# NP-318719: Direct measurement of pulse length and retrieval of longitudinal phase space distribution of electron beams with laser pulses


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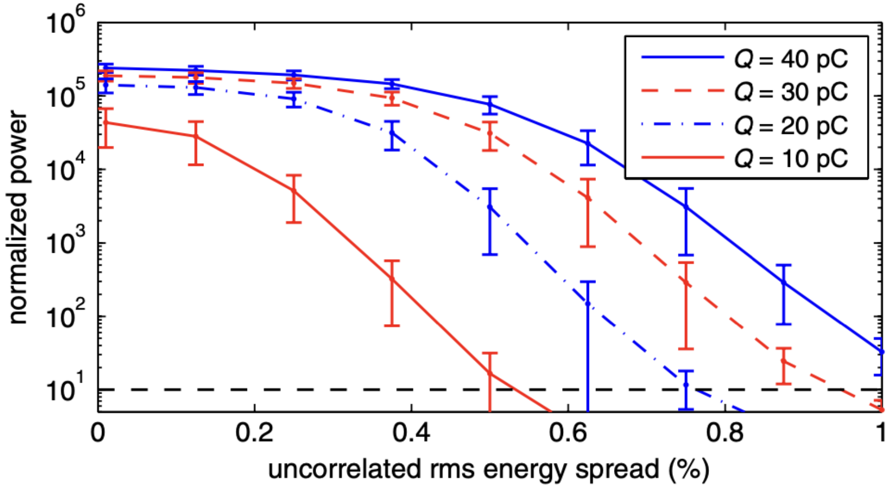
# Motivation: Diagnosis of electron longitudinal phase space distribution

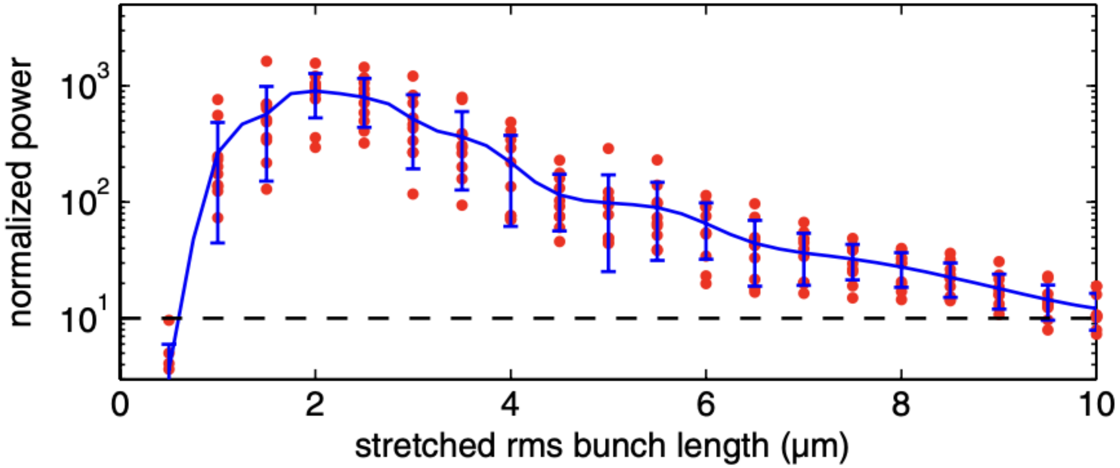
## Slice energy spread for XFEL

$$\sigma_\delta \ll \rho, \quad \rho = \left[ \frac{1}{16} \frac{I_0}{I_A} \frac{K_0^2 [JJ]^2}{\gamma_0^3 \sigma_\perp^2 k_u^2} \right]^{1/3}$$

Pierce FEL parameter, ~0.1%

FEL power VS energy spread & bunch length

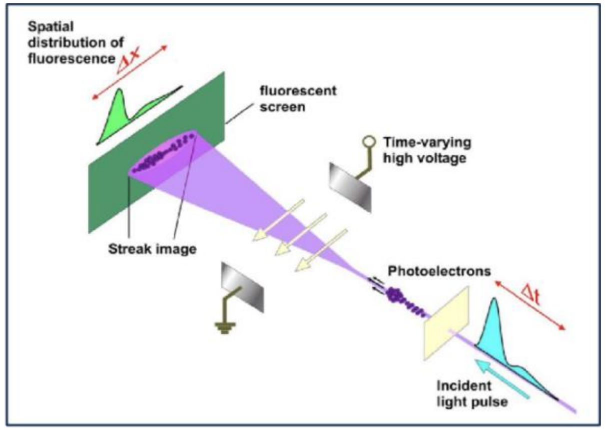



Maier et al., PRX 2, 031019 (2012)

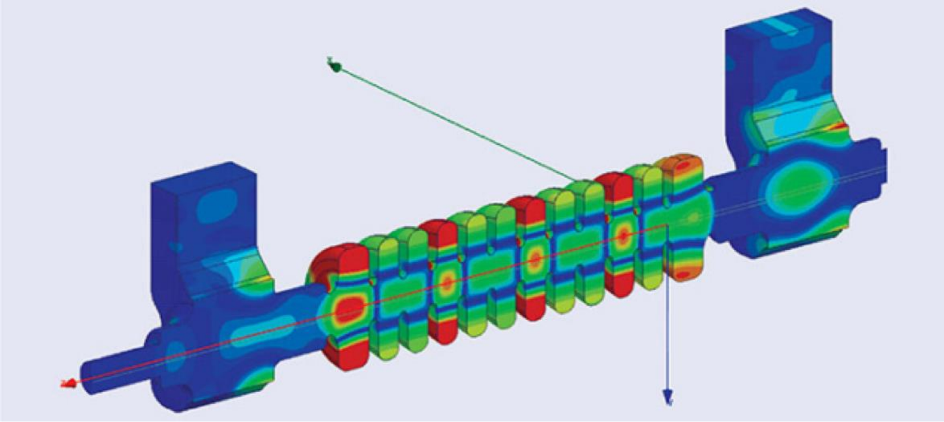
# Motivation: Diagnosis of electron longitudinal phase space distribution

**Streak camera**



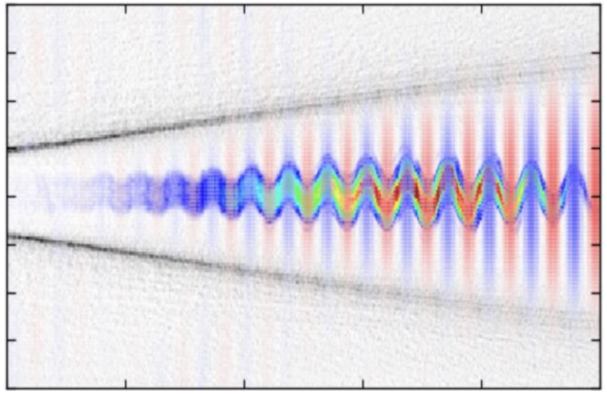

ps resolution

**TDS RF deflector for RF accelerators**



~10s - 100s fs resolution

**Laser deflector**



Sub-fs resolution (half-$\tau_L$)

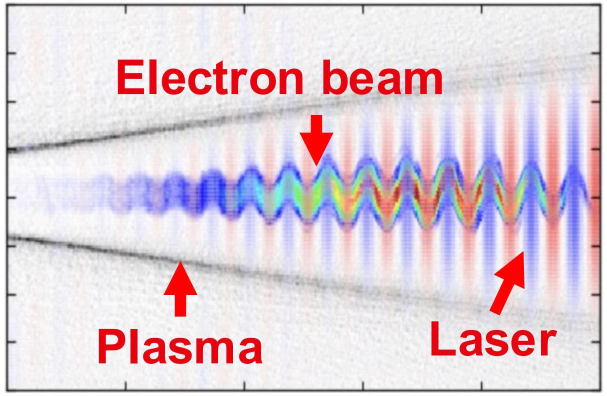
With or without plasma

Also indirect methods, such as CTR, EO, etc.

