AAC'22 Advanced Accelerator Concepts Workshop

November 6 - 11, 2022

Hyatt Regency Long Island, NY

# Working Group 4: Beam-Driven Wakefield Acceleration

## Summary Slides

Jens Osterhoff, DESY and Spencer Gessner, SLAC

# Plenary Speakers

Richard D’Arcy
FlashFoward/DESY

*Experimental progress towards an energy-efficient, high-quality, high-repetition-rate plasma-wakefield accelerator*

Severin Diederichs
DESY/LBNL

*Positron Acceleration in Plasmas*

Tatiana Nechaeva
AWAKE/CERN/MPP Munich

*Hosing of a long relativistic particle bunch induced by an electron bunch*

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# WG4 Sessions 1+3
# Experimental Results

# Progress towards high-repetition-rate operation of a beam-driven plasma wakefield accelerator

> Developing understanding of post-wakefield evolution at **FLASH**FORWARD▸▸ to define possible bunch-train pattern for 10 kW average-power plasma-booster at **FLASH**.

> Using the wakefield acceleration process itself as a probe to understand long-lasting plasma effects that may ultimately limit repetition-rate.

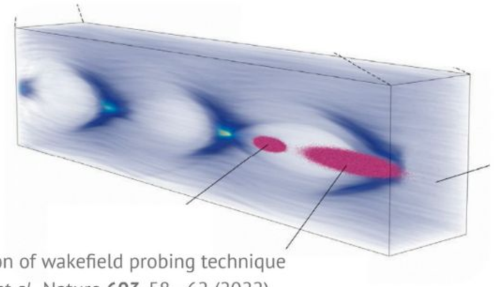
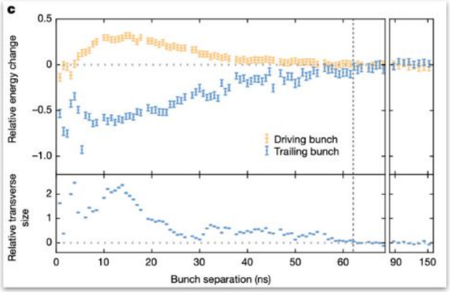
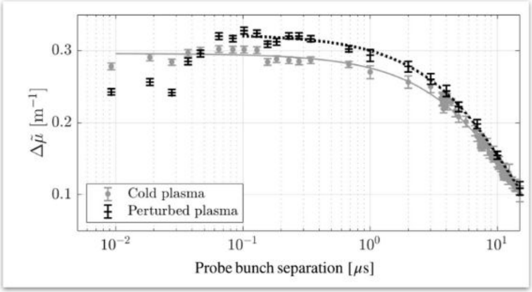


Illustration of wakefield probing technique
R. D'Arcy *et al.*, Nature **603**, 58–62 (2022)

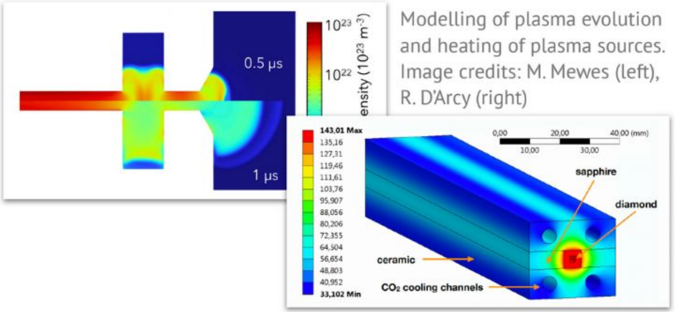



Dissipation of ion motion perturbation in 63 ns.
R. D'Arcy *et al.*, Nature **603**, 58–62 (2022)




Post-wakefield evolution over 20 μs.
J. Chappell, PhD thesis, University College London (2021)

> Next steps: using beam-based technique to characterise **cumulative heating effects** driven by a MHz-repetition-rate bunch train, both within the plasma and the target, to inform future operating modes and target designs.




Modelling of plasma evolution and heating of plasma sources. Image credits: M. Mewes (left), R. D'Arcy (right)

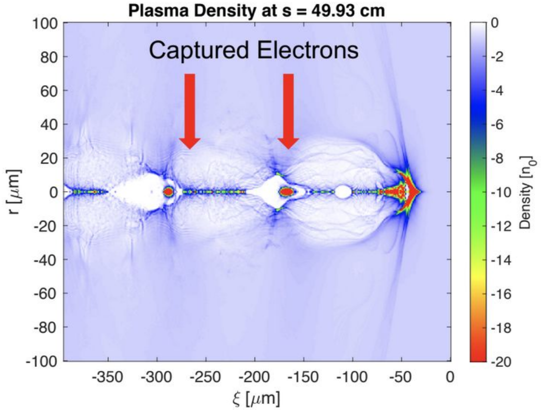
**FLASH**FORWARD▸▸ **is uniquely positioned to explore the opportunity for, and ultimately demonstrate, a 10 kW average-power plasma-booster…**

James Chappel, DESY

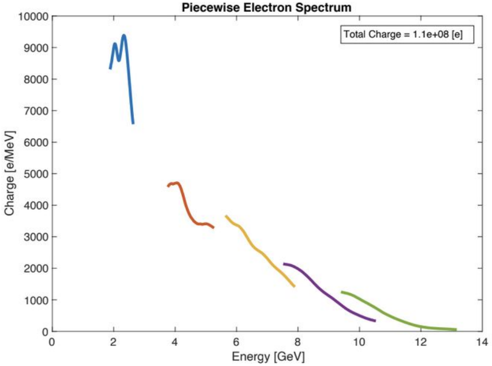
# Gigaelectronvolt Acceleration of Captured Electrons in a Positron Beam-Driven Plasma Wakefield Accelerator

- We can roughly reproduce the experimental results in simulation
  - Electron capture threshold at $10^{10}$ positrons.
  - Broad Spectrum up to 13 GeV
  - Similar spectrum shape and magnitude of charge.
- Simulations show electrons are captured over multiple buckets.
- Complicated evolution of the wake and plasma density.

Simulation:




Experiment:

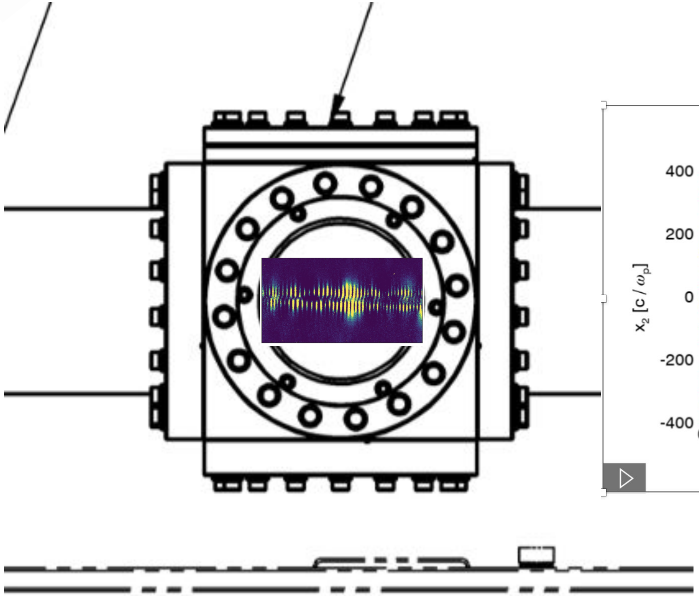


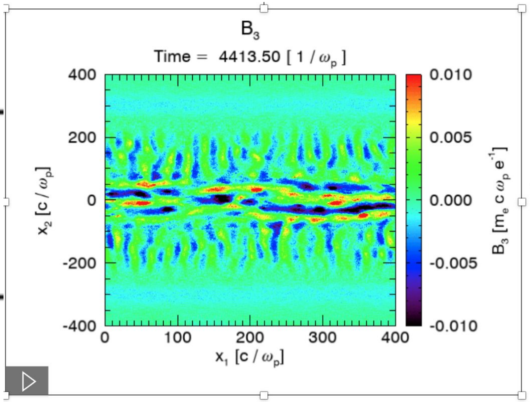

James Allen. AAC 2022

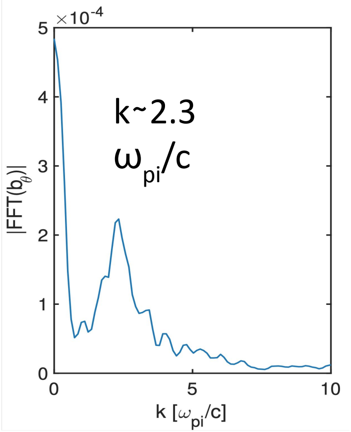
# Plasma Heating and Expansion in PWFA Experiments at FACET

