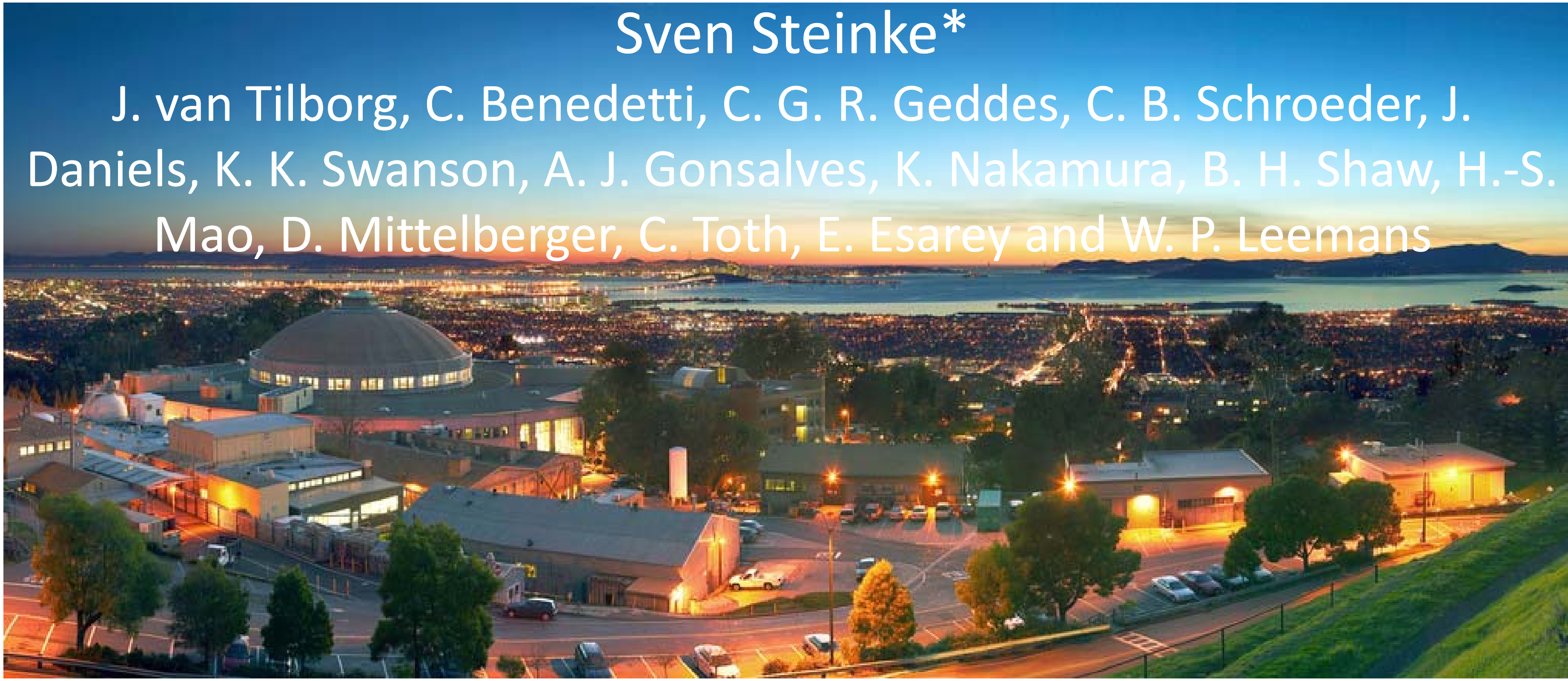
Staging of Independent Laser Plasma Accelerators (LPAs)

Sven Steinke*

J. van Tilborg, C. Benedetti, C. G. R. Geddes, C. B. Schroeder, J. Daniels, K. K. Swanson, A. J. Gonsalves, K. Nakamura, B. H. Shaw, H.-S. Mao, D. Mittelberger, C. Toth, E. Esarey and W. P. Leemans



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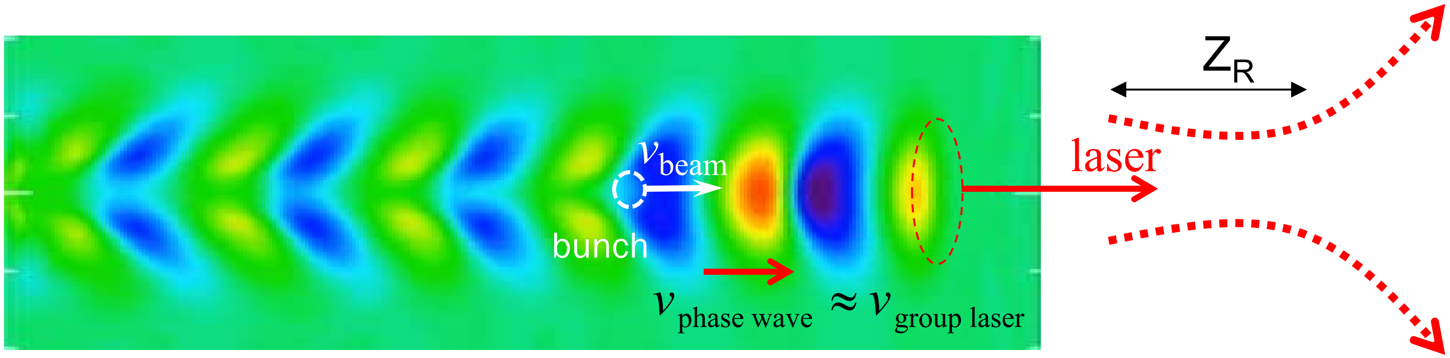
High gradient LPAs offer path to colliders

- Plasma provides a structure to sustain high field gradients (GeV/m)
- High field gradients require high peak power: laser driven, particle beam driven



Limits to single stage energy gain

- Laser Diffraction (~Rayleigh range)
  - mitigated by transverse plasma density tailoring (plasma channel)
- Beam-Plasma Wave Dephasing
  - mitigated by longitudinal plasma density tailoring (plasma taper)
- Laser Energy Depletion: energy loss into plasma wave excitation

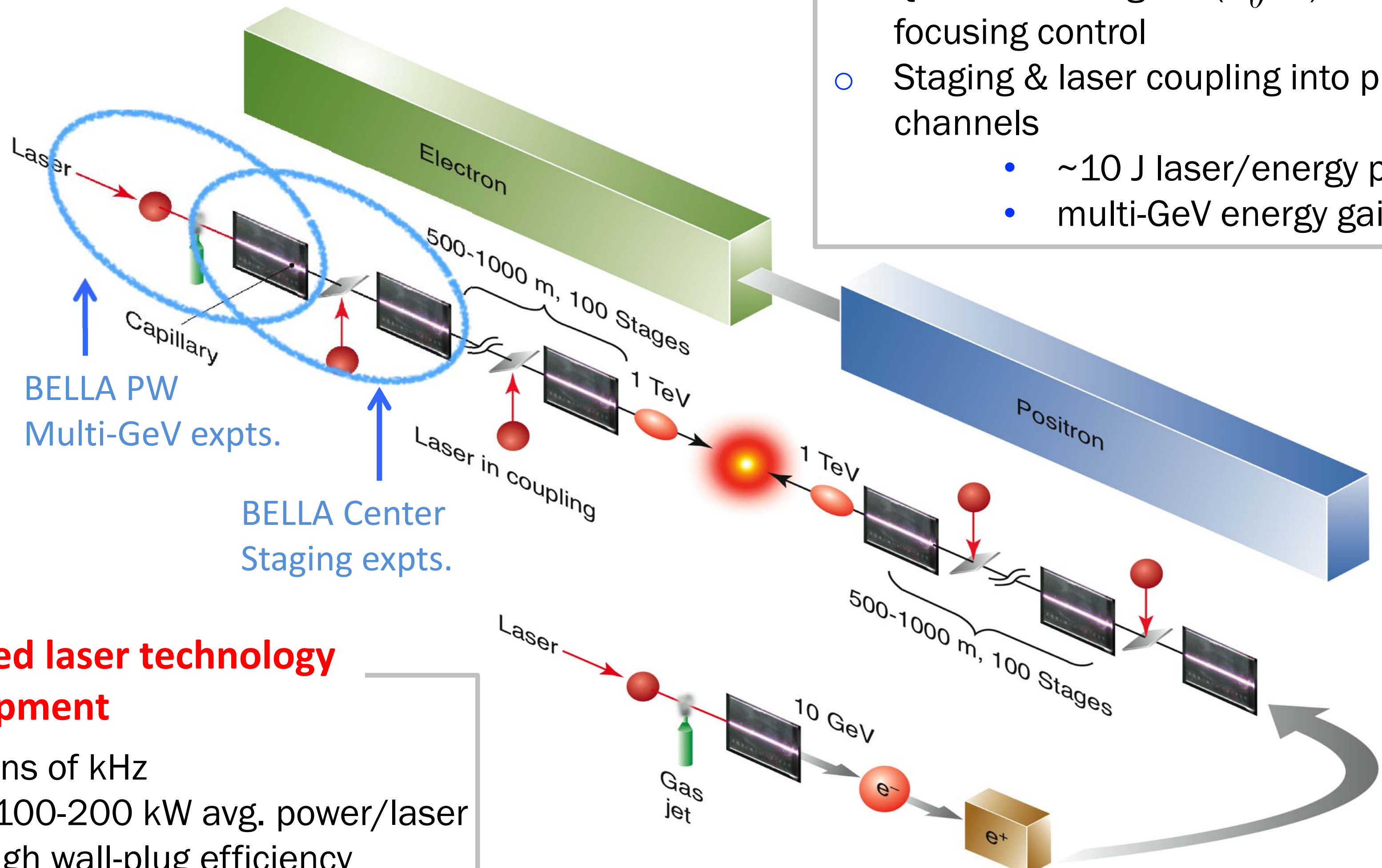
For high gradient, laser depletion necessitates staging laser-plasma accelerators

Vision: LPA linear collider concept

Leemans & Esarey, Phys Today (2009)
Schroeder et al., PRSTAB ***13****, 101301 (2010)*

Scaling laws indicate

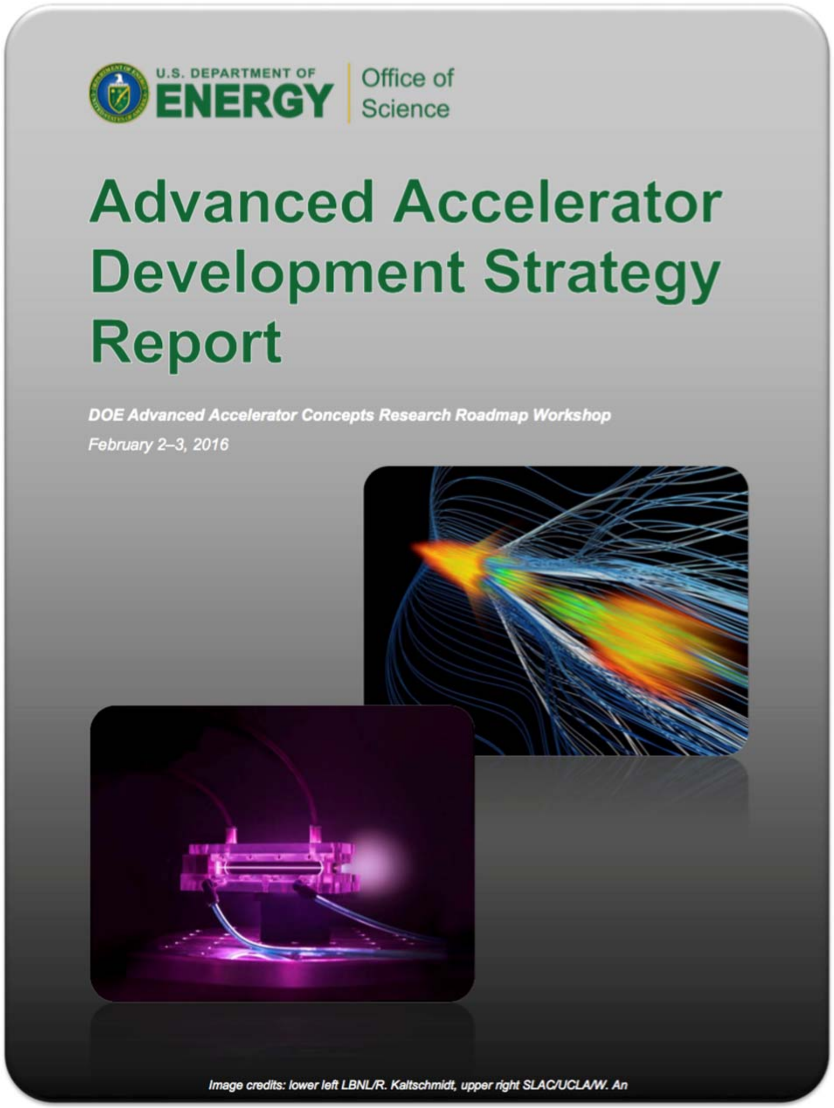
- operation at n_e~10^{17} cm^{-3}
- Quasi-linear regime (a_0~1): e^+ and e^-, focusing control
- Staging & laser coupling into plasma channels
  - ~10 J laser/energy per stage
  - multi-GeV energy gain/stage



