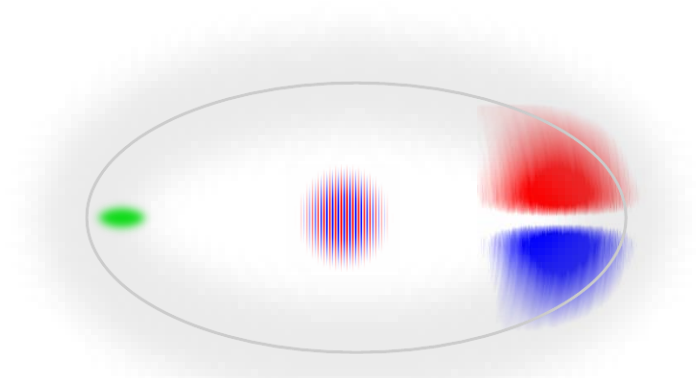
Havana, 2016-03-28
High Brightness Beams 2016

High-brightness beams from the Trojan Horse mechanism

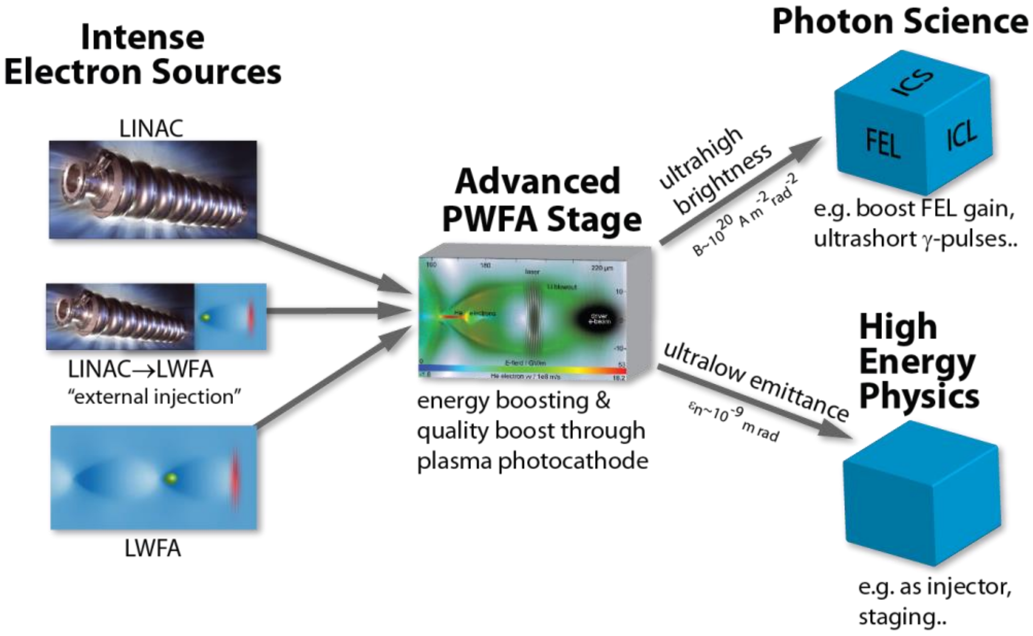
Bernhard Hidding et al.

Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde
& The Cockcroft Institute
& Department of Experimental Physics, University of Hamburg



Motivation & Main Goals

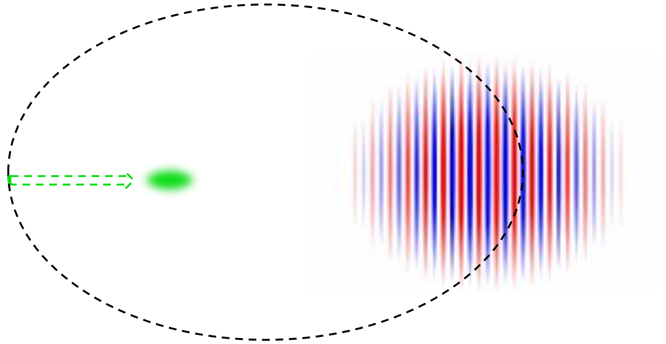
- Use plasma accelerators to obtain 10's to 100's of GeV/m acceleration fields, allowing for ultracompact accelerators
- Generate electron bunches with ultralow emittance (10^{-9} mrad scale), kA currents, brightness values orders of magnitude beyond state of the art -- 10^{20} Am^{-2} rad^{-2}!
- Combine robustness and controllability with flexibility and tuneability
- Allow designer bunch production
- Reduce chirp and (slice) energy spread to < 0.1%
- Use electron beams from a) linacs and b) from LWFA to drive the PWFA stage
- Build ultracompact, high performance light sources and enable other applications e.g. for HEP
- Do research with these facilities!



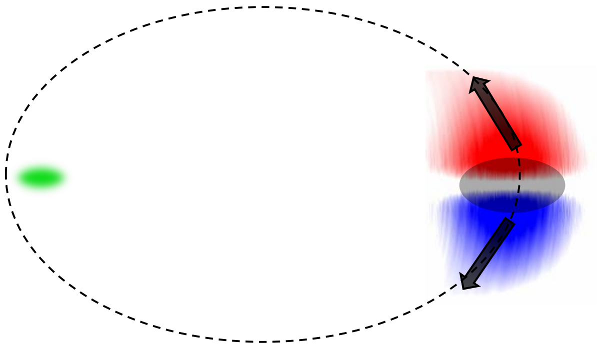
LWFA vs PWFA summarized

Hidding et al., J. Phys. B 47, special x-ray issue 2014

- Electron bunches: drive plasma wave efficiently due to unidirectional fields
- Lasers not straightforward to drive longitudinal plasma waves due to oscillating EM-field structure
- Lasers can easily ionize matter, because of diffraction can do so in very confined area
- Electron bunches can be produced with very high rep rate from state-of-the-art sources
- Electron bunches are not good for ionizing matter
- Electron bunches move with c, allow for dephasing-free accelerator systems
- No dark current in PWFA systems because of high gamma
- Electron bunches are stiff: don't expand much transversally (limited diffraction) – long acc. distances



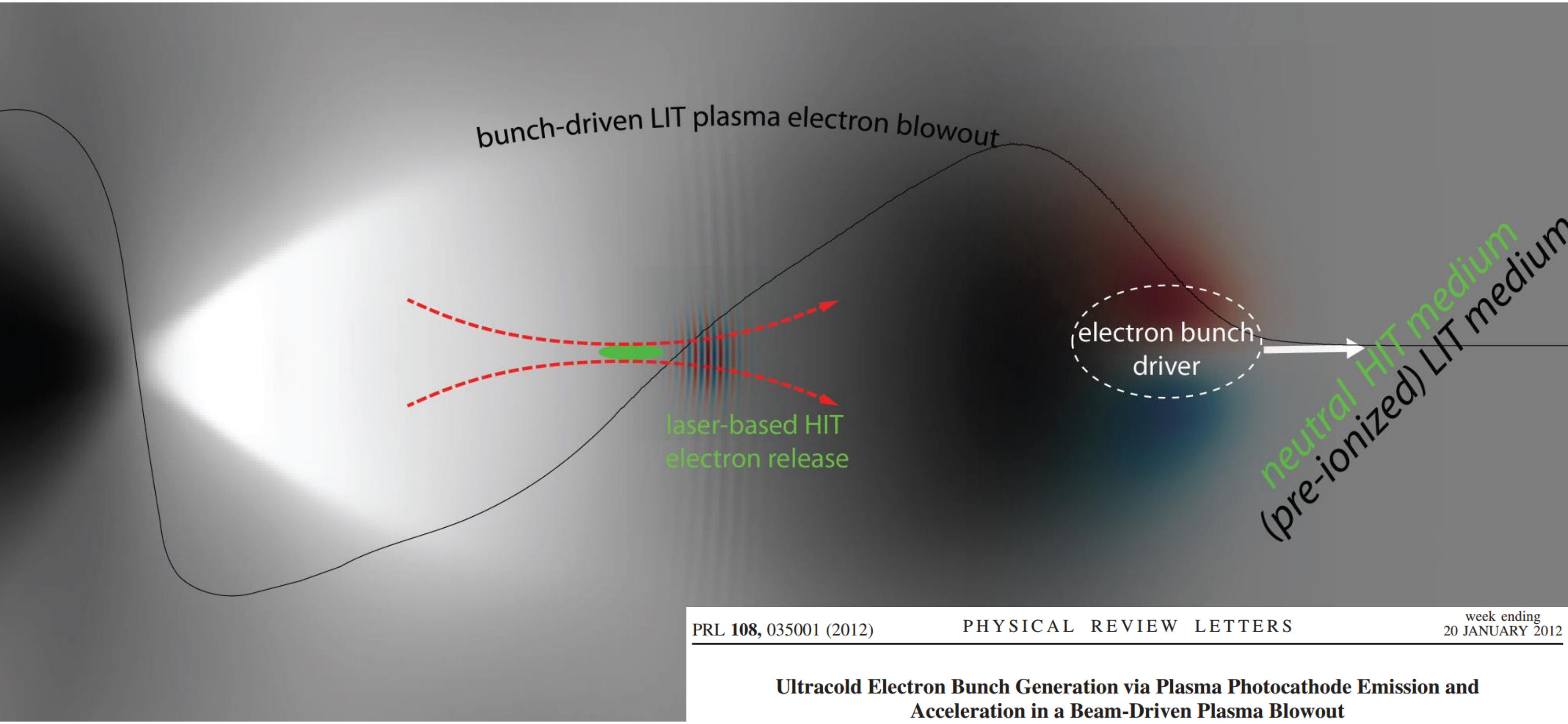
ionization @~10^{14} W/cm^2 (easy)
bubble @~10^{18} W/cm^2 (hard)



ionization if E_r > 5 GV/m (hard)
blowout if $n_b > n_e$ (easy)

⇒ ***Electron bunches are ideal plasma drivers, laser pulses great for injection!***

Take the best of both worlds: Hybrid Plasma Acceleration



PRL **108,** 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

B. Hidding,[1,2] G. Pretzler,[2] J. B. Rosenzweig,[1] T. Königstein,[2] D. Schiller,[1] and D. L. Bruhwiler[3]

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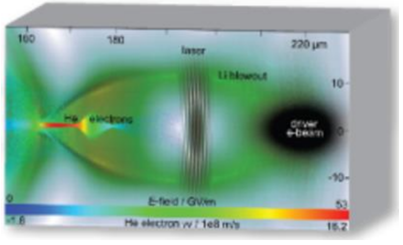
[2]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[3]*Tech-X Corporation, Boulder, Colorado 80303, USA*
(Received 30 March 2011; published 17 January 2012)

What's needed:

- LIT/HIT medium such as H2/He
- electron bunch driver to set up (preionized) LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout

Timeline

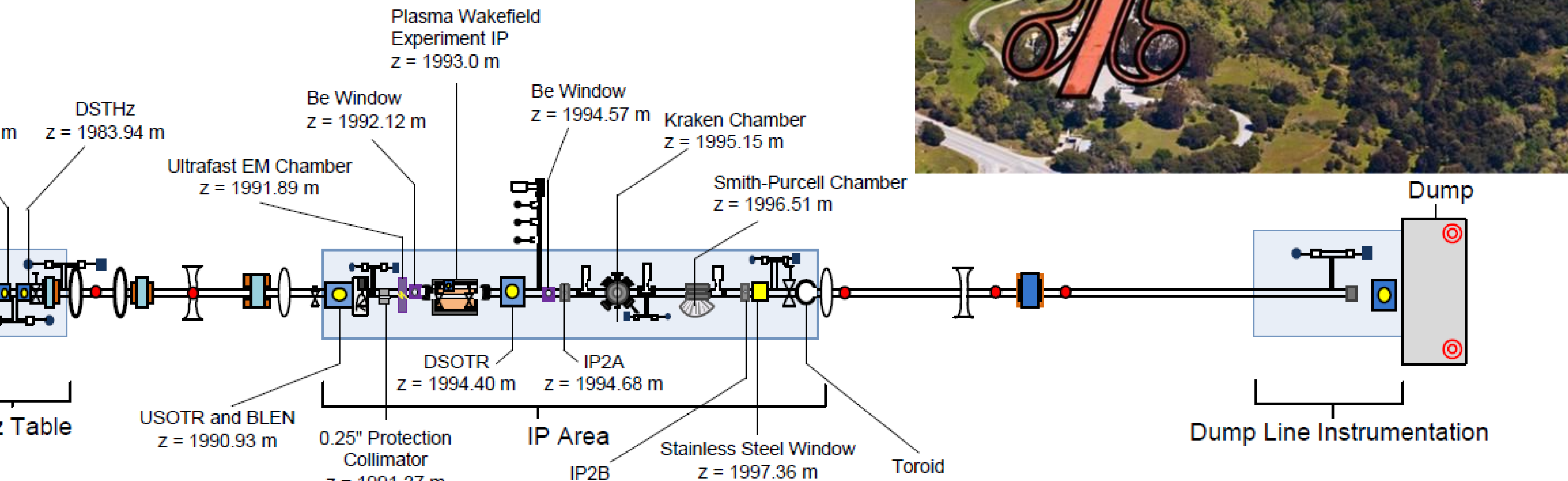
- …preliminary research & idea 2008-2011 (see e.g. PRL 2010 “Hybrid laser plasma accelerator”
- 2011: patent DE , 2012 patent US/PCT
- Jan 2011: submitted PRL “Ultracold electron bunch generation”, submitted abstract to LPAW 2011 China
- October 2011 proposed SLAC FACET experiment, approved as “E210 Trojan Horse PWFA”
- 2012 PRL “Ultracold electron bunch generation..” accepted for publication, 108, 035001



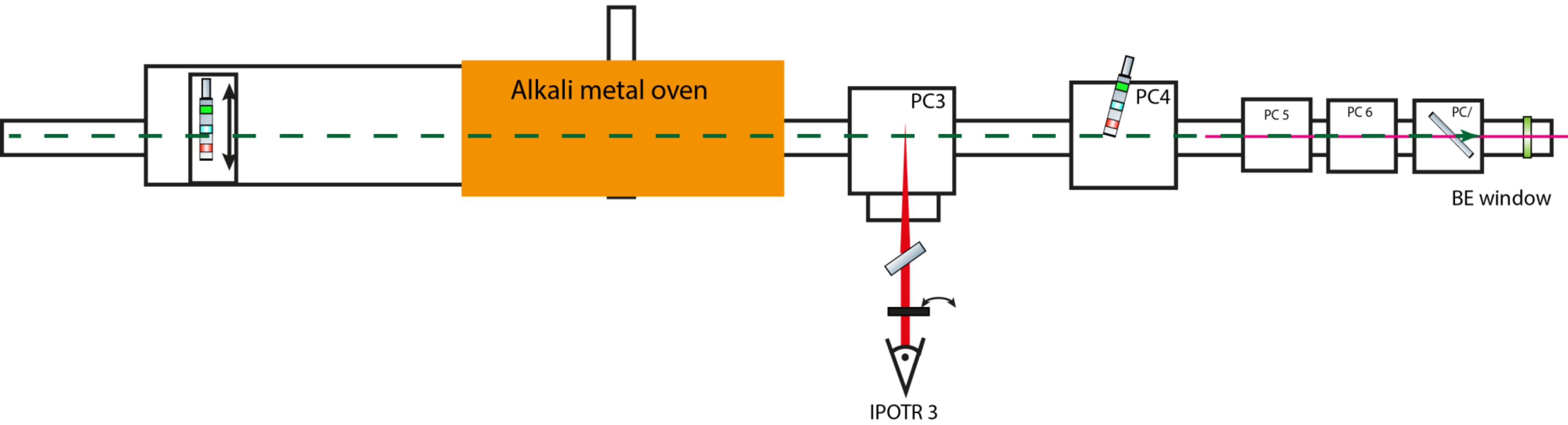
- Further theory research such as Xi et al., PRSTAB 2013, Li et al., PRL 2013; Bourgeois et al., PRL 2013, Yu et al., ArXiV 2013., G. Wittig et al, PRSTAB 2015, G.G. Manahan, PRSTAB 2016..
- Ramp up E210 at FACET: 2012-2016 (leap day)

