Experimental progress on staged laser-plasma acceleration

Satomi Shiraishi

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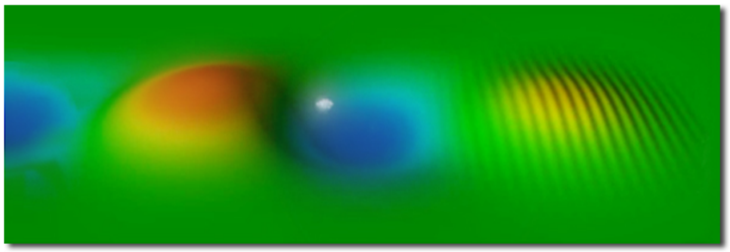
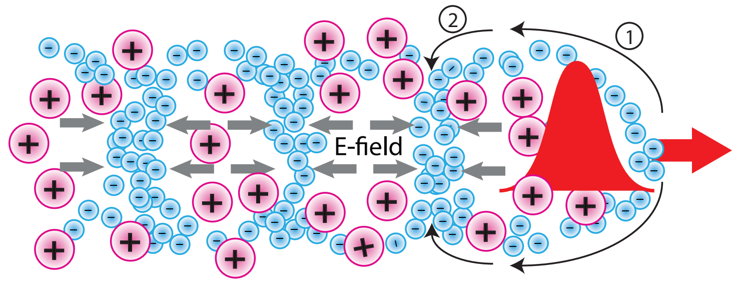
Faculty advisor: Prof. Y. K. Kim (Univ. of Chicago)

Outline

- How laser-plasma accelerators (LPAs) work
- Challenges of LPAs – why staged LPA is critical
- Staged LPA experiment at LBNL
- Experimental results so far on:
    - Injection module
    - Plasma mirror for coupling laser pulses
    - Acceleration module
- Summary of where we are and outlook

Laser-plasma accelerators (LPAs) can sustain high Ez





e⁻ density pertubation | Laser radiation pressure

$$\left(\frac{\partial^2}{\partial t^2} + \omega_P^2\right)\frac{\partial n}{n_0} = c^2 \nabla^2 \frac{a^2}{2}$$

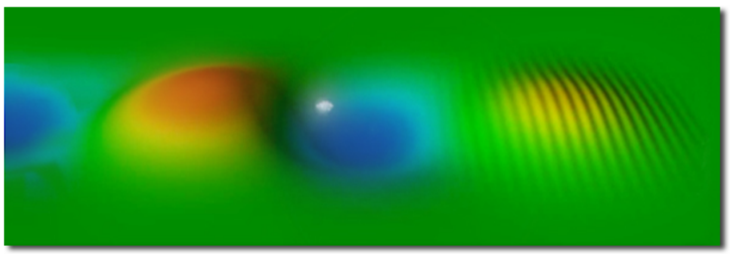
Laser strength parameter $a \propto \lambda I^{1/2}$

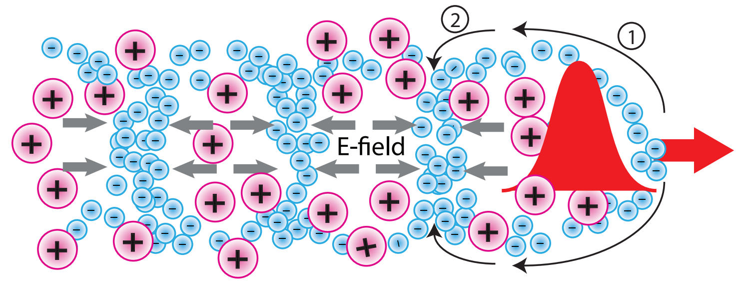
a >> 1: Non-linear

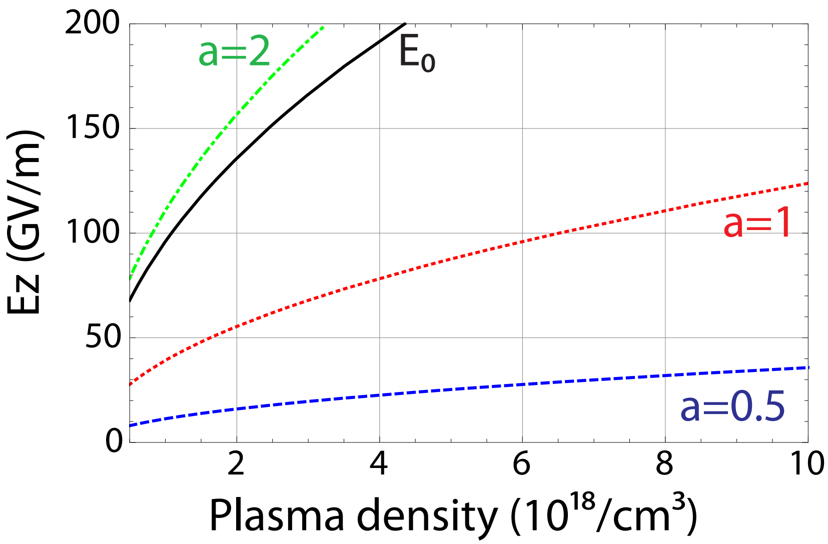
a ~ 1 : Quasi-linear

a << 1 : Linear

Laser-plasma accelerators (LPAs) can sustain high Ez







e$^-$ density pertubation

Laser radiation pressure

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a << 1 : Linear

Example:

a ~ 0.5 – 2

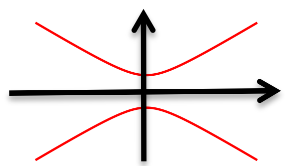
n_0 ~ 10^{18} cm^{-3}

E_z ~ 10 – 100 GV/m

Challenges of LPA

High accelerating gradient ~1 - 100GV/m

Laser **Diffraction**



- Reduces intensity, harder to excite wave

Electron **Dephasing**

$$L_d \propto n_0^{-3/2}$$

- Relativistic e^- outrunning the plasma wave

Pump **Depletion**

$$L_{Pd} \propto \frac{1}{a^2} n_0^{-3/2}$$

- Driving laser loses energy to plasma

Challenges of LPA

High accelerating gradient ~1 - 100GV/m

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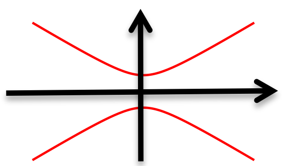

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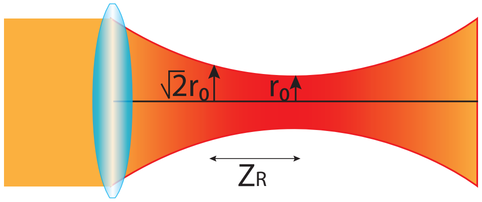
Laser guiding

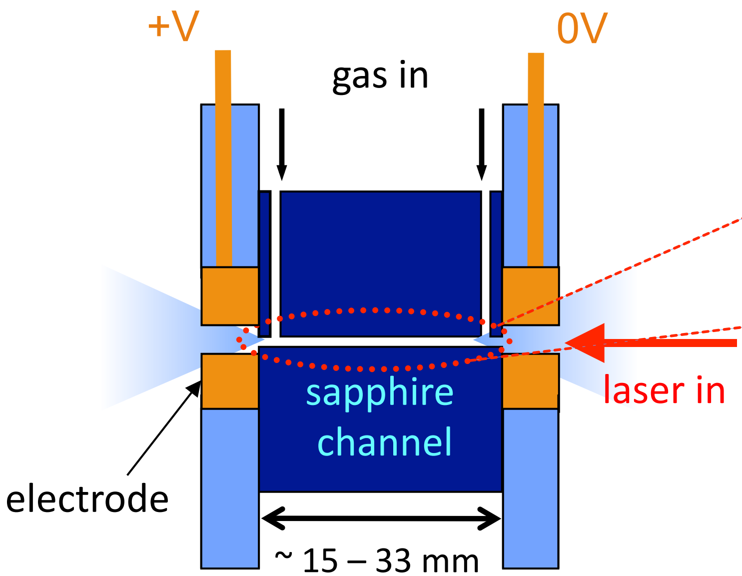
Lower plasma density

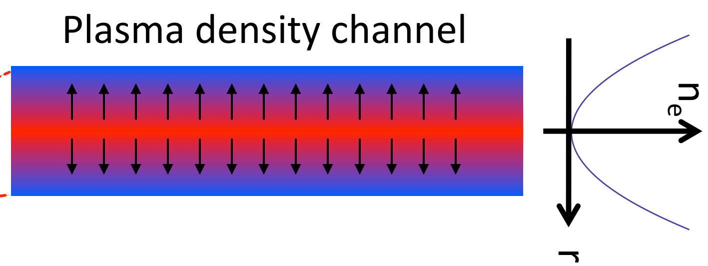
Staging

Capillary discharge waveguides mitigate laser diffraction

- Laser diffraction limits acceleration length to $\sim Z_R = \pi\, \omega_0^2/\lambda$







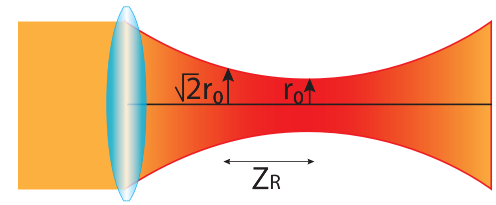
Parabolic density channel focuses laser

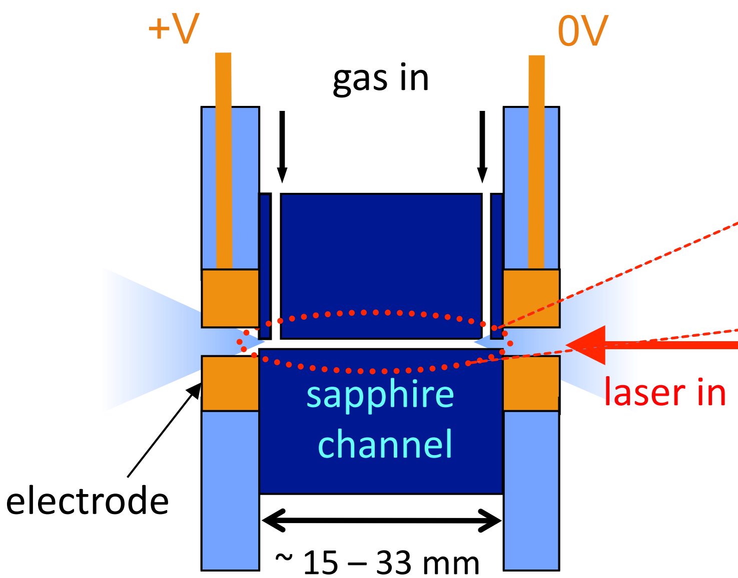
$$n_e(r) = n_e(0) + \frac{1}{2}\frac{d^2 n_e}{dr^2} r^2$$

A. Gonsalves et al. PRL 98 (2007)
D.J.Spence & S.M.Hooker PRE 63 (2001)
A. Butler et al. PRL 89 (2002)

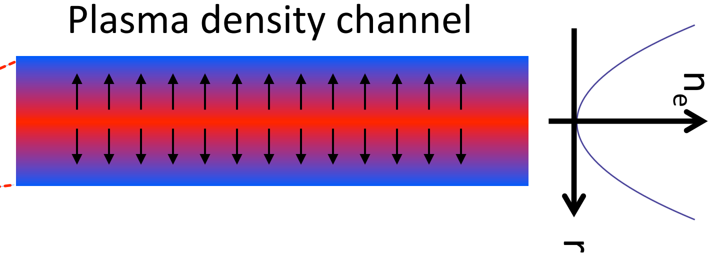
Capillary discharge waveguides mitigate laser diffraction

- Laser diffraction limits acceleration length to ~$Z_R = \pi\, \omega_0^2/\lambda$