Required laser technology development

- tens of kHz
- ~100-200 kW avg. power/laser
- High wall-plug efficiency

Strategy report for Advanced Accelerators from DOE covers laser and beam driven plasma + dielectric wakefield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Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

Document available on DOE-HEP website

in response to a recommendation by the HEPAP Accelerator R&D Subpanel:

"convene the university and laboratory proponents of advanced acceleration concepts to ***develop R&D roadmaps*** *with a series of milestones and common down selection criteria* ***towards the goal for constructing a multi-TeV*** e^+e^- ***collider****"*

Invited Participants

Thomas Antonsen	*University of Maryland*
Ilan Ben-Zvi	*Brookhaven National Laboratory*
Jerry Blazey	*Northern Illinois University*
Yunhai Cai	*SLAC National Accelerator Laboratory*
Weiren Chou	*Fermi National Accelerator Laboratory (retired)*
Michael Downer	*University of Texas-Austin*
Wei Gai	*Argonne National Laboratory*
Carl Schroeder	*Lawrence Berkeley National Laboratory*
Mark Hogan	*SLAC National Accelerator Laboratory*
Chungguang Jing	*Argonne National Lab/Euclid Techlab*
Chan Joshi	*University of California-Los Angeles*
Wim Leemans	*Lawrence Berkeley National Laboratory*
Michael Litos	*SLAC National Accelerator Laboratory*
Sergei Nagaitsev	*Fermi National Accelerator Laboratory*
James Rosenzweig	*University of California-Los Angeles*
Andrei Seryi	*John Adams Institute*
Bill Weng	*Brookhaven National Laboratory*

Other Participants

L.K. Len (DOE)

J. Siegrist (DOE)

G. Crawford (DOE)

J. Boger (DOE)

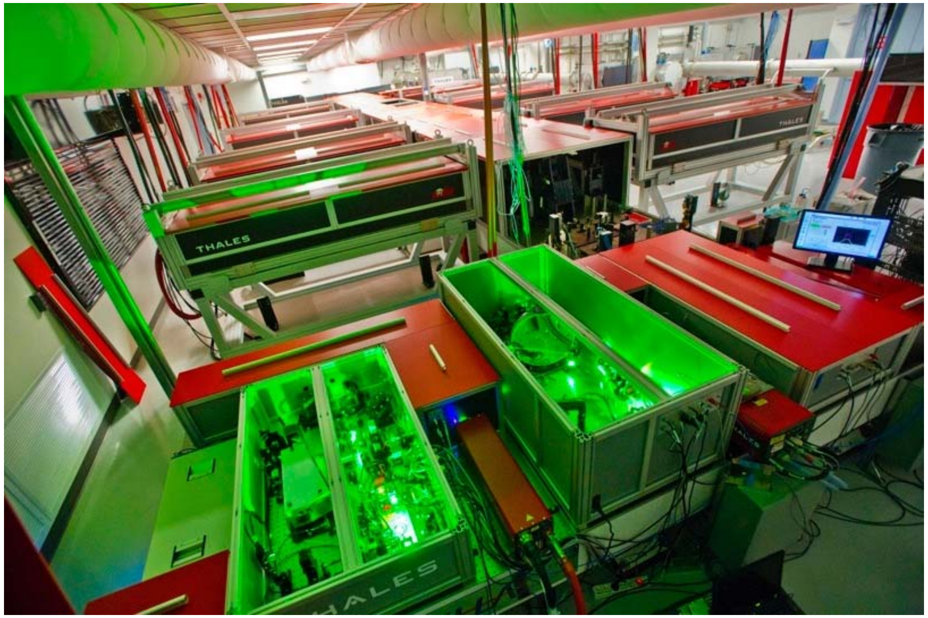
E. Colby (DOE)

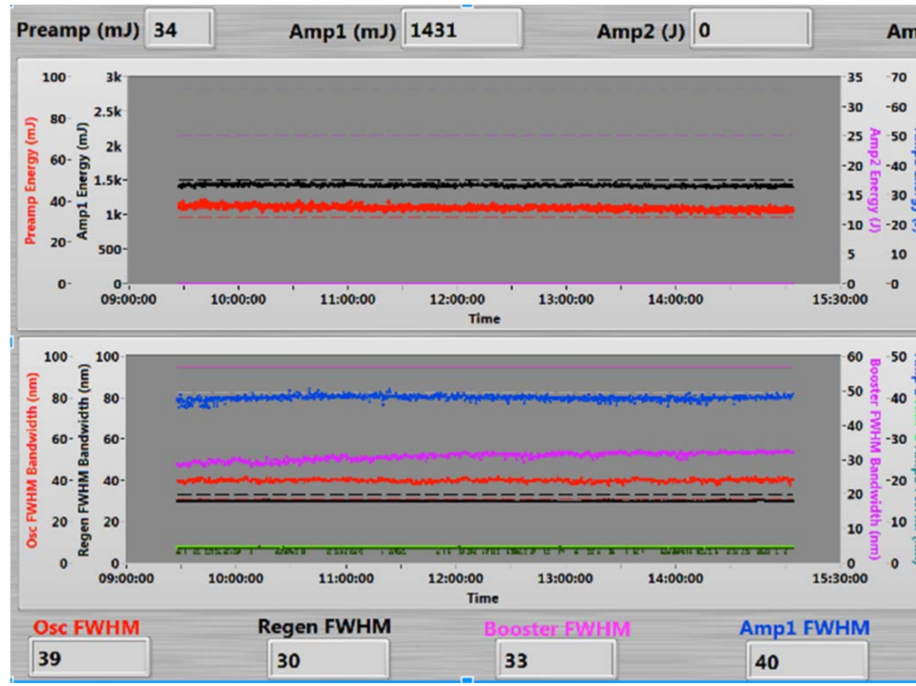
K. Marken (DOE)

A. Lankford (HEPAP)

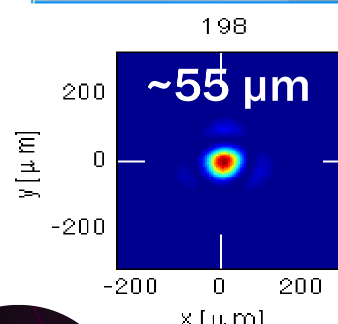
V. Lukin (NSF)

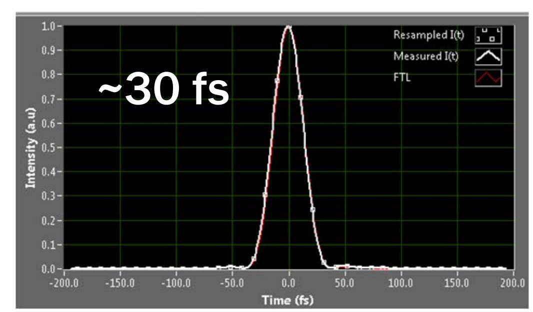
BELLA laser: (still) highest rep. rate PW-laser for high intensity LPA experiments towards 10 GeV

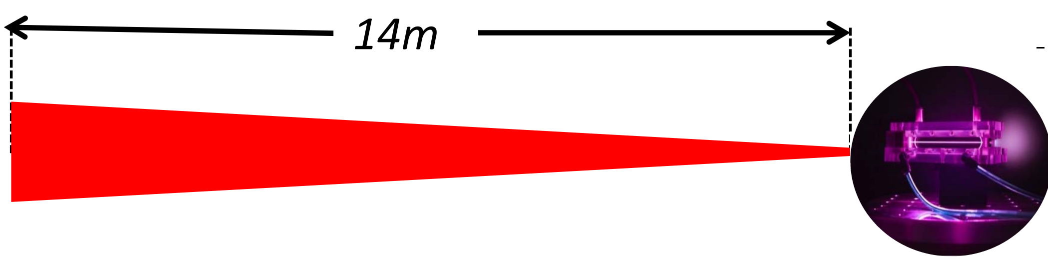




Petawatt laser operating at up to 42 J in ~30 fs at 1 Hz







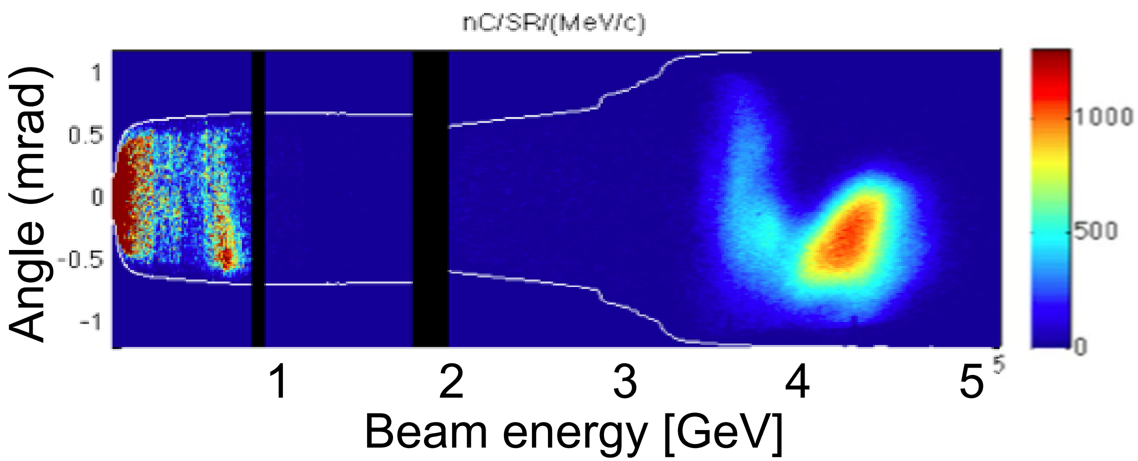
Intensity ~1.5x10^{19} Wcm^{-2}

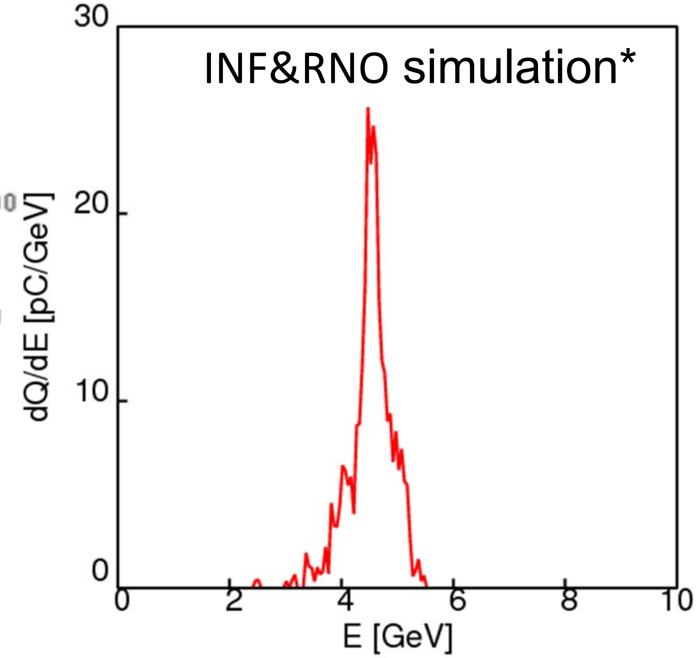
Acc. fields ~10-50GV/m

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

Electron beam spectrum





- **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); A.J. Gonsalves et al., PoP (2015)

Scaling towards 10 GeV requires lower densities

LPA scaling laws

- Laser-plasma interaction length:

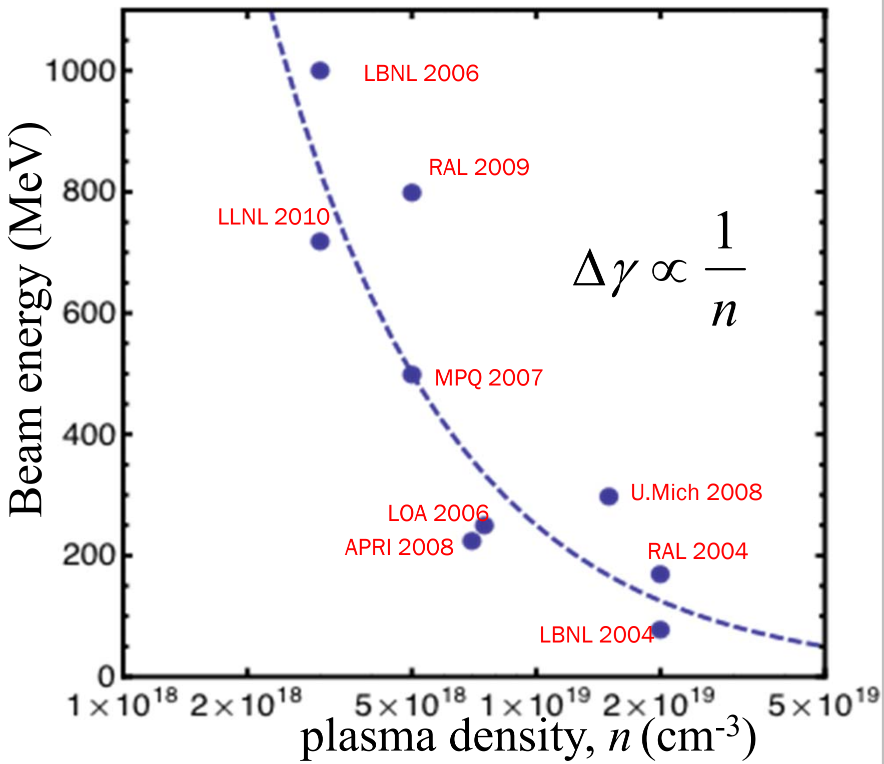
$$L_{\text{deplete}} \propto n^{-3/2}$$

- Accelerating gradient: (require > GV/m)

$$E_z \sim \left(m_e c \omega_p / e\right) \propto \sqrt{n}$$

- Energy gain (per LPA stage):

$$E_z \cdot L_{\text{int}} \propto 1/n$$



Schroeder et al., Phys. Rev ST, 13, 101301 (2010).

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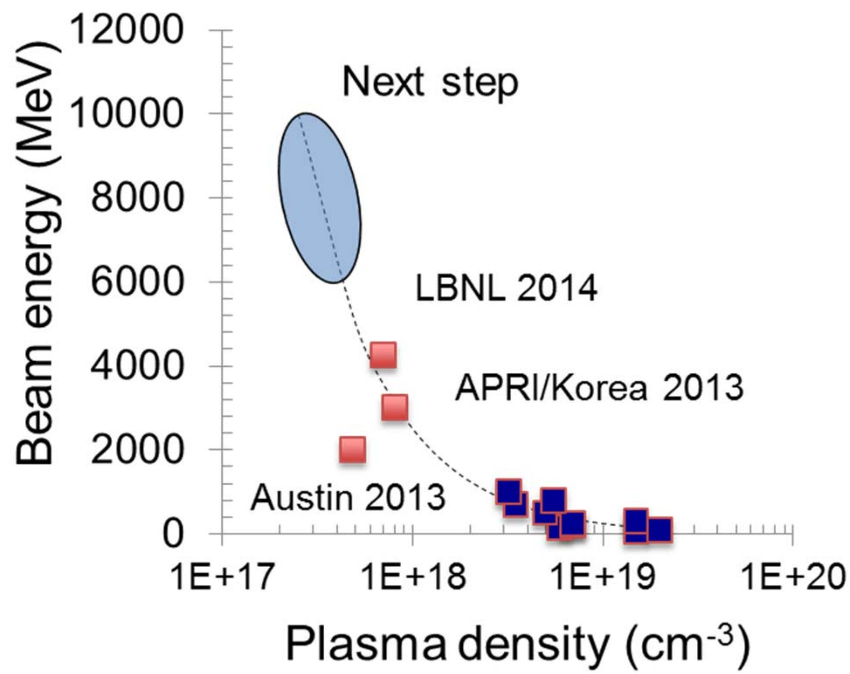

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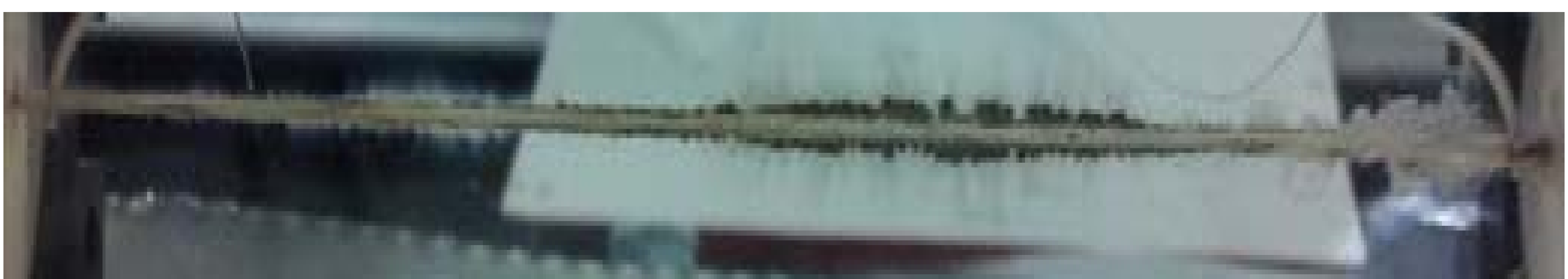
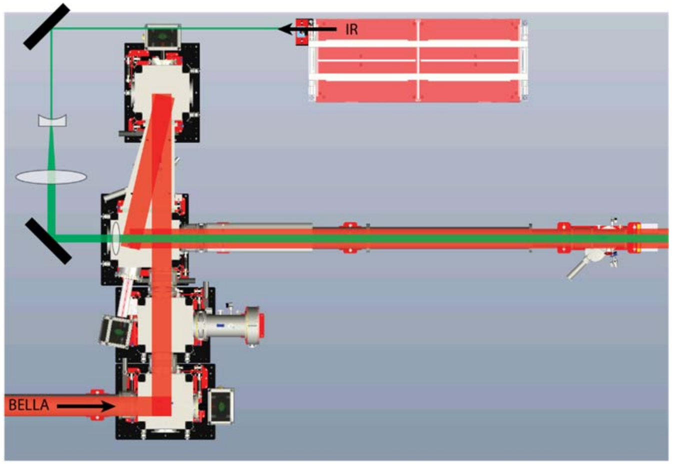
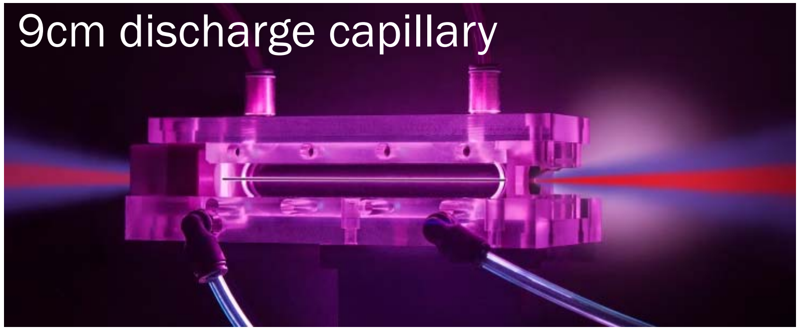


ns-scale Heater Pulse enables deeper channels with better mode matching

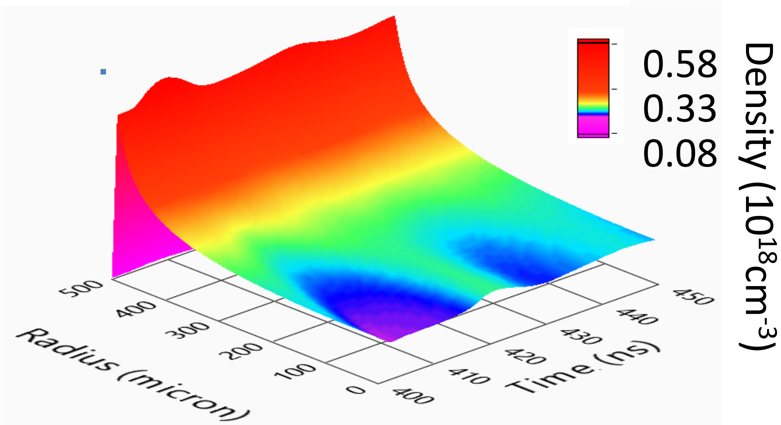
Decoupling of Ignitor and Heater

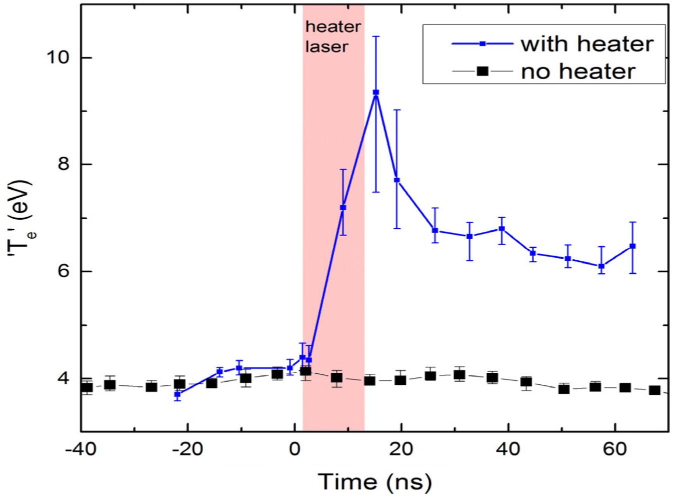




*Volfbeyn et al., PoP **6**, 2269 (1999)*
*Durfee and Milchberg PRL **71**, 2409 (1993)*

