Imperial College London

John Adams Institute for Accelerator Science

Science & Technology Facilities Council

ental Considerations fo Acceleration on Ast Gemini

HAPPY SAINT NICHOLAS DAY!

Jan-Niclas Grus
atory, Imperial College e16@imperial.ac.uk,

Imperial College London
Michael Backhouse
Elias Gerstmayr
Rob Shalloo
Stuart Mangles
Savio Rozario
Matthew Streeter
Jonathan Wood
Zulfikar Najmudin

Central Laser Facility
Nicolas Bourgeois
Rajeev Pattahil

DESY
Kristjan Poder

Queen's University Belfast
Thomas Audet
Gianluca Sarri

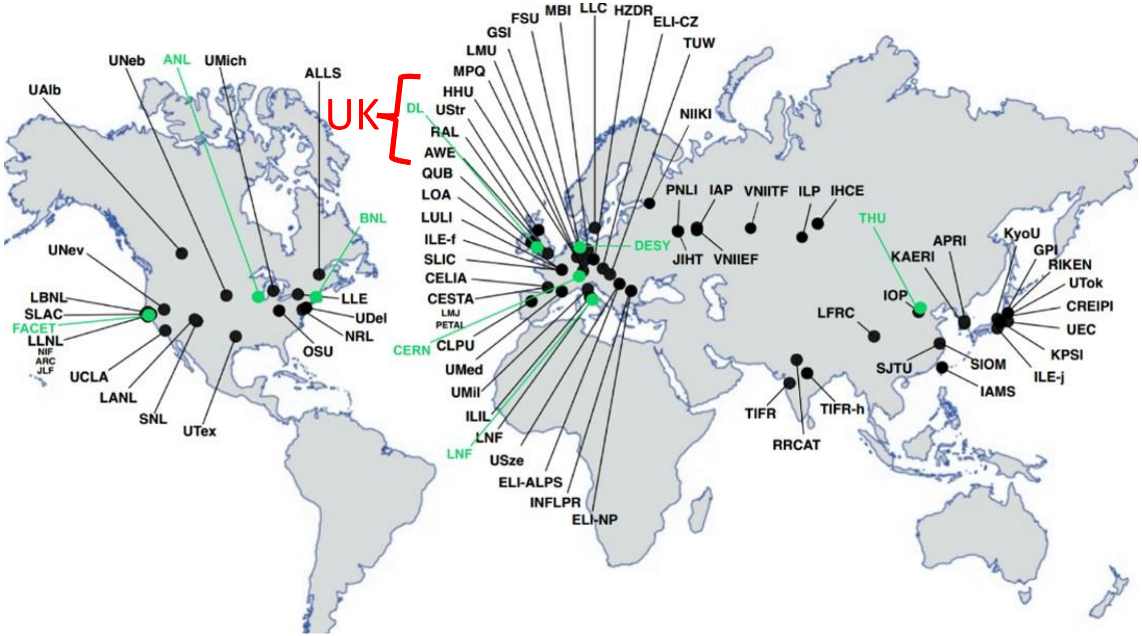
Instituto Superior Técnico
Nelson Lopes

The state of the art in LPWA

Advance accelerator concept strategies/road maps:

- *PWASC* in the UK (see right bottom →)
- *EuPRAXIA – Conceptual Design Report* (Europe)
- *Advanced Accelerator Development Strategy Report* (US)

From: *UK roadmap* (PWASC, 2019)



	E [GeV]	ΔE/E [%]	Q [pC]	ε_n [mm mrad]	f [Hz]
FLASHForward	0.4-1.25		50-800	1-3	$4 \cdot 10^4$-$3 \cdot 10^6$
SPARC_LAB	0.03-0.15	0.1-0.2	20-1000	1-5	10
CLEAR (CERN)	0.06-0.22	<0.2	10-500	3-20	1-25

Conceptual Design Concept (2019, EuPRAXIA)

$$\boxed{W_{\max} \approx (n_{\mathrm{cr}}/n_e)}$$

Why staging LPWA?

- Energy of the laser required does not scale linear with energy gain:
  - For self-injecting and self-guiding:
    - 1 GeV needs 10 J
    - 10 GeV will need 300 J

$$E_L \sim n_{\mathrm{cr}} \cdot mc^2 \cdot {a_0}^2 \cdot c\tau_L \cdot \pi {w_0}^2$$

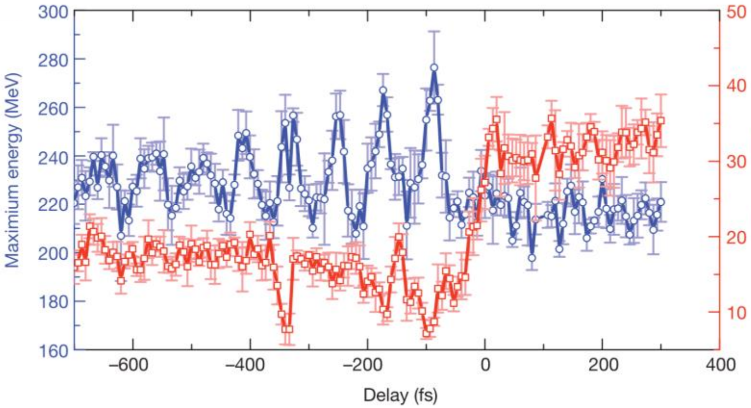
$$\tau_L \approx \pi c/\omega_p \quad w_0 \approx \lambda_p \sqrt{a}/\pi$$

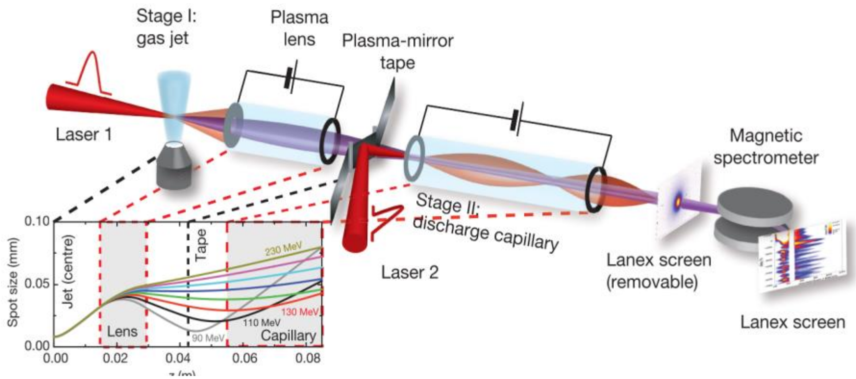
$$\propto {n_e}^{-1/2} \quad {w_0}^2 \propto {n_e}^{-1}$$

