Matched Guiding and Controlled Injection in Dark-Current-Free, 10-GeV-Class, Channel-Guided Laser Plasma Accelerators

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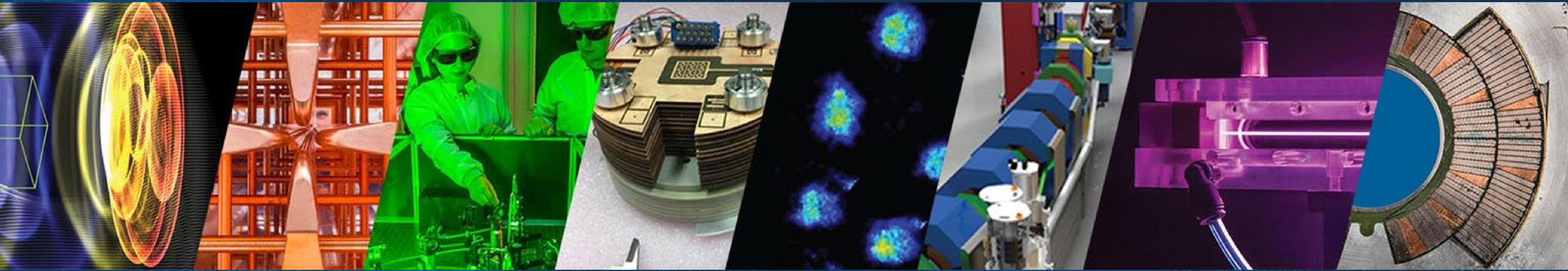

Laser-Plasma Accelerators Workshop 2025 – Ischia Island (Naples, Italy)
April 14th, 2025

BERKELEY LAB
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP
U.S. DEPARTMENT OF ENERGY | Office of Science

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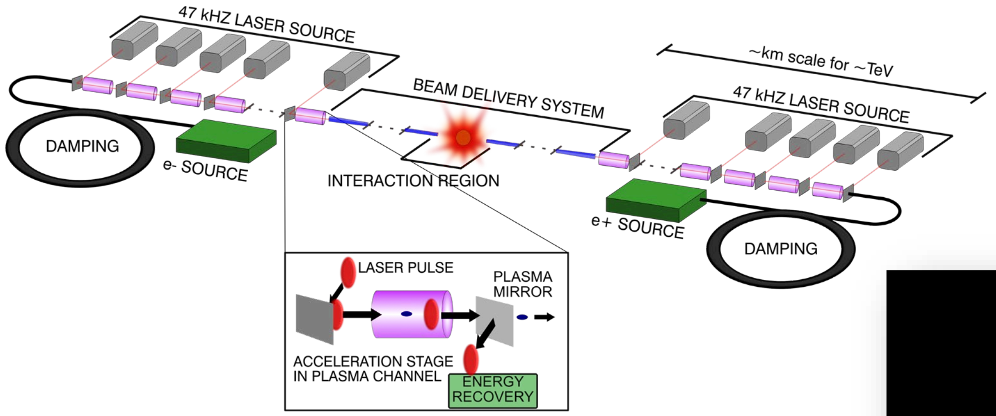
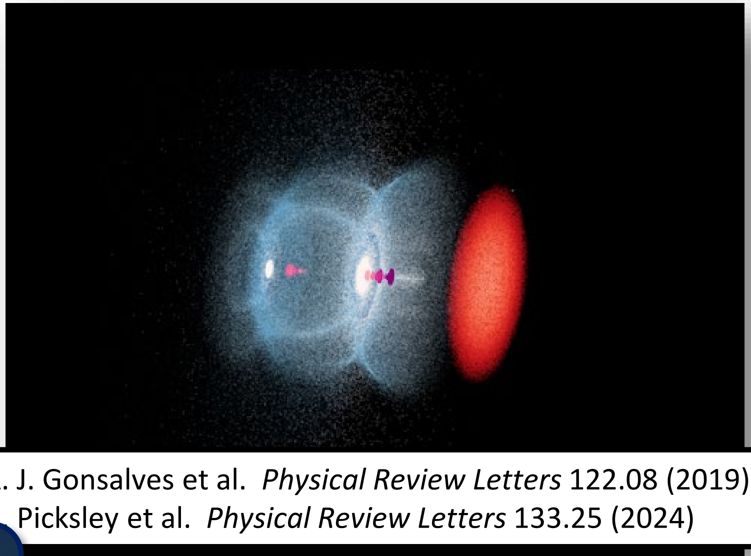
This work was supported by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC02- 05CH11231, the Defense Advanced Research Projects Agency, and used the computational facilities at the National Energy Research Scientific Computing Center (NERSC).

At the BELLA Center, our goal is to create compact drivers for linear colliders and secondary radiation sources

High energy physics colliders

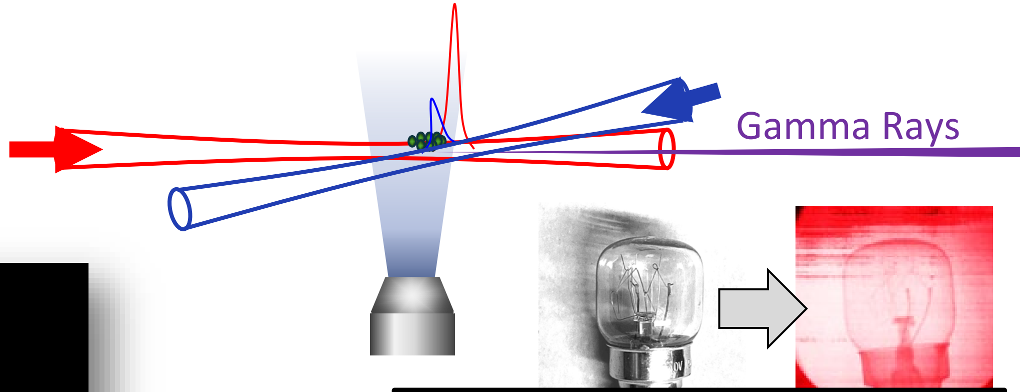


C. Schroeder, et al., *J. Instrum. 18*, T06001 (2023).



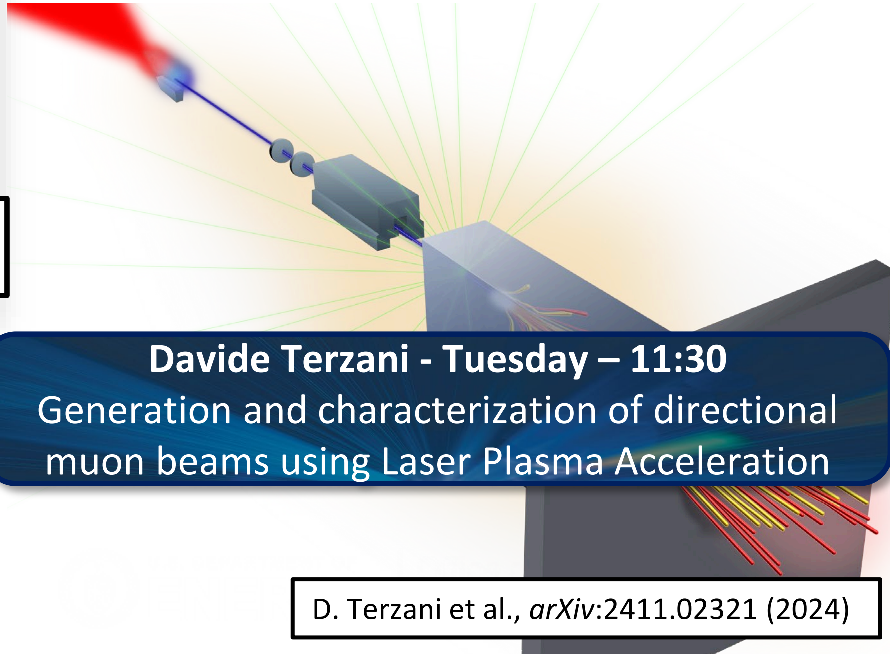
A. J. Gonsalves et al. *Physical Review Letters* 122.08 (2019)
A. Picksley et al. *Physical Review Letters* 133.25 (2024)

Thomson scatter γ-source



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

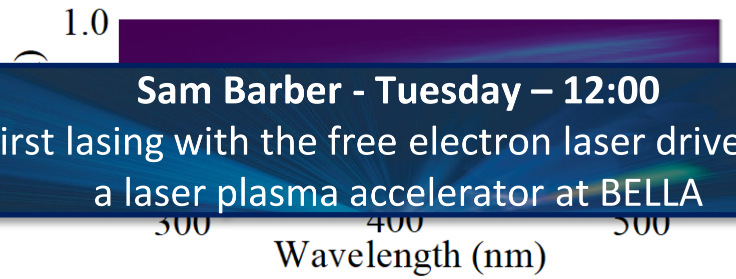
Compact muon sources



Davide Terzani - Tuesday – 11:30
Generation and characterization of directional muon beams using Laser Plasma Acceleration

D. Terzani et al., *arXiv*:2411.02321 (2024)

Free Electron Lasers



Sam Barber - Tuesday – 12:00
First lasing with the free electron laser driven by a laser plasma accelerator at BELLA

S. Barber, et al., *Submitted* (2025).

Talk Outline

1. **Importance of guiding in a laser-plasma accelerator**

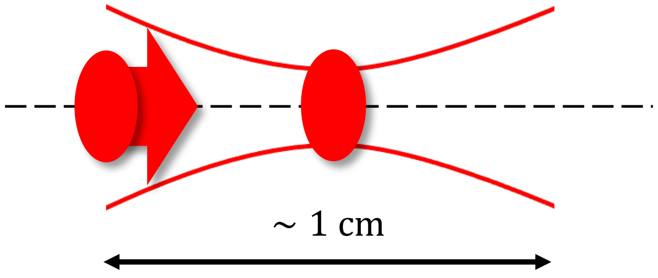
2. High-quality laser propagation and guiding in optically formed plasma channels

3. Controlled electron injection and acceleration of electron bunches up to 10 GeV

4. Outlook towards future development and conclusion

Acceleration to high energy gain requires techniques to overcome diffraction and extend accelerator length

Vacuum diffraction over Rayleigh length



Scaling laws

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

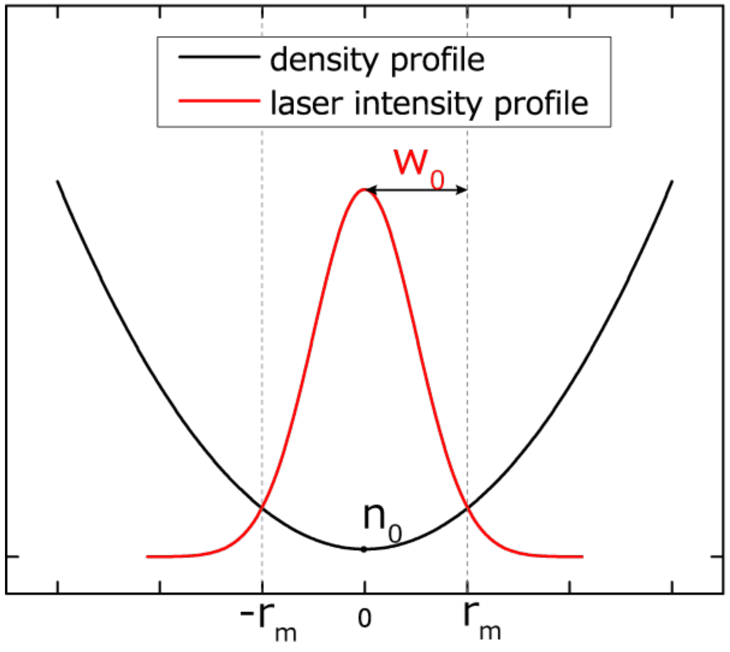
$$\text{Accelerator length} \propto \frac{1}{n_e^{3/2}}$$

Scaling laws for LPAs dictate parameters for 10-GeV-class stages:

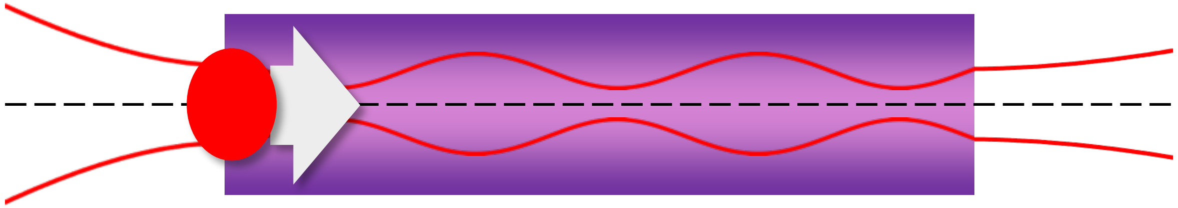
- Tens of centimeters long
- $n_{e0} \sim 10^{17}\ \mathrm{cm}^{-3}$

Guiding with either:

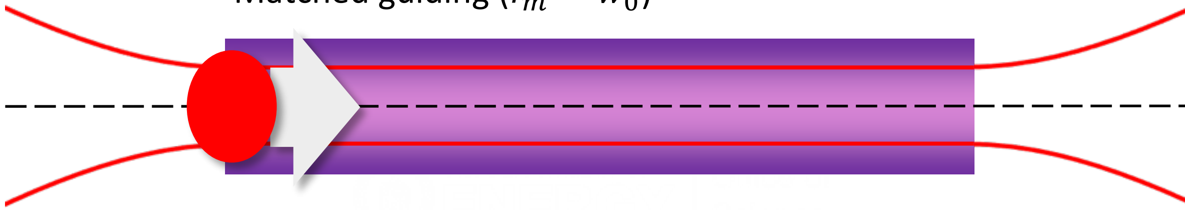
- Self-focusing through relativistic and ponderomotive effects
- Preformed plasma waveguide



Mismatched guiding ($r_m > w_0$)

