Experimental Progress on Staged Laser-Plasma Acceleration

Satomi Shiraishi

T. Sokollik, C. Benedetti, A. J. Gonsalves, N. H. Matlis, K. Nakamura, B. H. Shaw, S. Steinke, J. van Tilborg, C. G. R. Geddes, C. B. Schroeder, C. Toth, E. Esarey, & W. P. Leemans

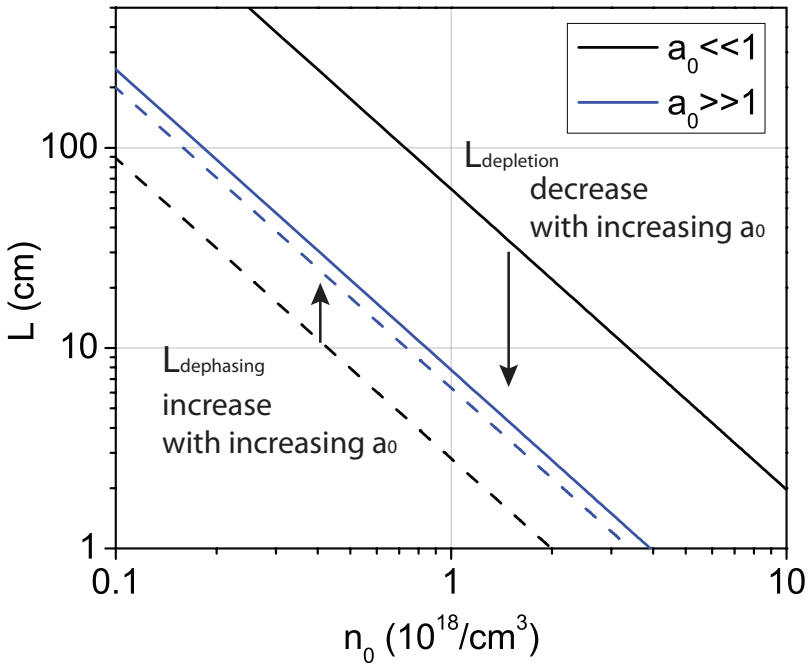
Lawrence Berkeley National Laboratory

NSF
DEFENSE THREAT REDUCTION AGENCY
U.S. DEPARTMENT OF ENERGY | Office of Science
BERKELEY LAB
Lawrence Berkeley National Laboratory

Outline

- Why staged LPA is necessary
- Staging experiment at LOASIS Program, LBNL
- Initial experimental results on:
    - Injection module
    - Plasma mirror for coupling laser pulses
    - Acceleration module
- Summary

Energy gain in a single stage LPA is limited



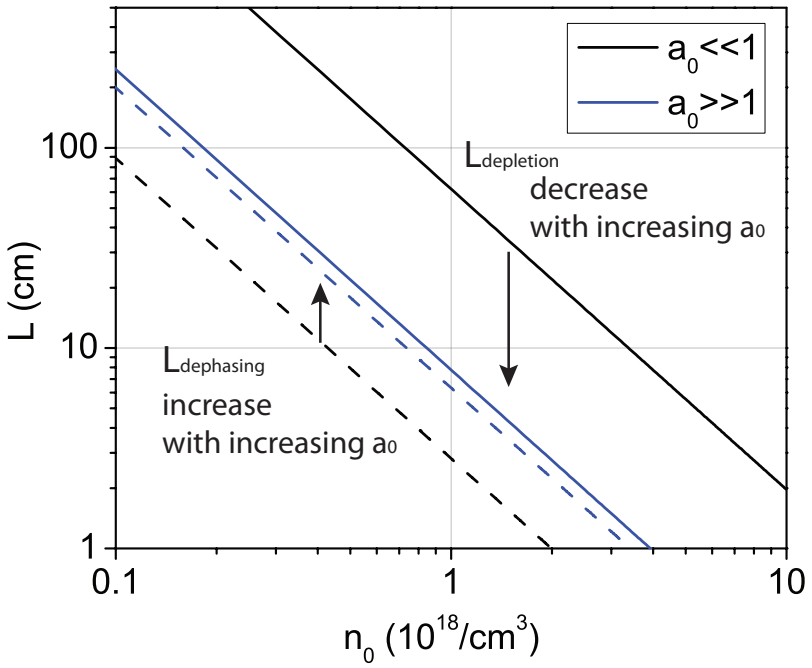
Dephasing:

- Relativistic e^- outrunning the plasma wave

Depletion:

- Driving laser loses energy to plasma

Energy gain in a single stage LPA is limited



Dephasing:

- Relativistic e^- outrunning the plasma wave

Depletion:

- Driving laser loses energy to plasma

Linear ($a_0 << 1$):
$L_d << L_{pd}$, no injection

Quasi-linear ($a_0 \sim 1$):
$L_d \sim L_{pd}$, no injection

Non-linear ($a_0 >> 1$):
$L_d \sim L_{pd}$, self-trapping

Optimal acceleration length ~ L_d ~ L_{pd}

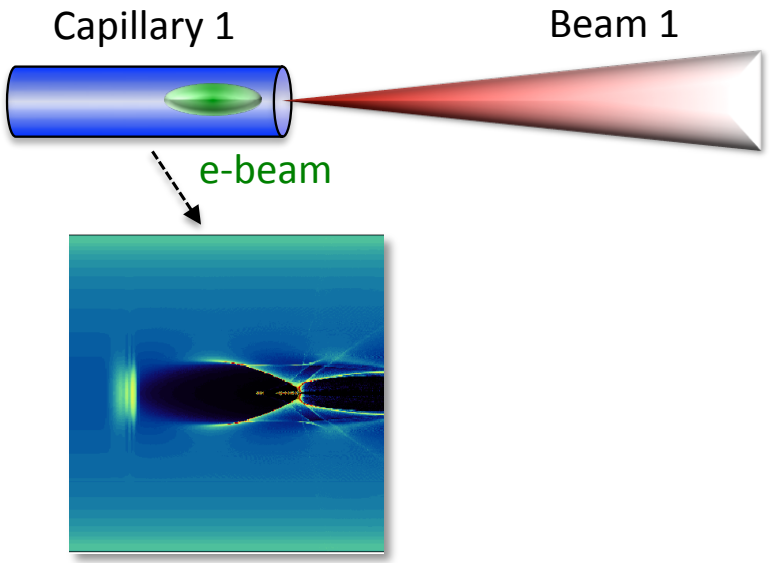
Total energy gain is limited: $\Delta W = eE_z L_{acc}$

