Petawatt laser guiding and electron beam acceleration to 7.8 GeV in a laser-heated capillary discharge waveguide

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Experiments and PIC simulations

Lawrence Berkeley National Laboratory – BELLA center

K. Nakamura, J. Daniels
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C. Benedetti, C.B. Schroeder
C. Toth, C. Geddes
E. Esarey, W. P. Leemans (now at DESY)

MHD simulations

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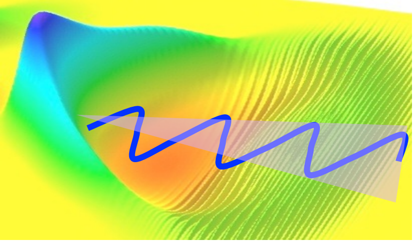
G. Bagdasarov, N. Bobrova, V. Gasilov

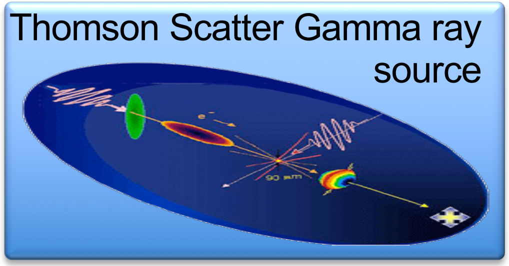
Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project

P. Sasorov, G. Korn

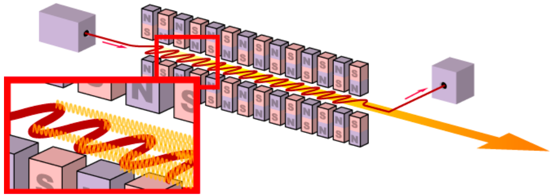
LPAs explored for Compact Drivers of Light Sources and Linear Colliders

keV Betatron radiation



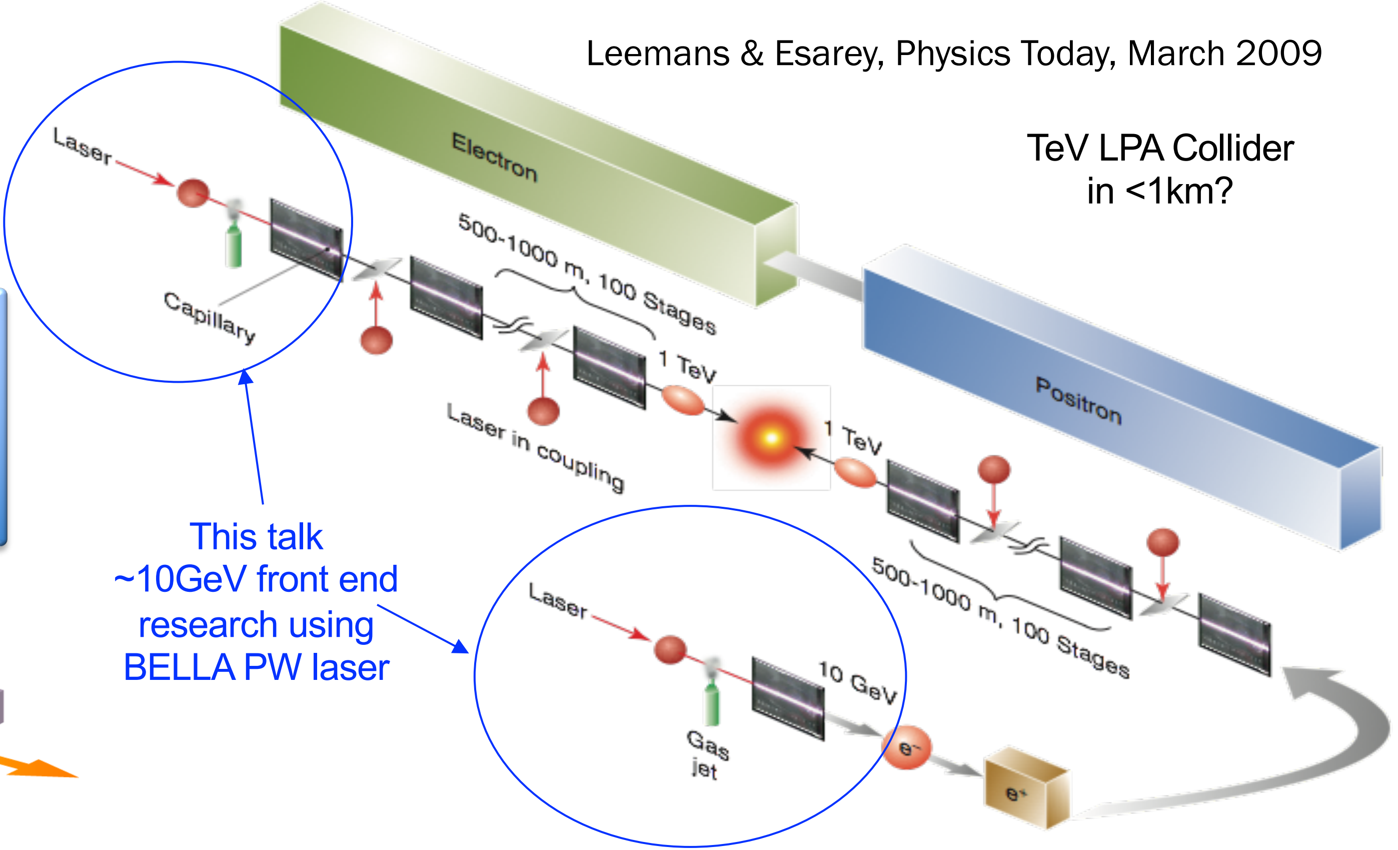


Free Electron Laser

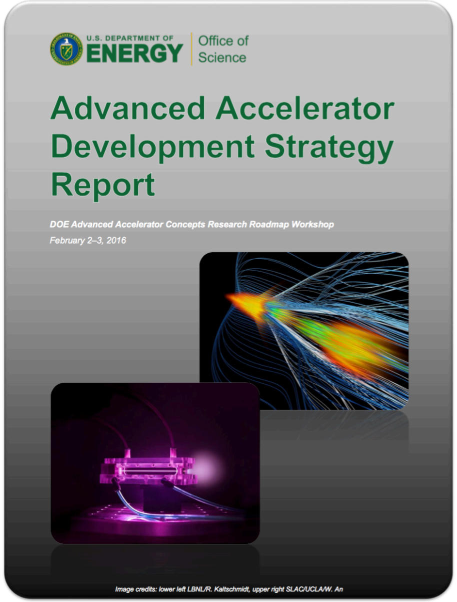


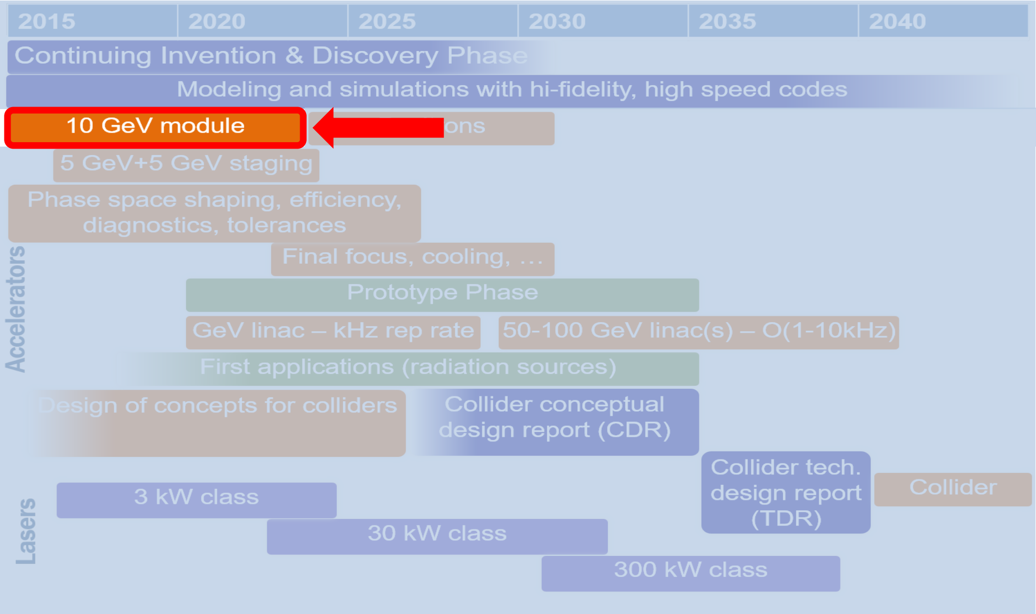
Leemans & Esarey, Physics Today, March 2009

TeV LPA Collider
in <1km?



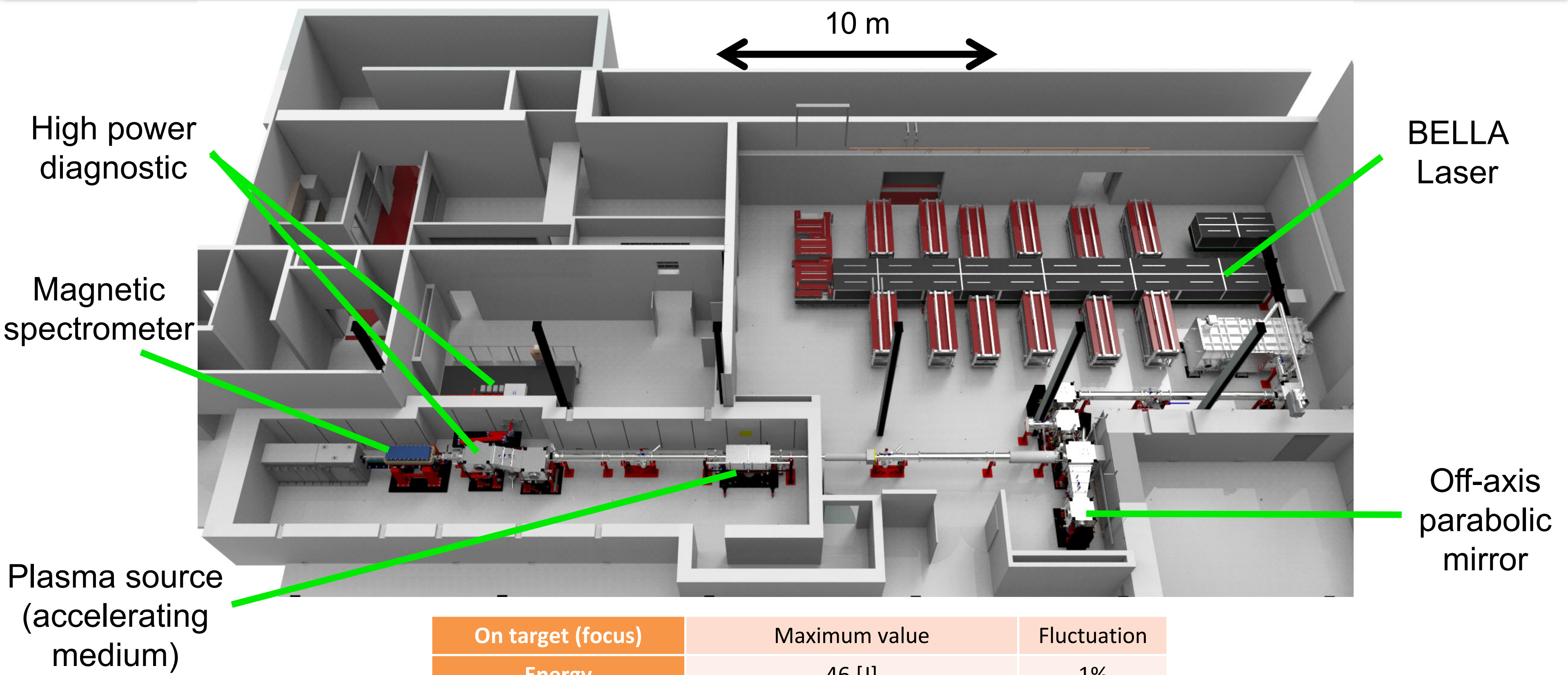
10GeV single-stage module driven by BELLA petawatt laser requires low density, guiding, and controlled injection





