AAC'22 Advanced Accelerator Concepts Workshop

November 6 - 11, 2022

Hyatt Regency Long Island, NY

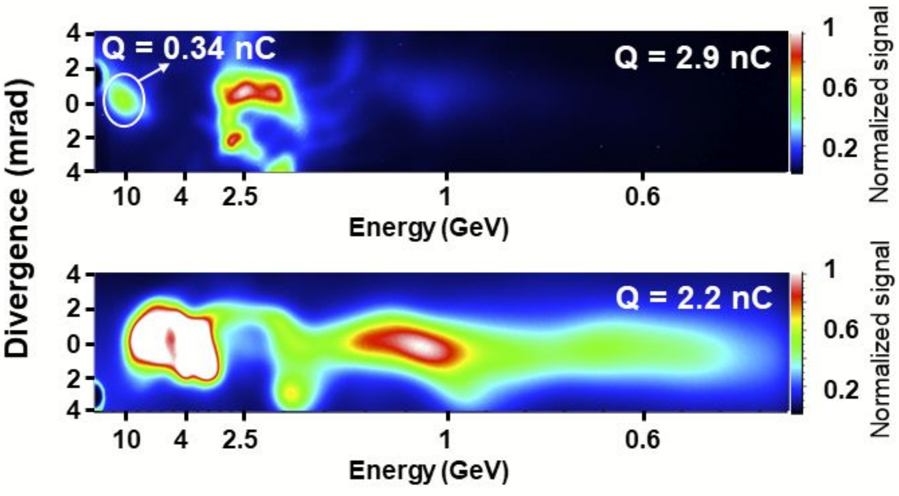
WG1 Summary: Laser Plasma Wakefield Acceleration

Y. Ma (University of Michigan), I. Petrushina (Stony Brook University),
M. Turner (LBNL)

WG 1 Plenary Contributions

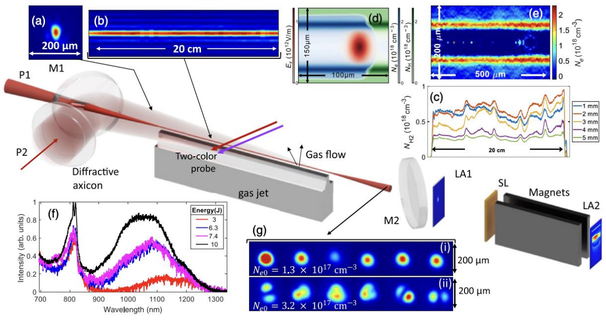
Acceleration beyond 10 GeV of a 340 pC electron bunch in a 10 cm nanoparticle-assisted wakefield accelerator

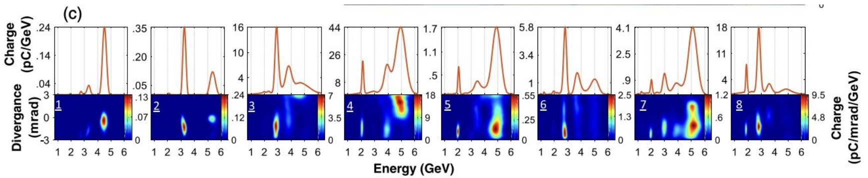
Constantin Aniculaesei (The University of Texas at Austin)



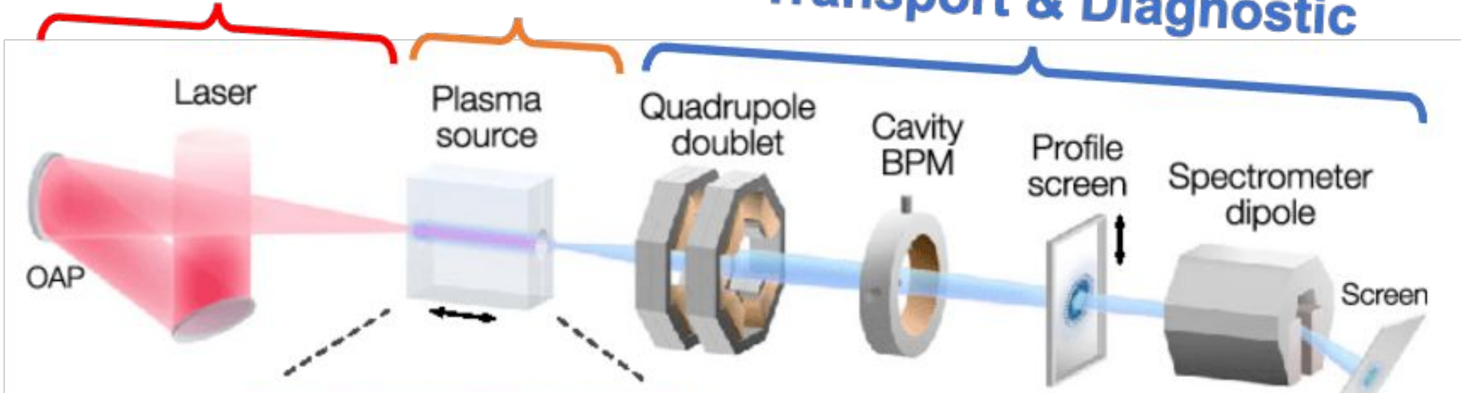
Multi-GeV electron bunches from an all-optical laser wakefield accelerator

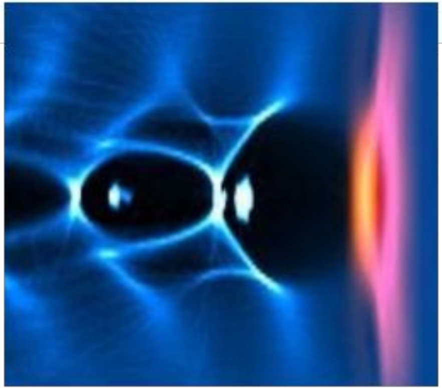
Bo Miao (University of Maryland), Jaron Shrock (University of Maryland, College Park) , Ela Rockafellow (University of Maryland, College Park)





Driver **Target** **Transport & Diagnostic**





Depletion

Dephasing

Diffraction

Plasma Wave & Injection

⇒ Contributed Sessions

Driving the Plasma Wakefield

Driver (e.g. Laser) is the energy source.

How to choose your driver:

- Laser technology (Ti:sapp, CO2 Lasers, Combined Fiber lasers, Thulium,…)
- Repetition rate (kHz,...)
- Energy per pulse (energy gain per stage,...)
- Wavelength (ponderomotive force)
- Shaping & Control (shape wakefields)
  - Arbitrary Structure
  - Pulse train (e.g. modulator or SRS)

Results from kHz systems

eli beamlines

kHz laser-driven electron beams up to 50 MeV at ELI Beamlines

Carlo Maria Lazzarini
CarloMaria.Lazzarini@eli-beams.eu

Idea:

Develop a compact source of high repetition rate (> 1 kHz) high energy (> 50 MeV) stable electrons open to Users

Main results:

I. New **ALFA kHz LWFA beamline** driven by multi-cycle (15 fs) OPCPA up to 1 kHz laser
II. Highest electrons energy **(50 MeV QME)** ever reached at kHz repetition rate
III. Very collimated high energy beams, average divergence **2.1 mrad (FWHM)**
IV. Higher power mode at tens of MeV, higher current (0.3 nA for > 20 MeV)
V. Possibility to accelerate in **continuous 1 kHz mode** over hours
VI. First irradiation tests with **in-air dos erate estimated > 1 Gy/s**

New applications made possible:

I. VHEE source for radiotherapy

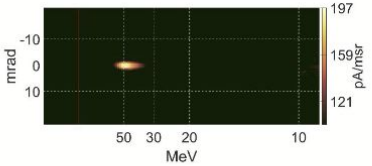
[Citrin, D. E. *N. Eng. J. Med.* **377**, 1065-1075 (2017);Svendsen, K. et al. *Sci. Rep.* **11**, 5844 (2021)**]**

I. X-ray sources for medical imaging

[Brummer, T. et al. *Phys. Rev. Accel. Beams* **23**, 031601 (2020)]

Next:

I. Power scalable laser system **up to 5 TW** (possible up to 10 TW)
II. Different geometries under study for reaching **100s of MeV e-beams**
III. Maximize the charge of the QME beams to reach **Watt-level e-beams**



C.M.Lazzarini, et al., submitted for review

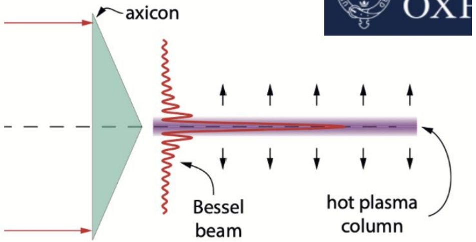
Talk summary for the 20° AAC Workshop, NY, 2022

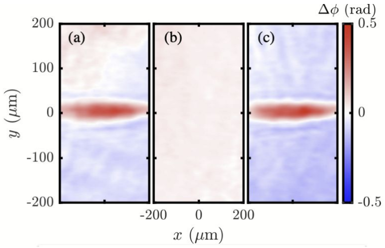
FZU Institute of Physics of the Czech Academy of Sciences
The Czech Academy of Sciences

Tuning your drive pulse and understanding its evolution

Experimental demonstration of kHz hydrodynamic optical-field-ionized plasma channels

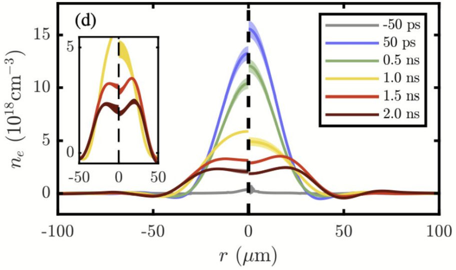
James Cowley
Univ. of Oxford



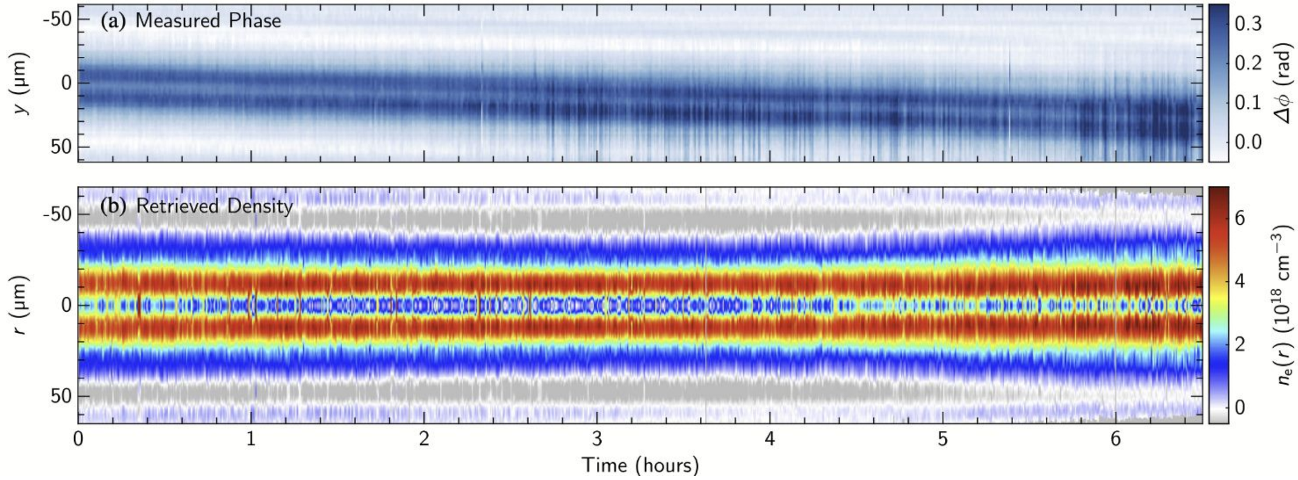


Single pulse

Second of two pulses (1 ms delay)



