

Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide

A. J. Gonsalves

Lawrence Berkeley National Laboratory

NAPAC, September 2019

Supported by U.S. DOE under contract No. DE-AC002-05CH11231 &
National Science Foundation, Grant No. PHY-1415596 & PHY-1632796



U.S. DEPARTMENT OF
ENERGY

Office of
Science

ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION

ATAP



Laser plasma accelerators (LPAs) are compact & provide femtosecond beams

Ultra-high axial electric fields lead to compact accelerators

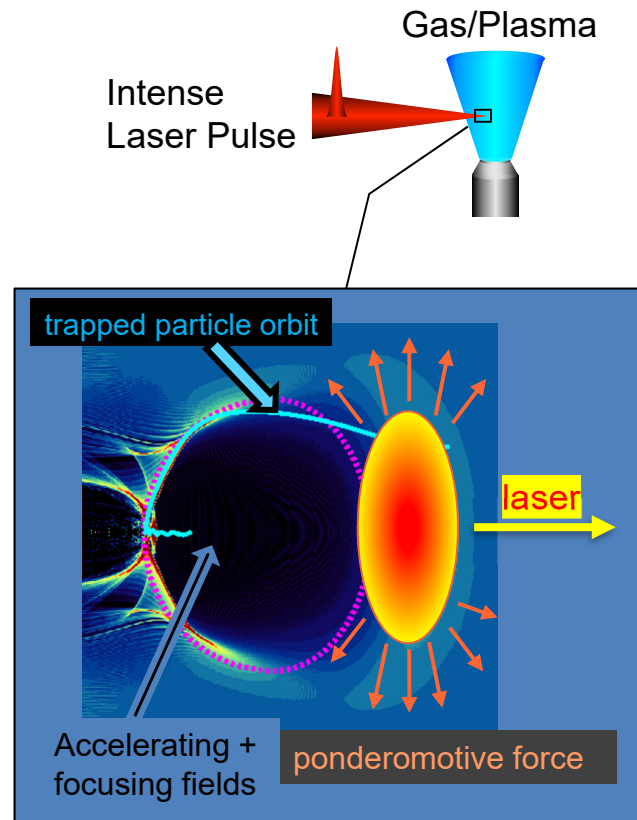
$$E_0 = \frac{cm_e \omega_p}{e}, \quad n_e = 2 \times 10^{17} \text{ cm}^{-3} \Rightarrow \boxed{E_0 \approx 40 \text{ GV/m}}$$

Beams are ultra-short (few fs)

$$\lambda_p \equiv \frac{2\pi c}{\omega_p} \approx 100 \text{ } \mu\text{m} \quad T_{\text{pulse}} \approx \frac{\lambda_p}{2\pi c} \approx 50 \text{ fs}$$

Can excite large plasma waves with intense laser pulse

Electrons from background plasma can be accelerated



T. Tajima and J.Dawson, *PRL*, 43, (1979) 267; Esarey et al., *RMP*, 81, (2009), 1229



U.S. DEPARTMENT OF
ENERGY

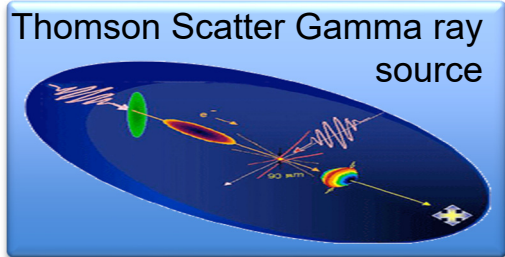
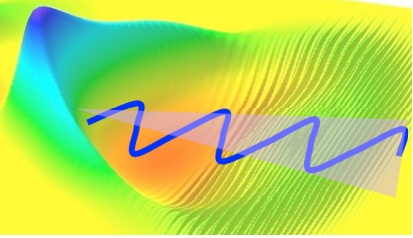
Office of
Science

ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION

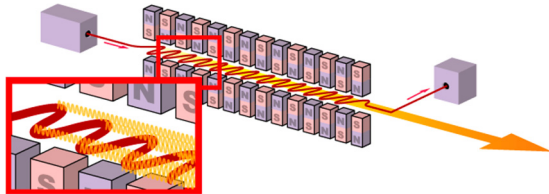


LPAs explored for Compact Drivers of Light Sources and Linear Colliders

keV Betatron radiation

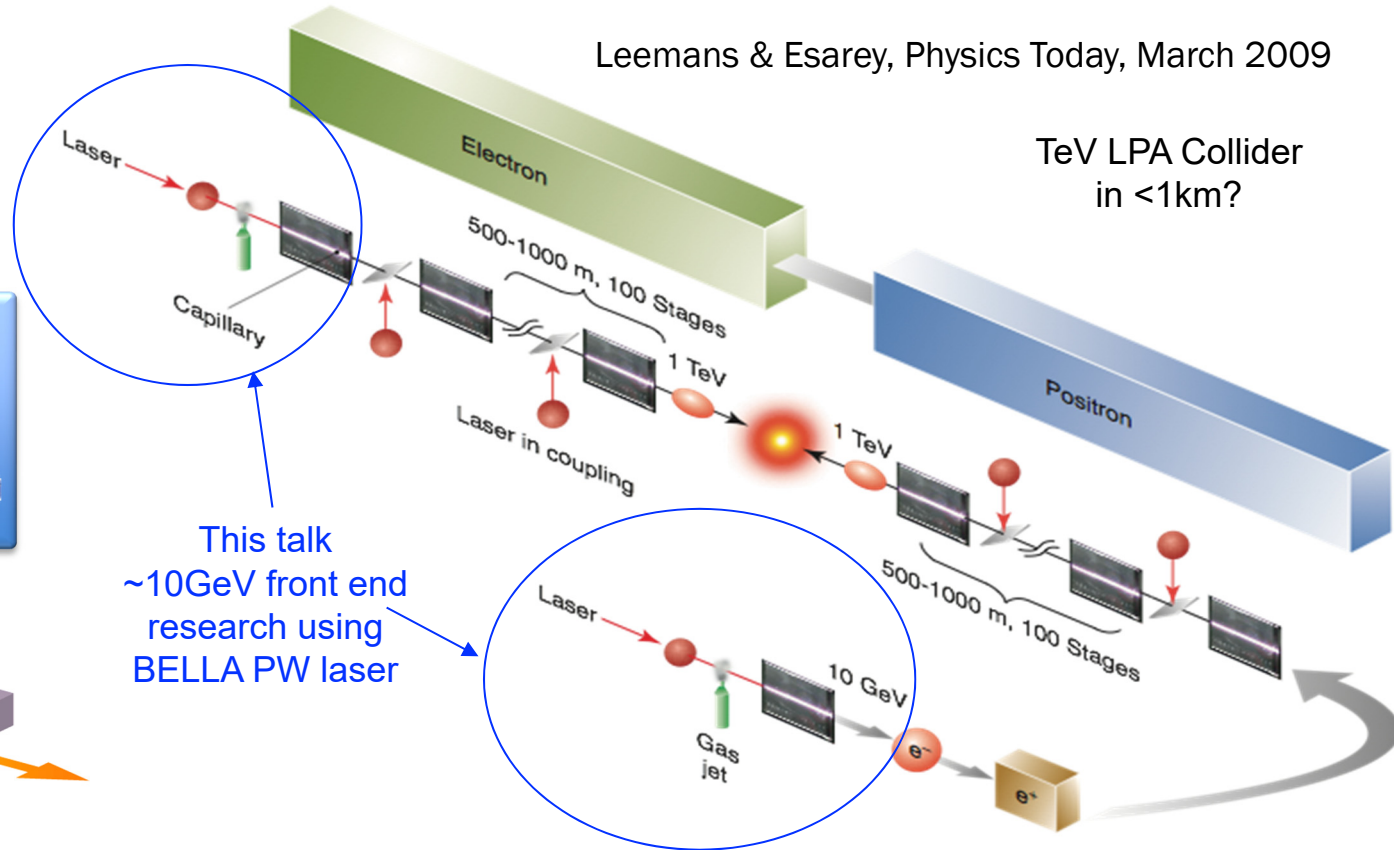


Free Electron Laser



Leemans & Esarey, Physics Today, March 2009

TeV LPA Collider
in <1km?



U.S. DEPARTMENT OF
ENERGY

Office of
Science

ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION



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



Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop
February 2-3, 2016

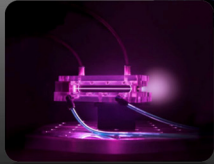
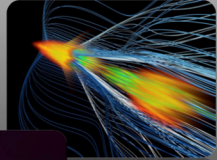
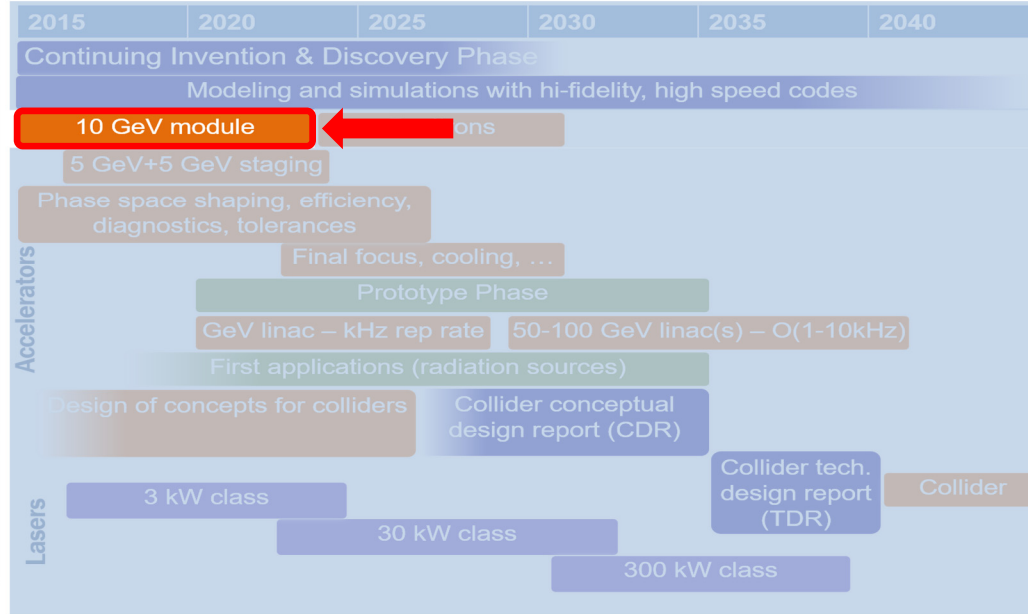
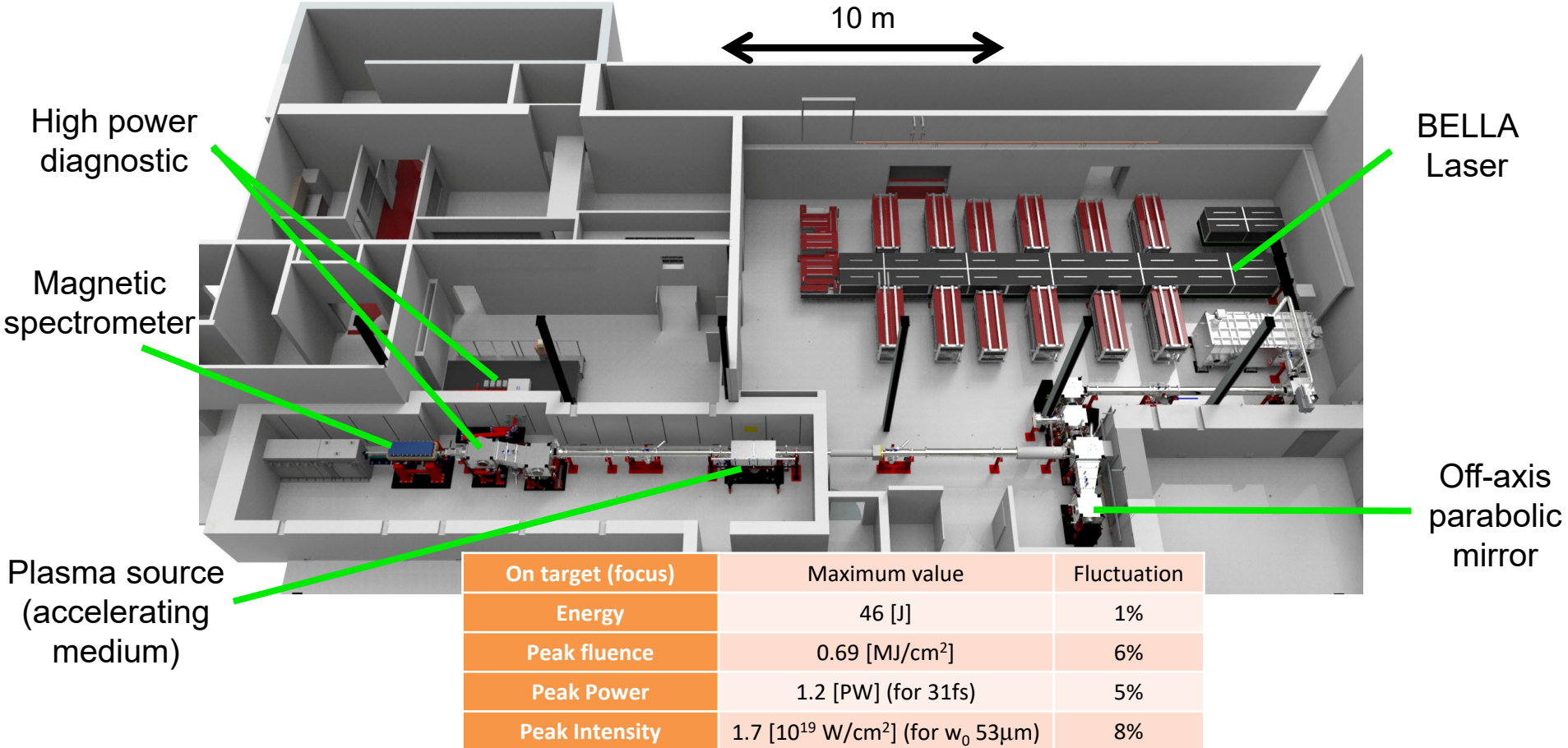


