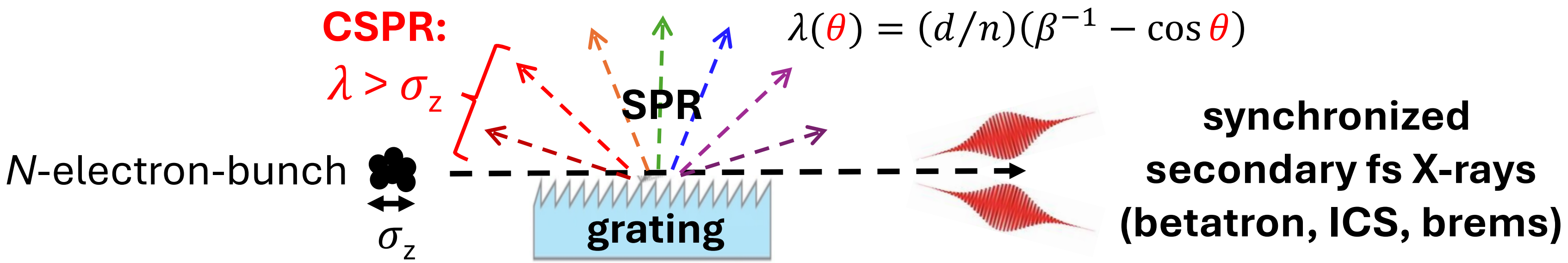


Coherent Smith-Purcell Radiation[1] from plasma-accelerated electrons:[2] a synchronized strong-field THz radiation source

Mike Downer, R. Rudzinsky, Z. Ouyang, J. Brooks, B. Dinh, L. Zhang, A. Raka, E. Martinez, R. Zgadzaj

The University of Texas at Austin

M. LaBerge, Y.-Y. Chang, A. Debus, J. M. Klopf, F. M. Herrmann, P. Ufer, S. Schöbel, T. E. Cowan, A. Irman, U. Schramm

Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Previous AAC 2026 presentations:

- Rudzinsky, The role of CSPR for LWFA beam diagnosis, WG5 Tu 13:50
- Rudzinsky, CSPR from plasma-accelerated electron bunches, M poster
- Martinez, Reconstructing LWFA e-bunch longitudinal profiles from CSPR, Tu poster.
- Raka, Reshaping CSPR from fs LWFA e-bunches into strong-field THz pulses, M poster.

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

[2] R. Rudzinsky *et al.*, *Optica* **13** (5), 810-821 (2026)

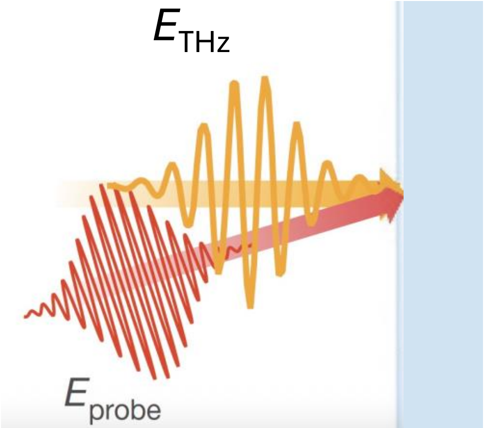
Advanced Accelerator Concepts (July 30, 2026)

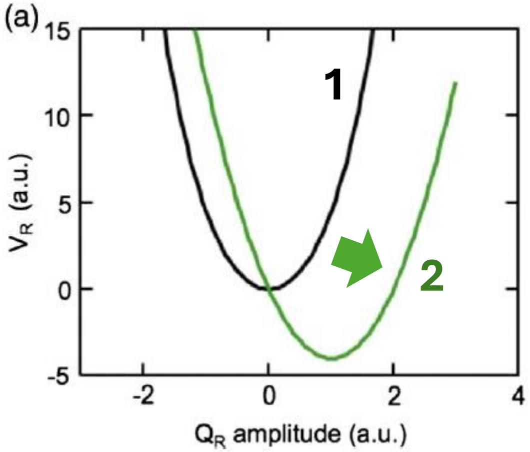
Nonlinear phononics: controlling matter w. THz light

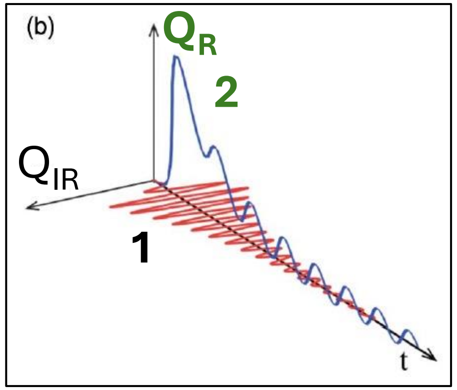
Nicoletti & Cavalleri, *Adv. Opt. Phot.* **8**, 403- (2016)

1) Strong THz pulse (≳ 1 GV/m) resonantly drives **IR-active lattice vibration Q_{IR}** to high amplitude.

Strong THz sources:
- laser-based
- accelerator-based





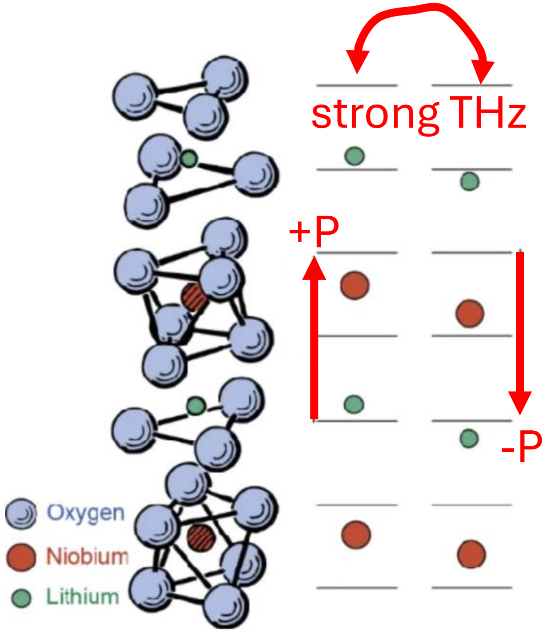


Types of fs probes:
- optical
- X-ray
- electron

probes of structural change, if synchronized with THz pump

2) Anharmonic lattice potential rectifies that vibration into displacement along **another structural coordinate Q_R**, producing a transient crystal with **different electronic & magnetic properties**.

e.g.
- insulator → metal
- antiferromagnet → magnetically disordered
- normal → superconducting
- charge-ordered → charge-disordered
- ferroelectric polarization reversal



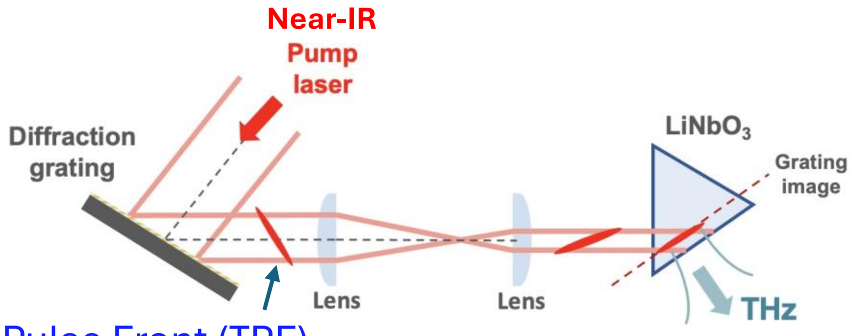
Ferroelectric polarization reversal in $LiNbO_3$ via strong resonant excitation of IR-active phonon.