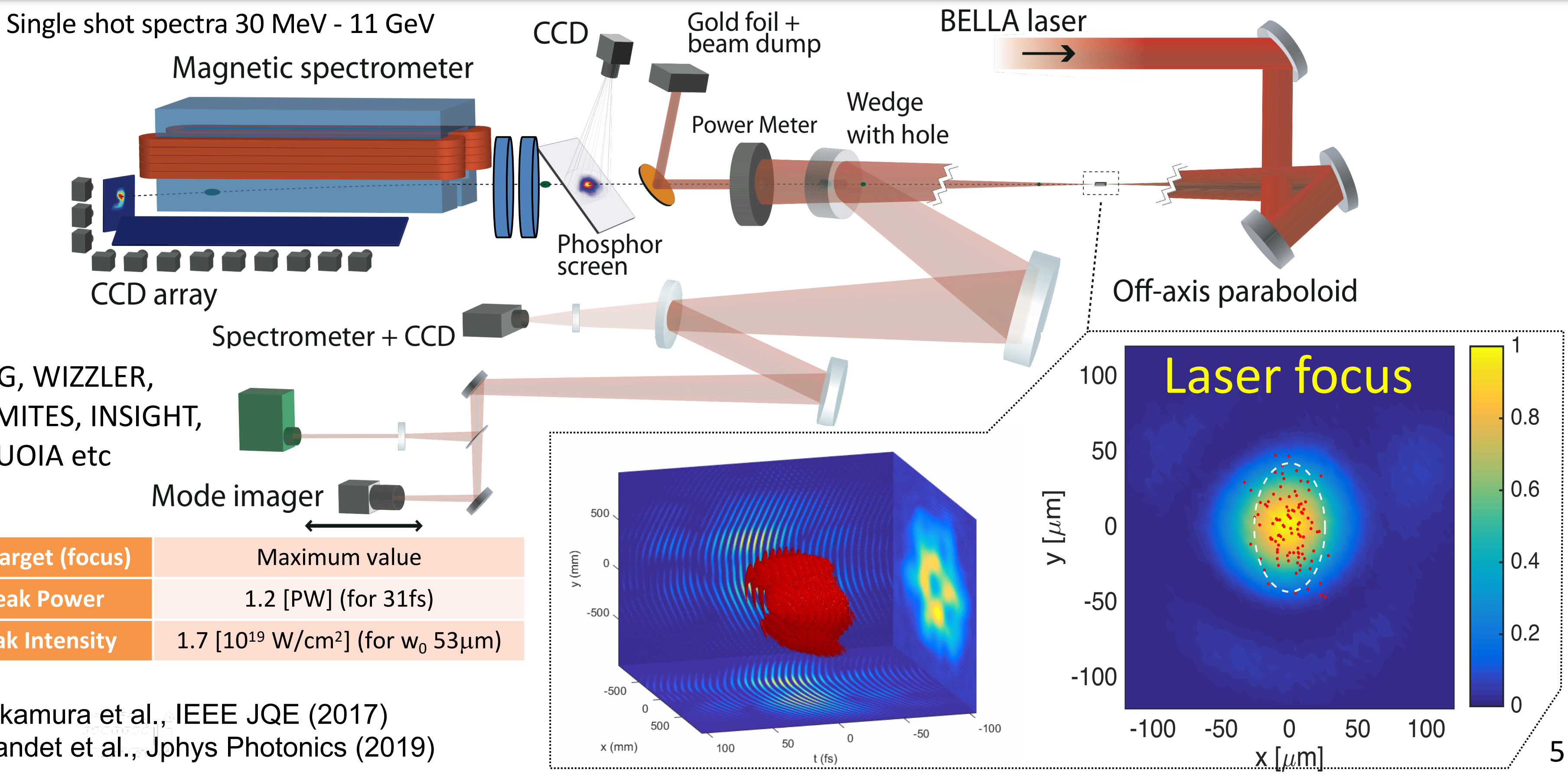
- Simulations show 10GeV possible with BELLA PW using pre-formed plasma channel
- At low density needed for 10GeV, capillaries previously used do not provide sufficiently strong channel
- Approach is to combine capillary discharge with laser-heating

BELLA Center Houses a 1Hz Repetition Rate Petawatt Laser for LPA Science



On target (focus)	Maximum value	Fluctuation
Energy	46 [J]	1%
Peak Power	1.2 [PW] (for 31fs)	5%

Simultaneous diagnostics for both laser and electron beam

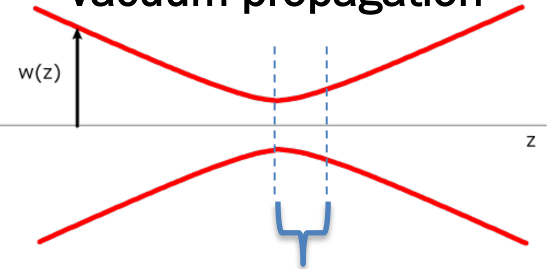


On target (focus)	Maximum value
Peak Power	1.2 [PW] (for 31fs)
Peak Intensity	1.7 [10^{19} W/cm^2] (for w_0 53μm)

K. Nakamura et al., IEEE JQE (2017)
A. Jeandet et al., Jphys Photonics (2019)

Waveguide can mitigate diffraction to increase acceleration length and beam energy

Vacuum propagation

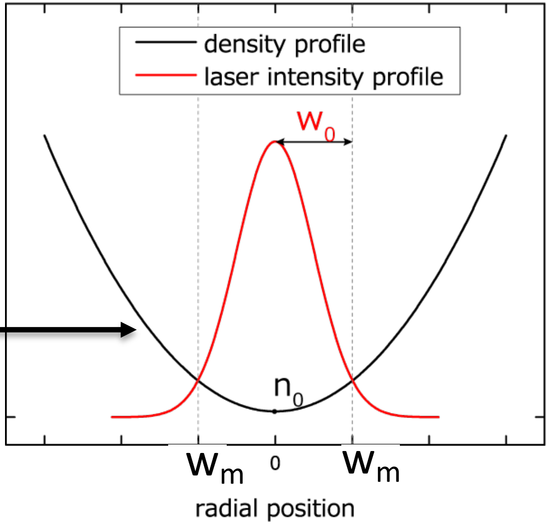


BELLA $Z_R \approx 1$cm

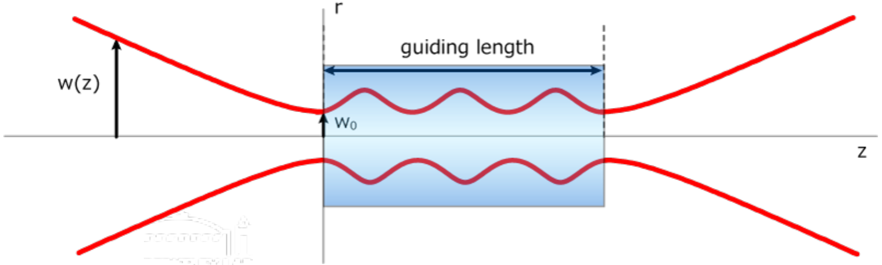
Guiding over 10s cm required to maximize beam energy

Density profile for guiding

$$n(r) = n_0 + \frac{r^2}{\pi r_e {w_m}^4}$$

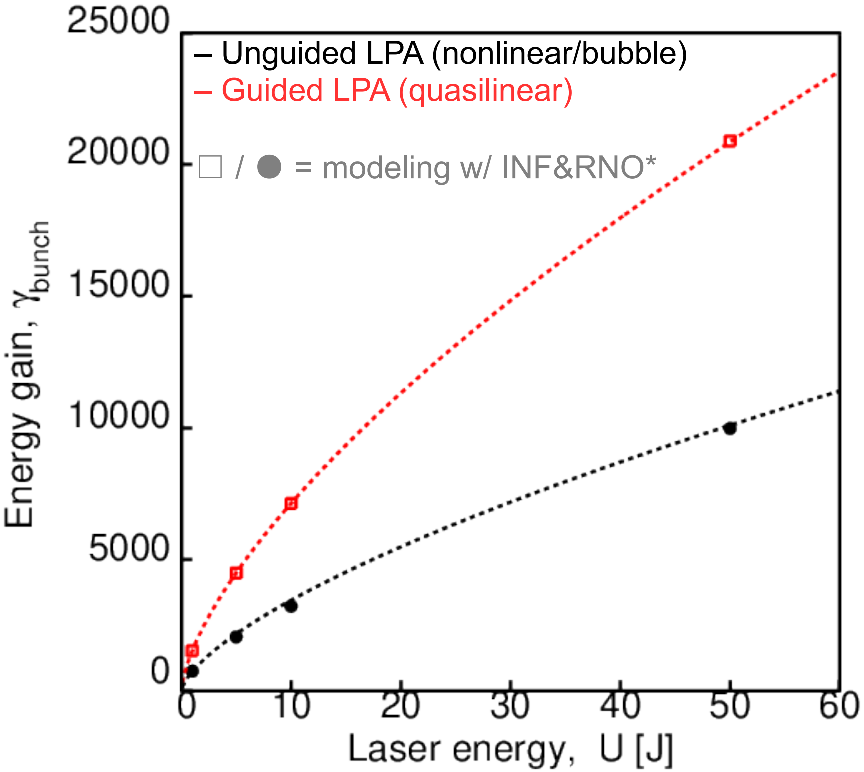


Mismatched guiding ($w_m > w_0$)