E210 Trojan Horse at FACET

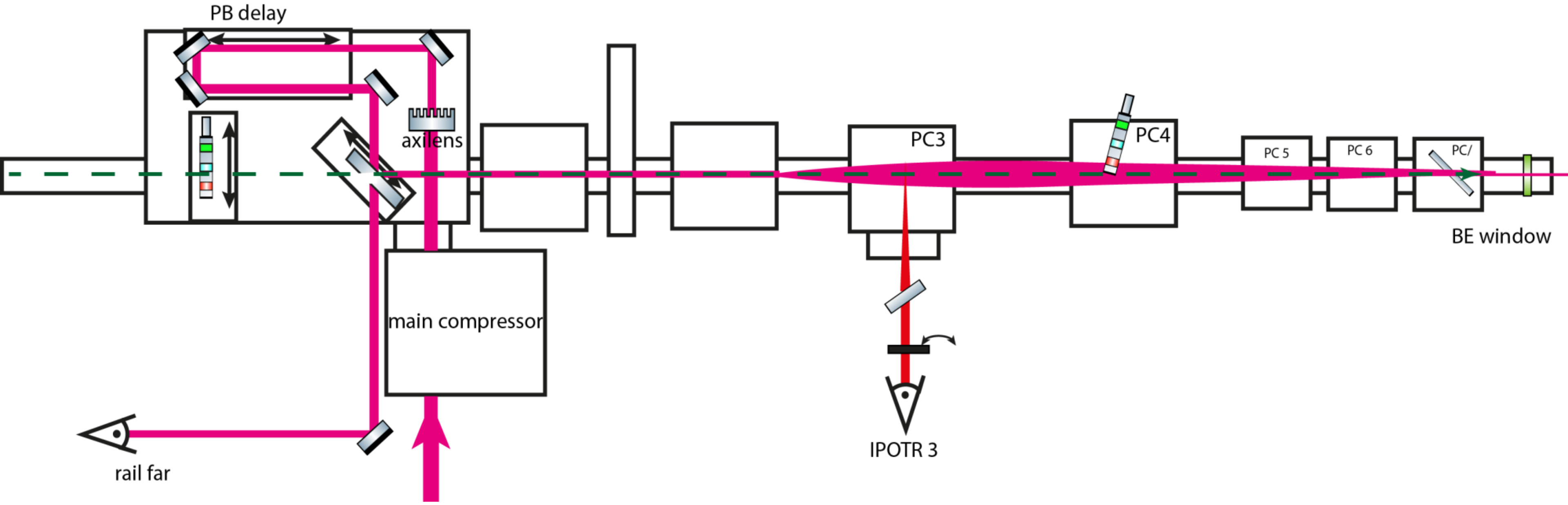
- Proposal submitted 2011
- Dramatic performance increase at FACET in last years:
- Started w/ self-ionized LIT alkali vapours, no laser
- Electron bunch quality boosted in 2012
- 10-20 TW synchronized Ti:Sa installed in 2013
- First laser-preionized argon/hydrogen in 2014/15
- Preionized H + He as HIT gas in 2015 (spring run)
- Synch. & time-of-arrival commissioning 2015 (spring run)
- Focused Trojan laser commissioning 2015
- **Full blown exp. with 4 laser arms in 2016 spring run**



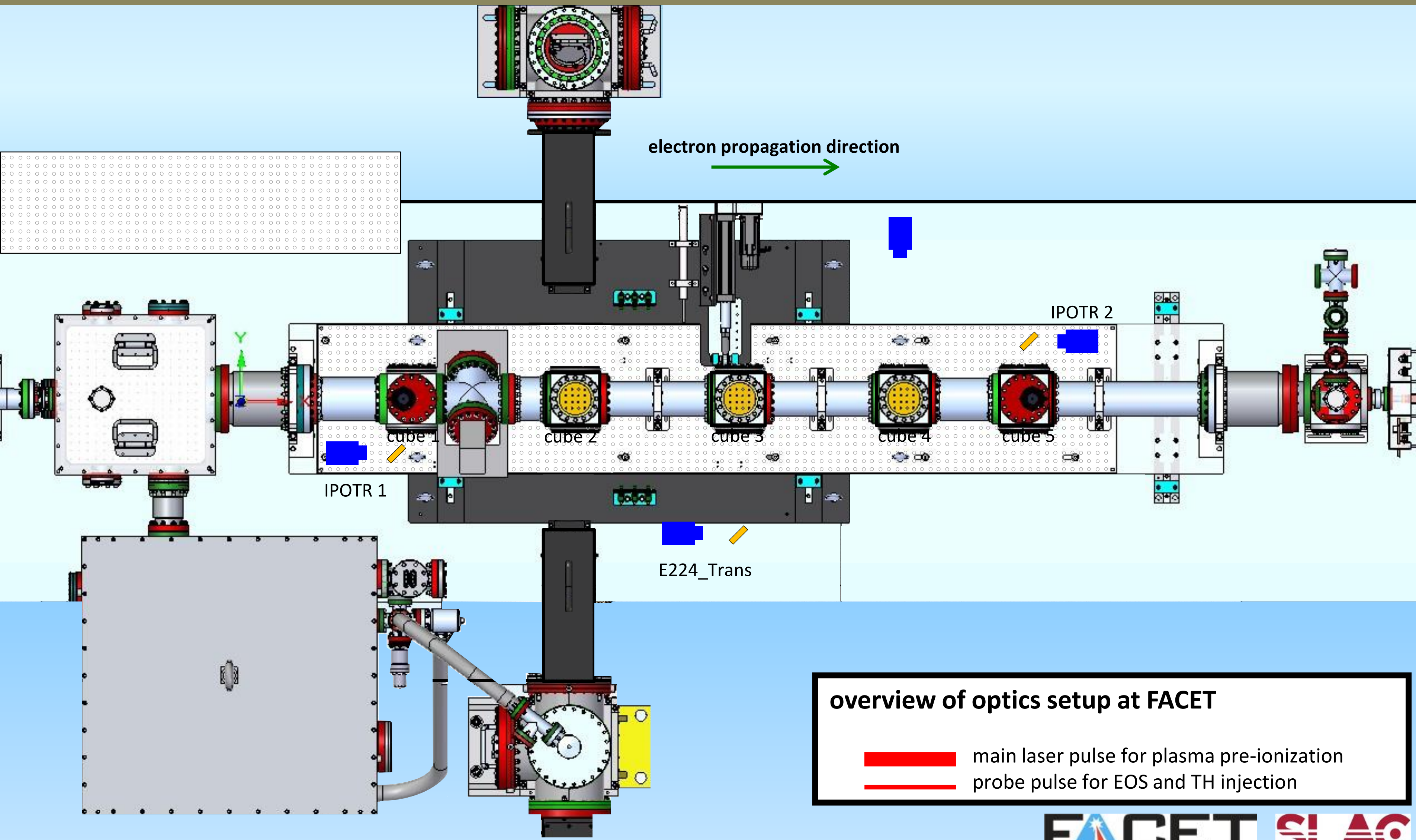
Pre-2012 setup: alkali metal oven, rely on FACET driver bunch self-ionization



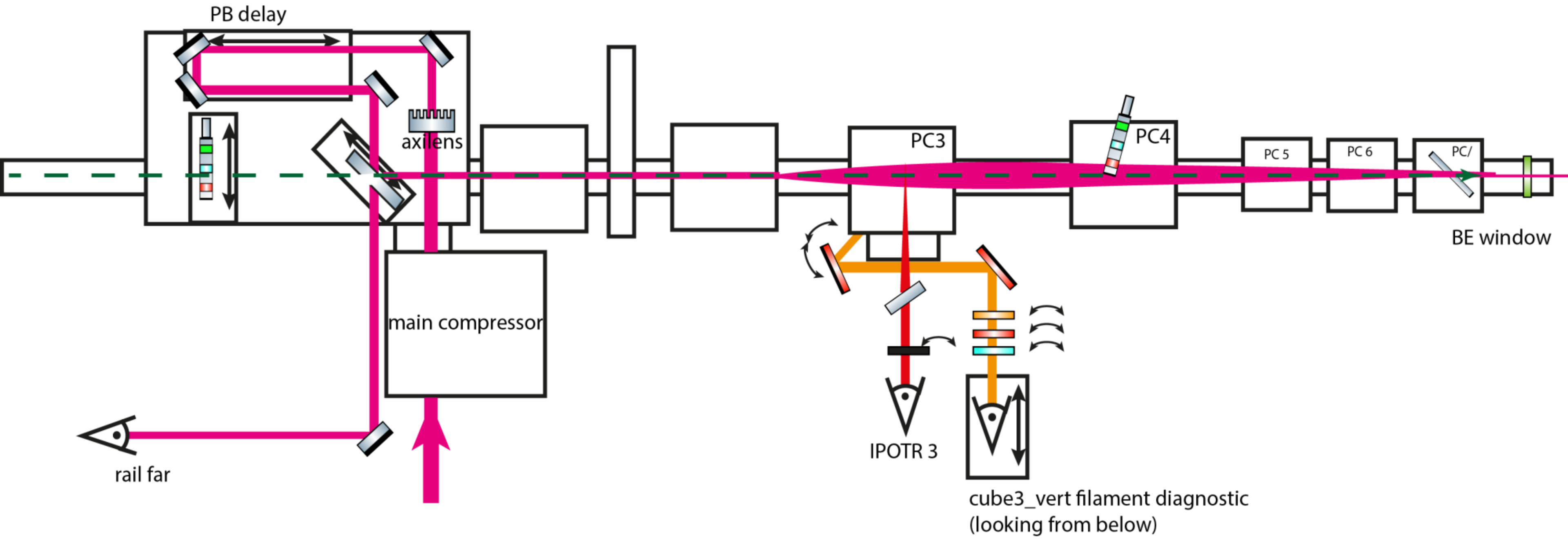
E210 setup: RadiaBeam "Picnic basket" chamber and 20 TW preionization laser integration



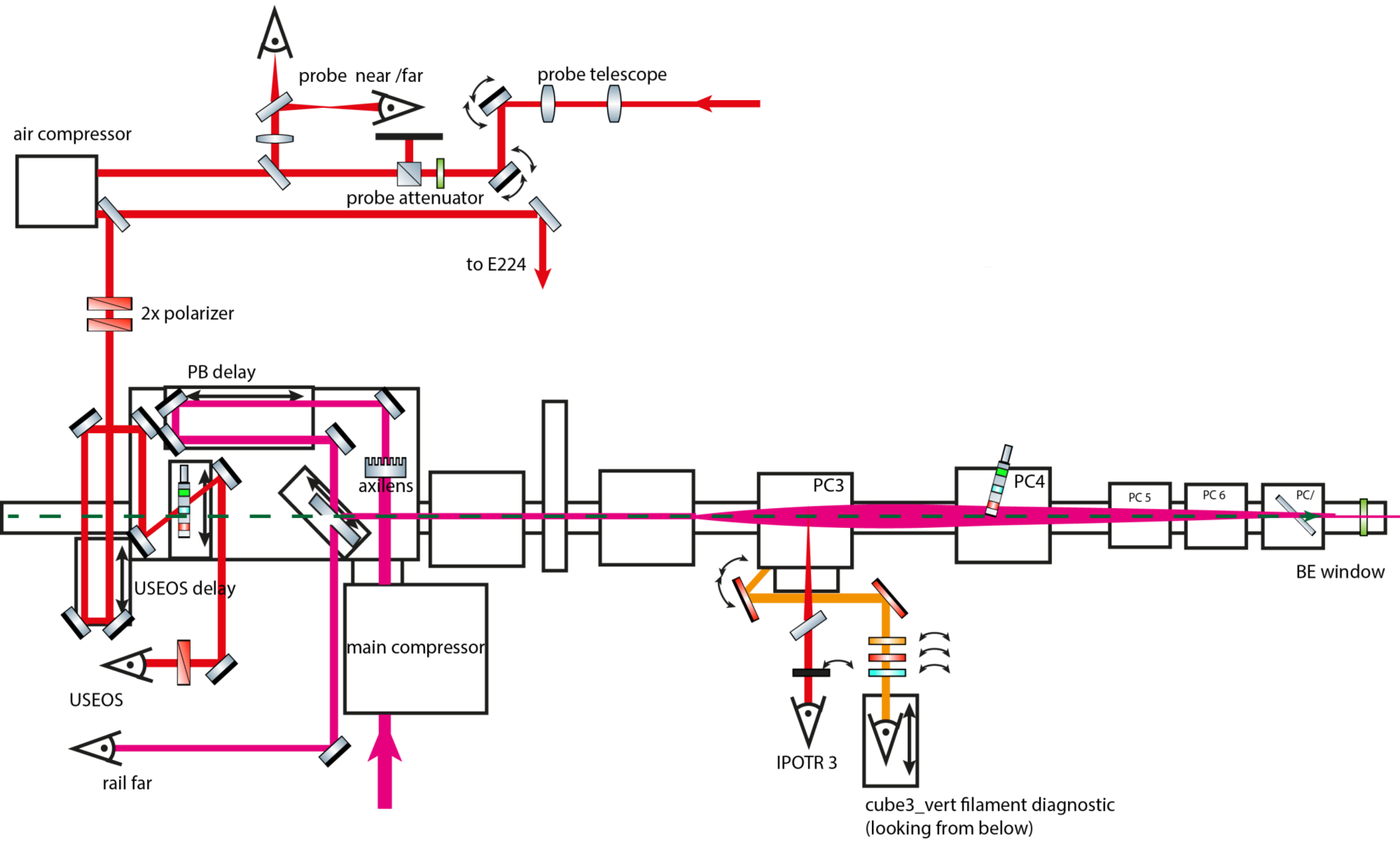
setup at FACET



E210 setup: cube 3 vertical plasma filament diagnostics



E210 setup: 2nd laser arm. Independently tunable air compressor and upstream EOS time-of-arrival diagnostics commissioning



