FACET-II Science Workshop
30 October 2019

E-324:
Optical visualization of beam-driven plasma wakefield accelerators

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University of Texas at Austin

+ SLAC staff: M. Hogan, V. Yakimenko & others
+ FACET-II collaborators: M. Litos (UC-Boulder) & students, K. Marsh (UCLA) & others
+ computational collaborators: T. Silva, J. Vieira (IST); K. Lotov & students (Budker Inst.)

E-324 Scientific Goal: Observe, analyze, understand on-axis PWFA structures* that were invisible to us in E-224 (FACET-I)

* (1) ion-density peak, hollow channel ($\Delta t \sim$ 10-20 ps); (2) blowout-regime electron-wake ($\Delta t \sim 0^+$)

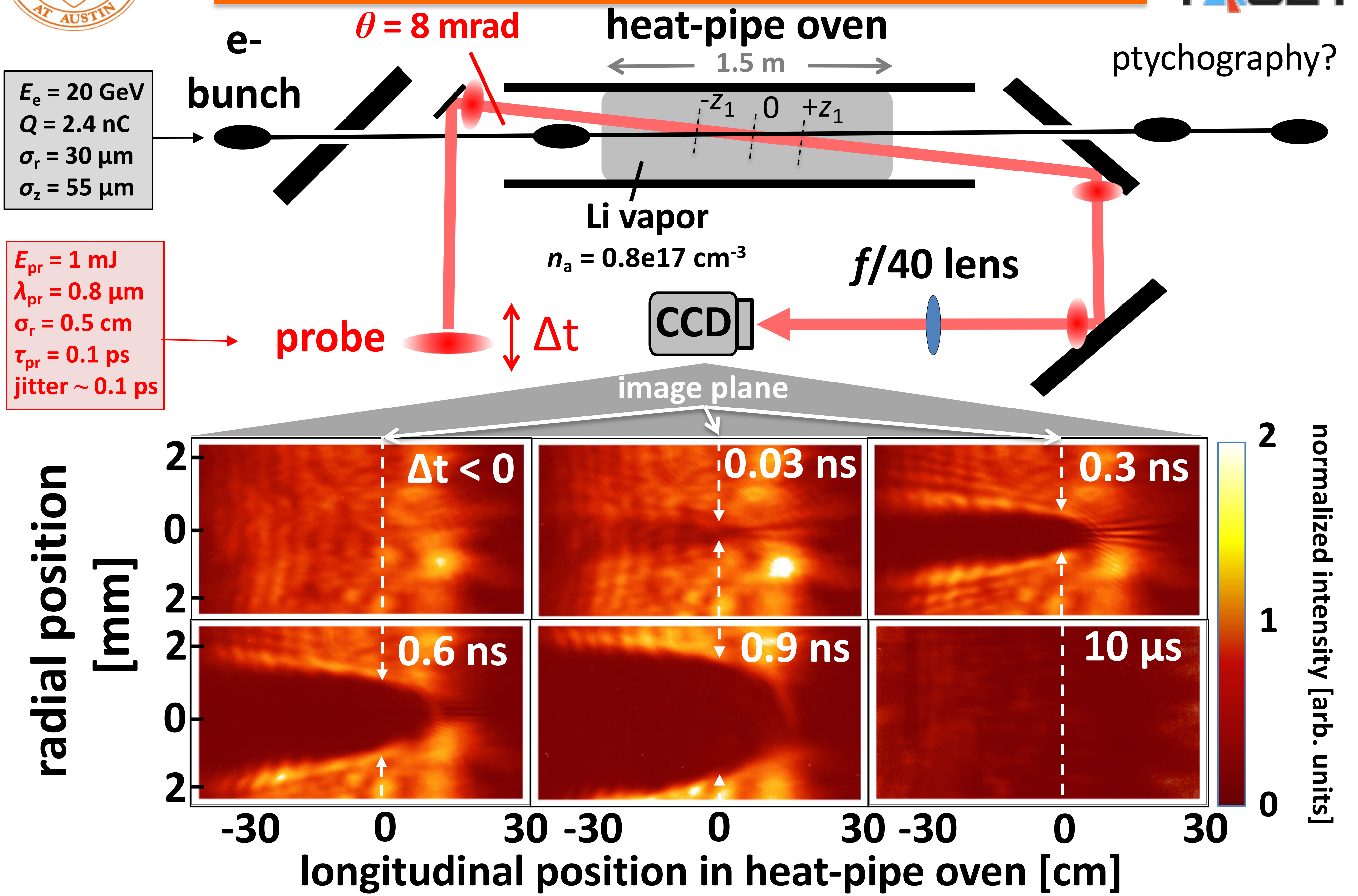
I. Summary of E-224 Results from FACET-I

R. Zgadzaj *et al.*, "Dissipation of electron-beam-driven plasma wakes," submitted for publication.

II. E-324 FACET-II experimental plans

(1) lower n_e; (2) shorter interaction region; (3) larger probe angle; (4) better optical resolution

In FACET-I, we imaged near-field diffraction patterns of an ion wake in a single shot

