# Coherent THz Smith-Purcell radiation from LWFA electron beams

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## Introduction

Smith-Purcell Radiation (SPR) is a special case of diffraction radiation produced when a charged particle passes parallel to the surface of a metallic-coated grating [1]. Using a Laser Wakefield Accelerators electron bunch, we generated 30-THz pulses by passing um-long electron (e) bunches from a laser-wakefield accelerator within a millimeter of a grating without damaging it or perturbing the e-bunches. Such radiation promises non-invasive, single-shot diagnosis of femtosecond e-bunch profiles, including inside free-electron lasers, and a highly configurable source of synchronized THz/hard X-ray pulses for ultrafast high-field THz spectroscopy.

## Theory of SPR

As shown in **Fig. 1**, when a group of charged particles move uniformly over a metallic grating surface it induces a surface current that moves in unison [2]. This current radiates as it crosses adjacent tooth interfaces. The interference of radiation from all teeth of the grating creates a dispersion relationship much like light incident on a grating, called the Smith-Purcell Relation. The relationship as a function of angle and order is given as:

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

Where $\beta$ = normalized electron velocity, $L$ = grating period, and $n$ = order of radiation. The differential energy emitted per solid angle for a single electron passing over the grating goes as:

$$\left(\frac{dI}{d\Omega}\right)_1 = 2\pi e^2 \frac{Z}{L^2} \times \frac{n^2\beta^3}{(1-\beta\cos\theta)^3} exp\left[\frac{-2x_o}{\lambda_e}\right] R^2 \qquad (2)$$

Where $Z$ = grating length, $x_o$ = electron height above grating, while $\lambda_e$ = evanescent wavelength and $R^2$ = grating efficiency [3], are:

$$\lambda_e = \frac{\beta\lambda\gamma}{2\pi\sqrt{1+\beta^2\gamma^2 sin^2\theta sin^2\phi}} \qquad (3)$$

and:

$$R^2 \approx \left[\frac{1}{\sin\theta - \tan\alpha_1\,(1+\cos\theta)}\right]^2 \text{x} \; tan^2\alpha_1 sin^2\theta \frac{sin^2\left[\frac{kh\sin\theta}{2}\right]}{\left[\frac{kh\sin\theta}{2}\right]^2} \qquad (4)$$

For a group of $N$ electrons the contributions from each individual particle produce either coherent or incoherent sources of radiation.

$$\left(\frac{dI}{d\Omega}\right)_{N_e} = \left(\frac{dI}{d\Omega}\right)_1 [NS_{inc} + N^2 S_{coh}] \qquad (5)$$

If the bunch size is much smaller than the wavelength of observation:

$$\sigma_x, \sigma_y, \sigma_z \ll \lambda_{obs}$$

There is significant constructive interference leading to $S_{coh} \approx 1$, and the coherent term ($N^2$ term) dominates. For LWFA bunches, bunches that are typically *fs*-scale (*~1 um*), emission in the THz regime (equal or longer than *10 um*) should be fully-coherent.

