Multi-GeV laser wakefield electron acceleration in an all-optical plasma channel

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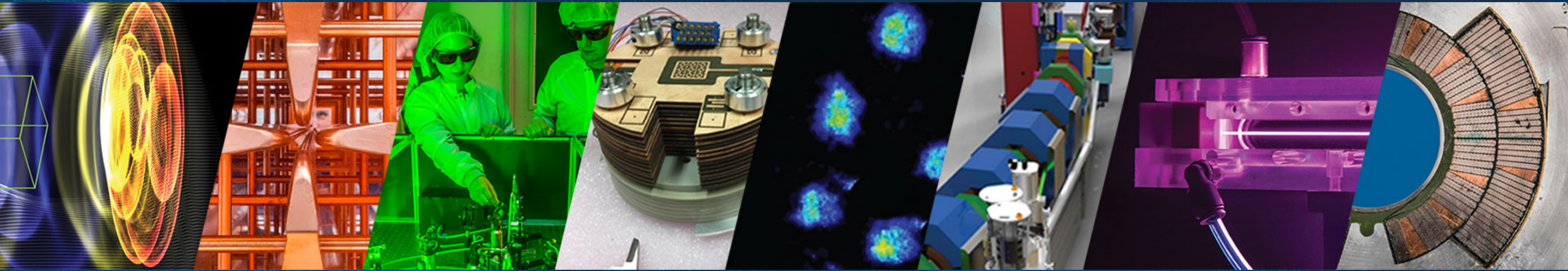

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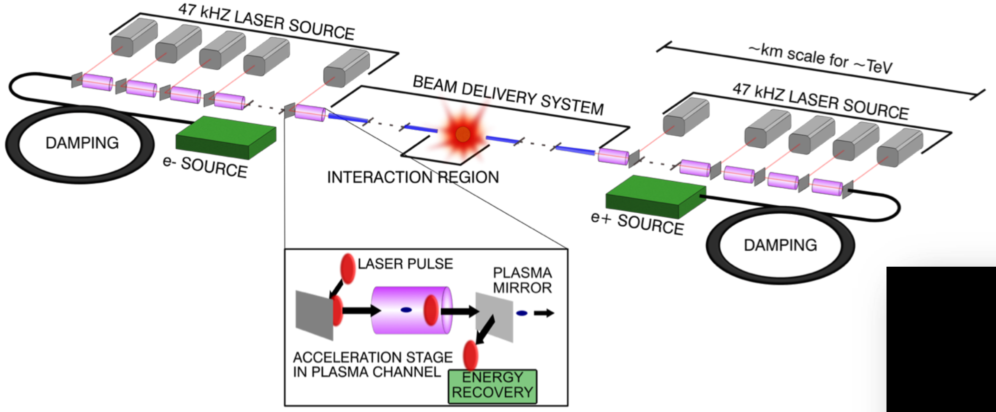
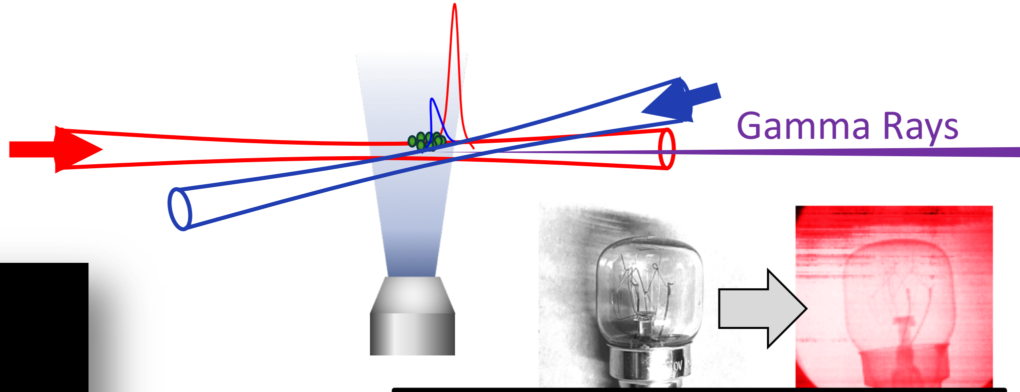
At the BELLA Center, we explore LPAs for compact drivers of linear colliders and secondary radiation sources

High energy physics colliders

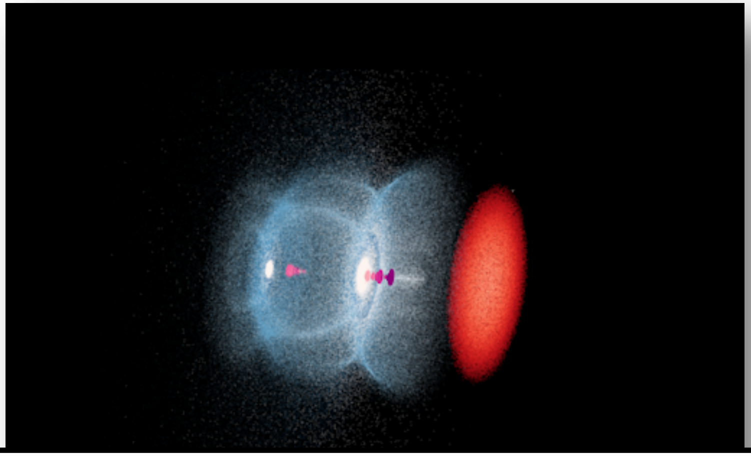


C. Schroeder, et al., *J. Instrum. 18*, T06001 (2023).

Thomson scatter γ-source

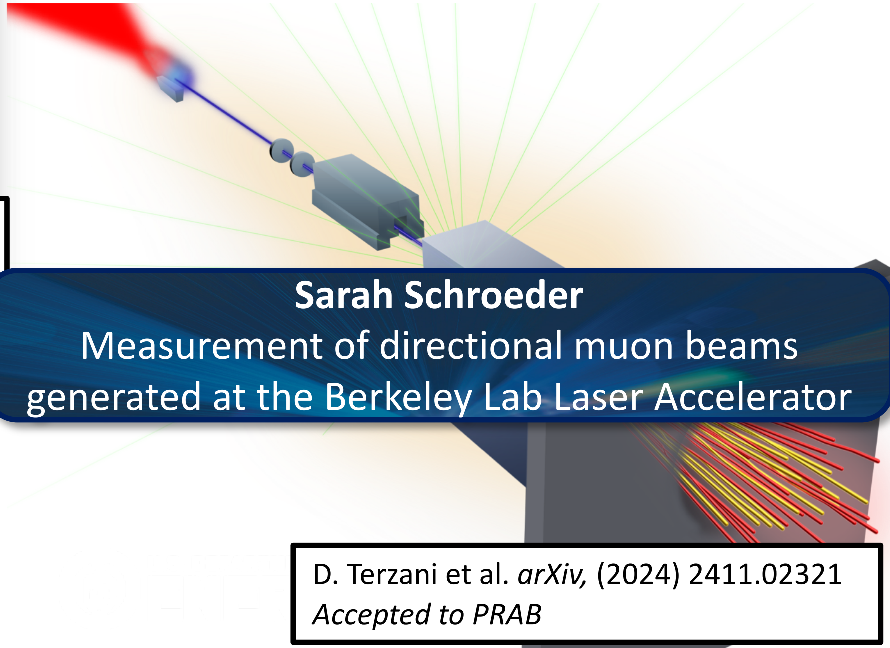


C. Thornton et al. *arXiv,* (2024) 2404.09270

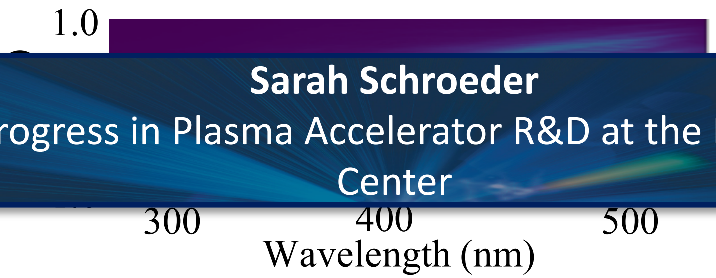


A. J. Gonsalves et al. *Physical Review Letters* 122.08 (2019)
A. Picksley et al. *Physical Review Letters* 133.25 (2024)

Compact muon sources for muography



Free Electron Lasers



Sarah Schroeder
Progress in Plasma Accelerator R&D at the BELLA Center

Sarah Schroeder
Measurement of directional muon beams generated at the Berkeley Lab Laser Accelerator