Image credits: lower left LINER, Karlsruhe; upper right SLAC/LAW An

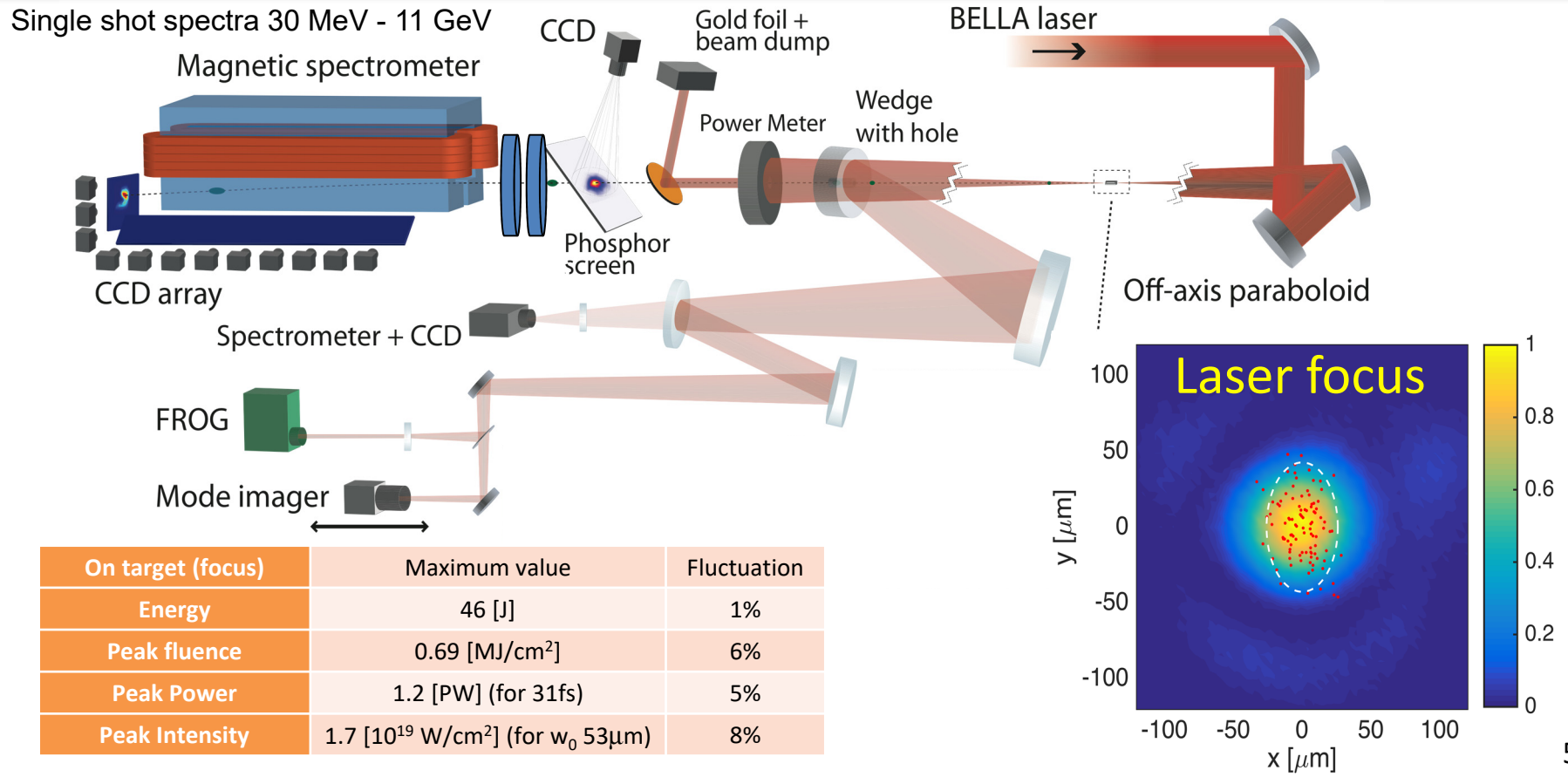


- Simulations show electron beam energy maximized with pre-formed plasma channel
- At low density needed for 10GeV, capillaries previously used do not provide sufficiently strong channel
- Approach is to combine capillary discharge with laser-heating

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



Single-shot diagnostics for both laser and electron beam



Waveguide can mitigate diffraction to increase acceleration length and beam energy

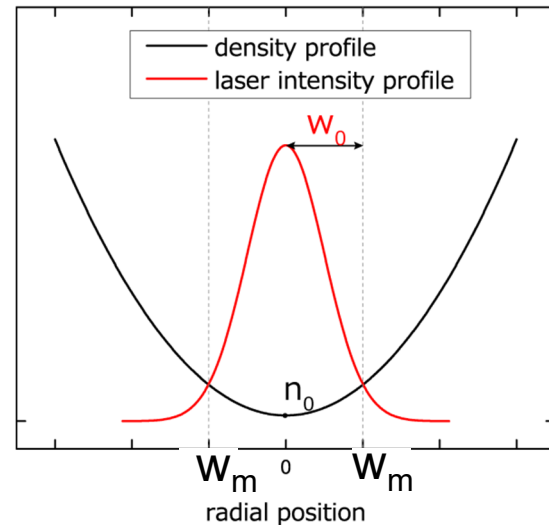
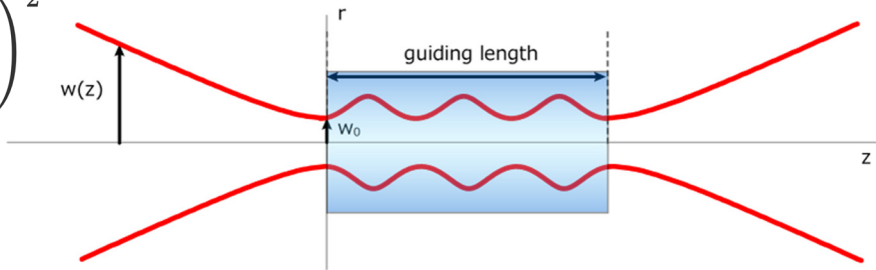
Vacuum propagation



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

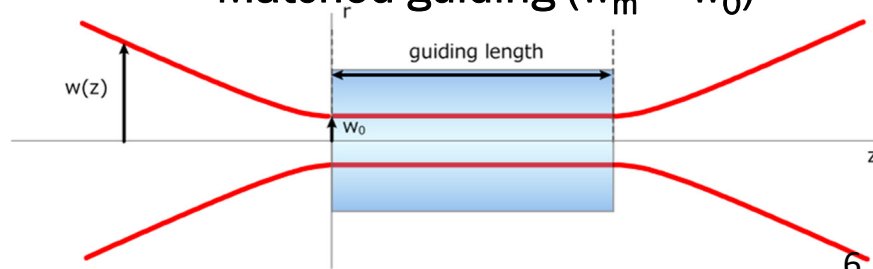
Mismatched guiding ($w_m > w_0$)

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

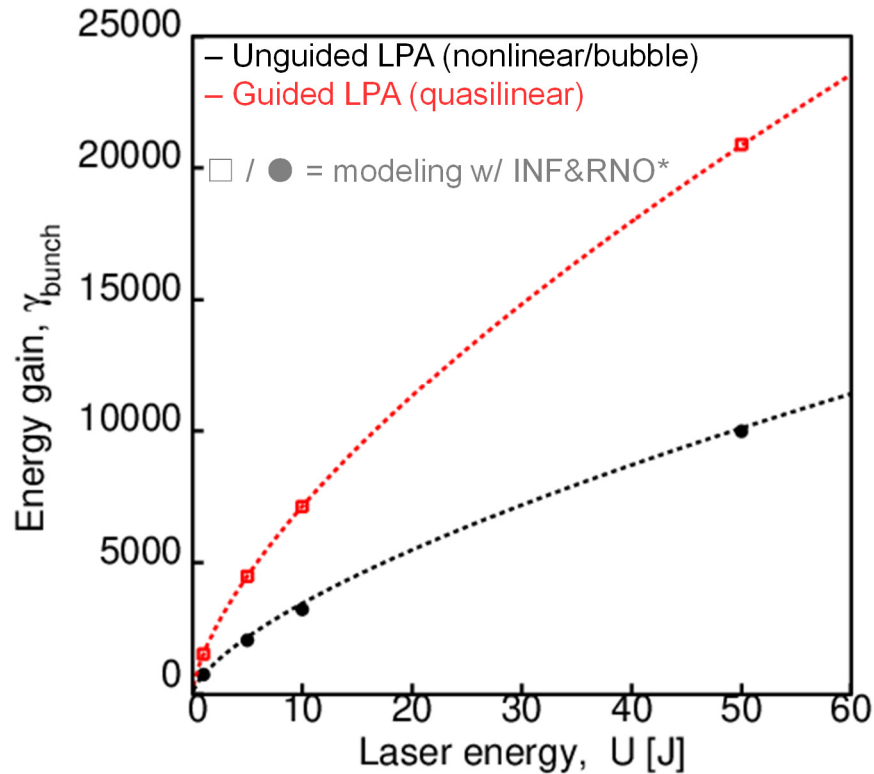


Matched guiding ($w_m = w_0$)

$$w^2(z) = \frac{w_0^2}{2} \left[1 + \frac{w_m^4}{w_0^4} + \left(1 - \frac{w_m^4}{w_0^4} \right) \cos \left(2 \frac{\lambda}{\pi w_m^2} z \right) \right]$$