Plasma density channel



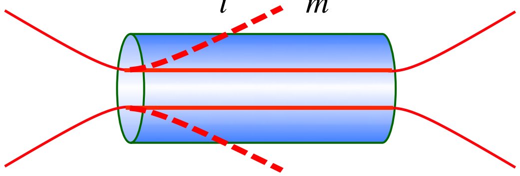
Parabolic density channel focuses laser

$$n_e(r) = n_e(0) + \frac{1}{2}\frac{d^2 n_e}{dr^2} r^2$$

Retains high laser intensity over many Z_R

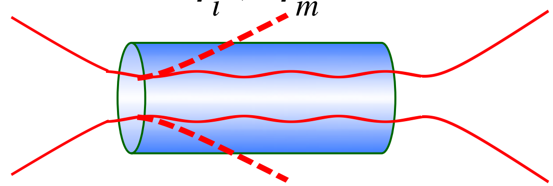
Matched guiding

$r_i = r_m$

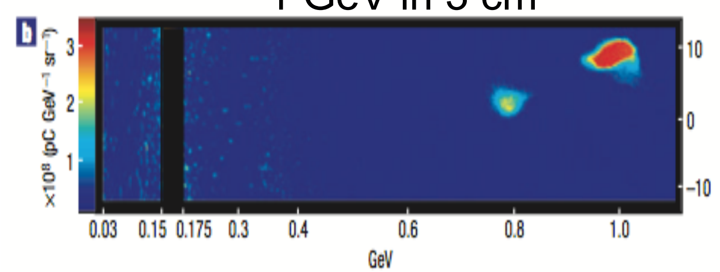


Mismatched guiding

$r_i \neq r_m$



1 GeV in 3 cm



W. P. Leemans et al. Nature Physics 418 (2006).

A. Gonsalves et al. PRL 98 (2007)
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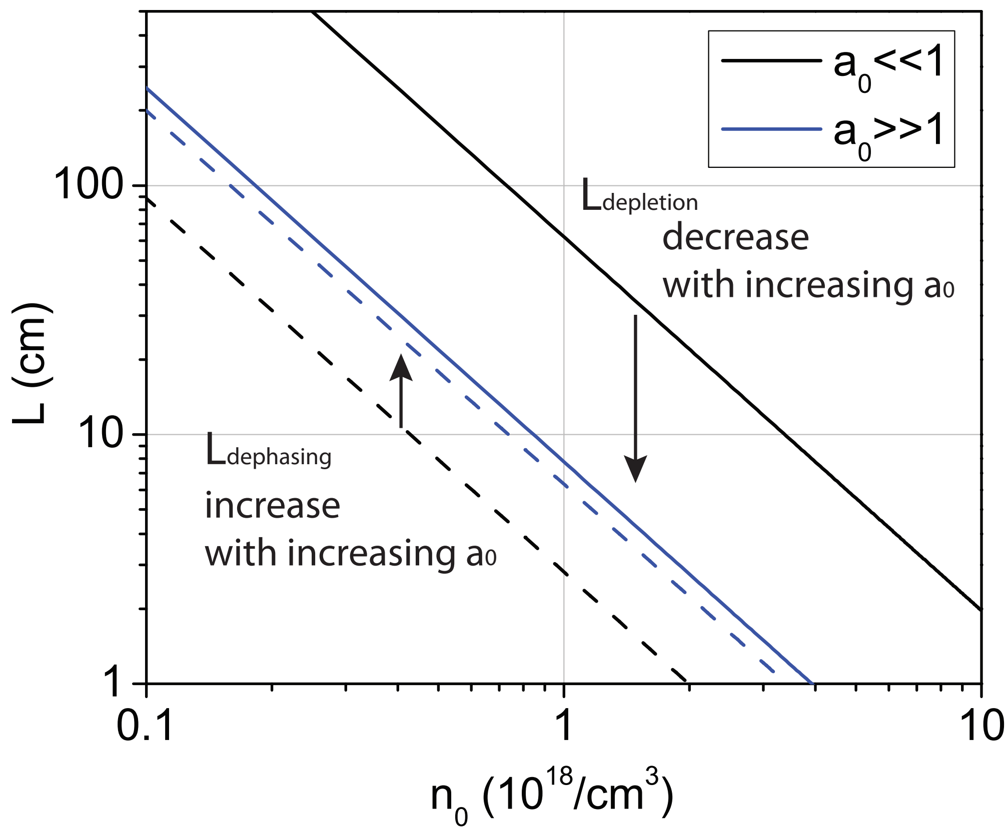
Density control and Staged acceleration critical to LPAs

- For a given laser strength a_0, there is an optimal acceleration length $\sim L_d \sim L_{pd}$



Density control and Staged acceleration critical to LPAs

Challenges of LPA

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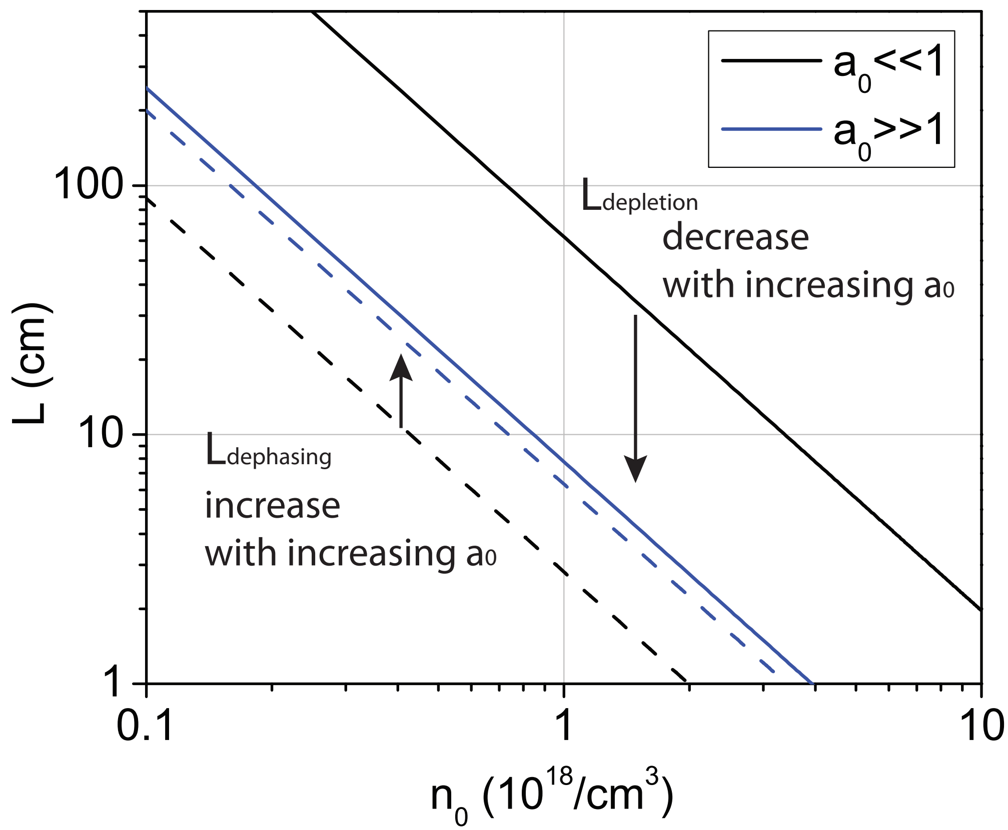
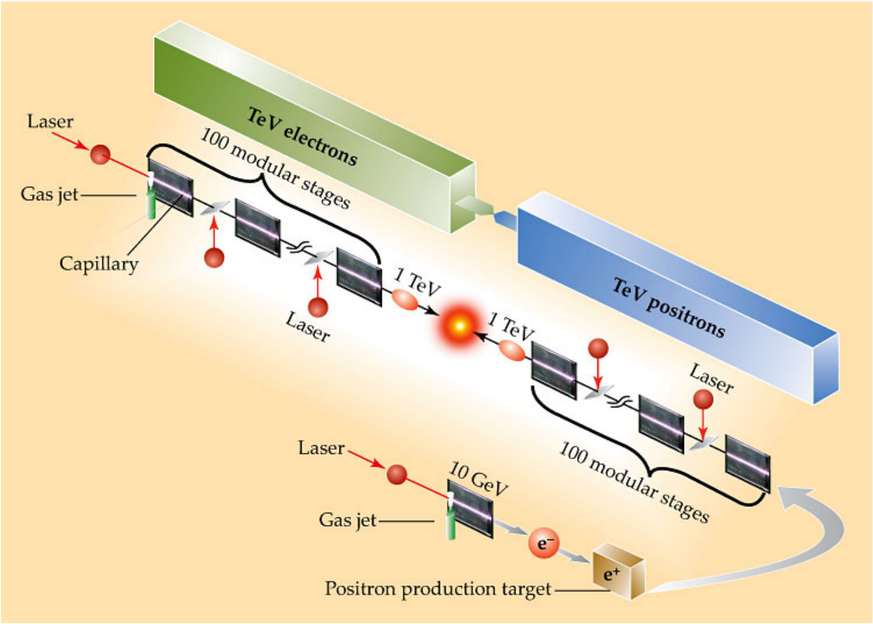


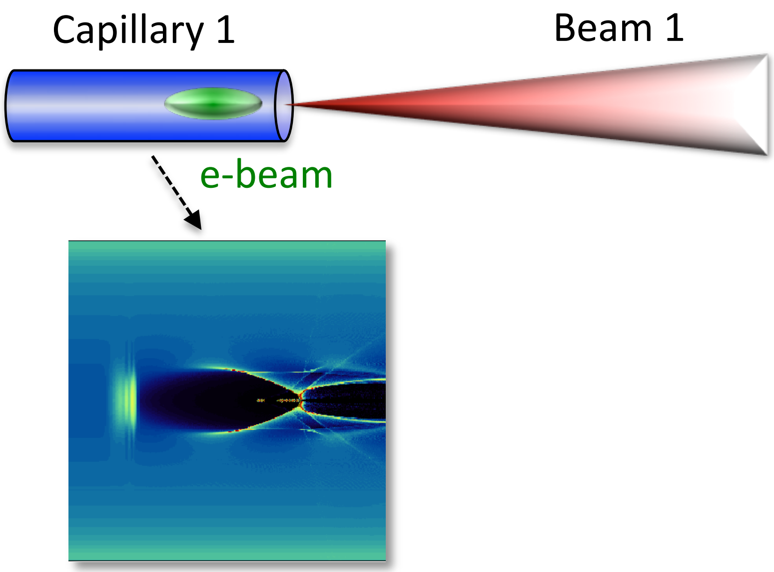
Staging supplies fresh laser pulses



W. P. Leemans & E. Esarey
Physics Today 2009

Staging experiment requires precision

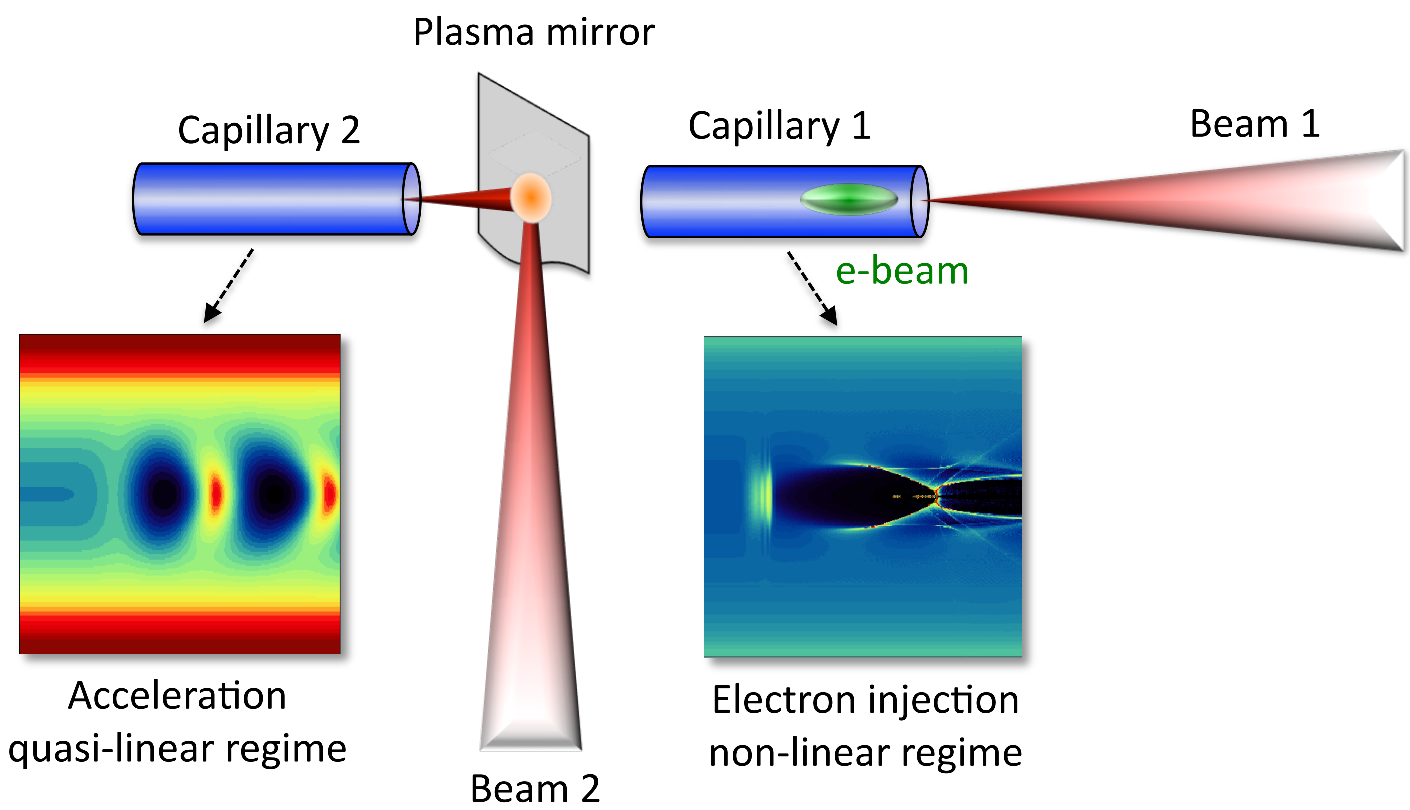
- Advantages:
  - Staged LPA can supply fresh laser pulses
  - Separate injection and acceleration