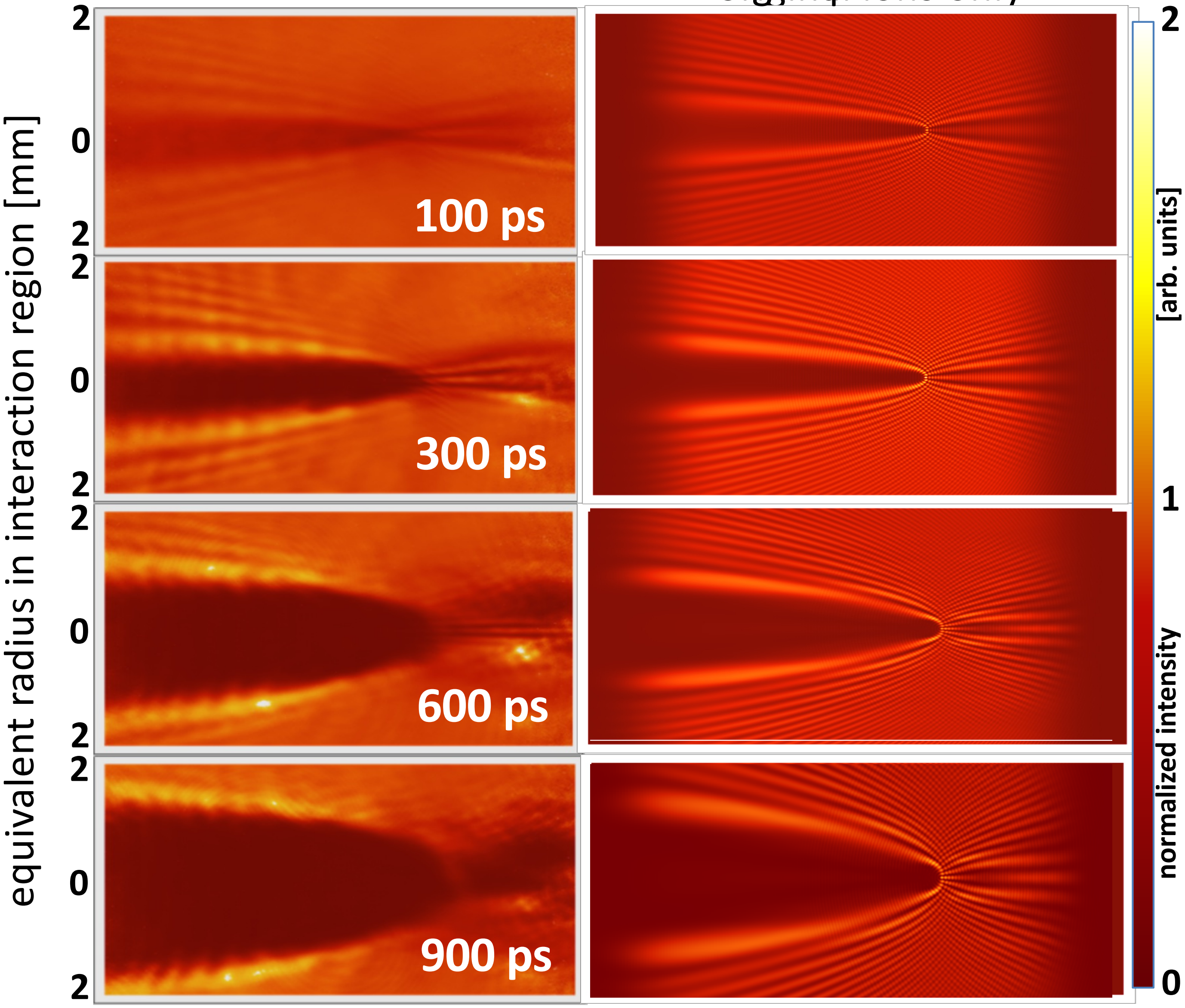


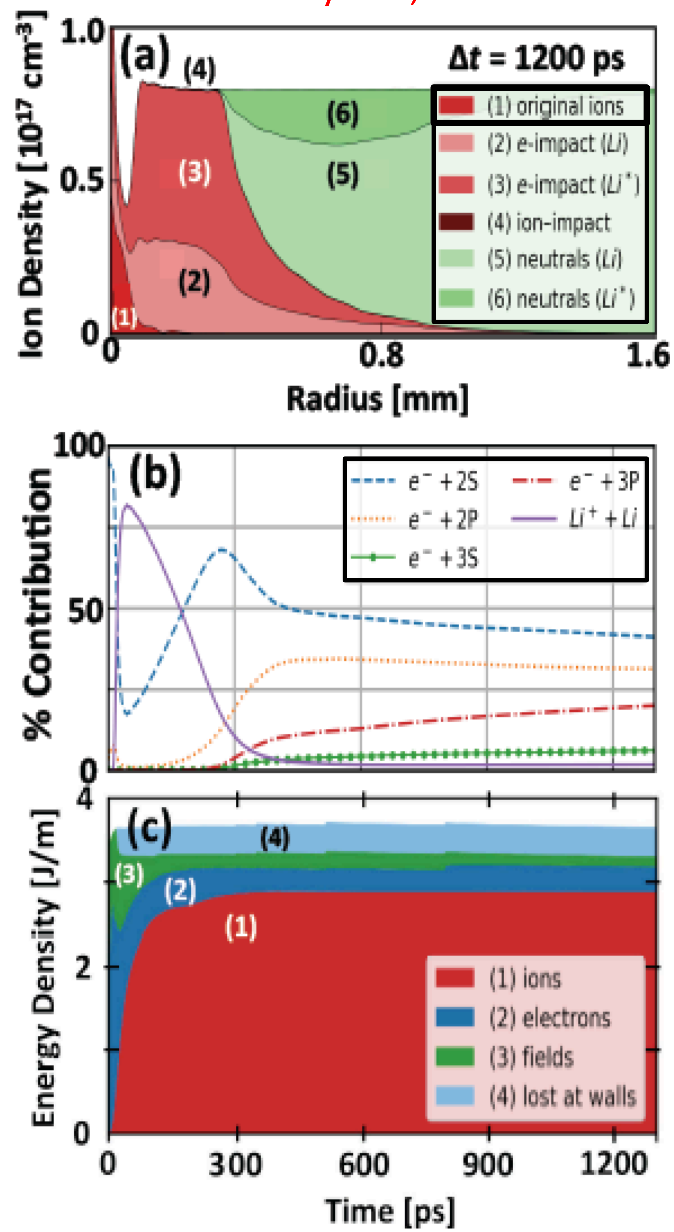
LCODE-simulated $n_e(r)$ profiles reconstruct observed fringe patterns at $\Delta t \geq 0.1$ ns

calculations by K. V. Lotov, V. K. Khudyakov, A. Sosedkin

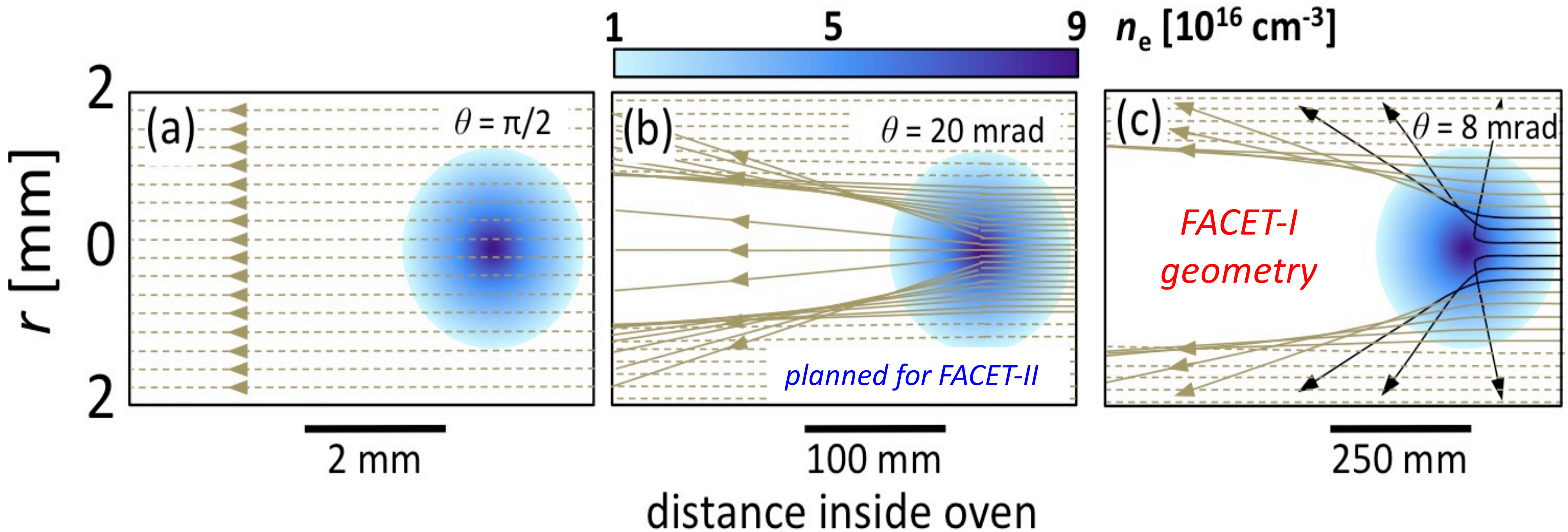
MEASURED | **CALCULATED**

including impact ionization / original ions only





Our FACET-II scientific goal: observe, analyze & understand *on-axis* PWFA structures*



* 1) At Δt ~ 10-20 ps: on-axis ion density peak, quasi-hollow channel favorable for focused positron accleration

