FACET-II Workshop,
SLAC October 2016

Hybrid Linac-Laser-Plasma Diagnostics and Kicker

Bernhard Hidding *et al.*

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Department of Physics, University of Strathclyde,
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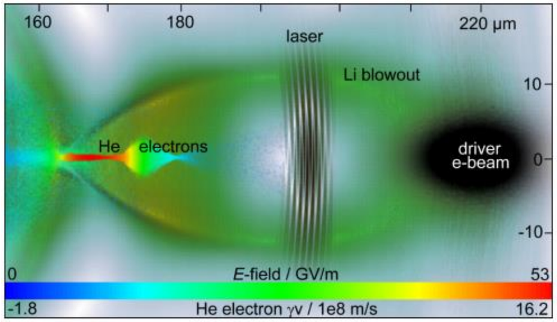
& The Cockcroft Institute, UK

Trojan Horse: Ultralow emittance / ultrahigh 5D brightness

- Manuscript submitted 2011, E210 experiment approved before paper was eventually published in 2012 (big kudos to SAREC&FACET!!)



PRL 108, 035001, (2012), PRSTAB 16, 031303 (2013), 18, 081304 (2015), 19, 011303 (2016), arXiv:1403.1109, arXiv:1412.4844(2014)

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

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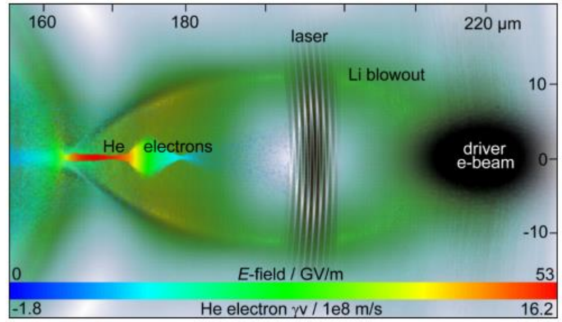

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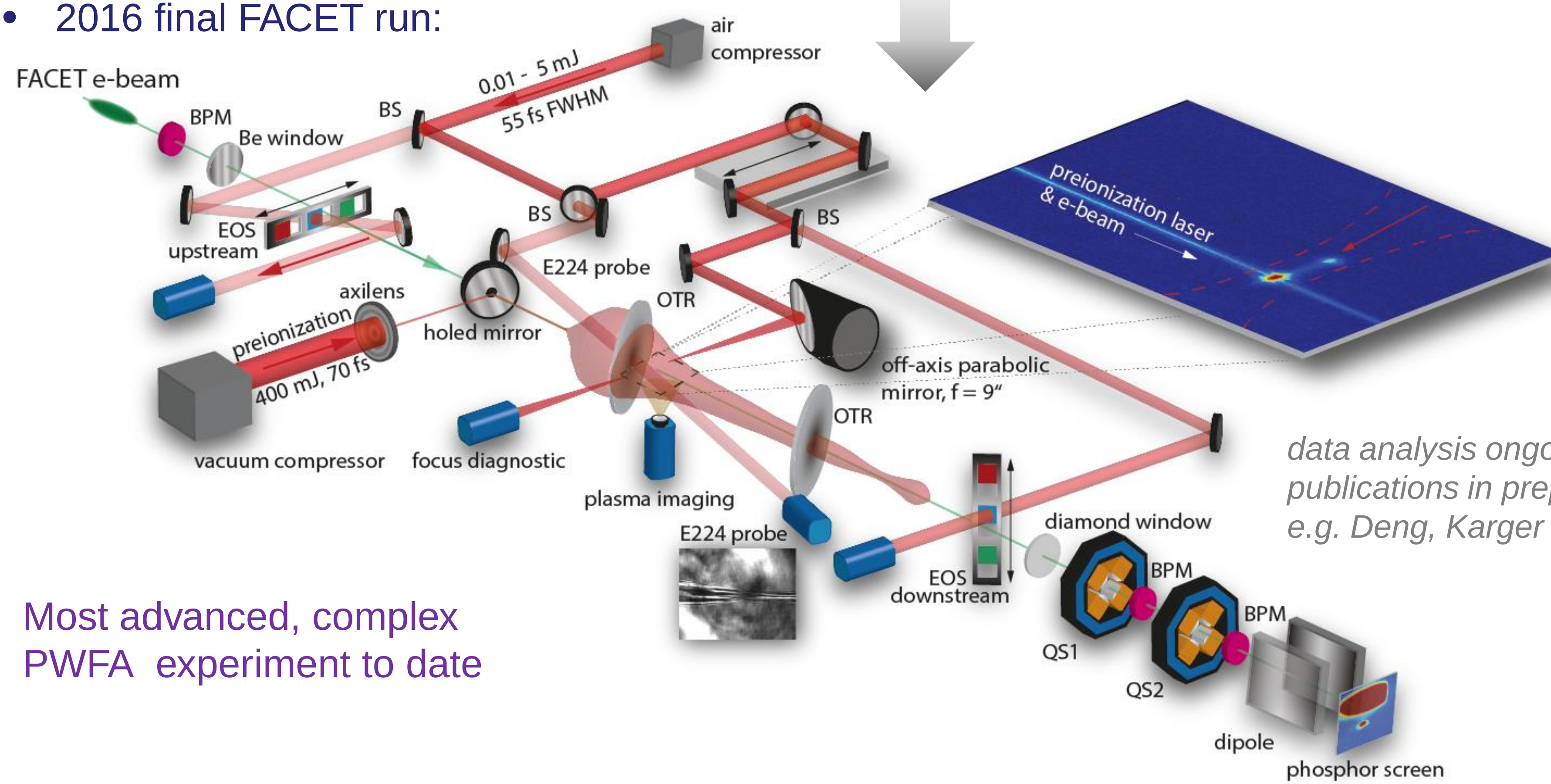
- 2016 final FACET run:



data analysis ongoing, publications in prep. e.g. Deng, Karger et al.

Most advanced, complex PWFA experiment to date

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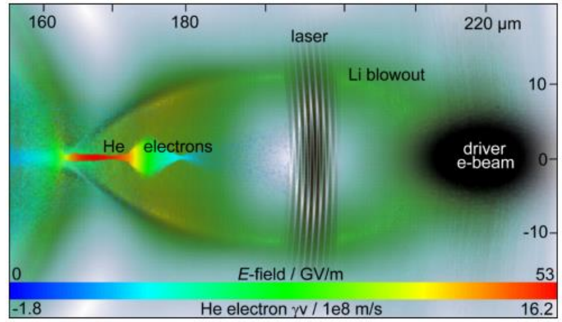

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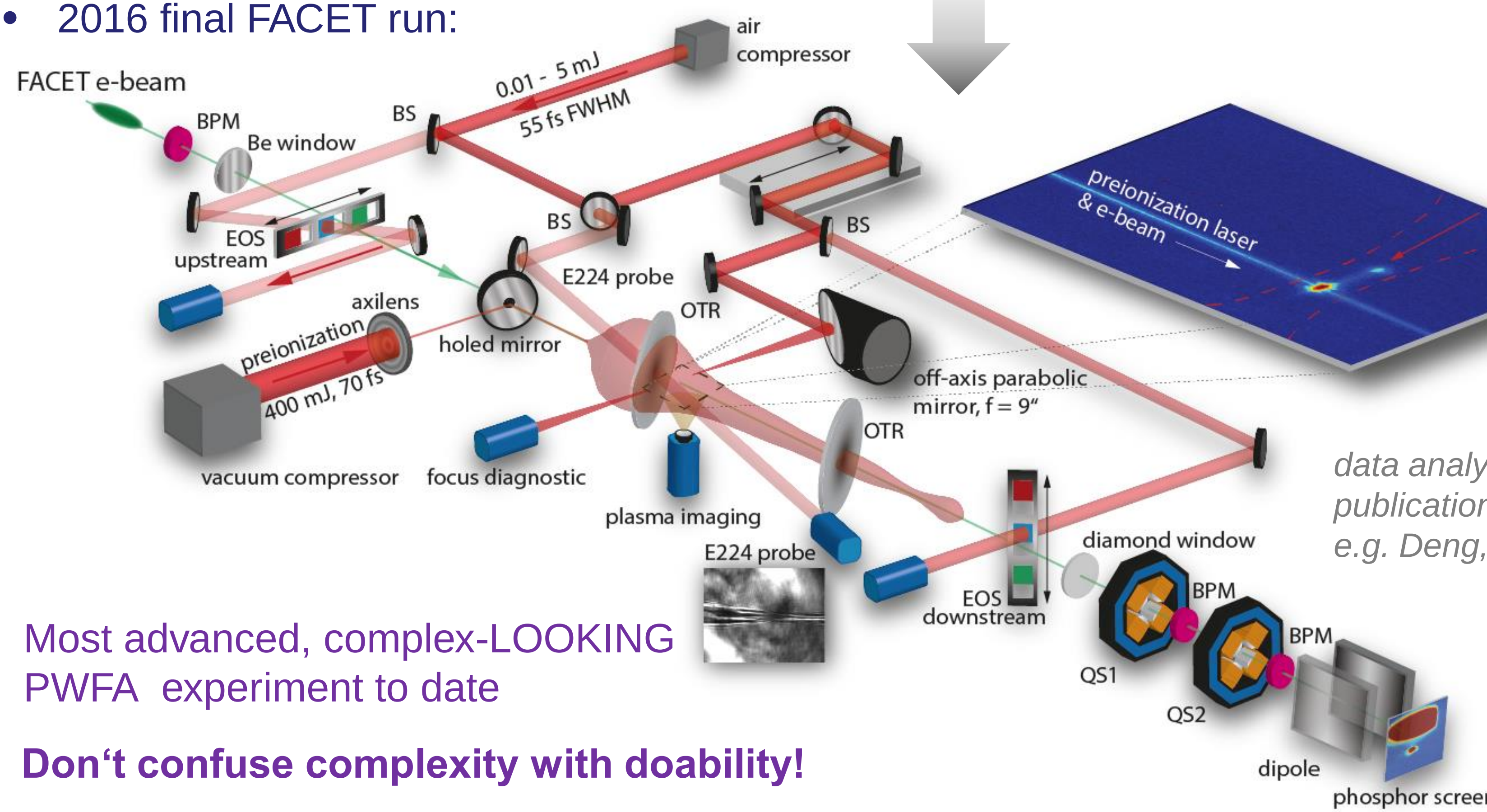

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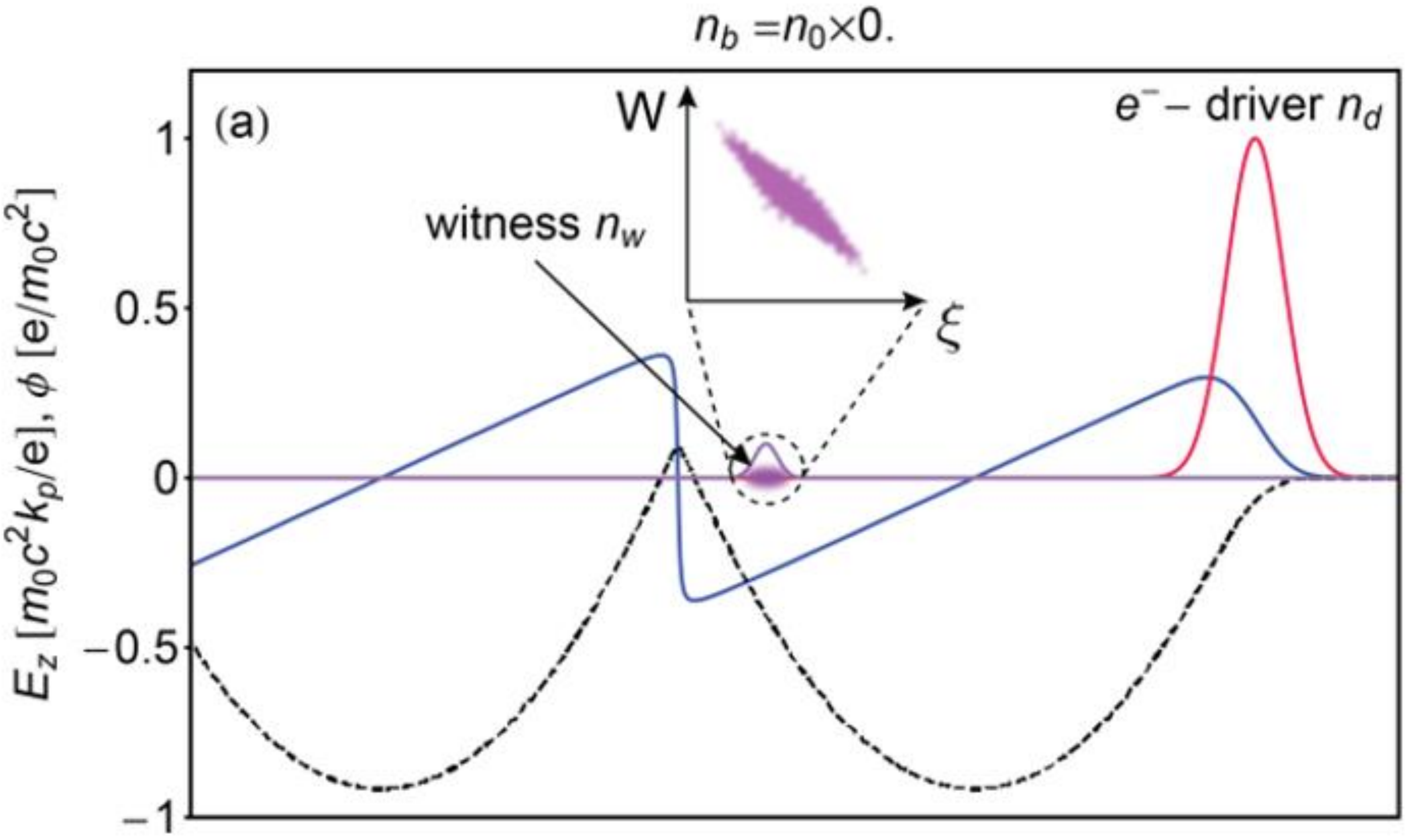
Most advanced, complex-LOOKING PWFA experiment to date

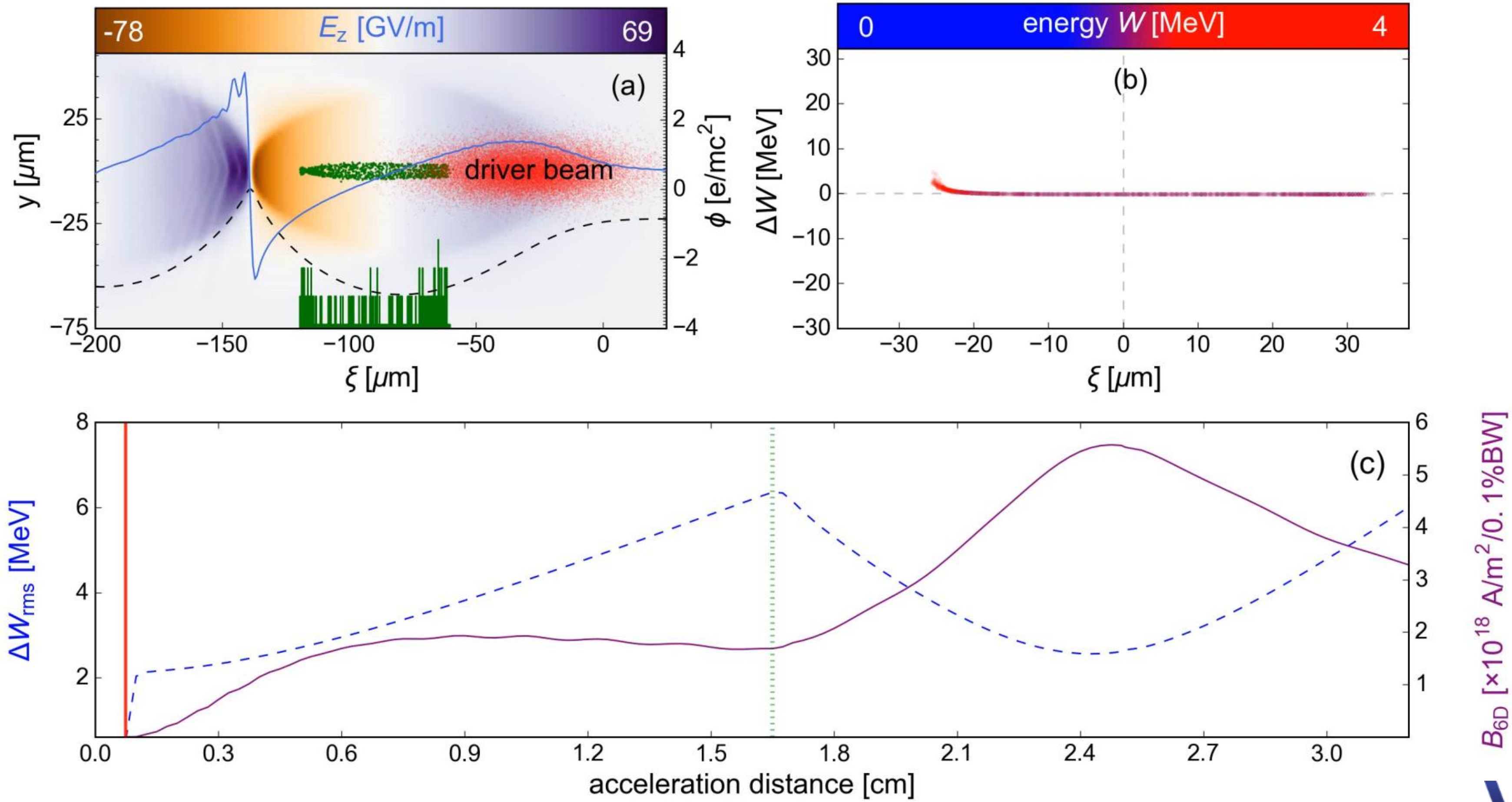
Don‘t confuse complexity with doability!

Ultralow TH emittance and ultrahigh 5D-brightness possibly transformative impact, but energy spread may kill beam during extraction and transport, showstopper for FEL



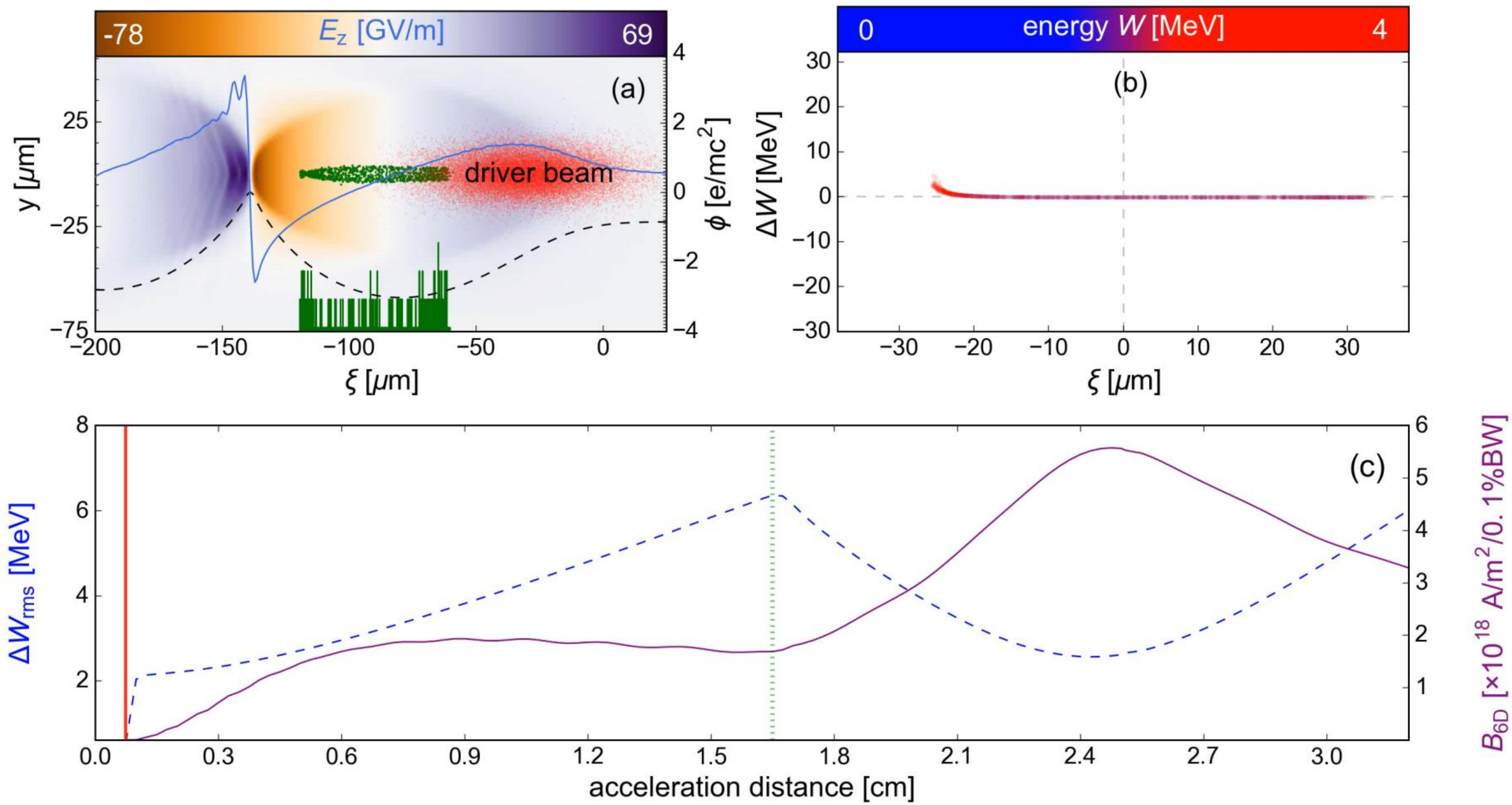
"the energy spread&chirp problem":
'steep' price to be paid for ultrahigh energy gradients

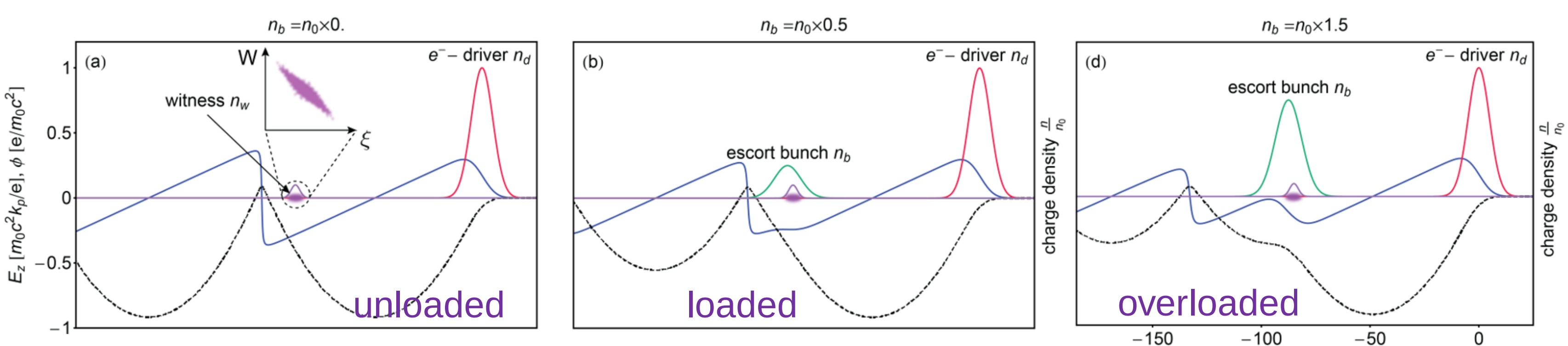
Ultrahigh 6D-brightness: concept of TH-released escort beam for chirp control