Electron injection
non-linear regime

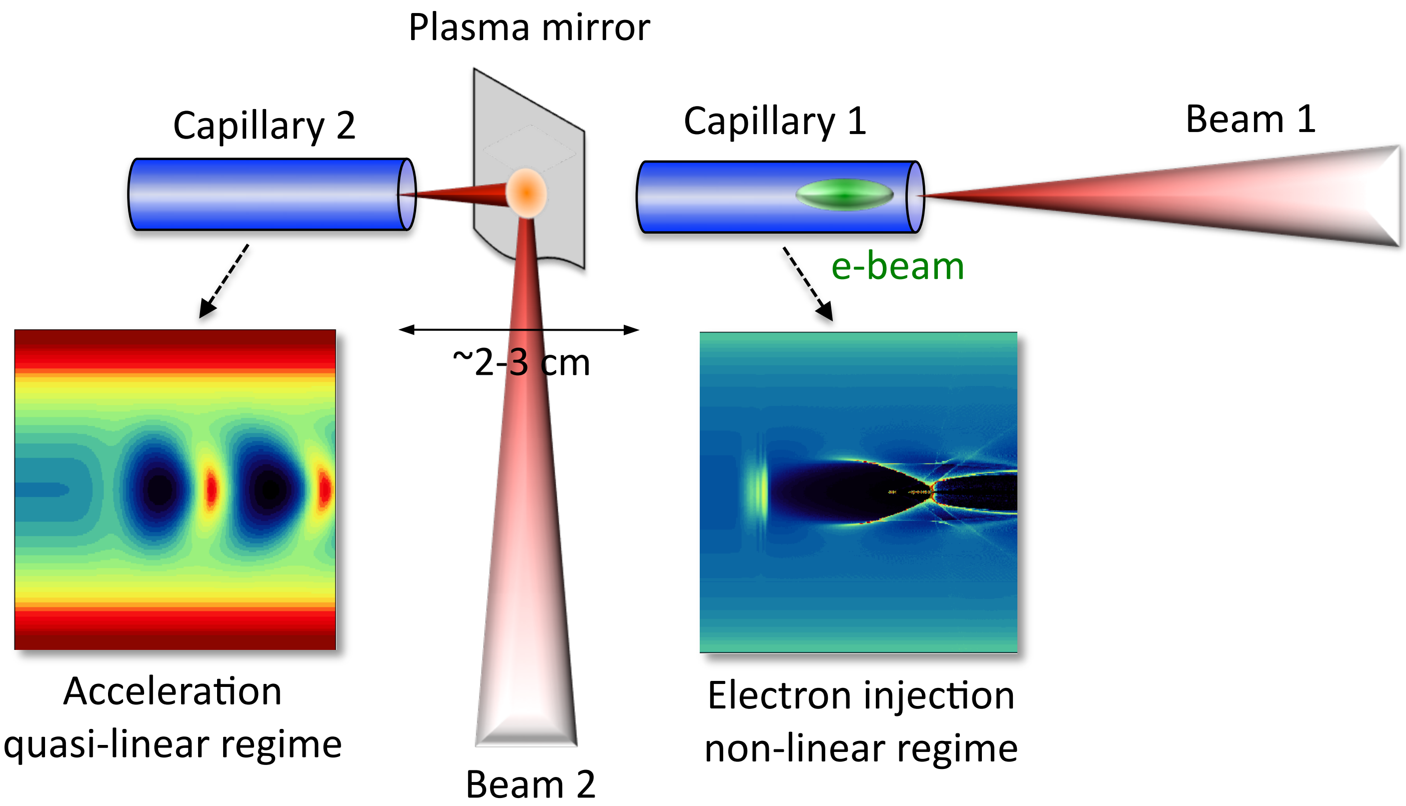
Staging experiment requires precision

- Advantages:
  - Staged LPA can supply fresh laser pulses
  - Separate injection and acceleration

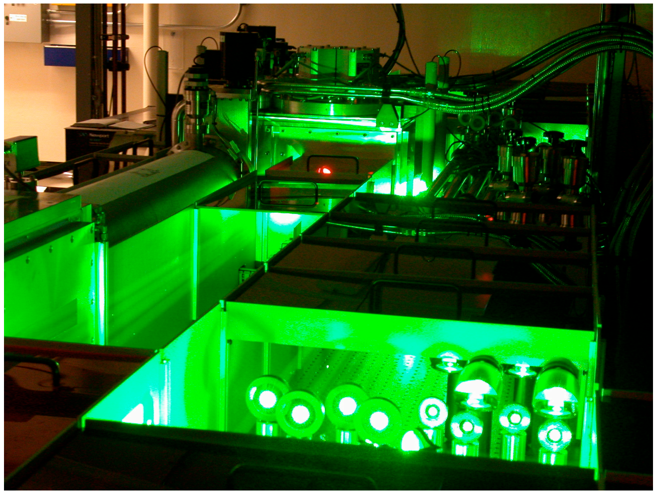


Staging experiment requires precision

- Advantages:
  - Staged LPA can supply fresh laser pulses
  - Separate injection and acceleration
- Challenges:
  - Laser spatial overlap ~um
  - Temporal overlap ~ fs
  - Two capillary + plasma mirror operation

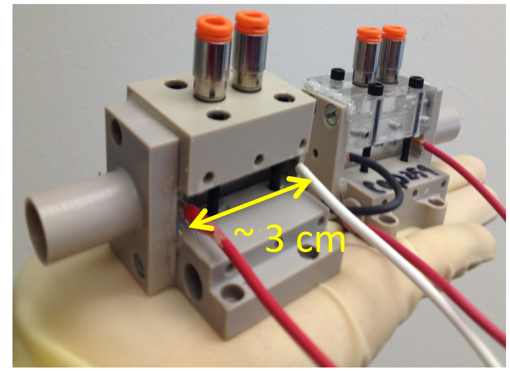


Staging experiment @ LOASIS Program

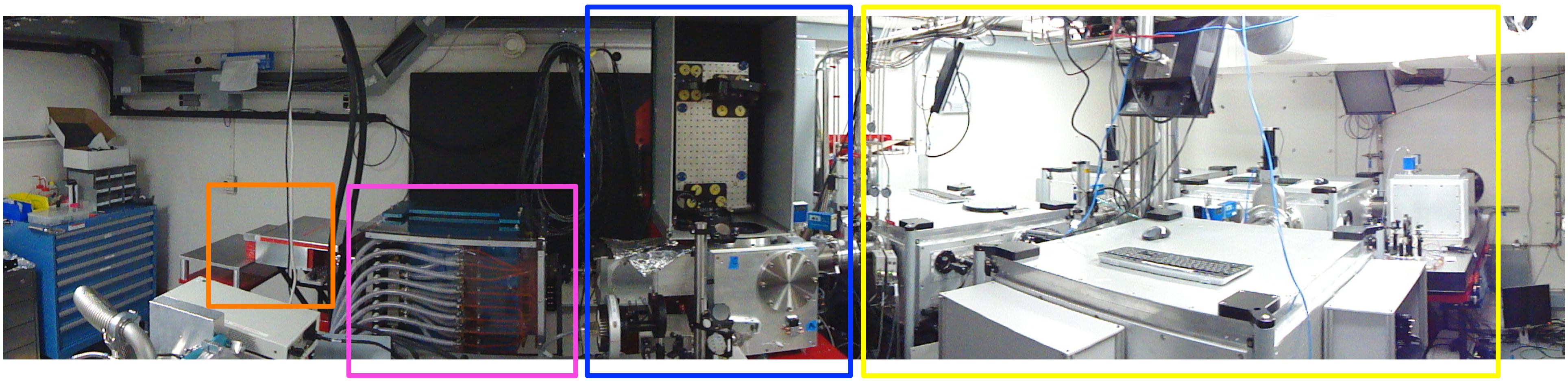


TREX laser
- ❖ Ti:Sapphire laser (λ = 805 nm)
- ❖ Peak power 40TW
- ❖ Optimum compression 40 fs
- ❖ Rep. rate 1 Hz

Staging capillaries



New beamline for staging experiment completed in Nov 2011
First high power laser operation in April 2012

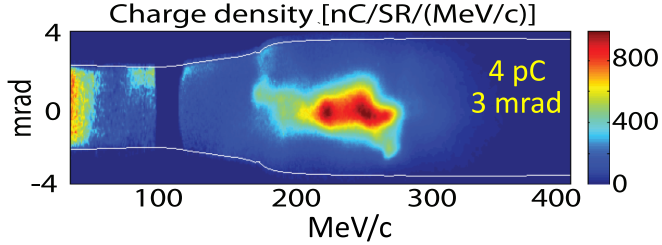


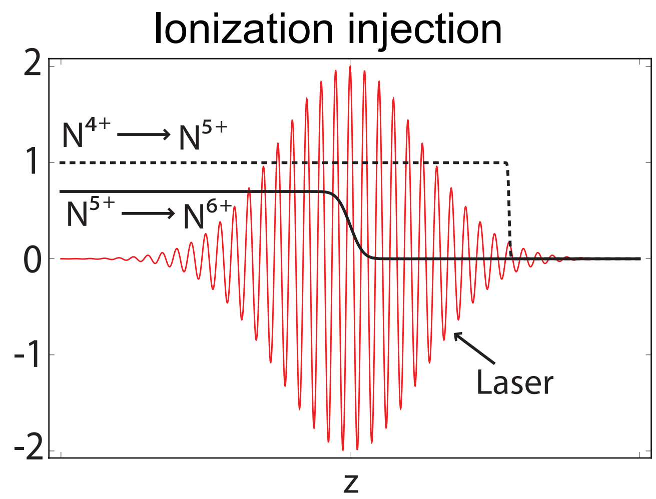
Electron beam dump | Electron spectrometer | High power laser diagnostics | Interaction chamber and beam transport chambers

Electron injected -- Optimization in progress

Injection module

- Capillary only injector was unstable
  - 1% N_2, He balanced mixed gas, 0-10pC, ~3mrad
  - Large fluctuations for energy and charge





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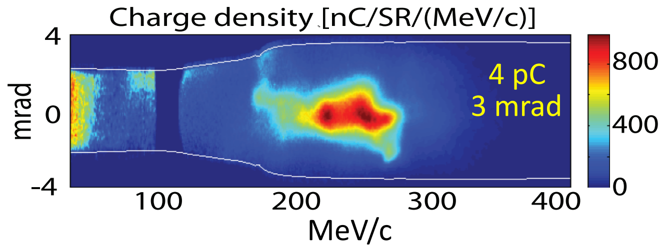
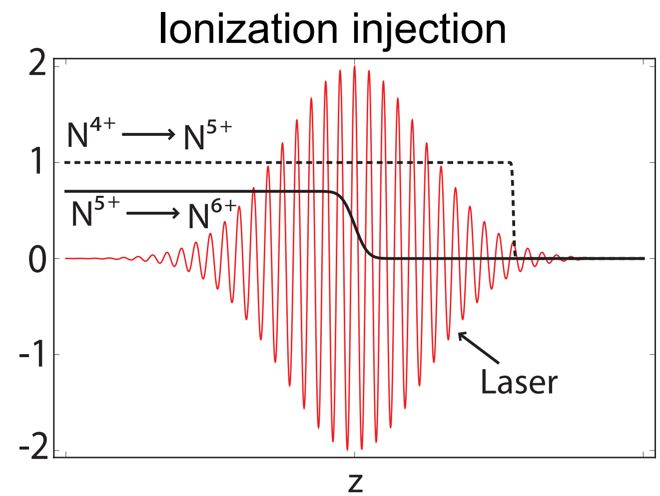
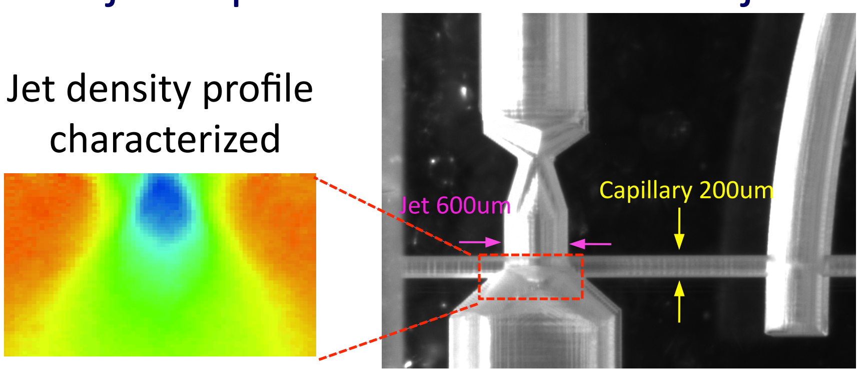
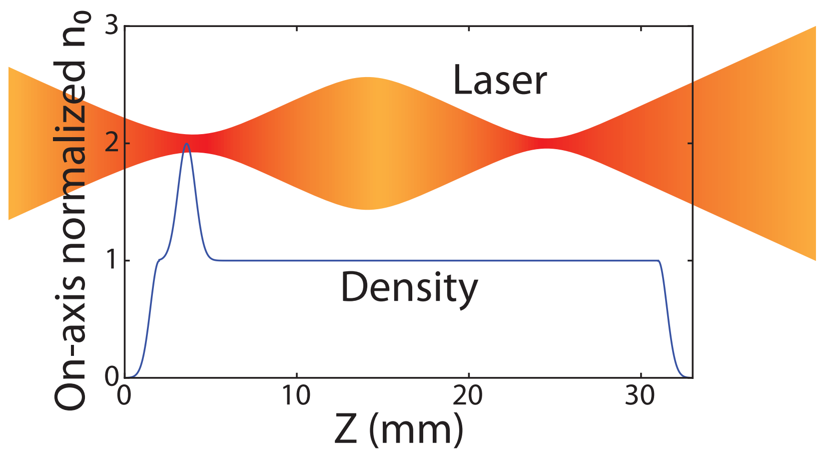