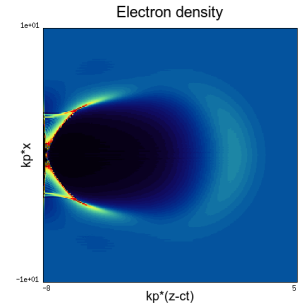
For given laser energy the energy gain with pre-formed waveguide is larger due to lower density and longer length



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

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

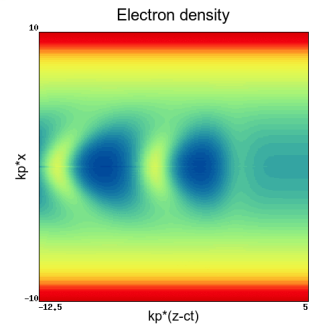
e.g., $n_0=1.5 \times 10^{18} \text{ cm}^{-3}$
for $U=10 \text{ J}$, $a_0=4.5$



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

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

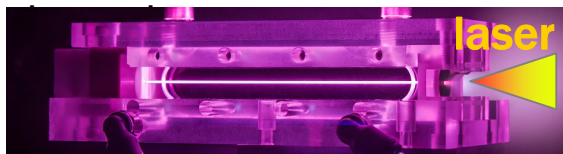
e.g., $n_0=2.6 \times 10^{17} \text{ cm}^{-3}$ for
 $U=10 \text{ J}$, $a_0=1.5$



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

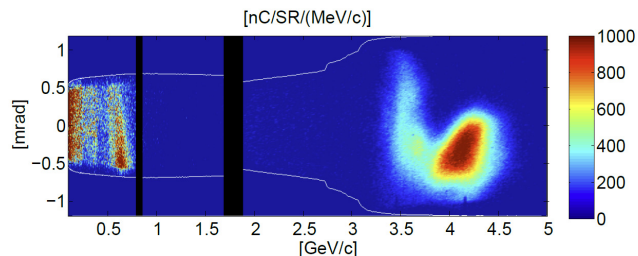
2014 Record LPA energy with BELLA

Capillary discharge plasma

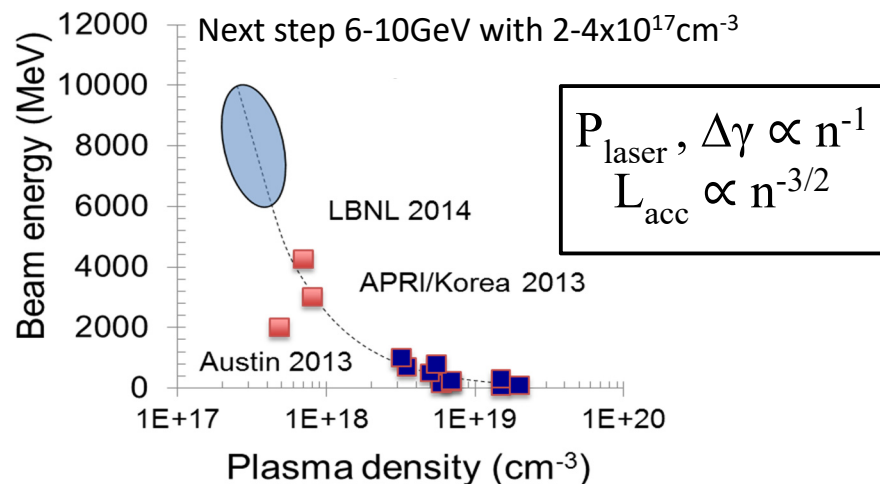


- Gas injected near ends
- Discharge creates plasma
- Guiding structure formed by heat conduction

Up to 4.2 GeV ($7 \times 10^{17} \text{ cm}^{-3}$) for 300TW

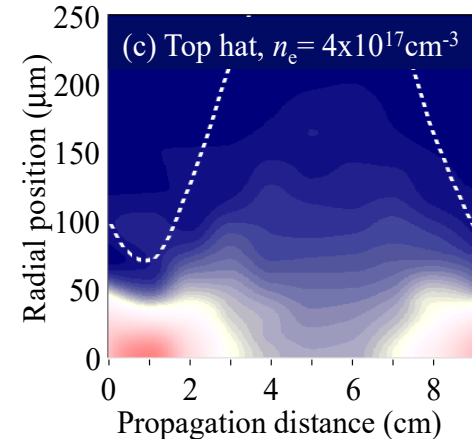
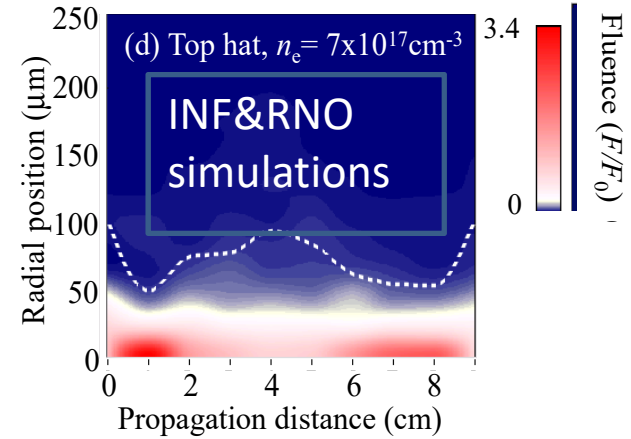
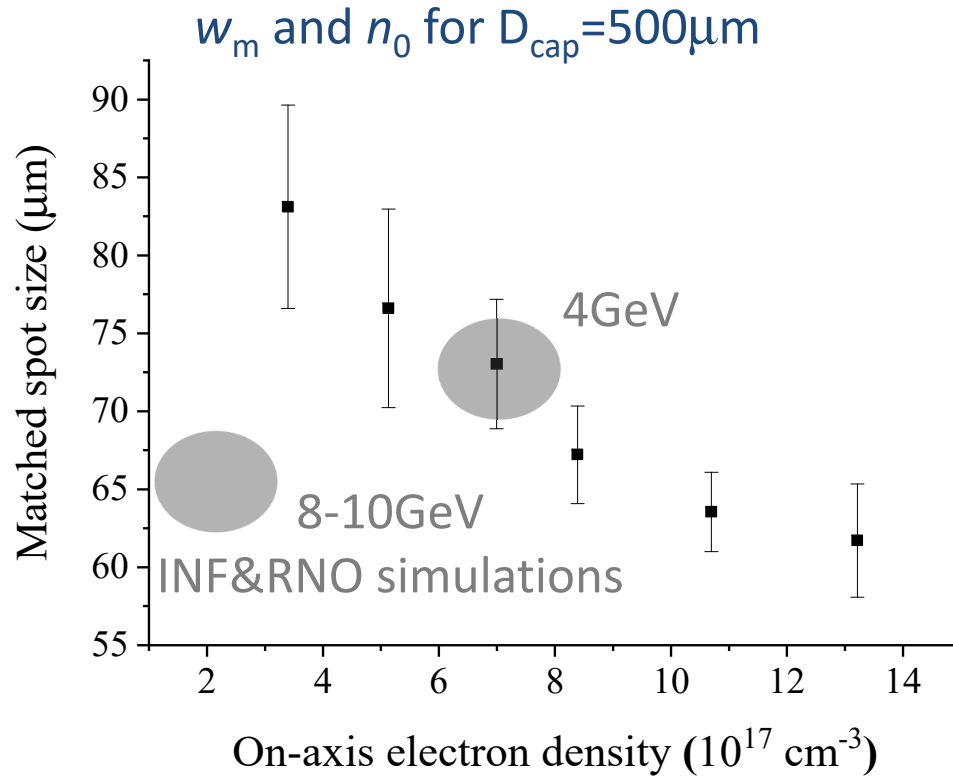


Need lower density & higher power

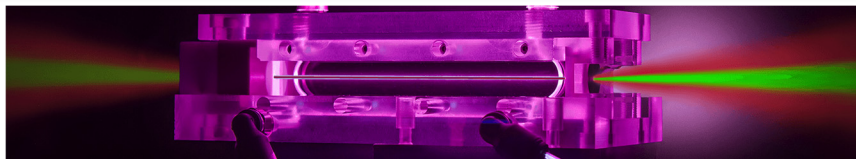


D. J. Spence & S. M. Hooker *PRE* 2001;
D. Jaroszynski, et al., *Phil. Trans. R. Soc. A* (2006);
Leemans et al., *PRL* 2014; A.J. Gonsalves et al., *PoP* 2015

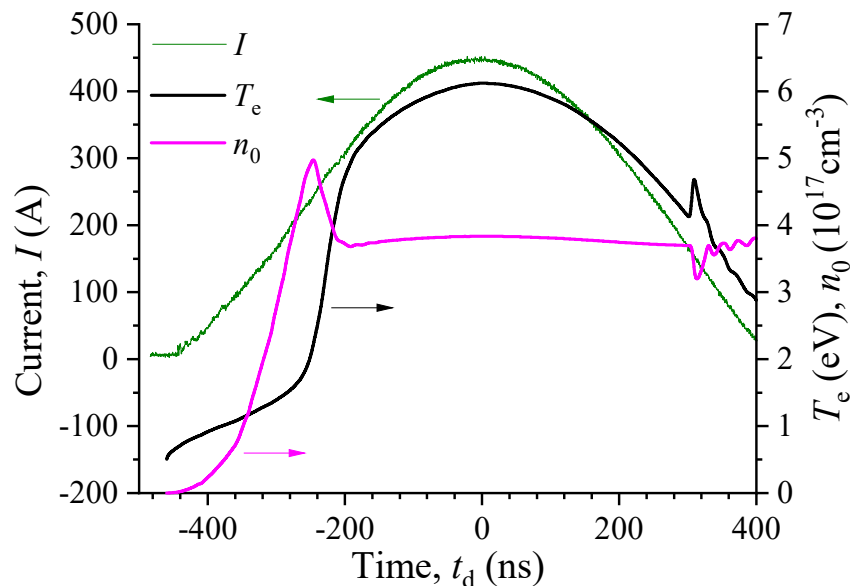
Capillary discharge channel too weak at low density for 10GeV