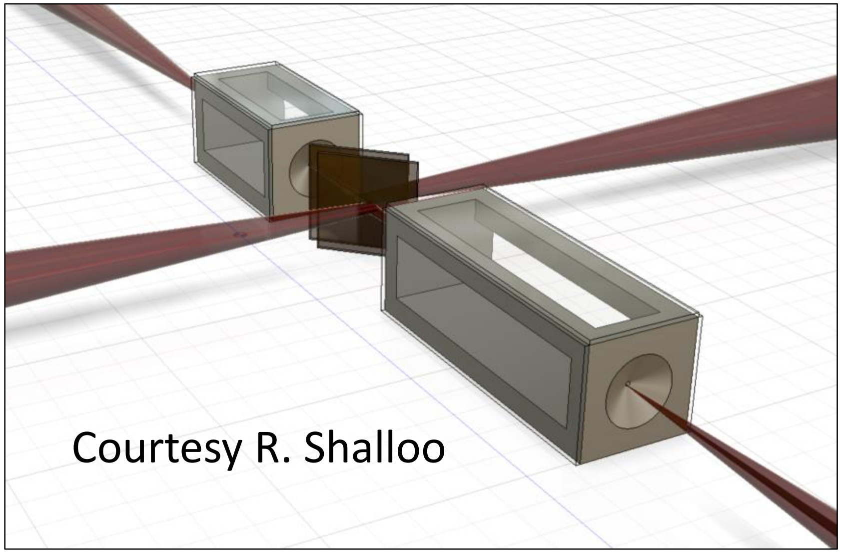
- Length of the plasma does not scale linear either: $L_{deph} = \left(\frac{n_{cr}}{n_0}\right)^{3/2} \lambda_0 \propto {n_e}^{-3/2}$
  - for 1 GeV, 3 cm dephasing length
  - For 10 GeV, 1 m dephasing length
  - Compensation of diffraction (and energy depletion) of laser pulse required
- Solution?
  - 10 systems with 10 J and 3 cm gas cells
  - (plus: compensation of energy chirp, *Multistage design for correlated energy spread compensation,* Ferran Pousan, 2018)

The road towards staging LPWA

- First staging around 100 MeV gain staging (Steinke, 2016)



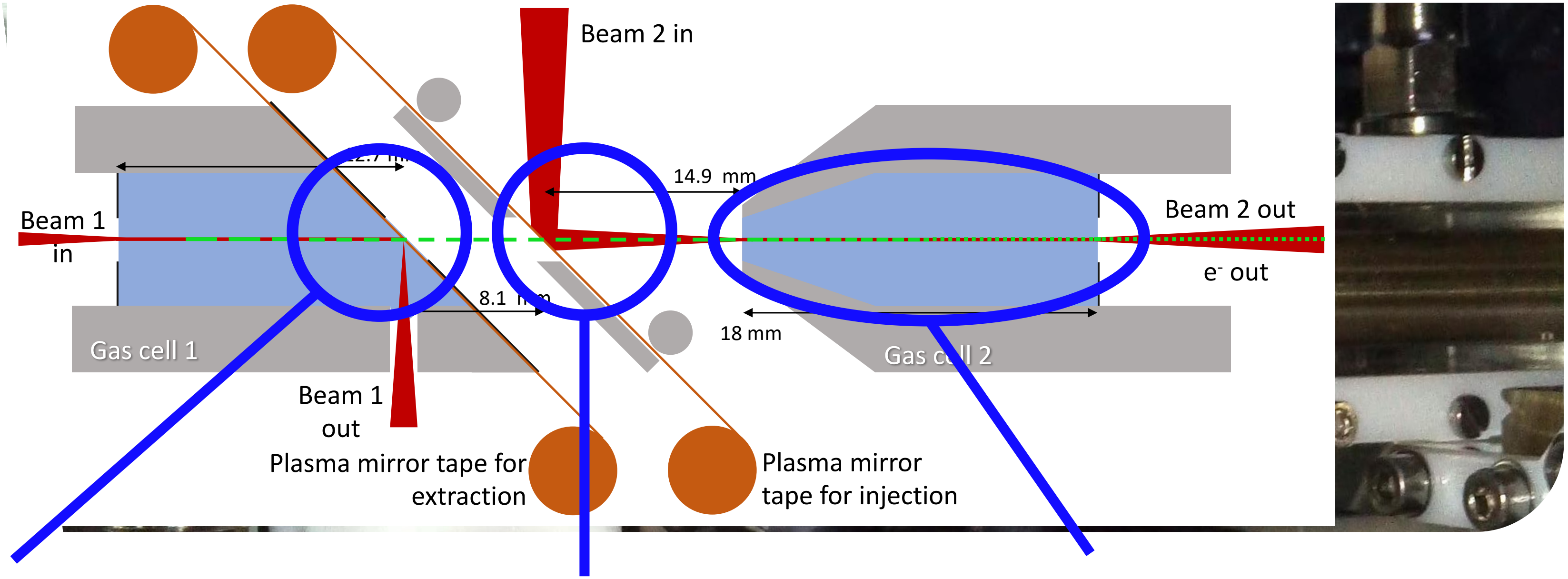




Courtesy R. Shalloo

- We performed first experiments in late 2017
- Another campaign took place in Spring 2019

The road towards staging LPWA

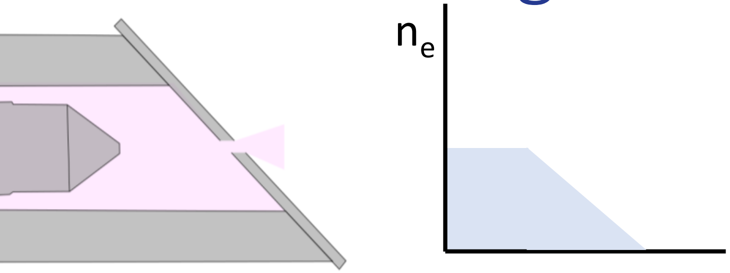


Emittance growth due to density transitions

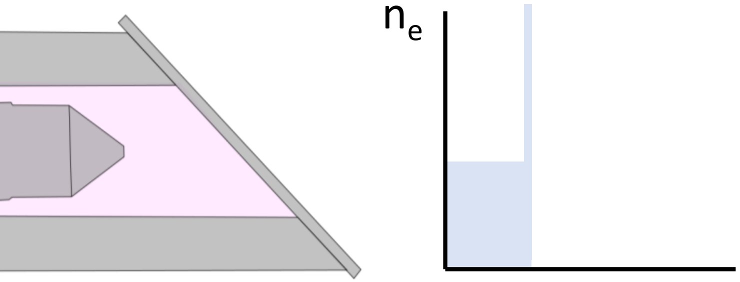
Reflectivity of the plasma mirror and beam quality

