BELLA: Multi-GeV electron beam generation and outlook

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Also: Euclid TechLabs, AASC, THALES, Coherent, CRD at LBNL, N. Bobrova, S.V. Bulanov

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feature article

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey

Staging

BELLA

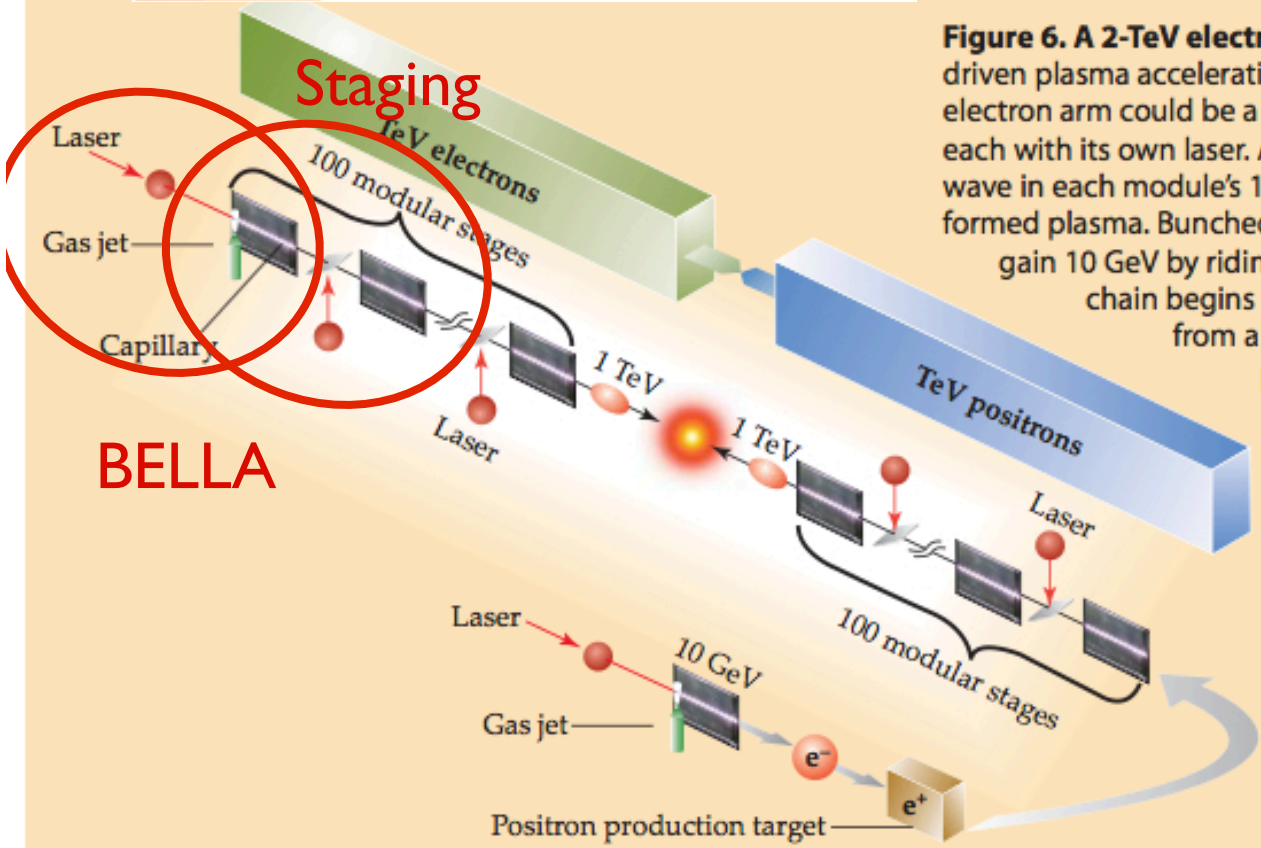

Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

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Physics considerations for laser-plasma linear colliders

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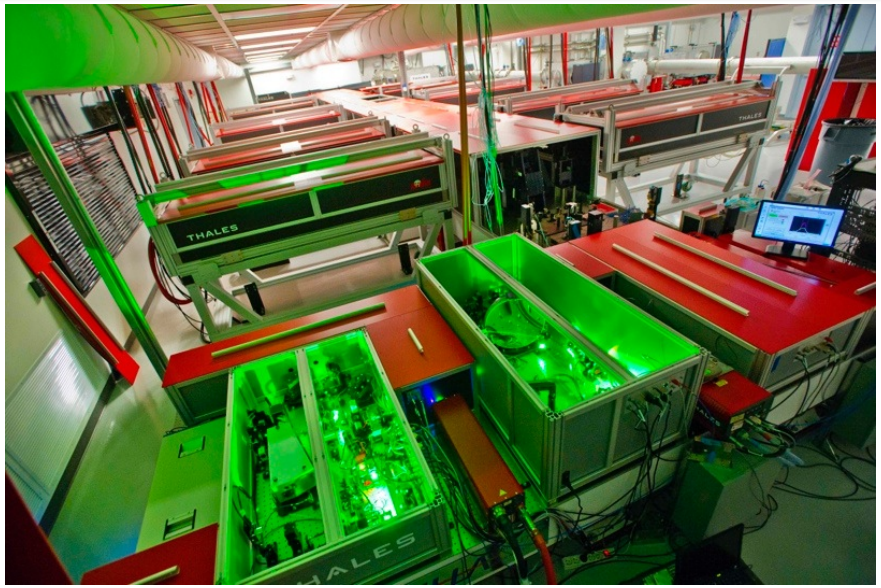
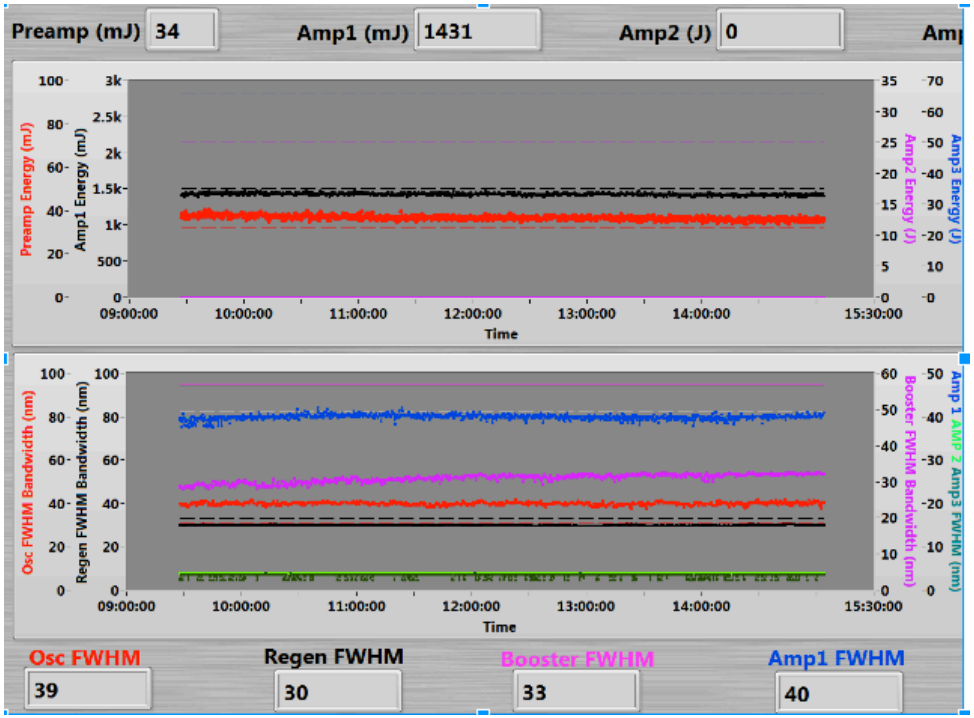
(Received 11 June 2010; published 4 October 2010)

Outline

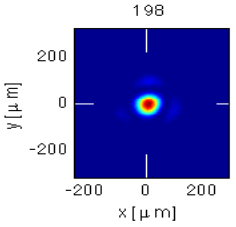
- Experiments with BELLA
- Staging experiment
- Other experiments and new initiatives

BELLA laser: (still) highest rep rate PW-laser for high intensity LPA experiments

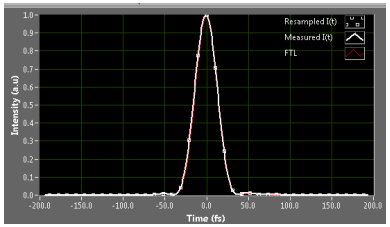




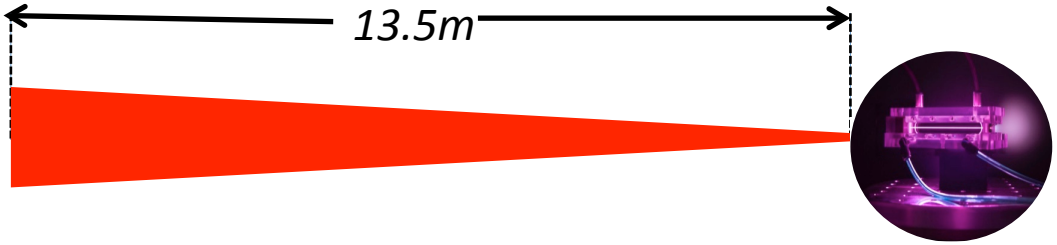
- Petawatt laser operating at up to 42 J in ~30 fs at 1 Hz



~ 55 micron spot

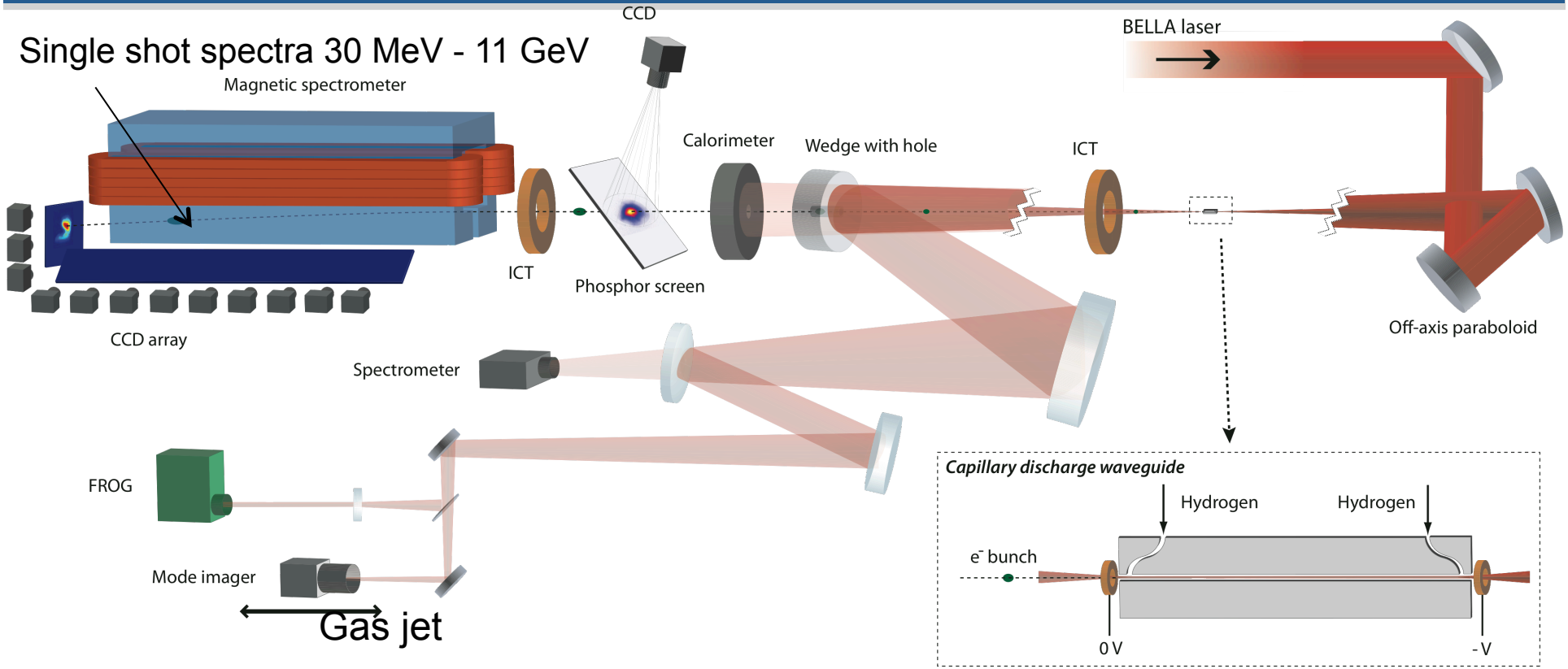


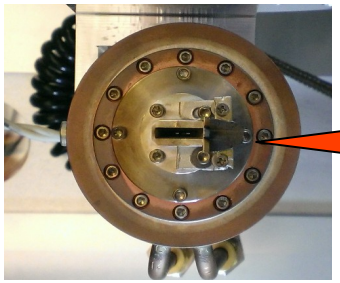
~30 fs



Intensity ~1.5x10^{19} Wcm^{-2}
Acc. fields ~10-50GV/m

Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets

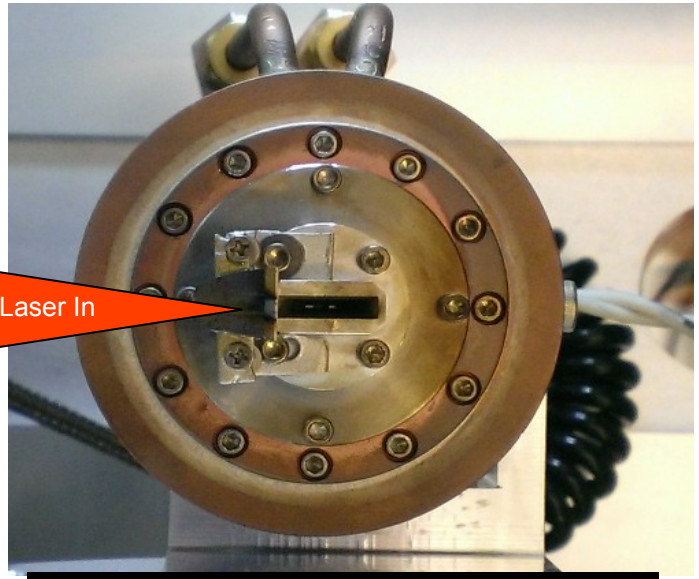


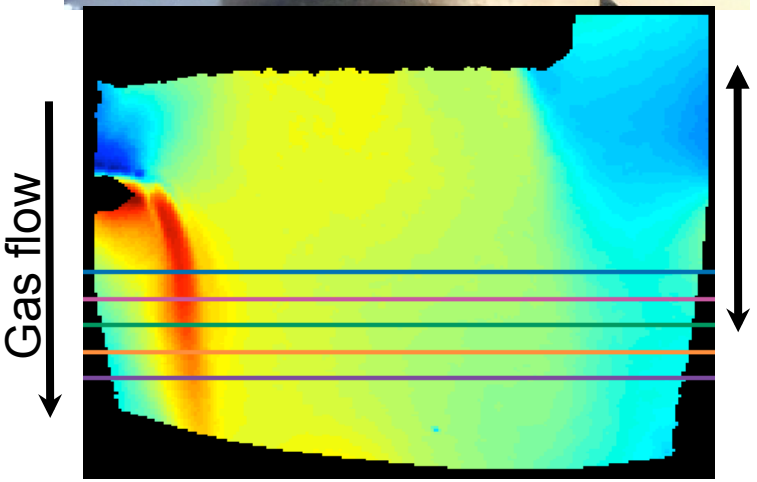


Capillary discharge

First experiments with BELLA were done on 1.8 cm long gas jets – e-beam limited to 2 GeV, in agreement with sims