Matched guiding ($w_m = w_0$)

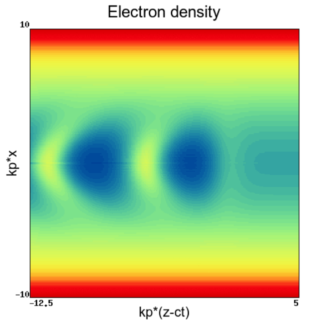
For given laser energy the energy gain with pre-formed waveguide is larger due to lower density and longer length



$$n_0[\mathrm{cm}^{-3}] \simeq 7.6 \times 10^{16} a_0^{4/3} (k_p w_0)^{4/3} (k_p L)^{2/3} (U[\mathrm{J}])^{-2/3}$$

a_0=1.6, $k_p w_0$= 4, $k_p L$=1.8

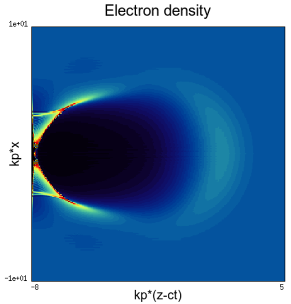
e.g., n_0=2.6x10^{17} cm^{-3} for U=10 J, a_0=1.5



a_0=4.5, $k_p w_0 = 2\sqrt{a_0}$, $L_{fwhm}=(2/3)w_0$

$$n_0[\mathrm{cm}^{-3}] \simeq 2.1 \times 10^{17} a_0^{7/3} (U[\mathrm{J}])^{-2/3}$$

e.g., n_0=1.5x10^{18} cm^{-3} for U=10 J, a_0=4.5



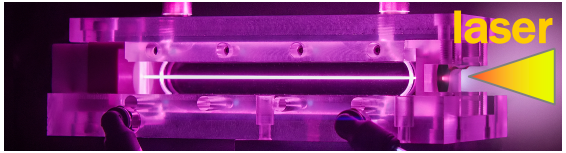
W. Lu et al., PR ST-AB (2007) C. Benedetti et al., AAC (2014), AAC (2016), PPCF (2017)

C. Benedetti et al, in preparation

Capillary discharge waveguide has allowed us to produce beams with energy up to 4.2GeV using 300TW laser power from BELLA

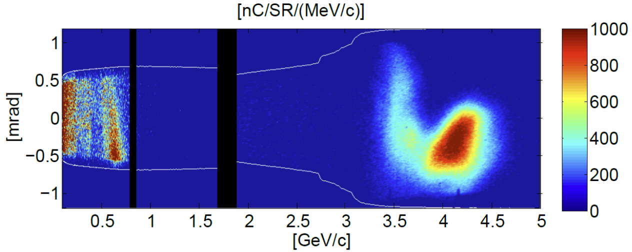
2014 Record LPA energy with BELLA

Capillary discharge plasma channel

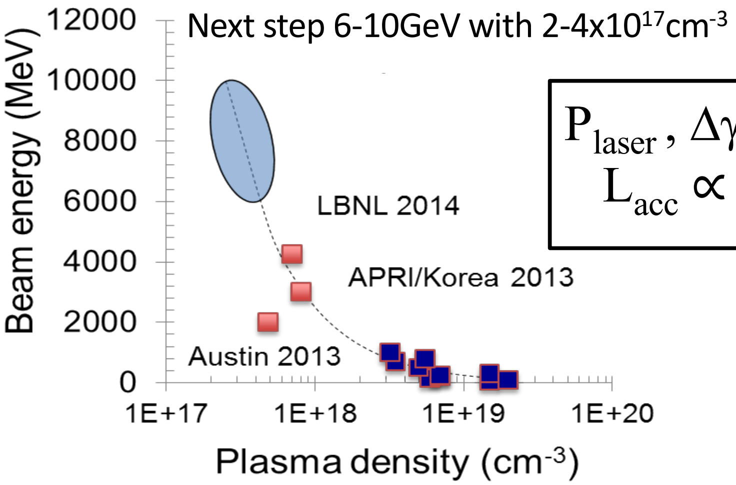


- Gas injected near ends
- Discharge creates plasma
- Guiding structure formed by heat conduction

Up to 4.2 GeV (7×10^{17} cm^{-3}) for 300TW



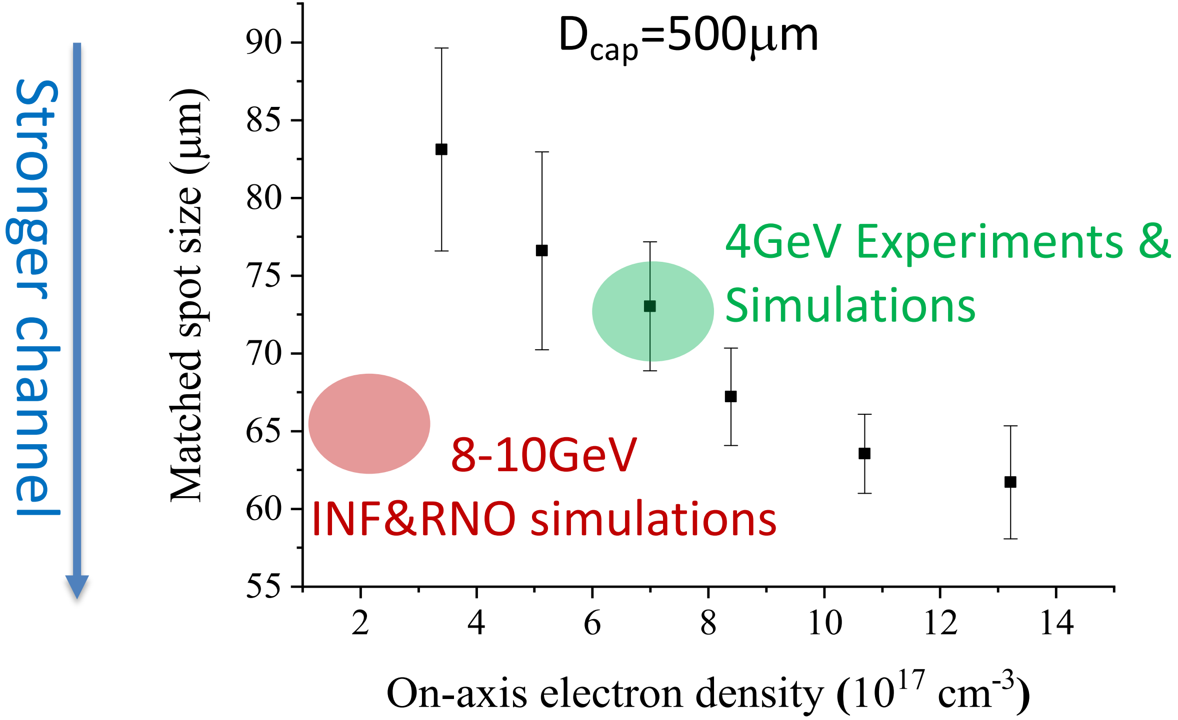
Need lower density & higher power



$$P_{laser},\ \Delta\gamma \propto n^{-1}$$
$$L_{acc} \propto n^{-3/2}$$

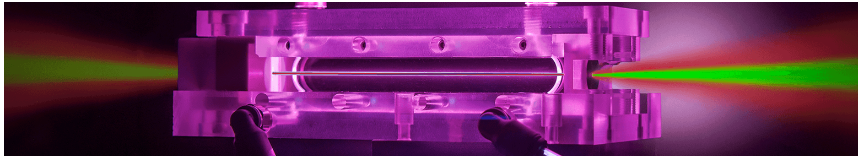
D. J. Spence & S. M. Hooker *PRE* 2001;
D. Jaroszynski, et al., Phil. Trans. R. Soc. A (2006);
Leemans et al., PRL 2014; A.J. Gonsalves et al., *PoP* 2015

Capillary discharge channel too weak at low density for 10GeV

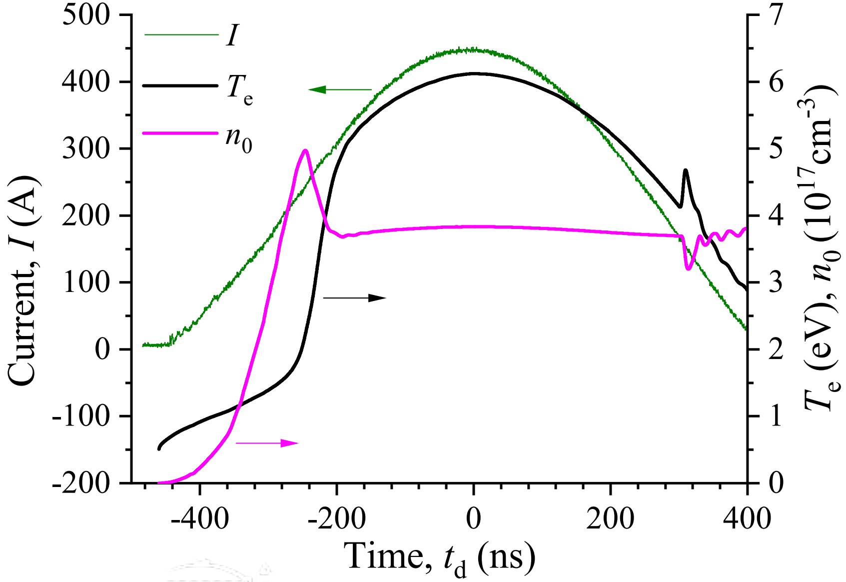


W. P. Leemans et al., PRL 113 245002 (2014); A. J. Gonsalves et al., Phys. Plasmas 22, 056703 (2015); A. J. Gonsalves et al., Phys Plasmas 17 (2010); J. Daniels et al., Phys. Plasmas 22, 073112 (2015); J. Van Tilborg et al., Phys. Rev. E 89, 063103 (2014)

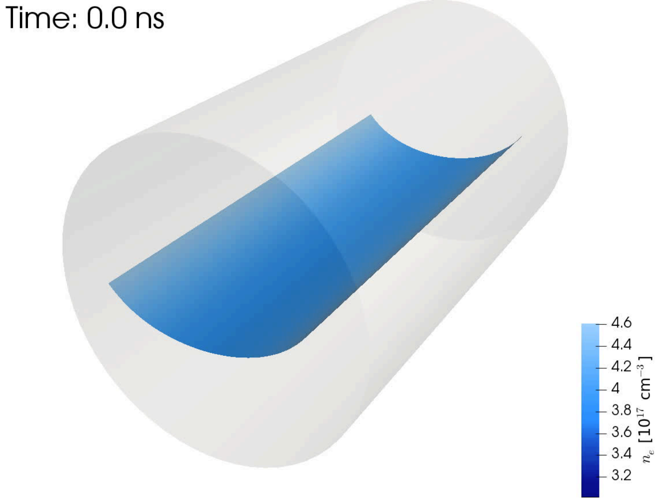
"Heater" laser can increase channel strength & guide laser pulses at lower density