Laser pulse guiding and wakefield generation

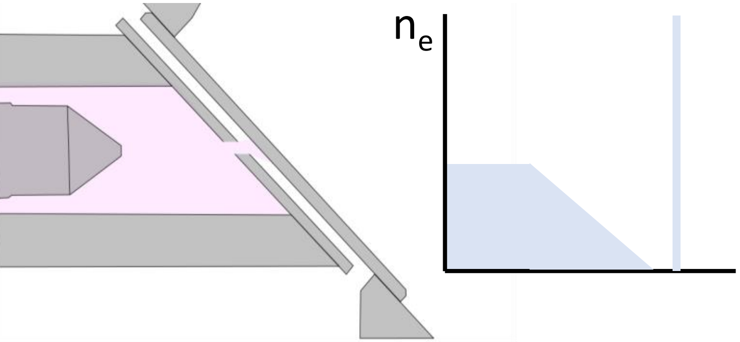
Emittance growth at different density ramps



CASE 1:
“STANDARD” GAS CELL

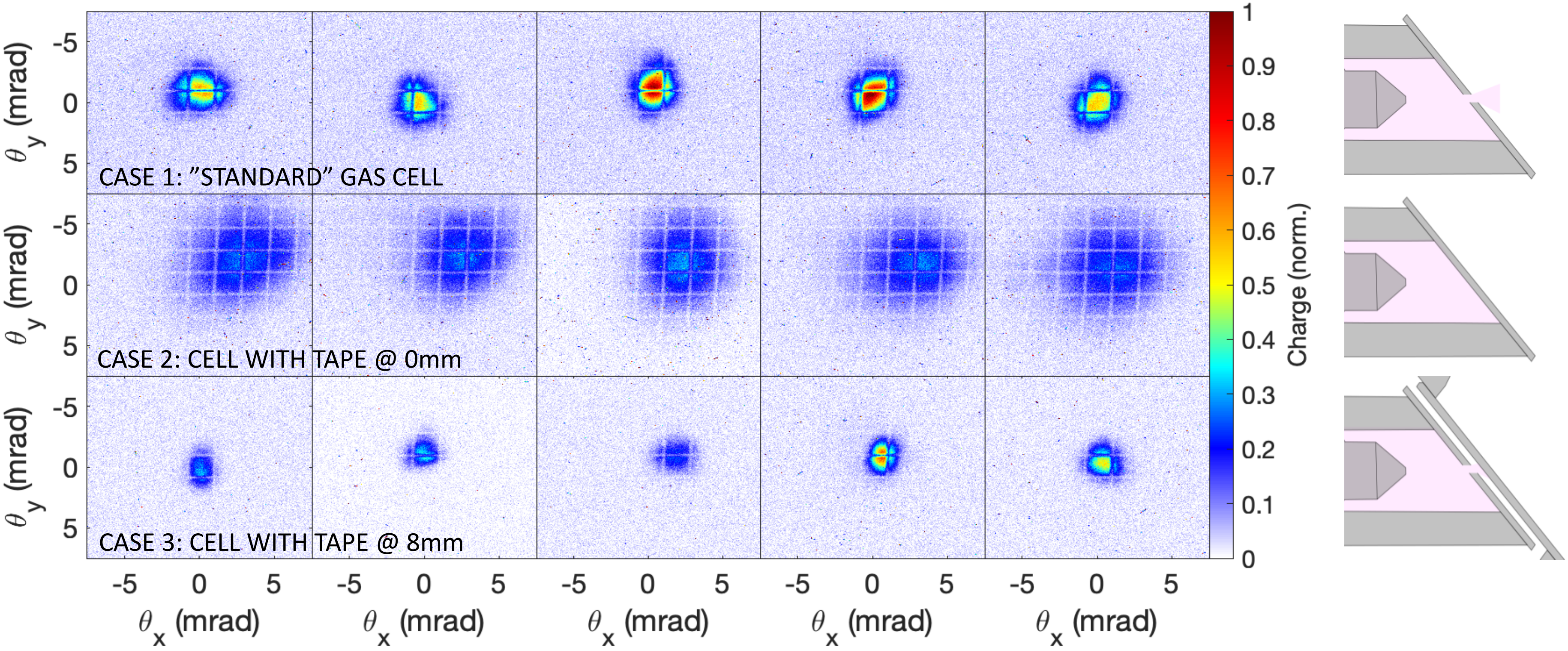


CASE 2:
GAS CELL WITH TAPE COVERING APERTURE
(0mm AFTER CELL)

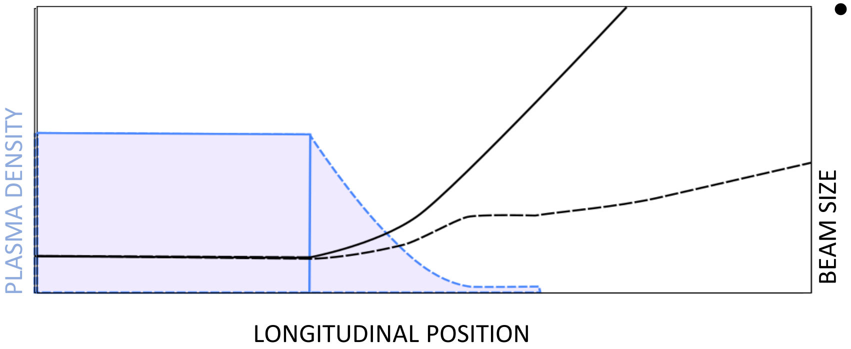


CASE 3:
GAS CELL WITH TAPE FAR FROM CELL EXIT
(8mm AFTER CELL)