- Gas jet implemented to control injection

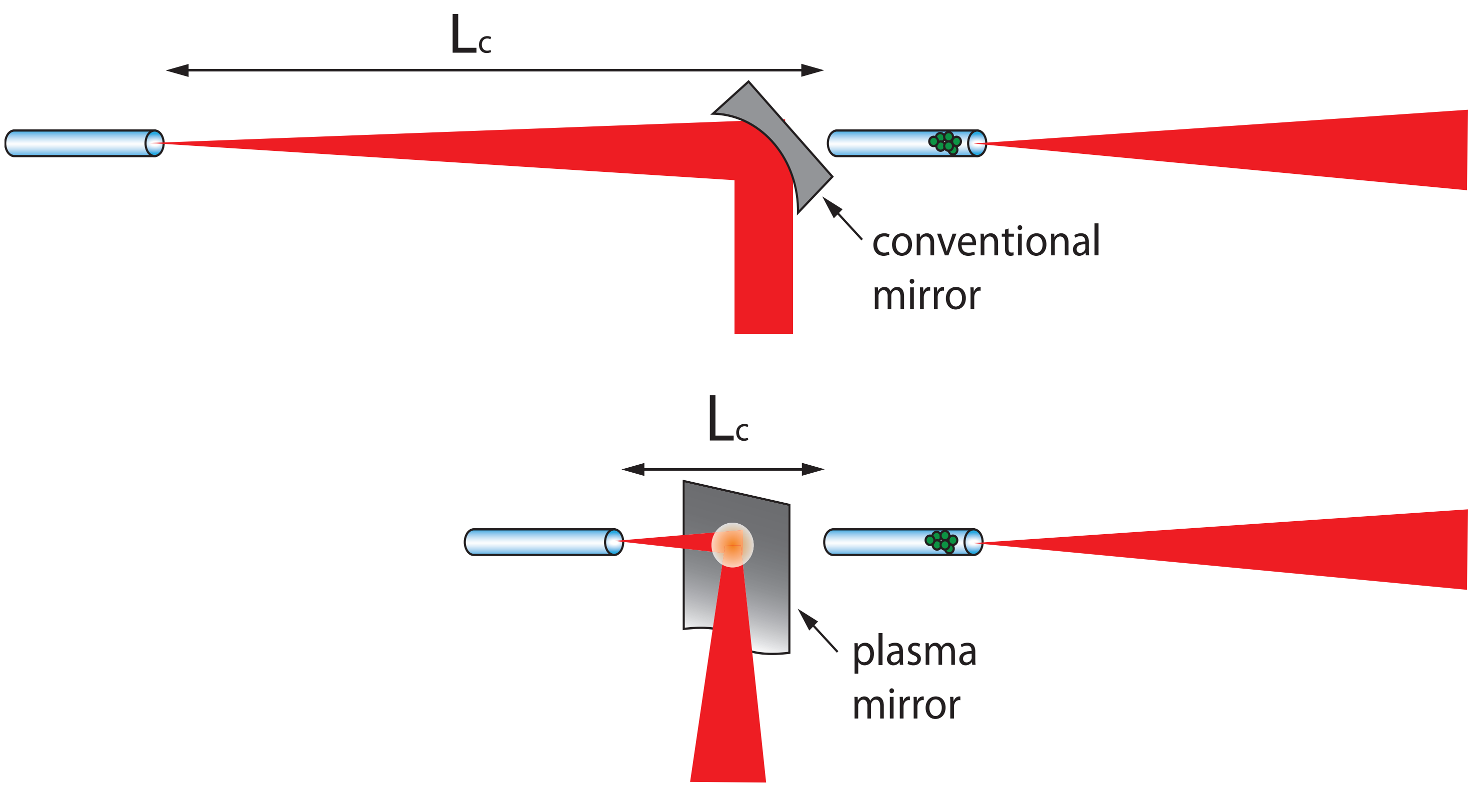
Jet density profile characterized





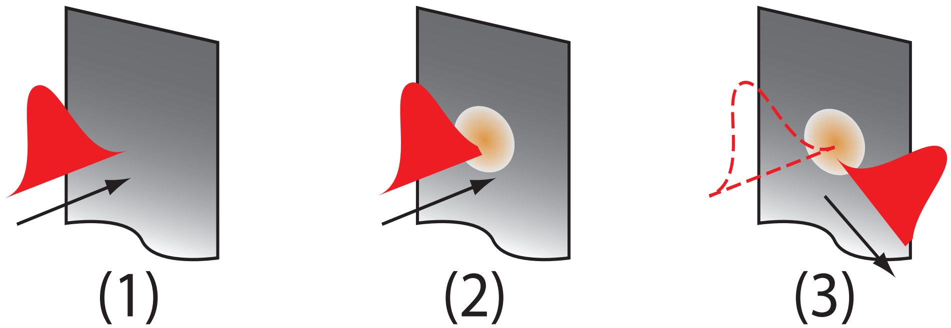
Plasma mirror used to reduce coupling distance

- Laser is too intense to use conventional optics close to focus



Plasma mirror is intensity dependent

- Plasma mirror triggers ~ Intensity 1E14 W/cm^2



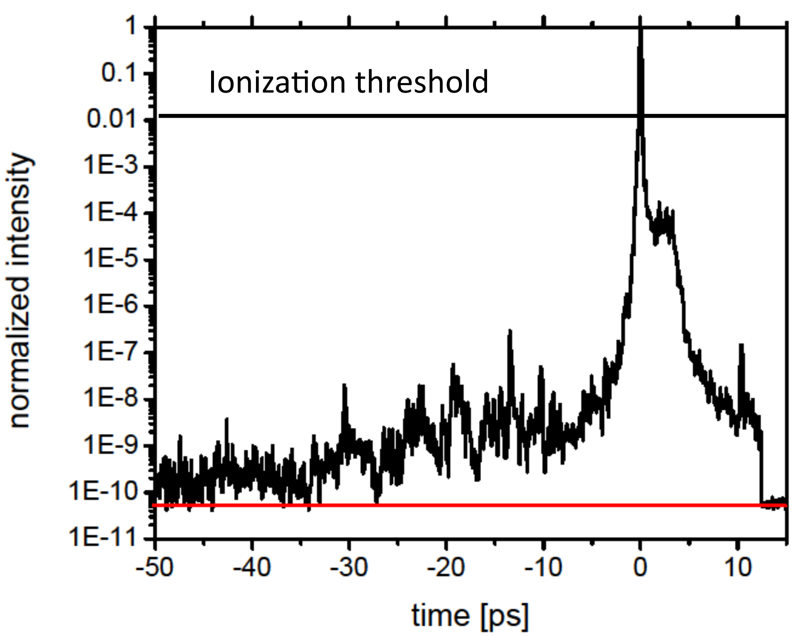
Step (2): Laser ionizes tape

$$n_R = \sqrt{1 - \frac{\omega_P^2}{\omega_L^2}}$$

$$\omega_P^2 = \frac{4\pi e^2 n_e}{m_e}$$

Step (3): Reflection at critical surface

$$\omega_P = \omega_L$$



Too low intensities:
only a small portion of the beam is reflected beam

Plasma mirror is intensity dependent

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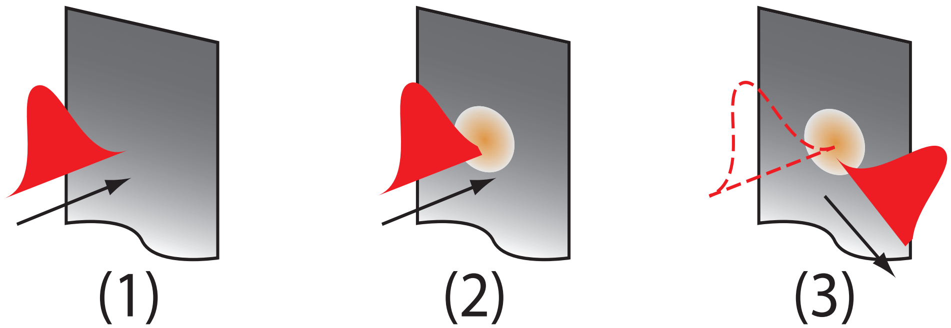

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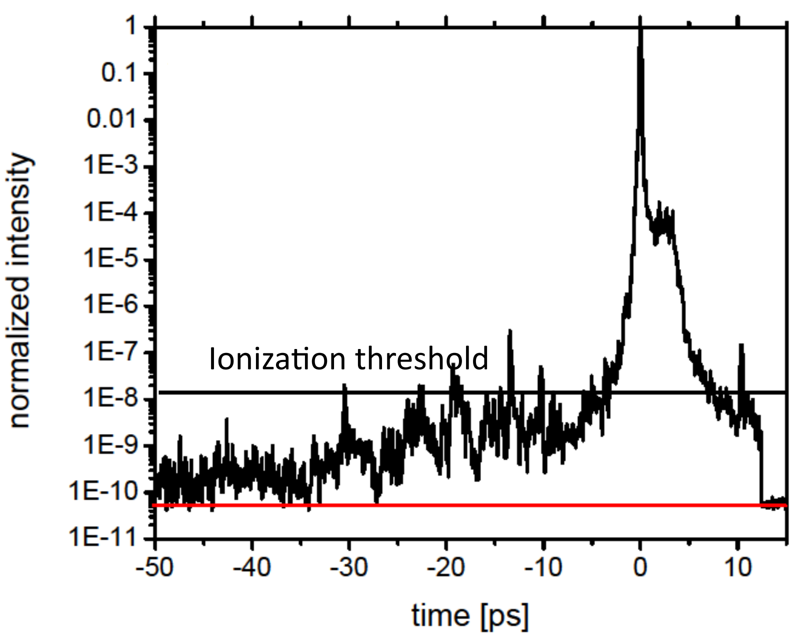


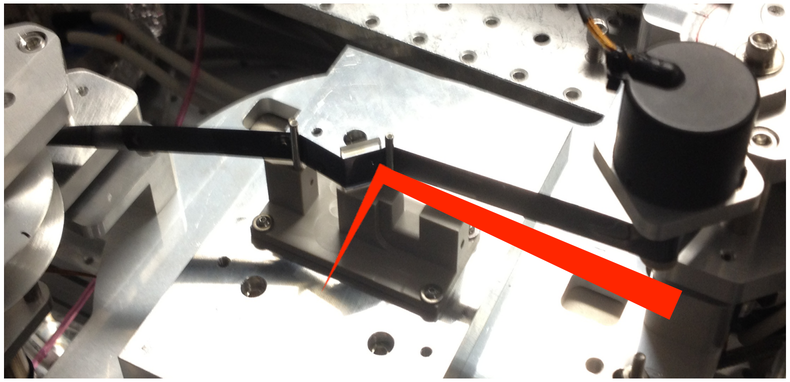
Too low intensities:
only a small portion of the beam is reflected beam