MARPLE simulation

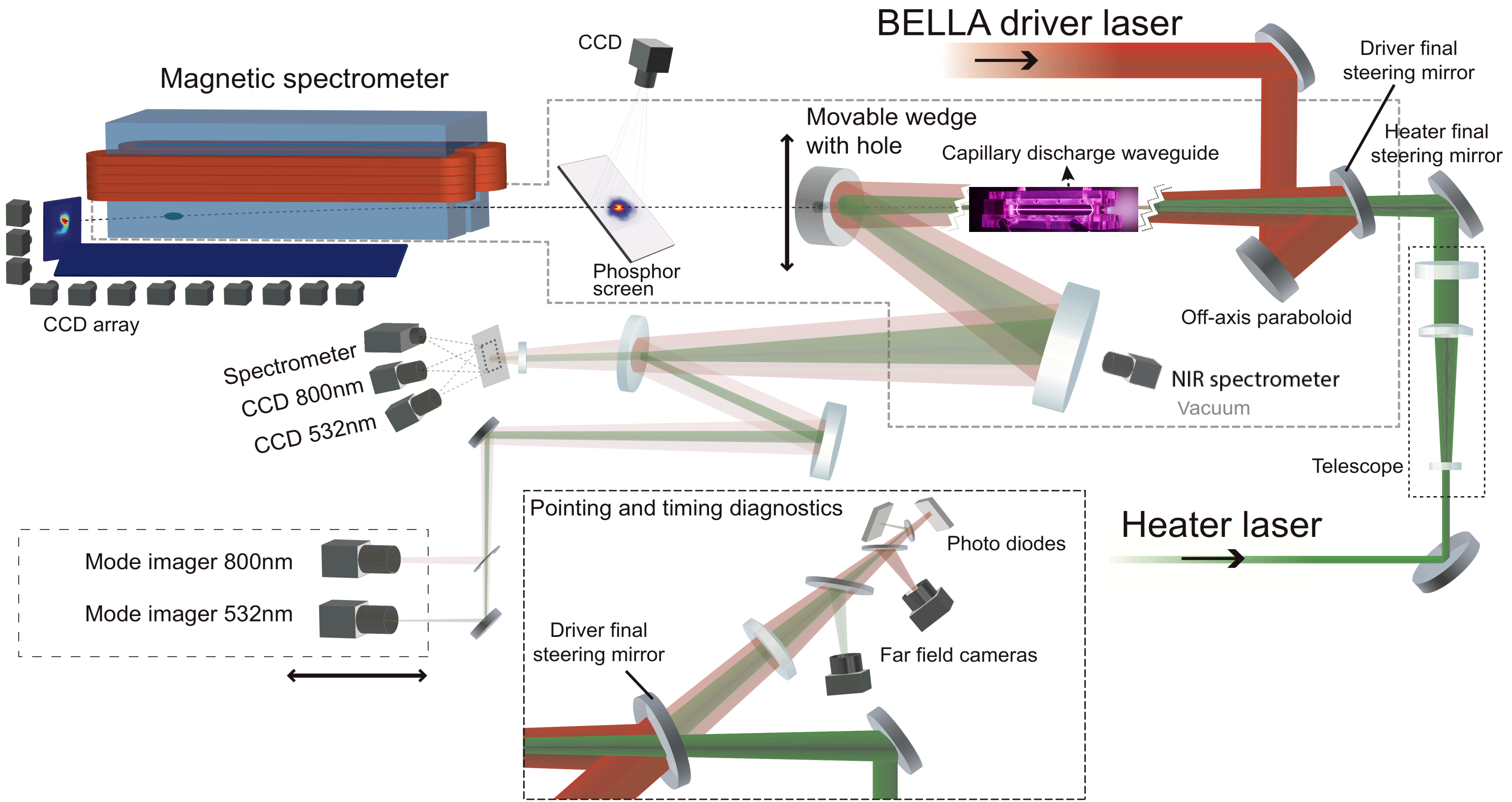


- Nanosecond pulse locally heats plasma through Inverse Bremsstrahlung (IB)
  - absorption of photons by free electrons
- Electron density distribution is changed
  - n_0 reduces
  - w_m reduces locally (faster rise of density from axis)

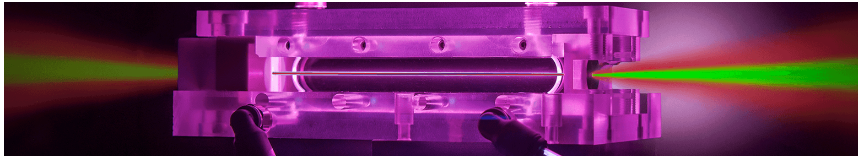


Gonsalves et al., PRL (2019); Bobrova *et al.*, *POP* 2013; Durfee *et al.*, *PRL* 1993; Volfbeyn *et al.*, *POP* 1999

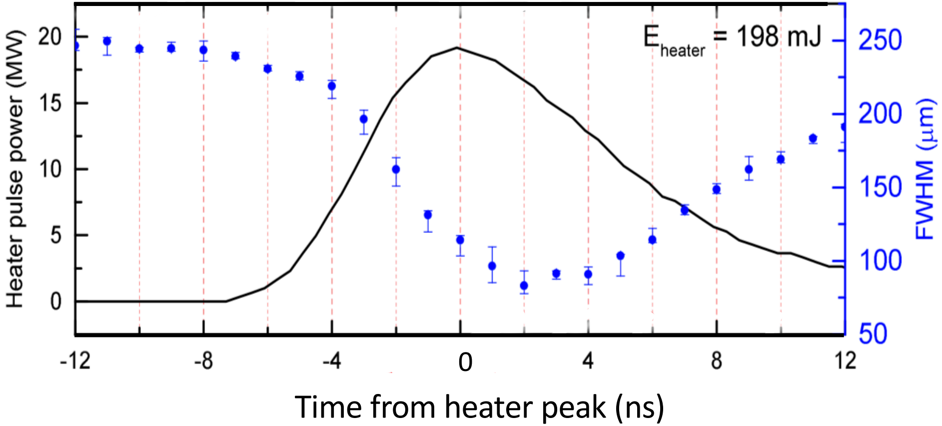
Heater laser added to BELLA petawatt beamline