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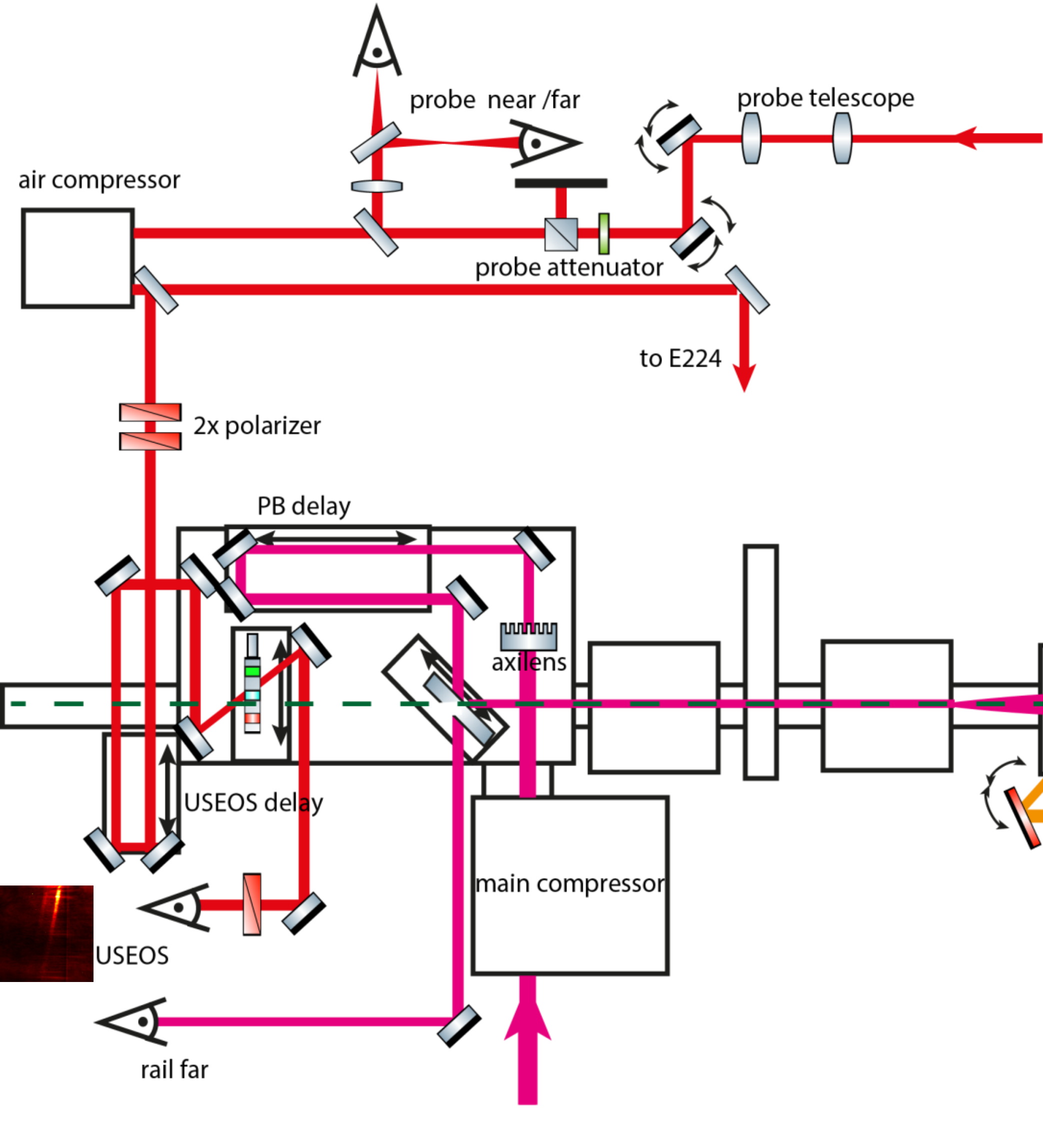
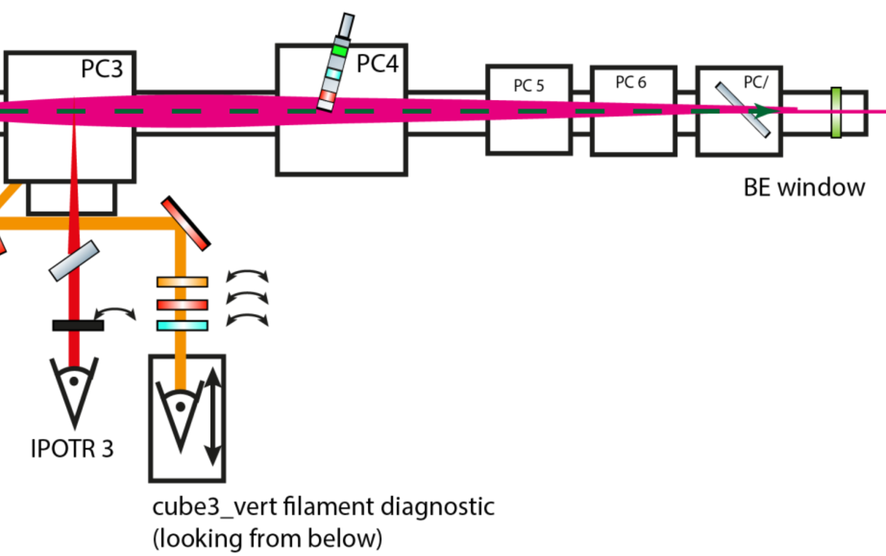
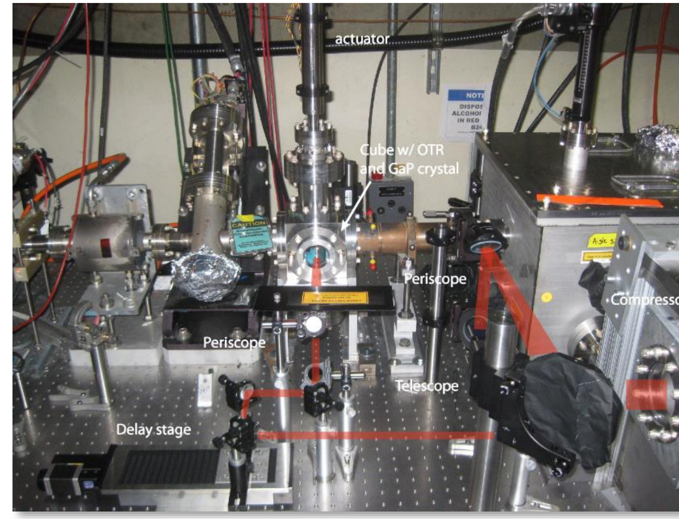
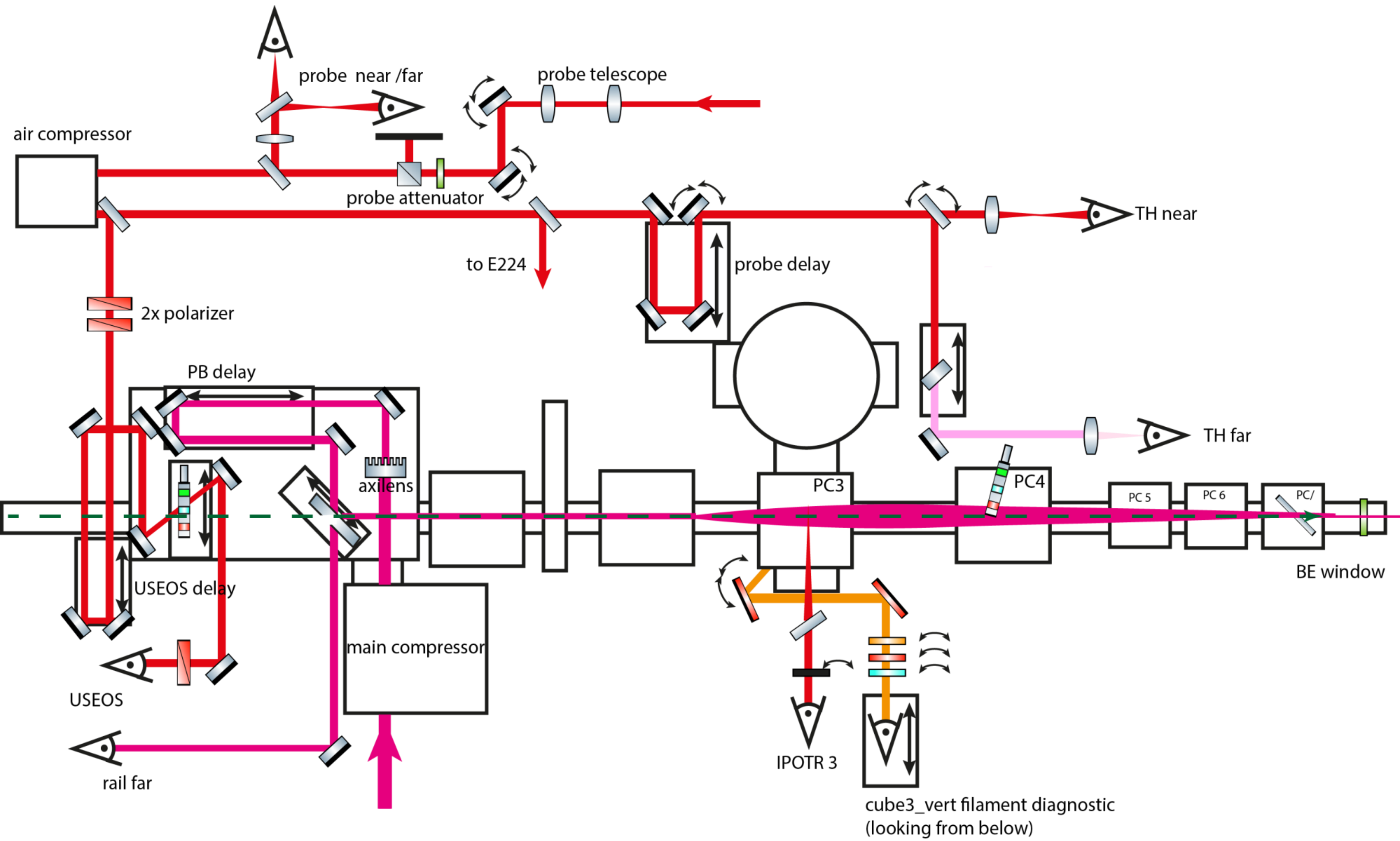






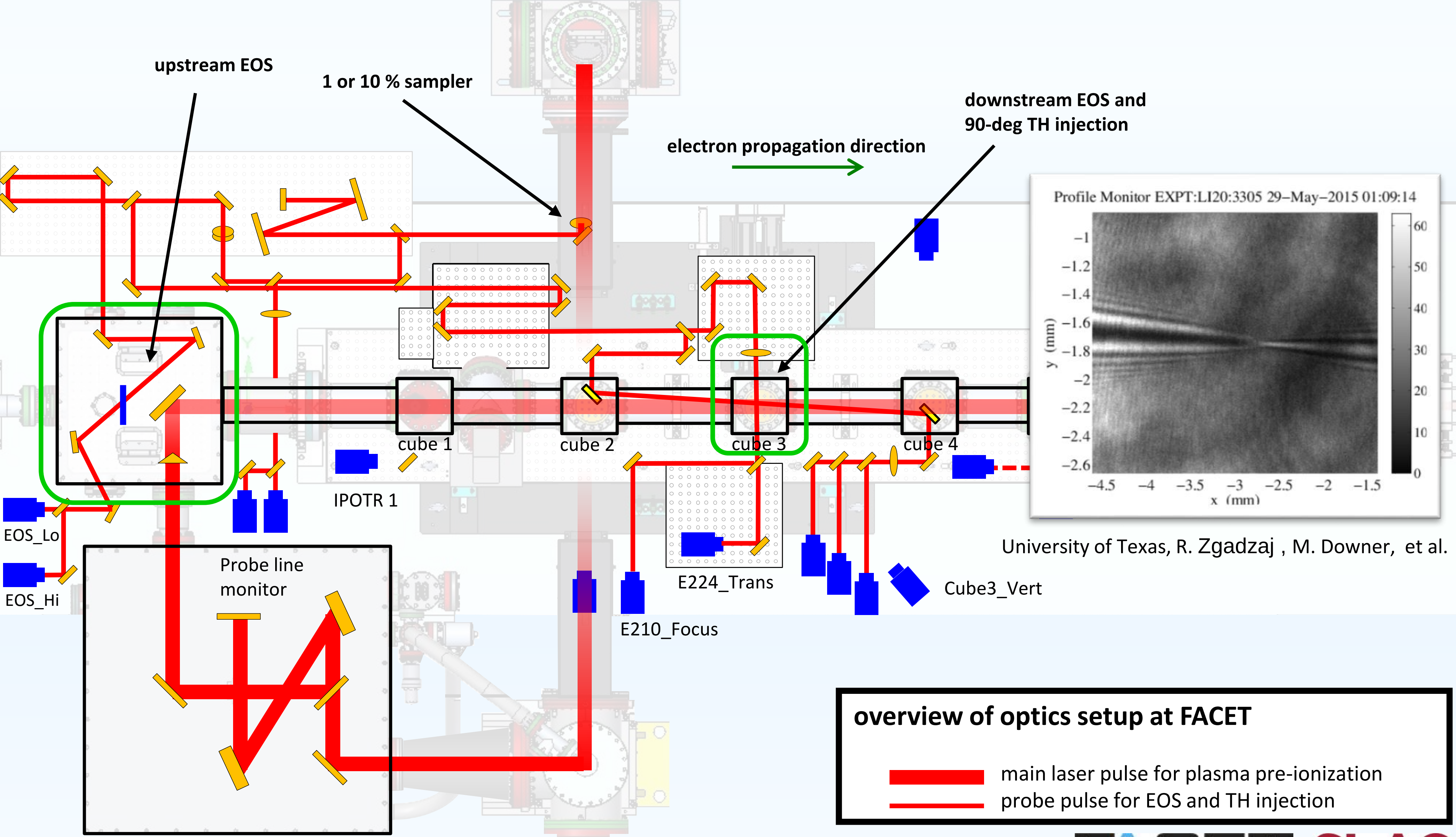
EOS: See Yunfeng Xi, poster

E210 setup: 3rd and 4th laser arm to E224 probing, downstream Trojan Horse (w/ independent delay line) and downstream EOS



setup at FACET

beam self-ionized experiments
laser pre-ionized experiments
Trojan Horse experiment
plasma imaging experiments



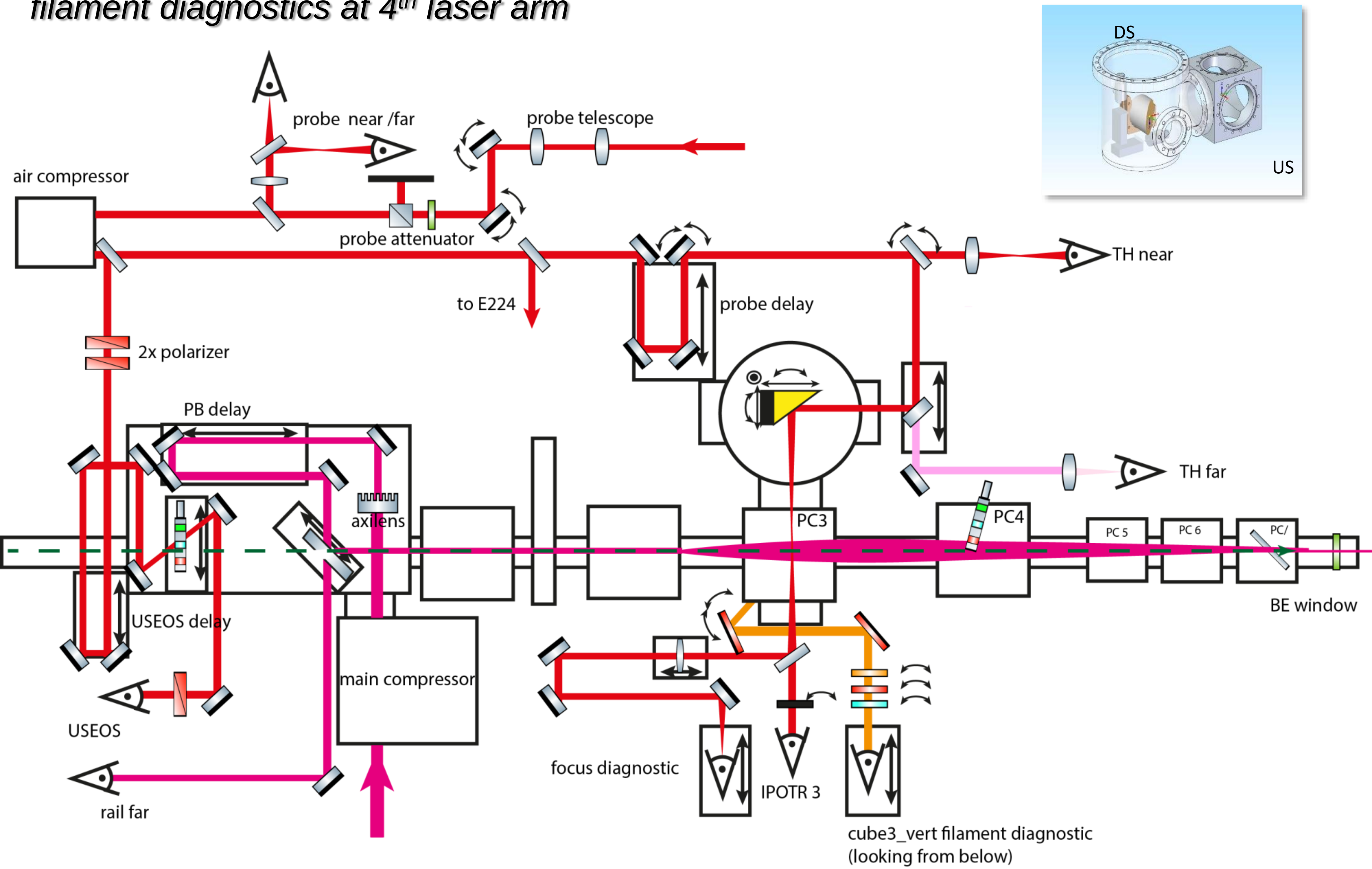
University of Texas, R. Zgadzaj , M. Downer, et al.