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

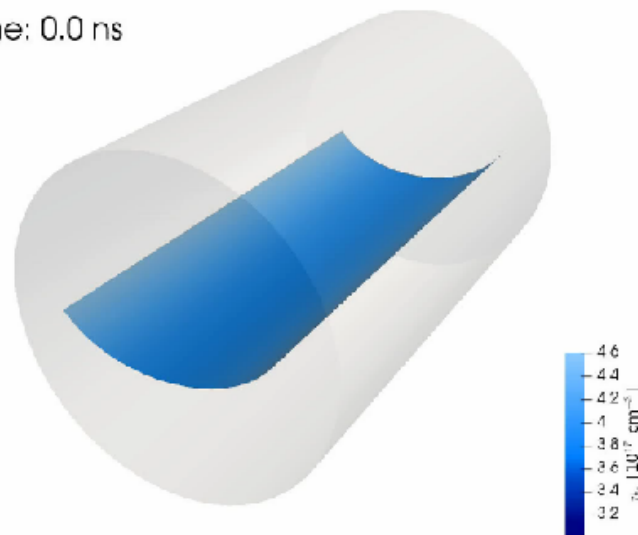


MARPLE simulation

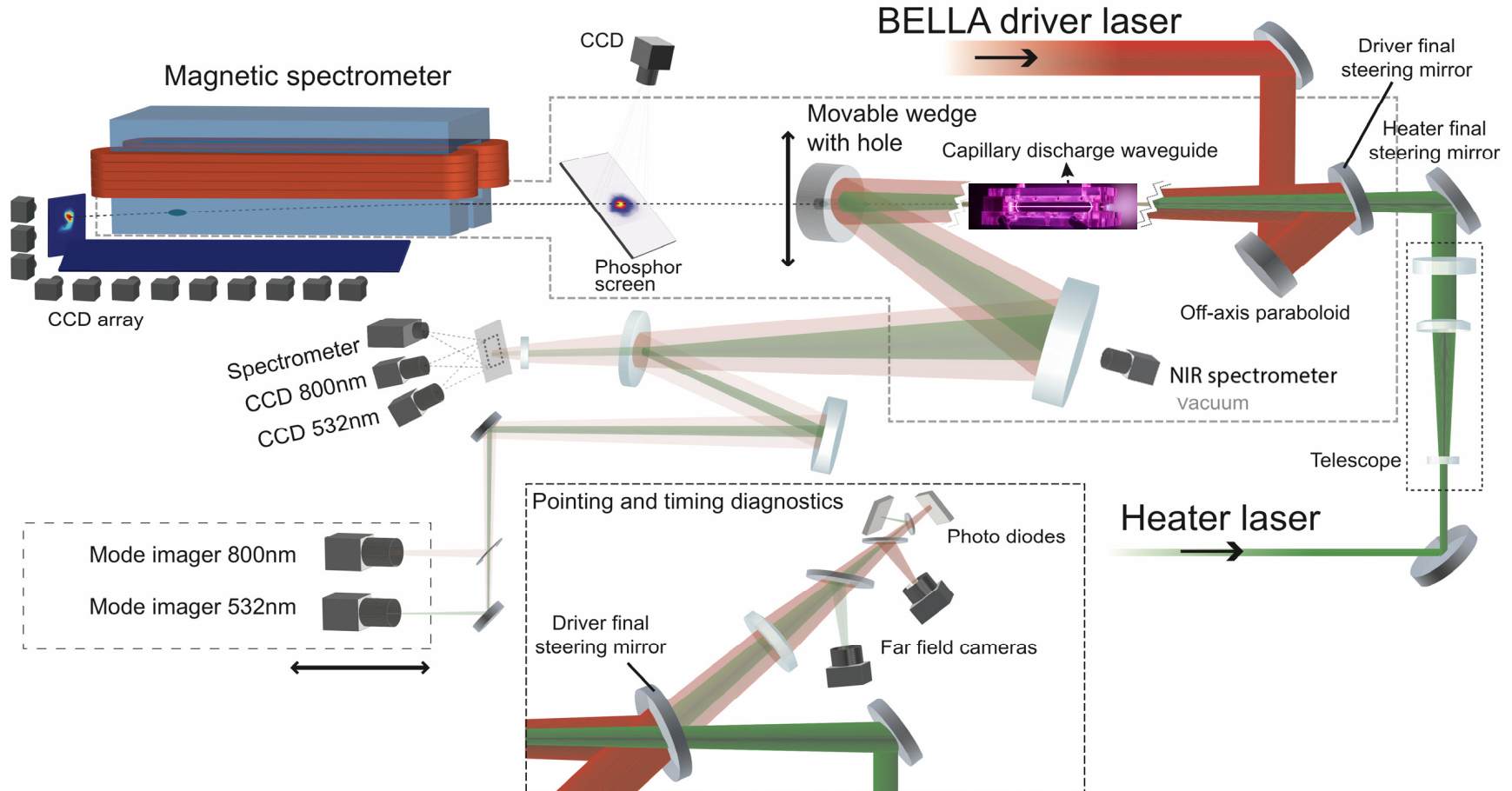


- Nanosecond pulse locally heats plasma through Inverse Bremsstrahlung (IB)
 - absorption of photons by free electrons
- Electron density distribution is changed
 - n_0 reduces
 - w_m reduces locally (faster rise of density from axis)

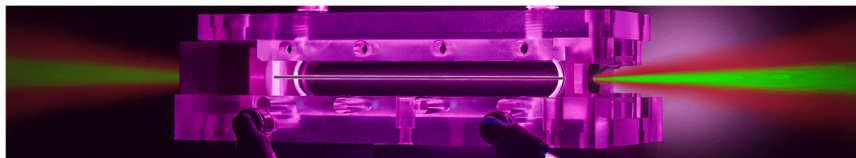
Time: 0.0 ns



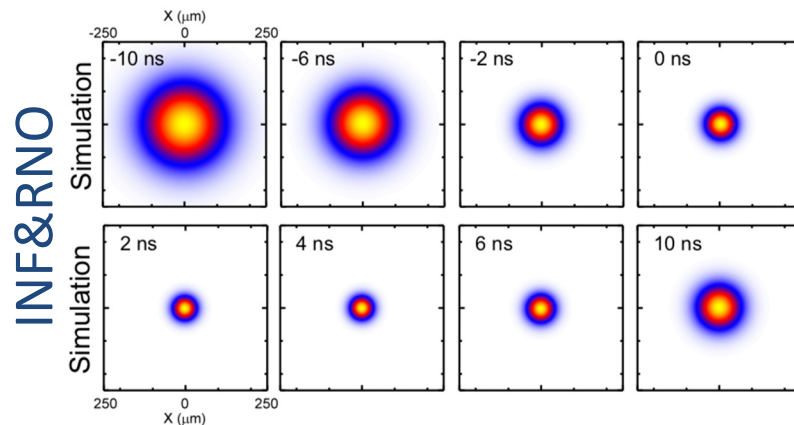
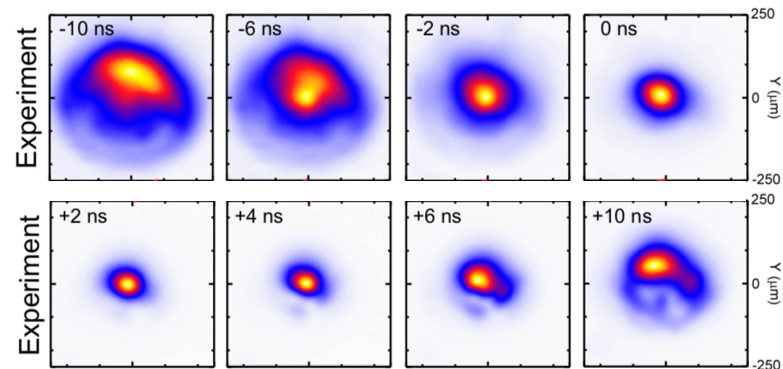
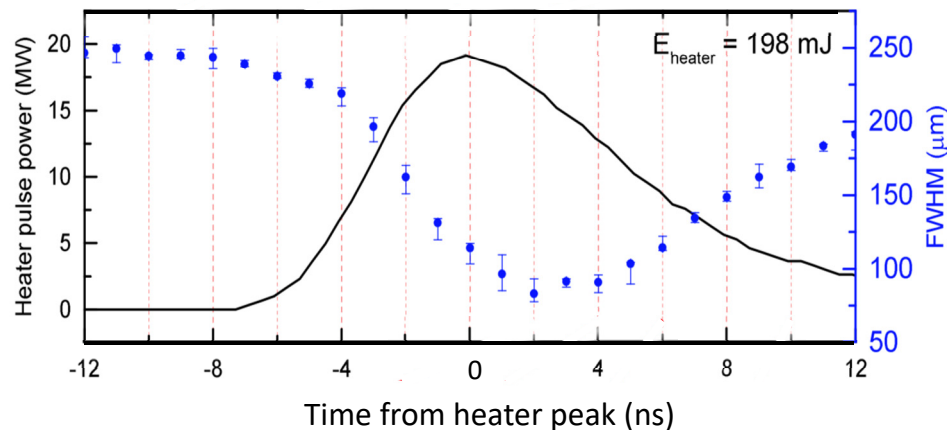
Heater laser added to BELLA petawatt beamline



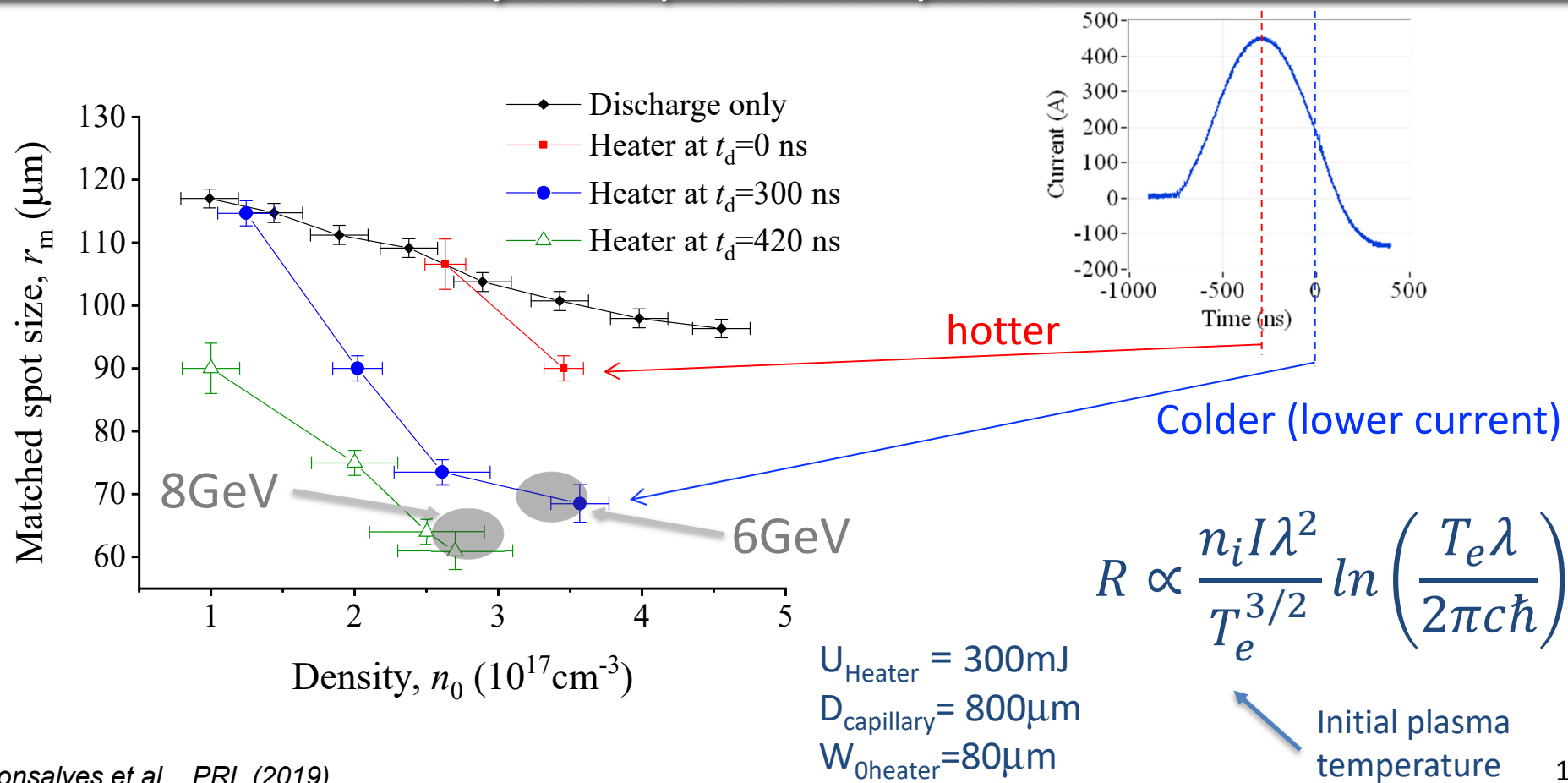
Guided low-power laser modes indicate plasma channel enhancement