S. Barber, et al., *Physical Review Letters* (2025) 135.5

D. Terzani et al. *arXiv,* (2024) 2411.02321
Accepted to PRAB

Talk Outline

1. Maximizing electron beam energy in a laser-plasma accelerator

2. Matched guiding and acceleration in a 10-GeV-class laser-plasma accelerator

3. Towards an LPA stage suitable for applications

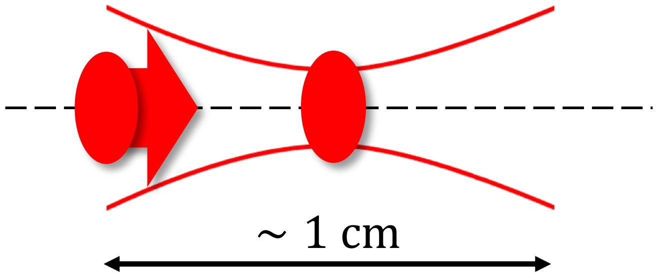
Diffraction mitigation essential for achieving high energy gain

Scaling laws

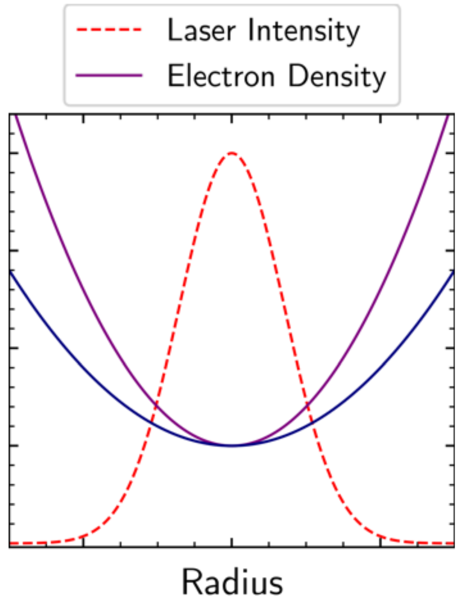
$$\text{Energy gain} \propto \frac{1}{n_e}$$

$$\text{Accelerator length} \propto \frac{1}{n_e^{3/2}}$$

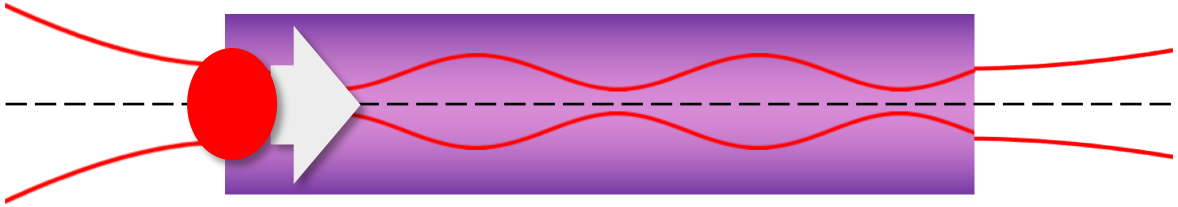
Vacuum diffraction over Rayleigh length



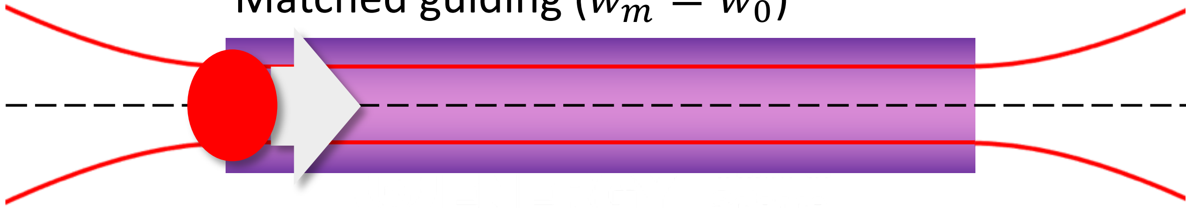
- Scaling laws for LPAs indicate that 10-GeV-class stages
  - Several centimeters long
  - Density $n_{e0} \sim 10^{17}\ \mathrm{cm}^{-3}$
- Guiding either:
  - Self-focusing through relativistic and ponderomotive effects
  - Preformed plasma waveguide



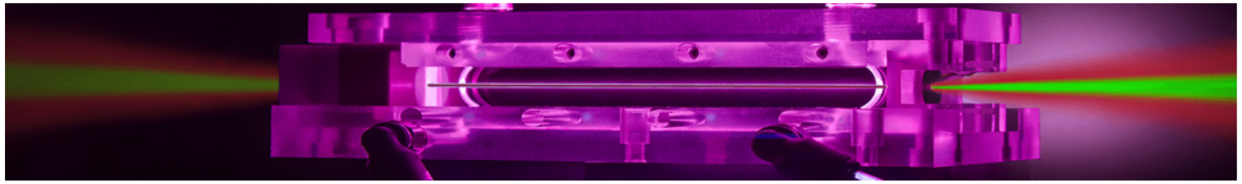
Mismatched guiding ($w_m > w_0$)



Matched guiding ($w_m = w_0$)

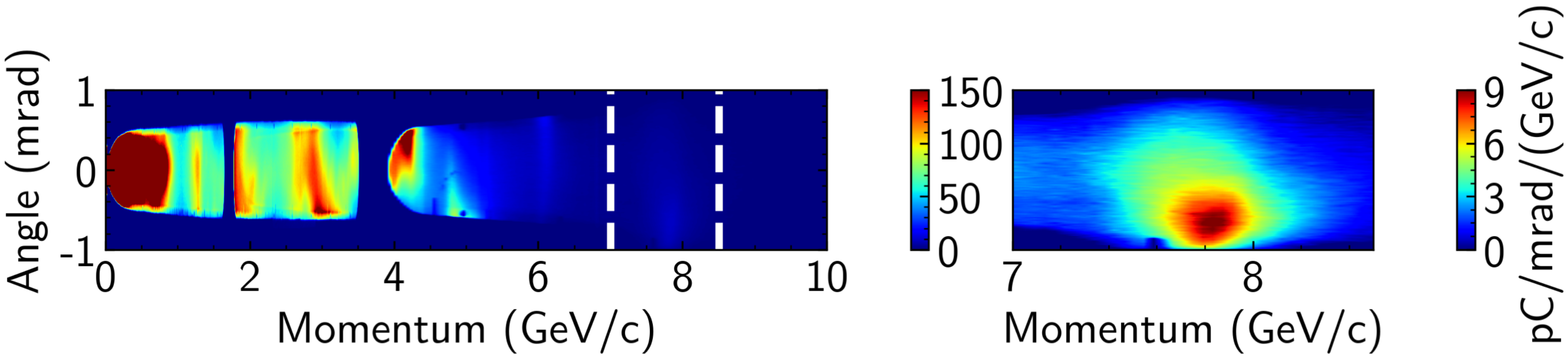


2019: Capillary discharge enhanced with ns-pulse enabled acceleration to 7.8 GeV



- Discharge creates plasma
- Weak guiding structure formed
- ns-pulse reheats plasma and deepens waveguide

- 7.8 GeV achieved:
  - 31 J laser energy required
  - $n_{e0} \approx 2.7 \times 10^{17}\ \mathrm{cm}^{-3}$
  - $w_m \approx 61\ \mu\mathrm{m}$

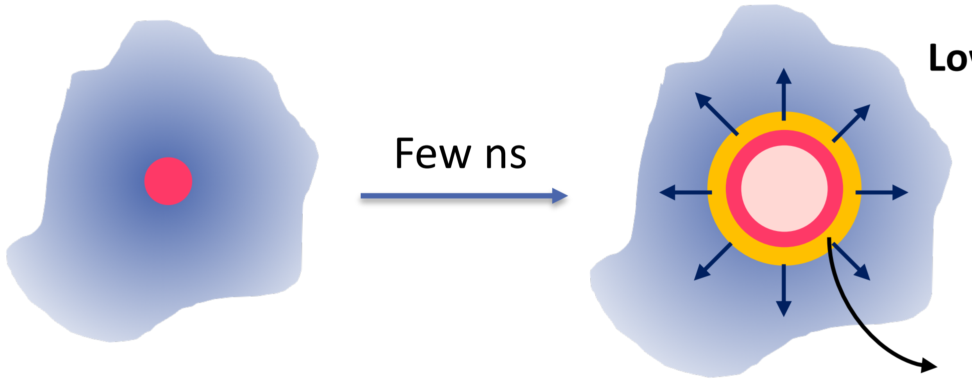


- Matched spot size limited by:
  - Capillary diameter (to avoid damage)
  - Inverse Bremsstrahlung heating (which relies on collisions)
- Lifetime limited by damage and heating
- Matched guiding **not possible**

