Multi-GeV Plasma Acceleration Results at BELLA

IPAC15

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LPAs are Compact Accelerators

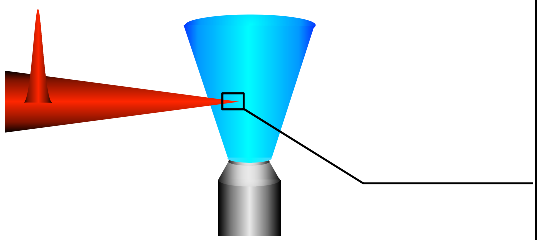
Plasma accelerators - Ultra-high axial electric fields

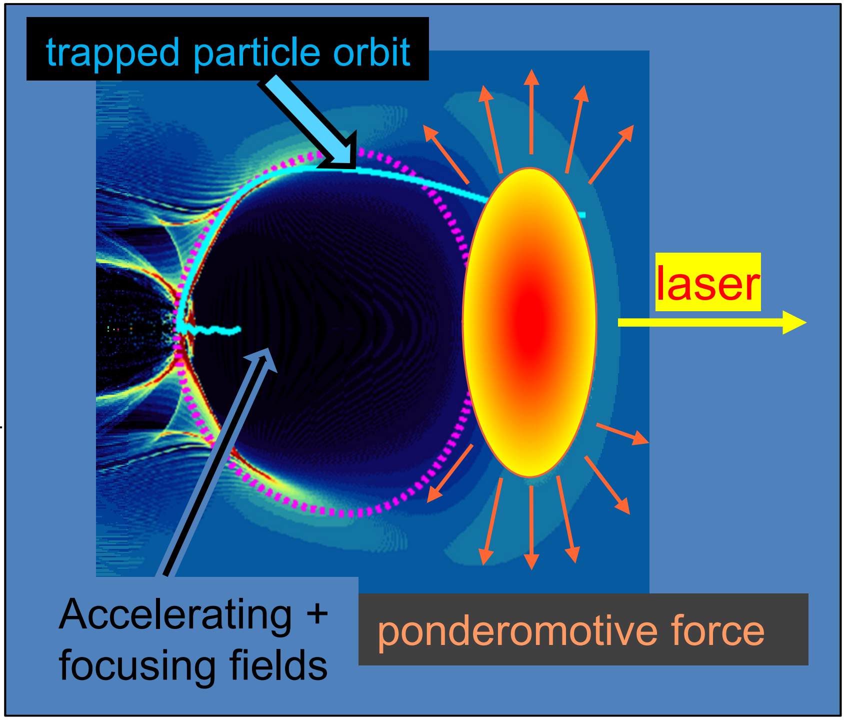
$$E_0 = \frac{m_e \omega_p c}{e} \approx 100\,\mathrm{GV/m} \quad \text{for} \quad n \approx 10^{18}\,\mathrm{cm}^{-3}$$

– COMPACT ACCELERATORS

Can excite large plasma waves with ponderomotive force of intense laser pulse

Electrons externally injected or trapped from background plasma

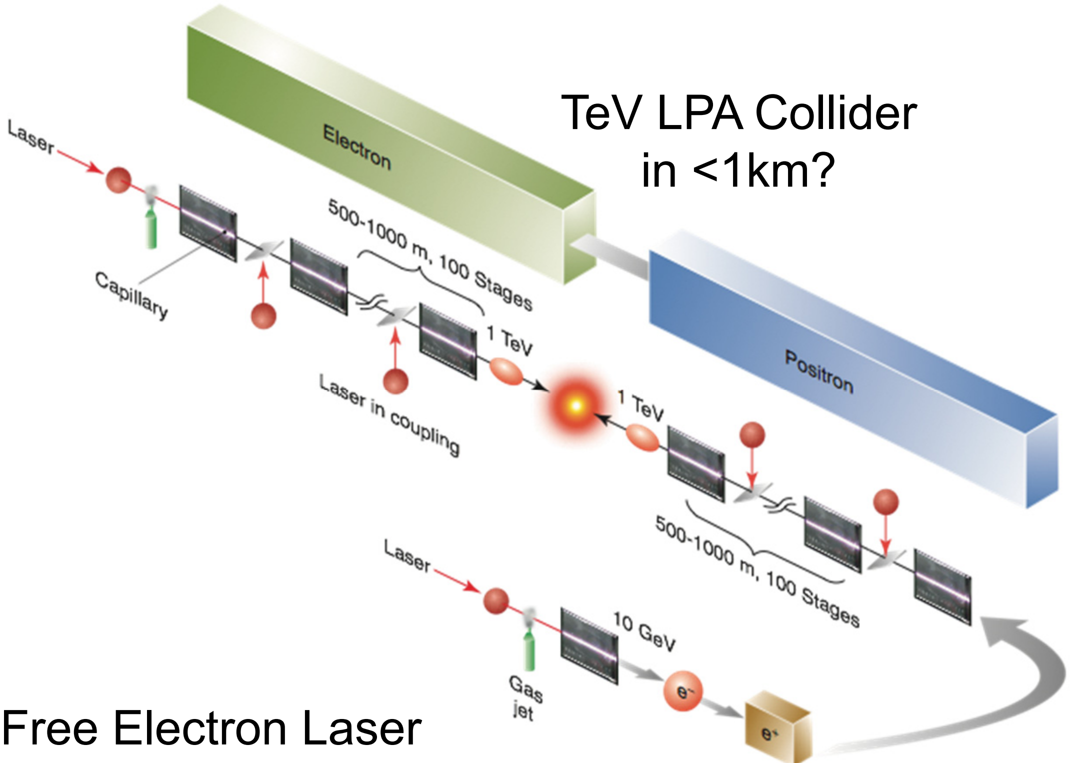




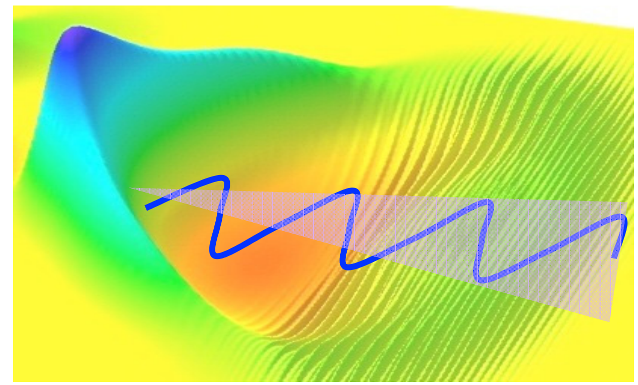
T. Tajima and J.Dawson, *PRL*, 43, (1979) 267
Esarey et al., RMP, 81, (2009), 1229

LPAs explored for Compact Drivers of Linear Colliders and Light Sources

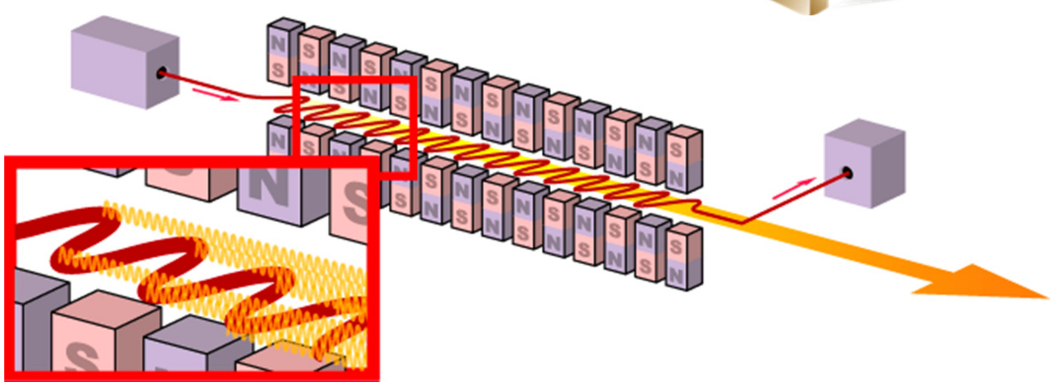
TeV LPA Collider in <1km?



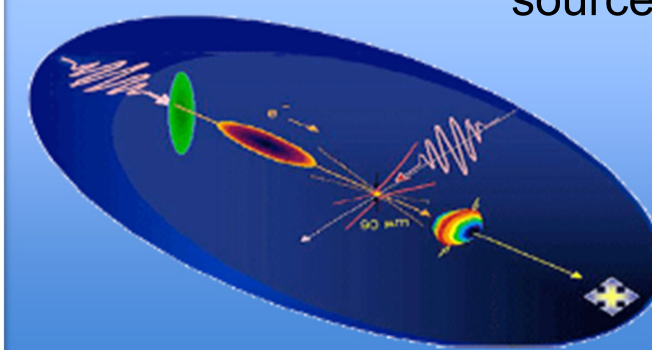
keV Betatron radiation



Free Electron Laser

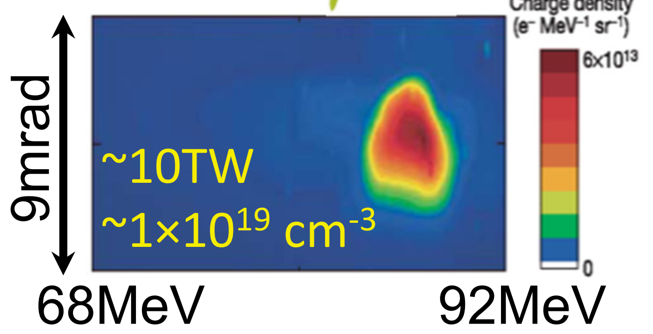


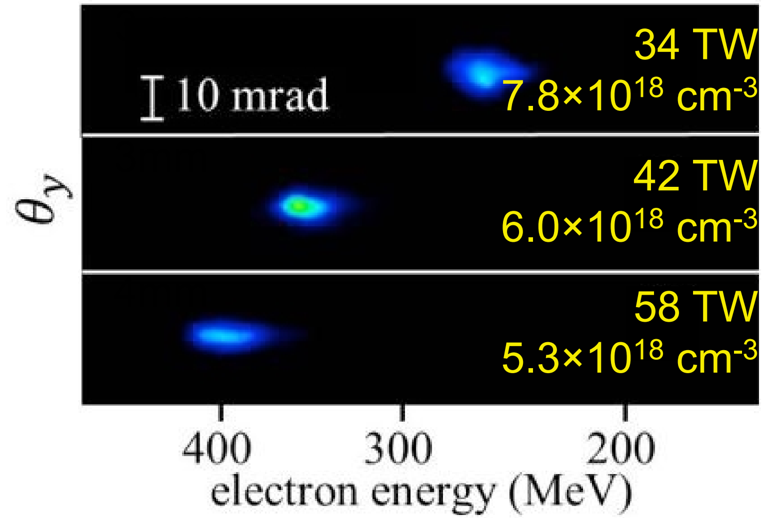
Thomson Scatter Gamma ray source

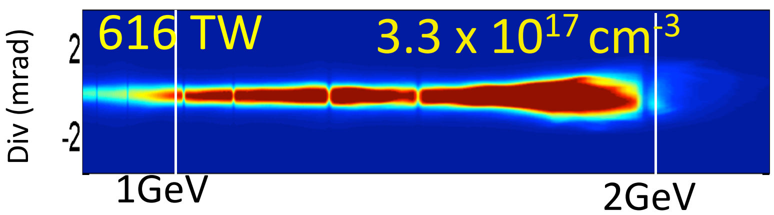


Lower Density and Higher Laser Power Increase Beam Energy

Dephasing (fast electrons entering defocusing region of wake) and laser depletion limited energy gain ⇒ **Energy Gain** $= E_0 L_{acc} \propto \frac{I}{n_e}$