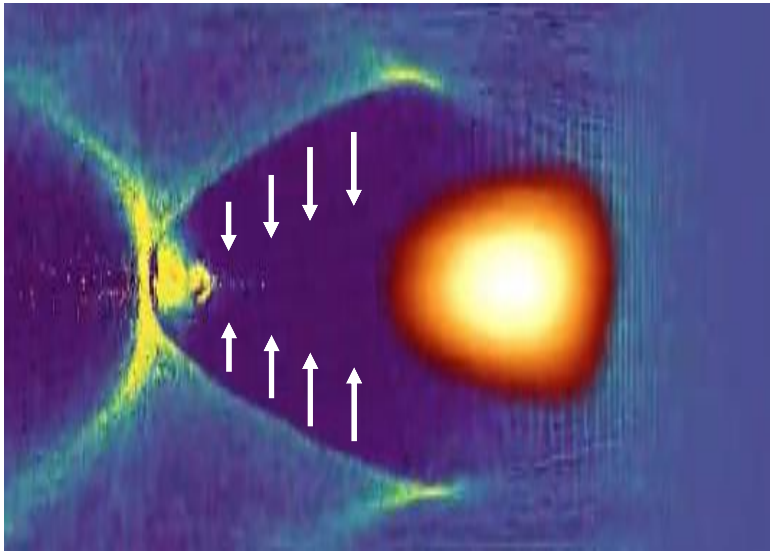
Emittance growth at different density ramps



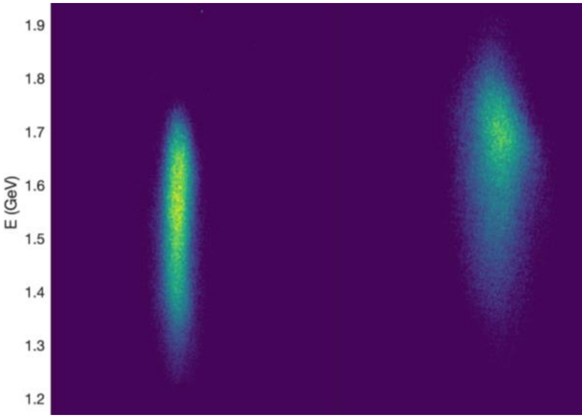
Emittance growth at different density ramps



- Laser effectively extracted with thin Kapton tape, *but:*
  - Tape placed at exit shows 1.8 x divergence increase. Possible causes are:
    - Sharp plasma density cut-off (no ramp)
    - Magnetic fields generated by laser solid interaction
  - Plasma density downramp produces low divergence (~2 mrad) beams

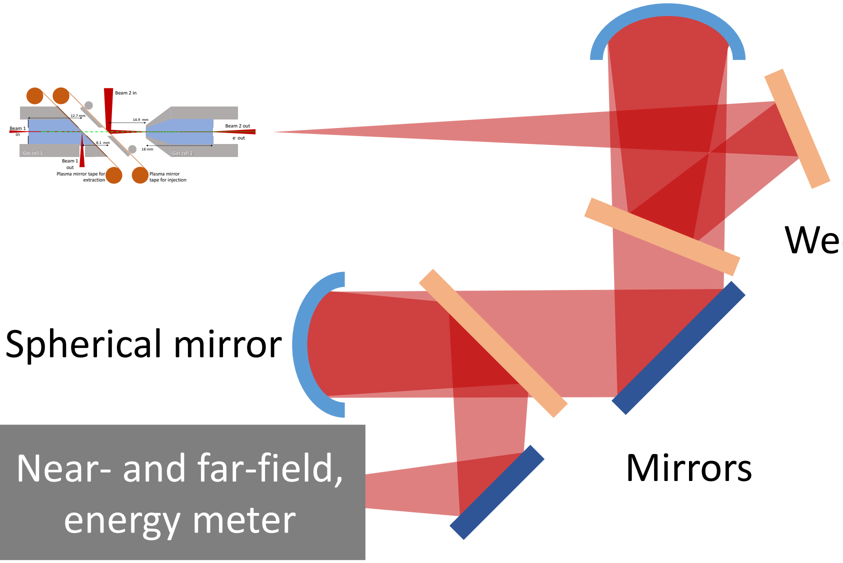


- Kapton tape (125 µm) shows to reduce charge throughput
  - for low energies, **but** the charge remains at high energies)



Reflectivity from the plasma mirror

- The second laser pulse reflected from the plasma mirror is analysed through their energy and spot size