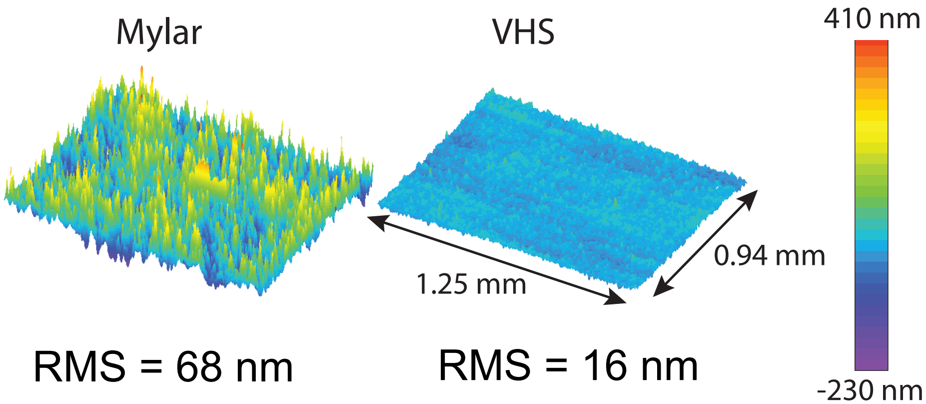
Too high intensities:
expansion of the plasma
→ increase of absorption
→ poor quality of reflected beam

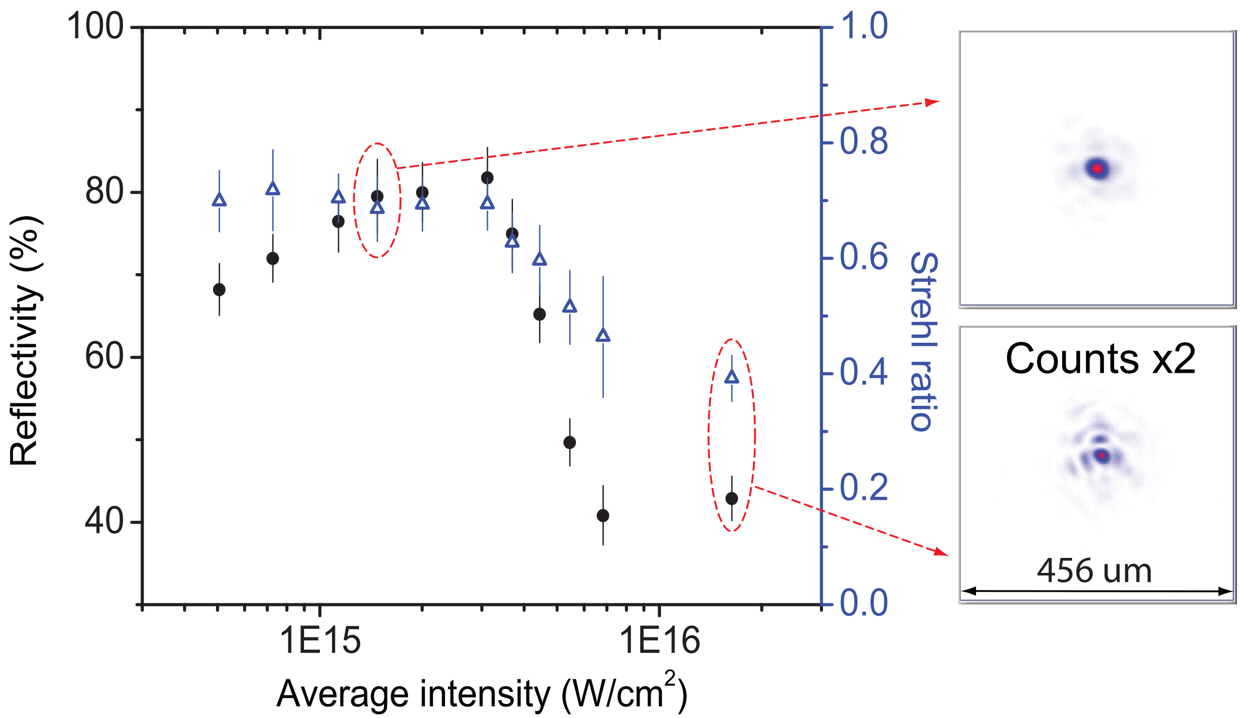
Tape drive based plasma mirror characterized

Laser coupling

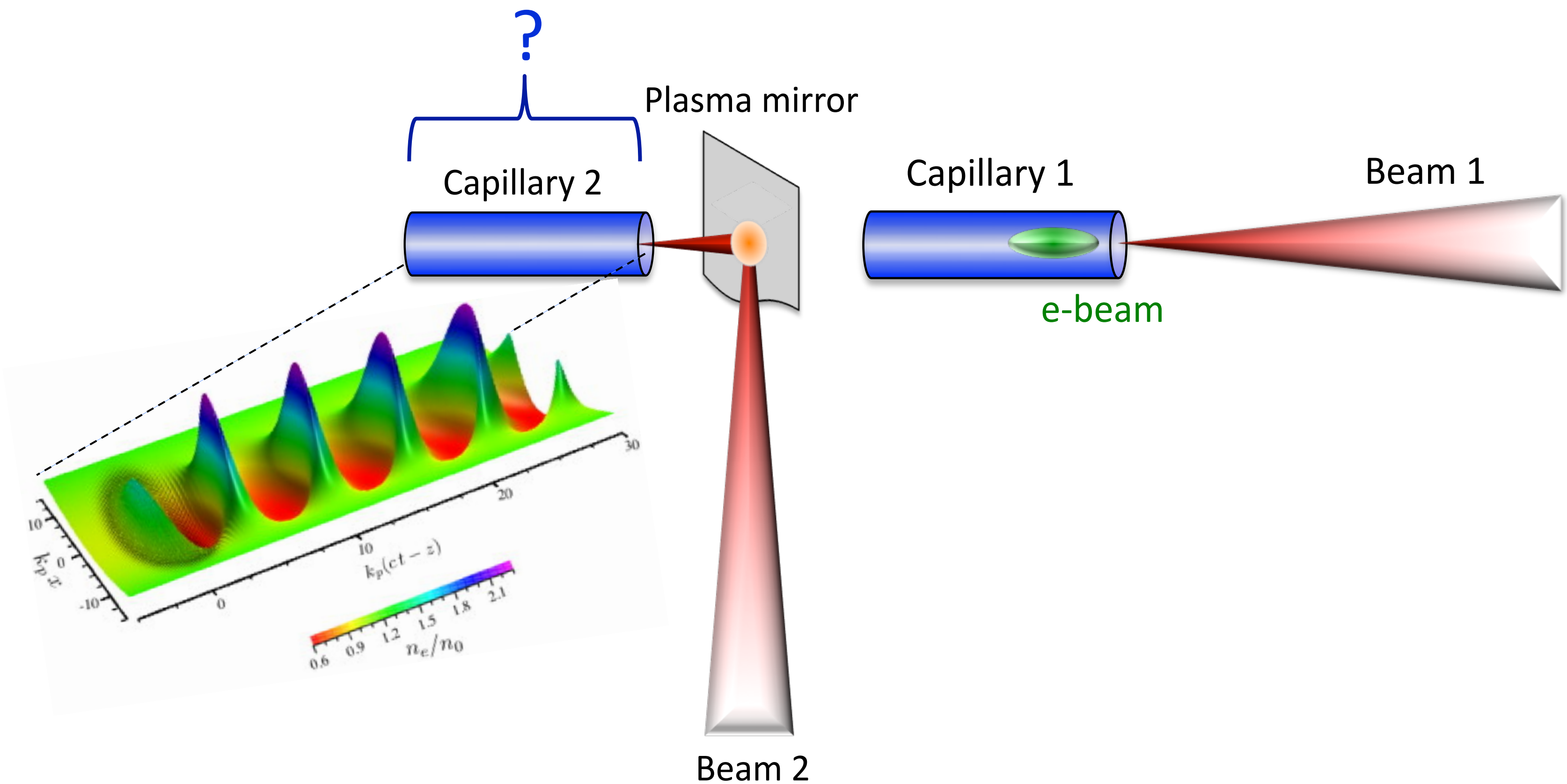
- Reflectivity and mode quality optimized







What is the energy gain expected from 2nd module?



S. Shiraishi et al., Phys. Plasmas **20** (2013).
C. Benedetti et al., AIP Conf. Proc. **1299**, 250 (2010).
B. A. Shadwick et al., Phys. Plasmas **16** (2009).

Optical spectra analyzed as wakefield diagnostic

Acceleration module

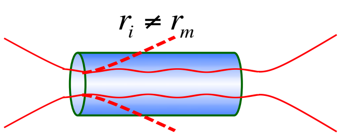
- Spectral shifts correlates with laser energy transferred into plasmas

$$\frac{\partial \left(\bar{k}/k_0\right)}{\partial z} = -\frac{k_P^2}{k_0^2}\left(\frac{E_{max}}{E_0}\right)^2$$

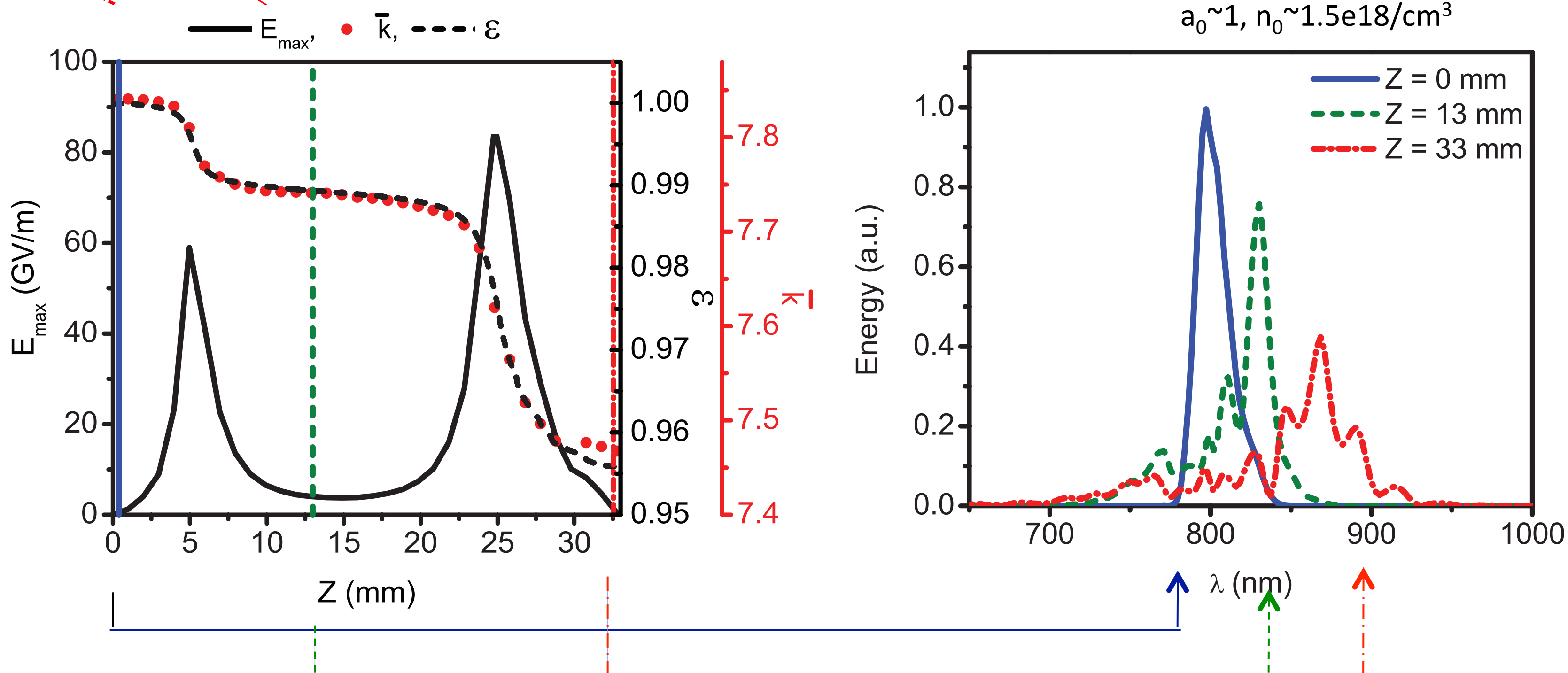
Change in laser energy
$\bar{k}/k_0 \sim \varepsilon$