## Experimental Setup

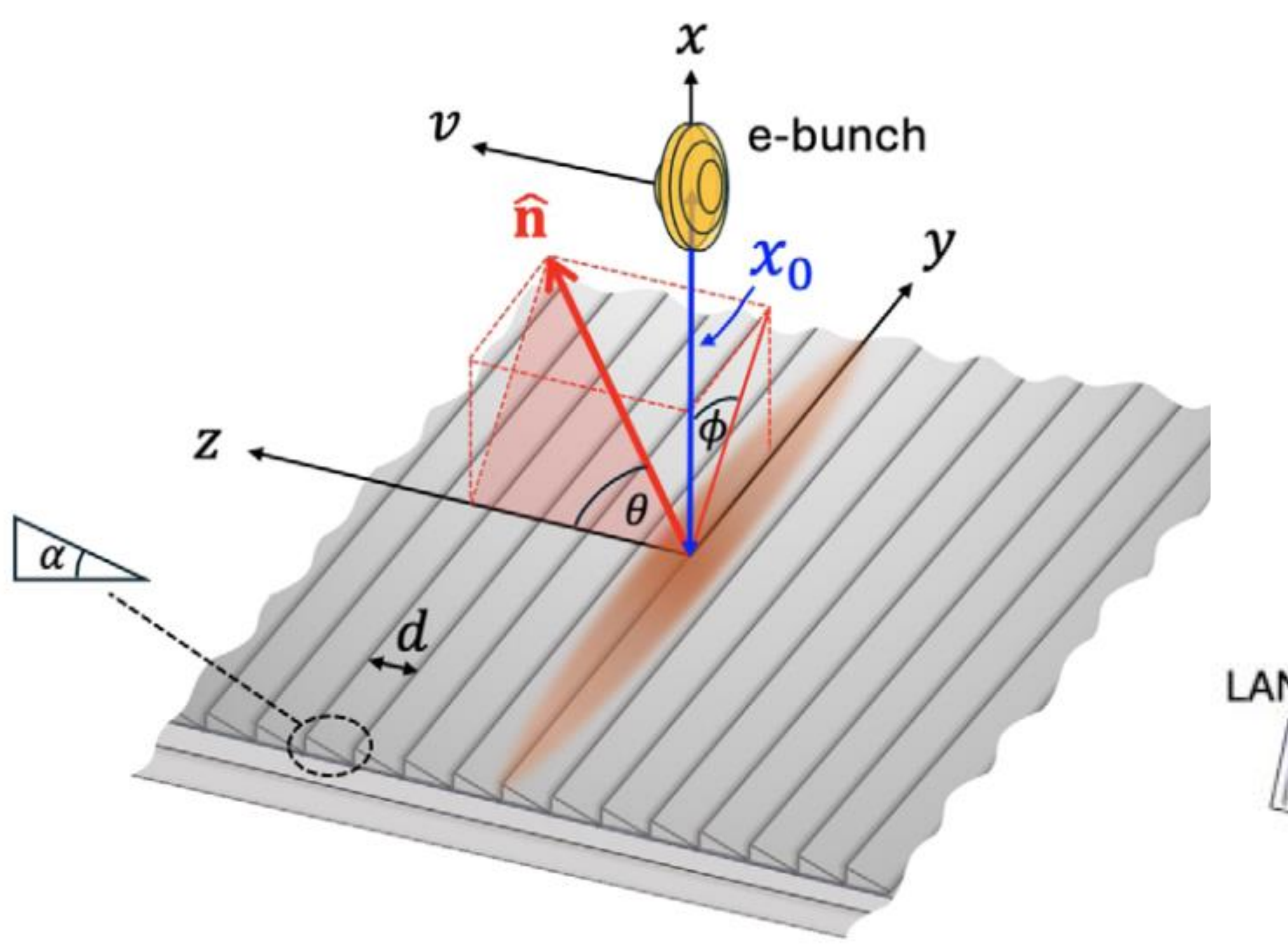


**Fig. 1.** An electron bunch traveling at a fixed speed in the z-direction passes near a blazed grating. The surface current (shown as an orange glow) gives rise to radiation, Eq. (1) demonstrates that the wavelength of emission depends purely on the angle θ.