Inverse Bremsstrahlung heating

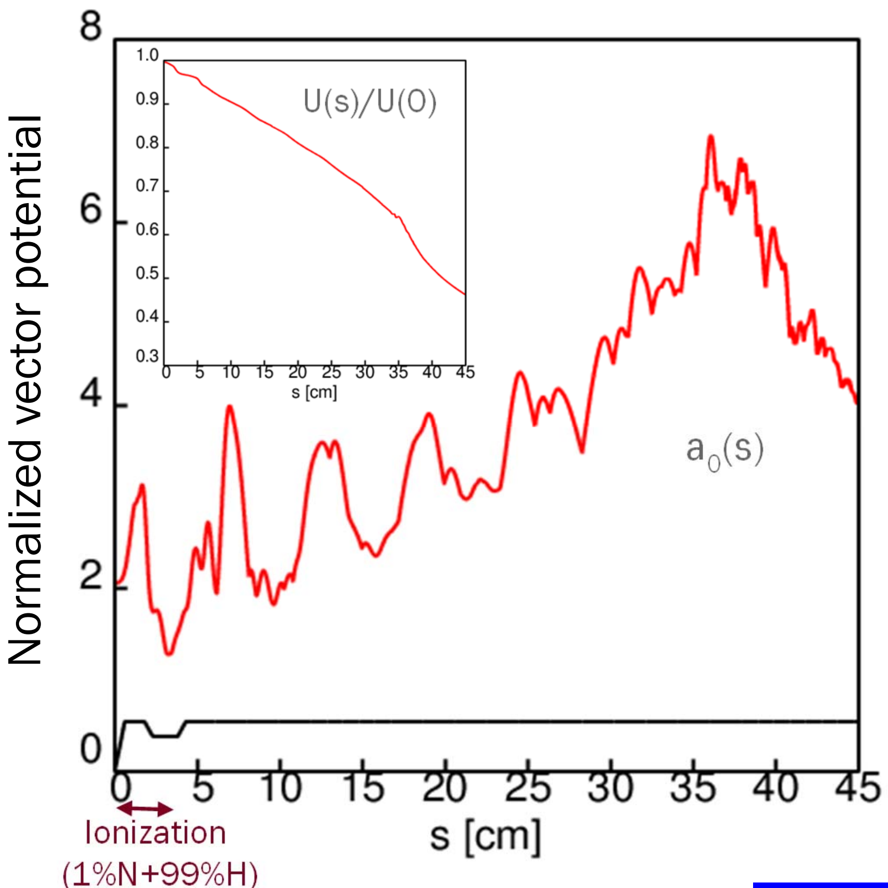


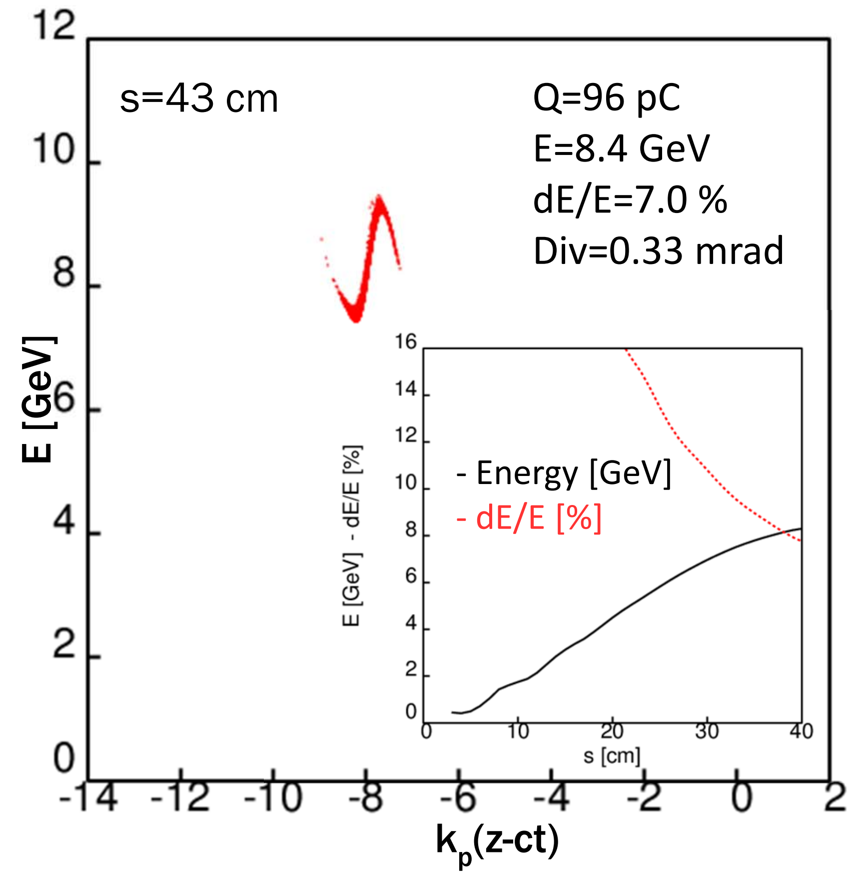


*Bobrova et al., PoP **20**, 020703 (2013)*

Electron beams at the 8-9 GeV level are expected from simulations that include as many measured properties of laser and plasma

Laser: U=36 J, w0=59.8 um, T=66 fs (FWHM of intensity)
Plasma: n_0=1.6x10^{17} cm^{-3}, Rcap=200 um, laser heater (2.3 J, 10 ns)





Laser heater required to deepen channel

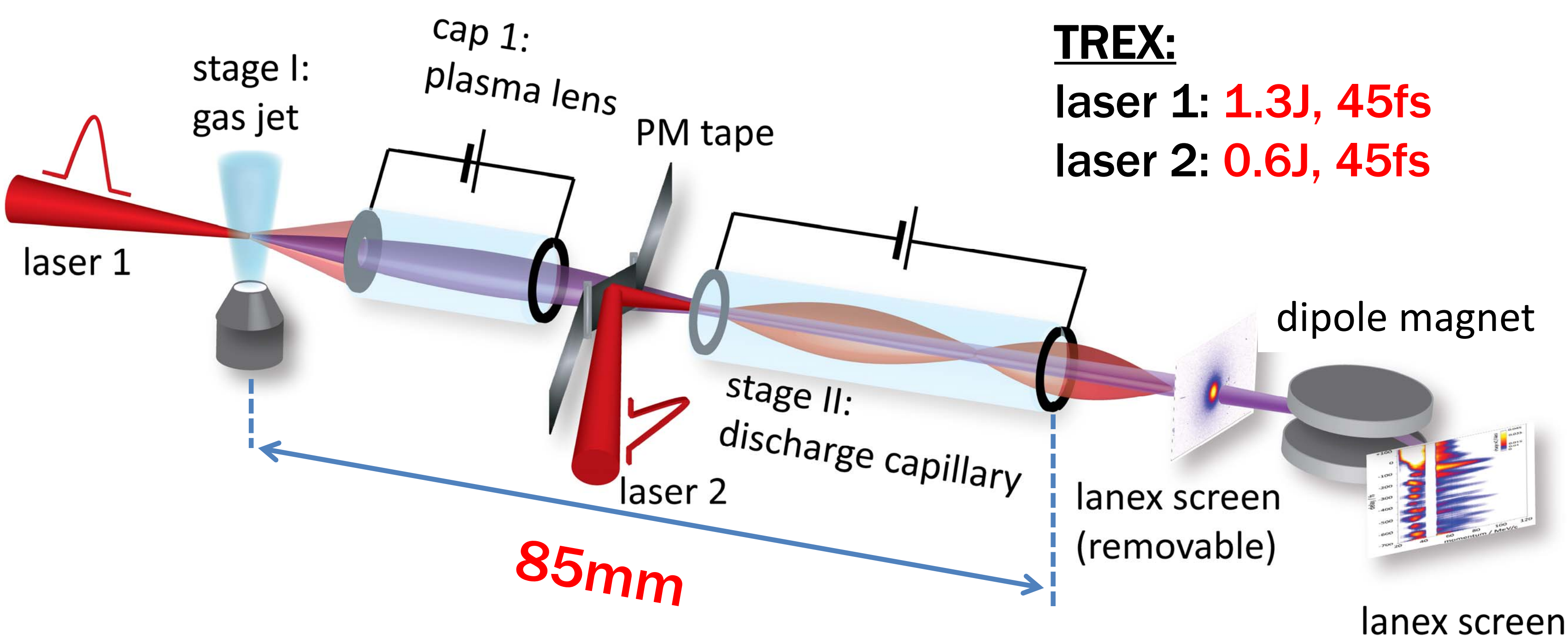
All plasma-based Staging of Laser Plasma Accelerators

Stage I: gas jet - injector

Coupling II: tape-driven plasma mirror

Coupling I: active plasma lens

Stage II: discharge capillary- accelerator



TREX:

laser 1: 1.3J, 45fs

laser 2: 0.6J, 45fs

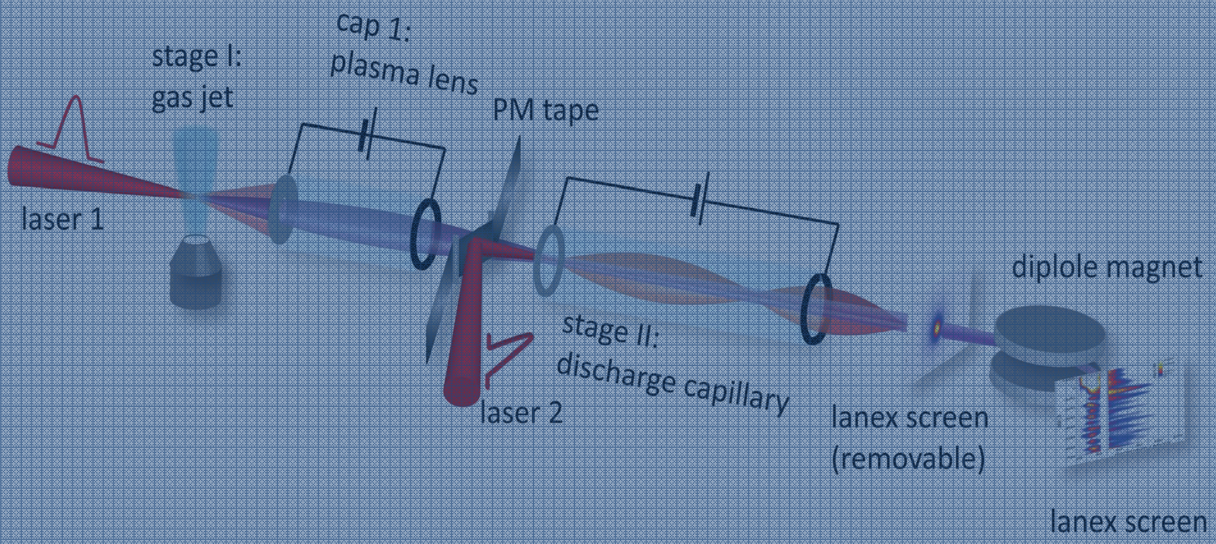
Multistage Coupling of two independent LPAs

Stage I: gas jet - injector

Coupling I: active plasma lens

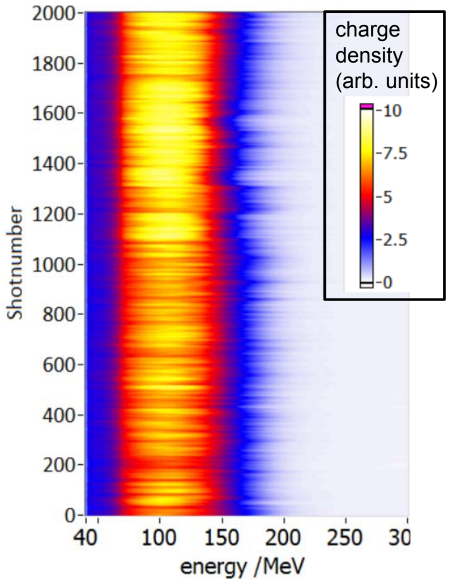
Coupling II: tape-driven plasma mirror

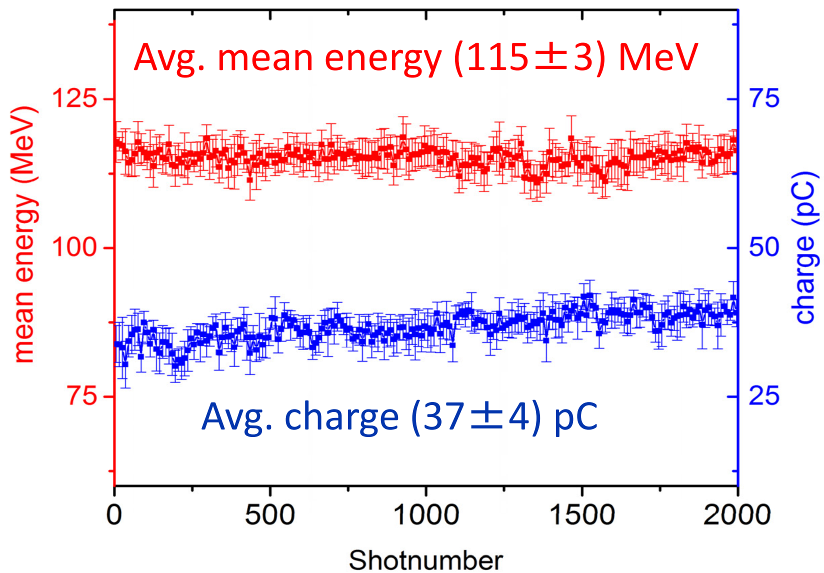
Stage II: discharge capillary- accelerator



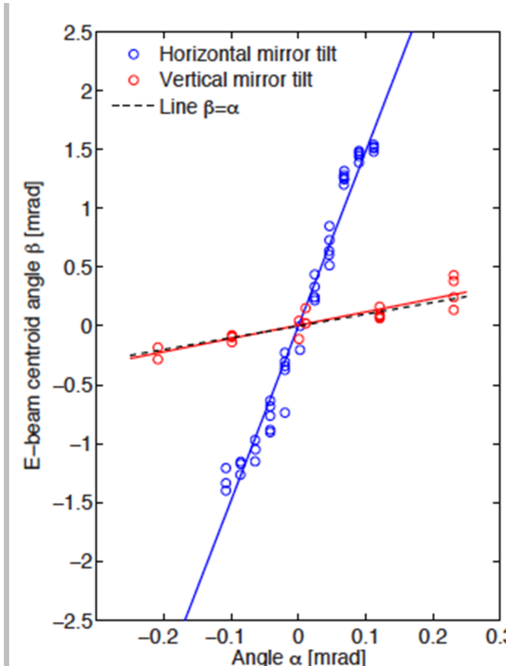
Stage I: Turnkey gas jet operation in ionization injection regime provides tunable injector beams of excellent stability