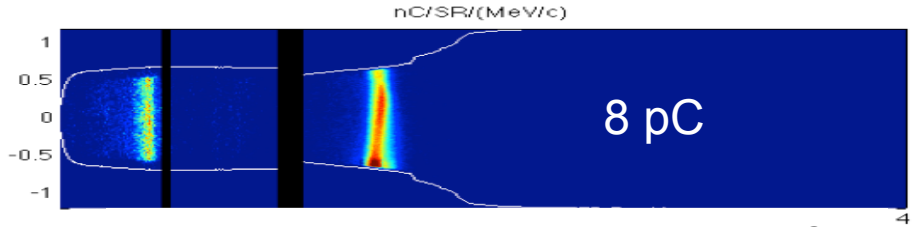
Gas jet experiments



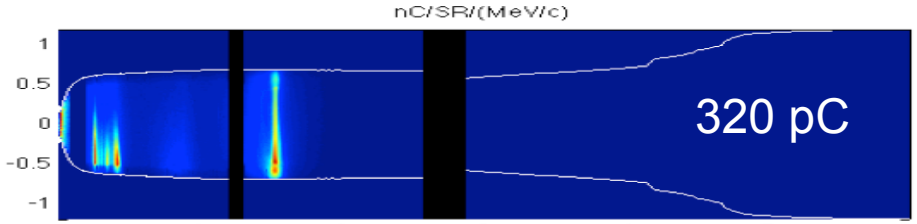


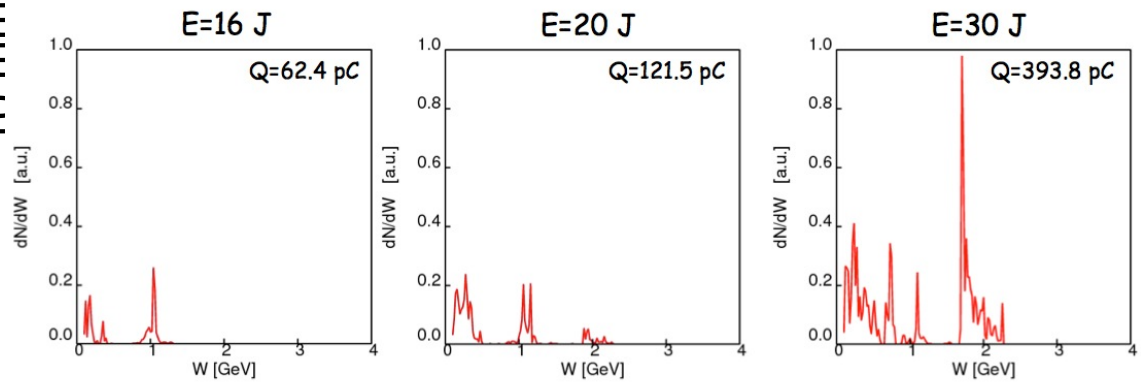
Measured Gas Density

16 J shot



30 J shot

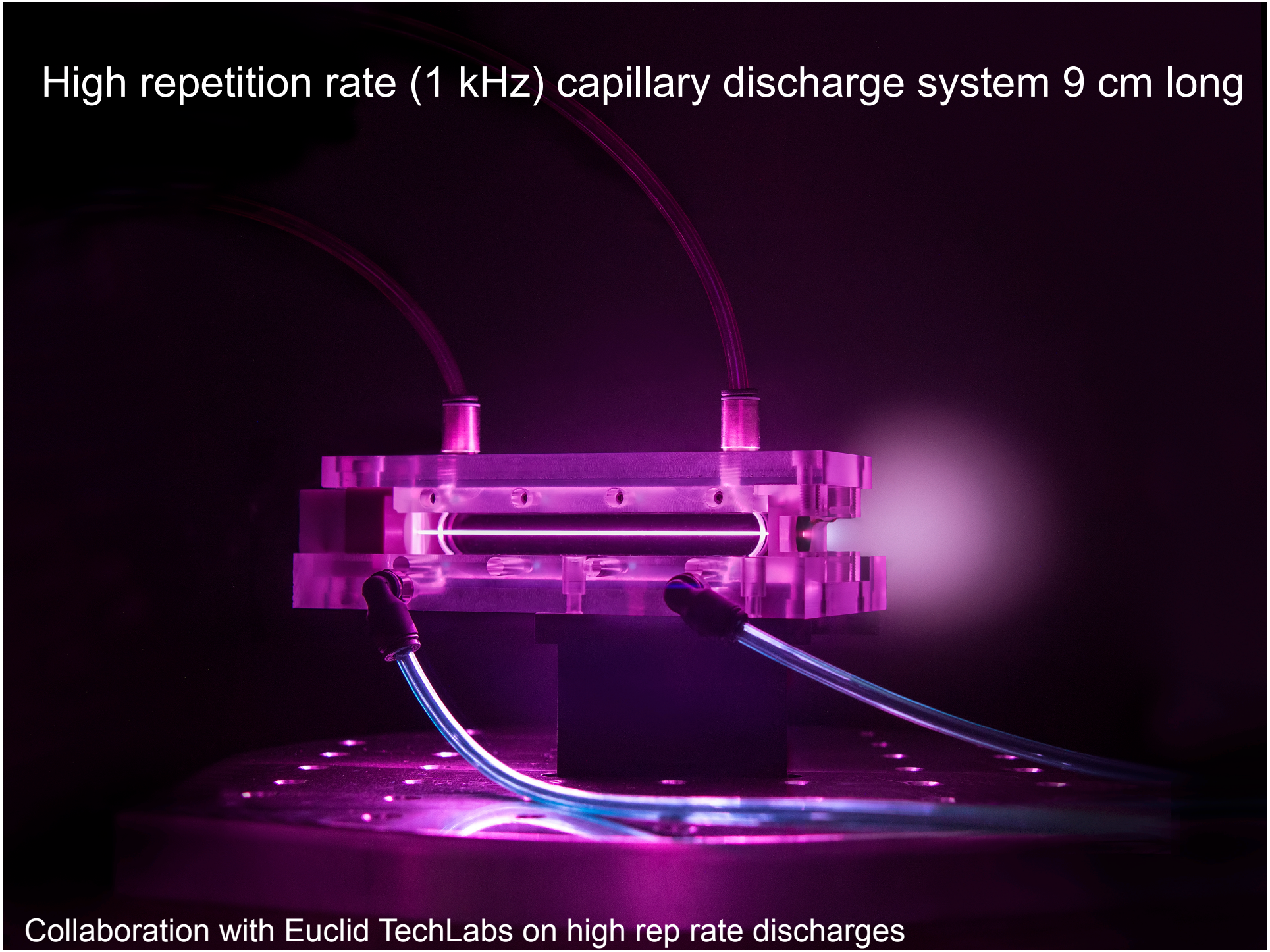




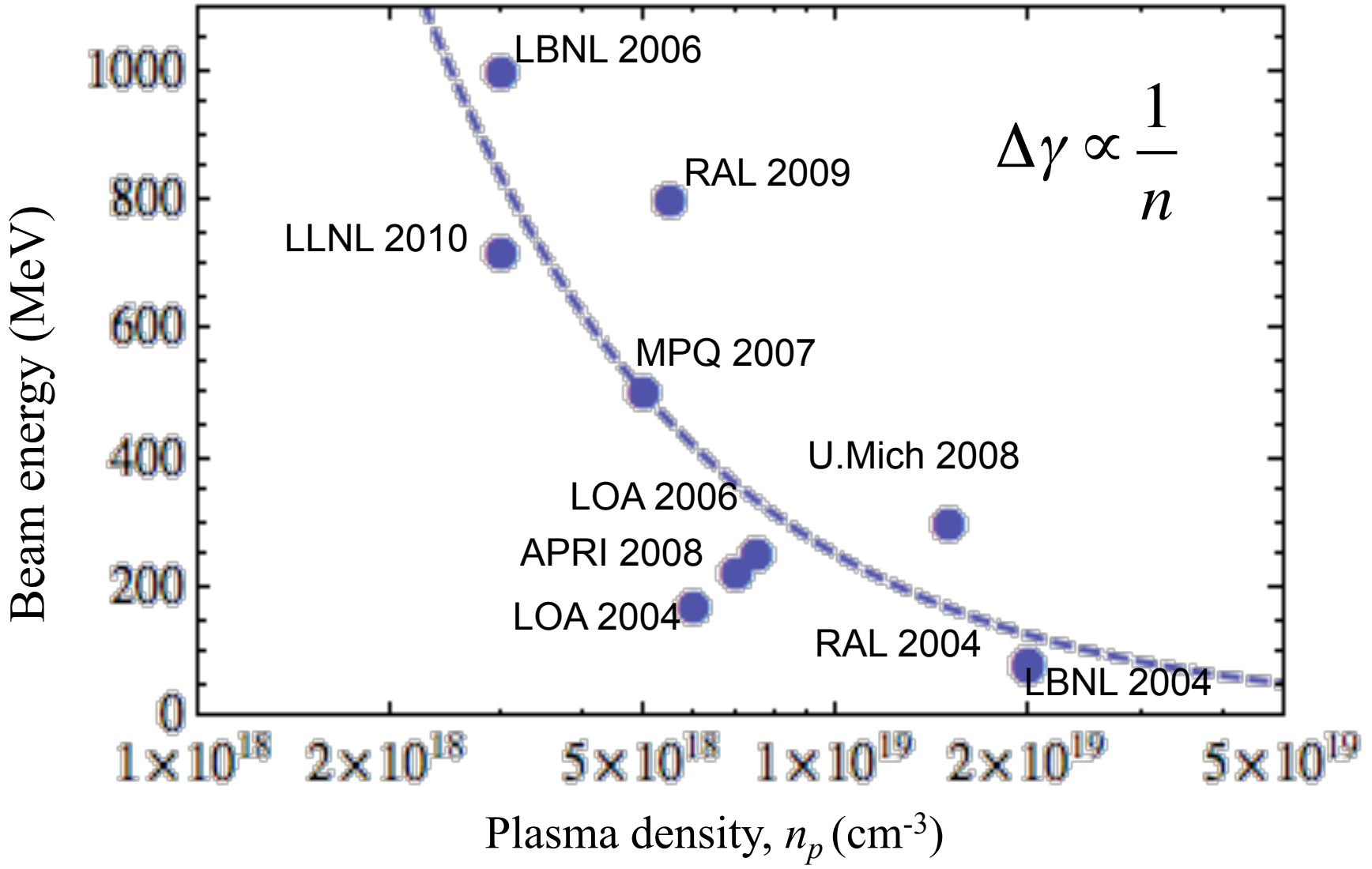
2nd bucket only

1st + 2nd bucket

1st + 2nd bucket


High repetition rate (1 kHz) capillary discharge system 9 cm long
Collaboration with Euclid TechLabs on high rep rate discharges

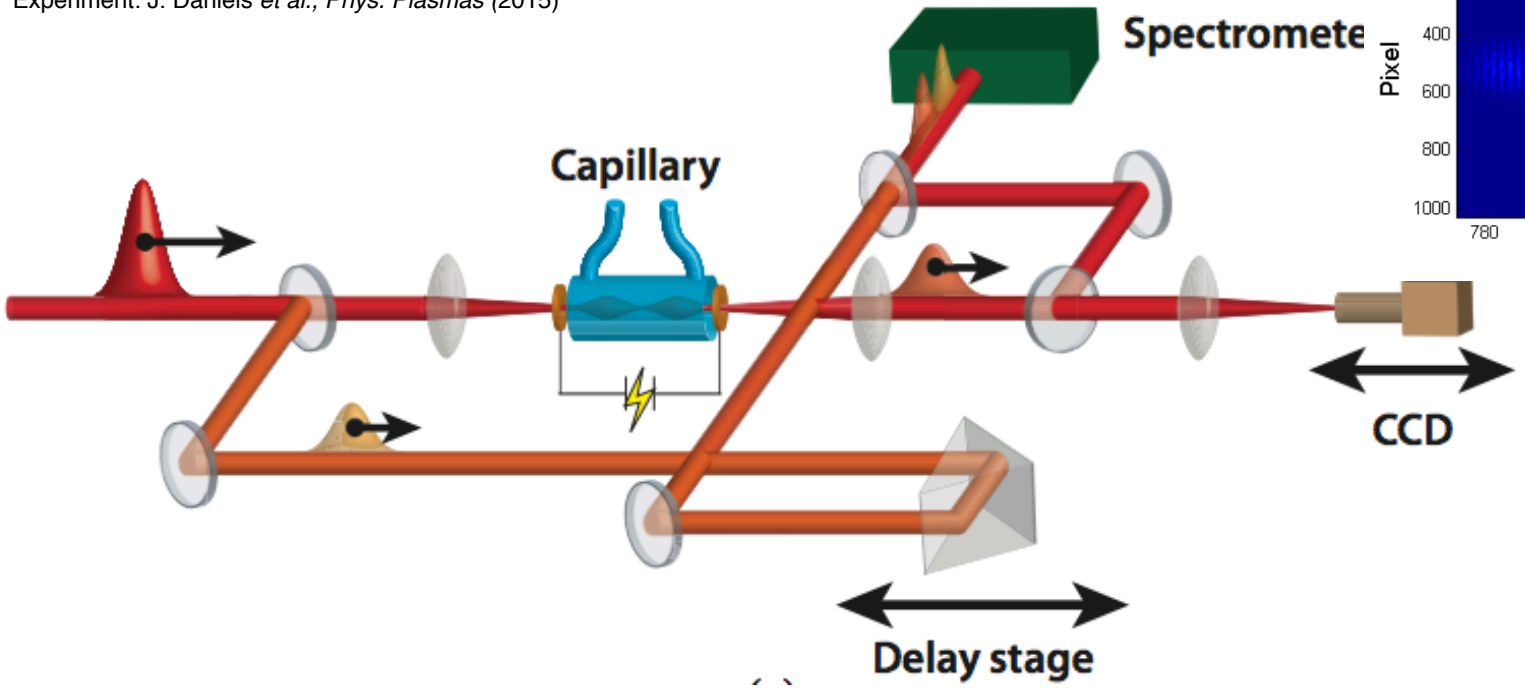
Previous experiments indicate that reaching higher energy gain requires operation at lower density, consistent with theory