Wakefield amplitude

Mismatched guiding



INF&RNO PIC simulation
a_0~1, n_0~1.5e18/cm^3



S. Shiraishi et al., Phys. Plasmas **20** (2013).
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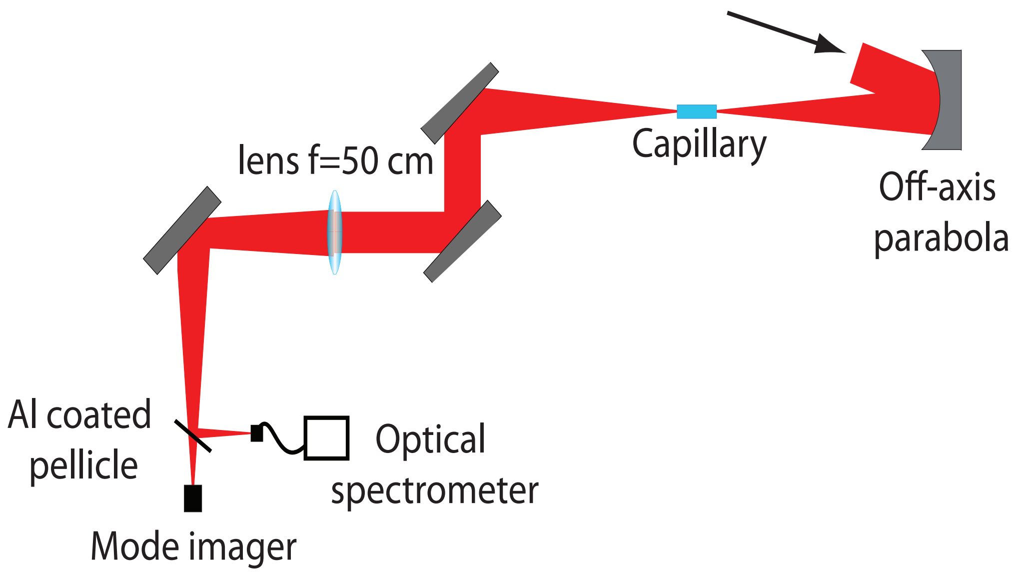
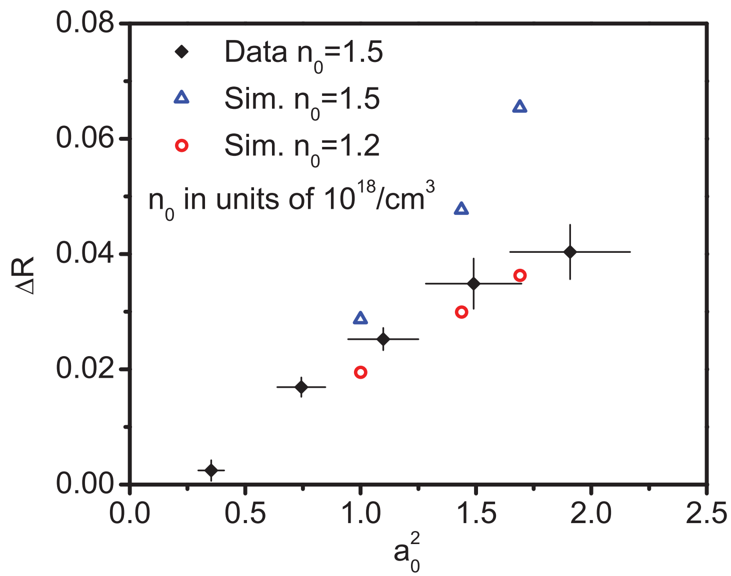
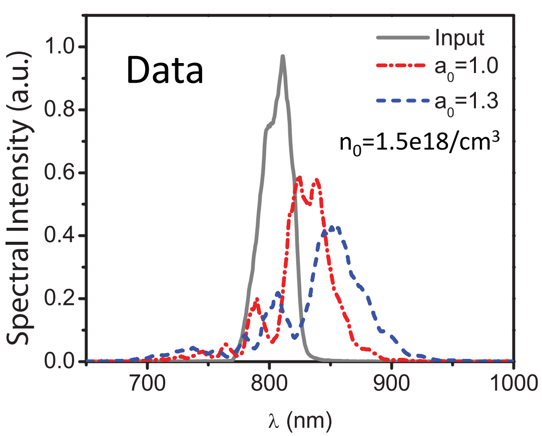
Data agrees with simulation within uncertainty

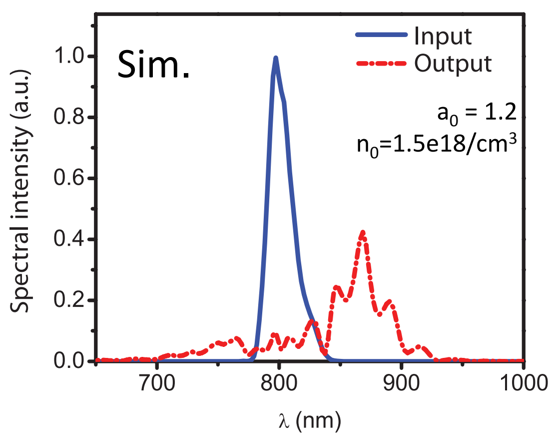
- Experimental setup



- INF&RNO PIC simulation performed to assist in interpretation of data







$$\Delta R = 1 - \bar{k} / k_0$$

E_z estimated for experimental data using simulation

Acceleration module

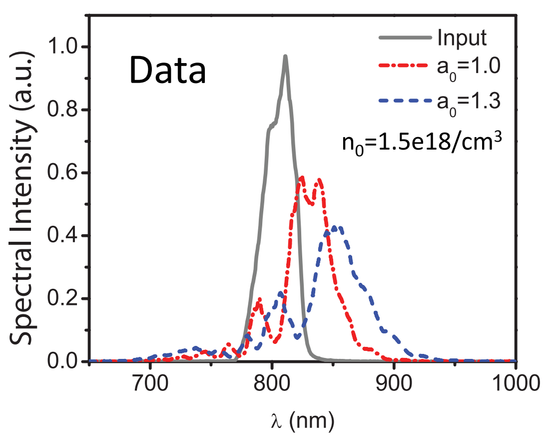
- Various experimental parameters studied for efficiency of laser energy transfer

  - Laser energy
  - Plasma density
  - Laser temporal profile
  - Laser focus position & estimated longitudinal density profile

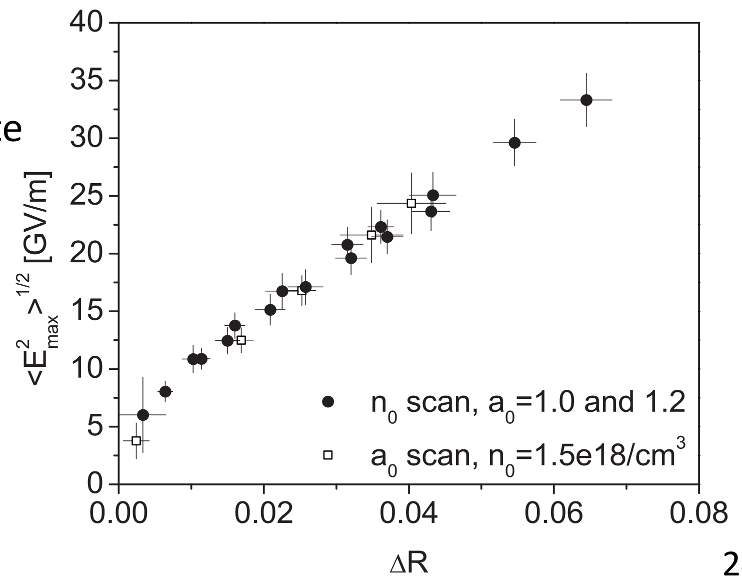
Input to simulation
Data & Sim. agree within uncertainty

  - Laser spatial profile

Affects wake profile but not redshift significantly



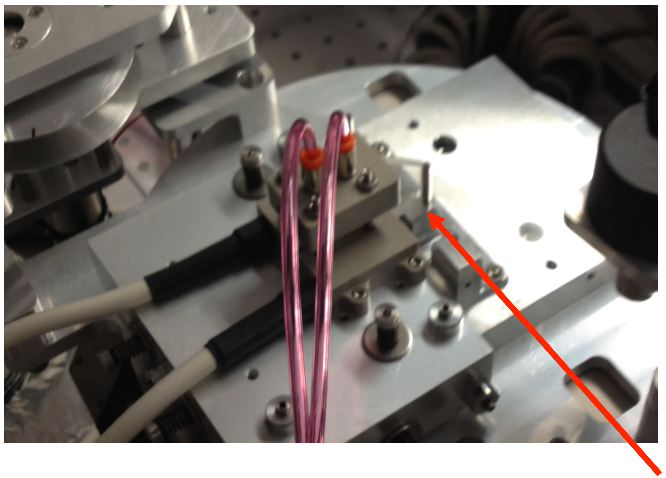
Based on measured ΔR, estimate Ez from simulation



1: S. Shiraishi et al., Accepted to Phys. Plasmas.

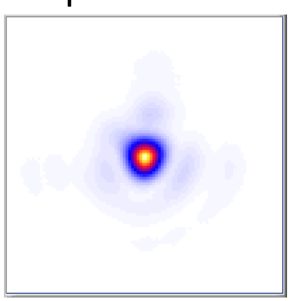
Acceleration module powered & improvements planned

- Good guiding with laser reflected off plasma mirror

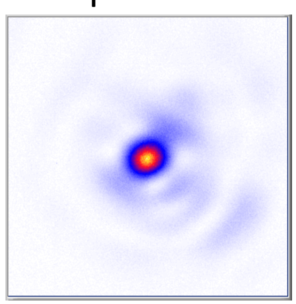


Total transmission ~65%
Plasma mirror ~75%
Guiding ~85%

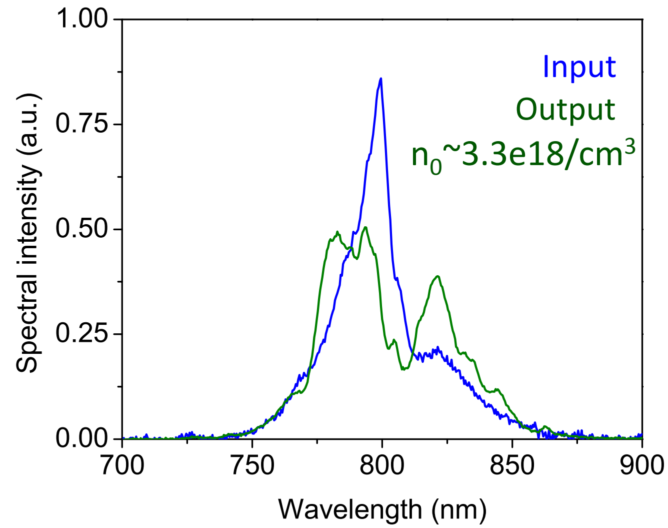
Input mode



Output mode



- Optimization of wake excitation in progress



Based on simulation <Ez> ~ 1 GV/m
(Preliminary)

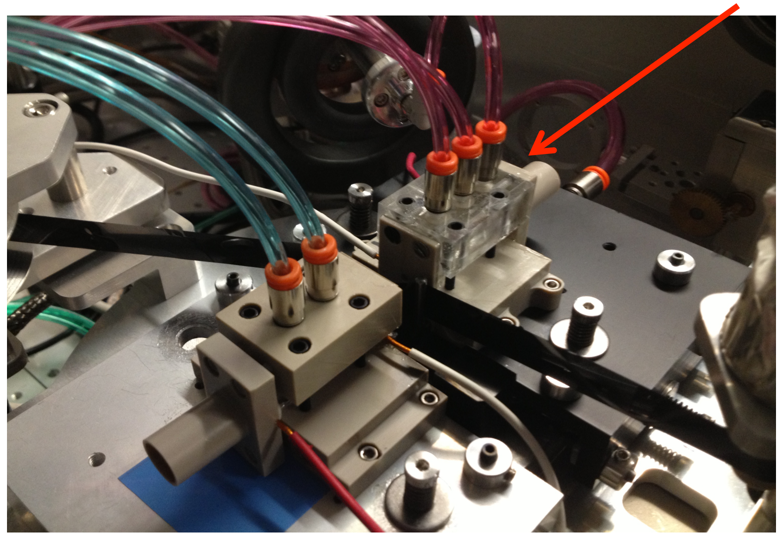
More efficient wake excitation expected with better matched guiding & optimization of pulse duration