G.G. Manahan, F. Habib et al., *submitted*

Ultrahigh 6D-brightness: concept of TH-released escort beam for chirp control





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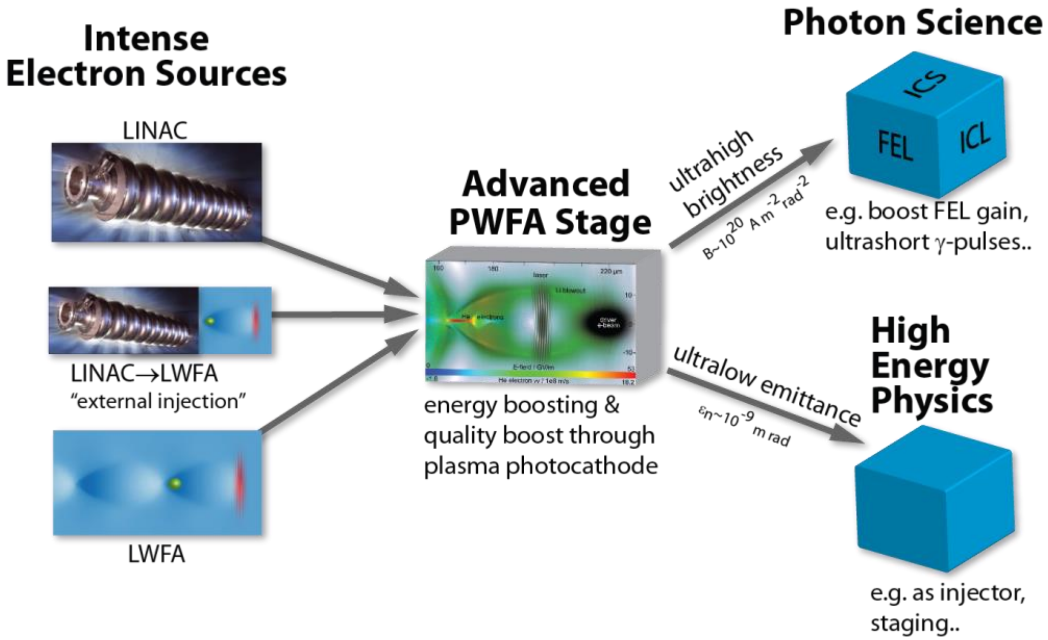
Ultrahigh 6D-brightness: enabling 5th generation light sources

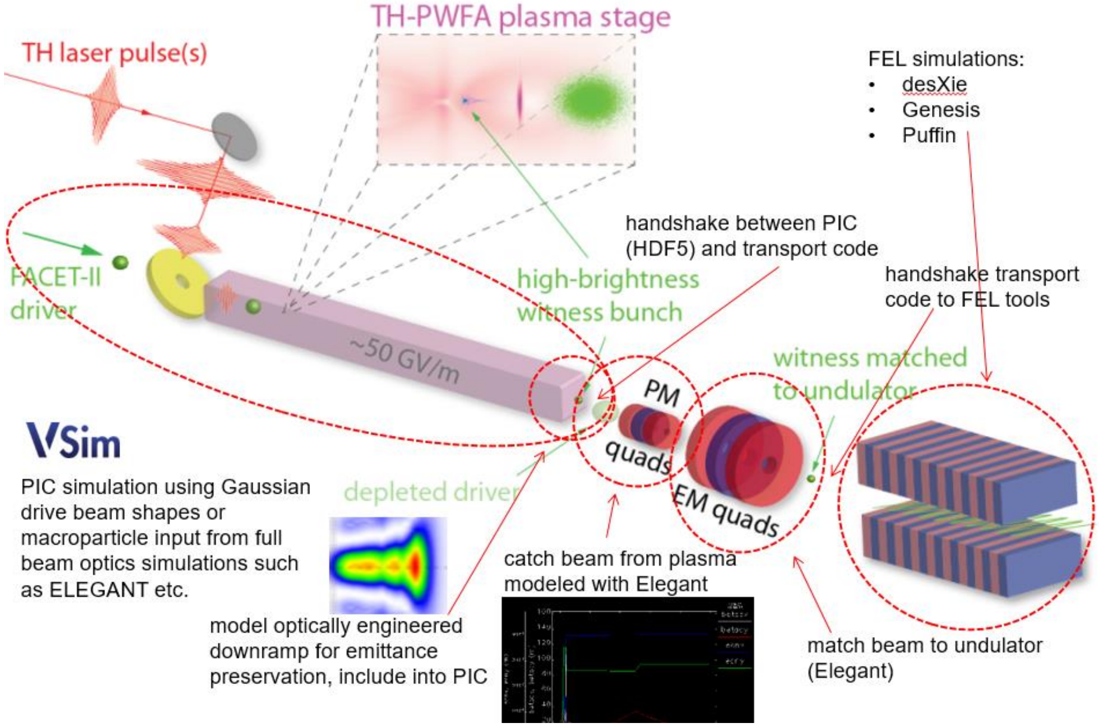


	Before dechirping	After dechirping
z_{acc}	14.8 cm	22.9 cm
Q	8 pC	8 pC
σ_z	2.6 μm	2.6 μm
I_{peak}	2.0 kA	2.0 kA
$\overline{E}$	922 MeV	1404.3 MeV
σ_{E}	1.12 %	0.033 %
ϵ_n	40 nm · rad	43 nm · rad

e.g. for advanced light sources:

- everything happens in a single plasma stage with uniform H/He density
- don‘t have to worry about electron witness beam injection
- dechirping within plasma
- “no“ extraction problems
- no qualitative additional complexity compared to Trojan: need 1 mJ laser pulse

Ultrahigh 6D-brightness: enabling 5th generation light sources at FACET-II



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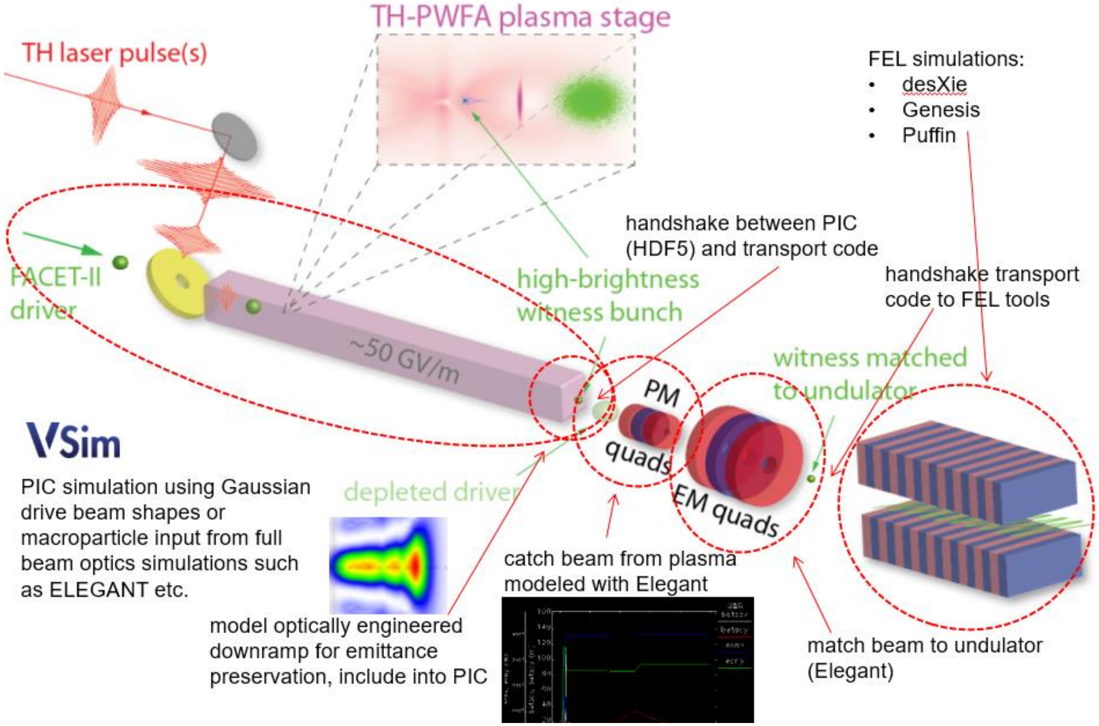
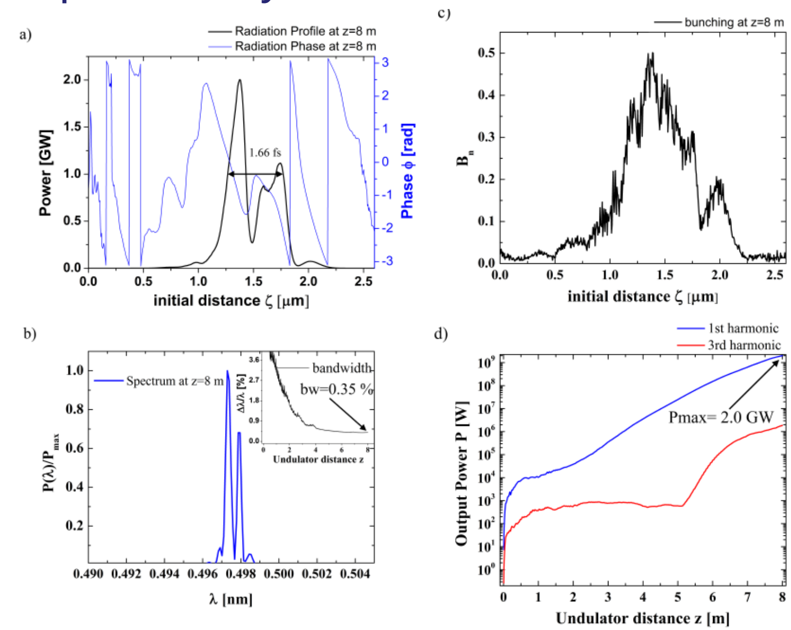
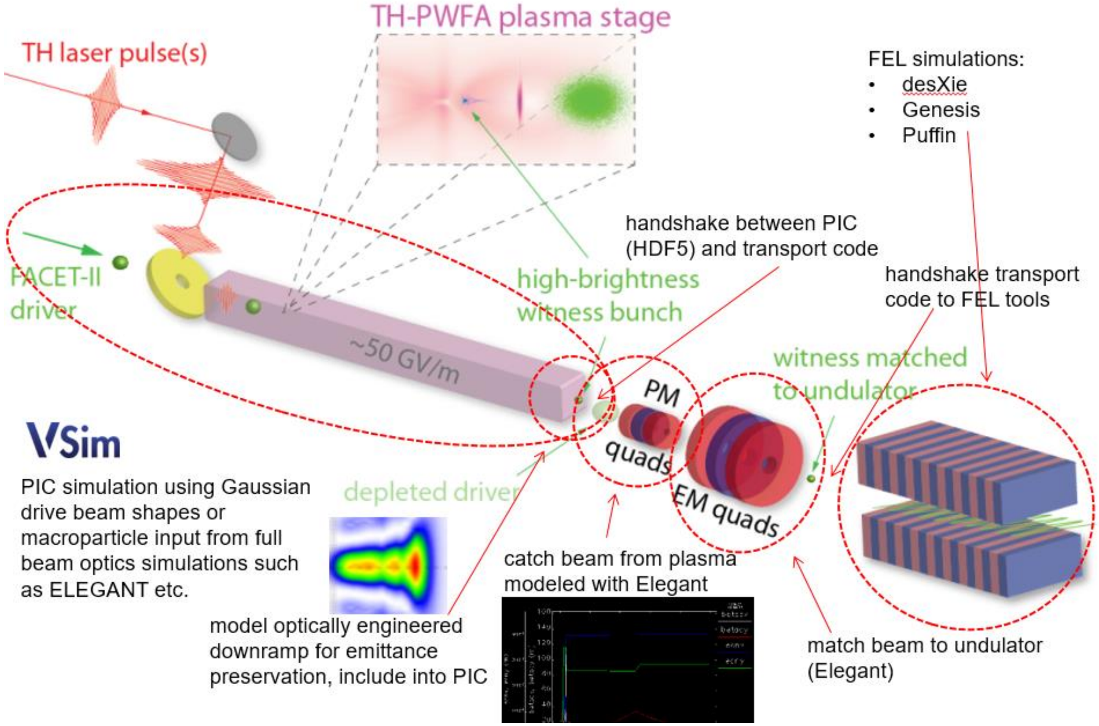


preliminary start-to-end simulations:



5 angstrom, GW power after ~10m

Ultrahigh 6D-brightness: enabling 5^th generation light sources at FACET-II



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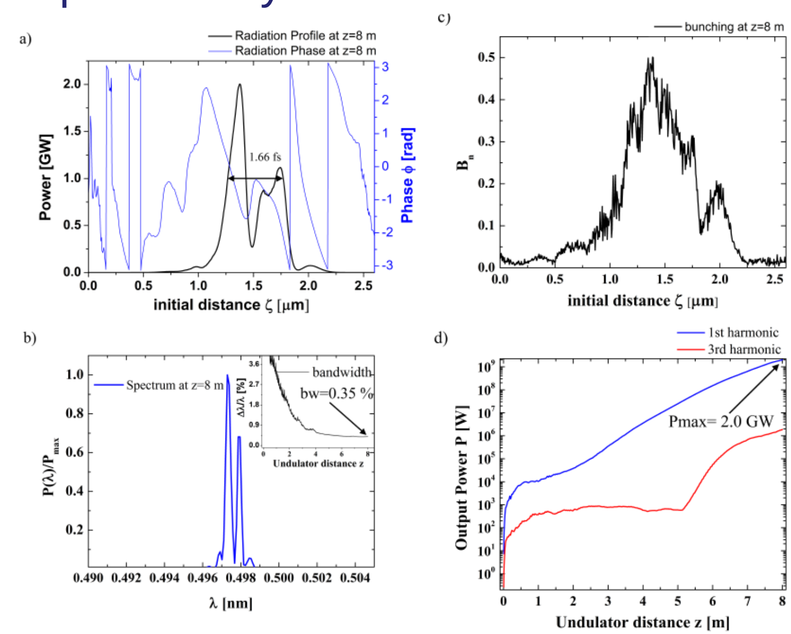
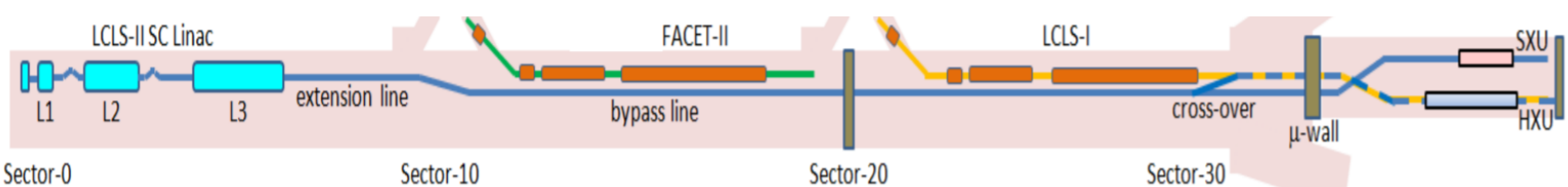


5 angstrom, GW power after ~10m

- exploit ultrahigh single stage PWFA electron energy gain
- fulfil Pellegrini criterion
- beat Pierce parameter (by large margin)
- exploit ultrahigh FEL gain

⇒ **realise 5th generation light sources, such as ultrahard x-ray FEL**



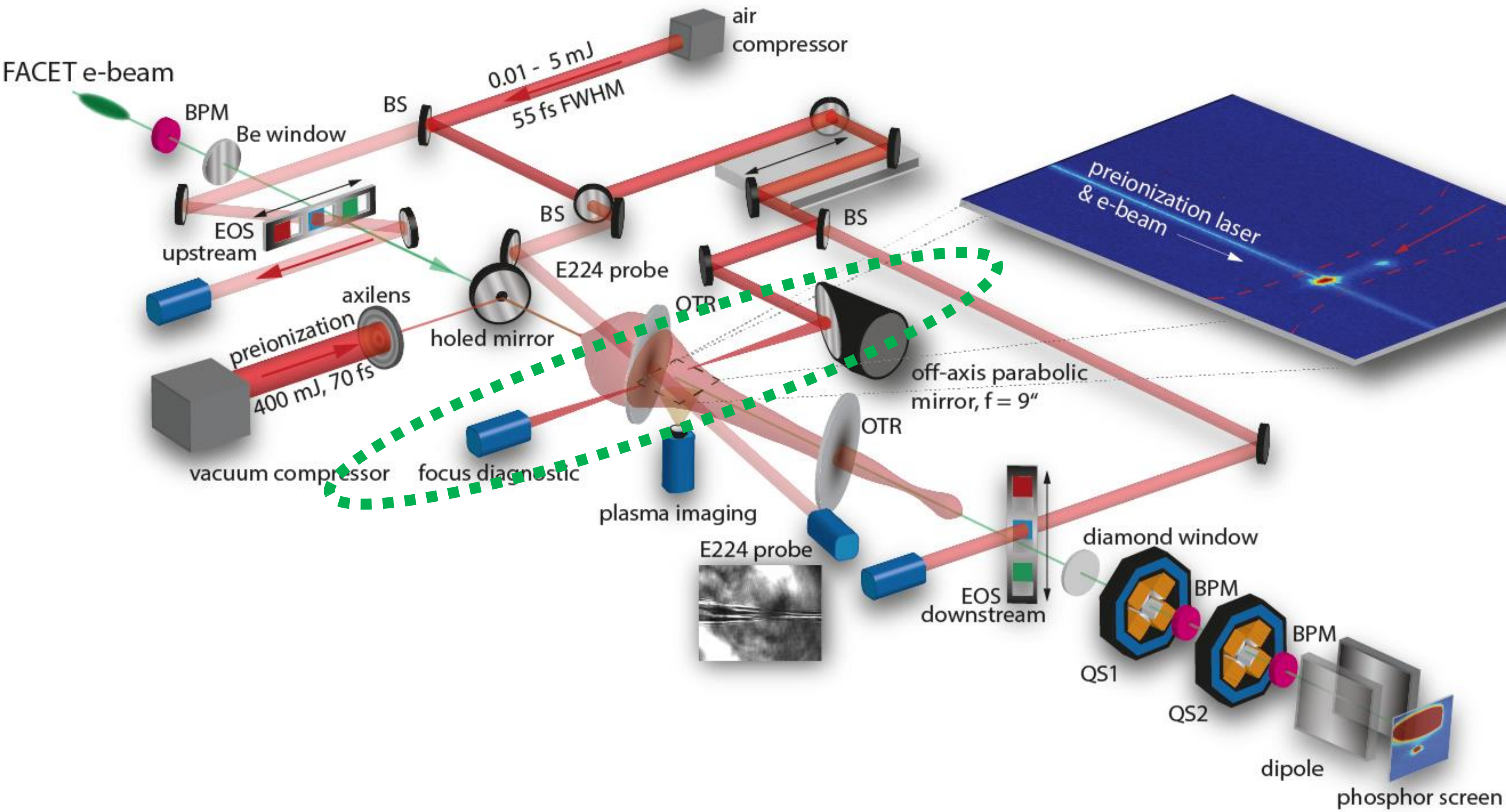
Ultralow emittance, low energy spread, ultrahigh 6D-brightness:
The price we're after at FACET-II

E210 lessons learned, techniques developed

FACET-II

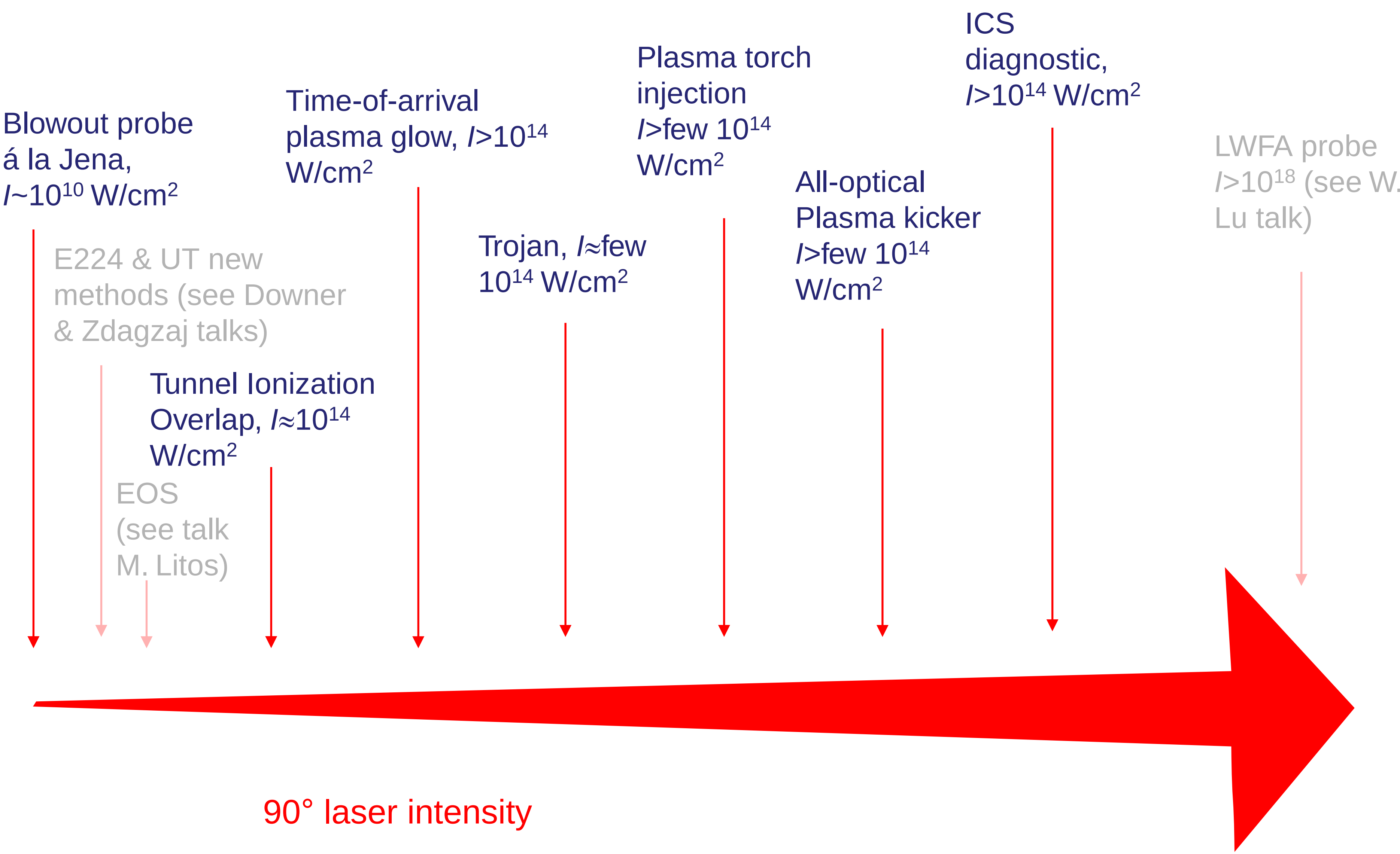
Facility for Advanced Accelerator Experimental Tests

Great experience with 90° Trojan setup in final FACET run
Multi-purpose tool for diagnostics and injection