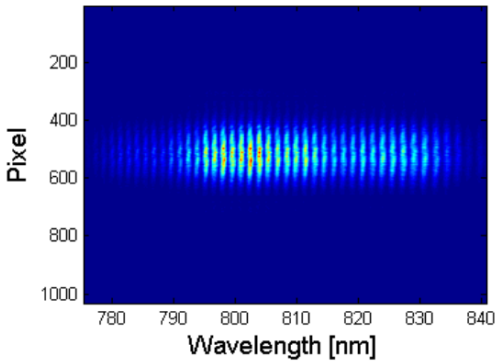


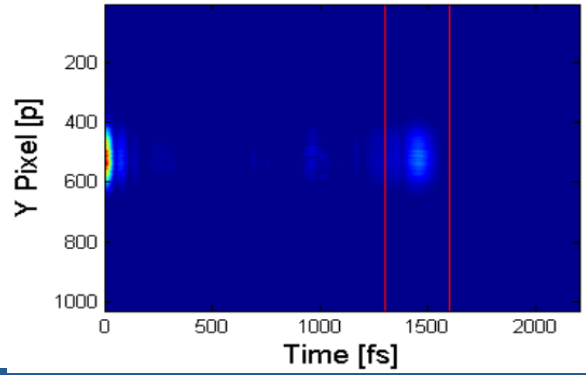
Shadwick et al., Phys. Plasmas (2009)

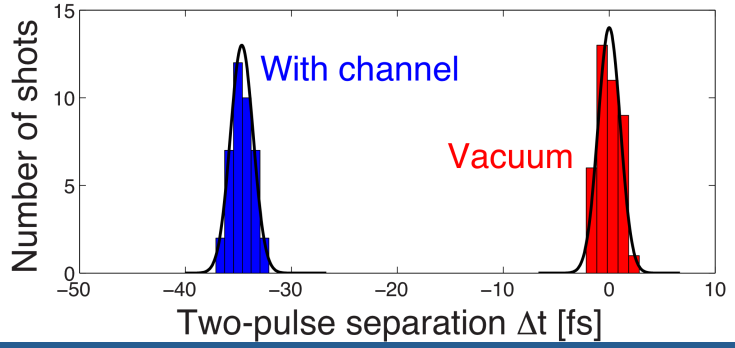
Plasma density in the capillary discharge can be measured with group velocity delay method

Theory: C. Schroeder *et al.*, Phys. Plasmas 18 (2011)
Experiment: J. van Tilborg *et al.* Phys. Rev. E (2014)
Experiment: J. Daniels *et al., Phys. Plasmas (*2015)

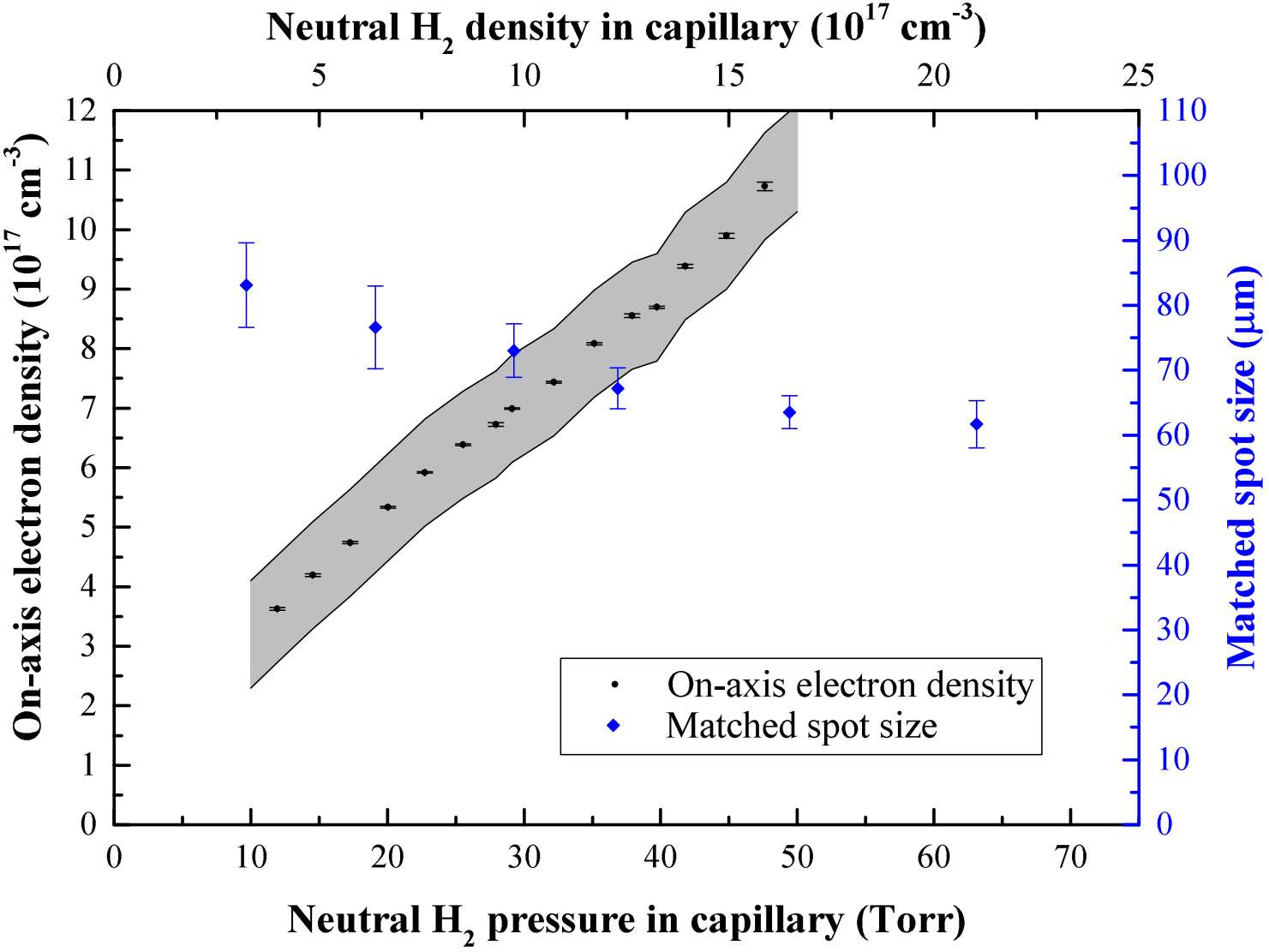




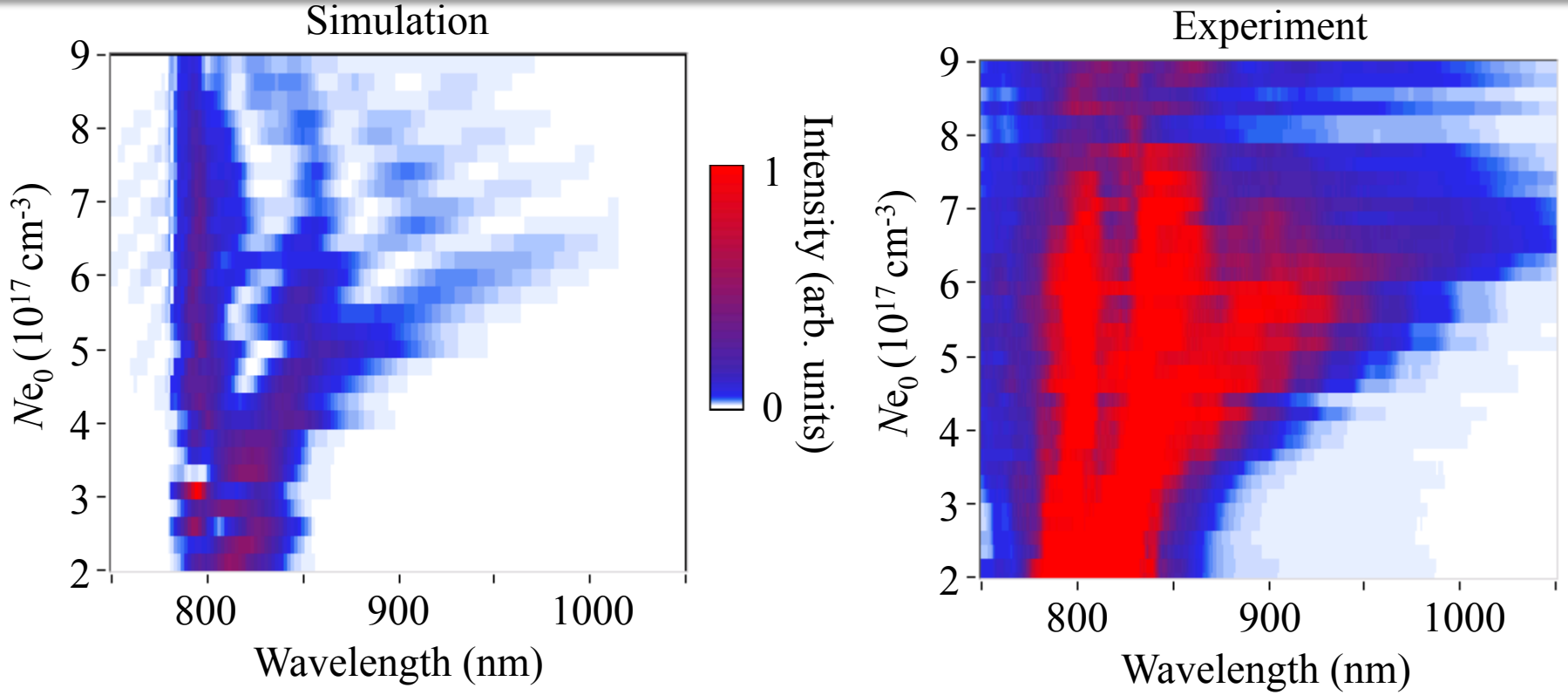




Waveguide density measured using group velocity. Matched spot size measured using transverse oscillations



Experiment shows similar laser red-shifting as simulation
Comparison used to cross-calibrate density



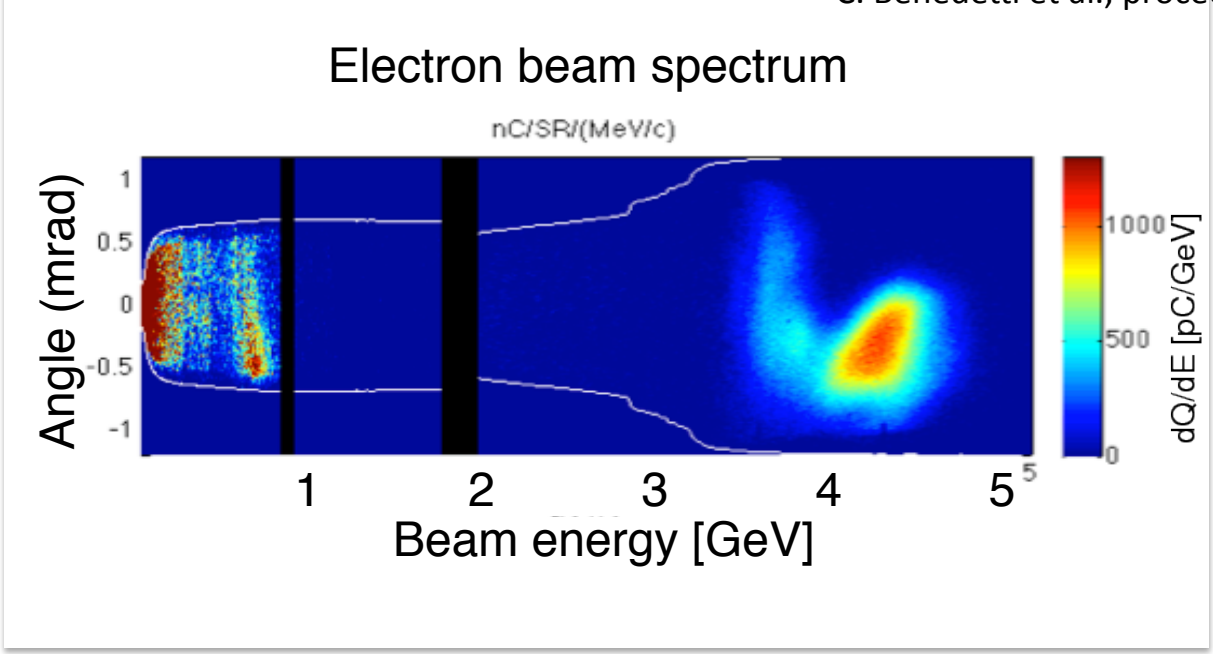
- Previous experiments on redshift in excellent agreement with simulation*
- Energy ~7.5J, Pulse length ~40fs, w_0~53 μm, L_{cap} = 9cm
- Large redshifting indicates deep depletion
- Detector response applied to simulated spectra