Results - long term operation



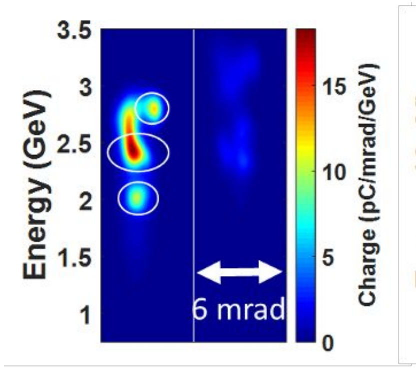
- No significant long-term evolution of channel properties
- Operation at 1 kHz seems to be no issue for HOFI channels alone

Using mode filtering and localized dopant to improve bunch quality in self-waveguided LWFA

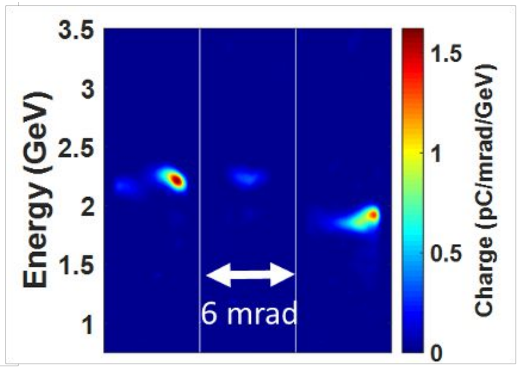
Jaron Shrock (University of Maryland)

Early portion of a leaky waveguide can be used to filter out higher order mode content from unavoidable coupling mismatch in real-world self-waveguiding LWFA

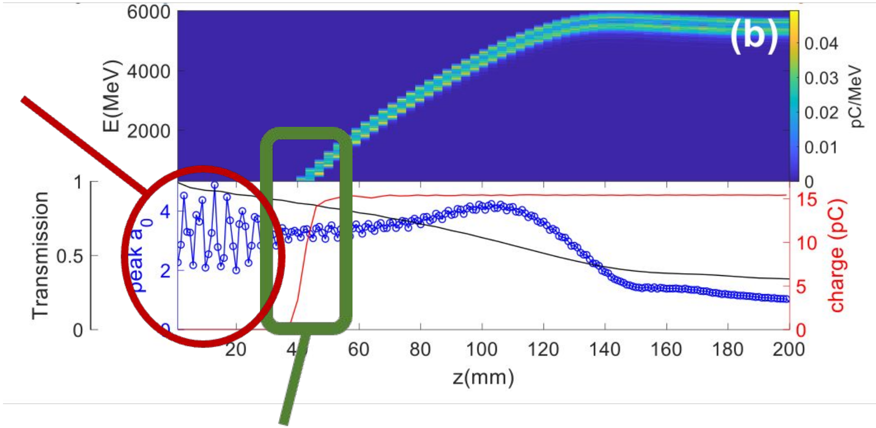
Recorded Spectra with dopant in entire 20 cm jet



Recorded Spectra with dopant in middle of 20 cm jet



Early experimental results implementing the technique show improved localized injection *manuscript in preparation*



Localizing dopant for ionization injection after this region can lead to more reliable injection and low energy spread bunches

B. Miao *et al*., PRL **125**, 074801 (2020).
L. Feder *et al*. Phys. Rev. Research **2**, 043173 (2020)
B. Miao *et al*. Phys. Rev. X **12**, 031038 (2022)
J. E. Shrock *et al*. Phys. Plasmas **29**, 073101 (2022)

"Optical mode filtering and electron injection in multi-GeV laser wakefieldacceleration", J.E. Shrock et al.

Spatiotemporal Optical Vortices and Relativistic Optical Guiding

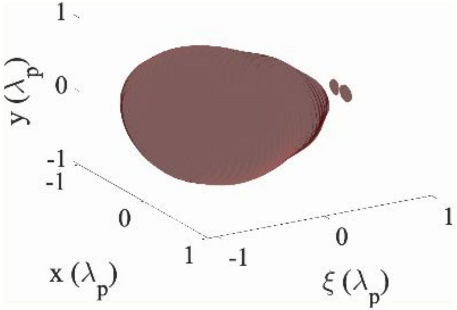
Manh Le, University of Maryland

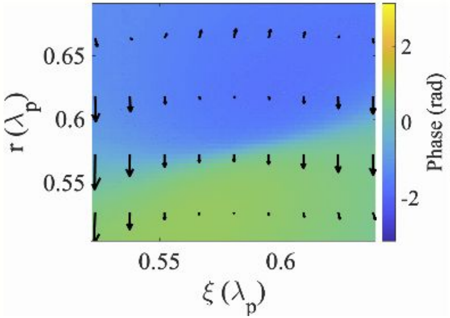
3D simulations of intense laser pulse propagation were performed to investigate formation and role of STOVs during relativistic self-focusing in plasma.

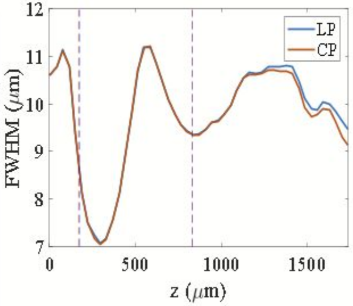
Spatiotemporal optical vortices (STOVs) were found to:

Emerge from phase shear from relativistic self-focusing in plasma.

Nucleate at points that rearrange themselves to form rings around the pulse







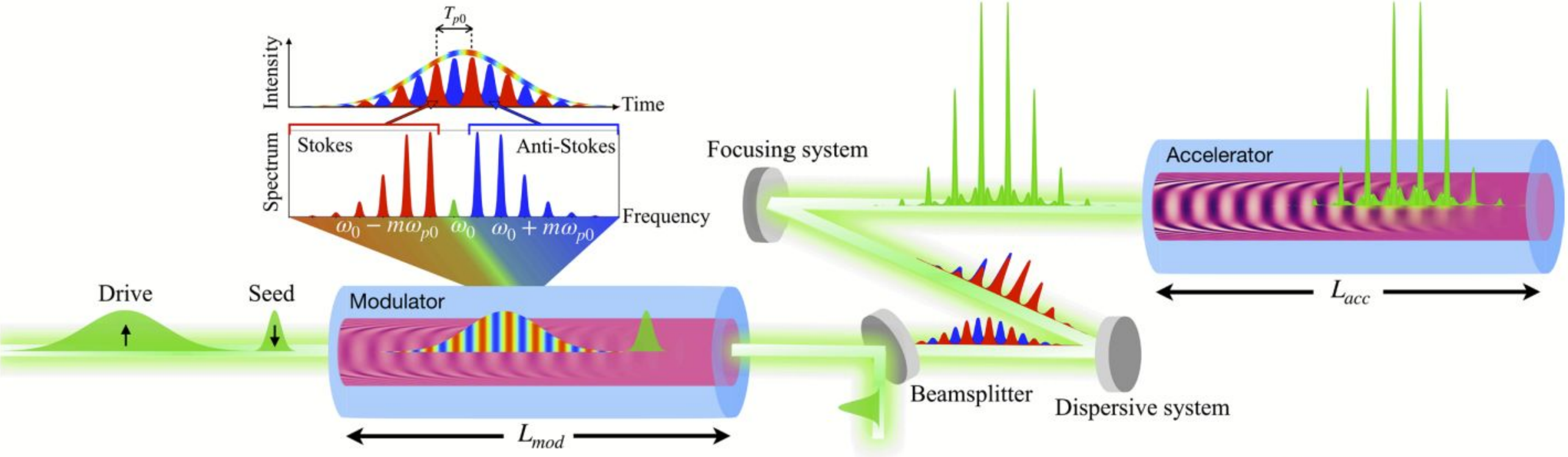
Mediate the flow of electromagnetic energy within the laser pulse and enable transition from inward to outward energy flow.

Shaping your drive pulse

Roman Walczak (University of Oxford)

Summary of P-MoPA ► PRL **127**, 184801 (2021)

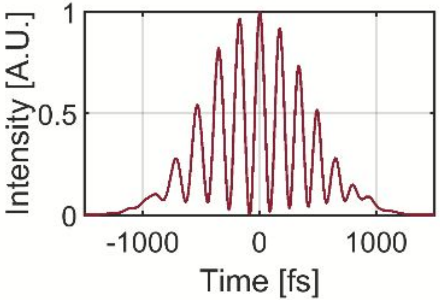
- ► PIC simulations demonstrate that a 1.7 J, 1 ps driver, and a 40 fs modulator plasma wake pulse can accelerate electrons to energies of 0.65 GeV in a plasma channel with axial density of 2.5 x 10^{17} cm^{-3}.
- ► This opens a route to high rep rate, GeV scale plasma accelerators driven by thin-disk lasers, which can provide joule-scale, ps-duration laser pulses at multi-kHz rep rate and high wall-plug efficiencies.



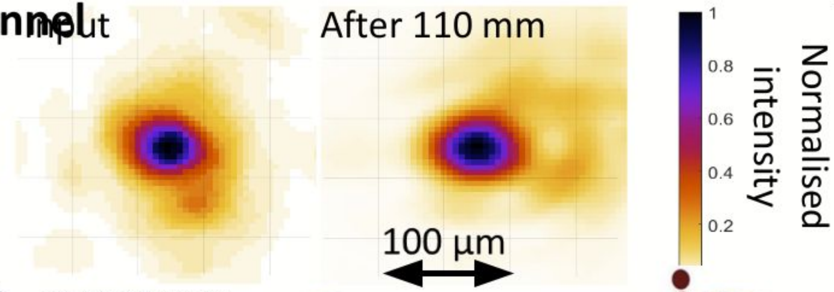
Observation of resonant wakefield excitation by pulse trains guided in long plasma channels

Simon Hooker, Roman Walczak, Emily Archer, James Chappell, James Cowley, Linus Feder, Oscar Jakobsson, Alex Picksley, <u>Aimee Ross</u>, Johannes van de Wetering, Wei-Ting Wang, Nicolas Bourgeois, Laura Corner, Harry Jones, Lewis Reid