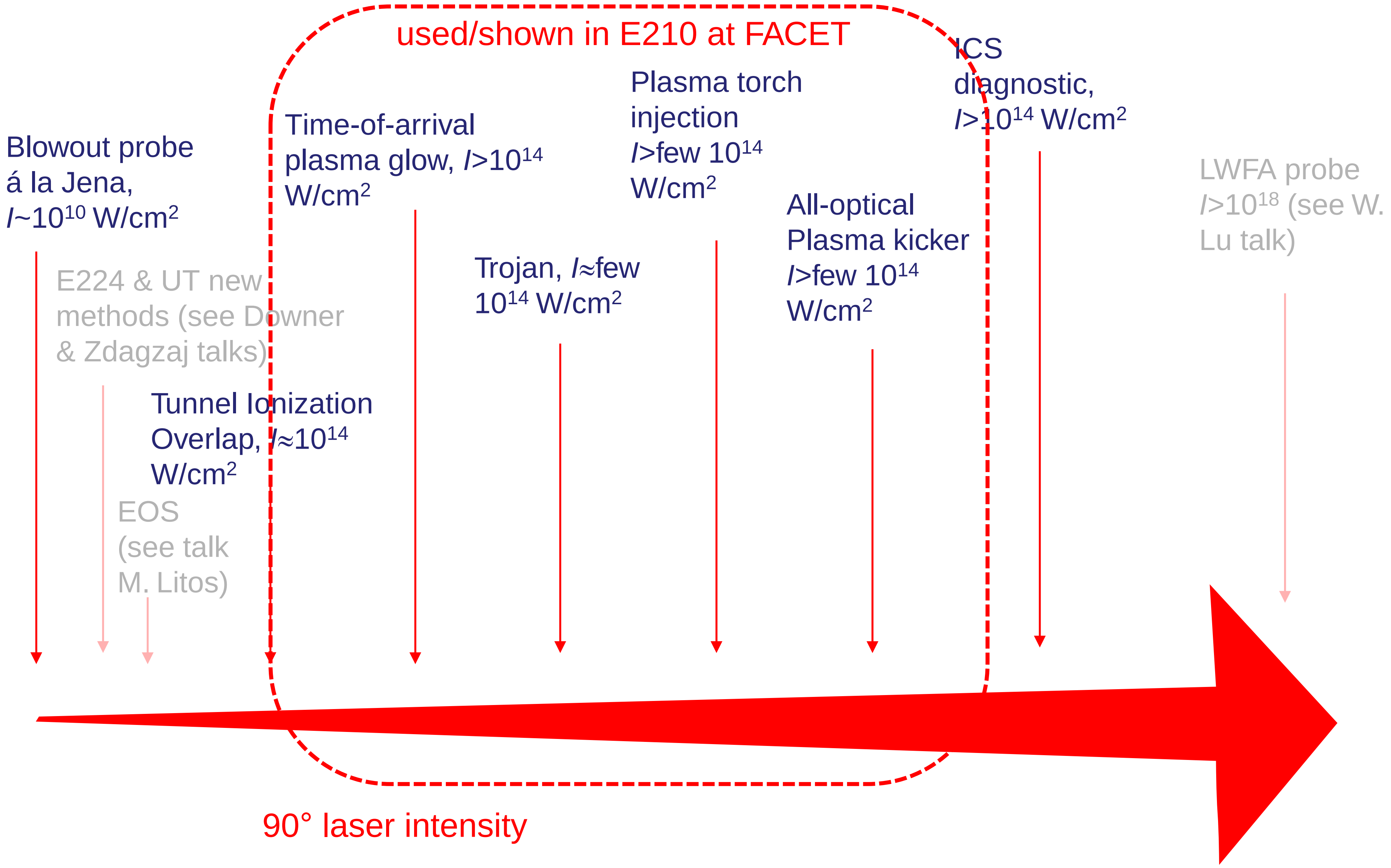


- Used in E210 for a) time-of-arrival, b) injection

Proposed uses of 90° laser pulse and implications



Proposed uses of 90° laser pulse and implications



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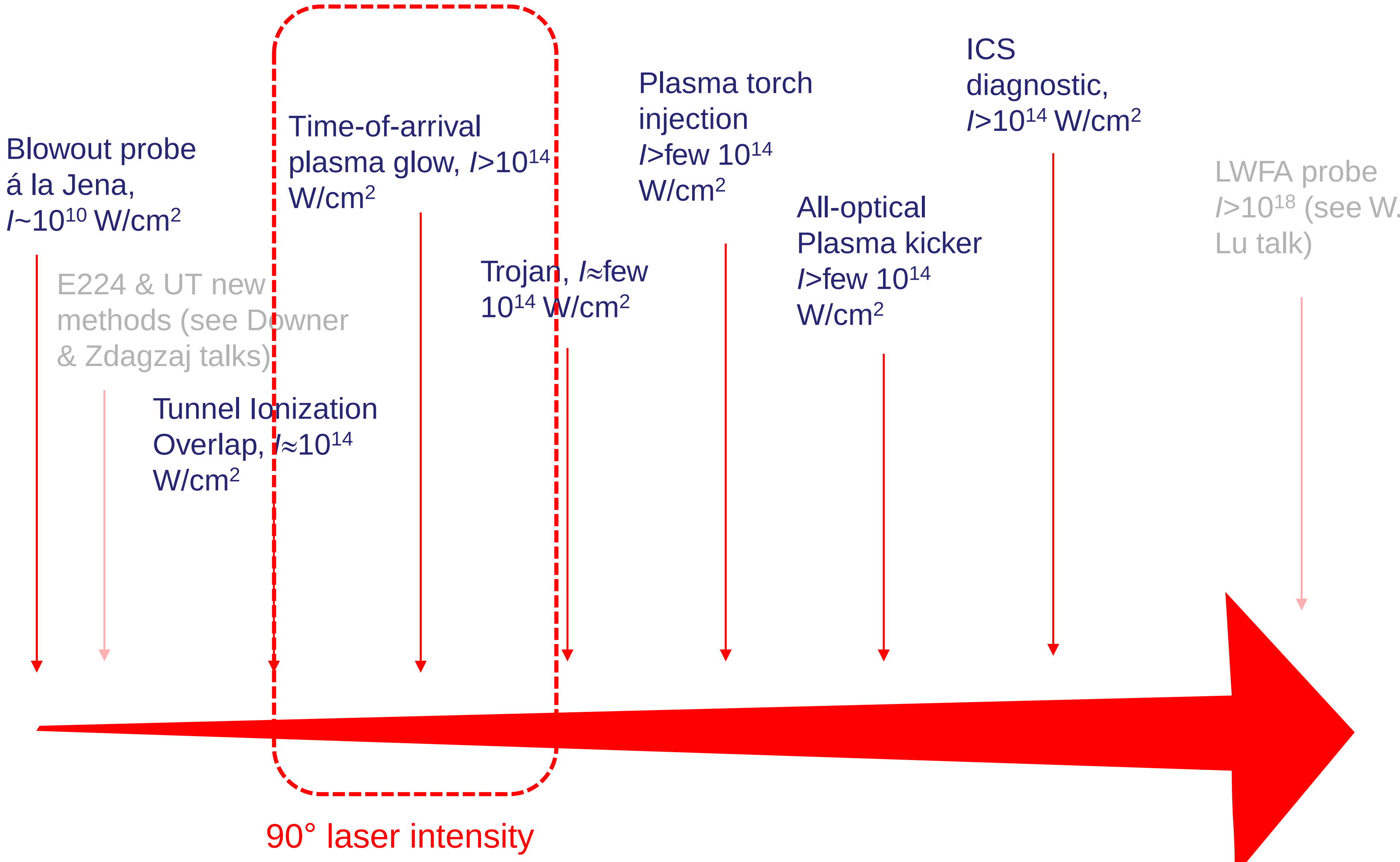
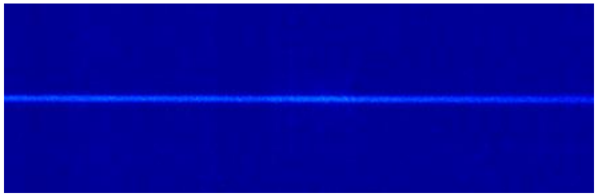


Time-of-arrival plasma glow

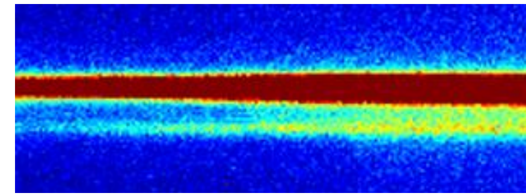
- used for E210, after digging into observation in longitudinal direction:

axicon laser only

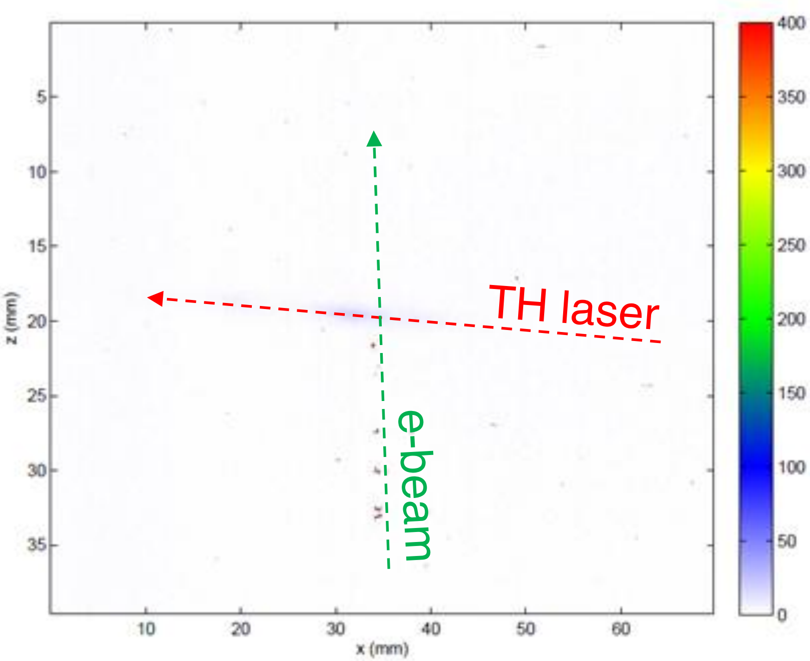


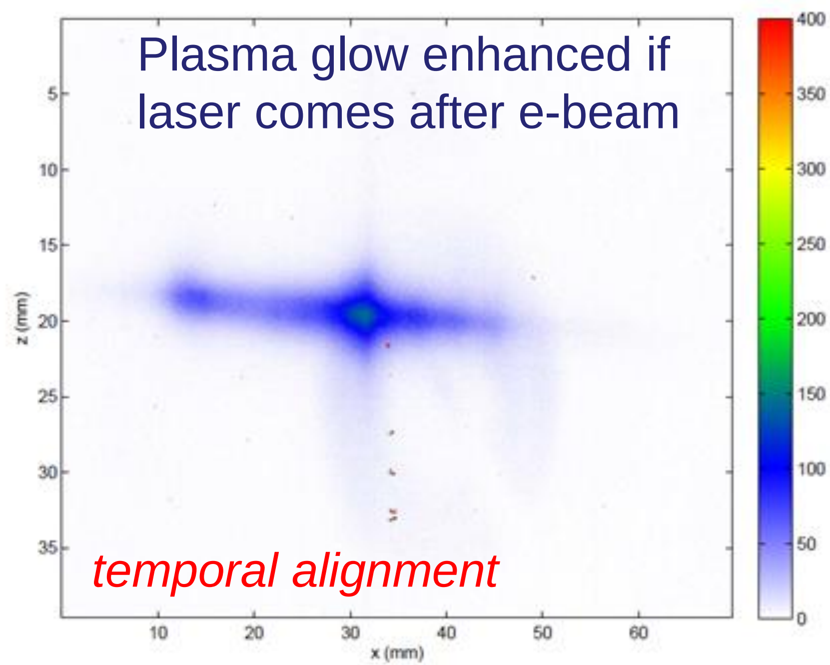
e-beam only

e-beam <u>after</u> axicon laser



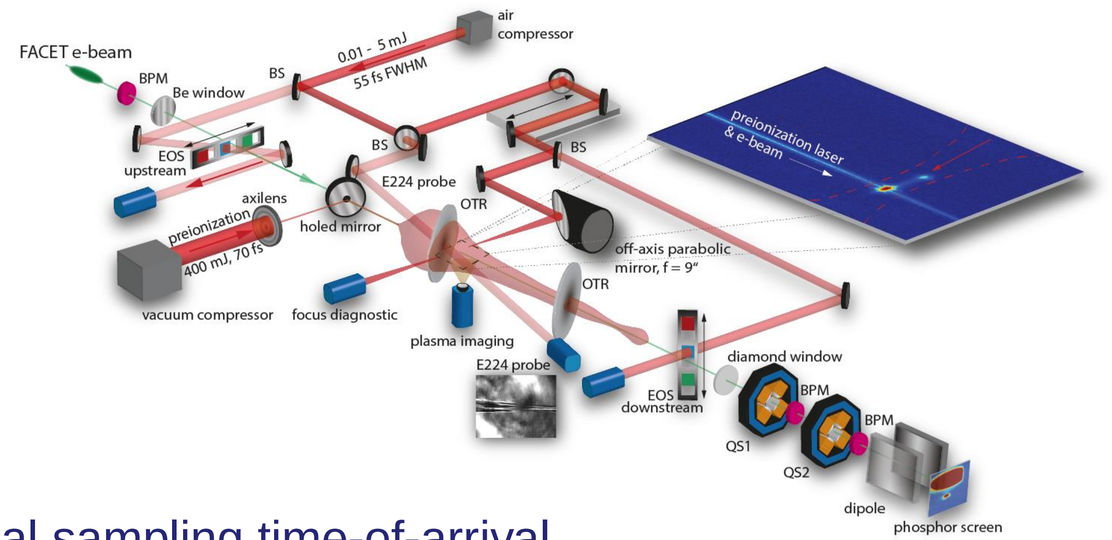
beam “heats” pre-ionized plasma, resulting in stronger recombination light signal: use for spatio-temporal alignment of TH laser and electron beam





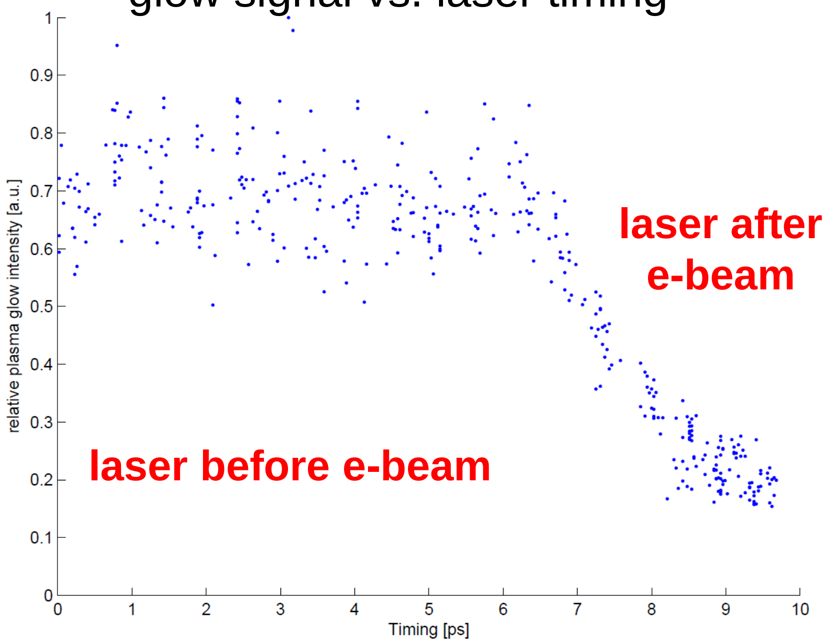
Time-of-arrival plasma glow

Extremely robust method, just scan laser jitter and count plasma glow on CCD

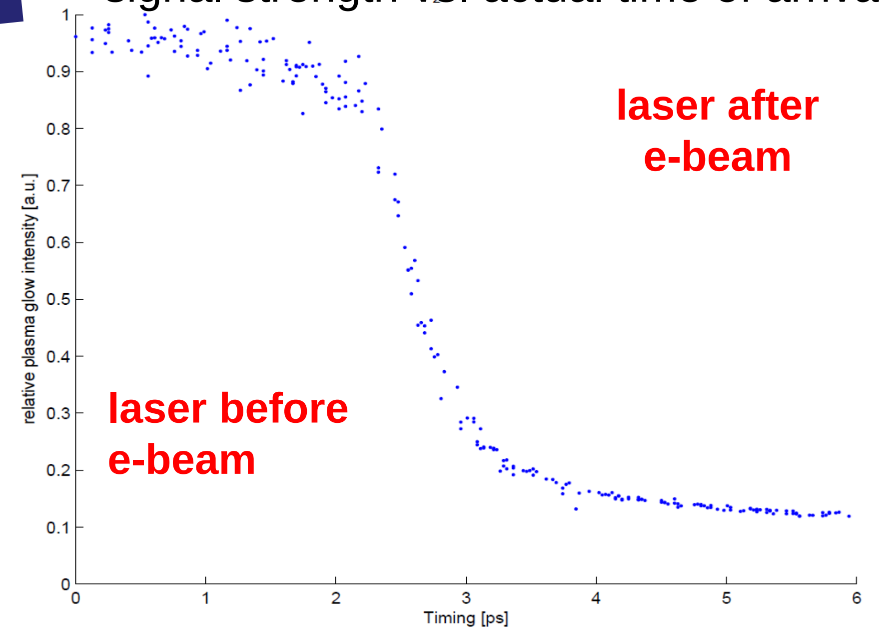


After sorting shots by electro-optical sampling time-of-arrival measurement: real TOA between e-beam and laser

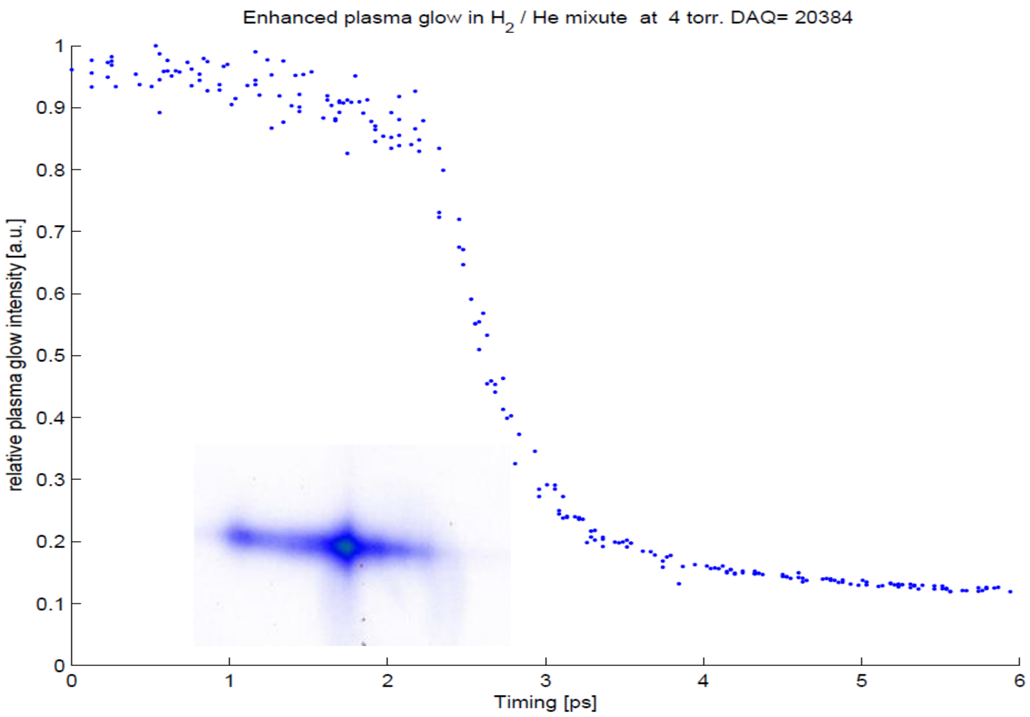
glow signal vs. laser timing



signal strength vs. actual time of arrival

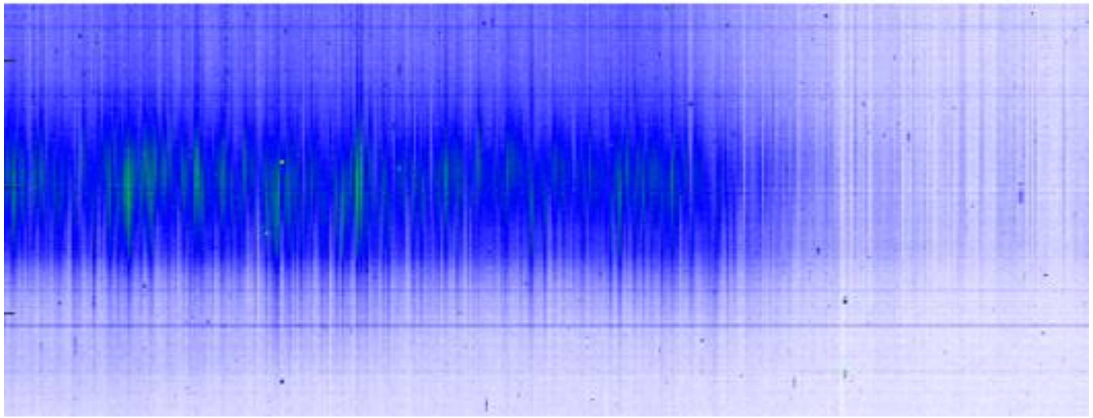


Time-of-arrival plasma glow

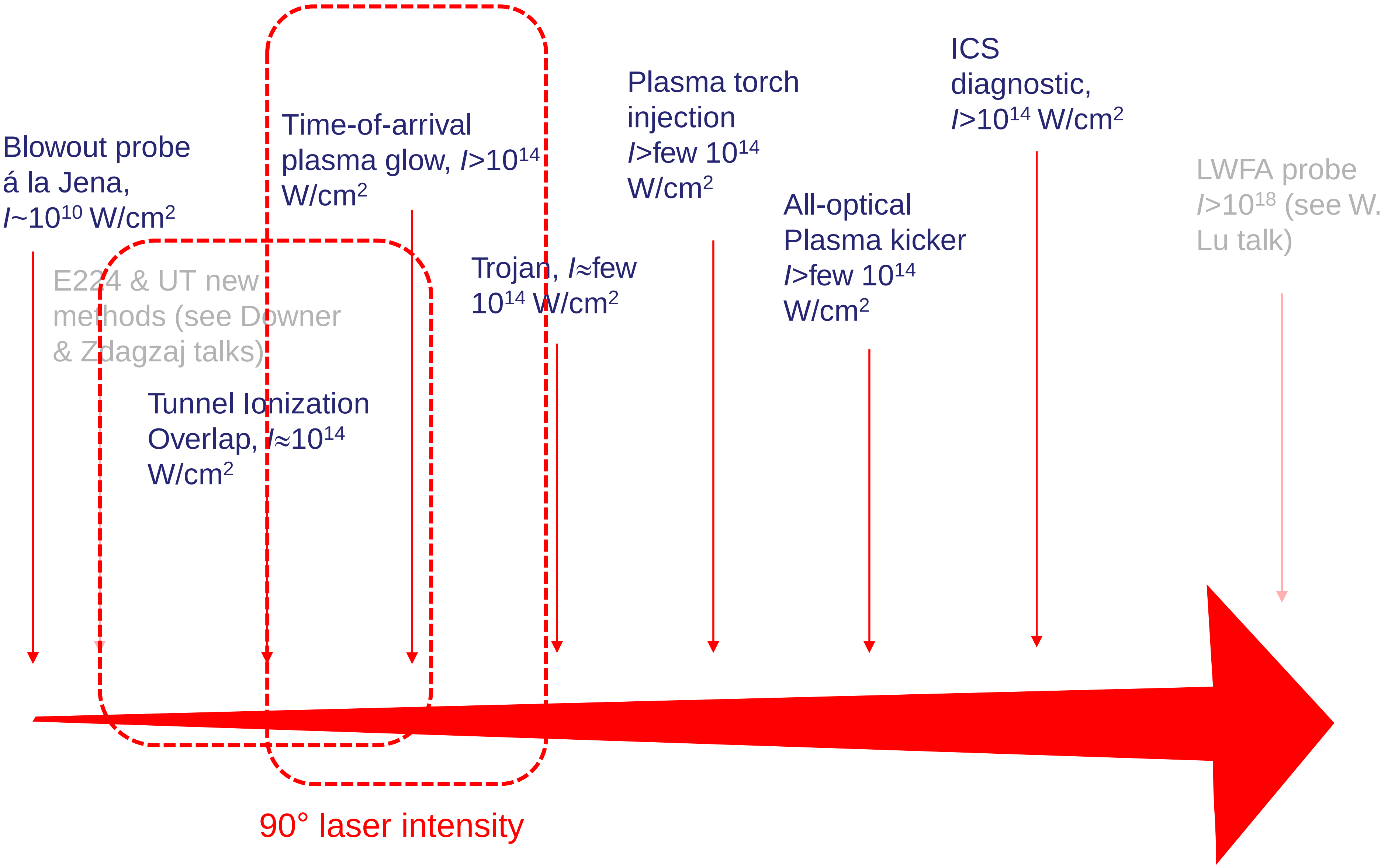


- fs-scale plasma TOA method
- also used for spatial alignment

…"but there is much more"