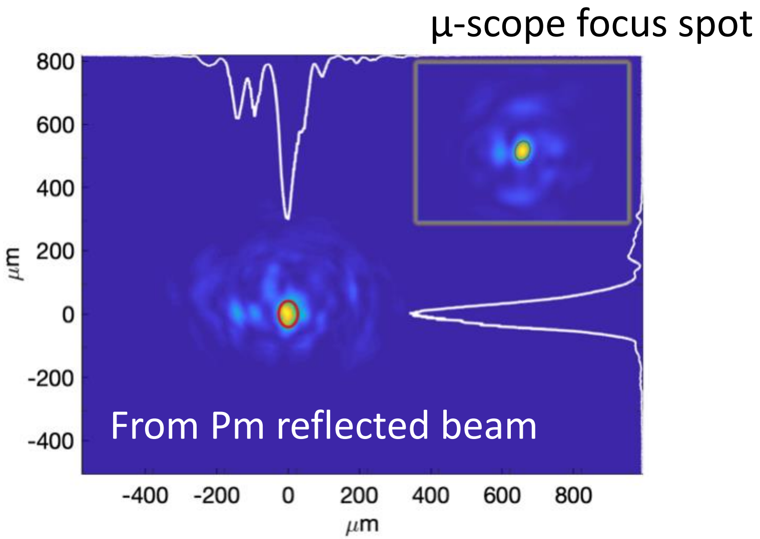
Spherical mirror

Wedges

Spherical mirror

Mirrors

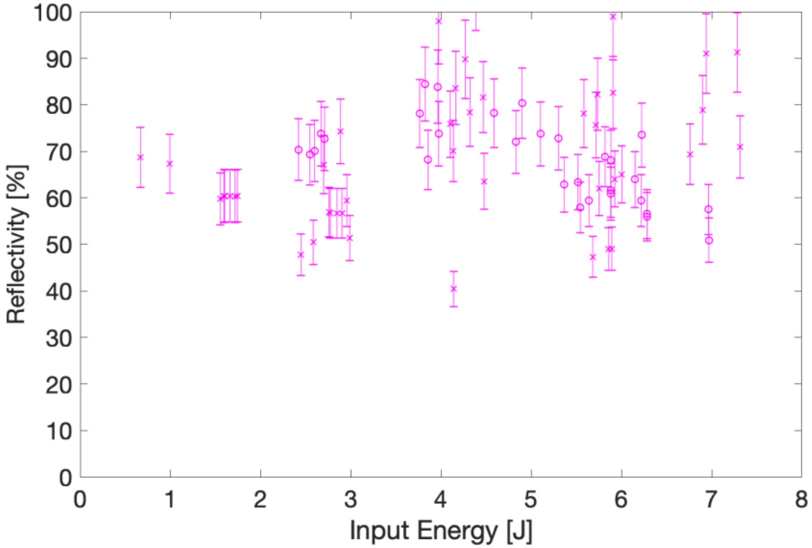
Near- and far-field, energy meter

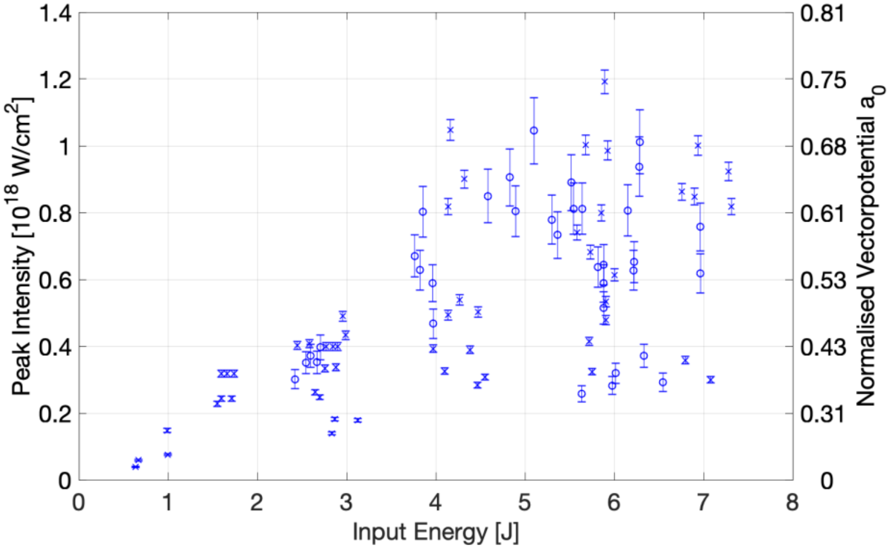


- Vanilla beam 19.2 (±1.8)% energy within FWHM

Reflectivity from the plasma mirror

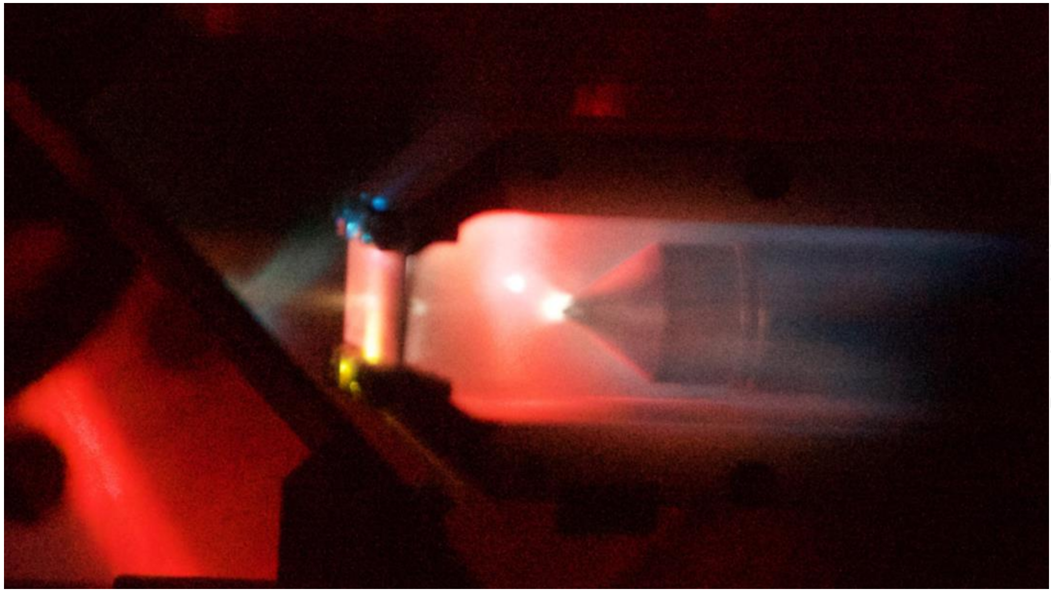
- High total reflectivity of >72% for above 5.5 J
- Continuous degradation of dielectric mirror before interaction
- a_0 of up to 0.7 into the 2nd gas cell