## Formation of Collisionless Shocks and Filamentation Instability

presenter Ken Marsh, UCLA AAC 2022






$k_{max} = (a_i/3)^{1/2} w_{pi}/c$

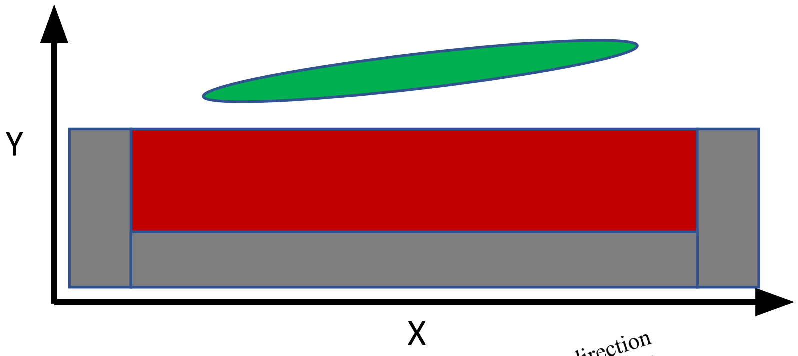
Measurement

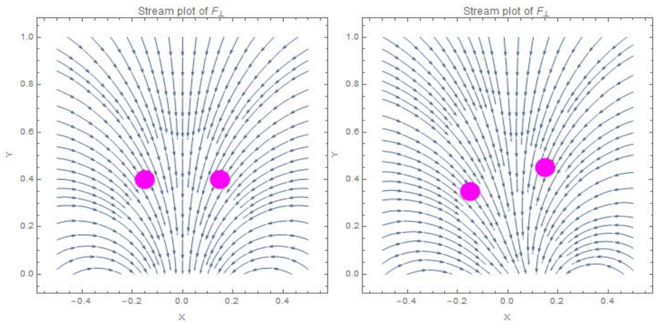
B field in PIC Simulation

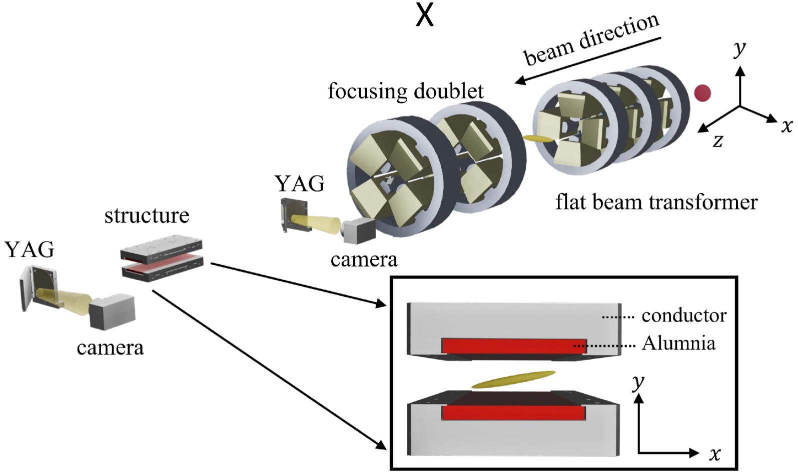
Theory

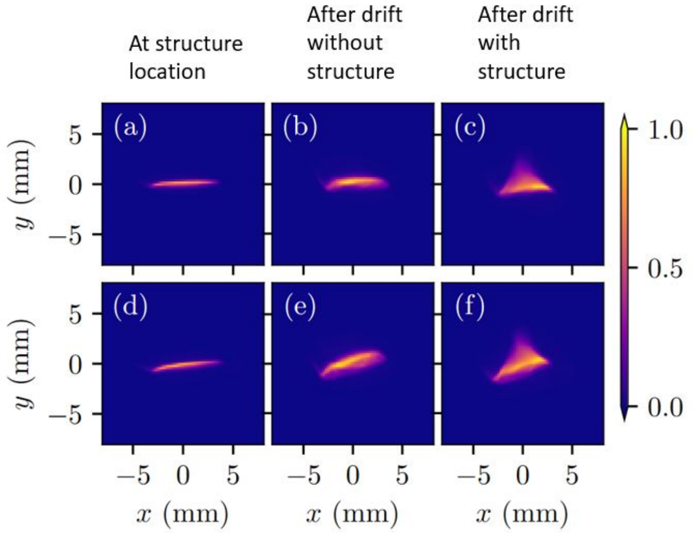
Walter Lynn, UCLA

# Observation of Skewed Electromagnetic Wakefields in an Asymmetric Structure Driven by Flat Electron Bunches



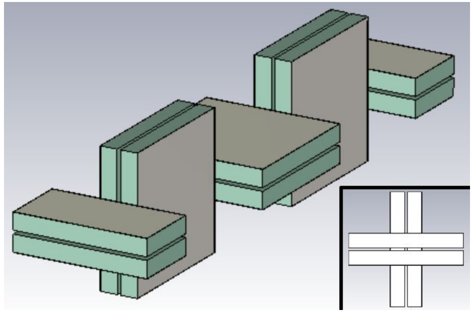



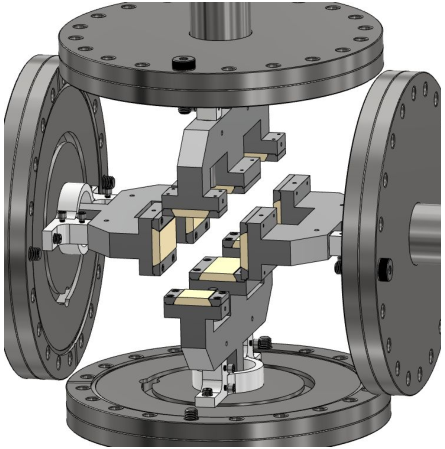



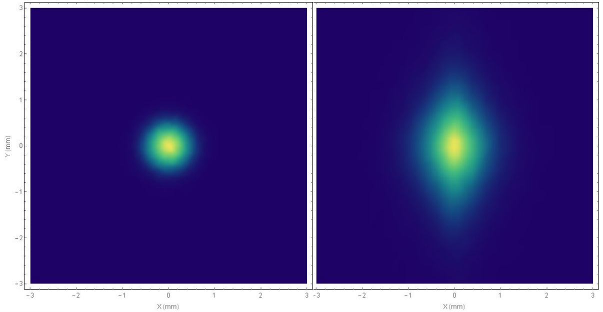



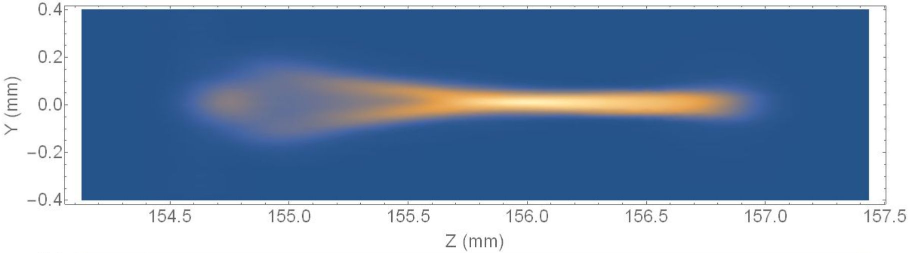
Walter Lynn, UCLA

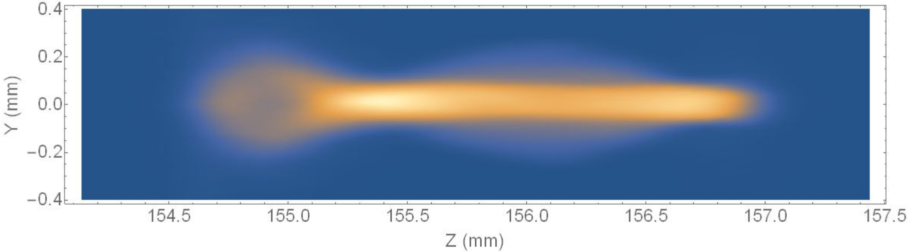
# Transverse Stability in an Alternating Gradient Planar Dielectric Wakefield Structure



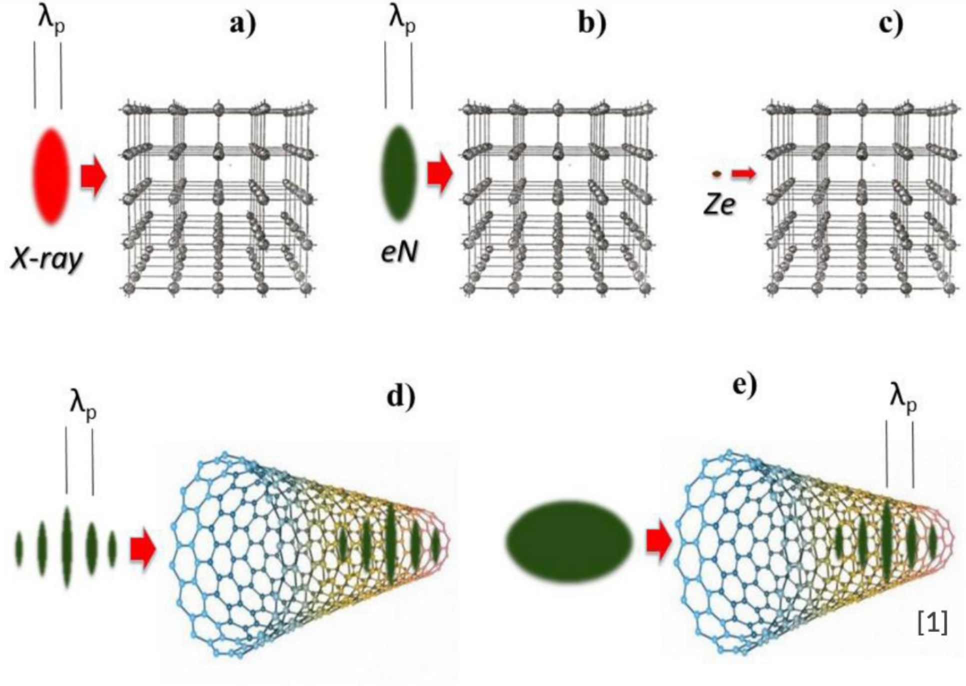






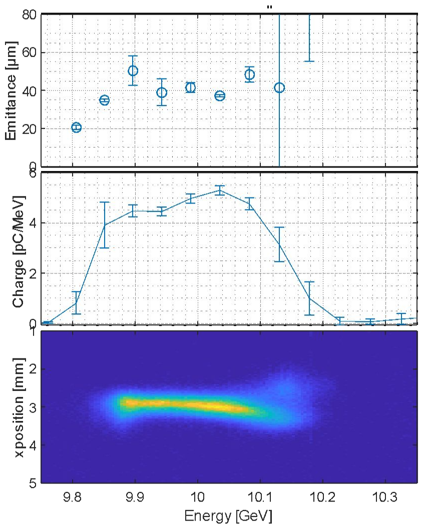
## Acceleration in in a nanostructure (crystal or carbon nanotube) limits scattering off the solid’s ions.



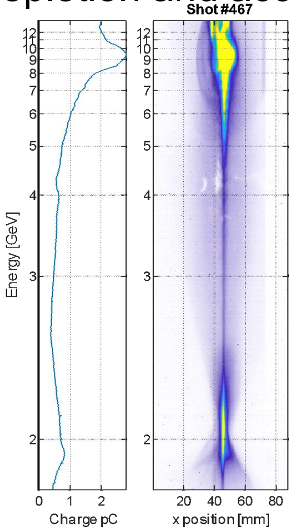
E300: Energy Doubling and Emittance Preservation through Beam Driven Plasma Wakefield Acceleration at FACET-II

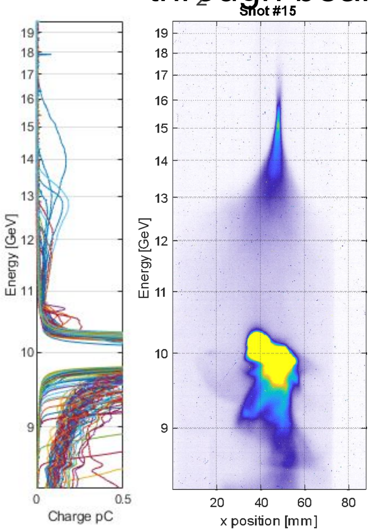
- Goal of E300: Demonstrate beam parameters required for a single stage of a PWFA future linear collider
- Progress made in diagnostics development (below) and readiness for PWFA studies at FACET-II
- Beam-ionized plasmas generated in He and $H_2$ up to 5 Torr in pressure, with differential pumping
- First run show energy depletion and acc through beam ionized PWFA

Emittance of incoming beam

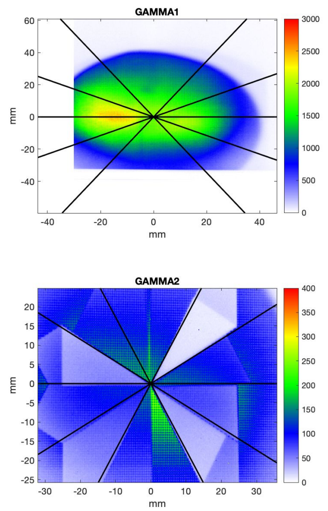



Electron Spectra from 1.5 Torr $H_2$ PWFA

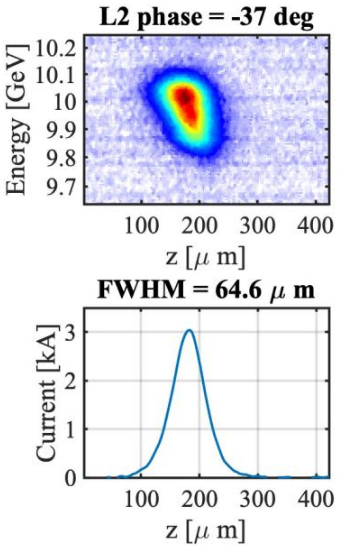



PWFA Betatron radiation




LPS via XTCAV



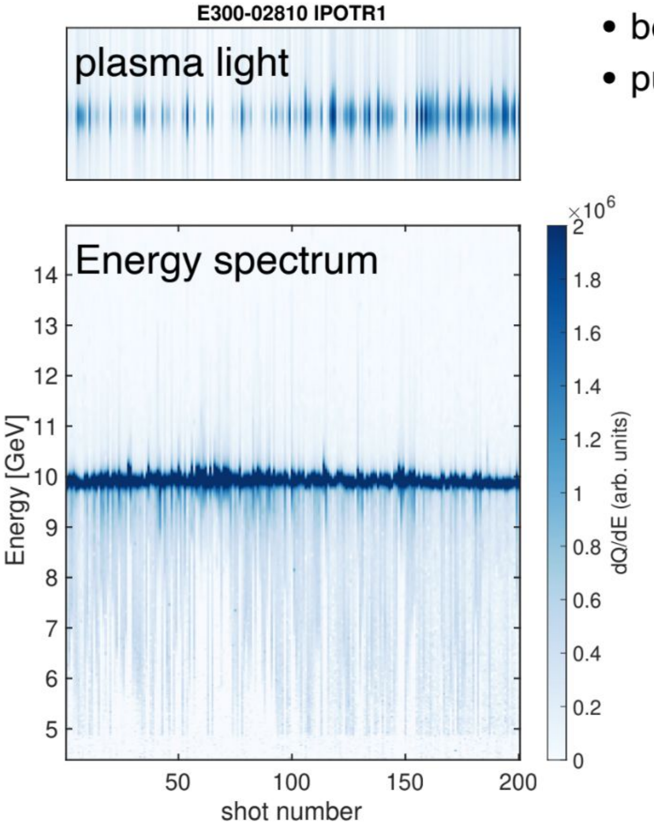
# Generating pre-bunched electron beams using modulated downramp injection

## Chaojie Zhang on behalf of the E300 collaboration

UCLA

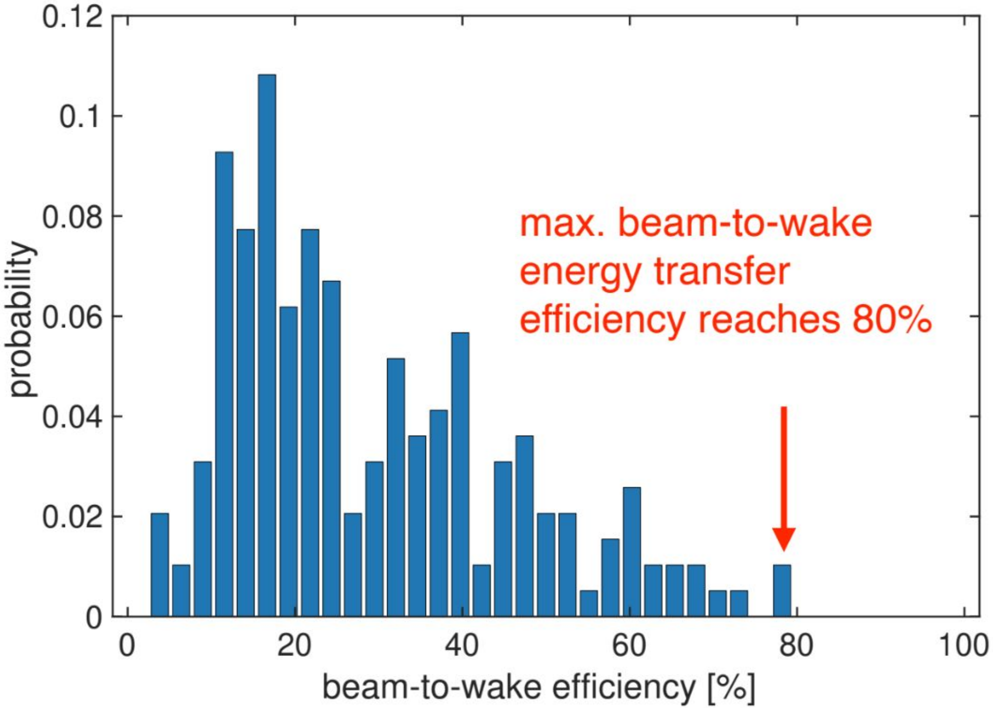
+Zan Nie

2.0 Torr $H_2$ static fill




**The first run of E300 experiment at FACET-II shows that**

- energy deposited into the plasma by the drive beam is up to 7 J
- beam-to-wake energy transfer efficiency approaching ~70% (best shots 80%)
- pump energy depletion: some electrons has lost all their 10 GeV energy