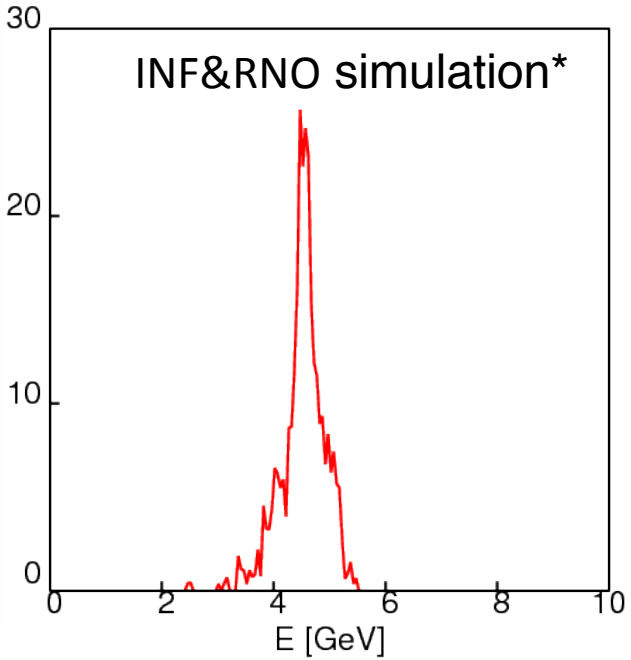
W.P. Leemans et al., PRL 2014

* S. Shiraishi et al., PoP 2013

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012



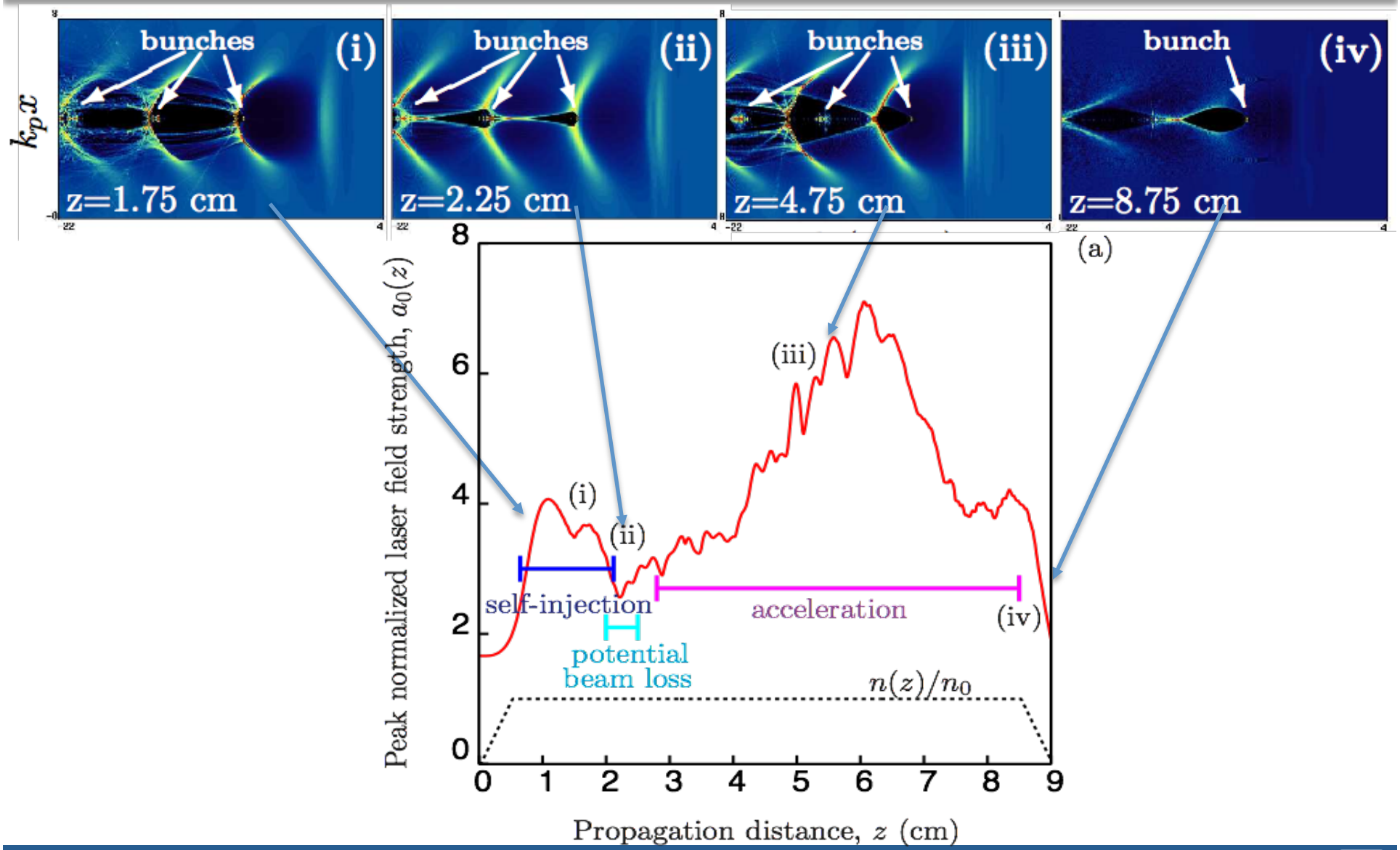


- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

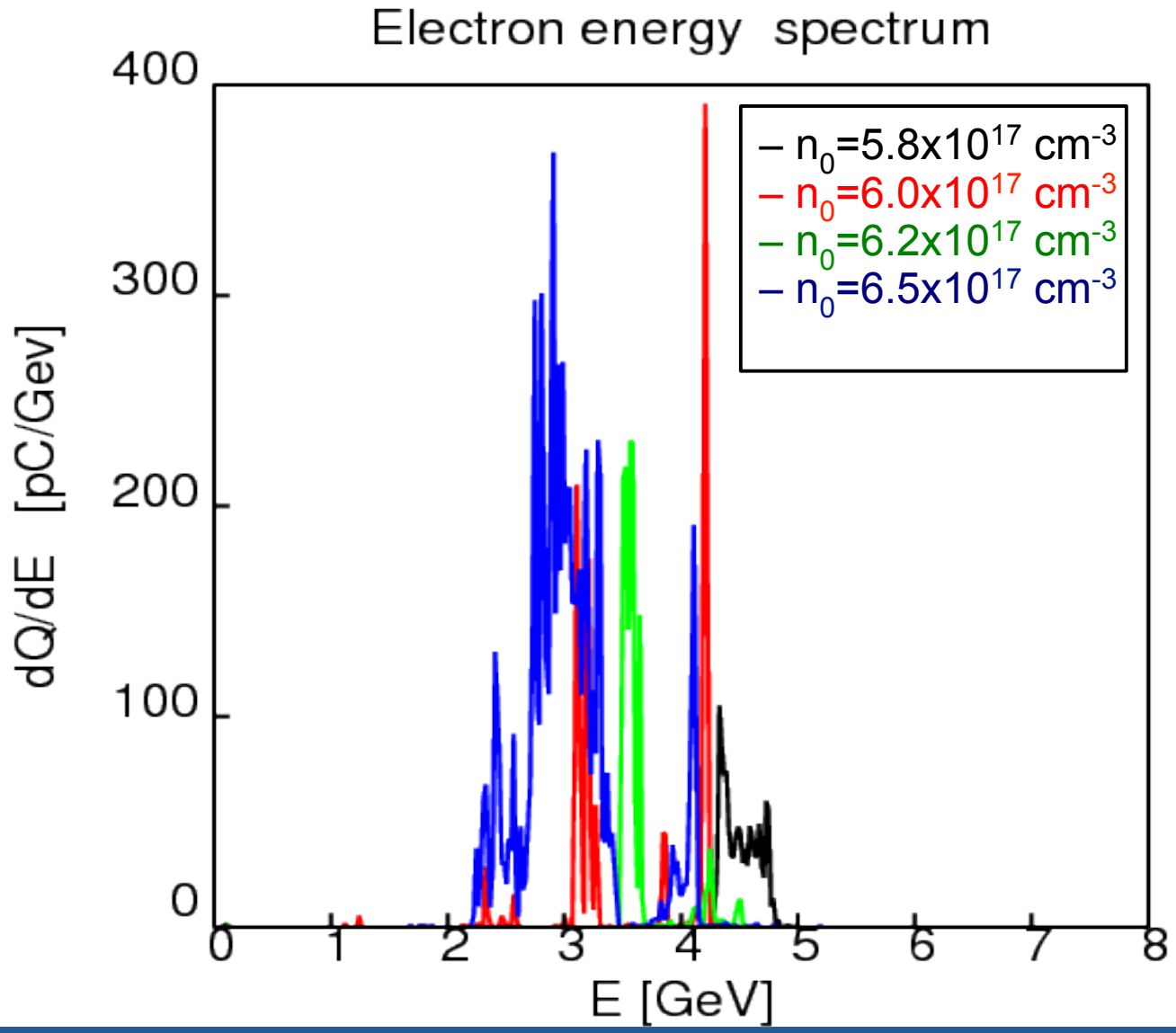
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014

Electron trapping and acceleration is complex in this density regime
Simulations based on measured input parameters

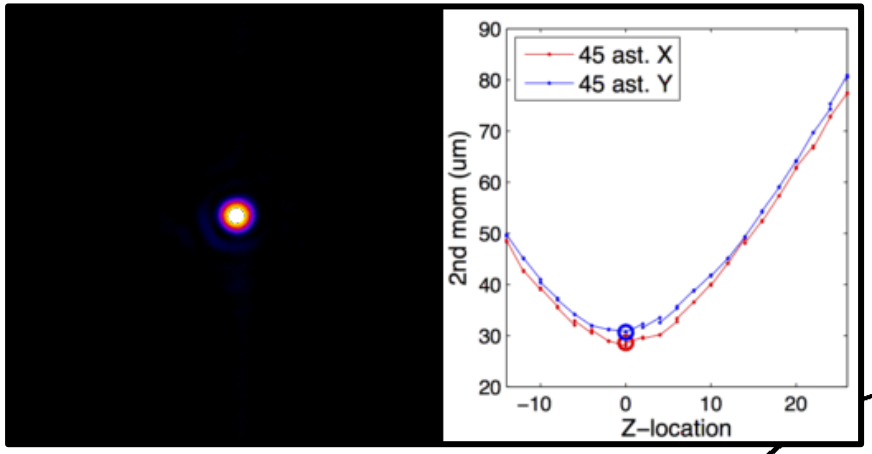


Simulations show strong sensitivity of self-injection physics from plasma density

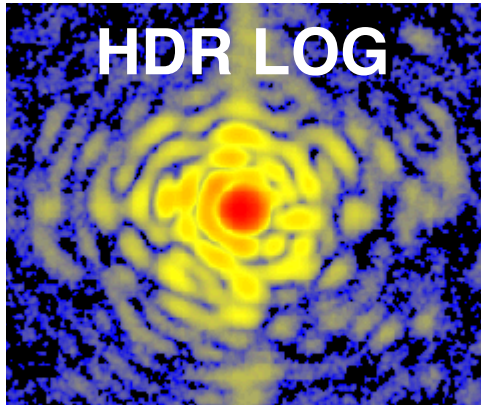


Mode quality and pointing stability are crucial for enabling capillary discharge experiments at ultra-high peak power

Energy in wings of beam or pointing fluctuations will cause damage

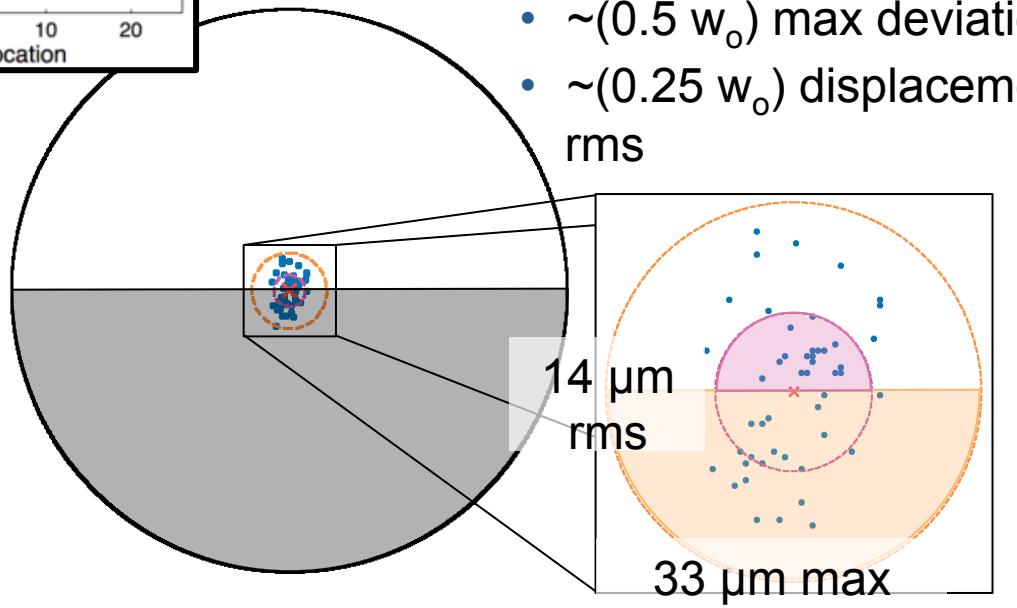


Energy in r=w_0: 0.82
Strehl: 0.91



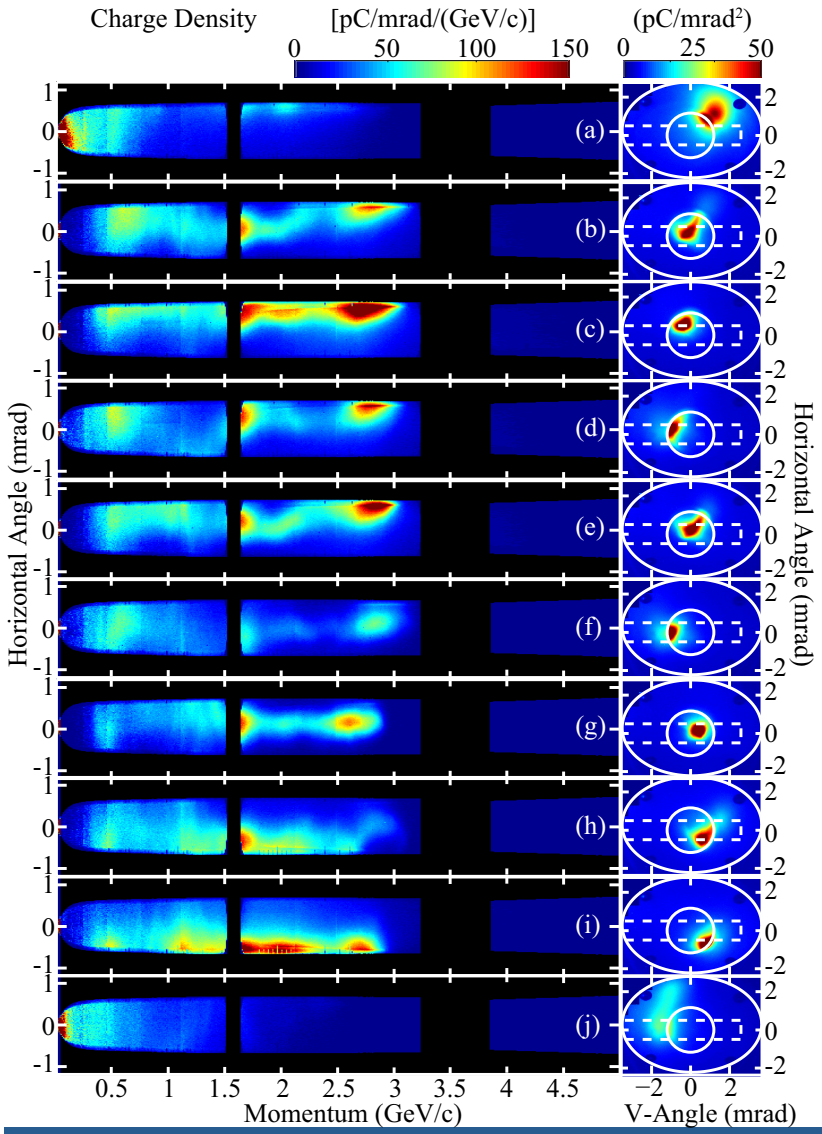
Energy in r=w_0: 0.78
Strehl: 0.89

- 50 shot sample
- w_o = 60 μm
- ~(0.5 w_o) max deviation
- ~(0.25 w_o) displacement rms

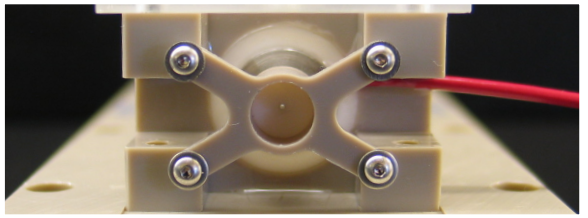


500 μm capillary waveguide

Improved target alignment and damage mitigation improves electron beam pointing and energy stability



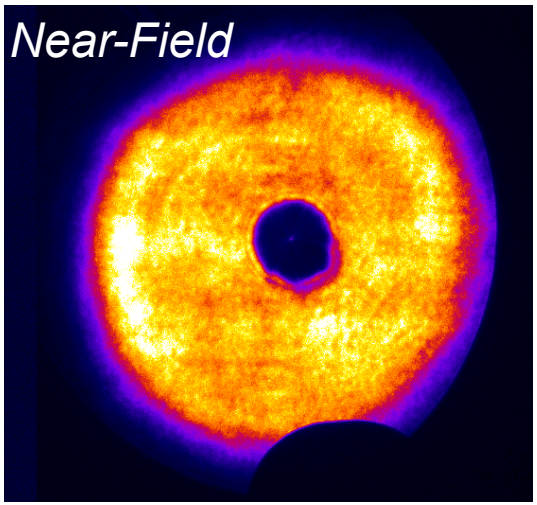
- ~ 3 GeV beams with 16 J
- n_e ~ 6x10^{17}cm^{-3}, 9 cm capillary
- Capillary alignment accuracy improved
- Ceramic disk added to protect capillary

