2017-05-16 IPAC, København

Bernhard Hidding *et al.*

First Measurements of Trojan Horse Injection in a Plasma Wakefield Accelerator

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Strathclyde Centre for Doctoral Training P-PALS
Plasma-based Particle and Light Sources

Strathclyde Space Institute

& The Cockcroft Institute

Trojan Horse: underdense plasma photocathode

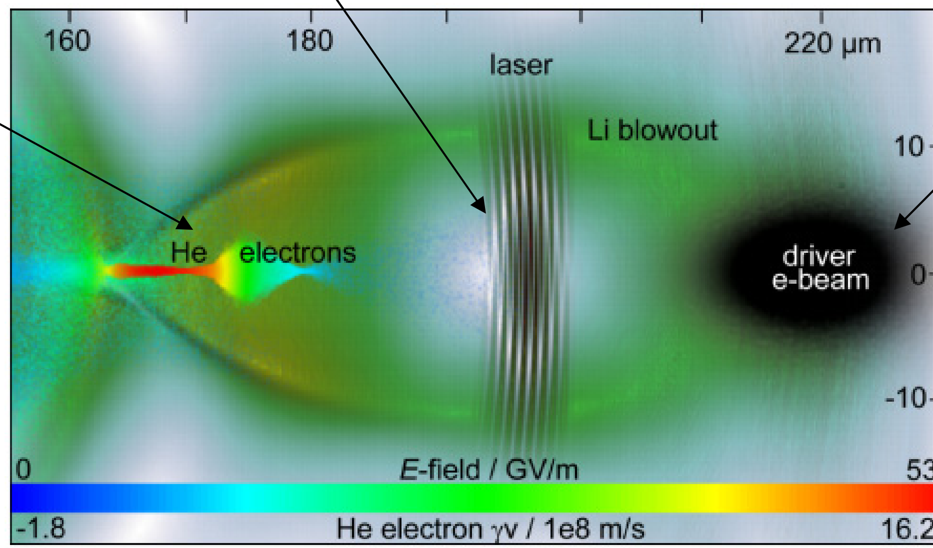
Hybrid concept: combines features of electron beam driven plasma wakefield acceleration (PWFA) and laser-driven plasma wakefield acceleration (LWFA)

Synchronized laser pulse tunnel ionizes in focus and releases ultracold electron population

Released electrons are rapidly accelerated and form bunch with ultralow emittance

Electron beam drives plasma wave over long distance

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



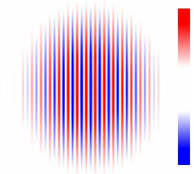
Phys. Rev. Letters 108, 035001 (2012)

- 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 transvere momentum), but must not ionize He
- Injector should impart very low transverse momentum to electron population *in statu nascendi*

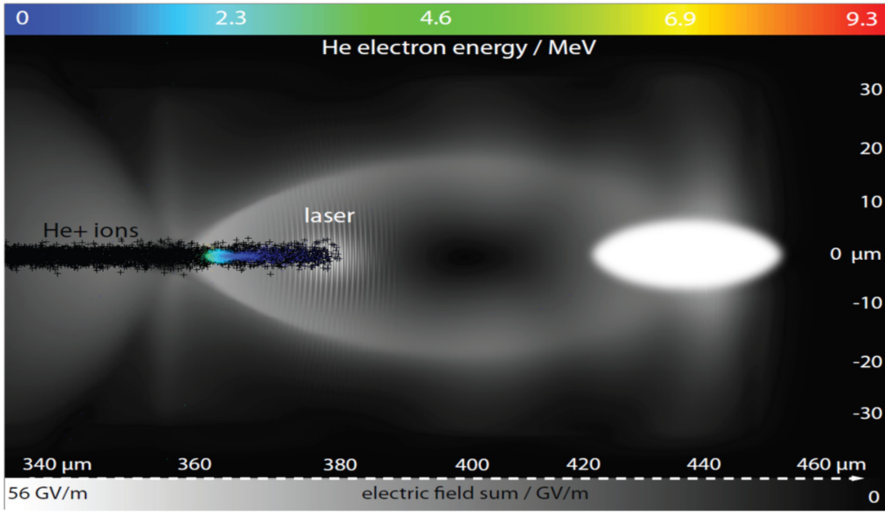
⇒ This is ideally achievable by a relativistic electron driver (dephasing-free, unipolar and low electric fields to expel electrons) and a laser pulse injector (oscillating, high electric fields)

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 ε_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 (γ^2 – scaling) emittance growth, produce kA currents I

⇒ **Normalized emittance down to few nm rad scale**

⇒ **Normalized 5D brightness $B_{5D} = I\,\varepsilon_n^{-2}$ up to 10^{20} A m^{-2} rad^{-2} levels**

Both is orders of magnitude better than state-of-the-art

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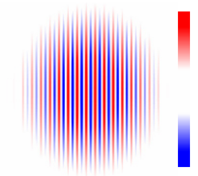

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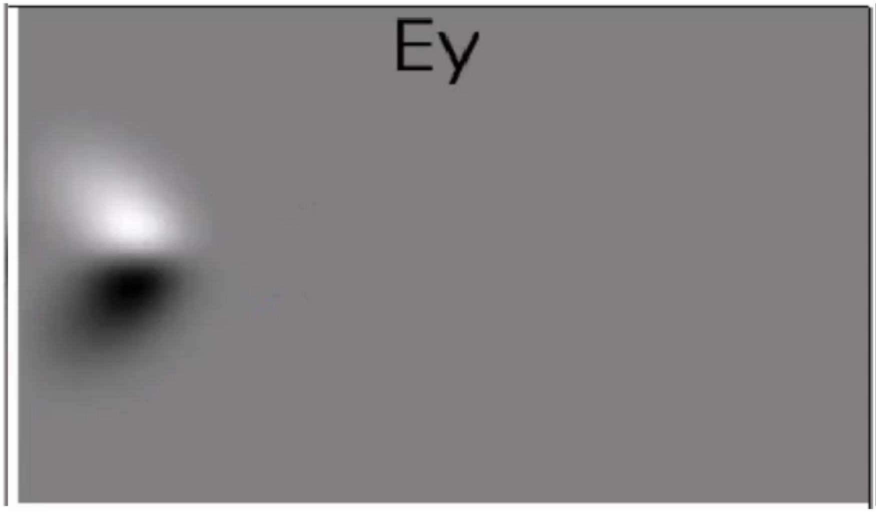

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Theory & simulation papers confirm idea – but is it experimentally doable?

DE102011104858A1 & WO patent (2011) Phys. Rev. Letters 108, 035001 (2012), submitted 03/2011
AAC proc. 1507, 570 (2012) PRSTAB 16, 031303 (2013) arXiv:1403.1109 (2013)

PRL 111, 015003 (2013), PRL 111, 155004 (2013), PRL 111, 245003 (2013), PRL 112, 035003 (2014), PRL 112, 125001 (2014), PRL 117, 034801 (2016)

Phys. B: At. Mol. Opt. Phys. 47, 234010 (2014), arXiv:1412.4844 (2014), PRSTAB 18, 081304 (2015), PRAB 19, 011303 (2016), NIM A 829, p. 83-87 (2016)

E210 Trojan Horse Experiment at

FACET – the premier facility for PWFA

SLAC

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

✓ High efficiency e^- acceleration (*Nature* **515**, Nov. 2014)