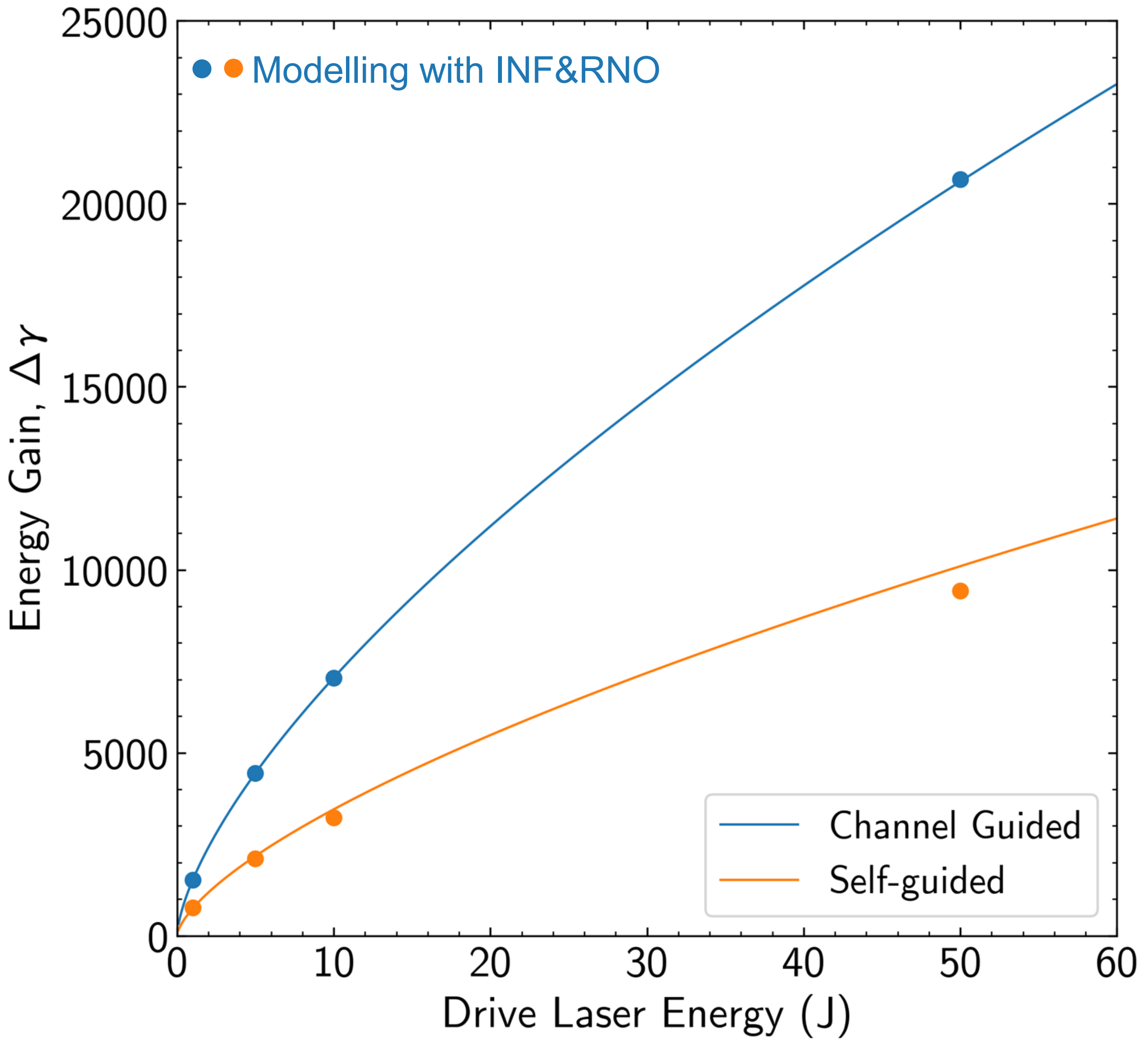


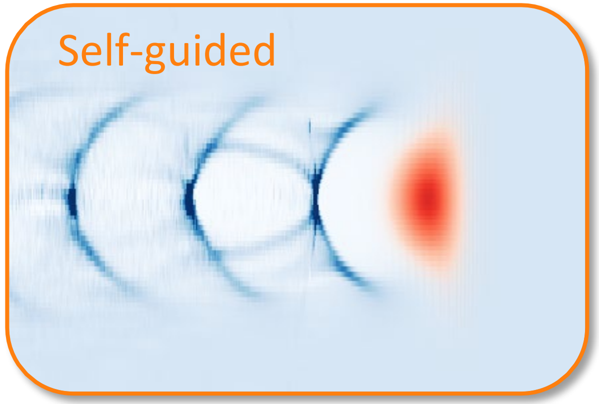
Matched guiding ($r_m = w_0$)



Accelerator length > 10 cm

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





Channel-guided
Quasilinear regime

$a_0 = 1.5$
$n_{e0} \approx 2.6 \times 10^{17}\ \mathrm{cm}^{-3}$

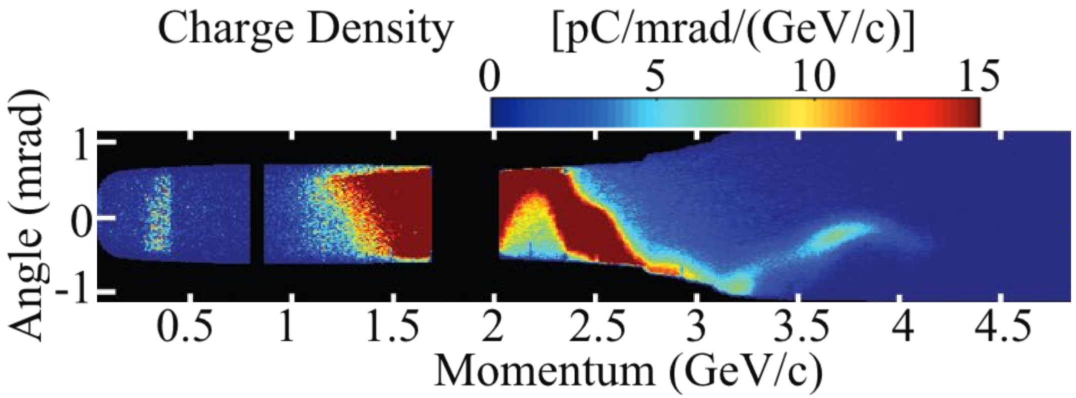
Self-guided
Bubble regime

$a_0 = 4.5$
$n_{e0} \approx 1.5 \times 10^{18}\ \mathrm{cm}^{-3}$

W. Lu et al., *PR-STAB* **10**.6 (2007)
C. Benedetti et al., *AAC* (2014), (2016), (2022)

C. Benedetti et al. *In preparation*

Previous experiments produced beams up to 7.8 GeV

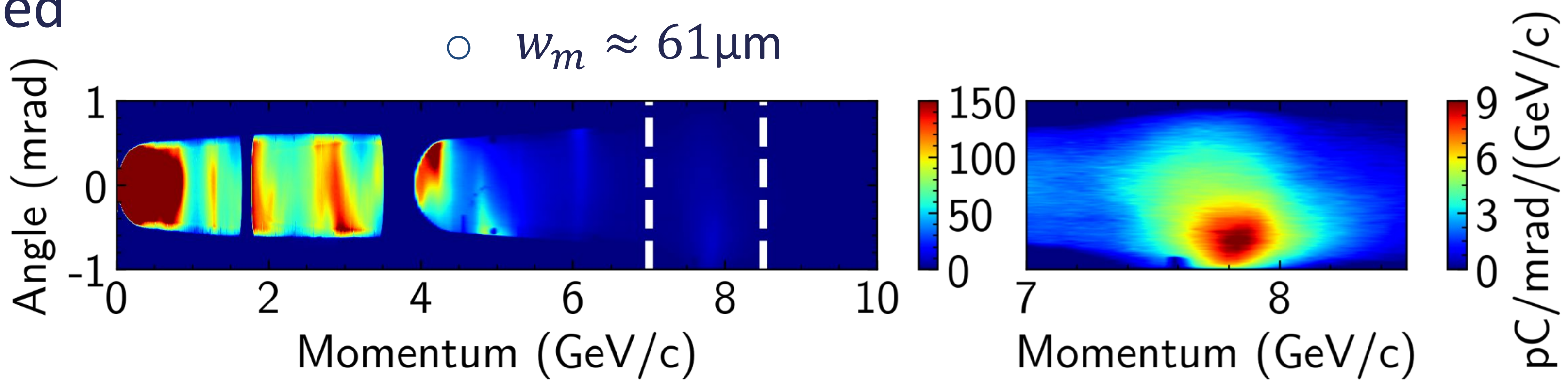


2014: Capillary discharge produced beams up to 4 GeV

- $n_{e0} \approx 7 \times 10^{17}$ cm^{-3}
- $w_m \approx 93$µm

2019: Laser-heating with ns-pulse enabled beams up to 8 GeV

- Heater pulse produced channel with lower matched spot size
  - $n_{e0} \approx 2.7 \times 10^{17}$ cm^{-3}
  - $w_m \approx 61$µm



Underlying challenge:

- Matched guiding at optimal density **not possible**

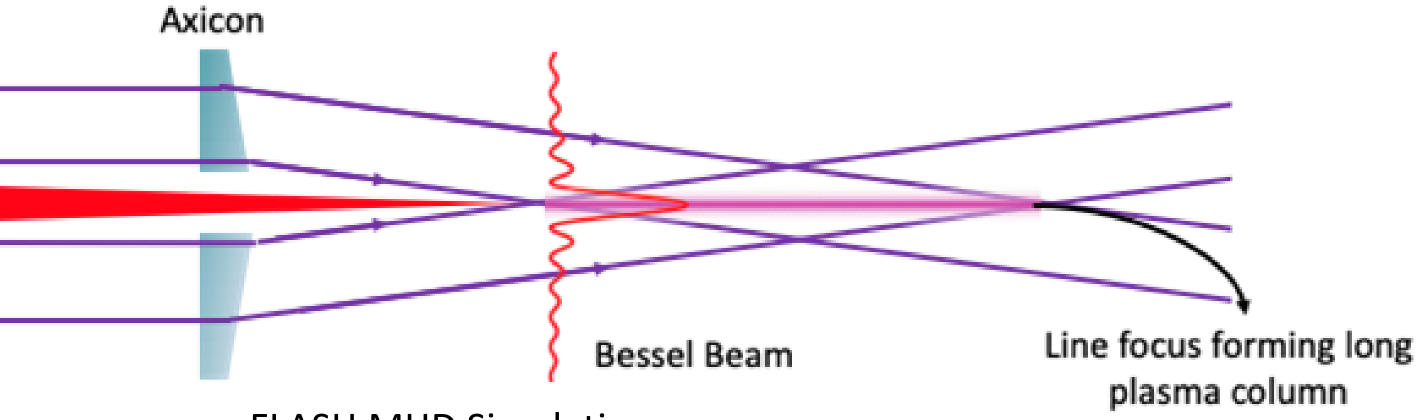
Capillary Discharge Waveguides
D.J. Spence and S.M. Hooker, *PRE* **63**.1 (2000)
A. Butler et al., *PRL* **89**.18 (2002)

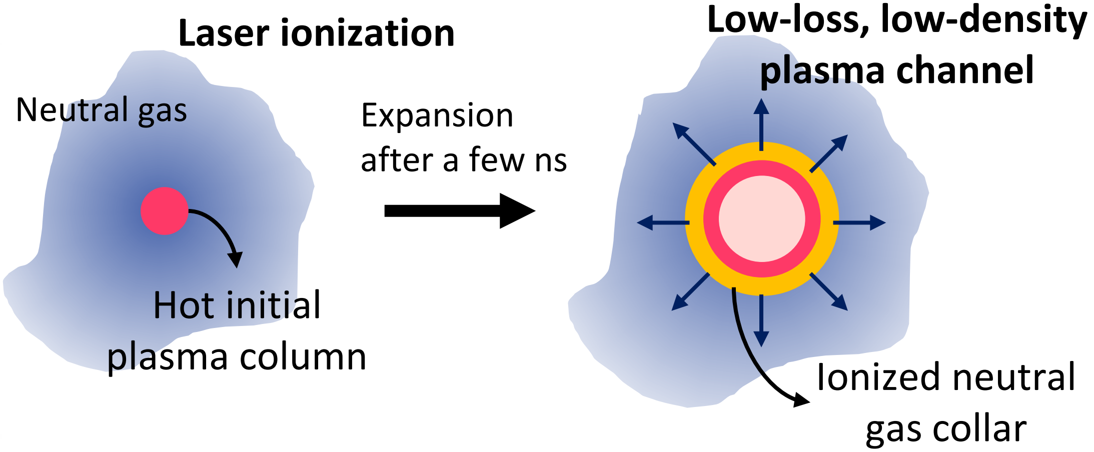
Leemans et al., *PRL* **113**.245002 (2014)
Gonsalves et al., *PoP* **22**.056703 (2015)

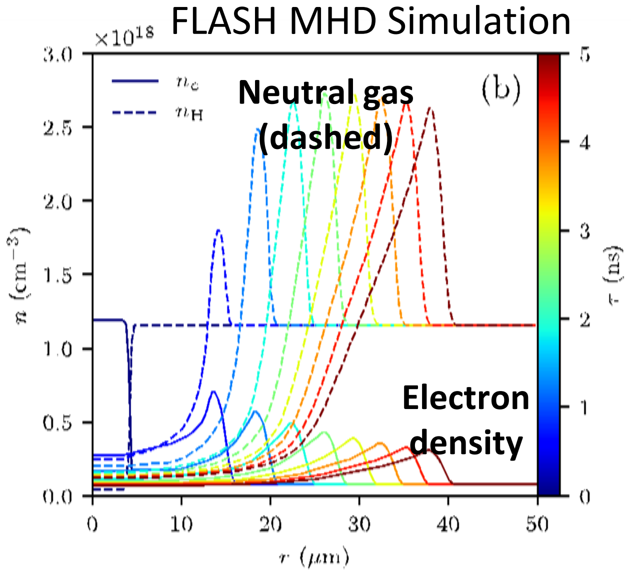
Laser-heated Capillary Discharge
Bobrova et al., *PoP* **20**.020703 (2013)

Gonsalves et al., *PRL* **122**.084801 (2019)
Pieronek et al., PoP **27**.093101 (2020)
Gonsalves et al., PoP **27**.053102 (2020)

Hydrodynamic optical-field-ionized (HOFI) channels can meet requirements for PW-class LPAs







- Can reach low densities with arbitrary width ideal for laser plasma accelerators
- Deep, low-loss channel created by ionization of surrounding collar of neutral gas by drive laser pulse

Recent results have demonstrated guiding of high intensity pulses and GeV electron acceleration

Hydro plasma channels at $n_0 > 10^{18}$ cm^{-3}
Durfee et al., *PRL* **71**.15 (1993)
Volfbeyn et al., *PoP* **6**.5 (1999)
Lemos et al., *PoP* **20**.6 (2013)

Low density plasma channels
SM Hooker, *AAC Workshop* (2016)
Shalloo *et al.*, *PRE* **97**.5 (2018)
Shalloo *et al.*, *PRAB* **22**.4 (2019)