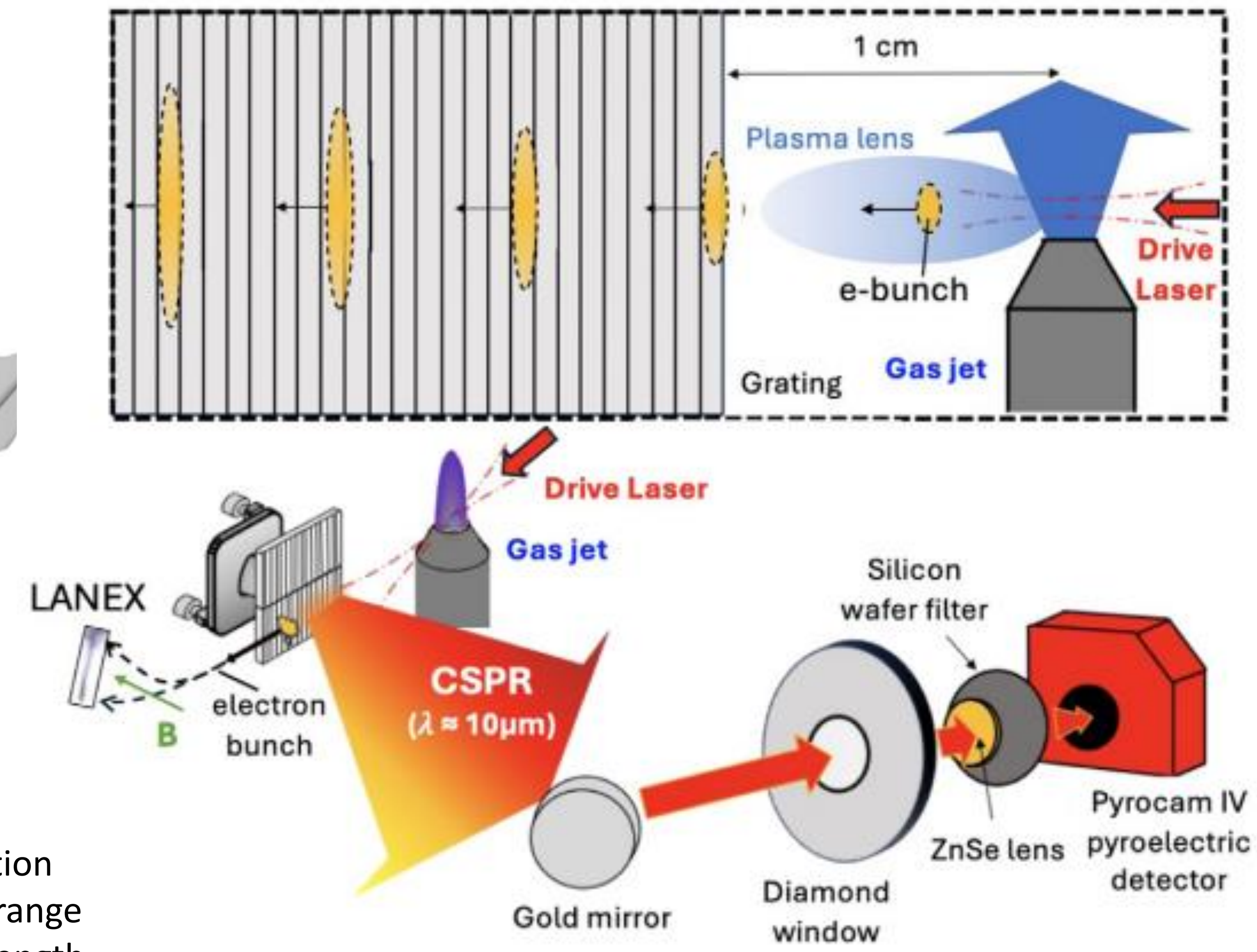


**Fig. 2.** Experimental setup at HZDR [4].

| Grating Parameters | |
|---|---|
| Grating Period (L) | 10 µm |
| Grating Length (Z) | 25 mm |
| Grating Width | 12.5 mm |
| Blaze Angle ($\alpha_1$) | 27.0° |
| Grating Efficiency ($R^2$) | 0.42 |

| Electron Parameters (over 113 shots) | |
|---|---|
| Ave. Mean Energy | 405 MeV |
| Ave. Total Charge | 538 pC |
| Divergence | 1-2 mrad |
| Pointing | -8 to 3 mrad |