# Motivation: laser wakefield deflector

**Theory:**

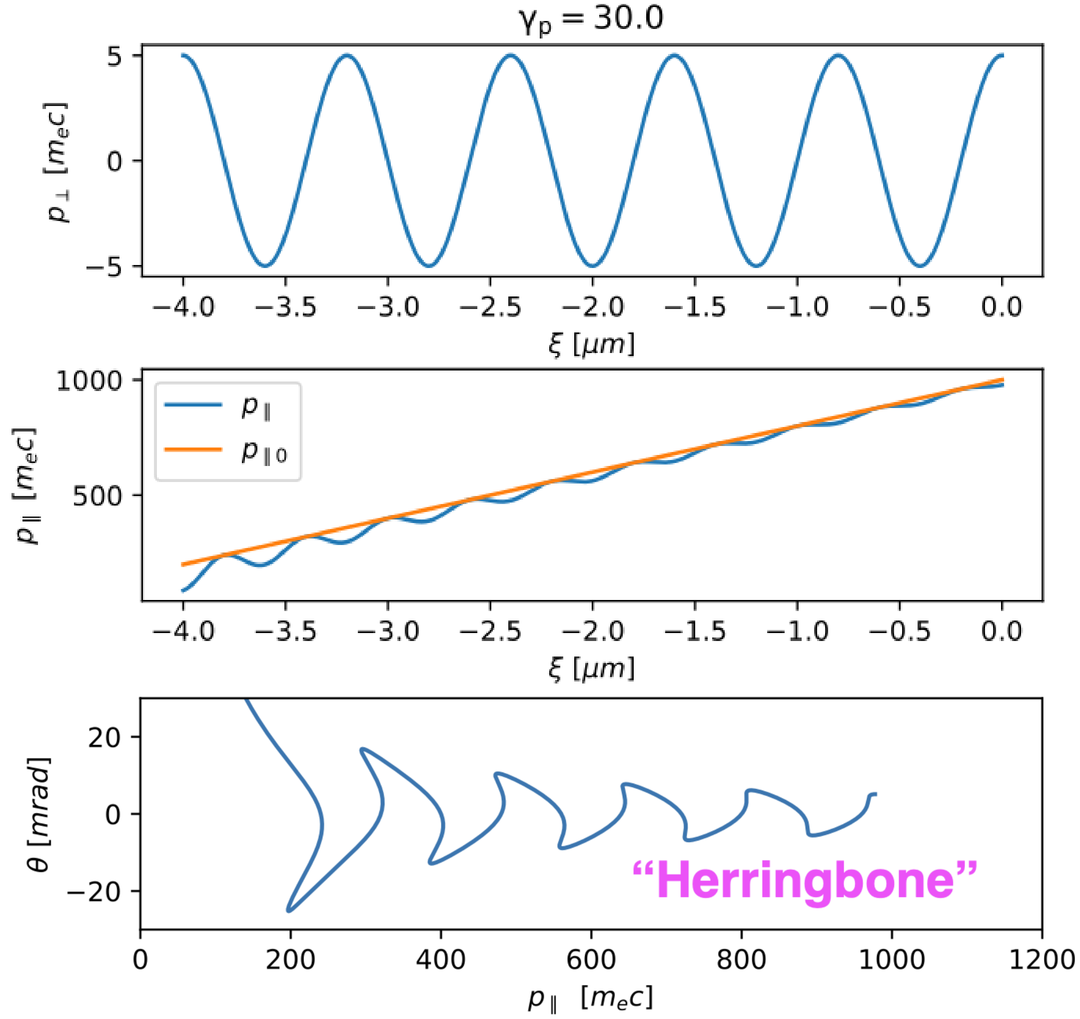
**Coupled motion of electrons in laser-plasma wakefield and oscillations in the laser fields**




$$\boxed{p_{\parallel} \simeq p_{\parallel 0} - \frac{\gamma_p^2}{p_{\parallel 0}}\left(\frac{1}{2}\alpha^2 p_{\parallel 0}\mathbf{x}_{\perp}^2 + \mathbf{p}_{\perp}^2\right)}$$

$$\mathbf{x}_{\perp} = \mathbf{x}_{\perp s} + \mathbf{x}_{\perp t} \qquad \mathbf{p}_{\perp} = \mathbf{p}_{\perp s} + \mathbf{p}_{\perp t}$$

(See details of the theory in the back-up slides)

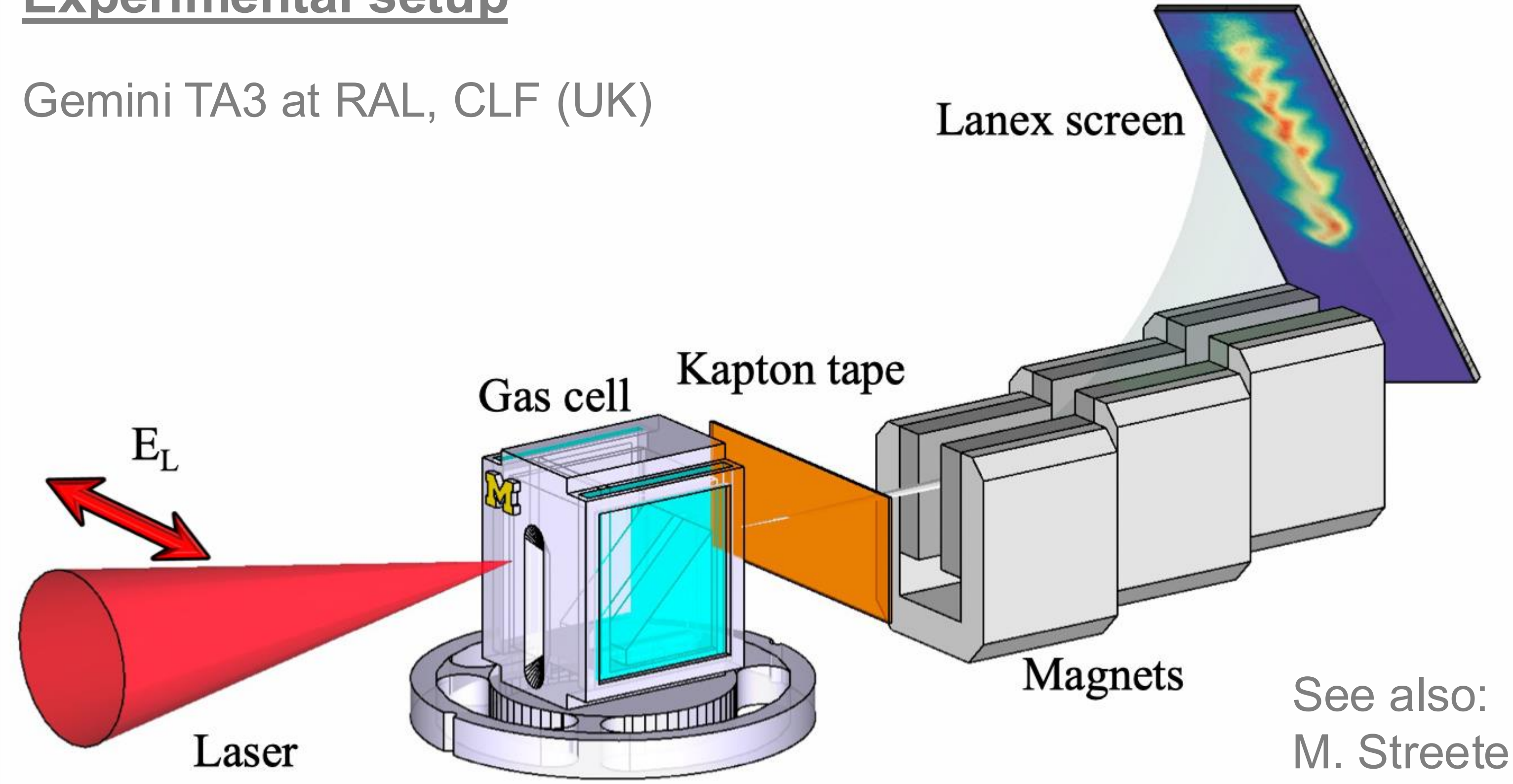



Angular energy spectrum

# Motivation: laser wakefield deflector

## Experimental setup

Gemini TA3 at RAL, CLF (UK)

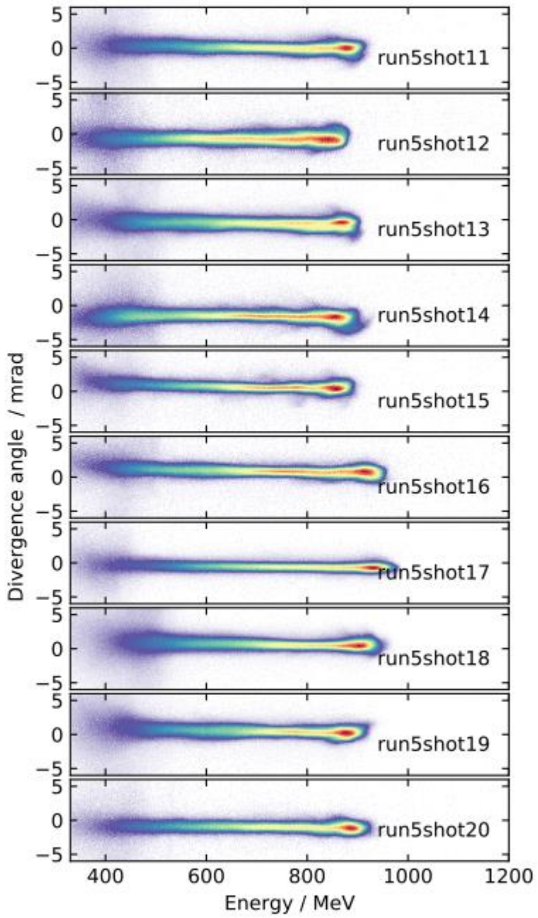



Laser polarization perpendicular to magnet deflection plane
Modulation of the electron spectral can be observed