Stable energy and charge





Steering possible

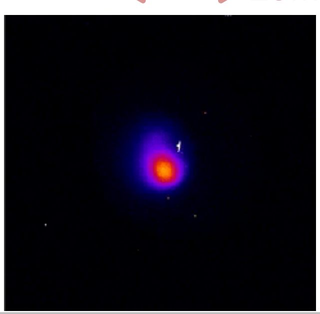


10mrad

Phosphor screen

Stable E-beam pointing

10mrad



Phosphor screen

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

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Multistage Coupling of two independent LPAs

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Coupling I: active plasma lens

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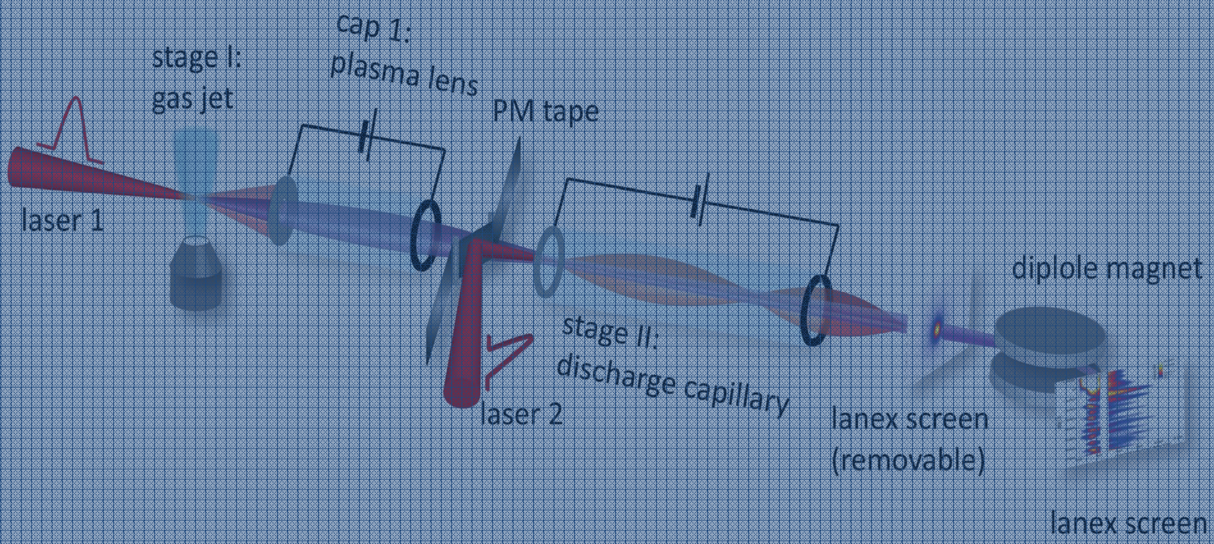
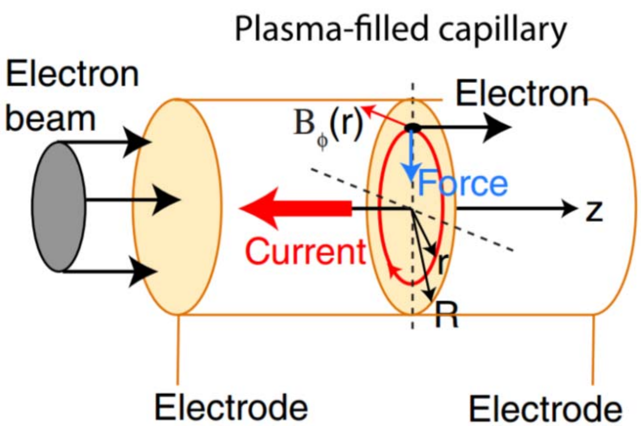
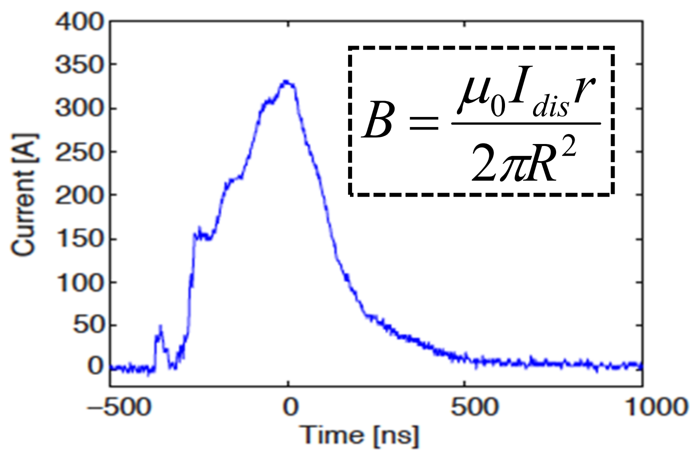


Developed Active Plasma Lens for efficient e-beam coupling to the 2^{nd} stage and emittance measurement

Tunable, ultra-high field Plasma lens

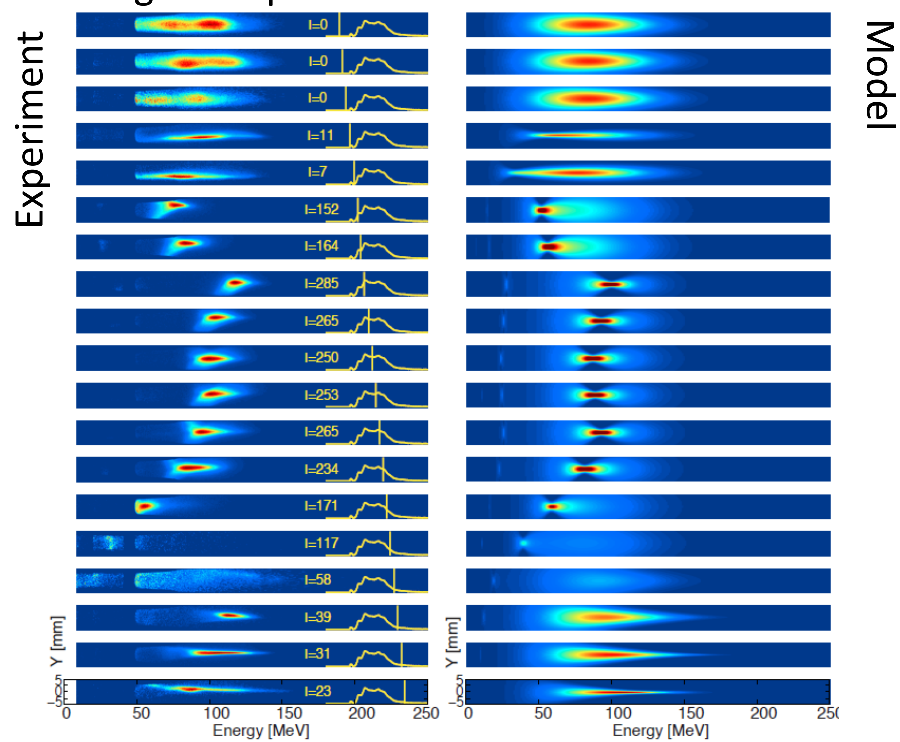


Discharge pulse enables gradients of **>3000 T/m:**

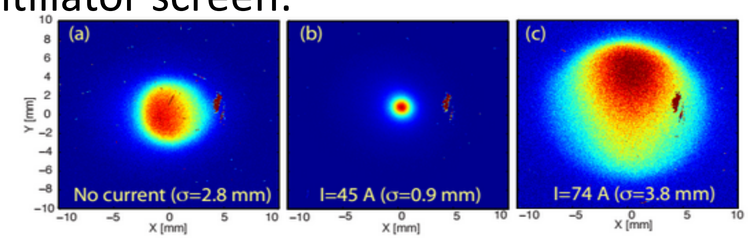


Emittance measurement: source size of 5 µm

Magnetic spectrometer:



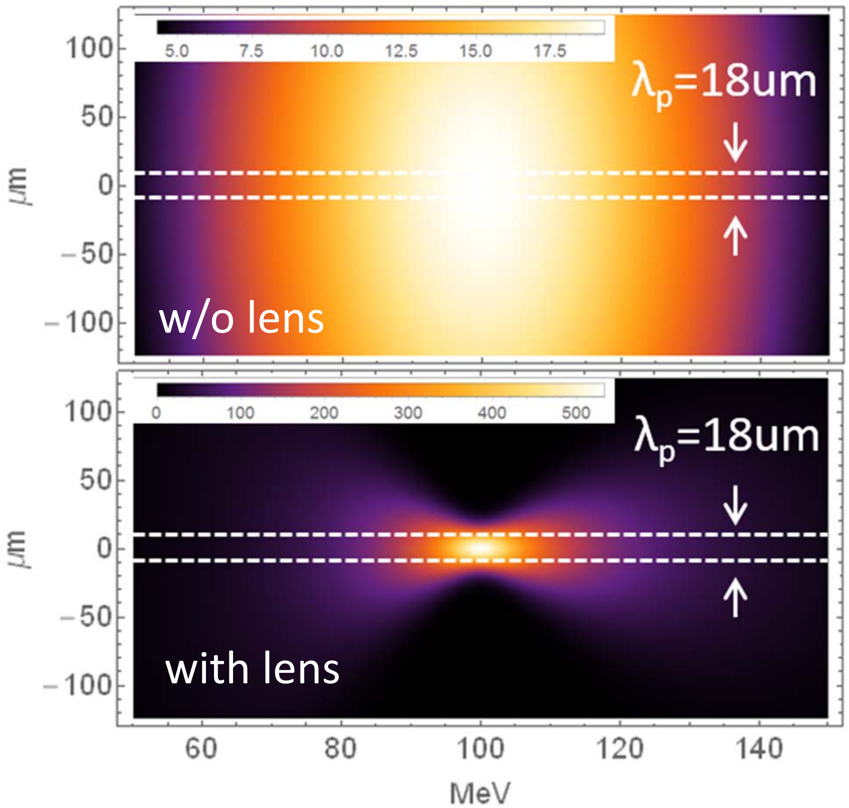
Scintillator screen:



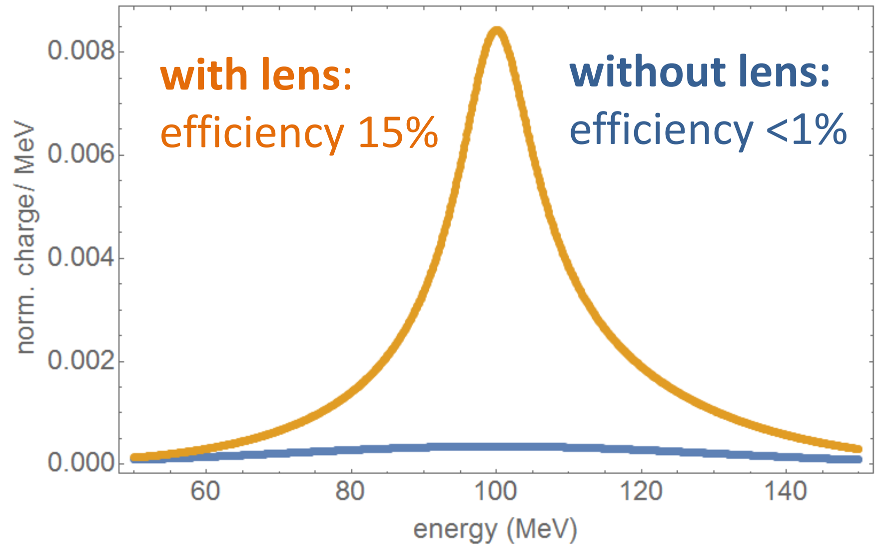
J. van Tilborg et al., PRL 184802 (2015)

Active Plasma Lens enables transport of 15% of the injector charge to a spotsize ≤ the wakefield acceptance

Beam profiles at Stage 2 entrance



Beam spectra within wake acceptance



Broad energy spread of the injector beam limits charge coupling to the 2nd stage wakefield due to the chromaticity of the plasma lens.