$\propto f(a)\, 1/n_e$

Staging experiment requires precision

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

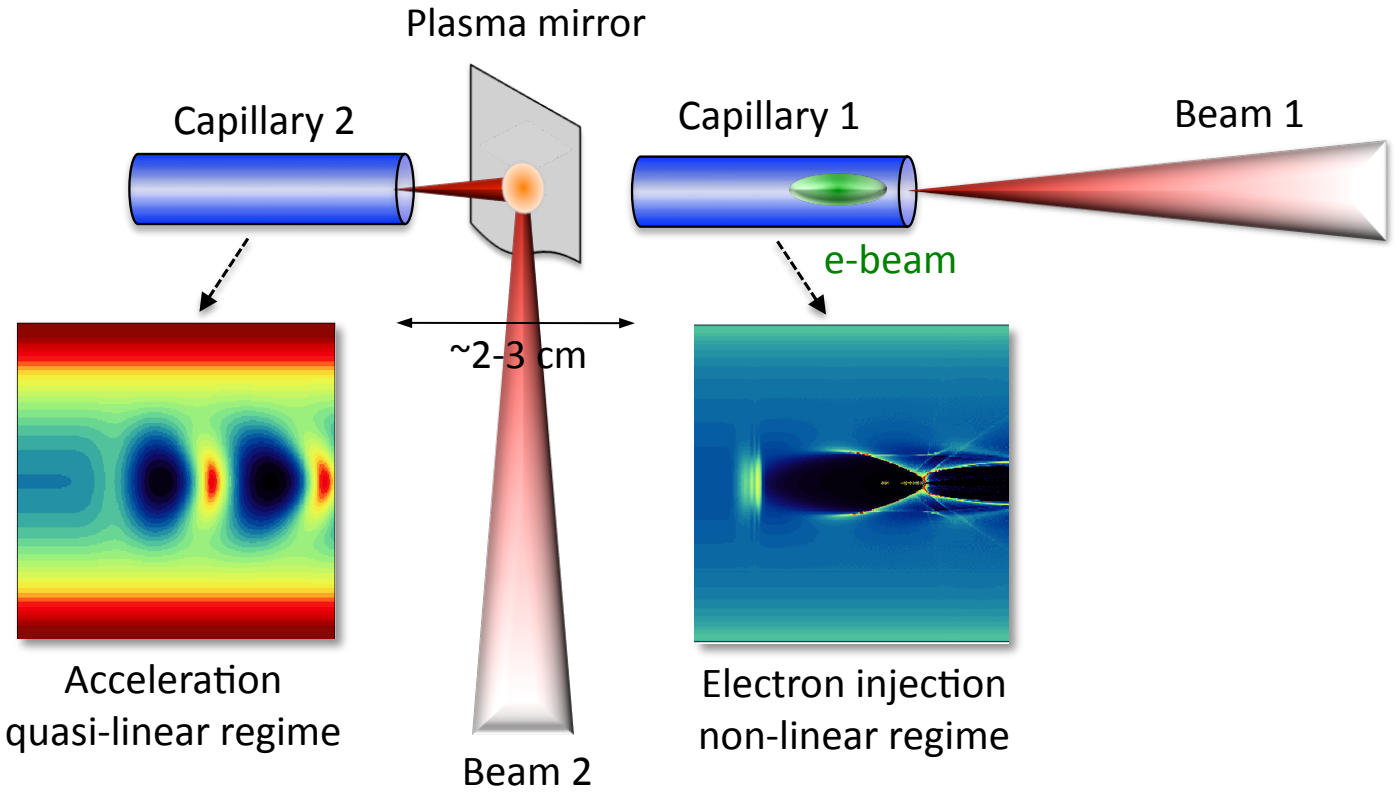
- Challenges:
  - Laser spatial overlap ~um
  - Temporal overlap ~ fs
  - Two capillary + plasma mirror operation



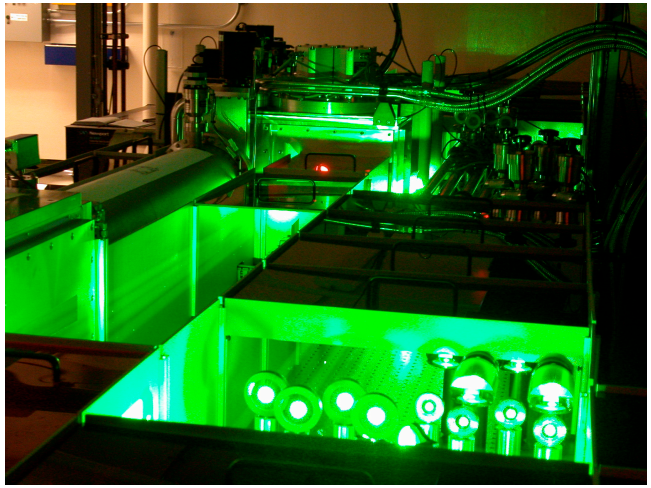
Electron injection
non-linear regime

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



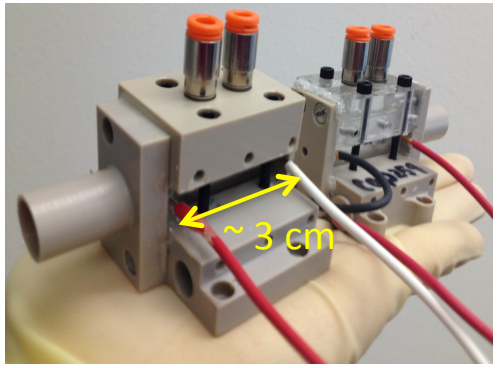
Experimental setup installed and ready



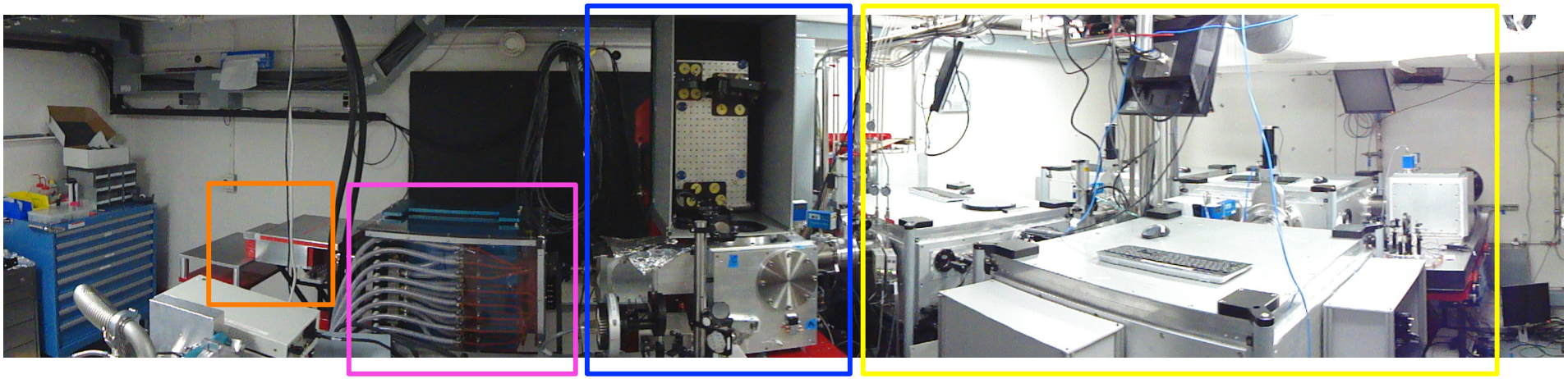
TREX laser

- 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

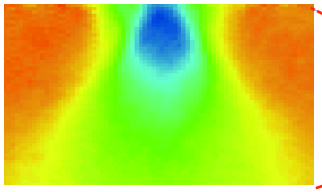
Interaction chamber and beam transport chambers

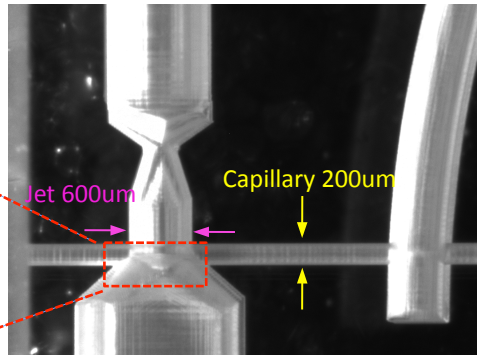
Electron injected -- Optimization in progress