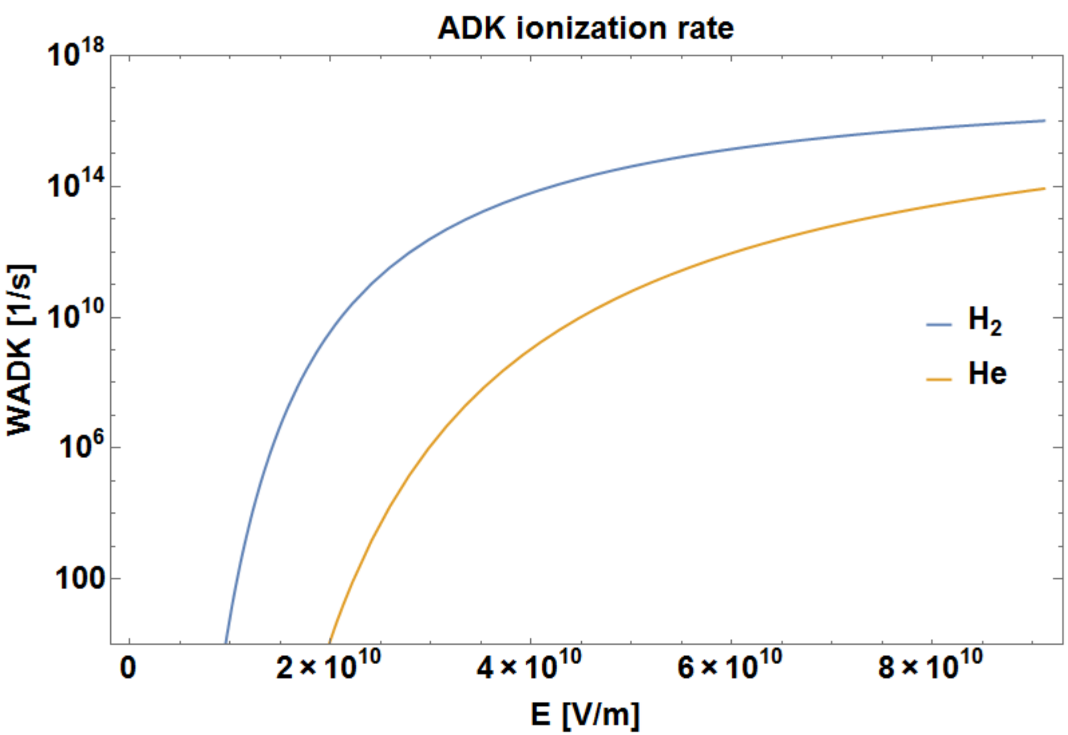
Proposed uses of 90° laser pulse and implications

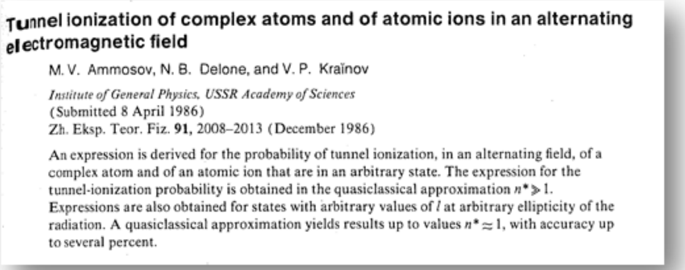


Time-of-arrival plasma glow

Field ionization depends largely on

- small field deviations can lead to large changes in ionisation rate





Tunnel ionization of complex atoms and of atomic ions in an alternating electromagnetic field

M. V. Ammosov, N. B. Delone, and V. P. Kraĭnov

Institute of General Physics, USSR Academy of Sciences
(Submitted 8 April 1986)
Zh. Eksp. Teor. Fiz. **91**, 2008–2013 (December 1986)

An expression is derived for the probability of tunnel ionization, in an alternating field, of a complex atom and of an atomic ion that are in an arbitrary state. The expression for the tunnel-ionization probability is obtained in the quasiclassical approximation $n^* \gg 1$. Expressions are also obtained for states with arbitrary values of l at arbitrary ellipticity of the radiation. A quasiclassical approximation yields results up to values $n^* \simeq 1$, with accuracy up to several percent.

[1]

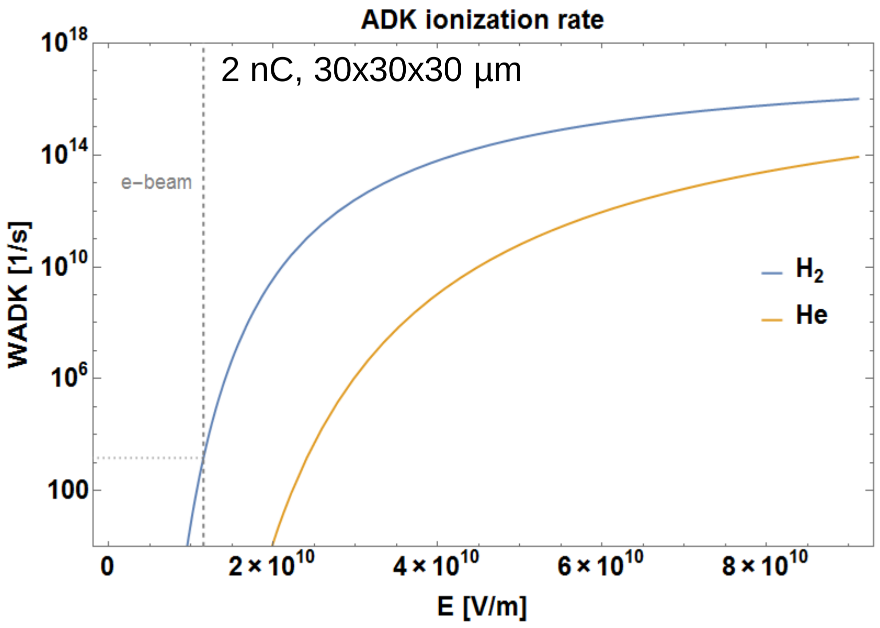
$$W(\mathrm{s}^{-1}) \sim 1.52\times10^{15}\frac{4^{n^*}\xi_i(\mathrm{eV})}{n^*\Gamma(2n^*)}\left(20.5\frac{\xi_i^{3/2}(\mathrm{eV})}{E[\mathrm{GV/m}]}\right)^{2n^*-1} \times\exp\left(-6.83\frac{\xi_i^{3/2}(\mathrm{eV})}{E(\mathrm{GV/m})}\right)$$

[2]

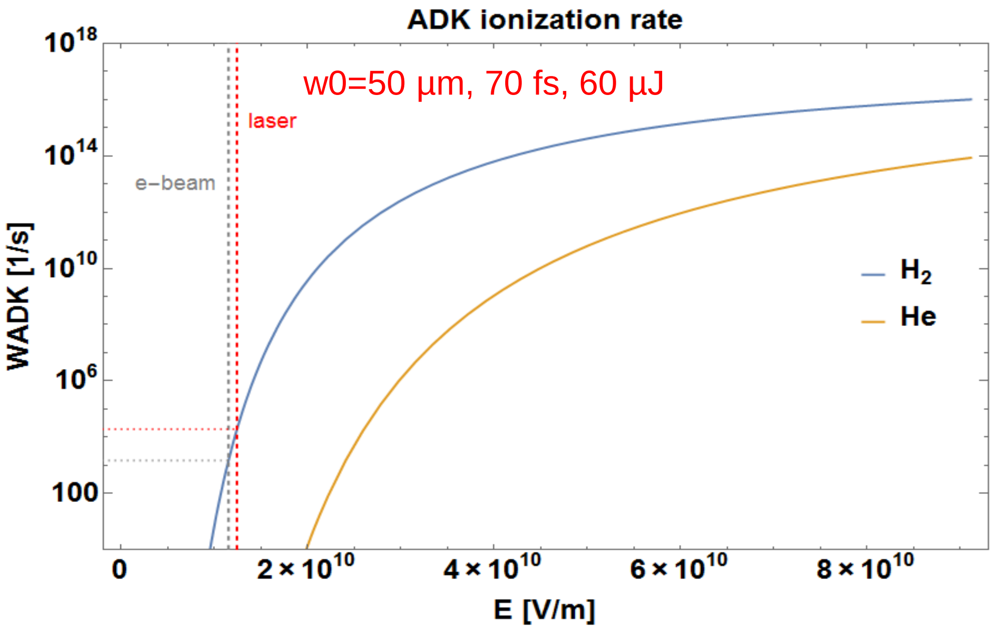
[1] Ammosov, Delone, Krainov. *Sov. Phys. JETP* (1986)
[2] Bruhwiler, David L., et al. *Physics of Plasmas* (2003): 2022-2030.

Time-of-arrival plasma glow

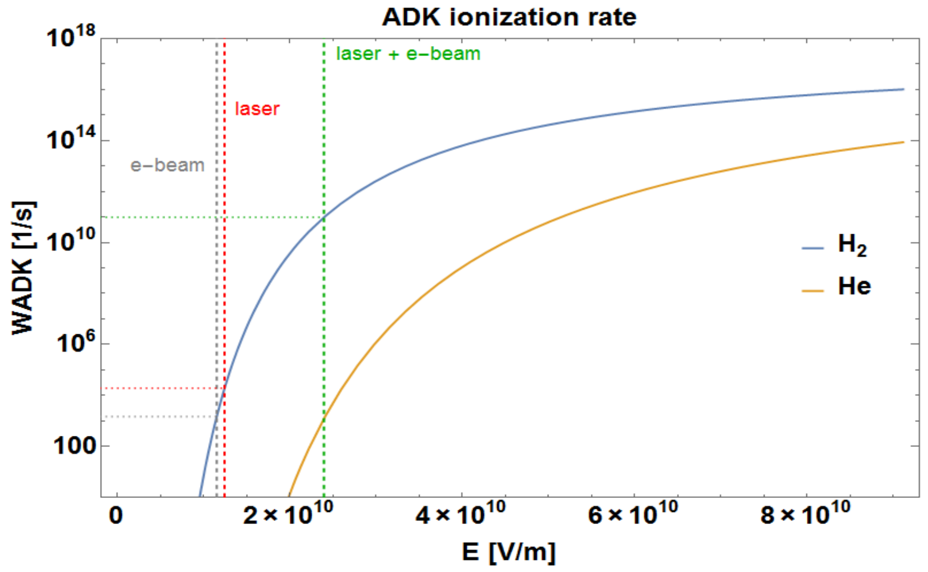
FACET-scale e-beam produces "only" e-fields barely ionizing H2



a laser beam can be tuned to easily produce similar fields



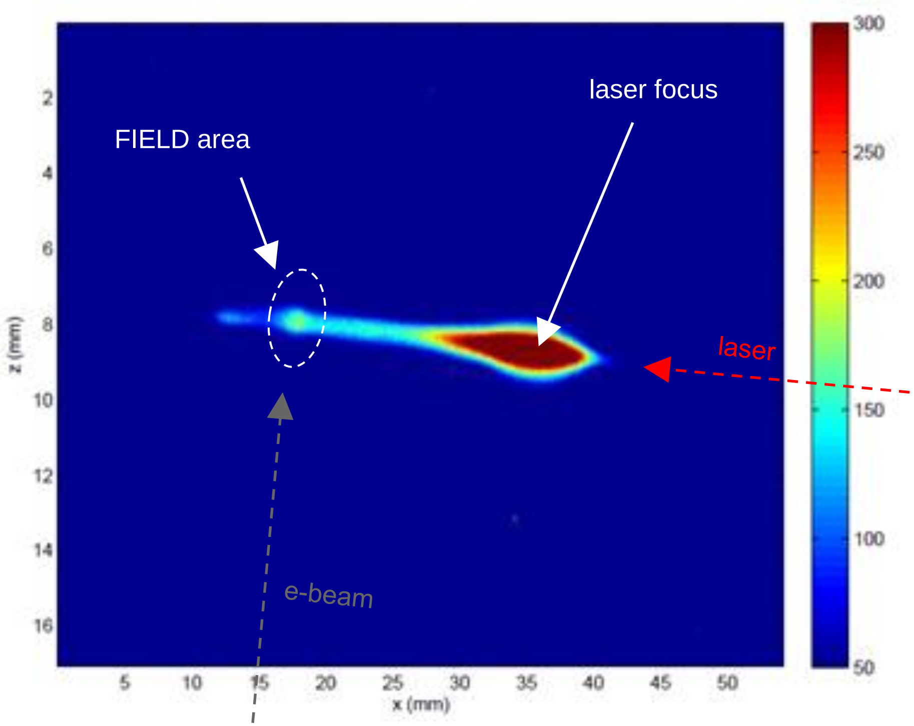
overlapping laser- and e-beam fields leads to increase in ionisation rate by several orders of magnitude due to ADK rates potentially ionizing even other gases



“FIELD” – Field Ionisation by an Electron-Laser Distribution

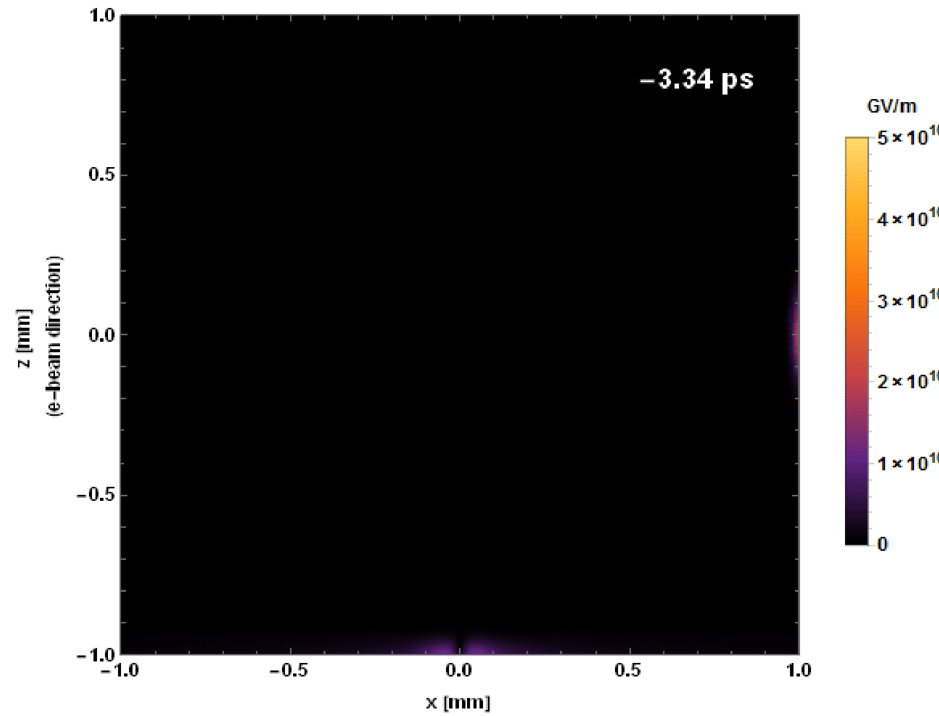
Transient overlap of laser and electron beam produces localized field ionisation and plasma glow

observed recombination light



overlap at x,z,t = 0,0,0

Electric Field



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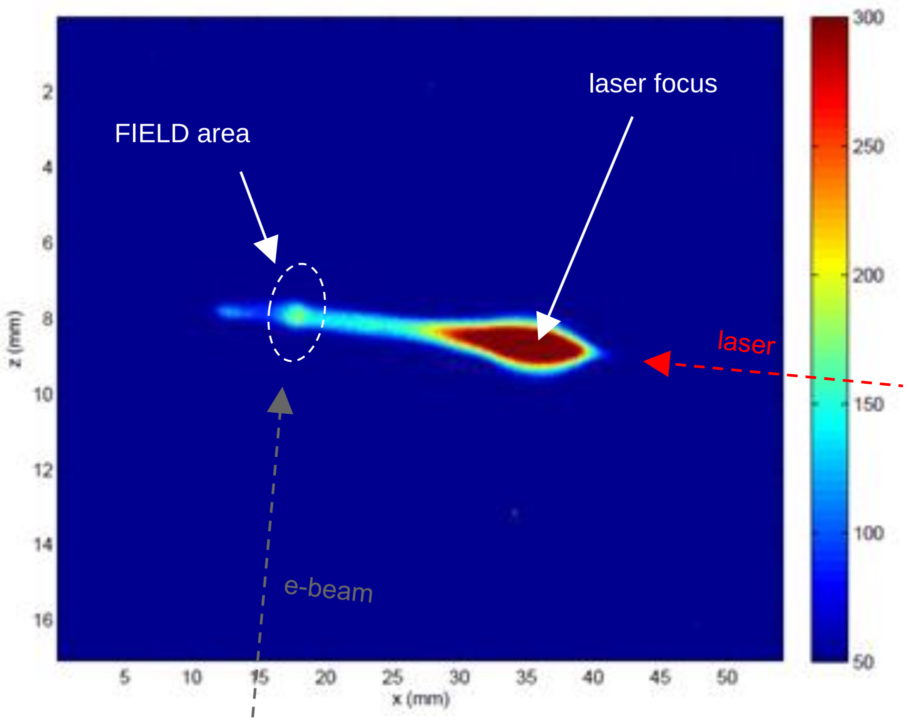
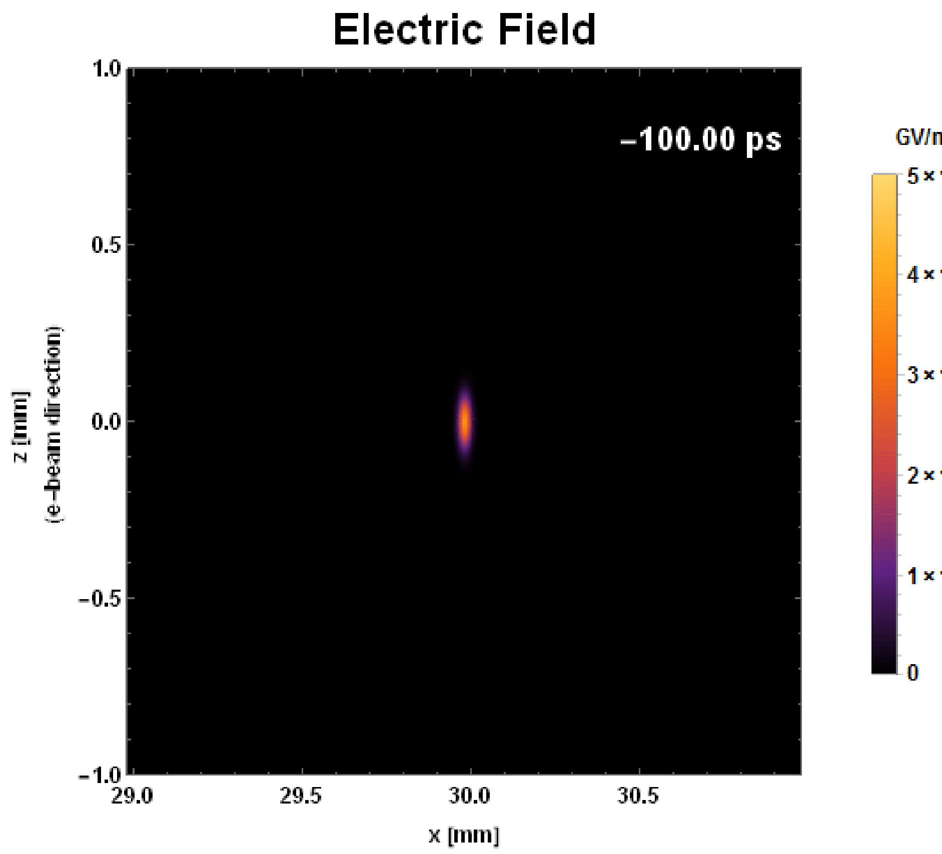


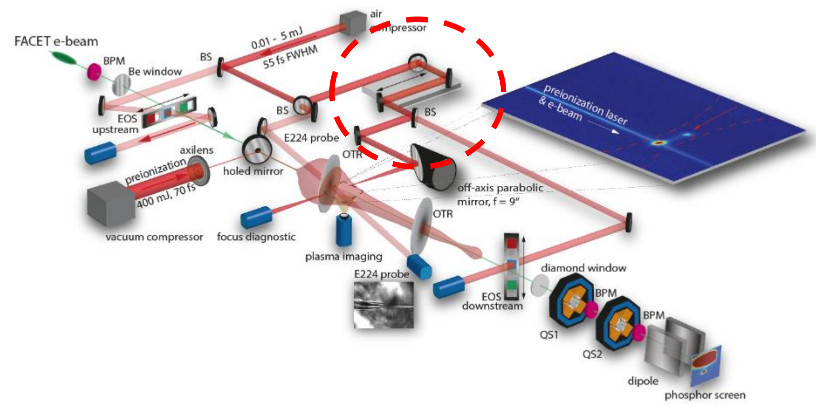
frame co-moving with laser



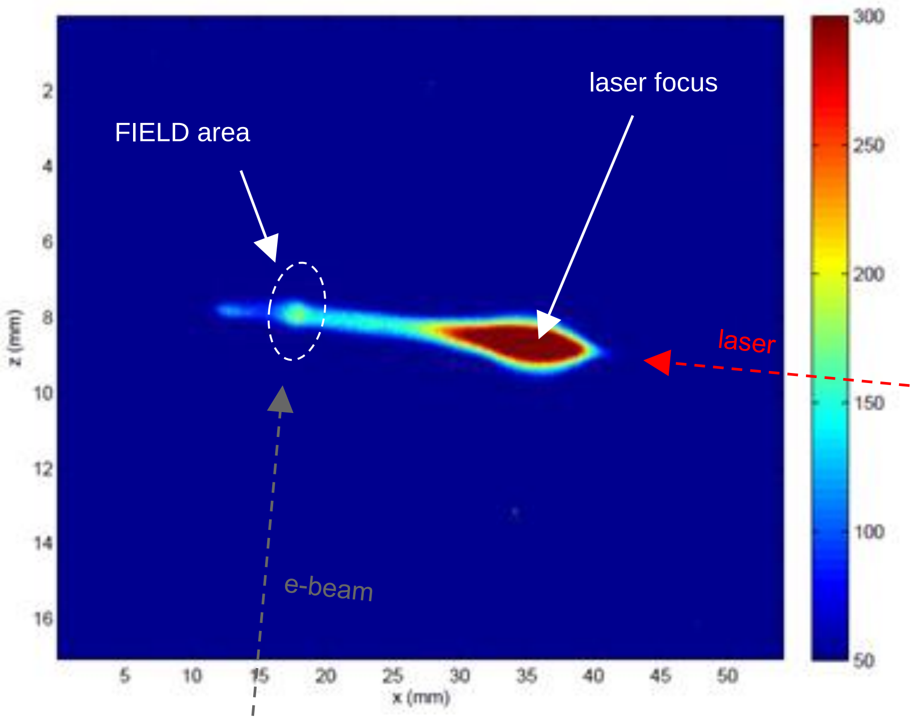
“FIELD” – Field Ionisation by an Electron-Laser Distribution

Timing scan using E210 delay line:

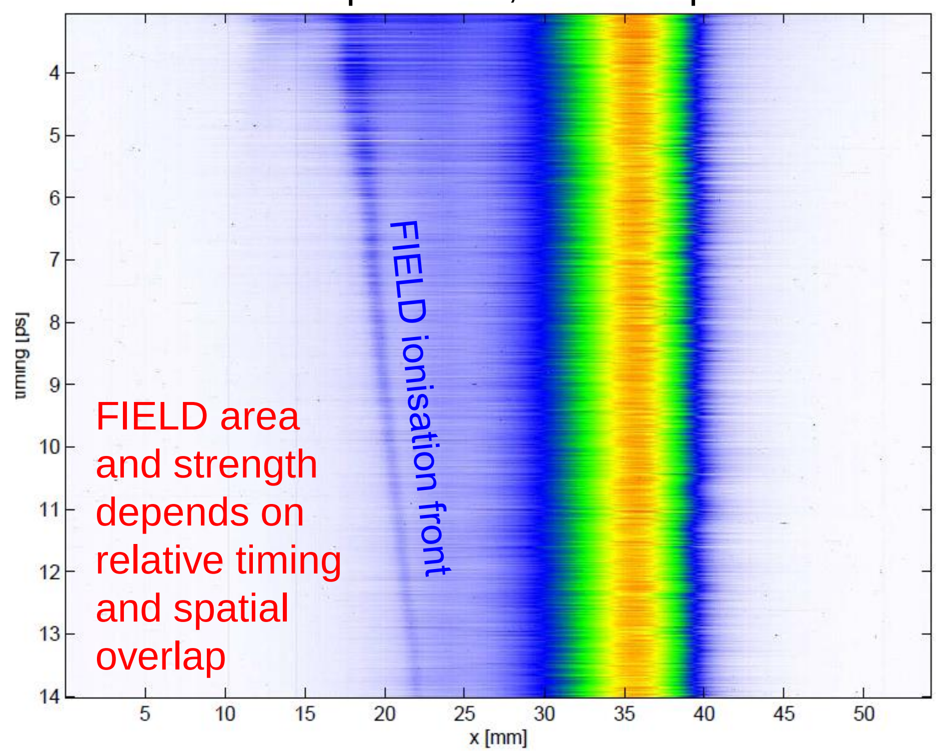
waterfall-plot reveals moving FIELD area for different timings



single shot



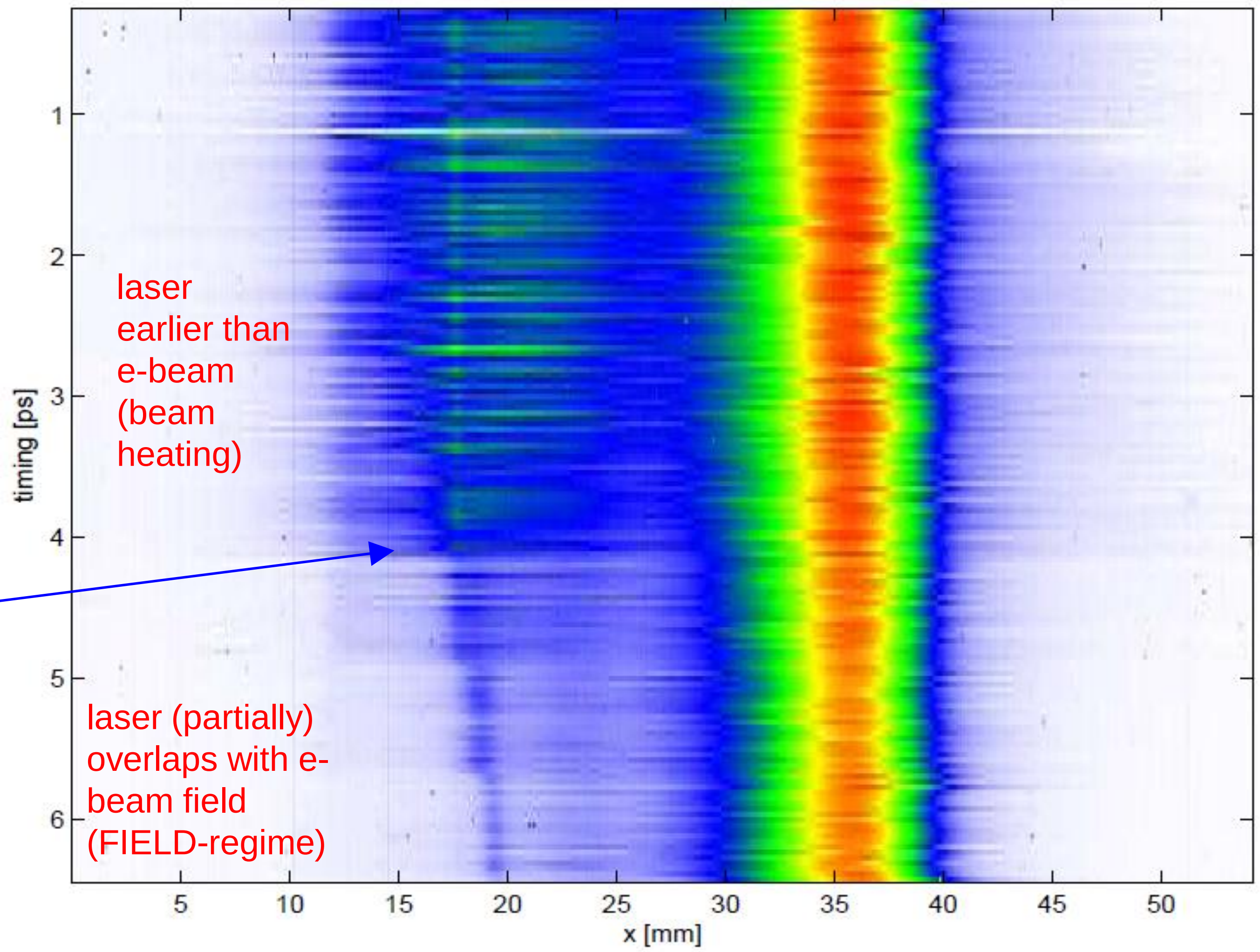
multiple shots, waterfall plot



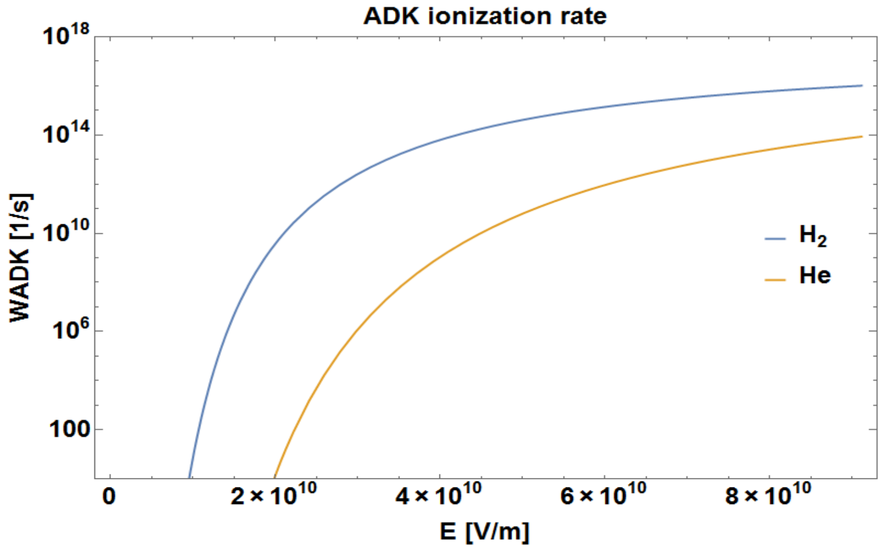
“FIELD” – Field Ionisation by an Electron-Laser Distribution

- beam heating enhanced plasma glow if e-beam shoots after laser has passed
- no change in plasma glow if laser shoots after e-beam

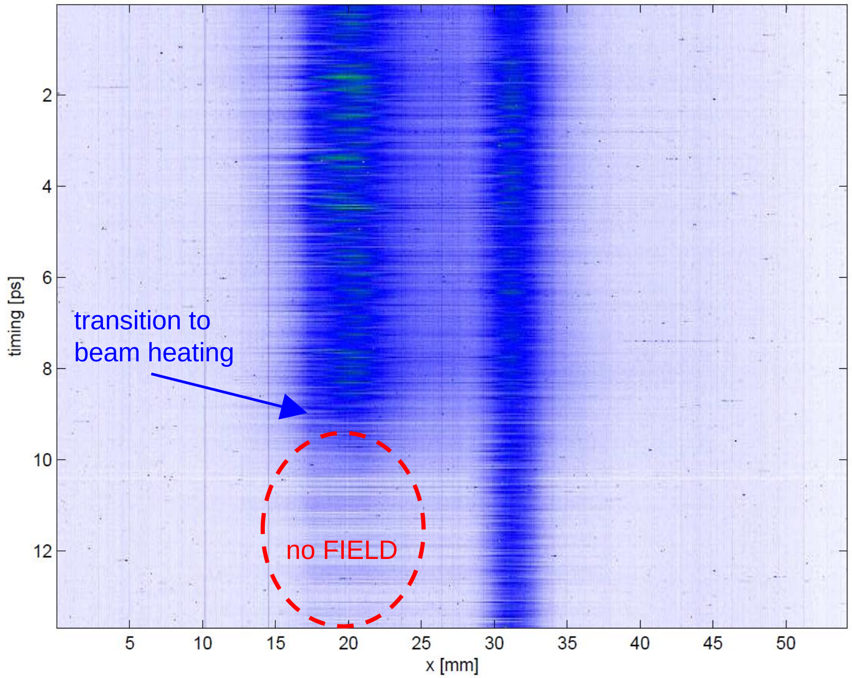
transition
= exact temporal alignment
of laser and e-beam
“T0“



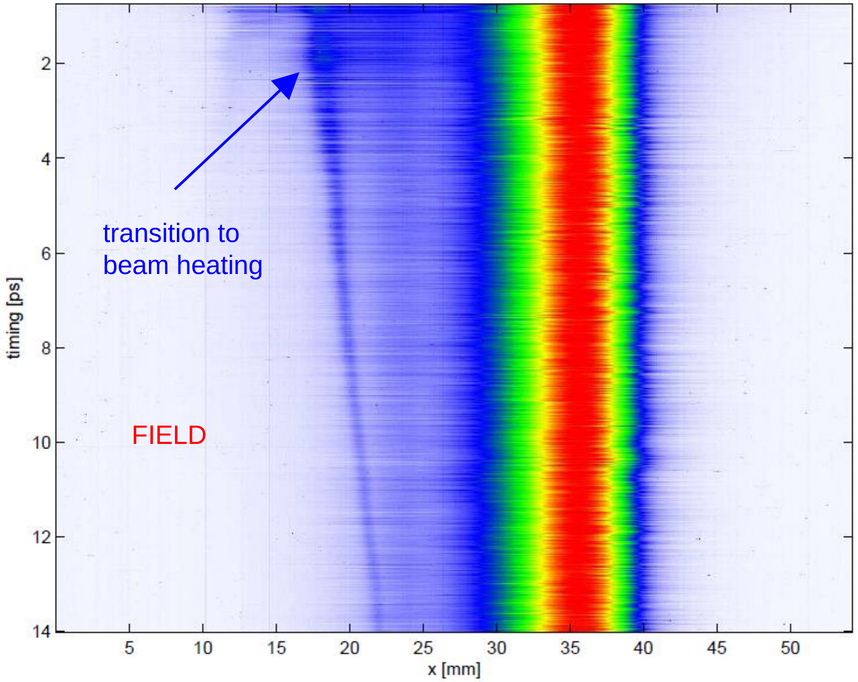
“FIELD” is naturally species selective



Pure He, no FIELD



Pure H2, FIELD observed

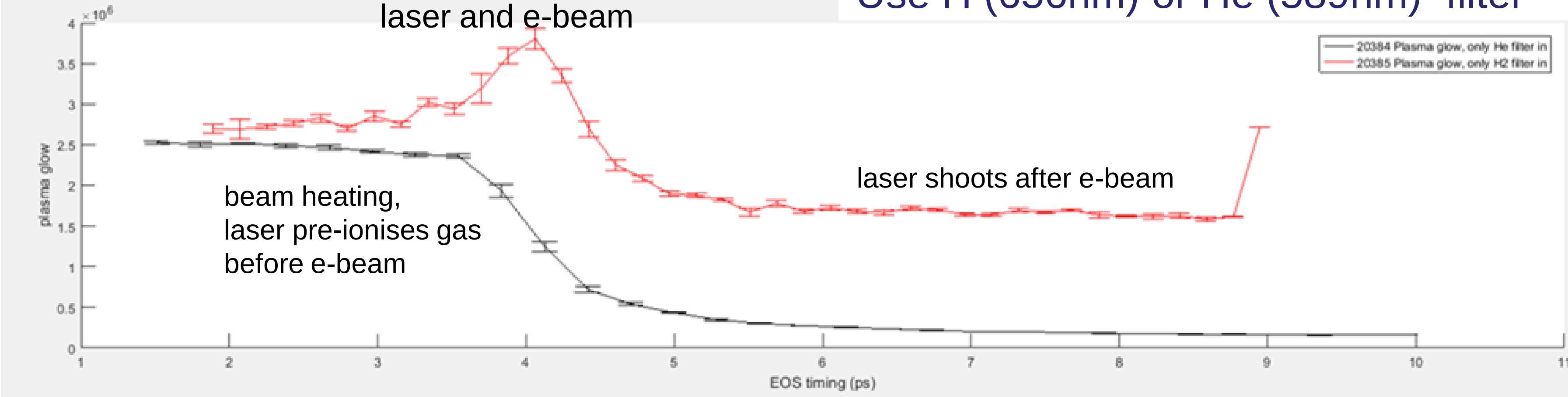


note: timing values are not absolute, hence different values between both plots

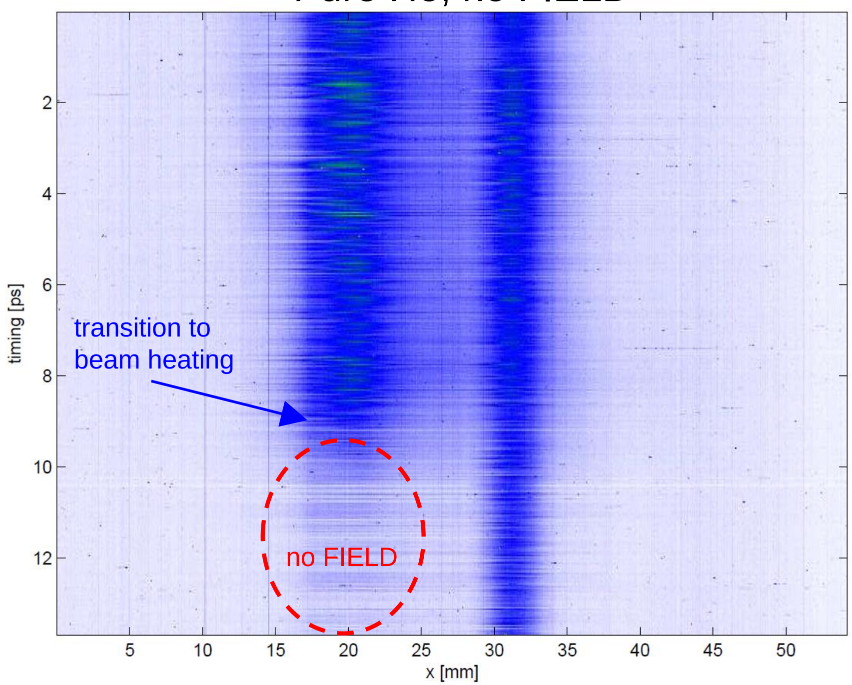
“FIELD” is naturally species selective

FIELD time range,
temporal overlap between
laser and e-beam

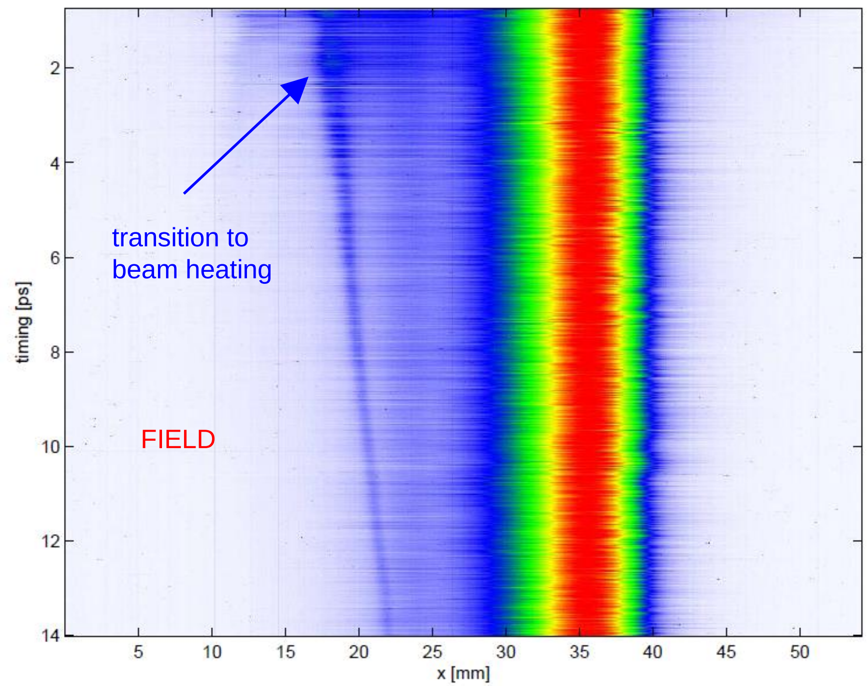
Works even in the mix!
Use H (656nm) or He (589nm) filter



Pure He, no FIELD



Pure H2, FIELD observed

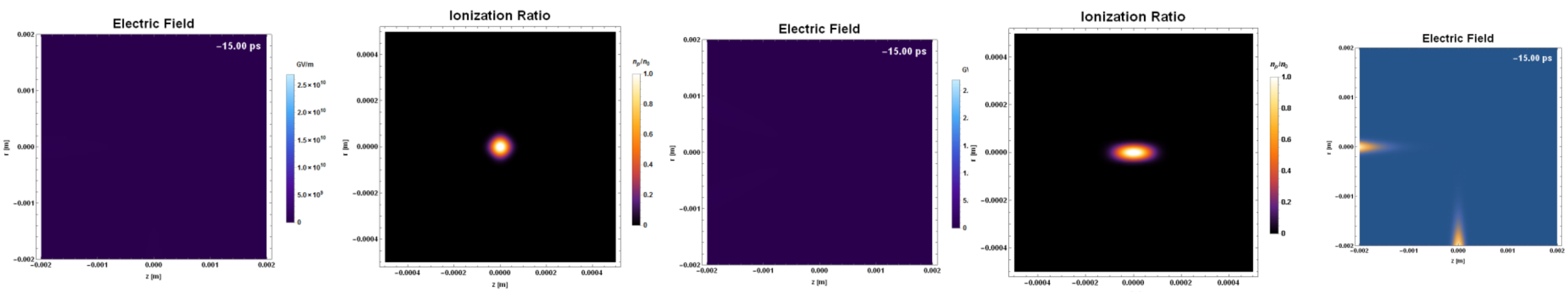


note: timing values are not absolute, hence different values between both plots

“FIELD” is an extremely powerful, robust, low-cost diagnostics

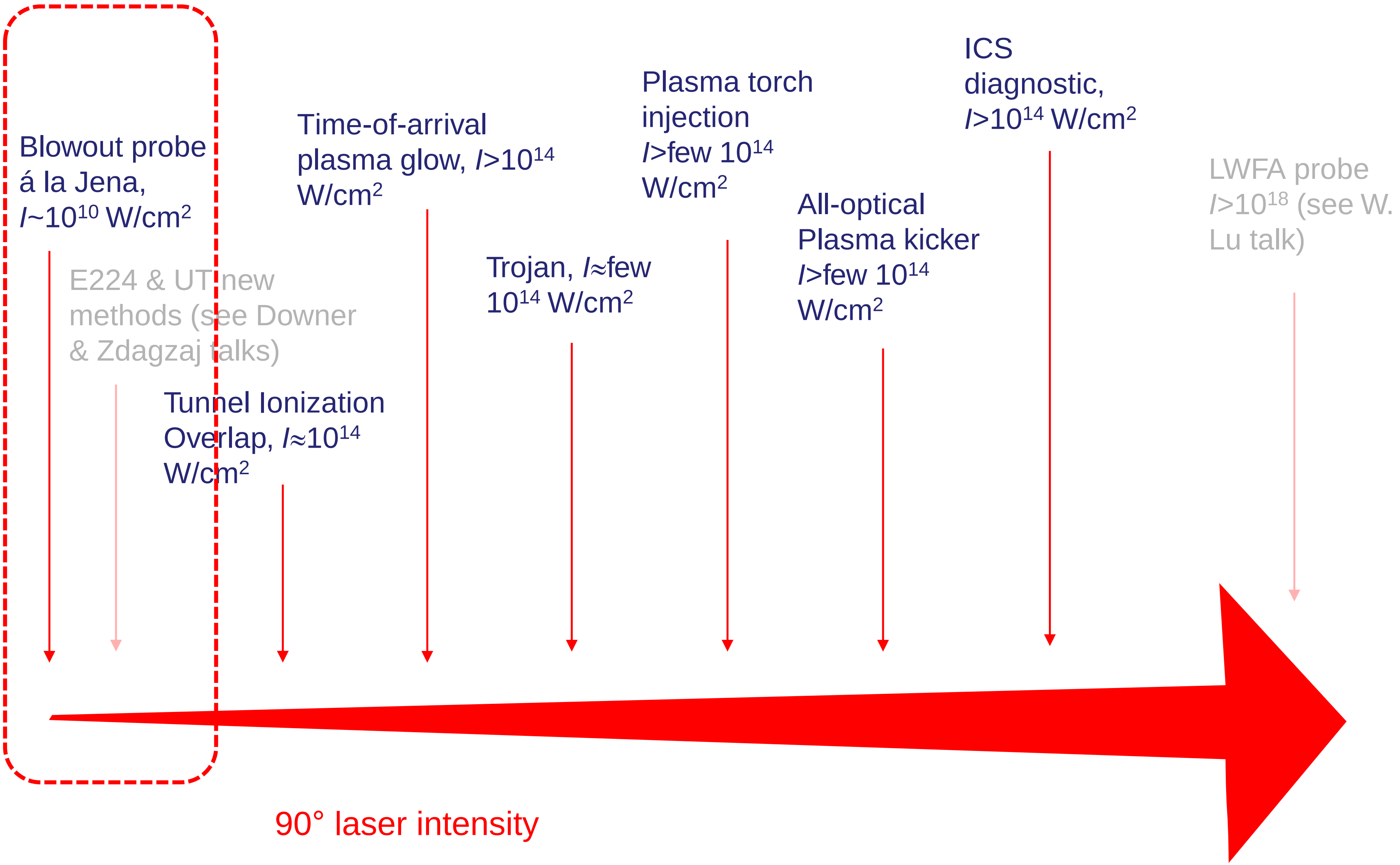
Transient overlap of laser pulse and particle beam leads to higher local ionisation rates and plasma glow

- tune laser intensity, spatial overlap and temporal overlap
- “scan” e-beam electric field with a laser pulse
- Measure size, charge and form factor of e-beam
- various gas media with different ionisation thresholds can be used
- Great tool to find synchronisation between laser and e-beam
- Measure (selective) gas density profiles
- Limits? Shorter laser pulses, shapes, geometries etc..
- Useful to explore atomic and atomic physics? E.g. H2 and other gases dissociation..
- Also possible with e-beam/e-beam, e-beam/e^{+}-beam, laser/laser or various other combinations..
- Terrible acronym..
- ....