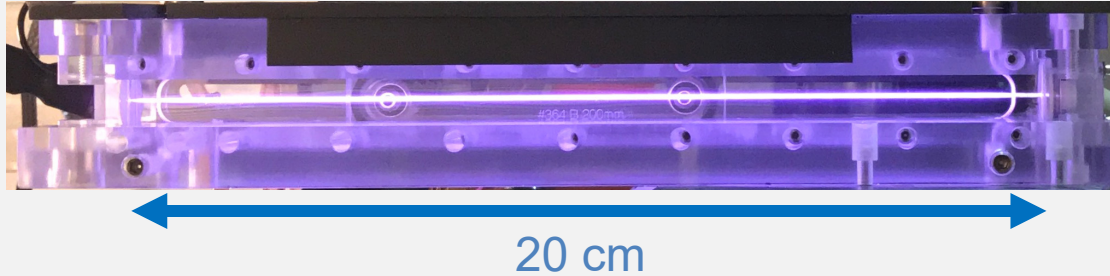
$$L_{\text{cap}}=6\text{cm}; W_{0\text{probe}}=60\mu\text{m}; n_e=0.4\times 10^{18}\text{ cm}^{-3}$$



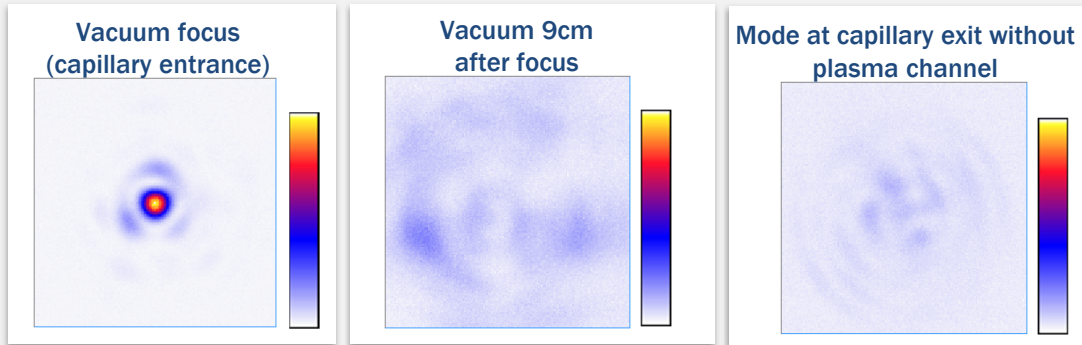
Heater significantly lowers matched spot size, which can be controlled by initial plasma temperature



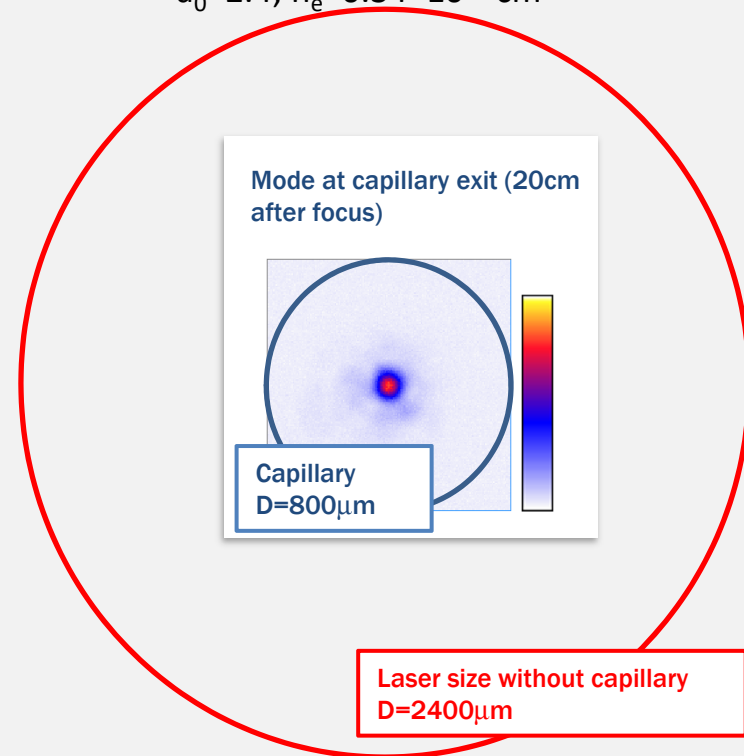
Petawatt pulses (“driver”) guided by 20 cm long heated discharge channels



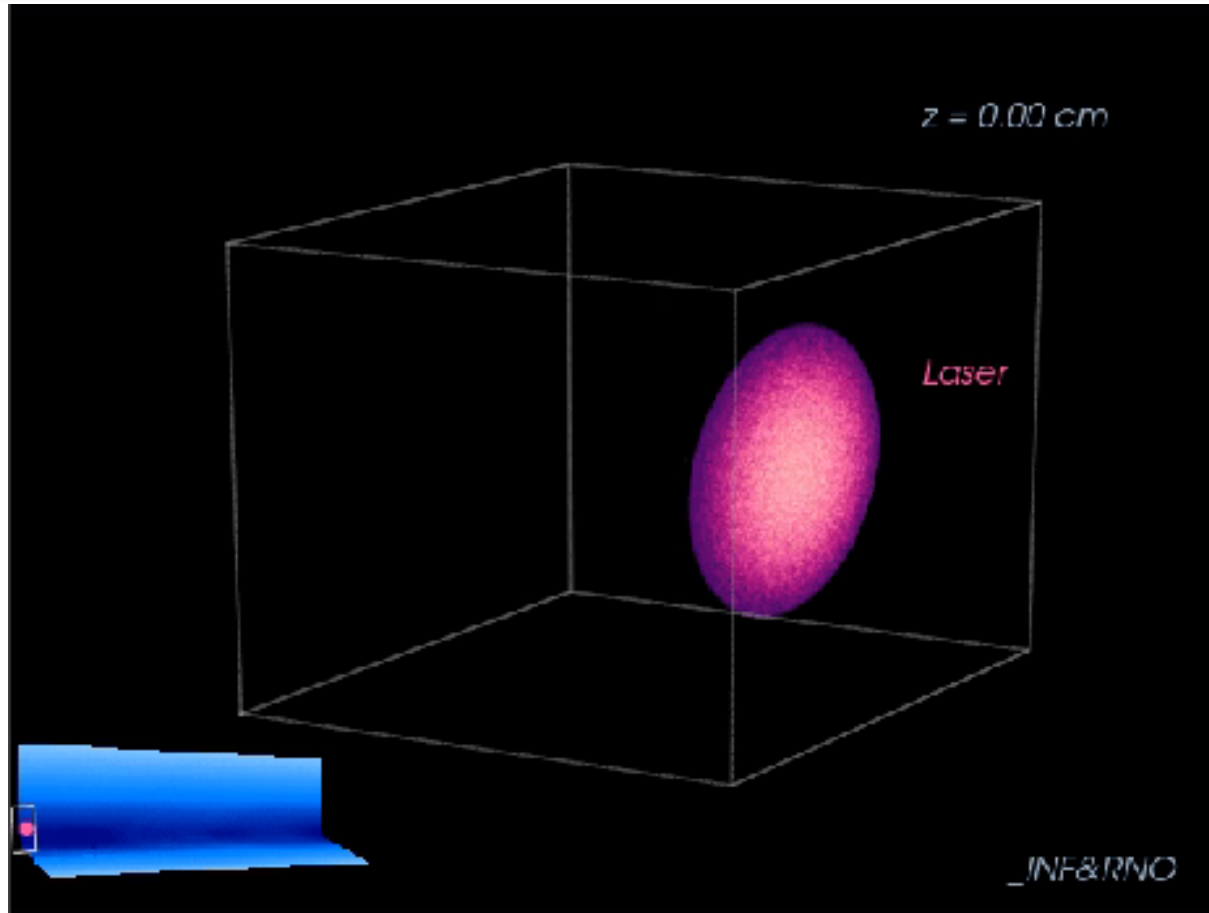
20 cm; 950 TW (~ 30 fs); $1.2 \times 10^{19} \text{ Wcm}^{-2}$;
 $a_0 = 2.4$; $n_e = 0.34 \times 10^{18} \text{ cm}^{-3}$



Spot size w_0 increased from $53 \mu\text{m}$ to $60 \mu\text{m}$ to increase Z_R

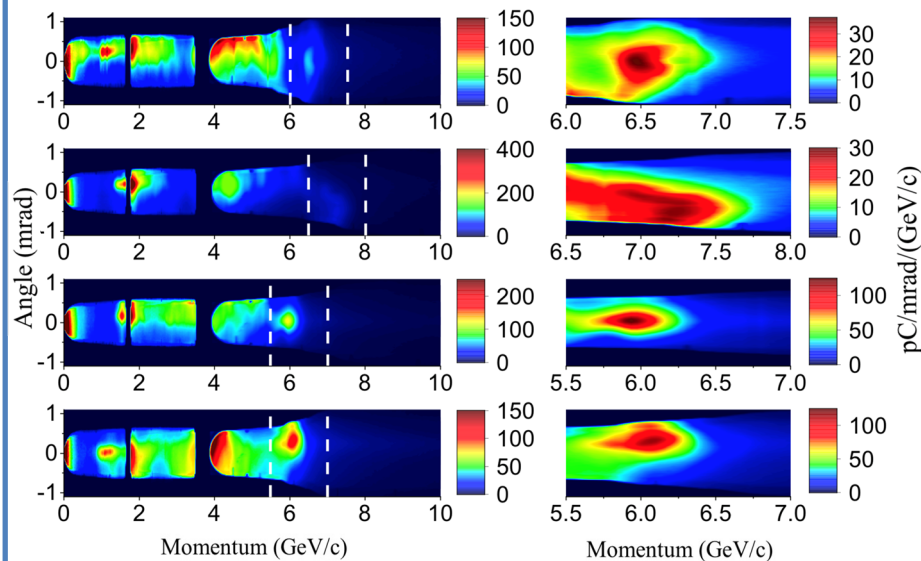


Simulation shows non-linear bubble regime with multiple electron bunches

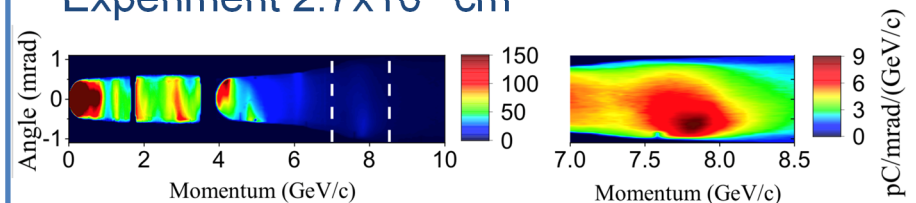


Electron beams with energy up to 7.8GeV observed

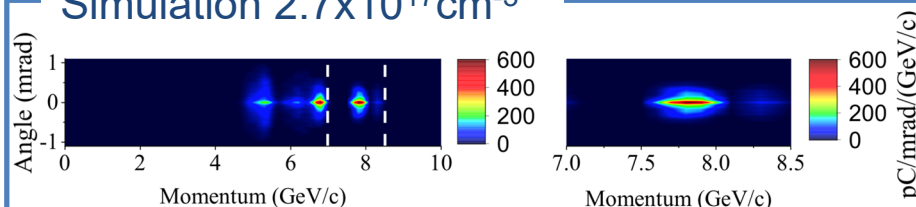
Experiment $3.4 \times 10^{17} \text{cm}^{-3}$