Mankowsky, *PRL* **118**, 197601 (2017)

Existing strong-field THz sources & fs LWFA-driven CSPR

Preliminary comparison

	Laser-Driven Sources		RF Accelerator-Driven Sources			fs CSPR
THz property	**Mid-IR [1,2] (Organic X-tals)**	**Near-IR [3-5] (TPF, $LiNbO_3$)**	**RF: FELBE/TELBE [6,7]** U37	U100	U300	**LWFA-driven [8] (this work)**
wavelength [µm]	30-3000	120-3000	5-40	18-250	120-3000	5 -30
frequency [THz]	0.1 - 10	0.1 - 3	7.5 - 60	1.2 - 17	0.1 – 2.5	10 - 60
time-synched to…	drive laser		drive e-bunch and secondary X-rays			
scale	tabletop		large user facility			tabletop



Tilted Pulse Front (TPF)

- configurable
- transportable

[1] Vicario, *PRL* **112**, 213901 (2014)
[2] Gollner, *APL Photonics* **6**, 046105 (2021)
[3] Hebling, *JOSA B* **25**, B6 (2008)
[4] Tóth, *Light Sci. Appl.* **12**, 256 (2023)
[5] Kroh, *Opt. Express* **30**, 24186 (2022)

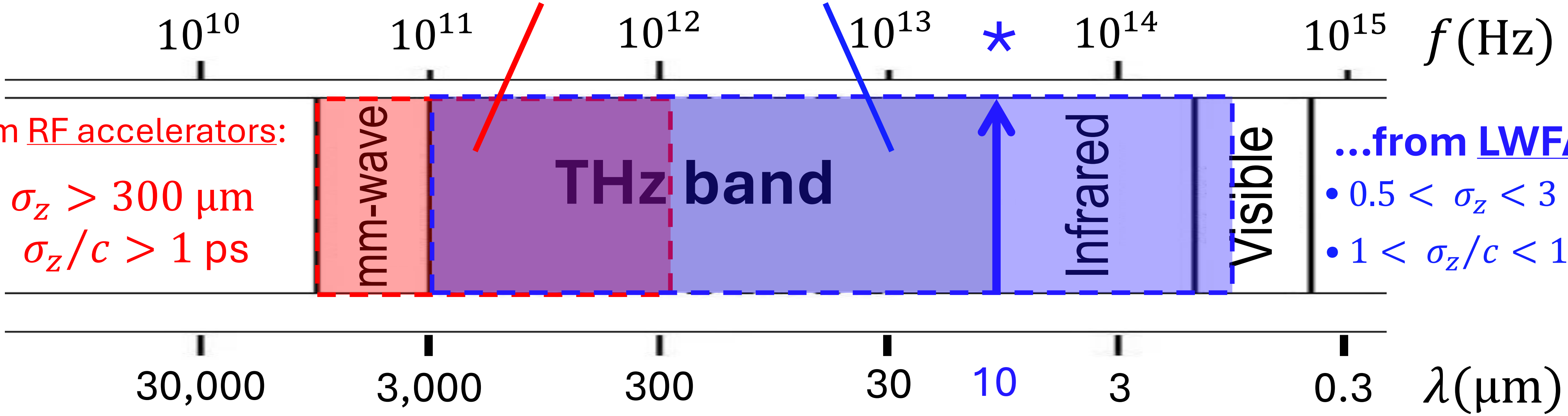
[6] Green, *Sci. Rpts.* **6**, 22256 (2016)
[7] Helm, *Eur. Phys. J. Plus* **138**, 158 (2023)

[8] Rudzinsky, *Optica* **13**, 810 (2026)

Coherent SPR (CSPR)...

...from RF accelerators:

- $\sigma_z > 300\ \mu m$
- $\sigma_z/c > 1$ ps



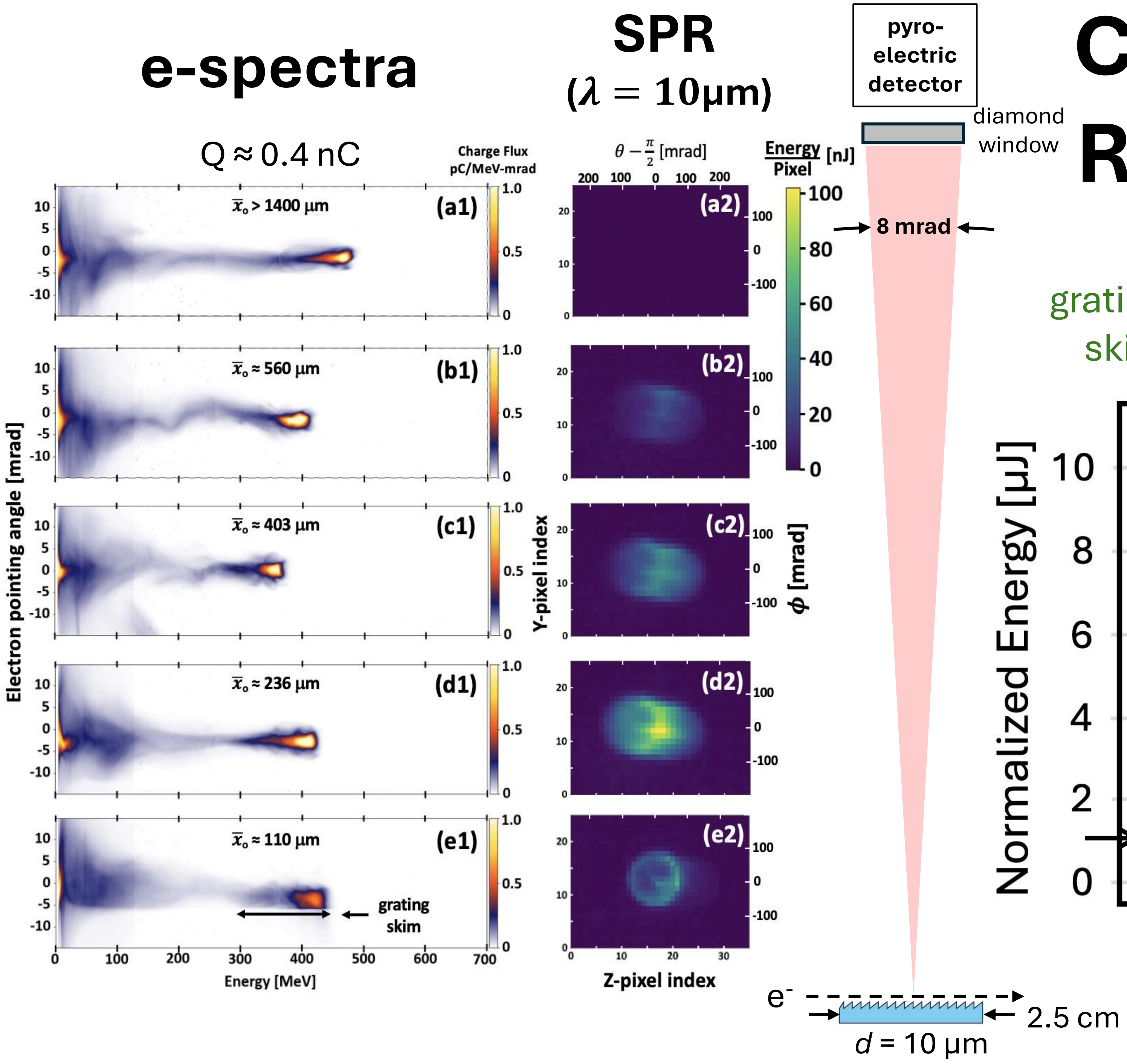
...from LWFAs:

- $0.5 < \sigma_z < 3\ \mu m$
- $1 < \sigma_z/c < 10$ fs

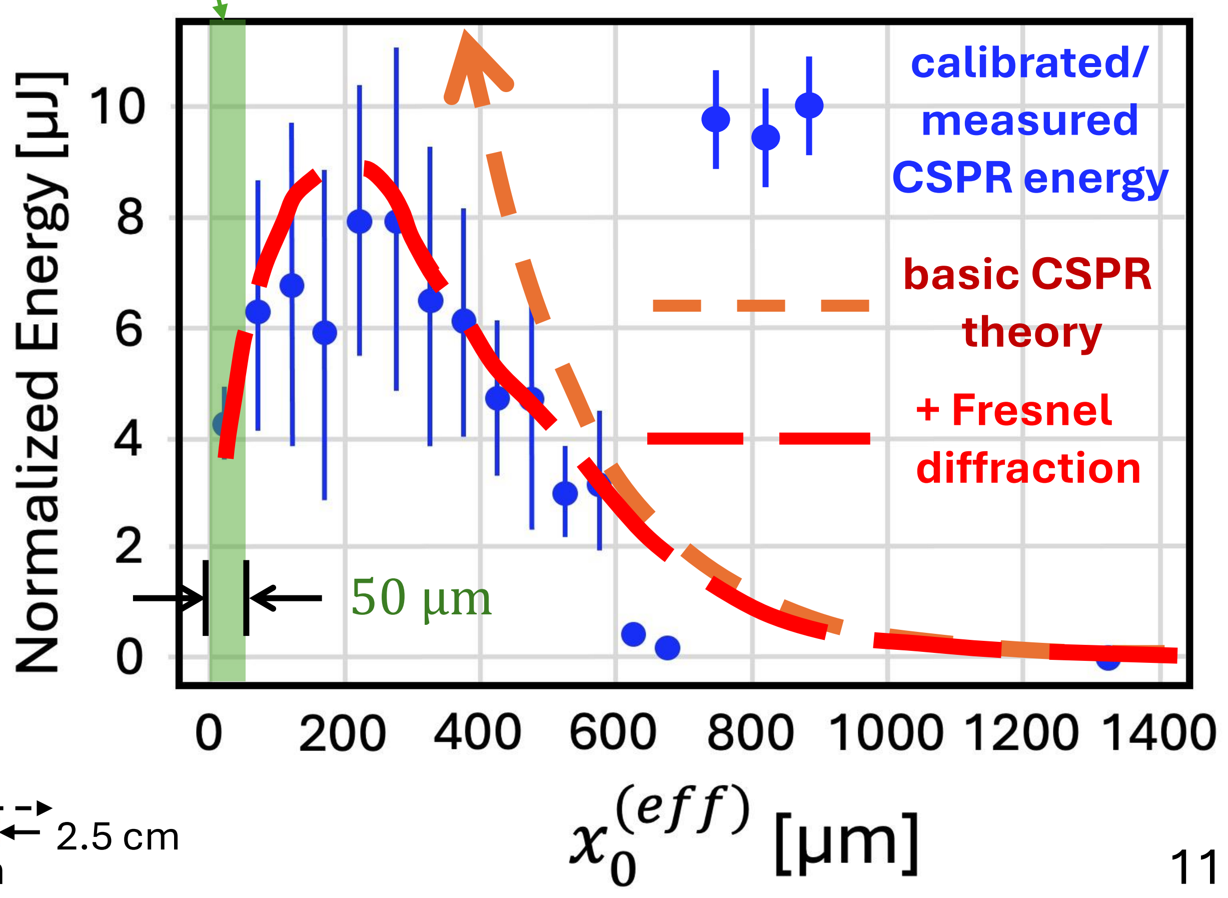
* Rudzinsky *et al.*, *Optica* **13**, 810 (2026)