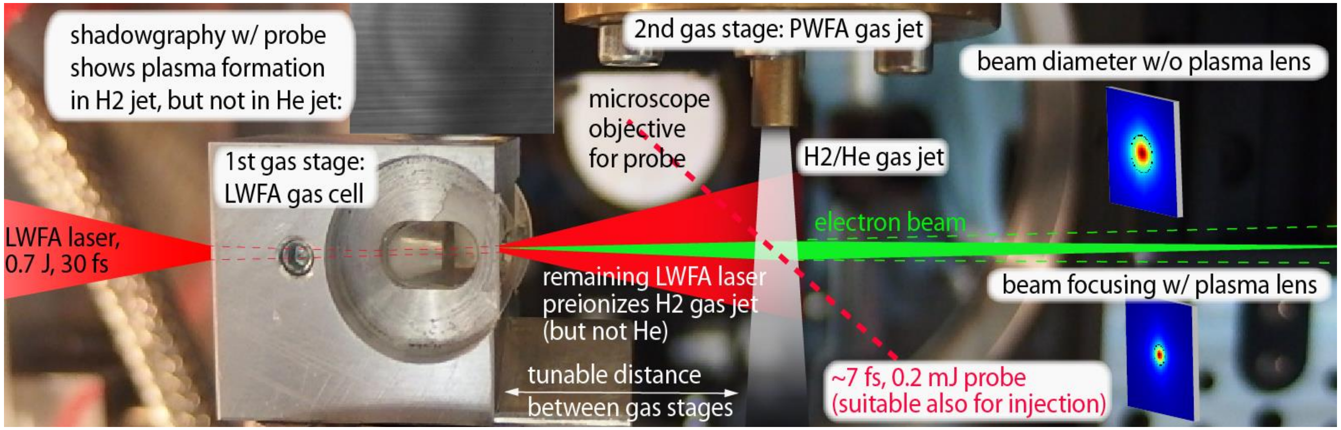
T. Heinemann, A. Knetsch et al.

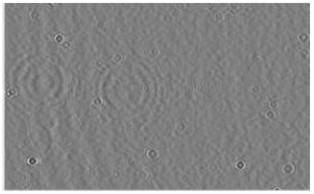
Proposed uses of 90° laser pulse and implications



90° probing of wakefield

- Few-cycle (sub-10 fs) pulses useful for probing wakefield dynamics (in addition to E224), but also useful for TH injection
- Pathway to short pulses hollow fibre compression but limited as regards power (up to 10^{16} W/cm^2). Alternative OPCPA for tens of mJ energies. Both shortens pulse, but adds complexity.
- Need few hundred µJ both for probing (collinear, ~1cm spot size at 10^{10} W/cm^2) as well as for TH (focused, ~10 µm spot size at 10^{14} W/cm^2)
- Experience since a decade with both collinear probing* as well as focused few-cycle pulses for ionization up to LWFA**



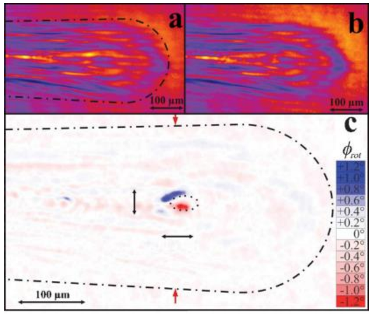


* Jena: S. Kuschel, T. Heinemann, O. Karger, D. Ullmann (now at Strathclyde), A. Knetsch .. B. Hidding et al., PRAB 19, 071301 (2016), Daniel Ullmann, MSC thesis, *Optical Diagnostics for LWFA Experiments*, 2015

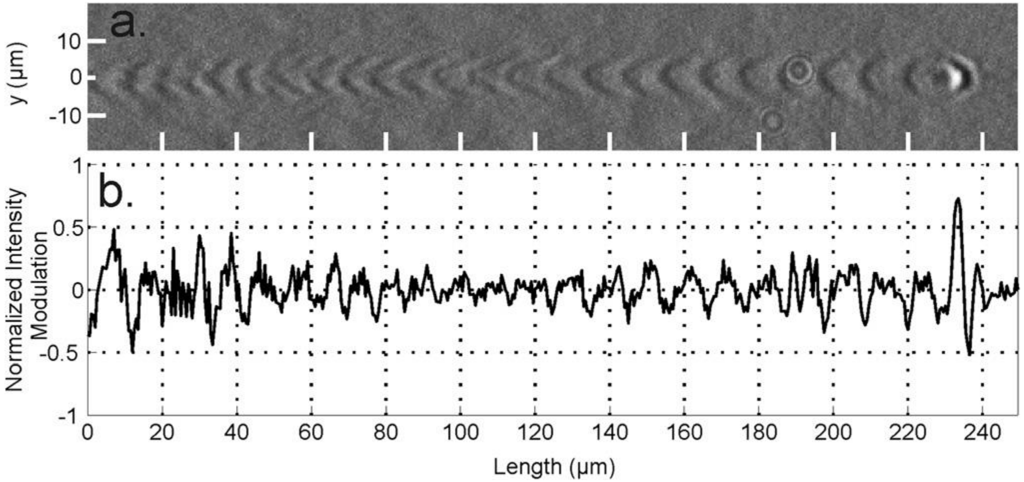
** Düsseldorf: 10^{16} W/cm^2 J. Osterholz .. B. Hidding et al., *Phys. Plasmas* 15, 103301 (2008); F. Brandl, B. Hidding et al., *PRL* 102, 195001 (2009);
Munich 10^{19} W/cm^2 via OPCPA: K. Schmid, F. Tavella (now at SLAC).. B. Hidding et al., *PRL* 102, 124801 (2009), Comptes Rendus Physique 10, 140 (2009)

90° probing of wakefield

- Either hollow-fibre or OPCPA "required" to get to short pulses
- Ideally at longer wavelengths (mid-IR) due to (comparably low densities (contrast trade-off)
- BMBF-funded projects underway at Jena (Kaluza/Paulus) to establish technique in mid-IR, for use e.g. at FLASHForward
- Faraday-rotation, polarimetry also useful



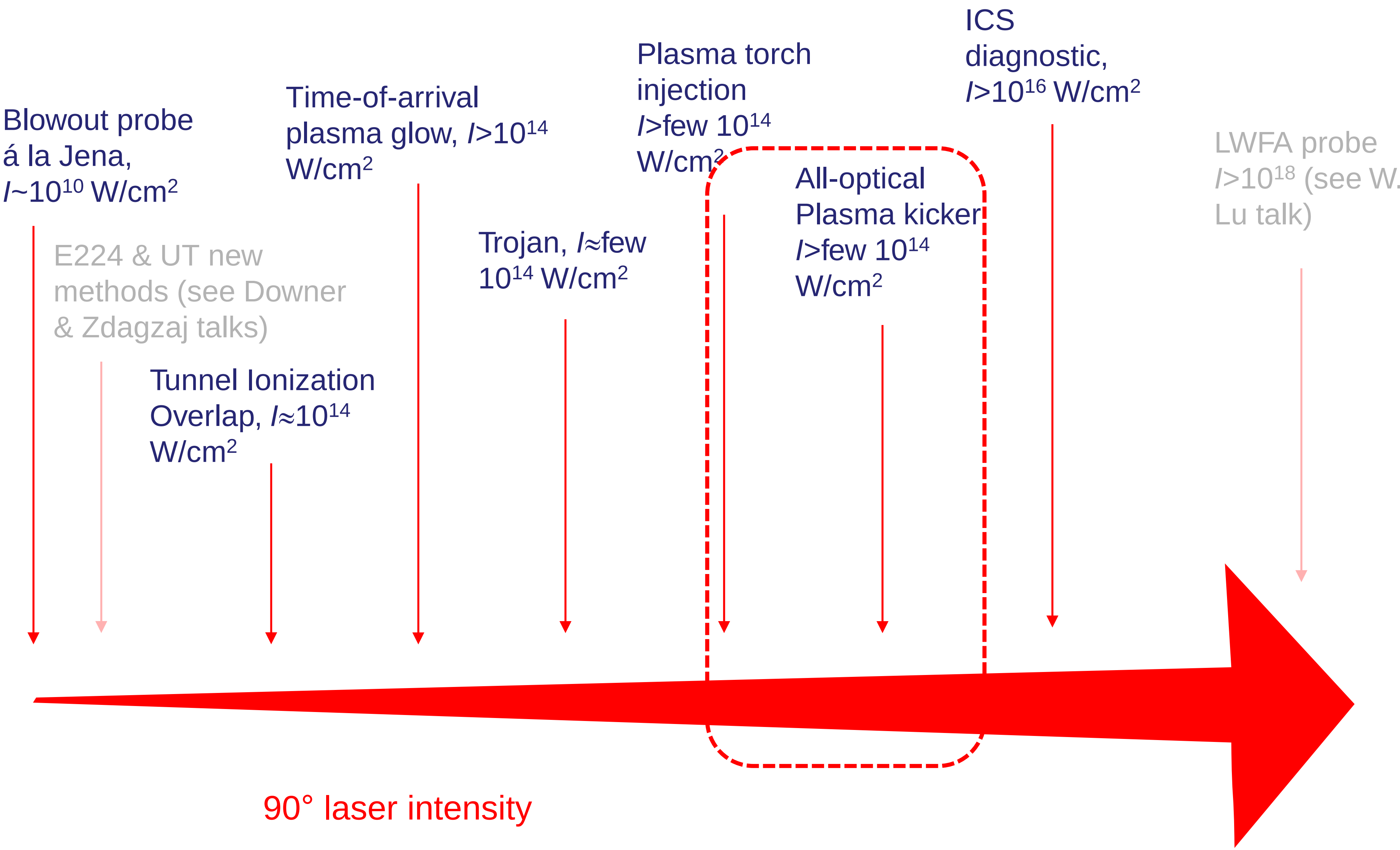
⇒ see talk by Mike on Monday



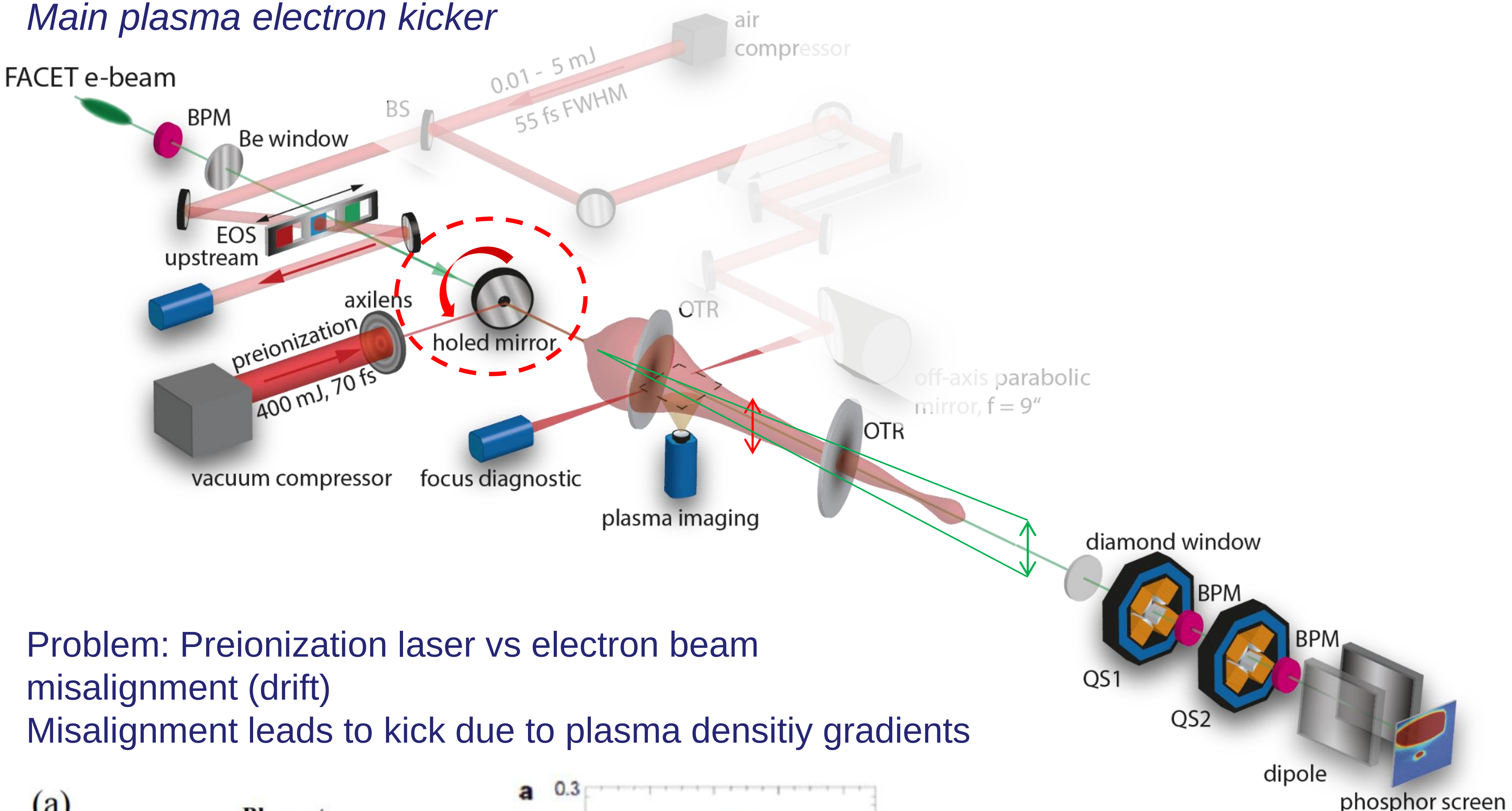
- Establishing these methods as part of "Lab in the Bubble" EPSRC project (D. Jaroszynski et al.) at SCAPA
- Co-funded PhD (Ullmann) with CLF

M. Schwab *et al.,* Appl. Phys. Lett. **103,** 191118 (2013)

Proposed uses of 90° laser pulse and implications

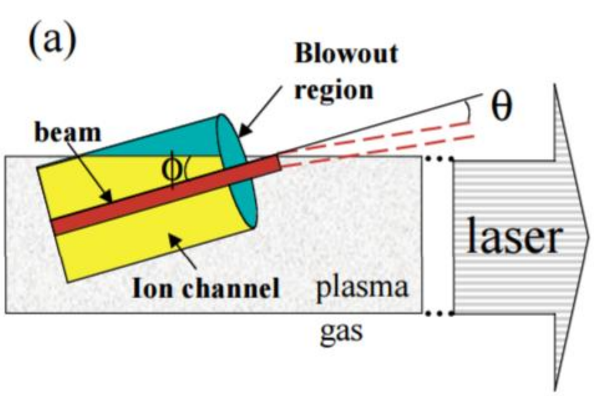


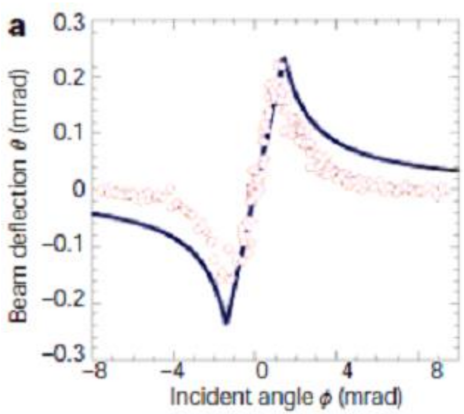
Main plasma electron kicker



Problem: Preionization laser vs electron beam misalignment (drift)

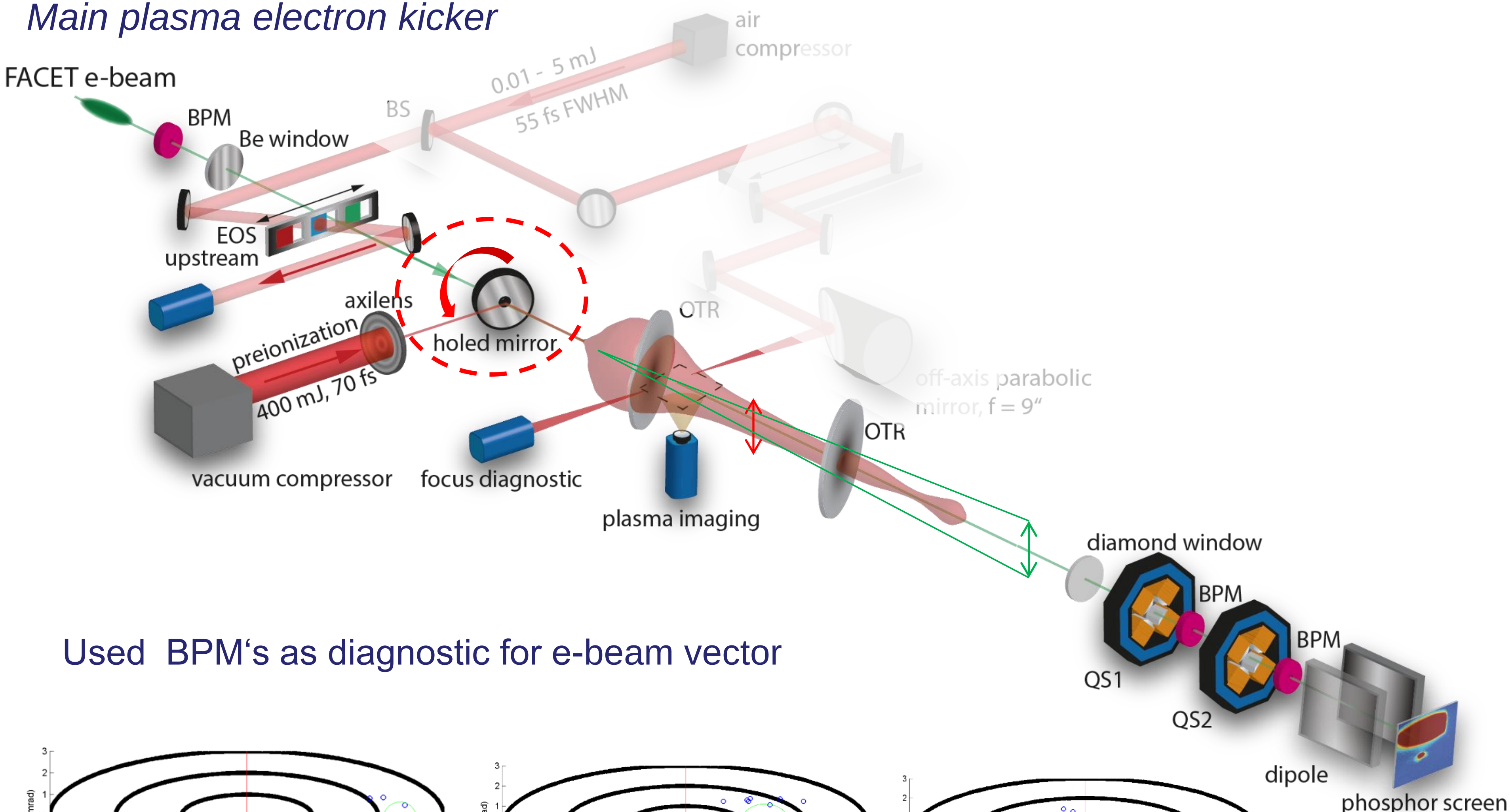
Misalignment leads to kick due to plasma densitiy gradients



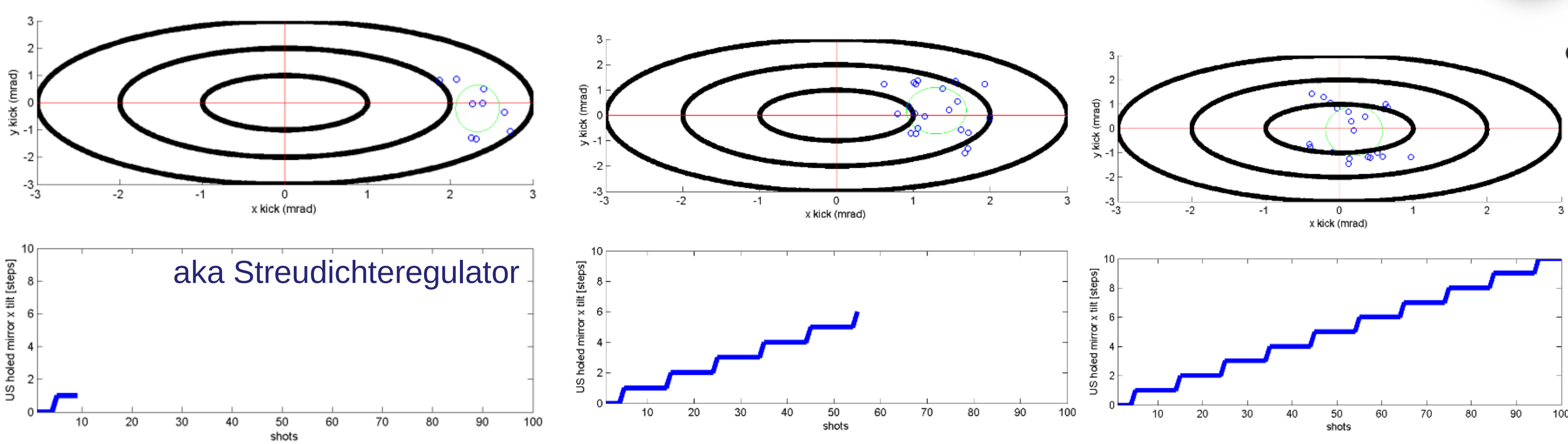


P. Muggli et al., Nature 411, 43 (2001), PRSTAB 4, 091301 (2001)

Main plasma electron kicker



Used BPM's as diagnostic for e-beam vector

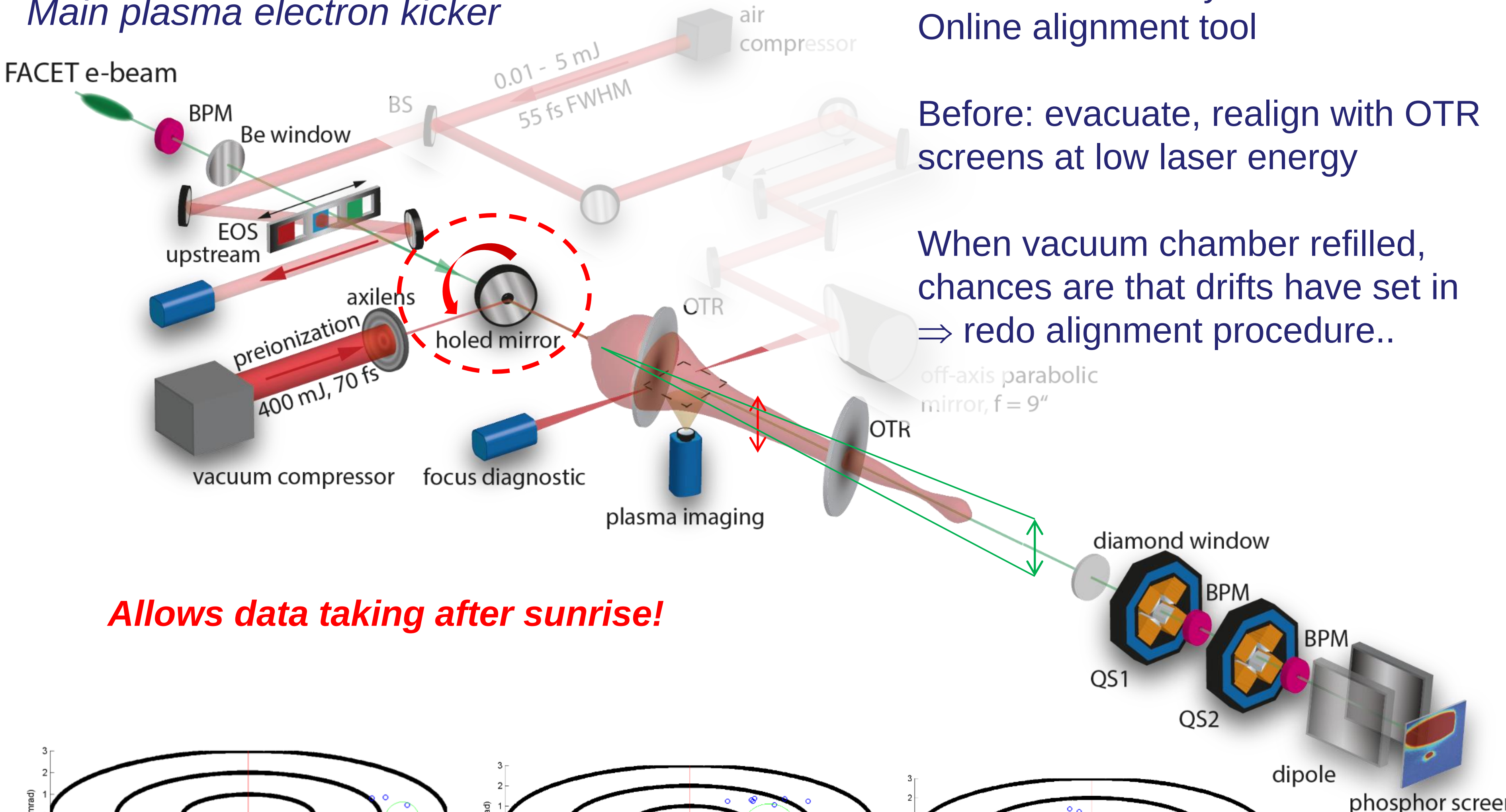


Main plasma electron kicker

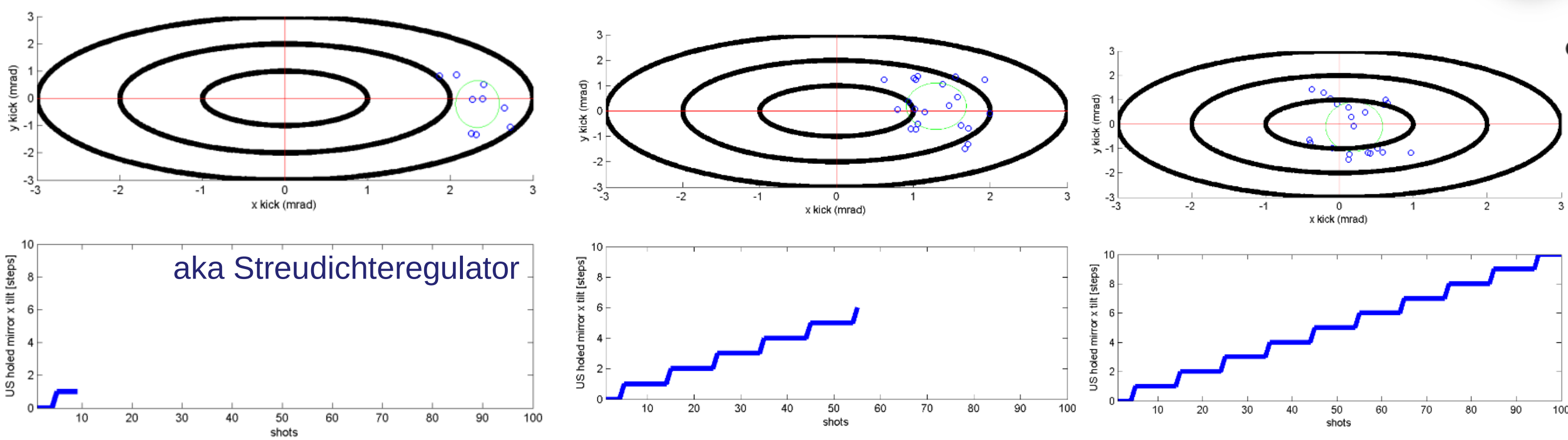
This saved the day:
Online alignment tool

Before: evacuate, realign with OTR screens at low laser energy

When vacuum chamber refilled, chances are that drifts have set in
⇒ redo alignment procedure..