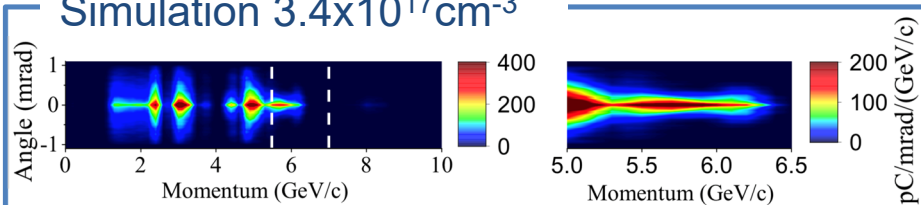
Experiment $2.7 \times 10^{17} \text{cm}^{-3}$



Simulation $2.7 \times 10^{17} \text{cm}^{-3}$



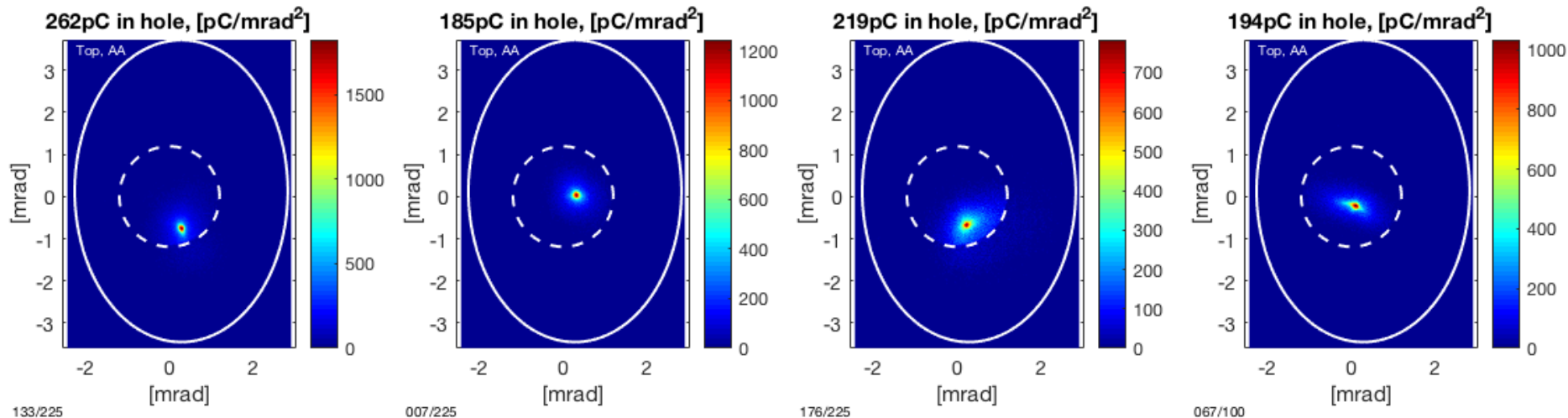
Simulation $3.4 \times 10^{17} \text{cm}^{-3}$



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

Phosphor screen before magnet shows beam divergence down to 150 μ rad FWHM

Shots shown are based on whether beams are well centered along beamline. Most shots do not pass through the diagnostic acceptance (white dashed circle).



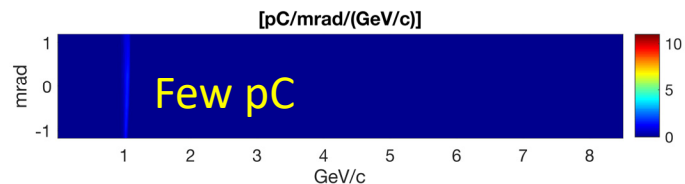
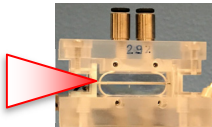
Laser-heated channel narrower. Expect accurate alignment and low pointing jitter more critical.

When optimally aligned, pointing fluctuations similar to gas cell & jet ($\sim$ mrad and 3 orders of magnitude larger than laser pointing). Spatio-temporal mode fluctuations need to be improved (which requires kHz repetition rates for active correction)

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

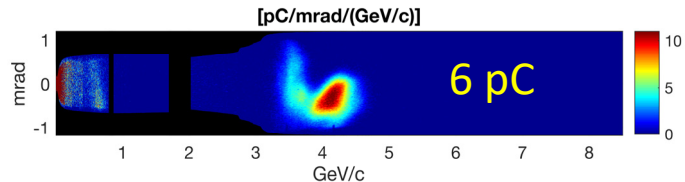
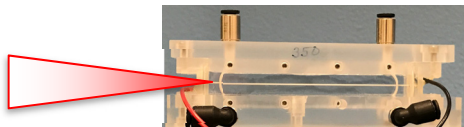
TREX: W. P. Leemans et al., *Nat. Phys.* (2006)

3 cm; 40 TW; $\sim 5 \times 10^{18} \text{ cm}^{-3}$



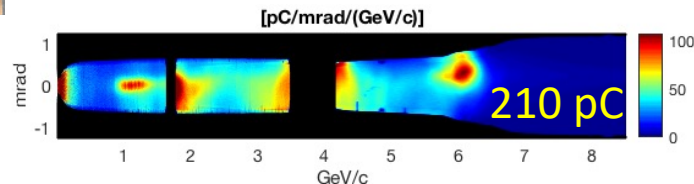
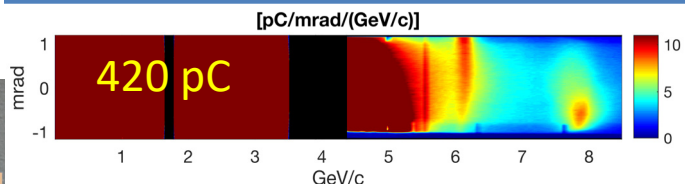
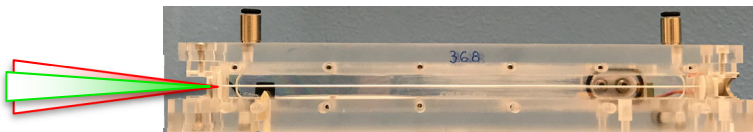
BELLA: W. P. Leemans et al., *PRL* (2014)

9 cm
300 TW
 $\sim 0.7 \times 10^{18} \text{ cm}^{-3}$



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

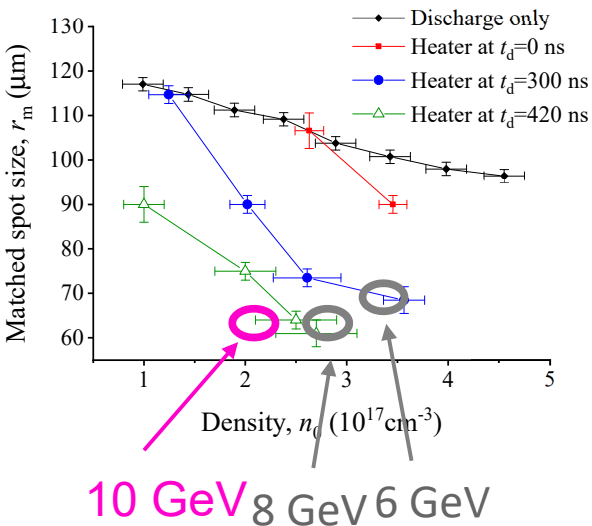
20 cm; 850 TW; $0.3 \times 10^{18} \text{ cm}^{-3}$



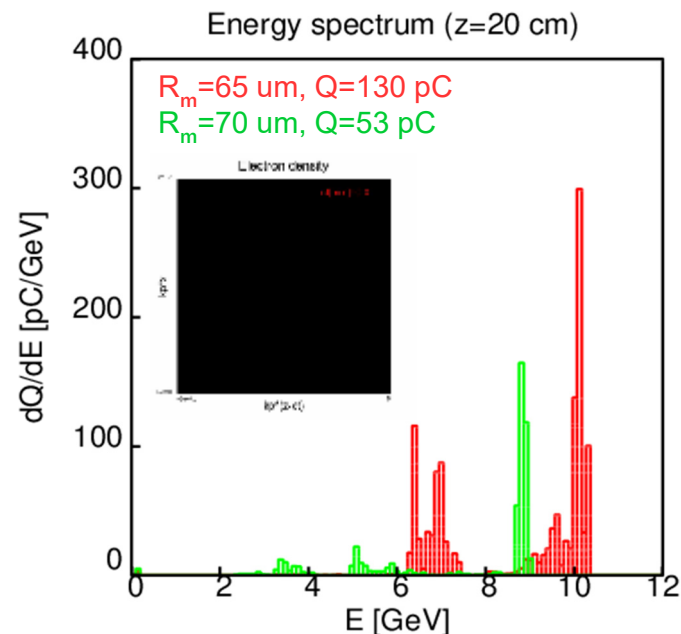
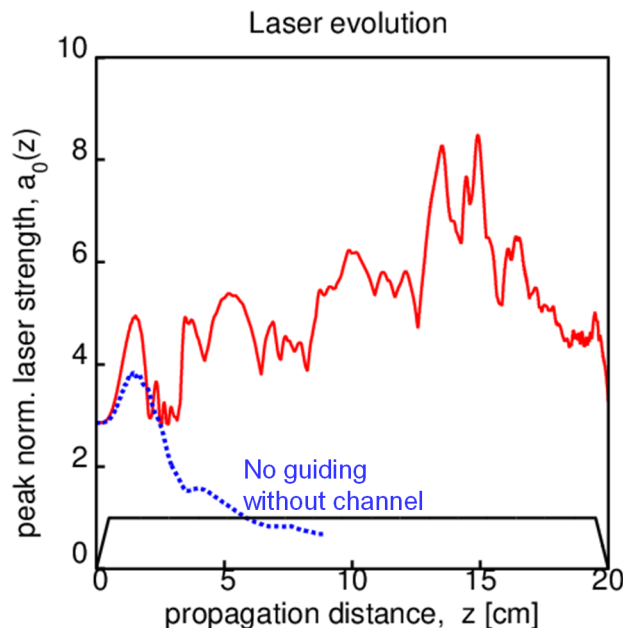
Charge density axis x10



INF&RNO simulations predict that demonstrated heated-channel parameters close to those needed for 10 GeV using BELLA @ full power

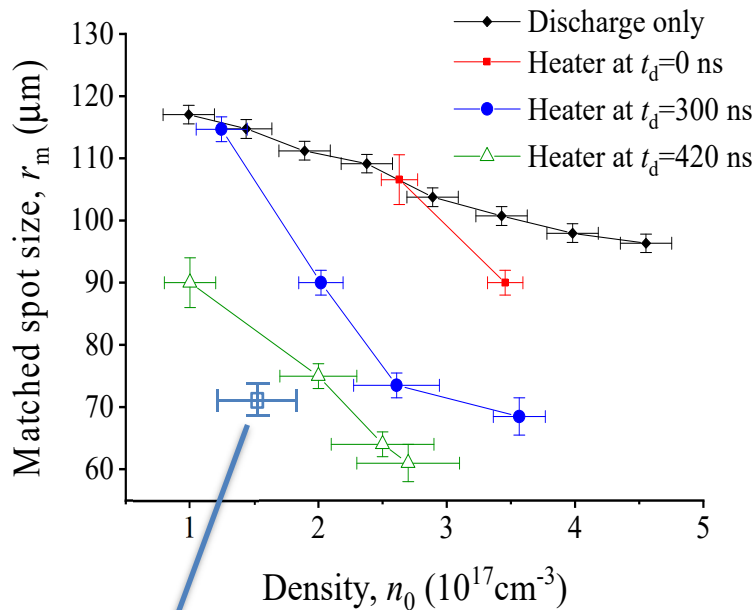


On-axis density: $n_0=2.2 \times 10^{17}/\text{cc}$ (long. uniform), $R_m = 65 \mu\text{m}$
 Laser: $T_0 = 30$ fs (exp.), $w_0=63 \mu\text{m}$ (jinc), $U=39$ J