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

High intensity guiding
Miao et al., *PRL* **125**.7 (2020)
Picksley et al., *PRAB* **23**.8 (2020)

Electron acceleration
Miao et al., PRX **12**.3 (2022)
Oubrerie et al., LSA **11**.180 (2022)
Picksley et al., PRL **131**.24 (2023)

Talk Outline

1. Importance of guiding in a laser-plasma accelerator

2. **High-quality laser propagation and guiding in optically formed plasma channels**

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Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)

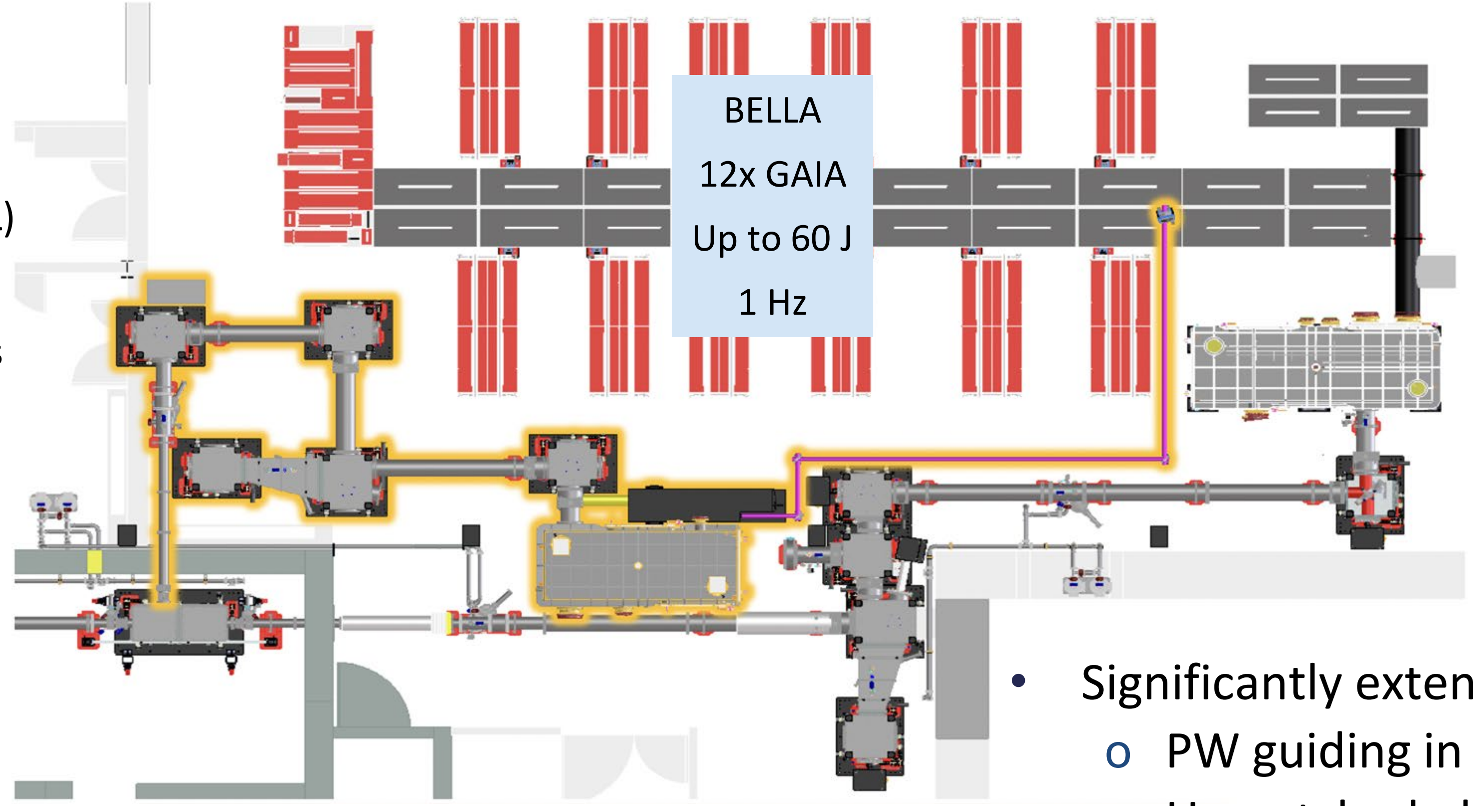
Second beamline enables experiments with optically formed channels at the BELLA PW facility

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

Second beamline (2BL)

Up to 40 J, 1 Hz

Adjustable final focus



Existing beamline (1BL)

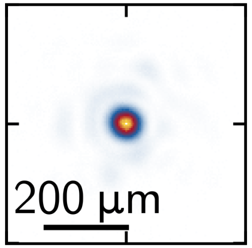
Up to 40 J, 1 Hz

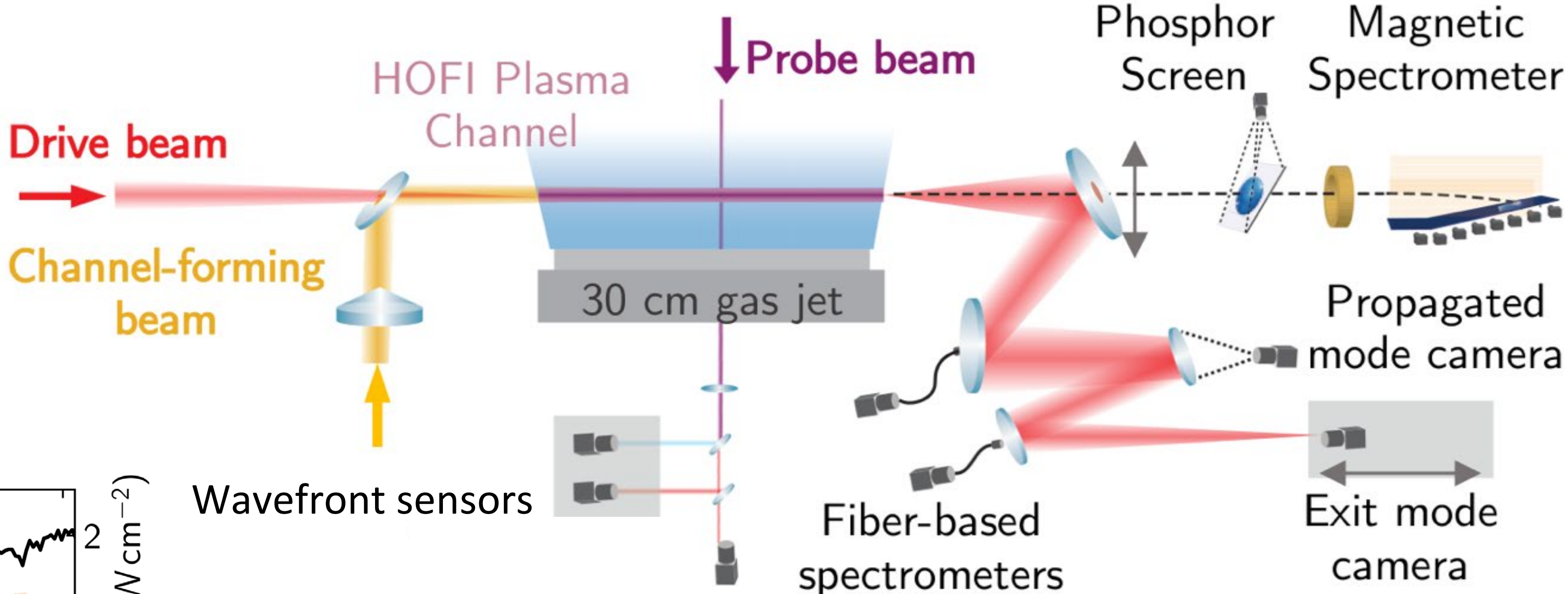
f = 13.5 m

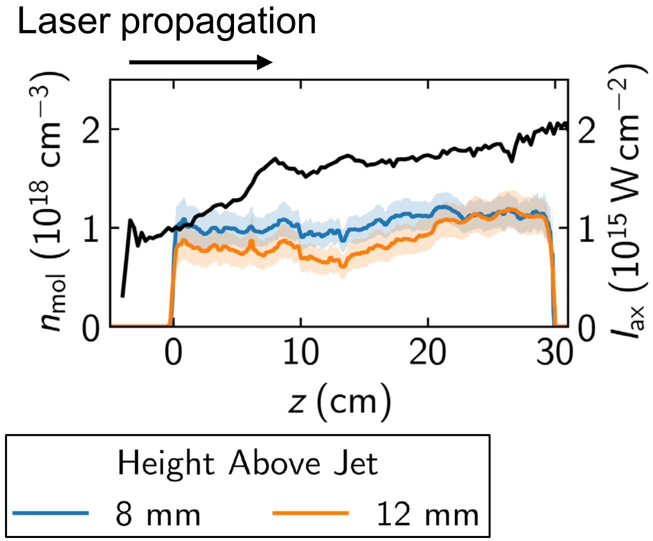
Target Chamber

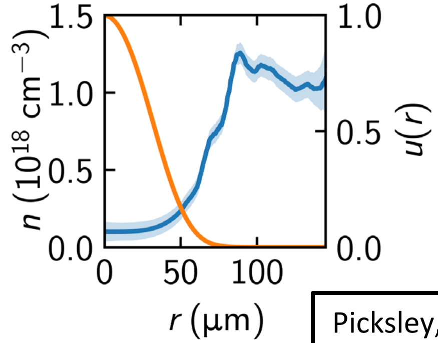
- Significantly extends science reach of BELLA PW:
  - PW guiding in HOFI plasma channels
  - Unmatched platform to study physics of multi-stage, multi-GeV LPAs
  - Optical injection
  - QED

We can leverage the BELLA PW infrastructure and diagnostics for HOFI channel experiments



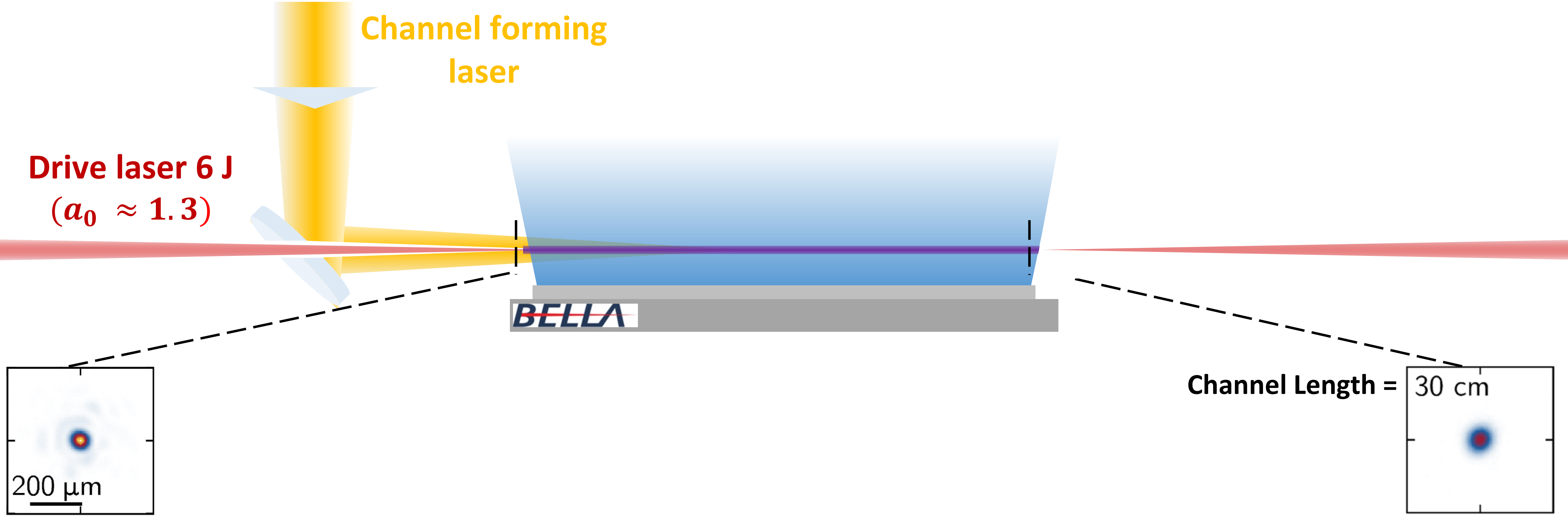






Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)
Nakamura, K., et al. *IEEE JQE* **53**.4 (2017)

Control over plasma length provides insight into laser propagation inside HOFI channels



Vacuum focal spot

Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)

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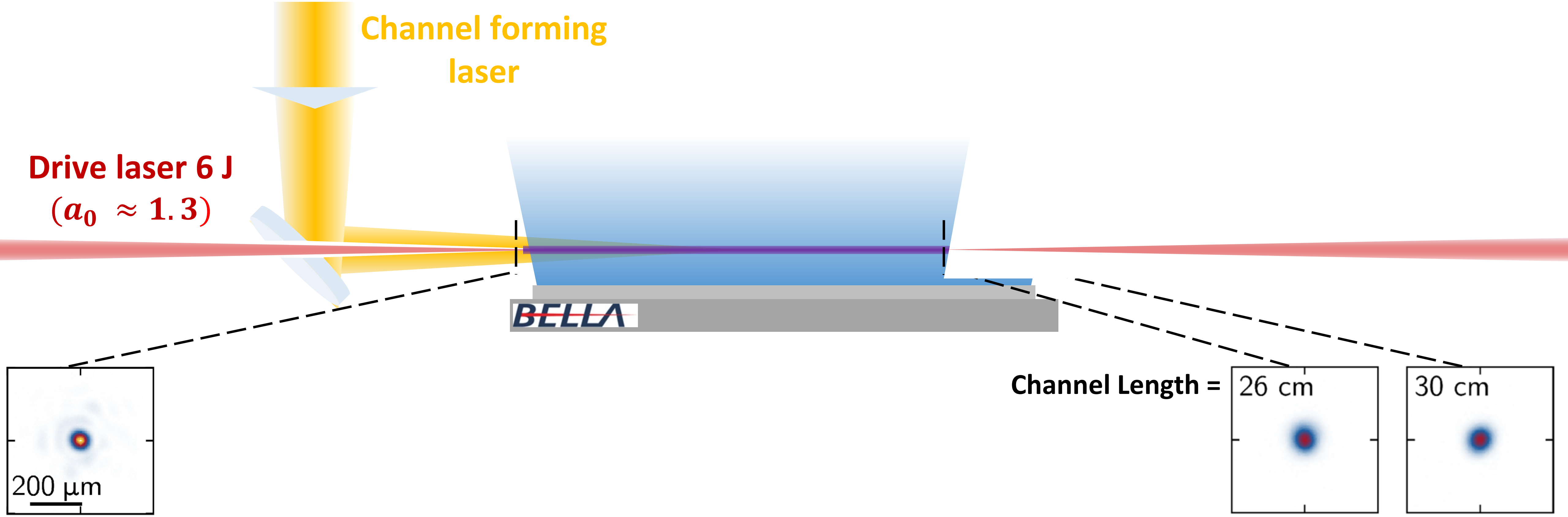