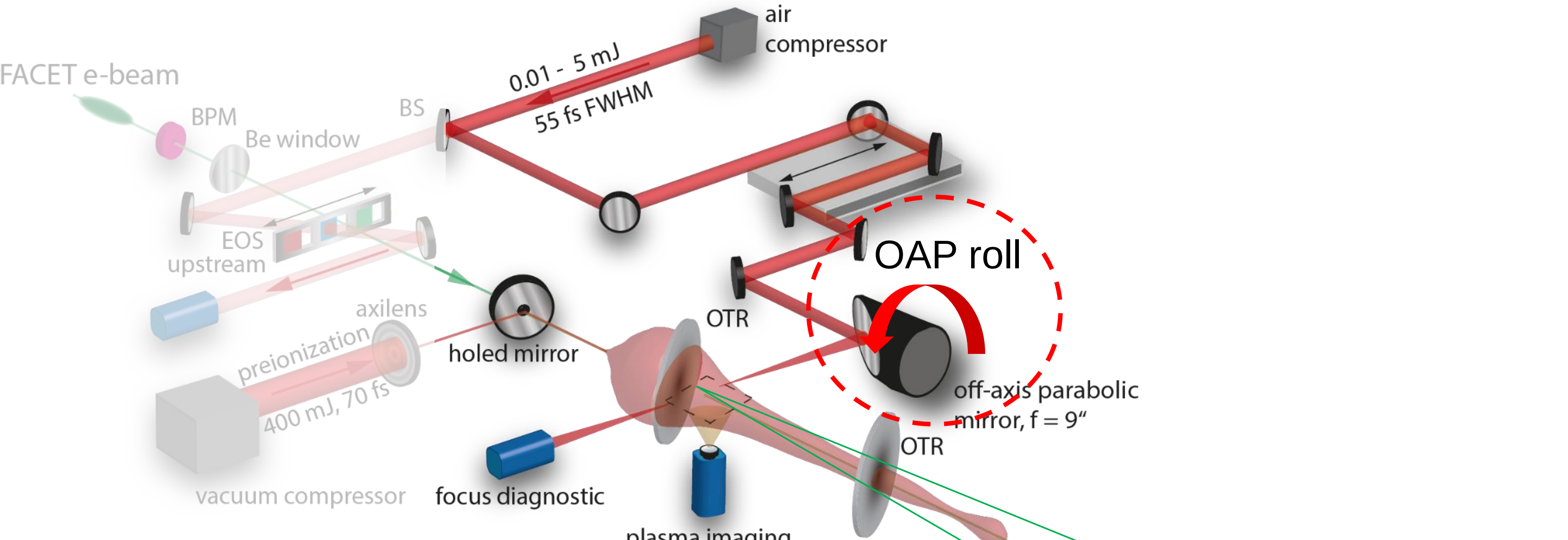
Allows data taking after sunrise!

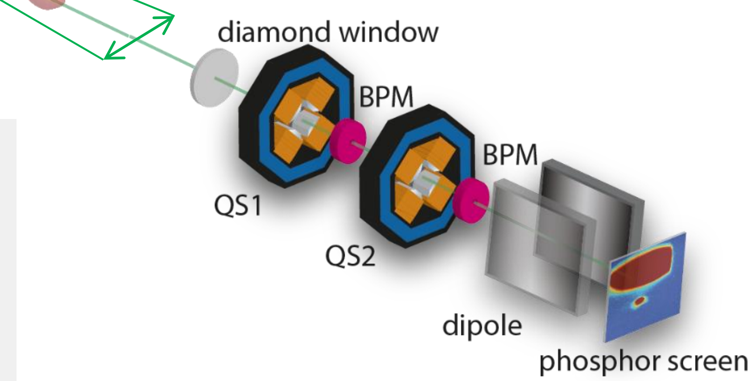


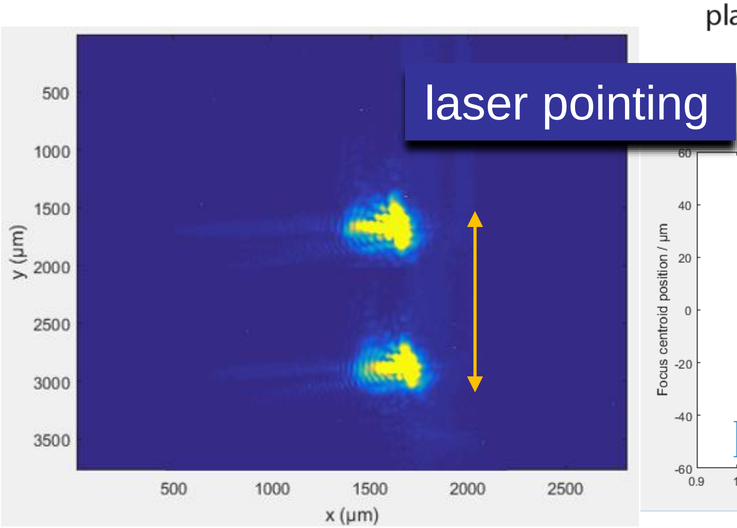
OAP roll scan plasma torch ultrafast plasma kicker

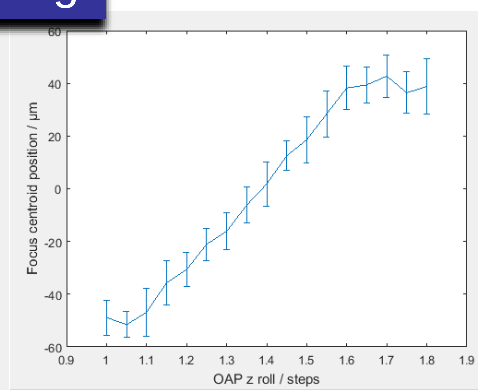
- Generate off-axis plasma torch, bunch(es) see density gradients, are kicked

Theory: G. Wittig et al., NIM A 829 (2016)



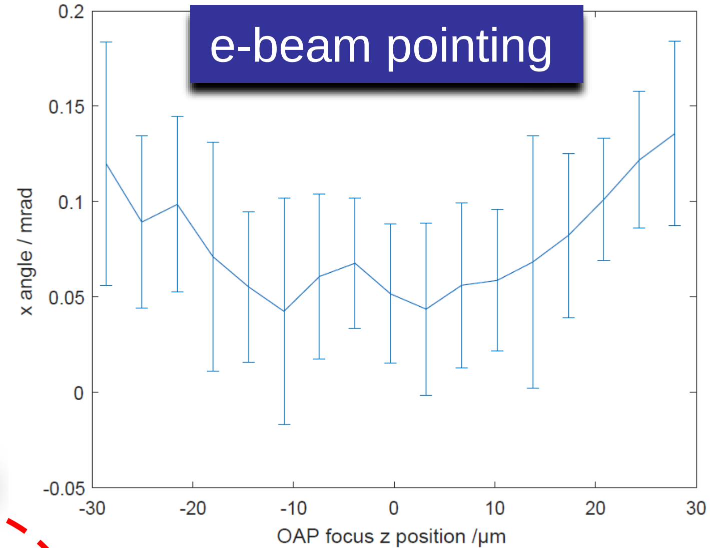


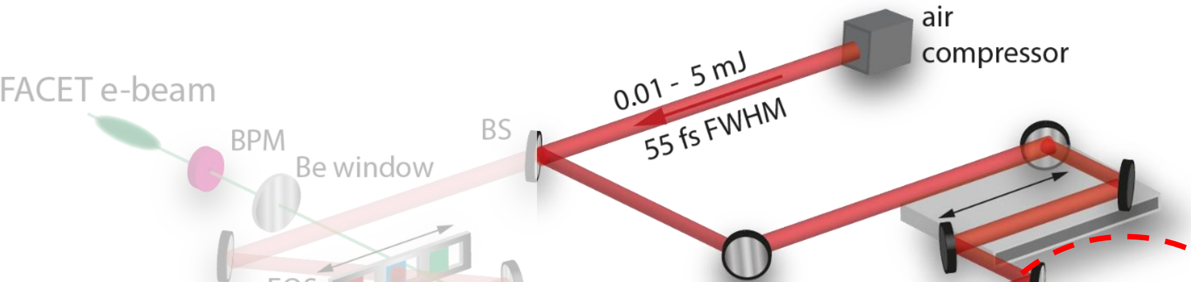


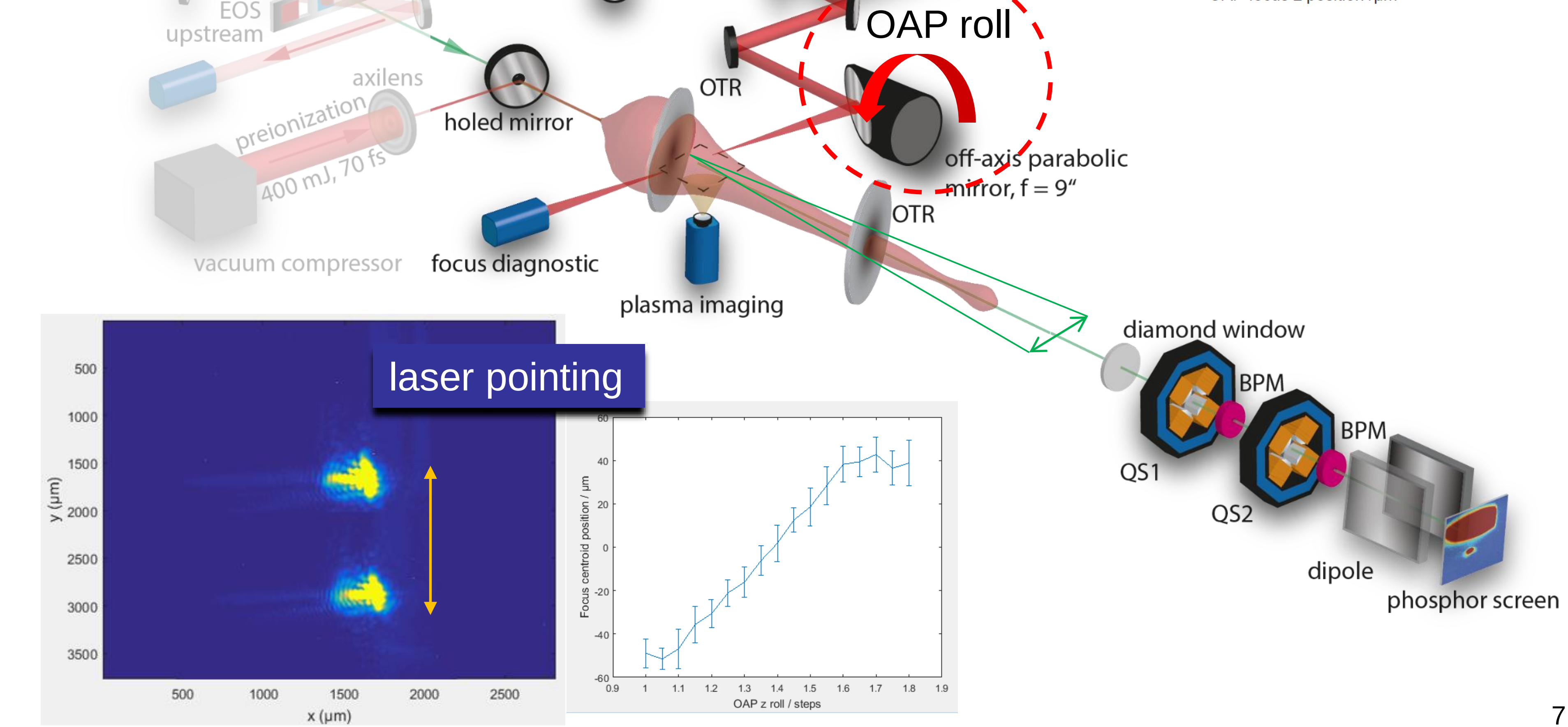


OAP roll scan ultrafast plasma Kicker

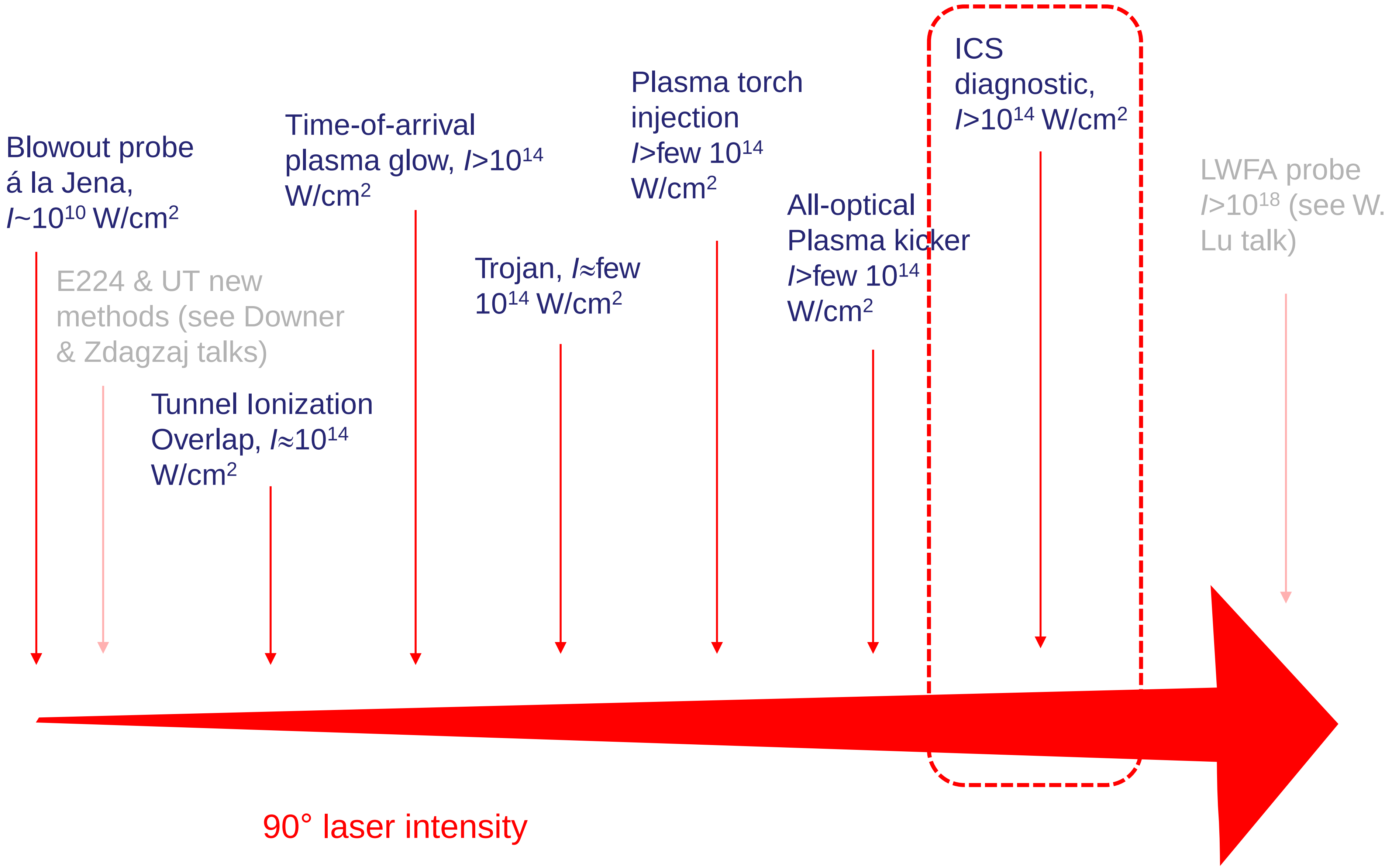
- Generate off-axis plasma torch, bunch(es) see density gradients, are kicked



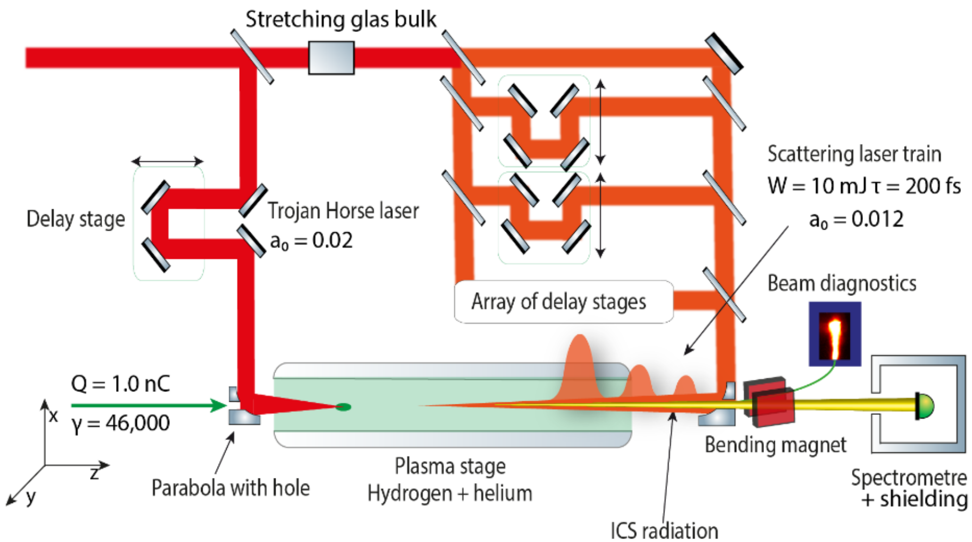




Proposed uses of 90° laser pulse and implications



Useful in 90°, but in head-on configuration potential pathway to ultralow emittance diagnostics



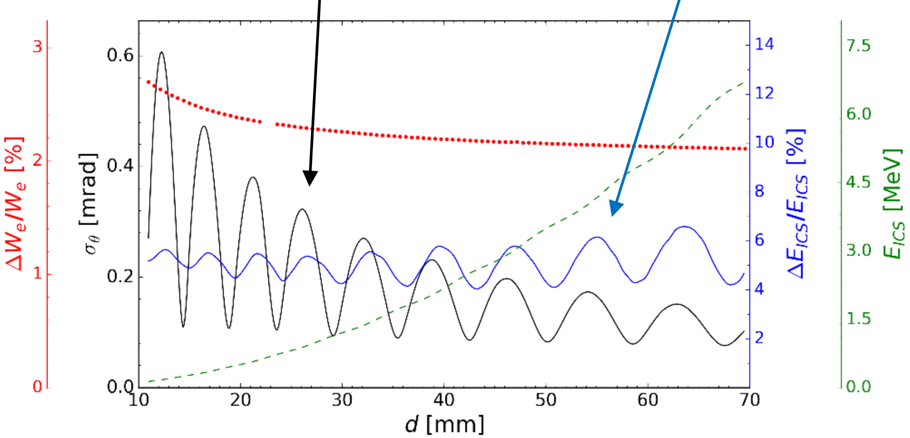
Sample betatron oscillations with multiple ICS events

⇒ β modulates ICS spectrum

⇒ Use β to determine transverse emittance

$$\epsilon_n = \gamma \epsilon_{rms} = \gamma \cdot \frac{\sigma_x^2}{\beta}$$

$$\frac{\Delta\omega_{\mathrm{ICS}}}{\omega_{\mathrm{ICS}}} \approx \frac{\gamma^2 \sigma_{\theta,\mathrm{FWHM}}^2}{4}$$



⇒ Bunchsize σ_x needs to be measured independently (multishot or by using ICS spot size, or FIELD...)