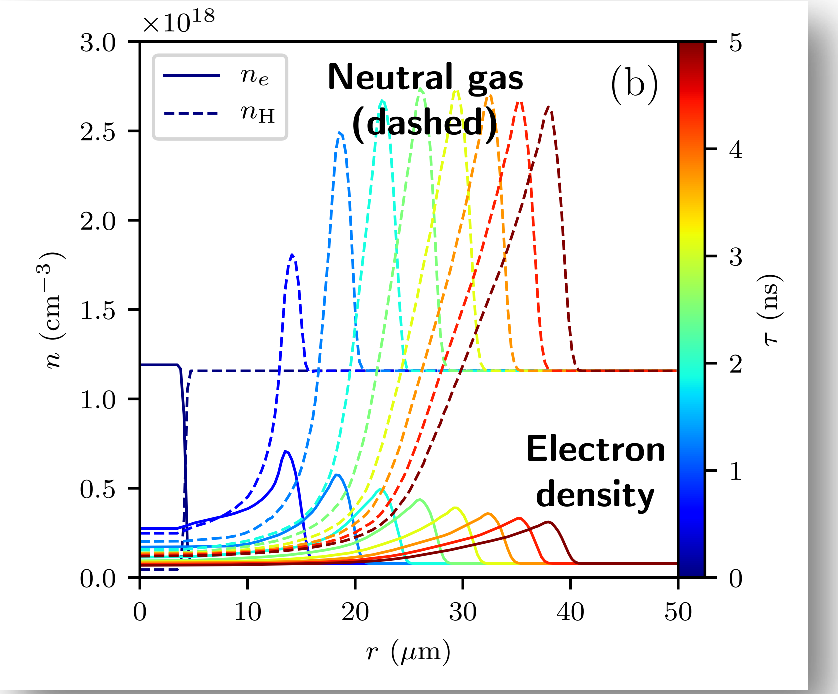
Capillary Discharge Waveguides
DJ Spence and SM Hooker. *PRE* 63.1 (2000)
A. Butler et al, *PRL* 89.18 (2002)

A. J. Gonsalves et al. *PRL* 122.08 (2019)
C. Pieronek et al., *PoP* 27.9 (2020)
A. J. Gonsalves et al. *PoP* 27.5 (2020)

Hydrodynamic expansion of optical field ionised plasmas (HOFI) provides route to steep, low density plasma channels



- Optical field ionisation by femtosecond pulse of permits **low densities**



- HOFI plasma channels were originally too "leaky" due to low wall depth, limiting useful length

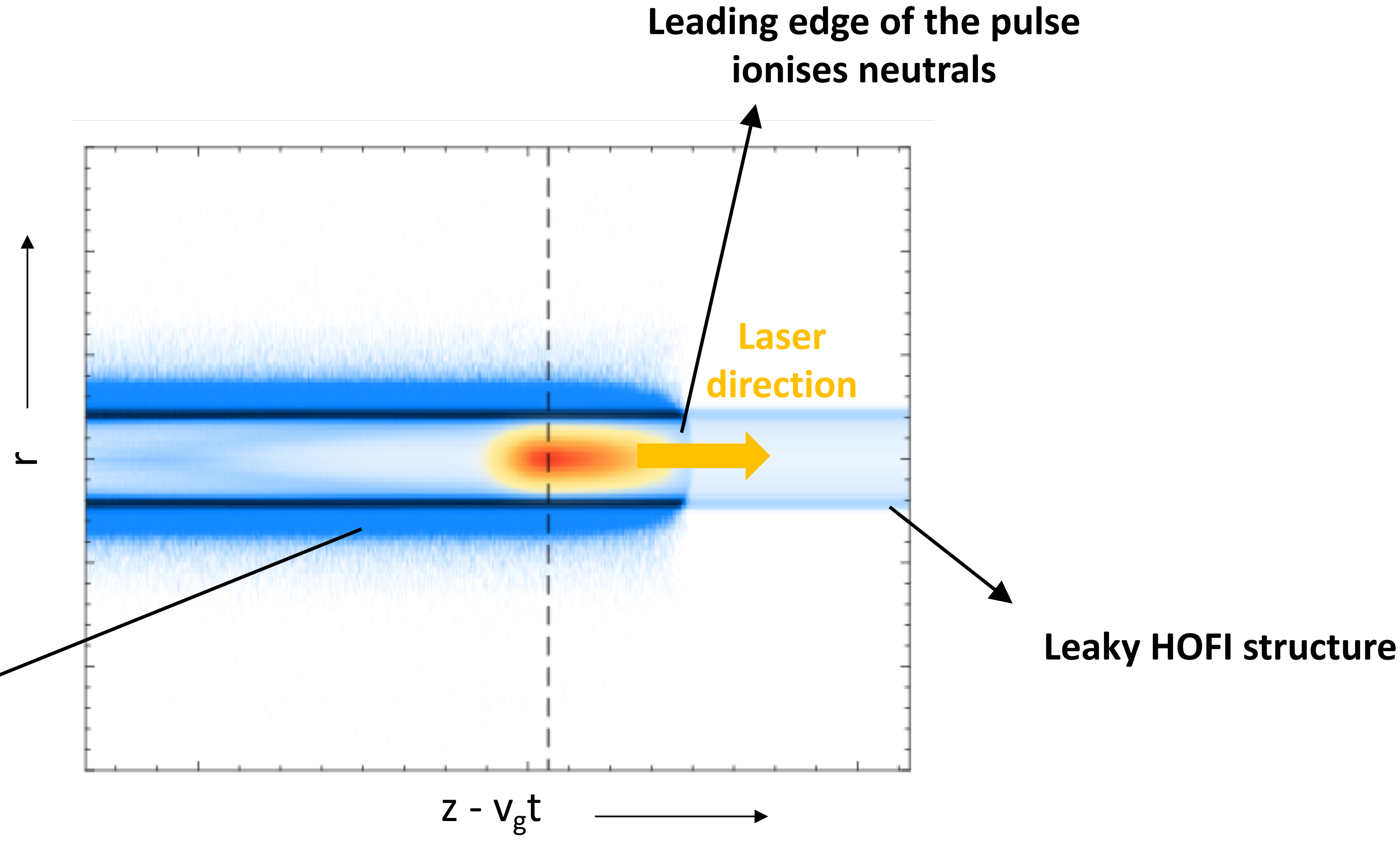
- The expanding cylindrical shock is ionized by the head of a guided laser pulse to create a deep, thick plasma channel with extremely low losses

Hydro plasma channels at $n_0 > 1{\times}10^{18}$ cm^{-3}
C Durfee et al, *PRL*, 71(15) (1993).
P Volfbeyn et al. *PoP* 6.5 (1999).
N Lemos et al. *PoP* 20.6 (2013).

Low density Plasma Channels
Hooker, S. M. *AAC Workshop* (2016)
Shalloo, R. J.,*et al.*, (2018), *PRE, 97*(5)
Shalloo, R. J.,*et al.* (2019), *PRAB*, *22*(4)

Overcome leakage by ionizing neutrals:
Morozov, A et al. (2018). *PoP*, *25*(5)
Shalloo, R. J. *Thesis 2018*
Picksley, A., et al. (2020). *PRE*, *102*(5)
Feder, L., et al. (2020). *PRR*, *2*(4)

Hydrodynamic expansion of optical field ionised plasmas (HOFI) provides route to steep, low density plasma channels



PIC simulations of low loss channel generation:
Picksley, A., et al. (2020). *PRE*, *102*(5)
Picksley *Thesis* 2021