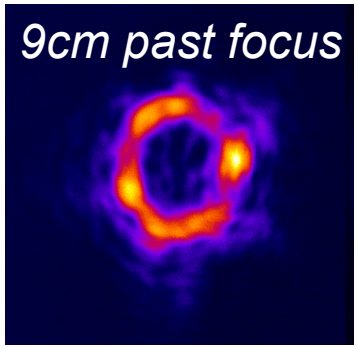


- 90% of beams now within the ~1 mrad acceptance (0.6mrad rms)
- ~1000 shots without drop in performance

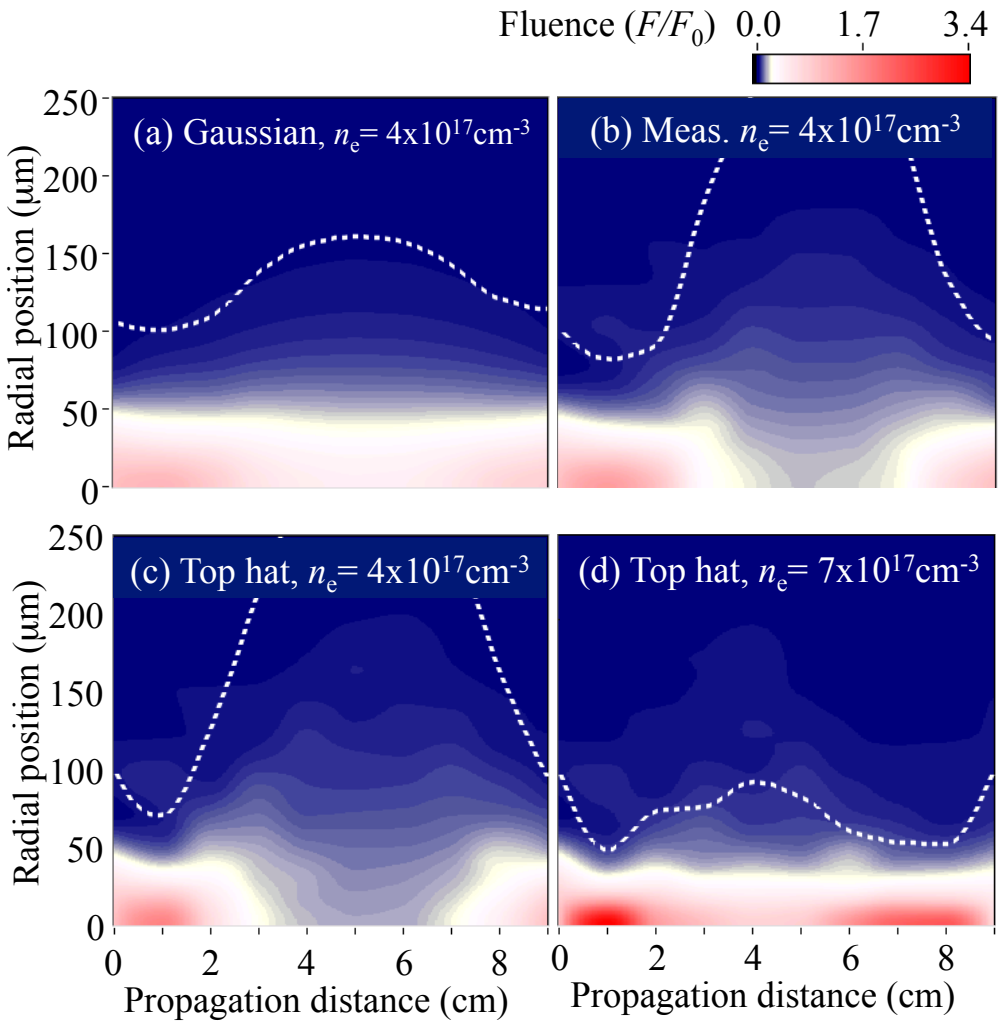
Gonsalves et al., Phys. Plasmas **22**, 056703 (2015)

SuperGaussian near field used in experiments reduces guiding efficacy. Compensated by higher density.





High-power laser propagation



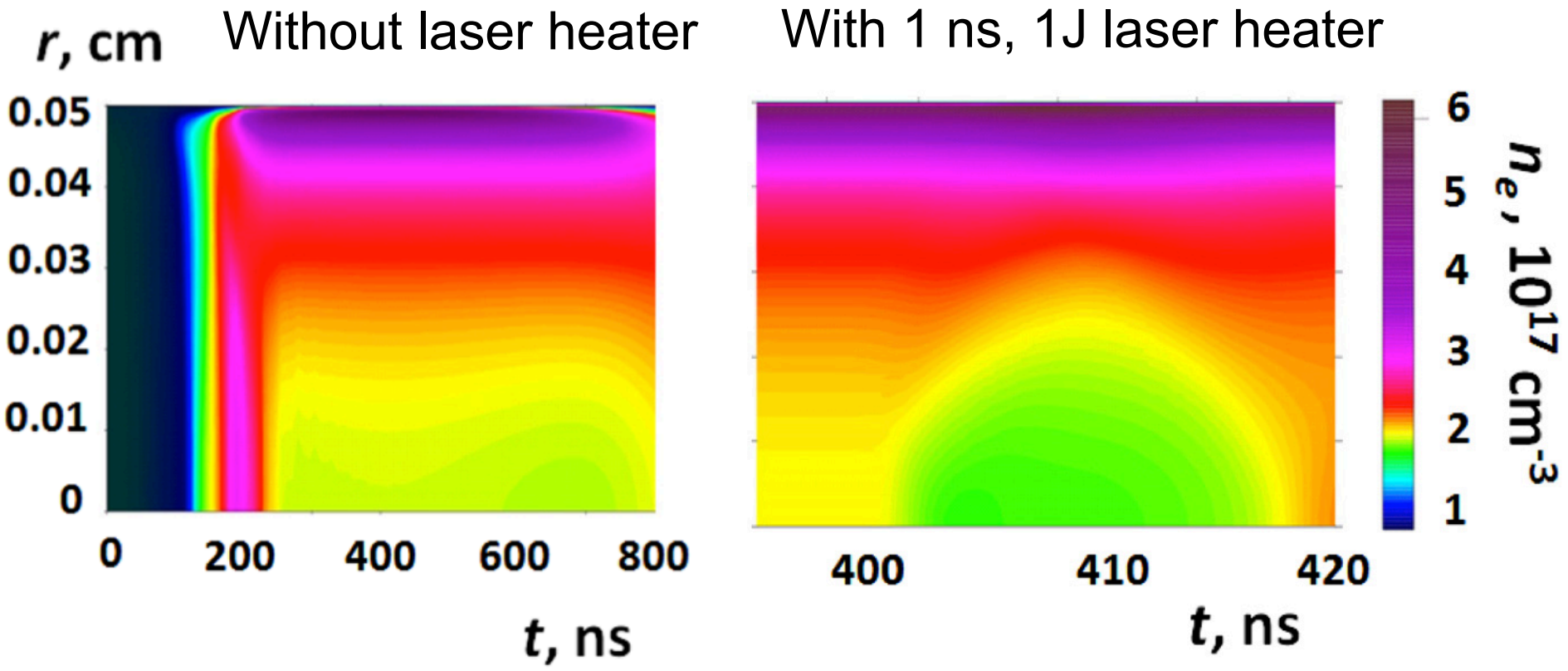
Operating in the Right Plasma Density Regime is Key for the BELLA Experiments

Operating at the wrong density (too high or too low) leads to damage

- Both guiding and injection criteria must be satisfied
  - Drilling out the channel with a heater beam
  - Control injection while operating at low density
- Super stable laser is also essential
  - Pointing and **power**

- Extensive simulations indicate that 10 GeV will be achievable at proper density

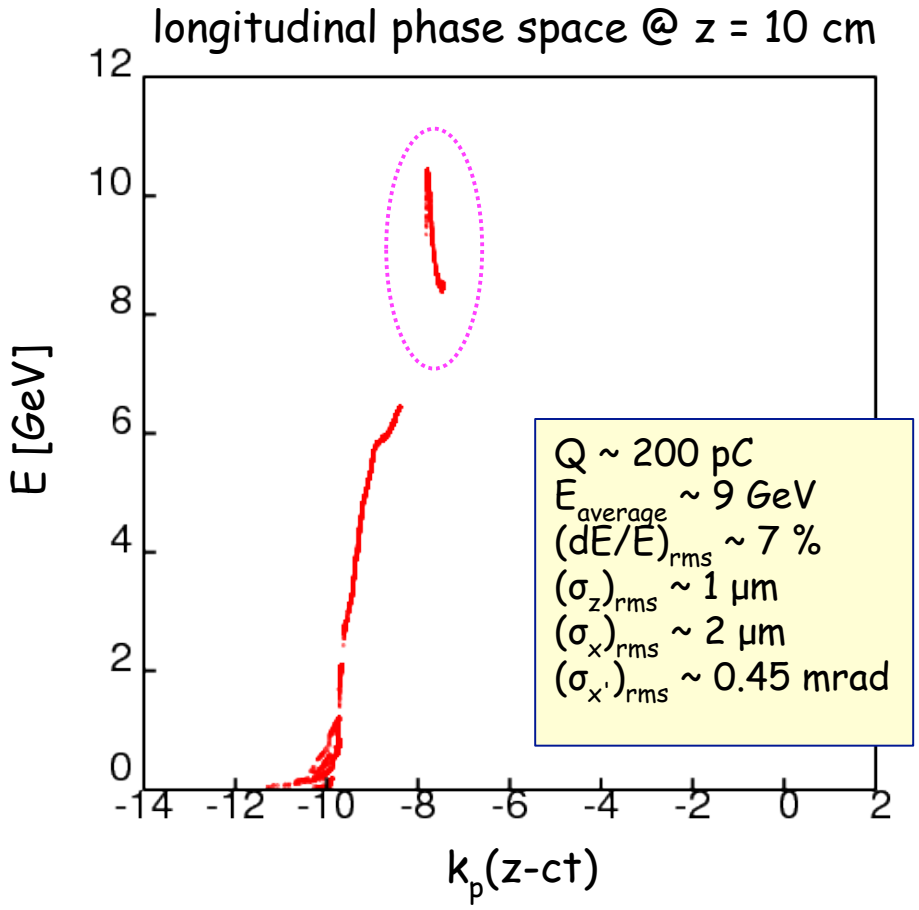
Laser Assisted Deepening of the Plasma Channel will be used to Provide Further Control of the Mode Guiding and Lower Density

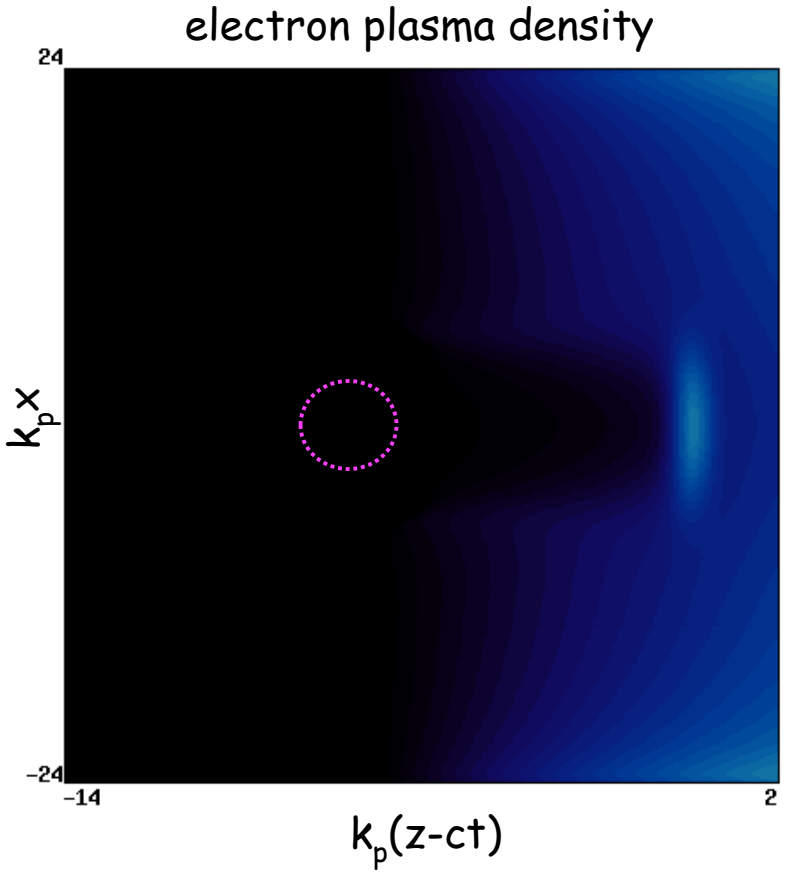


- Inverse bremsstrahlung heats plasma and produced dynamic channel
- Optimum guiding conditions for a pulse with a=1.7 is obtained at 2.5 ns after heater pulse

N.A. Bobrova et al., Physics of Plasmas **20**, 020703 (2013)

Simulations indicate 10 GeV quasi-monoenergetic beams can be obtained in ~ 10 cm capillary in non-linear regime





Initial a0~3.5-4.0

Plasma density ~ 3 x 10^{17} cm^{-3}

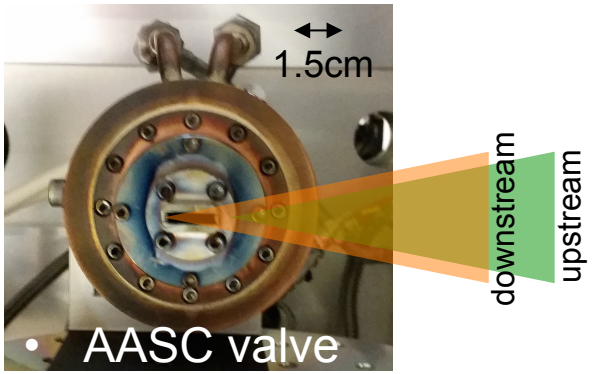
Laser heater required to deepen channel

Gas jet experiments with 1.5 cm jet provide insight into propagation physics and e-beam generation without external guiding structure