overview of optics setup at FACET

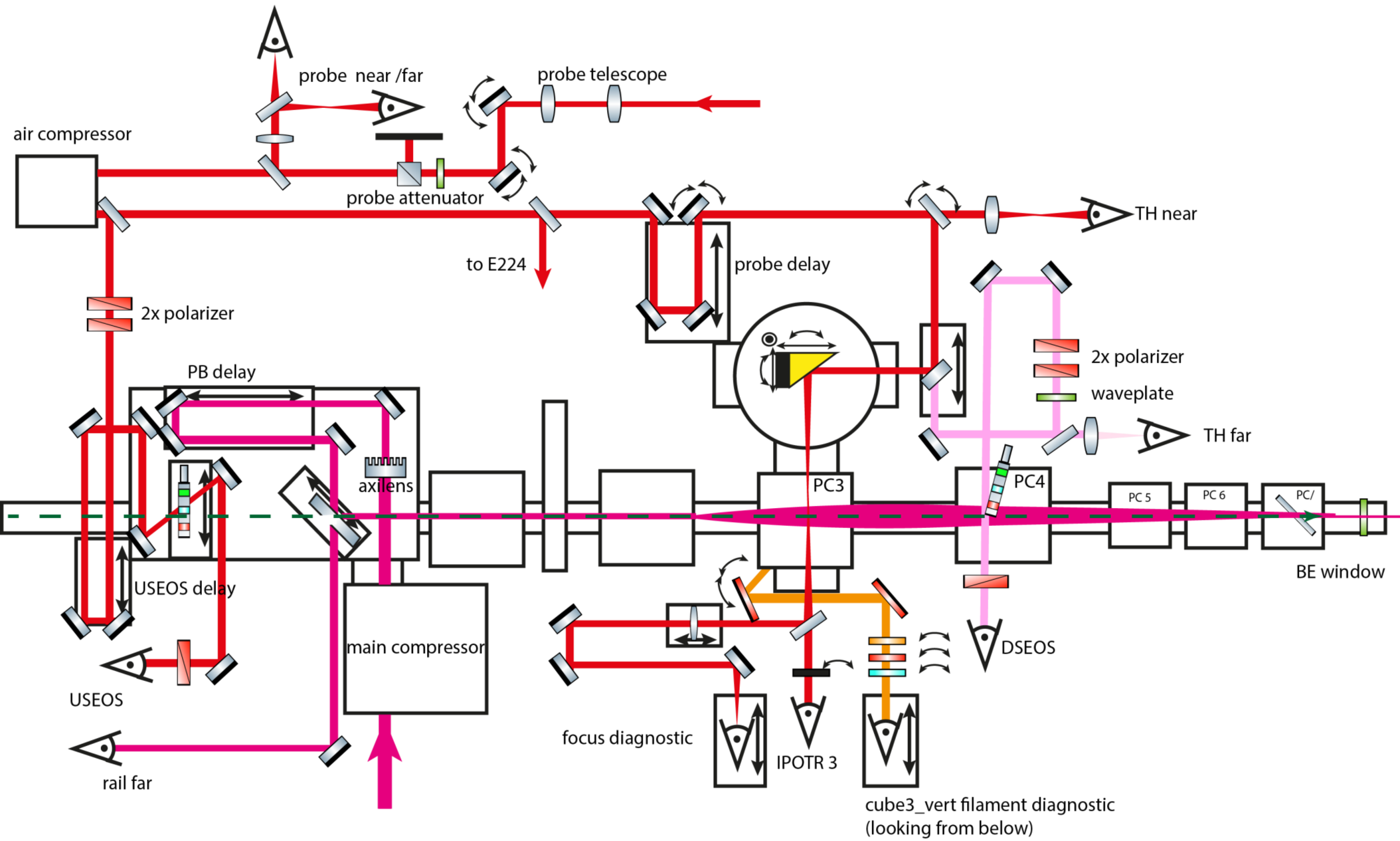
main laser pulse for plasma pre-ionization
probe pulse for EOS and TH injection

FACET SLAC NATIONAL ACCELERATOR LABORATORY

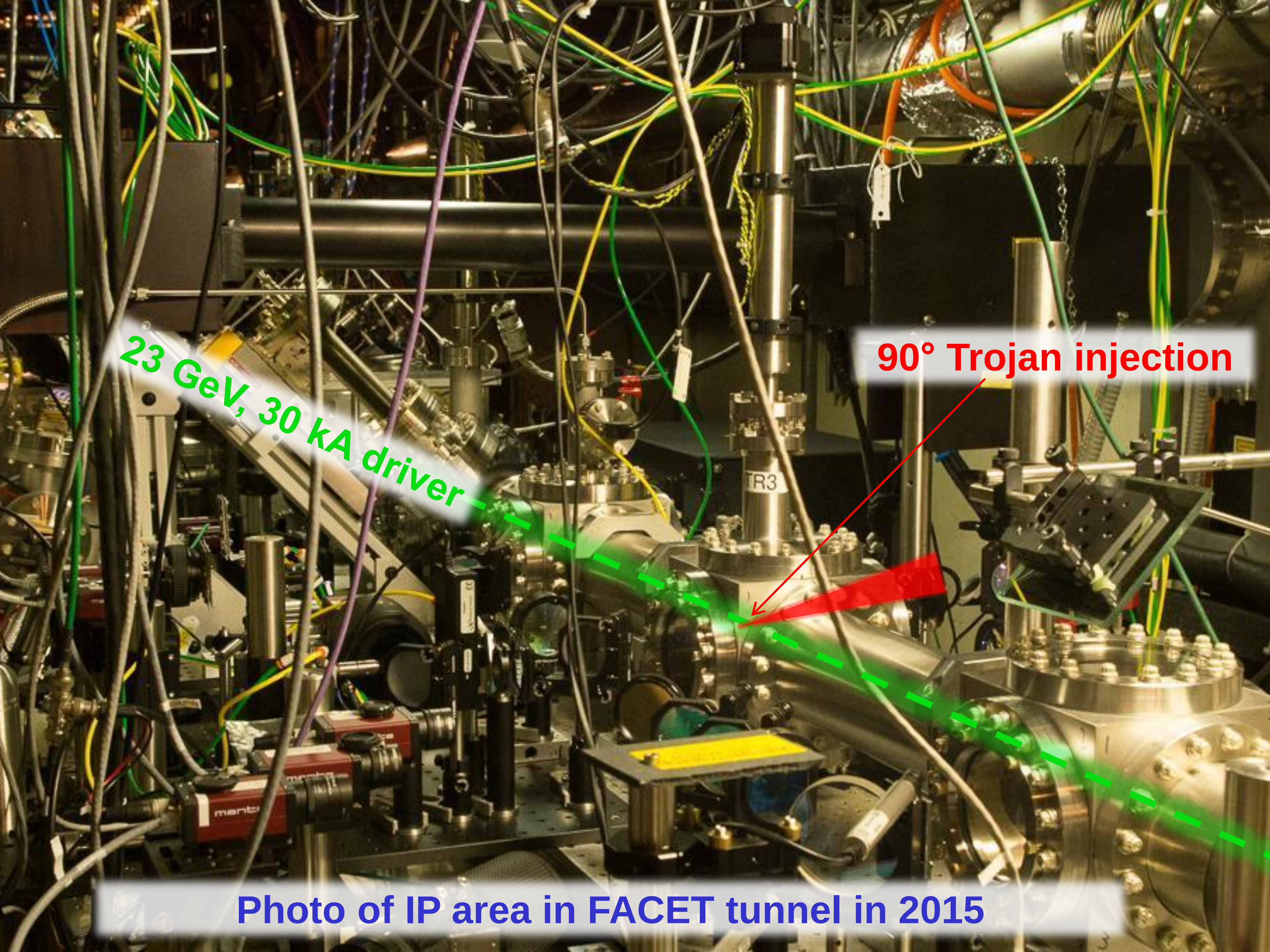
E210 setup: implement vacuum chamber off-axis parabola focusing and Trojan Horse filament diagnostics at 4th laser arm



E210 setup final: w/ downstream EOS (E224 probe not shown for simplicity)

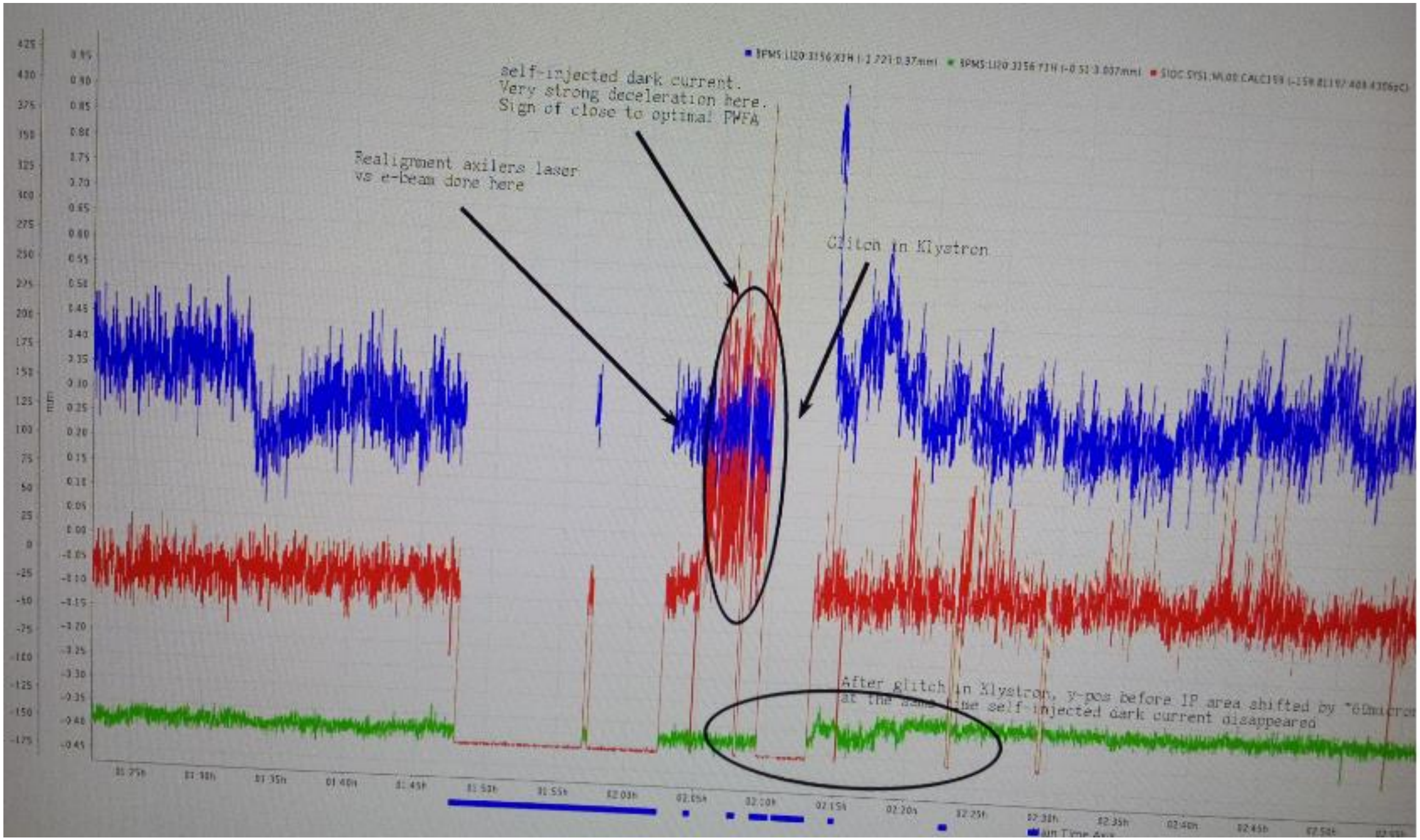


..most complex experiment at FACET to date..


23 GeV, 30 kA driver
90° Trojan injection
TR3
Photo of IP area in FACET tunnel in 2015

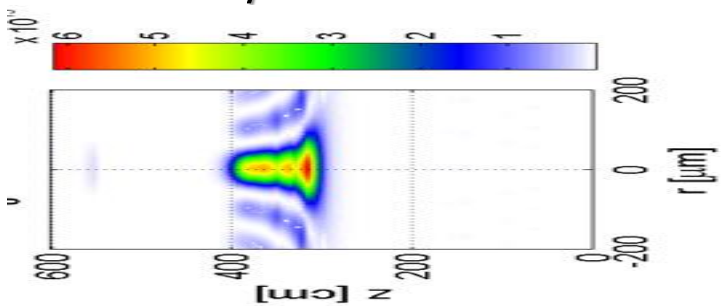
Spatiotemporal alignment between e-beam driver, upstream EOS, H2 preionization laser & plasma channel, He Trojan Horse laser crucial

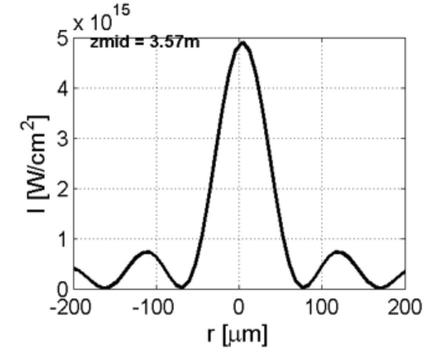
Example for jump in y-position of incoming e-beam vector (on BPM 3156) which killed the laser-triggered injection

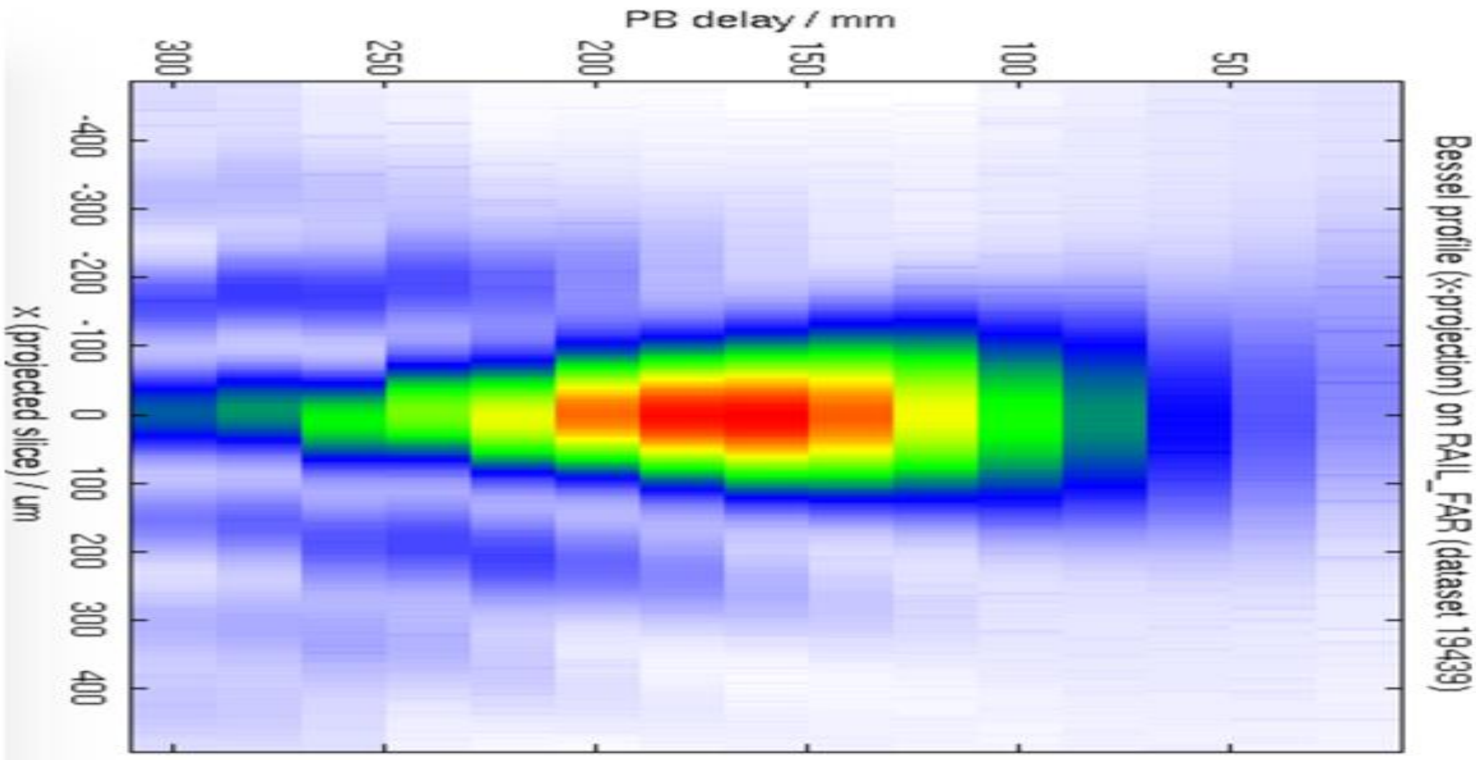


Alignment between e-beam driver and preionization laser

Calculated plasma profile obtained from Axilens laser intensity profile & tunnel ionization rates