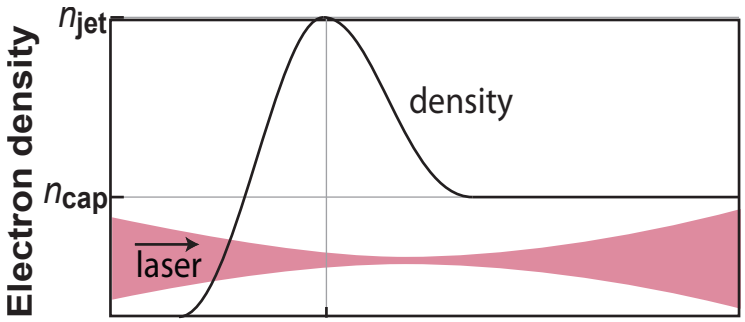
Injection module

- Gas jet implemented to control injection

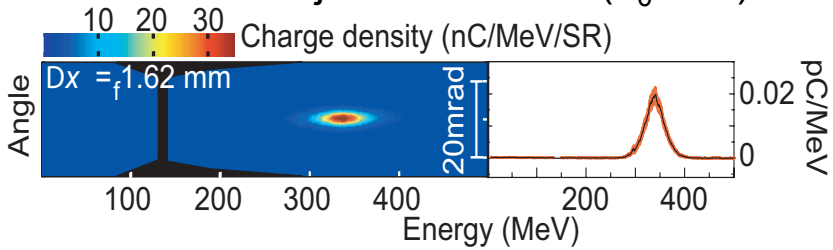
Jet density profile characterized







Stable injection at 1.4 J (a_0~1.5)



A. J Gonsalves et al., Nature Physics **7** (2011)

Q ~ 1 pC

E ~ 340 MeV

$\Delta E/E$ ~ 5%

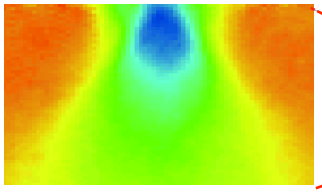
σ_θ ~ 1 mrad

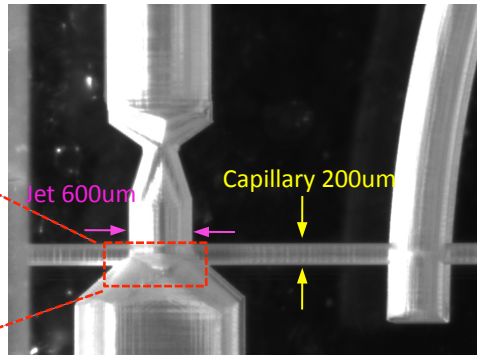
Electron injected -- Optimization in progress

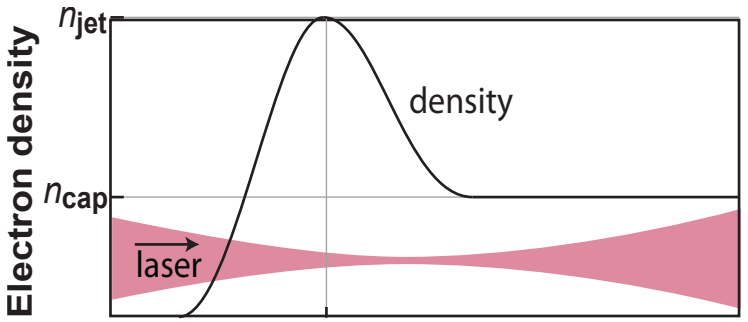
Injection module

- Gas jet implemented to control injection

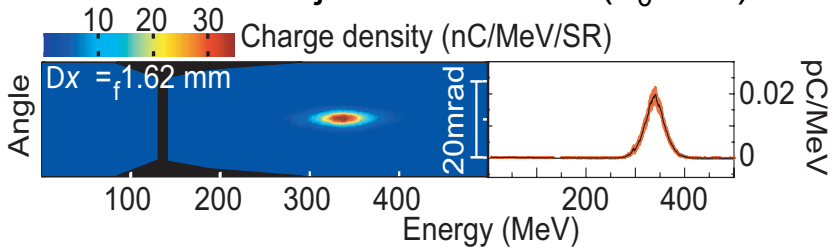
Jet density profile characterized







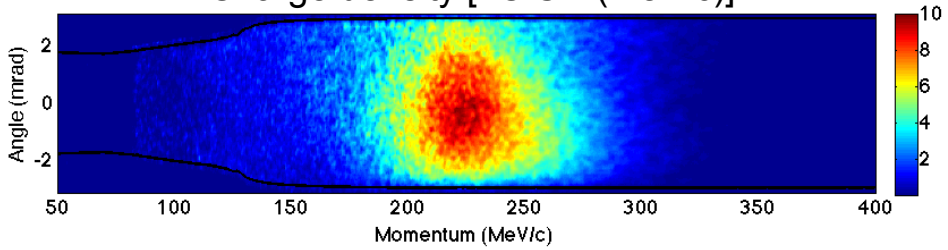
Stable injection at 1.4 J (a_0~1.5)

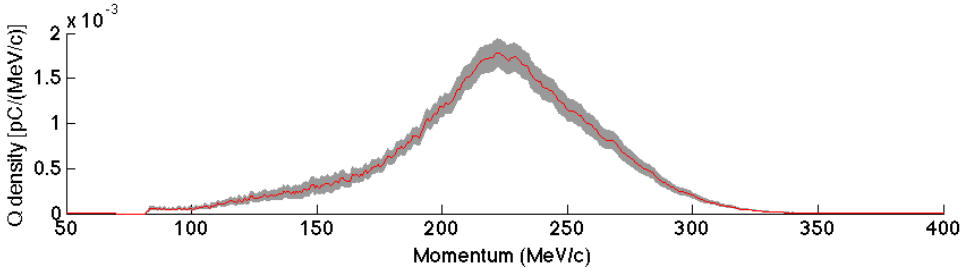


A. J Gonsalves et al., Nature Physics **7** (2011)

Injection at 1 J (a_0 ~ 1.3)

Charge density [nC/SR/(MeV/c)]