Downstream focus on 1.5 cm long gas jet yields high stability electron beams

Ph.D. thesis D. Mittelberger

- Slit geometry gas jet target



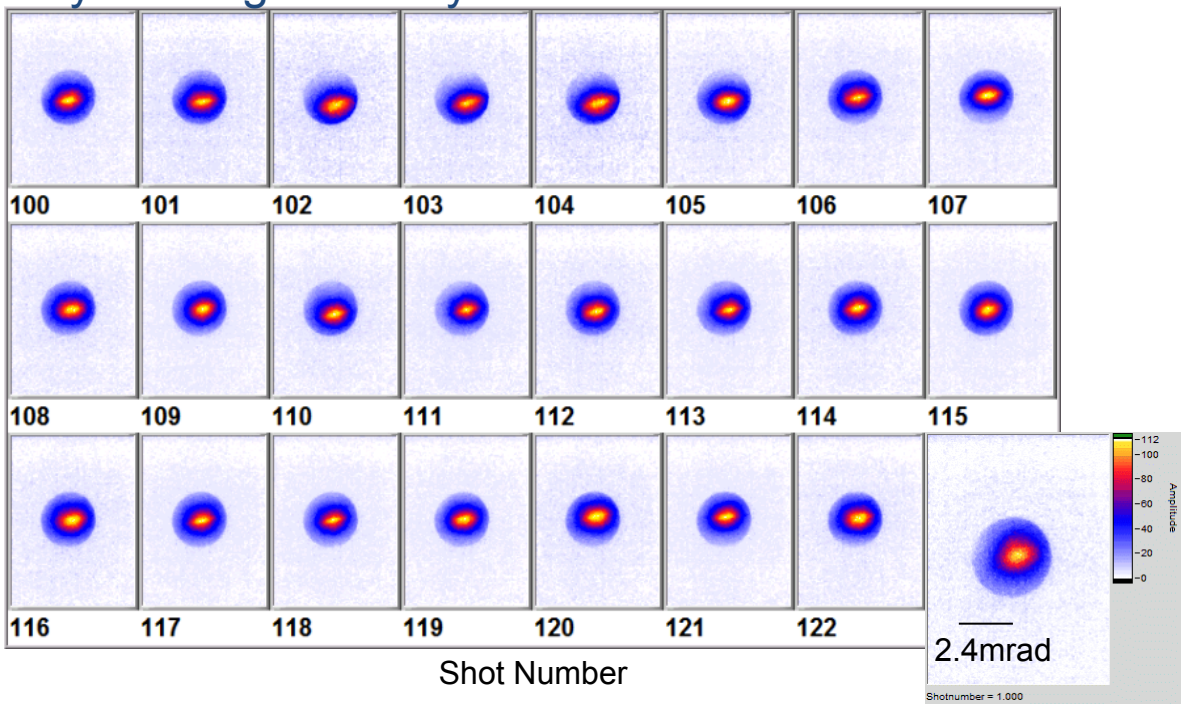
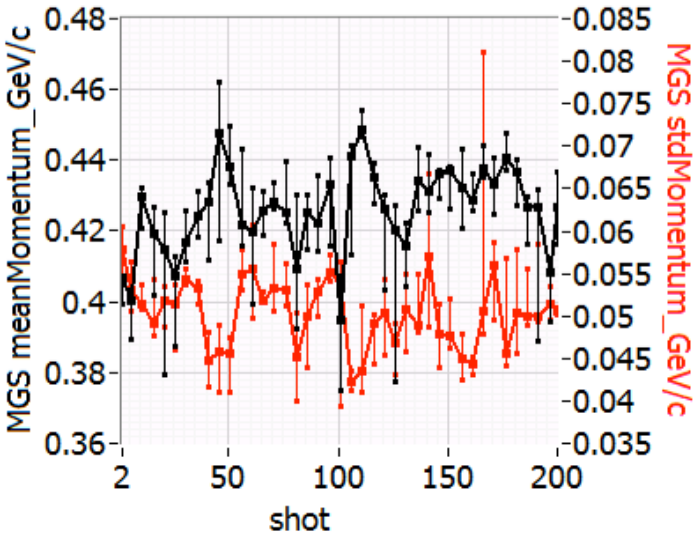


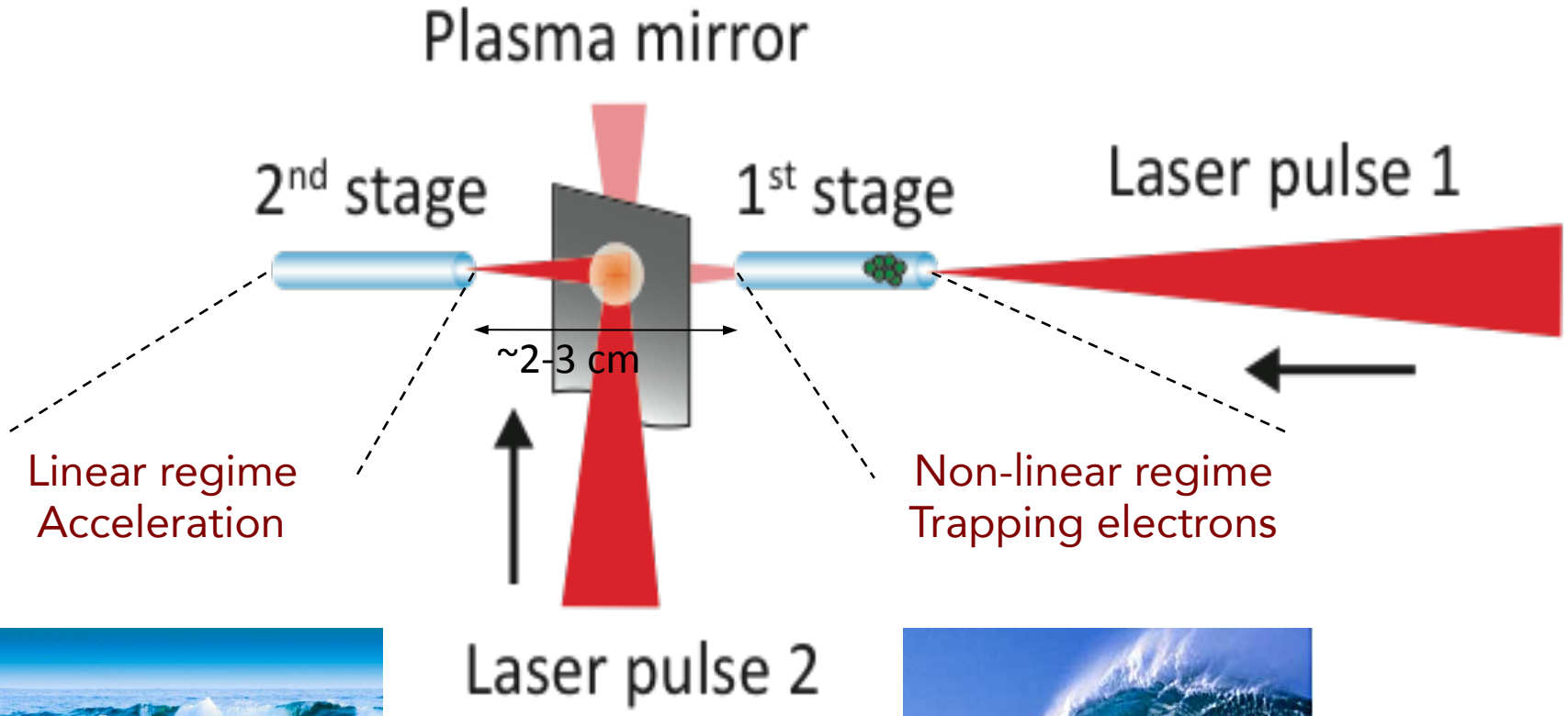
Image on phoshor screen – 12 m from gas jet



- **Pointing fluctuations ~0.16 mrad rms**
- Stable bunch charge (~ 10 pC)
- Reproducible energy spectrum

Staging Experiment Aims at Demonstrating Key Element of Collider Concept

W. P. Leemans and E. Esarey, Physics Today (2009).



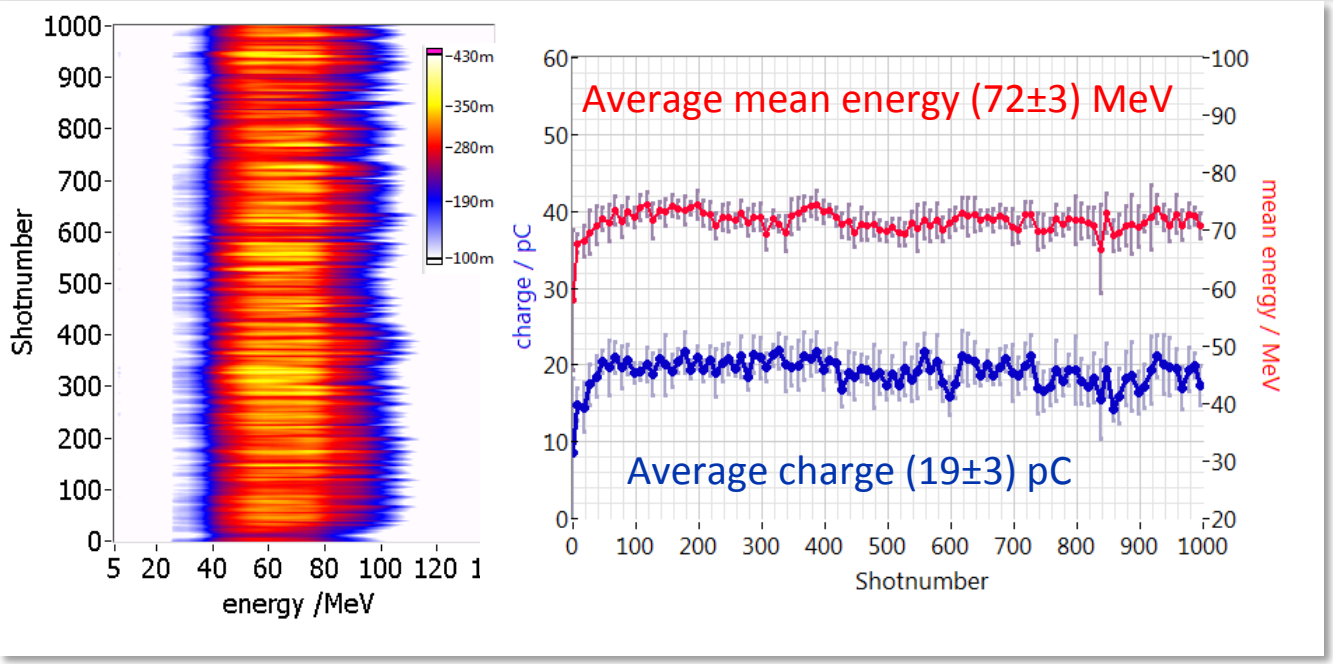
Ph.D. thesis S. Shiraishi, B. Shaw, K. Swanson

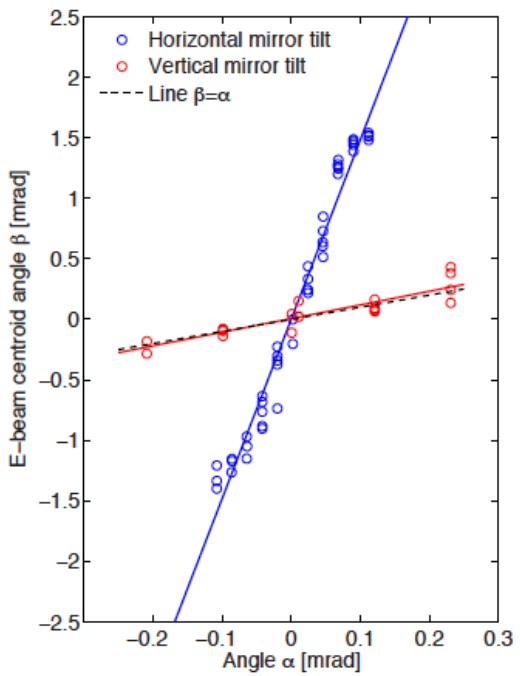
Talk by Sven Steinke

Compact setup for staging two LPAs in sequence

TO BE RELEASED WHEN PUBLICATION IS ACCEPTED

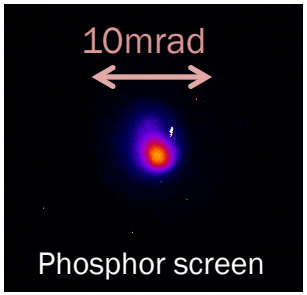
Stage I: Turnkey gas jet operation in ionization injection regime provides **tunable** injector beams of excellent stability

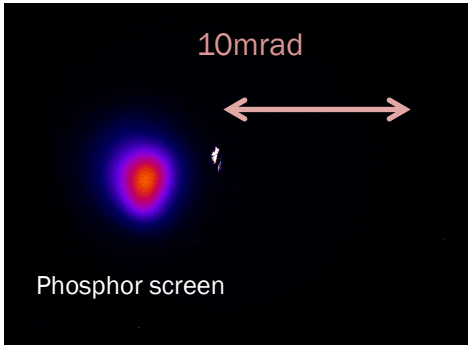




e-beam pointing

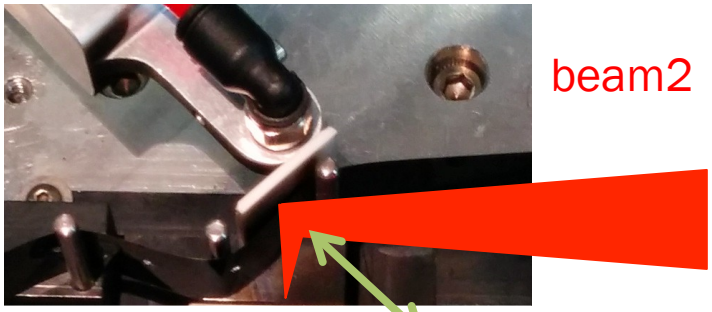
- Pointing stability ±0.3 mrad
- Divergence FWHM (2.3±0.3) mrad

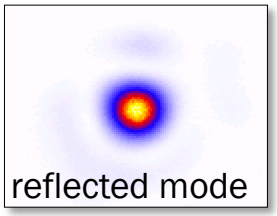


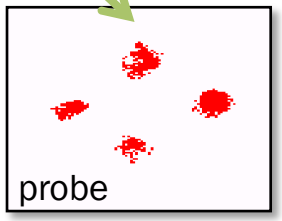


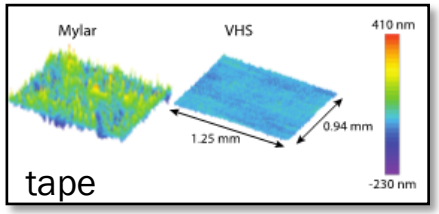
Tape-driven Plasma Mirror (PM) to couple in the laser pulse driving the dark-current-free 2nd stage accelerator