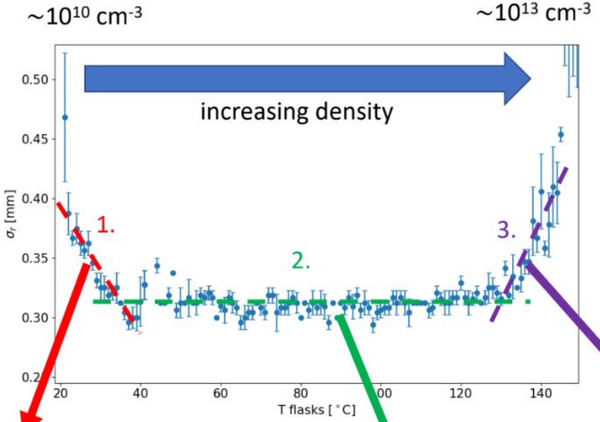
# Focusing of a Long Relativistic Proton bunch in Underdense Plasma

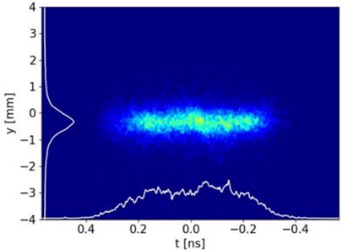
- We observed three regimes when increasing the plasma electron density ($r_{plasma}$~ 1 mm)

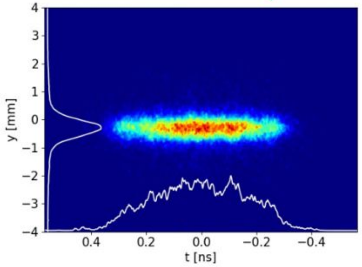
  1. $n_{pe} << n_b$ → underdense plasma
     no full space-charge compensation
     filament of plasma electrons on-axis

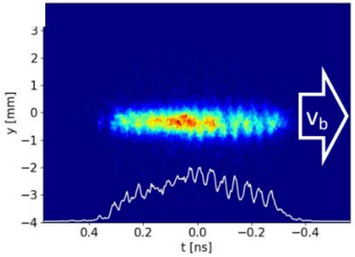
  2. $n_{pe} < n_b$ → full space-charge compensation
     equilibrium radius
     no wakefields

  3. $n_{pe} \sim n_b$ → Transition to wakefields
     Self-Modulation



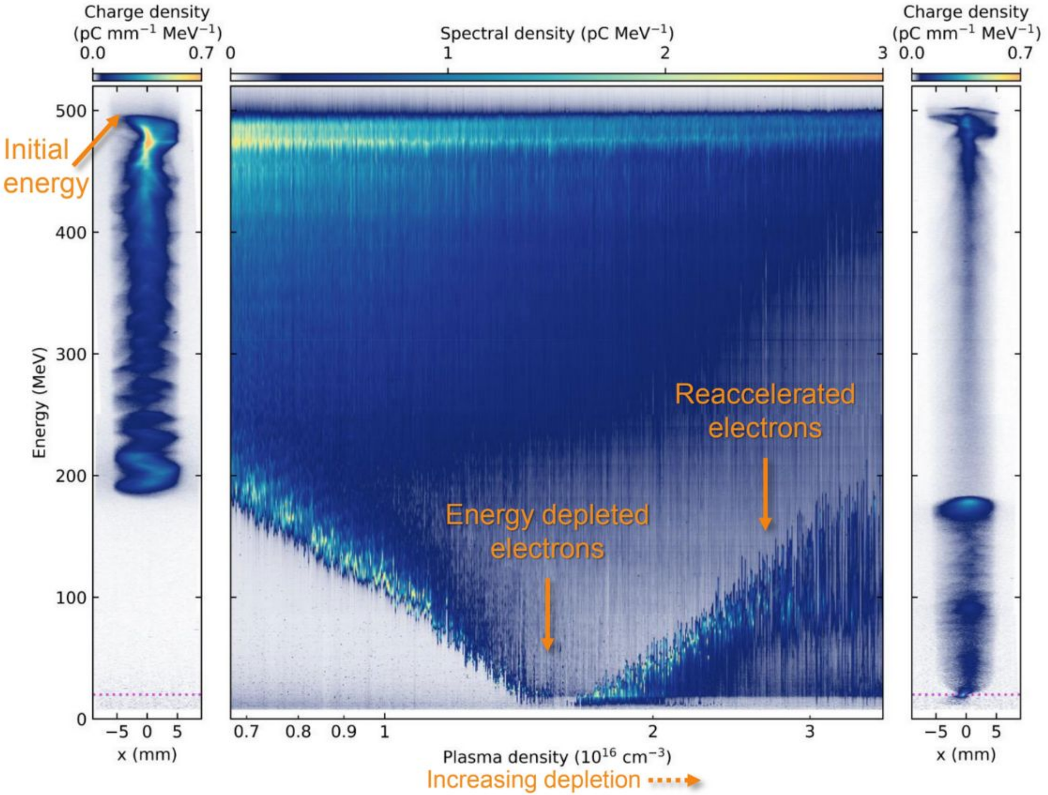



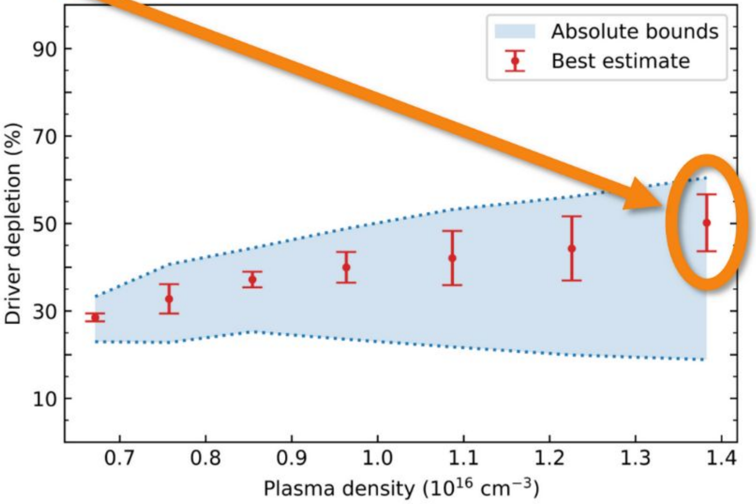




- Relevant for understanding of Self-Modulation
- Concept for beam transport over long distances

L. Verra

# Drive bunch energy depletion by (50±7) %




Overall efficiency is a product of:

1. Wall-plug-to-driver [1] η = 55 % ✓ (beam driven)
2. Driver-to-plasma η = 50 % ✓
3. Plasma-to-trailing-bunch [2] η = 42 % ✓

**If combined experimentally**:

CLIC-like!

**Wall-plug-to-trailing-bunch efficiency: 12%**


[1] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)
[2] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

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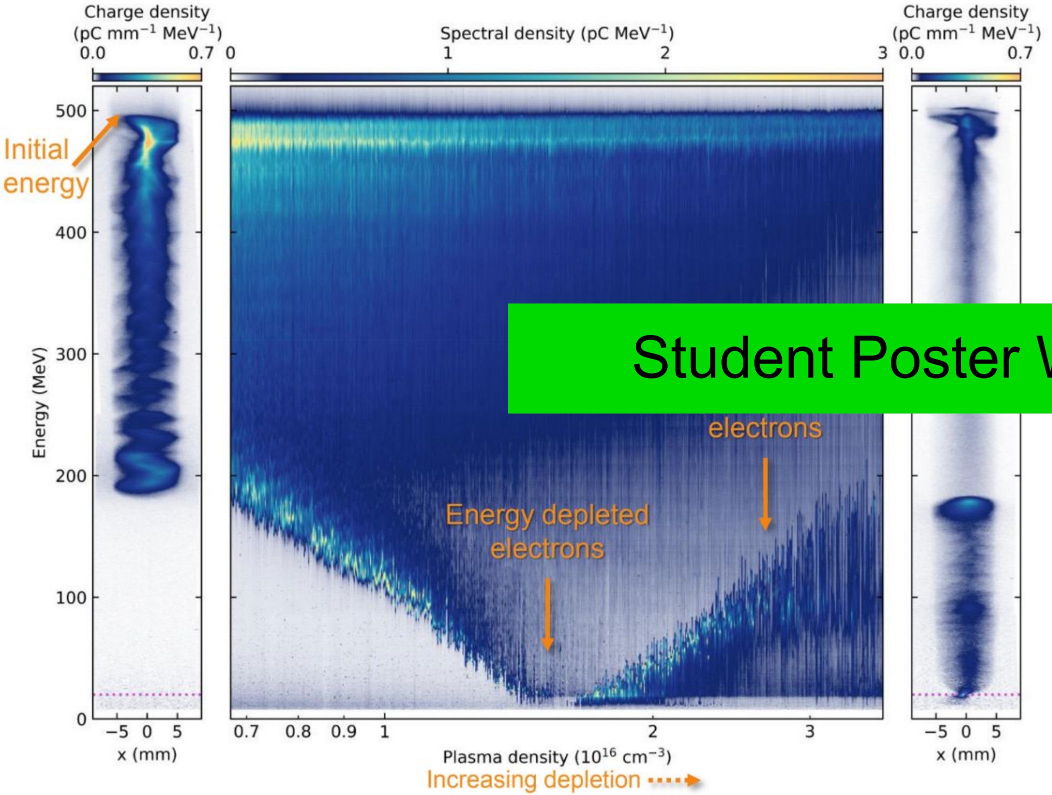


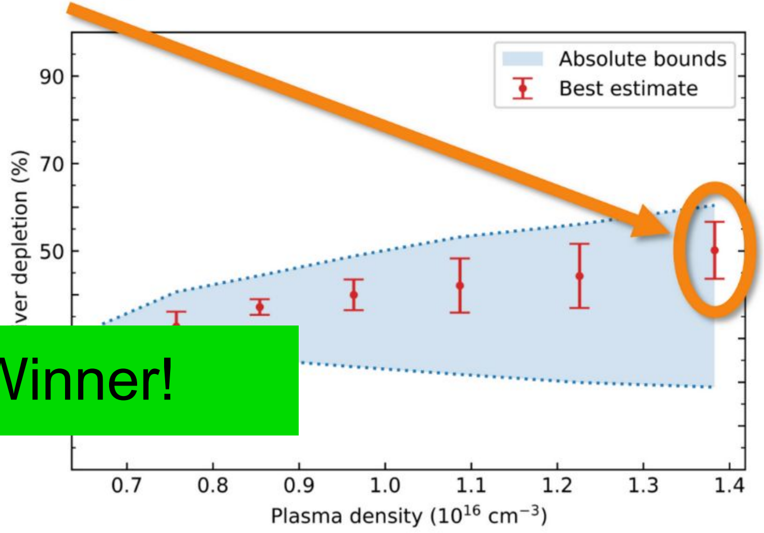


Student Poster Winner!

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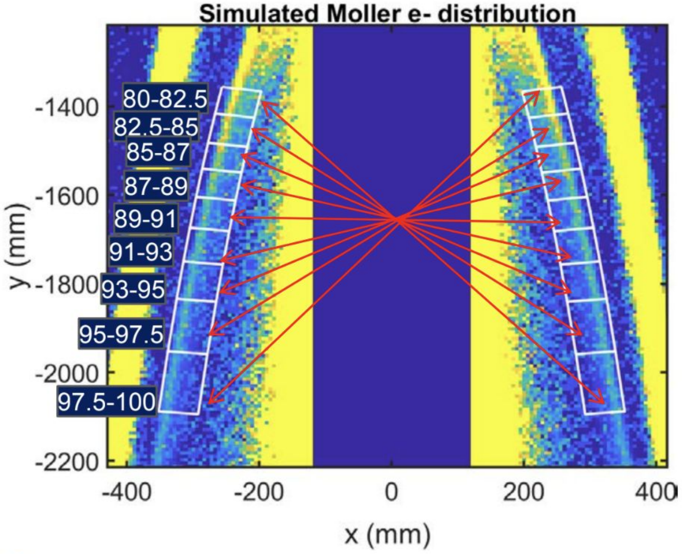
# WG4+WG4 Sessions 2+4

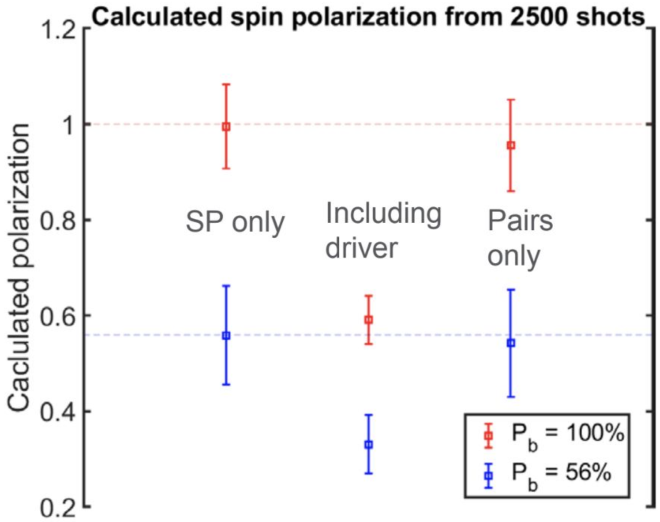
# Sources/Methods/Diagnostics

# Møller scattering for electron spin polarization measurement

Noa Nambu, Zan Nie, UCLA

- Møller scattering can be used to measure spin polarization of GeV electrons from PWFA
- Scattering of spin-polarized beams was simulated in GEANT4
- Possible to measure SP with 10% error by accumulating 2500 shots