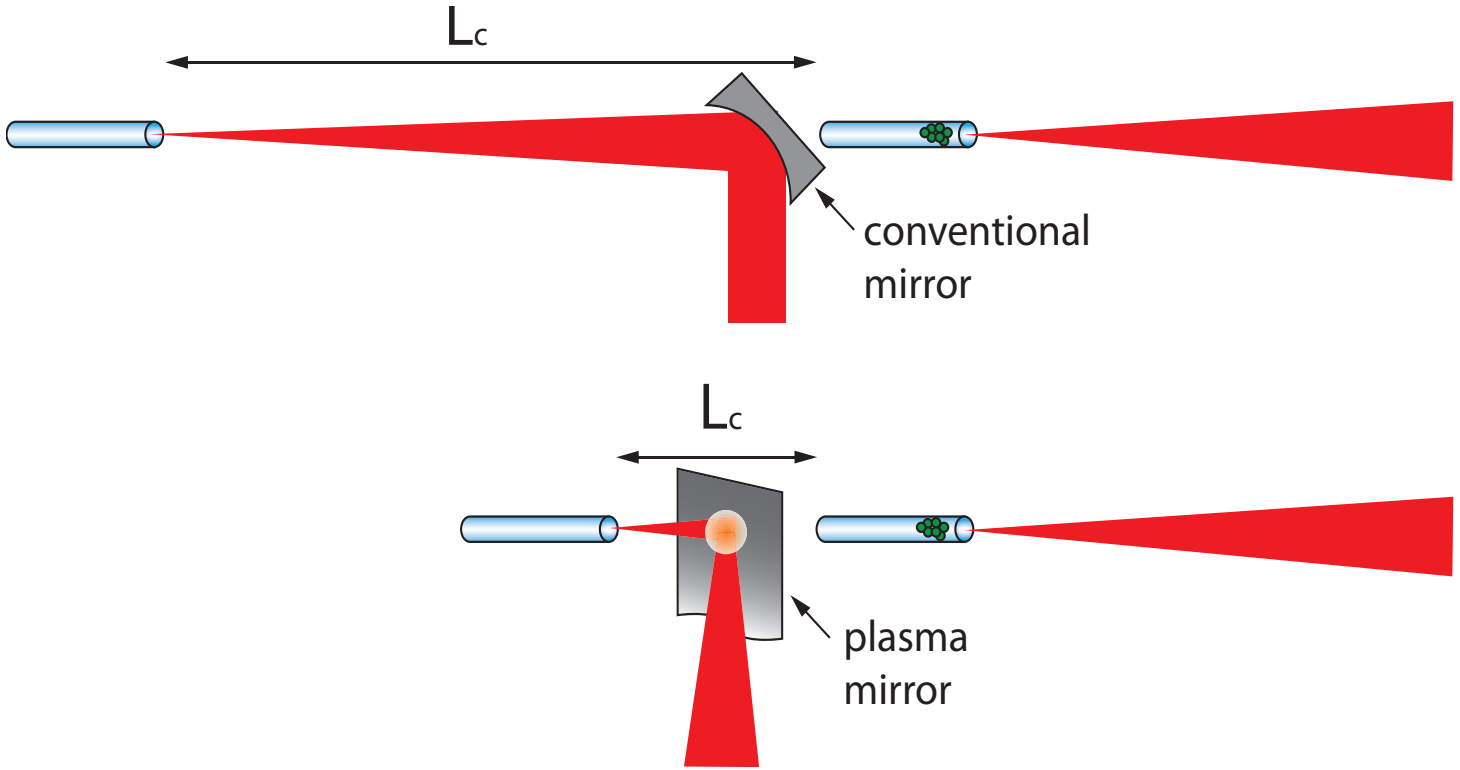


Q ~ 0.15 pC
E ~ 220 MeV
$\Delta E/E$ ~ 15%
σ_θ ~ 1.4 mrad

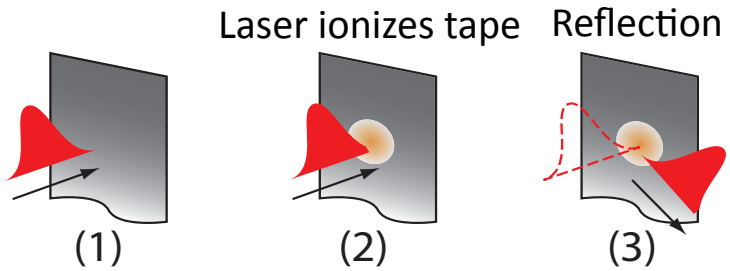
Q ~ 1 pC
E ~ 340 MeV
$\Delta E/E$ ~ 5%
σ_θ ~ 1 mrad

Plasma mirror used to reduce coupling distance

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



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



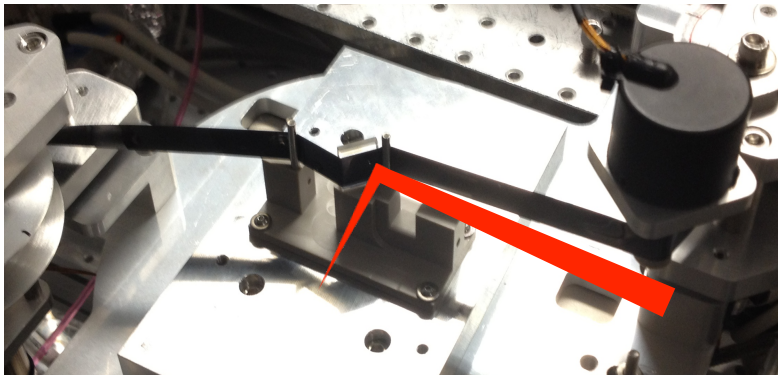
$$n_R = \sqrt{1 - \frac{\omega_P^2}{\omega_L^2}}$$

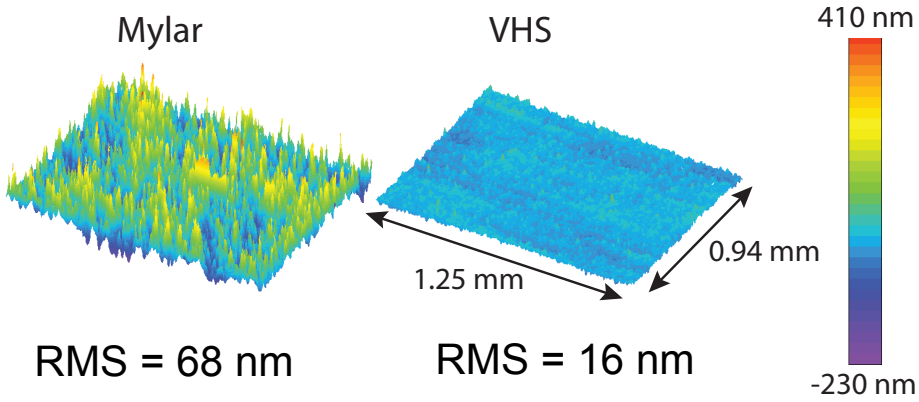
Panasenko, D. et. al., J. Appl. Phys. **108** (2010).

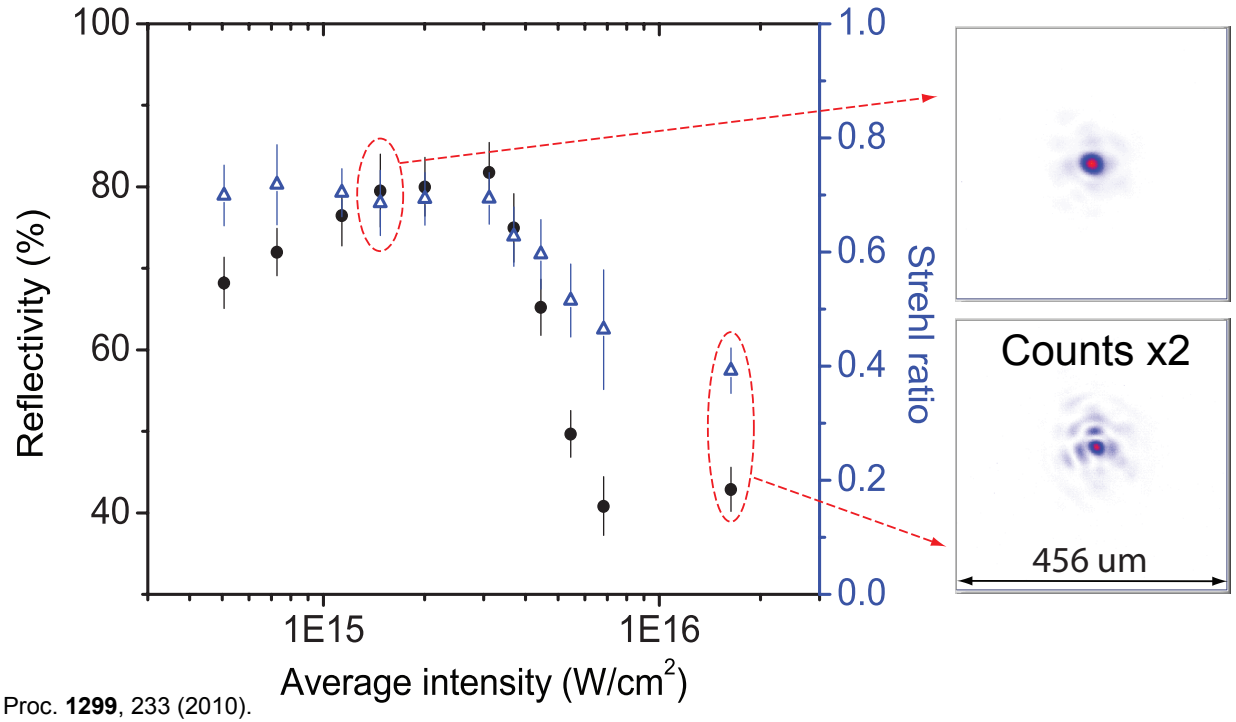
Tape drive based plasma mirror characterized