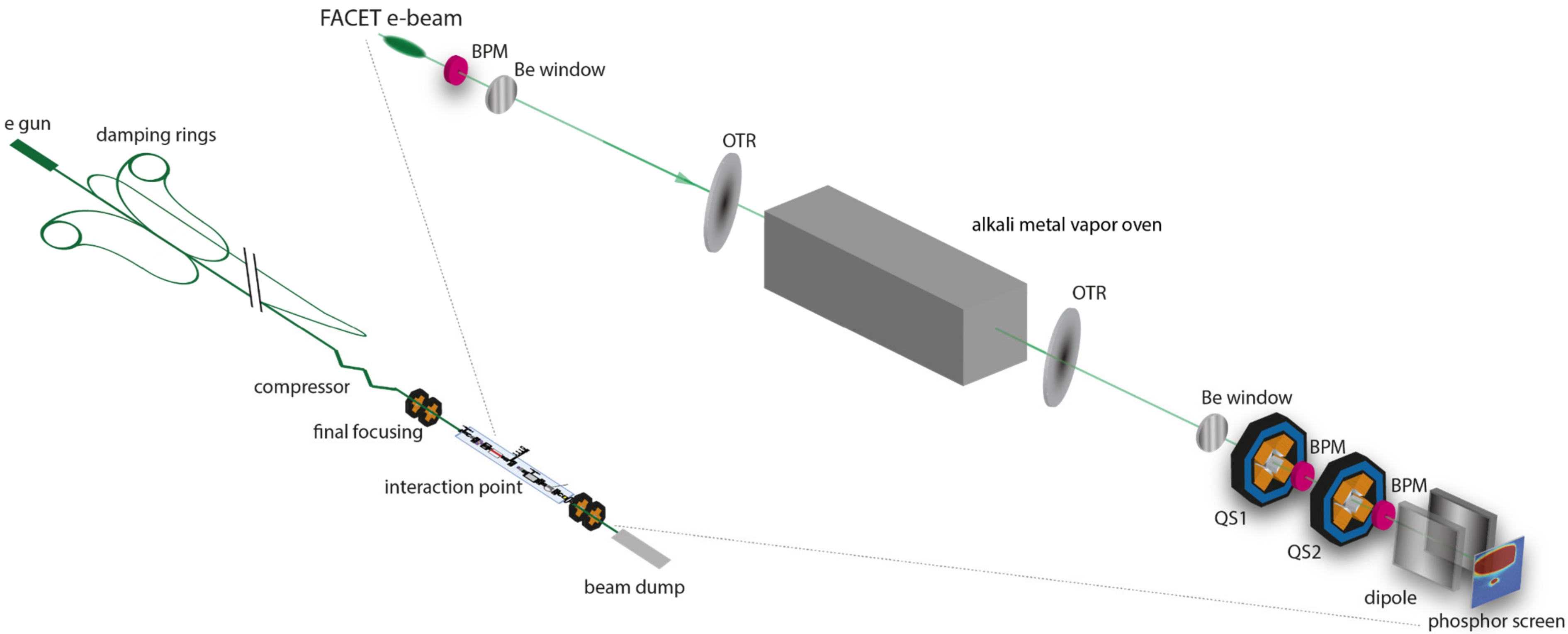
✓ First high-gradient e^+ PWFA (*Nature* **524**, Aug. 2015)

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

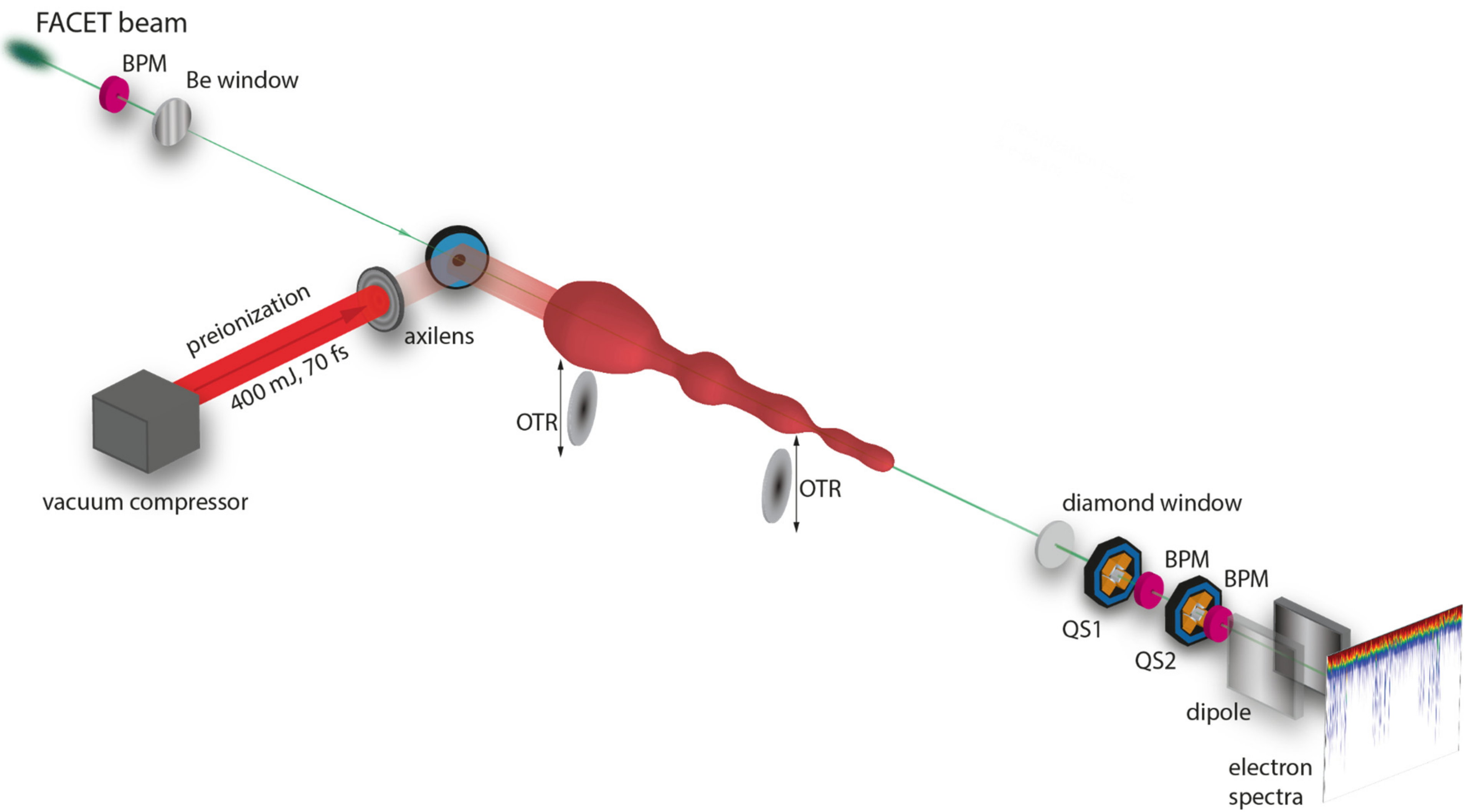
PI's B. Hidding (Strathclyde) & J.B. Rosenzweig (UCLA)