CSPR Experimental Results at $\lambda = 10$ μm

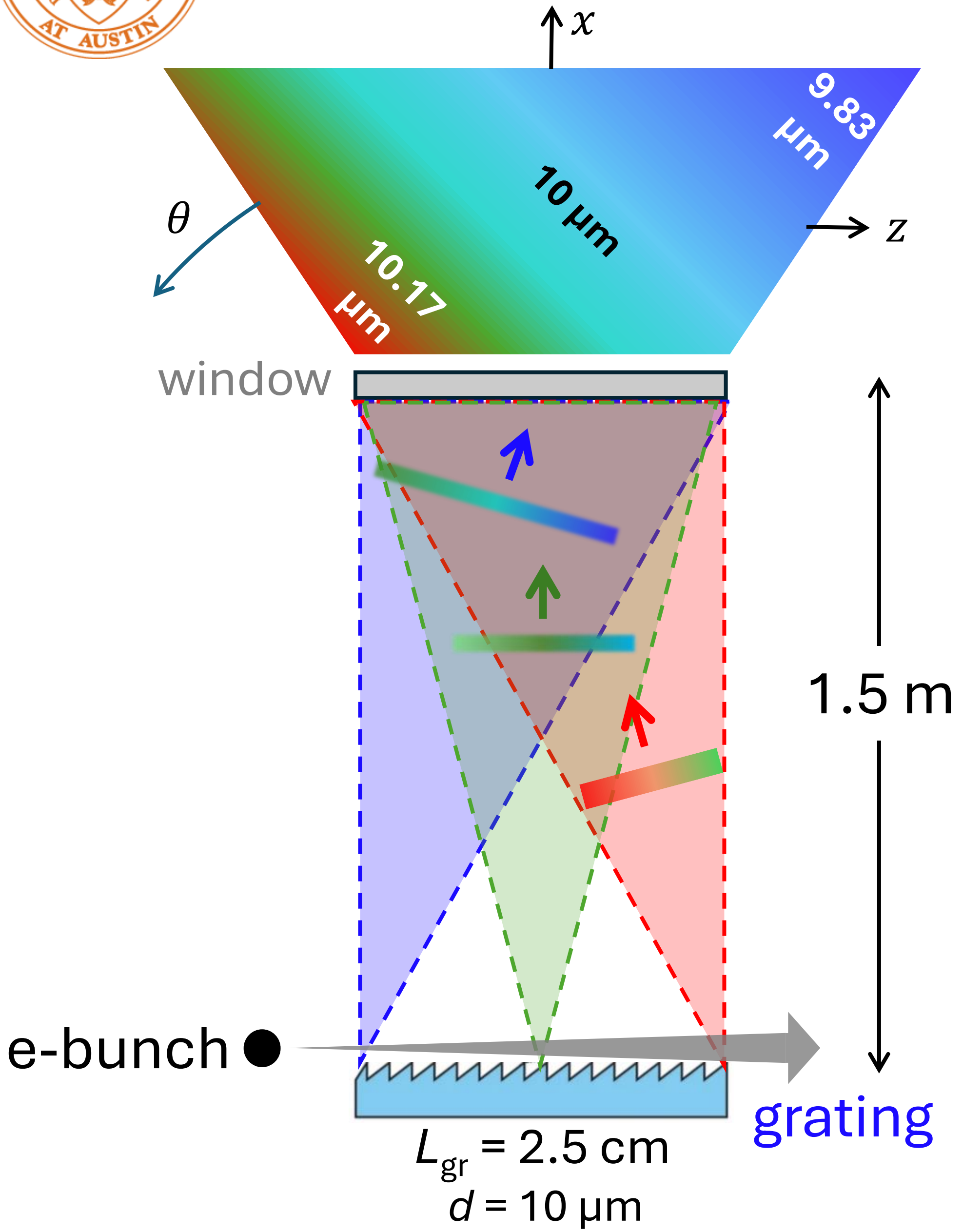
Rudzinsky *et al.*, *Optica* **13**, 810-821 (2026)



The good agreement with calculated energy shows that the SPR is fully coherent at $\lambda \approx 10$ μm.



CSPR pulses have complicated space-time structure...



$\tau \approx L_{gr}/c \approx 83$ ps

1st step

- ~~angular chirp~~
- ~~transverse spatial chirp~~
- longitudinal chirp

For CSPR pulses to be useful for strong-field THz experiments, we must remove these chirps.