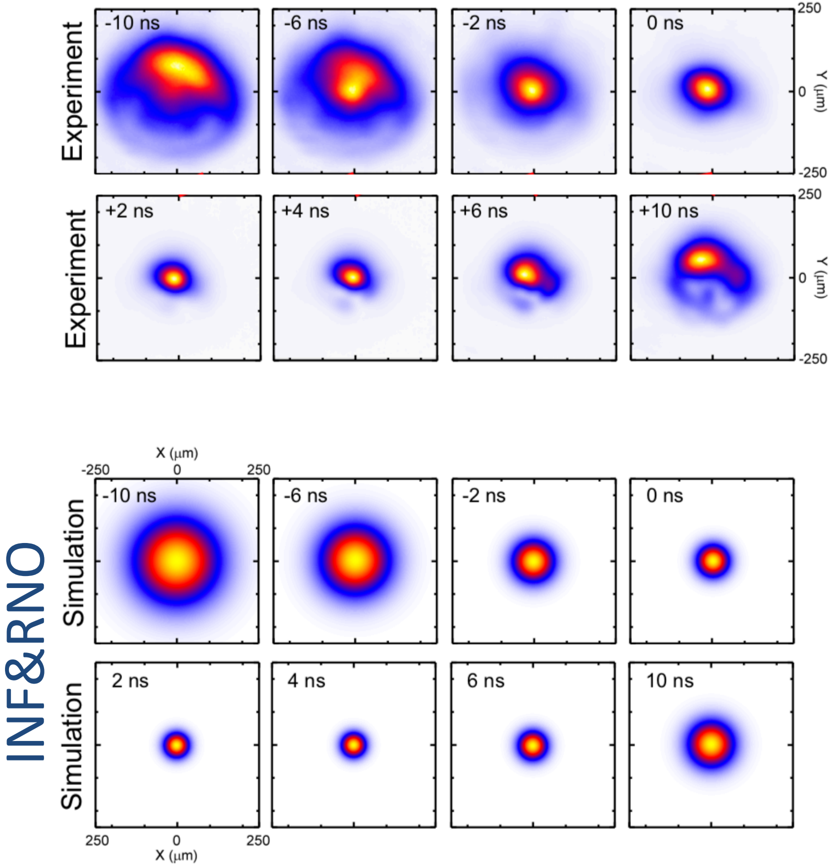


Guided low-power laser modes indicate plasma channel enhancement



L_{cap}=6cm; W_{0probe}=60μm; n_e=0.4×10^{18} cm^{-3}



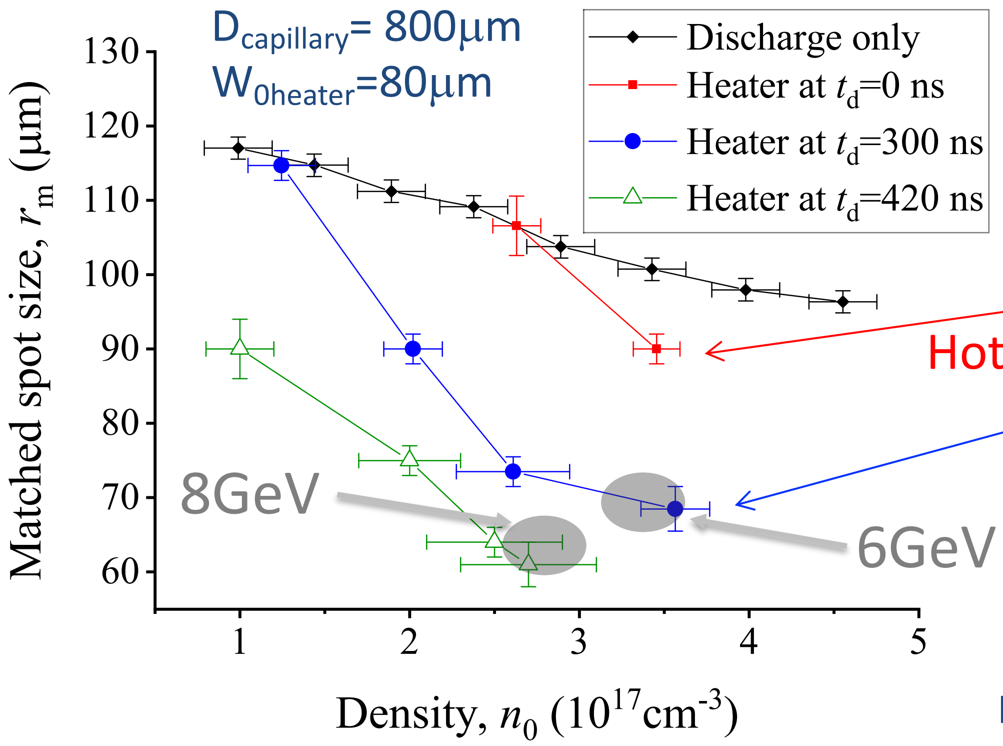


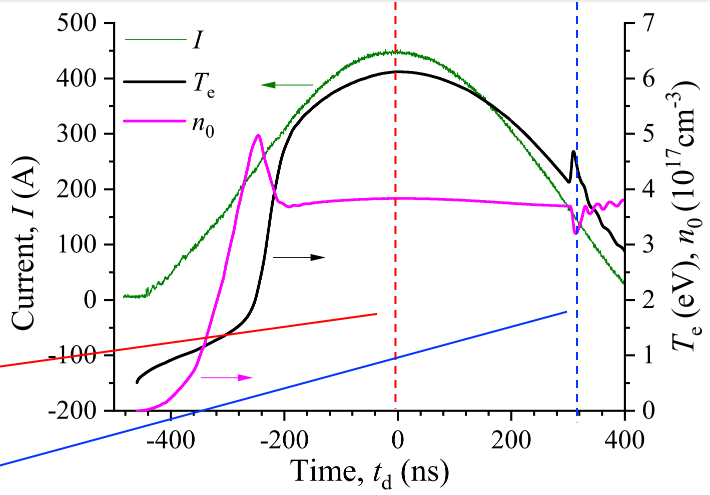
Heater significantly lowers matched spot size, which can be controlled by initial plasma temperature

U_{Heater} = 300mJ

$D_{capillary}$= 800μm

$W_{0heater}$=80μm





Hotter

Colder (lower current)

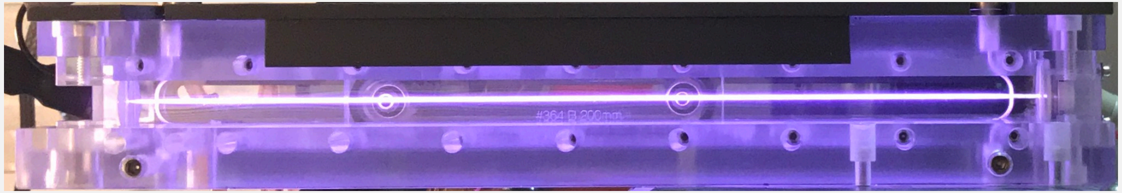
$$R \propto \frac{n_i I \lambda^2}{T_e^{3/2}} ln\left(\frac{T_e \lambda}{2\pi c \hbar}\right)$$

Initial plasma temperature

Gonsalves et al., PRL (2019); A. Y. Polishchuk and J. Meyer-Ter-Vehn, PRE (1994); N. David et al., PRE (2004).

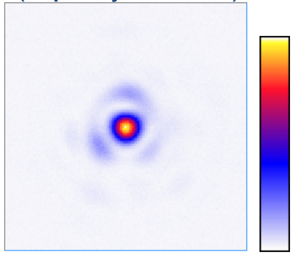
Petawatt pulses ("driver") guided by <u>20 cm long</u> heated discharge channels

20 cm; 950 TW (~30fs); 1.2×10^{19} Wcm^{-2};
a_0=2.4; $n_e=0.34\times10^{18}$ cm^{-3}

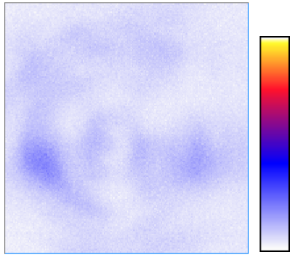


20 cm

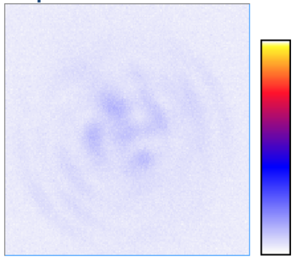
Vacuum focus (capillary entrance)



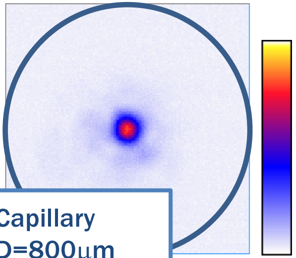
Vacuum 9cm after focus



Mode at capillary exit without plasma channel



Mode at capillary exit (20cm after focus)

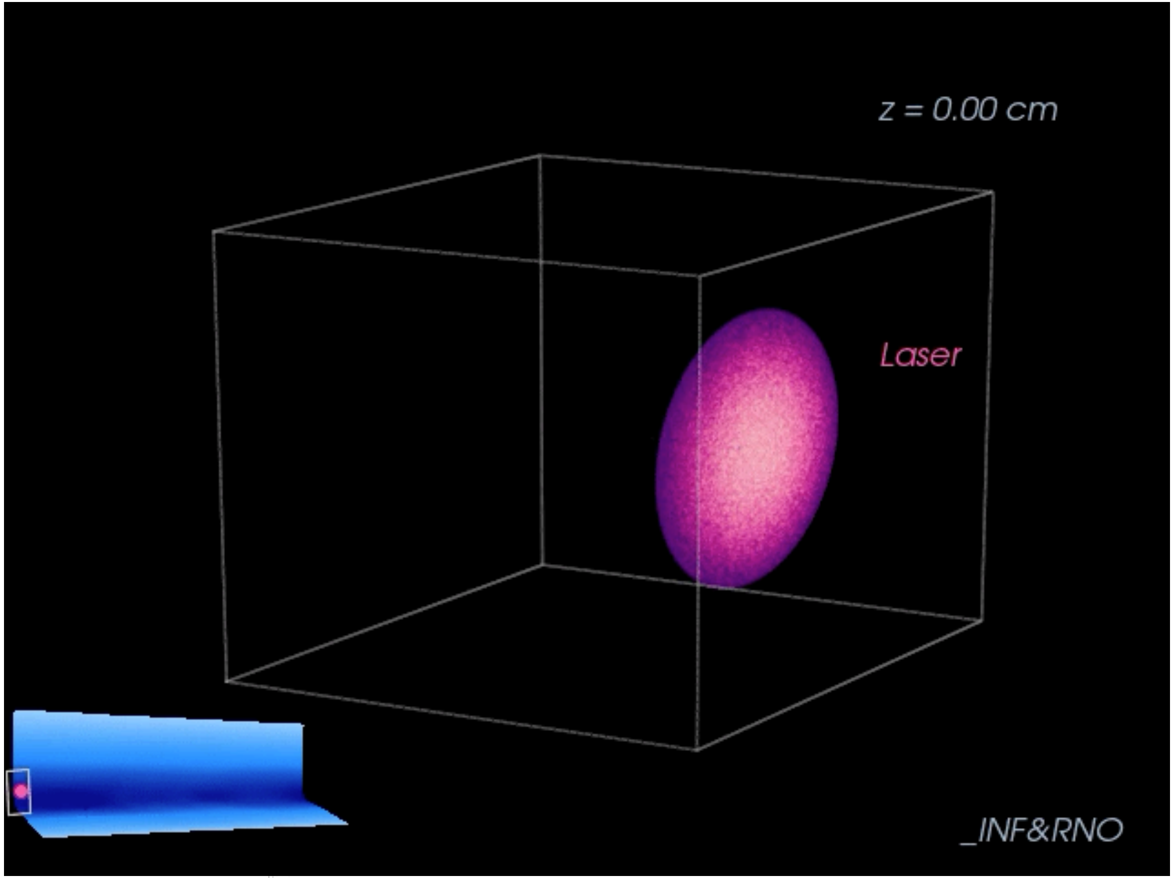


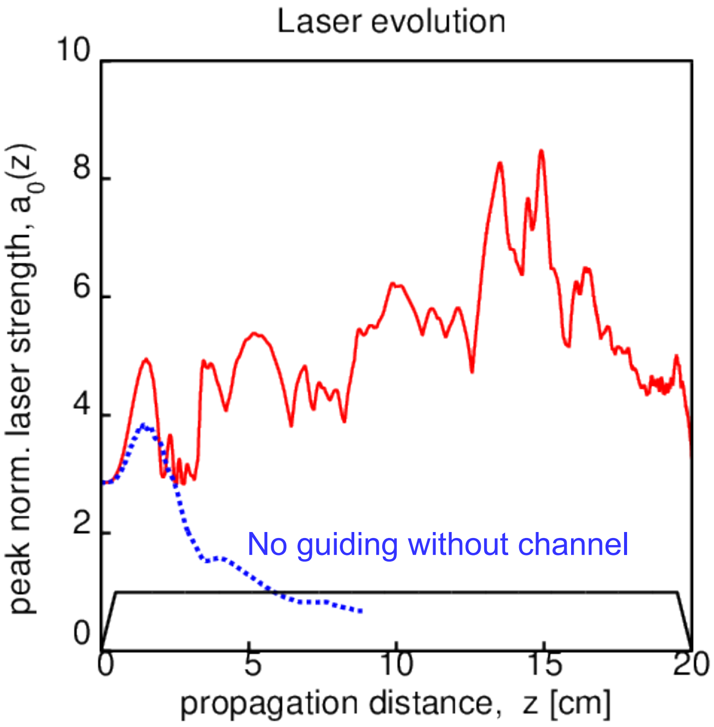
Capillary D=800μm

Laser size without capillary D=2400μm

Spot size w_0 increased from 53μm to 60μm to increase Z_R

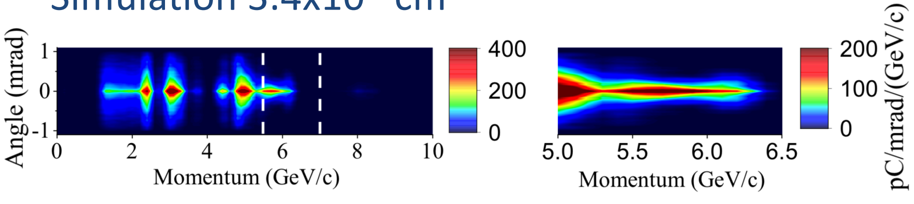
Simulation shows non-linear bubble regime with multiple electron bunches