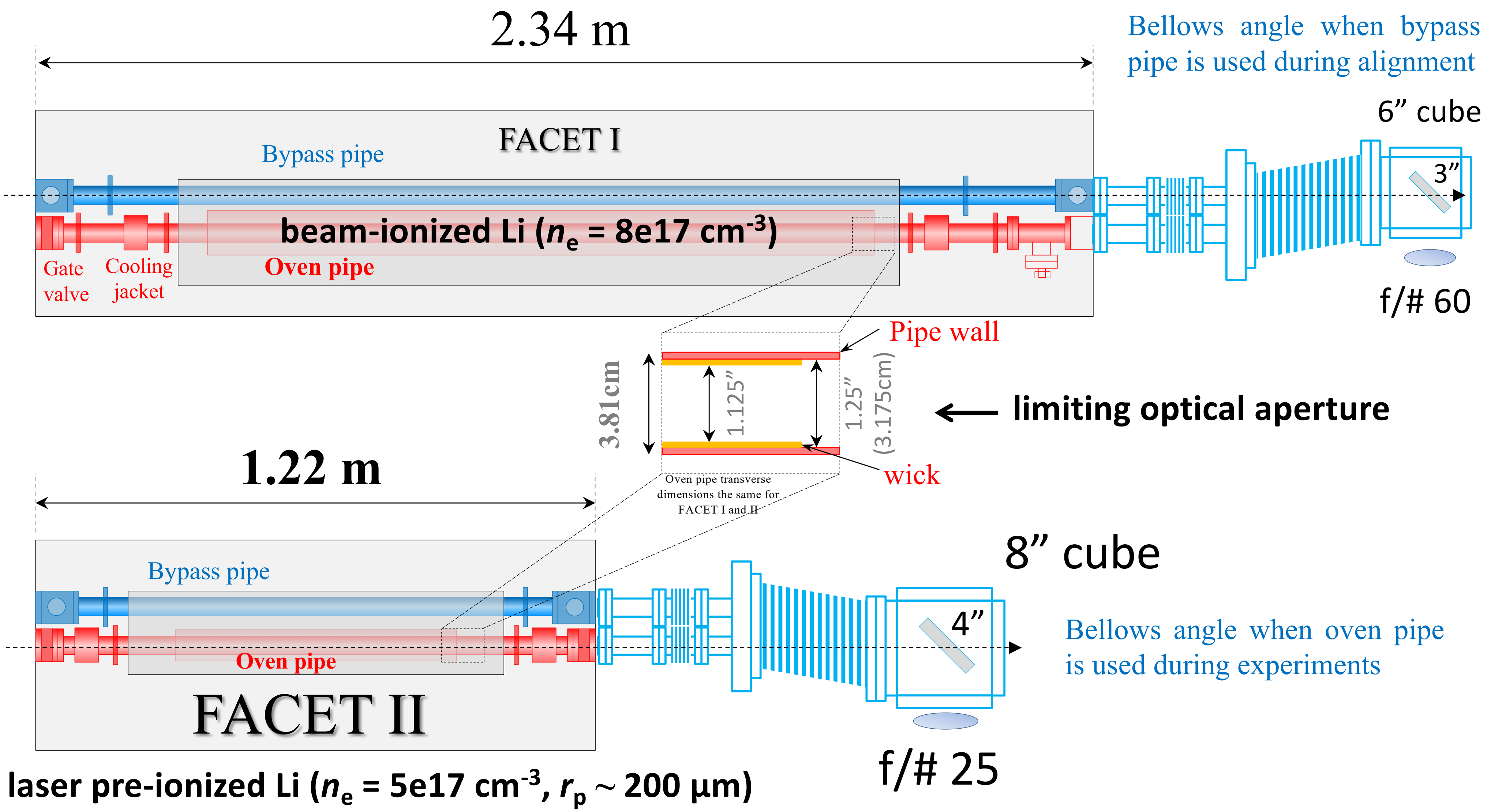
- A. A. Sahai, *Phys. Rev. Accel. Beams* **20**, 081004 (2017)
- T. Silva, J. Vieira *et al.*, forthcoming presentation at this workshop.

* 2) At Δt < 1 ps: strongly nonlinear electron wake

a) pre-ionized vs. self-ionized plasma b) e^- vs. e^+ driven wakes

c) transverse wake instabilities: dependence on drive bunch shape, pre-formed plasma

FACET-II's shorter Li oven & lower n_e enable steeper θ_{probe}, optical access to interior plasma structures

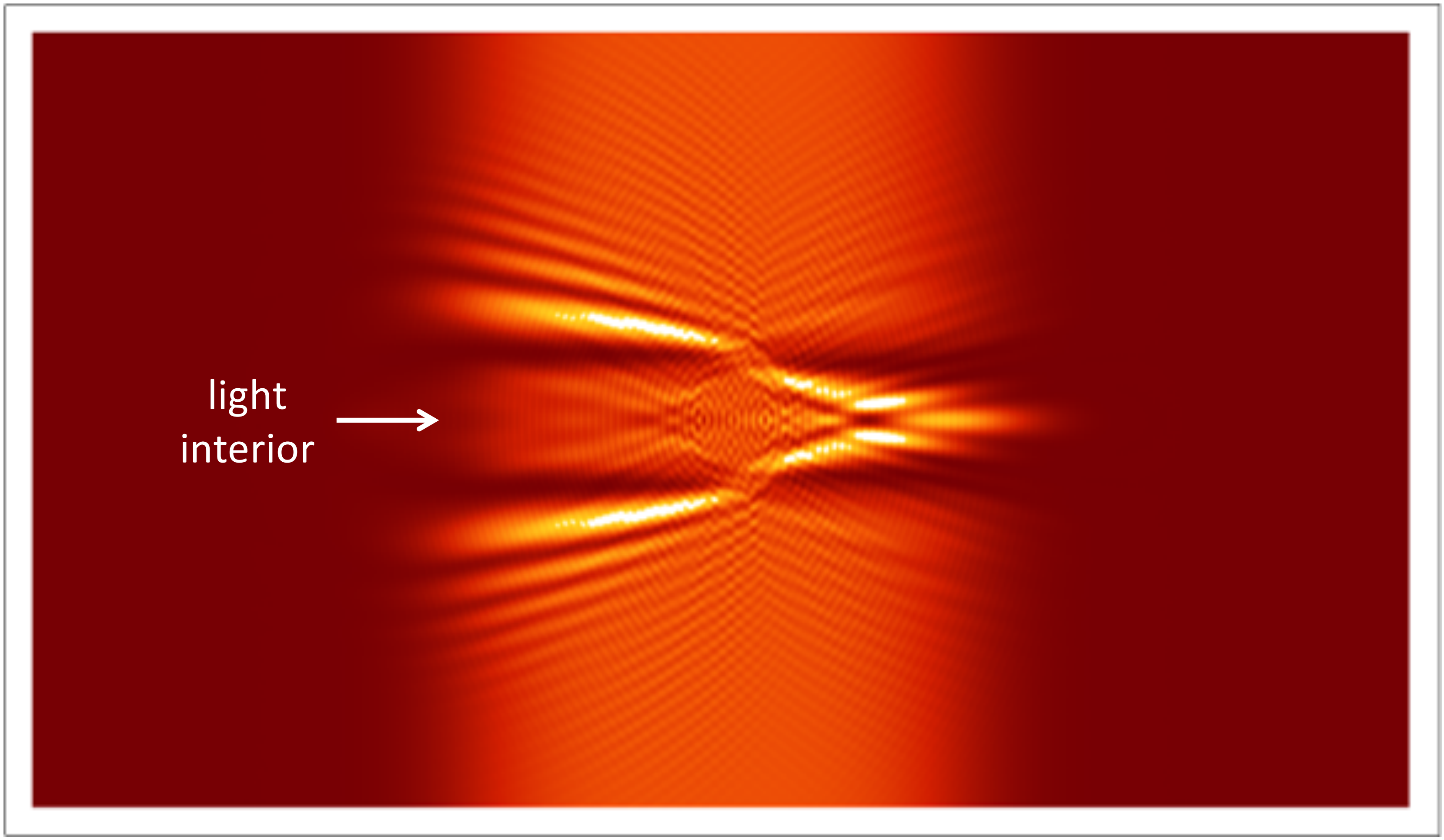


Enlarged output cube (6" → 8") & output mirror (3" → 4" diam.) improve probe collection efficiency. Lower $f^{\#}$ lens (60 → 25) improves imaging resolution.

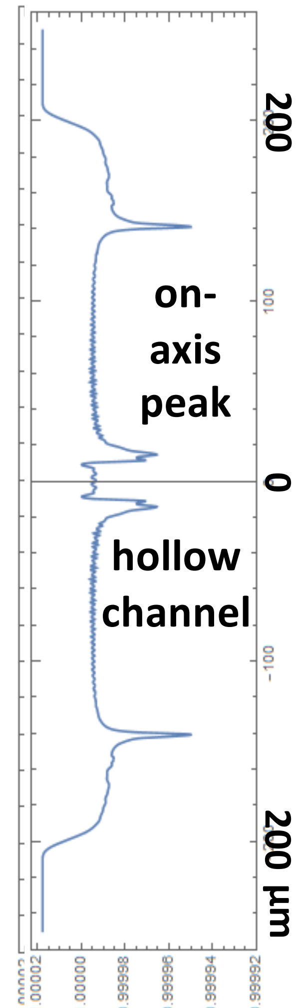
Simulated probe images show signatures of evolving on-axis ion density maxima

- laser pre-ionized Li plasma
- $n_e = 3.5 \times 10^{16}$ cm^{-3}
- $r_p \approx 200$ µm
- $\theta_{pr} = 20$ mrad
- $\lambda_{pr} = 800$ nm