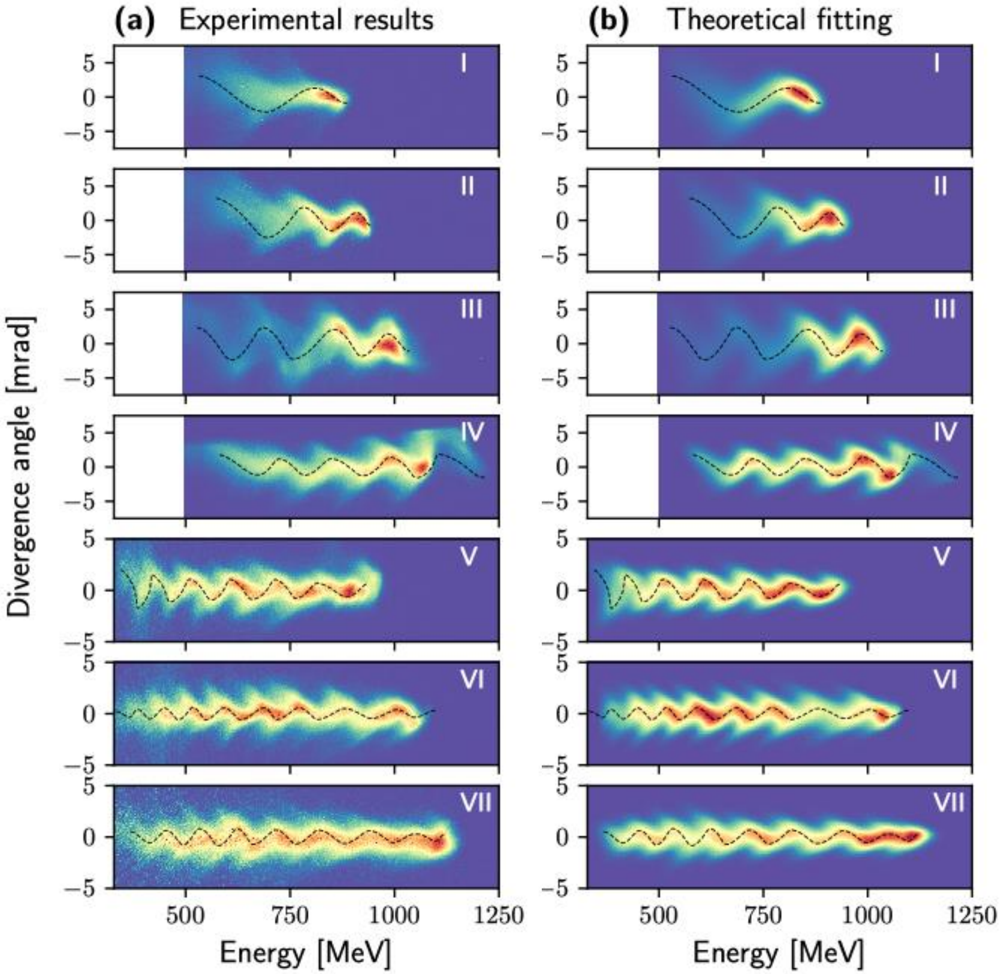
See also:
M. Streeter et al., PRAB 25, 101302 (2022) ;
A. Hussein et al., Scientific Reports (2019) 9:3249;
B. Kettle et al., PRL 123, 254801 (2019);
R. Spesyvtsev et al., Proc. SPIE 11036 2019

# Motivation: laser wakefield deflector

Typical unmodulated spectra




“Herringbone” structures




Fitting process reveals great details of electron beam, i.e., phase space distribution

# Motivation: laser wakefield deflector

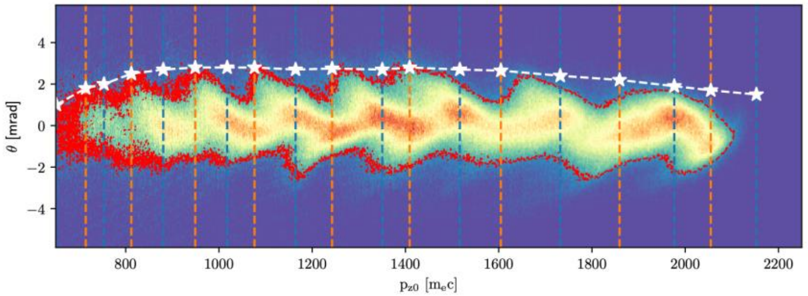
$$p_{\parallel} \simeq p_{\parallel 0} - \frac{\gamma_p^2}{p_{\parallel 0}}\left(\frac{1}{2}\alpha^2 p_{\parallel 0}\mathbf{x}_{\perp}^2 + \mathbf{p}_{\perp}^2\right)$$

$$p_x(\zeta) = \hat{p}_{xs}(\zeta) a_0 \cos(k_z\zeta + \Omega) + \hat{p}_{xt}(\zeta) p_{xt}$$

$$p_{xt} = \sigma_{p_{xt}} \cdot \mathcal{N}$$

transient solutions represented by standard normal distributions $\mathcal{N}$

$$p_z = p_{z0} - \sigma_{\Delta p_z} - \frac{\gamma_p^2}{p_{z0}}\left[\frac{1}{2}\alpha^2 p_{z0}\left(\frac{\hat{x}_s a_0}{k_z \eta Z}\sin(k_z\zeta + \Omega) + \hat{x}_t \sigma_{xt}\mathcal{N}\right)^2 + \left(\frac{\hat{p}_{xs} a_0}{Z}\cos(k_z\zeta + \Omega) + \hat{p}_{xt}\sigma_{p_{xt}}\mathcal{N}\right)^2\right]$$




1. Extracted from experimental spectrum

- Longitudinal momentum distribution (chirp)
- Temporal beam charge profile
- Transverse momentum envelope (steady state)

Transverse momentum width (transient)

$$\gamma_p,\ \alpha,\ a_0,\ \sigma_{p_{xt}},\ \sigma_{x_t},\ \Omega,\ \text{and}\ \sigma_{\Delta p_z}$$

2. Guessed parameters (all single value):

- $\gamma_p$ (plasma density)
- $\alpha$ (wake strength)
- $a_0$ (laser intensity *)
- $\sigma_{pxt}$ Transient momentum
- $\sigma_{xt}$ Transient real space
- $\Omega$ Phase
- $\sigma_{\Delta pz}$ Slice energy spread

* (eta, Z are not independent parameter)