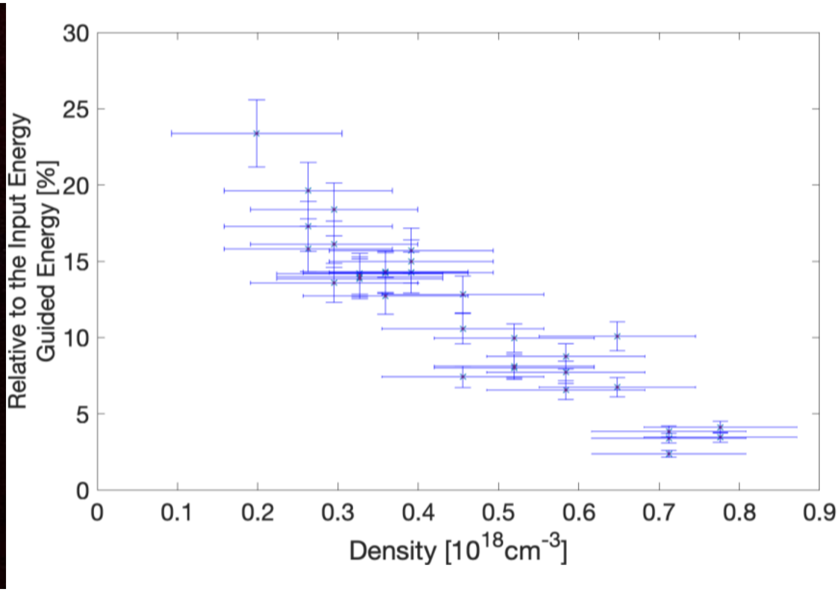




Guiding through the 2nd gas cell

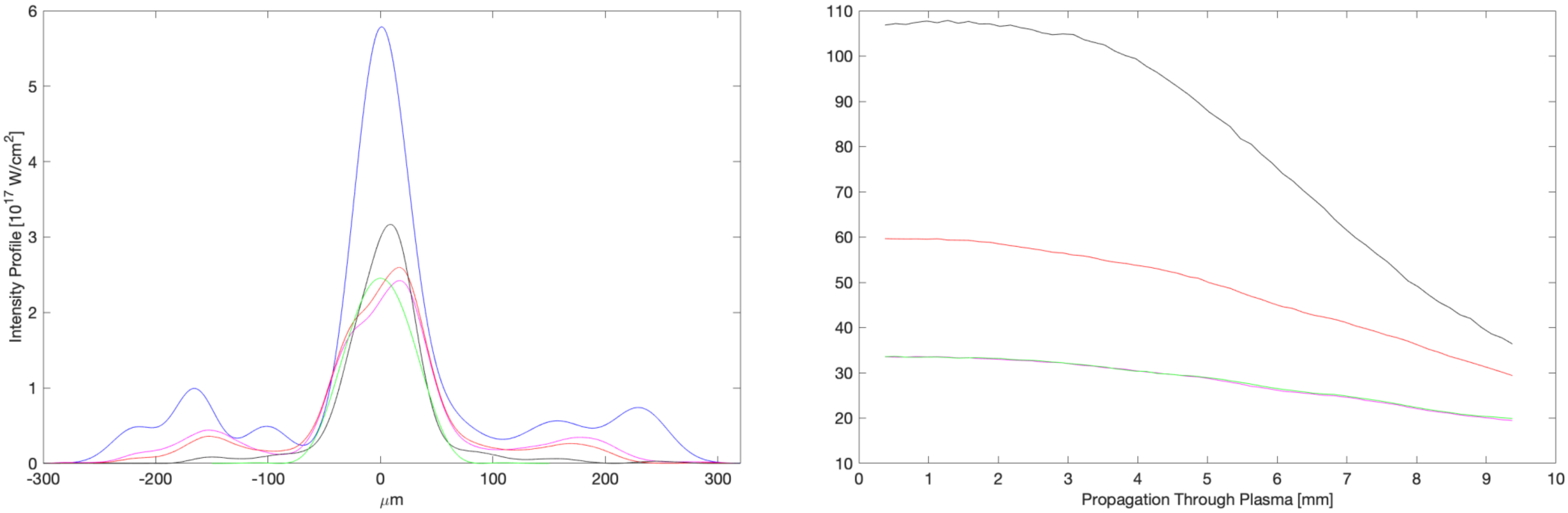
- Total energy increased with lowering the density





Guiding through the 2nd gas cell – EPOCH 2D

- Input beam modelled with 7 Gaussians (blue)
- Density at 0.3$\cdot 10^{18}$cm^{-3} matched the spot size (magenta)
- Simple Gaussian spot with the same intensity at the matched density (green)
- Doubled density (red) and 5 times density (black)



Future Work and remarks

- Another attempt?
    - We are working on a new design and new ideas of the experiment
    - Include a density ramp with 2 tapes
- 2nd beam quality has to be improved
    - a_0 higher than 1 (-> simulation great for that)
    - Reduce the flux on the last mirror -> change the geometry of the set-up

- The first part of this talk will be available first half of next year in a publication by Michael Backhouse
- Second part as a proceeding to the EAAC early next year by J.-N. Gruse

Thank you for the attention

Jan-Niclas Gruse*[1], N. C. Lopes[3], J. C. Wood[1], M. J. V. Streeter[5], R. J. Shalloo, M. Backhouse, E. Gerstmayr, S. Rozario, K. Põder, T. L. Audet[5], G. Sarri[5], N. Bourgeois[2], P. P. Rajeev[2], S. P. D. Mangles[1], Z. Najmudin[1]

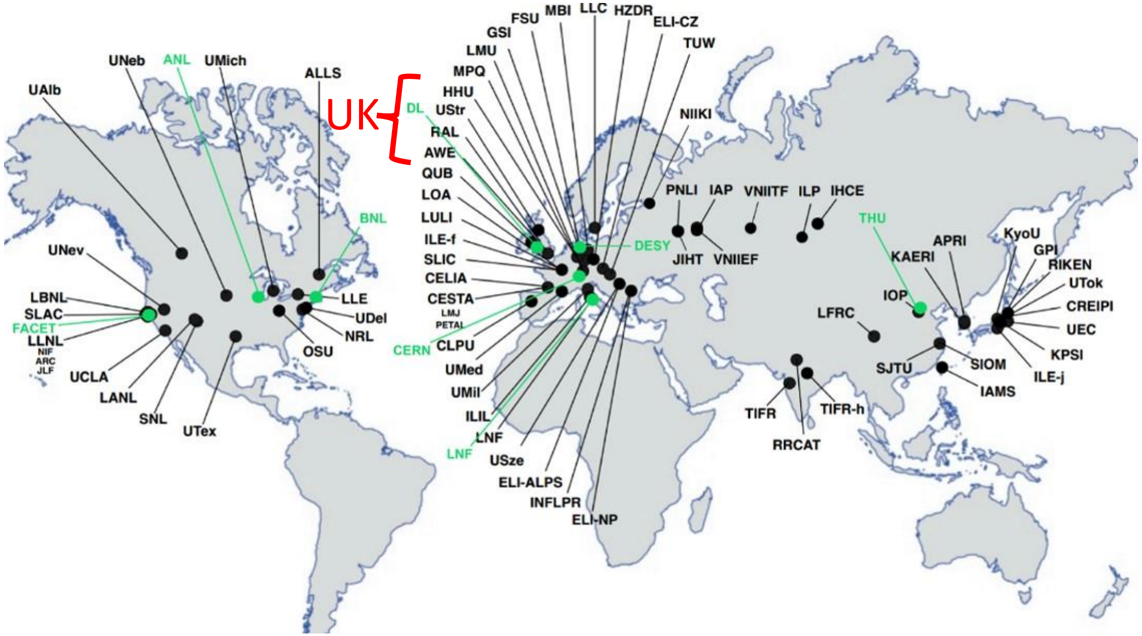
**The Blackett Laboratory, Imperial College London*, j.gruse16@imperial.ac.uk, [1] JAI for Accelerator Science Imperial College London; [2] Central Laser Facility, STFC Rutherford Appleton Laboratory; [3] GoLP, IPFN, Instituto Superior Technico, U. Lisboa; [4] Deutsches Elektronen-Synchrotron DESY, Hamburg; [5] School of Mathematics and Physics, The Queen's University of Belfast

The state of the art in LPWA

From: *UK roadmap* (PWASC, 2019)

Advance accelerator concept strategies/road maps:

- *PWASC* in the UK (see right bottom →)
- *EuPRAXIA – Conceptual Design Report* (Europe)
- *Advanced Accelerator Development Strategy Report* (US)



	E [GeV]	ΔE/E [%]	Q [n[illegible]	ε_n [mm m[illegible]d]	f [H[illegible]]
FLASHForward	0.4-1.25	[illegible]	800	[illegible]	[illegible]3 · 10^6
SPARC_LAB	0.0[illegible]	0.1-0.[illegible]	[illegible]	[illegible]	10
CLEAR (CERN)	0.06-0.22	[illegible]0.2	1[illegible]	3-20	1-25