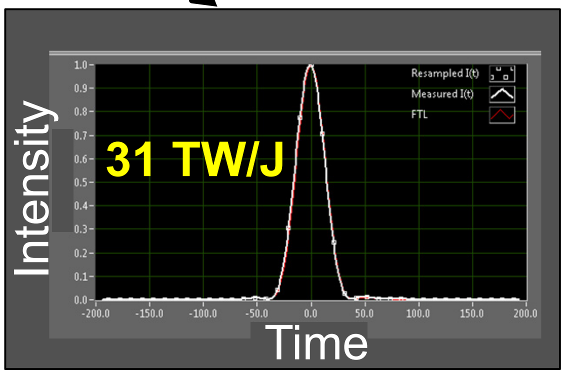


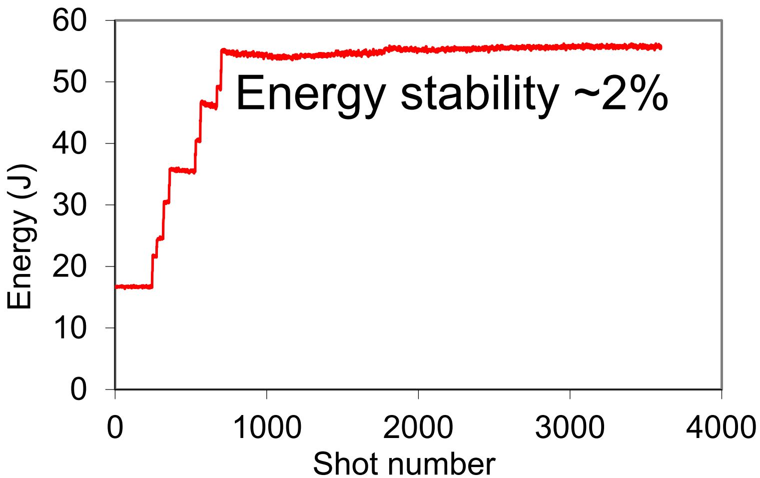


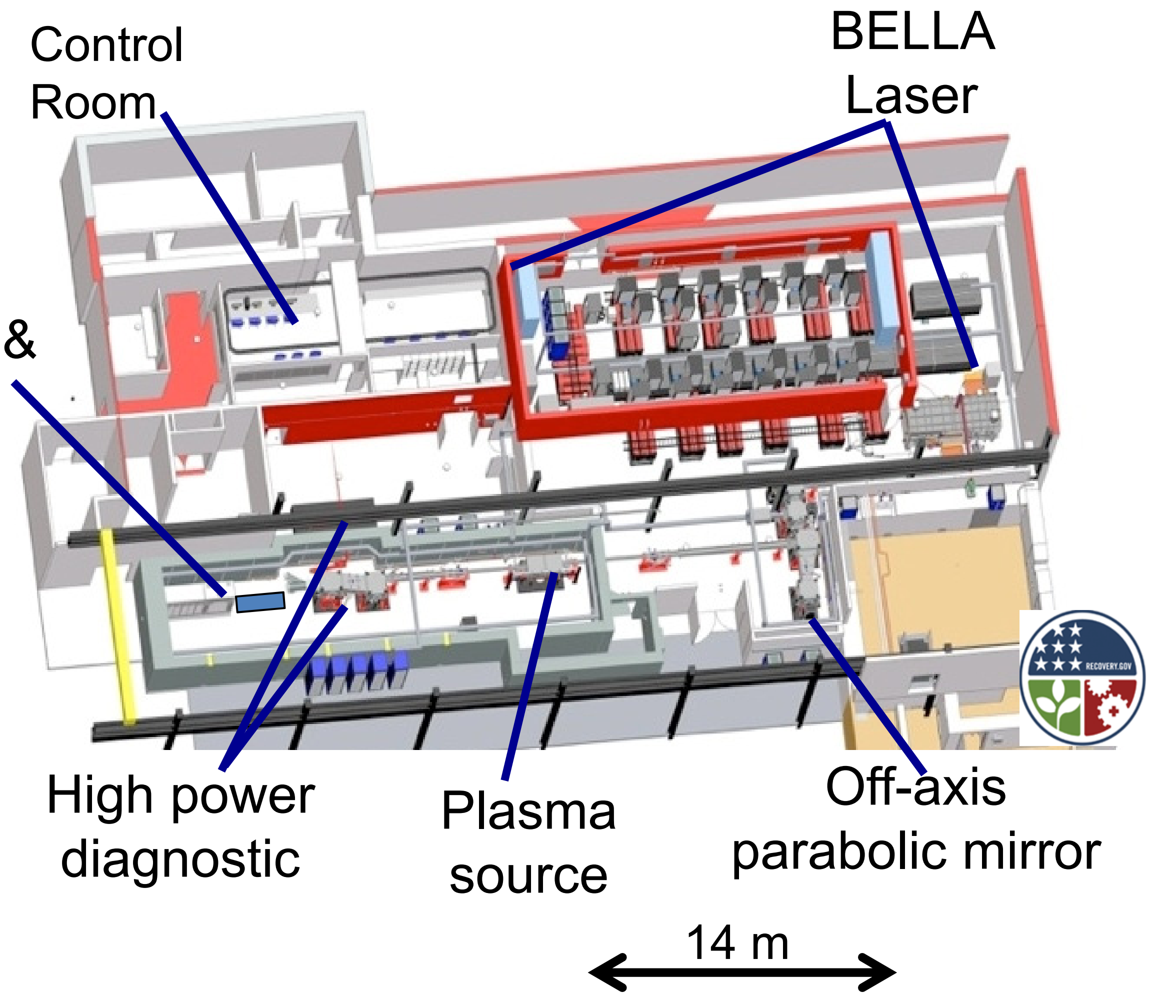
C. G. R. Geddes,et al, Nature,**431**, p538 (2004); S. Mangles et al., Nature **431**, p535 (2004); J. Faure et al., Nature **431**, p541 (2004); Leemans et al., Nature Phys. **2**, 696–699 (2006); Banerjee et al., Phys. Plasmas **19**, 056703 (2012); X. Wang et al., in press (2012).

BELLA Center Houses a High Repetition Rate Petawatt Laser for LPA Science

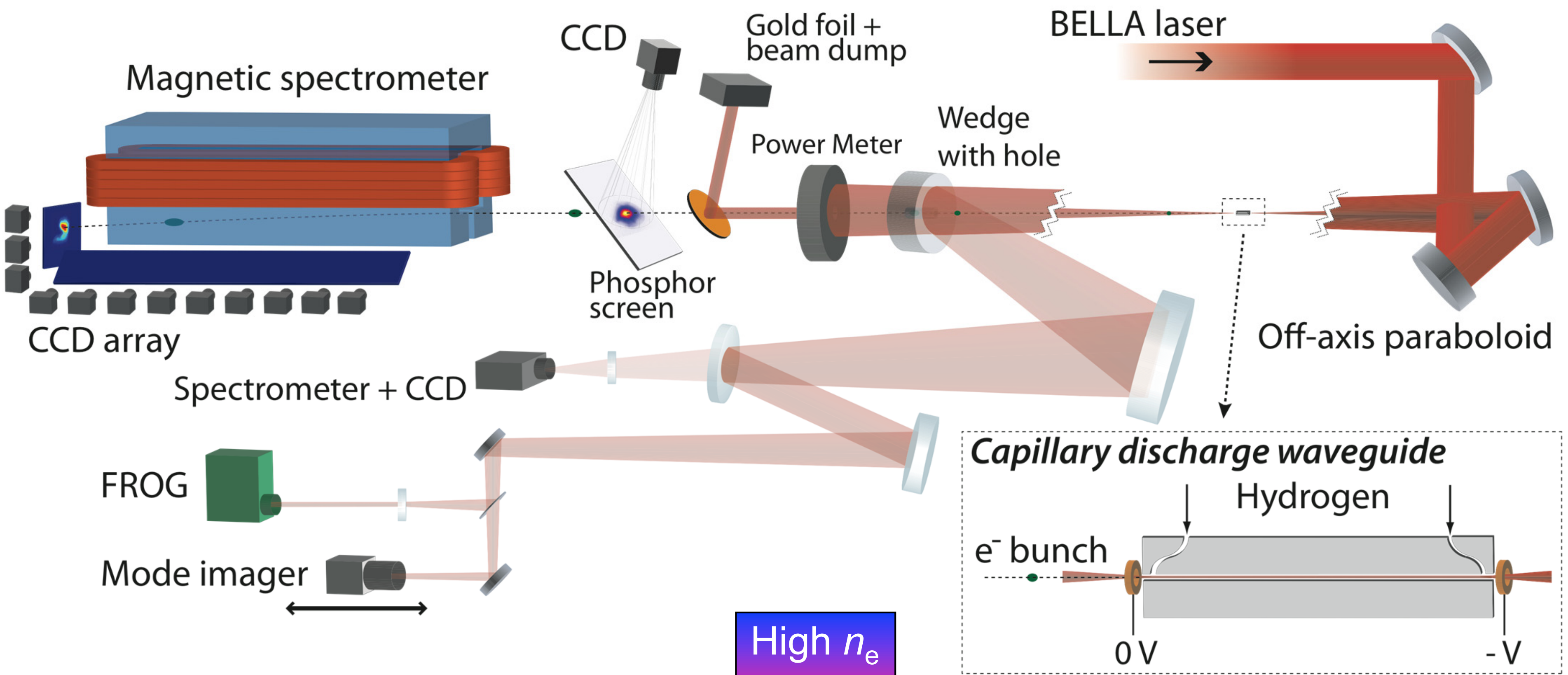
- > 1 PW peak power at 1 Hz repetition rate
- > 40 J laser energy
- 30 fs min. pulse length

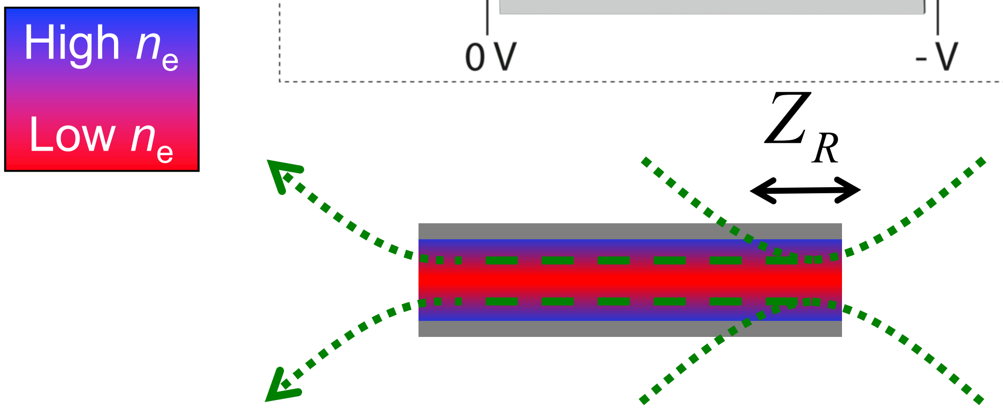






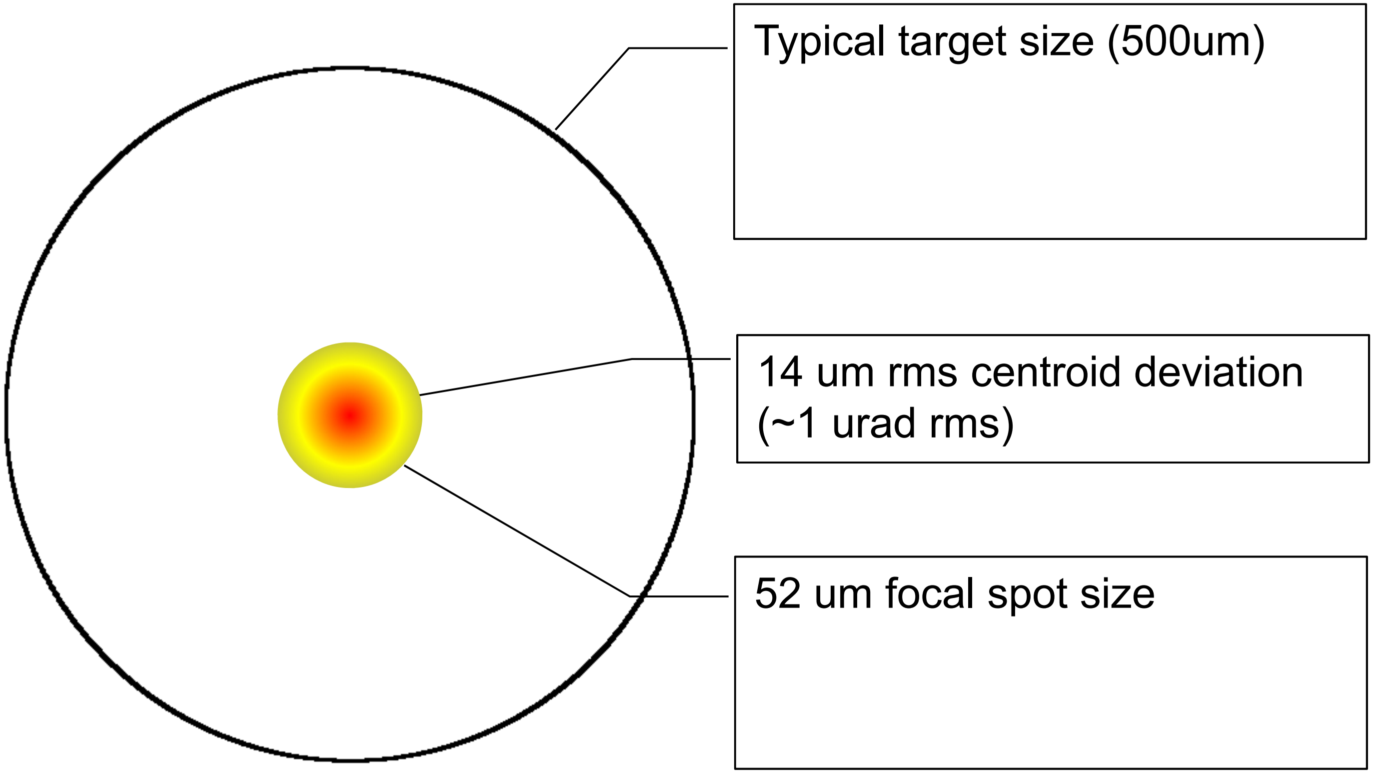
Single-shot diagnostics for both laser and electron beam