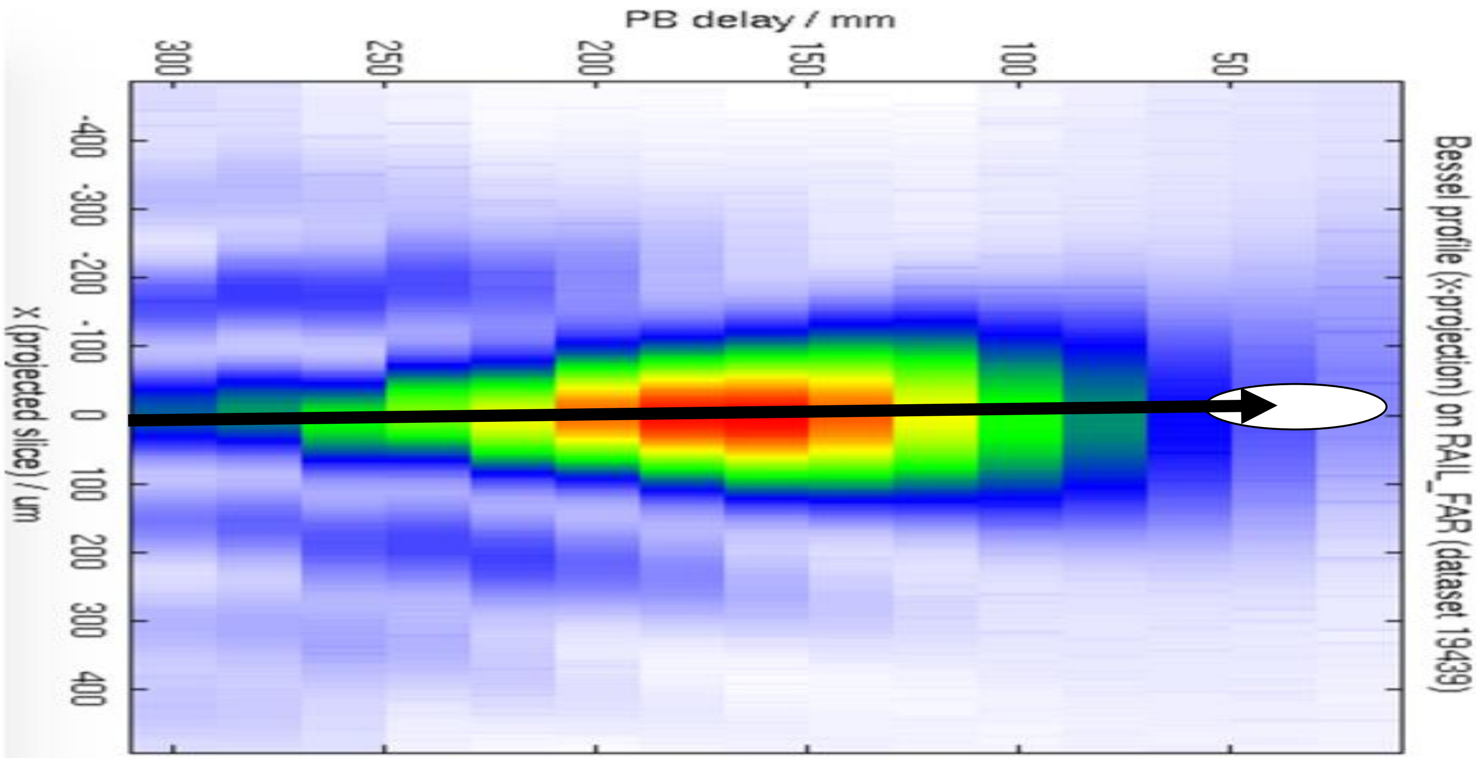




Measured Bessel profile of axilens laser (meters long, but ~150 ´µm wide)

Alignment between e-beam driver and preionization laser

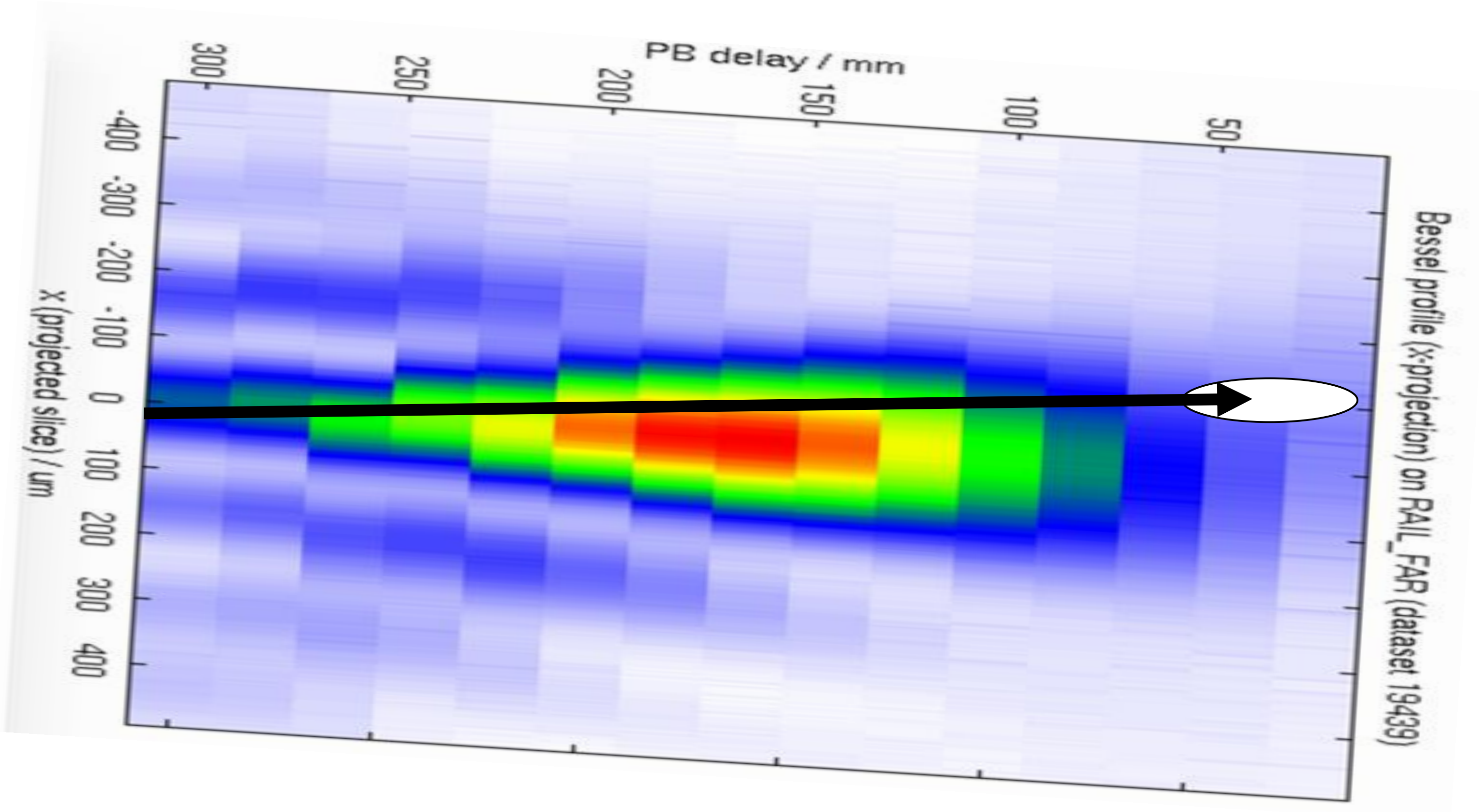
Preionization laser has to be exactly aligned with electron beam axis.
Laser and electron beam just right:



Measured Bessel profile of axilens laser (meters long, but ~150 ´µm wide)

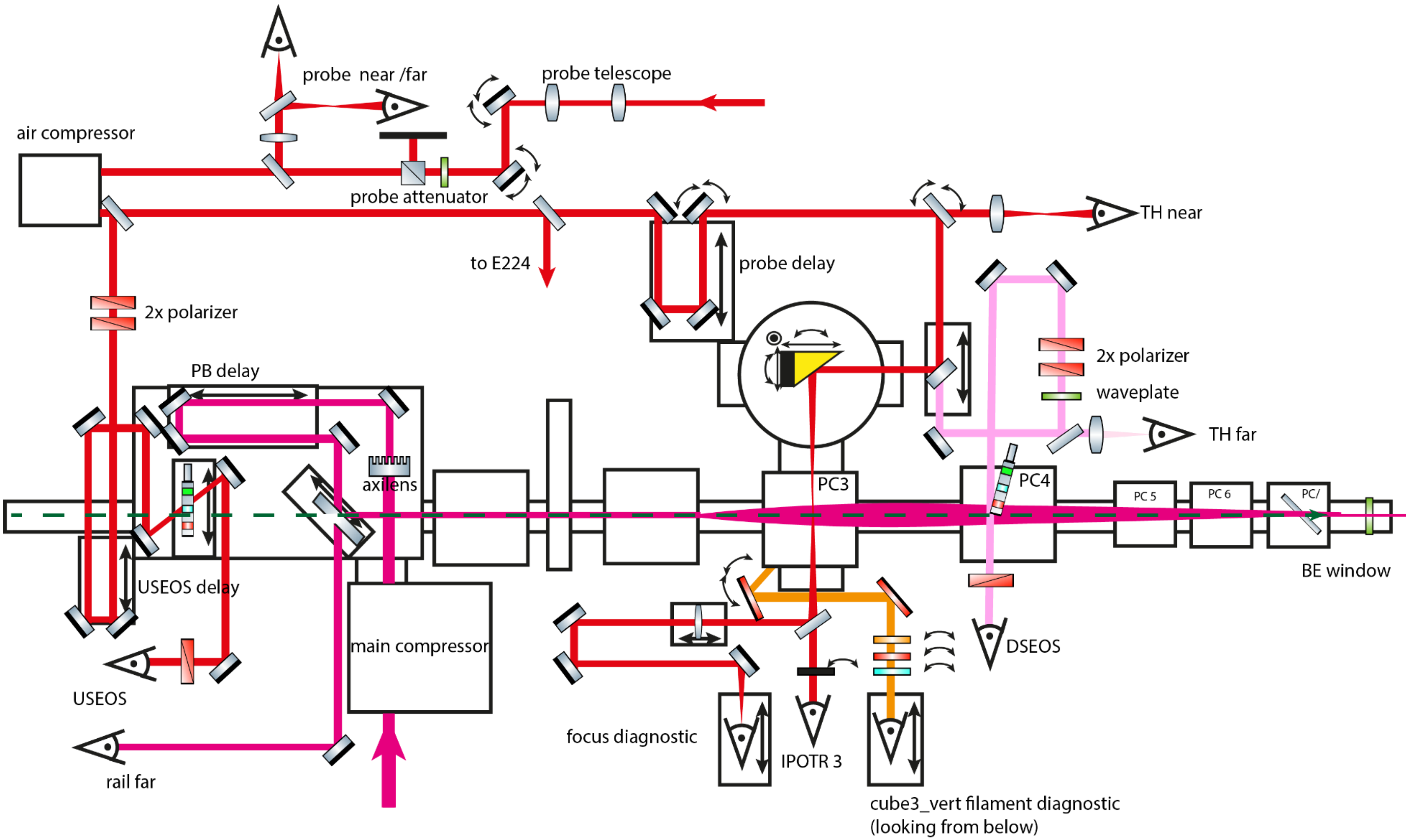
Alignment between e-beam driver and preionization laser

Preionization laser (or e-beam) slightly off:
Already if blowout touches walls at some point, the blowout collapses!
One wants to have a large plasma wavelength e.g. due to timing issues.
This is a real bottleneck!

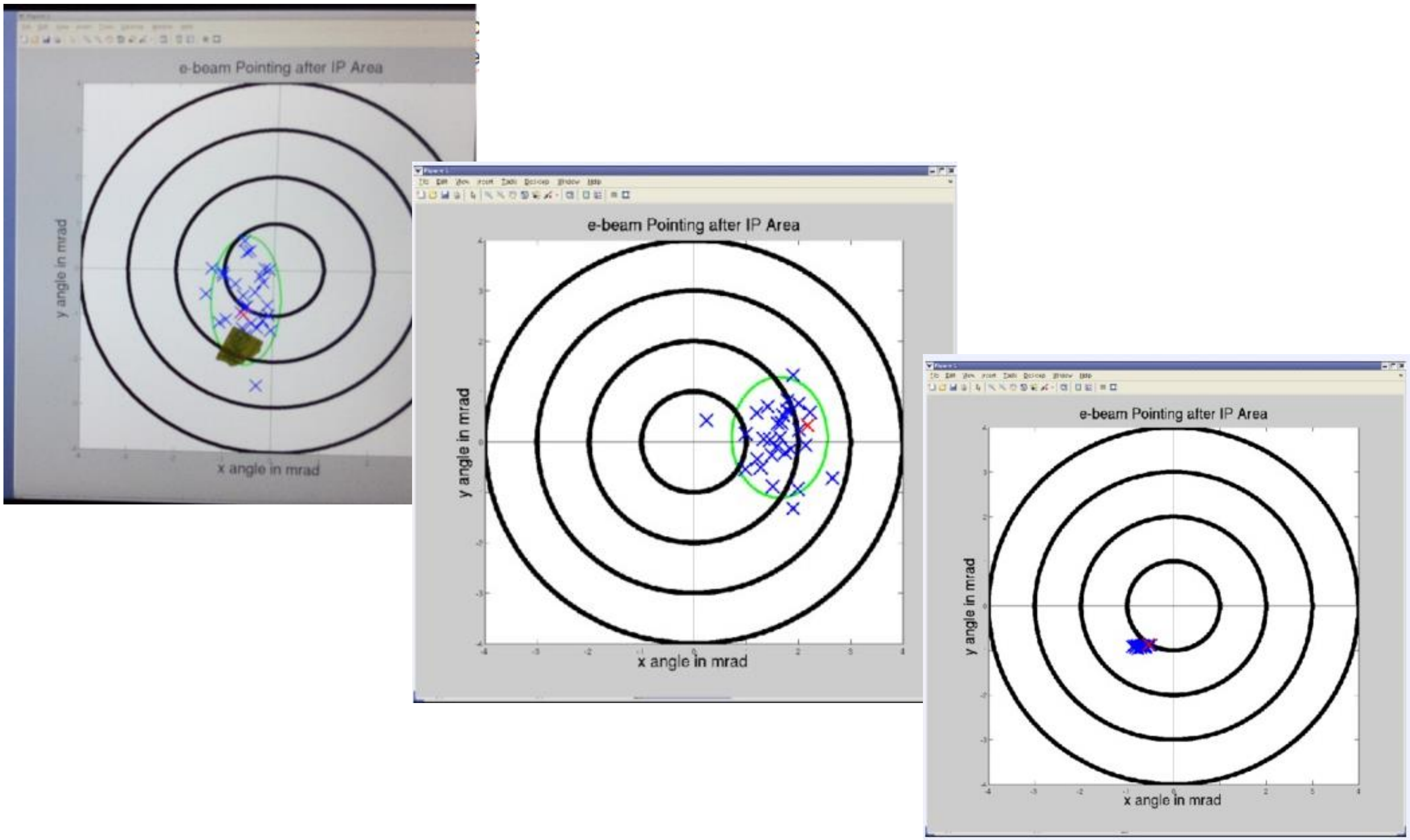


Measured Bessel profile of axilens laser (meters long, but ~150 ´µm wide)

Normal procedure: evacuate plasma chamber, realign laser beam (at low intensity) to electron beam axis (takes 1-2 hours w/safety procedures).. Then re-fill chamber with gas and hope alignment stands for a while



Advanced procedure in 2016: Make use of downstream BPMs and plasma response to find alignment (i.e. avoid “ultrafast plasma kicker”)



New diagnostic tool made life considerably easier, even allowed data taking after sunrise (thermal drift) because realignment could be done online.