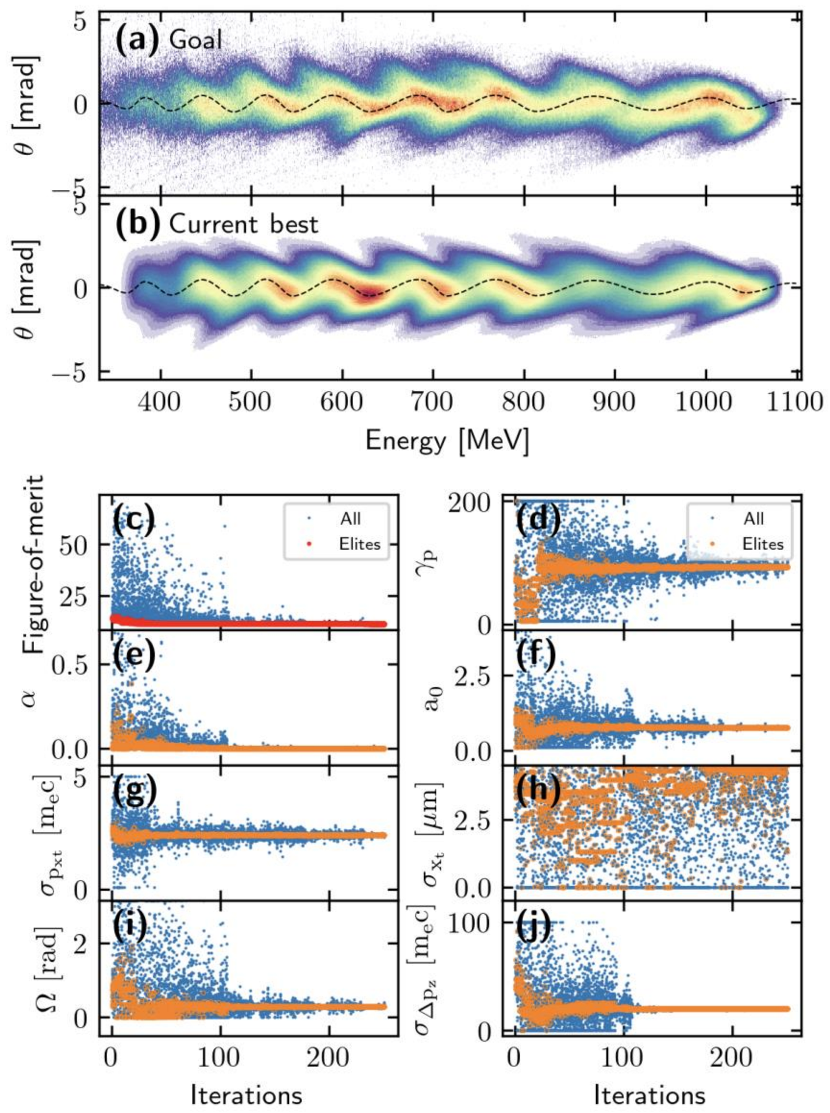
# Motivation: laser wakefield deflector

**Problem of multi-parameter optimization:**
**Electron spectral reconstruction**

Goal:
Experimental spectrum

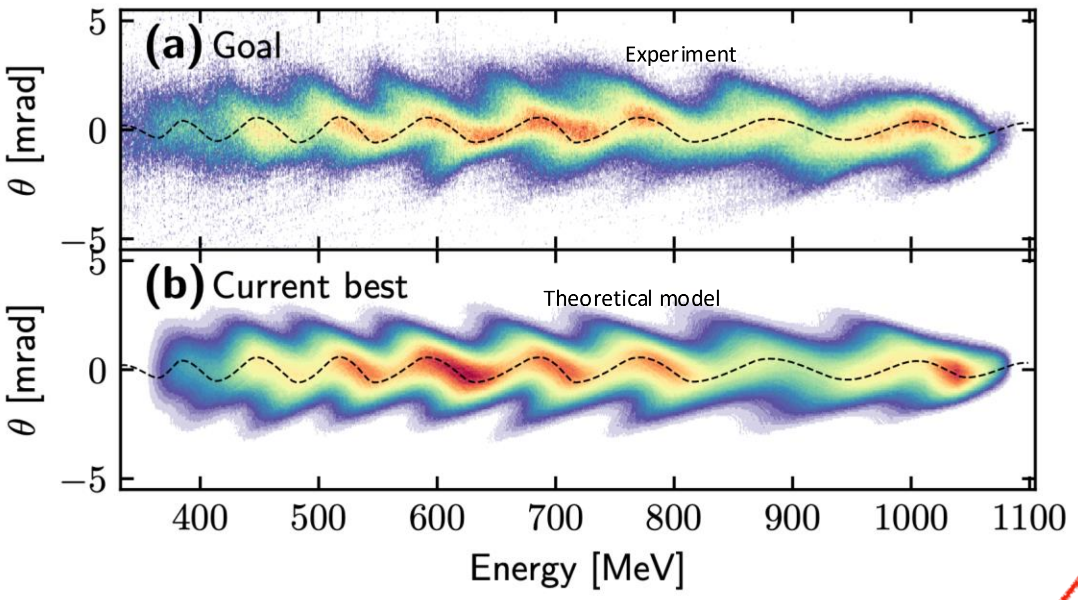
Genes:
$\gamma_p$, $\alpha$, $a_0$, $\sigma_{p_{xt}}$, $\sigma_{x_t}$, $\Omega$, and $\sigma_{\Delta p_z}$

Figure-of-merit:
Difference between "guessed spectrum" and exp spectrum

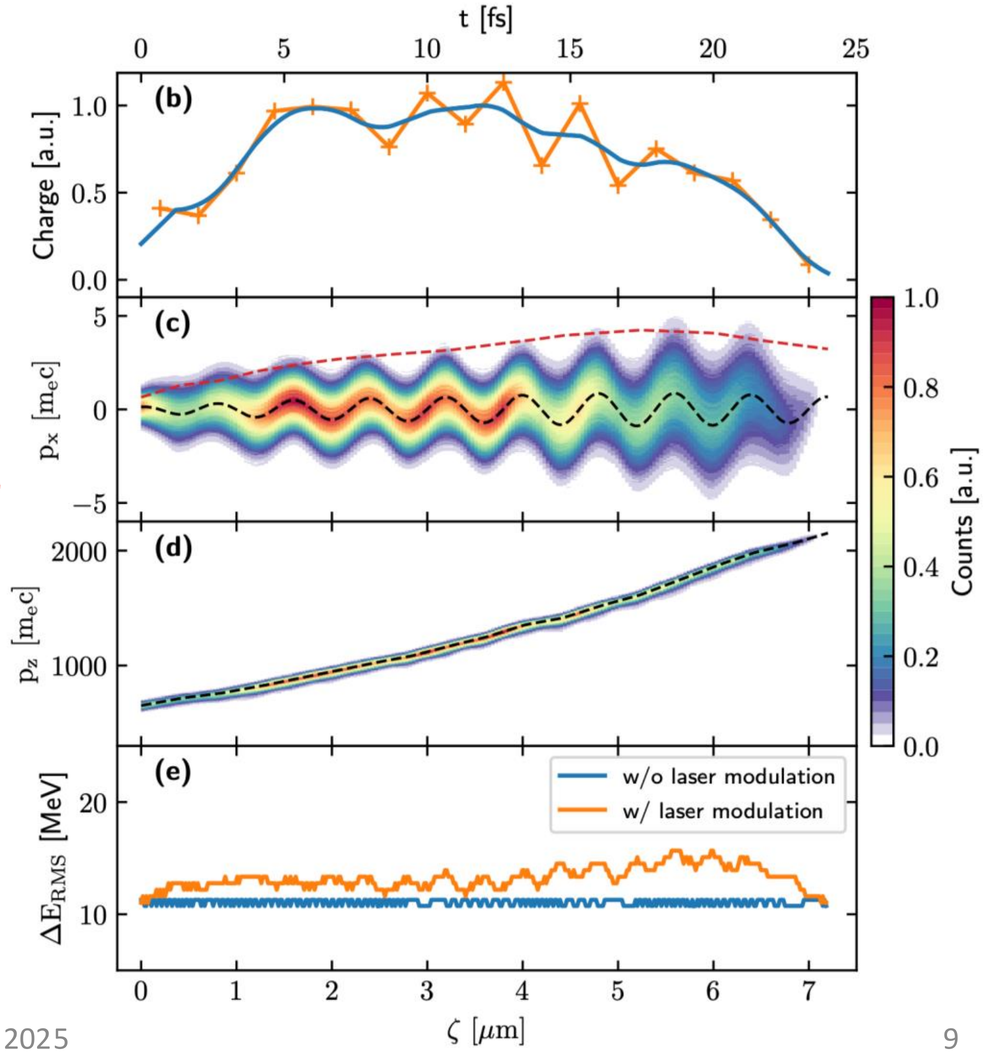


# Motivation: laser wakefield deflector

## Information retrieved



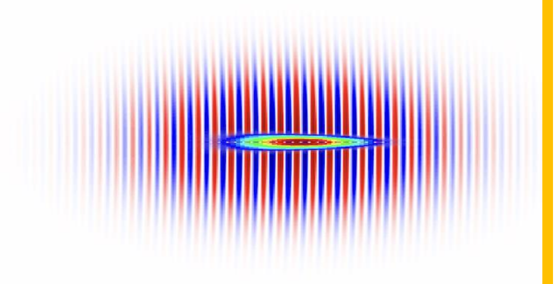

- Temporal profile (also gives pulse duration)
- Transverse momentum
- Longitudinal momentum (energy chirp)
- Slice energy spread




Y. Ma et al., Phys. Rev. X (under review)

# Motivation: laser deflector

## Direct laser electron interaction



Decouple from plasma
Free space interaction

Method can be used for electron beams from any type of accelerators

### Simplified with plane wave

$$\beta_{ph}\mathbf{P} - \gamma\hat{\mathbf{z}} + \phi\hat{\mathbf{z}} = \beta_{ph}\mathbf{P}_0 - \gamma_0\hat{\mathbf{z}} + \phi_0\hat{\mathbf{z}} \ , \tag{1}$$

$$\begin{cases} \mathbf{p}_\perp - \mathbf{a}_\perp = \mathbf{p}_{\perp 0} - \mathbf{a}_{\perp 0} \ , & (2) \\ \gamma - p_z = \gamma_0 - p_{z0} \ . & (3) \end{cases}$$

$$p_x = p_{x0} + a_x - a_{x0} \ , \tag{4}$$

$$p_y = p_{y0} \ , \tag{5}$$

$$p_z = \frac{1 + (a_x - a_{x0} + p_{x0})^2 + p_{y0}^2 - (\gamma_0 - p_{z0})^2}{2(\gamma_0 - p_{z0})} \ . \tag{6}$$

$$\Delta p_z = p_z - p_{z0} = \frac{(a_x - a_{x0})^2 + 2(a_x - a_{x0})p_{x0}}{2(\gamma_0 - p_{z0})} \ . \tag{7}$$