T. Sokollik et al. AAC proc. (2010)

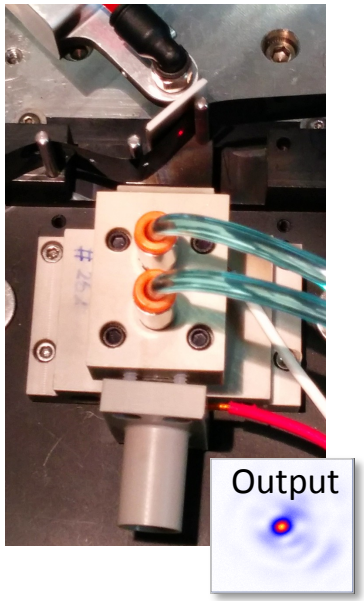




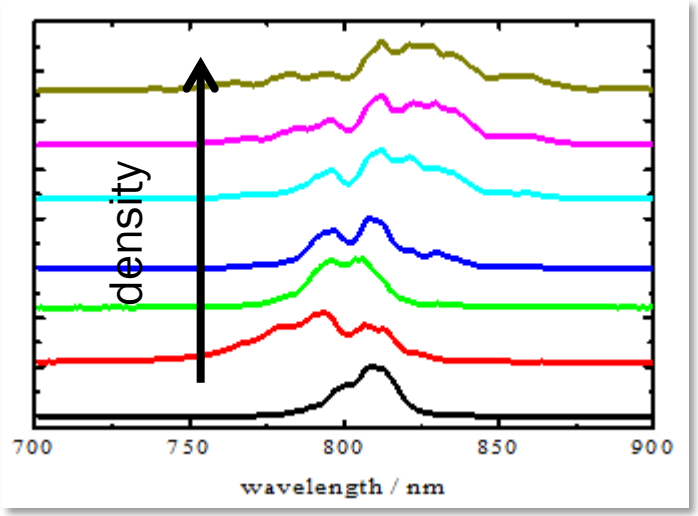


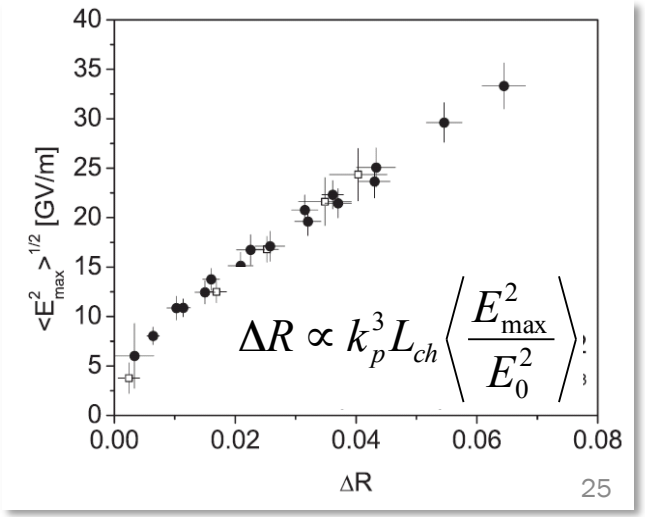


- Active feedback control
- High reflectivity (80%)
- Excellent mode quality (Strehl ratio >0.8)
- Small pointing fluctuation (~9µm)
- Stable operation over hours of run time



Non-invasive, optical wake diagnostic:



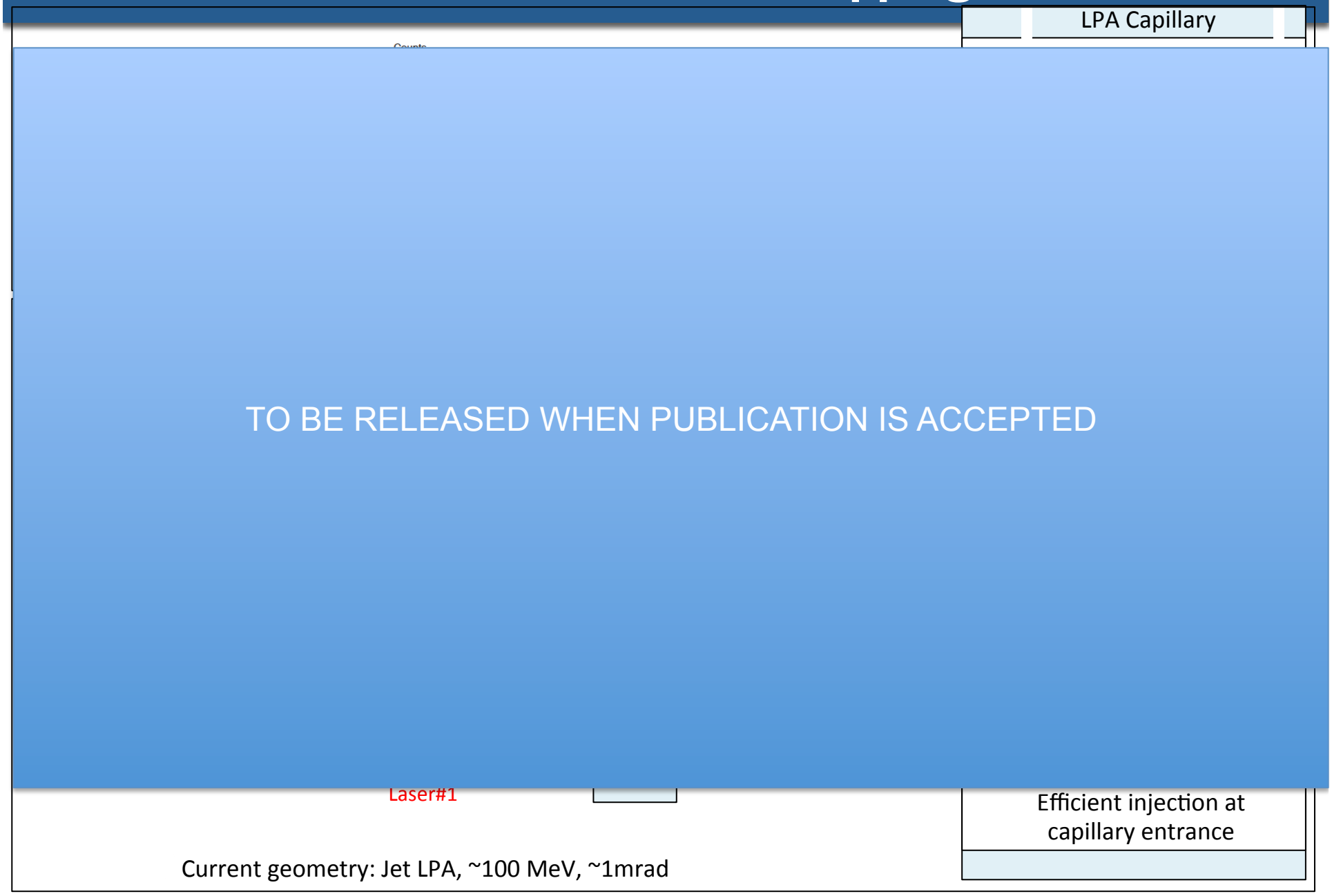


S. Shiraishi et al. PoP (2013)

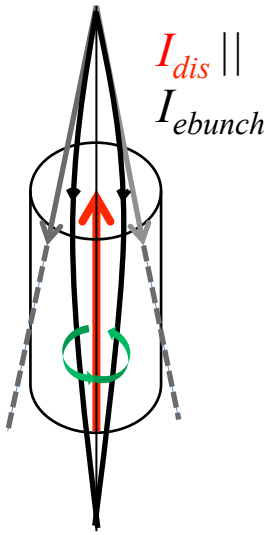
A prototype two-stage system was built using a gas jet (first stage), plasma mirror and capillary discharge (stage 2) and two independent laser pulses

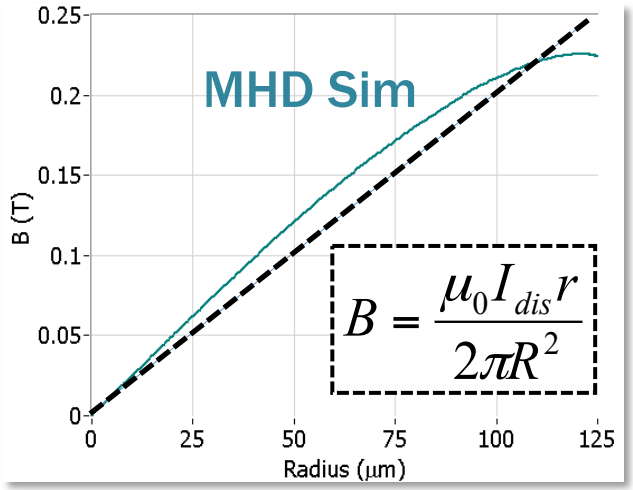
- First experiments aimed at understanding wake structure and probing it with e-beam

Improving the e-beam coupling at the entrance of stage two is essential to increase trapping fraction

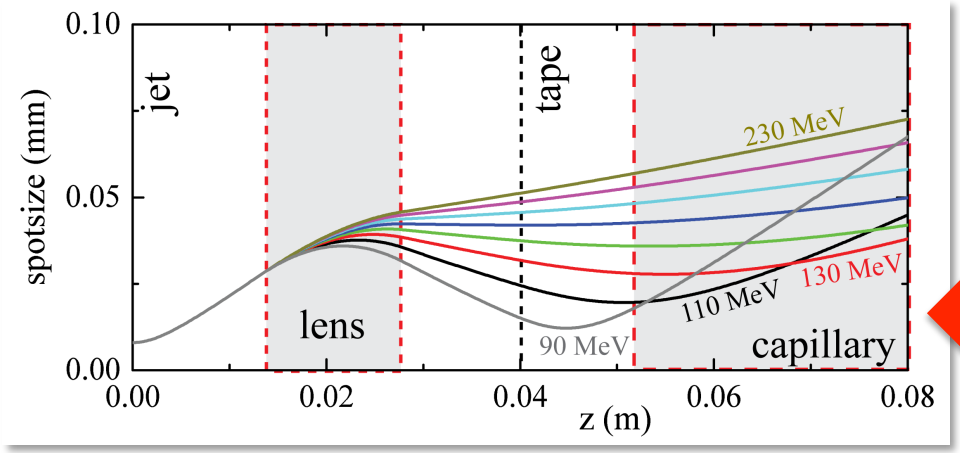


Active plasma lens based on capillary discharge provides ultra-high gradient symmetric focusing – more than 3,000 T/m





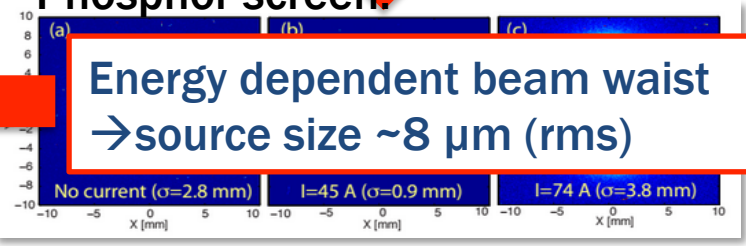
Evolution of the e-beam waist:



Magnetic spectrometer:

TO BE RELEASED WHEN PUBLICATION IS ACCEPTED

Phosphor screen:



Energy dependent beam waist →source size ~8 μm (rms)

J. van Tilborg et al., submitted to PRL

Active plasma lens was implemented to improve trapping fraction: staging setup (version 2.0)

TO BE RELEASED WHEN PUBLICATION IS ACCEPTED

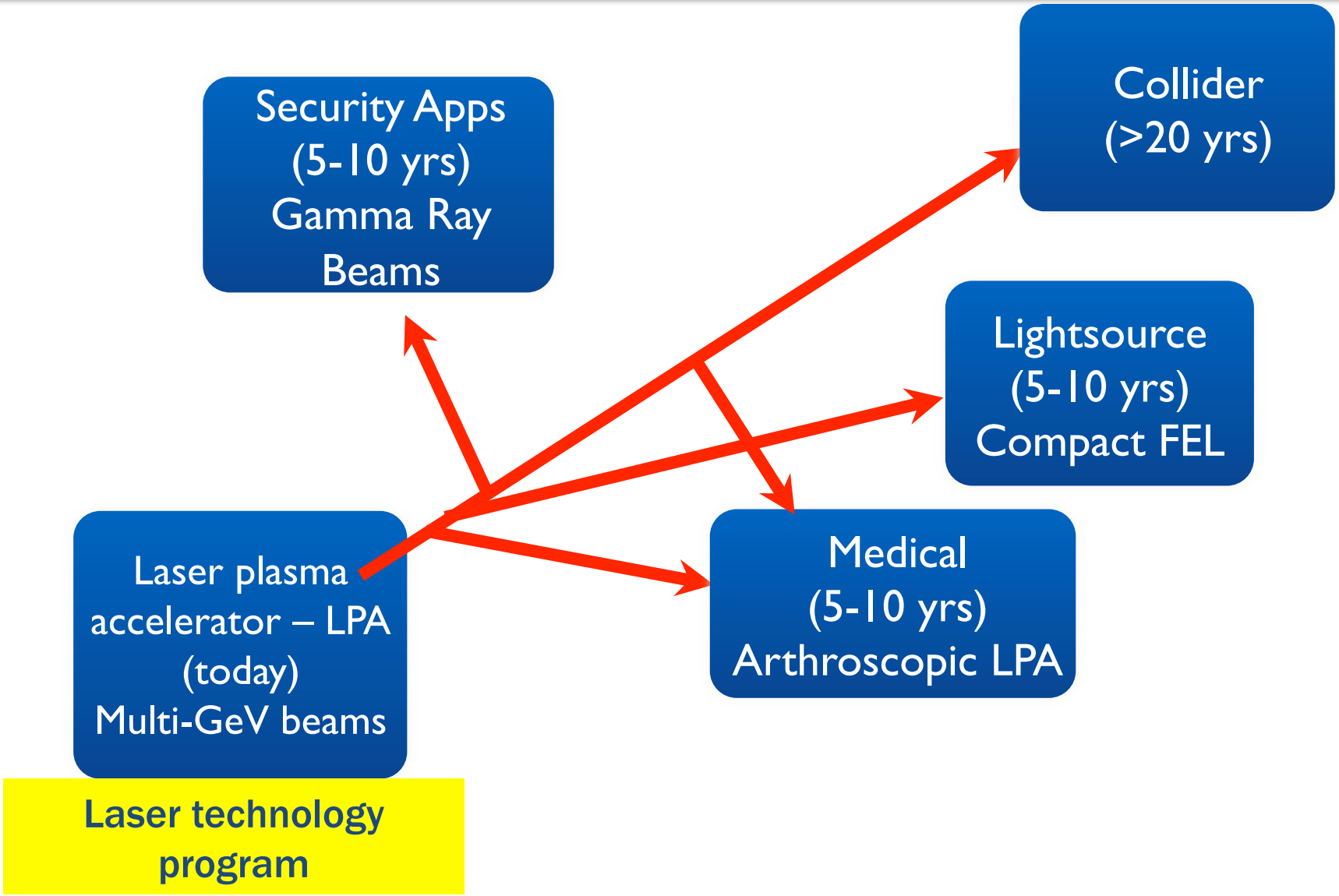
Quasi-linear wake properties probed and energy gain/loss of witness beam observed

TO BE RELEASED WHEN PUBLICATION IS ACCEPTED

Simulation reproduce staging signatures at correct magnitude

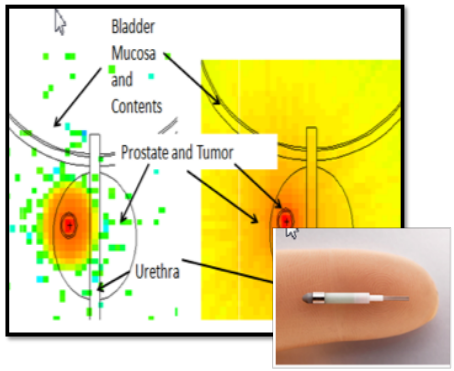
TO BE RELEASED WHEN PUBLICATION IS ACCEPTED