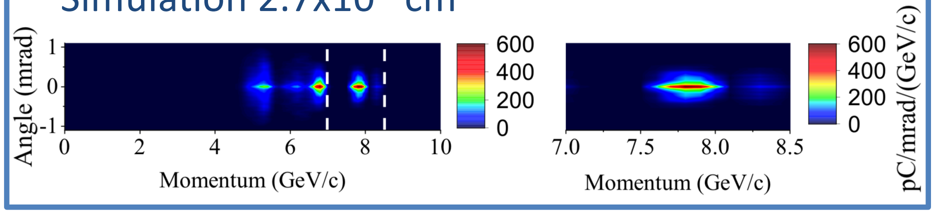


Electron beams with energy up to 7.8GeV observed

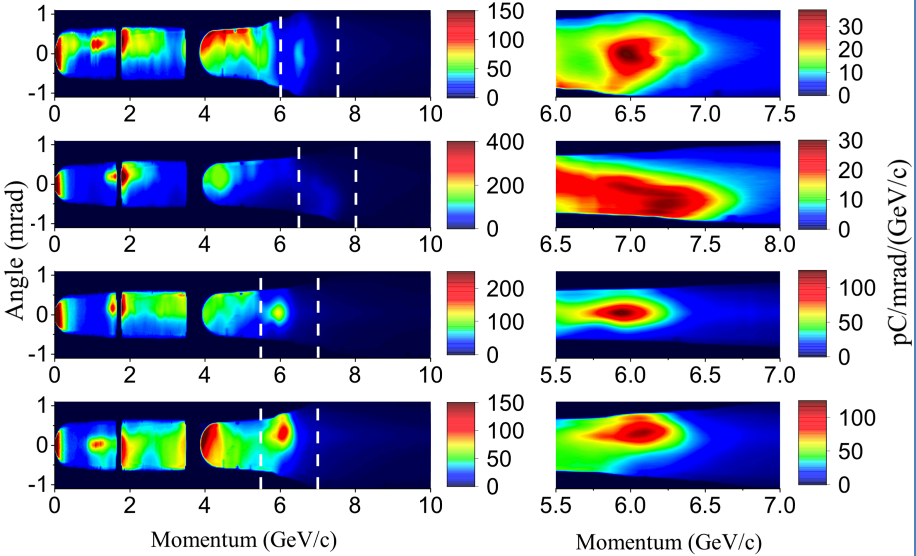
Simulation 3.4x10^{17}cm^{-3}



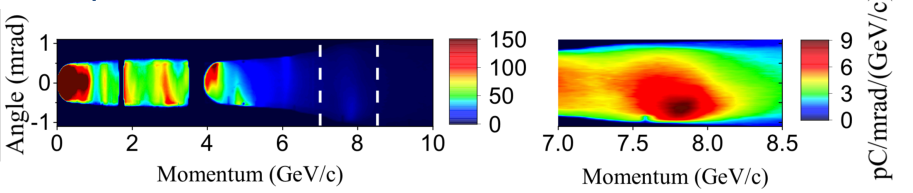
Simulation 2.7x10^{17}cm^{-3}



Experiment 3.4x10^{17}cm^{-3}



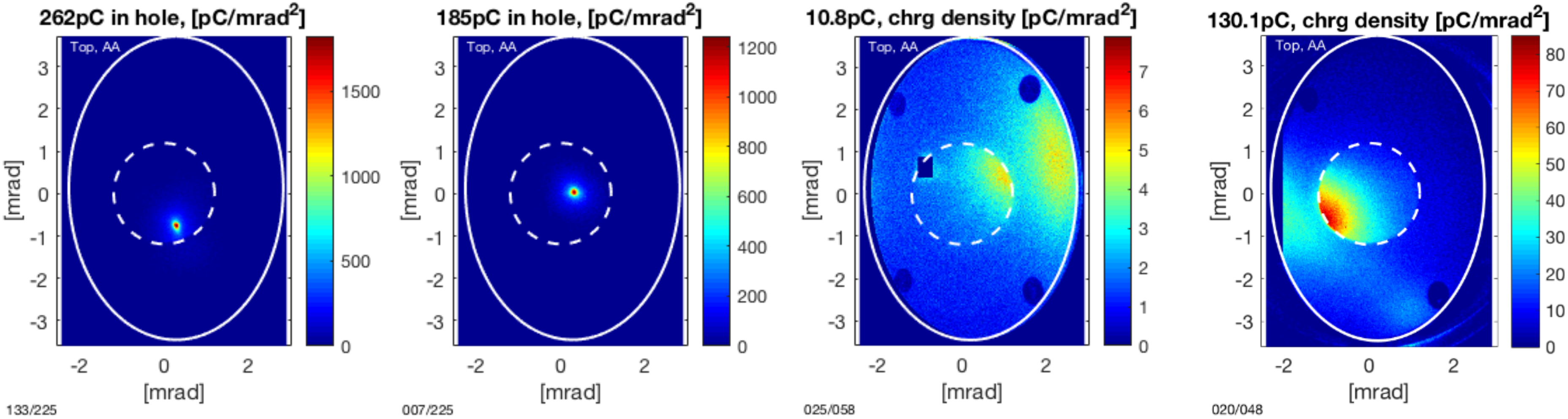
Experiment 2.7x10^{17}cm^{-3}



- Non-localized injection produces large energy spread
- Up to 60pC (of >200pC) in 6 GeV peaks
- Highest energy bunches dE/E~10%
- 0.5-1 joule energy in e beam

Gonsalves et al., PRL (2019)

Electron beam divergence 150urad FWHM, but pointing stability 1 mrad

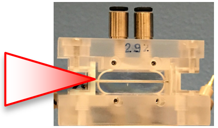


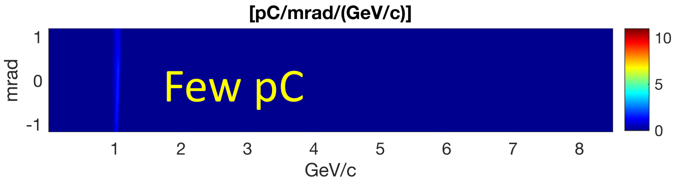
- When optimally aligned, electron beam pointing fluctuations similar to gas cell & jet targets
  - 3 orders of magnitude larger than laser pointing fluctuations
- Need highest quality spatio-temporal mode with low fluctuations *Popp et al., PRL (2010)*
  - Need kHz repetition rates for active correction

Increasing laser power and reducing plasma density has increased charge and maximum energy to 8GeV

TREX: W. P. Leemans et al., *Nat. Phys.* (2006)

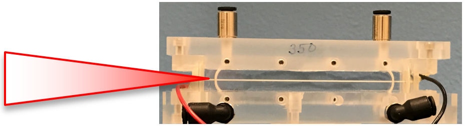
3 cm; 40 TW; ~$\mathbf{5\times10^{18}\ cm^{-3}}$

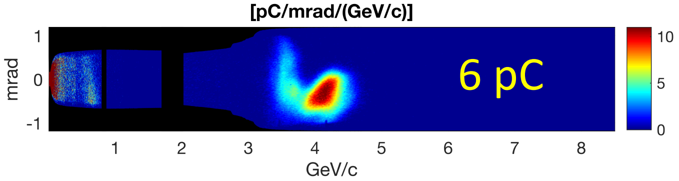




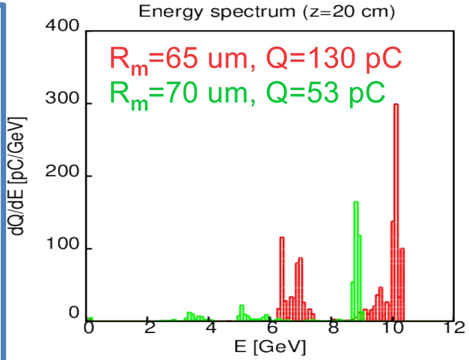
BELLA: W. P. Leemans et al., *PRL* (2014)

9 cm
300 TW
~$\mathbf{0.7\times10^{18}\ cm^{-3}}$



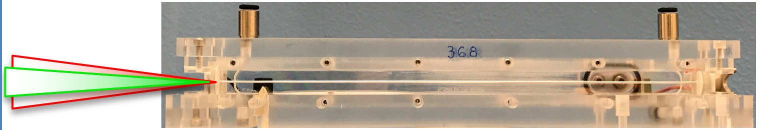


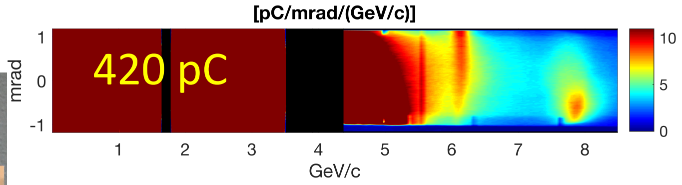
10GeV simulation @ n_0=0.22x10^{18} cm^{-3}

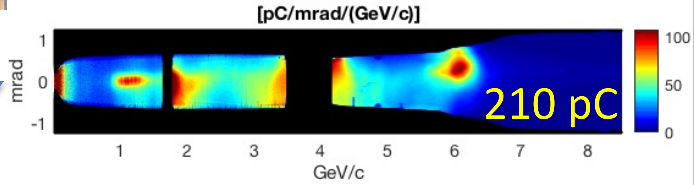


BELLA with heater: Gonsalves et al., *PRL* (2019)