- Final beam properties **sensitive to** laser-plasma parameters
- Potential for tuning with heater laser spot size and delay

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

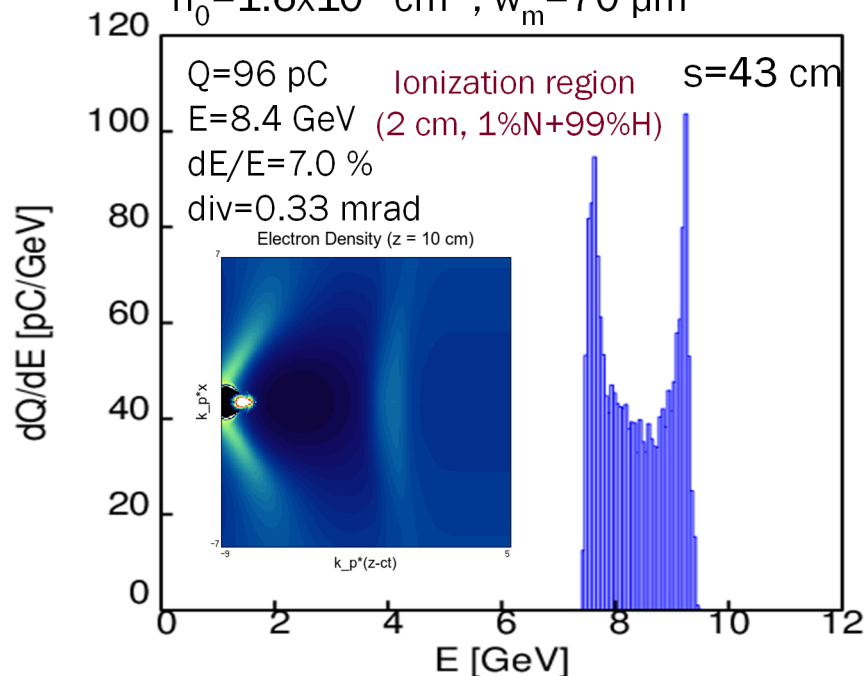


$t_d=420\text{ns}$ but heated channel has evolved for an additional 6ns

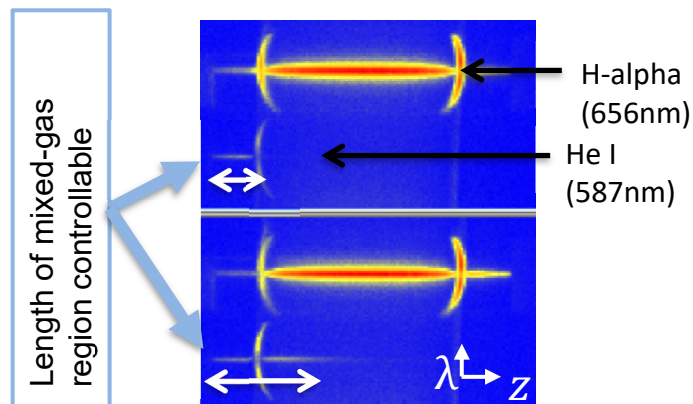
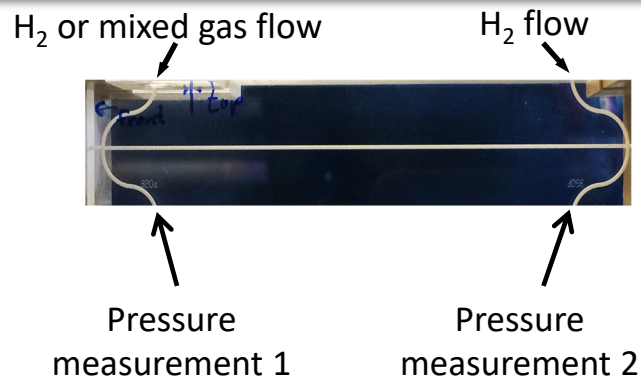
INF&RNO simulation using ionization injection

Laser: $U=36$ J, $w_0=60$ μm , $T=66$ fs

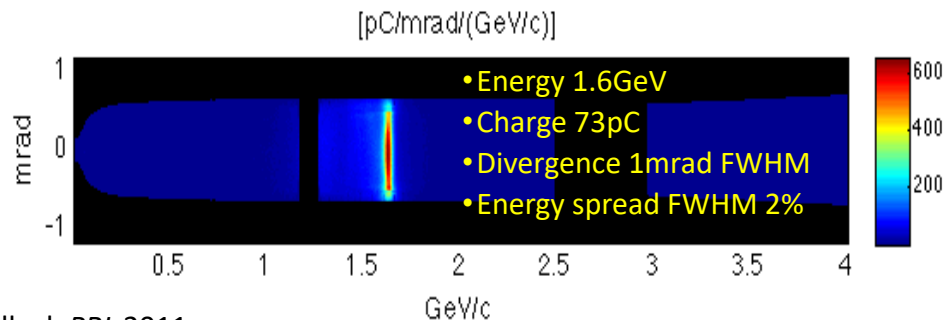
$n_0=1.6 \times 10^{17}\text{cm}^{-3}$, $w_m=70$ μm



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



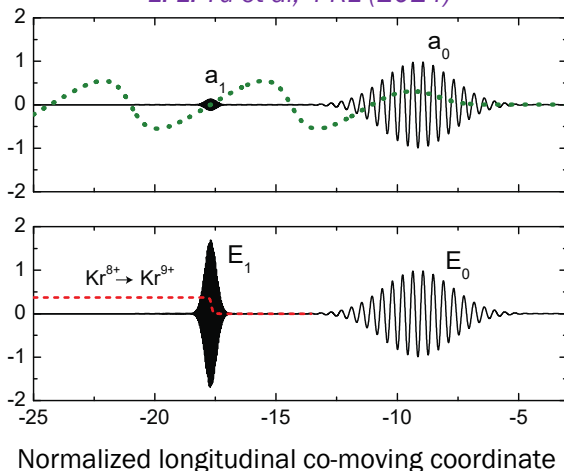
- First BELLA capillary localized ionization injection in $D=500\mu\text{m}$ $L=3\text{cm}$ capillary
- Laser energy 20J
- High-quality beams but capillary damage
- Next step is to combine with laser heater for better confinement & damage mitigation



Two-color ionization injection: method to 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)

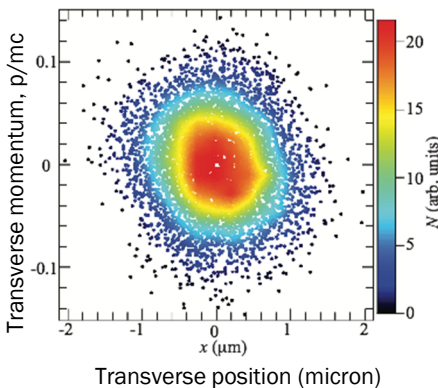


- Laser ponderomotive force (laser intensity) drives plasma wave:

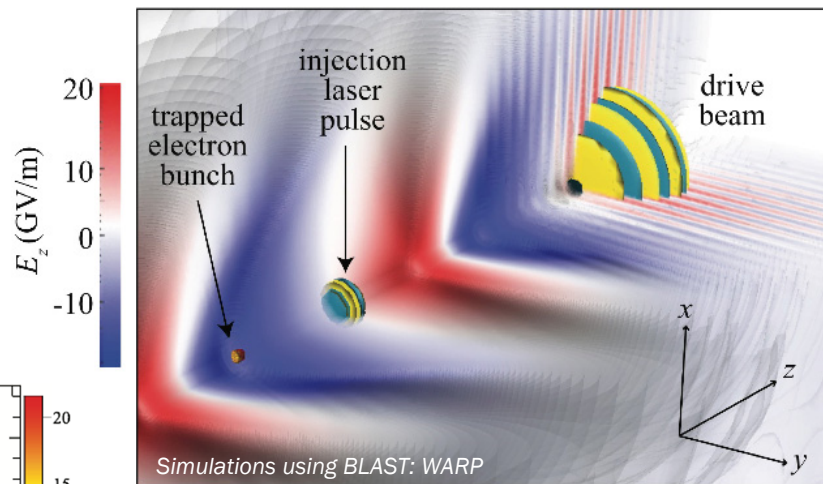
$$F_{\text{PMF}} = m_e c^2 \nabla a^2 / 2$$

- Peak laser electric field determines ionization

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



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



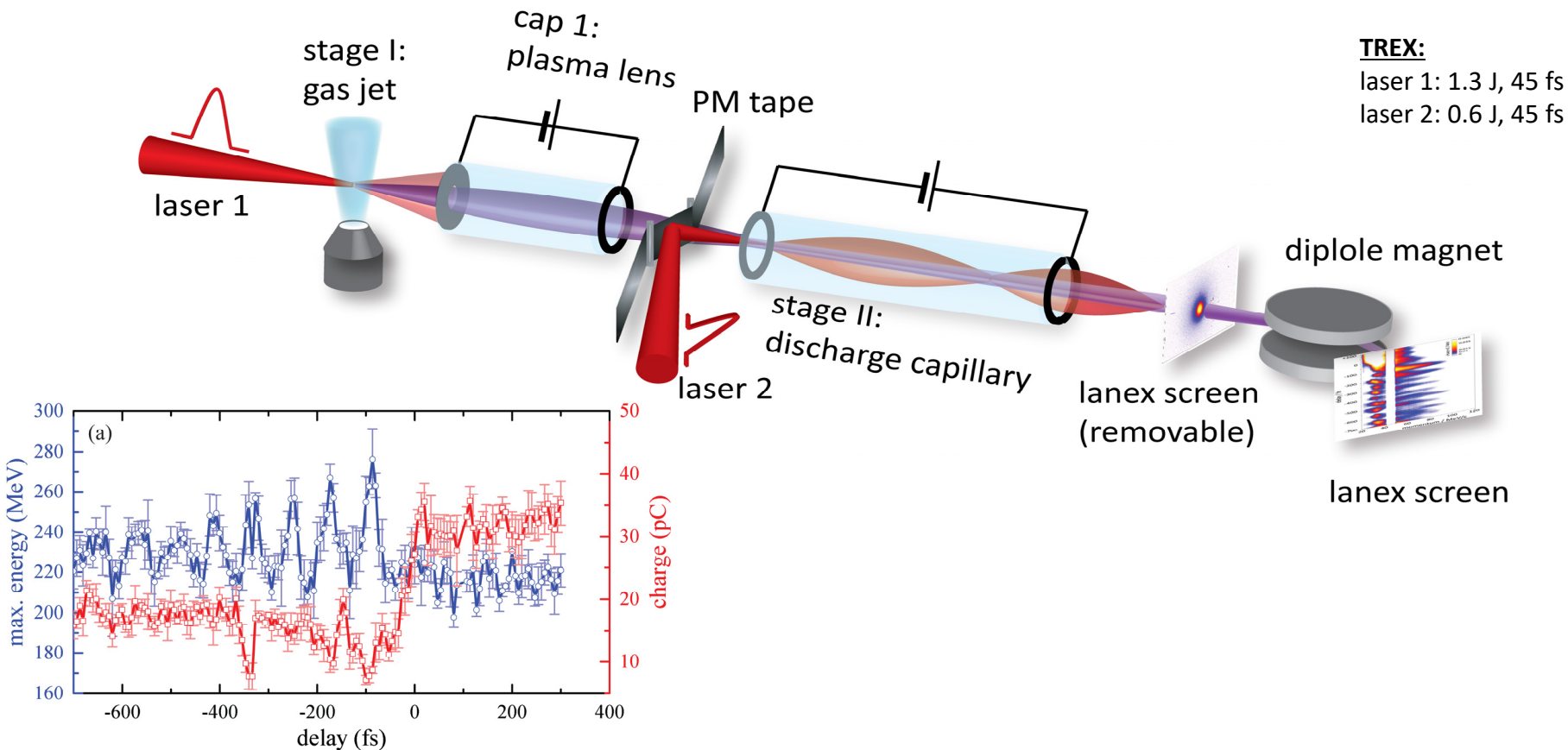
Thermal emittance from ionization injection:

$$\epsilon_y \simeq \epsilon_x = k_p w_i^2 a_i \left(\frac{3\pi r_e}{4\sqrt{2}\alpha^4 \lambda_i} \right) \left(\frac{U_H}{U_I} \right)^{3/2}$$

normalized beam
emittance ~ 20 nm

- experiment to be implemented on **BELLA 2nd beamline**: 0.8μm drive laser and 0.27μm injection laser