Alignment and timing of e-beam driver & preionization laser with 90° Trojan injection laser:

beam diameter = 10 mm

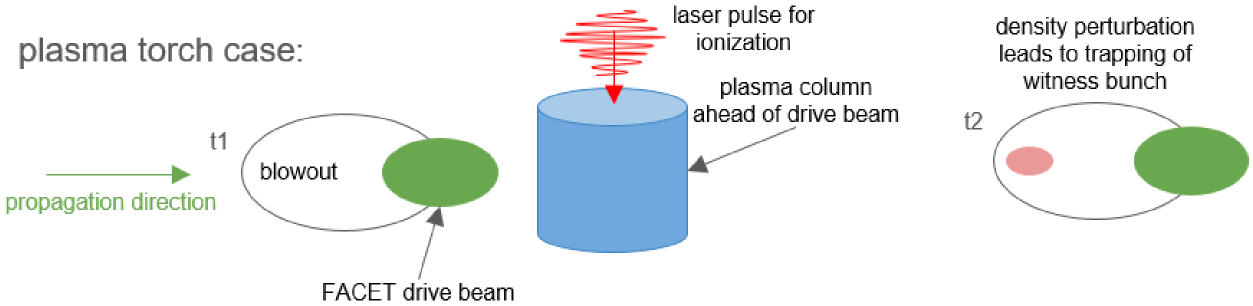
w0 = 11.64 µm

zR = 532 µm

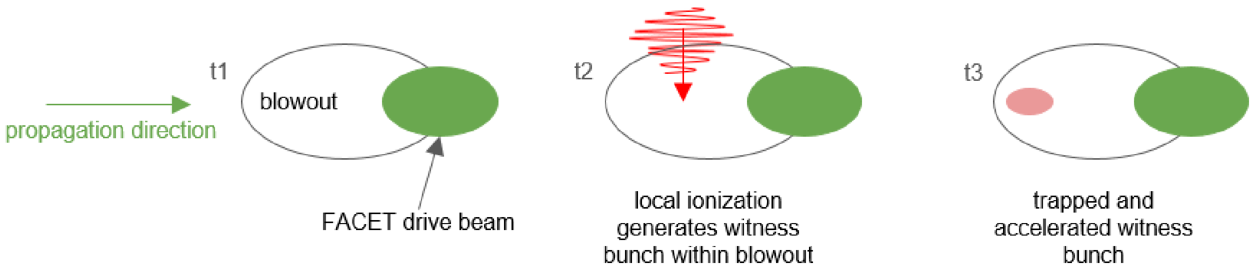
f = 9″ = 228.6 mm

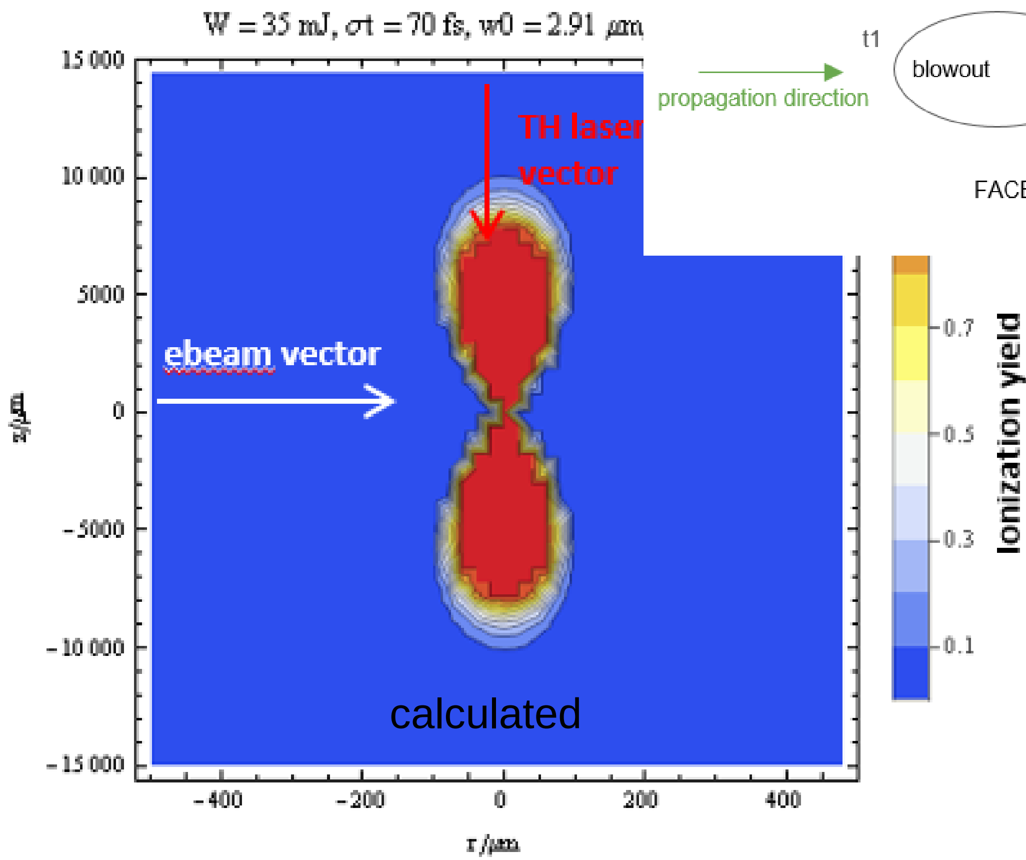
F/# = 22.86

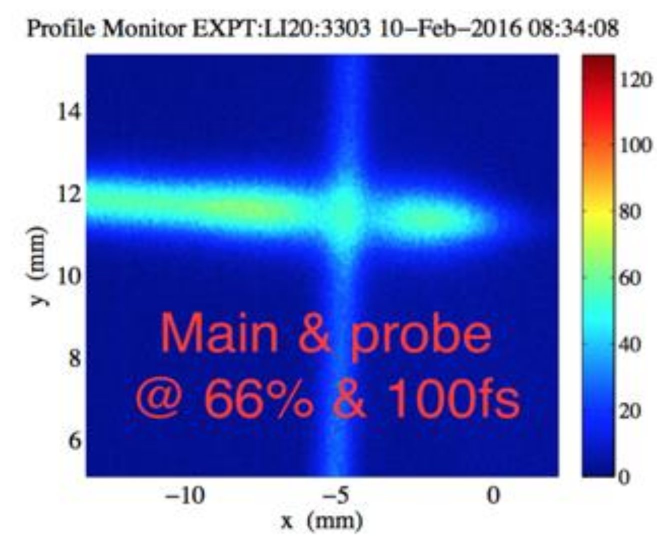
plasma torch case:



Trojan Horse case:

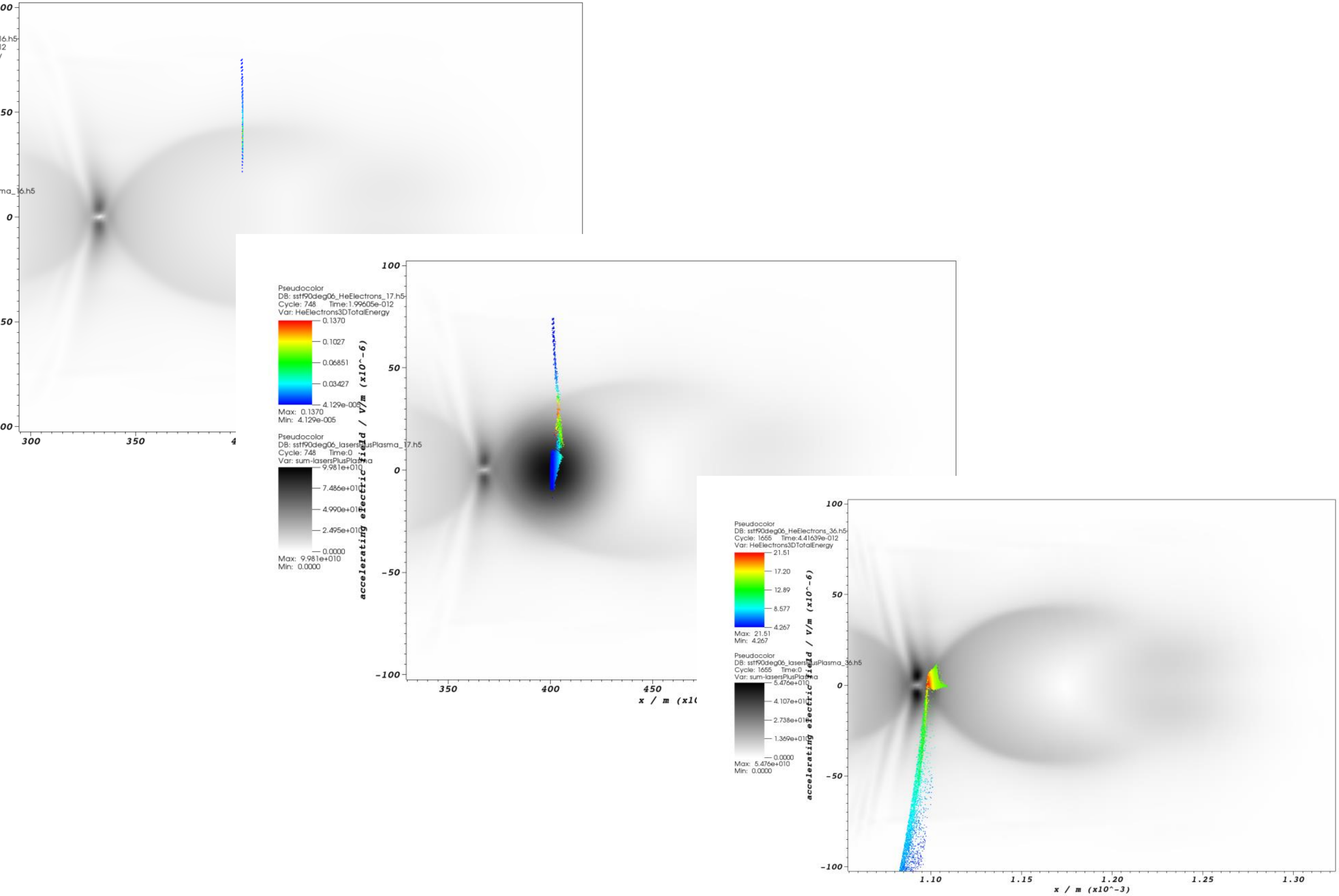




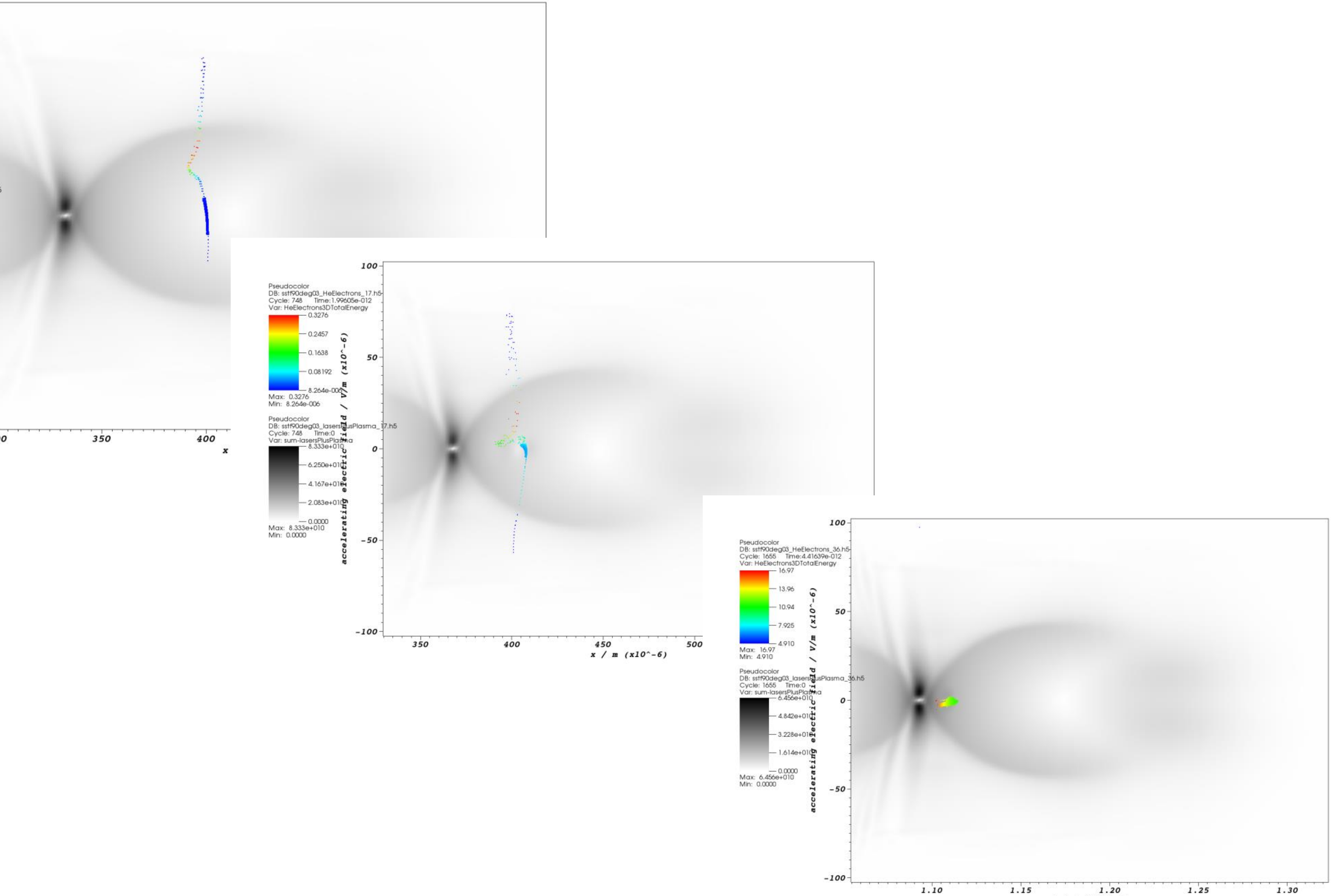


measured

3D PIC-simulation w / Vsim (high laser intensity case)



3D PIC-simulation w / Vsim (low laser intensity)



Experimental: Laser-triggered injection very robust: charge injected each shot

Embargoed – publication pending

Correlated Trapped charge on Spectrometer & DS BMP

Embargoed – publication pending

few 100pC charge increase

After solving alignment and timing issues, data taking was boosted (best results were obtained on leap day Feb 28th!) and laser-triggered injection works surprisingly stable

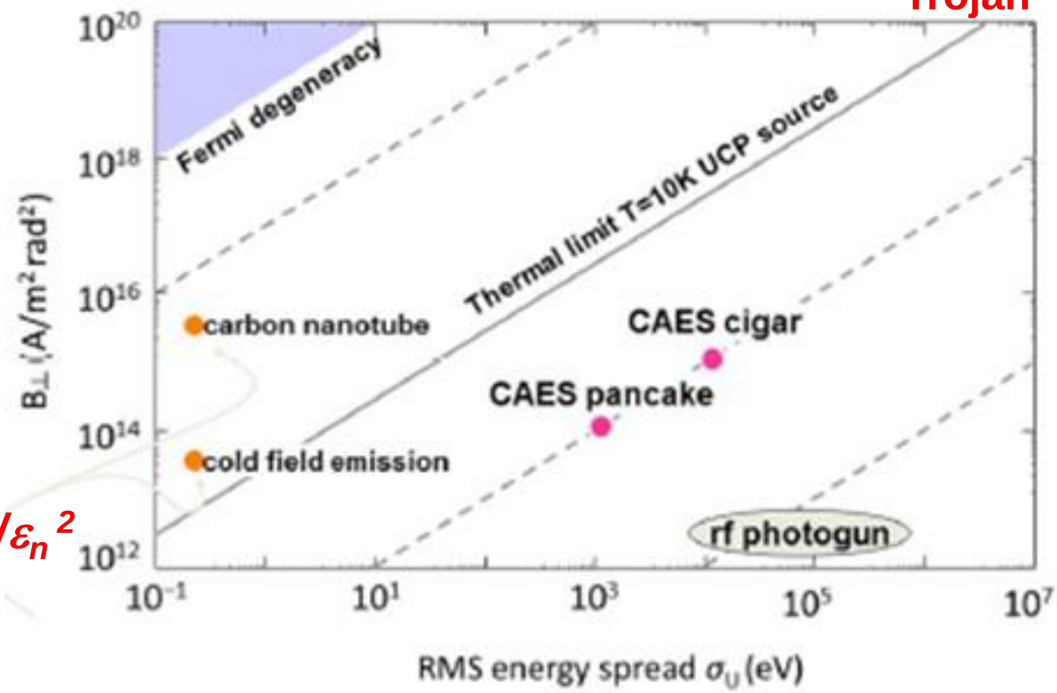
More details see talk Aihua Deng, Wednesday 1200

BRIGHTNESS (5D)

$$B = \frac{2I}{\epsilon_{\rm n}^2}$$

- Ultrashort, currents kA-scale
- Ultracold, norm. emittance 1e-9 scale

→ ***Ultrahigh electron brightness B~2I/ε_n^2 up to 10^{20} Am^{-2} rad^{-2}*** *(maybe more)*



From J. Luiten

That's many orders of magnitude brighter than e.g. the LCLS.

Electron beam brightness is key for l sources (see Rosenzweig 5th gen. talk)..