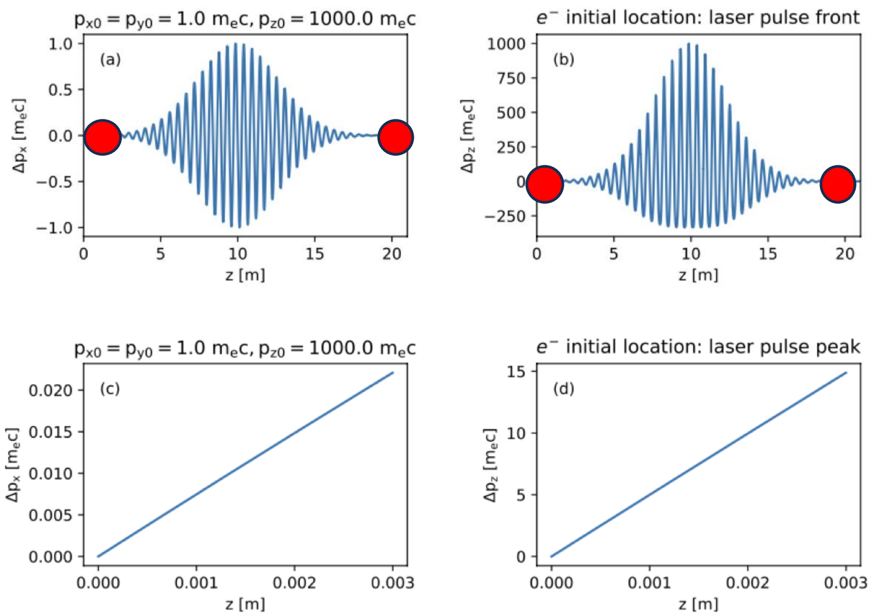
Constant of motion

Conservation of transverse canonical momentum

Longitudinal momentum modulation

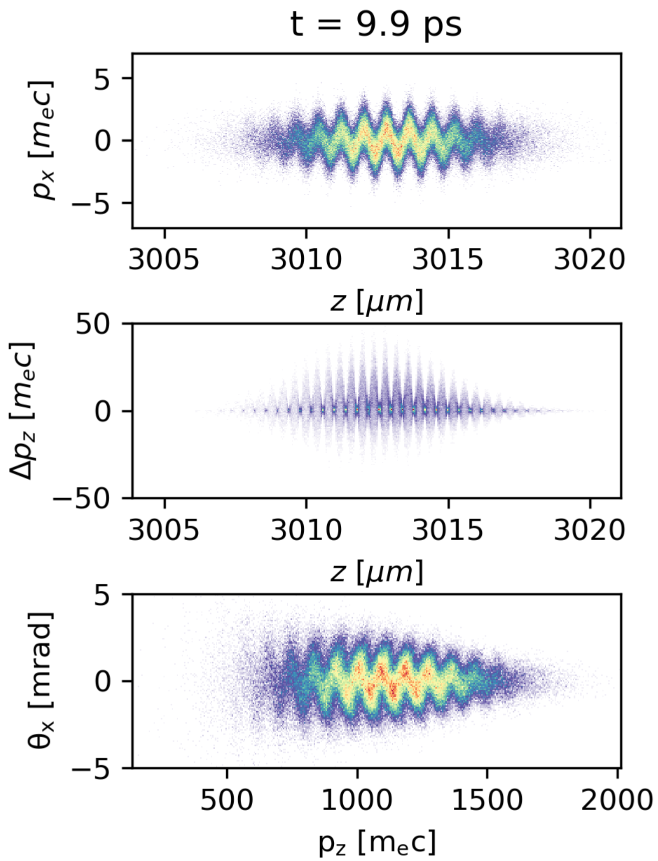
# Motivation: laser deflector

## Electron momentum gain in laser field

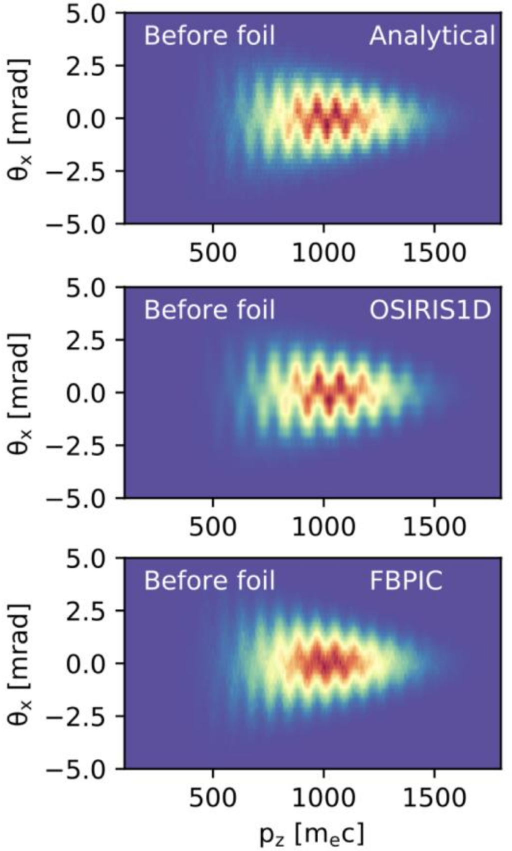



Net gain due to broken symmetry

## Considering 3D focused laser

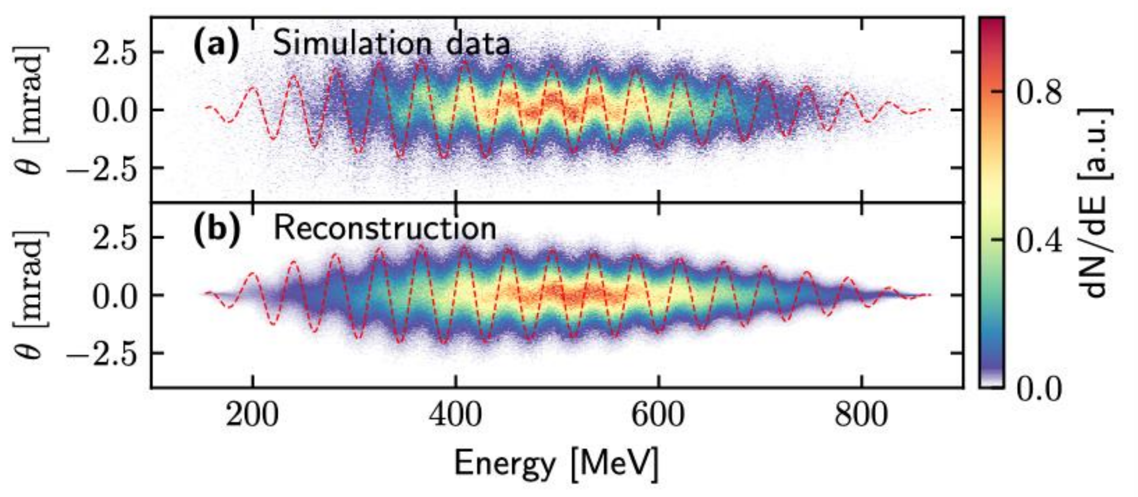


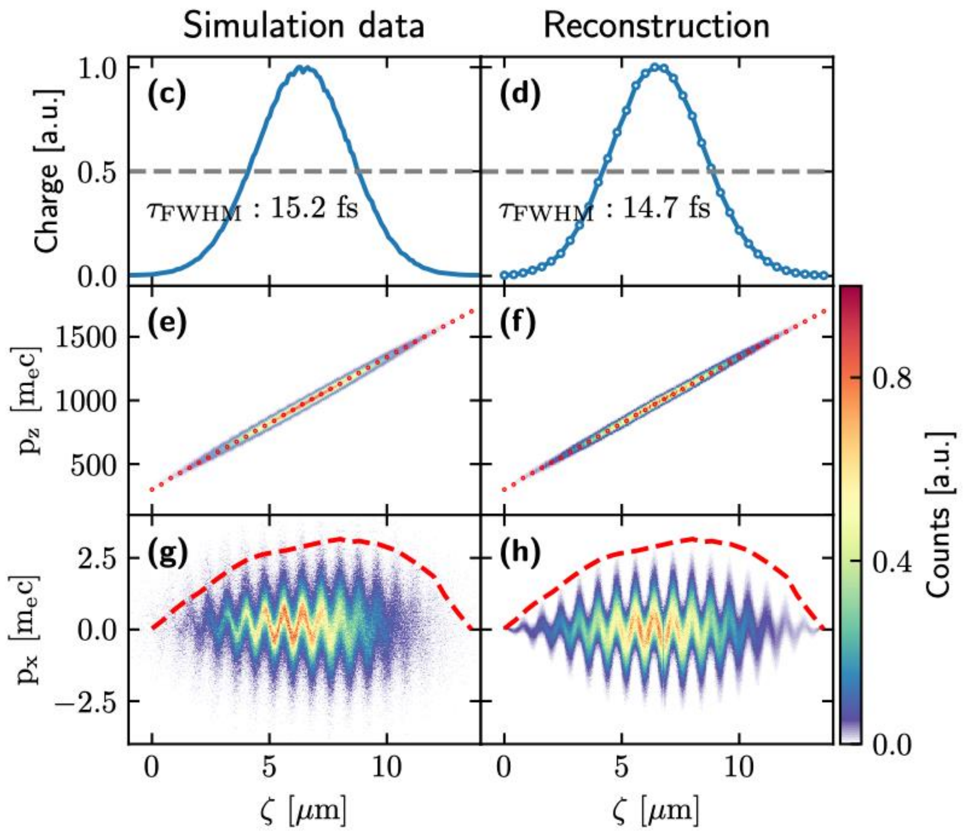

## Benchmarking with PIC simulations



# Motivation: laser deflector

## Reconstruction of electron beam longitudinal phase space and transverse momentum distribution

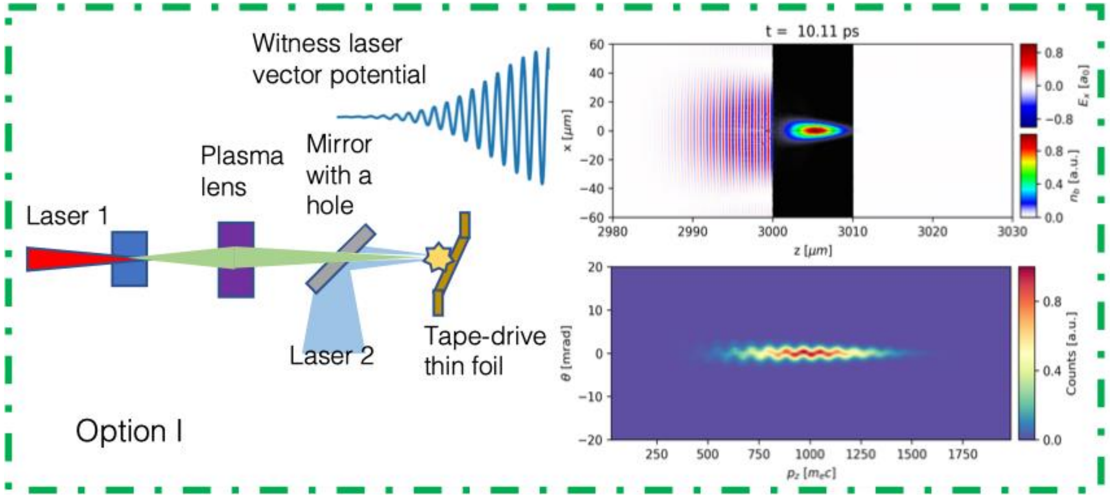


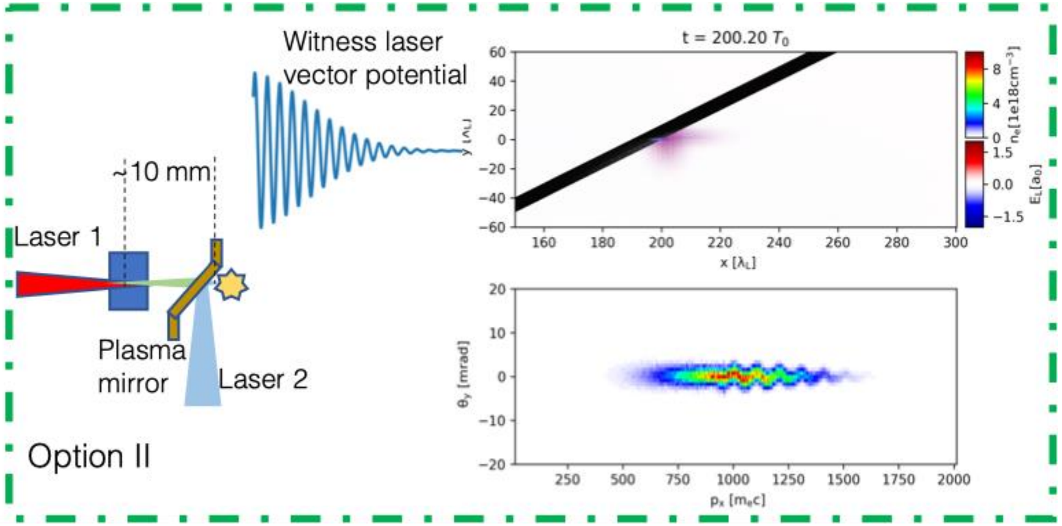




**Agreement between simulation and reconstruction: Validation of the method**

# Motivation: laser deflector

## Laser deflector for LWFA electrons




Tape-drive plasma mirror to truncate the laser pulse

Accepted by ELI-Beamline (Exp: FY2026)

# Why ATF?

**Uniqueness of ATF:**
**Linac + multi-wavelength lasers**

**ATF**

- Independent LINAC electron beams and laser pulses
- Stable electron beams with chirp control
- High quality electron beams, e.g., small slice energy spread
- Multi-wavelength lasers, i.e., NIR & $CO_2$ laser.
- …

**Laser deflector with LWFA**

- Unstable electron source: high shot-shot fluctuations on energy, charge, pointing jitter, etc.
- Hard to control beam chirp
- Engineering challenges: e-beam transportation, focusing, etc.