## Analysis + Future Plans

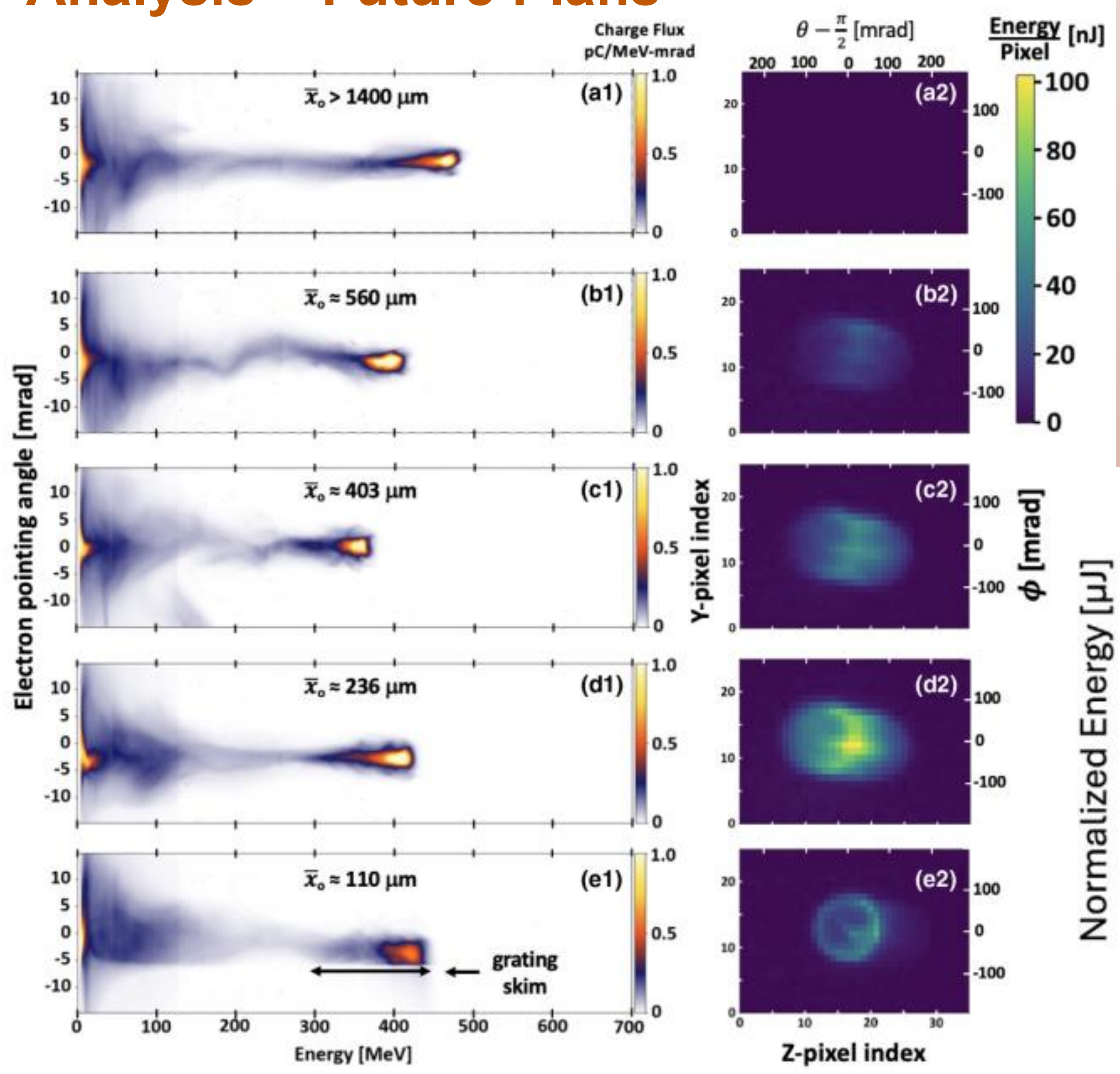


**Fig. 3.** SPR on Pyrocam IV pyroelectric detector for a range of e-beam heights away from the grating face. Take note of the initially increasing signal with decreasing distance, up until a certain point, followed by a decrease due to Fresnel diffraction of SPR before our collecting optic.