8 GeV (2019, Gonsalves)

1.2· 10^{-3} (Ferran Pousan, 2018)

0.5 nC in Peak (Couperus, 2017)

Conceptual Design Concept (2019, EuPRAXIA)

What laser do you need for a ~ GeV wakefield accelerator

Fast enough:

$$W_{\max} \approx (n_{\rm cr}/n_e) \approx 1000 \qquad \rightarrow \qquad n_e \approx 2 \times 10^{18}\,{\rm cm}^{-3}$$

Short enough:

$$c\tau_L \approx \pi c/\omega_p \qquad \rightarrow \qquad \tau_L \approx 40\,{\rm fs}$$

Intense enough:

$$a_0 \gtrsim 4 \qquad \rightarrow w_0 = \left(\frac{\sqrt{a_0}}{\pi}\right)\lambda_p \approx 15\ \mu{\rm m}$$

Enough laser?:

$$E_L \sim n_{\rm cr} \cdot mc^2 \cdot {a_0}^2 \cdot c\tau_L \cdot \pi {w_0}^2 \approx 18\,{\rm J}$$

The state of the art in LPWA

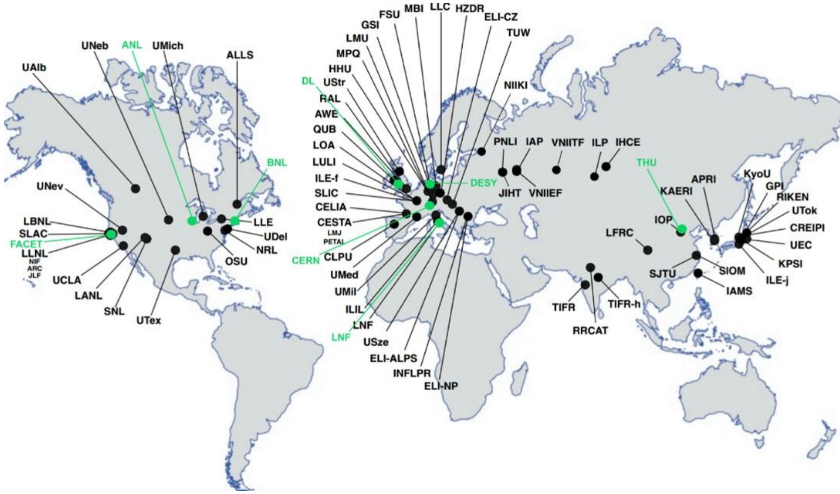
Advance accelerator concept strategies/road maps:

- *PWASC* in the UK (see right bottom →)
- *EuPRAXIA – Conceptual Design Report* (Europe)
- *Advanced Accelerator Development Strategy Report* (US)

- Self-injection
  - First acceleration of mono-energetic ($\Delta E/E \approx 3\%$) in 2003 by 3 groups including ICL
  - Acceleration to >GeV "standard" with self-injection (2016, Põder)
  - Records show 8 GeV in a laser-heated capillary (2019, Gonsalves)

- Self-injection
  - First acceleration of mono-energetic ($\Delta E/E \approx 3\%$) in 2003 by 3 groups including ICL
  - Acceleration to >GeV "standard" with self-injection (2016, Põder)
  - Records show 8 GeV in a laser-heated capillary (2019, Gonsalves)

Conceptual Design Concept (2019, EuPRAXIA)



Plasma Wakefield Accelerator Research 2019-2020
A community-driven UK roadmap compiled by the Plasma Wakefield Steering Committee (PWASC)

The state of the art in LPWA

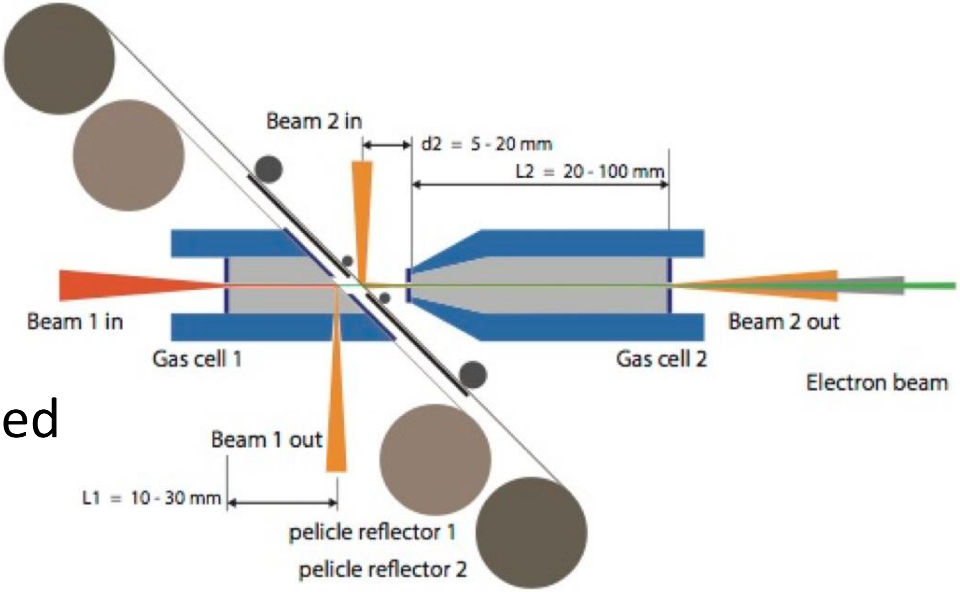
- Advanced Injection methods
  - Downward density transition (Suk, 2001)
  - Laser-induced transient density ramp (Chien 2005)
  - Plasma-density gradient injection for low absolute-momentum-spread (2008, Geddes)
  - Ionization-induced injection (Clayton, 2010) → 1.45 GeV in 1.3 cm
  - Shock assisted ionization injection (Thaury, 2015) → supersonic gas jet to localise injection
  - Dual-energy electron beam (Wenz, 2019) → combine shock injector and colliding pulse
  - Controlling self-injection threshold (Kuschel, 2018)
  - Ionization injection with transverse magnetic field (Zhao, 2018)
- High charge
  - nC charge (Couperus, 2017)
- Ultra-short electron bunches
  - Near-threshold Injection for fs bunches (Islam, 2015)
  - Controlling self-injection via plasma density modulation toward as bunches (Tooley, 2017)
  - as bunches via plasma density upramp (Weikum, 2016)