Talk Outline

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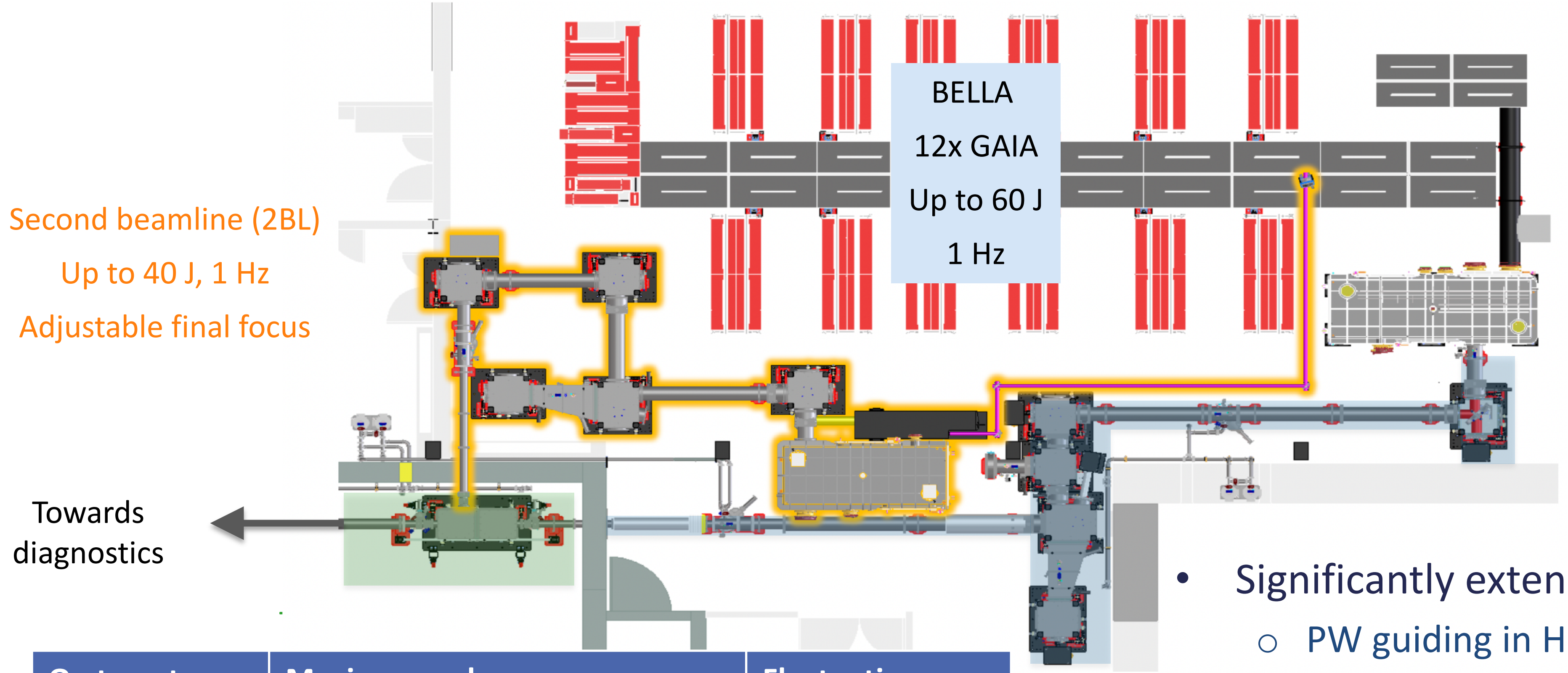
3. Towards an LPA stage suitable for applications

Picksley, A., et al. *Physical Review Letters* 133.25 (2024)

Studies enabled by dual beamline capability of BELLA PW

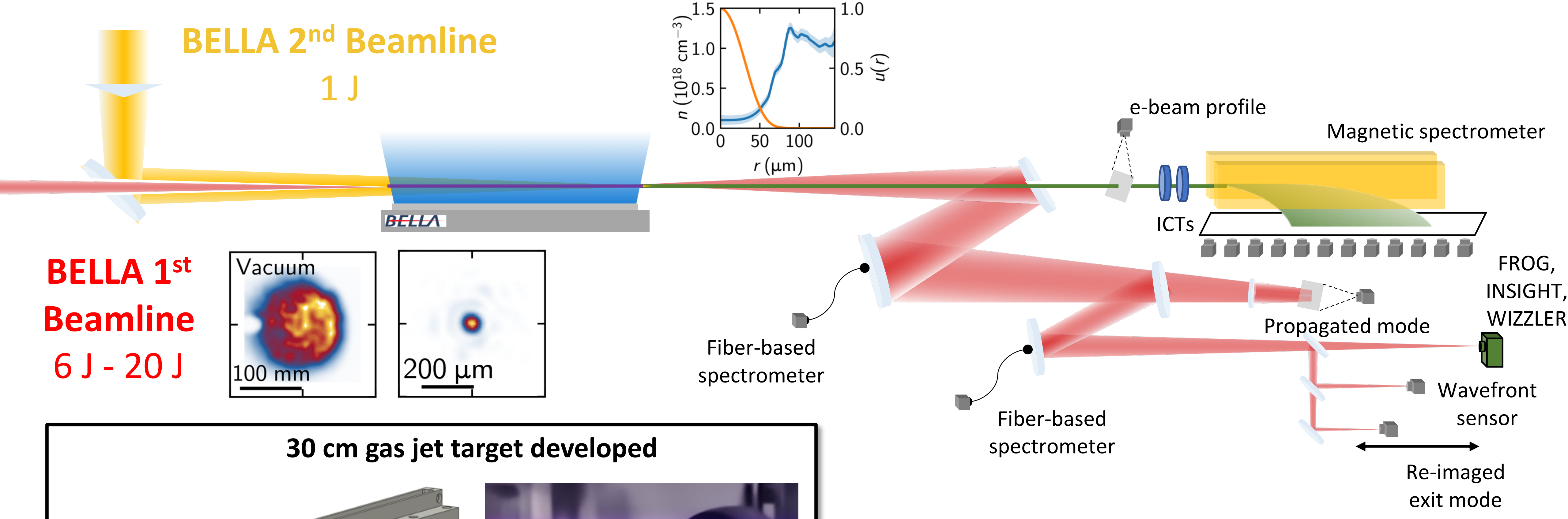
- Second beamline project funded by DOE HEP (first light April 2022)



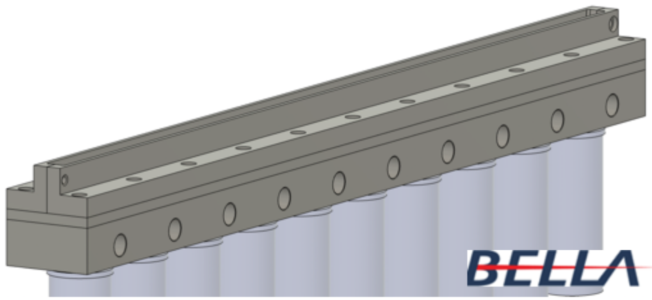
On target	Maximum value	Fluctuation
Energy	46 [J]	1-2 %
Peak Power	1.2 [PW] (for 31fs)	5 %
Peak Intensity	1.7 [10^{19} W/cm^2] (for w_0 53 µm)	< 10%

- Significantly extends science reach of BELLA PW:
  - PW guiding in HOFI plasma channels
  - Unmatched platform to study physics of multi-stage, multi-GeV LPAs
  - Optical injection, and QED

BELLA PW provides unmatched opportunity to study physics of guiding in HOFI plasma channels