Potentially game-changing: may allow plasma based accelerators to produce bunches with **much better** key characteristics (such as emittance, brightness, shortness (~as-regime),) than w/ conv. accelerators

When looking back, disruptive emittance and brightness improvements have been prerequisites for next-gen. light sources…

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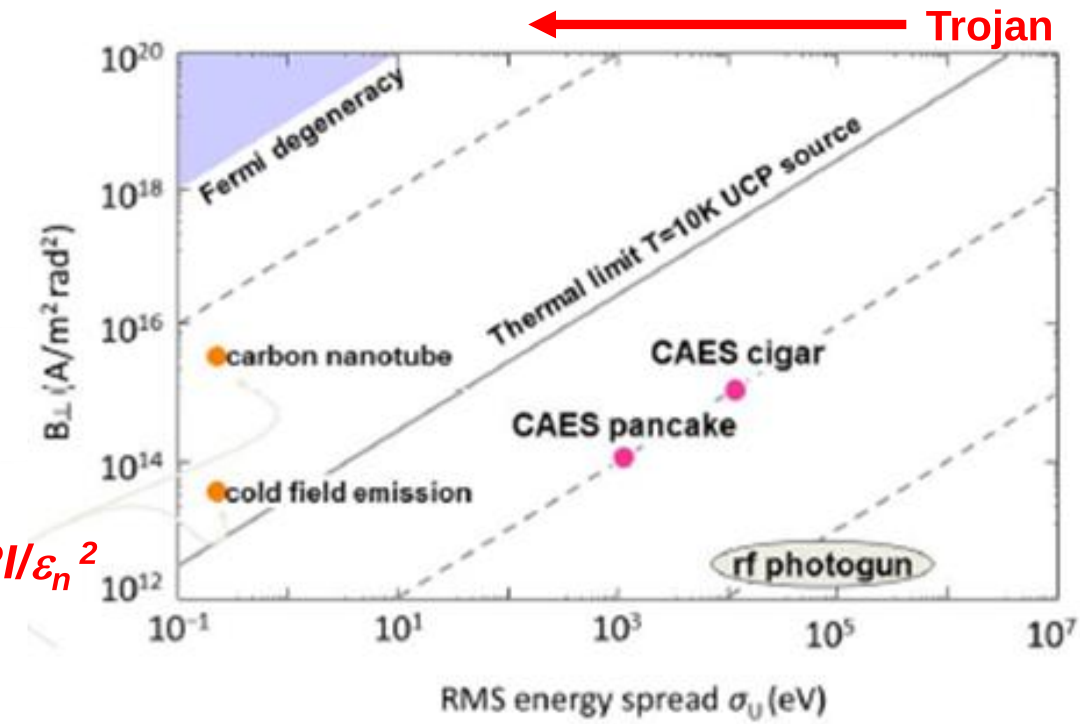

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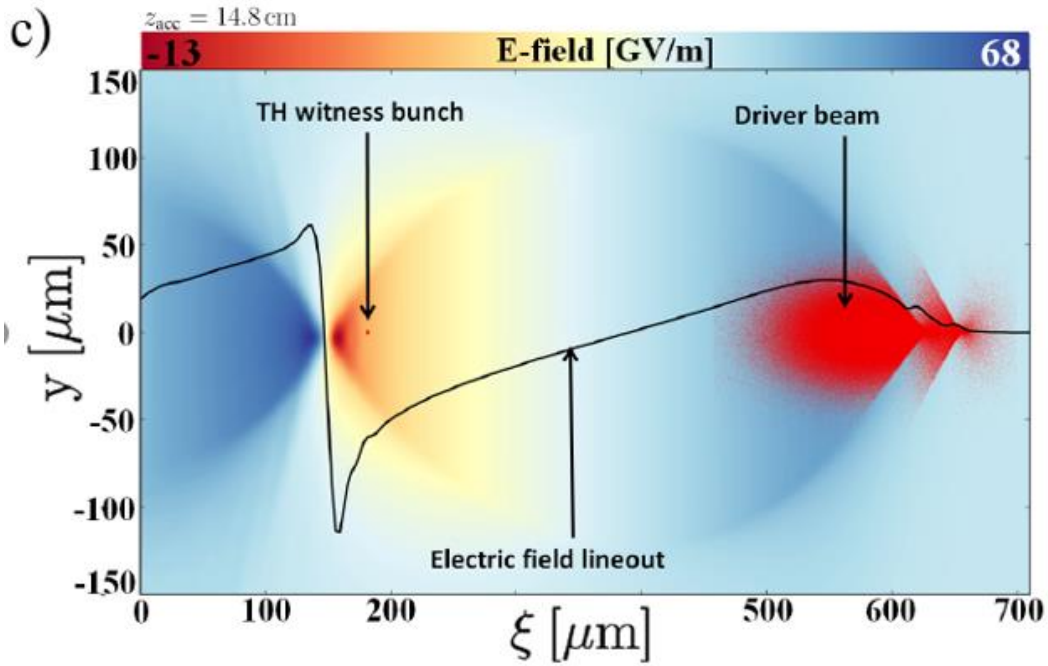
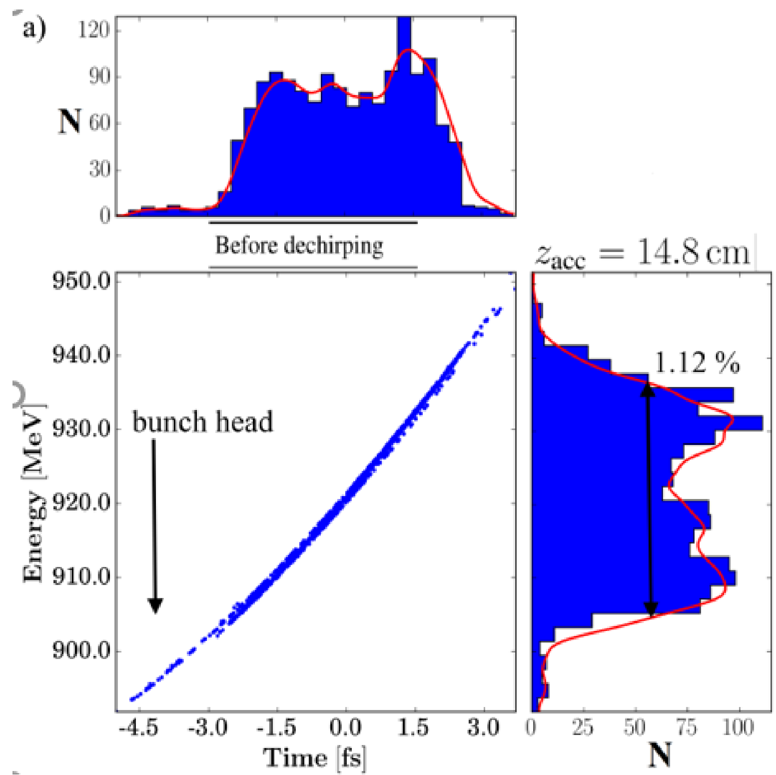
When looking back, disruptive emittance and brightness improvements have been prerequisites for next-gen. light sources…

Energy spread can be a killer e.g. for FEL -- can we move the Trojan further to the left in the plot, i.e. can we reduce energy spread?

TH energy chirp



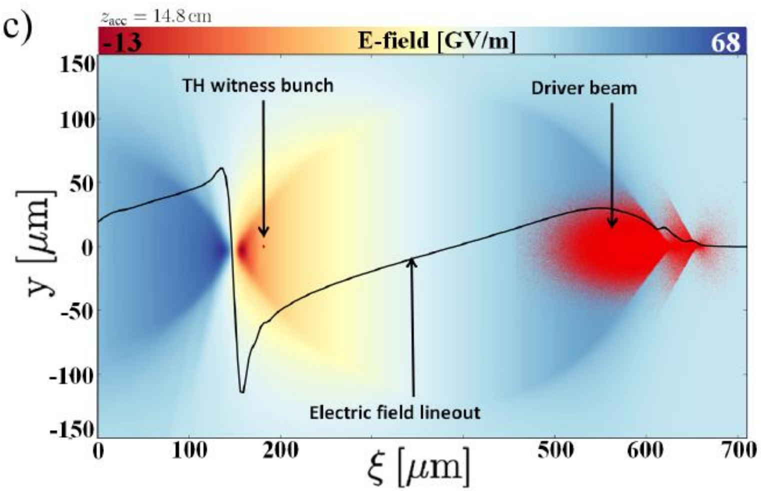
Reason for energy chirp is the small (100 µm-scale) plasma cavity size and the strong accelerating electric field gradients



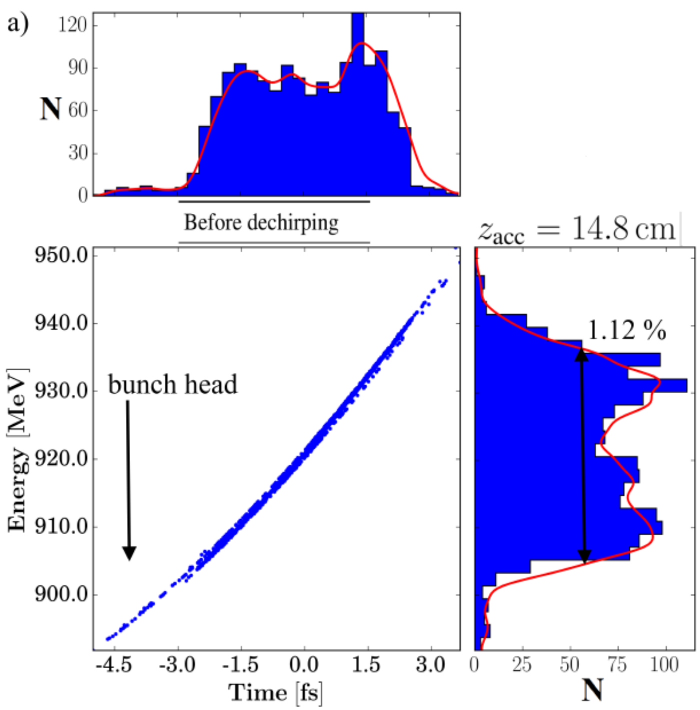
Although produced bunches are ultrashort (few µm), the resulting energy spread is of the order of 1%

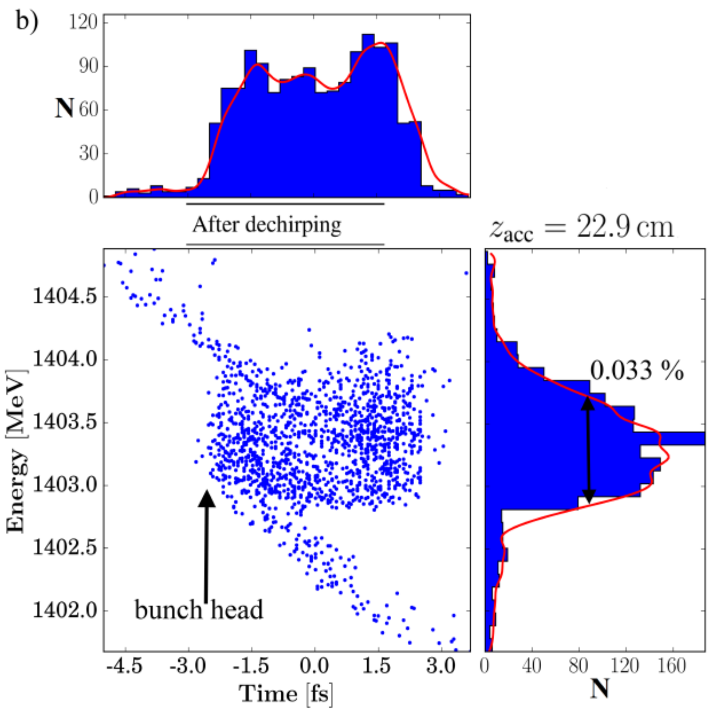
Yes we can: TH energy chirp reduction

Patent pending



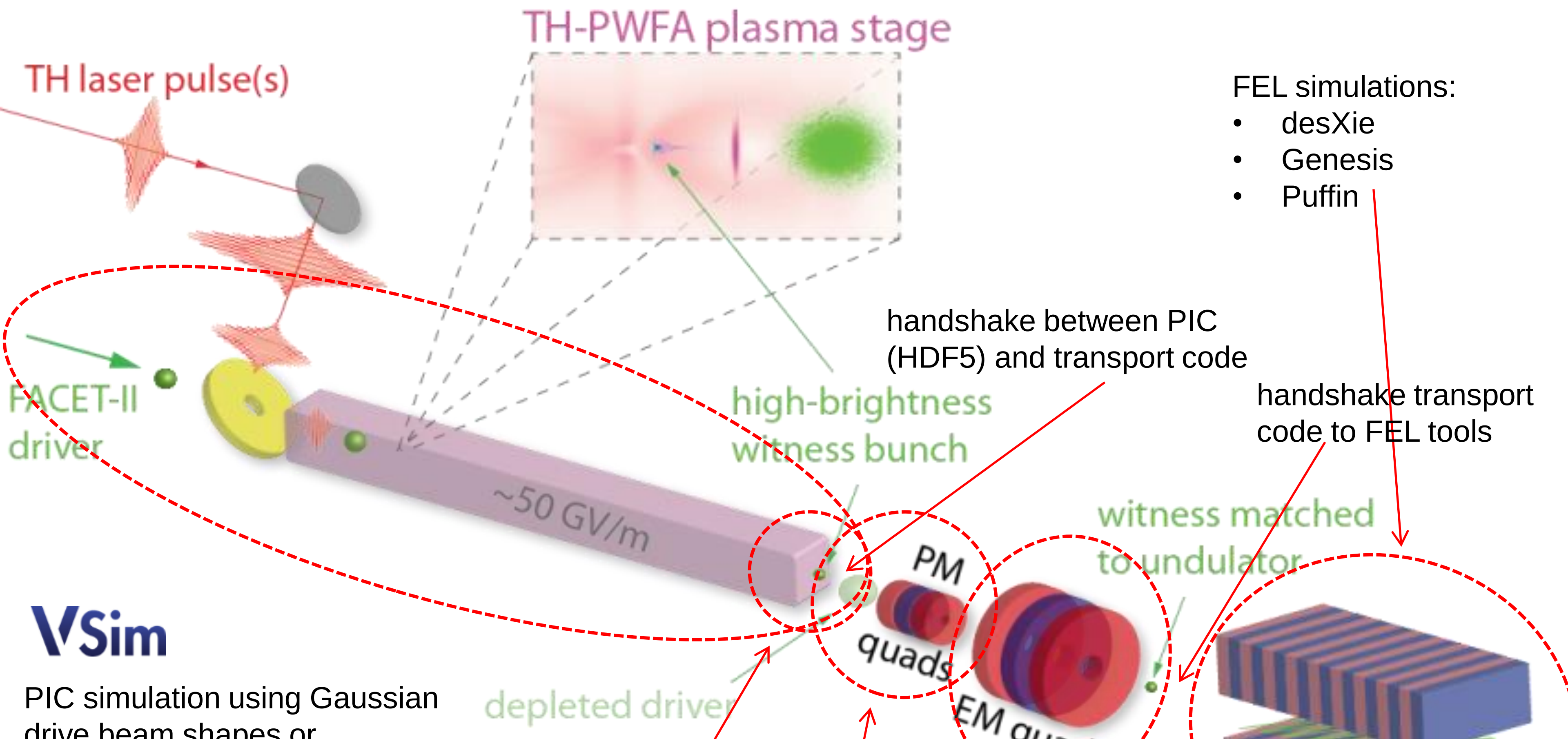
	Before dechirping	After dechirping
z_{acc}	14.8 cm	22.9 cm
Q	8 pC	8 pC
σ_z	2.6 μm	2.6 μm
I_{peak}	2.0 kA	2.0 kA
$\overline{E}$	922 MeV	1404.3 MeV
σ_E	1.12 %	0.033 %
ϵ_n	40 nm · rad	43 nm · rad





More details see poster Fahim Habib

Full 3D start-to-end simulations



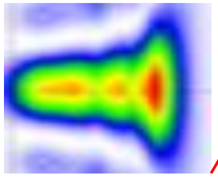
FEL simulations:

- desXie
- Genesis
- Puffin

handshake between PIC (HDF5) and transport code

handshake transport code to FEL tools

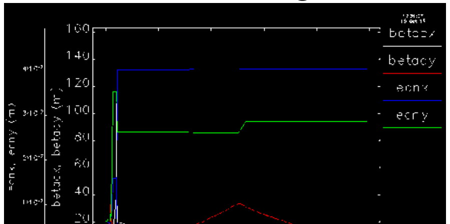
PIC simulation using Gaussian drive beam shapes or macroparticle input from full beam optics simulations such as ELEGANT etc.