1 ps, 2.5 J pulse train of ~10 pulses

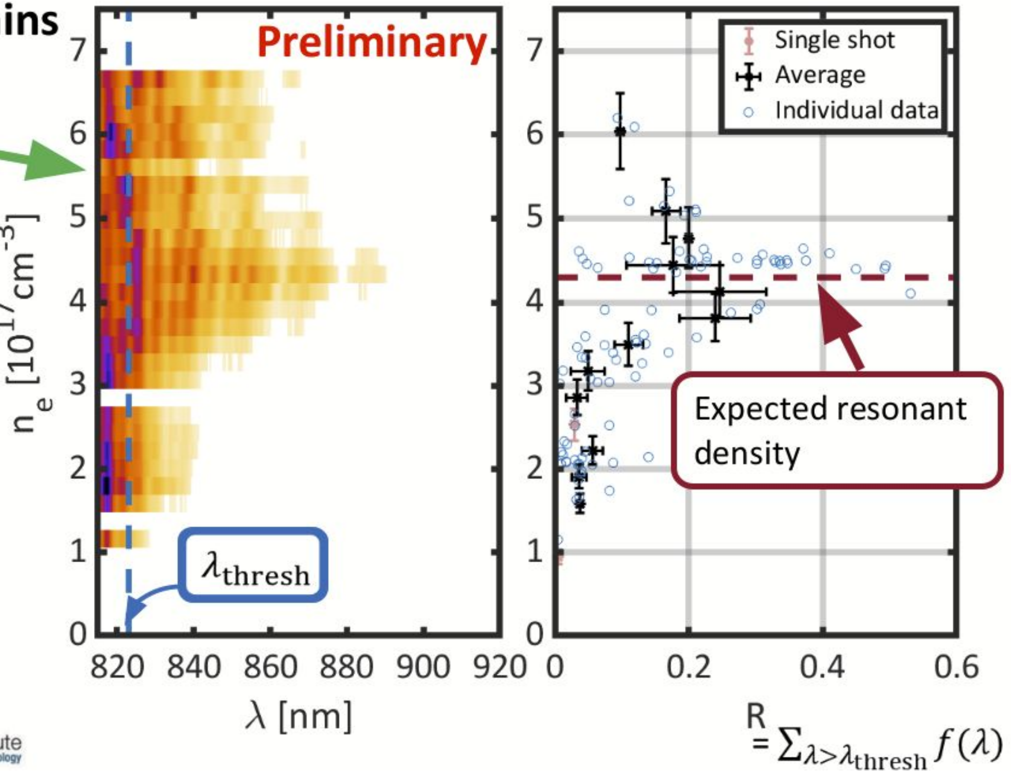


Pulse trains guided in HOFI channel



Resonant wakefield excitation by guided pulse trains

Transmitted spectra $f(\lambda)$ of pulse trains

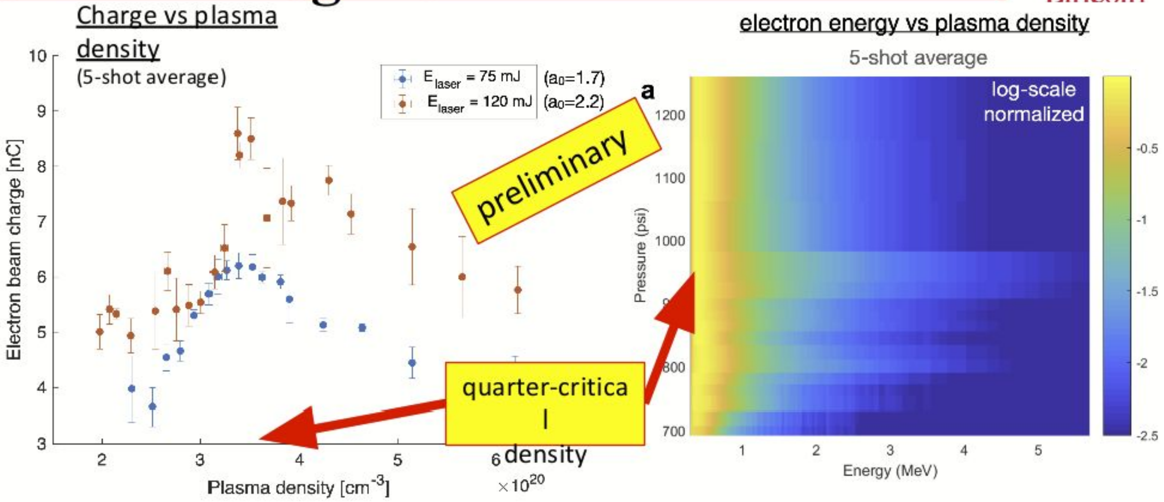


$R = \sum_{\lambda > \lambda_{\mathrm{thresh}}} f(\lambda)$

High-Efficiency Laser-Plasma Acceleration: A Novel* LPA Regime

(Mathias Fuchs)

- Generation of high-charge (~10 nC) electron bunches with high efficiency (12% laser-to-electron bunch) using 3 TW laser (a_0=2.2) & 20 µm gas jet
- Narrow resonance at quarter critical plasma density
- Efficient excitation of plasma waves through absolute Stimulated Raman Scattering instability
- Relaxation of requirements on LPA laser driver properties (intensity and laser pulse duration)
- Interestingly, no significant shift of resonance with a_0 (both, in experiment and simulation)


Charge vs plasma density

(5-shot average)

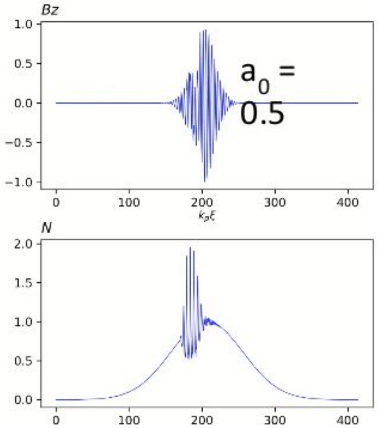
electron energy vs plasma density

5-shot average

preliminary

quarter-critical density

PIC simulation showing excitation of large-amplitude plasma wave through absolute SRS



Laser pulse

Plasma density (normalized)

mfuchs@unl.edu

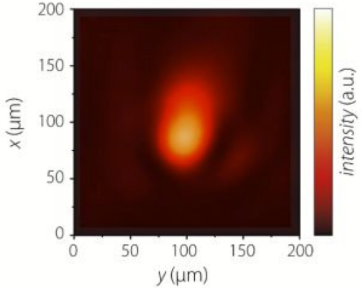
HI JENA
HELMHOLTZ
Helmholtz-Institut Jena

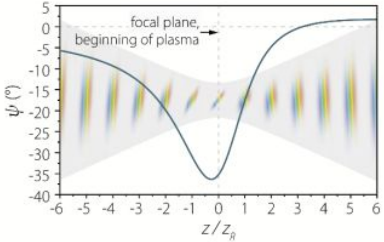
The Role of Spatio-Temporal-Couplings in Stimulated Raman Side Scattering

Alexander Sävert, Carola Zepter, Andreas Seidel, Matt Zepf, Malte Kaluza

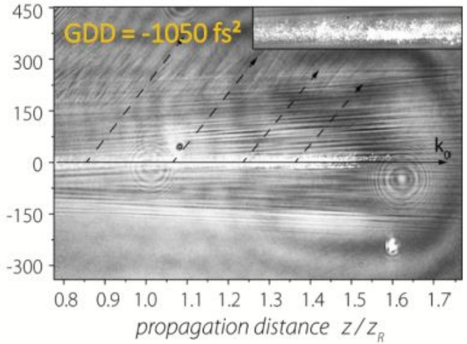
FRIEDRICH-SCHILLER-
UNIVERSITÄT
JENA

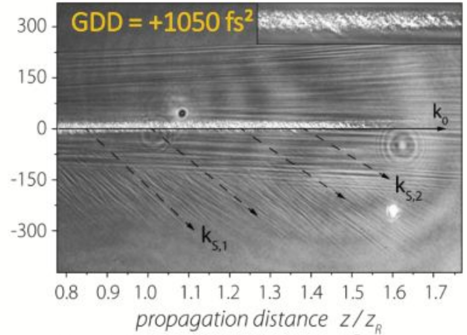
spatial chirp
in focus + linear chirp
= pulse front tilt

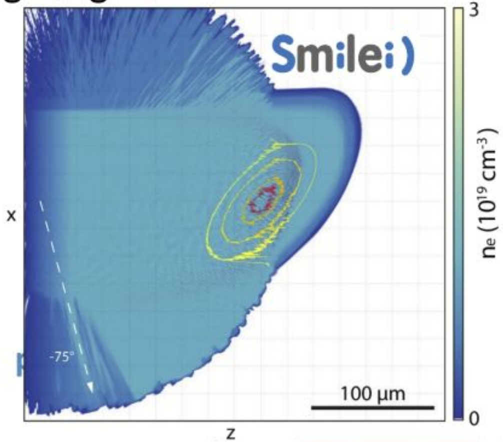


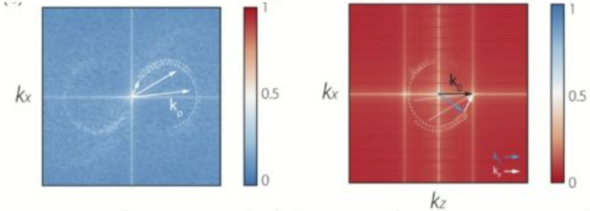


asymmetric SRSS under large angles







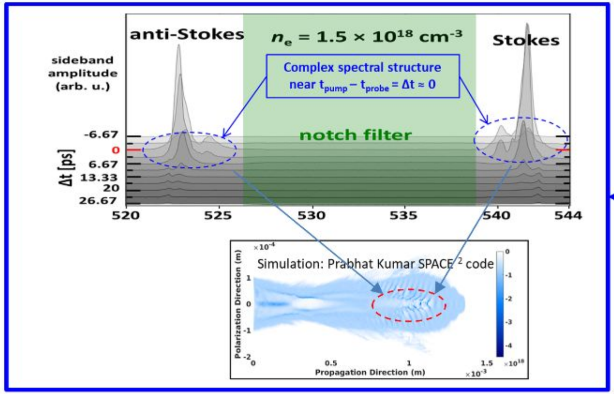


oberserve phase matching under larger angles

scattering angle α =PFT angle ψ+ sgn(ψ)+ SRSS angle θ

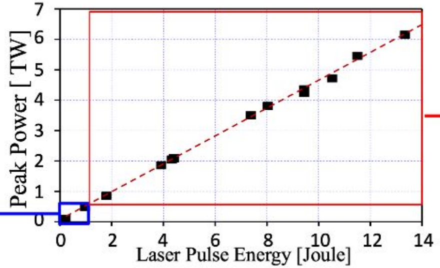
CO_2-laser-driven wakefield acceleration

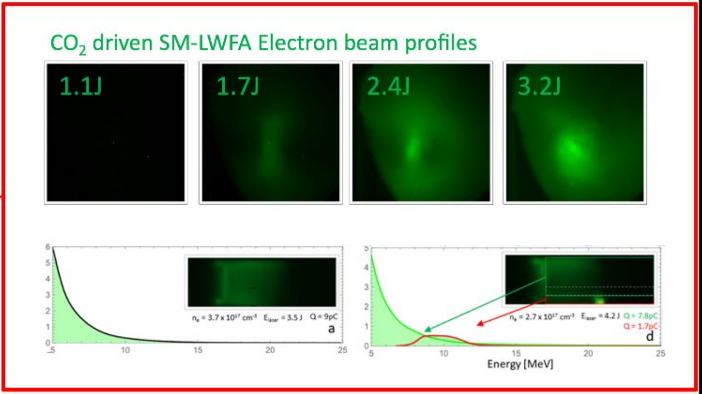
R. Zgadzaj (UT), I. Petrushina (SBU), Yuxuan Cao (UT) et al.



CO_2 laser power <0.5TW
Optical detection and characterization of SM-LWFA

CO_2 laser power 5TW
First demonstration of electron injection and acceleration





What the HEP community demands[1] from plasma accelerators:

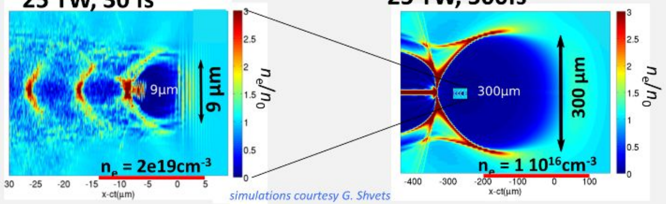
Already in hand:
- **10 fs bunch duration:** high peak current at IP, minimize beamstrahlung

Unsolved problems:
- **0.1% energy spread:** observation of resonant particle creation processes.
- **high spin-polarization:** detection of parity-violating interactions, nuclear spin
- **nC charge:** high luminosity at IP.
- **staging:** easier with large LWFAs..