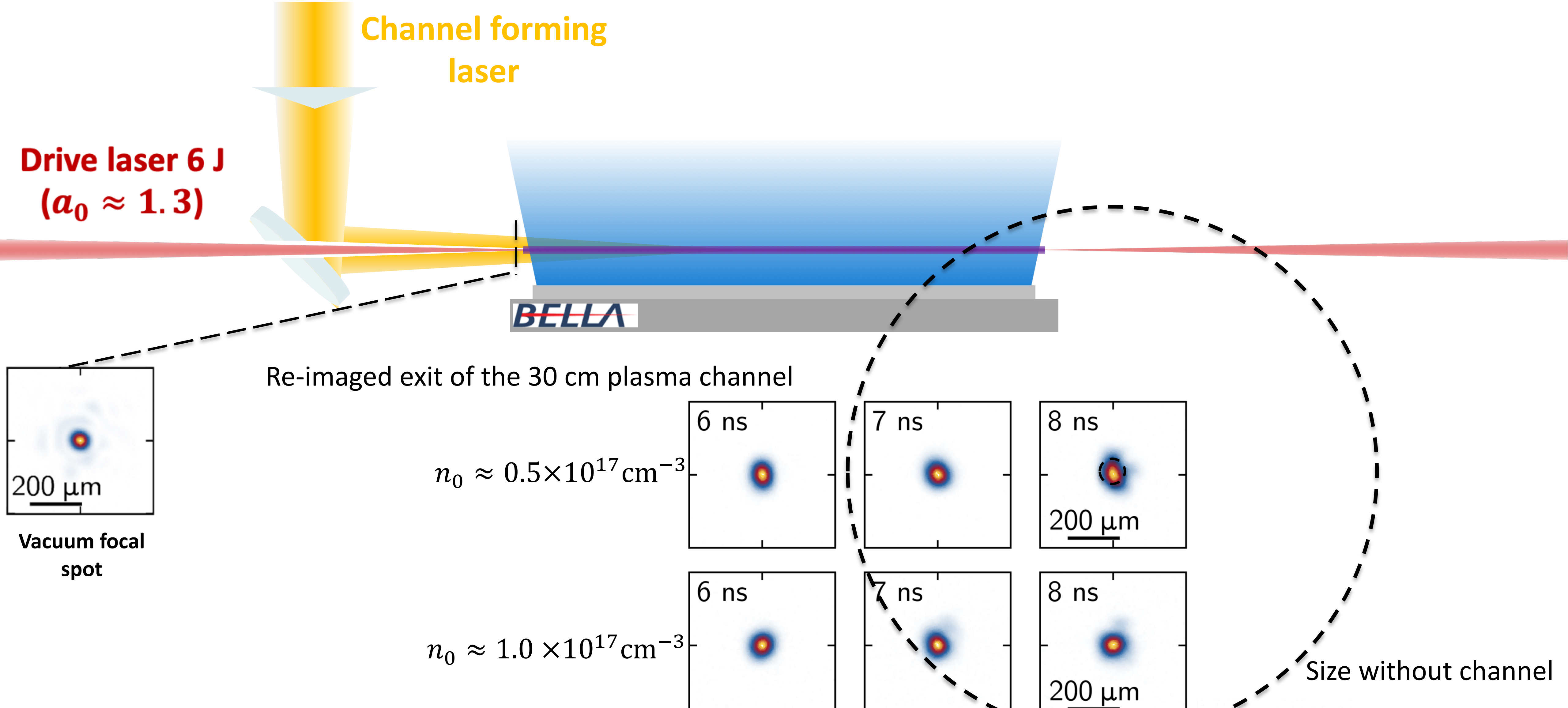
30 cm gas jet target developed



Advanced diagnostic suite for both guided laser and electron beams developed since 2012

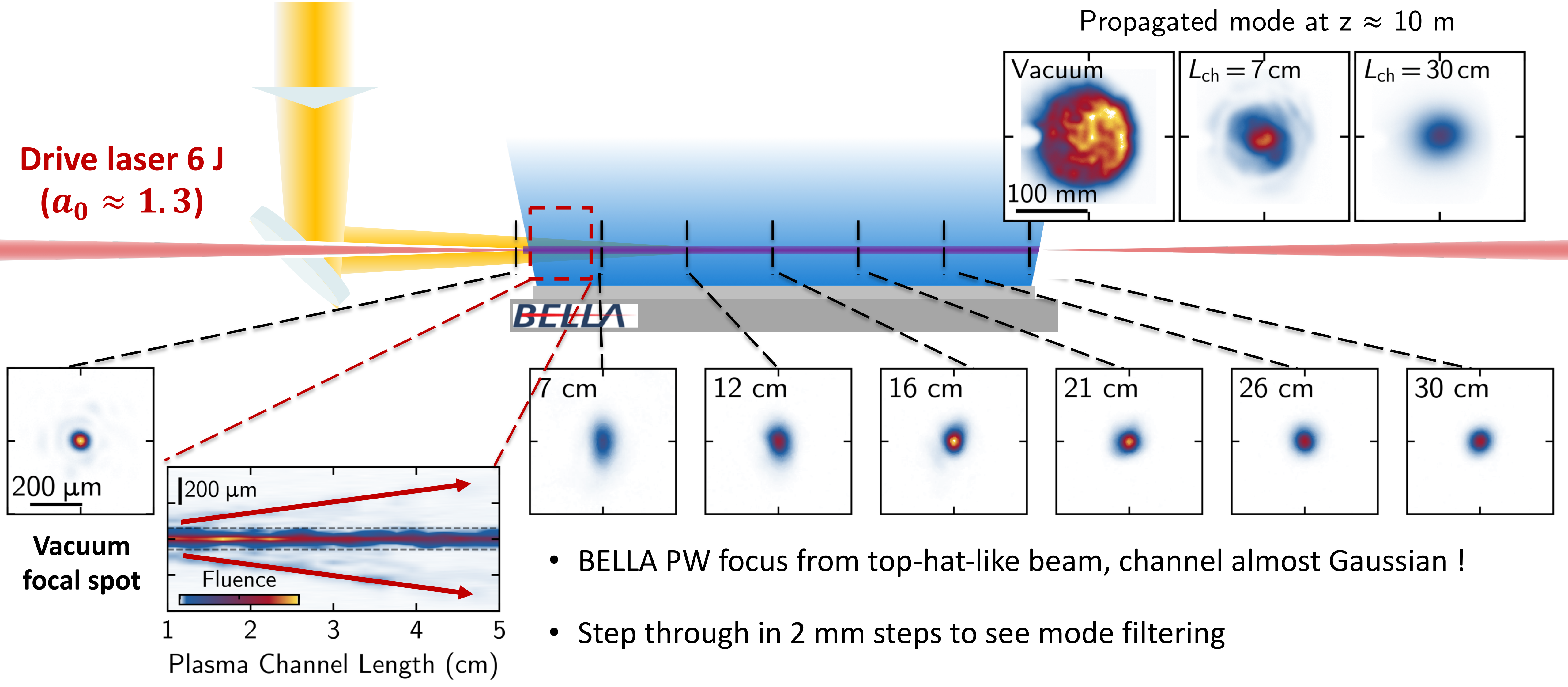
Collaboration with University of Maryland

High quality guiding of the BELLA PW laser pulse was observed over the 30 cm gas jet



Picksley, A., et al. *Physical Review Letters* 133.25 (2024)

By varying the gas jet length, we gain insight into mechanisms of laser propagation in HOFI plasma channels



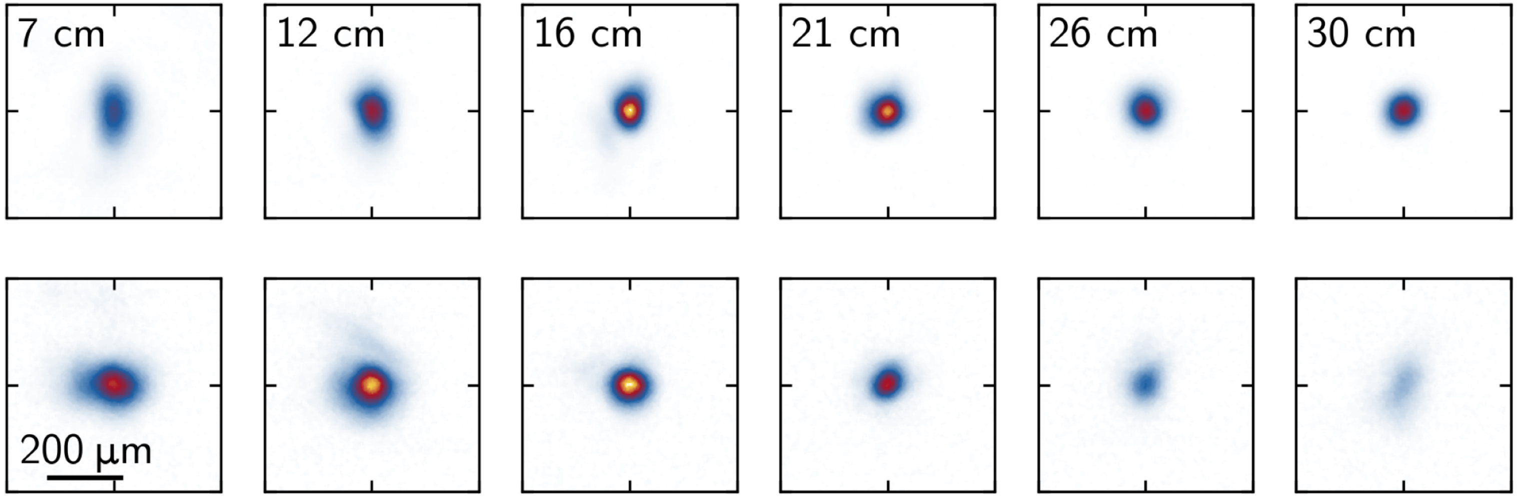
- BELLA PW focus from top-hat-like beam, channel almost Gaussian !
- Step through in 2 mm steps to see mode filtering
- Spot-size does not change for $z \gtrsim 12$ cm indicating matched guiding !