2012-2017, experiments at FACET ramping up from 2013-2016

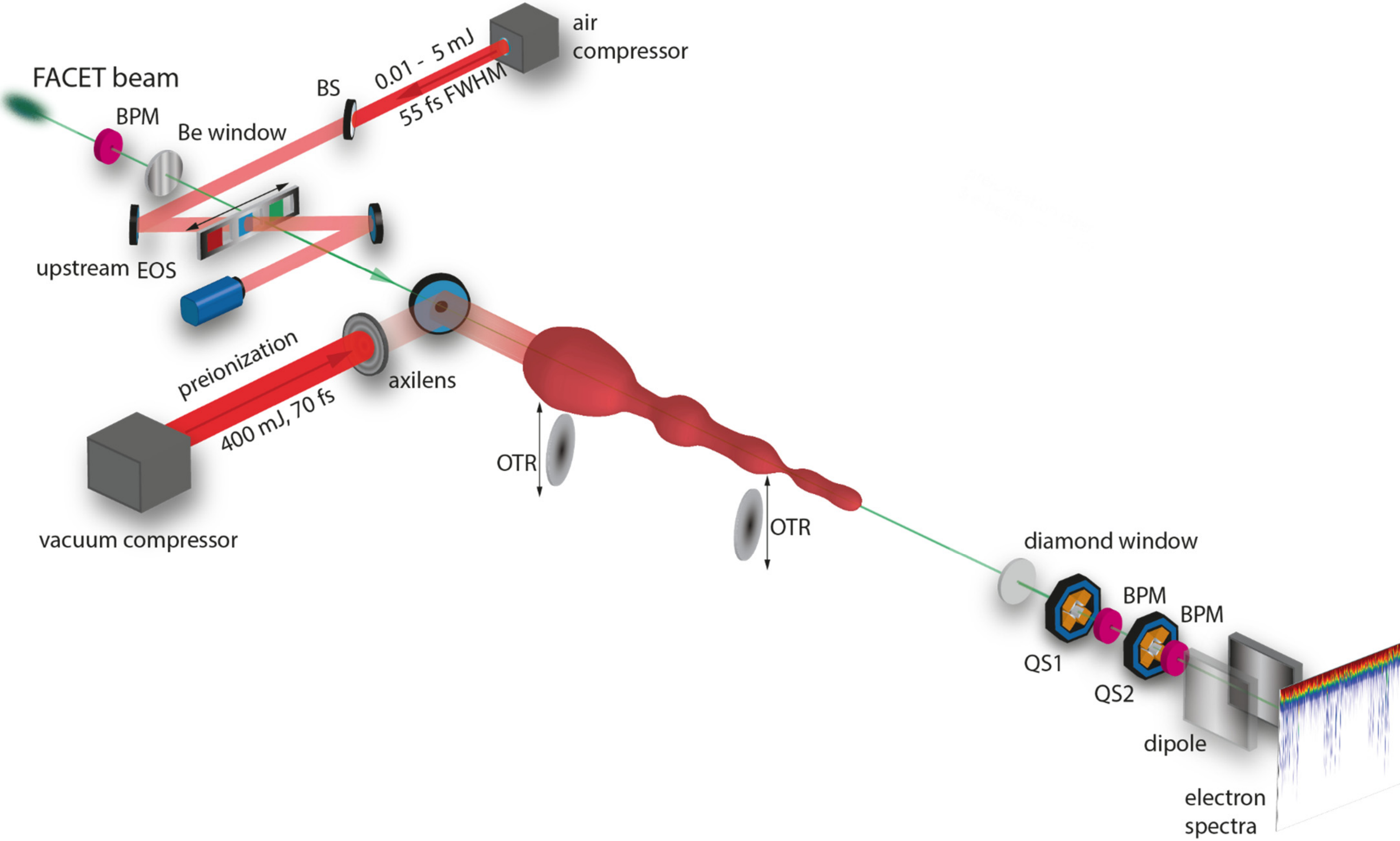
2012 at FACET: use hot alkali metal vapor, self-ionized by driver beam



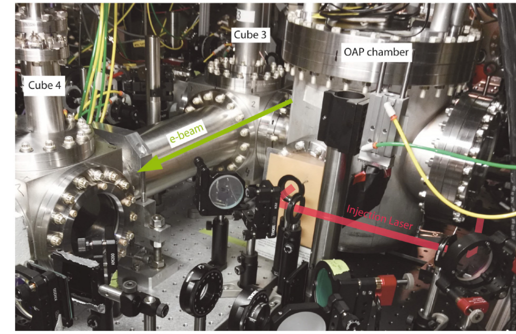
2013/14:
Ti:Sapphire commissioning, optical pre-ionization of (noble) gas

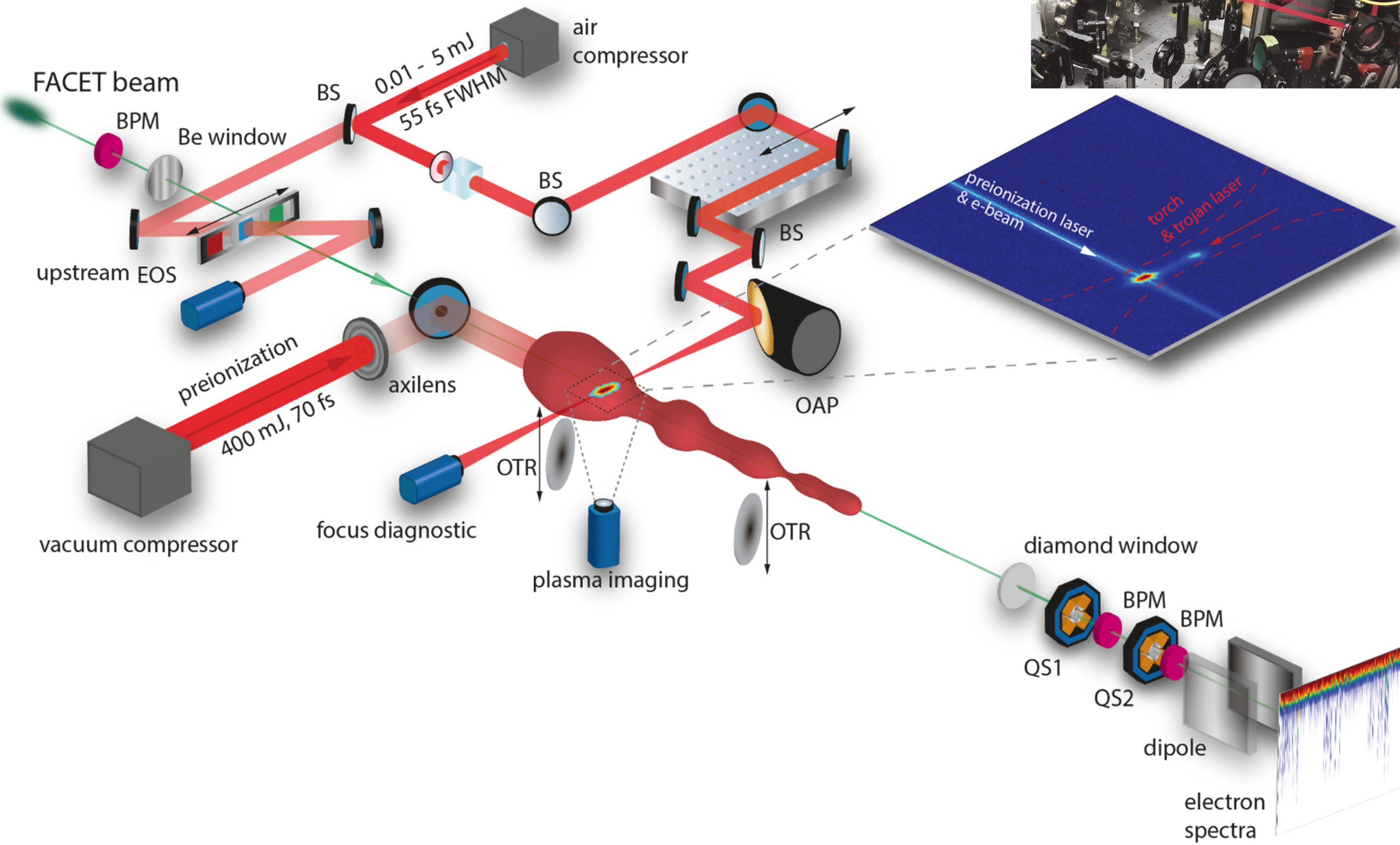


2013/14:
Commissioning of electro-optical sampling based time-of-arrival diagnostics, separate air compressor to allow for independently tunable beams