Vision: Quasi-mono-energetic LWFAs based on large, controlled mid-IR laser-driven bubbles

λ_{drive}= 0.8 μm (UT)
25 TW, 30 fs

λ_{drive}= 10 μm
25 TW, 500fs



simulations courtesy G. Shvets

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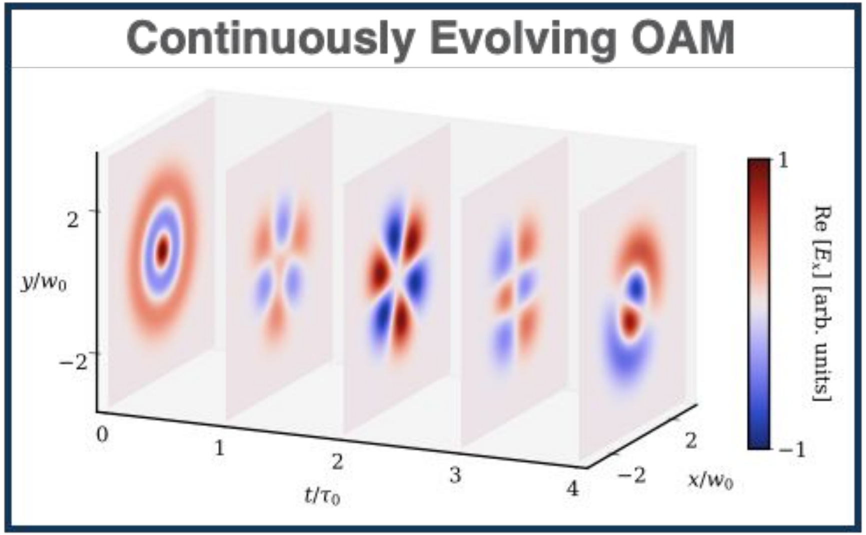
[1] *Accelerating Discovery: A Strategic Plan for Accelerator R&D in the U.S.*, High Energy Physics Advisory Panel report (2015)

[2] K. Yu, R. Samulyak, "SPACE code for beam-plasma interactions," Proc. IPAC, 728 (2015)

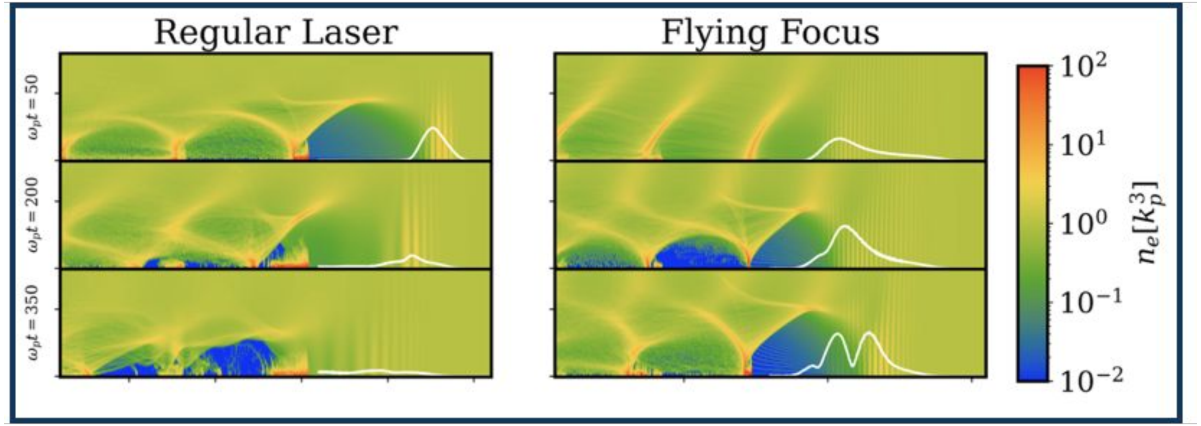
This work is supported by U. S. DoE grants:
DE-SC0014043, DE-SC0011617, and DE-SC0012704.

Arbitrarily Structured Laser Pulses - Jacob Pierce (UCLA)

1. Arbitrarily Structured Laser (ASTRL) pulses are superpositions of laser pulses with varying properties, yielding controllable emergent phenomena (e.g., continuously evolving spot size or OAM)
2. Mathematical description of ASTRL pulses enables theoretical and computational studies, including concepts for LWFA with flying focus pulses
3. New ASTRL pulses may enable novel techniques for advanced acceleration and radiation generation concepts
4. ASTRL pulses can be synthesized by dedicated optical assemblies or by a new proposed technique based on divided pulse amplification



For more information, see Pierce et al., arXiv:2207.13849, 2022

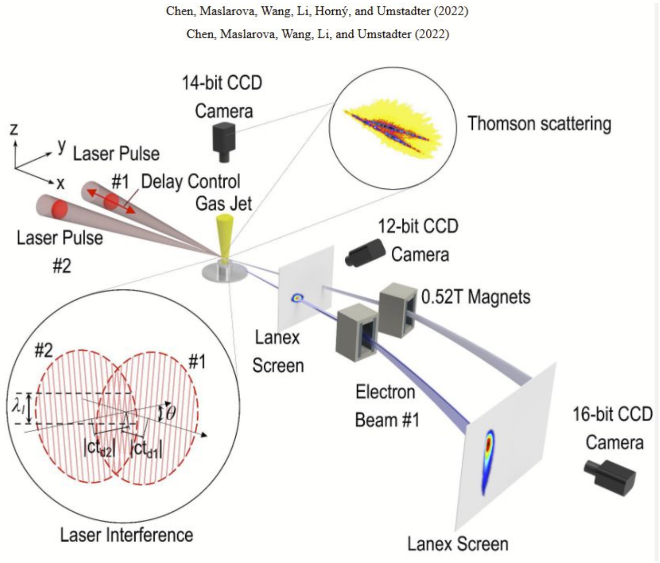


Electron Injection and Trapping

- Self-injection
  - NIR & CO2
- Colliding pulse injection
  - Nearly collinear
  - Nearly counter-propagating
- Density transition injection
  - Modulated down-ramp injection
  - HOFI shock injection
- Two-color ionization injection
- External injection

Nearly collinear optical injection of electrons into wakefield accelerators

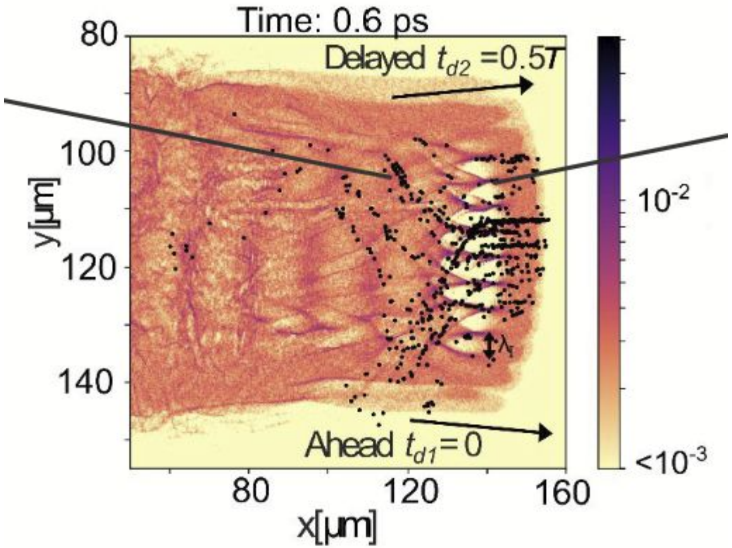
Qiang Chen et al., University of Nebraska-Lincoln



Chen, Maslarova, Wang, Li, Horný, and Umstadter (2022)

Chen, Maslarova, Wang, Li, and Umstadter (2022)

Plasma grating

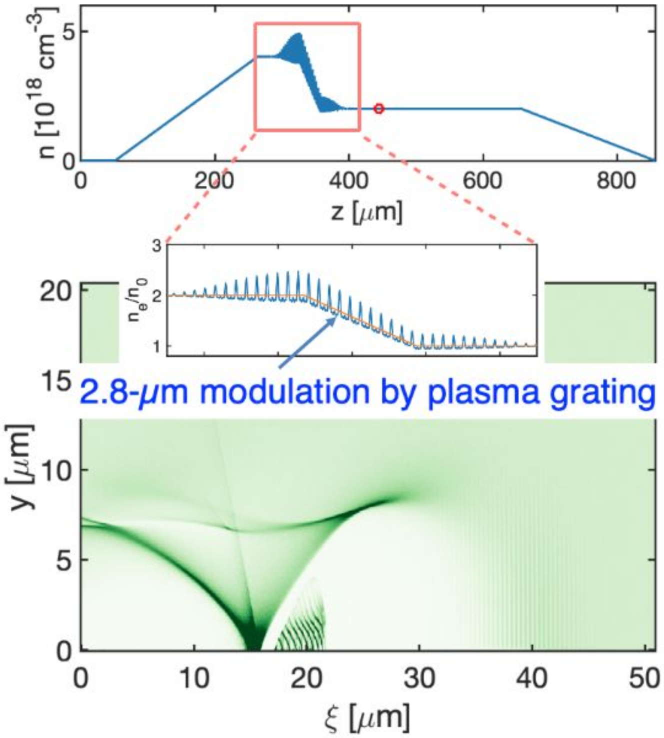


- Nearly collinear colliding pulse injection was demonstrated, with the injector as intense as the LWFA driver;
- The injection was sensitive to the delay between two laser pulses and various e-beam splitting was observed.
- Transverse interference initiated the injection process, by kicking electrons to form a relativistic plasma grating.
- Strong interference caused a strong plasma grating, which splits lasers, plasma wakefields and e-beams.

Generating pre-bunched electron beams using modulated downramp injection

Chaojie Zhang et al, UCLA

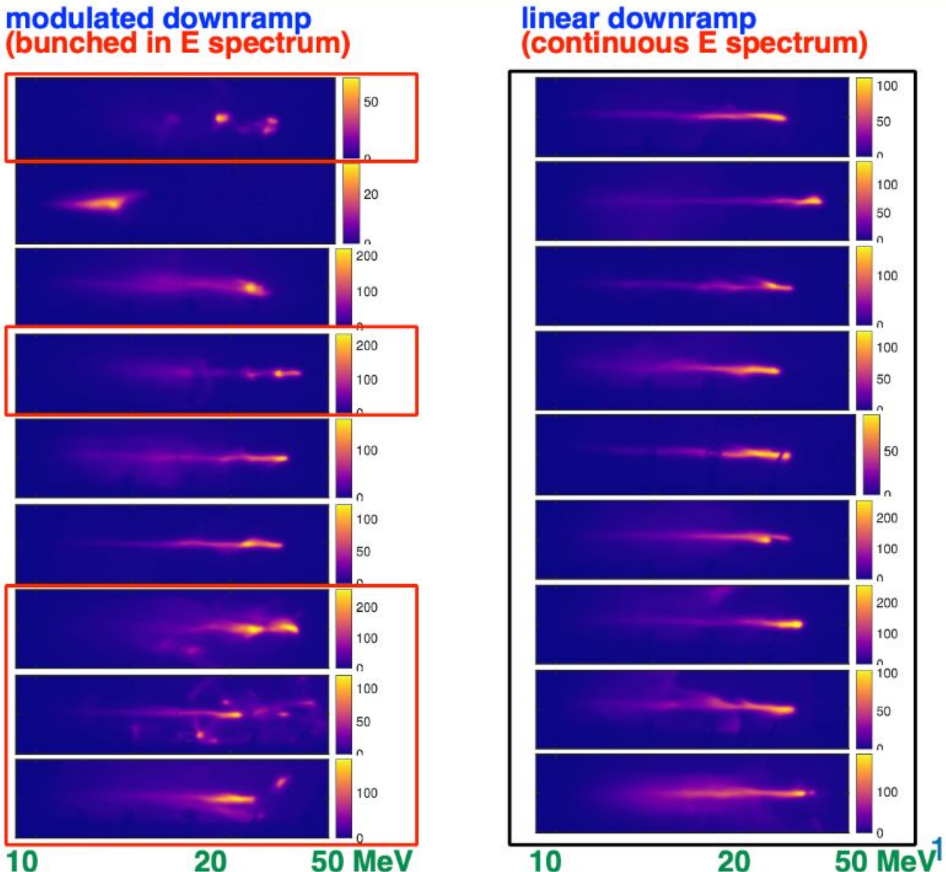
PIC simulation:



2.8-μm modulation by plasma grating

Chaojie Zhang et al, PPCF 63 (2021)
Xu et al, Nat. Comm. (2022)

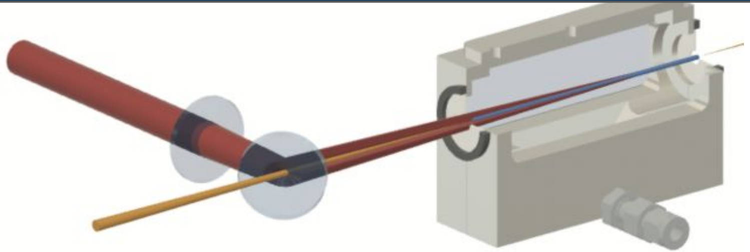
evidence of electron energy spectrum being affected by modulated downramp


modulated downramp
(bunched in E spectrum)

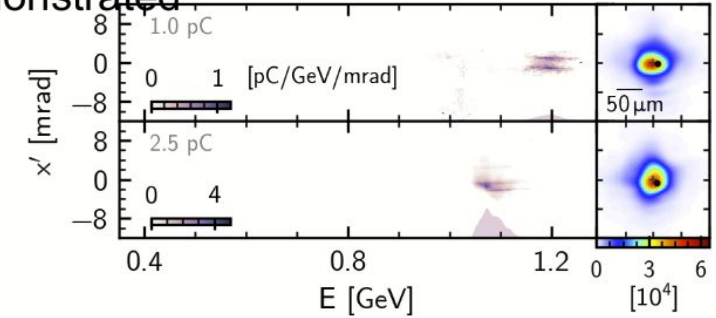
linear downramp
(continuous E spectrum)

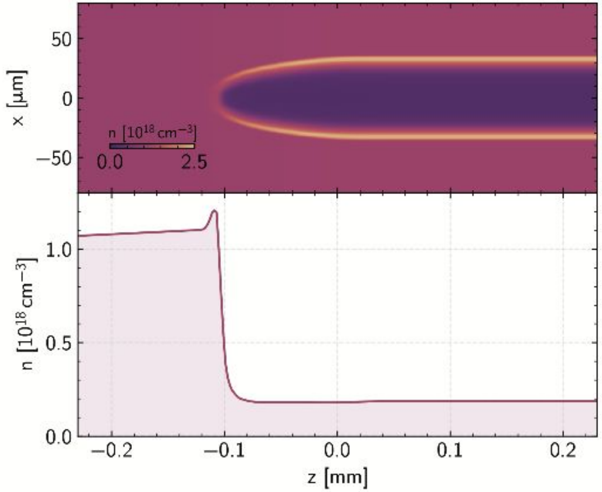
Achieved low energy spread bunches in low-density plasma channels

Alex Picksley et al, University of Oxford



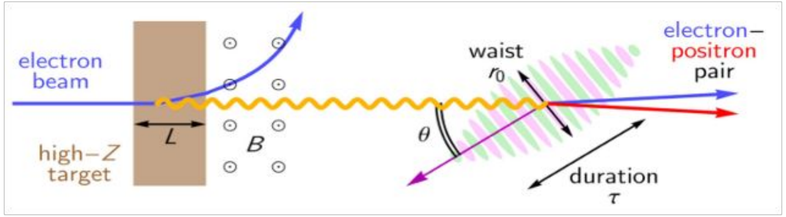
- Plasma channels generated by Hydrodynamic Optical Field Ionisation (HOFI) are capable of achieving **low densities**
- Sculpting of the plasma channel by delaying the start of the axicon focus natural forms **down-ramp.**
- GeV electron bunches with percent-level energy spreads demonstrated



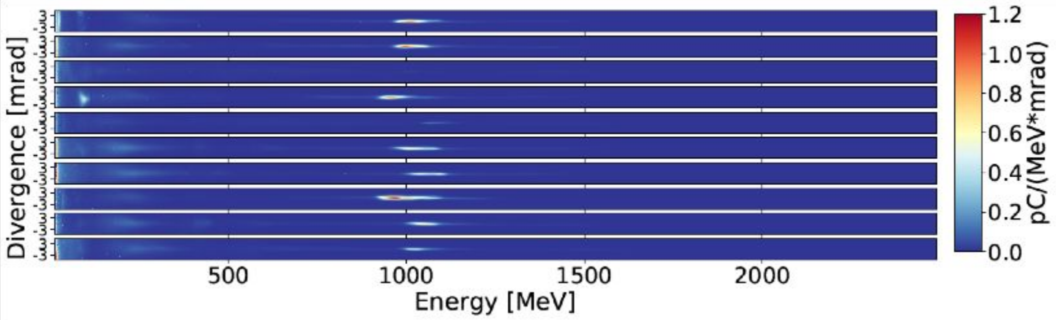


Laser wakefield acceleration to GeV electron energies for the Breit-Wheeler experiment

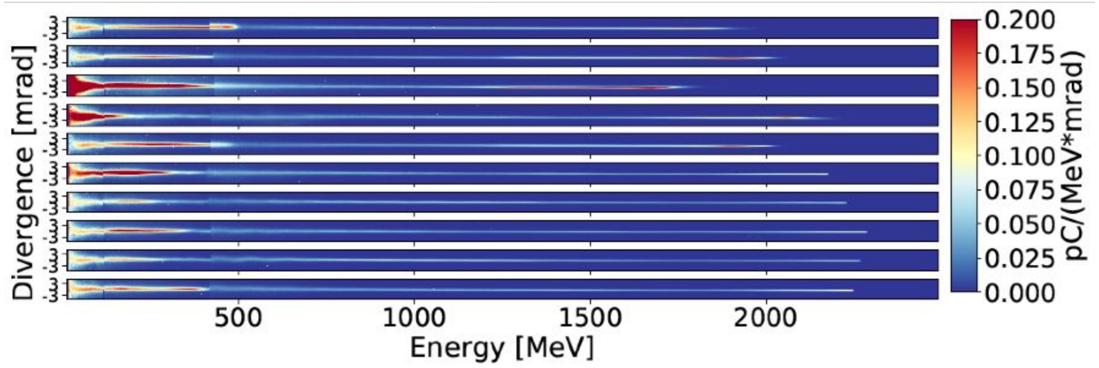
Goal: 2.5 GeV high quality electron bunches from LWFA for Breit-Wheeler Experiment

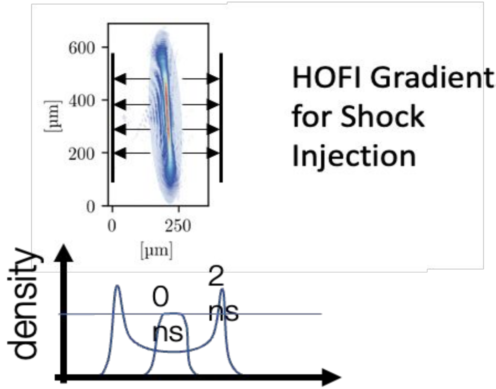


Slit Nozzle with HOFI Shock Injection: high quality beams



Gas Cell with Self Injection: over 2 GeV

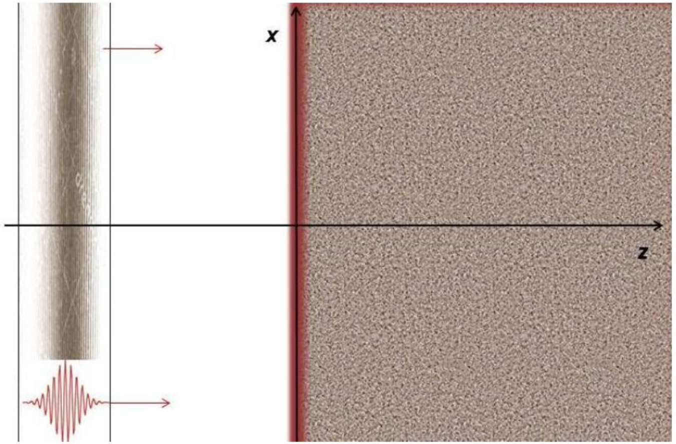


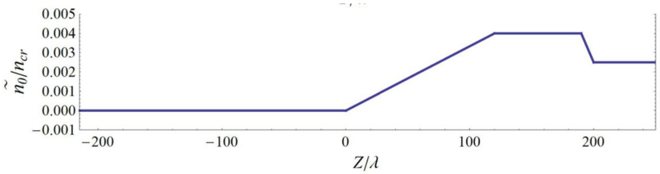


HOFI Gradients for Shock Injection

A preliminary analysis for efficient laser wakefield acceleration

Gaetano Fiore, INFN, Napoli





Hydrodynamic description of the impact of a very short and intense laser pulse onto a cold diluted plasma, study the induced PW and its wave-breaking (WB) at density inhomogeneities

Preliminary analysis of the input parameters based on a simpler model

Self-injection process in laser-wakefield accelerators driven by CO2 laser pulses

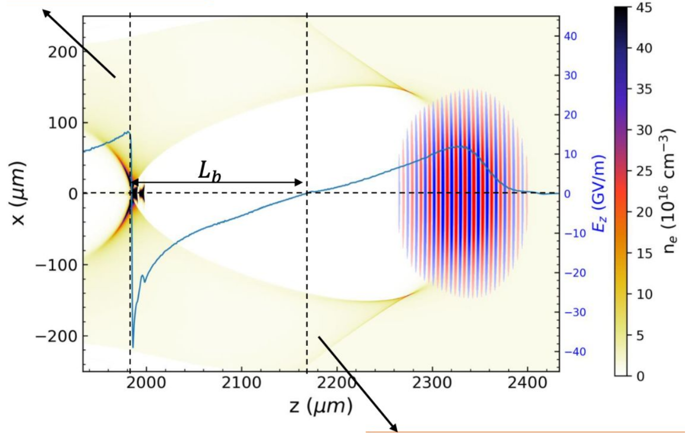
Arohi Jain et al, Stony Brook University

- ➔ Demonstrated a **good agreement between the simulations with an empirical formula** for the self-injection threshold.

$$a_0^* \approx 2.75\left[1+\left(\frac{\gamma_0}{22}\right)^2\right]^{1/2}$$

- ➔ Showed that there is a **strong correlation between injected charge and back of the bubble velocity**.
- ➔ Presented a **parameter range that suppresses self-injection** in fully blown-out bubbles which is an essential requirement in the experiments of controlled injection in LWFA.