$t_3 \approx 22$ ps



probe simulations by R. Zgadzaj, UT-Austin



OSIRIS plasma simulations by T. Silva, IST

Li refractive index

Probe at θ_{pr} = 8 mrad less sensitive to on-axis plasma structures

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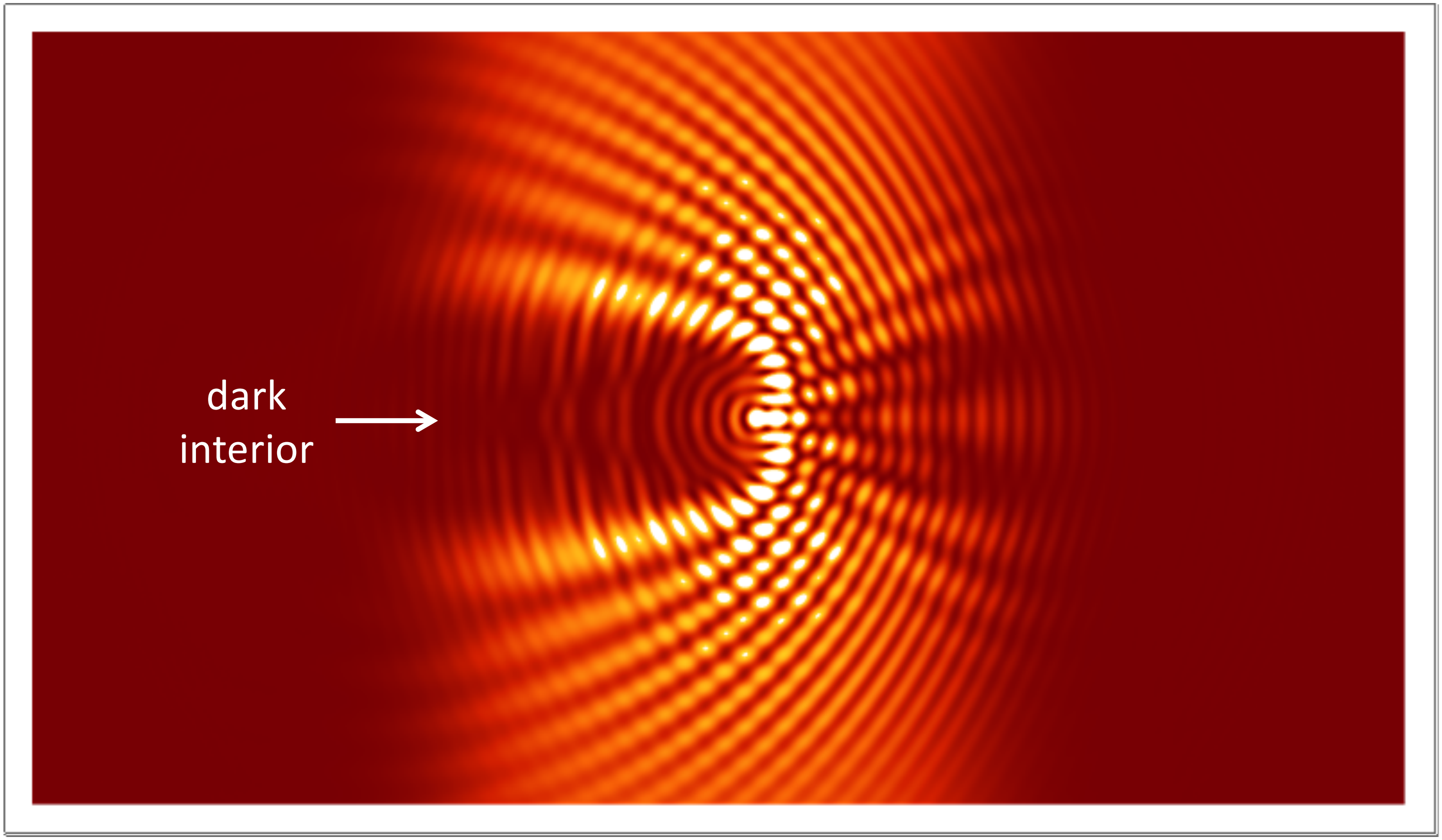

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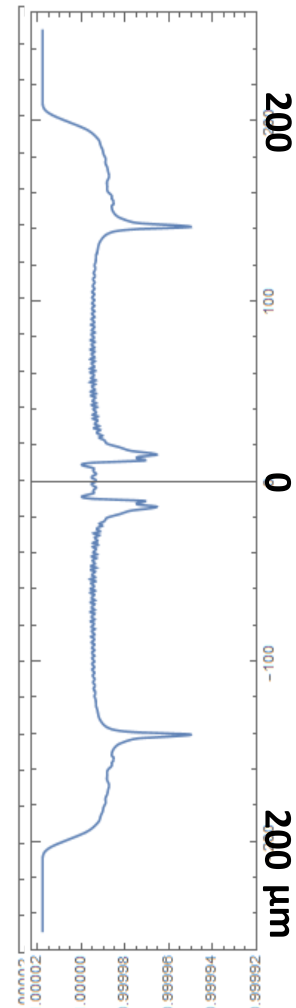

OSIRIS plasma simulations by T. Silva, IST

Li refractive index

Shape of plasma column edge influences how on-axis structures modify probe image

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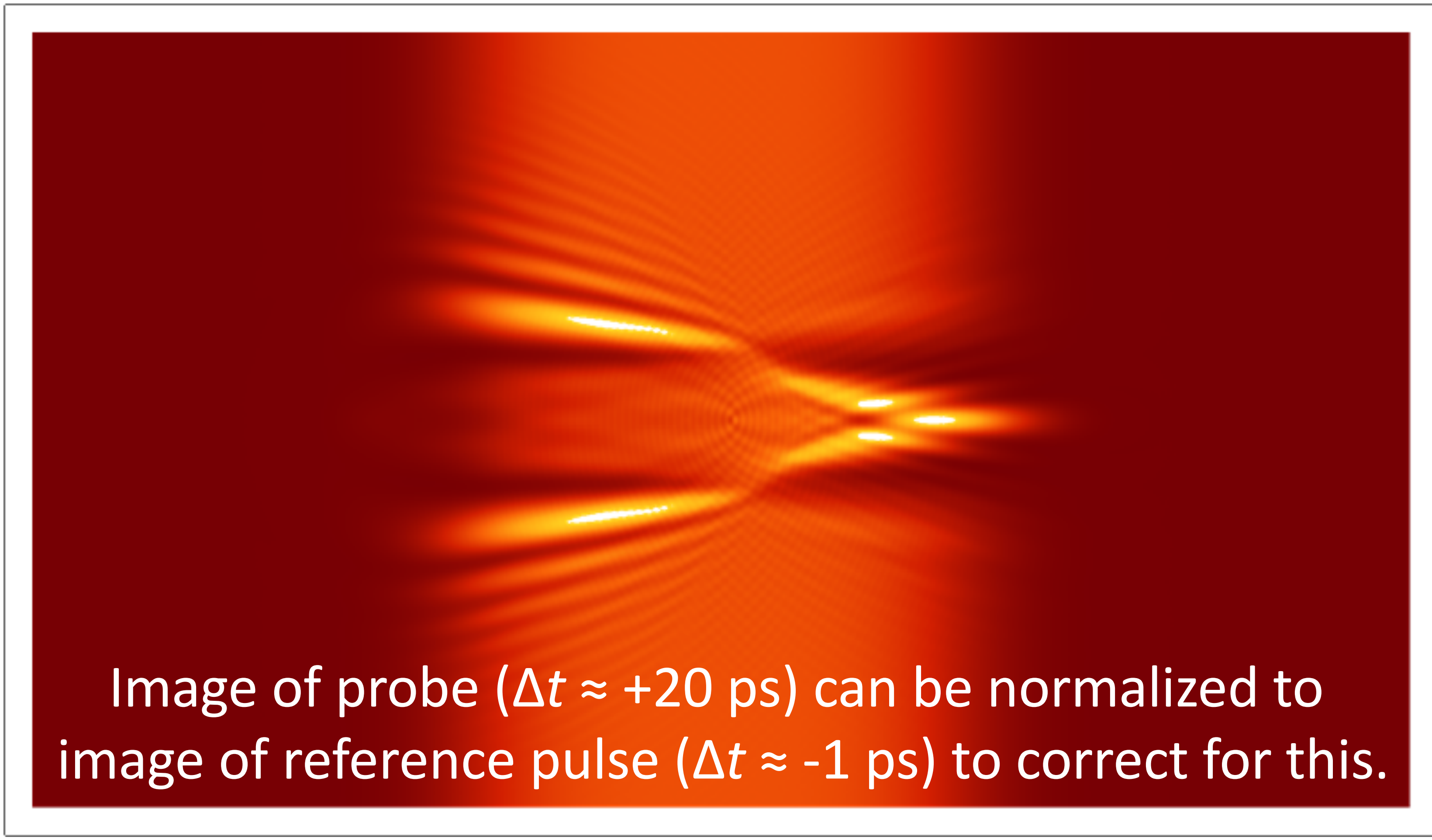
- λ_{pr} = 800 nm