Laser coupling

- Reflectivity and mode quality optimized



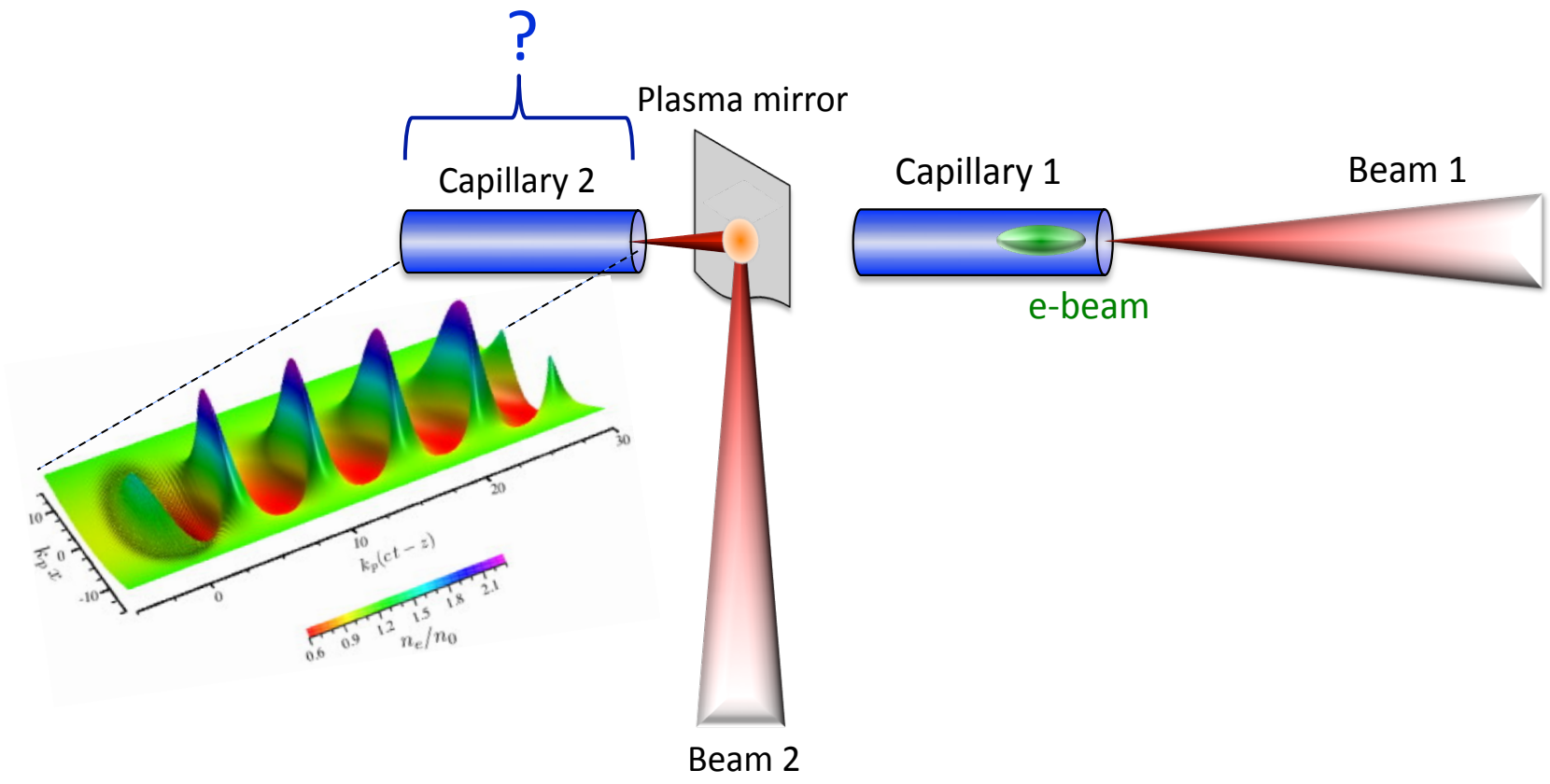




T. Sokollik et al., AIP Conf. Proc. **1299**, 233 (2010).

What is the energy gain expected from 2nd module?

Acceleration module



Optical spectra analyzed as wakefield diagnostic

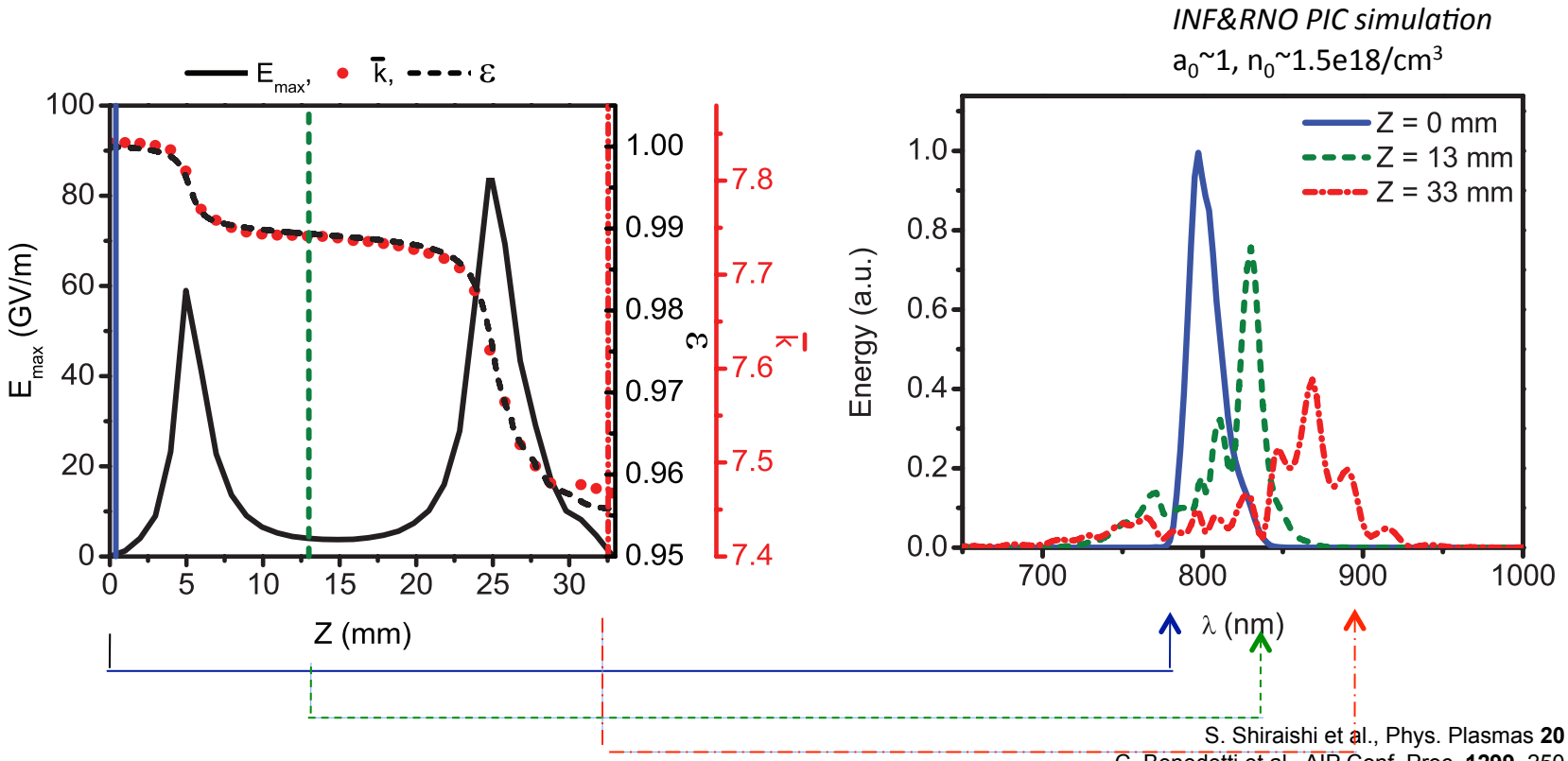
Acceleration module

- 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



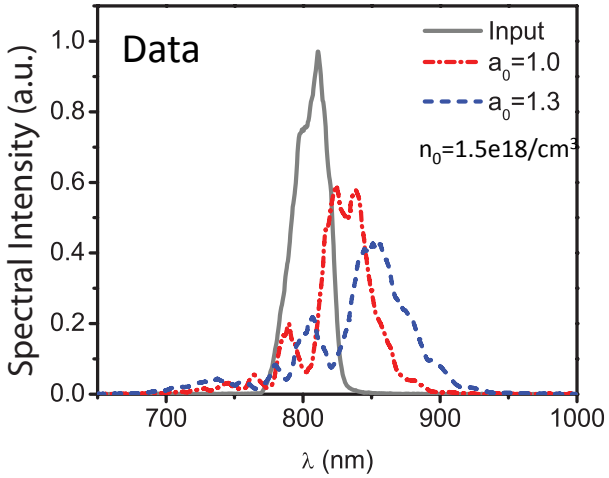
S. Shiraishi et al., Phys. Plasmas **20** (2013).
C. Benedetti et al., AIP Conf. Proc. **1299**, 250 (2010).
B. A. Shadwick et al., Phys. Plasmas **16** (2009).