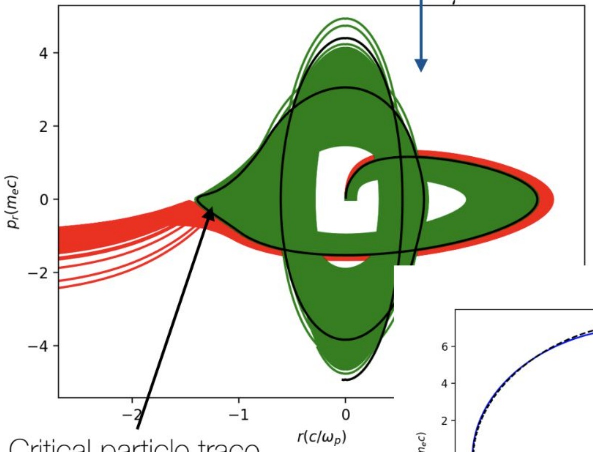



# Investigating transverse trapping conditions in B-III in PWFAs

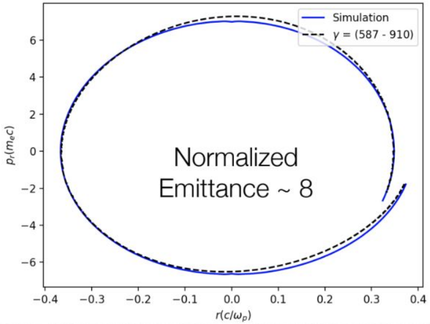
**Jiayang Yan**, Xuan Zhang, Derek Teaney,
Navid Vafaei-Najafabadi
Stony Brook University

Transverse Phase Space

$$\frac{p_r^2}{2\gamma(H_0+\psi_0)-1}+\frac{r^2}{4(H_0+\psi_0)-\frac{2}{\gamma}}=1$$




Critical particle trace

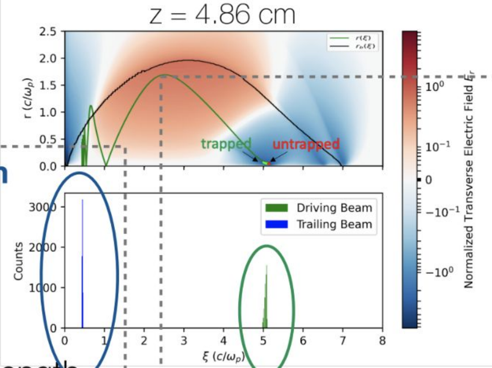



Normalized Emittance ~ 8

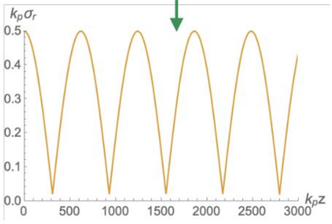
**Injection Beam**

Longitudinal Space

Pulse length suppressed as $\frac{E_{z_i}}{E_{z_f}}$




**Beam-Induced Ionized Beam**




Beam Envelope Evolution

$$\sigma_r(z)=\left|\left(\sigma_{r_0}-\Delta\sigma_r\right)\cos\left(k_\beta z\right)\right|+\sqrt{\frac{2}{\gamma}}\frac{\epsilon_N c}{\omega_p\sigma_{r_0}}$$

Transverse trapping condition dominates the trapping process

# Investigating transverse trapping conditions in B-III in PWFAs


**Jiayang Yan**, Xuan Zhang, Derek Teaney,
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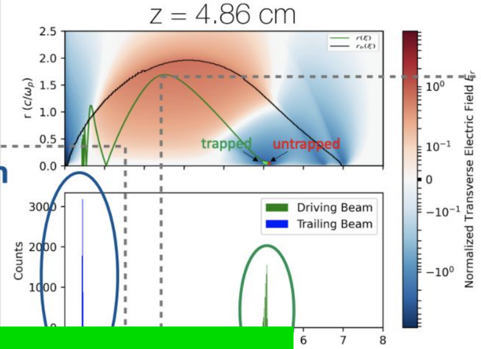
Transverse Phase Space

$$\frac{p_r^2}{2\gamma(H_0+\psi_0)-1}+\frac{r^2}{4(H_0+\psi_0)-\frac{2}{\gamma}}=1$$

**Injection Beam**

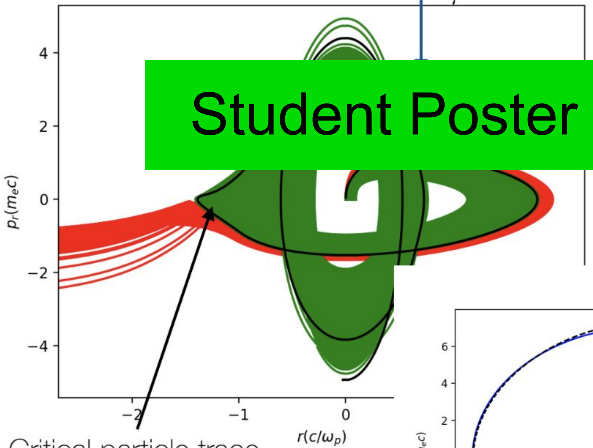
Longitudinal Space




## Student Poster Honorable Mention!

suppressed as $\overline{E_{z_f}}$

**am-Induced**
**onized Beam**

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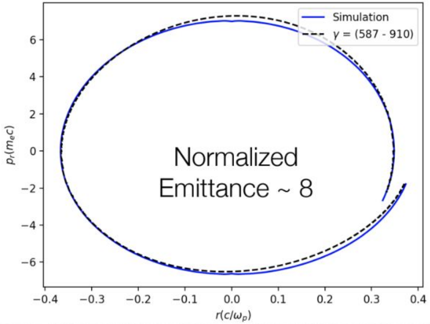


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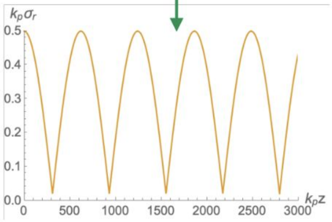


Beam Envelope Evolution

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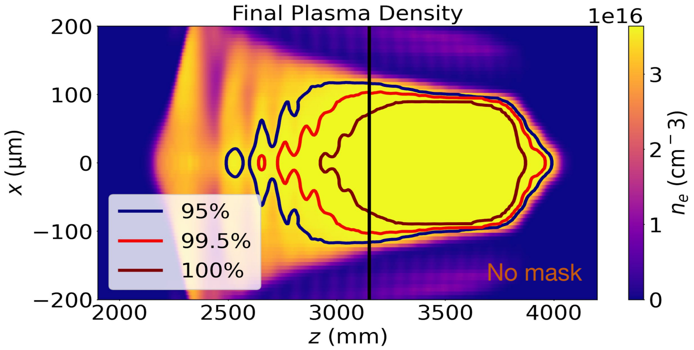
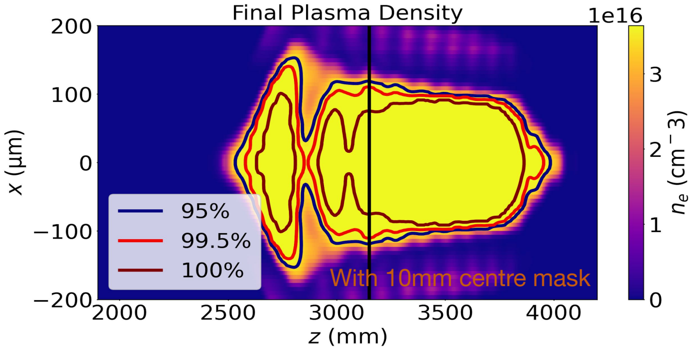
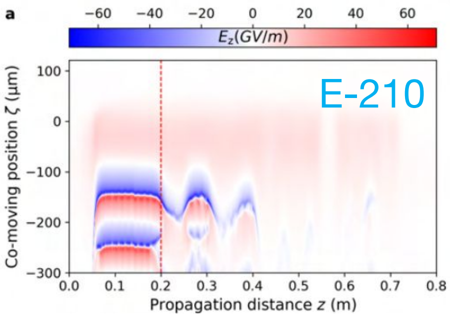
Transverse trapping condition dominates the trapping process

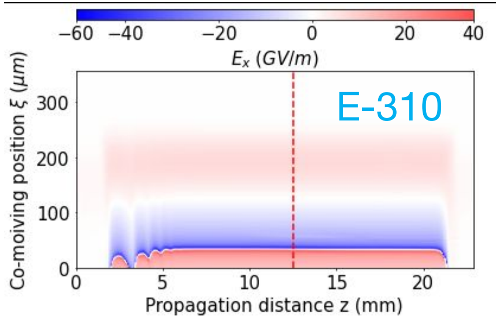
# Trojan Horse-II at FACET-II: prospects and experimental plans

Andy Sutherland, Strathclyde



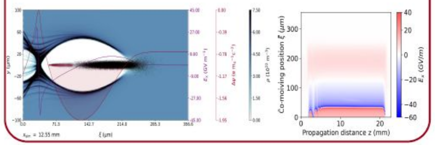



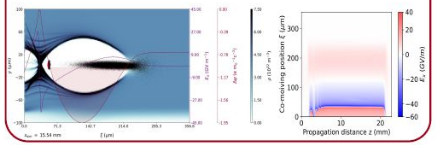

**Nominal Case – no offset**

| Charge | Emittance | Energy | Spread |
| --- | --- | --- | --- |
| 31.1 pC | 0.19 mm mrad | 128.9 MeV | 3.7% |



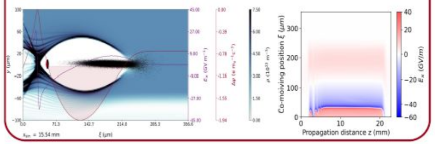
**Offset by 25 µm**

| Charge | Emittance | Energy | Spread |
| --- | --- | --- | --- |
| 31.1 pC | 0.22 mm mrad | 125.2 MeV | 3.7% |



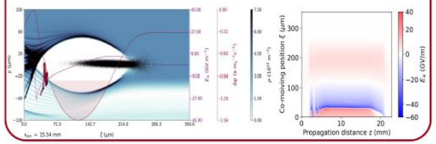
**Offset by 50 µm**

| Charge | Emittance | Energy | Spread |
| --- | --- | --- | --- |
| 31.1 pC | 0.29 mm mrad | 113.4 MeV | 3.6% |



**Offset by 75 µm**

| Charge | Emittance | Energy | Spread |
| --- | --- | --- | --- |
| 25.9 pC | 10.7 mm mrad | 56.8 MeV | 12.4% |



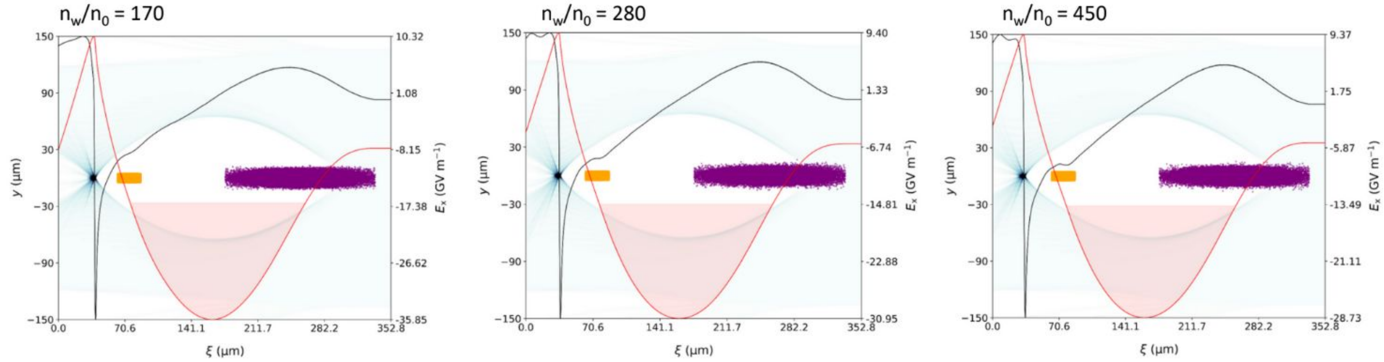
- Building on the science generated at FACET, we have developed an optimised plasma channel.
  - Studies performed on acceptable injection tolerances
  - Plasma profile generation and optic fabrication
  - Experimental implementation ongoing

# Towards a soft x-ray PWFA-FEL via Trojan Horse single bunch injection

- Trojan Horse could have the potential to produce beams in the **‘high charge’ regime** (10s pC) with **multi-kA current, few 100 nm rad emittance and few 0.1 % slice energy spread** using chirp-suppression via beam-loading

- Such beams should have sufficient quality to produce XFEL radiation in the soft x-ray region. This will be the subject of upcoming start-to-end simulations

- Beam-loading with Trojan Horse could be demonstrated using the planned E310 setup in collinear geometry simply by changing photocathode laser parameters and gas density

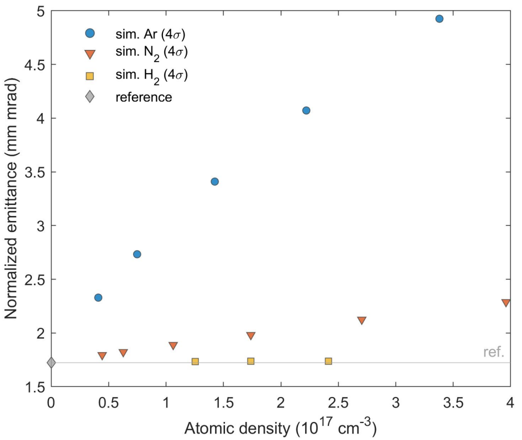


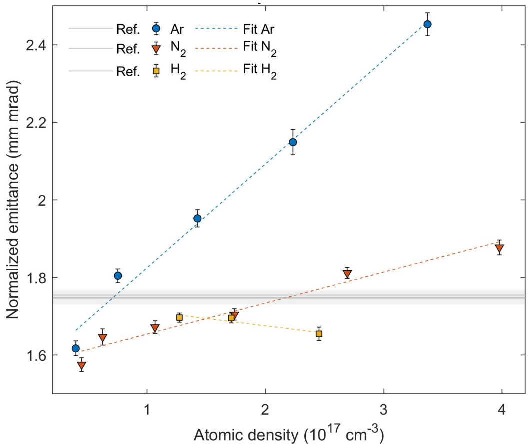

University of Strathclyde Glasgow

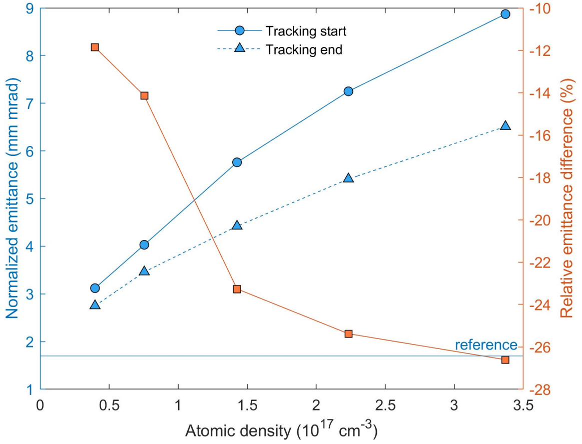
# Direct measurements of emittance growth from Coulomb scattering on neutral gas atoms in a plasma lens – summary slide