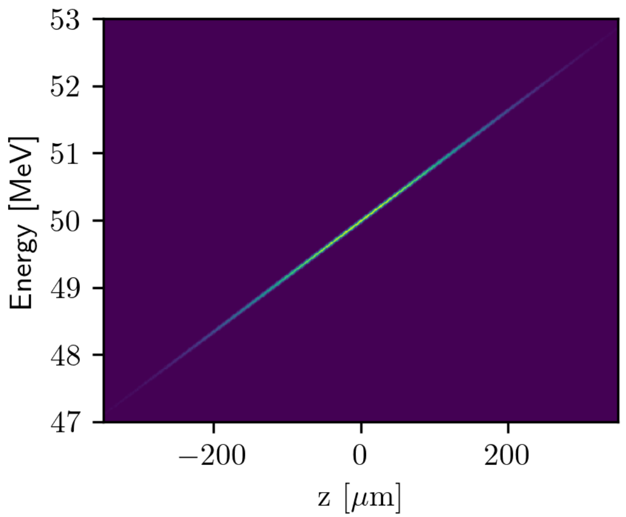
# Laser deflector with a CO2 laser

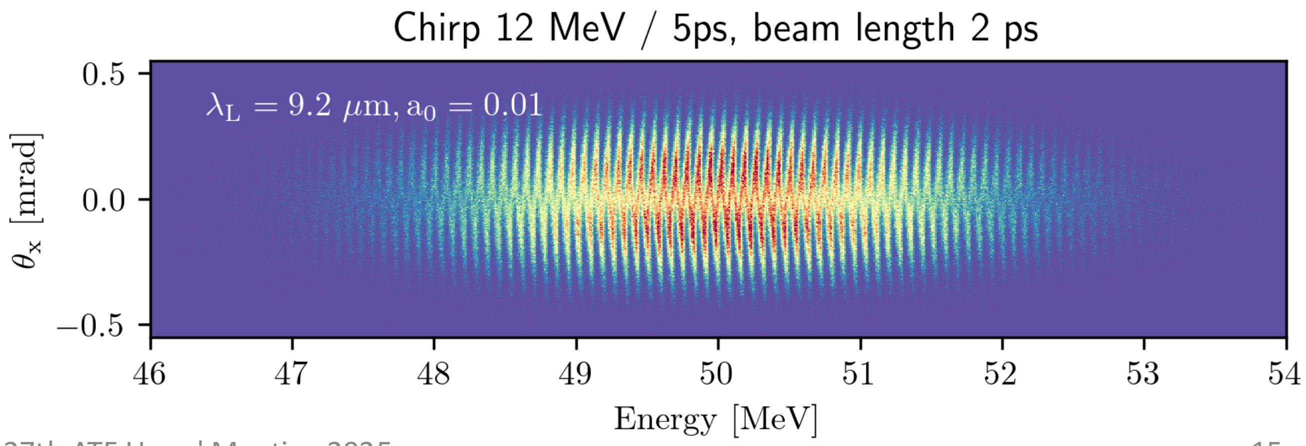
**Electron beam**

- Beam energy, 47 – 53 MeV
  Energy chirp, 2.4 MeV / ps
- Slice energy spread, ~ 50 keV
- Bunch length, ~2 ps

**CO2 laser**

- Wavelength, 9.2 um
- Pulse length, 2 ps
- Spot size, 300 um
- $a_0$, 0.01



# Laser deflector: basic requirements (for periodic modulations)

**Electron beam chirp $\mathcal{S}$, slice energy spread $\delta\mathcal{E}$ and laser wavelength $\lambda_{\mathcal{L}}$**

Slice energy spread < energy range covered by a laser wavelength

$$\delta\mathcal{E} < (\mathcal{E}_{max} - \mathcal{E}_{min}) \;/\; \mathcal{N}$$

$$\mathcal{N} = c\, \tau_{\mathcal{L}} \;/\; \lambda_{\mathcal{L}}$$

$$\delta\mathcal{E} < [(\mathcal{E}_{max} - \mathcal{E}_{min}) \;/\; \tau_{\mathcal{L}}\,]\; (\lambda_{\mathcal{L}} / \; c)$$

$$= \mathcal{S}\; (\lambda_{\mathcal{L}} / \; c)$$

Therefore, $\boxed{\lambda_{\mathcal{L}} > \delta\mathcal{E}\; c \,/\, \mathcal{S}}$

$\delta\mathcal{E}$ = 50 – 100 keV

$\mathcal{S}$ = 2.4 MeV / ps for a beam length of 2 ps.

With $\delta\mathcal{E}$ = 100 keV, $\lambda_{\mathcal{L}}$ > 12.5um.

With $\delta\mathcal{E}$ = 50 keV, $\lambda_{\mathcal{L}}$ > 6.25 um.

The CO2 laser $\lambda_{\mathcal{L}}$ = 9.2 um will work

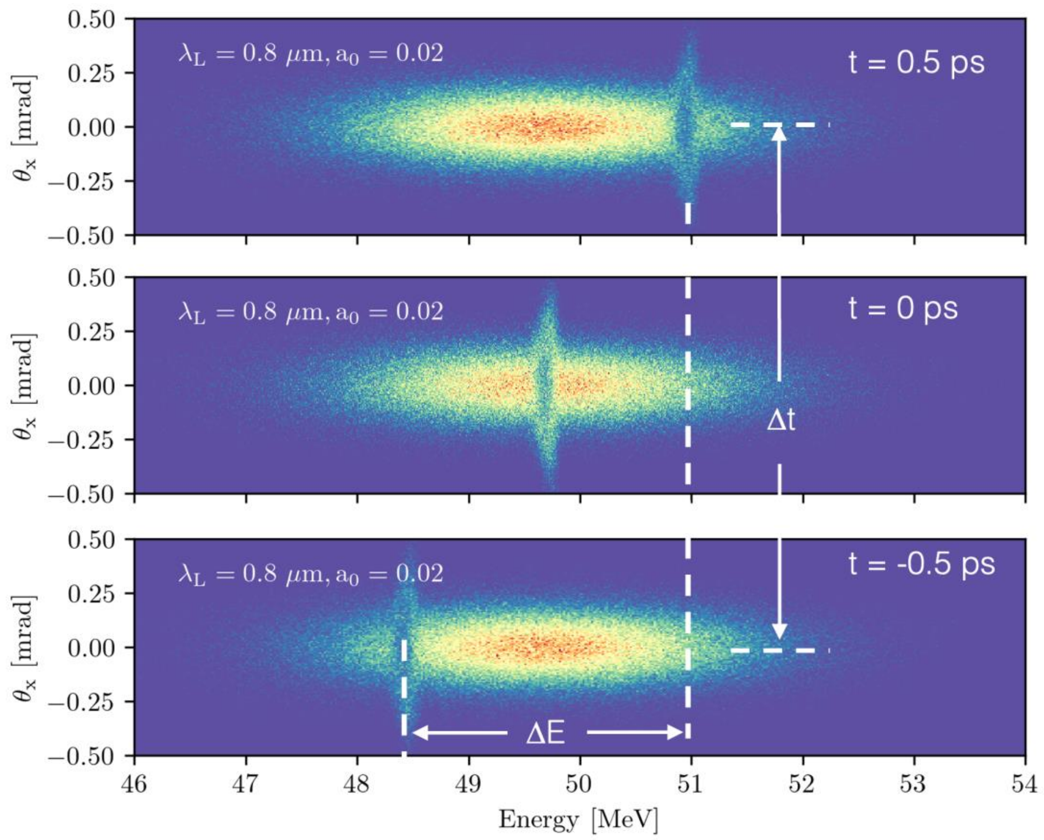
But not the NIR lasers with $\lambda_{\mathcal{L}}$ ~ 1 um.