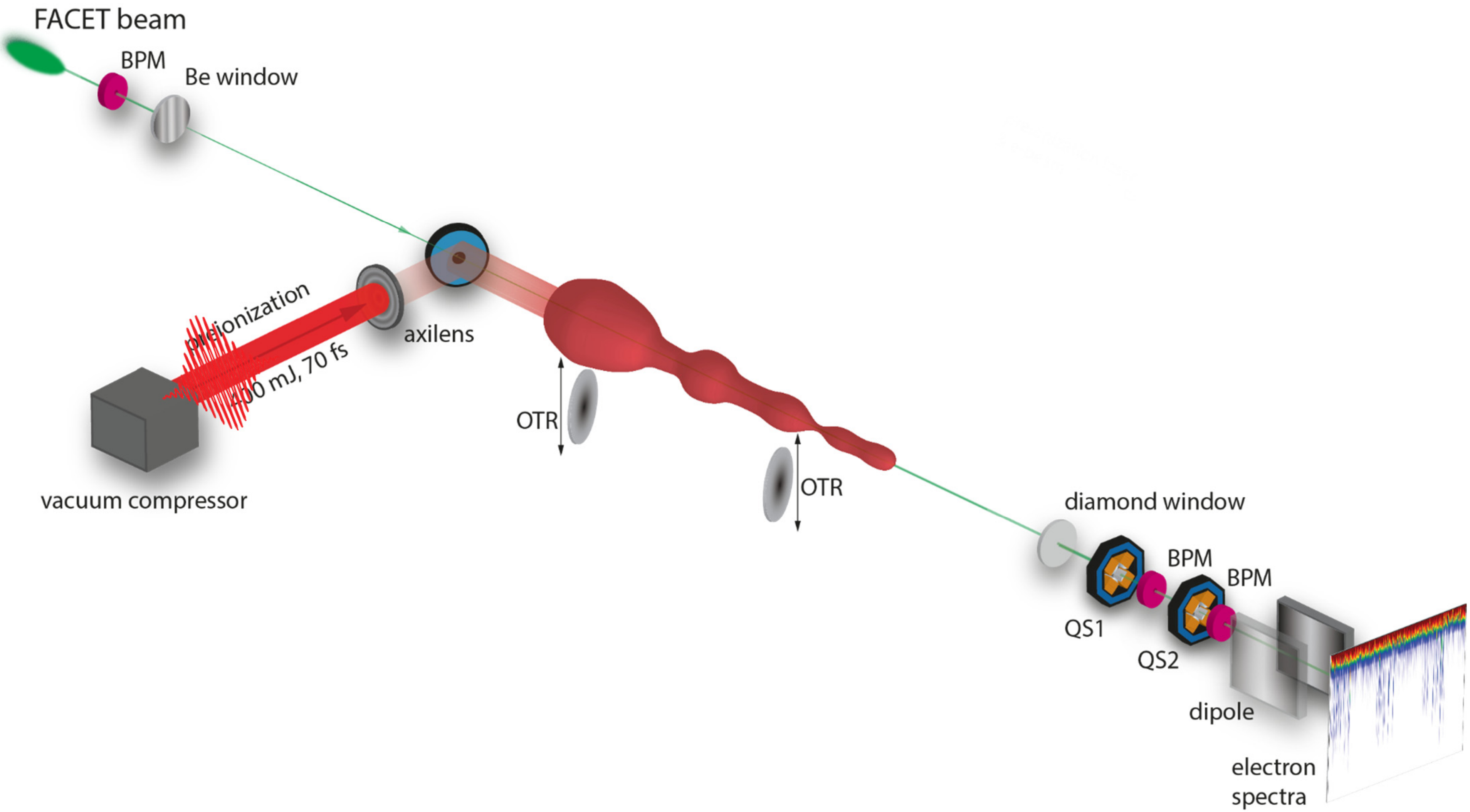


2015: Add Trojan Horse plasma photocathode laser (in 90° geometry)





Spatiotemporal alignment of beams is a key challenge: Preionization laser pulse and electron beam



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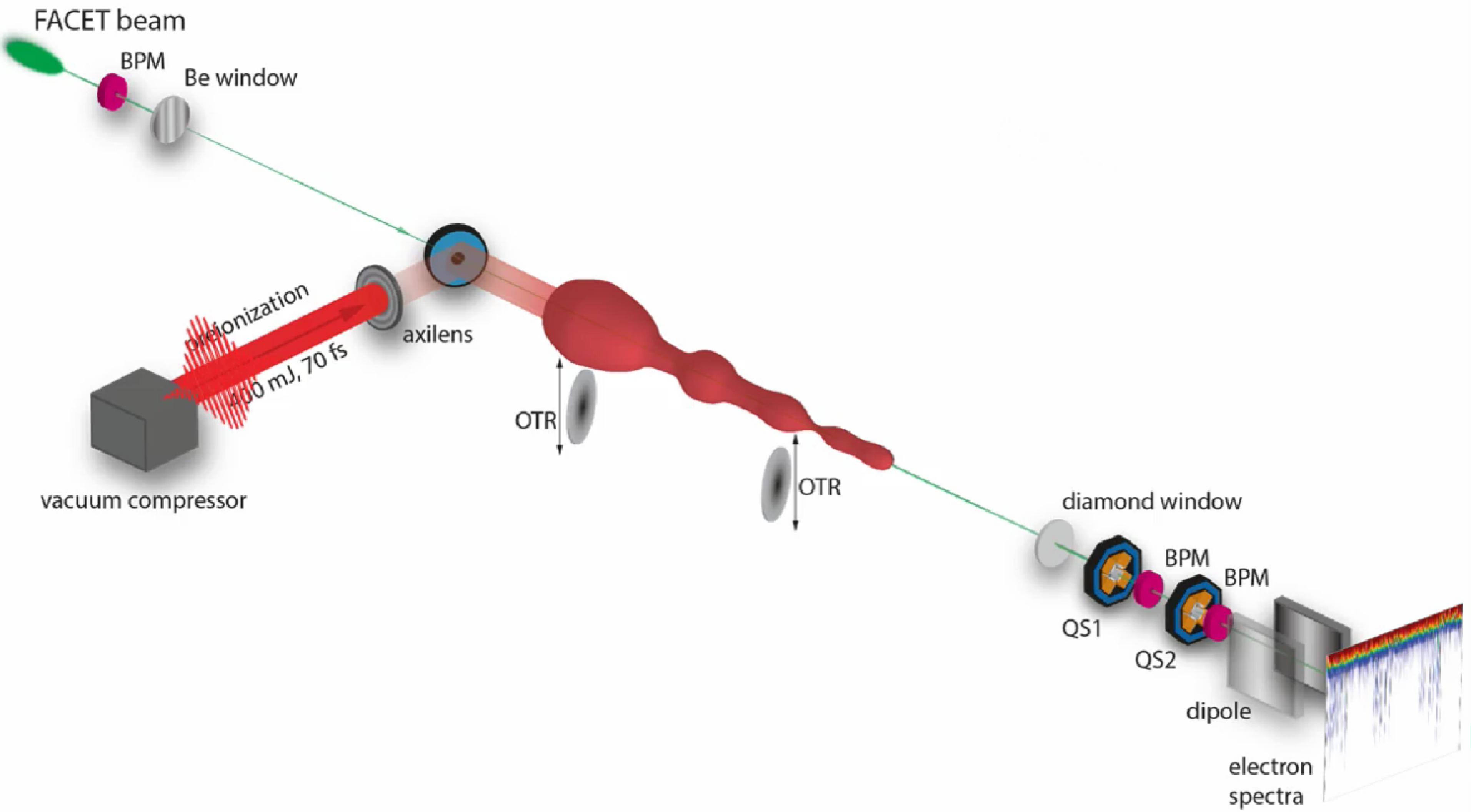
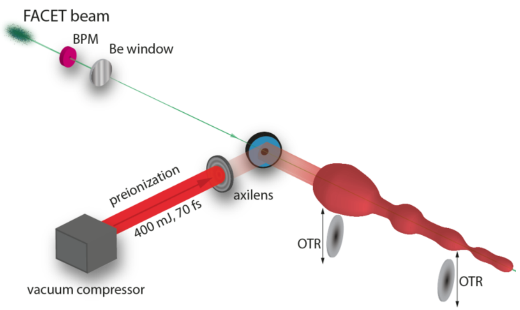
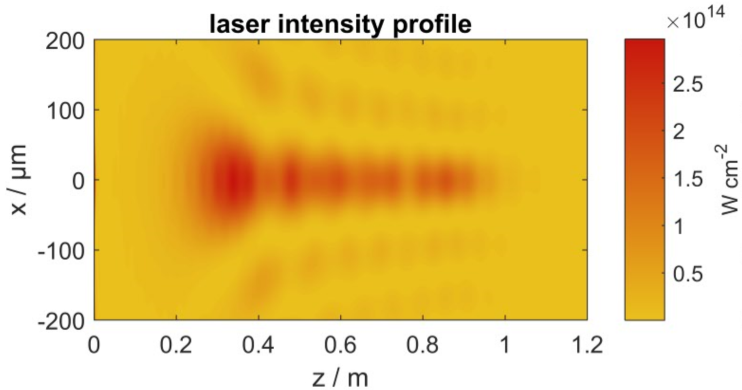
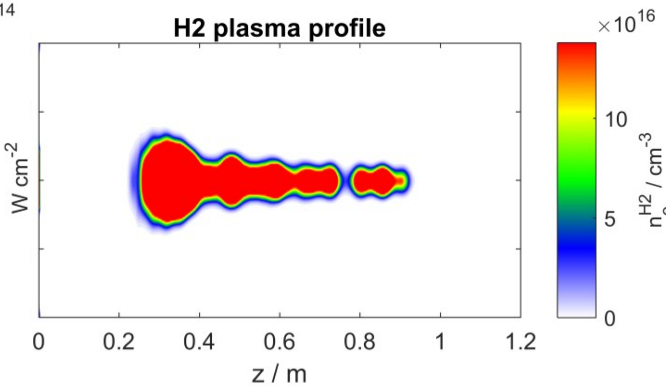