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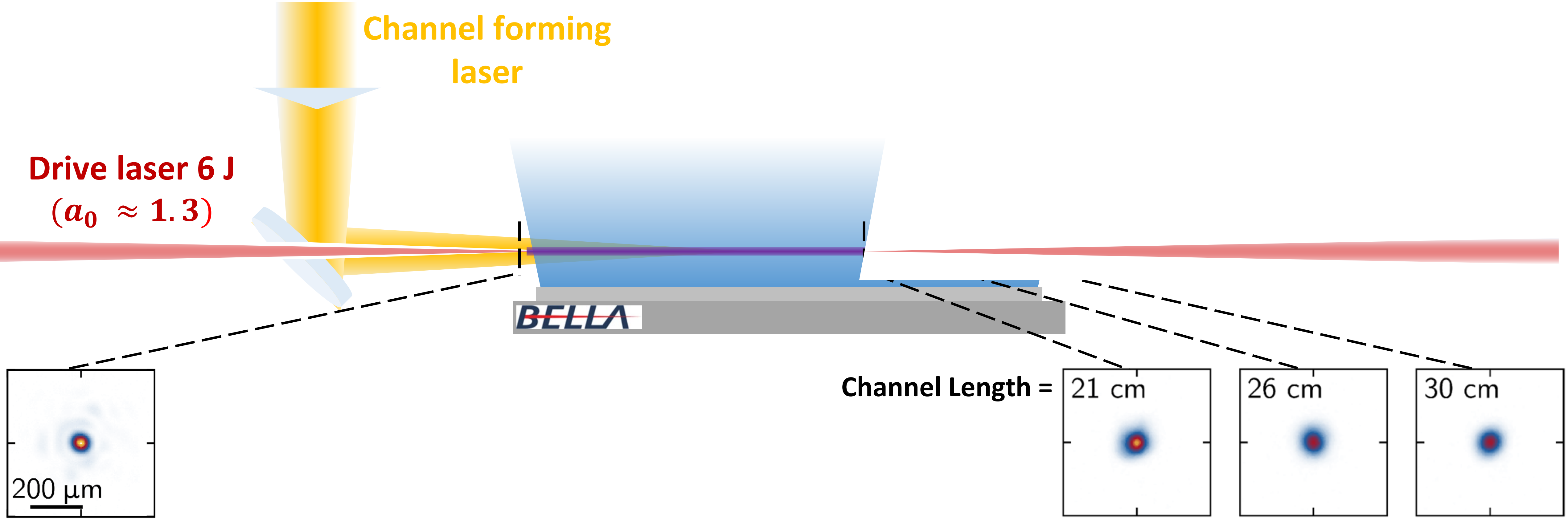

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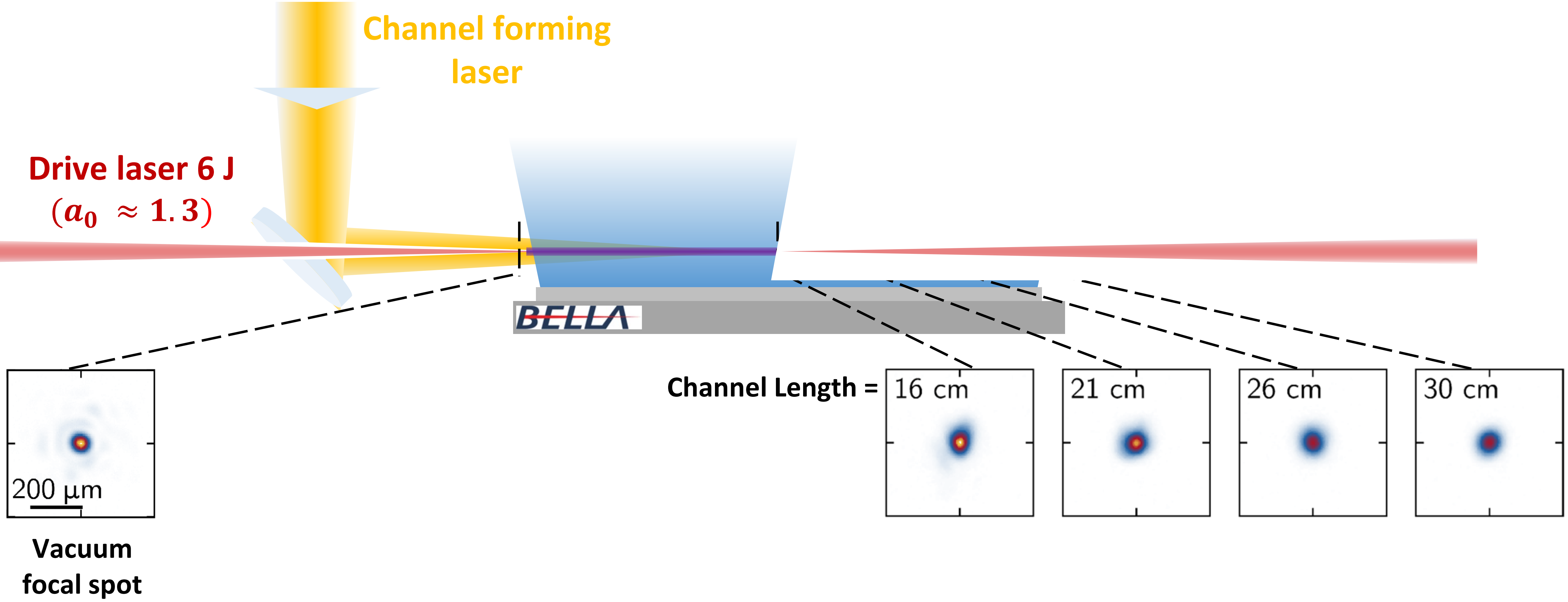

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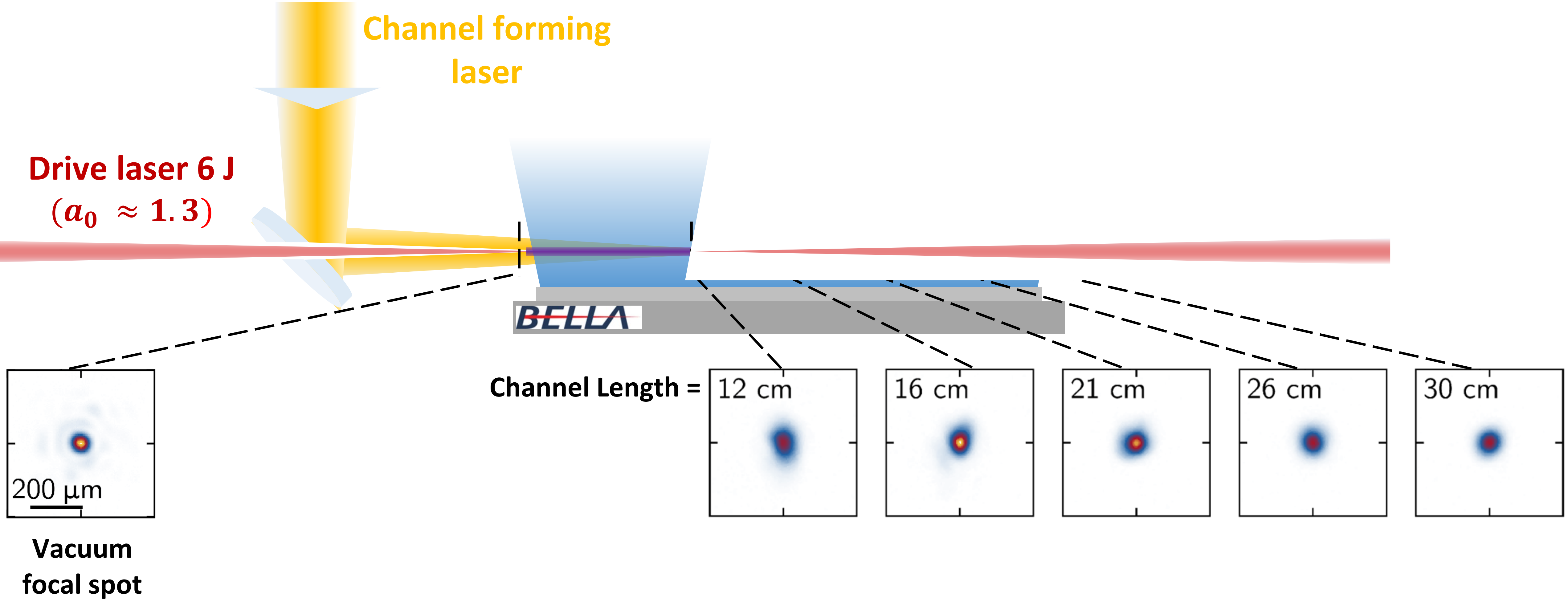

Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)

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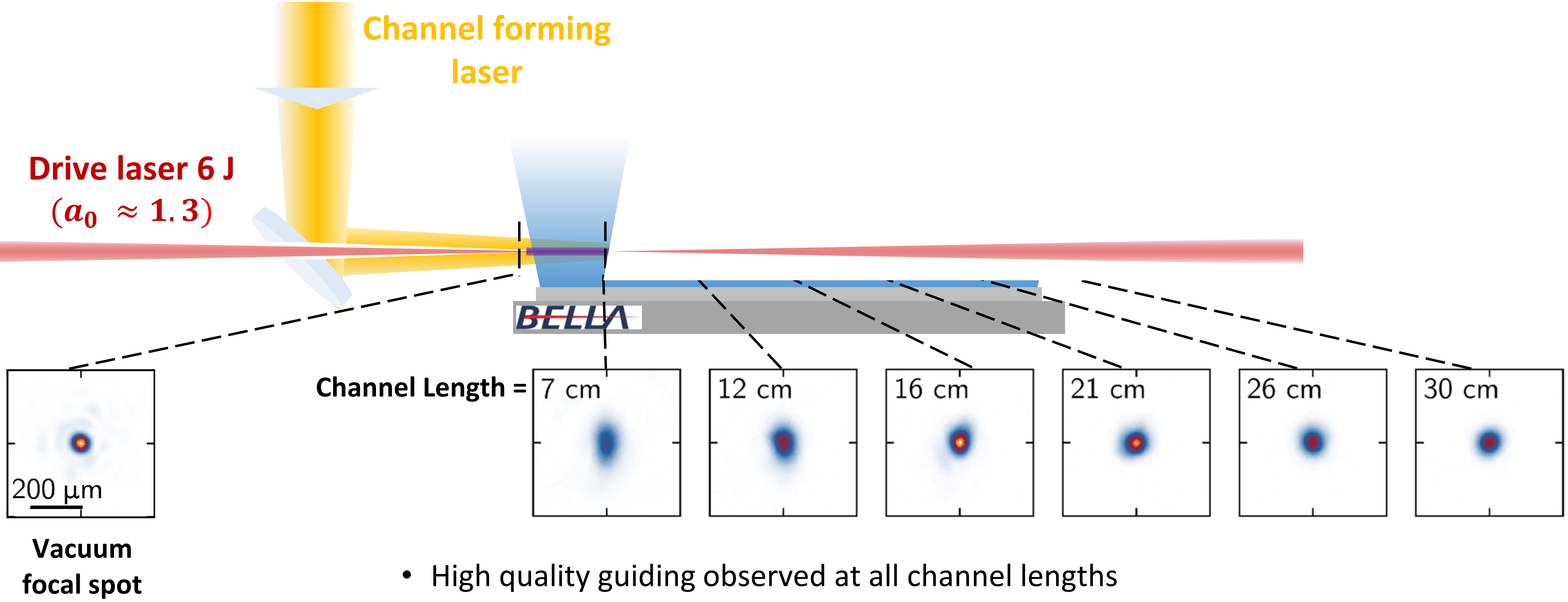

- High quality guiding observed at all channel lengths
- Minimal laser mode evolution beyond z = 12cm indicates matched guiding

Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)

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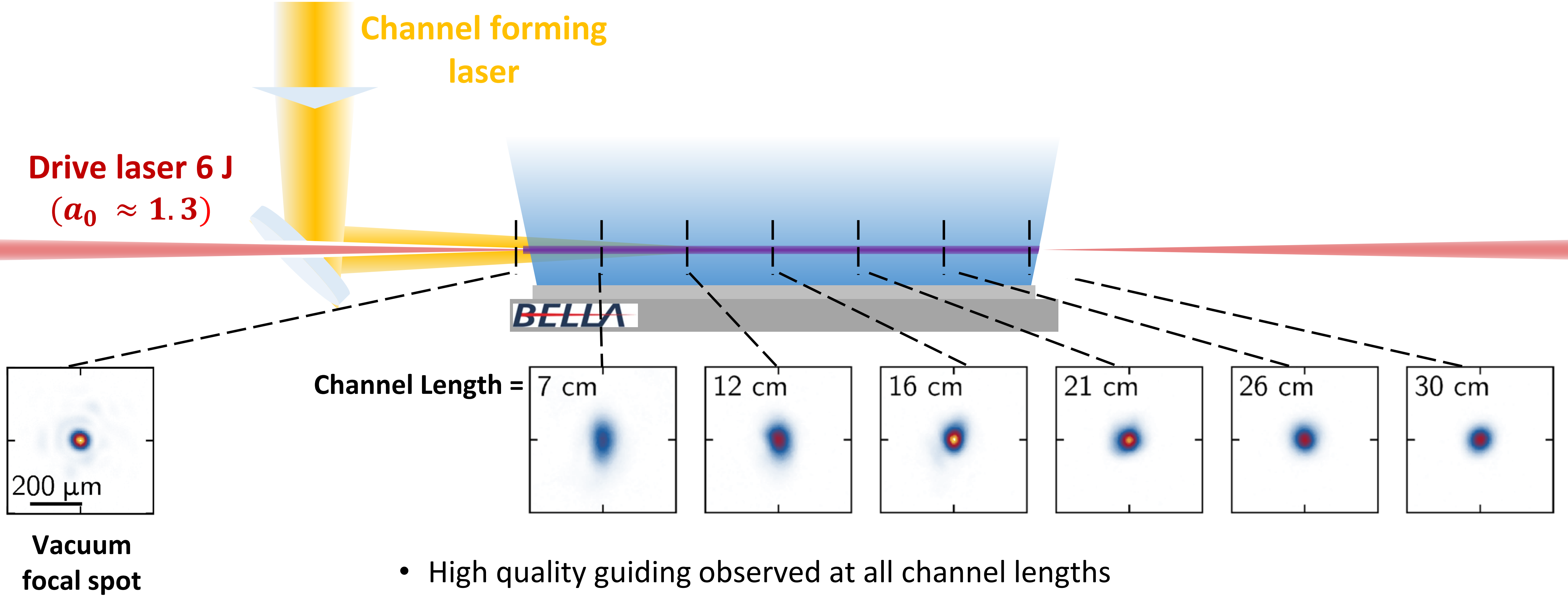