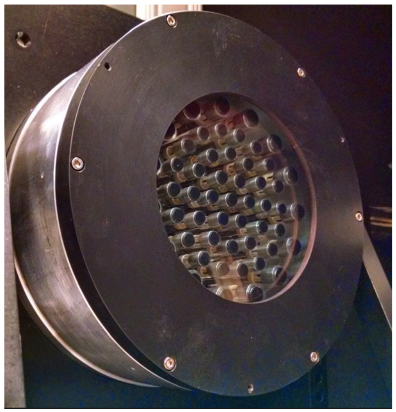
- Electron beam Diagnostics
  - Single shot spectra 30 MeV - 11 GeV
  - Two ICTs
  - Phosphor screen

BELLA is a Precision LPA Tool: Low Pointing Jitter

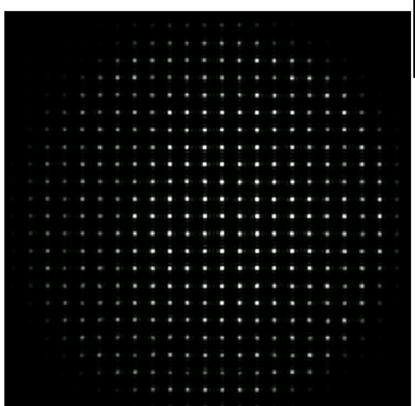


BELLA is a Precision LPA Tool: High Mode quality

Deformable Mirror



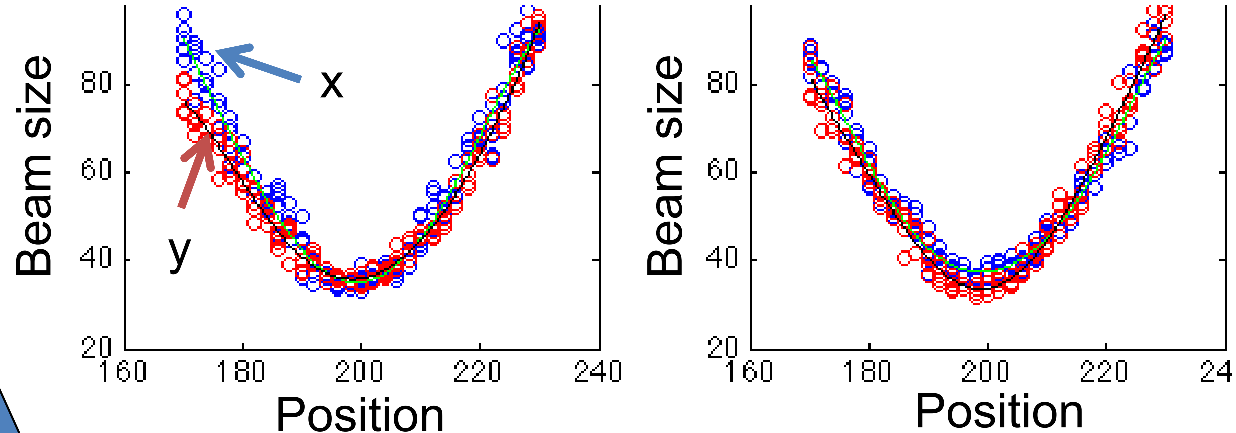
Wavefront Sensor



Correct Aberrations

Negligible 0° Astigmatism

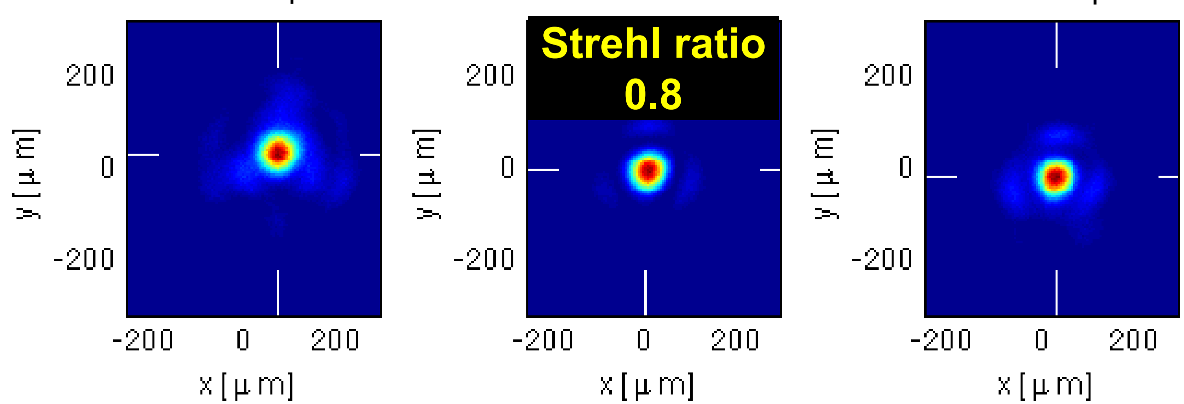
Negligible 45° Astigmatism



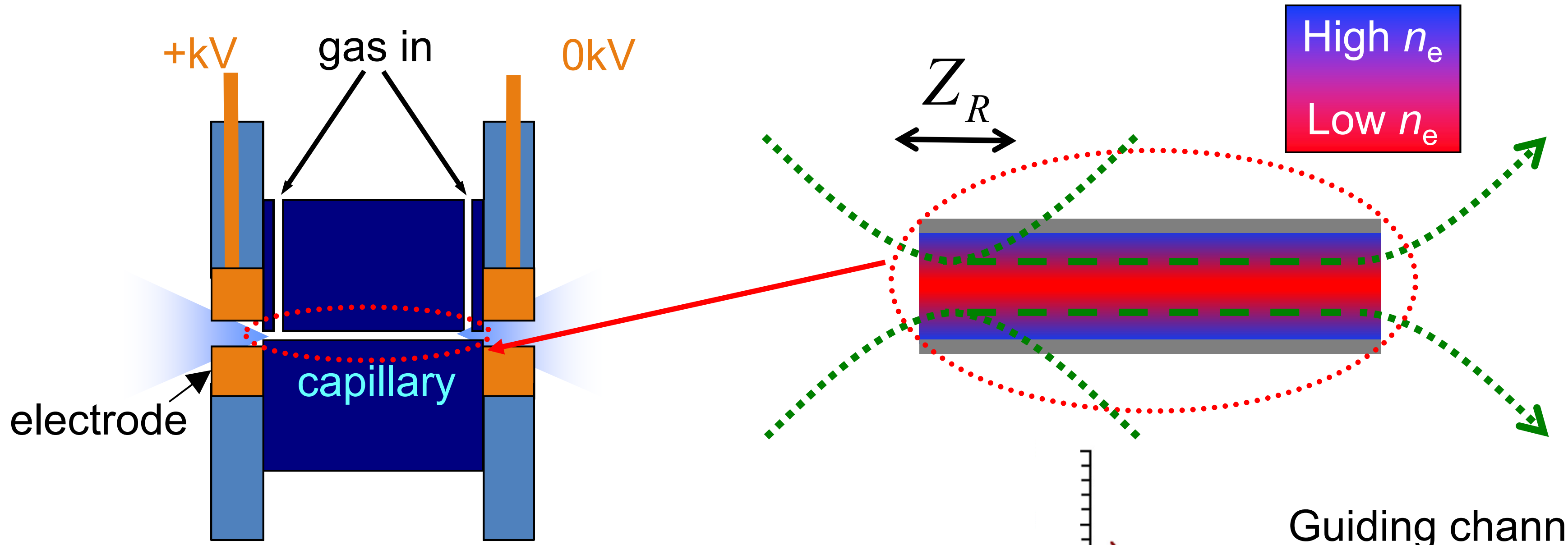
~$-Z_r$

Focus

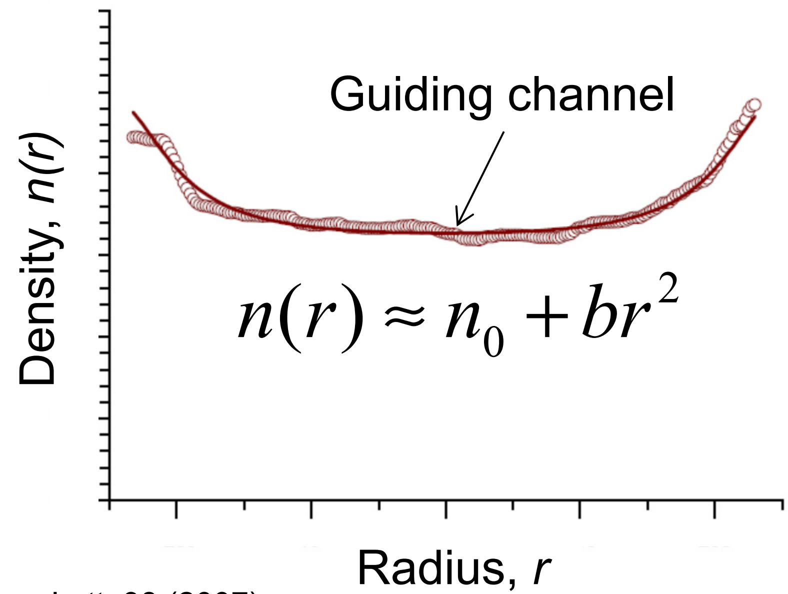
~$+Z_r$



Capillary waveguides mitigates diffraction and increases interaction length (energy gain)

