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
  - 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. Bagdasarova, 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

Thomson Scatter Gamma ray source

Free Electron Laser

This talk ~10GeV front end research using BELLA PW 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

<table>
<thead>
<tr>
<th>On target (focus)</th>
<th>Maximum value</th>
<th>Fluctuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>46 [J]</td>
<td>1%</td>
</tr>
<tr>
<td>Peak Power</td>
<td>1.2 [PW] (for 31fs)</td>
<td>5%</td>
</tr>
</tbody>
</table>
Simultaneous diagnostics for both laser and electron beam

- Single shot spectra 30 MeV - 11 GeV
- Magnetic spectrometer
- CCD array
- Spectrometer + CCD
- Gold foil + beam dump
- Power Meter
- Wedge with hole
- Off-axis paraboloid
- BELLA laser
- FROG, WIZZLER, TERMITES, INSIGHT, SEQUOIA etc

**On target (focus)**
- Maximum value
- Peak Power: 1.2 [PW] (for 31fs)
- Peak Intensity: 1.7 $[10^{19} \text{ W/cm}^2]$ (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.

Density profile for guiding:

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

BELLA \( Z_R \approx 1 \text{cm} \)
Guiding over 10s cm required to maximize beam energy

Mismatches 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.

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

\[ a_0=1.6, \ k_p w_0 = 4, \ k_p L=1.8 \]

e.g., \( n_0=2.6\times10^{17} \ \text{cm}^{-3} \) for \( U=10 \ \text{J}, \ a_0=1.5 \)

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

e.g., \( n_0=1.5\times10^{18} \ \text{cm}^{-3} \) for \( U=10 \ \text{J}, \ a_0=4.5 \)


C. Benedetti et al, in preparation
Capillary discharge waveguide has allowed us to produce beams with energy up to 4.2 GeV 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 (7x10^{17} cm^{-3}) for 300TW

Need lower density & higher power

Next step 6-10 GeV with 2-4x10^{17} cm^{-3}

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

- 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

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

![Image](image.png)

Experiments and simulations showing the evolution of the plasma channel with time from the heater peak.
Heater significantly lowers matched spot size, which can be controlled by initial plasma temperature.

$U_{\text{Heater}} = 300 \text{mJ}$

$D_{\text{capillary}} = 800 \mu\text{m}$

$W_{0_{\text{Heater}}} = 80 \mu\text{m}$

Initial plasma temperature $T_e$ can be controlled by initial plasma temperature.

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

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 20 cm long heated discharge channels

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

Spot size $w_0$ increased from 53 $\mu$m to 60 $\mu$m to increase $Z_R$
Simulation shows non-linear bubble regime with multiple electron bunches.
Electron beams with energy up to 7.8 GeV observed

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

Gonsalves et al., PRL (2019)
Electron beam divergence 150μrad 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
  • Need kHz repetition rates for active correction

Popp et al., PRL (2010)
Increasing laser power and reducing plasma density has increased charge and maximum energy to 8GeV

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; $0.27 \times 10^{18} \text{ cm}^{-3}$

10GeV simulation @ $n_0=0.22 \times 10^{18} \text{ cm}^{-3}$

$R_m=65 \text{ um}$, $Q=130 \text{ pC}$
$R_m=70 \text{ um}$, $Q=53 \text{ pC}$

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.

$U=36 \text{ J}, w_0=60 \mu\text{m}, T=66 \text{ fs}$

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

$Q=96 \text{ pC}$, Ionization region $(2 \text{ cm}, 1\% \text{N}+99\% \text{H})$

dE/E=7.0 %, div=0.33 mrad

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

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

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)

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

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

- Peak laser electric field determines ionization

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

- Normalized beam emittance tens of nm

- Proof of principle experiment planning underway
Multi-GeV staging is a key next step on the LPA collider roadmap

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)
\[ W_m = 70 \text{ um} \quad W_0 = 53 \text{ um}, \text{ density } 2.2 \times 10^{17} \text{cm}^{-3} \]

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

→ 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.
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