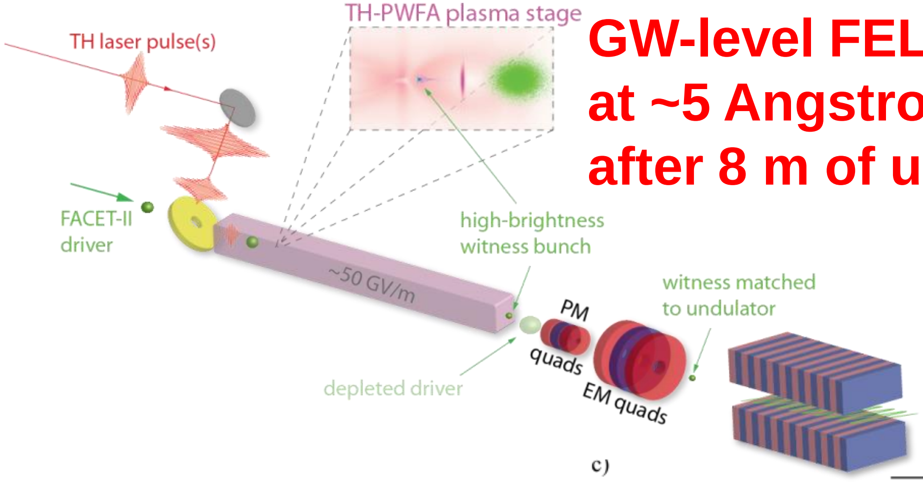
catch beam from plasma modeled with Elegant

match beam to undulator (Elegant)

model optically engineered downramp for emittance preservation, include into PIC

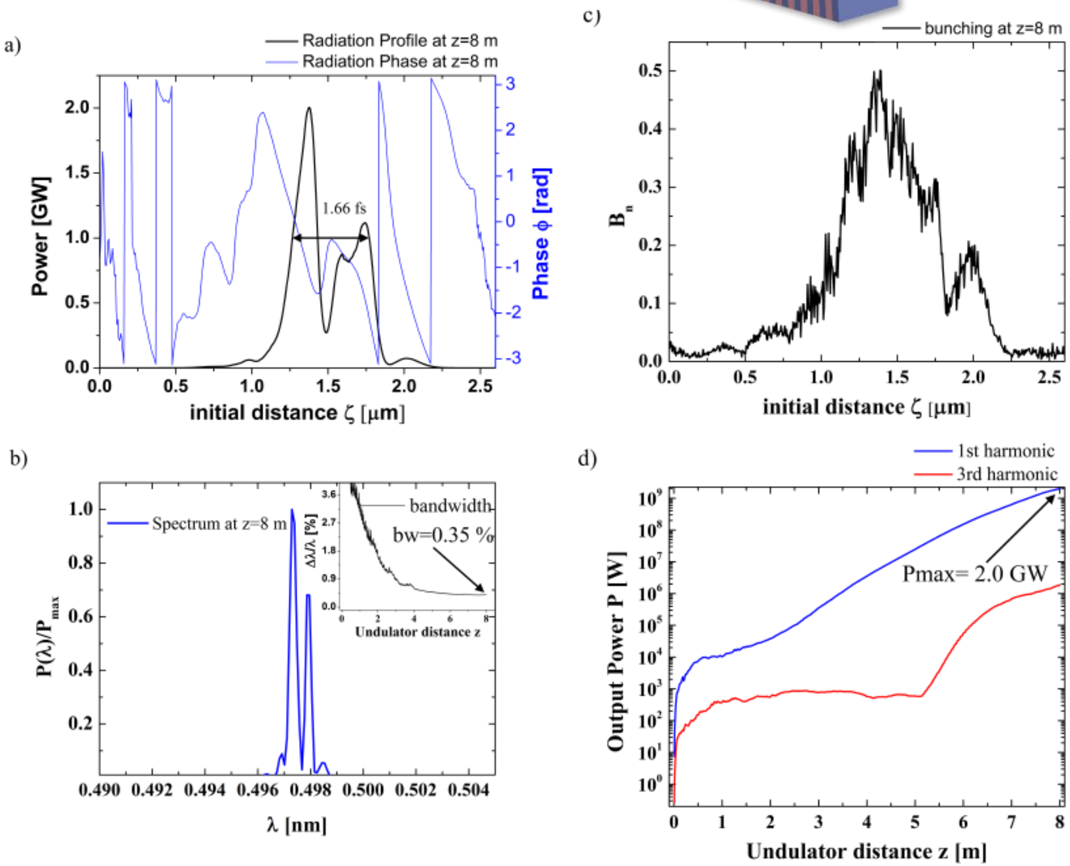


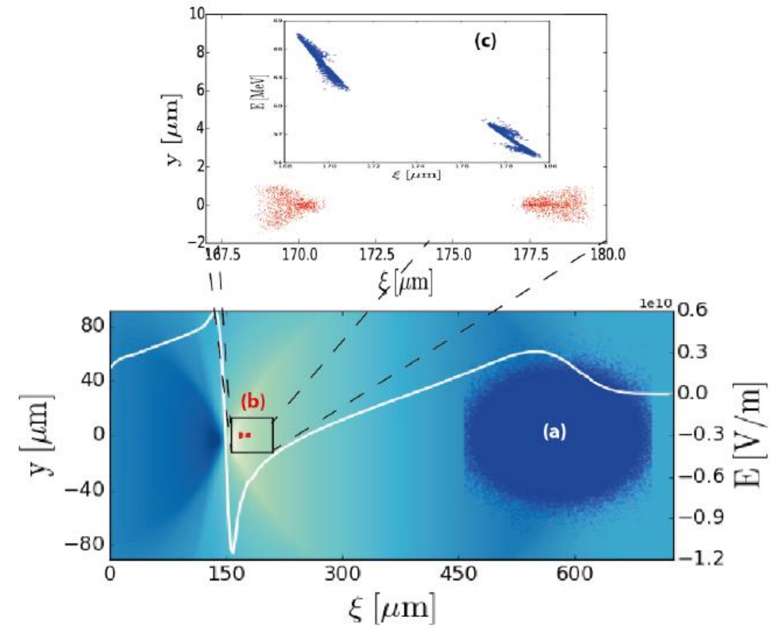
Ultrahigh – now 6D – brightness transformative to hard x-ray FEL?



GW-level FEL power
at ~5 Angstrom
after 8 m of undulator?

More details see poster Fahim Habib

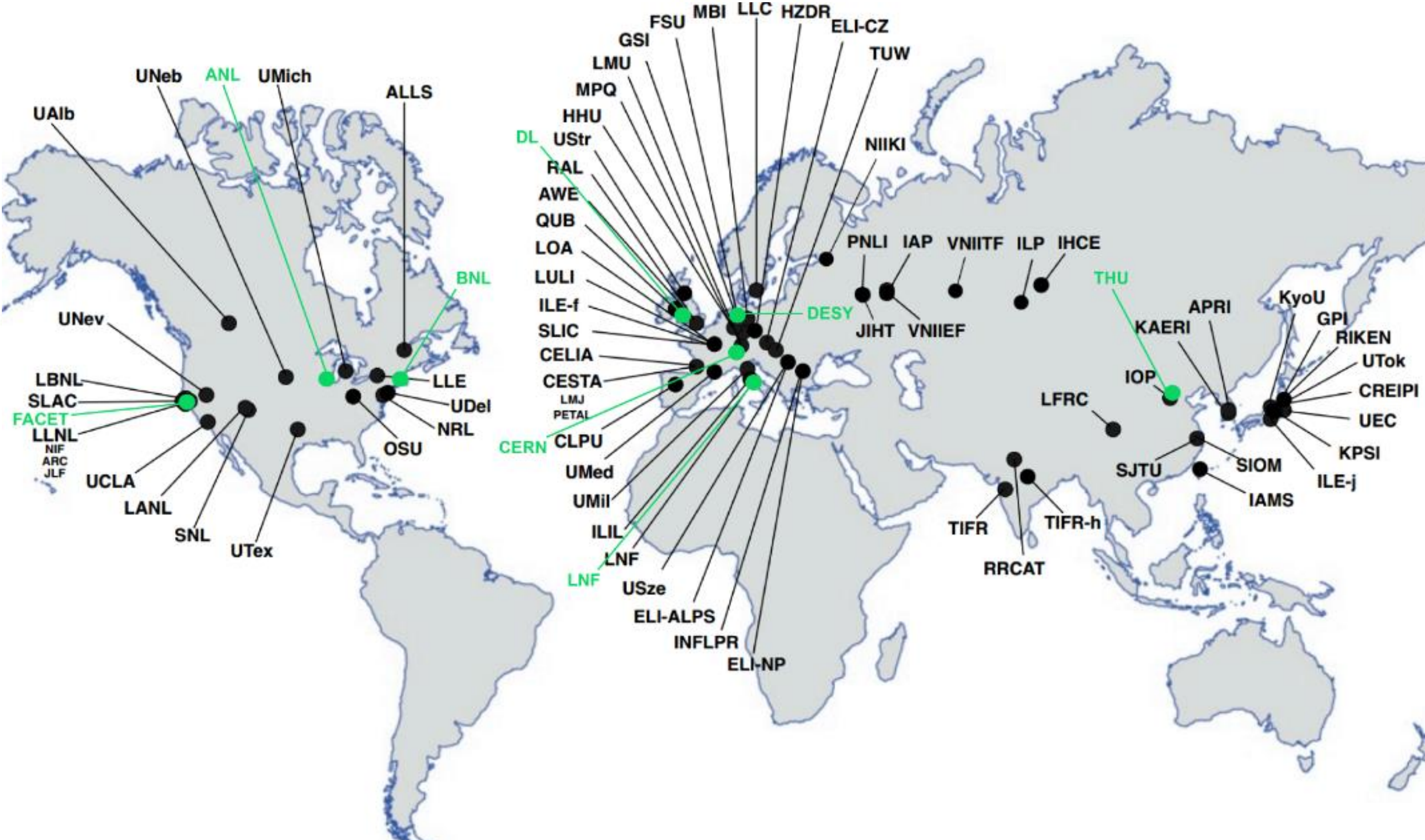




Ultra-monochromatic
ICS?

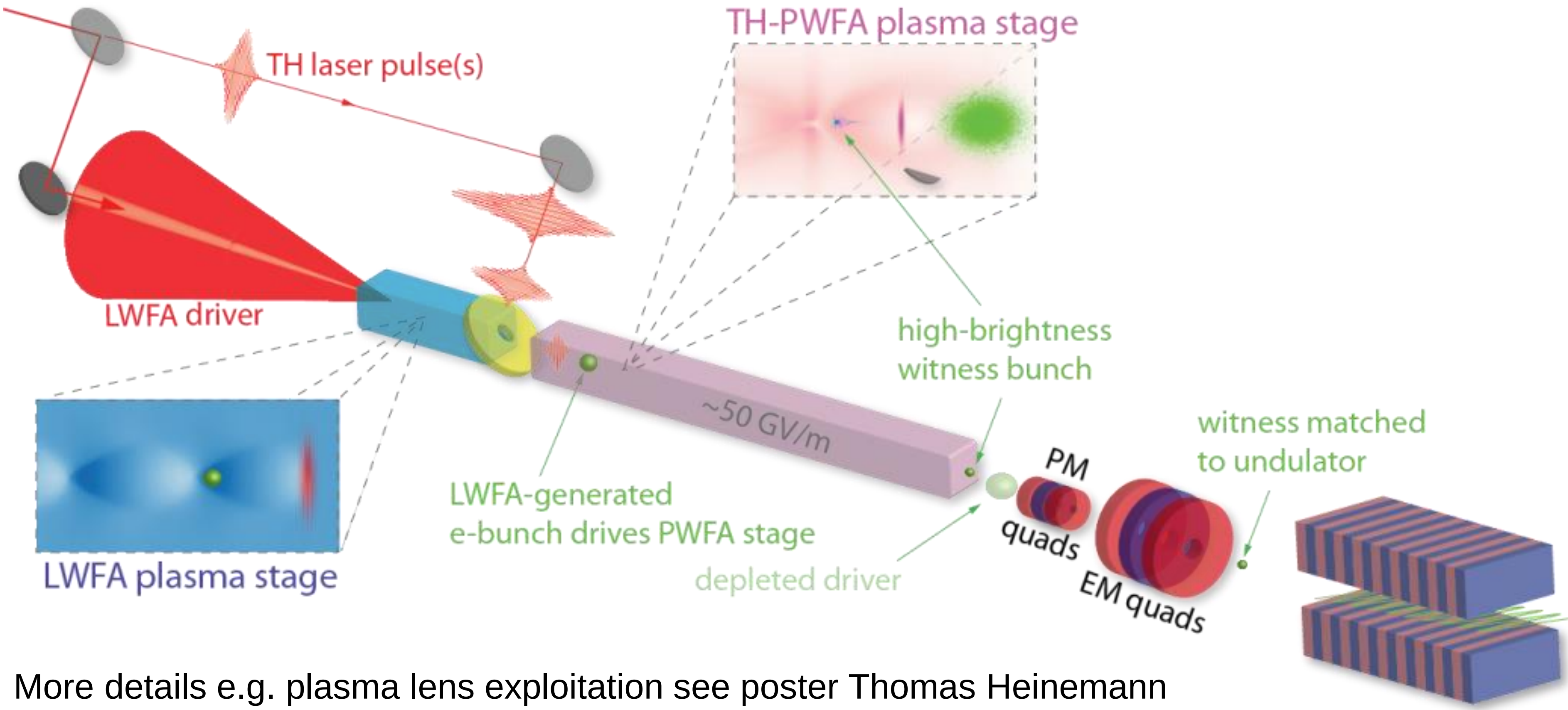
More details see poster Paul Scherkl

Export the Trojan Horse?

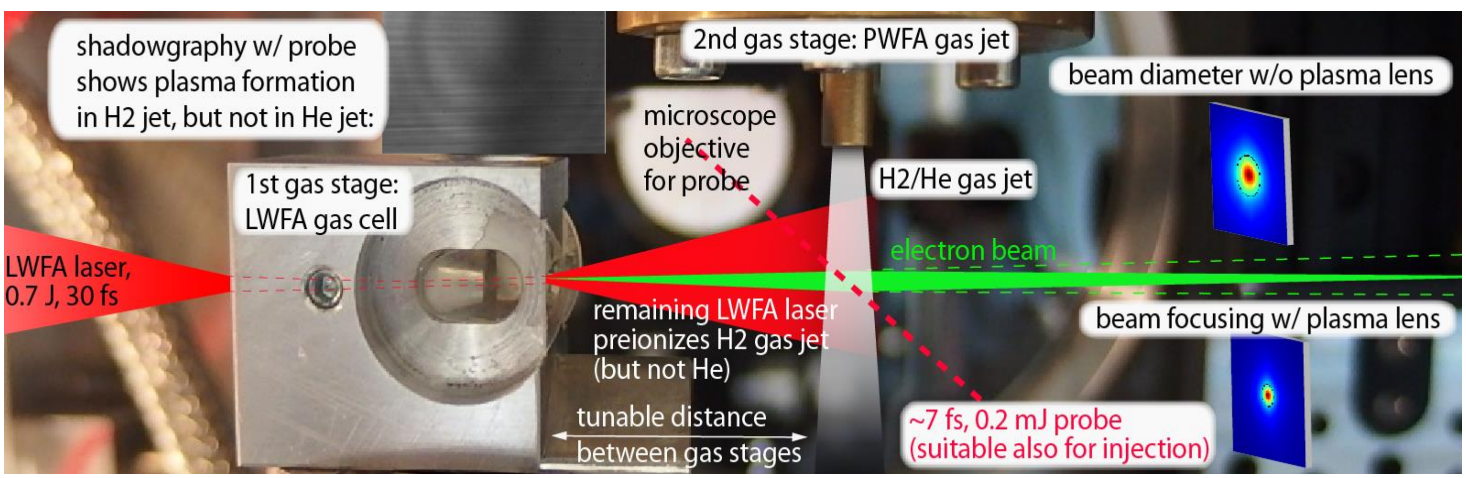


adapted from ICUIL

Use LWFA-produced electron bunches as drivers for PWFA-TH stages



More details e.g. plasma lens exploitation see poster Thomas Heinemann



Summary

- Shown proof-of-concept of hybrid laser-spiked PWFA and laser-triggered injection / plasma torch / Trojan Horse in +5-ear program at FACET
- While not measured (how measure ultrashort bunch emittance at 1-e9 mrad level?) and optimized to the limits, the confidence level is now widespread that this “solves” the emittance problem of plasma accelerators
- Orders of magnitude higher 5D brightness than state-of-the-art
- New technique (patent pending) seems to “solve” the energy chirp/spread problem e.g. to ~0.03% level. No details can be revealed here but as regards complexity: if you can realize TH, what is additionally needed to dechirp is surely feasible
- Preionized plasma channel generation is a real “bottleneck” – key R&D area. E.g. use longer wavelength (CO2) lasers!
- Use LWFA to produce drive bunches for TH-PWFA to allow for truly compact setups
- Realize (LWFA-)TH-PWFA based light sources and other applications