⇒ Can also be fitted to spectral shape! (e.g. Plateau, Geddes, et al., PRL 109, 064802 (2012)

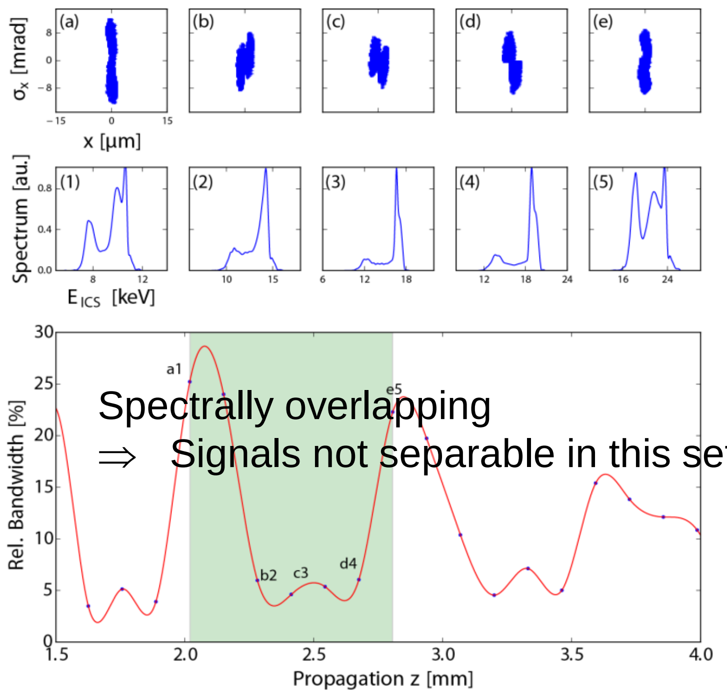
⇒ ICS process is non-invasive

⇒ *in situ* single-shot (?)

emittance measurement during propagation in plasma

P. Scherkl, in preparation

“Normal“ TH bunch



Spectrally overlapping

⇒ Signals not separable in this setup

Bandwidth strongly oscillating

⇒ Nice contrast

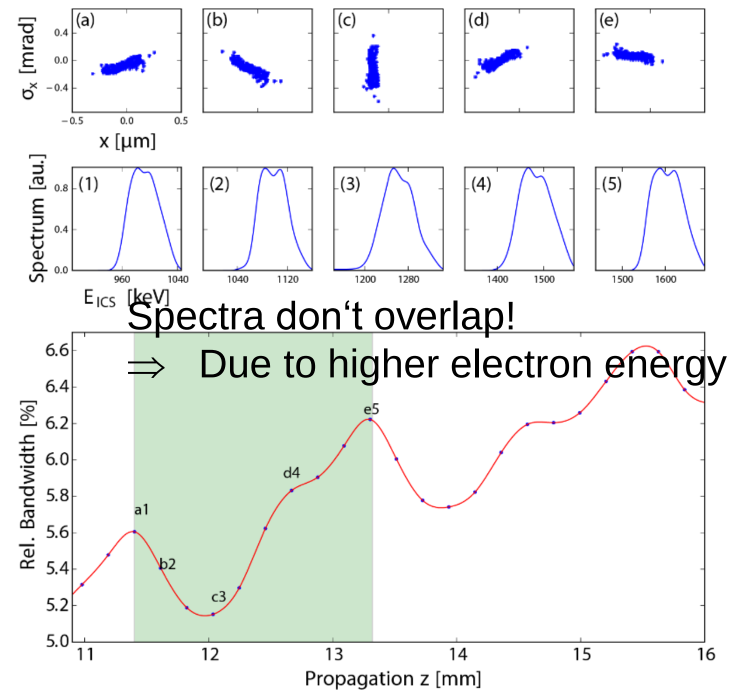
Obtained emittance:

$$\epsilon_n = 7.5 \times 10^{-8} \text{ m rad}$$

Statistical emittance:

$$\epsilon_n = 5.0 \times 10^{-8} \text{ m rad}$$

SSTF TH bunch



Spectra don‘t overlap!

⇒ Due to higher electron energy

Bandwidth weakly oscillating

⇒ Low contrast

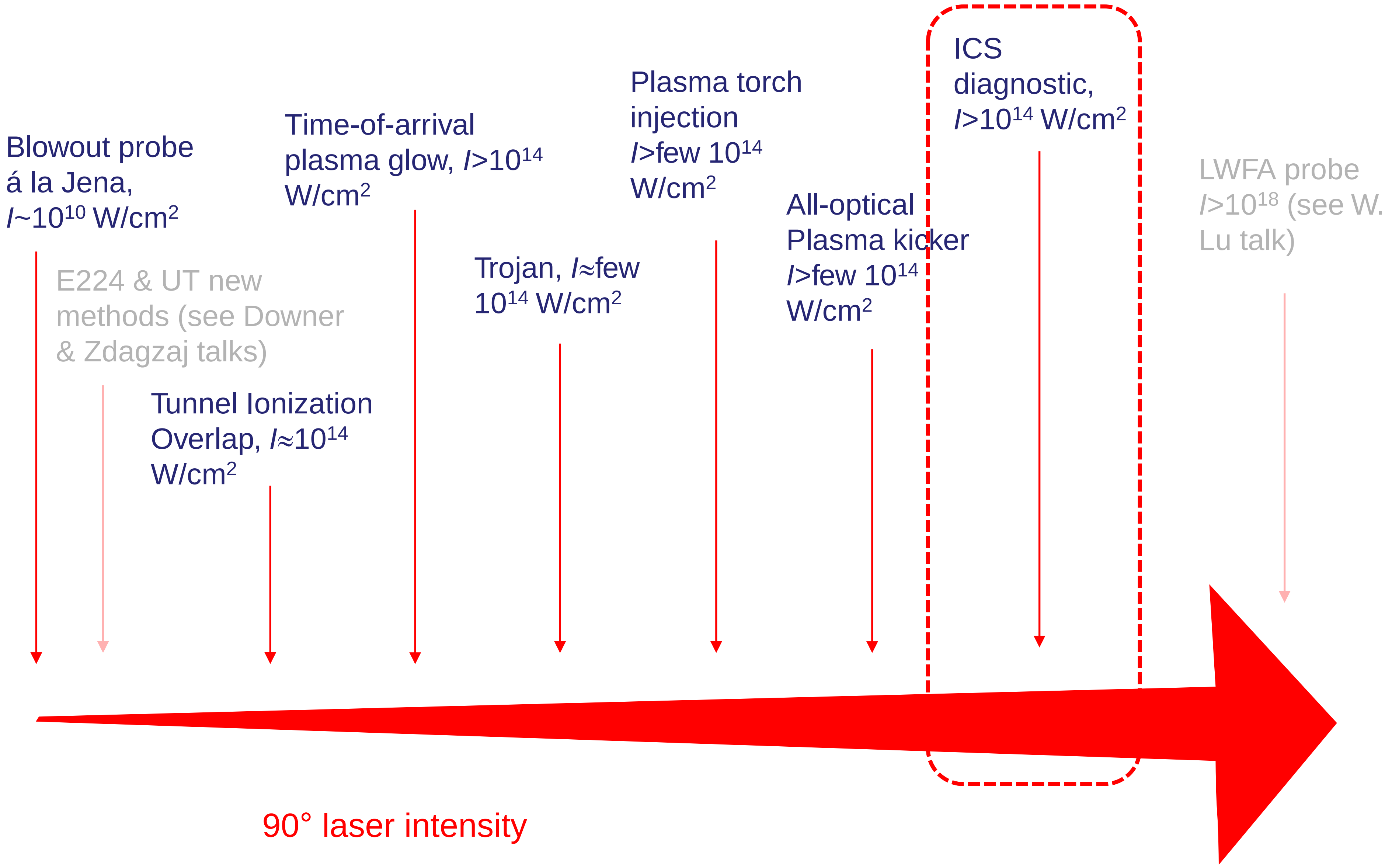
Obtained emittance:

$$\epsilon_n = 8.9 \times 10^{-8} \text{ m rad}$$

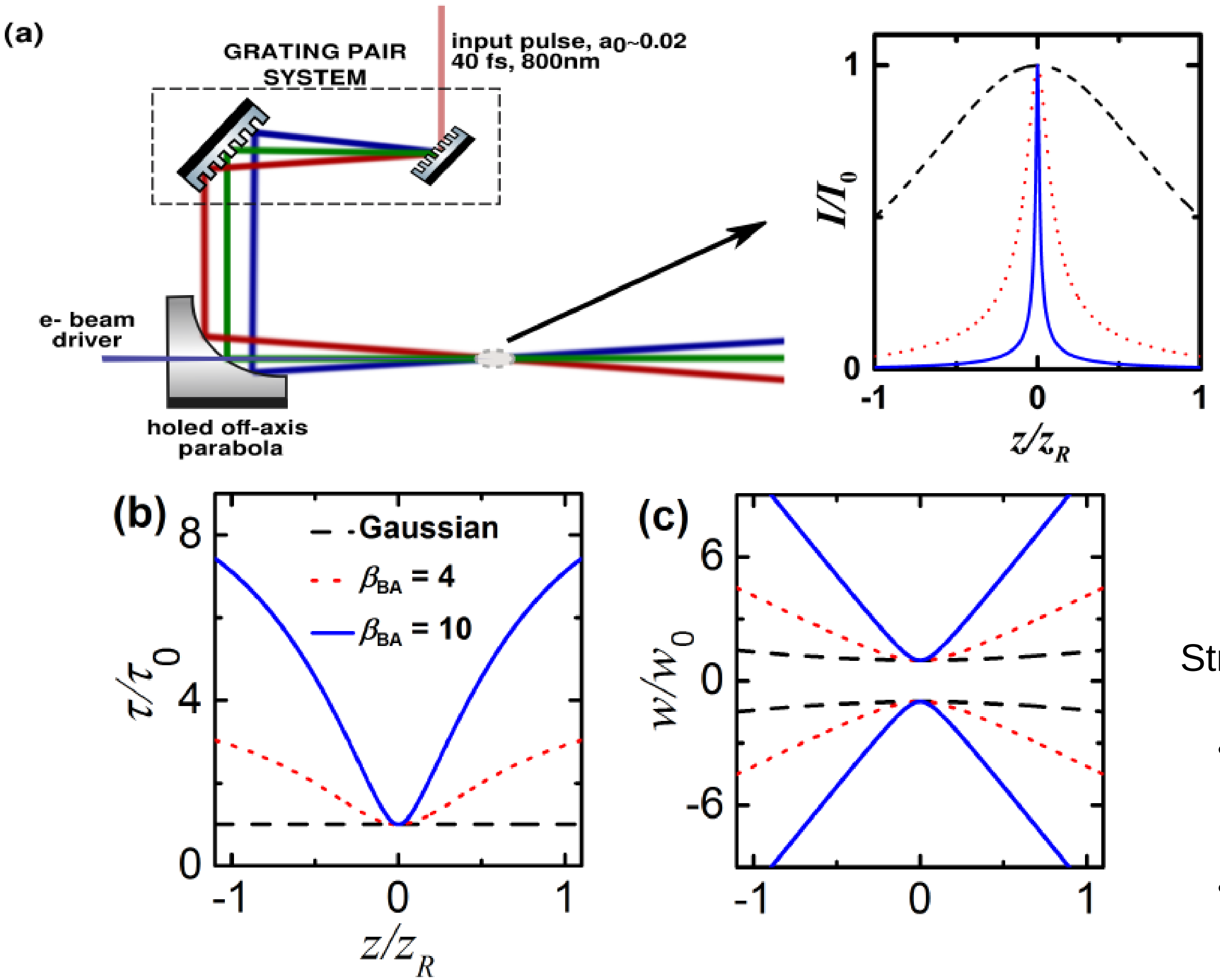
Statistical emittance:

$$\epsilon_n = 1.0 \times 10^{-9} \text{ m rad}$$

Proposed uses of 90° laser pulse and implications



SSTF (Simultaneous Space Time Focusing)

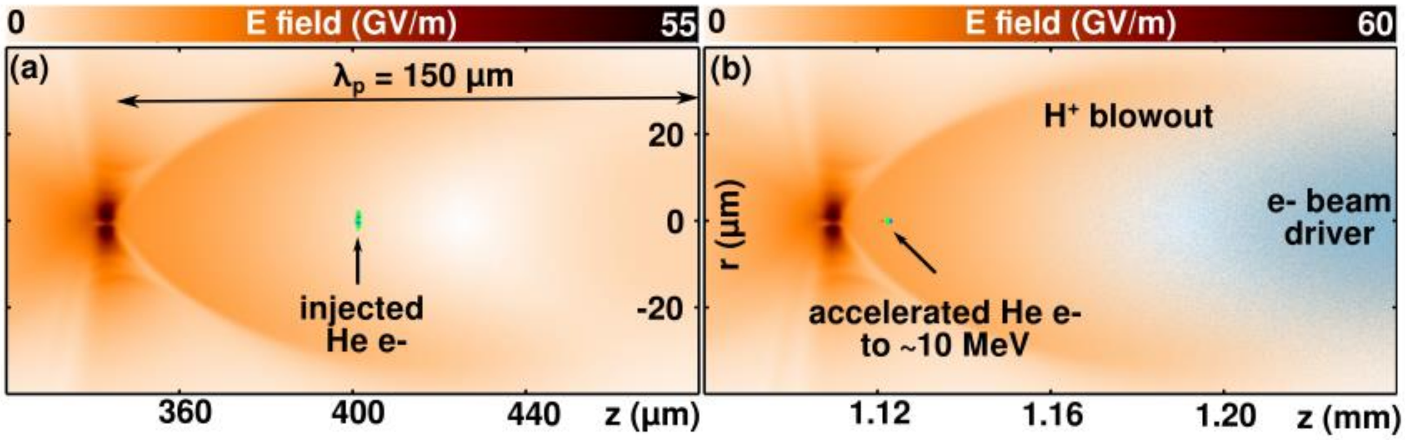


$$I(z)=\frac{I_0}{\sqrt{\left(1+\beta_{BA}^4\frac{z^2}{z_R^2}\right)\left(1+\frac{z^2}{z_R^2}\right)}}$$

Structure of SSTF beams:

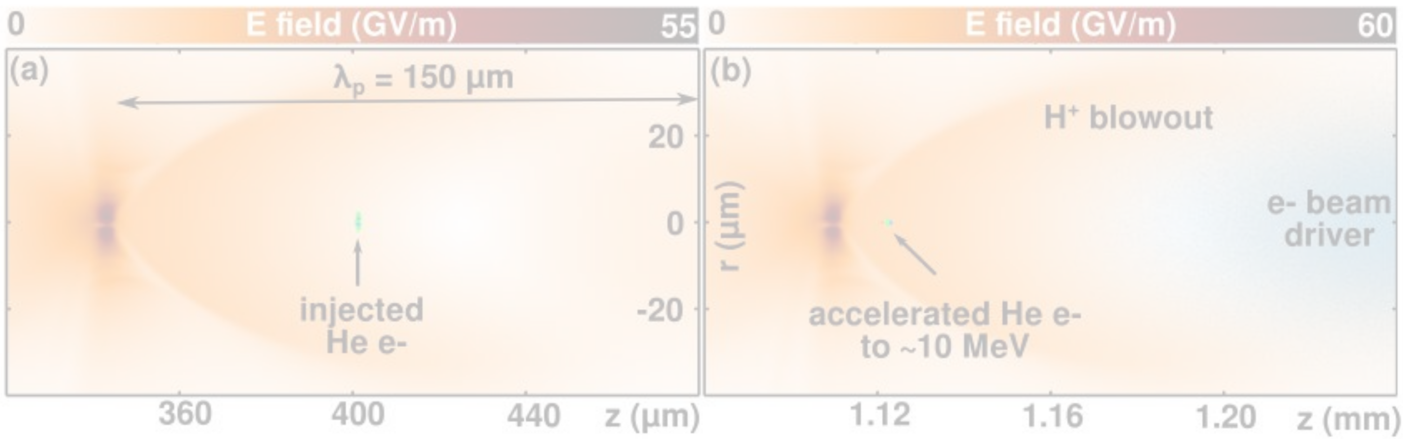
- Frequencies are spatially separated (spatial chirp)
- The amount of spatial chirp rate (β) is related to a dimensionless parameter called beam aspect ratio (β_{BA})
- Temporal overlap only occurs at the focal region

SSTF (Simultaneous Space Time Focusing)



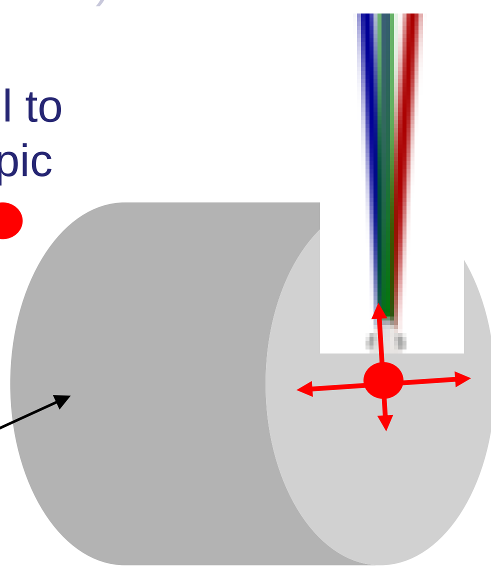
- Can be used (e.g. In longitudinal direction) for TH to generate extremely short (as-level) and low emittance witness beams (Rayleigh length small, electrons are released very confined, no betatron phase mixing) albeit low charge beams (presented this for Iliad FACET proposal in Sep 2014)

SSTF (Simultaneous Space Time Focusing)



- Can be used for TH to generate extremely short (as-level) and low emittance witness beams (Rayleigh length small, electrons are released very confined, no betatron phase mixing) albeit low charge beams (presented this for Iliad FACET proposal in Sep 2014)

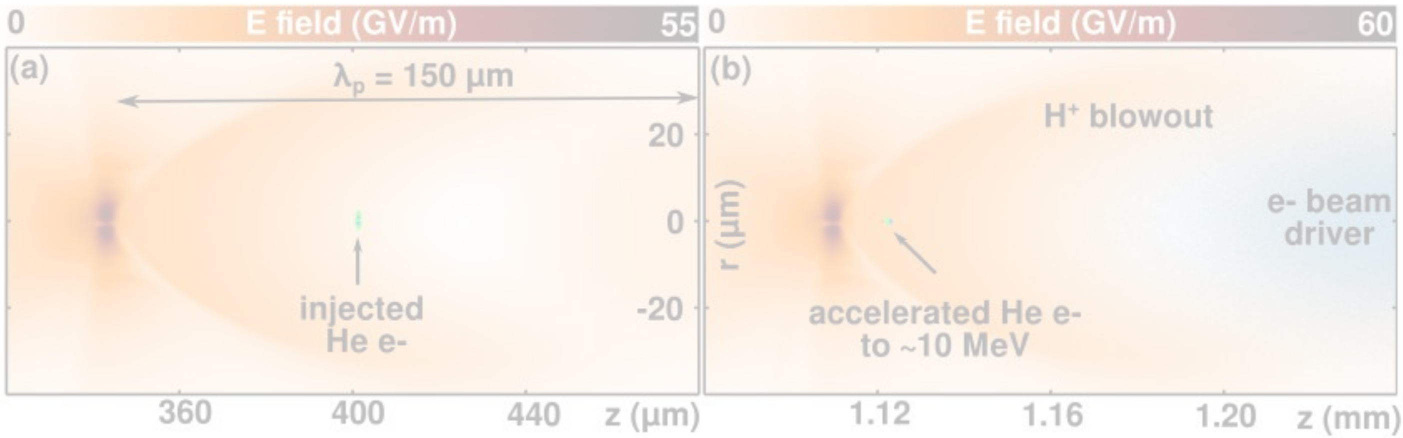
- But are also useful to produce microscopic intensity spike(s)



electron beam (e.g. 10 microns diameter)

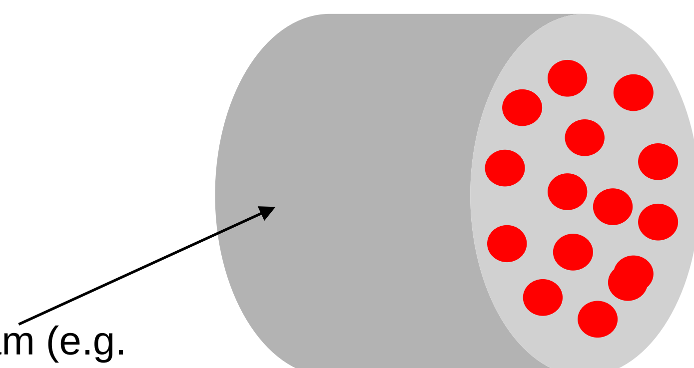
Explore for plasma glow FIELD method:
Scan electron beam and observe plasma glow, produce electron beam tomography data

SSTF (Simultaneous Space Time Focusing)

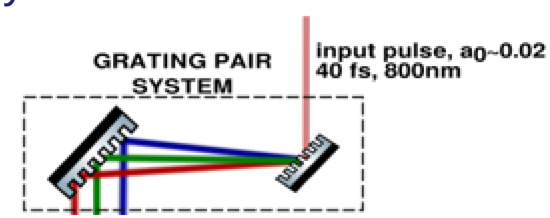


- Can be used for TH to generate extremely short (as-level) and low emittance witness beams (Rayleigh length small, electrons are released very confined, no betatron phase mixing) albeit low charge beams (presented this for Iliad FACET proposal in Sep 2014)

- Or maybe even produce microscopic intensity spike array:



electron beam (e.g.
10 microns diameter)



Everything in one shot (beam heating and plasma glow to be avoided)

Need a lot of laser pulses!

Blowout probe á la Jena, I~10^{10} W/cm^2

E224 & UT new methods (see Downer & Zdagzaj talks)

EOS (see talk M. Litos)

Tunnel Ionization Overlap, $I \approx 10^{14}$ W/cm^2

Time-of-arrival plasma glow, $I > 10^{14}$ W/cm^2

Trojan, $I \approx$ few 10^{14} W/cm^2

Plasma torch injection I>few 10^{14} W/cm^2

All-optical Plasma kicker I>few 10^{14} W/cm^2

ICS diagnostic, $I > 10^{14}$ W/cm^2

LWFA probe $I > 10^{18}$ (see W. Lu talk)

90° laser intensity

D. Ullmann cand. PhD (ex Jena, now Strathclyde, co-funded by CLF)

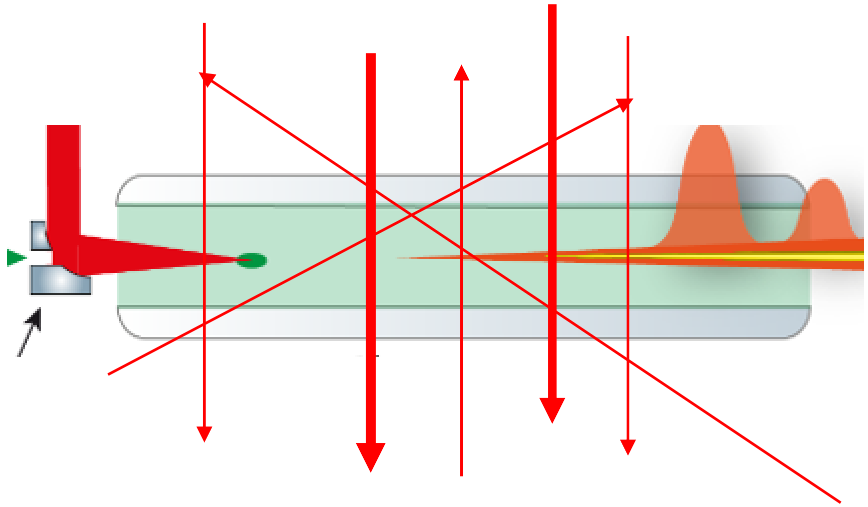
T. Heinemann cand. Phd, (co-)funded by DESY

A. Sutherland cand. Phd, (co-)funded by SLAC

P. Scherkl cand. Phd,

Important impact on FACET-II development and setup

- **Need optical access** with laser focus intensities up to 10^{16} W/cm^2 or more
- E210 TH, EOS, E224 lasers were going through window (B-integral)
- Problem gets more and more complex as required laser intensities increase
- Focusing optics may need to be inside the vacuum/gas chamber



- Need more laser pulses (e.g. sub-10 fs)
- Need as good as possible beam profiles e.g. for FIELD

⇒ **Need additional laser systems!**

Summary

- Want to pursue ultralow emittance, HEP, 6D-brightness, 5^{th} gen. light source
- Lessons learned at E210 FACET are invaluable
- Need to massage the plasma with laser beams
- Laser beams also highly useful for diagnostics: timing&synchronization, spatio-temporal alignment of beams, hybrid electron-laser-plasma diagnostics..
- Many of these diagnostics have dual (actually, multi-) use: crucial for Trojan, but also useful already for commissioning e.g. electron beam in first three months
- Can get work done on the ground at SLAC already with Ti:Sapphire (no need to wait until 2019)
- Need a lot of laser pulses with different parameters: Need additional laser system(s)! Prioritization will have to be done..
- The “access challenge“ (12hrs per 2 weeks): robustness and simplicity trumps! Still may need double or triple redundancy for some systems
- Need improved vibrational/thermal stability
- Need to have optical access from various angles to plasma source!