**J. Björklund Svensson**[1], L. Boulton[1,2,3], M. J. Garland[1], C. A. Lindstrøm[1], F. Peña[1,4], S. Schröder[1], S. Wesch[1]. J. Wood[1], J. Osterhoff[1] and R. D'Arcy[1]

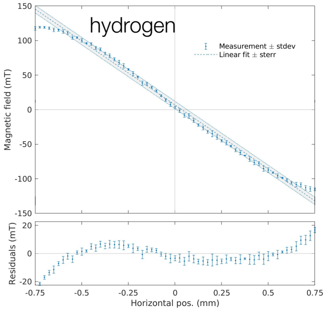
[1]Deutsches Elektronen-Synchrotron DESY, [2]SUPA, Department of Physics, University of Strathclyde, [3]The Cockcroft Institute, [4]Universität Hamburg

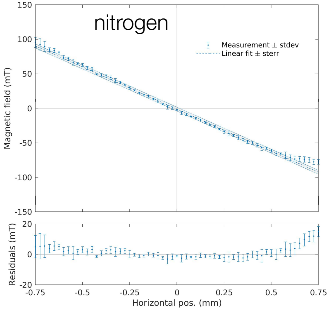


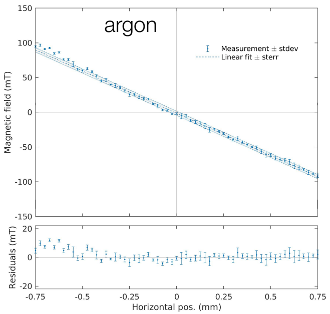




1. *Single-scattering regime* – limited, but noticeable, emittance growth in GEANT4 simulations
2. Measurement trends similar to simulation but no quantitative agreement, also see emittance *decrease*
3. Charge loss in beamline likely culprit – tracking simulations indicate larger decrease for more scattered beams
4. Bonus data: focusing gradient measurements indicate linear gradients also in nitrogen – nitrogen *could* be better candidate for APLs than argon
5. Refined experiments and simulations underway

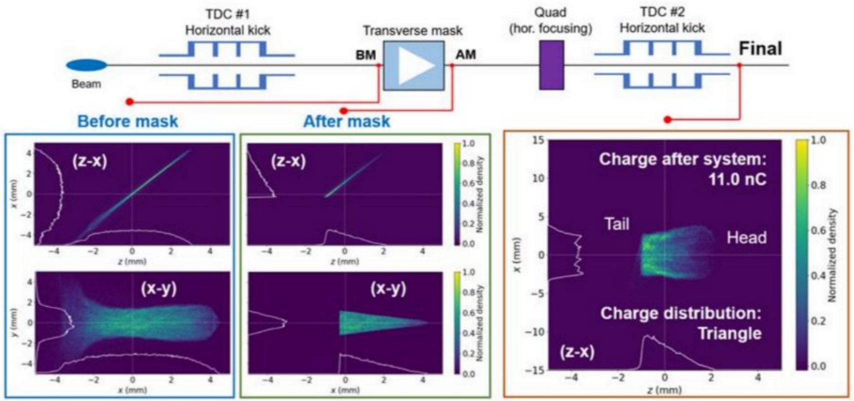


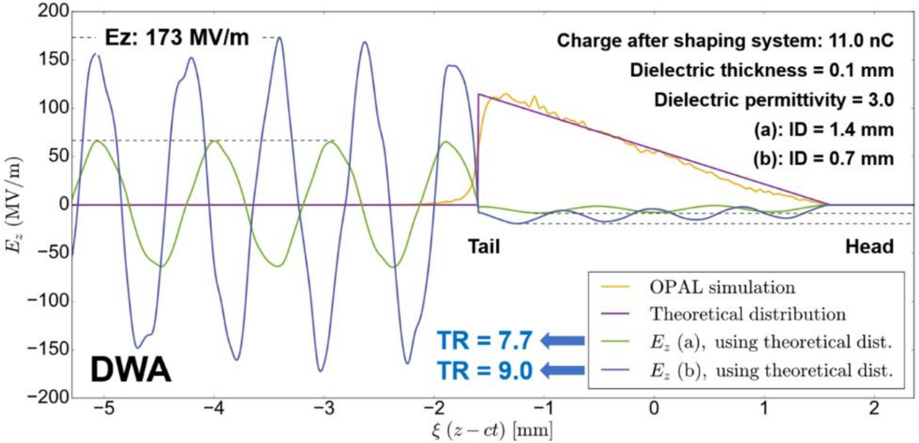



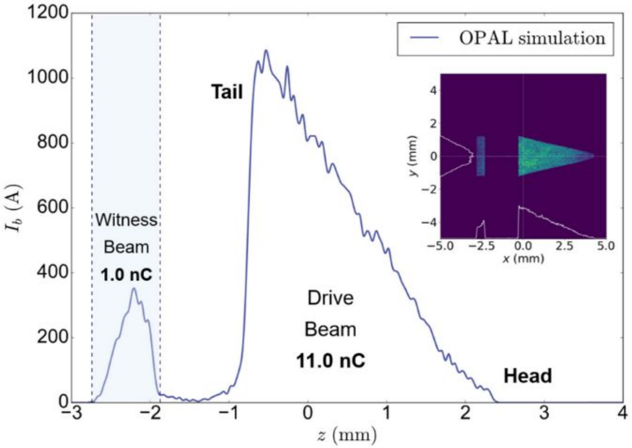
# TDC-based longitudinal bunch shaping at AWA

Argonne NATIONAL LABORATORY | euclid TECHLABS | Northern Illinois University

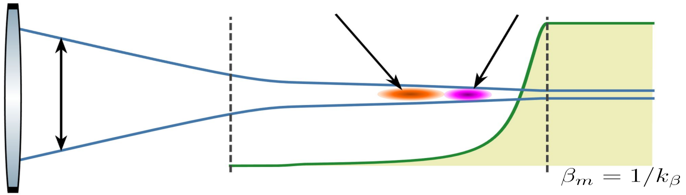


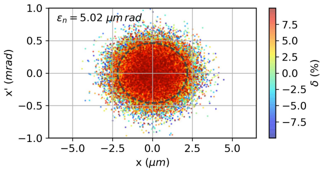

- Prior to TDC shaping method, challenges: collective effects due to high charge: CSR, space charge
- High charge beam manipulation for **high TR (9) + high gradient (173 MV/m)** can be made possible
- Witness beam generation for i) quality preservation ii) wake diagnostics
- Future plan: Experimental demonstration of bunch shaping using L-band TDCs @ AWA



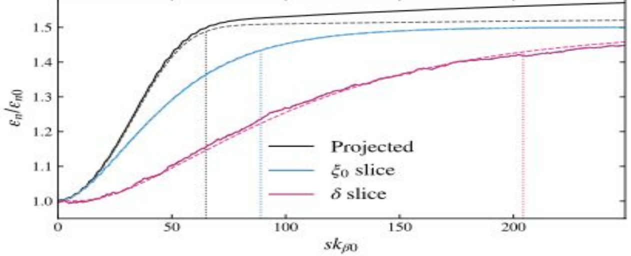



# Goal: emittance preservation by matching beam into plasma with density ramp



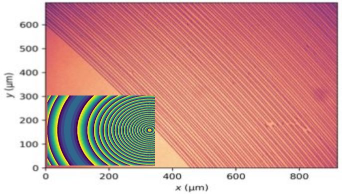



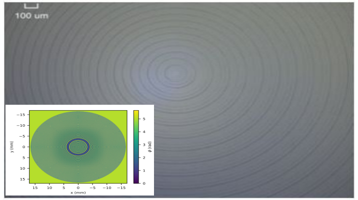

Emittance Evolution



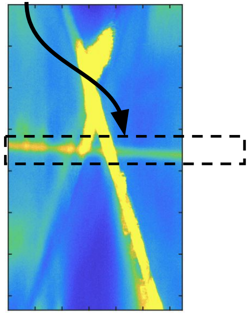

R. Ariniello

Diffractive Lenses

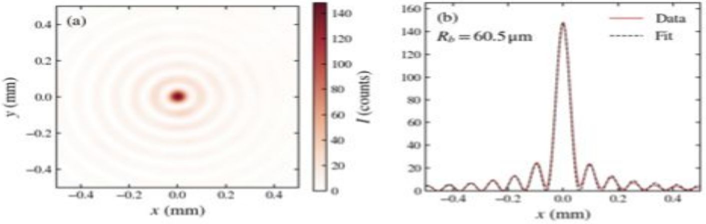


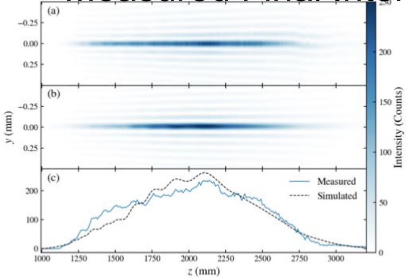

First Plasma from Tandem Lens Pair(!)



Measured Bessel Int. Profile




Measured Final Intensity






SLAC UCLA FACET-II

# WG4 Summary Slide (Underdense Plasma Lens)

- Early commissioning of plasma lens experiment at FACET-II demonstrated some beam-plasma interactions with a single electron bunch and laser-ionized elongated gas jet.

- Gained experience and observed rough trends through preliminary data analysis.

- Looking forwards to future experimental efforts at FACET-II with the underdense plasma lens:

  - Side-Ionization of Gas Jet for Thin, Adjustable Thicknesses

  - PWFA Matching with Plasma Lens to Preserve Emittance

  - Electron Beam Deflections from Linear Density Gradients

  - Reaching Oide Limit due to Hard Synchrotron Radiation

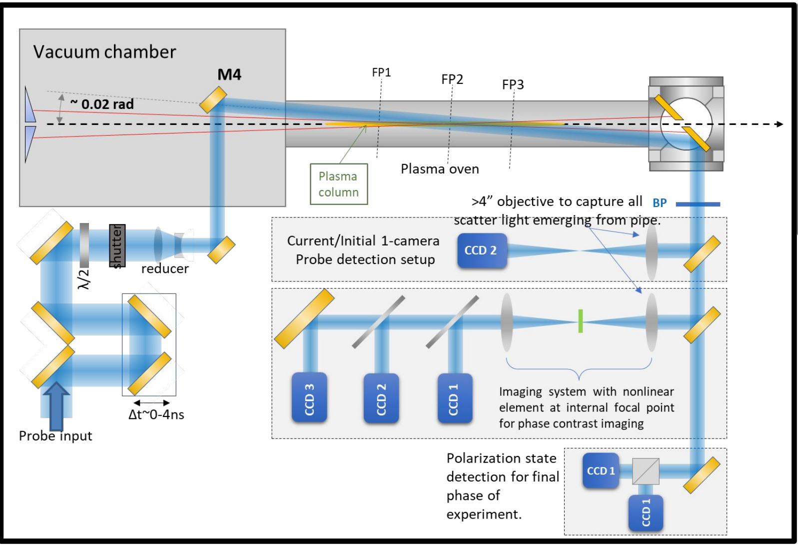


**This work was funded by the U.S. Department of Energy grant number DE-SC0017906.**

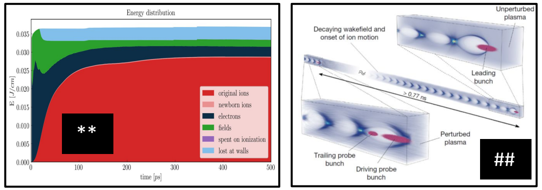
# Optical visualization of e-beam-driven plasma wakes at FACET-II    Experiment E-324

*Rafal Zgadzaj*, Jason Brooks , **M. C. Downer** *et al.*

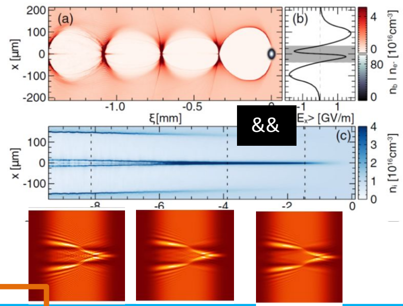
The aim of experiment E-324 in FACET-II is to study plasma dynamics covering a broad timescale, from the creation of the wake, which deposits an enormous amount of energy in the plasma, all the way to the return of the medium to its initial state.

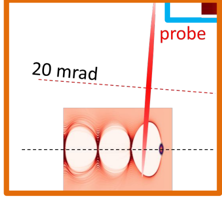



## Phase 1



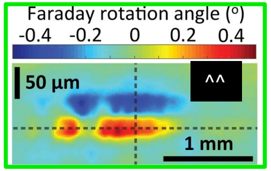

## Phase 2




Phase 3

Phase 4




## Experimental phases, in anticipated sequence:

**1) 0 to >>microsecond.** Long-time dynamics of post-wake plasma (with and without pre-ionization). In FACET-I, E-224 obtained data covering <1.4ns delays, with a small amount of data reaching 10microseconds using electronic delay. In FACET-II we aim to observe the medium until its return to its original state.