Axilens produces long (m-scale) and wide (up to 150 μm) hydrogen channel







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: λ_p > 90 μm required

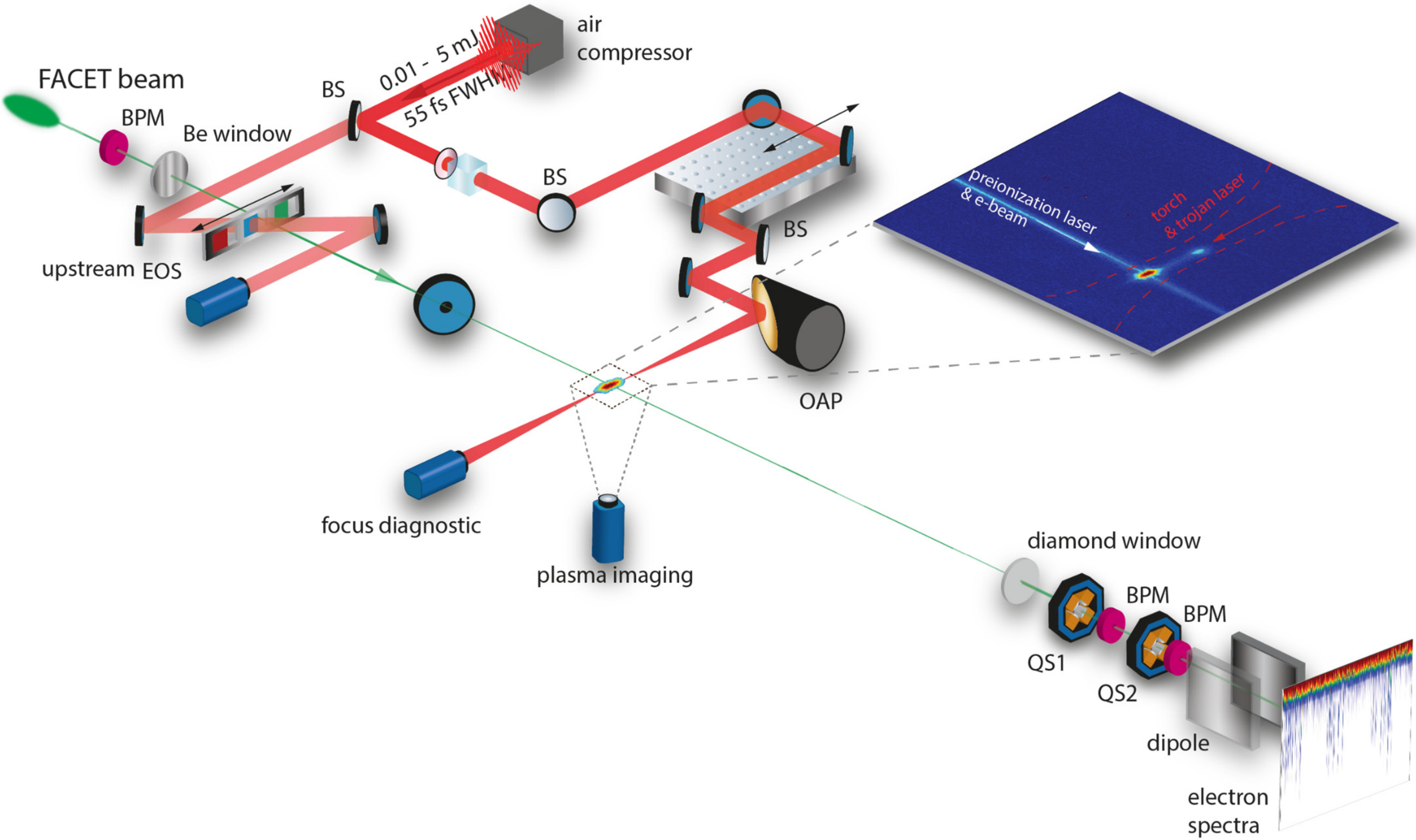
Plasma blowout size must not be ***too large***, or blowout hits plasma channel boundaries and wake collapses: λ_p < 100 μm

tight sweet spot at $\lambda_p \approx 98$ μm, $n_e(H_2) \approx 1.1\ 10^{17}$ 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.

VSim
TECH-X

Spatiotemporal alignment of injector laser and driver beam:
How do you hit a 100 µm size target moving with the speed of light?