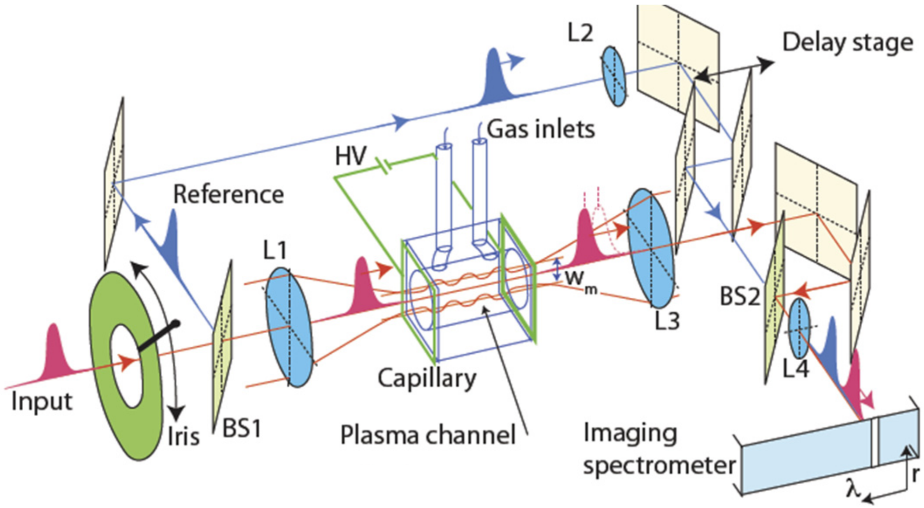


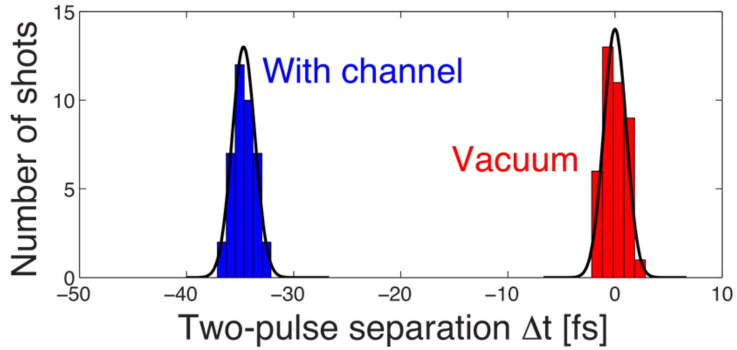
- Gas injected near each end of channel
- $n_e \sim 10^{17}$ - 10^{19} cm^{-3}
- Gas ionized and heated by discharge
- Guiding channel formed by heat conduction to capillary wall



D. J. Spence & S. M. Hooker Phys. Rev. E 63 (2001); A. J. Gonsalves Phys. Rev. Lett. 98 (2007)

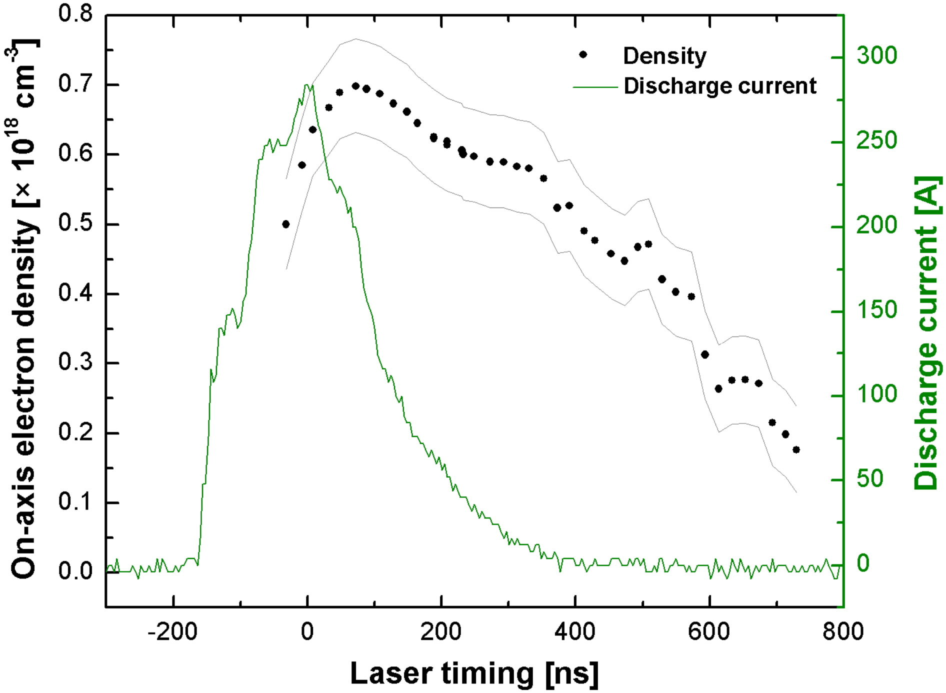
Group Velocity Meaurement Yields Plasma Denstiy





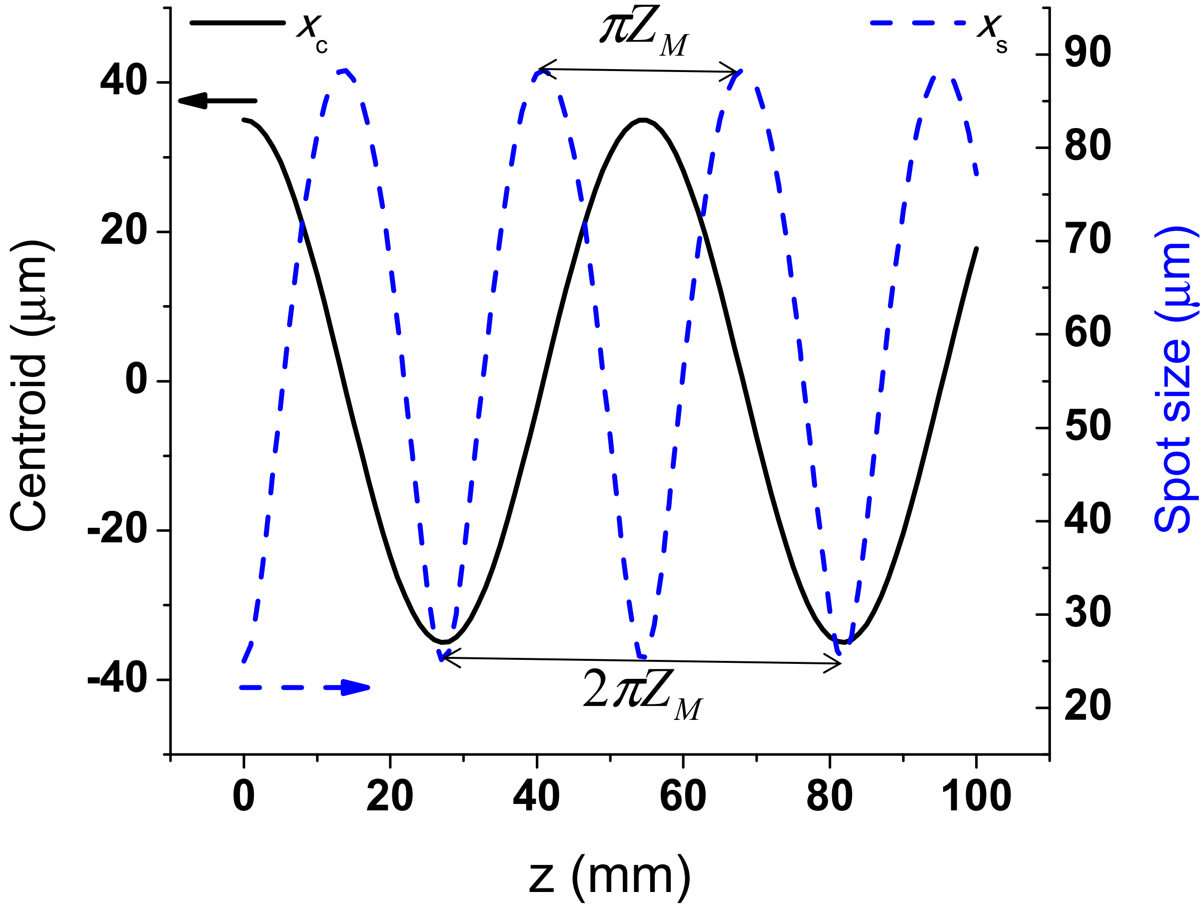
Plasma channel: ~30 fs delay for L=3 cm at 10^{18} cm^{-3} density.
Measure with highly sensitive interferometry measurements.

$$n(r) \approx n_0 + br^2$$



Theory: C. Schroeder *et al*., Phys. Plasmas 18 (2011)
Experiment: J. van Tilborg *et al.* Phys. Rev. E 89 (2014)
Experiment: J. Daniels *et al.* (submitted to POP)