Picksley, A., et al. *Physical Review Letters* 133.25 (2024)
Mode Leakage: Clark, T. R., et al. *PRE* 61.2 (2000).

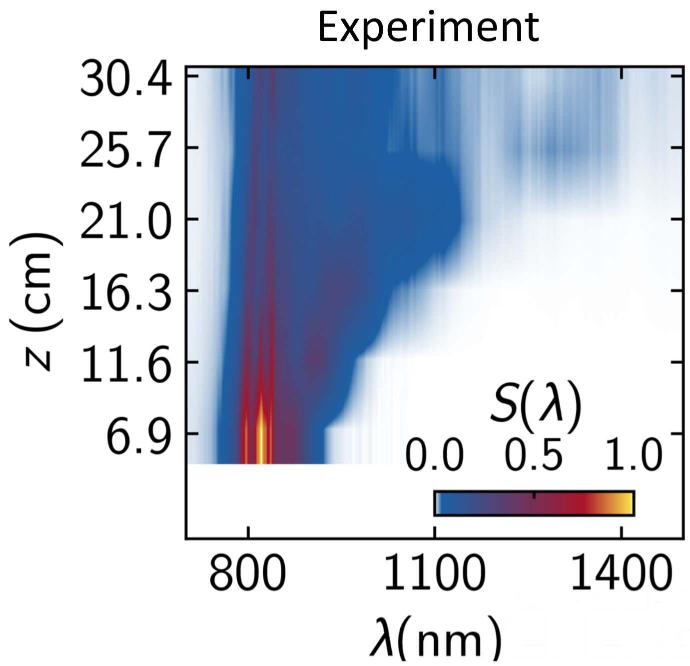
With increased drive energy, we explicitly observed gradual depletion of laser energy to the plasma wave

6 J ($a_0 \approx 1.3$)

20 J ($a_0 \approx 2.2$)

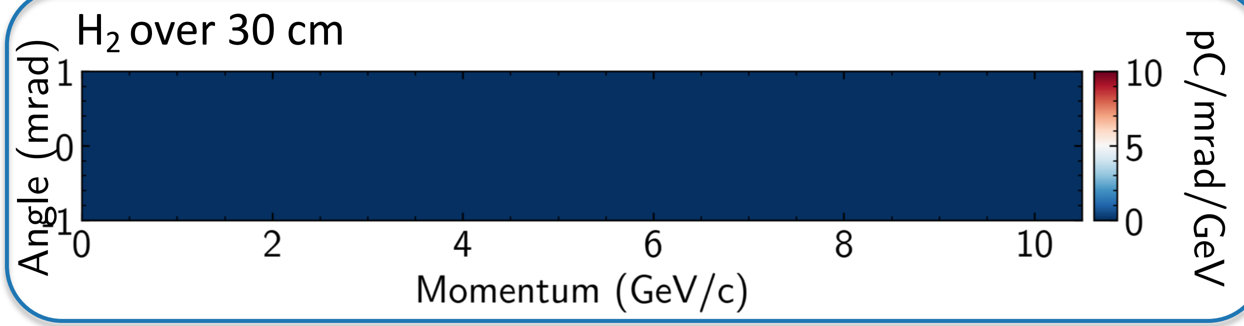


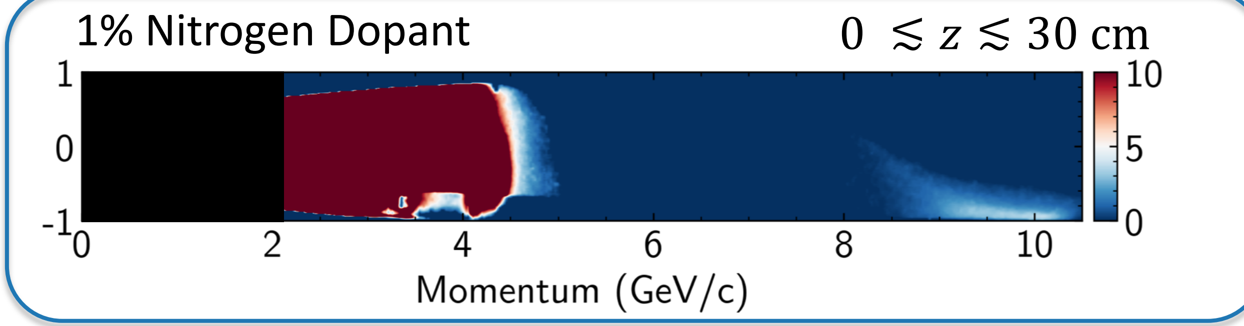
- Similar guiding behavior, but decreased energy transmission
- Redshift diagnostic indicated gradual, depletion of laser energy to the wake over the length of the plasma
- Verified by PIC simulations using INF&RNO

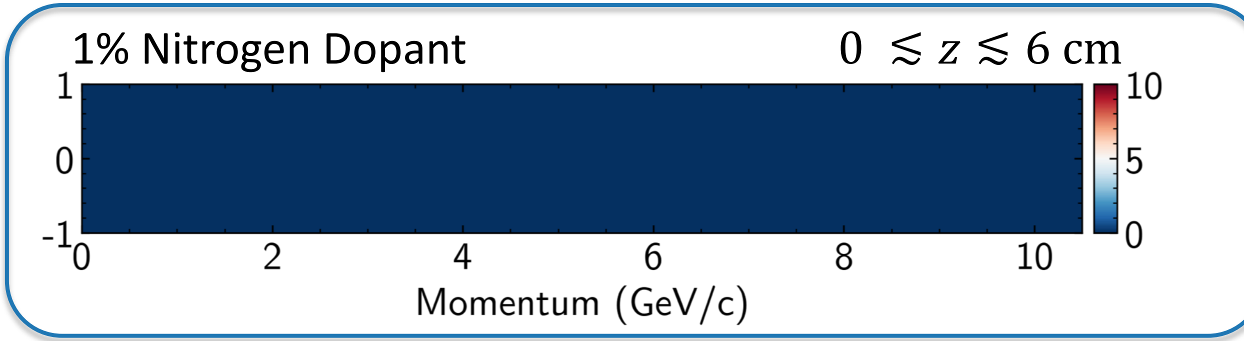


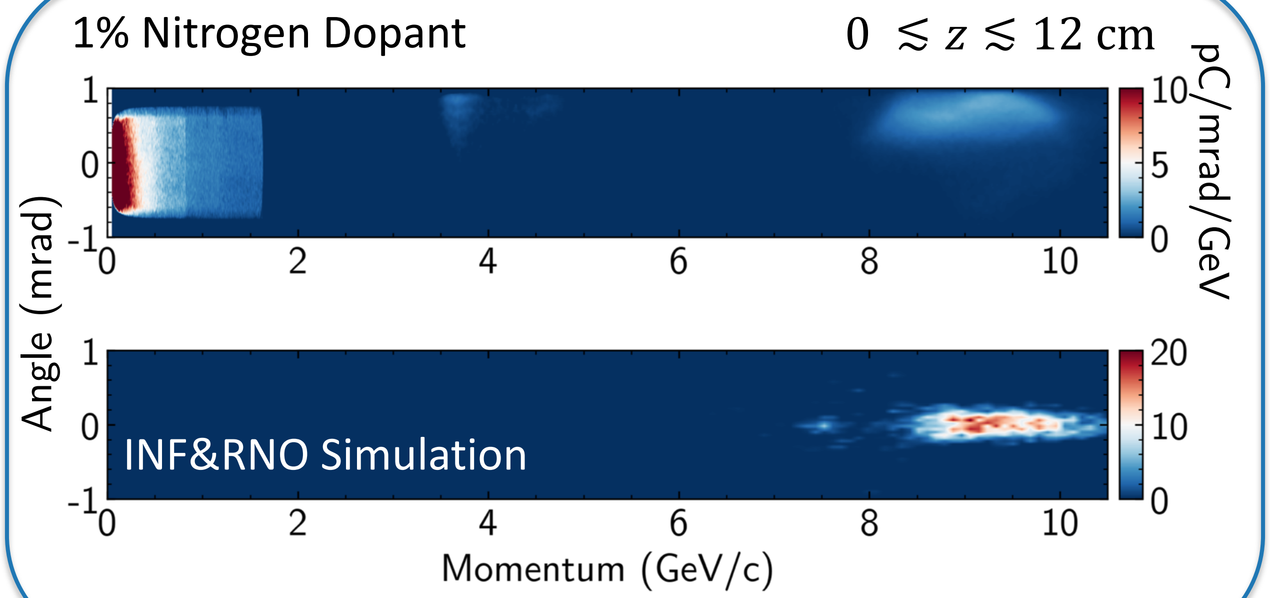
λ (nm)