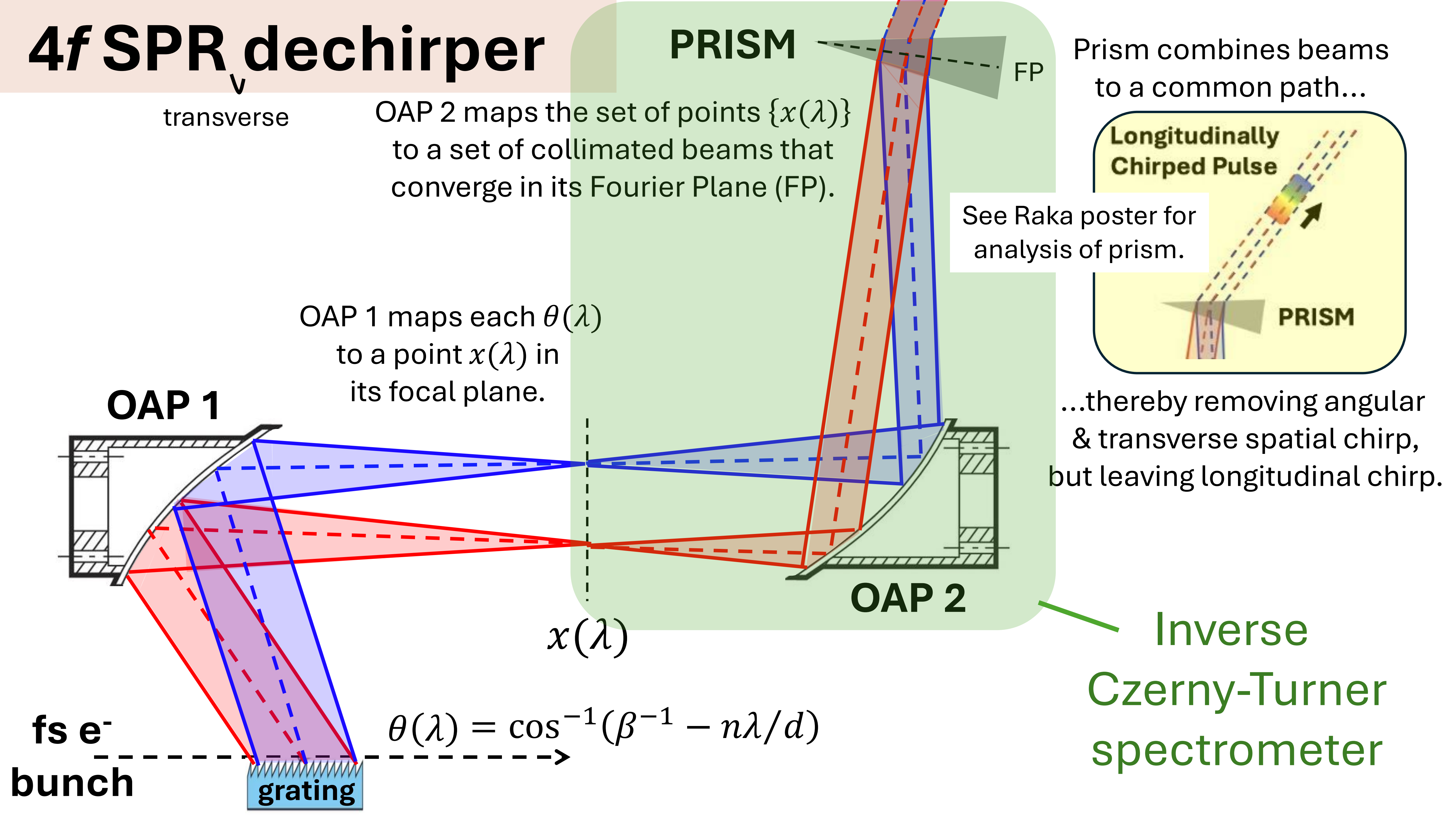
Doing so requires precise phase control

⇓

- Radiation must be highly coherent
- Losses must be minimized

4*f* SPR dechirper

transverse

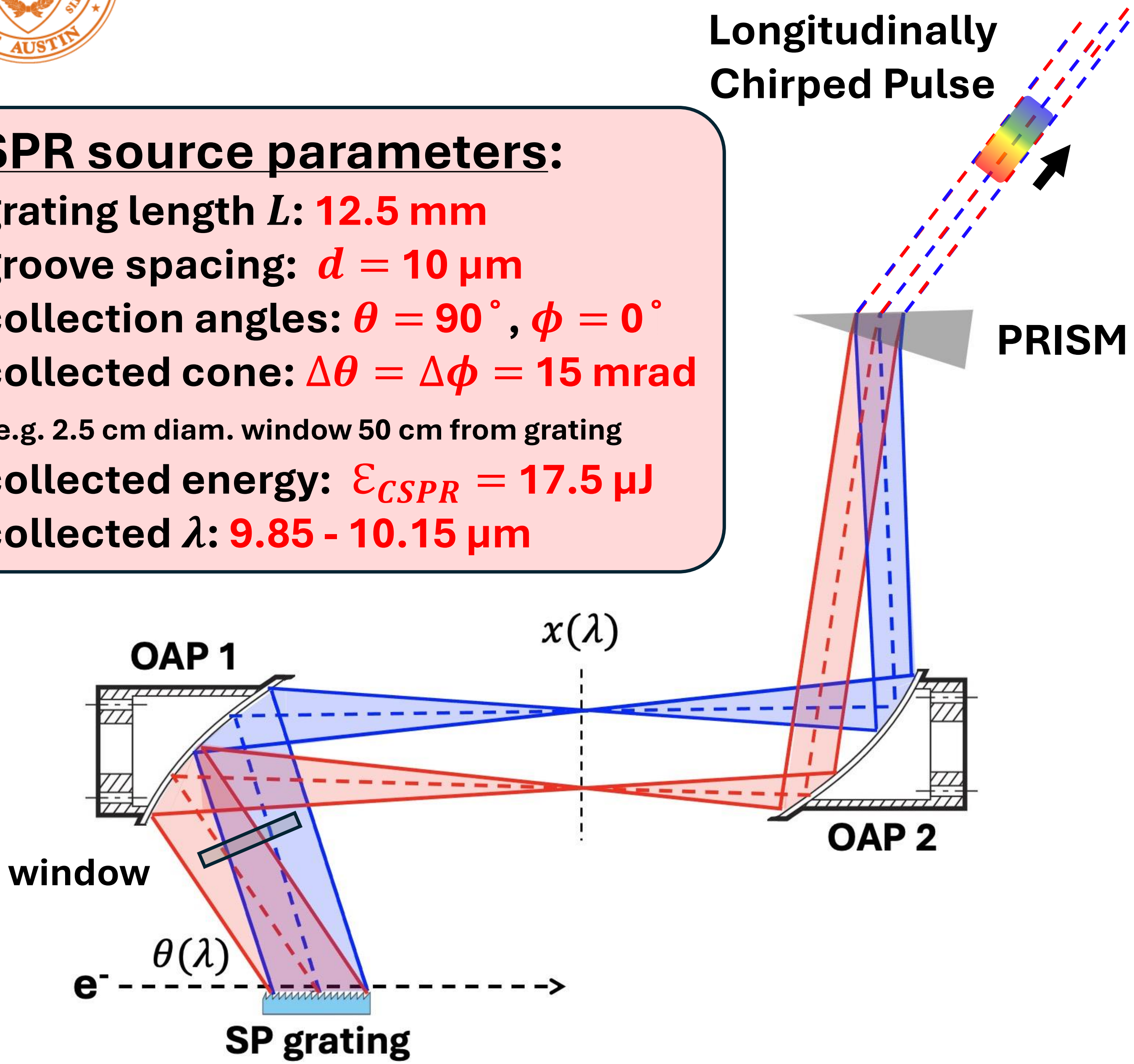


4*f* SPR transverse dechirper: numerical example

CSPR source parameters:

- grating length L: 12.5 mm
- groove spacing: $d = 10$ µm
- collection angles: $\theta = 90^\circ$, $\phi = 0^\circ$
- collected cone: $\Delta\theta = \Delta\phi = 15$ mrad

  e.g. 2.5 cm diam. window 50 cm from grating
- collected energy: $\mathcal{E}_{CSPR} = 17.5$ µJ
- collected λ: 9.85 - 10.15 µm



4f collimator parameters:

- OAPs: $f = 10$ cm; 10 cm clear aperture; $R = 0.98$ (protected gold)
- Prism: Ge; apex angle 28˚; AR-coated; 0.9 energy throughput

⇓

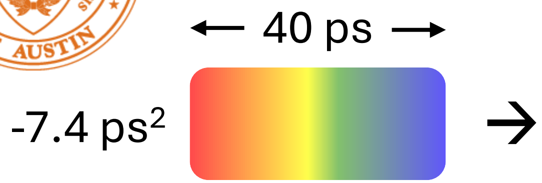
Ray-tracing / Fourier optics simulation

⇓

Output pulse parameters:

- collimated, 3 cm diam.
- duration: ~ 40 ps
- chirp: -7.4 ps^2
- energy: 15 µJ (86% throughput)

Compressing -7.4 ps², 40 ps pulses at $\lambda_0 \approx 10$ μm



Options in principle:

Bulk GDD > 0 THz-transparent material

- ☒ several m. of e.g. Ge, ZnSe needed
- ☒ high absorption losses + TOD

Chirped Mirrors

- ☒ not available at high THz frequencies
- ☒ insufficient positive GDD

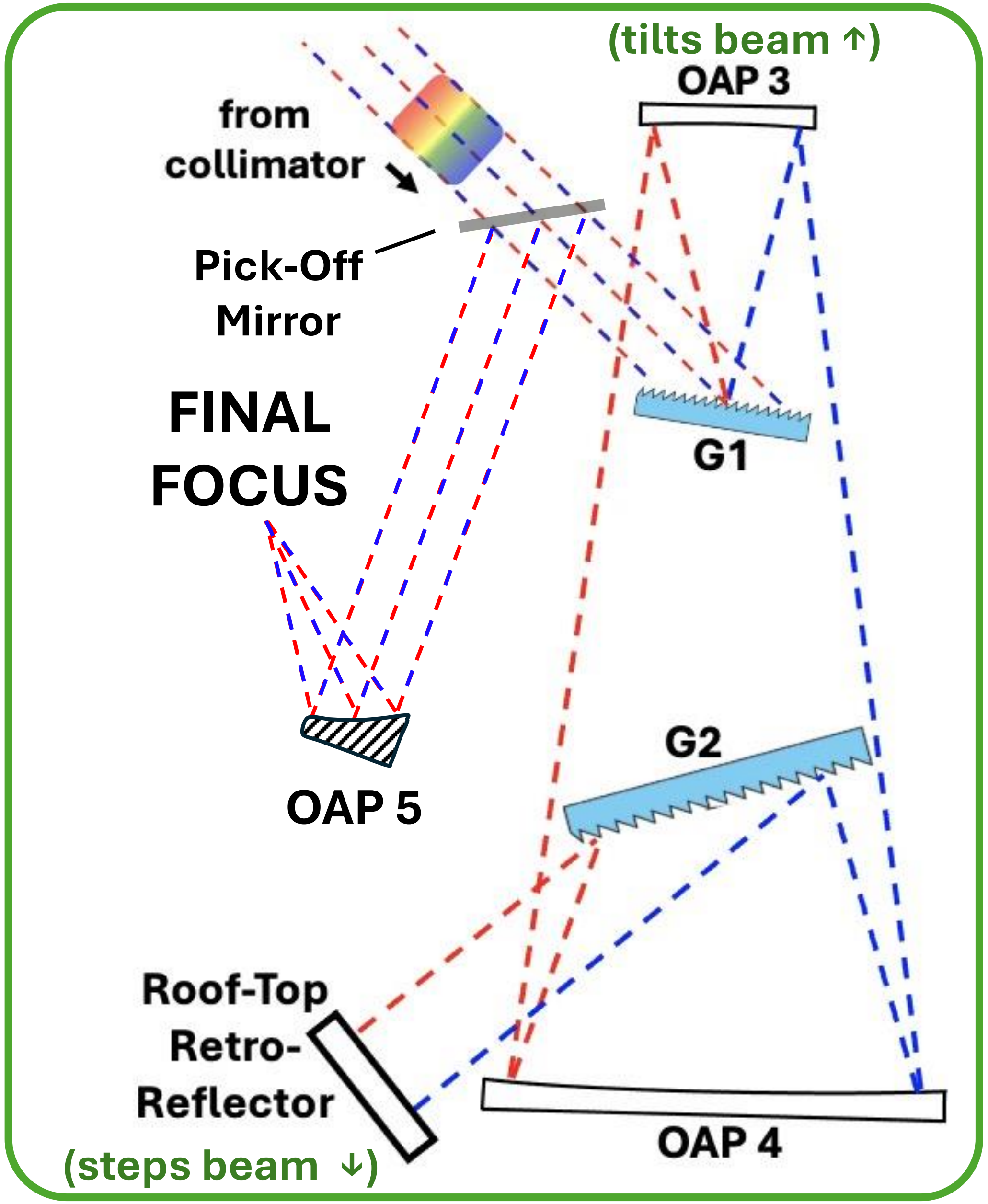
Prism Compressor

- ☒ insufficient positive GDD at small separations

Martinez "stretcher" (compressor for GDD < 0 input)

Martinez, *IEEE J. Quant. Electron.* **23**, 1385 (1987)

- ☑ readily achieves positive 5-10 ps²
- ☑ manageable loss, TOD



Martinez compressor: numerical example

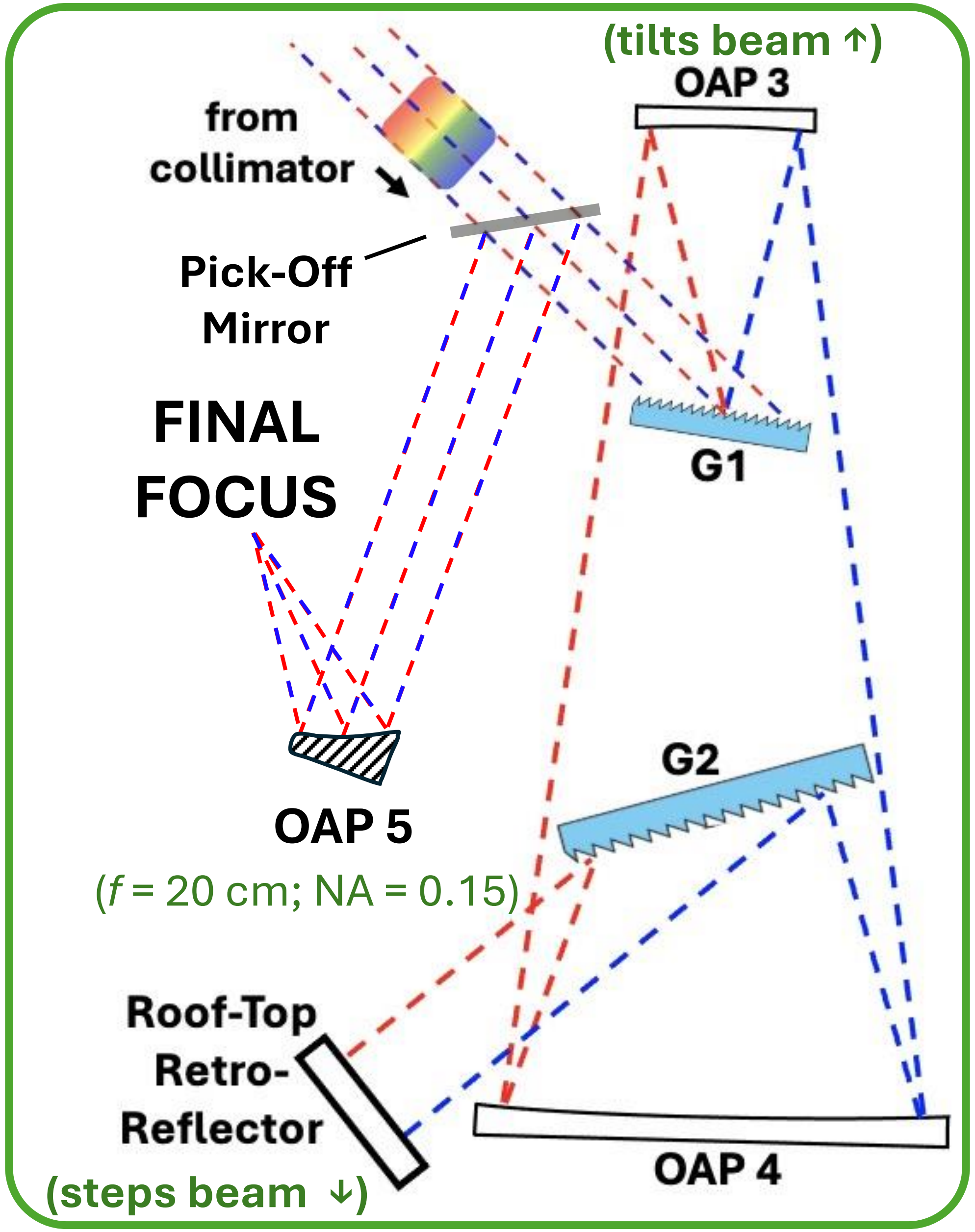
<u>Input pulse parameters</u>: $\mathcal{E}$ = 15 μJ; $\lambda \approx$ 10 μm; $D \approx$ 6 cm; $\tau \approx$ 40 ps; GDD ≈ -7.4 ps^2

<u>Compressor parameters</u>:

- Gratings: 100 lines/mm (1st order); $R \approx$ 0.8 each; 2-pass throughput 0.4 – 0.5
- OAPs 3,4: same as for OAPs 1,2
- 3 Flat Mirrors: $R \approx$ 0.98 each

<u>Simulated output beam parameters</u>:

- **Duration**: **0.6 < τ < 1 ps** (FWHM, intensity)
- **Energy**: **4.5 < $\mathcal{E}$ < 7 μJ** (25-40% total thru-put)
- **Final Focus**: **0.6 < I_0 < 1.6 x 10^{16} W/m^2**
  2 < E_{peak} < 4 GV/m ($w_0 \approx$ 20 μm)