Measuring oscillation wavelength yields plasma channel strength

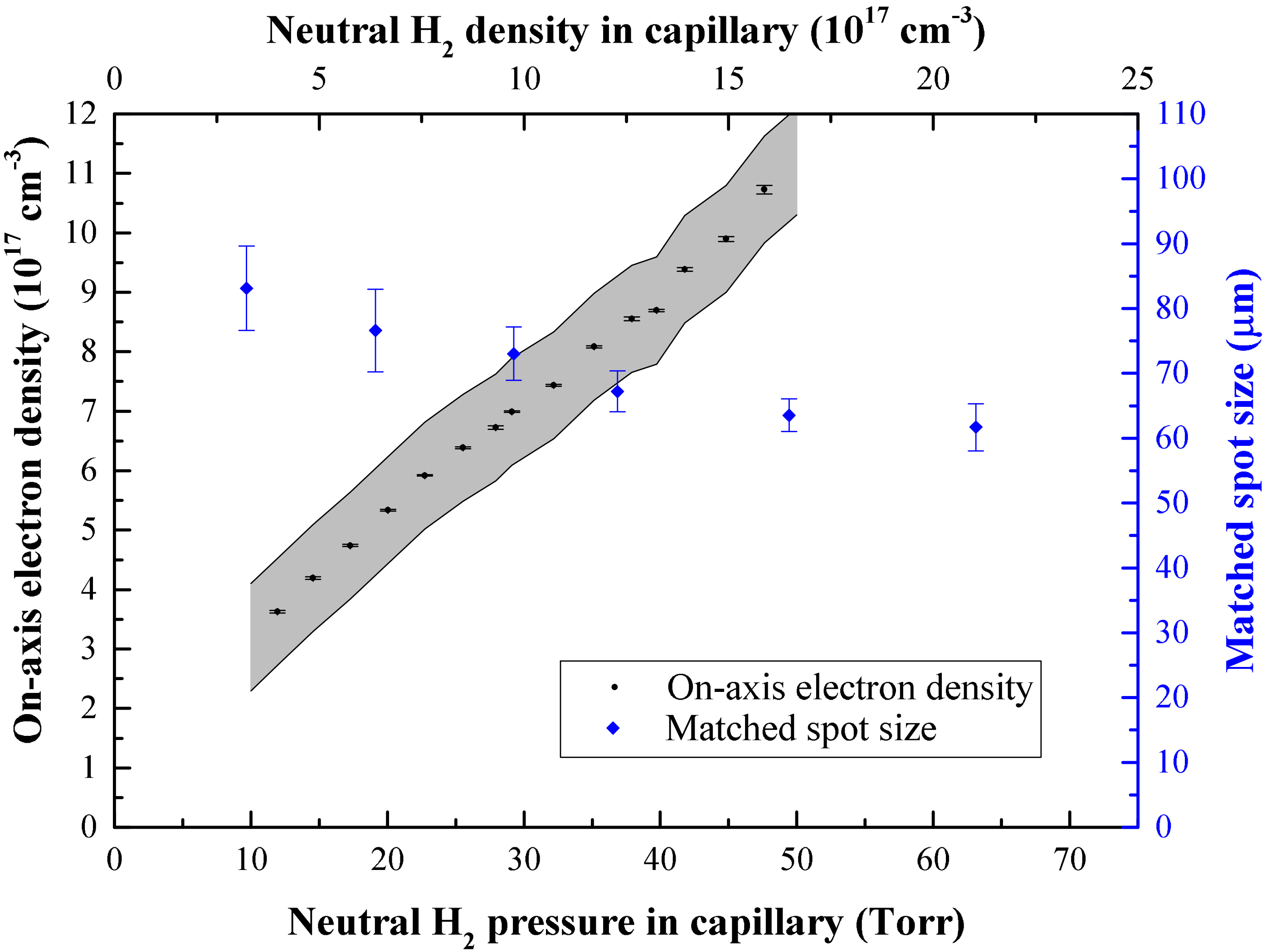


$$n(r) \approx n_0 + br^2$$

$$r_m = (\pi r_e b)^{-0.25}$$

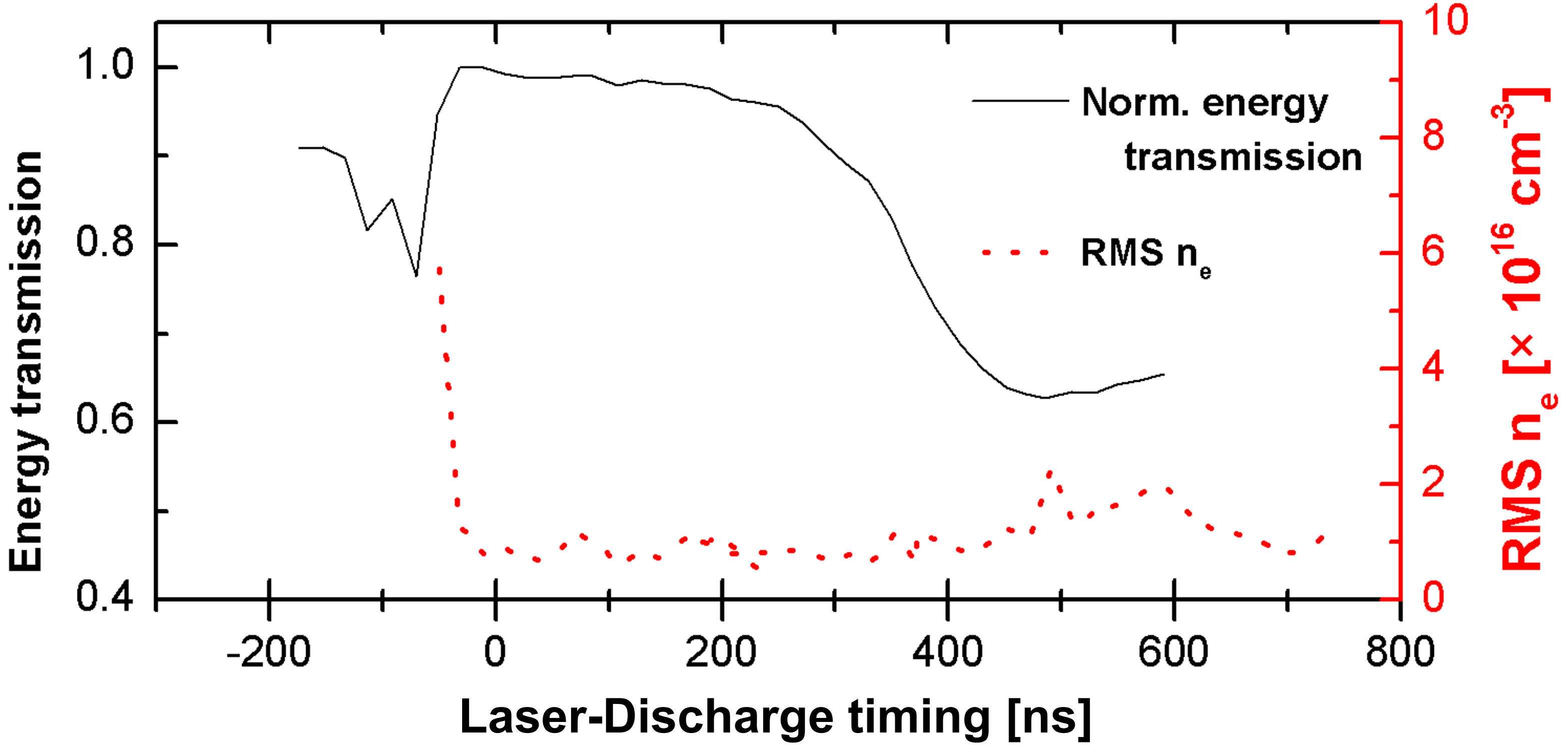
Gonsalves et al., Phys Plasmas 17 (2010)

GV Technique and Laser Centroid Oscillations used to Measure BELLA Target Density & Profile vs Pressure



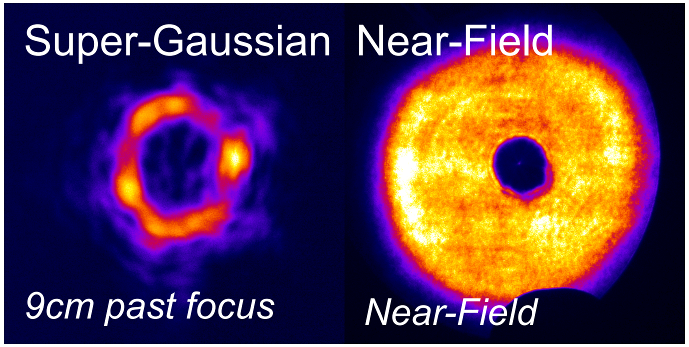
Capillary discharge waveguide produces stable plasma density

Shot-to-shot stability ~10^{16} cm^{-3}

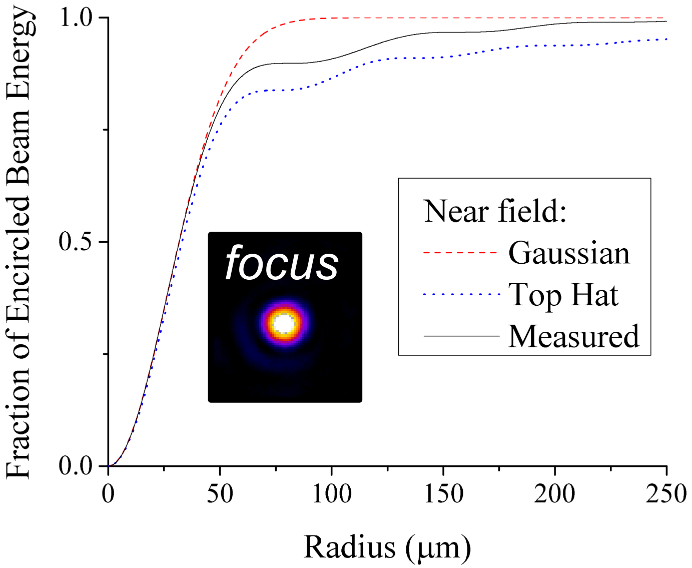


J. Daniels *et al.*, "*Plasma density diagnostic for embedded capillary-discharged plasma channels*", submitted to *Phys. Plasmas*

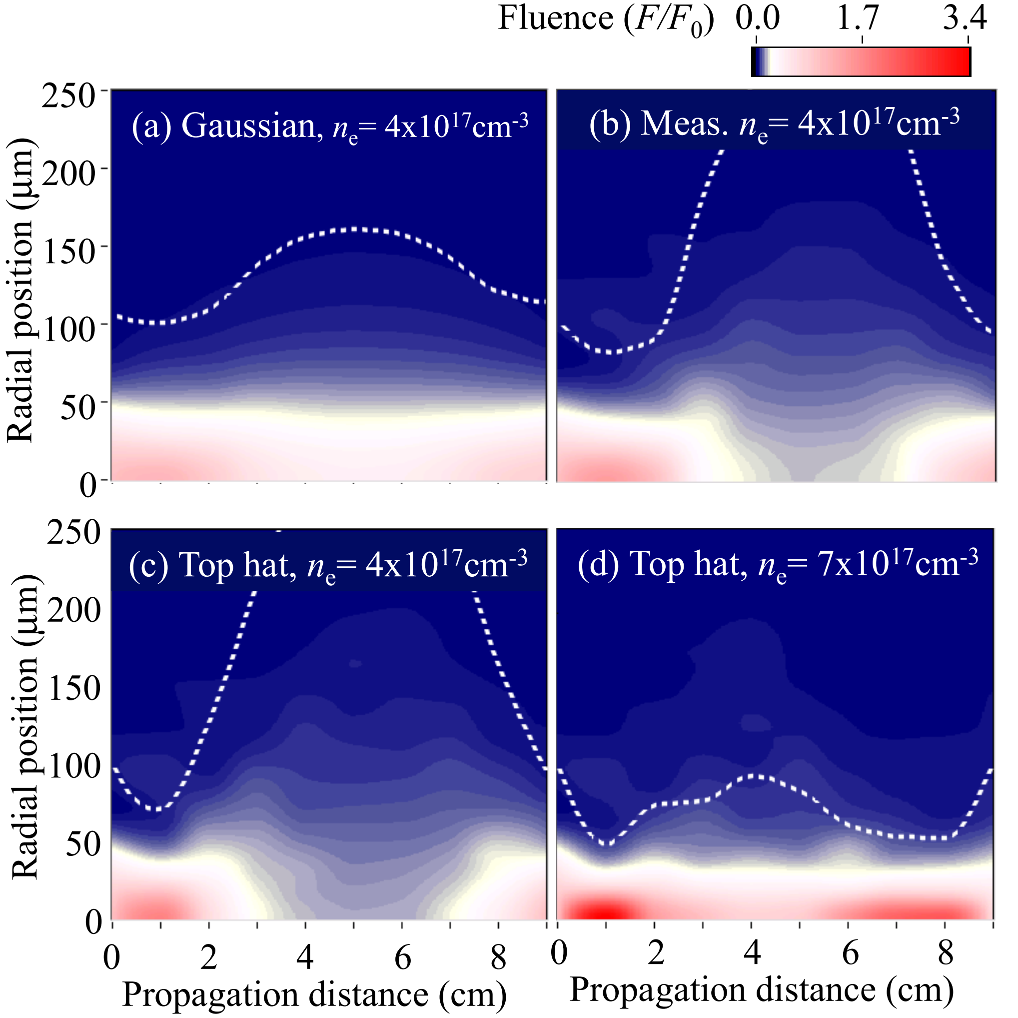
Simulation shows typical SuperGaussian near field reduces guiding efficacy. Compensated by higher density.



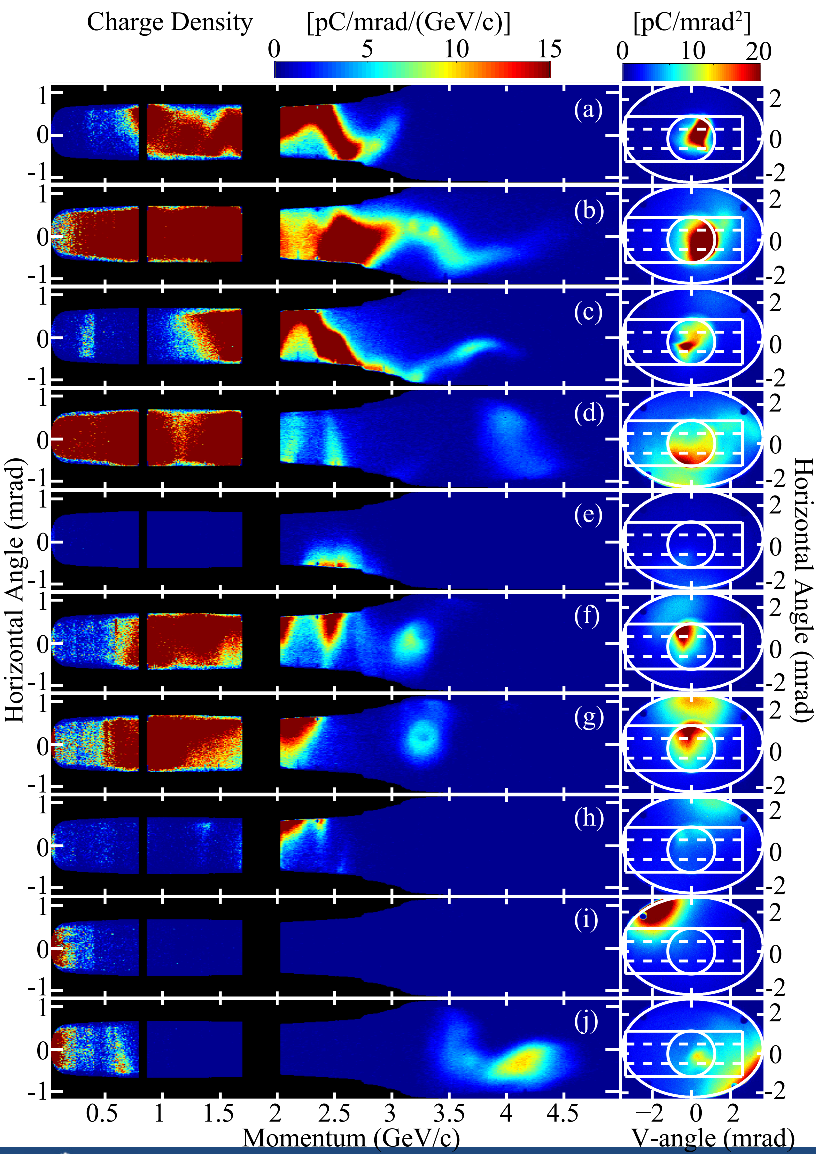
Far-field energy distribution



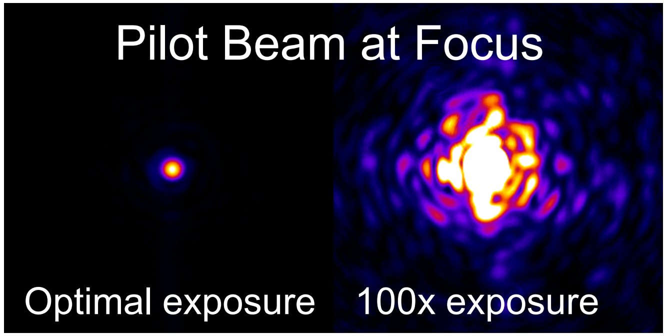
High-power laser propagation



BELLA @ 300TW produced beams with energy up to 4GeV. Pointing fluctuation larger than beamline acceptance