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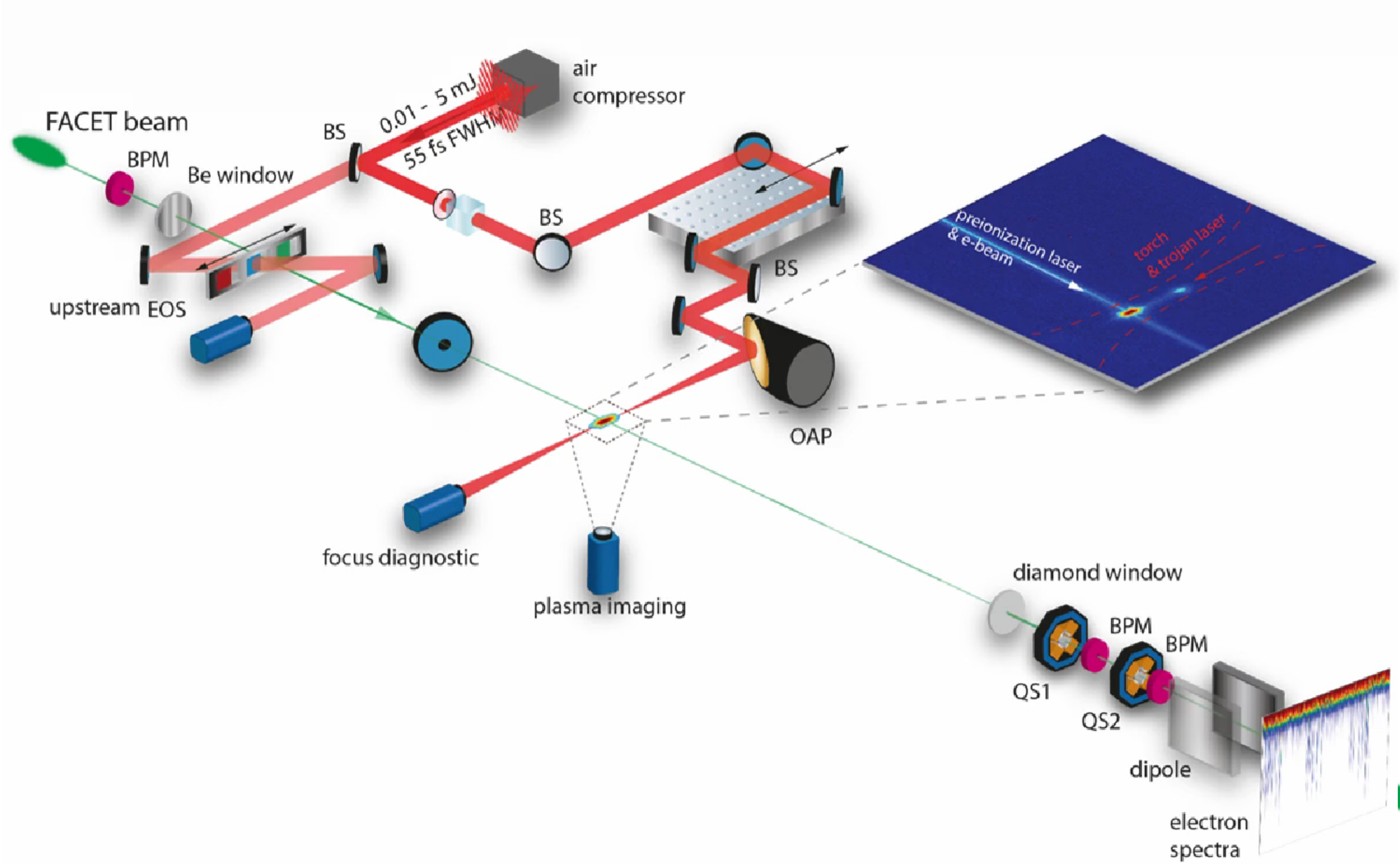
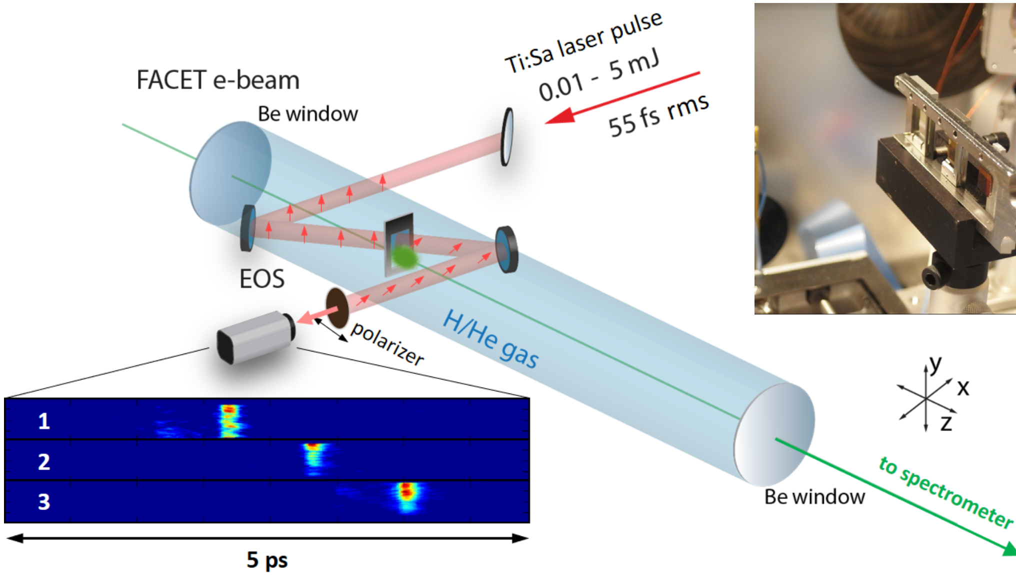
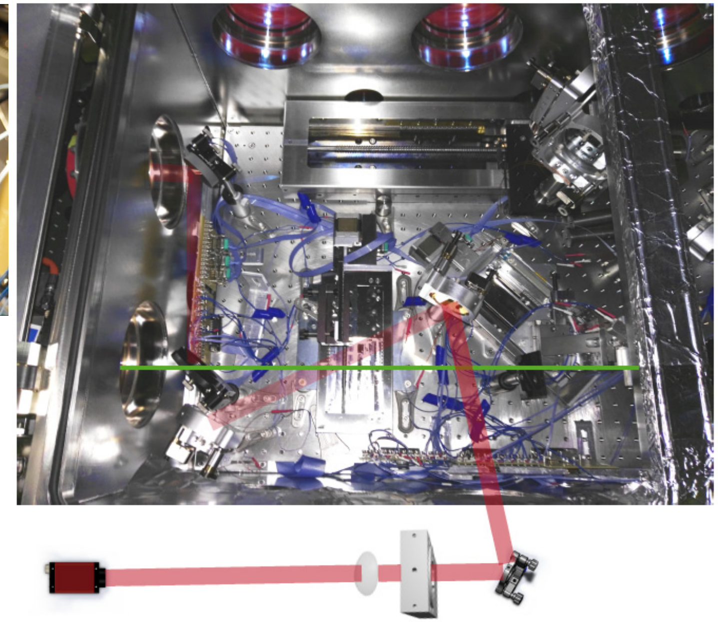
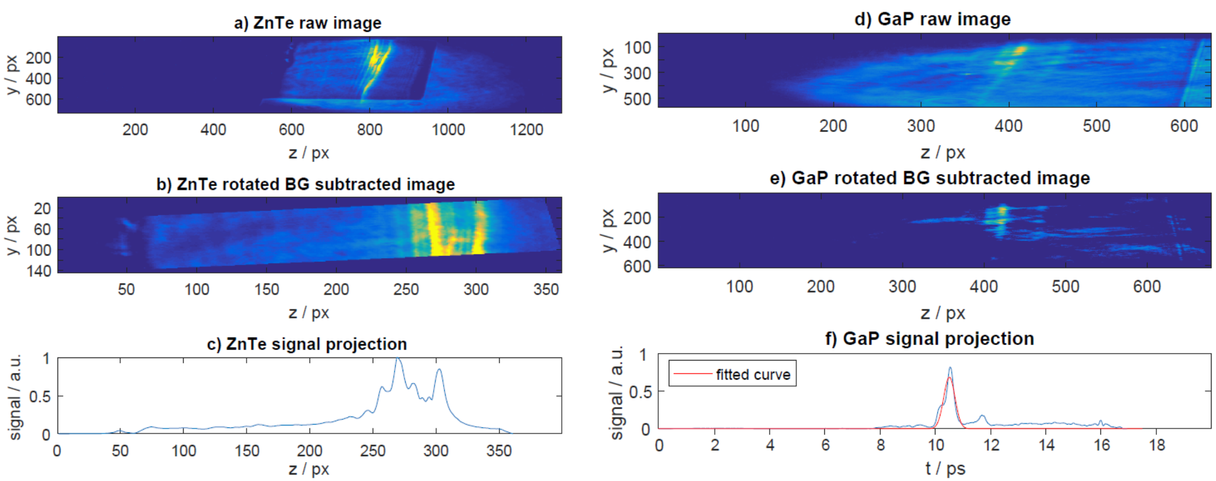
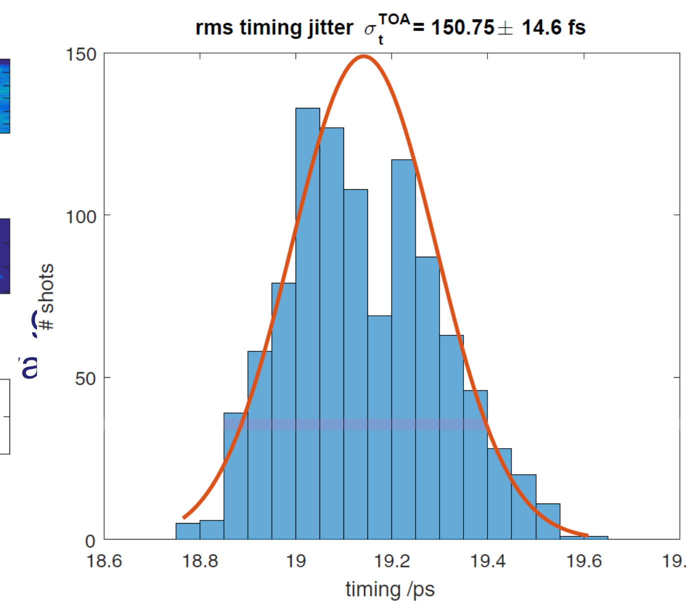


Electro-optical sampling (upstream, in “picnic basket“)