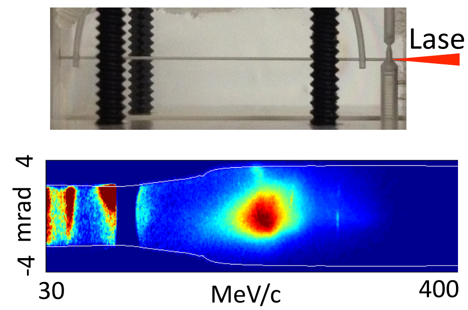
Summary and outlook of Staged LPA

Staging beamline commissioned in April 2012

- E-beam injected in acceleration module

Optimization for energy spread and shot to shot fluctuation in progress

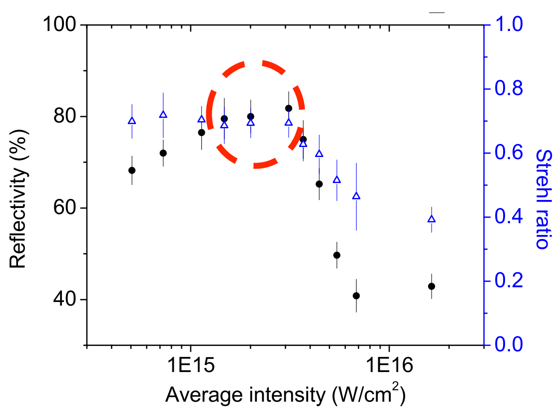




Summary and outlook of Staged LPA

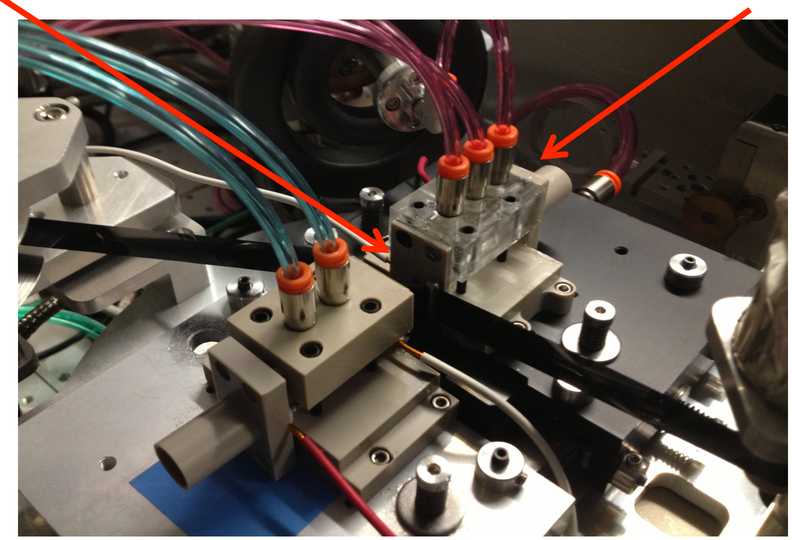
Staging beamline commissioned in April 2012

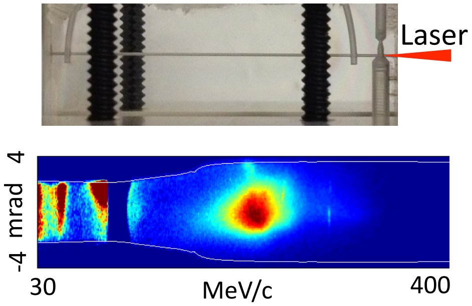
- Tape drive based plasma mirror is characterized



- E-beam injected in acceleration module

Optimization for energy spread and shot to shot fluctuation in progress





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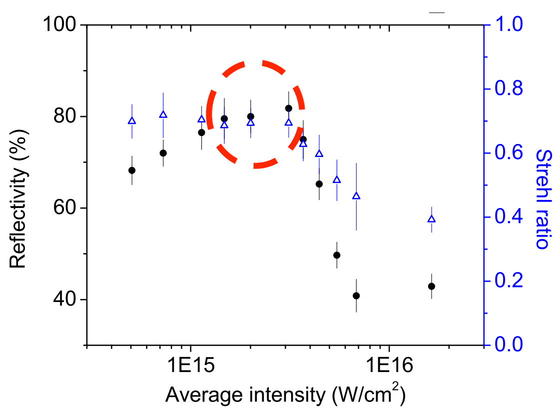

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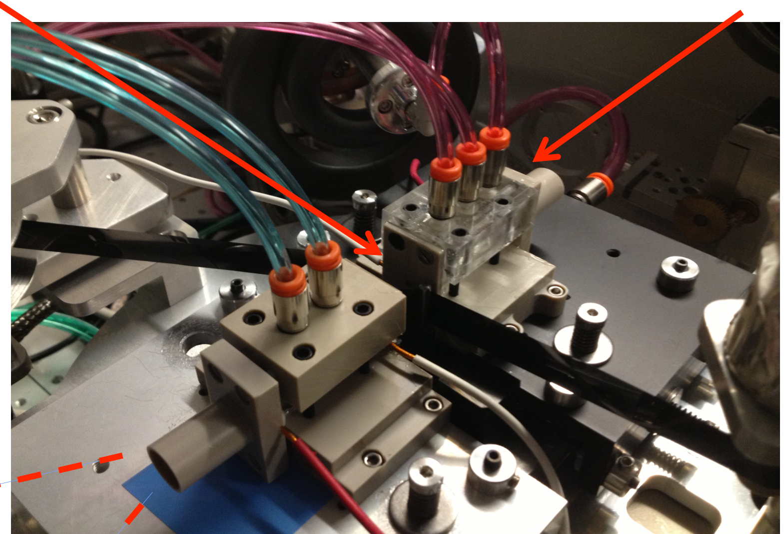
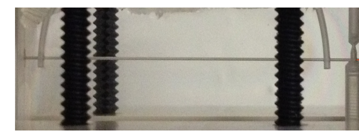
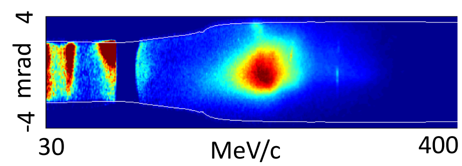
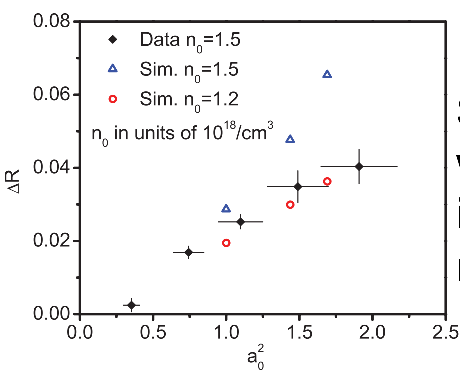






- Spectra analyzed to diagnose wake excitation



Step towards wakefield diagnostic in acceleration module

Summary and outlook of Staged LPA

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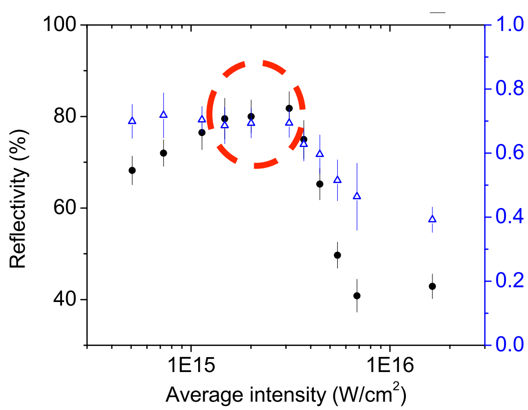

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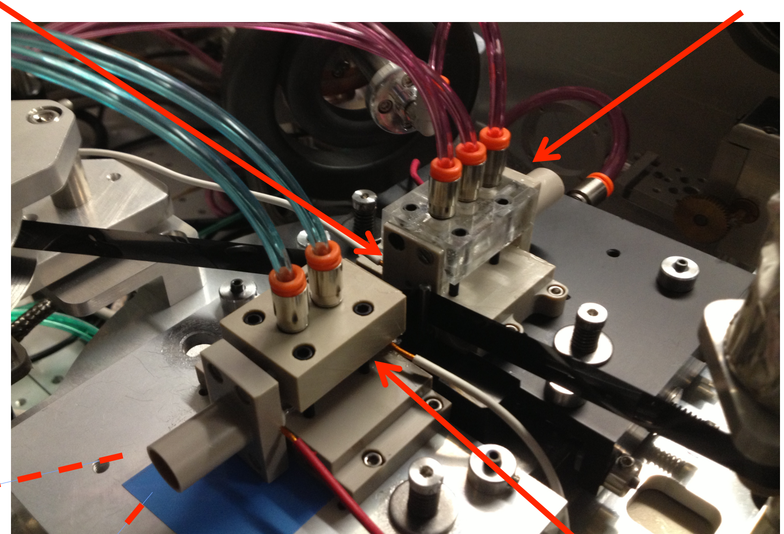

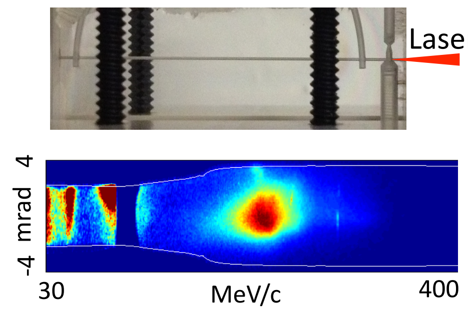

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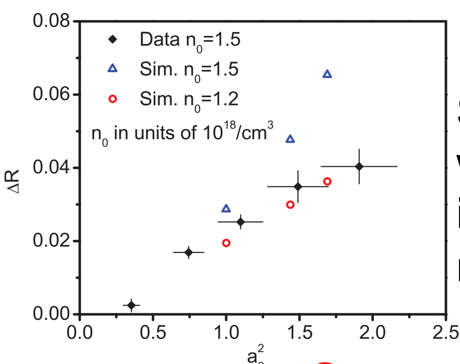
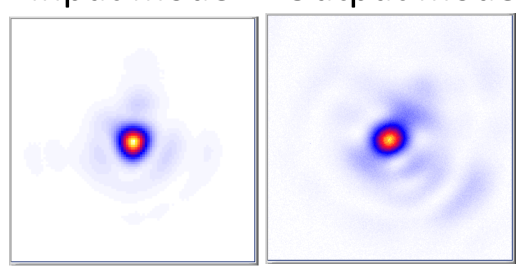


Step towards wakefield diagnostic in acceleration module

- Good guiding achieved with laser reflected off plasma mirror

Input mode Output mode



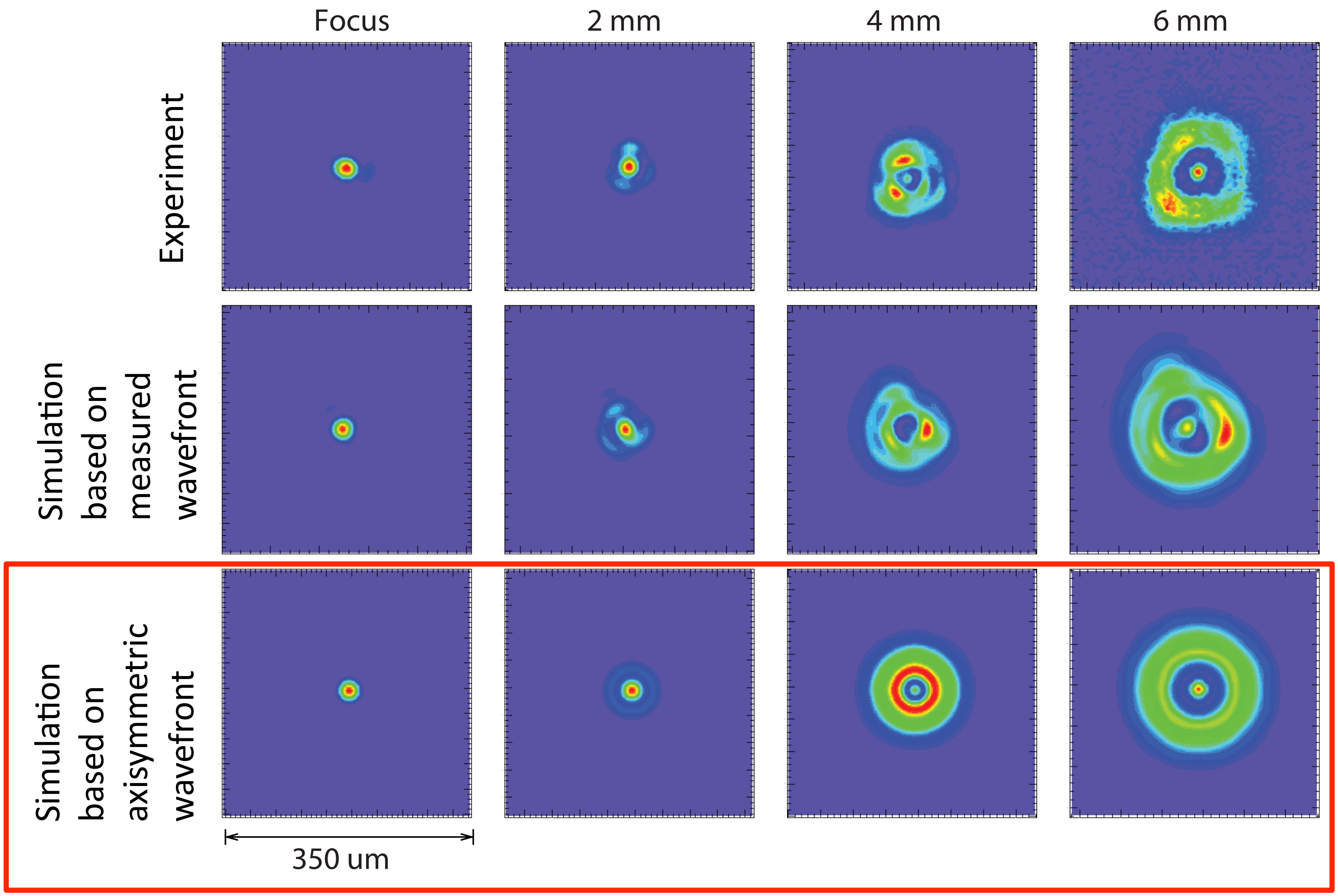
Optimization for wake excitation in progress

