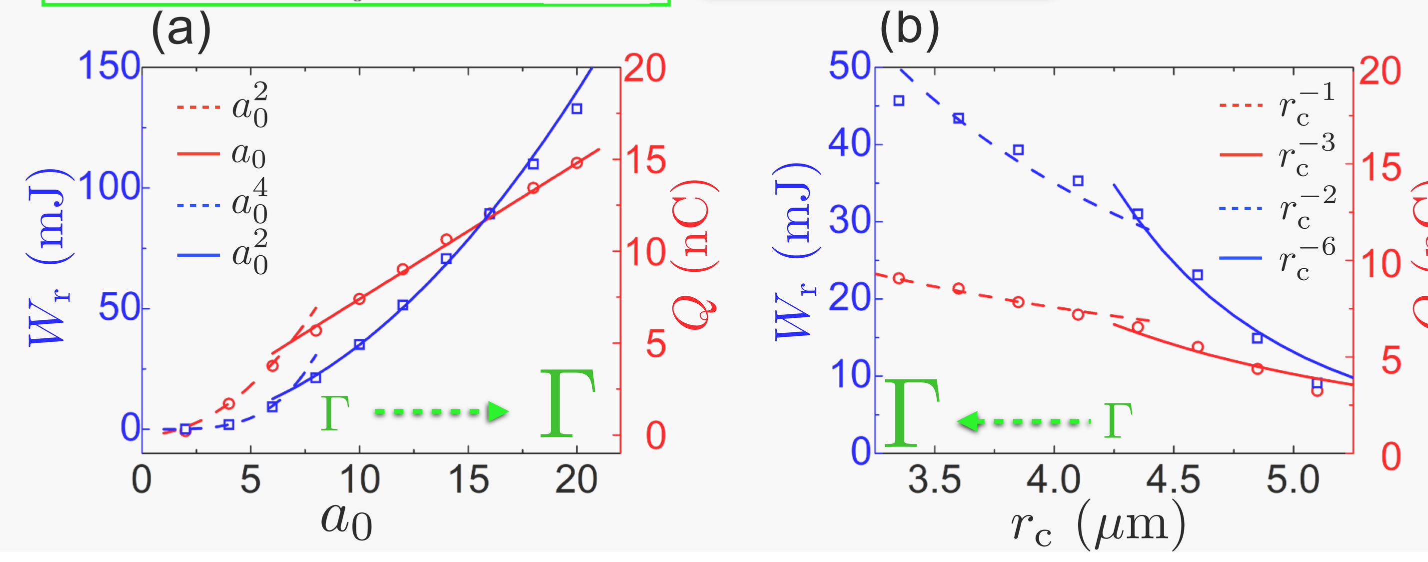
$$Q \approx \frac{x_1^2 a_m}{4k_0 r_0}\frac{mc^3}{e}\tau_0 \propto a_0^2 \text{ (fixed MPW)}, \propto r_c^{-3} \text{ (fixed laser)} \quad (\Gamma \ll 1)$$

$$\Gamma \equiv \frac{T^2 a_m^2}{k_0^2} = \frac{x_1^2 a_m^2}{k_0^2 r_c^2}$$

$a_m = a_0 \quad (w_0 \geq r_0)$

$a_m = a_0 w_0 / r_0 \quad (w_0 < r_0)$

→ $W_{\rm r} \propto Q^2$



Summary

❖ Laser-MPW interaction provides an alternative electron source that can potentially achieve high beam charge, relatively small divergence, and hundreds MeV energy.

❖ Such electron beam can generate relativistic pulses via coherent diffraction radiation with frequencies ranging from infra-red to sub-THz.

❖ Radiation energy ~ 100 mJ, with conversion efficiency ~ 1%, which can be maintained when scaling towards higher laser intensities.

References

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3. L. Q. Yi *et. al.*, Bright X-ray source from a laser-driven microplasma waveguide. *Phys. Rev. Lett.* **116**, 115001 (2016)
4. L. Q. Yi and T. Fülöp, Coherent diffraction radiation of relativistic terahertz pulses from a laser-driven microplasma waveguide. *Phys. Rev. Lett.* **123**, 094801 (2019)

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