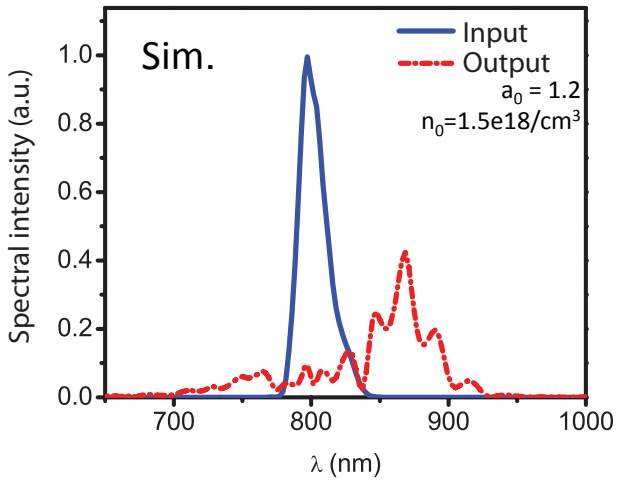
Data agrees with simulation within uncertainty

Acceleration module

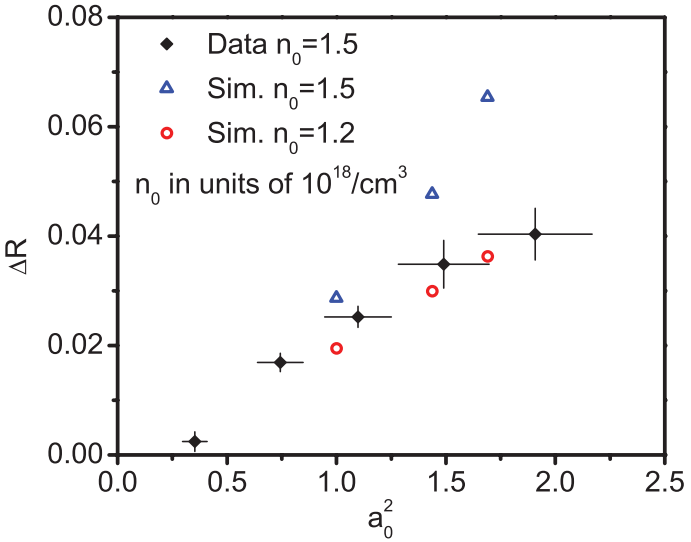
- INF&RNO PIC simulation performed to assist in interpretation of data

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





Data & Sim. agree within uncertainty

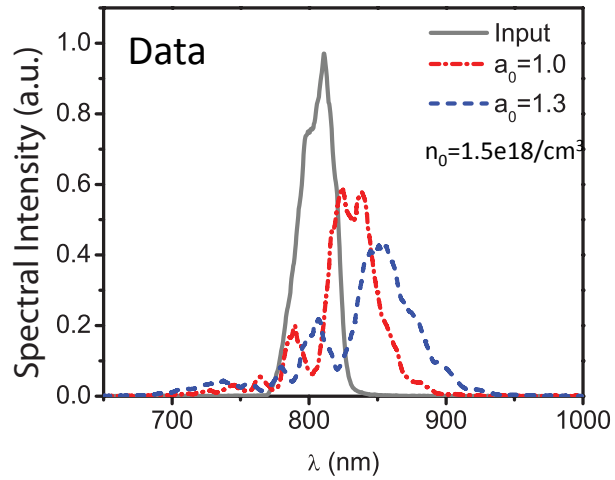


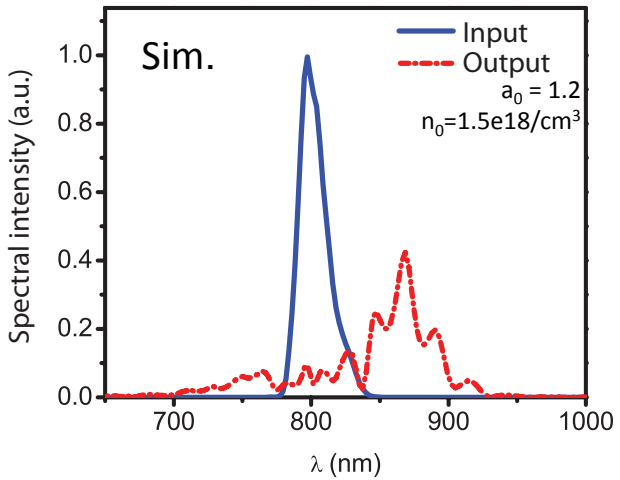
Data agrees with simulation within uncertainty

Acceleration module

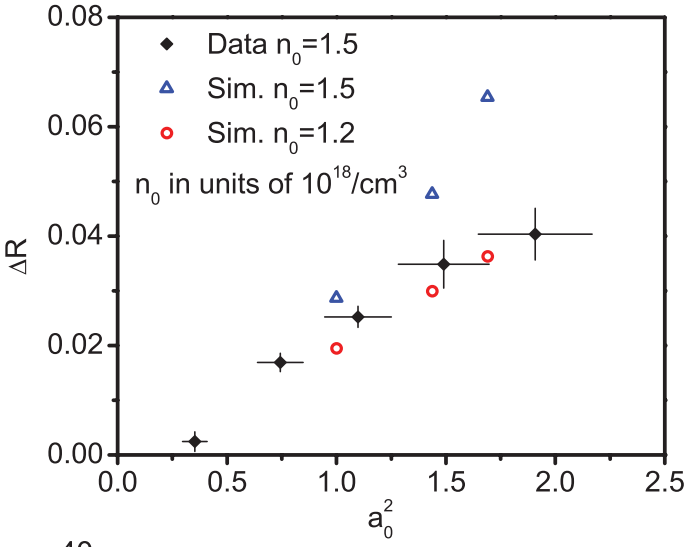
- INF&RNO PIC simulation performed to assist in interpretation of data