Variotion of this point where $E_z = 0$ is used to calculate bubble velocity at the back β_b

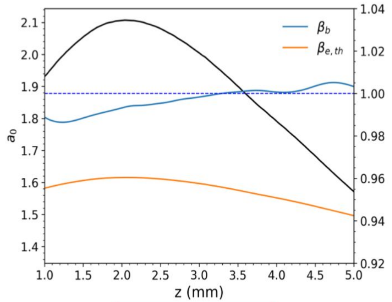


Variation in the position of dephasing point where $E_z = 0$- used to calculate β_d

$$\gamma_e \sim 2\left(1+\frac{a^2}{2}\right)^{1/2} \rightarrow \beta_e = \left(1-\frac{1}{\gamma_e^2}\right)^{1/2}$$

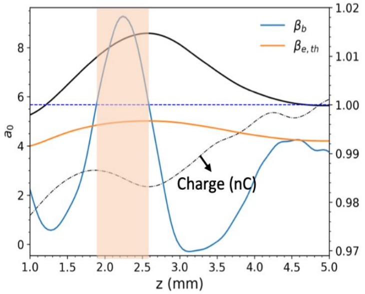
$a = \frac{eE_0}{m\omega c}$ is normalized laser amplitude

$P = 5.7\ TW, n_e = 4 \times 10^{16} cm^{-3}$



No self-injection

$P = 46\ TW, n_e = 1 \times 10^{16} cm^{-3}$

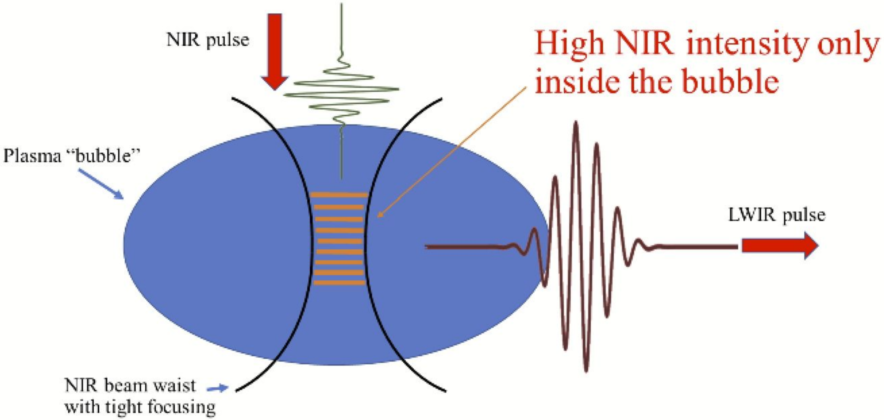


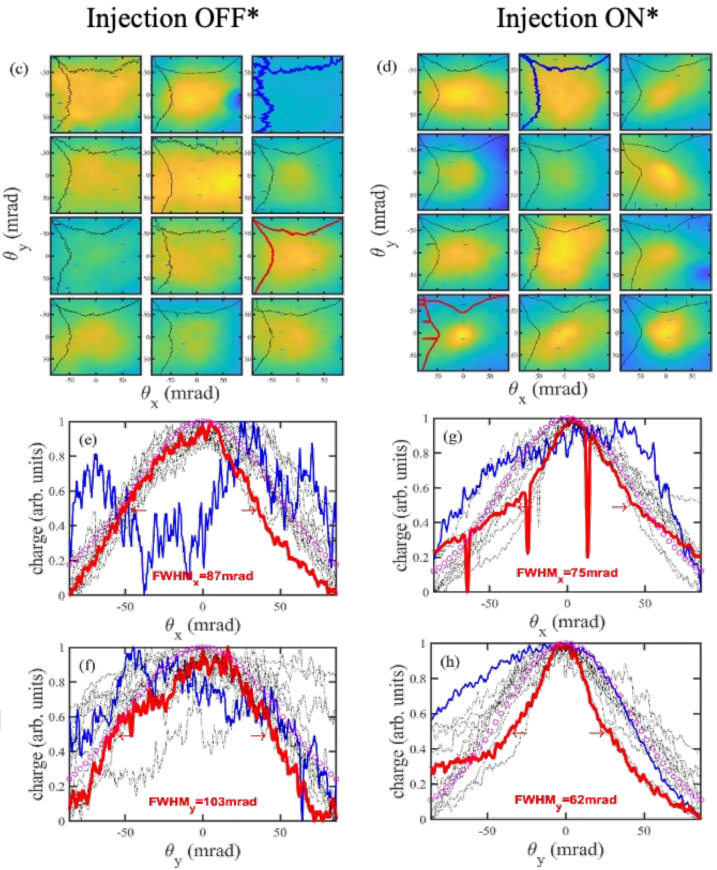
Self-injection

- **Velocity imparted to electrons β_e by laser pulse decreases with laser amplitude a_0- $a_0 \uparrow \beta_e \uparrow, a_0 \downarrow \beta_e \downarrow$**
- **No charge injection - bubble velocity at the back $\beta_b >$ velocity of the electron β_e**

First results of the two-color LWFA experiments at ATF

Navid Vafaei-Najafabadi et al, BNL

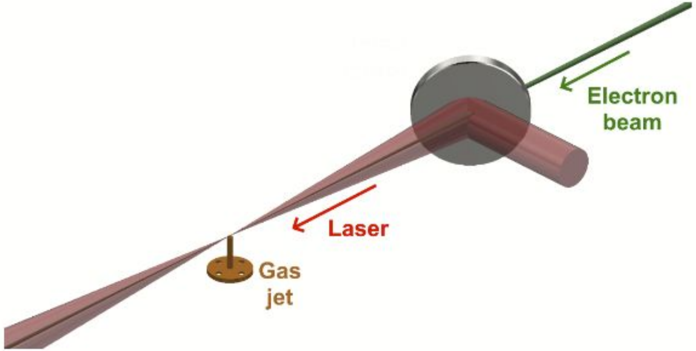


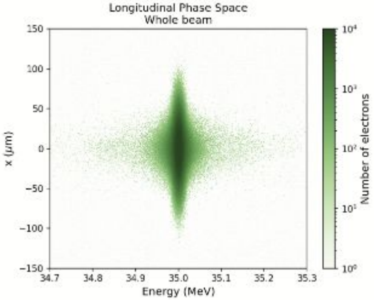


- **A first attempt at a two-color experiment using an LWIR in transverse geometry was made at ATF**
- Confirmed Ti:Sapphire's ability to create highly ionized Krypton state
- Alignment and synchronization methods were successfully demonstrated with the LWIR and NIR lasers
- **Impact of NIR ionization on LWIR-driven wakefield in self-modulated regime was investigated**
- **Multi-level ionization was implemented in simulations with preliminary results showing agreement with experiments**

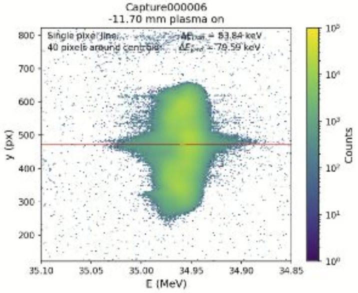
External injection at CLARA

Laura Corner, University of Liverpool





Simulation



Experiment

Experiment:

Inject 6ps electron bunch into nitrogen plasma wakefield driven by up to 40mJ laser pulse at CLARA facility, Daresbury Laboratory, UK

Expect broadened electron energy spectrum.

Results:

Max. energy gain ~ **100 keV.**

8mm plasma (overestimate): gradient ~ **12.5 MV/m.**

Simulation accounting for camera response – **25MV/m.**

Future:

Upgraded 100TW laser and new experimental area at CLARA being installed.

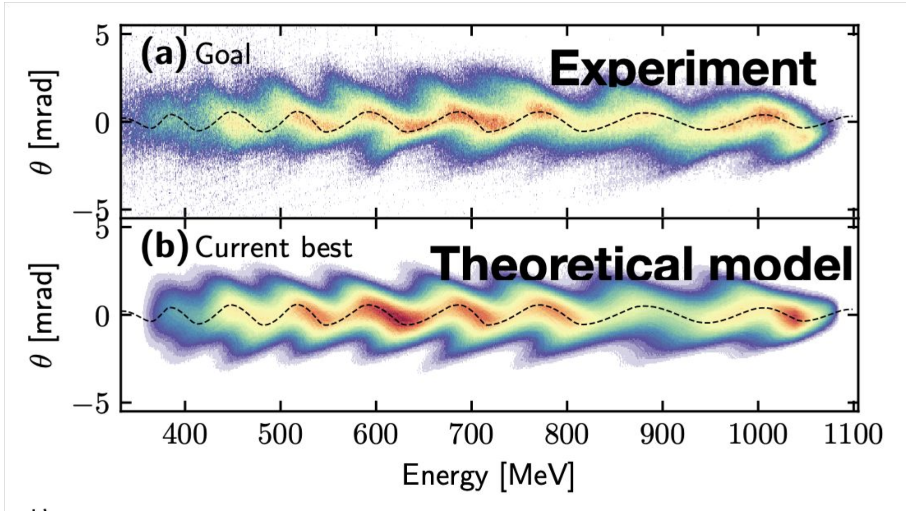
Sims show 2GeV in 140mm with minimal energy spread and emittance growth.

Diagnostics, Stability & Control

- Key methods and techniques used to characterize the accelerating structures (i.e. wakes) and accelerated beams
- Improvement of the beam quality and stability: limitations, challenges and possible solutions
- Use of machine learning and neural networks for the advancement of the LWFA performance

Single-Shot Reconstruction of Electron Beam Phase-Space in a Laser Wakefield Accelerator

Yong Ma, University of Michigan

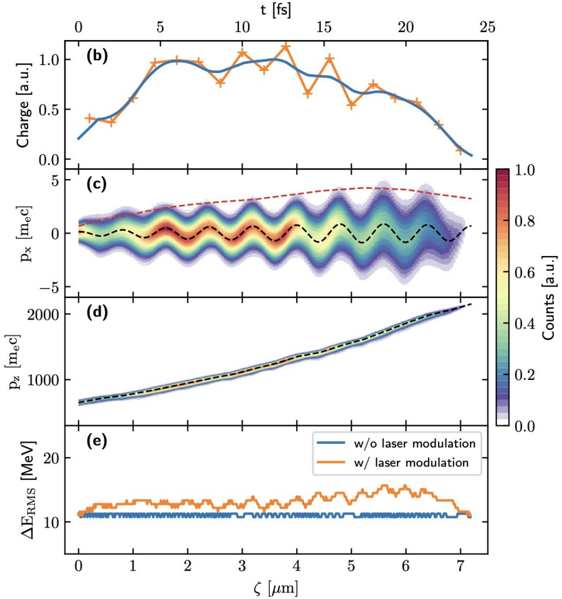


$$p_{\parallel} \simeq p_{\parallel 0} - \frac{\gamma_p^2}{p_{\parallel 0}}\left(\frac{1}{2}\alpha^2 p_{\parallel 0}\mathbf{x}_{\perp}^2 + \mathbf{p}_{\perp}^2\right)$$

Wakefield acceleration

Transverse modulation

- Theoretical model describes coupled motion of electrons in laser driven plasma wakefields and oscillations in the laser fields.
- Experimental observation of modulated electron spectra which can be fitted with the theoretical model.
- **Reconstruction of the electron beam characteristics** including: longitudinal momentum distribution (energy chirp), transverse momentum distribution, temporal profile (pulse duration), slice energy spread. (**All at a single shot!**).