$t_1 \approx 7$ ps



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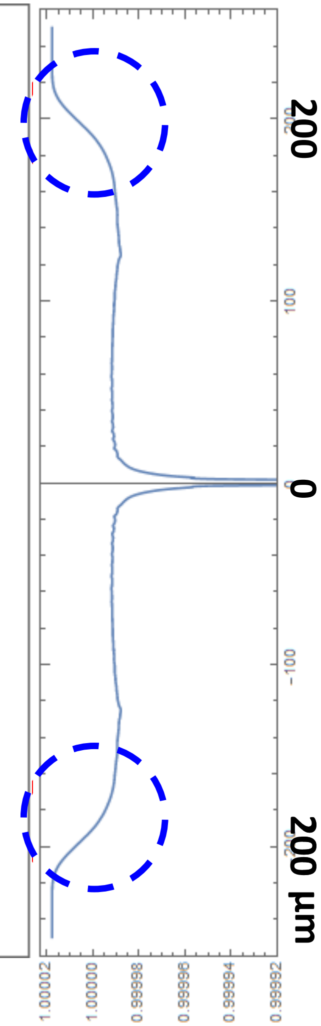

OSIRIS plasma simulations by T. Silva, IST

plasma edge: *super-Gaussian order 8*

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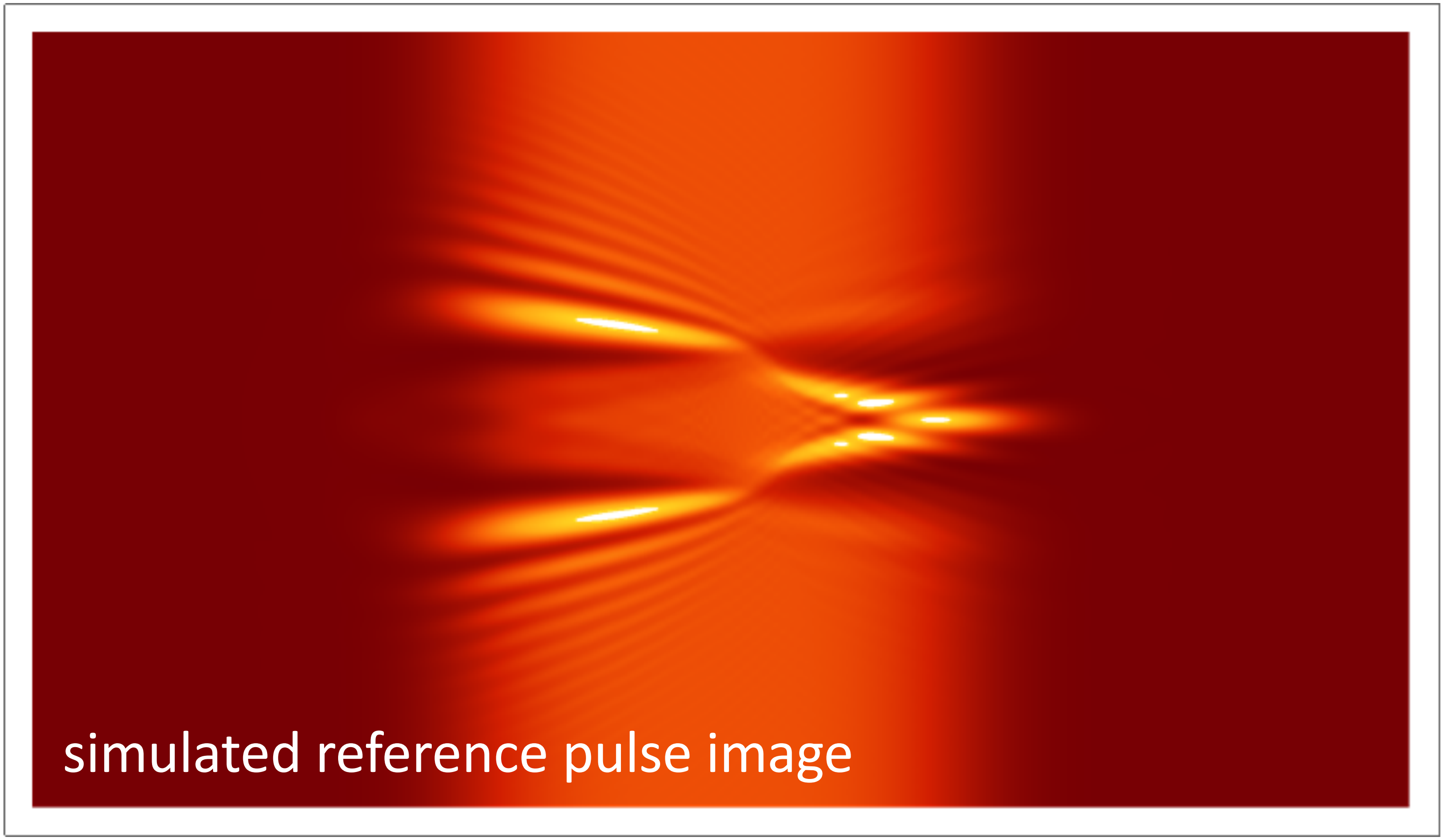
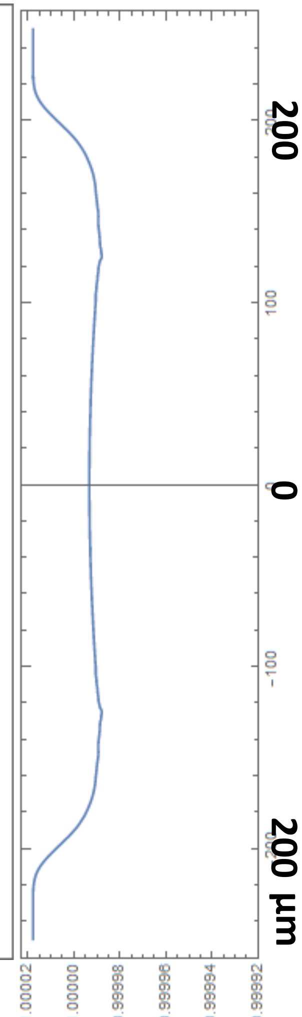