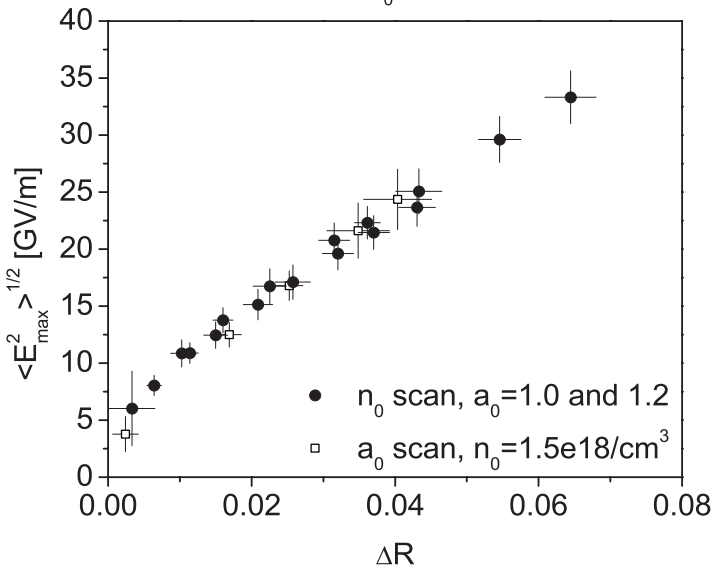
$$\Delta R = 1 - \bar{k}/k_0$$





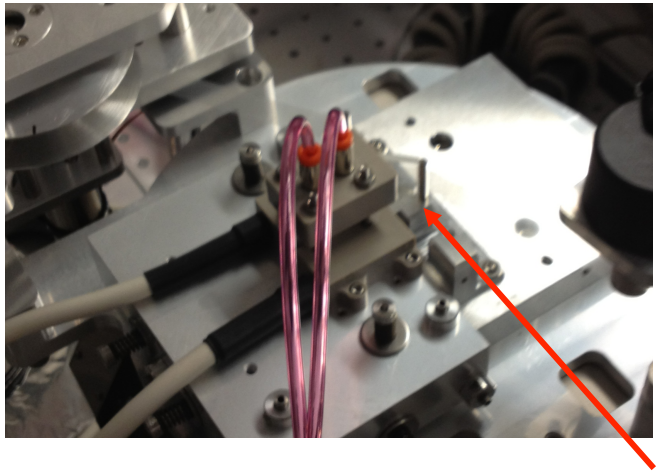
Data & Sim. agree within uncertainty





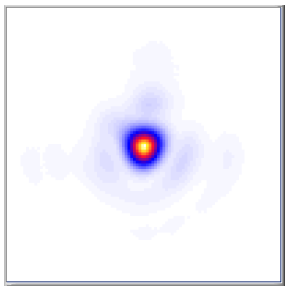
Acceleration module powered & improvements planned

- Good guiding with laser reflected off plasma mirror

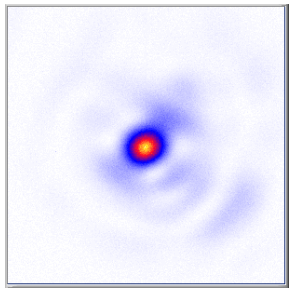


Total transmission ~73%
Plasma mirror ~80%
Guiding ~91%

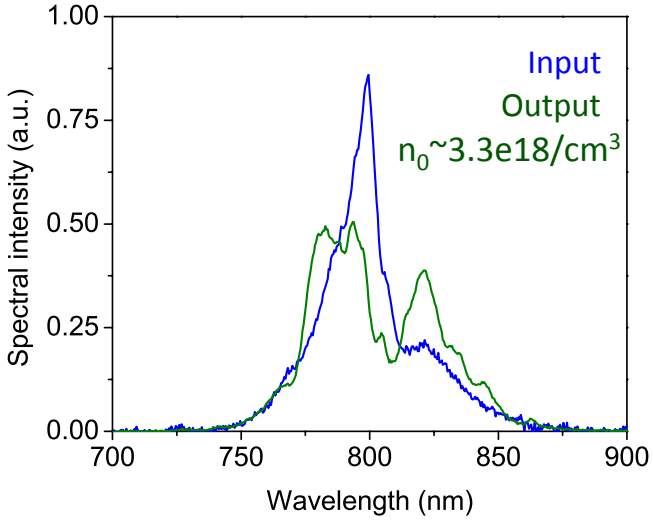
Input mode



Output mode



- Optimization of wake excitation in progress



Based on simulation <Ez> ~ 1 GV/m

(Preliminary)

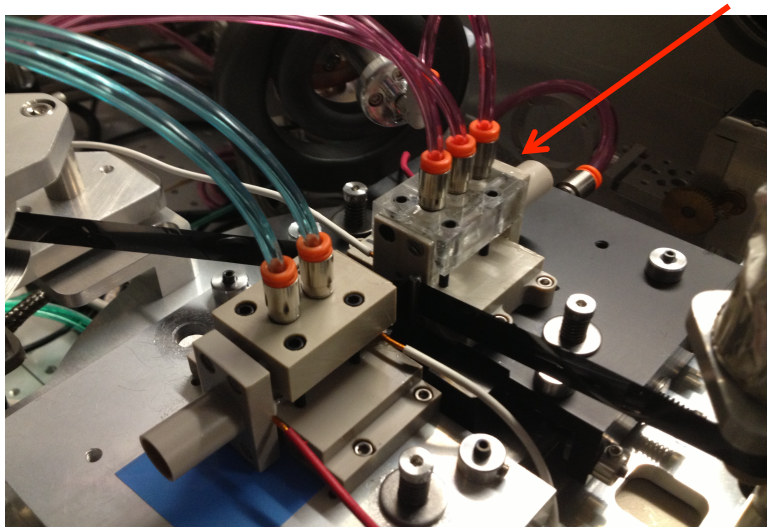
Laser pulses were modulated from splitting process

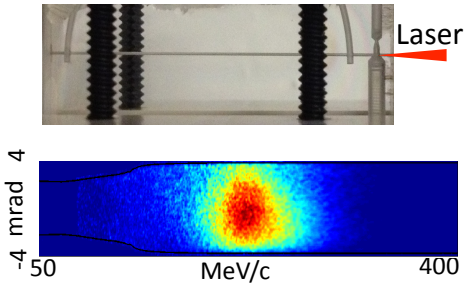
More efficient wake excitation expected with optimization of pulse duration

Summary and outlook

- E-beam injected in acceleration module

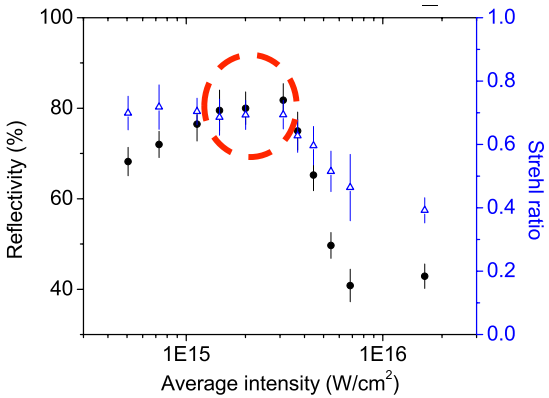
Optimization for energy spread and shot to shot fluctuation in progress





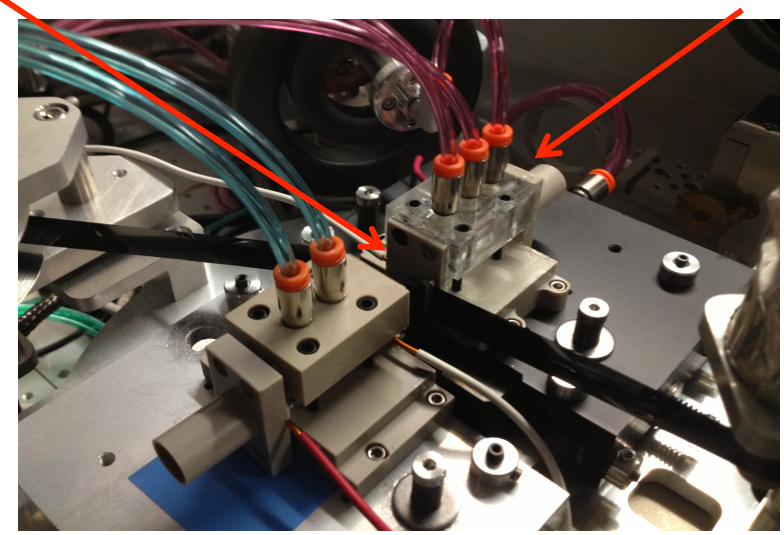
Summary and outlook

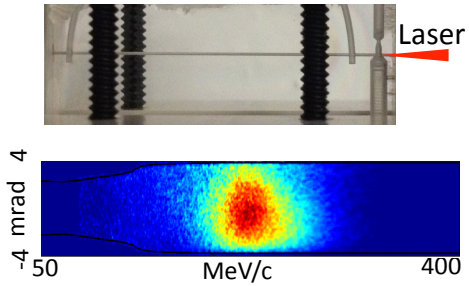
- Tape drive based plasma mirror is characterized