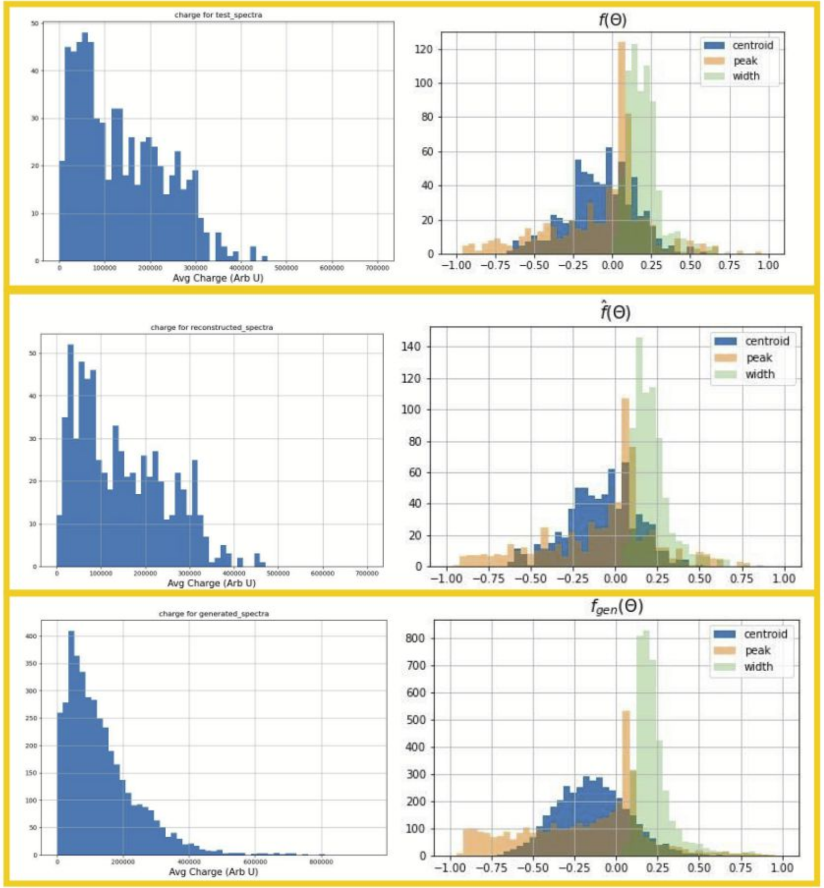


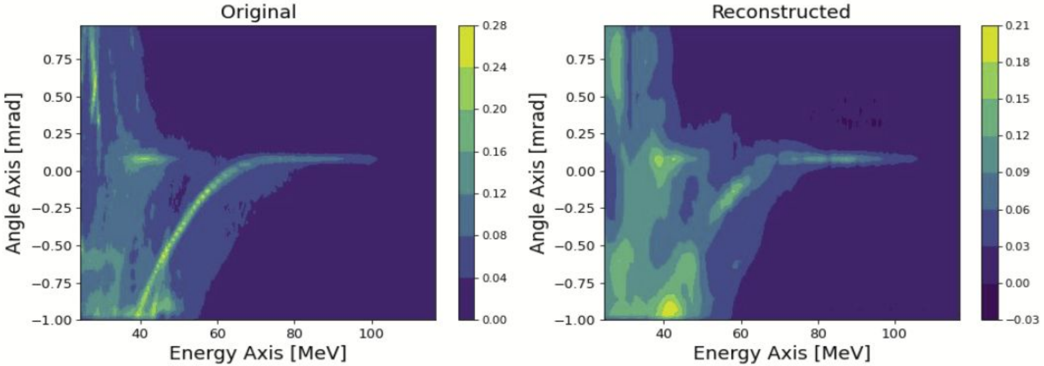
Data-driven modelling of laser-plasma experiments enabled by large datasets

André Antoine, University of Michigan

Data-driven modelling of laser-plasma experiments enabled by large datasets

- Synthetic generation of complex data empowers predictive modeling
    - With clever techniques the data sample size can still provide efficient latent representation

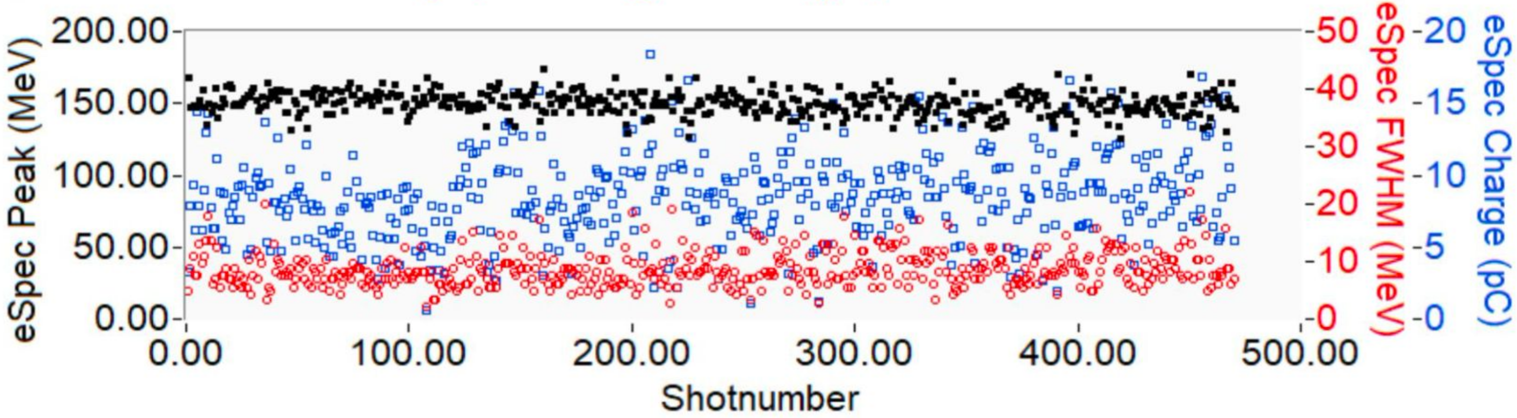




Stable injection into a laser plasma accelerator with colliding laser pulses

Qiang Chen, Tobias Ostermayr, Robert Jacob, Camille Woicekowski, Remi Lehe, Axel Huebl, Jeroen van Tilborg, Anthony Gonsalves, Carl Schroeder, Eric Esarey, Cameron Geddes
BELLA Center, Accelerator Technology & Applied Physics Division, Lawrence Berkeley National Lab

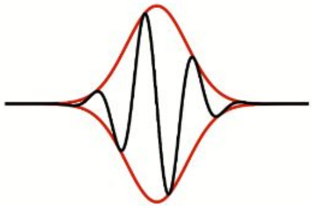
Stable in the charge, peak energy and energy spread of the electron beam.

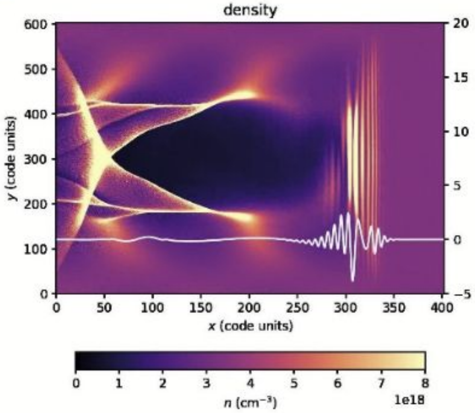


This work was supported by the U.S. Department of Energy National Nuclear Security Administration Defense Nuclear Nonproliferation R&D (NA-22) and by the Office of Science Office of High Energy Physics and Fusion Energy Sciences under LaserNetUS by the Contract No. DE-AC02-05CH11231.

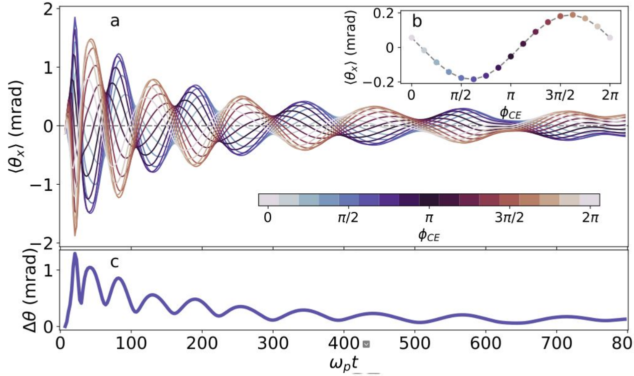
Polarization and CEP Dependence of the Transverse Phase-Space in Laser-Driven Accelerators

Andreas Seidel (Friedrich-Schiller-University Jena)

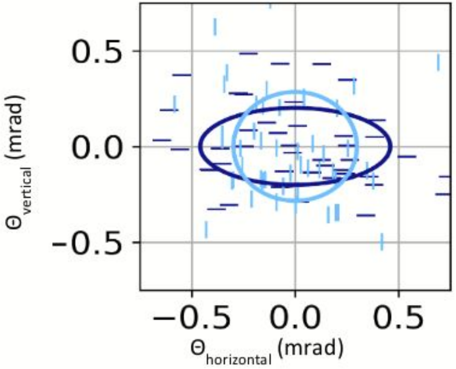




Increased steepening of the laser pulse front due to long propagation in plasma coupled with CEP slippage causes asymmetric transverse deflection of the electrons.



Controlling CEP within 500 µrad constrains electron beam pointing jitter below 50 µrad.



Electron beam pointing jitter exhibits a significant increase in direction of the laser polarization.

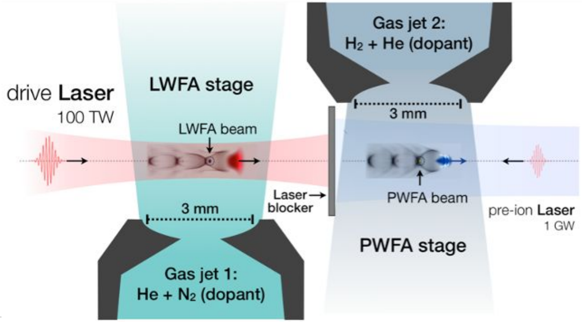
HI JENA
Helmholtz Institute Jena

Facilities & LPA Applications

- ❑ Current status of the facilities and recent results of commissioning (WG1+WG8)
- ❑ Applications of the LWFAs

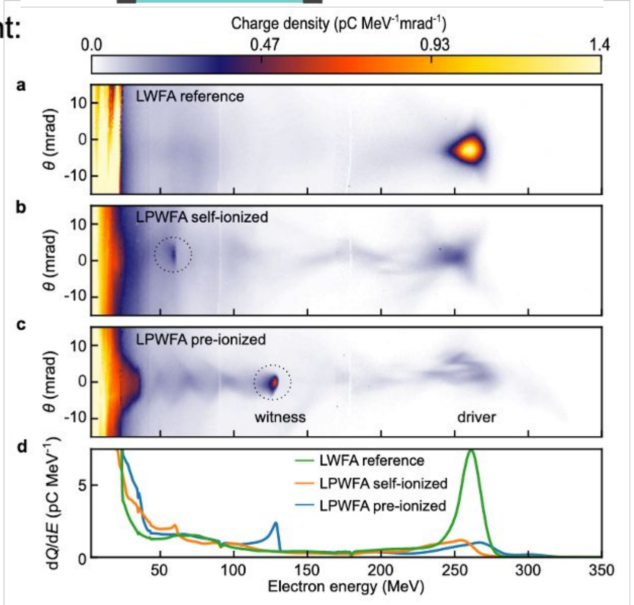
Accompanying the hybrid LPWFA experiment campaign with a computer simulation campaign: What we model, what we learn, and where we need to become better(WG1+2)

Klaus Steiniger, HZDR

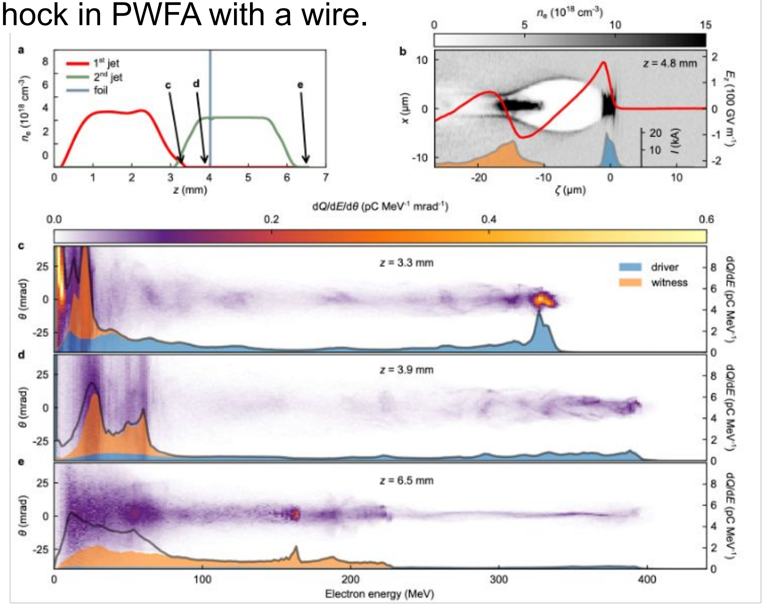


- ➔ Laser modelling is key to improve LWFA stage predictions (correct for real energy, intensity profiles).
- ➔ Modelling of gas and laser according to experiment allow to achieve good agreement with the experiment.
- ➔ Simulation observations lead to improvements of LPWFA setup: prompted to increase the distance between the LWFA & PWFA, and to introduce shock in PWFA with a wire.