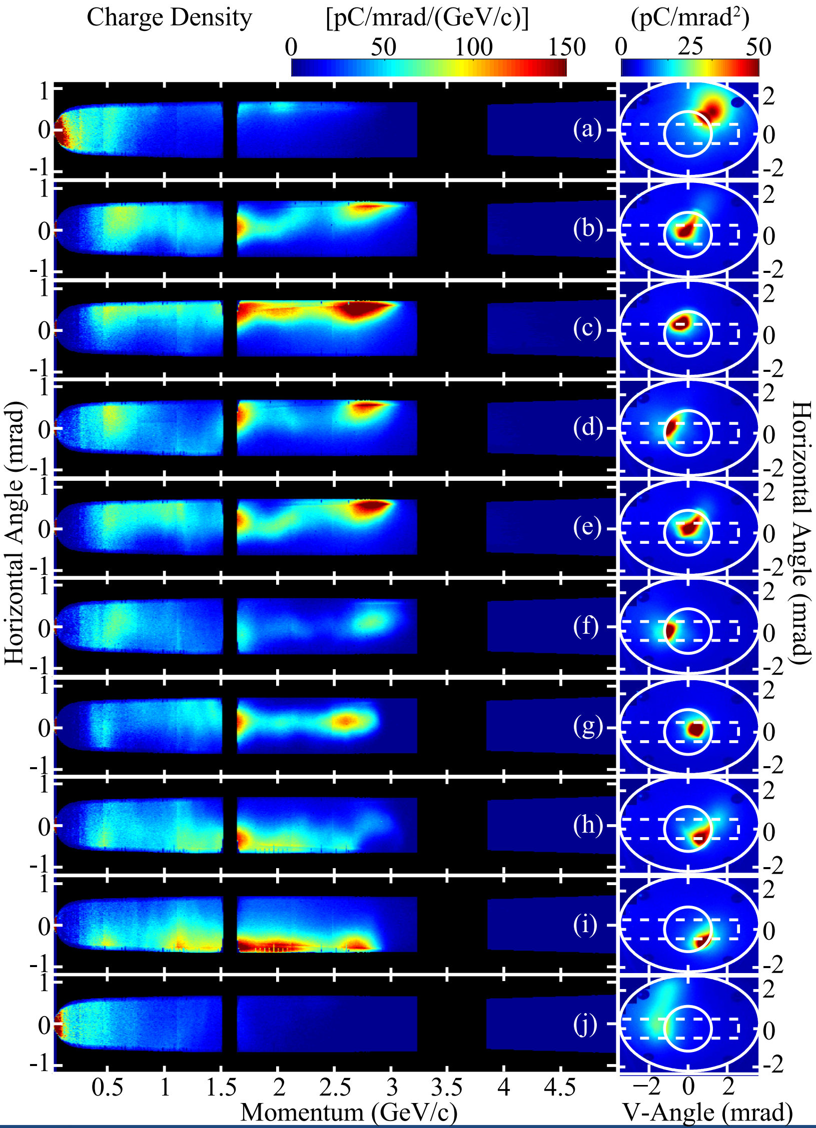


- Density range 6-8 $\times 10^{17}$ cm^{-3}
- Majority charge on most shots are outside measurement angle
- Capillary damage -> pressure change, necessitating spectral measurement of density and reducing stability
  - Potential causes are misalignment and non-ideal laser mode

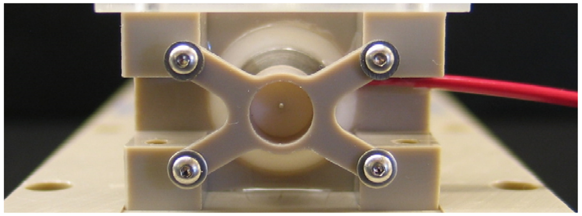


Gonsalves et al. POP (accepted); Leemans et al., PRL 113 (2014) 245002.

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



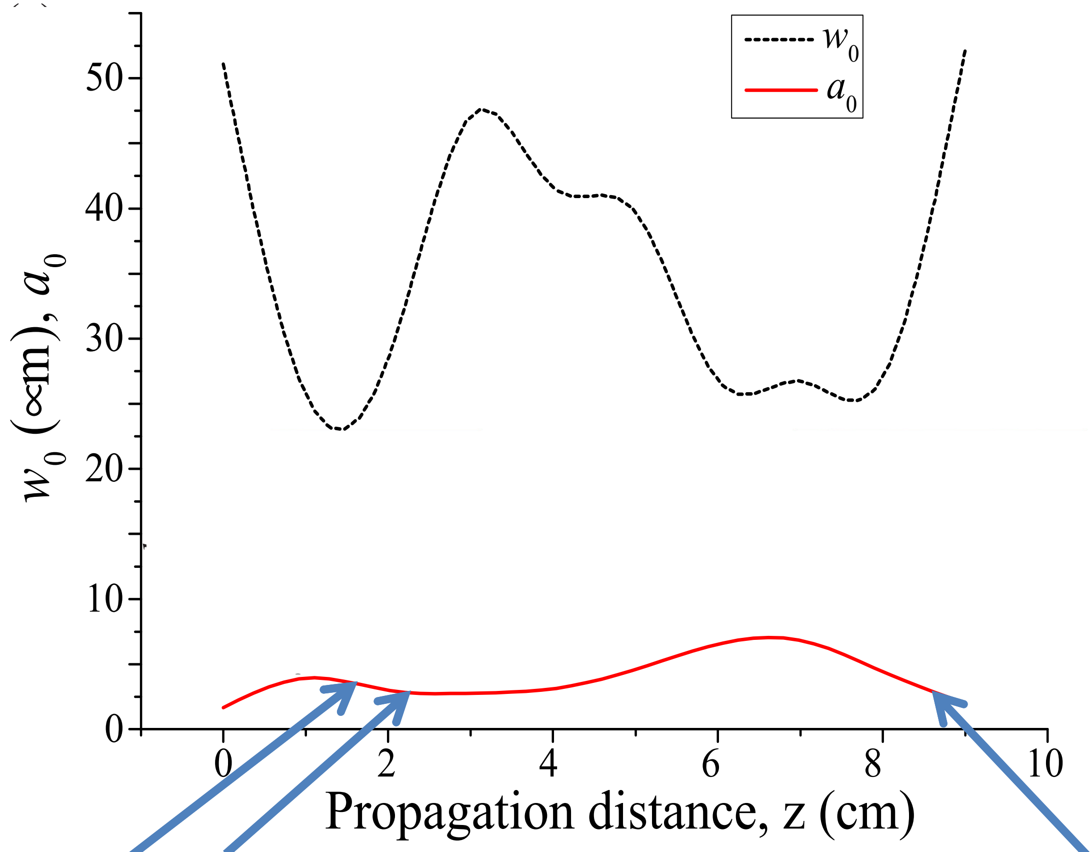
- Capillary alignment techniques refined
  - Match beam position and angle of beam exiting capillary to beam without capillary
- Ceramic disk added to protect capillary

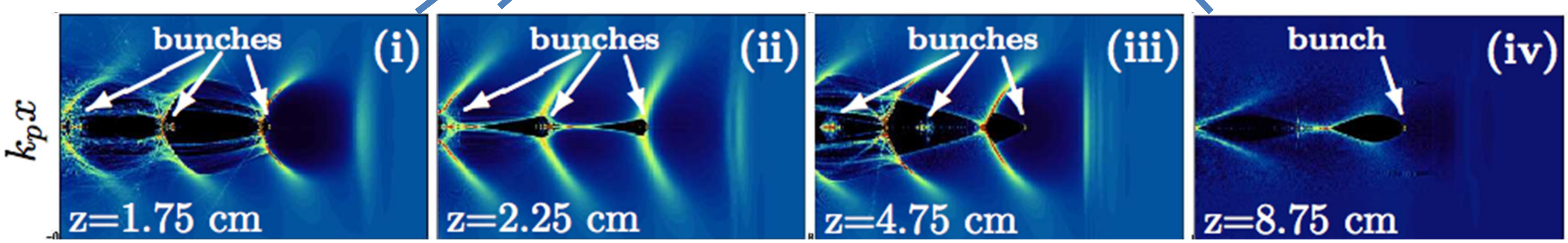


- 90% of beams now within the ~1 mrad acceptance (0.6mrad rms)
- ~1000 shots without drop in performance

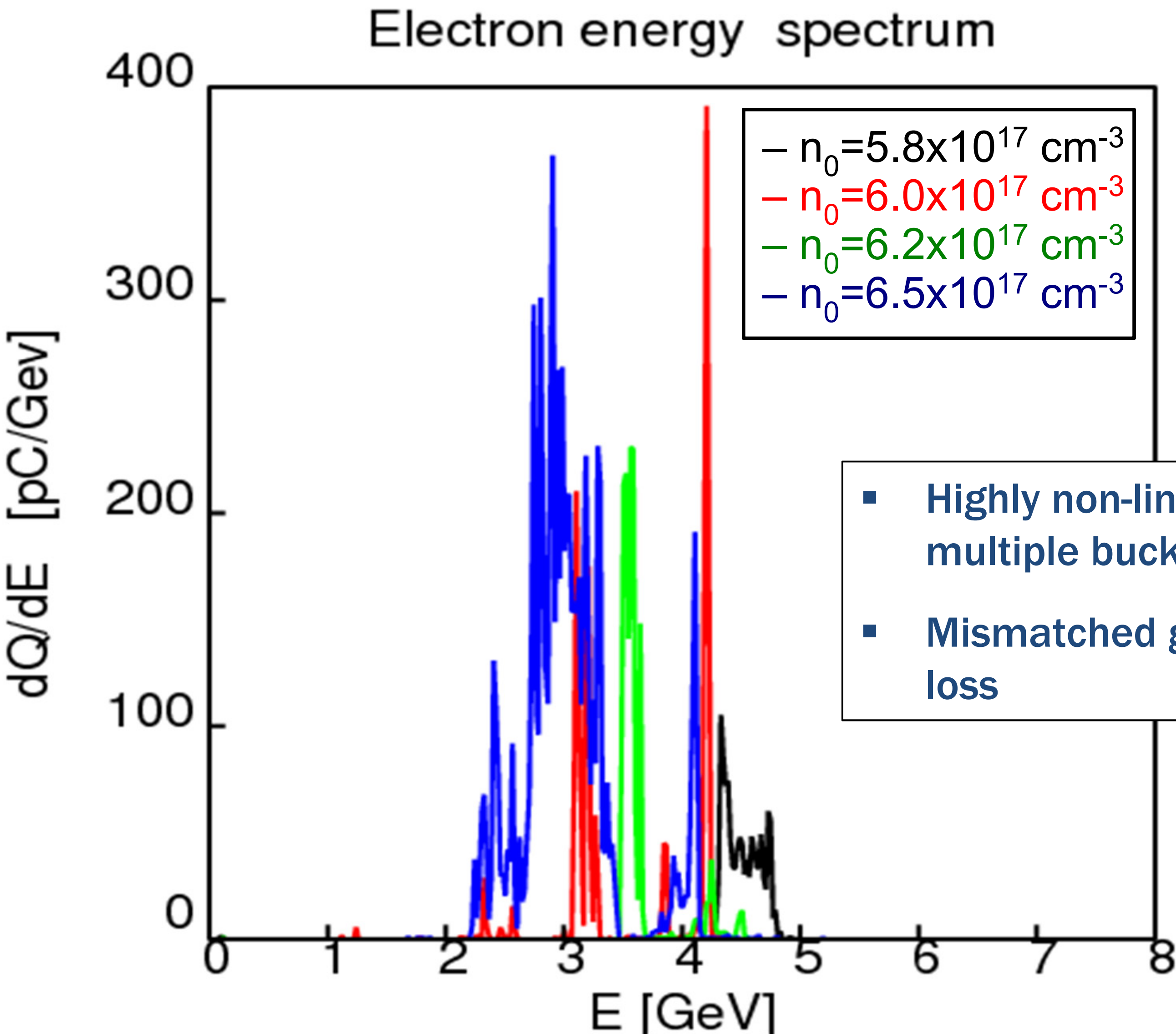
Gonsalves et al. POP (accepted)

