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First Measurements of Trojan Horse Injection in a Plasma Wakefield Accelerator

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Trojan Horse: underdense plasma photocathode

Hybrid concept: combines features of electron beam driven plasma wakefield acceleration (PWFA) and laser-driven plasma wakefield acceleration (LWFA)

Key is to have two plasma components, one with low ionization threshold (LIT) and one with high ionization threshold (HIT)

- Driver pulse interacts only with LIT (e.g. H), the injector pulse only with HIT (e.g. He)
- Driver has to expel H electrons strongly off axis (large transverse momentum), but must not ionize He
- Injector should impart very low transverse momentum to electron population in statu nascendi

⇒ This is ideally achievable by a relativistic electron driver (dephasing-free, unipolar and low electric fields to expel electrons) and a laser pulse injector (oscillating, high electric fields)
Path to ultralow emittance designer bunches with ultrahigh brightness

Plasma photocathode laser has intensity ~4 orders of magnitude less than in LWFA

\[ E_0 = a_0 \frac{2\pi m_e c^2}{e\lambda} \]

- Normalized emittance \( \varepsilon_n \) scales with intensity \( a_0 \) and spot size \( w_0 \) of release laser

- Accelerating 10’s of GV/m field and transient ion shielding prevent space charge-related \( (\gamma^2 - \text{scaling}) \) emittance growth, produce kA currents

\( \Rightarrow \) Normalized emittance down to few nm rad scale

\( \Rightarrow \) Normalized 5D brightness \( B_{5D} = I \varepsilon_n^{-2} \) up to \( 10^{20} \text{ A m}^{-2} \text{ rad}^{-2} \) levels

Both is orders of magnitude better than state-of-the-art
Path to ultralow emittance designer bunches with ultrahigh brightness

Plasma photocathode laser has intensity \( \sim 4 \) orders of magnitude less than in LWFA

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Theory & simulation papers confirm idea – but is it experimentally doable?


FACET – the premier facility for PWFA

Timeline:
- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

“E210: Trojan Horse PWFA” experiment approved in 2011

A National User Facility:
- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:
- Mono-energetic $e^-$ acceleration
- First high-gradient $e^+$ PWFA (*Nature* 524, Aug. 2015)

E210: Multi-institutional, cross-continental collaboration of academia (Strathclyde—UCLA—Hamburg—Oslo—Texas—Boulder), research centers (SLAC—DESY) and industry (RadiaBeam—Tech-X—Radiasoft)

PI's B. Hidding (Strathclyde) & J.B. Rosenzweig (UCLA)

2012-2017, experiments at FACET ramping up from 2013-2016
2012 at FACET: use hot alkali metal vapor, self-ionized by driver beam
2013/14:
Ti:Sapphire commissioning, optical pre-ionization of (noble) gas
2013/14: Commissioning of electro-optical sampling based time-of-arrival diagnostics, separate air compressor to allow for independently tunable beams.
2015: Add Trojan Horse plasma photocathode laser (in 90° geometry)
Spatiotemporal alignment of beams is a key challenge: Preionization laser pulse and electron beam
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Axilens produces long (m-scale) and wide (up to 150 µm) hydrogen channel

Electron beam driver has to be aligned with preionization laser very accurately

Plasma blowout size must not be **too small**, or wake/driver field hot spots ionize He and produce dark current: $\lambda_p > 90$ µm required

Plasma blowout size must not be **too large**, or blowout hits plasma channel boundaries and wake collapses: $\lambda_p < 100$ µm

Tight sweet spot at $\lambda_p \approx 98$ µm, $n_e(H_2) \approx 1.1 \times 10^{17}$ cm$^{-3}$

3D particle-in-cell modelling of accurate 3D plasma profile over m-scale distance (combat numerical hosing, etc.) reveals highly complex transverse plasma width effects, transition into wakeless regime etc.
Spatiotemporal alignment of injector laser and driver beam: How do you hit a 100 µm size target moving with the speed of light?
Spatiotemporal alignment of injector laser and driver beam: How do you hit a 100 µm size target moving with the speed of light?
Surprisingly good jitter in view of thermionic gun: 150 fs rms. 
Still, that's ~half a plasma wave length $\lambda_p$ ...
Selection of scientific firsts in E210

- Pioneered plasma-photonic spatiotemporal alignment technique. Key to understanding is electron impact ionization – needs to be considered in PWFA!