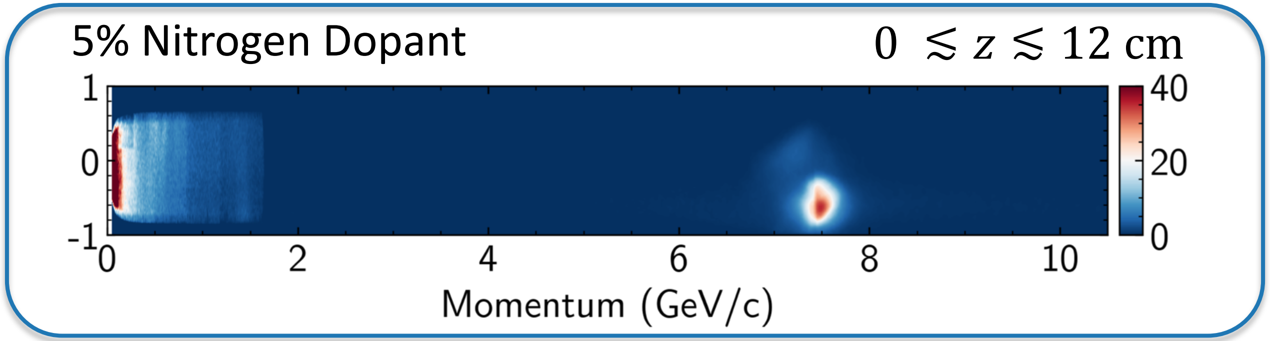
Dopant region could be adjusted by addressing valves separately, resulting in first high quality beams at the 10 GeV level









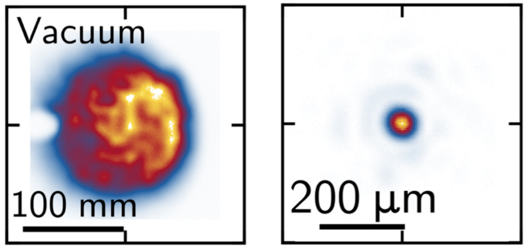


Ionization Injection - Pak, A, et al. *PRL* 104.2 (2010).
McGuffey, C., et al. *PRL* 104.2 (2010).
Chen, M., et al. *PoP* 19.3 (2012).

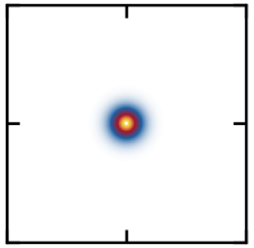
Picksley, A., et al. *Physical Review Letters* 133.25 (2024)

INF&RNO modelling gave clear insight into the guiding process, and how to maximize laser-to-bunch efficiency

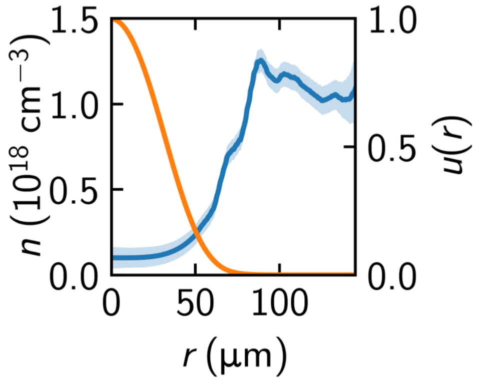
Experimental Mode

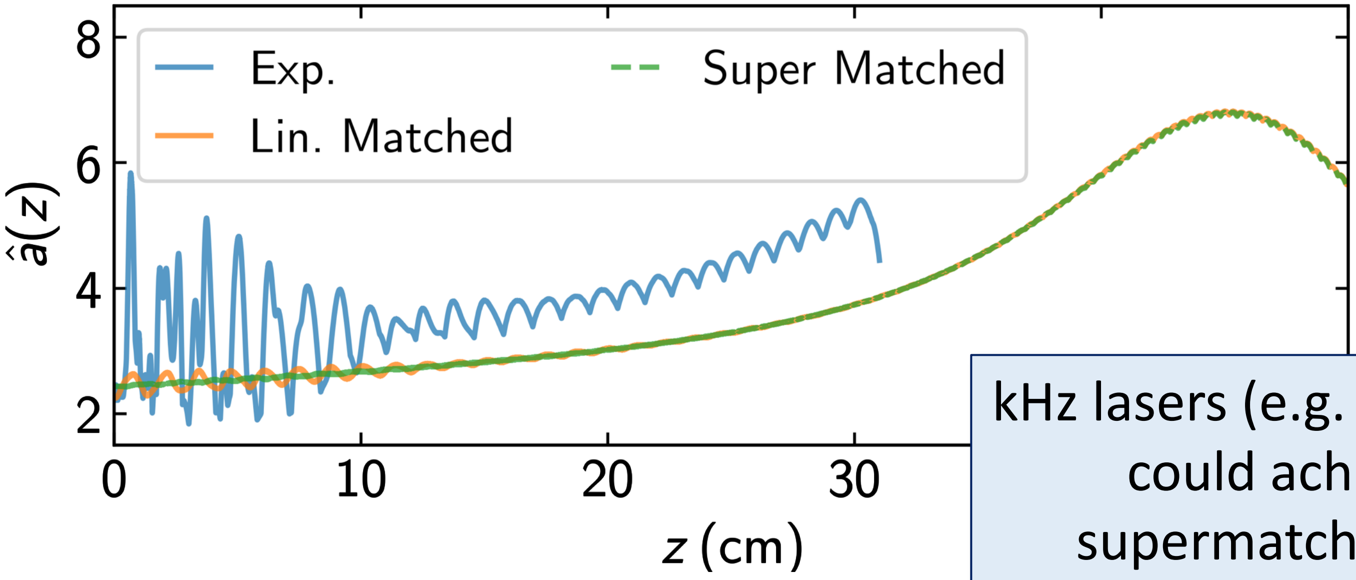


Linearly Matched



- Mode beating causes prevents high charge for $L_{\mathrm{dop}} \lesssim 6$ cm – as shown in experiments !
- Matching to the channel maintains charge injected at $z \sim 0$





9.2 GeV, 9 pC

13.0 GeV, 65 pC

13.1 GeV, 105 pC

kHz lasers (e.g. fiber lasers, kBELLA) could achieve linear and supermatched laser modes !

Picksley, A., et al. *Physical Review Letters* 133.25 (2024)
Mode beating Esarey et al 1999, 2000
Mode beating in optical channels: Shrock, J. E., et al. *PRL (2024)*

Benedetti, C., et al. *PRE* 92.2 (2015),
Benedetti, C., et al. PoP (2012)

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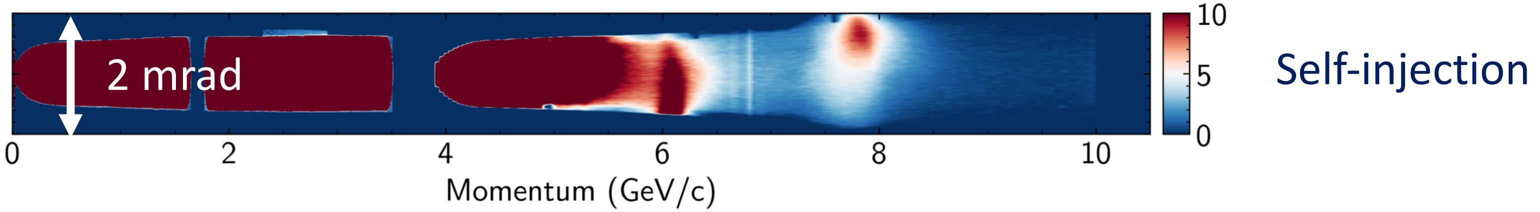
HOFI plasma channels allowed operation at a density where the accelerator could be powered without injecting unwanted charge