Experiment:



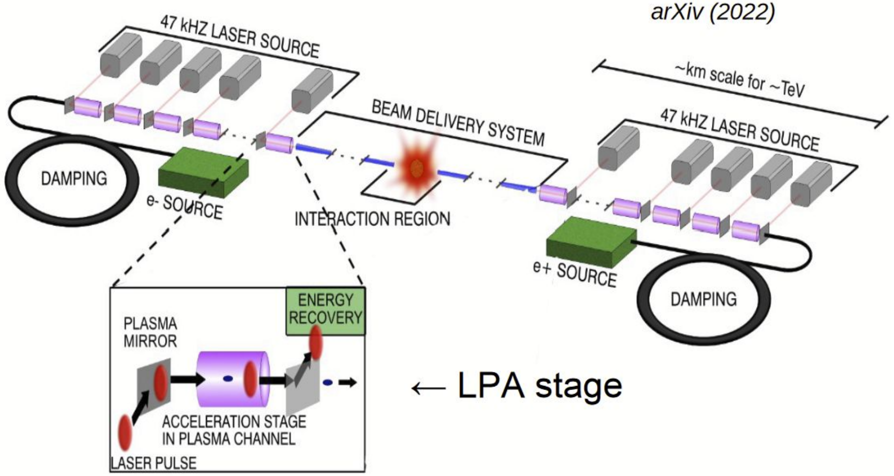
Simulation:



High-efficiency and high-quality laser-plasma accelerator stages for a plasma-based linear collider (WG1+8)

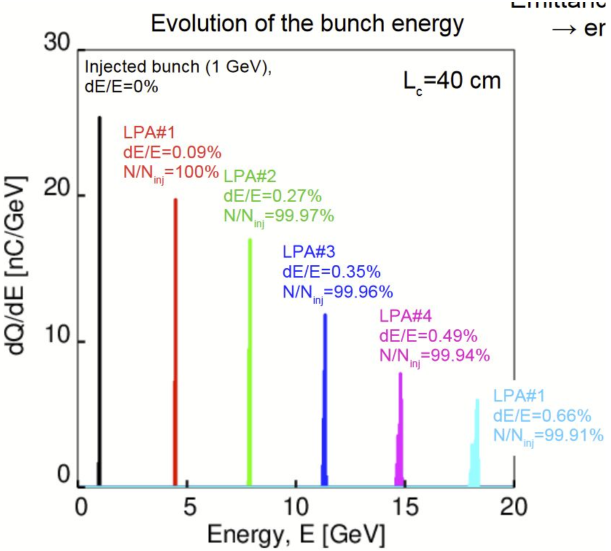
C. Benedetti, LBNL

Energy gain in channel-guided and self-guided LPAs driven by a laser with given (fixed) energy has been investigated:



Benedetti et al., arXiv (2022)

← LPA stage



Channel-guided LPAs provide higher energy gains;

Optimal charge in self-guided LPAs (i.e., operating in the nonlinear/bubble regime) is larger than that in channel-guided LPAs;

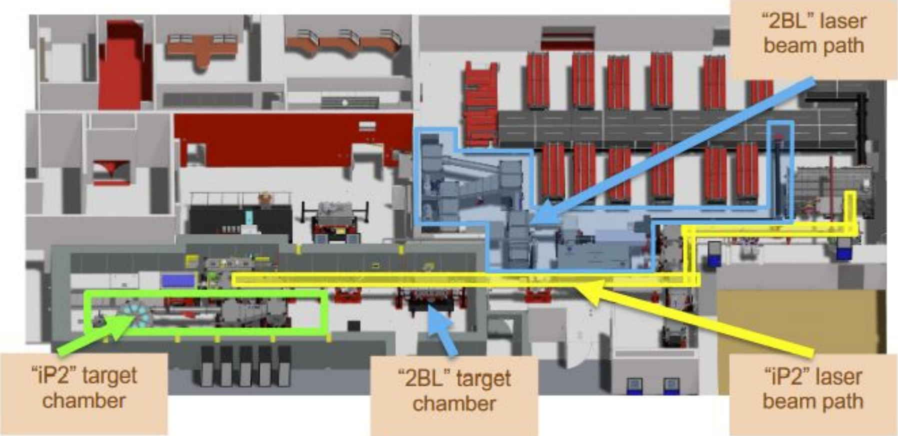
Scaling laws with laser energy and wavelength for energy gain and charge discussed;

Technique to reduce final energy spread based on wake overloading has been discussed;

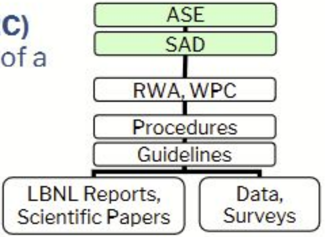
A self-guided LPA stage operating in the bubble regime providing high-gradient, high-charge, high-efficiency, and quality-preserving acceleration for collider applications has been presented.

The BELLA PW iP2&2BL Upgrades – Radiation and Laser Safety considerations and implementations for safe and efficient user experiments

Csaba Toth, LBNL



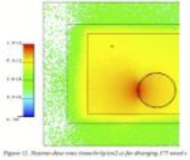
DOE Accelerator Safety Order (ASO 420.2C) requires the development and maintenance of a Safety Assessment Document (SAD), Accelerator Safety Envelope (ASE), established Credited Controls, and continuous Safety Assurance process

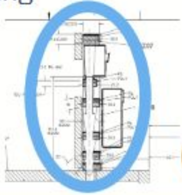

ASE
SAD
RWA, WPC
Procedures
Guidelines
LBNL Reports, Scientific Papers
Data, Surveys

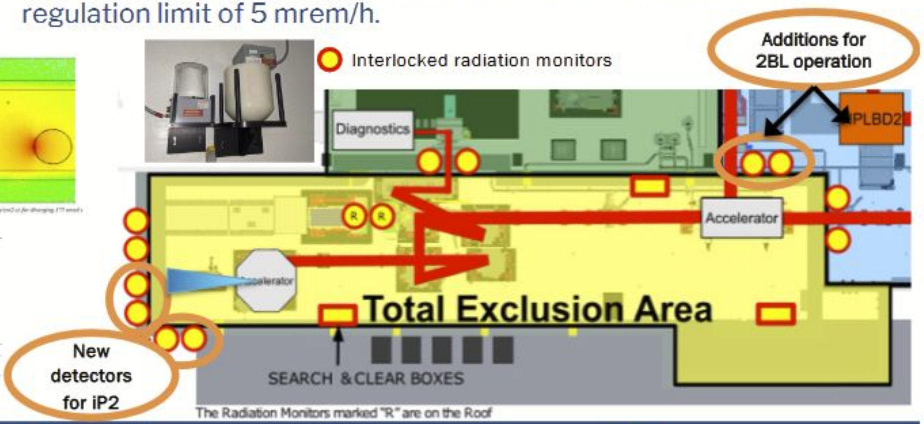
The combined "laser & radiation" Personnel Protection System (PPS) consists of old and newly-installed interlocked gamma and neutron monitors, and laser shutters. The PPS ensures that the dose rate outside of the target caves never goes beyond the regulation limit of 5 mrem/h.

The DOE regulated planning, design, and implementation includes:

a) analysis of hazards (originated from new beam paths)
b) development of hazard mitigation strategies (new shielding components, laser shutters and interlocked monitors)
c) clear separation and control of low- and high-energy operation modes (LAM vs. HEM); online telemetry
d) configuration control and commissioning procedures
e) rigorous training and periodic checks of safety systems





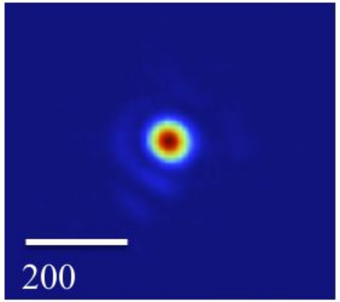


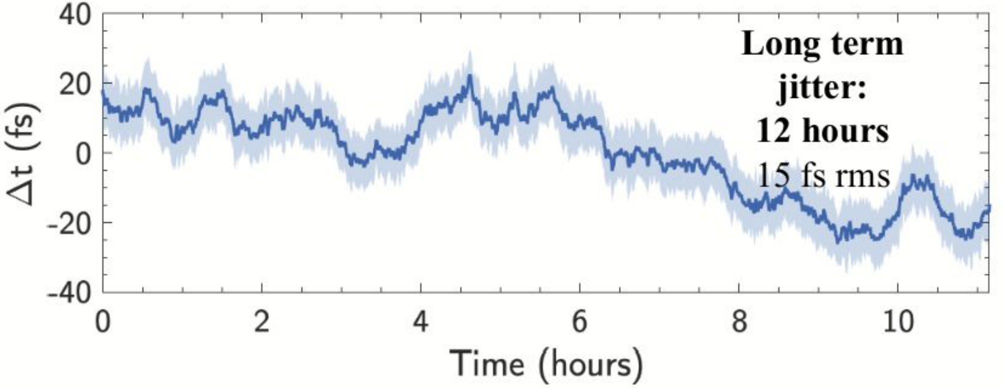
Updates and Commissioning results of the Second Beamline Upgrade to BELLA PW

Alex Picksley, LBNL

Demonstrated:

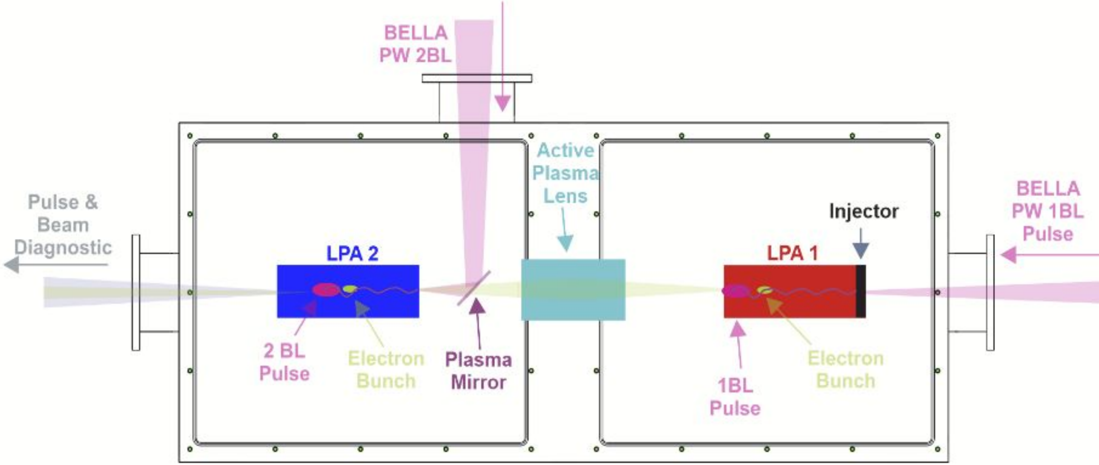
- High quality focal spot
- Compression to 37 fs
- Low temporal drift compared to 1BL





Opens up possibilities for experiments:

- Staging of two LPAs
- OFI Plasma Channels
- Two-Color Ionisation Injection
- SF-QED



Concluding remarks

WG1:

- 2 plenary talks
- 8 sessions (2 joint WG1&WG2 sessions; 1 joint WG1&WG8 session)
- 25 oral presentations
  - 10 talks on driver
  - 8 talks on various injection concepts
  - 4 talks on diagnostic, stability & control
  - 3 talks on facility updates and LPA applications
- 17 posters (13 student + 4 contributed)

AAC'22 Advanced Accelerator Concepts Workshop

November 6 - 11, 2022

Hyatt Regency Long Island, NY

Thank you!