probe simulations by R. Zgadzaj, UT-Austin



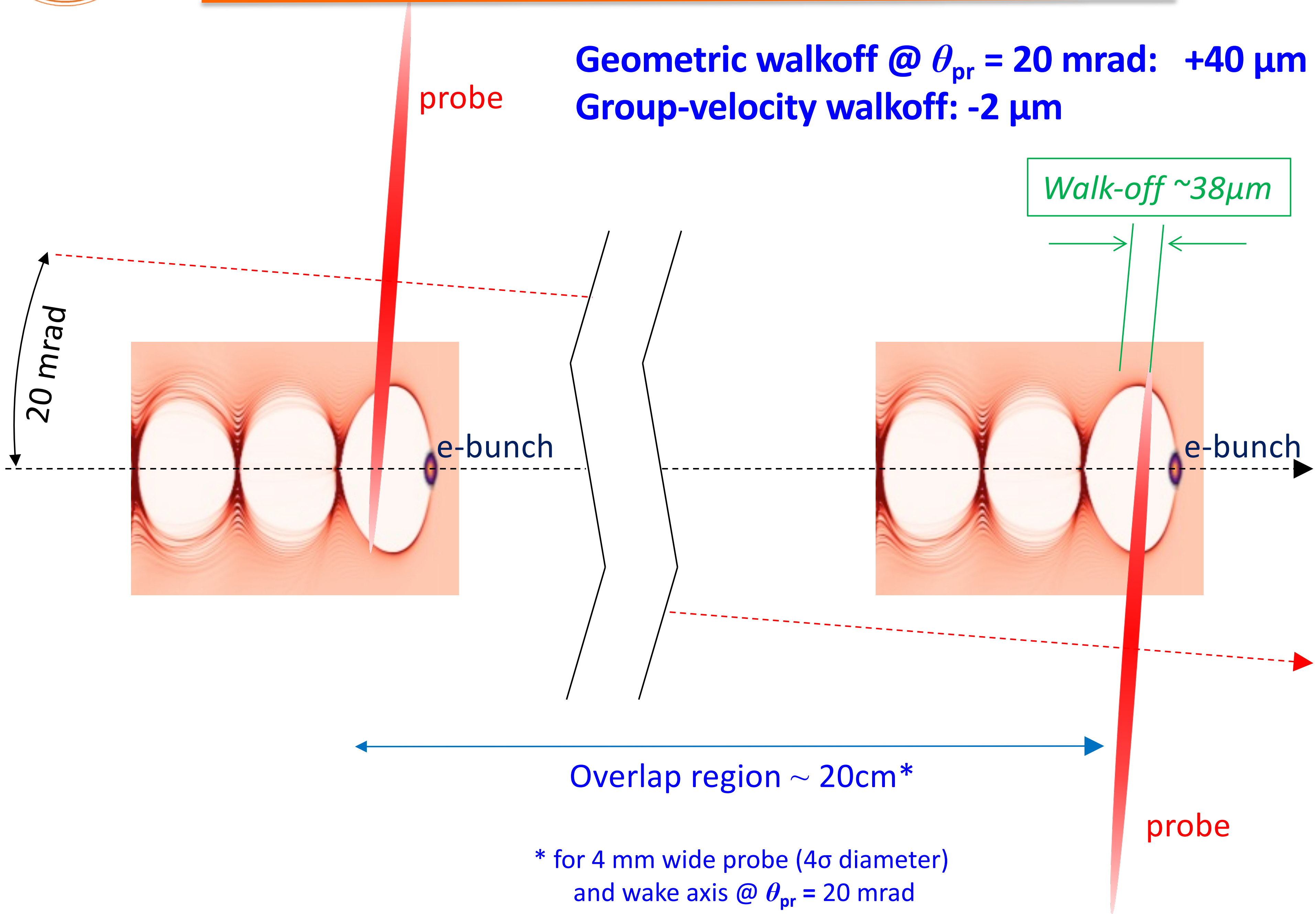
Li refractive index

OSIRIS plasma simulations by T. Silva, IST

plasma edge: *super-Gaussian order 8*

At 0.5 > Δt > 0.2 ps, probe remains within 1st bucket of electron wake for 20 cm

Geometric walkoff @ θ_{pr} = 20 mrad: +40 μm
Group-velocity walkoff: -2 μm



Overlap region ~ 20cm*

* for 4 mm wide probe (4σ diameter)
and wake axis @ θ_{pr} = 20 mrad

Under FACET-II conditions, a fully-blown-out e-beam-driven wake will be visible

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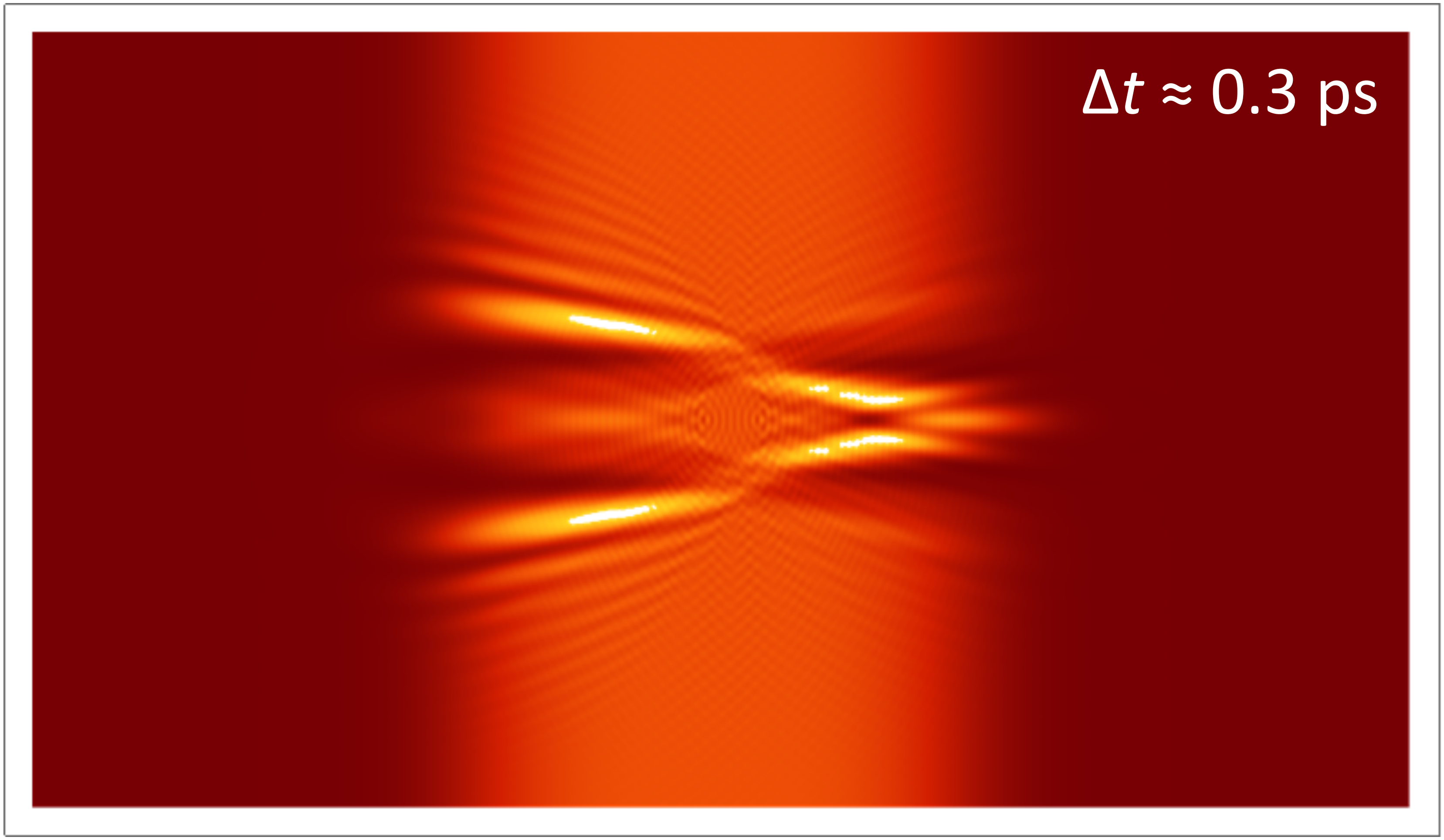
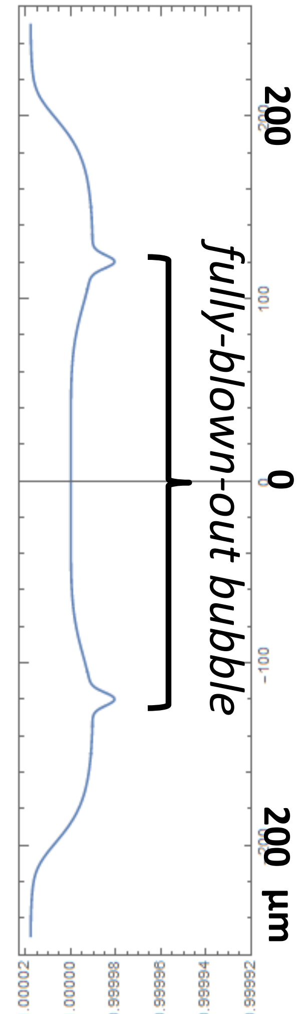
- λ_{pr} = 800 nm