**2) 0 to ~ 100ps.** Formation and evolution of ion wake (including central density peak and its decay into a channel)

**3) 0 to ~ 1ps.** Plasma wake structure

**4) 0 to >>microsecond.** Faraday and Cotton-Mouton effect based measurements of magnetic fields.


*** Zgadzaj, R., Silva, T., Khudyakov, V.K. et al. Dissipation of electron-beam-driven plasma wakes. Nat Commun 11, 4753 (2020).*
*## D'Arcy, R., Chappell, J., Beinortaite, J. et al. Recovery time of a plasma-wakefield accelerator. Nature 603, 58–62 (2022).*
&& T. Silva et al., "Stable Positron Acceleration in Thin, Warm, Hollow Plasma Channels," *Phys. Rev. Lett. 127, 104801, 2021*
*^^ Cheng Y-y, et al., Phys. Plasmas 28, 123105 (2021);*

*Work is supported by NSF grant PHY-2010435 and U. S. DoE grant DE-SC0011617*

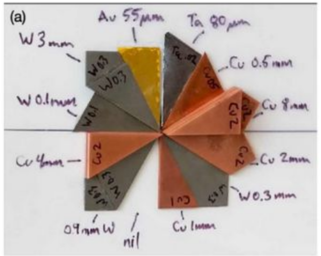
# WG4+WG7 Sessions 2+4

# Radiation Generation

# First X-ray and Gamma-ray measurements at FACET-II

First set of X-ray and ɣ-ray diagnostics at FACET have been designed, installed and commissioned.

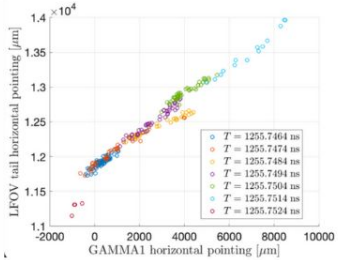
- Integrated and angular information (GAMMA1)
- Spectral information (GAMMA2)



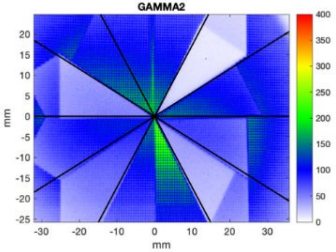

During the first user beamtime, these diagnostics have been successfully used to measure:

- Bremsstrahlung (E332)
- Inverse Compton Scattering (E320)
- Betatron radiation (E300) → Evidence of beam self-focusing in beam-ionized plasma

GAMMA1-LFOV correlation

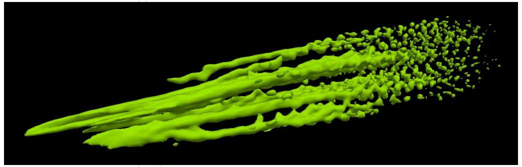


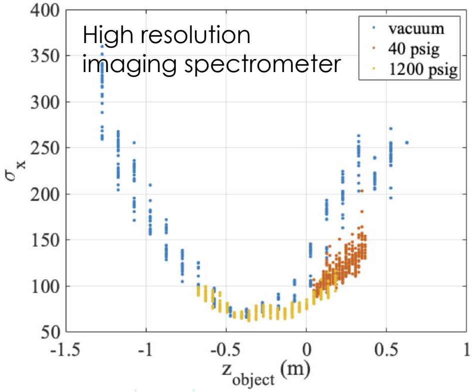

GAMMA2

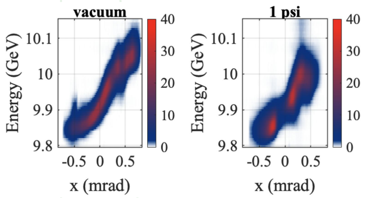


# FACET-II E-305: Beam filamentation and bright gamma-ray bursts – First results

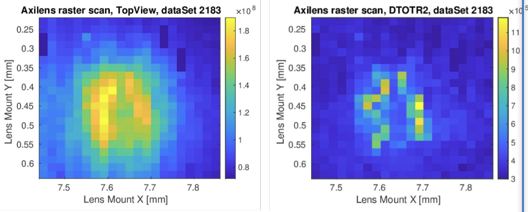
Study of relativistic streaming instabilities with the FACET-II electron beam

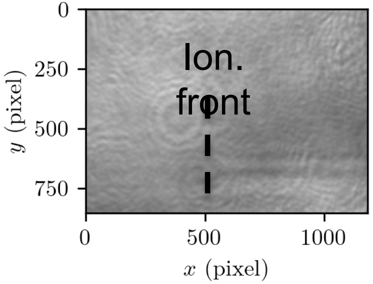


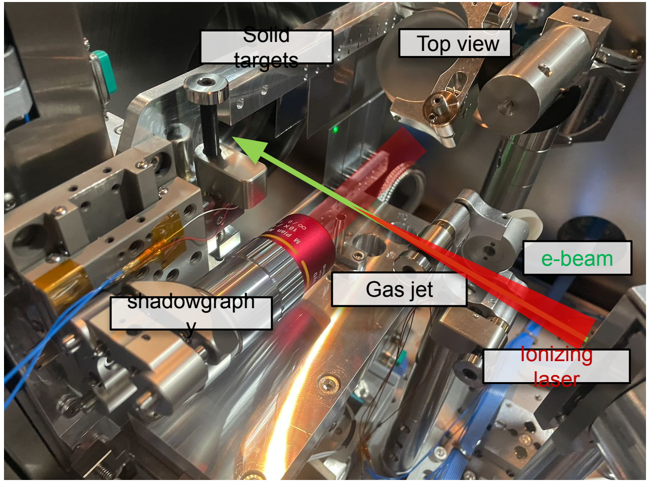


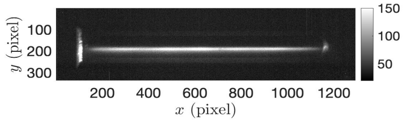

## Alignment and synchronisation




Laser-ionized high pressure gas jet

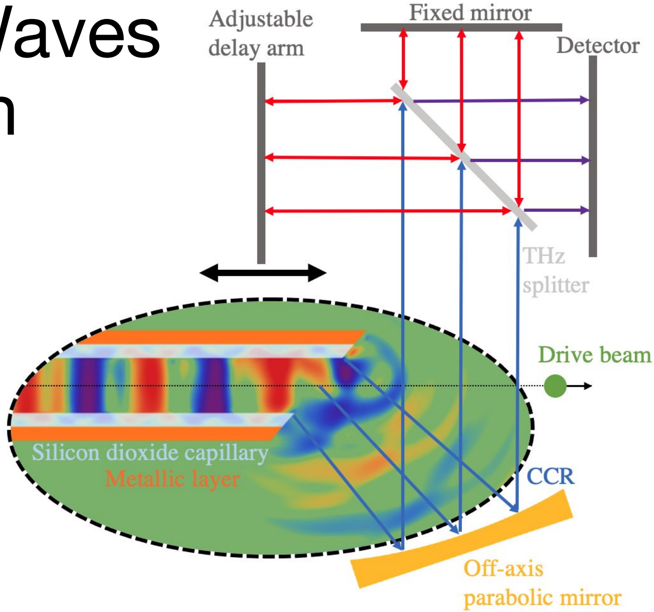



- Good progress on setup commissioning
- First experiments reveal important observables and the path forward

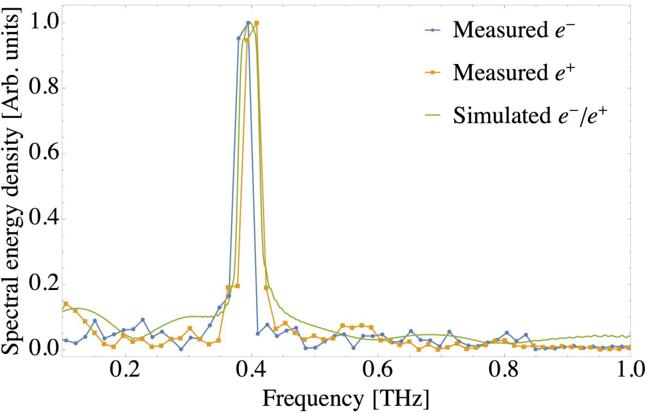


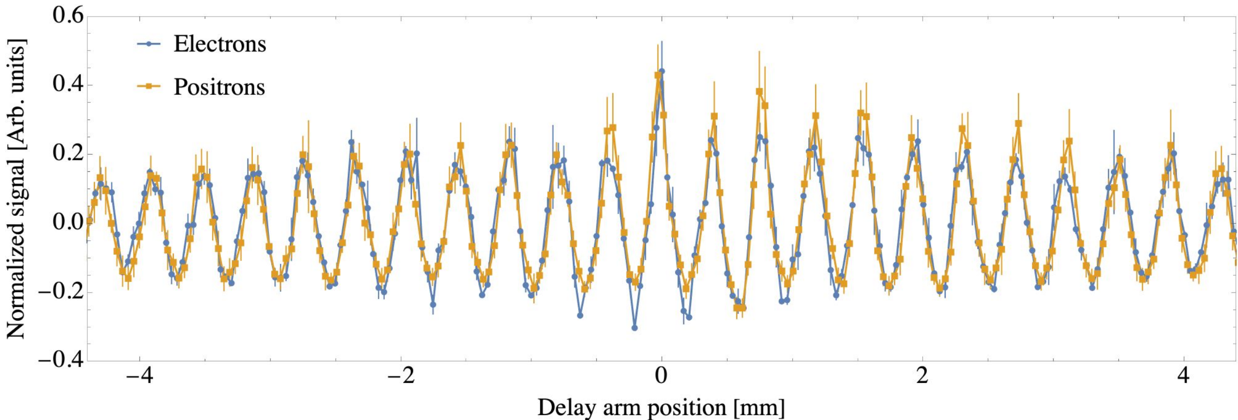
loa

# Positron Driven High-Field Terahertz Waves via Dielectric Wakefield Interaction




- Experimental results of **first ever positron DWA** with witness-bunch-relevant beam parameters show that higher order effects are not induced
  - 500 MV/m gradient
- Statistically equivalent with respect to charge sign
- Important progress towards dielectric wakefield acceleration of positrons



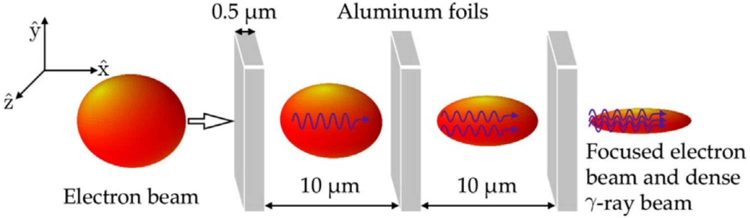
# First results from the E332 Experiment: NF-CTR Self Focusing @ FACET-II

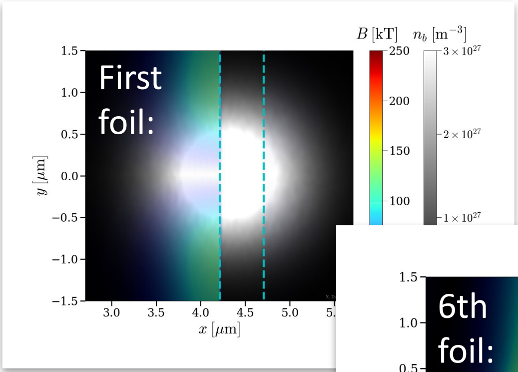
- Near Field Coherent Transition Radiation (NF-CTR) can result in strong transverse fields at a foil surface boundary that can have a strong impact on the beam:
  - Strong self focusing to achieve electron beams of solid-density
  - Drives the generation of an intense, collimated gamma beam

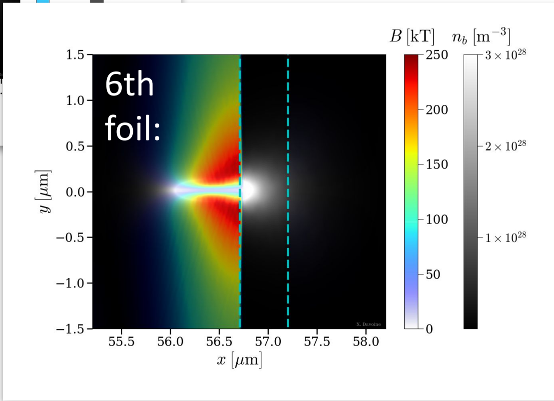
- E332 aims to demonstrate and probe these effects

- Progress and next steps:
  - Diagnostics and acquisition tools developed
  - Studies to understand target damage mechanism underway
  - NF-CTR self focusing not resolvable under current conditions

- Resolution of the NF-CTR effects are expected in upcoming run with smaller emittance beams and multi-foil targets



# WG4+WG2 Sessions 2+4

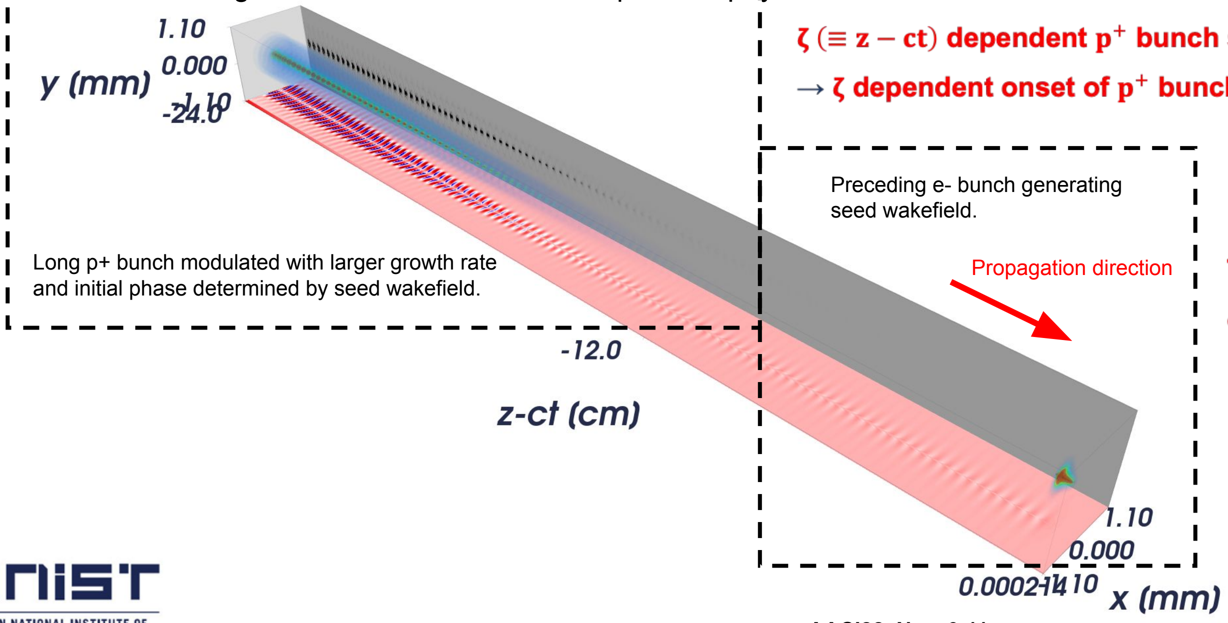
# Simulations

# Dominance of the seed from a tightly-focused electron bunch over the self-modulation of a long proton bunch in an over-dense plasma

Kook-Jin Moon, UNIST, Korea, kookjine@unist.ac.kr

- **Electron bunch preceding a long proton bunch generates wakefield for seeding the proton bunch modulation for PWFA.**
- Seed and the long proton bunch parameters decoupled.
- More degrees of freedom with new aspects of physics.