# Laser deflector with IR lasers

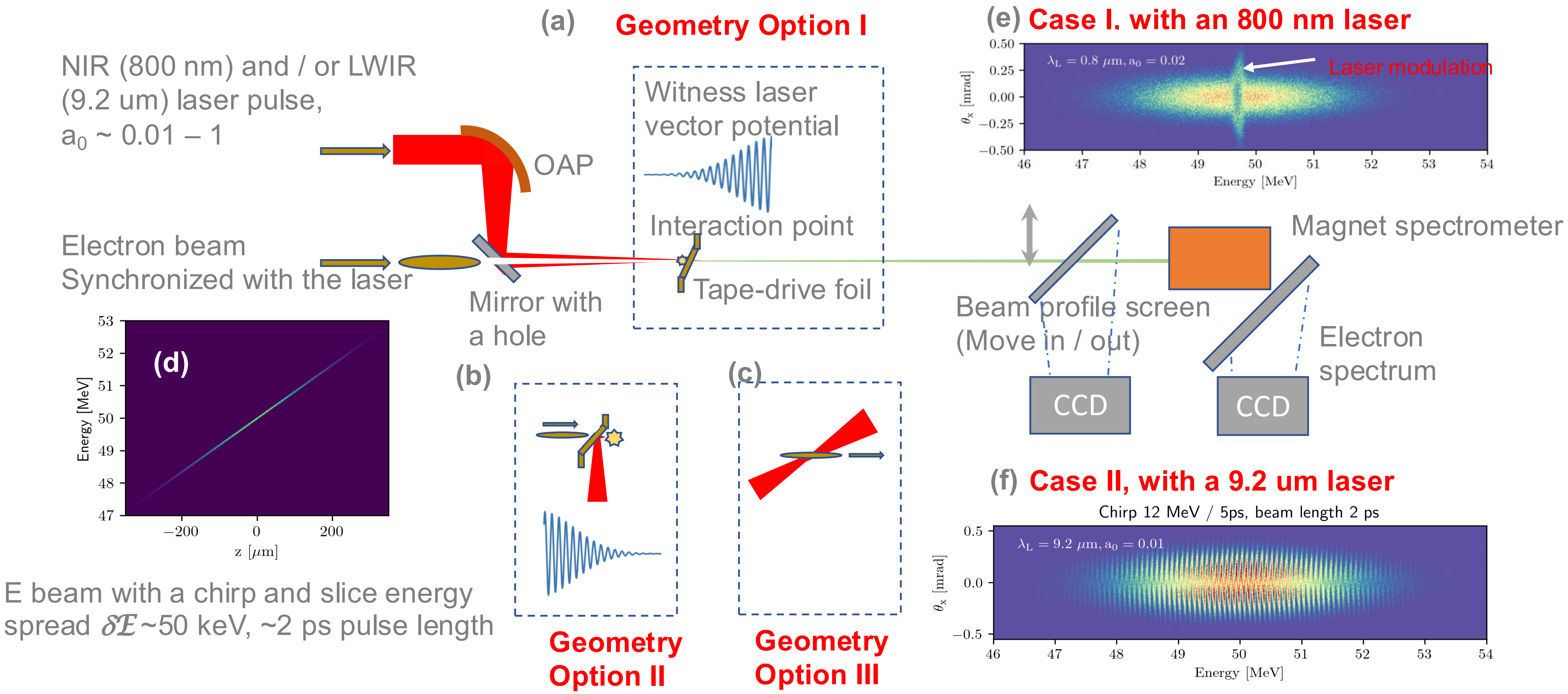
We cannot achieve single-shot longitudinal phase space reconstruction with NIR lasers due to their too short wavelengths.

But, we can still reconstruct the energy chirp & temporal profile by multi-shot scanning with stable electron beams and a short laser pulse.

NIR laser @ 800 nm, 100 fs pulse duration



# Proposed setup on ATF



# Experimental requirements

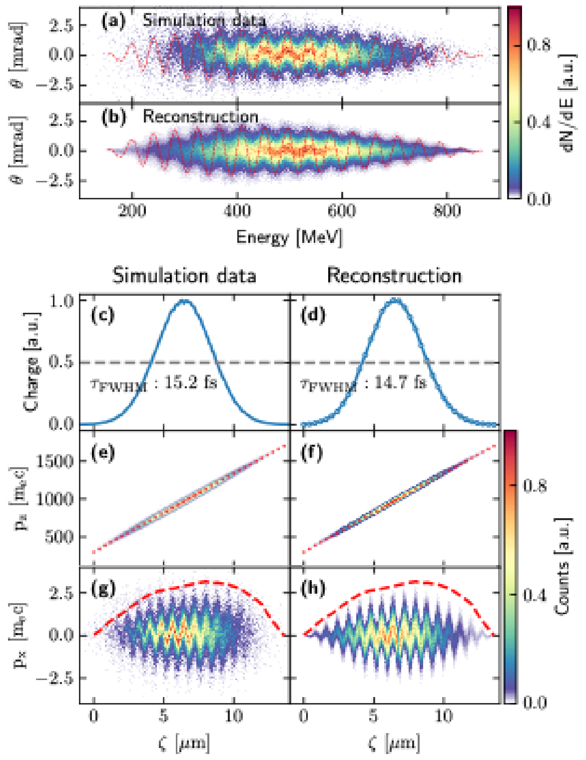
**Electron beam (provided by ATF)**
- Beam energy, 50 – 55 MeV *
  Energy chirp, 2.4 MeV / ps or bigger
- Slice energy spread, ~ 50 keV
- Bunch length, ~2 ps
- Transverse size at IP, ~300 um or smaller.

**CO2 laser**
- Wavelength, 9.2 um
- Pulse length, 2 ps
- Spot size, ~100 - 300 um
- $a_0$, 0.01 – 0.1
- Rep. Rate, 0.01 Hz

**Ti:Sapphire laser**
- Wavelength, 0.8 um
- Pulse length, ~100 fs
- $a_0$, 0.01 – 0.1

- *Central energy doesn't matter much, as long as we have the same energy chirp
- Rep. Rate of e-beam 1.5 Hz setup or sync with lasers for experiments

# Summary




We propose a platform for single-shot reconstruction of electron longitudinal phase space using a laser deflector

Utilize the unique capability at ATF, i.e., electron beam, CO2 laser and NIR laser.

Experimental goal: to observe clear electron spectrum modulations caused by laser pulses.

# THANK YOU

# Electron Beam Requirements

| Parameter | Units | Typical Values | Comments | Requested Values |
|---|---|---|---|---|
| Beam Energy | MeV | 50-65 | *Full range is ~15-75 MeV with highest beam quality at nominal values* | *Typical value* |
| Bunch Charge | nC | 0.1-2.0 | *Bunch length & emittance vary with charge* | *Typical value* |
| Bunch Length | ps | 1-10 | *Bunch charge & emittance vary with length* | *~2 ps* |
| Peak current | A | 100 | *Variable with bunch charge and length* | *Typical value* |
| Compression | fs | Down to 100 fs (up to 1 kA peak current) | *A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.*<br><br>*NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level* | *NO NEED* |
| Focused transverse size at IP (s) | μm | 30 – 100 (dependent on IP position) | *It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.* | *<300 μm* |
| Normalized Emittance | μm | 1 (at 0.3 nC) | *Variable with bunch charge* | *Typical value* |
| Rep. Rate (Hz) | Hz | 1.5 | *3 Hz also available if needed* | *Typical value* |
| Trains mode | --- | Single bunch | *Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.* | *Single* |

# $CO_2$ Laser Requirements

| Configuration | Parameter | Units | Typical Values | Comments | Requested Values |
|---|---|---|---|---|---|
| **$CO_2$ Regen. Amplifier** | Wavelength | mm | 9.2 | *Wavelength determined by mixed isotope gain media* | *Typical value* |
| | Peak Power | GW | ~3 | | *Typical value* |
| | Pulse Mode | --- | Single | | *Typical value* |
| | Pulse Length | ps | 2 | | *Typical value* |
| | Pulse Energy | mJ | 6 | | *Typical value* |
| | Repetition Rate | Hz | 1.5 | *3 Hz also available if needed* | *Typical value* |
| **$CO_2$ CPA Beam** | Wavelength | mm | 9.2 | *Wavelength determined by mixed isotope gain media* | *Typical value* |
| *Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.* | Peak Power | TW | 2-3 | *Up to 5 TW operation will be available in a limited number of shots upon the user's request.* | *Typical value* |
| | Pulse Mode | --- | Single | | *Typical value* |
| | Pulse Length | ps | 2 | *3-year development effort to achieve <500 fs at >10 TW and deliver to users is in progress.* | *Typical value* |
| | Pulse Energy | J | ~5 | *10J will be available in a limited number of shots upon the user's request.* | *Typical value* |
| | Strehl Ratio | --- | ~0.5 | *Recommended conservative estimate subject to verification.* | *Typical value* |
| | Repetition Rate | Hz | 0.01 | *Burst operation at up to 0.05 Hz for a limited period is possible upon user's request. This regime should be avoided to extend the lifetime of the HV spark gaps in the amplifier's PFN* | *0.01* |
| | Polarization | | Linear | *Adjustable linear polarization along with circular polarization can be provided upon request* | *Linear and Circular* |