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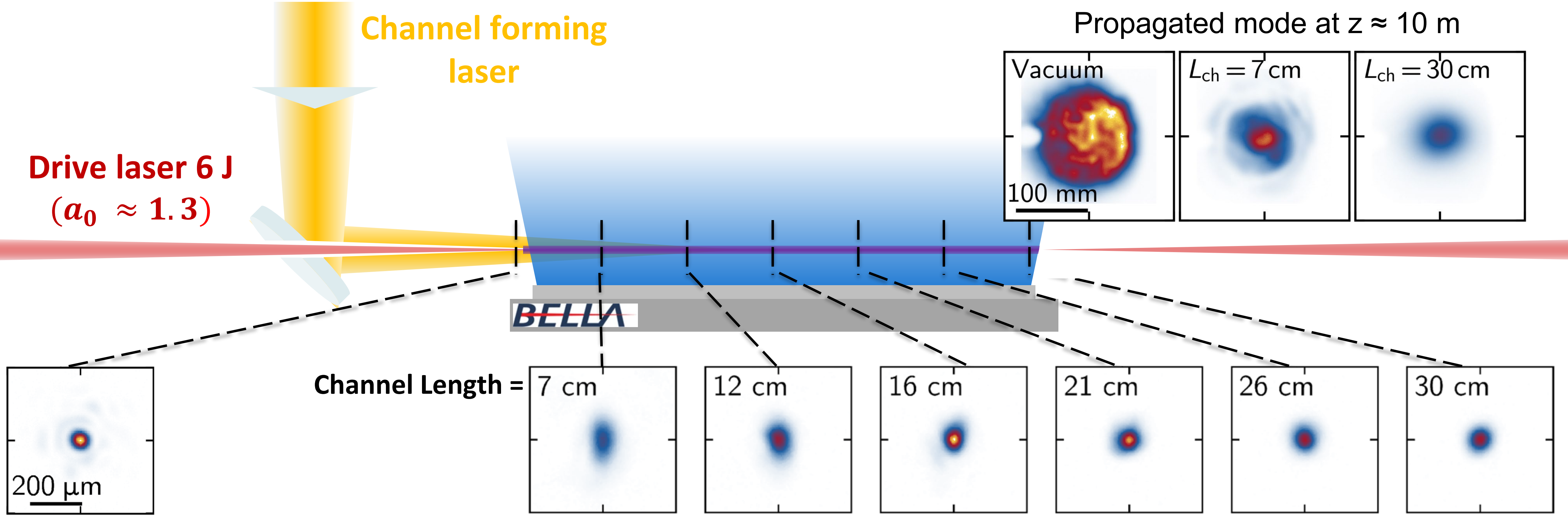

Vacuum focal spot

- Propagated modes also illustrate laser evolution at the start of the channel
- Initial vacuum mode is supergaussian then transforms to approximately gaussian

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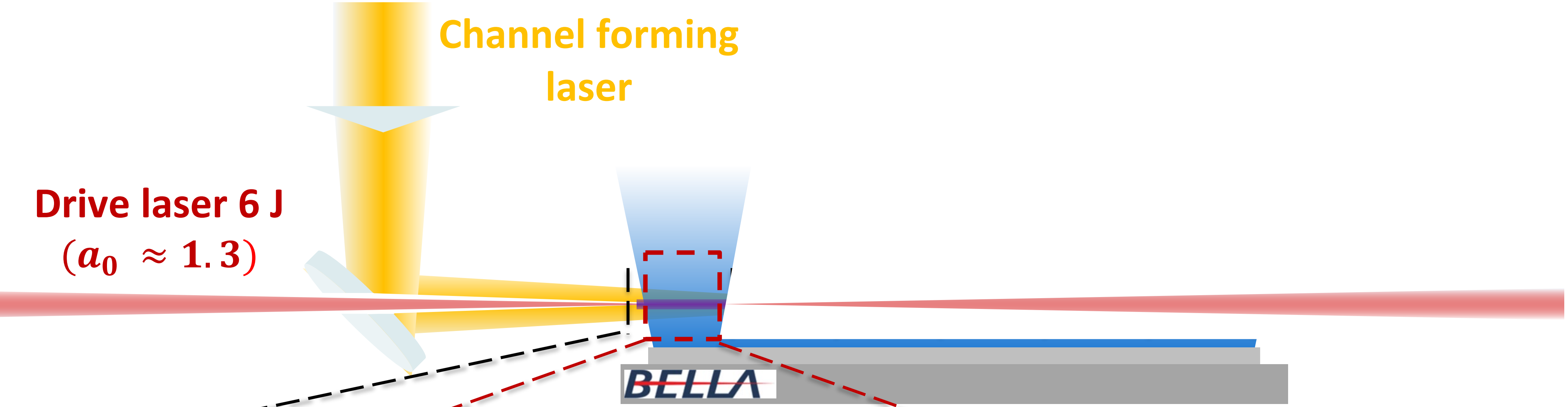
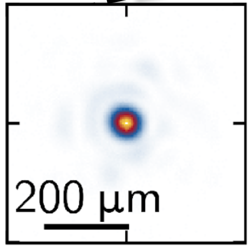
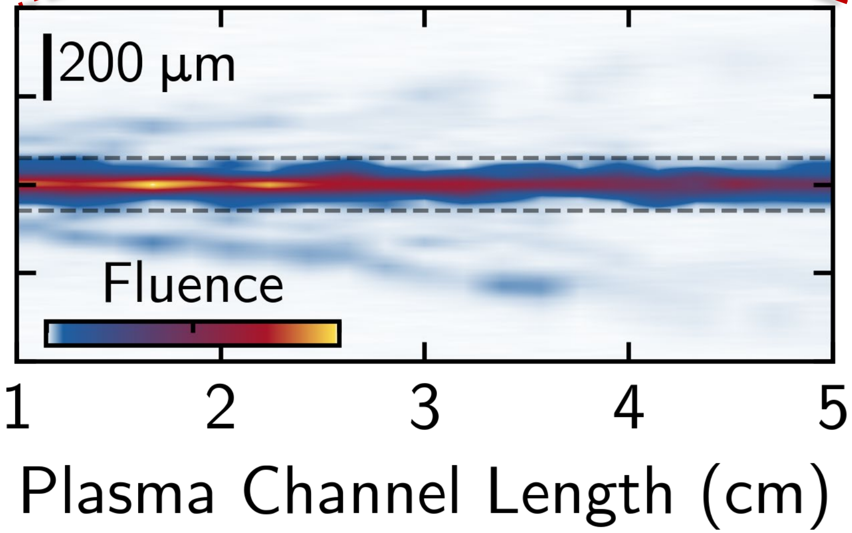
Control over plasma length provides insight into laser propagation inside HOFI channels





Vacuum focal spot

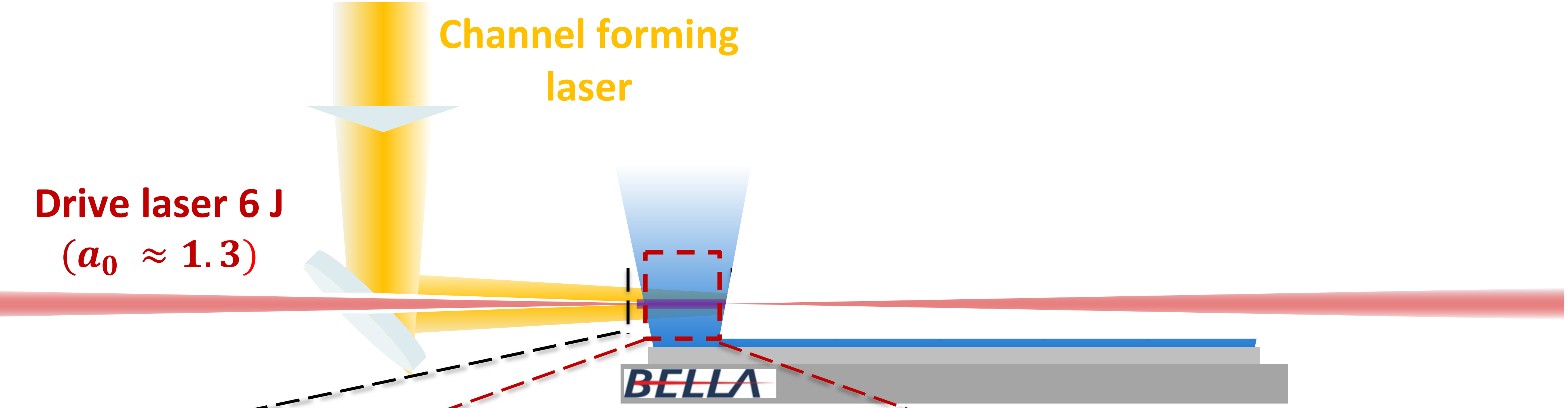


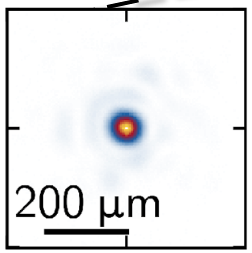
Propagation in the initial section of plasma

- First 5 cm with 2 mm step
- Evidence of mode leakage
- Central fluence peak surrounded by ring of higher order modes "leaking" out of the channel

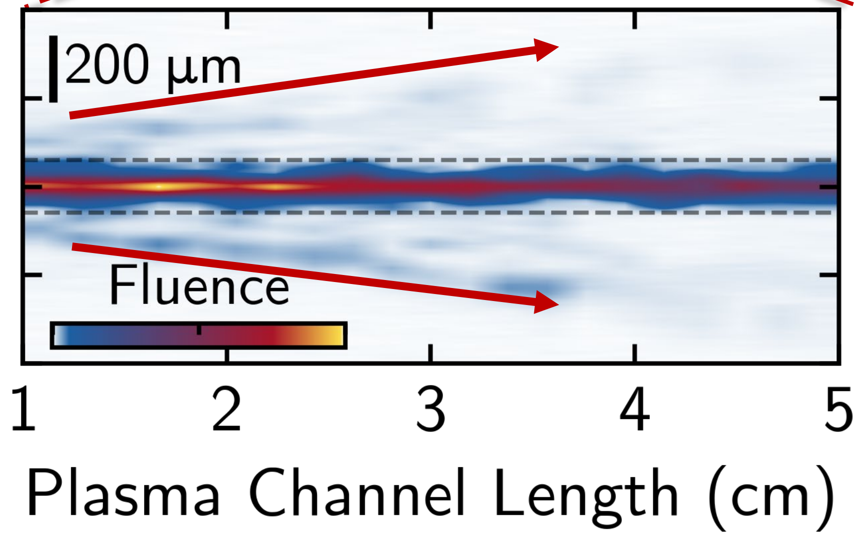
Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)
Mode Leakage: Clark, T. R., et al. *PRE* **61**.2 (2000).

Control over plasma length provides insight into laser propagation inside HOFI channels





Vacuum focal spot



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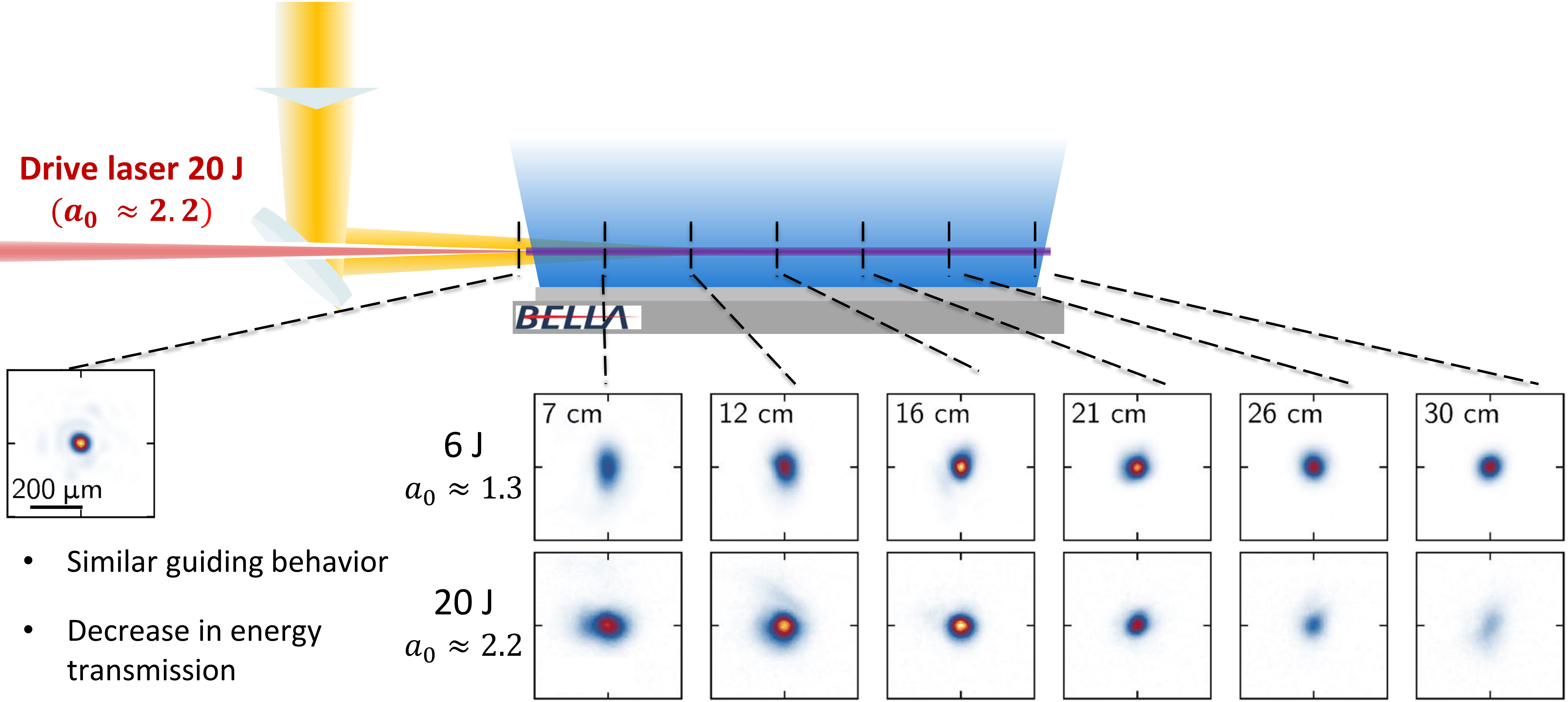
With higher drive laser energy, we see increased laser depletion as more energy is transferred to the wakefield