bkgd. plasma + electron wake



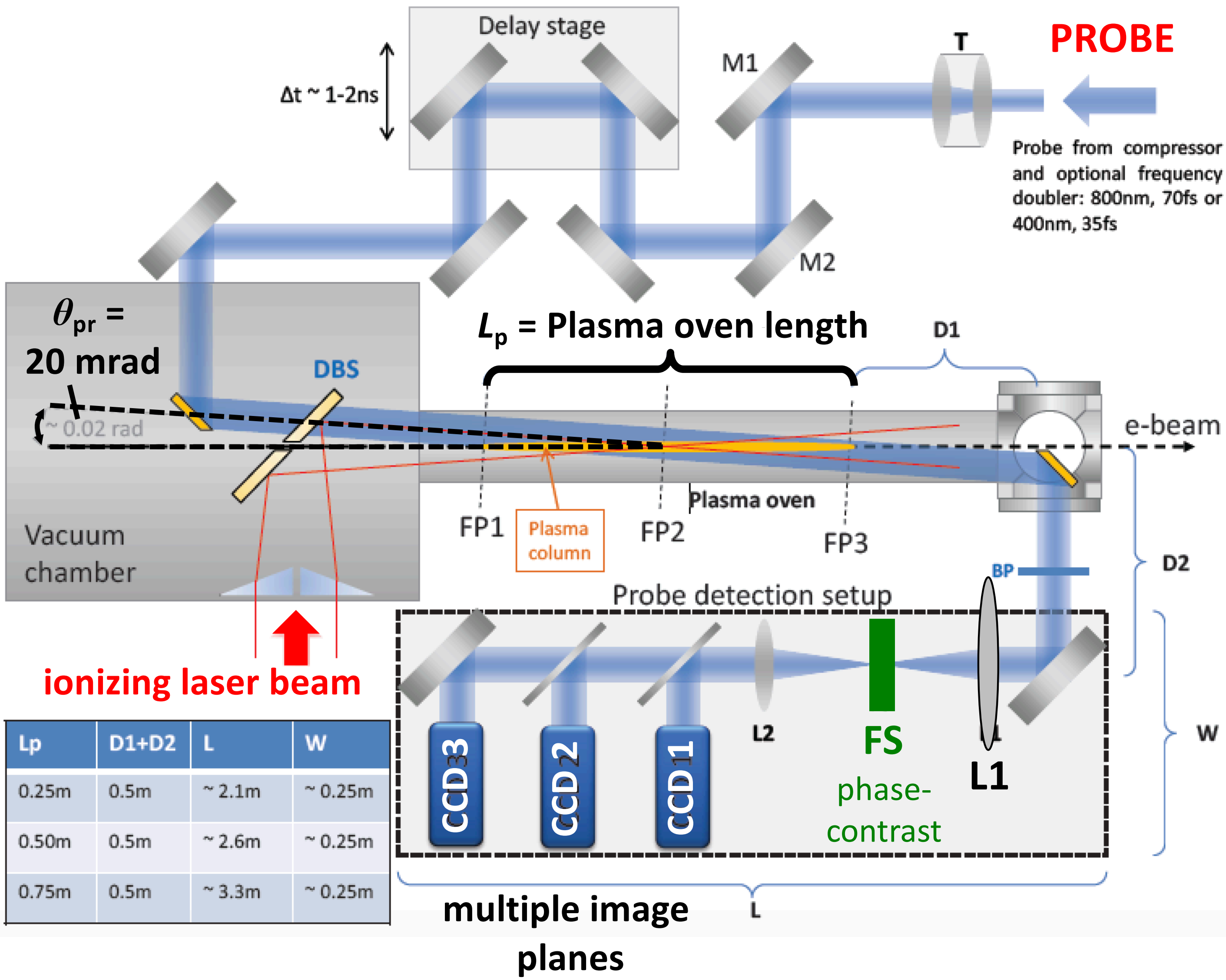


Li refractive index

probe simulations by R. Zgadzaj, UT-Austin

The simulations motivate additional experimental upgrades for PWFA imaging

PROBE independent of ionizing laser



Lp	D1+D2	L	W
0.25m	0.5m	~ 2.1m	~ 0.25m
0.50m	0.5m	~ 2.6m	~ 0.25m
0.75m	0.5m	~ 3.3m	~ 0.25m

UPGRADES:

(1) double θ_{pr} → probe interior plasma structures

(2) reduce $f^{\#}$ → higher image resolution

[a]**(3) install NL phase contrast optics** → improve sensitivity to $n_e < 10^{16}$ cm^{-3}

(4) install multiple image-object planes + reference → distinguish on-axis from edge structures.

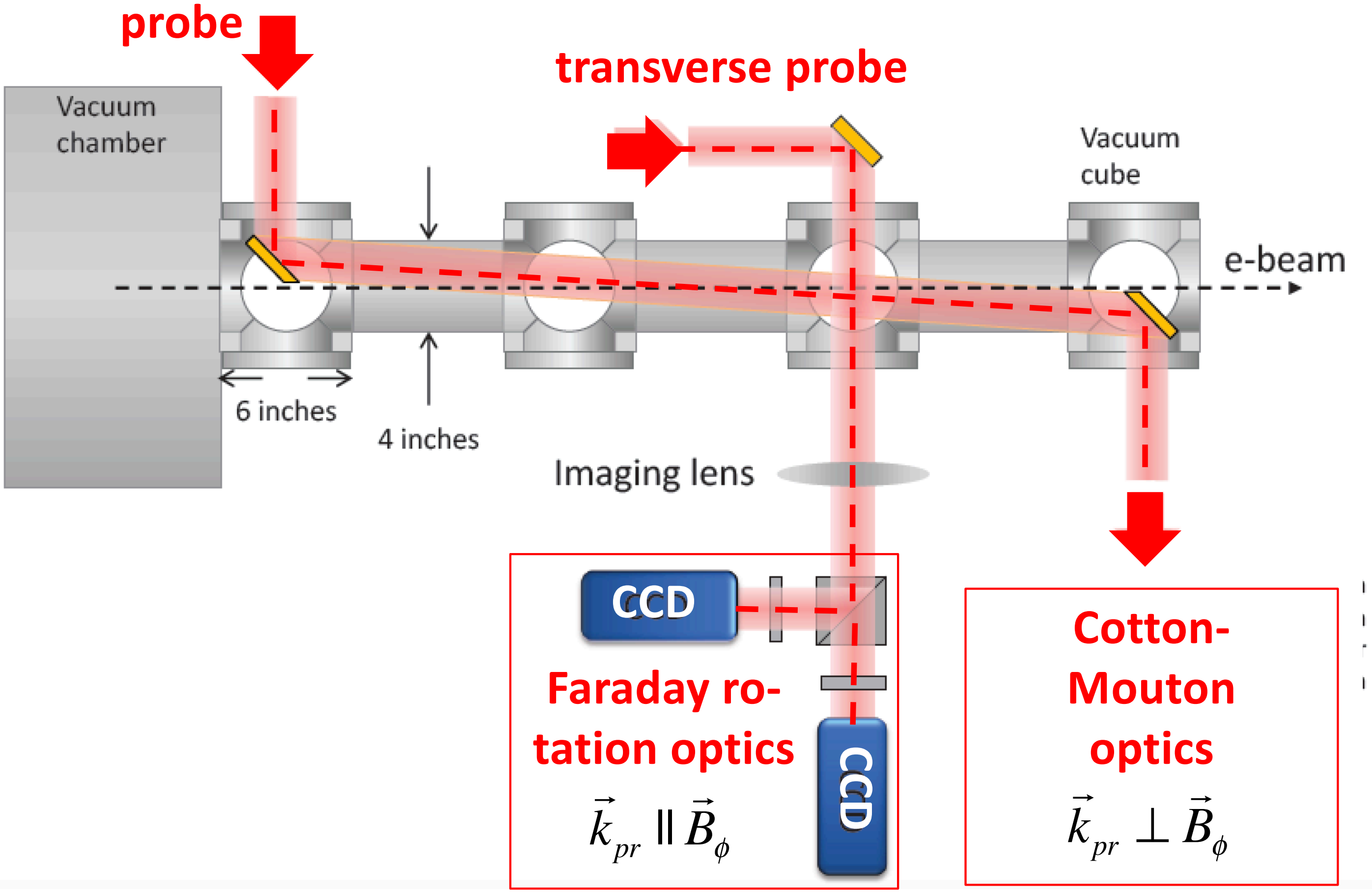
[a]pre-tested in our U. Texas lab Li, *Opt. Lett.* **38**, 5157 (2013)