Multistage Coupling of two independent LPAs

Stage I: gas jet - injector

Coupling I: active plasma lens

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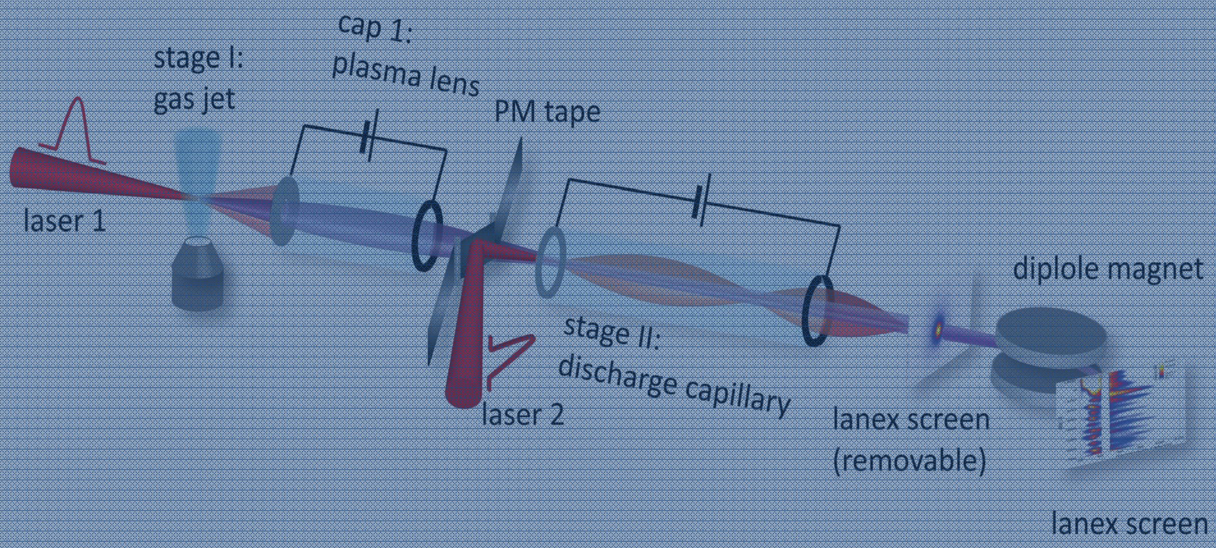
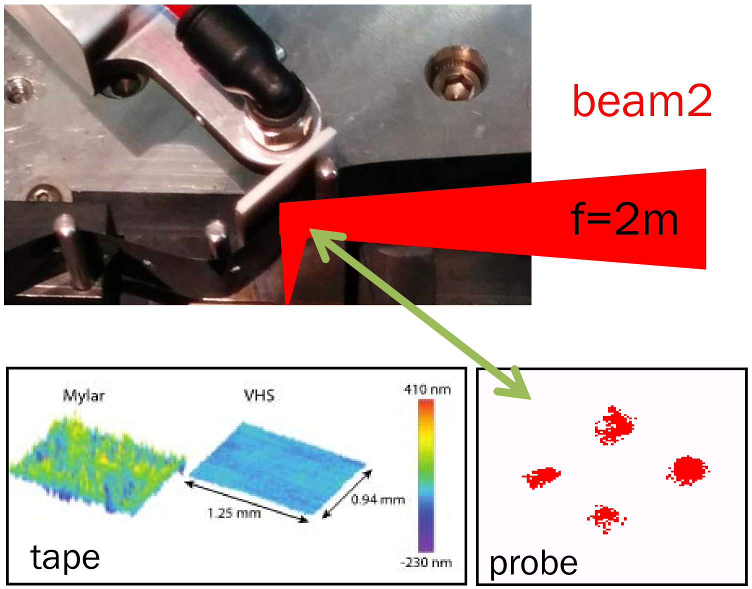
Stage II: discharge capillary- accelerator



Tape-driven Plasma Mirror (PM) to couple in the 2nd stage laser pulse at cm-scale to maintain the overall acceleration gradient

Plasma Mirror design

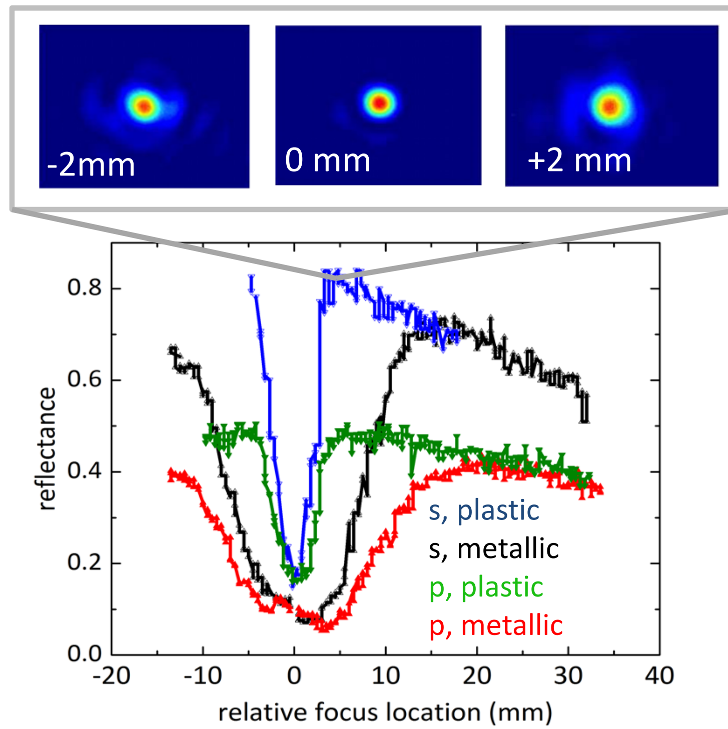


- Active feedback control
- Stable operation over hours of run time

Sokollik et al. AAC proc. (2010)

Plasma mirror performance

- High reflectivity (80%)
- Excellent mode quality (Strehl ratio >0.8)
- Small pointing fluctuation (~9μm)



Optimize material and laser polarization

Shaw et al. PoP **23**, 063118 (2016)

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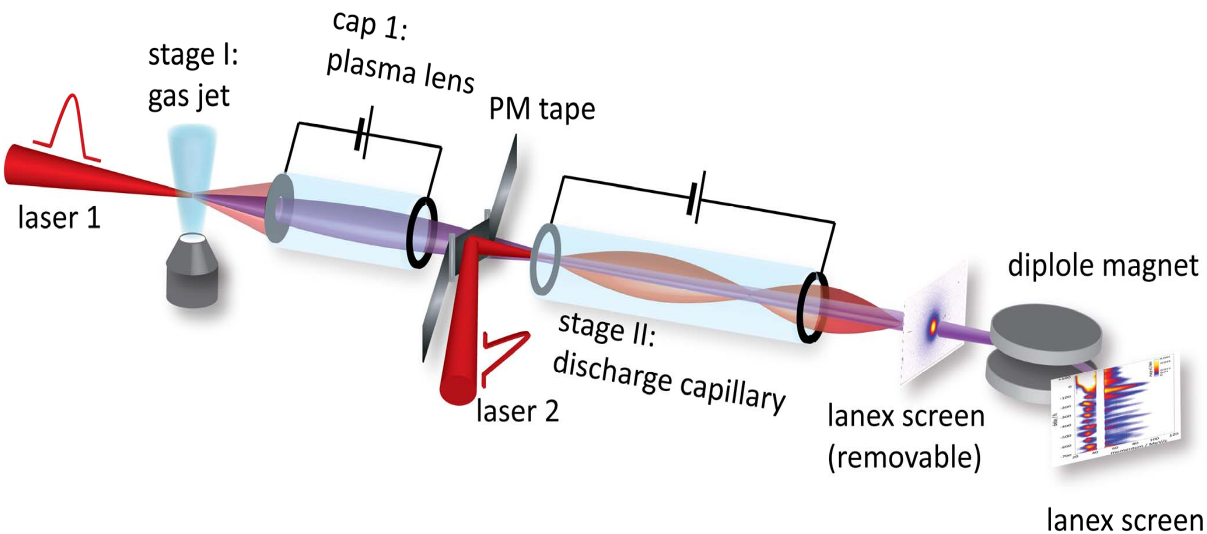
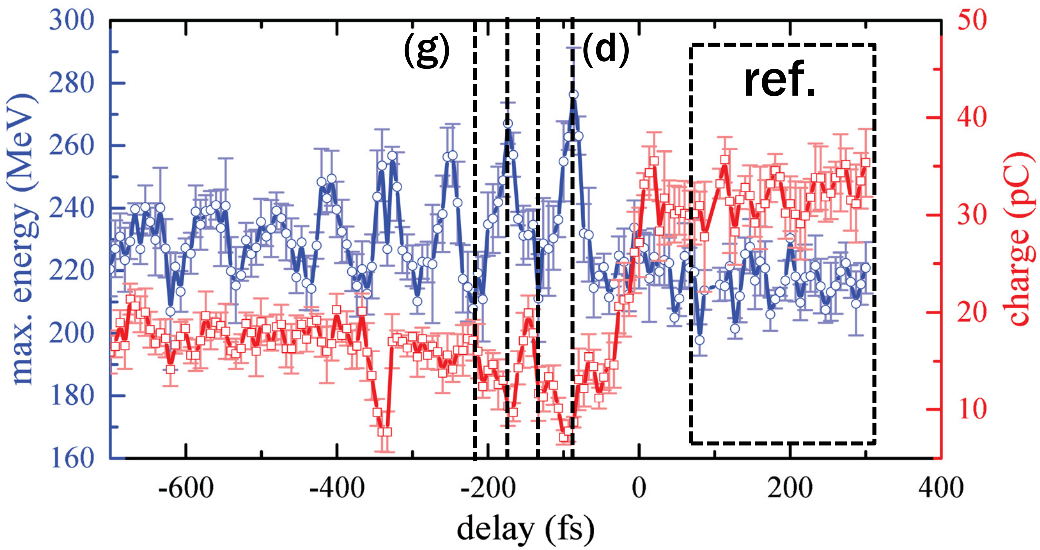
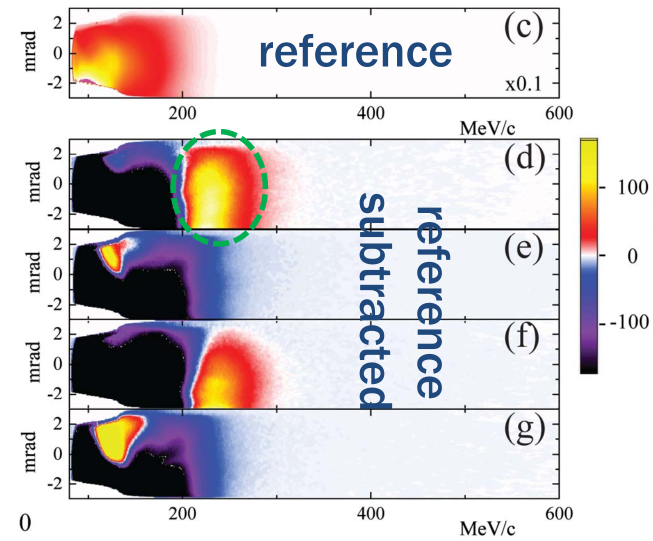


- Relative delay of both laser arms is controlled by an optical delay stage with fs-precision

Staging Experiment: Energy gain of witness beam by timing of second laser (wake phase)

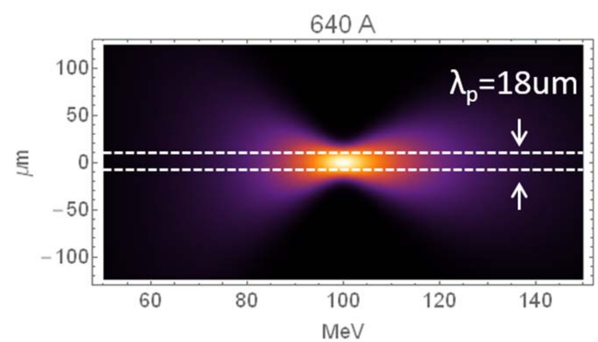
Modulation period of 80fs consistent with a plasma frequency at a density of $2\times10^{18}cm^{-3}$