- E-beam injected in acceleration module

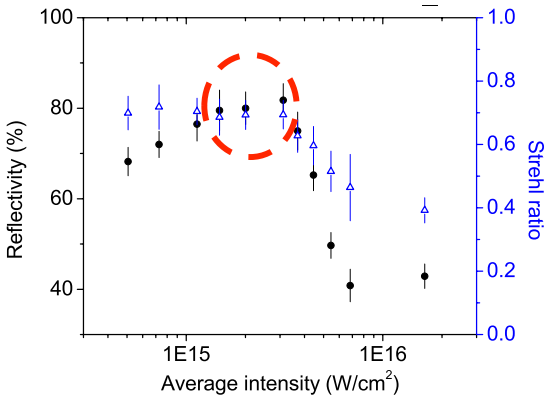
Optimization for energy spread and shot to shot fluctuation in progress





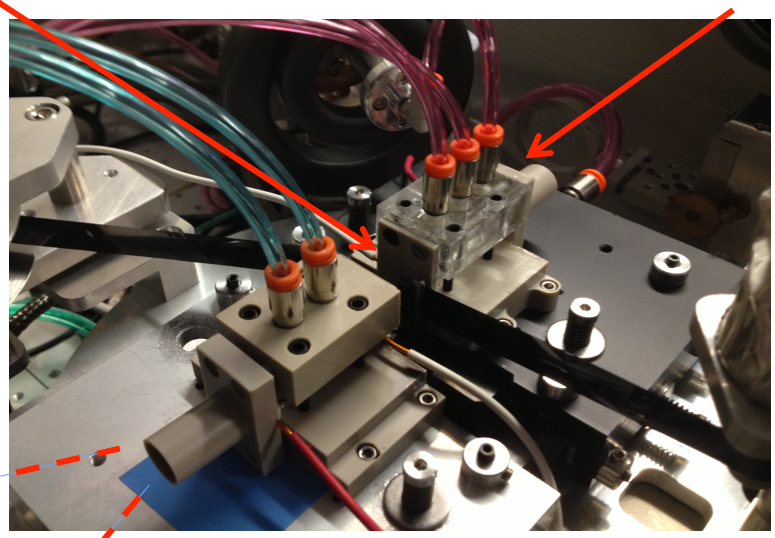
Summary and outlook

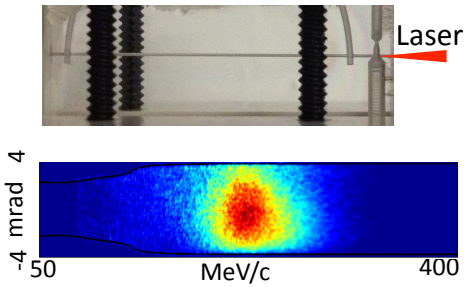
- Tape drive based plasma mirror is characterized



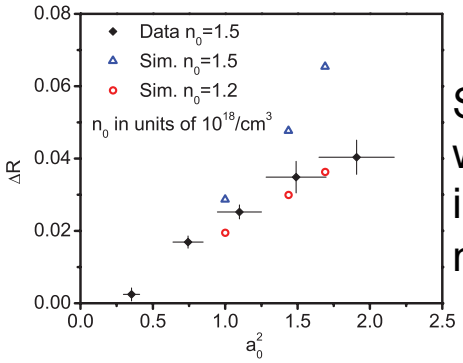
- E-beam injected in acceleration module

Optimization for energy spread and shot to shot fluctuation in progress





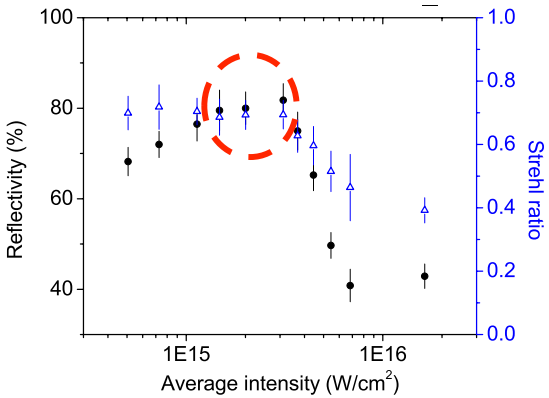
- Spectra analyzed to diagnose wake excitation



Step towards wakefield diagnostic in acceleration module

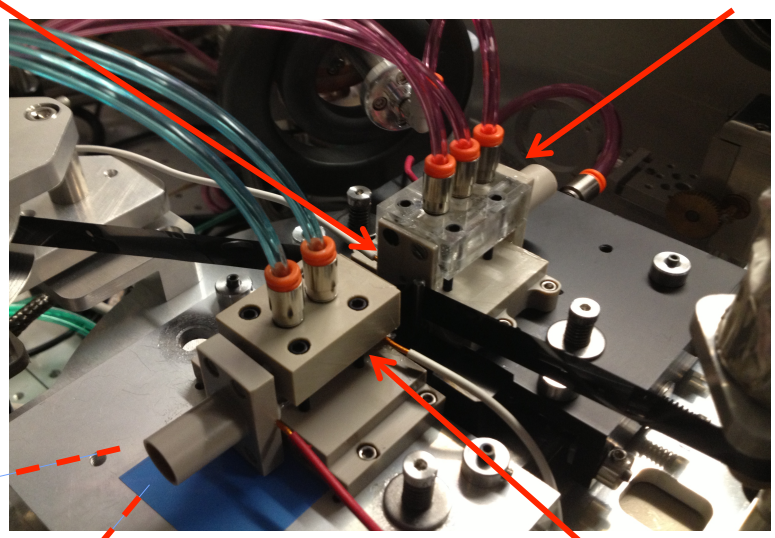
Summary and outlook

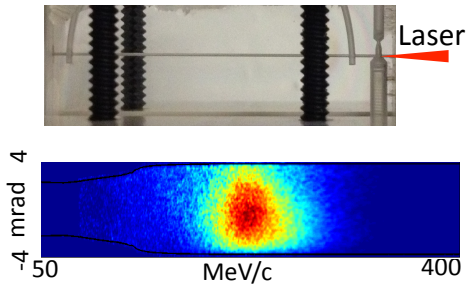
- Tape drive based plasma mirror is characterized



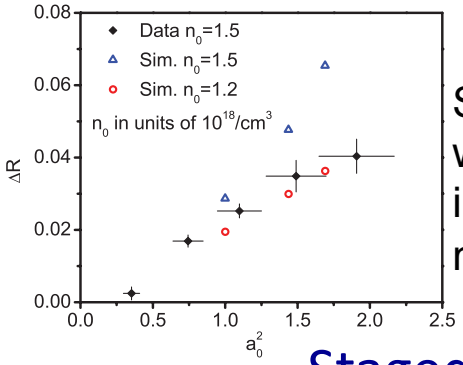
- E-beam injected in acceleration module

Optimization for energy spread and shot to shot fluctuation in progress





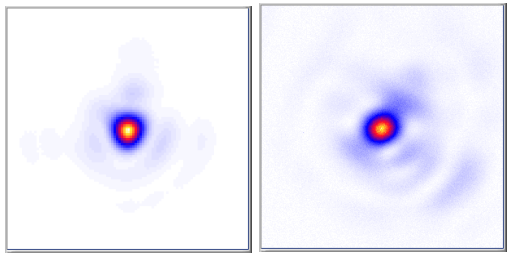
- Spectra analyzed to diagnose wake excitation



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