Existing strong-field THz sources & fs LWFA-driven CSPR

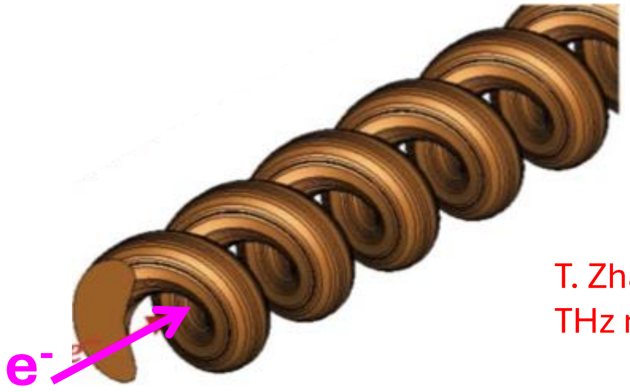
Further comparison

	Laser-Driven Sources		RF Accelerator-Driven Sources			fs CSPR
THz property	**Mid-IR [1,2] (Organic X-tals)**	**Near-IR [3-5] (TPF, $LiNbO_3$)**	**RF: FELBE/TELBE [6,7]** U37	U100	U300	**LWFA-driven [8] (this work)**
Pulse duration [ps]	0.1 - 10	0.3 - 10	1 - 5	2.5 - 30	0.5 - 10	0.6 -1
Pulse energy [μJ]	< 100	< 14,000	< 2	< 2	< 10	5 – 7 [c]
E_{peak} [GV/m] [a]	< 4	< 0.5	< 3 [b]	< 0.5	< 0.18	2 - 4
Rep. rate	10 - 1000	10 - 10^5	13 x 10^6	13 x 10^6	0.5 x 10^6	1 – 10 [d]

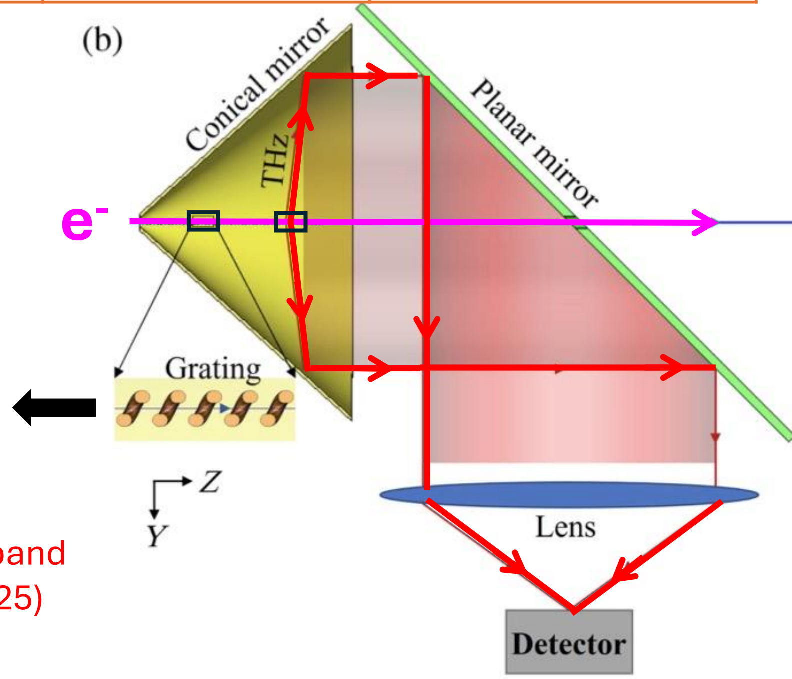
[a] Peak focused field for Gaussian pulse focused to beam waist $w_0 = 2\lambda$.

[b] Varies with λ; value for λ = 10 μm is 1 GV/m, assuming 2 μJ energy.

[c] 3D grating & SPR collection geometries can potentially approach mJ energy



T. Zhang, R. Ischebeck, *et al.*, "Boosting the efficiency of narrowband THz radiators via 3D emission-collection," *PR-AB* **28**, 054501 (2025)



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[c] 3D grating & SPR collection geometries can potentially approach mJ energy [Zhang *et al.*, *PR-AB* **28**, 054501 (2025)]

[d] LWFAs operating at 100 Hz exist [Eichner *et al.*, *Opt. Lett.* **50**, 4890 (2025)].
LWFAs operating at 1 kHz are under development:

- Rovige *et al.*, *Phys. Rev. Accel. Beams* **23**, 093401 (2020)
- Salehi et al., *Phys. Rev. X* **11**, 021055 (2021)].

SUMMARY

- Few-fs LWFA bunches ($\sigma_z < 10$ μm) propagating over planar metal gratings of period $d > \sigma_z$ recently generated ps SPR pulses at f up to 30 THz (λ down to 10 μm). The measured energy $\mathcal{E} \approx 10$ μJ proved the high coherence of the radiation.*

  * Rudzinsky *et al*., *Optica* **13**, 810 (2026)

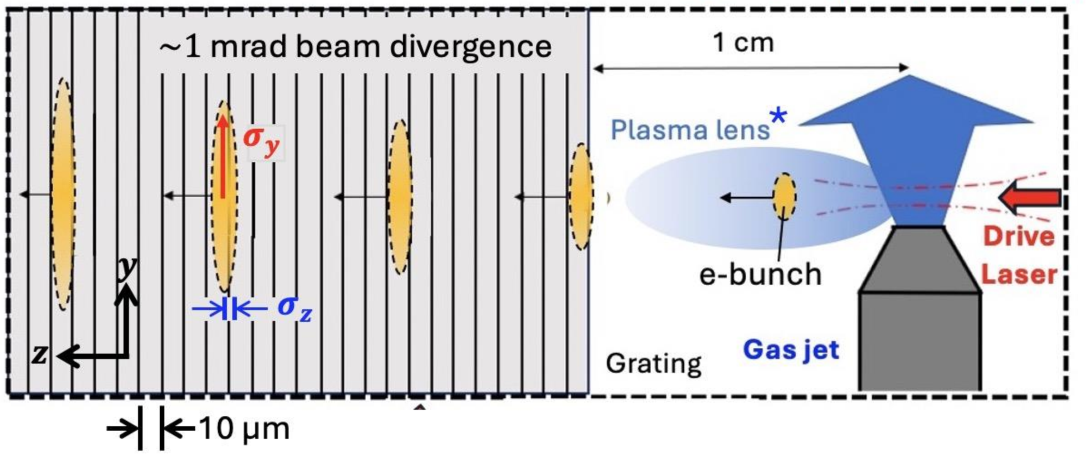
- Simulations show that selected cones of the CSPR "fan" can be de-chirped, compressed to τ < 1 ps, and focused to ***E*** $\boldsymbol{E_{peak}}$ **~ several GV/m** using standard CPA optics.
  Presented scheme not optimized; many improvements possible.