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





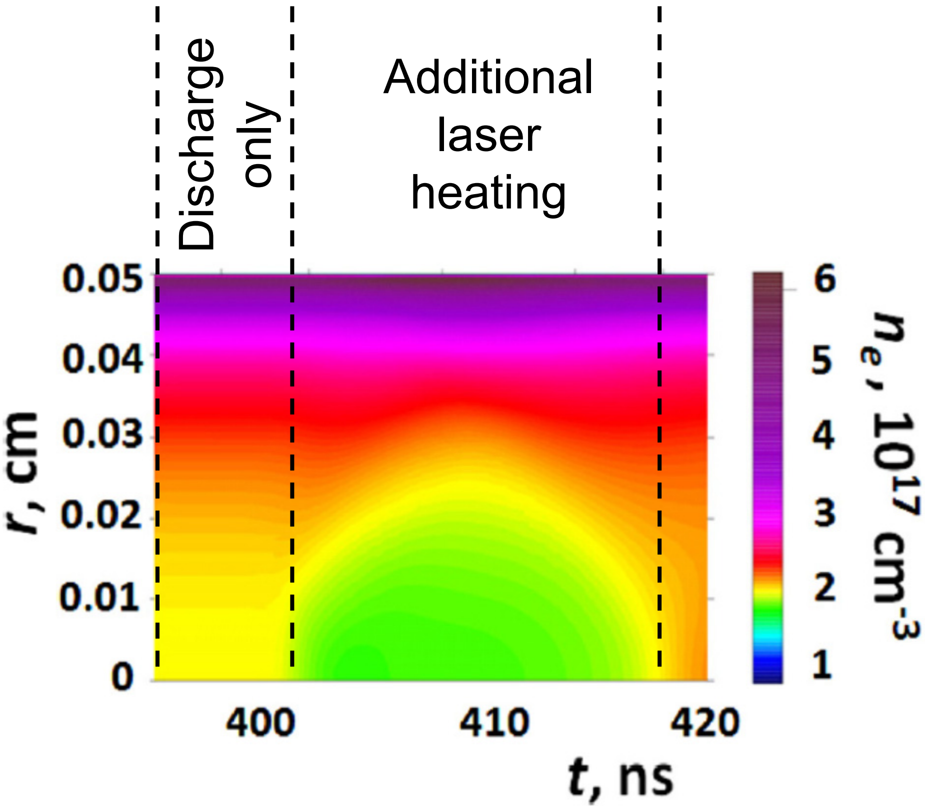
Simulations show strong sensitivity of self-injection physics from plasma density

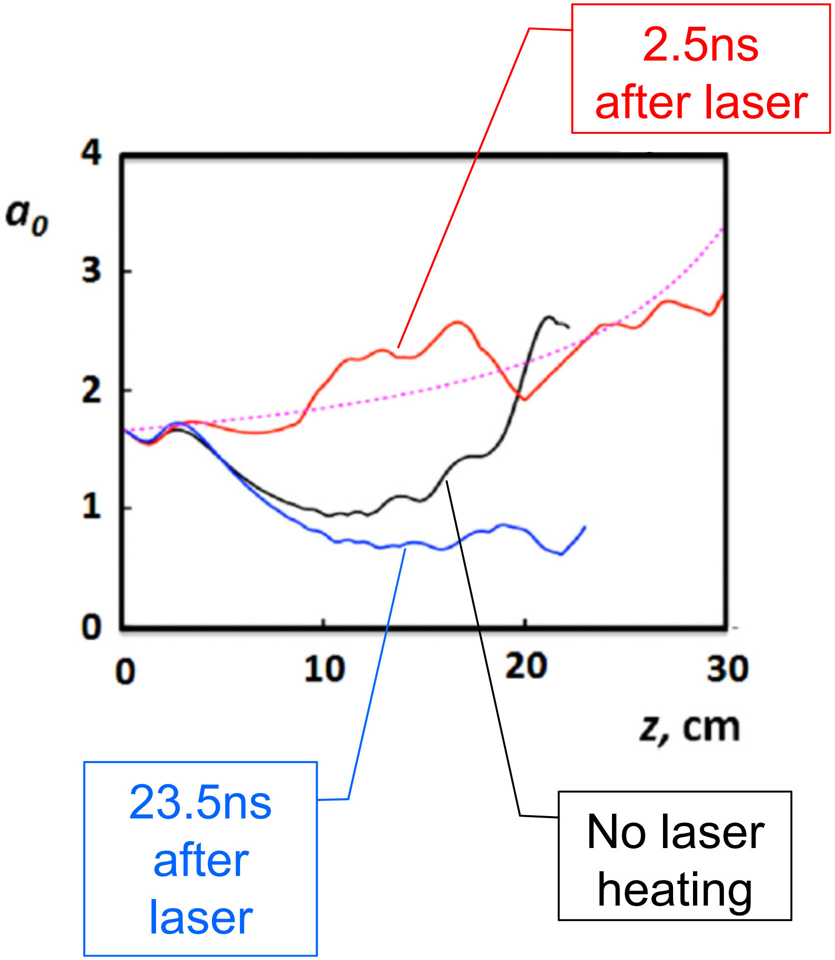


- Highly non-linear regime → injection multiple buckets → large energy spread
- Mismatched guiding → potential beam loss

Laser-heater deepens plasma channel which is expected to improve guiding and allow for lower density

Lower density➔ less self-focusing➔ lower a0➔ dark-current-free structure➔ longer acceleration length➔ higher e beam energy ➔ need deeper plasma channel

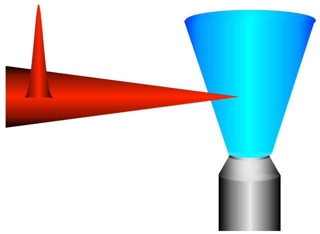




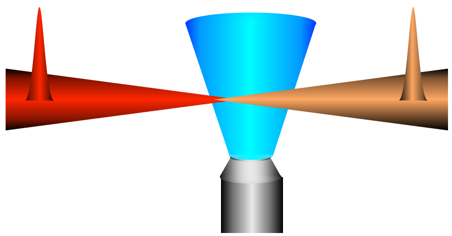
Bobrova et al. POP **20**, 020703 (2013)

Controlled Injection to reduce energy spread, emittance, and allow for matched guiding