Later FACET-II Experiments

He/H_2 chamber with transverse optical access will enable Faraday profiling* of magnetized PWFAs

*LWFA expts.: Kaluza, *PRL* **105**, 11502 (2010); Buck, *Nat. Phys.* **7**, 453 (2011) [$n_e > 10^{19}$ cm^{-3}]
Chang, PhD (2018) [$n_e \sim 10^{17}$ cm^{-3}]

~ longitudinal probe



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[b]**(5) install Faraday/C-M probes** → sensitive profiling of low-n_e structures

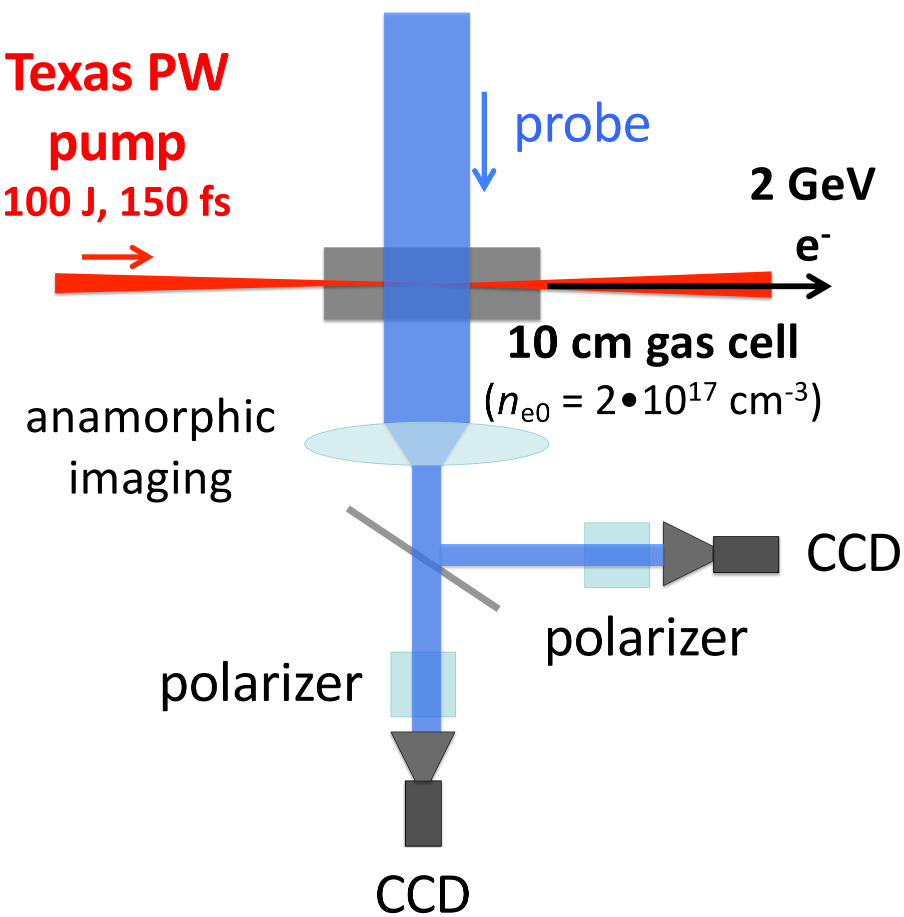
[b]pre-tested in Texas PW expts. Chang, PhD dissertation (2018)

probe of: (1) bubble sheath structure & dynamics
(2) external or Trojan horse e^--injection

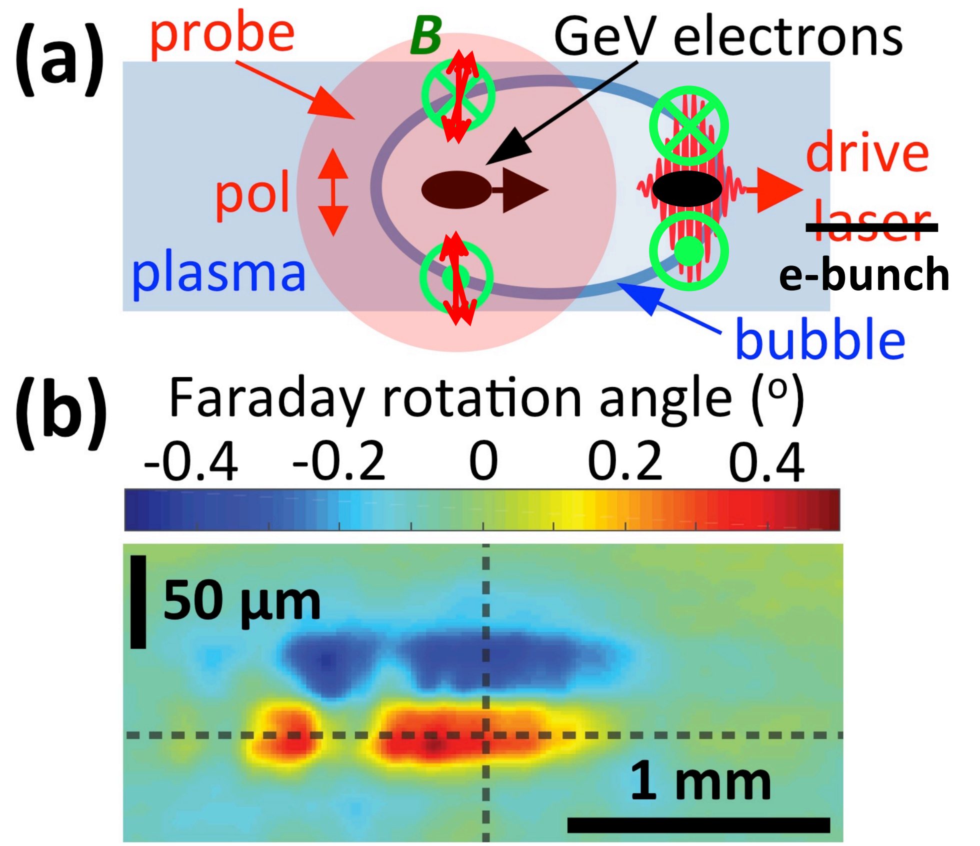
Faraday rotation picks out dense bubble wall in tenuous plasma

Based on technique developed by: Kaluza, *PRL* **105**, 115002 (2010); Buck, *Nat. Phys*. **7**, 453 (2011) in $n_e > 10^{19}$ cm^{-3} plasma; results shown from Chang, PhD dissertation, UT-Austin (2018)

Faraday probe setup



Faraday rotation results



4 measure-ments

- *separation of ± lobes:* **bubble size**
- $|\Delta\phi_{Faraday}|$: **bubble wall density**
- *width of each lobe:* **bubble wall thickness**
- *longitudinal variations:* **bubble evolution**

SUMMARY

- In FACET-II, we will visualize on-axis e- and ion-wake structures, taking advantage of larger θ_{pr}, higher-resolution imaging, lower n_e than in FACET-I.

$\Delta t \geq 30$ ps	**$\Delta t < 1$ ps**
(1) on-axis ion-density peak	(3) e-wake structure & propagation dynamics
(2) hollow-channels	(4) transverse & longitudinal e-wake instabilities

- Our simulations show that our probe will illuminate these structures well, and provide clear optical signatures of them...

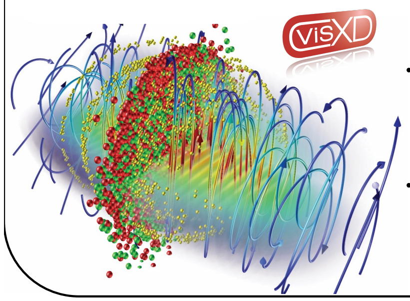
- ... but there are challenges. Probe images are...
  ... low contrast → use phase-contrast imaging
  ... convolved with plasma-edge signatures → use probe-reference pulse pair.

OSIRIS[1] simulations show nonlinear e-wake excitation & early (Δt < 40 ps) ion response

simulations by T. Silva, J. Vieira (IST)

OSIRIS[1] framework

- Massivelly Parallel, Fully Relativistic PIC Code
- Visualization & Data Analysis Infrastructure
- Developed by Osiris Consortium, **UCLA + IST**



[1] Fonseca *et al.*, *PPCF* **55**, 124011 (2013)