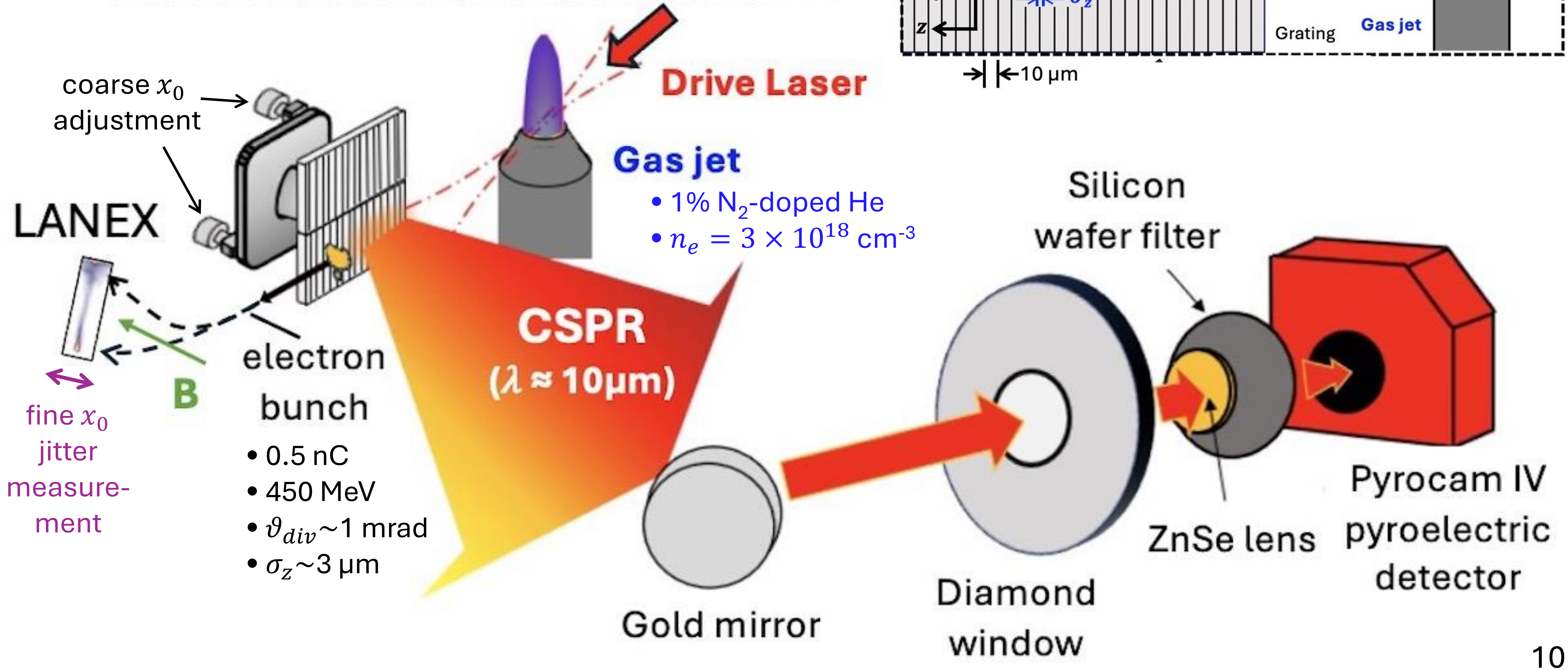
- Since these pulses { 1) originate from a table-top source; 2) readily reach tens-of-THz frequency; and 3) are intrinsically synchronized with the fs LWFA e-bunch & its secondary X-rays, } they offer unique capabilities for ultrafast high-field THz spectroscopy that complement existing laser-based and RF accelerator-based THz sources.

Funding:
U. S. Dept. of Energy, Office of HEP (DE-SC0011617)
Helmholtz Association (Matter & Energy)

1st Generation SPR Experimental Setup

Rudzinsky *et al.*, *Optica* **13**, 810-821 (2026)

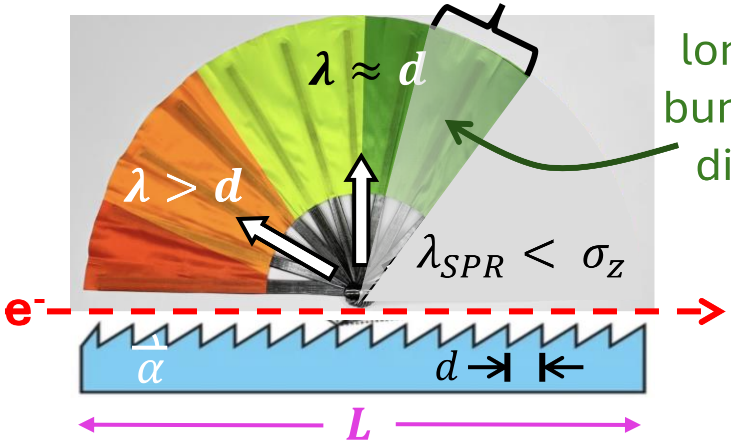




Smith-Purcell Radiation (SPR)

Stephen J. Smith
1925-2017
(EMP PhD student)

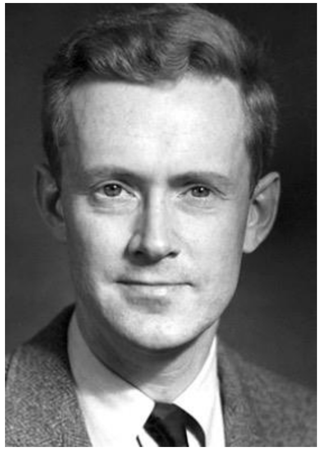
S. J. Smith and E. M. Purcell, "Visible light from localized surface charges moving across a grating," *Phys. Rev.* **92**, 1069 (1953).



longitudinal bunch-profile diagnostic band

PRIDE* fan:

*<u>P</u>urcell <u>R</u>adiation <u>I</u>nto <u>D</u>irections according to <u>E</u>nergy



Edward M. Purcell
1912-1997

For X GeV electron and $\lambda = 10$ μm: $\lambda_e(\theta, \phi = 0) = X$ mm

measured from e⁻ propagation direction

Dispersion relation:

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

grating efficiency factor

evanescent field length: $\lambda_e(\theta,\phi) = \dfrac{\gamma\lambda}{2\pi\sqrt{1+\gamma^2\sin^2\theta\sin^2\phi}}$

Angular distribution of SPR energy (1 e⁻):

Brownell, *Phys. Rev. E* **57**, 1975 (1998)

$$\left(\frac{dW}{d\Omega}\right)_1 = 2\pi e^2 \frac{L}{d^2}\frac{n^2\beta^3}{(1-\beta\cos\theta)^3} R^2(\alpha,\theta,\phi)\, e^{-2x_0/\lambda_e}$$

distance from e⁻ to grating

Angular distribution of SPR energy (N e⁻):

Brownell, *Phys. Rev. E* **57**, 1975 (1998)

$$\left(\frac{dW}{d\Omega}\right)_N = \left(\frac{dW}{d\Omega}\right)_1^{(x_0=\bar{x}_0)} \left(N^2 S_{coh} + N S_{inc}\right)$$