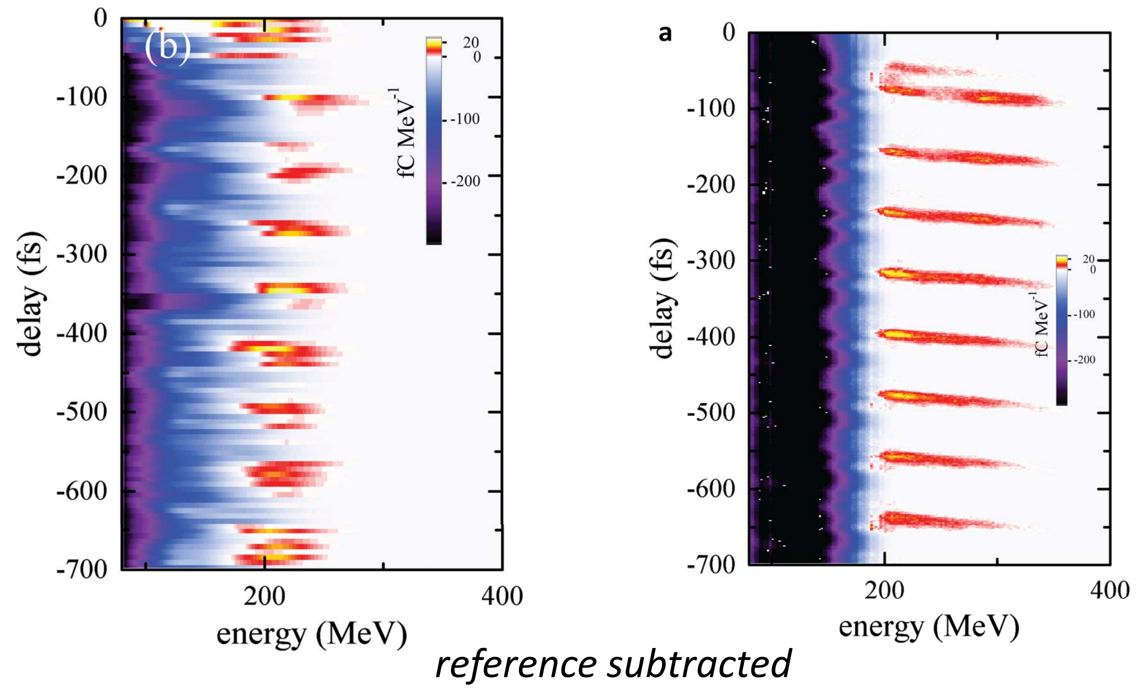
S. Steinke et al., Nature **530**, 190 (2016)

Previous plasma lens calculation suggest that 1.2pC of trapped charge corresponds to a wake trapping efficiency of 30%



Simulation reproduce staging signatures at correct magnitude

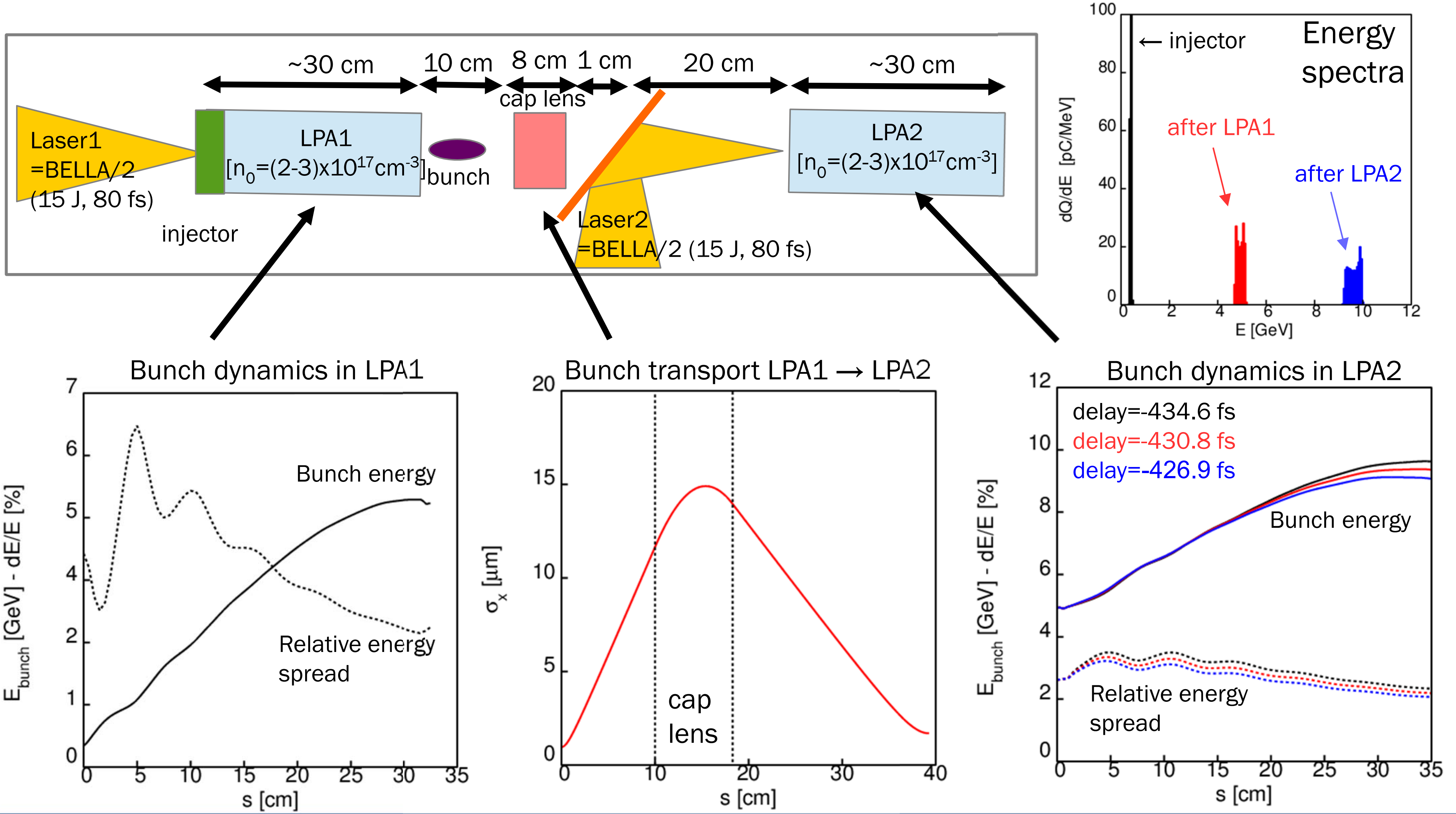
Comparison of experiment and simulation



S. Steinke et al., Nature ***530****, 190 (2016)*

- Recurring post acceleration (100 MeV) at the plasma frequency
- ~1pC of charge at energies >200MeV
- Analysis of simulation results unravels details of the acceleration/ deceleration processes

~10 GeV electron beams from STAGING experiment using BELLA: simulations show high efficiency capturing and acceleration in LPA2 of the bunch produced by LPA1



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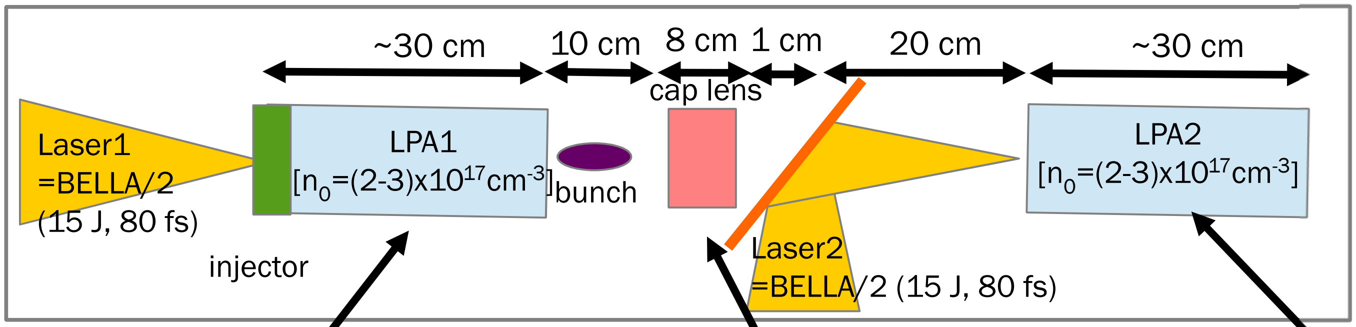
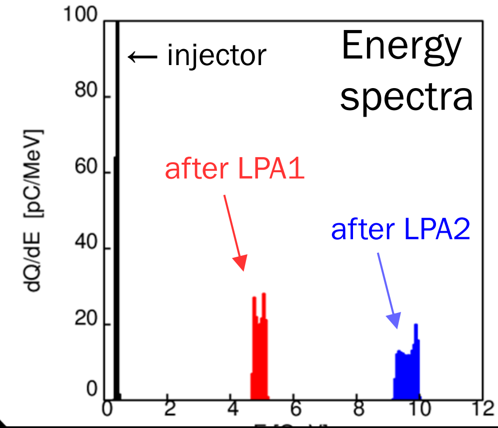
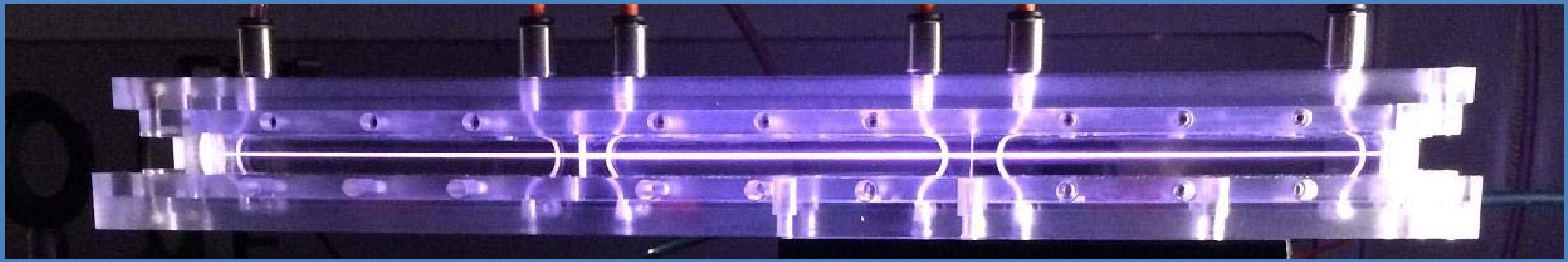