**$\zeta\ (\equiv z - ct)$ dependent $p^+$ bunch self-fields and noise + "quasi static" seed**
**$\rightarrow \zeta$ dependent onset of $p^+$ bunch modulation**



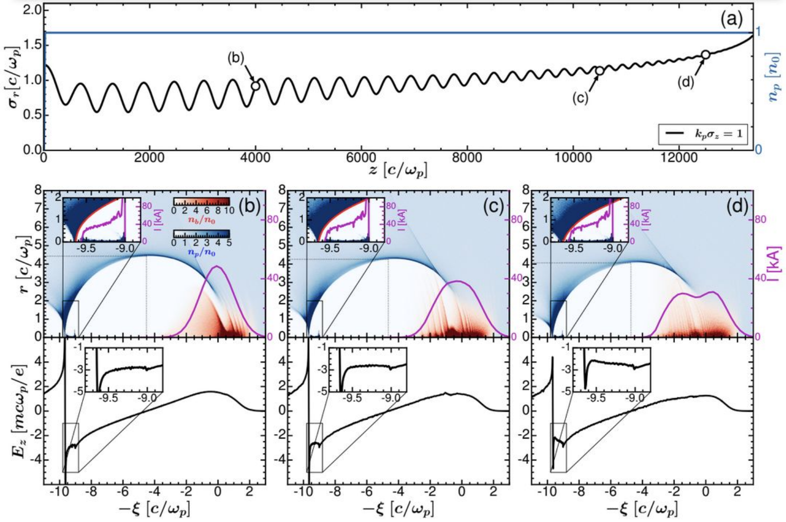

**Tightly-focused $e^-$ bunch makes onset of $p^+$ bunch modulation $\zeta$ independent!**

ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

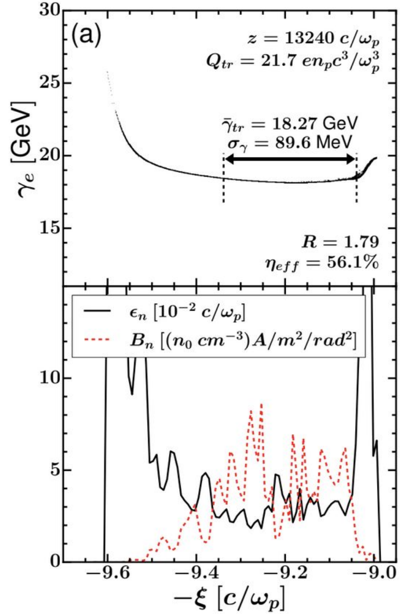
# Optimal Beam Loading to 20 GeV through Wakefield Slope Rotation using an Electron Driver

Thamine N. Dalichaouch[1], Xinlu Xu, Fei Li[1], Frank S. Tsung[1], Warren B. Mori[1]

- **Wakefield slope rotation triggered by driver evolution!**
- **Spot size expansion and dephasing alter beam loading.**
- **Net zero slope $\langle d_\xi E_z \rangle_{acc} \approx 0$ over pump depletion.**




- **Injection and optimal acceleration to 18.3 GeV and beyond with sub-percentile spreads.**



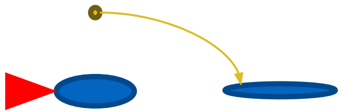

[1]*Department of Physics and Astronomy, UCLA, CA 90095, USA*

# Witness beam realignment in plasma wakefield accelerators in the linear collider regime – Summary Slide

L. Hildebrand, Y. Zhao, W. An, F. Li, X. Xu, W. B. Mori, C. Joshi

UCLA

- If we use a narrower drive beam (or unmatched) this will seed ion motion before witness beam arrives.
- Hildebrand et al. (2018) shows a proof of concept for the FACET-II parameters with 50 times smaller emittance for both beams.
- There's a trade off between hosing suppression/alignment and emittance growth.



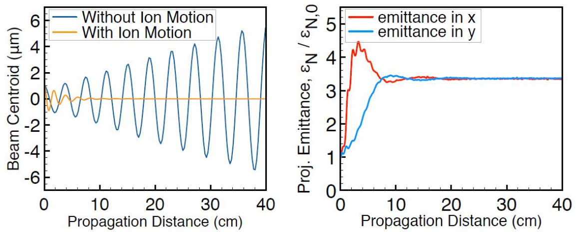



Fig. 10. Ion Motion. (a) Beam centroid evolution with and without ion motion. (b) Projected normalized emittance evolution in transverse directions with ion motion. The centroid is measured at the tail, $\xi = +\sigma_z$.

- LC regime has used wide drive beams in the past to avoid this extra ion motion but this causes severe head erosion.

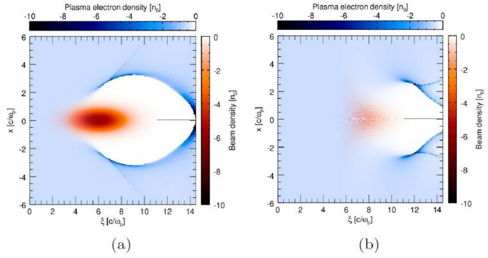
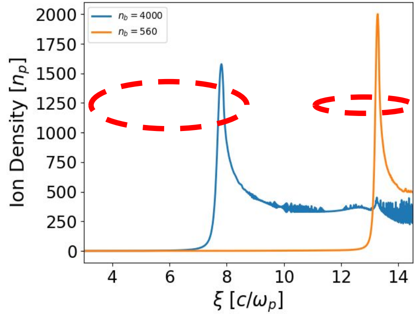
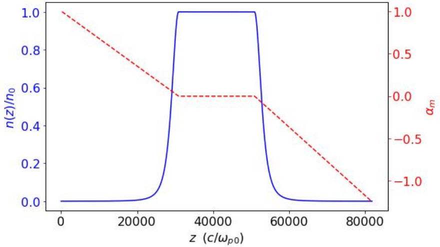



FIG. 1. (a) Initial nonlinear plasma wake from [9]. (b) Plasma wake after $t = 20{,}000\ \omega_p^{-1} = 33.6$ cm.

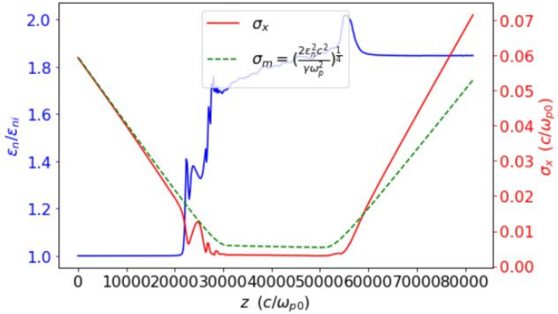
- Different spot size drivers lead to different ion structures.




- We can design an adiabatic plasma ramp that matches the beams with ion motion.



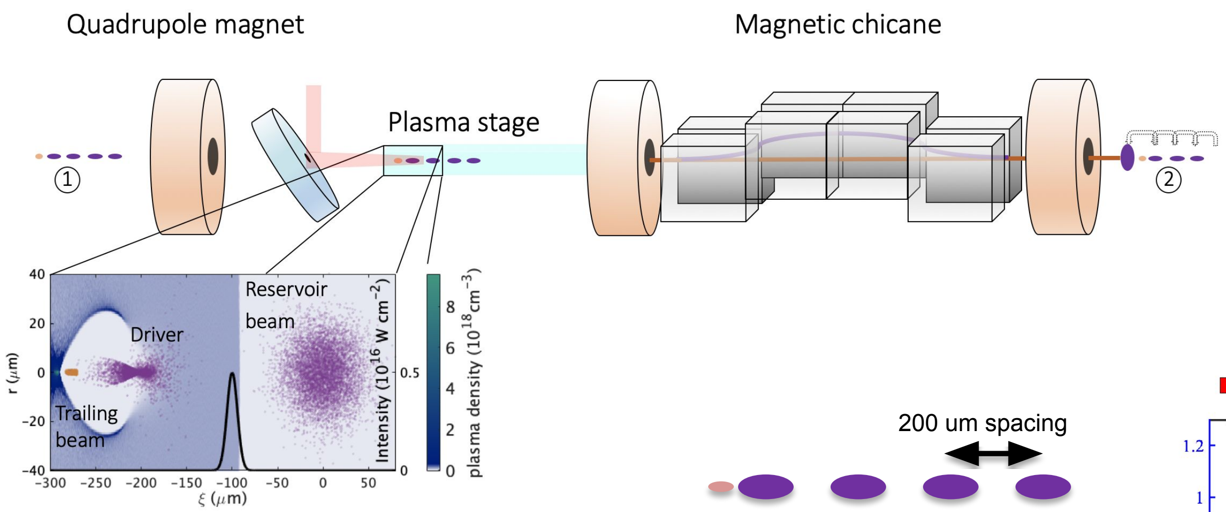

- Full PWFA-LC stage with Li plasma and adiabatic ramps and offset witness beam. We show elimination of centroid with ~85% emittance growth.
- Many ramps/drive beam parameters can be tested.



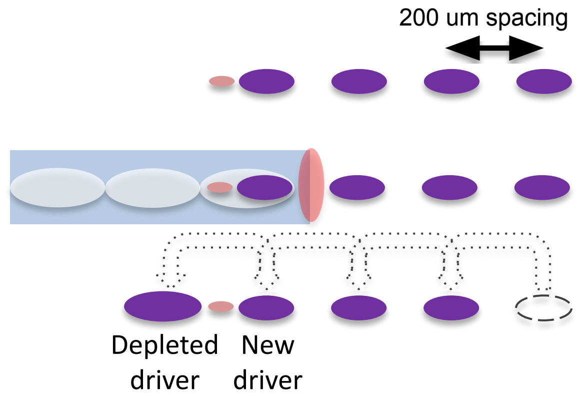
# WG4+WG2 Sessions 7+8

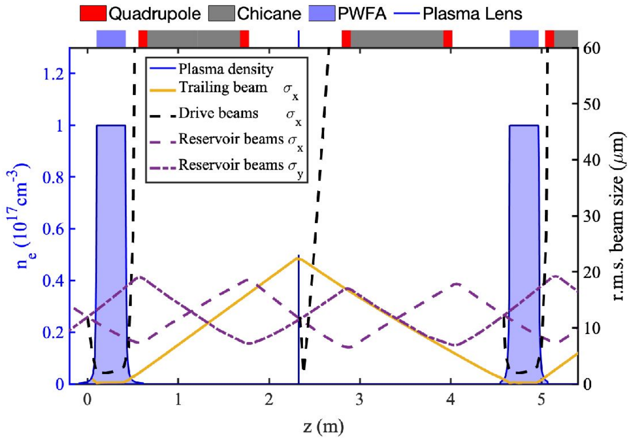
## Concepts

# High average gradient in a laser-gated multistage plasma wakefield accelerator




- Temporarily separated lattices
- Laser-ionization as PWFA gating mechanism
- 1 GV/m average gradient at final beam energies up to 1 TeV

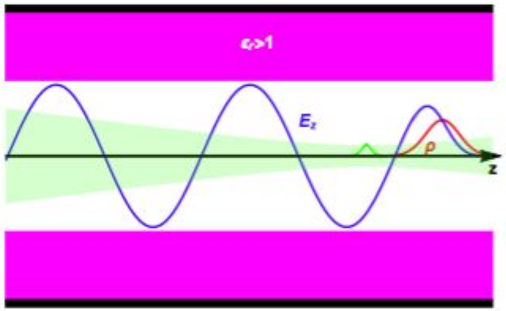


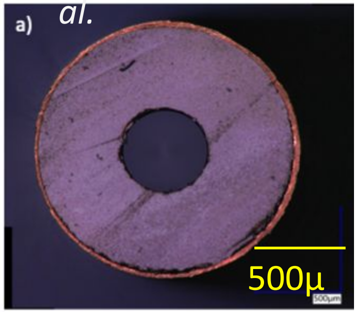



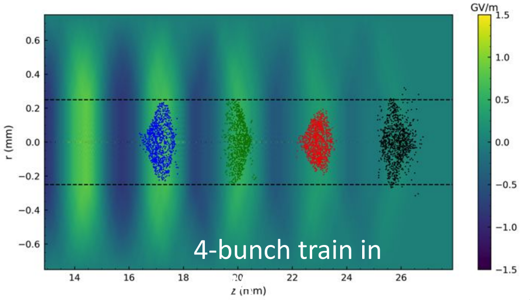
# Beam-Driven Dielectric Wakefield Acceleration with a Plasma Photocathode at the AWA