Staged LPA experiments following the optimizations

Various experimental parameters studied for efficiency of laser energy transfer

Acceleration module

- Experimentally used laser profile modeled and investigated



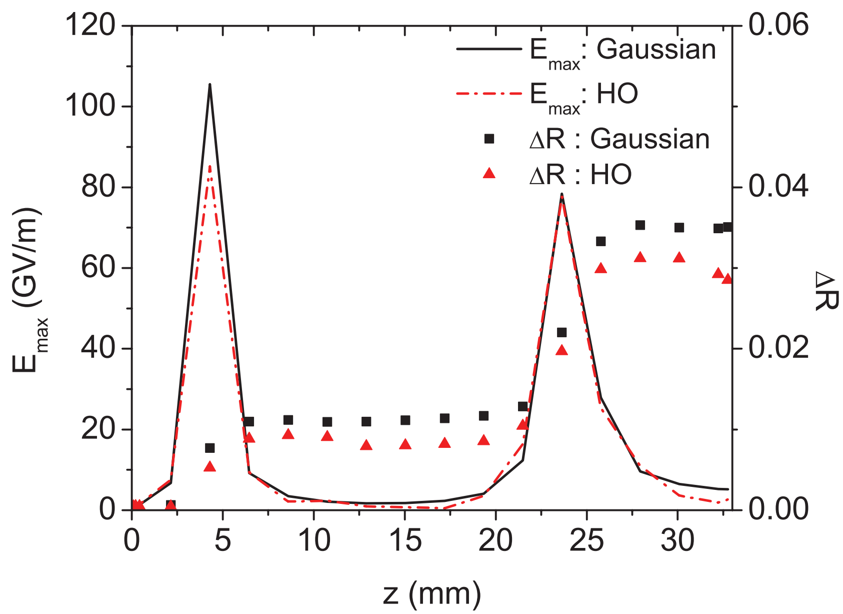
S. Shiraishi et al., Phys. Plasmas **20** (2013).
E. Cormier-Michel et al., Phys. Rev. STAB **14** (2011).

Various experimental parameters studied for efficiency of laser energy transfer

Acceleration module

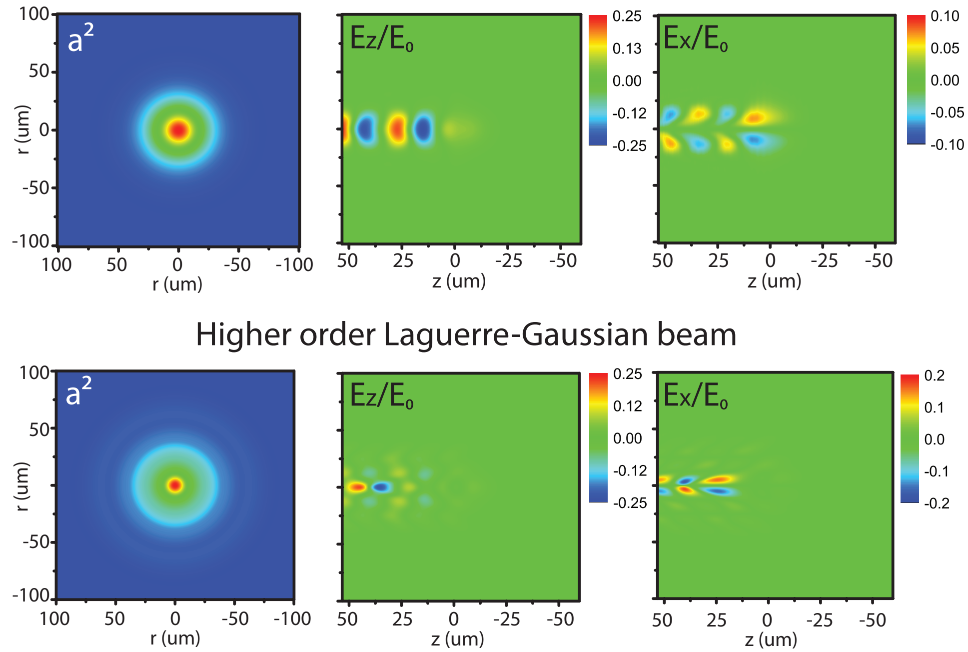
- Spatial profile affects wake profile but not redshift

Peak Ez & redshift similar for both profiles



Wakefield structures very different

Gaussian beam

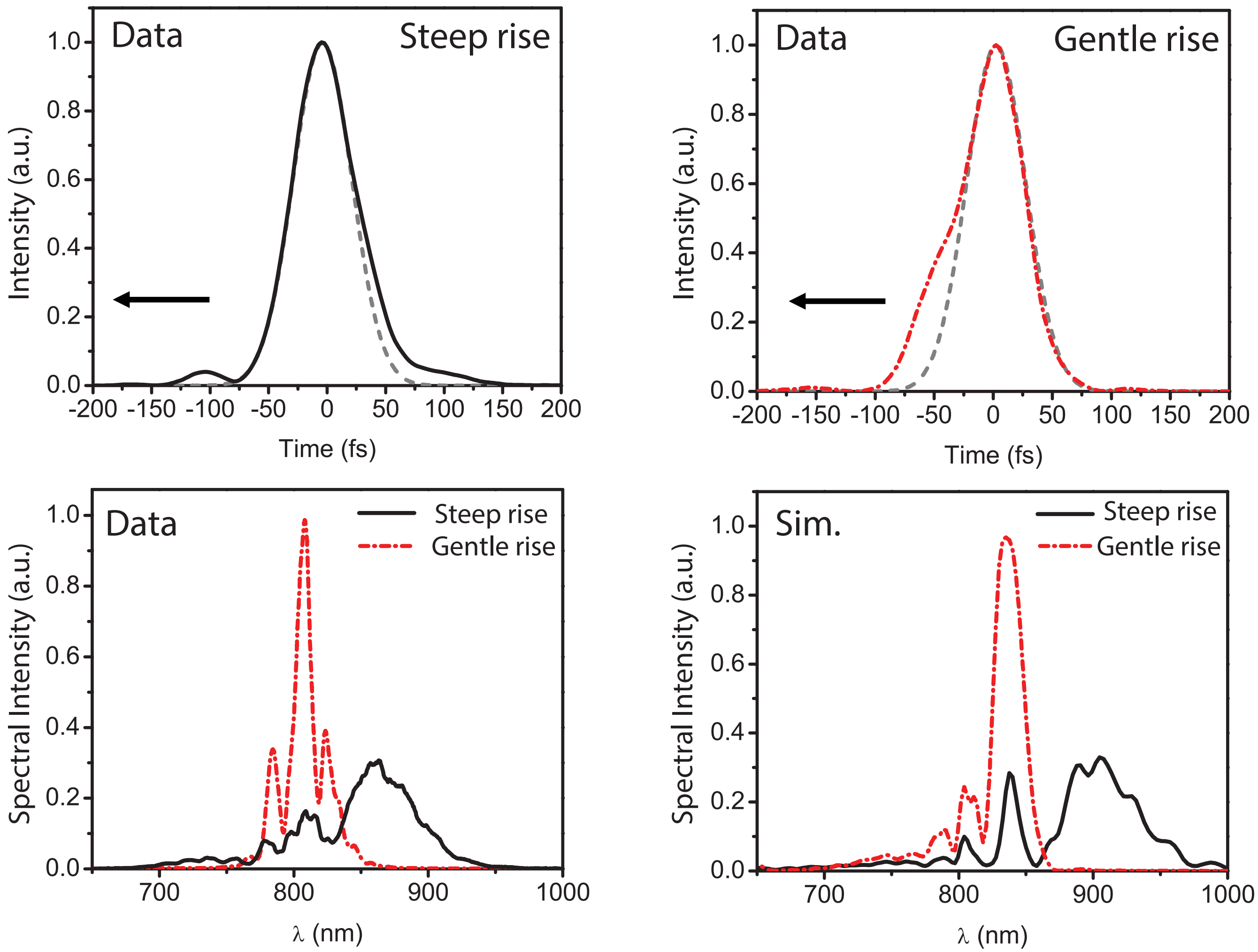


S. Shiraishi et al., Phys. Plasmas **20** (2013).
E. Cormier-Michel et al., Phys. Rev. STAB **14** (2011).

Various experimental parameters studied for efficiency of laser energy transfer

Acceleration module

- Laser temporal pulse shape affects wake excitation significantly



S. Shiraishi et al., Phys. Plasmas **20** (2013).
W. P. Leemans et al., Phys. Rev. Lett. 89 (2002).
C. B. Schroeder et al., Phys. Plasmas **10** (2003).

Step towards understanding and control of plasma wakefield

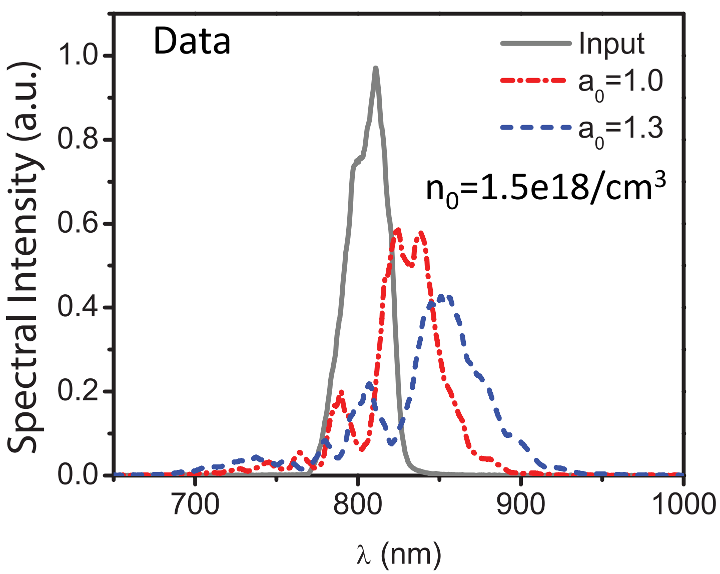
Acceleration module

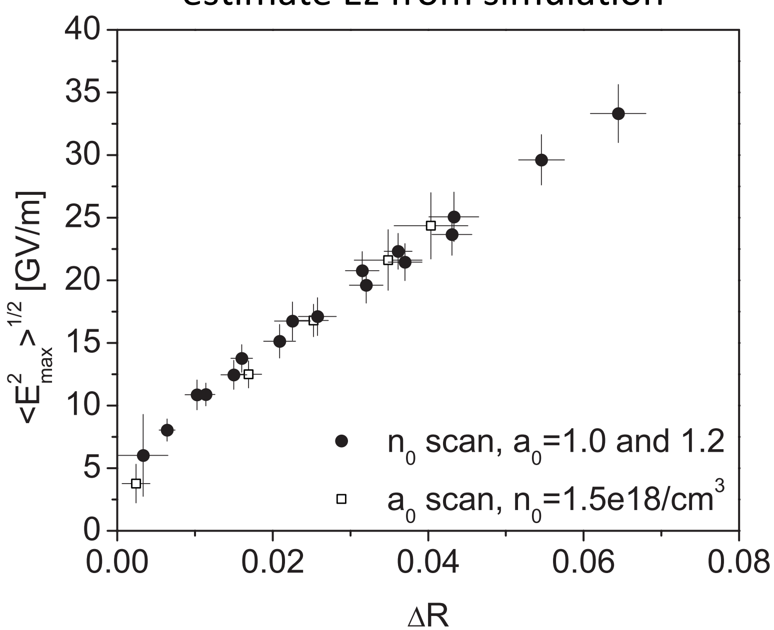
- Step towards better understanding wake excitation and structures, particularly comparing experiment and simulations

  - Laser energy
  - Plasma density
  - Laser temporal profile
  - Laser focus position & estimated longitudinal density profile

Input to simulation
Data & Sim. agree within uncertainty

Based on experimentally measured ΔR, estimate Ez from simulation





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