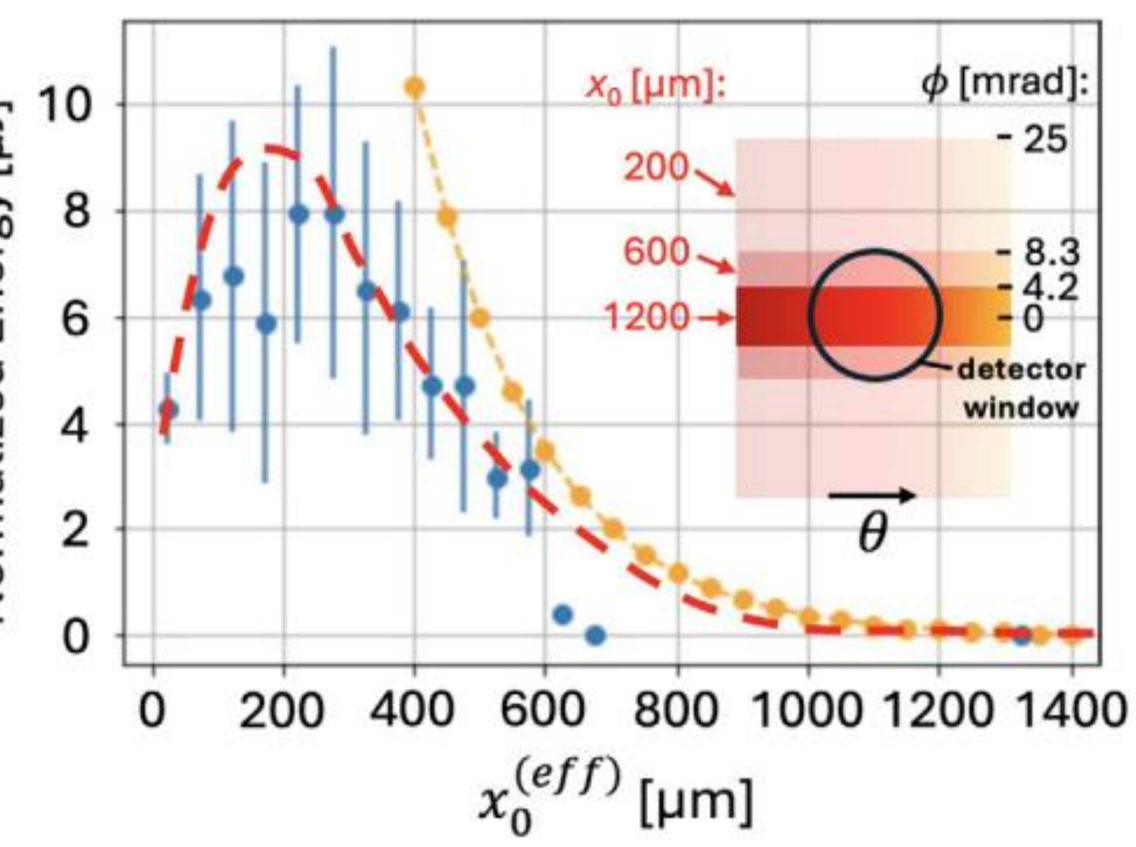


**Fig. 4.** Plot of energy vs. separation distance between grating and electron beam. Shown in orange is the theoretically predicted energies, in blue are the experimental results, and in red are the corrected predicted energies taking into account losses due to diffraction of radiation before the capturing optic.