20 cm; 850 TW; $\mathbf{0.27\times10^{18}\ cm^{-3}}$

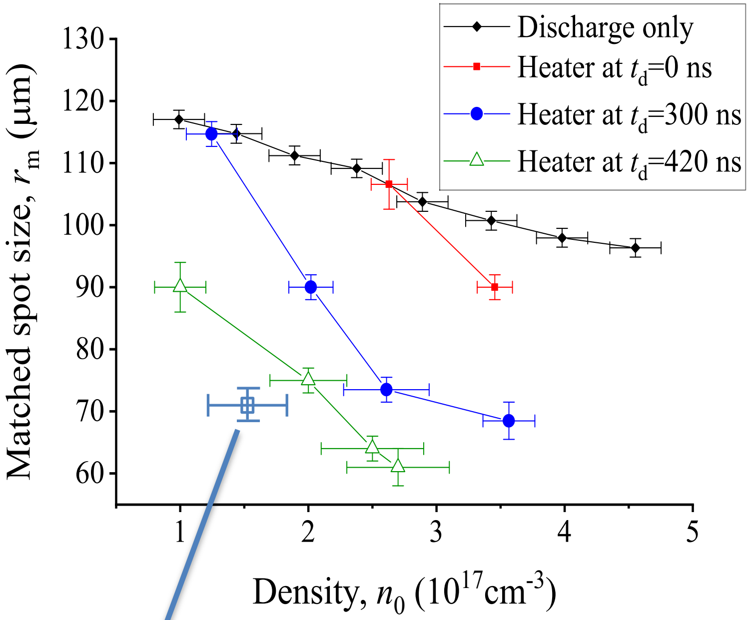






Charge density axis x10

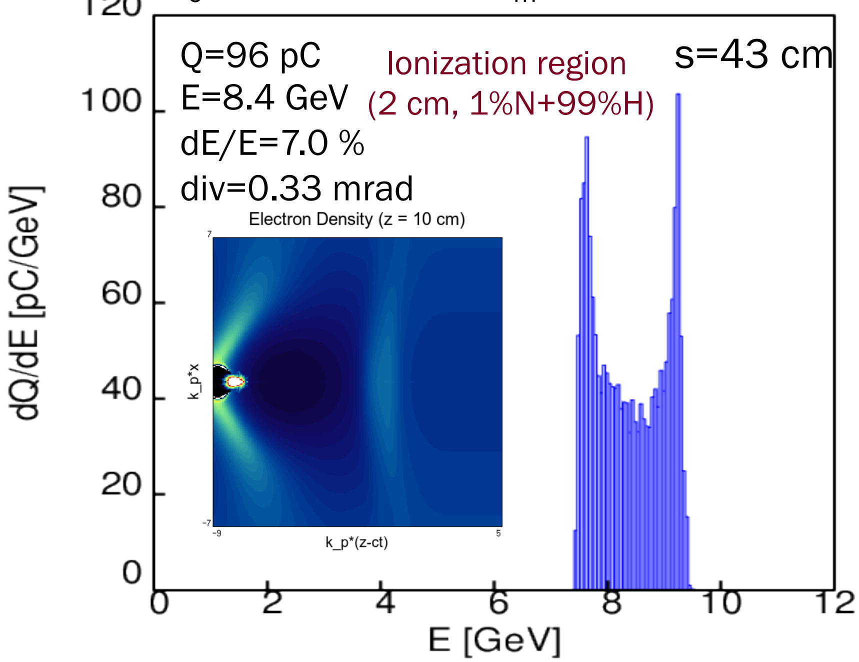
Channel density lowered further by adjusting heater-driver timing. Simulations show this could enable controlled injection and elimination of dark current.



t_d=420ns but heated channel has evolved for an additional 6ns

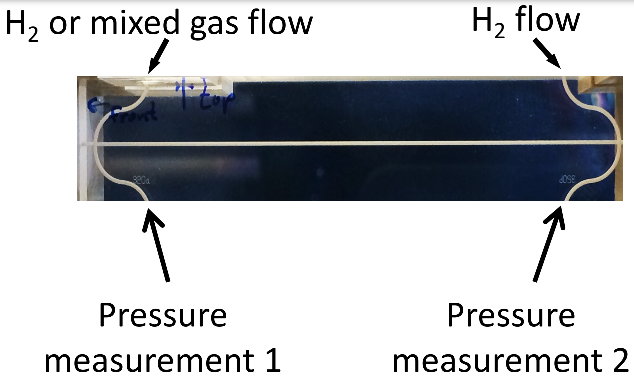
INF&RNO simulation using ionization injection

Laser: U=36 J, w_0=60 μm, T=66 fs
$n_0=1.6\times10^{17}$cm^{-3}, w_m=70 μm

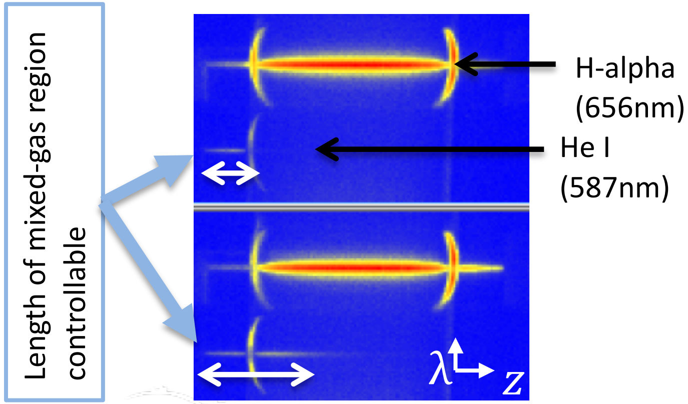


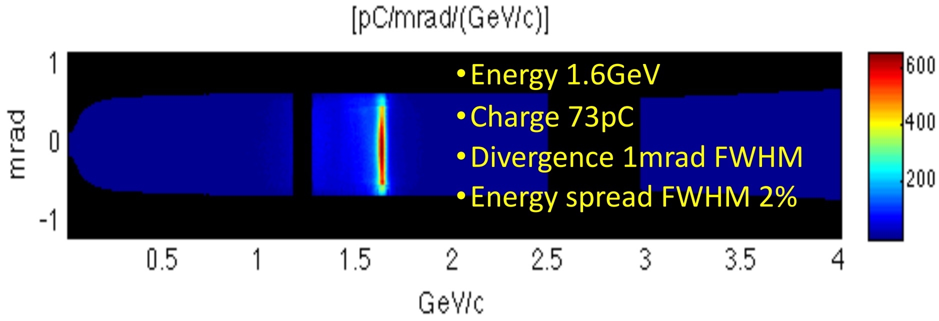
C. Pieronek et al., in prep

Localized region of mixed-gas for ionization injection can be produced in capillary waveguide and experiments at 20J yielded low-energy-spread beams



- Initial test of localized ionization injection in capillary for
  - D=500μm L=3cm
  - Laser energy 20J
- High-quality beams but capillary damage
- Next step: combine with laser heater for better confinement & damage mitigation



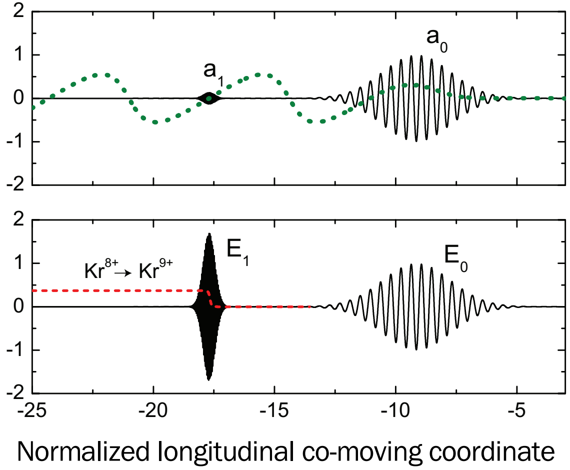


A. J. Gonsalves et al. *Nat. Phys.* 2011; *N. Matlis* et al. JAP 2016; Polluck *PRL* 2011

Two-color ionization injection method could generate ultralow emittance beams

- **Two-color ionization injection:** uses two lasers of different wavelengths to separate plasma wave excitation (long wavelength) and ionization (short wavelength)

L.-L. Yu et al, PRL (2014)

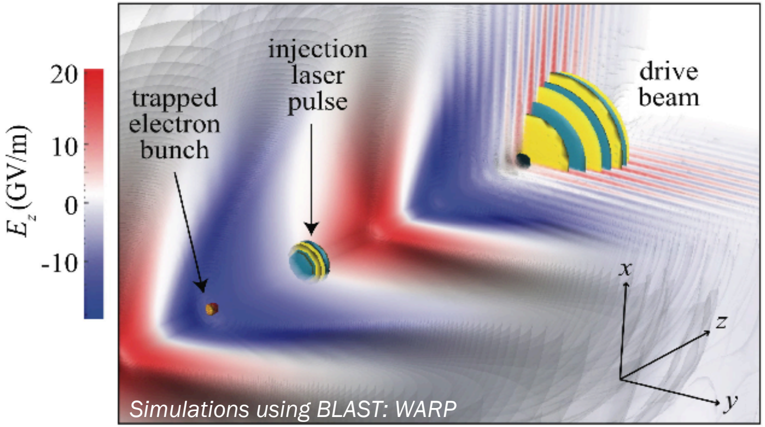


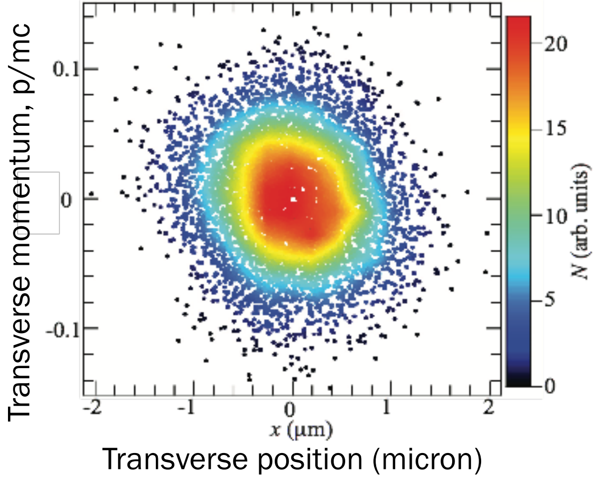
- Laser ponderomotive force (laser intensity) drives plasma wave:

$$F_{\mathrm{PMF}} = m_e c^2 \nabla a^2 / 2$$

- Peak laser electric field determines ionization

$$E = (2\pi m_e c^2 / e)\frac{a}{\lambda}$$

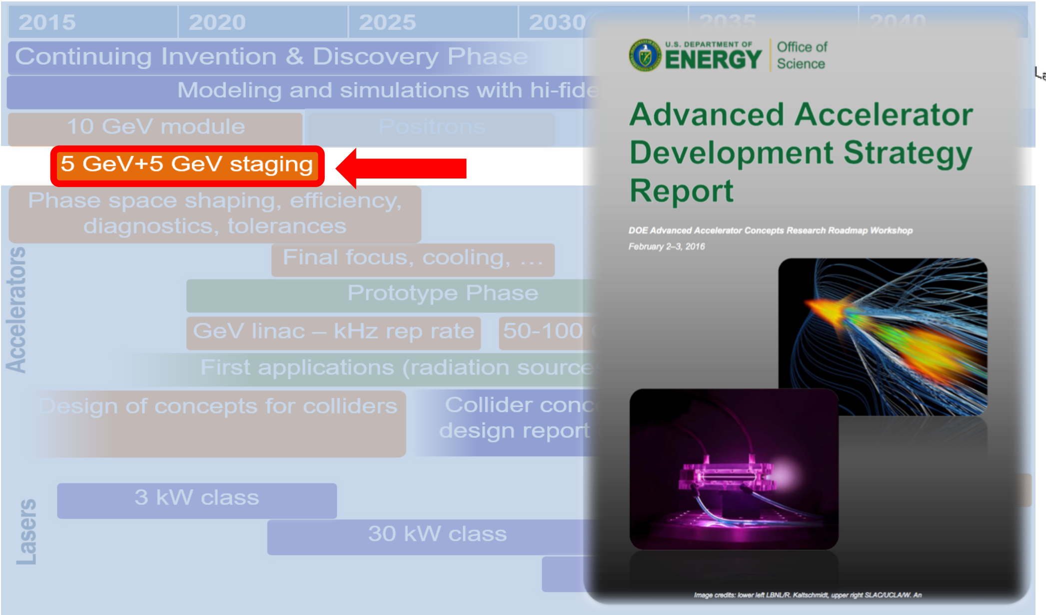


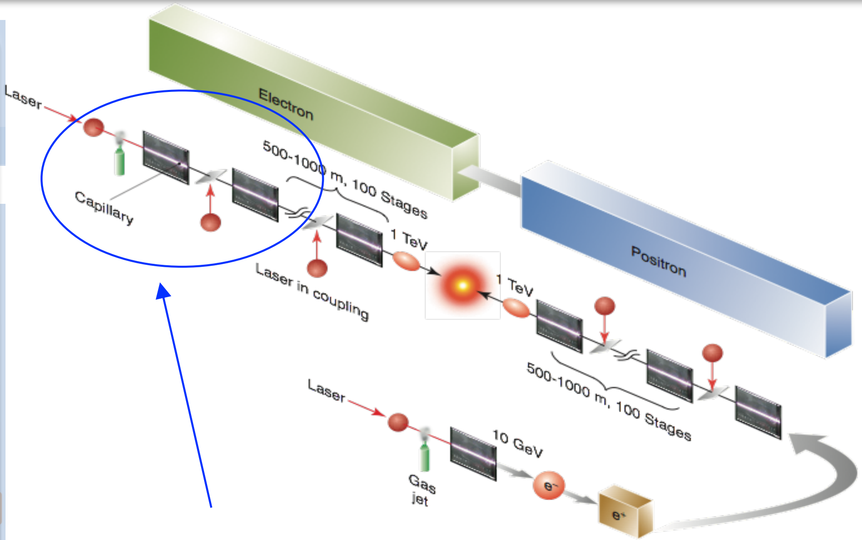


- Normalized beam emittance tens of nm
- Proof of principle experiment planning underway