Multistage coupling of two independent LPAs successfully demonstrated with 100MeV beams using 30 TW laser (but low capture efficiency)



Staging design with optimized injector and guiding parameters shows 100% bunch capture and acceleration

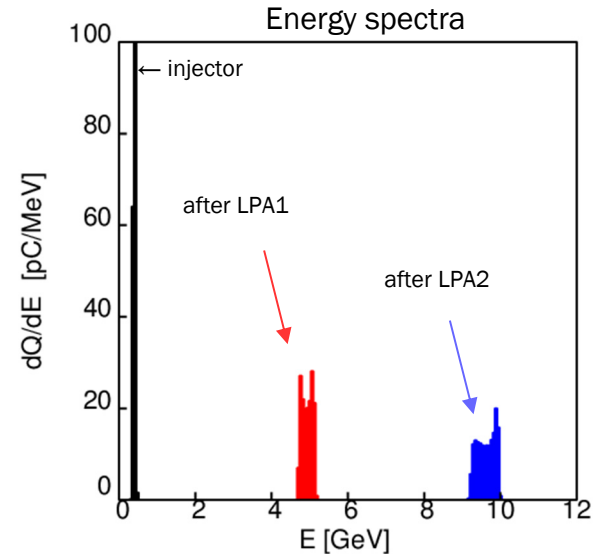
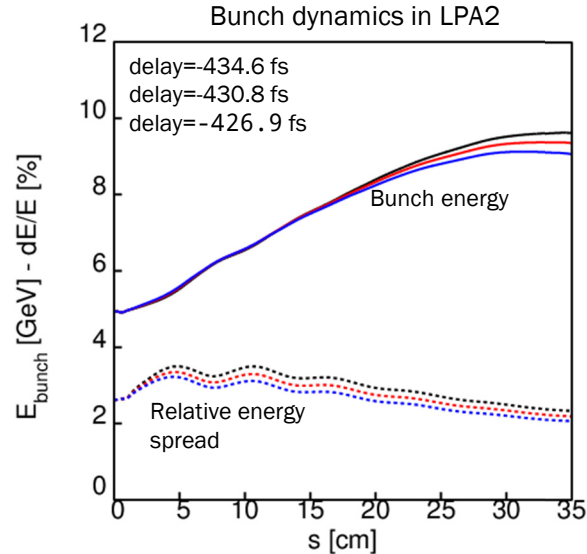
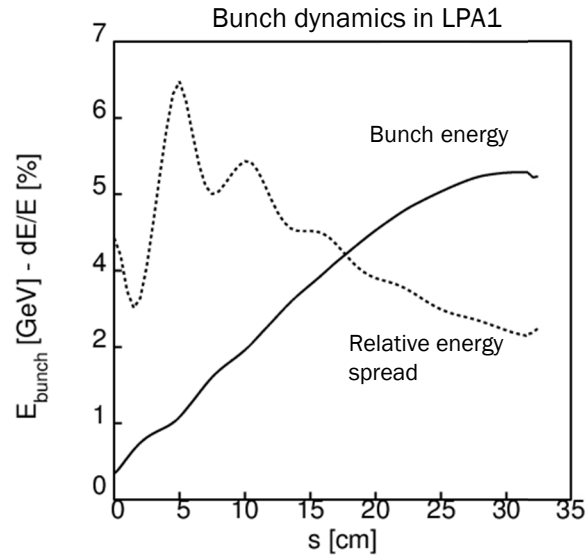
→ Assuming laser matching (heater) in LPA1 and LPA2 and operating in a quasi linear regime (i.e., less wake evolution)

$W_m = 70 \text{ } \mu\text{m}$ $W_0 = 53 \text{ } \mu\text{m}$, density $2.2 \times 10^{17} \text{ cm}^{-3}$

→ Assuming following injector parameters:

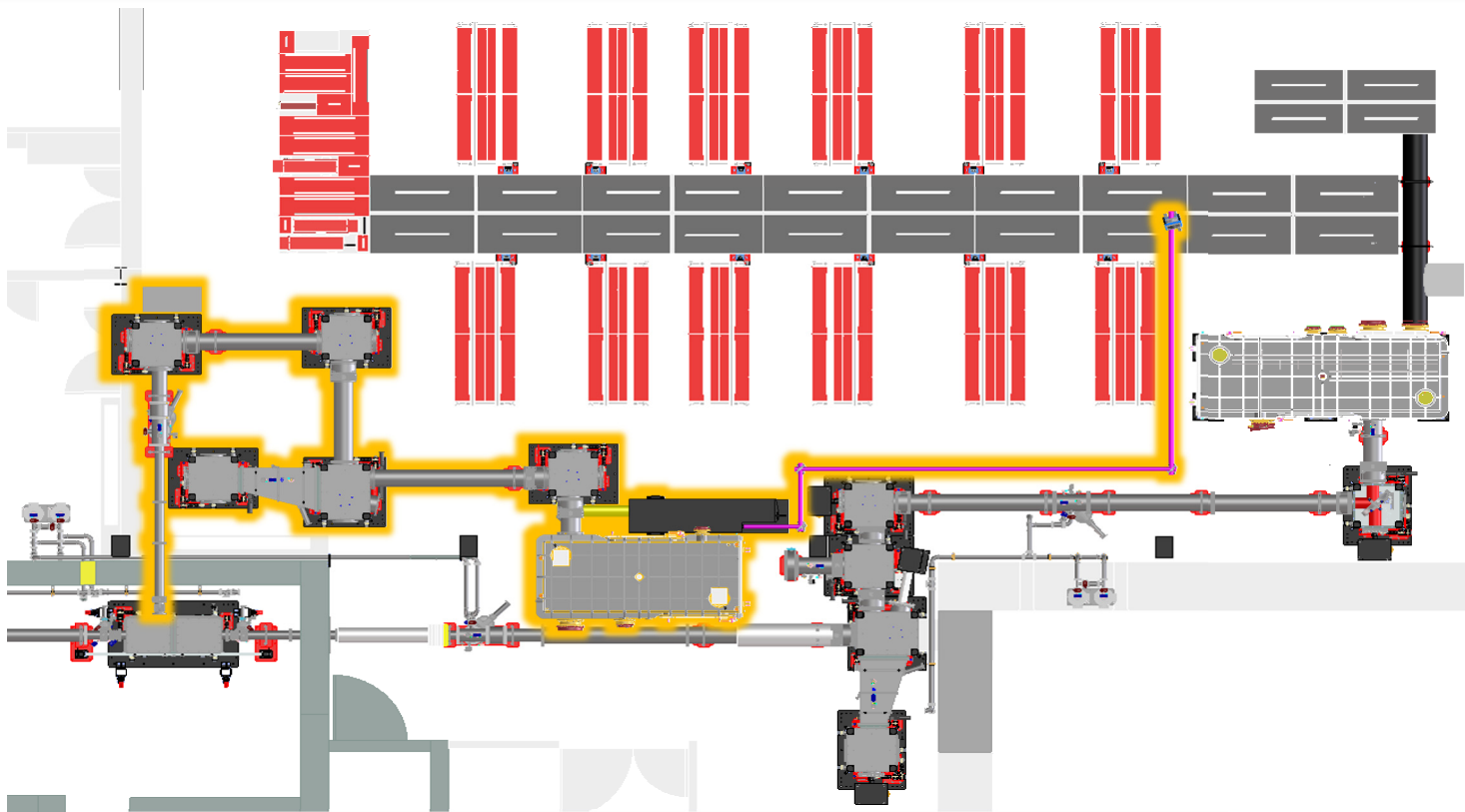
- $E = 400 \text{ MeV}$, $dE/E = 4\%$ (rms)

- $Q = 10 \text{ pC}$, $L_b = 2 \text{ } \mu\text{m}$, $x' < 1 \text{ mrad}$ (rms)



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

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



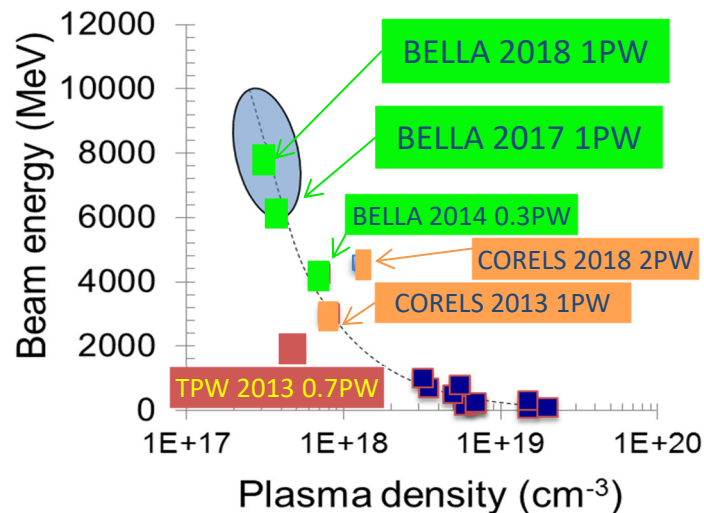
BELLA's Second Beamline highlighted in orange

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 density $2 \times 10^{17} \text{ cm}^{-3}$
- Localized injection with PW laser power and in longer capillaries (single bunch and reduced energy spread)
- Multi-GeV staging with high capture efficiency



Acknowledgements

Experiments and PIC simulations

Lawrence Berkeley National Laboratory – BELLA center

K. Nakamura, J. Daniels
C. Pieronek, T. de Raadt
J. H. Bin, S. Bulanov
K. Swanson, S. Steinke
C. Benedetti, C.B. Schroeder
C. Toth, C. Geddes
E. Esarey, W. P. Leemans (now at DESY)

MHD simulations

Keldysh Institute of Applied Mathematics RAS

G. Bagdasarov, N. Bobrova, V. Gasilov
**Institute of Physics ASCR, v.v.i. (FZU),
ELI-Beamlines Project**
P. Sasorov, G. Korn