2019 – Laser heated capillary discharge

$n_{e0} \approx 2.7 \times 10^{17}\ \mathrm{cm}^{-3}$

$w_m \approx 61\ \mu\mathrm{m}$

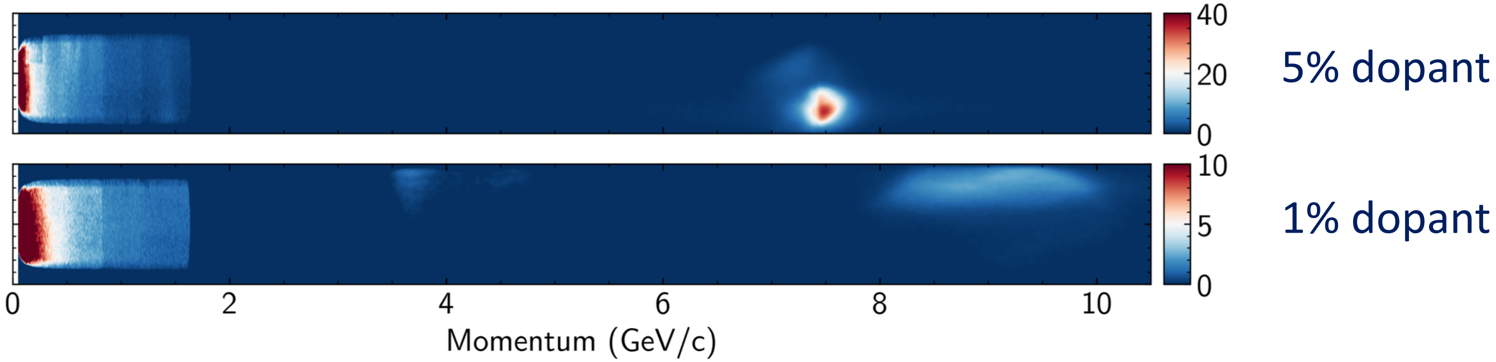


2024 – HOFI Plasma Channel

+ Localised Dopant

$n_{e0} \approx 1.0 \times 10^{17}\ \mathrm{cm}^{-3}$

$w_m \approx 40\ \mu\mathrm{m}$

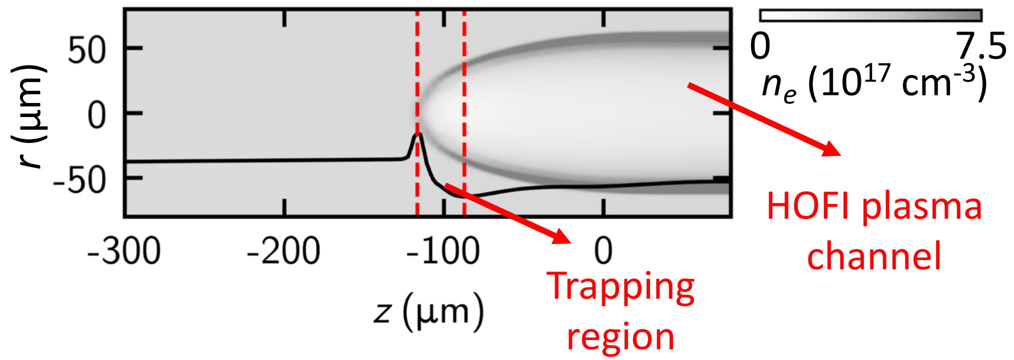


- Dark current free operation vital for future applications, and for studies of staged LPAs
- Previously 0.5 – 1 J in electron beam across 0-8 GeV range
- Now up to 0.5 J in singly peaked beam
- In both cases, e-beam pointing stability similar **and** much worse than laser pointing

Single stage could be improved further by addressing injection and longitudinal density gradient

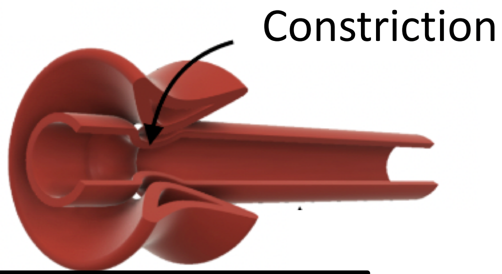
- Ionization injection limits beam quality
- Schemes proposed to achieve high quality electron beams directly in a HOFI plasma channel

Density Transition Injection



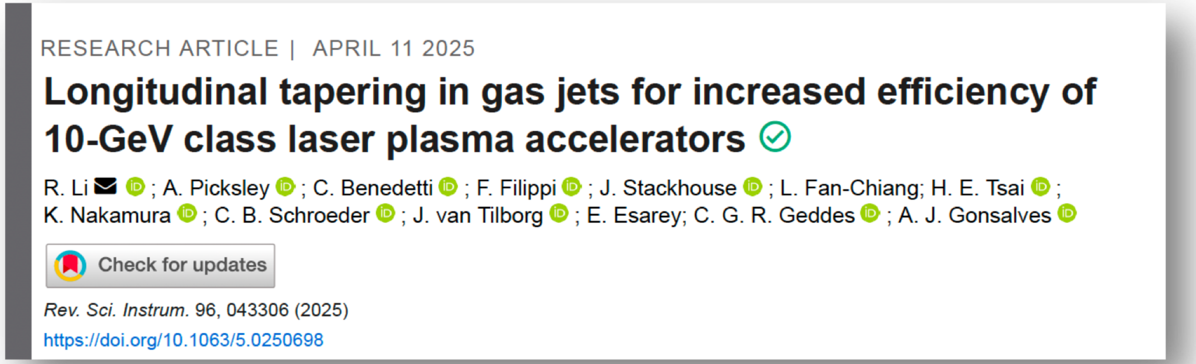
Oxford- Picksley, A., et al. *Physical Review Letters* 131.24 (2023)

Constricted Waveguide



DESY- R Shalloo et al. *arXiv,* (2024) 2410.15937

- Density gradient can maximize laser depletion
- Increases overall energy and bunch charge


RESEARCH ARTICLE | APRIL 11 2025

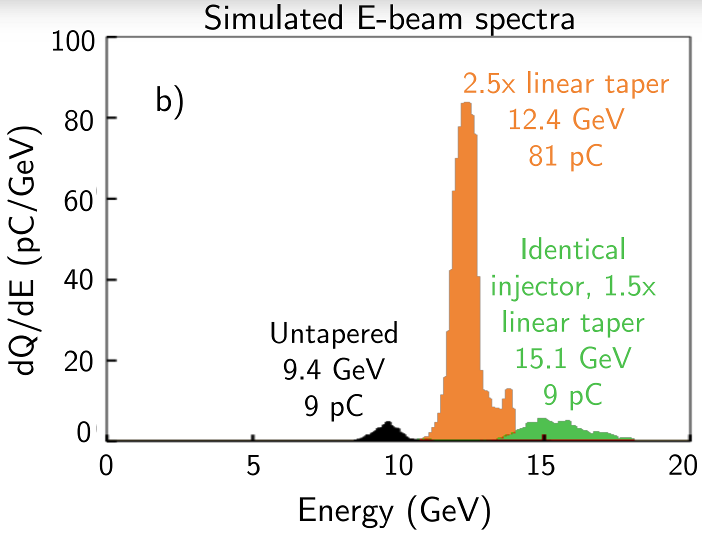
Longitudinal tapering in gas jets for increased efficiency of 10-GeV class laser plasma accelerators

R. Li; A. Picksley; C. Benedetti; F. Filippi; J. Stackhouse; L. Fan-Chiang; H. E. Tsai; K. Nakamura; C. B. Schroeder; J. van Tilborg; E. Esarey; C. G. R. Geddes; A. J. Gonsalves

Check for updates

Rev. Sci. Instrum. 96, 043306 (2025)

https://doi.org/10.1063/5.0250698



BELLA- R Li et al. *Review of Scientific Instruments* 96.4 (2025).

Conclusions

- Plasma channels formed by the hydrodynamic expansion of optical-field-ionised plasmas offer a route to steep, low-density, freestanding plasma channels suitable for 10-GeV-class laser plasma accelerators
- By varying the plasma channel length, we demonstrated mode filtering followed by matched guiding in 30-cm-long HOFI plasma channels
- Controlled injection into the dark current free structure led to singly peaked electron beams with peak energy of 9.2 GeV and charge extending beyond 10 GeV
- This could pave the way to stable, high repetition rate stages required for future applications