- Demonstrated first density downramp injection in PWFA

- Going beyond hydrodynamic density downramps: Demonstrated first all-optical density downramp injection in PWFA: Plasma Torch injection

- Demonstrated ultrafast plasma kicker

- Demonstrated experimental feasibility of Trojan Horse injection

- Were operating at FACET‘s capacity and capability limits, as well as pushing the boundaries of what‘s measureable

- Extremely encouraging experimental results (e.g. stability, timing jitter etc. will be an order of magnitude better at FACET-II, collinear geometry etc.)

- Future implementations at various further facilities both linac-driven (FACET-II, DESY, BNL ATF-II, CLARA, INFN) but also laser-driven via hybrid LWFA→PWFA (e.g. SCAPA, Jena, Dresden...), EuPRAXIA...
Path is open to ultralow TH emittance and ultrahigh 5D-brightness, but energy spread may destroy beam quality during extraction & transport ⇒ showstopper e.g. for FEL

“the energy spread&chirp problem“:
‘steep‘ price to be paid for ultrahigh energy gradients. How to get rid of energy chirp/spread, how to generate ultrahigh 6D brightness bunches?
Ultrahigh 6D-brightness: concept of TH-released escort beam for chirp control

Tailored beam loading via escort bunch allows chirp control:

(a) $n_b = n_0 \times 0$

(b) $n_b = n_0 \times 0.5$

(c) $n_b = n_0 \times 1.5$

G.G. Manahan, F. Habib, accepted in *Nature Communications*, 2017
Ultrahigh 6D-brightness: concept of TH-released escort beam for chirp control

Tailored beam loading via escort bunch allows chirp control:

![Graphs showing different beam loading conditions](image)

G.G. Manahan, F. Habib, accepted in *Nature Communications*, 2017
Energy spread compensation and ultrahigh 6D brightness: NeXource project

- TH mechanism for ultralow emittance and unprecedented 5D-brightness
- However, substantial correlated energy spread (chirp) is side-effect of GV/m fields
- New chirp compensation technique NeXource allows to remove correlated energy spread and generate ultrahigh 6D-brightness beams (reduction of energy spread by 2 orders of magnitude)

- This is a key step towards key applications such as 5th generation light sources
- E.g. for the race towards plasma-based FEL which is a main driver in the worldwide community: Beat Pierce parameter, fulfil Pellegrini criterion, and harness ultrahigh gain to realise compact hard x-ray FELs

\[ \epsilon_n < \lambda_r \langle \gamma \rangle / 4\pi \quad \checkmark \quad \langle \sigma_\gamma / \gamma \rangle \ll \rho \quad \checkmark \quad L_{g,1D} = \frac{\lambda_u}{4\pi \sqrt{3} \rho_{1D}} \propto B_e^{-1/3} \]

- Preliminary start-to-end simulations look extremely exciting: 4 Angstrom, 0.1% bandwidth, 35 GW saturation power after 20 m
Summary and outlook

• E210 programme concluded with breakthrough results at FACET

• Powerful plasma-photonic spatiotemporal alignment techniques developed

• Laser-triggered injection shown in two modes: Plasma Torch / all-optical density downramp injection, and Trojan Horse in 90° geometry

• 6D-brightness technique potentially game-changing for light sources such as FEL: beat Pellegrini criterion, Pierce parameter at the same time and exploit ultrastrong gain

• Trojan Horse / NeXource as gateway towards ultrahigh beam quality and highest performance applications e.g. for photon science and possibly HEP