The state of the art in LPWA

- Low energy spread
    - Ultracold electron bunch generation (Hidding, 2012) → Colliding pulses and ionization injection
    - Energy chirp control (Wang, 2016)
    - Chirp mitigation by a modulated plasma density (Brinkmann, 2017)
    - Multistage design for correlated energy spread compensation (Ferran Pousan, 2018)
- **Preserving Emittance**
    - Transverse emittance growth in staging (Mehrling, 2012)
    - Tailored focusing profiles in plasma accelerators (Dornmair, 2015)
    - Longitudinally tailored plasma profiles (Xu, 2016)
- Overcoming Rayleigh lengths
    - Pre-formed plasma waveguides for pointing stabilization (Gonsalves, 2015)
    - Hydrodynamic optical-field-ionized plasma channels (Shalloo, 2018)
- High gradient focussing
    - Active plasma lensing (van Tilborg, 2015)

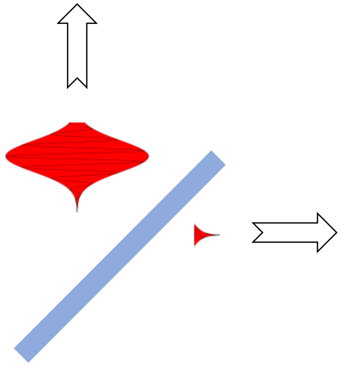
Challenges of Staging LPWA Gas Cells

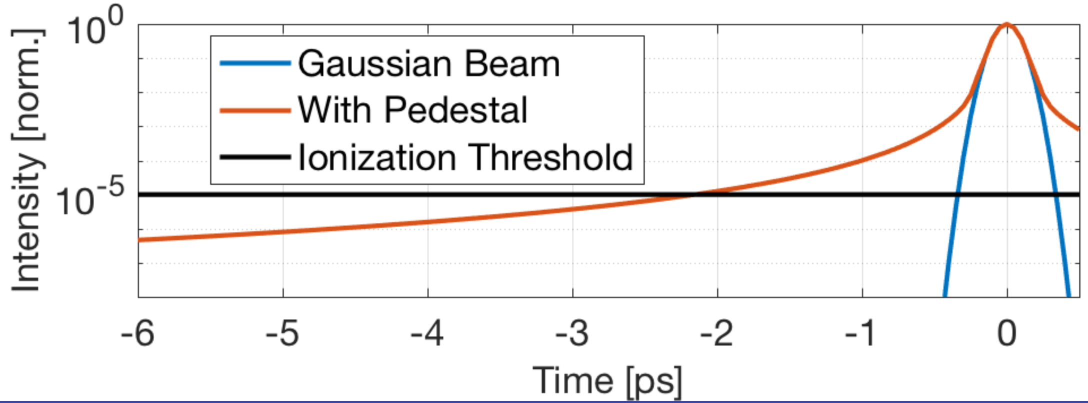
- First laser pulse determines the transverse position and angle of the electron bunch
    - Transverse overlap of first and second laser pulse
    - Angle of propagation must agree
- Second laser pulse creates another wakefield for further acceleration
    - Temporal overlap of the pulses within a fraction of the plasma wavelength
- The second laser pulse gets reflected close to the focal plane



Plasma Mirrors (PM)

- Conventional optics are destroyed by ultra high intensities
- Plasma mirrors:
    - Low reflectivity under a certain intensity threshold
    - The laser pulse ionizes the surface and creates a plasma over a threshold and the overdense plasma reflects light
- Advantages:
    - Enhancing the time contrast
    - Reflecting high intense laser beam, while letting high energetic electrons pass





Notes

- Intense laser pulse is injected into a plasma
  - Density modulations create plasma cavities with high electric fields
  - Electrons can be injected and exploit these fields
- Crucial is the normalized vector potential/nomalised momentum

$$a_0 \sim \lambda_0 \sqrt{I_0}$$

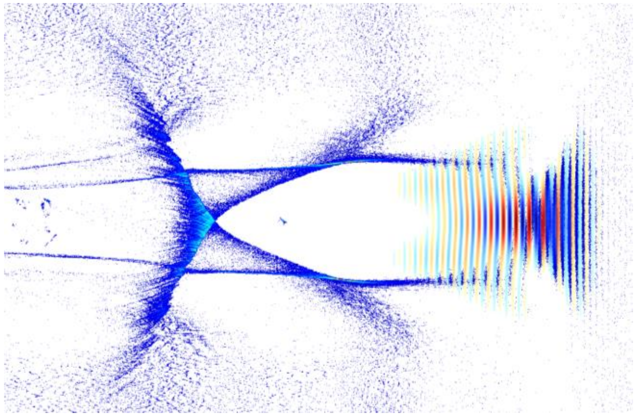
- Ponderomotive force repels the electrons from higher intensity regions

$$\vec{F} \sim -\vec{\nabla} a_0^2 \sim -\vec{\nabla} I_0$$

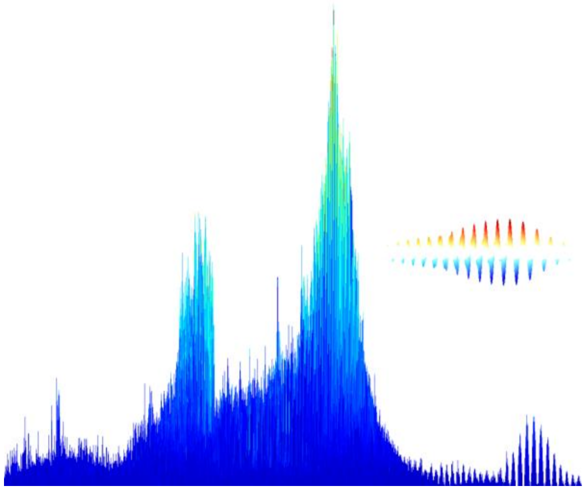
- Plasma cavities are in size of the plasma wavelength

$$\lambda_p \sim \sqrt{n_e}^{-1}$$

What is Laser Plasma-Wakefield Acceleration?



Top



Side

- Intense laser pulse is injected into a plasma
    - Density modulations create plasma cavities with high electric fields
    - Electrons can be injected and exploit these fields
- Crucial is the normalized vector potential/normalised momentum

$$a_0 \sim \lambda_0 \sqrt{I_0}$$

- Ponderomotive force repels the electrons from higher intensity regions

$$\vec{F} \sim -\vec{\nabla} a_0^2 \sim -\vec{\nabla} I_0$$

- Plasma cavities are in size of the plasma wavelength

$$\lambda_p \sim \sqrt{n_e}^{-1}$$