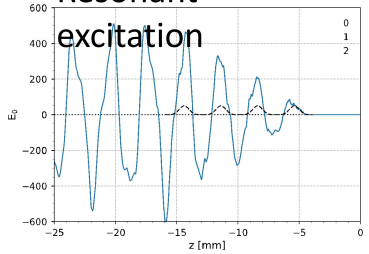
*G. Andonian, et al.*

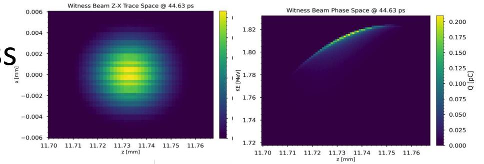
- ”Dielectric Trojan Horse” replaces PWFA bubble with DWA structure
- Laser injected witness beam inside gas-filled DWA
- GV/m acceleration and low-emittance witness beams
- AWA experiment using 4-bunch train (4nC/bunch)
  - $E_z$ ~ 650MV/m
- First test run:
  - generated drive bunch train
  - gas delivery (windowless)
  - laser delivery at IP
- Next run: generate/measure witness beam



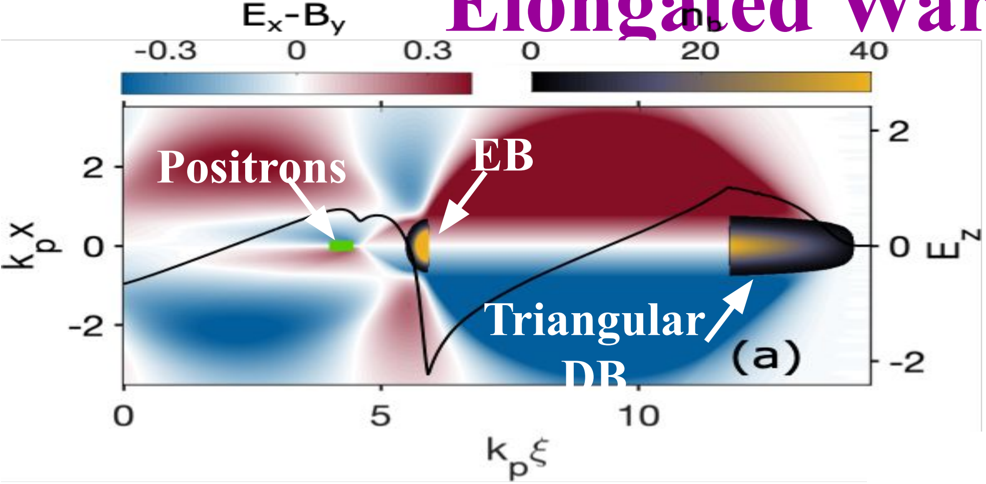



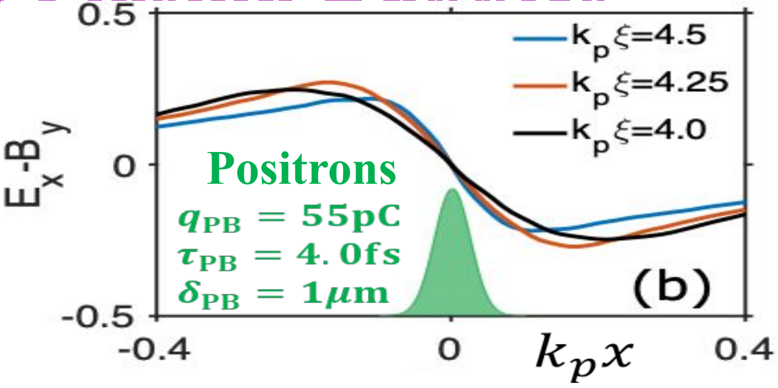



# Acceleration/Focusing of Positrons in Elongated Warm Plasma Bubbles



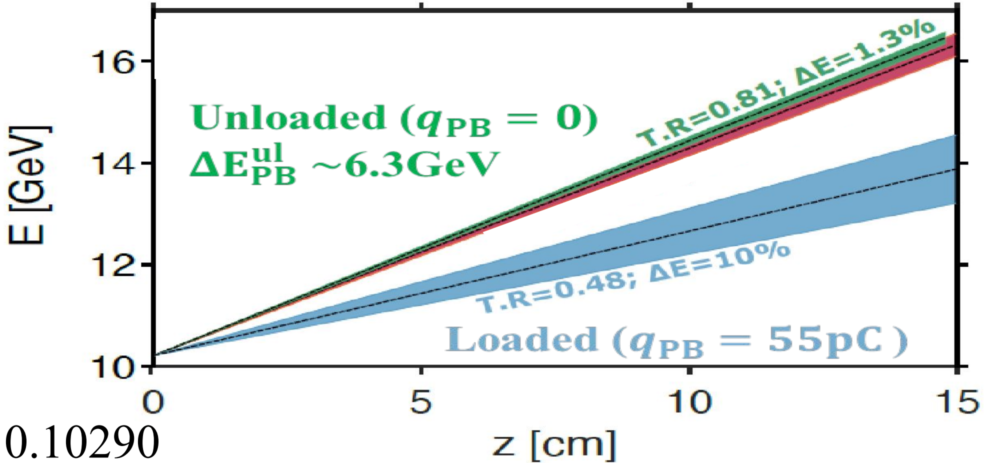

DB: $q_{DB} = 0.85$nC, $\tau_{DB} = 31$fs, $\delta_{DB} = 5\mu$m

EB: $q_{EB} = 0.34$nC, $\tau_{EB} = 4.2$fs, $\delta_{EB} = 4\mu$m

Hi-DEF: $D_{lf} = 0.3k_p^{-1}$, $l_{lf} = 0.5k_p^{-1}$

DB-EB Separation: $\Delta T = 160$fs

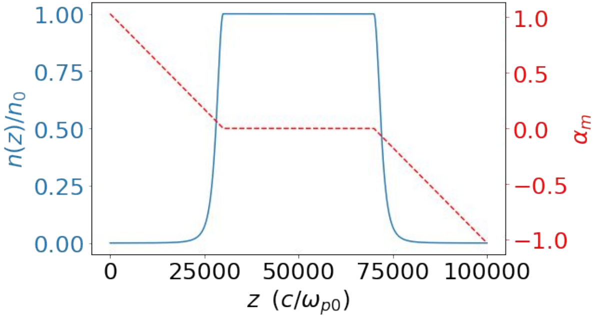
Plasma: $n_0 = 5 \times 10^{17}$cm$^{-3}$



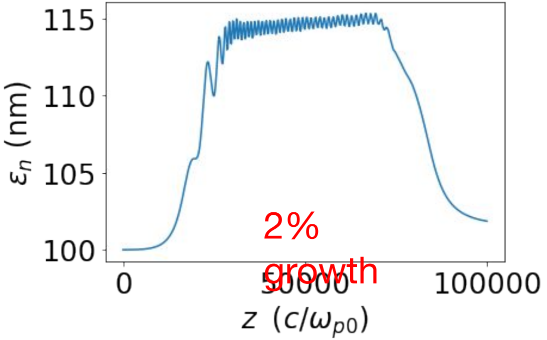

T. Wang, V. Khudik, and G. Shvets, arXiv:2110.10290

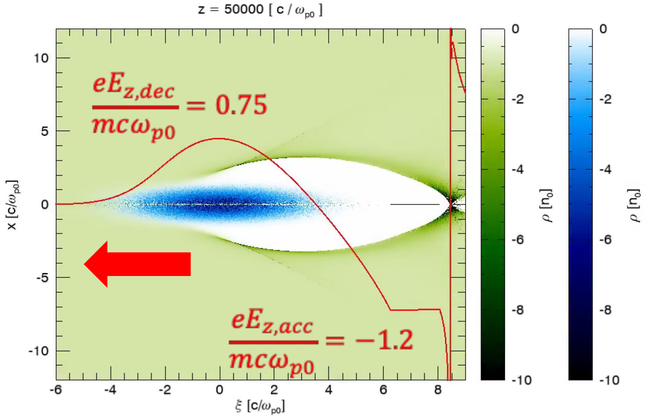
# Only 2% emittance growth in a PWFA-LC stage!

- Drive beam:
  25GeV, Q = 4.8nC, $\sigma_r = 10\mu m, \sigma_z = 30\mu m. \frac{n_{b0}}{n_0} = 6$, non-evolving.
- Witness beam:
  25GeV, Q = 1.6nC ($I_{head} = 25.26$ kA, $I_{tail} = 6.42$ kA, $L = 30\mu m$)
  $\epsilon_n = 100$ nm.
- QPAD simulation: $\Delta r = 5\times10^{-4}\ c/\omega_{p0}$ (8.4 nm). 24000 cells.
  $\Delta\xi = 0.01 c/\omega_{p0}$ (170 nm). 1500 cells. m=0 mode. $3\times10^4$ core hours.




$\leftarrow$ 1.7 $m$ $\rightarrow$



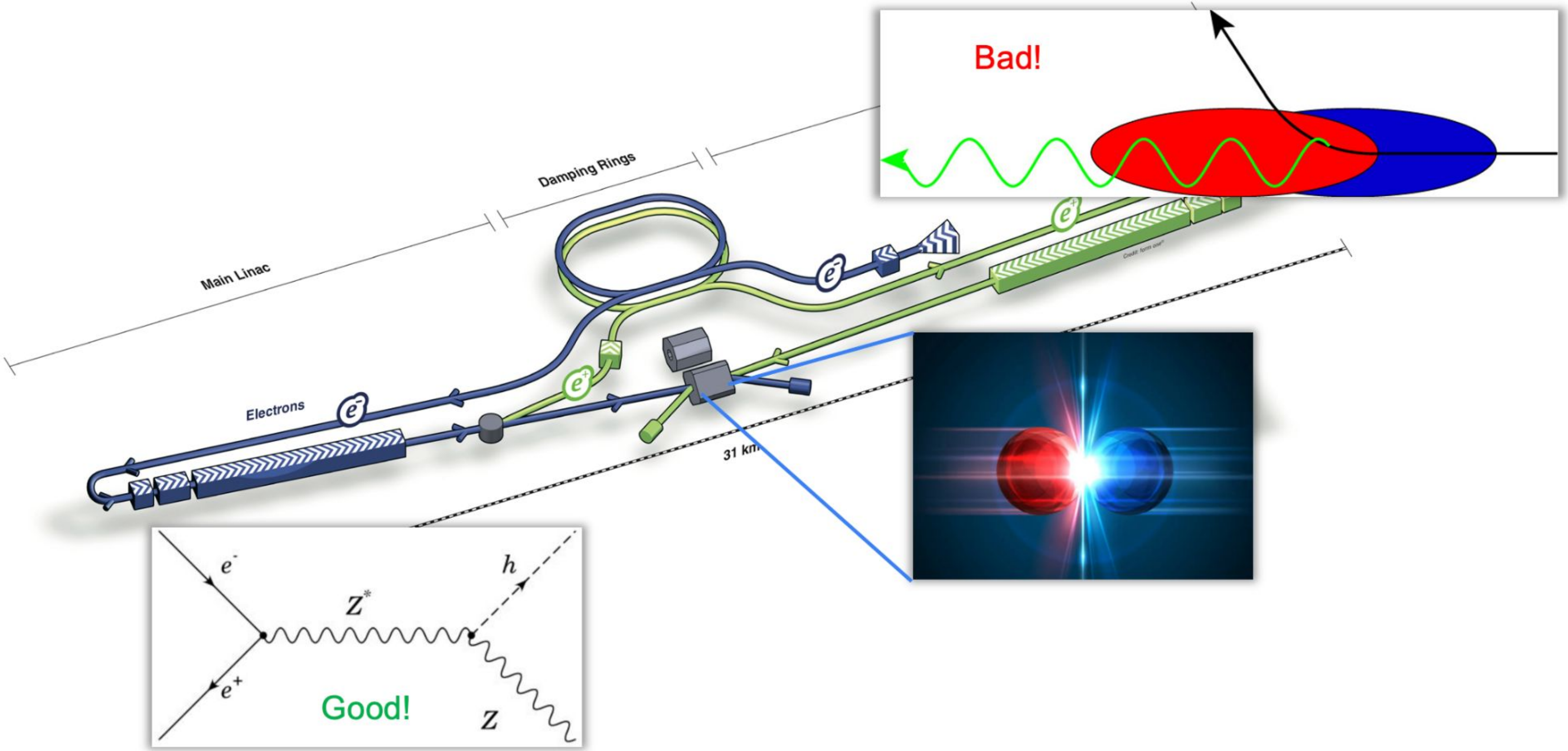




**25GeV → 50GeV**
**$\sigma_\gamma/\bar{\gamma}$ : 0 → 0.1%**


- M. Tzoufras et al., PRL 101, 145002 (2008)
- T. N. Dalichaouch et al., POP, 28, 063103 (2021)
- F. Li et al., Comput. Phys. Comm. 261, 107784 (2021)

# Beam-Beam Interactions

S. Gessner, SLAC



# WG4

40 Contributed Talks!

10 Student Posters!

5 Joint Sessions!