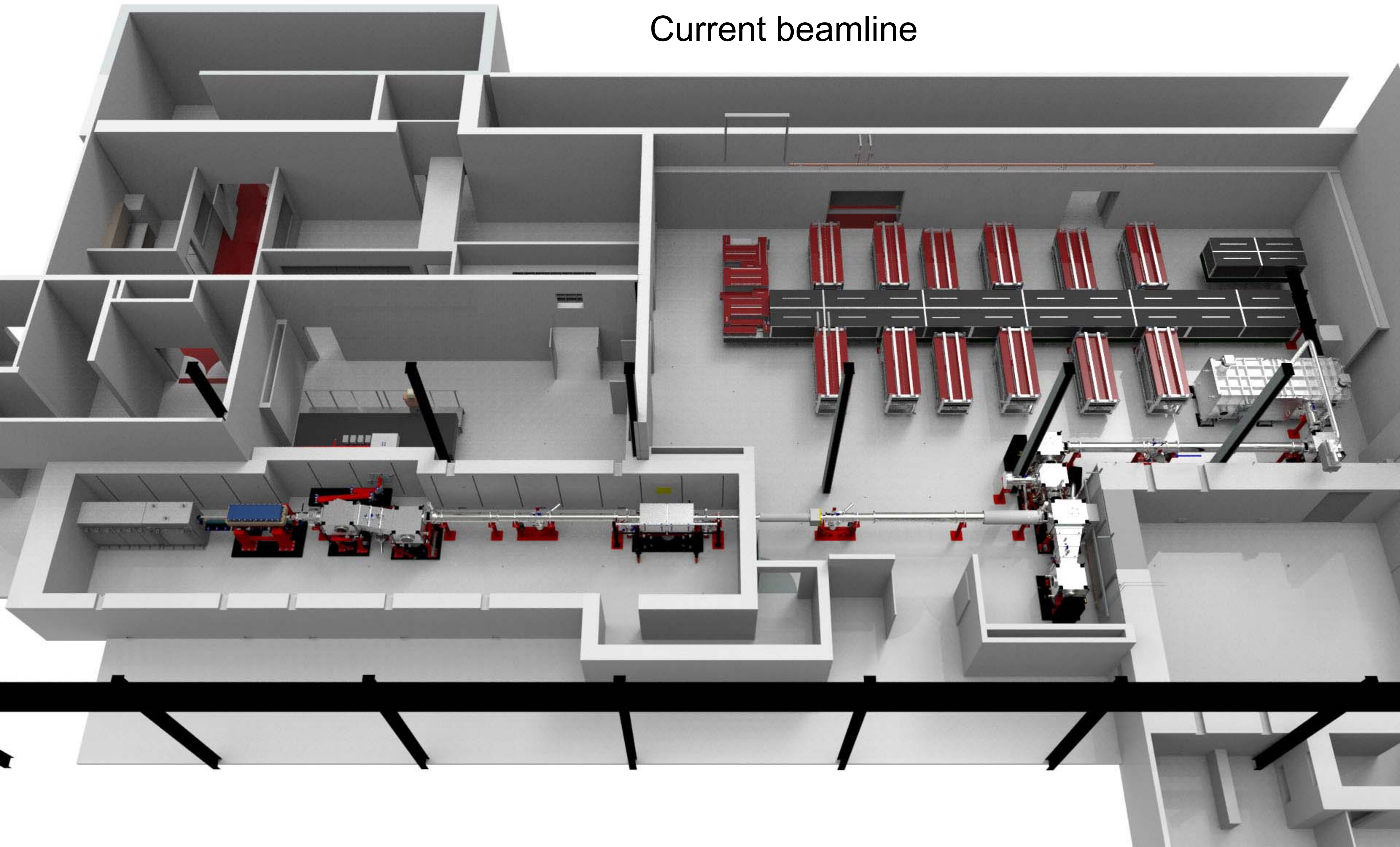


Longer capillary discharges are being developed and tested



27cm

A second beamline on BELLA is proposed for 5 GeV+5GeV staging and will enable ultra-high intensity experiments



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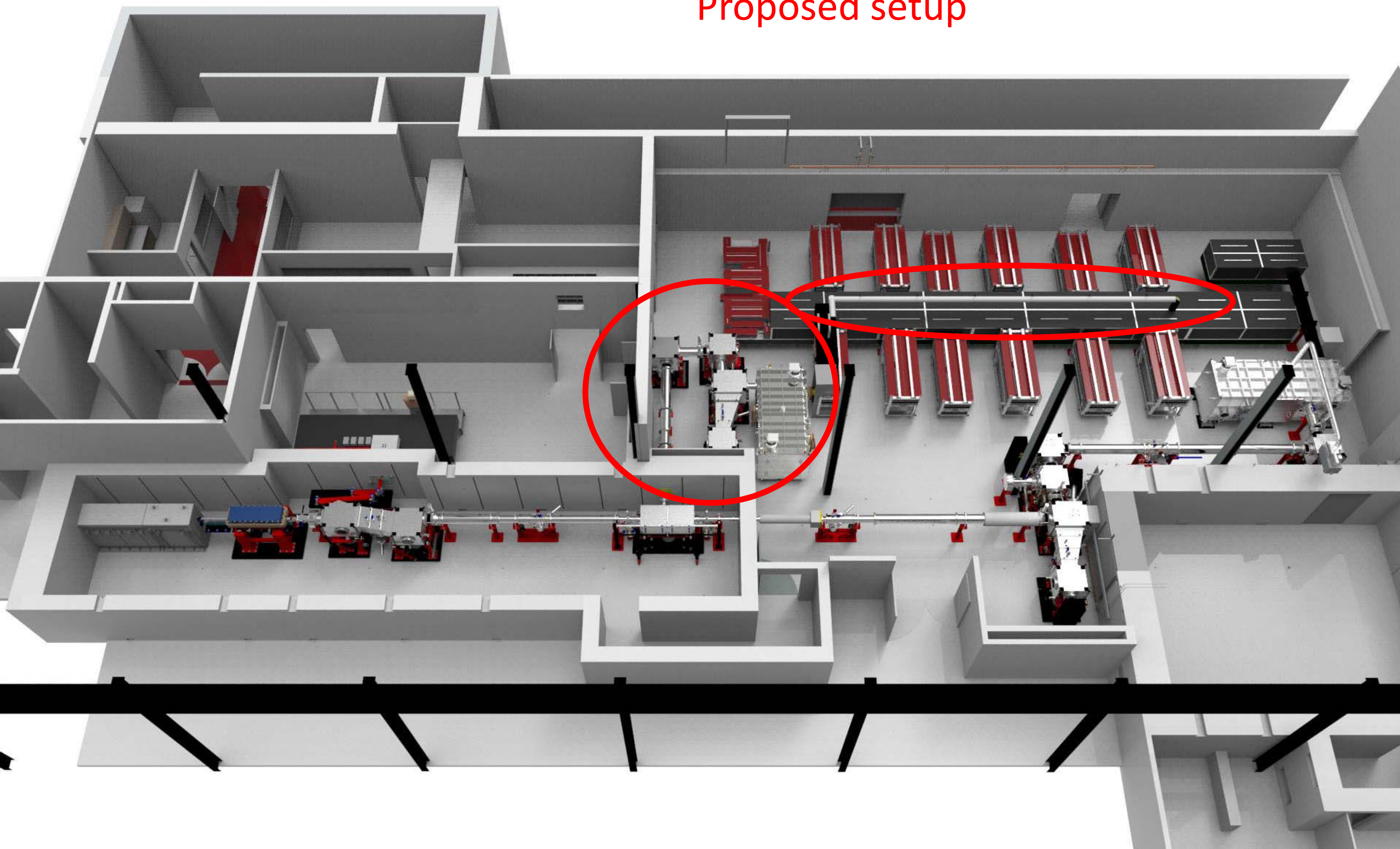
Proposed setup



Conclusions

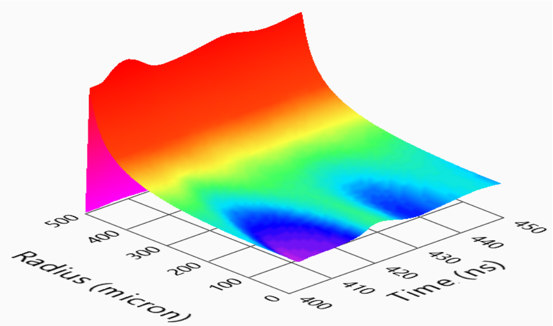
- Inverse Bremsstrahlung heating necessary to deepen the plasma channel for 10GeV

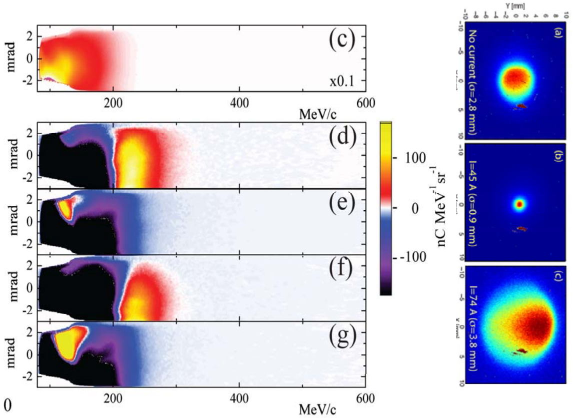
- Turnkey operation of 100 MeV injector by ionization injection with gas jet

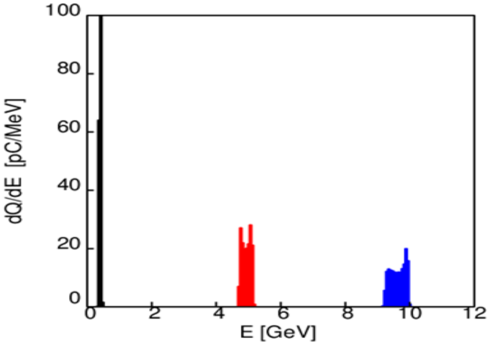
- Developed active plasma lens with gradients in excess of 3000 T/m to focus GeV-level e-beams for efficient coupling of accelerator stages

- First demonstration of external injection in an all-LPA staged accelerator experiment

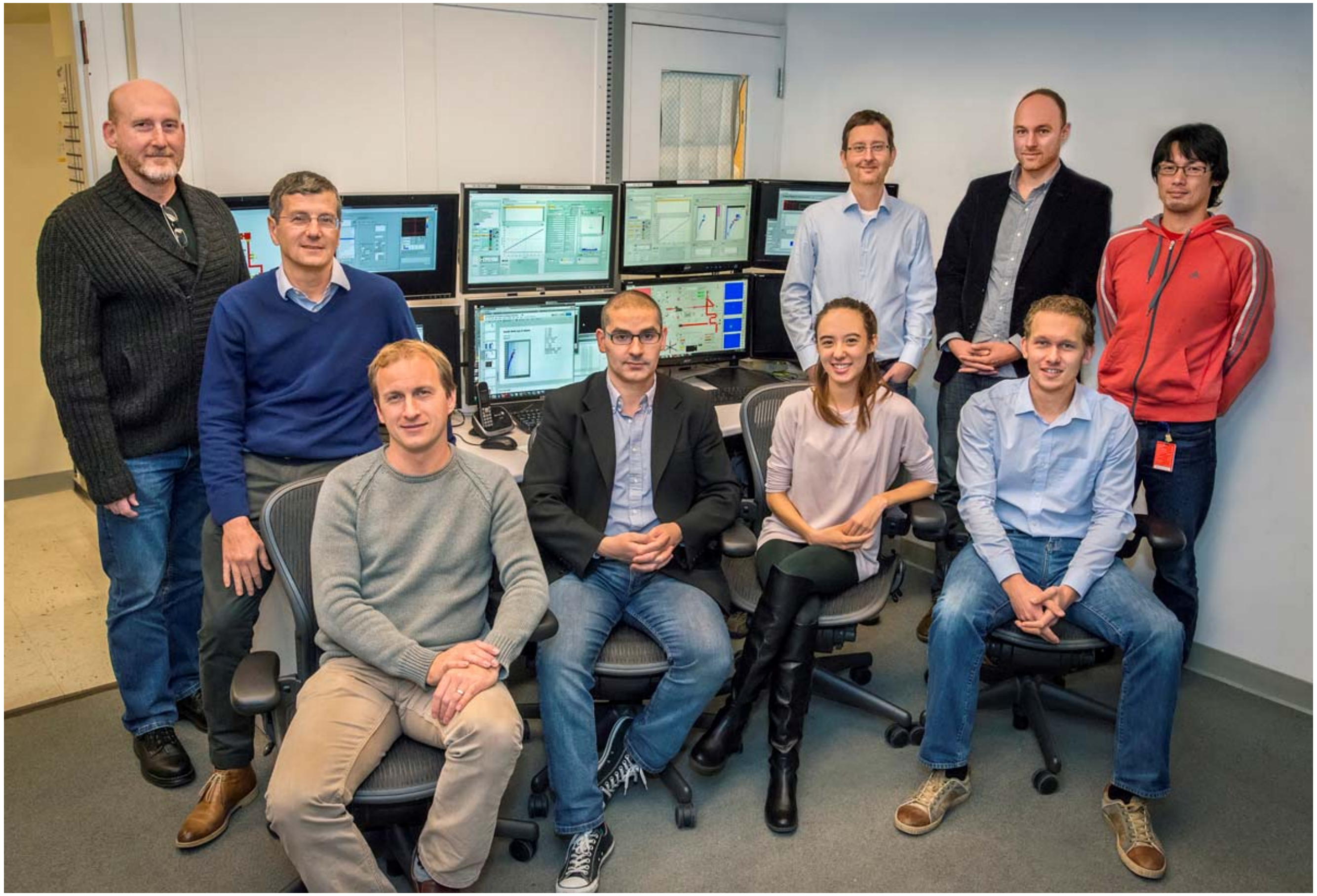
- Future plan: Prototype the first two stages (10 GeV) of an LPA based collider







Key to success: Staging Team



BELLA Center staging experiment team, from left, are **Eric Esarey, Wim Leemans, Jeroen van Tilborg, Carlo Benedetti, Kelly Swanson, Anthony Gonsalves, Joost Daniels, Sven Steinke, and Kei Nakamura**. Not pictured are: **Cameron Geddes, Carl Schroeder, Nicholas Matlis, and Brian Shaw.** (Photo credit: Roy Kaltschmidt/Berkeley Lab)