C. B. Schroeder et al., PR ST-AB (2014)

Multi-GeV staging is a key next step on the LPA collider roadmap





BELLA PW laser will also be used to demonstrate multi-GeV staging

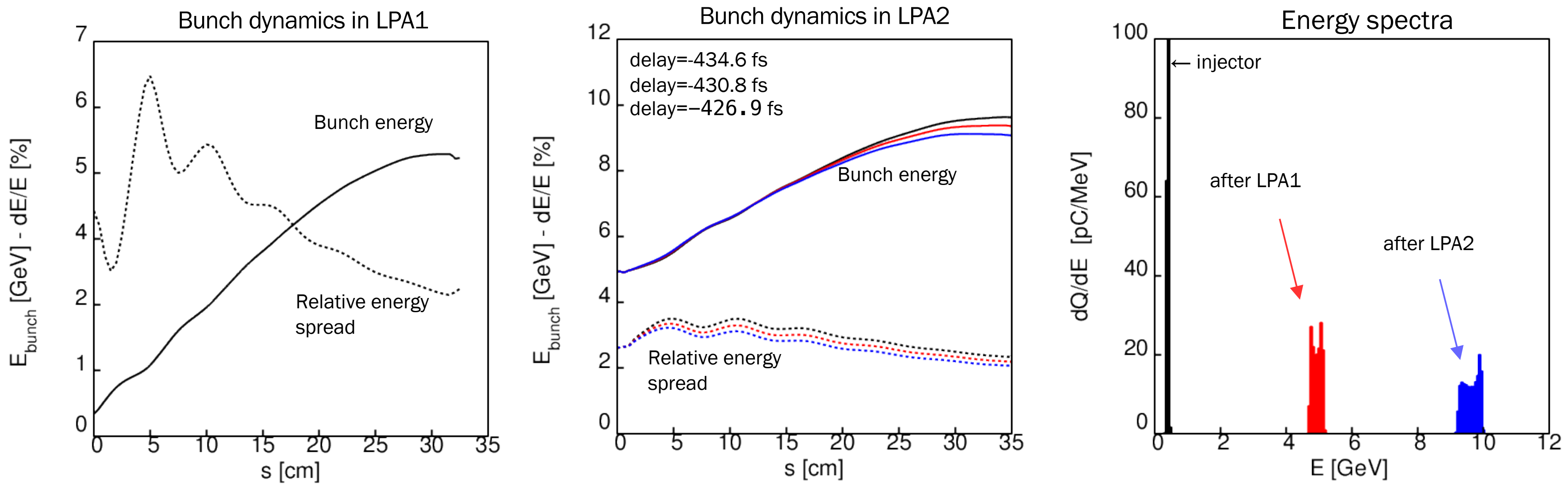
- Staging at ~100MeV using 30TW (BELLA TREX laser) in 2016, but low capture efficiency
- BELLA PW laser will be used to investigate multi-GeV staging with high efficiency

S. Steinke PoP 23, 056705 (2016); B. H. Shaw, PoP 23, 063117 (2016); J. van Tilborg, PRL **115**, 184802 (2015); S. Steinke, Nature **530**, 190 (2016)

BELLA PW staging design shows 100% bunch capture and acceleration

→ Assuming laser matching (heater) in LPA1 and LPA2 and operating in a quasi linear regime (i.e., less wake evolution)
W_m = 70 um W_0= 53 um, density $2.2x10^{17} cm^{-3}$

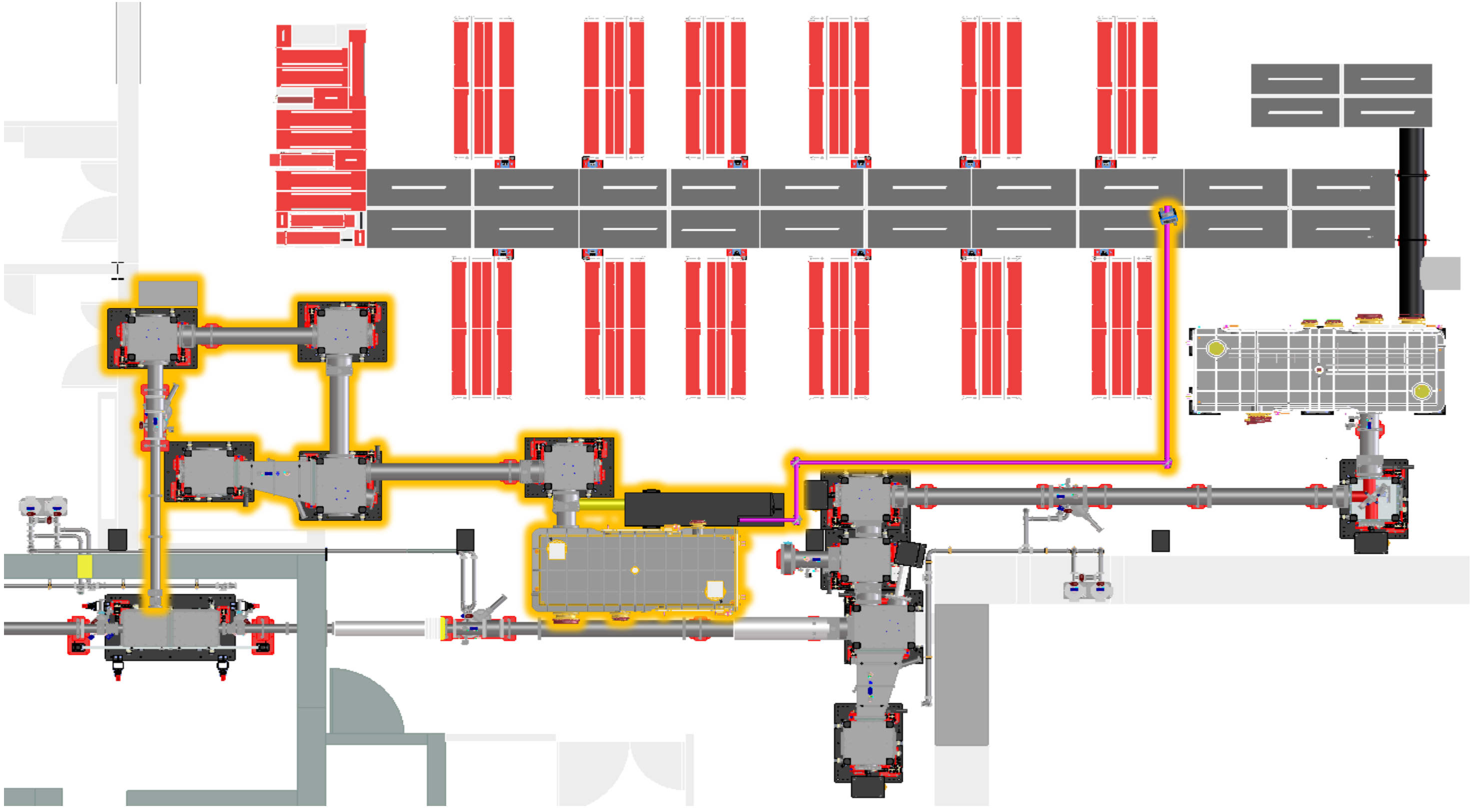
→ Assuming following injector parameters:
- E=400 MeV, dE/E= 4% (rms)
- Q=10 pC, L_b=2 um, x' < 1 mrad (rms)



→ Producing and maintaining low energy spread is key element for 100% bunch capture

S. Steinke PoP 23, 056705 (2016)

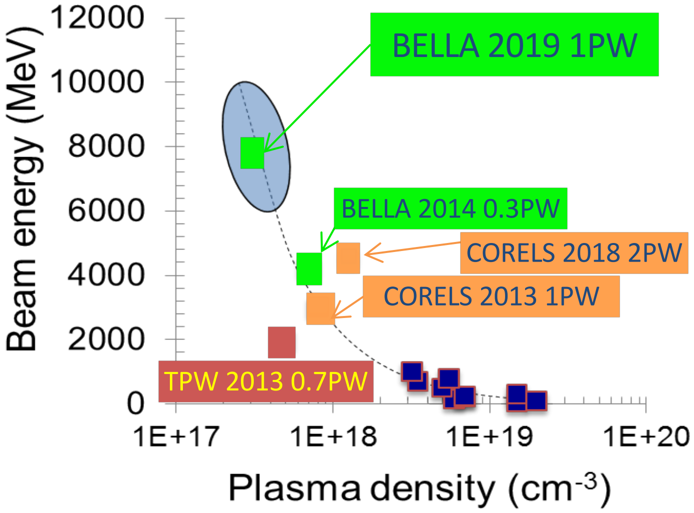
A second beamline will be installed at BELLA for multi-GeV staging experiments



BELLA's Second Beamline highlighted in orange

Summary and outlook

- Laser-heater with large-diameter capillaries provided improved driver confinement while mitigating damage
- Guided PW pulses in 20 cm long channels
- High energy beams up to 8 GeV observed
- PW pulses produced broad energy spread electron beams (non-localized self-injection)



Next:

- PW experiments at lower density
- Localized injection with PW laser power and in longer capillaries (single bunch and reduced energy spread)
- Multi-GeV staging with high capture efficiency