- Similar guiding behavior
- Decrease in energy transmission

Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)

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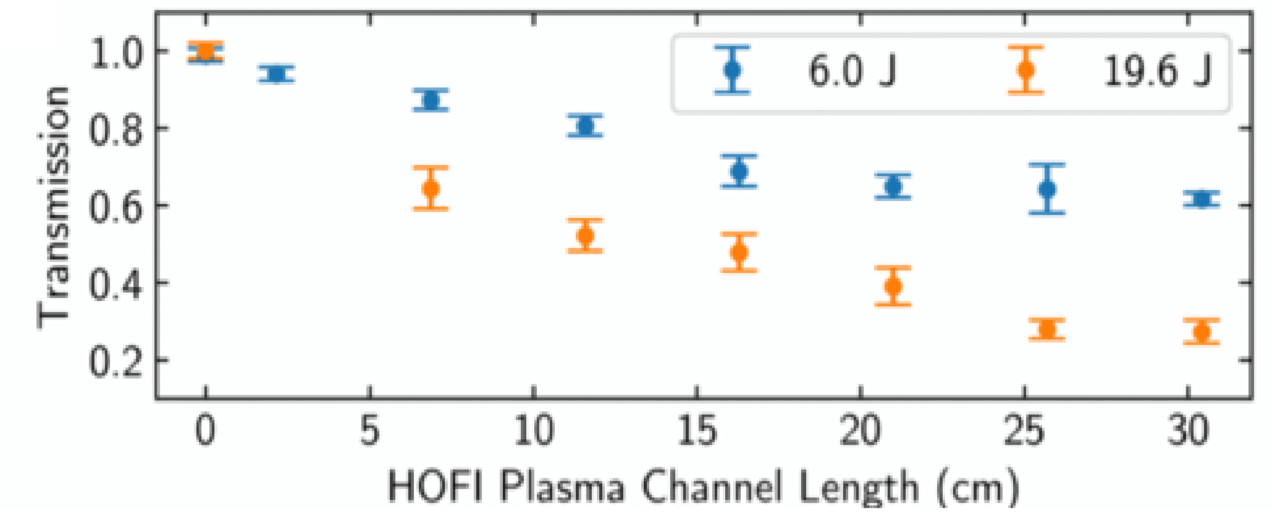
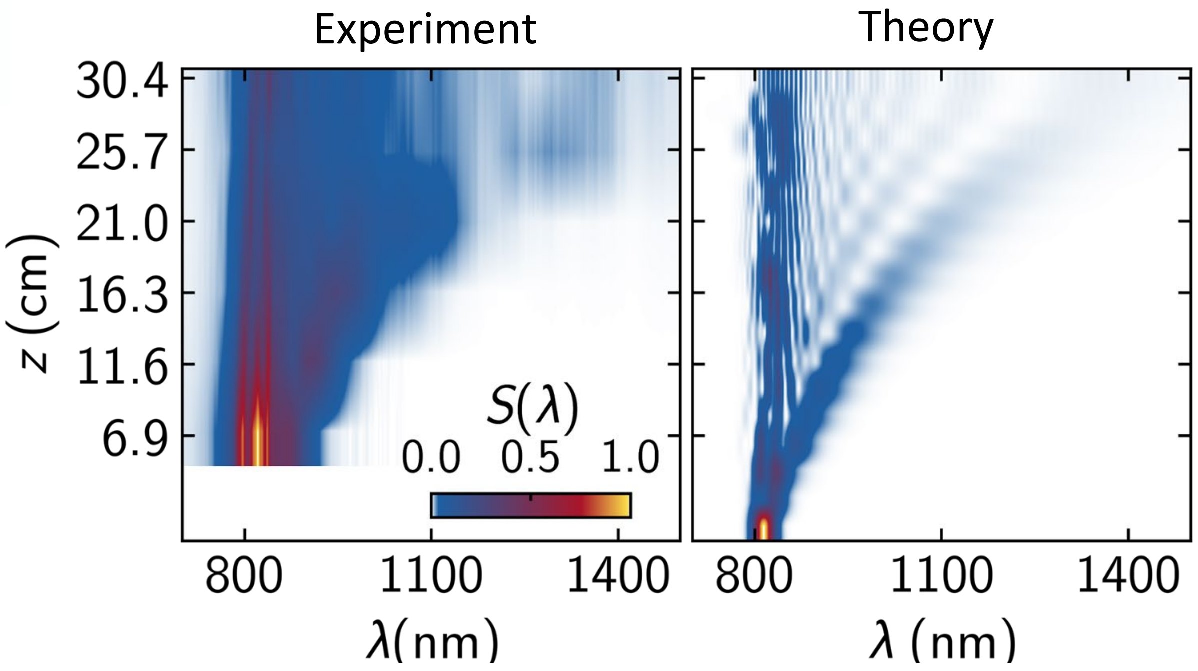


- Decrease in transmission at higher laser energy
- Optical spectrum shows gradual redshifting
- Results supported by simulations using INF&RNO



Maximizing laser-to-wake energy transfer important to LPA efficiency

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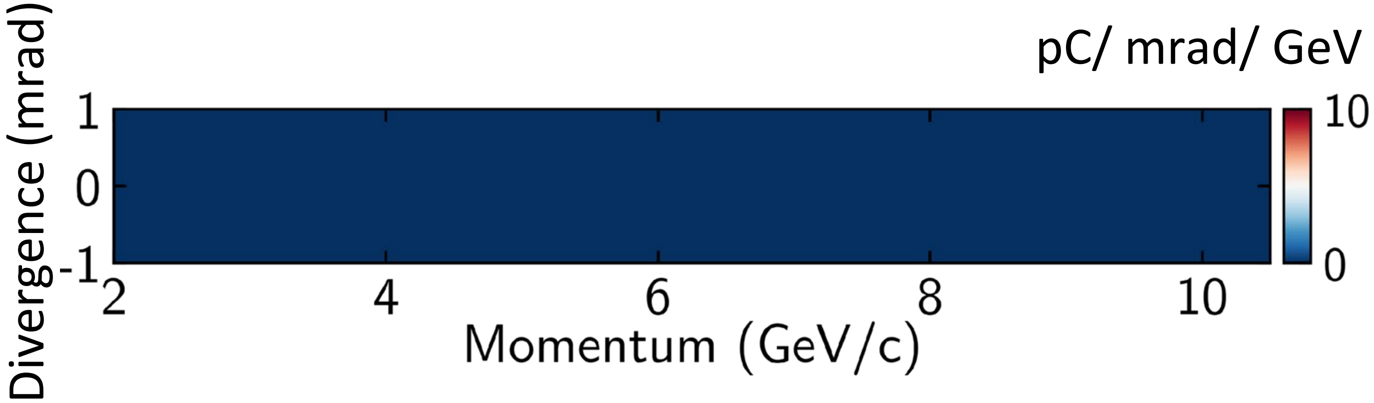
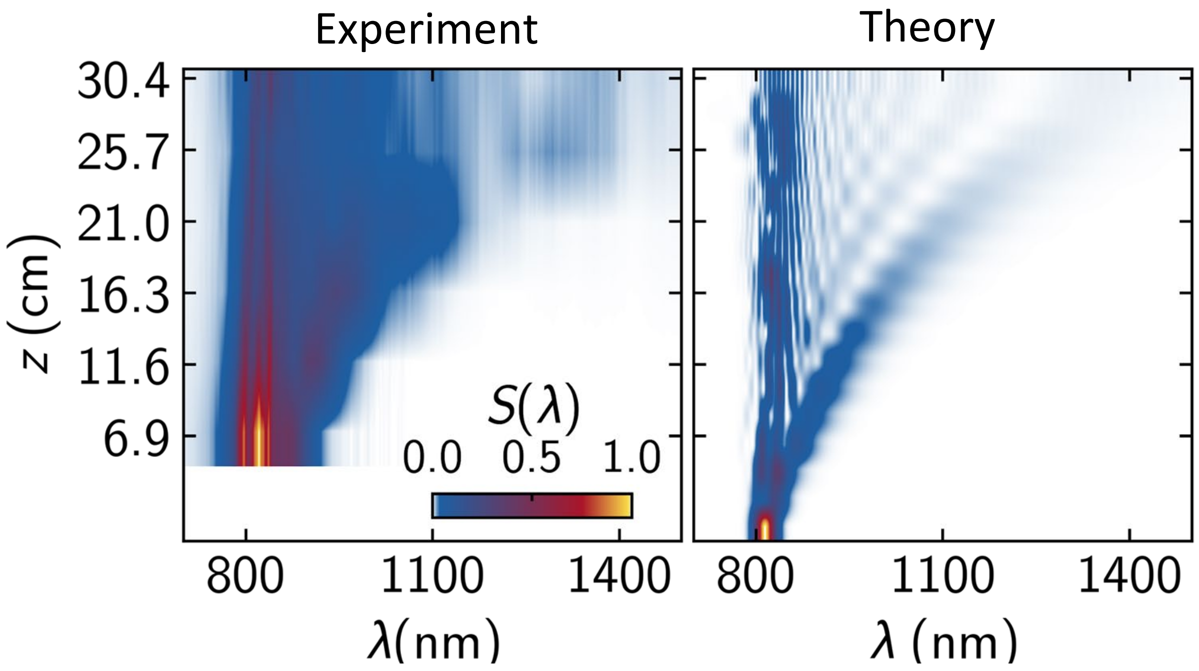
While driving a wakefield, we do not inject any charge via self-trapping



20 J laser energy $(a_0 \approx 2.2)$



- Due to lower plasma density, we suppress self-trapping
- **Dark-current-free accelerator!**

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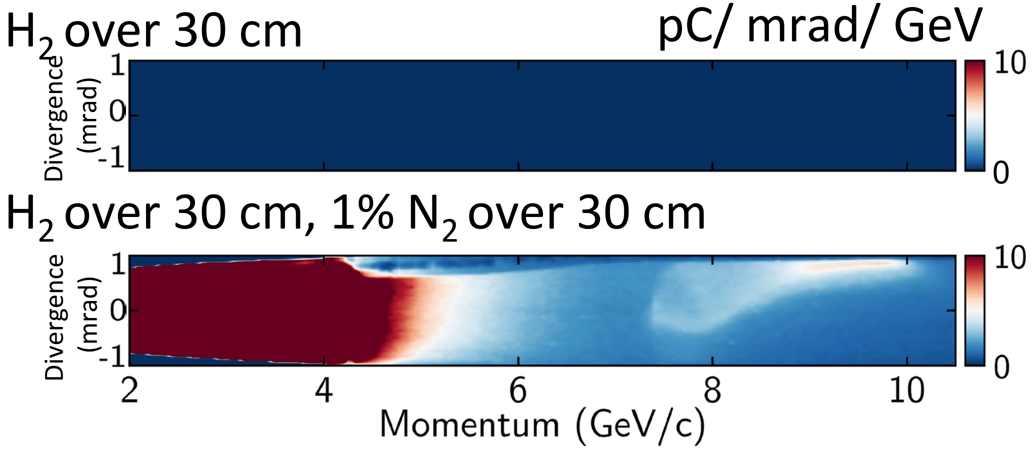
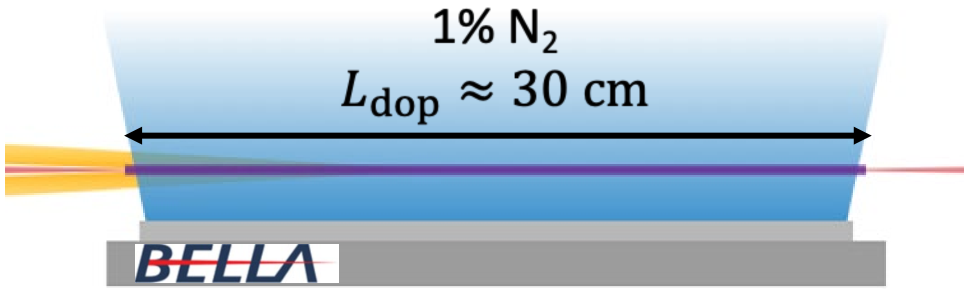
By adding a nitrogen dopant, we could trigger injection



482 pC



- Ionization injection triggered throughout
- Broad energy spread with most charge < 5 GeV & some charge exceeding 10 GeV
- Beams with charge up to ~1nC