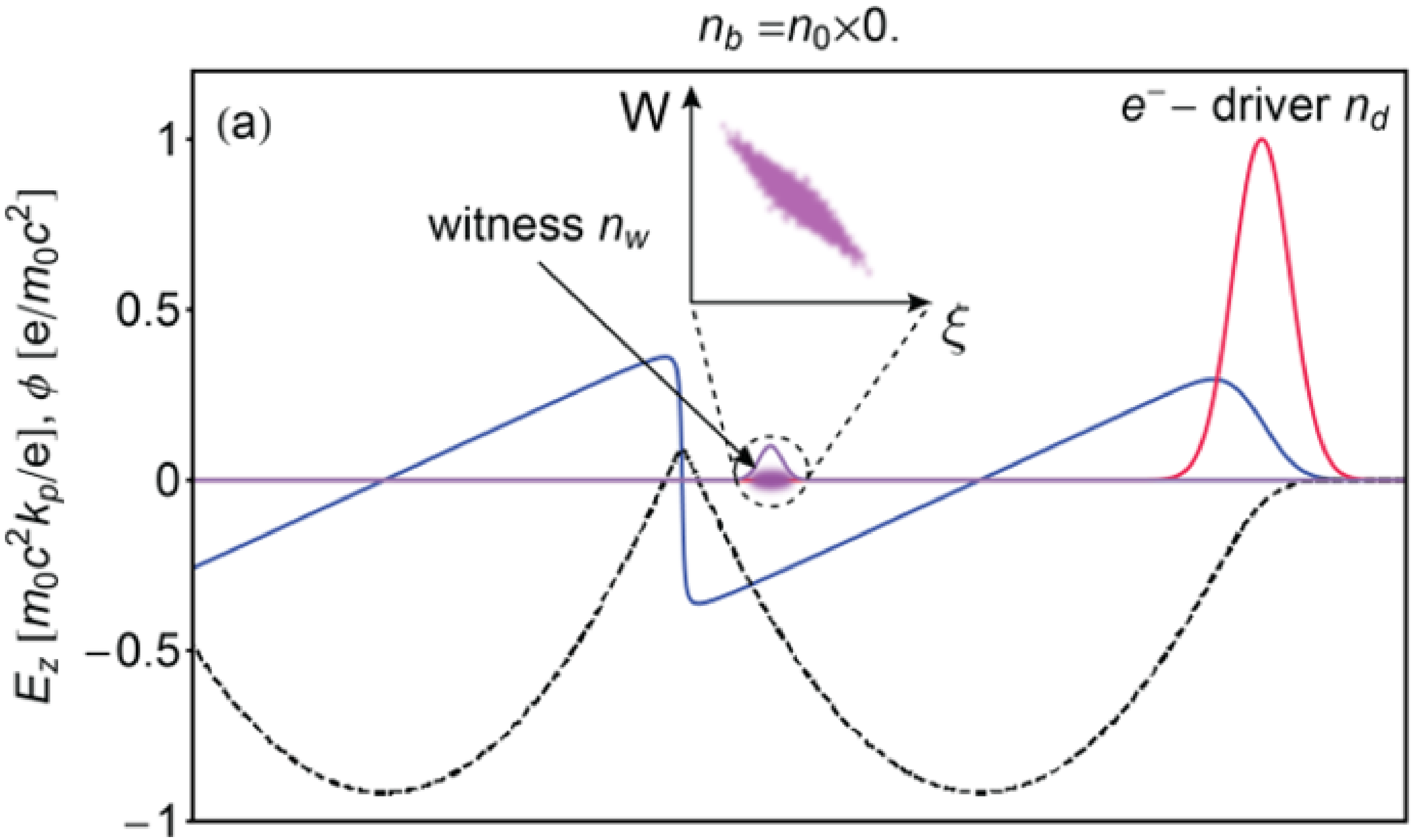


Surprisingly good jitter in view of thermionic gun: 150 fs rms.
Still, that‘s ~half a plasma wave length λ_p ...

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...

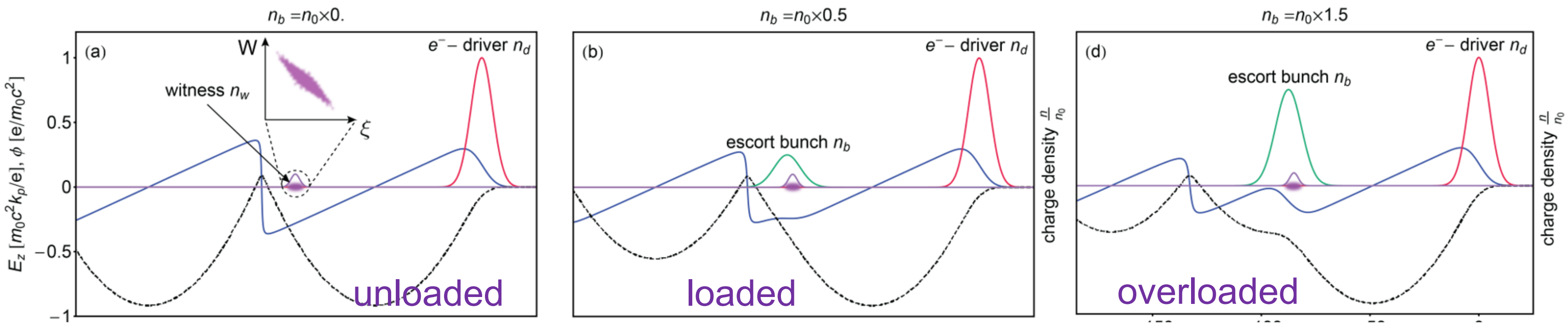
Path is open to ultralow TH emittance and ultrahigh 5D-brightness, but energy spread may destroy beam quality during extraction & transport
⇒ showstopper e.g. for FEL



“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:



G.G. Manahan, F. Habib, accepted in *Nature Communications*, 2017

VSim

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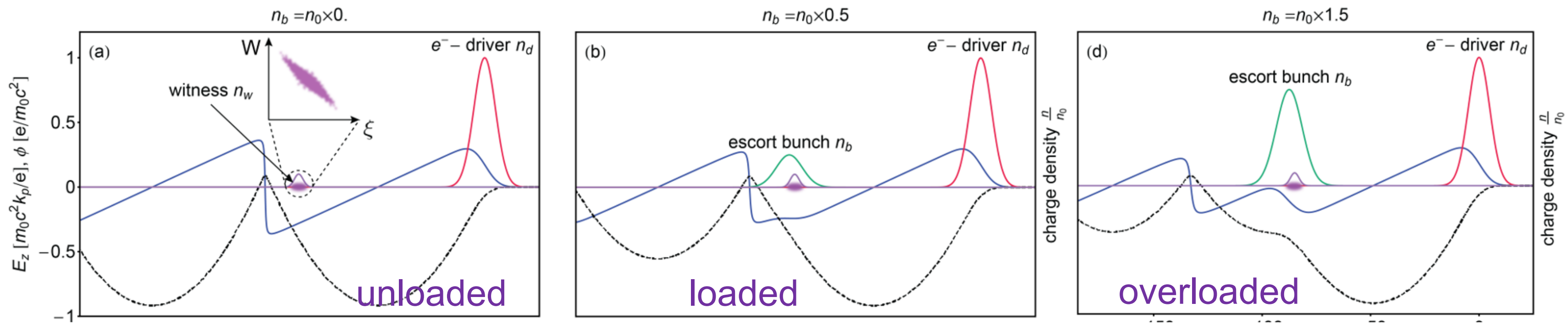
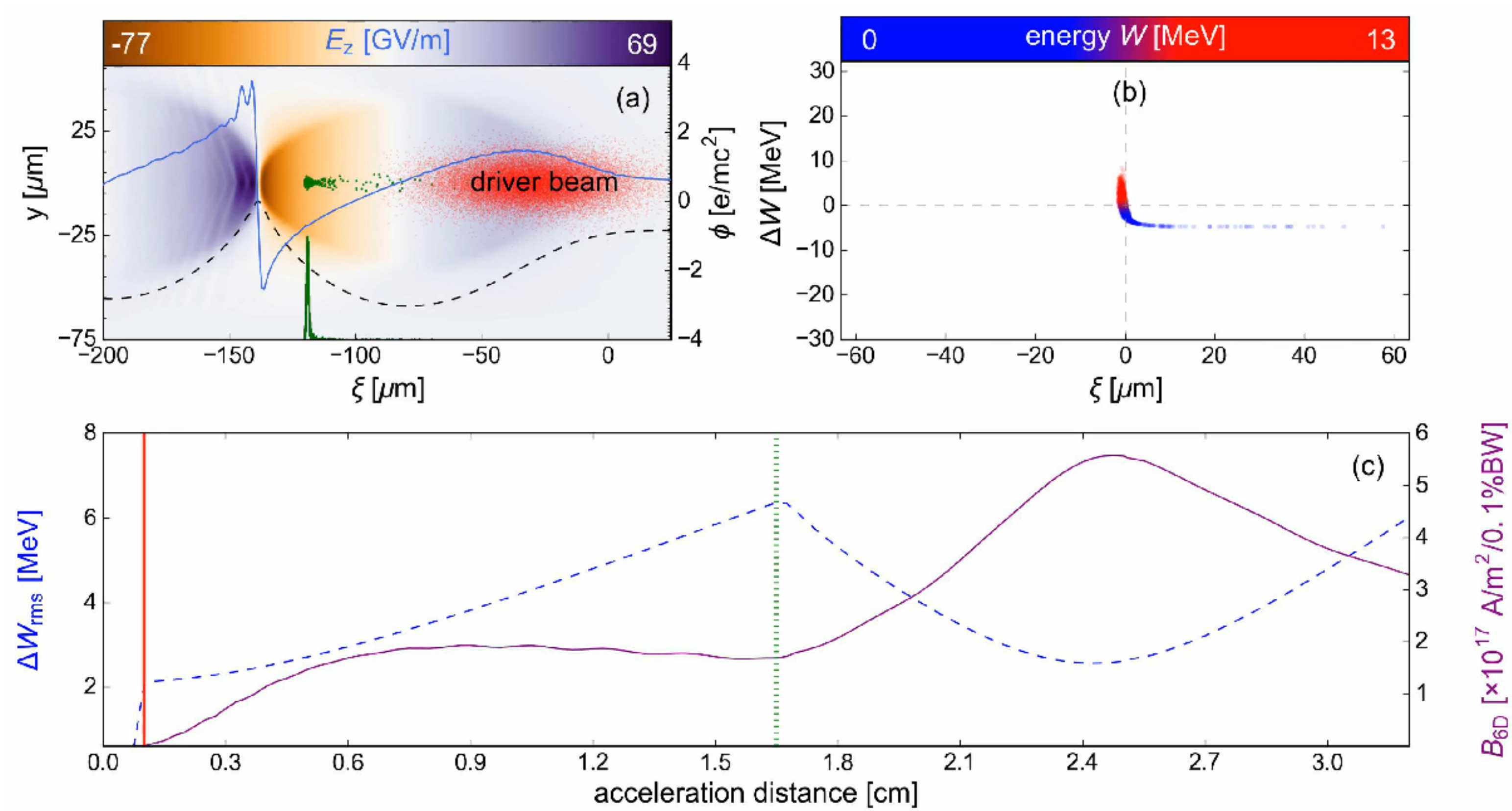
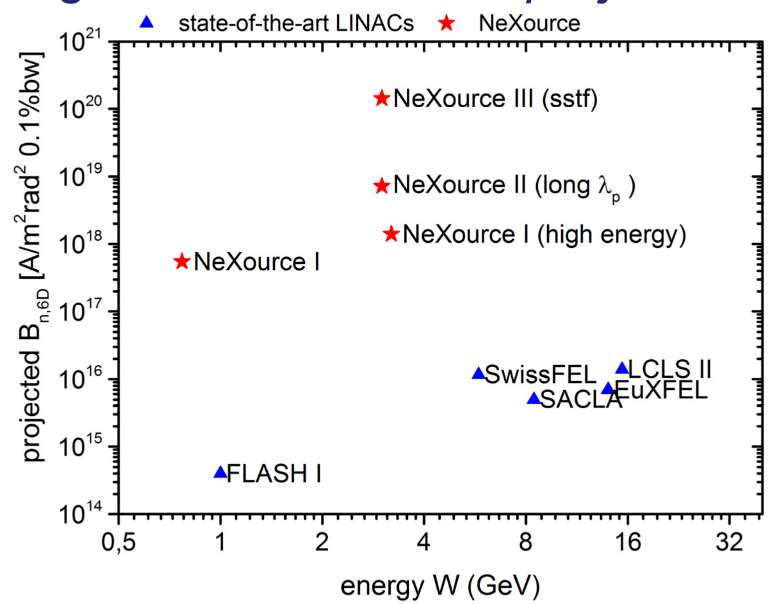