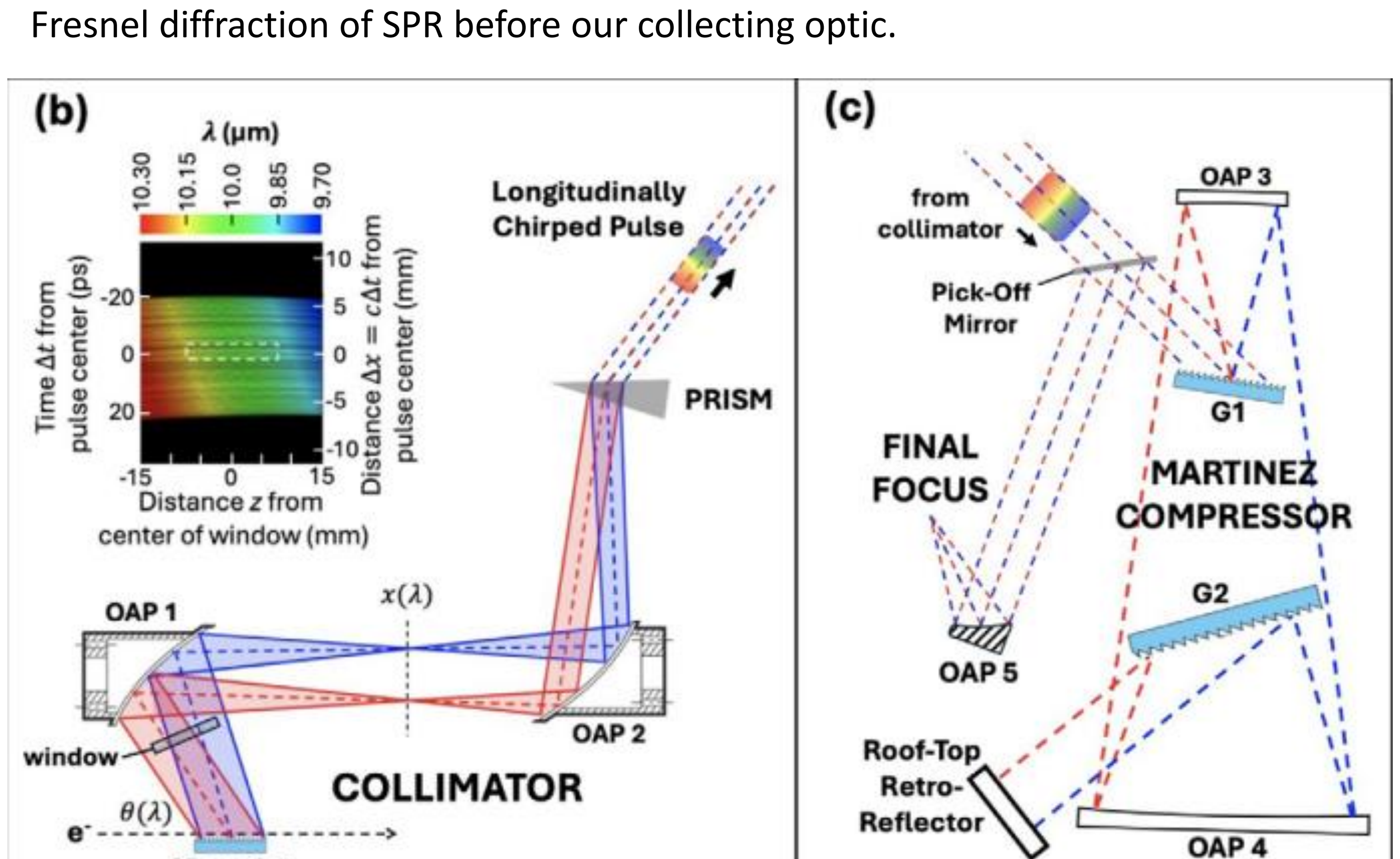


**Fig. 5.** Representing a potential design for an optical compressor to compress the SPR pulse down to sub-ps duration.

### *Future plans:*

LWFAs provide a unique opportunity to produce copious amounts of THz SPR. We intend to follow this experiment up with a similar one at ELI-NP with the hopes of using higher energy 3 GeV electron bunches positioned 1 mm away from the grating to generate radiation. The hope is also in the future to make a 3d SPR generator with an accompanying collection system to increase the amount of radiation 100-fold.

## References

[1] S. J. Smith and E. M. Purcell, Phys. Rev. 92, 1069 (1953).
[2] J.H. Brownell, J.E. Walsh, and G. Doucas, Phys. Rev. E 57, 1075 (1998).
[3] J.H. Brownell and G. Doucas, Phys. Rev. Spec. Top.- Accelerators Beams 8 091301 (2005).
[4] R. Rudzinsky, et al., "Coherent terahertz Smith–Purcell radiation from laser-wakefield-accelerated electron bunches," Optica 13, 810-821 (2026)