# Other Experimental Laser Requirements

| Ti:Sapphire Laser System | Units | Stage I Values | Stage II Values | Comments | Requested Values |
|---|---|---|---|---|---|
| Central Wavelength | nm | 800 | 800 | *Stage I parameters are presently available and setup to deliver Stage II should be available summer 2025* | *800* |
| FWHM Bandwidth | nm | 20 | 13 | | *13* |
| Compressed FWHM Pulse Width | fs | <50 | <75 | *Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.* | *75* |
| Chirped FWHM Pulse Width | ps | ≥50 | ≥50 | | |
| Chirped Energy | mJ | 10 | 200 | | |
| Compressed Energy | mJ | 7 | ~20 | *20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.* | *6* |
| Energy to Experiments | mJ | >4.9 | >80 | | |
| Power to Experiments | GW | >100 | >1000 | | *1* |

| Nd:YAG Laser System | Units | Typical Values | Comments | Requested Values |
|---|---|---|---|---|
| Wavelength | nm | 1064 | *Single pulse* | |
| Energy | mJ | 100 | | |
| Pulse Width | ps | 14 | | |
| Wavelength | nm | 532 | *Frequency doubled* | |
| Energy | mJ | 0.5 | | |
| Pulse Width | ps | 10 | | |

# Special Equipment Requirements and Hazards

- Electron Beam
  - Beam chirp of 2.4 MeV / ps or bigger
  - Slice energy spread ~ 50 -100 keV
- $CO_2$ Laser
  - Linear and circular polarization
- Ti:Sapphire and Nd:YAG Lasers
  - No special requirements
- Hazards & Special Installation Requirements
  - Large installation (chamber, insertion device, etc.): N/A
  - Cryogens: N/A
  - Introducing new magnetic elements: N/A
  - Introducing new materials into the beam path: Tape-drive plasma mirror (plastic or copper)
  - Any other foreseeable beam line modifications: No.

# Experimental Time Request

## CY2025 Time Request

| Capability | Setup Hours | Running Hours |
|---|---|---|
| Electron Beam Only | 10 | |
| Laser* Only (in Laser Areas) | 10 | |
| Laser* + Electron Beam | 20 | 80 |

## Total Time Request for the 3-year Experiment (including CY2025-27)

| Capability | Setup Hours | Running Hours |
|---|---|---|
| Electron Beam Only | 30 | |
| Laser* Only (in Laser Areas) | 30 | |
| Laser* + Electron Beam | 60 | 240 |

* Laser = Near-IR or LWIR ($CO_2$) Laser

# Backup – Electron beam chirper

## Reversed procedure for introducing a linear chirp

Article

# Active energy compression of a laser-plasma electron beam

https://doi.org/10.1038/s41586-025-08772-y

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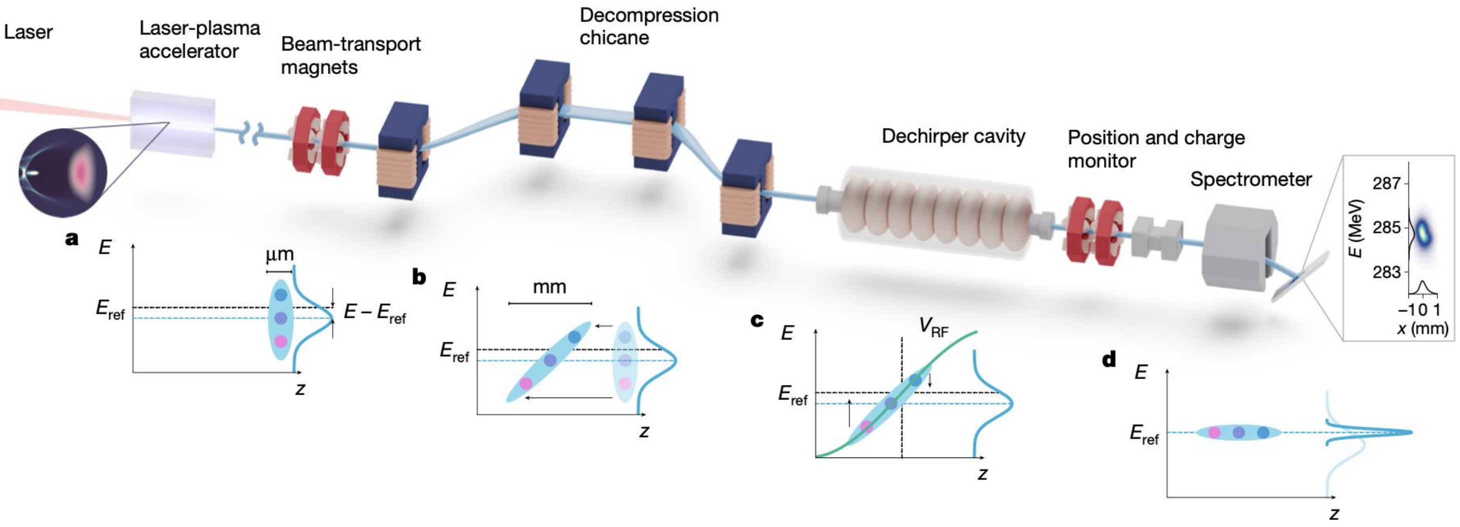

# Backup – Coupled motion of electrons in laser driven plasma wakefields and oscillations in the laser fields

$$H = \sqrt{1 + (\mathbf{P}_\perp - \mathbf{a}_\perp(\mathbf{x}_\perp, \xi, t))^2 + p_\parallel^2} - p_\parallel v_p - \psi(\mathbf{x}_\perp, \xi)$$ 1

$$\frac{dP_i}{dt} = \frac{(\mathbf{P}_\perp - \mathbf{a}_\perp)}{\gamma} \cdot \frac{\partial \mathbf{a}_\perp}{\partial x_i} + \frac{\partial \psi}{\partial x_i}$$ 2

$$\left(\frac{d^2}{d\zeta^2} + 2\Gamma\frac{d}{d\zeta} + \kappa_\beta^2\right)\mathbf{x}_\perp = -\frac{ik_\parallel \mathbf{a}_{\perp 0}(\zeta)}{2\eta} e^{ik_\parallel \zeta} + c.c.$$ 3

Driven oscillator

$$\mathbf{x}_{\perp s} = \frac{\mathbf{a}_{\perp 0}(\zeta)}{k_\parallel \eta \mathcal{Z}} \sin(k_\parallel \zeta)$$ 4 $$\mathbf{p}_{\perp s} = \frac{\mathbf{a}_{\perp 0}(\zeta)}{\mathcal{Z}} \cos(k_\parallel \zeta)$$

**Steady state solutions** Laser

$$\mathbf{x}_{\perp t} = \mathbf{x}_1 \cos \kappa_\beta \zeta + \mathbf{x}_2 \sin \kappa_\beta \zeta$$ 5 $$\mathbf{p}_{\perp t} = \mathbf{p}_1 \cos \kappa_\beta \zeta + \mathbf{p}_2 \sin \kappa_\beta \zeta$$

**Transient solutions** Wakefield

$$\mathbf{x}_\perp = \mathbf{x}_{\perp s} + \mathbf{x}_{\perp t}$$ 6 $$\mathbf{p}_\perp = \mathbf{p}_{\perp s} + \mathbf{p}_{\perp t}$$

**General solutions**



A.G.R.Thomas. arXiv:2007.03930

# Backup – Coupled motion of electrons in laser driven plasma wakefields and oscillations in the laser fields

$$\gamma - P_{||} v_p - \psi \simeq C_1 \quad (7)$$

**conservation of Hamiltonian**

$$p_{||} = \gamma_p^2 (C_1 + \psi) \left( v_p + \sqrt{1 - \frac{1 + \mathbf{p}_\perp^2}{\gamma_p^2 (C_1 + \psi)^2}} \right) \quad (8)$$

$$p_{||} \simeq p_{||0} - \frac{1}{2} \alpha^2 \gamma_p^2 \mathbf{x}_\perp^2 - \frac{\mathbf{p}_\perp^2}{2(C_1 + \psi_0(\xi))} \quad (9)$$

$$p_{||0} \simeq 2\gamma_p^2 (C_1 + \psi_0(\xi))$$

$$p_{||} \simeq p_{||0} - \frac{\gamma_p^2}{p_{||0}} \left( \underline{\frac{1}{2} \alpha^2 p_{||0} \mathbf{x}_\perp^2 + \mathbf{p}_\perp^2} \right) \quad (10)$$

**Wakefield acceleration** **Transverse modulation**

$$\mathbf{x}_\perp = \mathbf{x}_{\perp s} + \mathbf{x}_{\perp t}$$

$$\mathbf{p}_\perp = \mathbf{p}_{\perp s} + \mathbf{p}_{\perp t}$$

**Laser** **Wakefield**



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α = 1, — “bubble” regime