The program aims at colliders for the HEP mission and applications with shorter term benefits



New initiatives on applications of LPAs have been launched – key is stability and tunability+power

Arthroscopic accelerator for biomedical applications



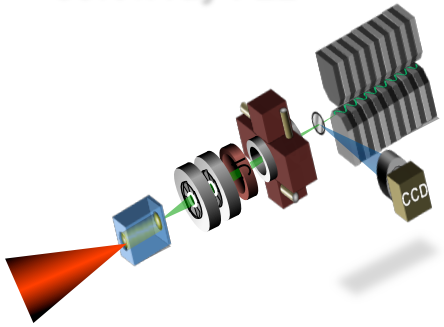
Lab funded

Compact MeV Thomson gamma ray source

S. G. Rykovanov, C.G.R. Geddes et al., J. Phys. B, 47 234013 (2014)

DOE funded

Laser plasma accelerator driven soft x-ray FEL

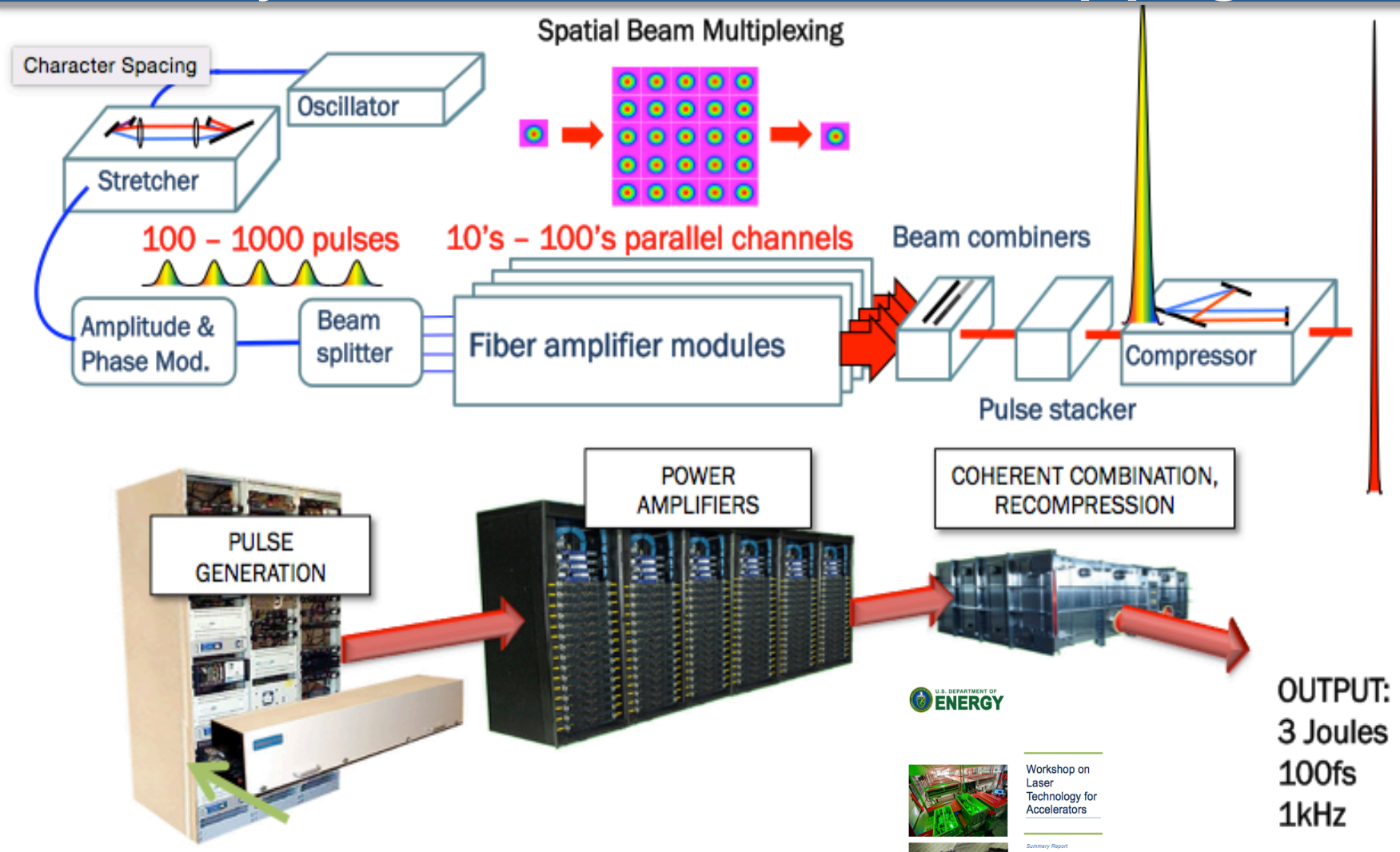


C. B. Schroeder et al. FEL Proc (2013)

Moore Foundation funded

- Need high average power ultrafast system
  - Commercial 100kW, 35% wall plug efficient fiber lasers available, but CW
  - Ultrafast fiber lasers peak power limited to ~1mJ in <10 fs (!)

We are developing Innovative laser concepts under the newly launched DOE-HEP Stewardship program



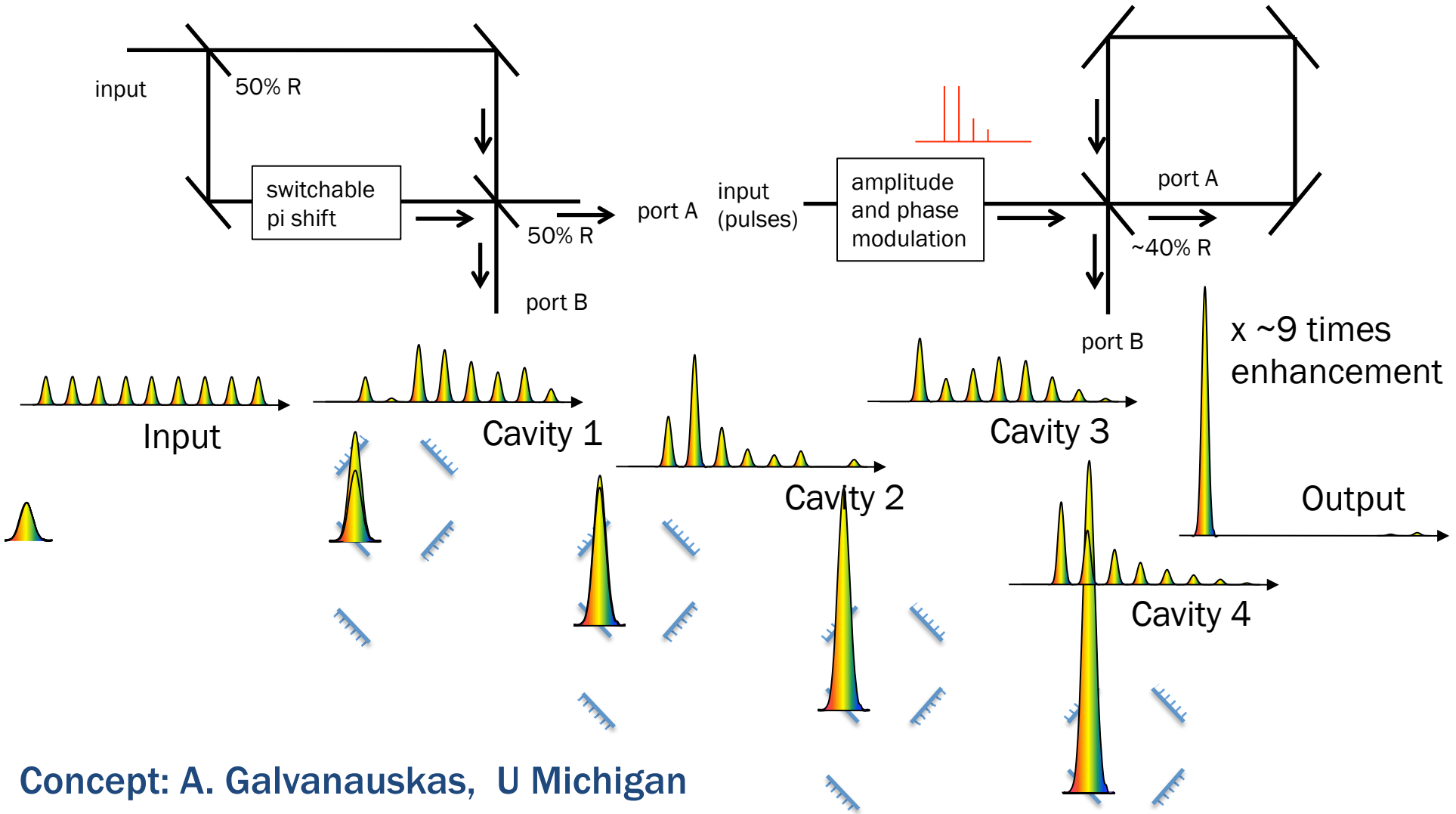
Workshop on Laser Technology for Accelerators

Summary Report

January 23–25, 2013

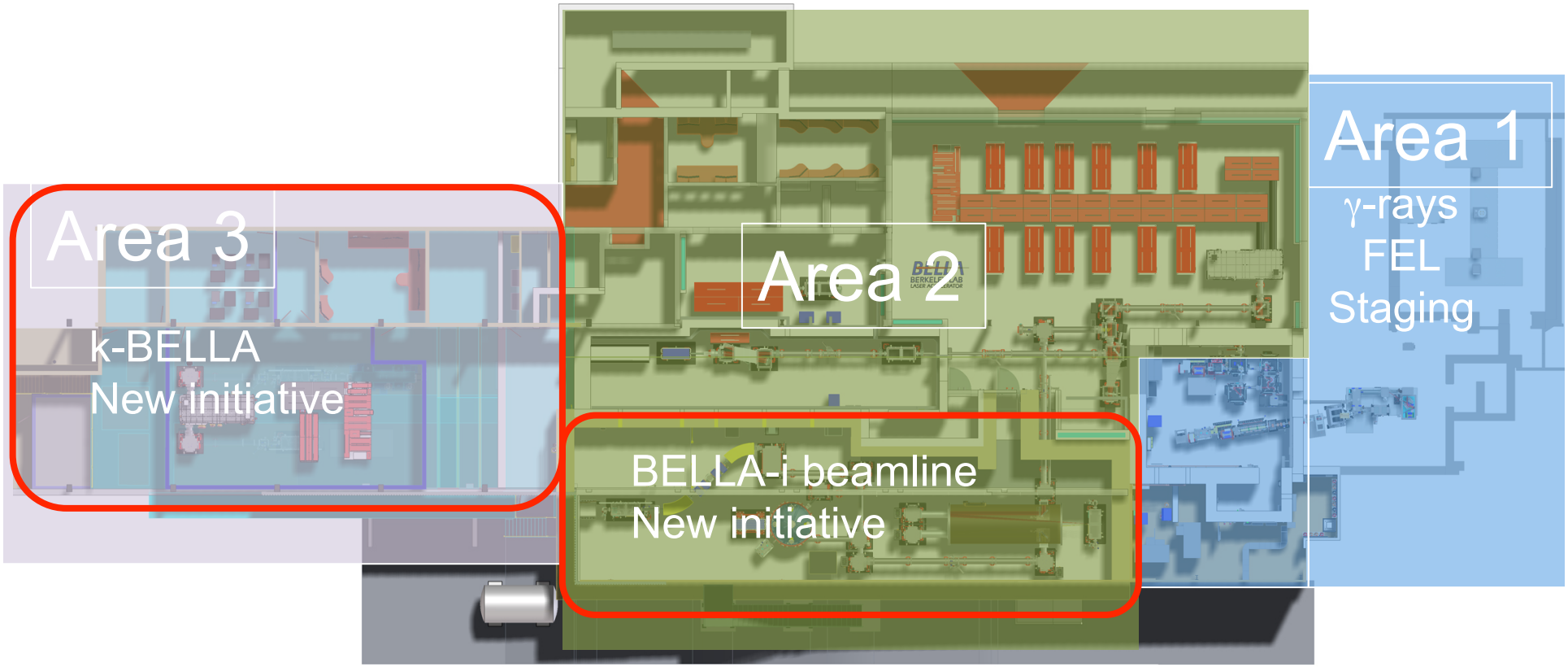
LBNL, LLNL, U Michigan partnership

How a pulse train is stacked into a single pulse



Concept: A. Galvanauskas, U Michigan

We are proposing BELLA-i and k-BELLA initiatives as part of the development of BELLA towards a user facility



Summary

- BELLA facility is up and running and has set new records on laser performance and electron beam energy (up to 4.3 GeV) from an LPA
- We are implementing novel concepts to reach 10 GeV, generation of ultra-cold beams and focusing on stability
- Staging experiment shows feasibility – mode matching is key issue
  - Planning experiment to demonstrate 5 GeV boost on 5 GeV beam
- New initiatives on γ-ray source, FEL and medical applications
- We are proposing
  - BELLA-i as an important addition to the facility
  - k-BELLA as a new facility for high average power applications
- We are discussing with DOE making BELLA a user facility

- Presented at DOE-FES Townhall, July 1, 2015 – white papers available
- 2015 APS-DPP evening meeting and Workshop in January 2016 for community input

We are planning a workshop on science with BELLA-i

January 20-22, 2016 at LBNL

Please contact me or Sven Steinke if you would like more information and or want to attend

BELLA Center staff (FY14-15)

Scientific Staff:


Wim Leemans


Csaba Toth


Kei Nakamura


Cameron Geddes


Eric Esarey


Carl Schroeder


Jean-Luc Vay

Guest Researchers:


Prof. Andy Roberts

Until June 2015


Anthony Gonsalves


Jeroen van Tilborg


Carlo Benedetti


Stepan Bulanov


Nicholas Matlis

Until Feb 2015


Feng Liu

Until July 2015

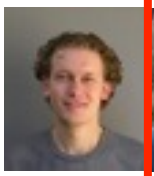

Remi Lehe


Sven Steinke


Hann-Shin Mao

Names in blue are at U.C. Berkeley

PhD, Masters, undergrad students:


Joost Daniels


Daniel Mittelberger


Brian Shaw


Chris Pieronek


Kelly Swanson


Julius Huijt

Until July 2014


Francesco Rossi


Patrick Lee

Samuel Barber


Sergei Rykovanov

Until June 2014


Henri Vincenti


Alexandre Bonatto

New PhD students: Fumika Isono, Blagoje Djordevic

New Postdoc: Sam Barber

Engineering & Technical Support:

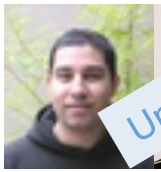

Don Syversrud


Dave Evans


Mark Kirkpatrick

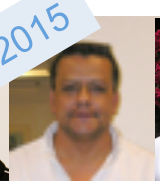

Tyler Sipla


Nathan Ybarrolaza


Greg Mannino


Aalhad Deshmukh

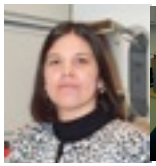
Until June 2015


Art Magana


Joe Riley

Ken Sihler

Administrative Support:


Martha Condon


Wes Tabler