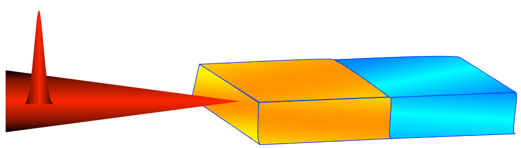
External Injection



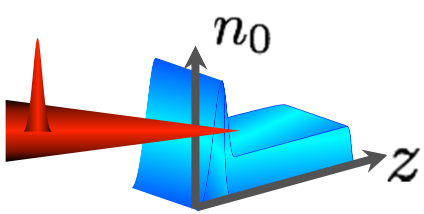
Colliding pulse

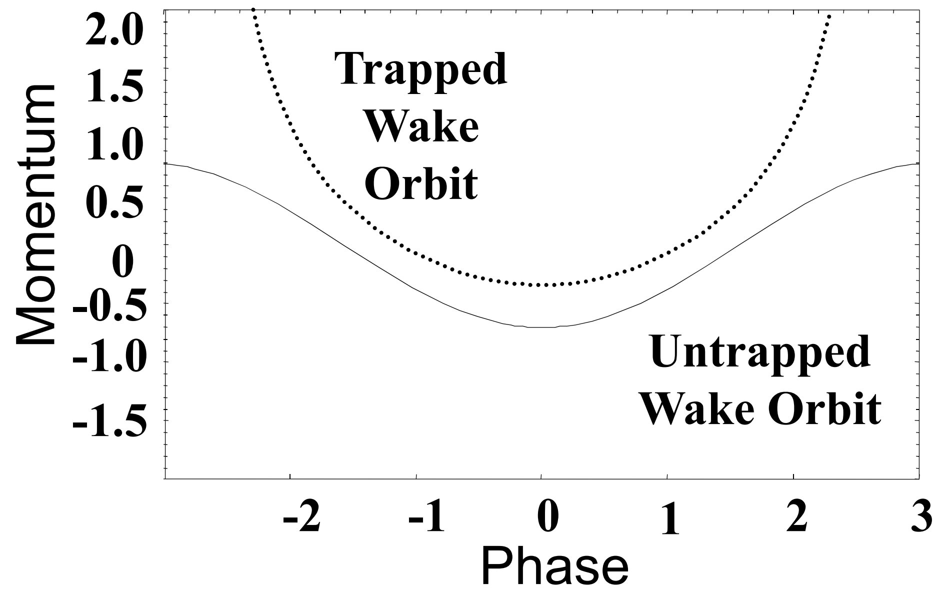


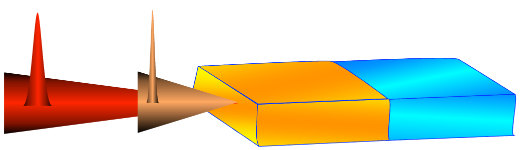
Ionization



Density tailoring





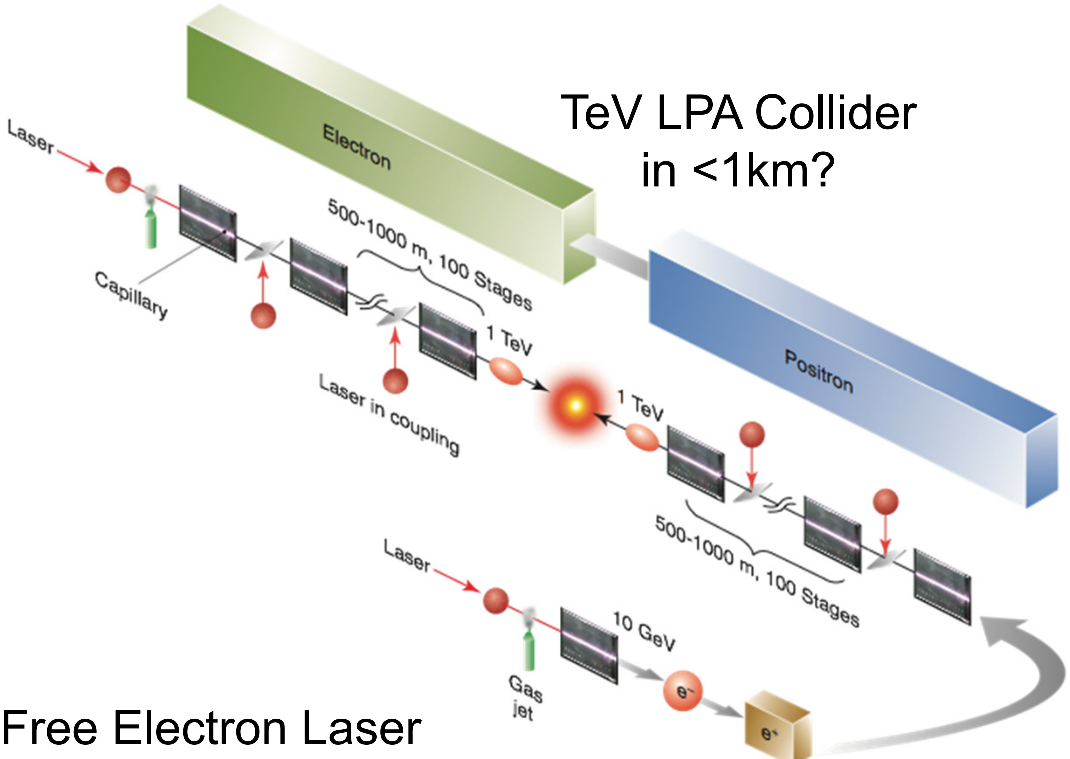


Two-color ionization

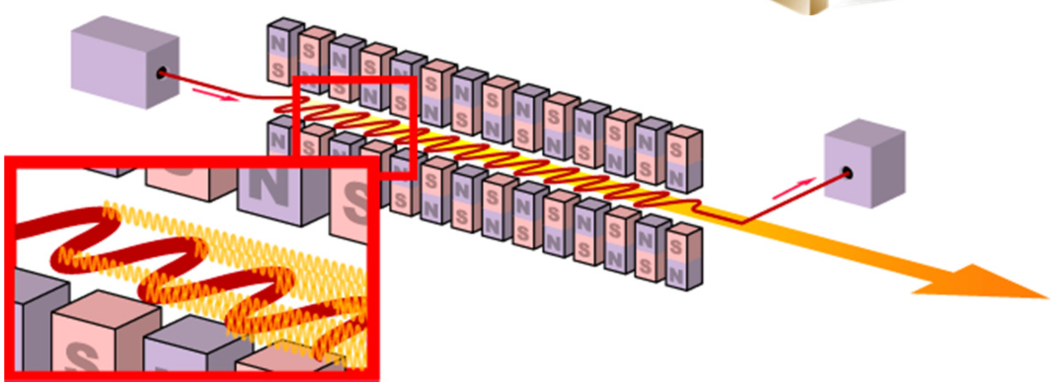
M. Chen et al., JAP **99** (06), T. Rowlands-Rees et al., PRL **100** (08) Pak et al., PRL **104**, (10); C. McGuffey et al., PRL **104**, (10); Gonsalves et al., Nat. Phys. **7** (11); Yu et al., PRL **112** (14); Schroeder et al., PRSTAB **17** (14); Geddes et al., PRL **100** (08); Faure et al., Nature **444** (06); Esarey et al., PRL **79** (97)

Applications require kHz repetition rates

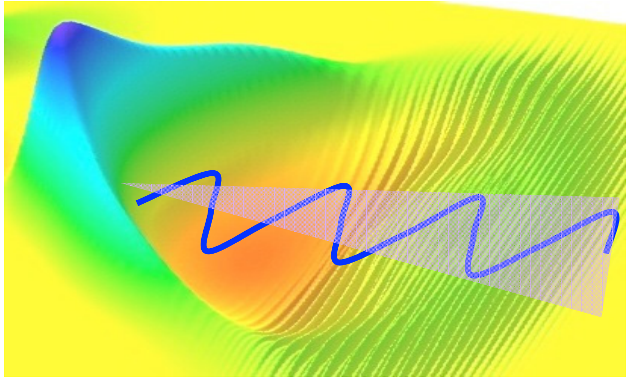
TeV LPA Collider
in <1km?



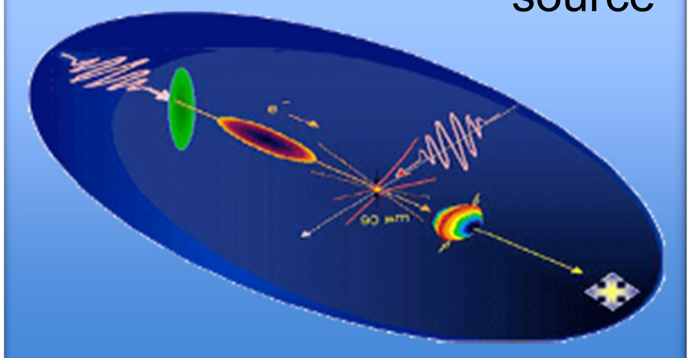
Free Electron Laser



keV Betatron radiation



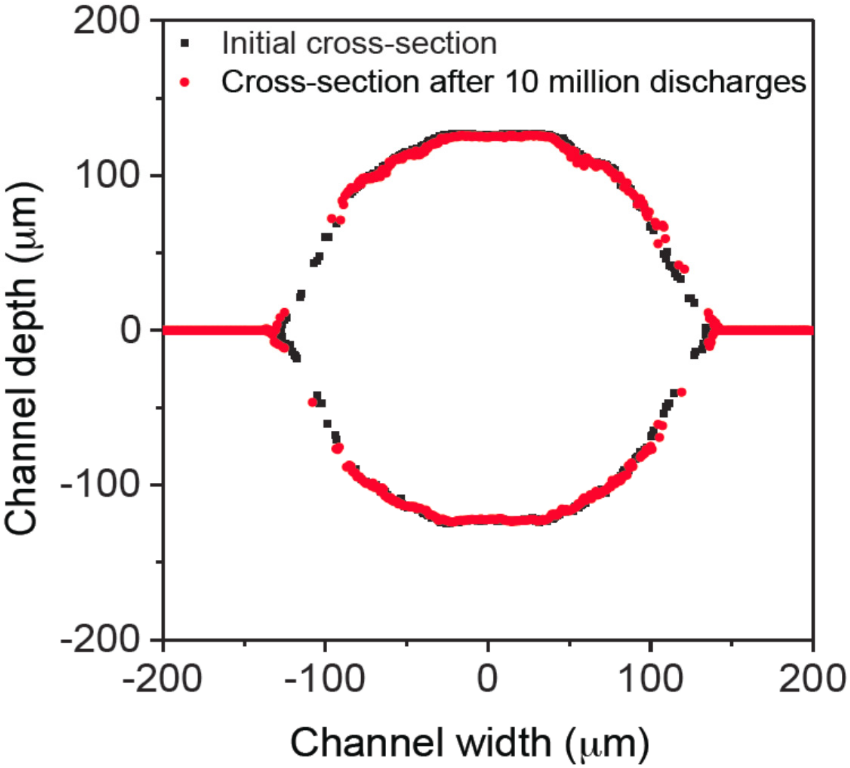
Thomson Scatter Gamma ray source



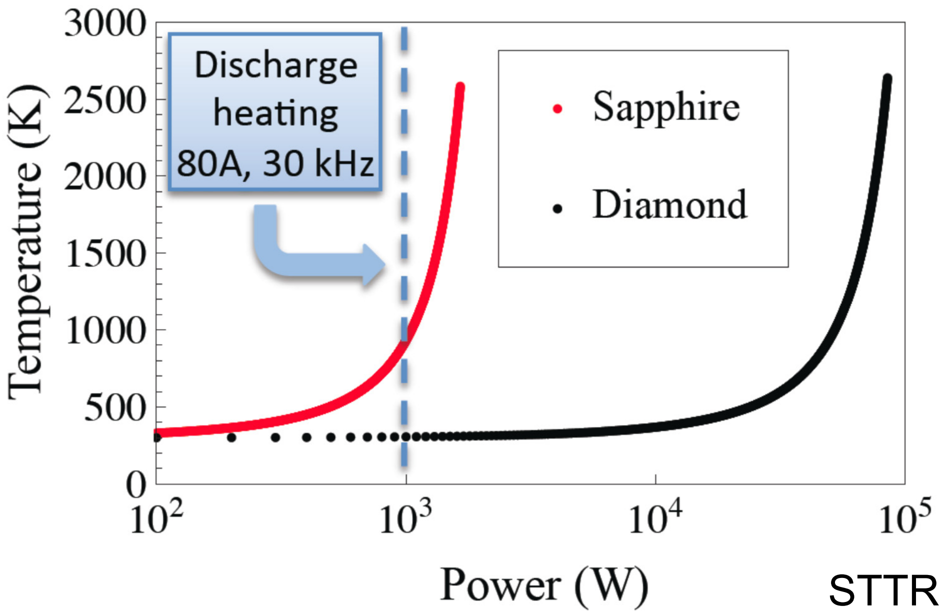
Capillary Discharge Plasma source can operate at kHz repetition rates

Potential limitations to repetition rate
- average heat load (discharge and LPA)
- peak heat load

10^7 shots @ kHz and negligible erosion



Calculated wall temperature due to average heat load



D_{cap}=250µm; L_{cap}=33mm; $N_e(0)$~$10^{18}cm^{-3}$

STTR Euclid Techlabs & LBNL. Gonsalves et al. in prep.

Current multi-terawatt lasers 10s W average power. Fiber lasers demonstrated 100s kW average power. Fiber laser peak power increase required

Advantages of fiber lasers:

- High avg. power
- High efficiency
- Compact integration

Peak power low due to:

- Self-focusing
- Self-phase modulation
- Optical damage

Example of a commercial 100kW cw fiber laser:

10kW cw module

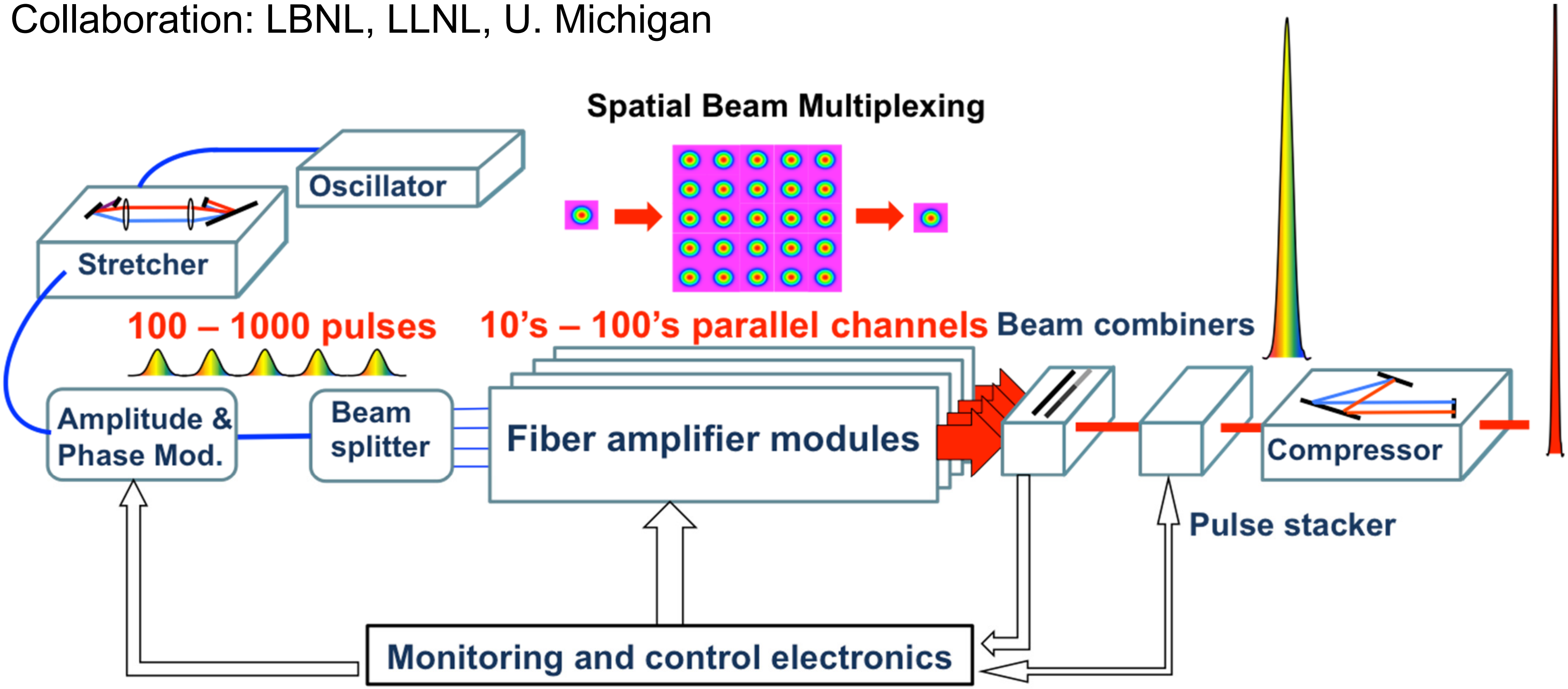
IPG PHOTONICS

37.5% Wall-plug efficiency

Recently funded stewardship program: LBNL, LLNL, U. Michigan

Spatial and temporal multiplexing to achieve high peak and average power

Collaboration: LBNL, LLNL, U. Michigan



Potential for femtosecond fiber lasers with:

- **Pulse energies to >10J**
- **Average powers to >100kW**

Baseline technology for proposed k-BELLA (few J, 1kHz)

Acknowledgements

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