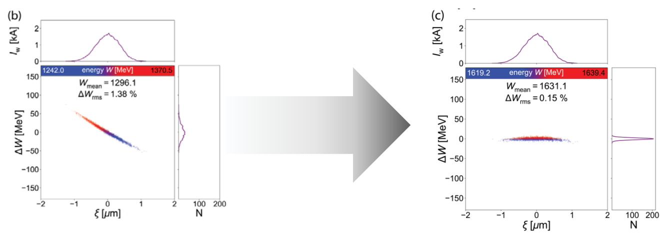


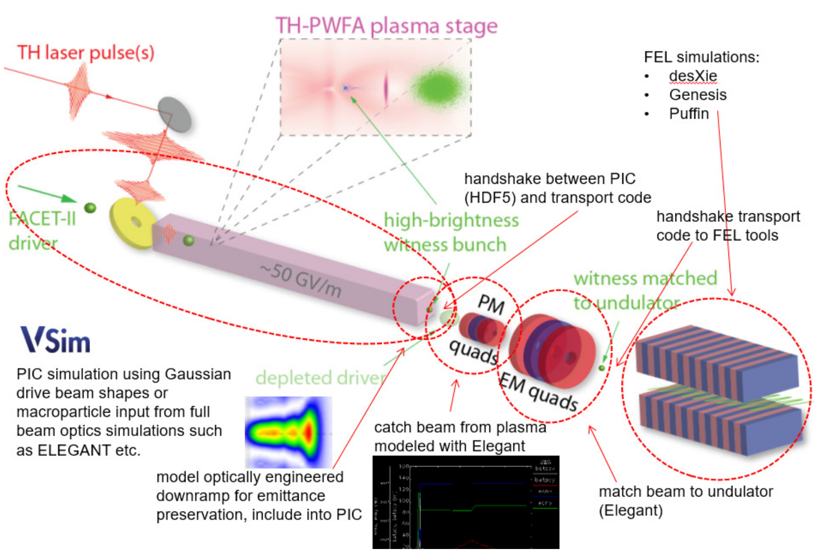
G.G. Manahan, F. Habib, accepted in *Nature Communications*, 2017

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)







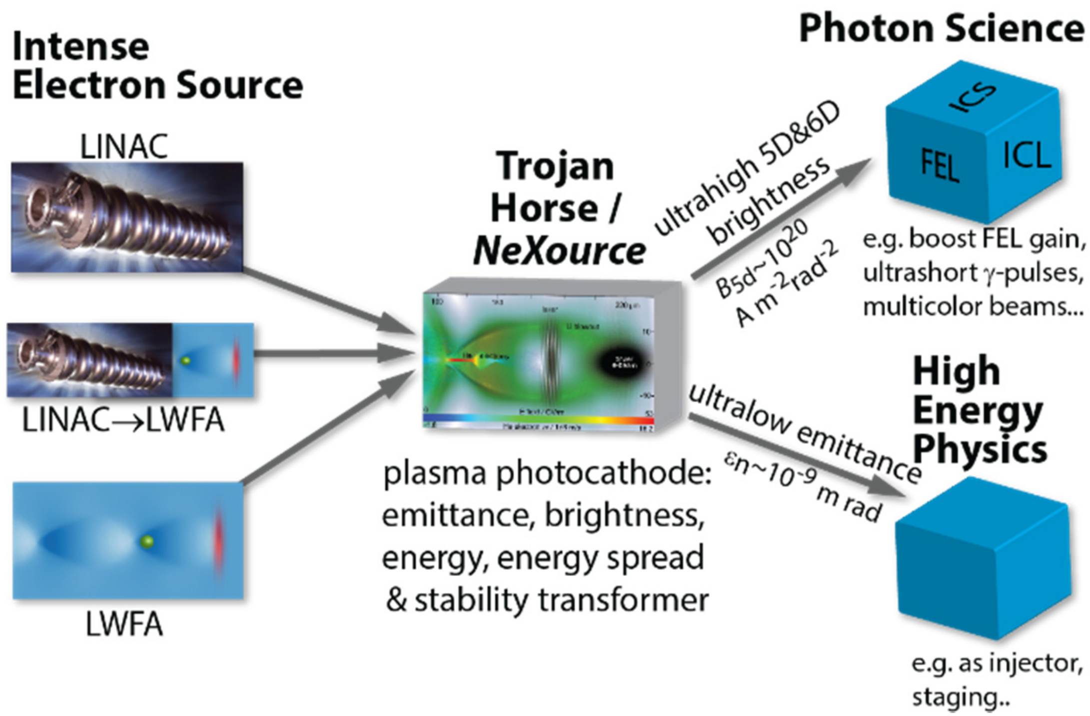
- This is a key step towards key applications such as 5th generation light sources
- E.g. for the race towards plasma-based FEL which is a main driver in the worldwide community: Beat Pierce parameter, fulfil Pellegrini criterion, and harness ultrahigh gain to realise compact hard x-ray FELs

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

- 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