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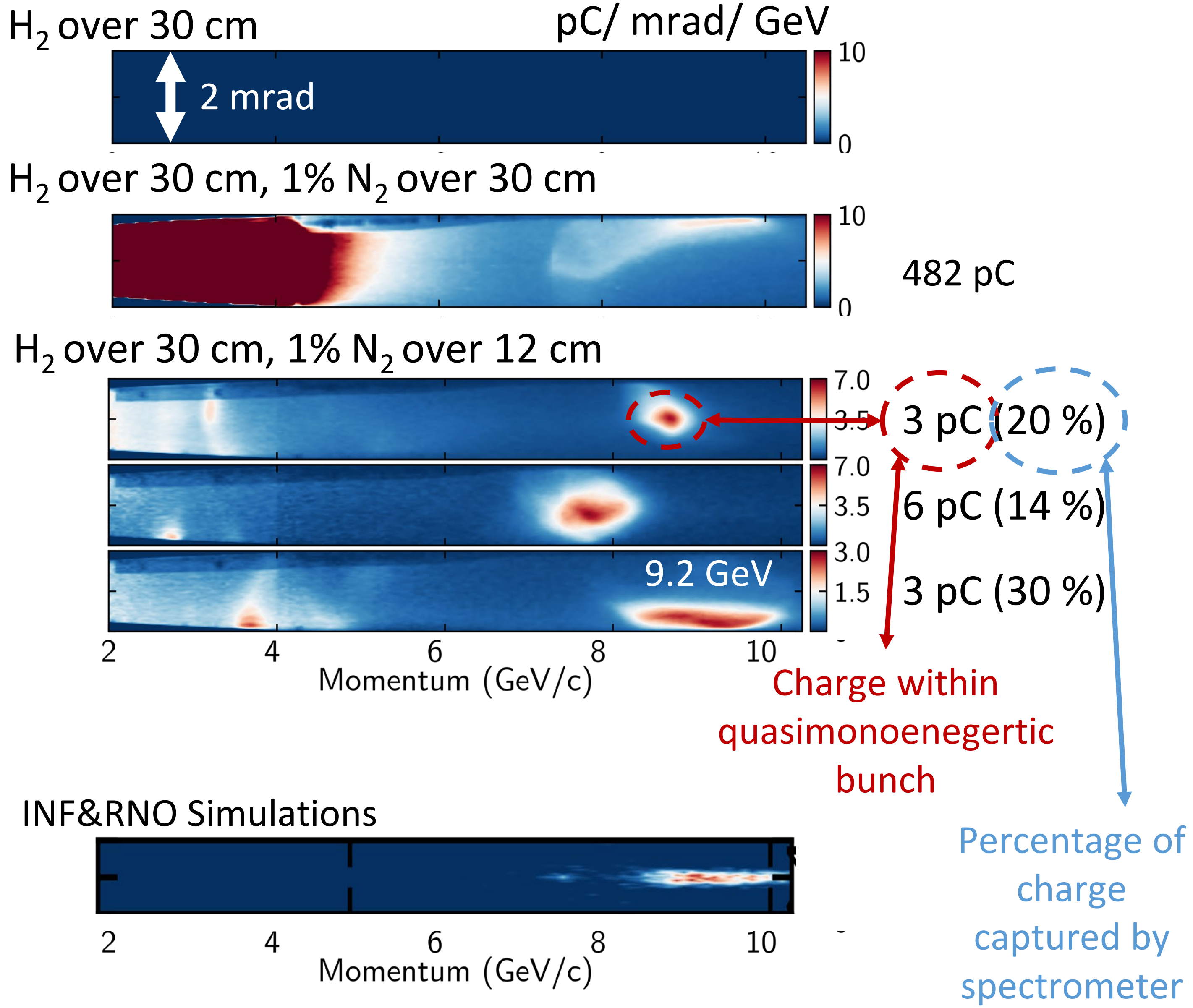
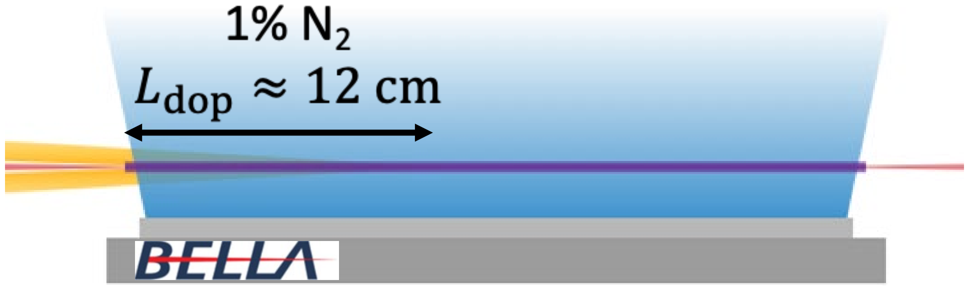
Controlling electron trapping using a restricted nitrogen dopant generated high quality beams at the 10 GeV level





- Dopant restricted within jet: $L_{dop} \approx 12$cm
  - Single, quasimonoenergetic peaks
- No significant beams observed with $L_{dop} \approx 6$cm
  - Trapping must occur in the $6 \lesssim z \lesssim 12$ cm region
- Good agreement with simulations

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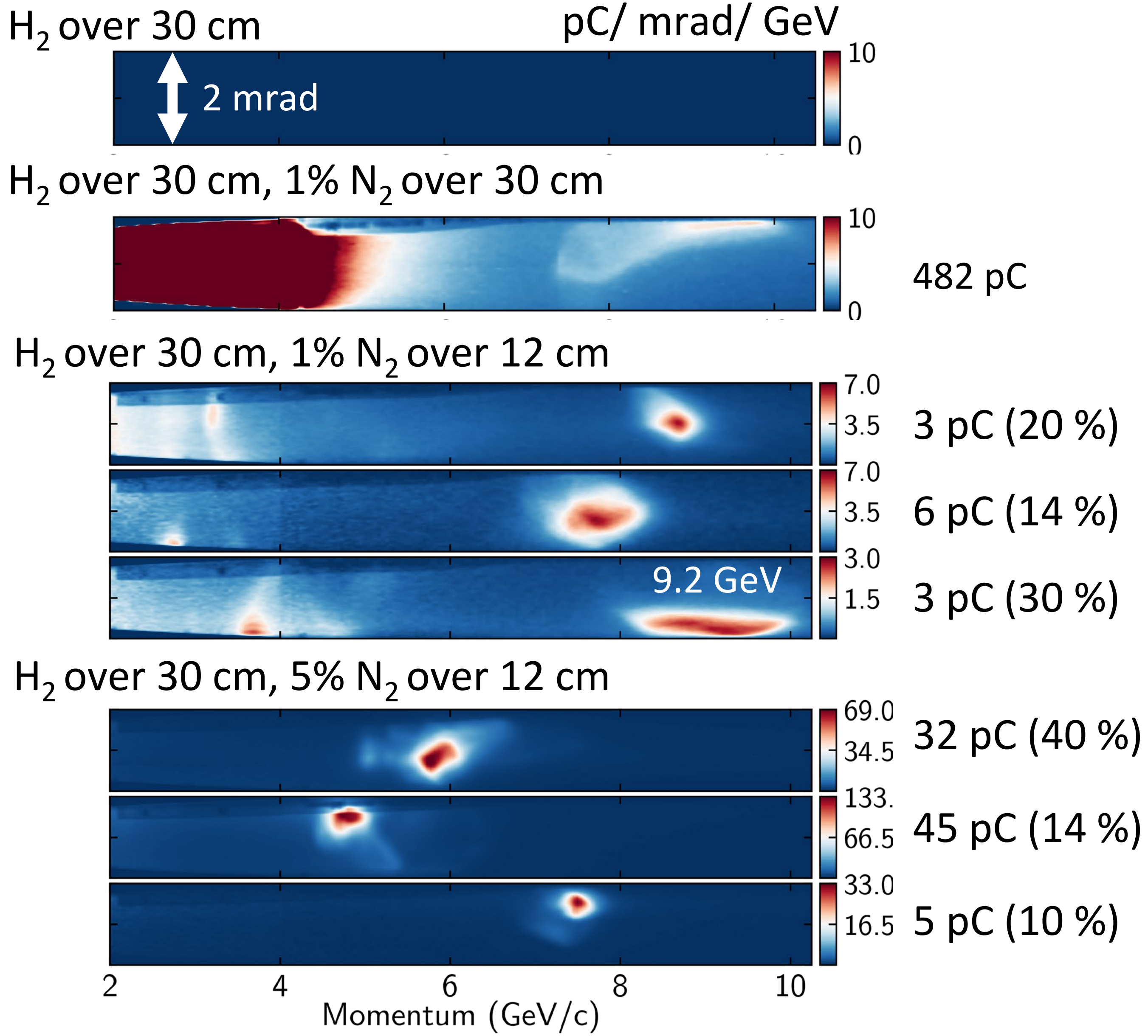
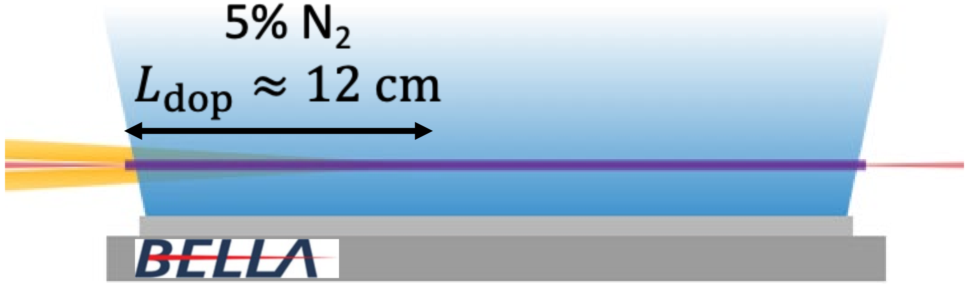
Increasing the dopant concentration to 5% provided high charge (~ 100 pC) beams with relative energy spread as low as 3 %





- Increased dopant concentration to 5% over the same region
- Observed effects consistent with beam loading
  - Increased beam charge
  - Reduced energy spread
  - Lower maximum energy

Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)

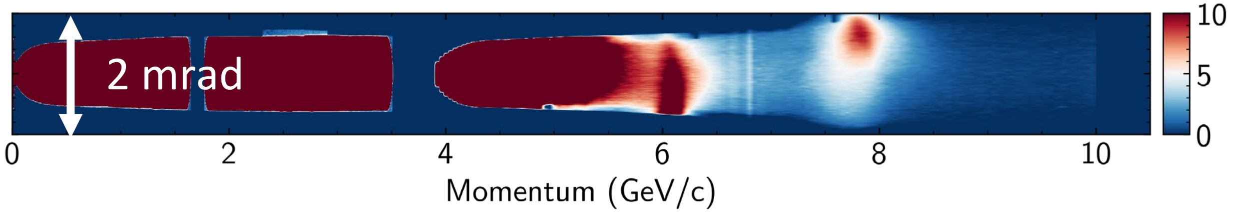
HOFI plasma channels enable accelerator operation at optimal density suppressing injection of unwanted charge

2019 – Laser heated capillary discharge

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

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

$U_{\mathrm{laser}} \approx 31\ \mathrm{J}$



Self-injection

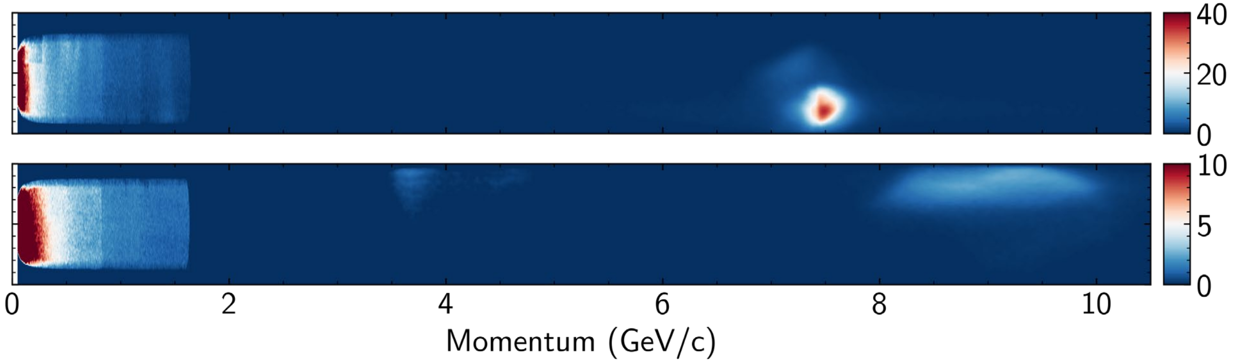
2024 – HOFI Plasma Channel

+ Localised Dopant

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

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

$U_{\mathrm{laser}} \approx 20\ \mathrm{J}$

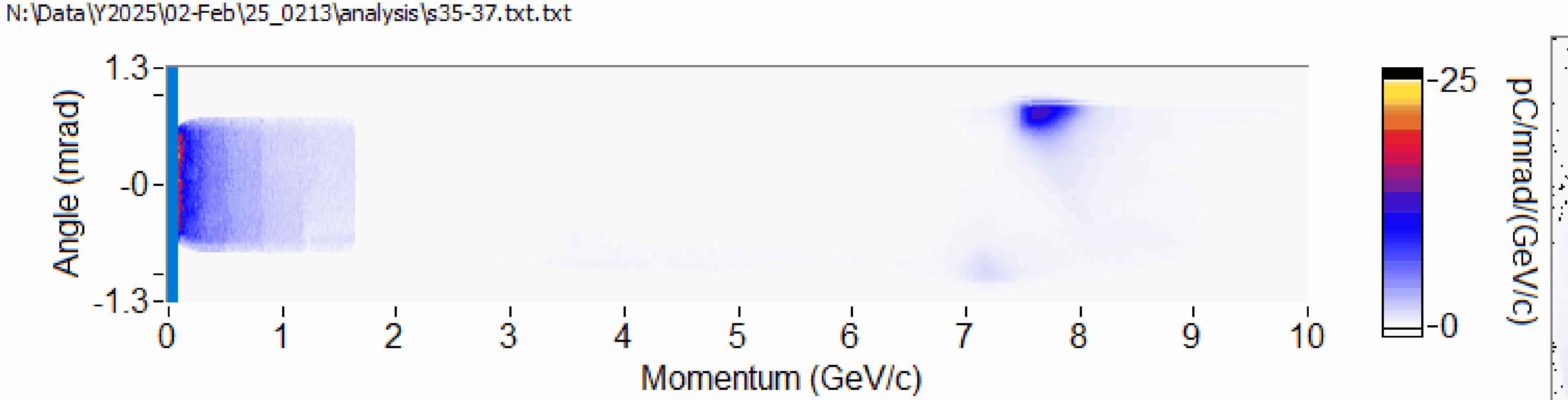


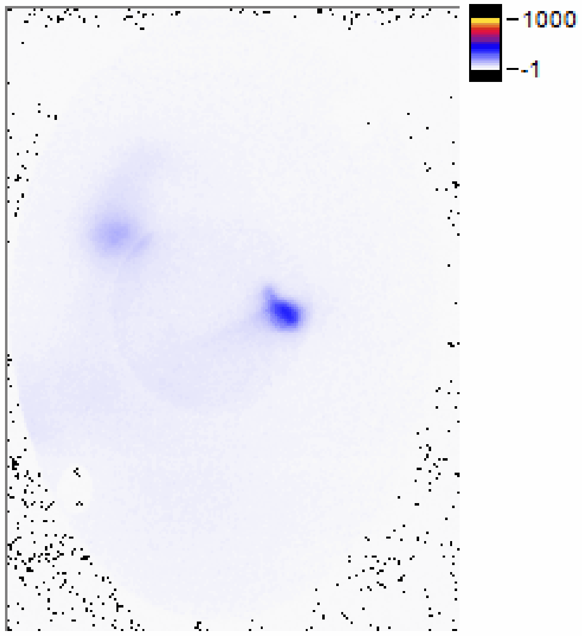
5% dopant

1% dopant

- 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

Recent experiments successfully replicate results



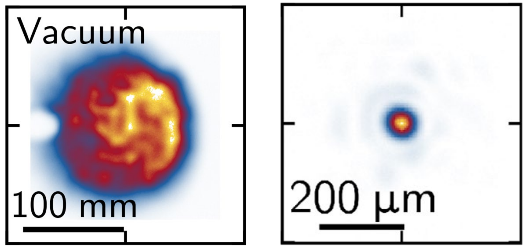


Note:

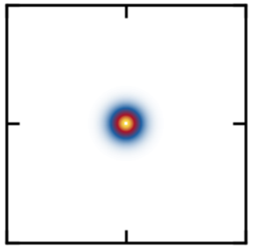
- Many shots do not make pass the acceptance of our electron spectrometer
  - As a result, this is a filtered percentage of our data
- We are currently working to improve stability in upcoming experiments

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

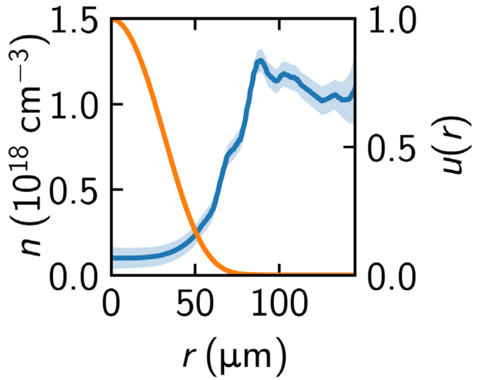
Experimental Mode

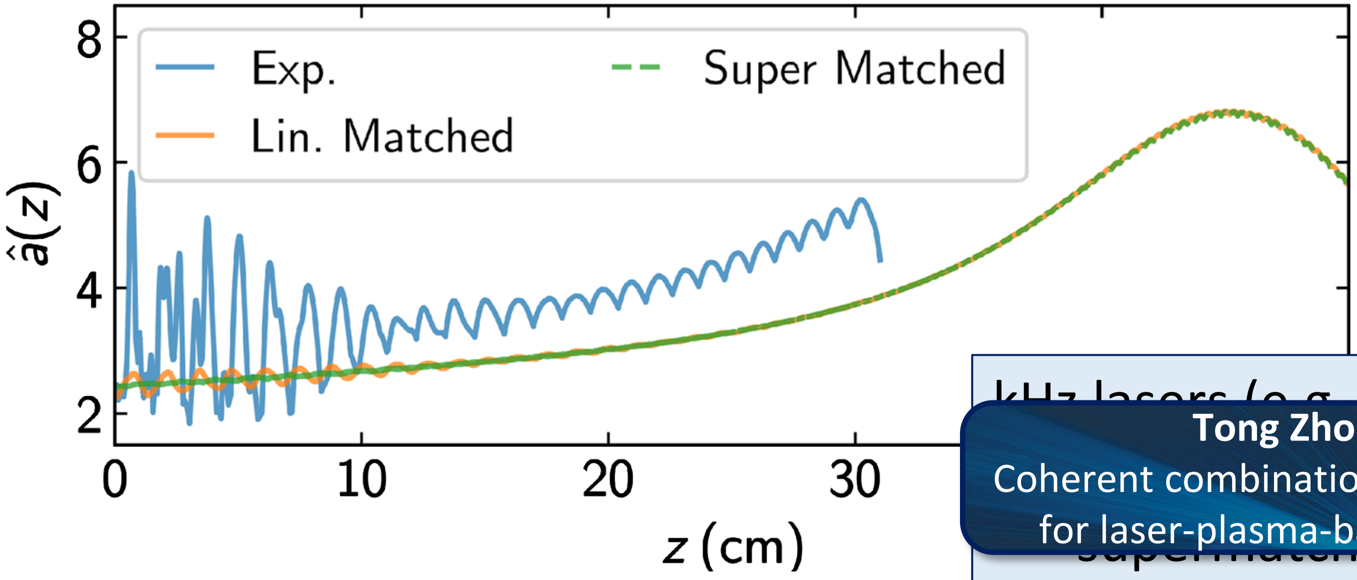


Linearly Matched



- Mode beating causes intensity oscillations that prevent high charge for $L_{\text{dop}} \lesssim 6$ cm – as shown in experiments!
- Matching laser pulse to the channel reduces mode beating and maintains charge injected at $z \approx 0$





9.2 GeV, 9 pC

13.0 GeV, 65 pC

13.1 GeV, 105 pC

Tong Zhou - Friday – 9:30
Coherent combination of high-power fiber lasers for laser-plasma-based collider applications

Picksley, A., et al. *Physical Review Letters* **133**.25 (2024)
Mode beating: Esarey, E., et al. *PRE* **59**.10 (1999), *PRL* **84**.30 (2000)
Mode beating in optical channels: Shrock, J. E., et al. *PRL* **133**.4 *(2024)*

Benedetti, C., et al. *PoP* **19**.5 (2012)
Benedetti, C., et al. *PRE* **92**.2 (2015)

Talk Outline

1. Importance of guiding in a laser-plasma accelerator

2. High-quality laser propagation and guiding in optically formed plasma channels

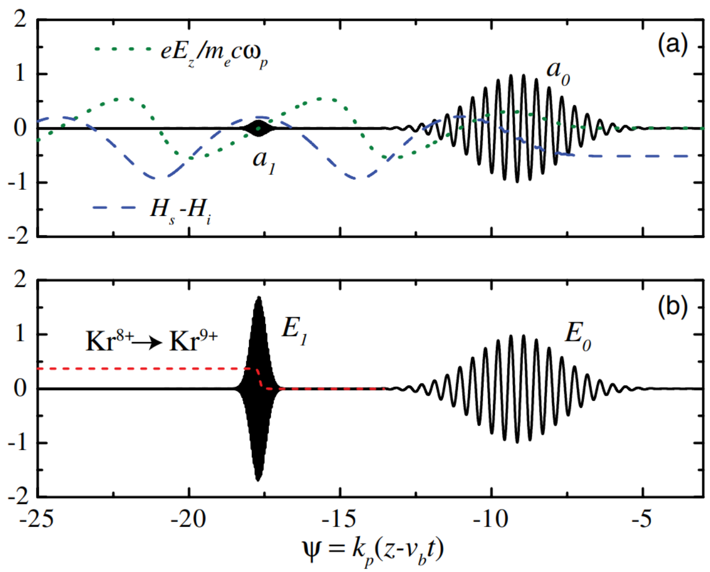
3. Controlled electron injection and acceleration of electron bunches up to 10 GeV

4. **Outlook towards future development and conclusion**

Single stage accelerators could be improved with injection techniques and longitudinal density gradients

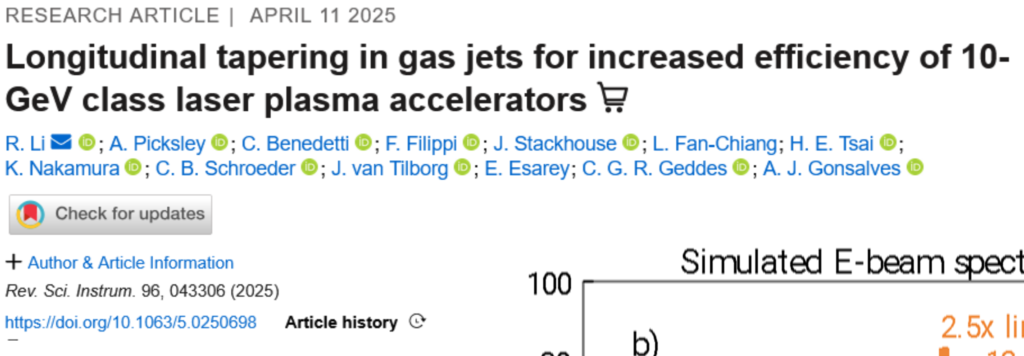
- Ultralow-emittance trapping schemes for requirements of future compact accelerators

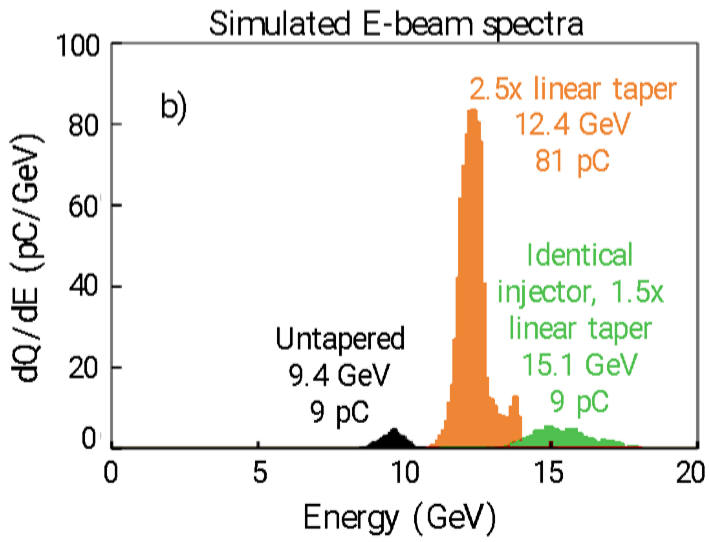
Two-color ionization injection



L.L. Yu et al., *Physical Review Letters* **112**.12 (2014)

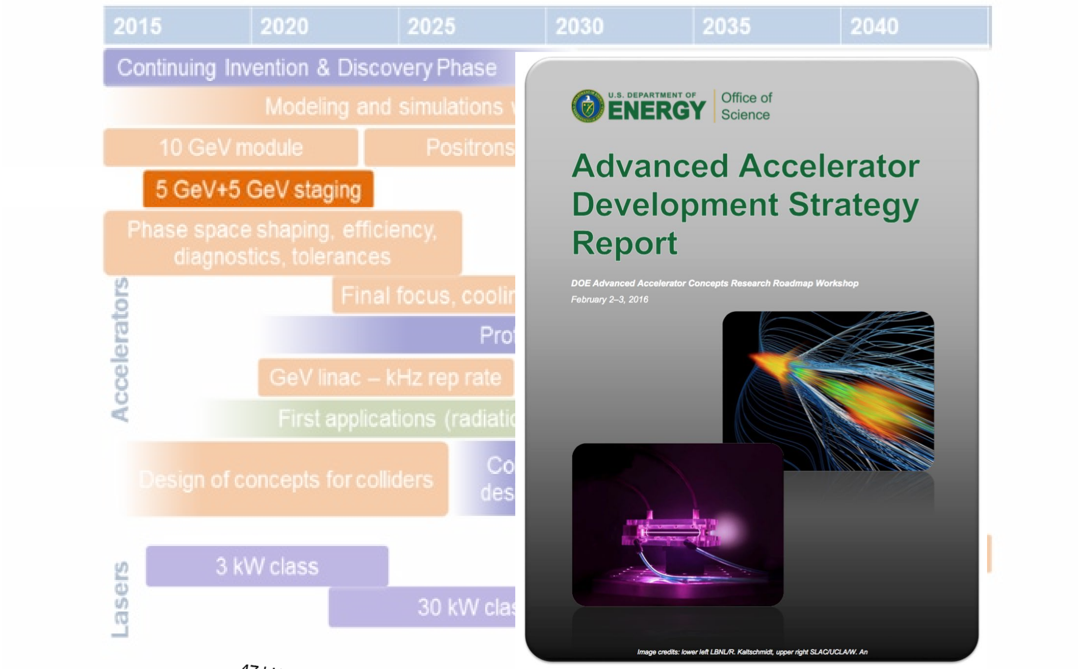
- Density gradient can maximize laser depletion and increase overall energy and bunch charge

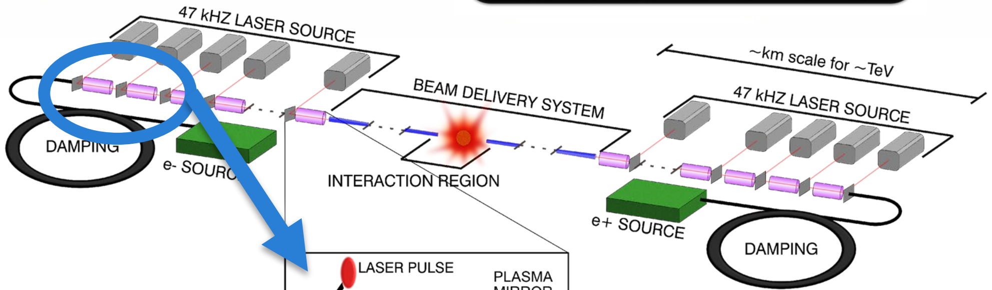


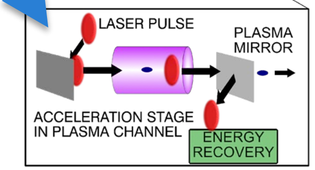


R. Li et al., *Rev. Sci. Instrum.* **96**.4 (2025)

Multi-GeV Staging is an important next step in the LPA collider roadmap

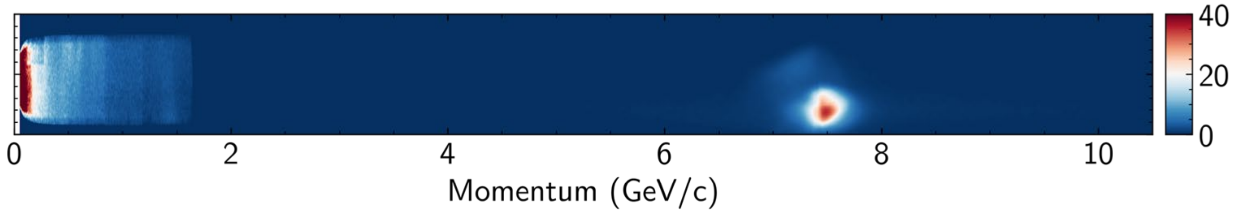






Also enabled by second beamline upgrade

- Staging at 100 MeV level demonstrated with low capture efficiency
- Here, demonstrated high-quality, > 5 GeV beam production using just half BELLA PW energy
  - Provides platform for dual stage experiments



- Next steps – investigate high capture efficiency staging

S. Steinke et al., *Nature* **530** (2016)

Conclusions

- Plasma channels formed by hydrodynamic expansion are suitable for 10-GeV-class laser plasma accelerators
- By varying the plasma channel length, mode filtering followed by matched guiding in 30-cm-long HOFI plasma channels present a path to improved efficiency
- 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

Thank you

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