EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Design of High Gradient Laser Plasma Accelerating Structure (WP3) Accelerating Structures

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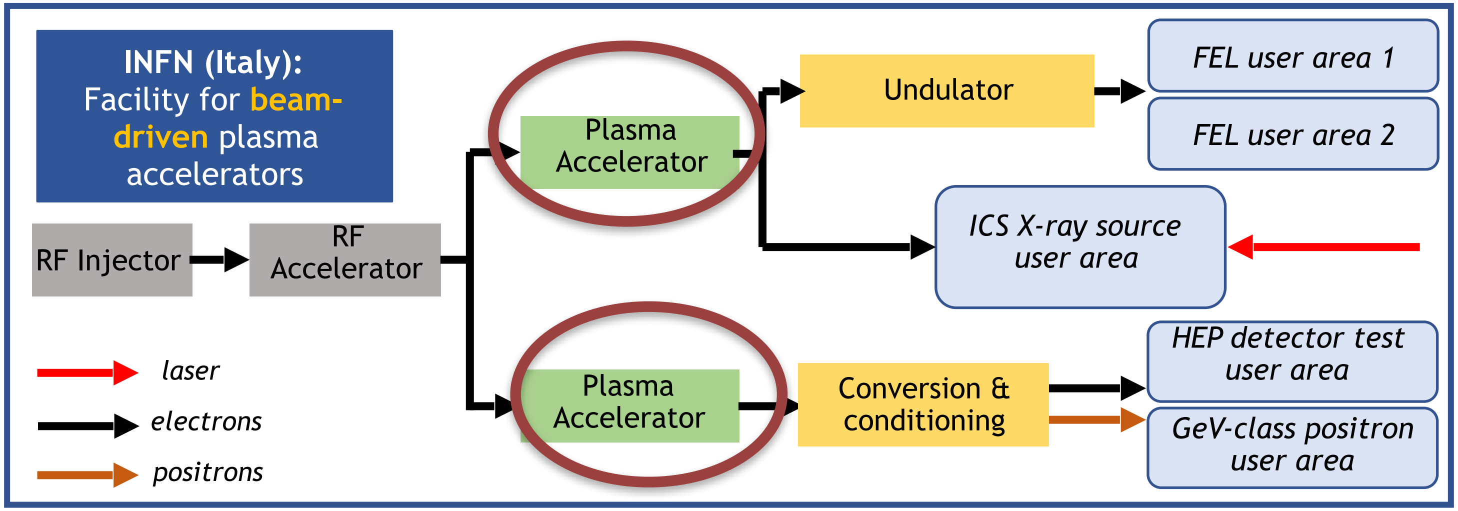
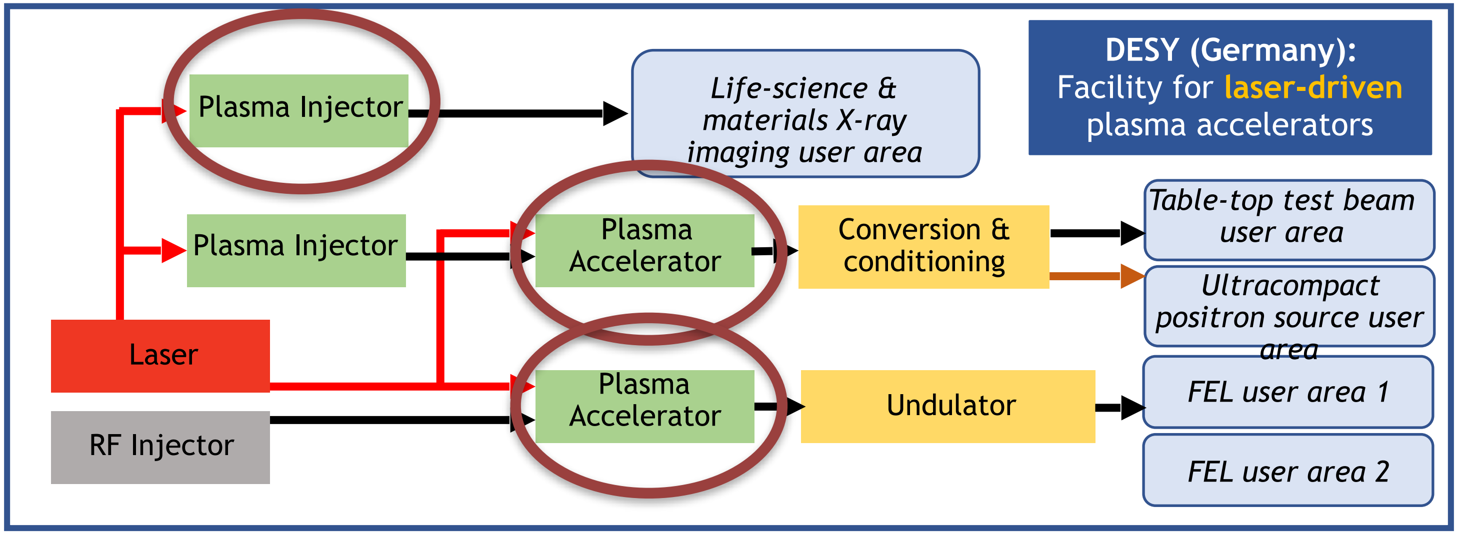
27th February 2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

EuPRAXIA concepts





LWFA density regimes

Energy gain in laser wakefield accelerator:

Linear Regime ($a_0 \simeq 1$):

$$W_{\max} = 2a_0^2 {\gamma_{\rm ph}}^2 mc^2 \approx a_0^2 (n_{\rm cr}/n_e)\,\text{MeV}$$

Non-linear Regime ($a_0 \gtrsim 2$):

$$W_{\max} = \tfrac{2}{3} a_0 {\gamma_{\rm ph0}}^2 mc^2 \approx \tfrac{1}{3} a_0 (n_{\rm cr}/n_e)\,\text{MeV}$$

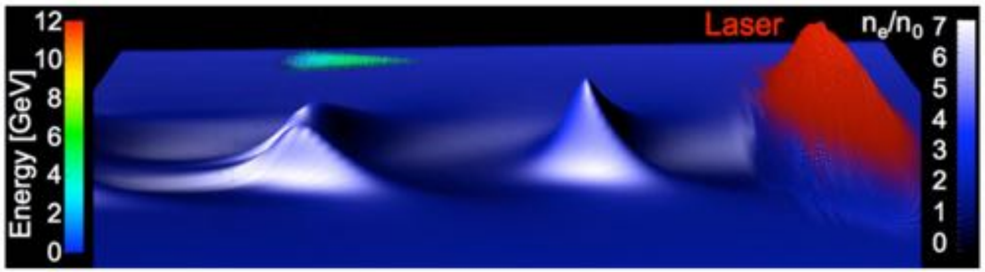
Sets density for interaction

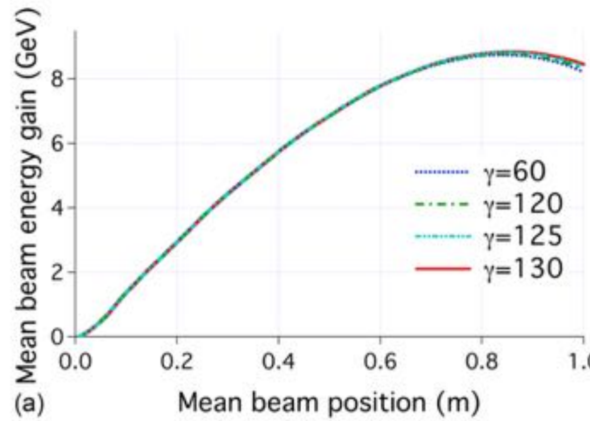
For 1 GeV gain: $n_e \approx 10^{-3}\, n_{\rm cr} \approx 2 \times 10^{18}\,\text{cm}^{-3}$

For 4 GeV gain: $n_e \approx 2.5\times 10^{-4}\, n_{\rm cr} \approx 5 \times 10^{17}\,\text{cm}^{-3}$

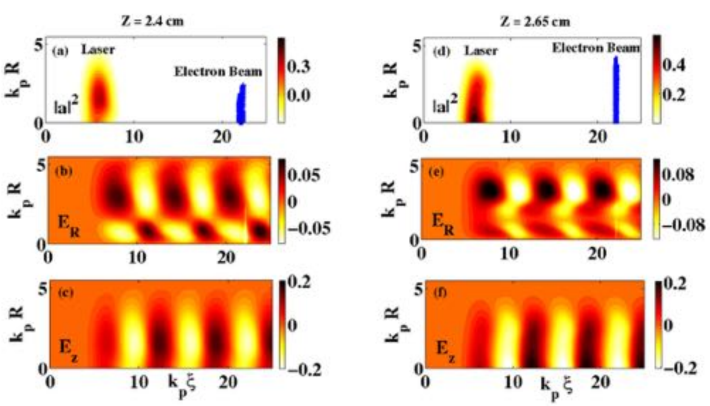
LWFA density regimes

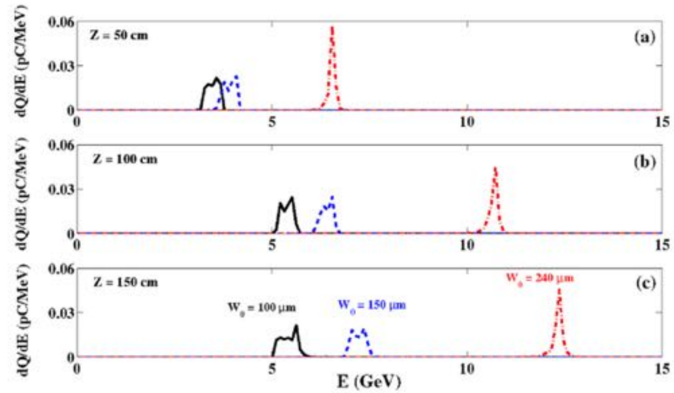
Simulations of multi-GeV stages:





J. Vay, et al. Modeling of 10 GeV-1 TeV laser-plasma accelerators using Lorentz boosted simulations, 18, 123103 (2011).





B. S. Paradkar et al, Numerical modeling of multi-GeV laser wakefield electron acceleration inside a dielectric capillary tube, 20, 083120 (2013).

Interaction lengths

Interaction (dephasing) length:

$$L_{\rm dp} \approx {\gamma_{\rm ph}}^2 \lambda_p \approx \left(n_{\rm cr}/n_e\right)^{3/2} \lambda_0$$

$$\text{For 1 GeV gain:} \quad \left(n_{\rm cr}/n_e\right) \approx 1000, \quad L_{\rm dp} \approx 3\,\text{cm}$$

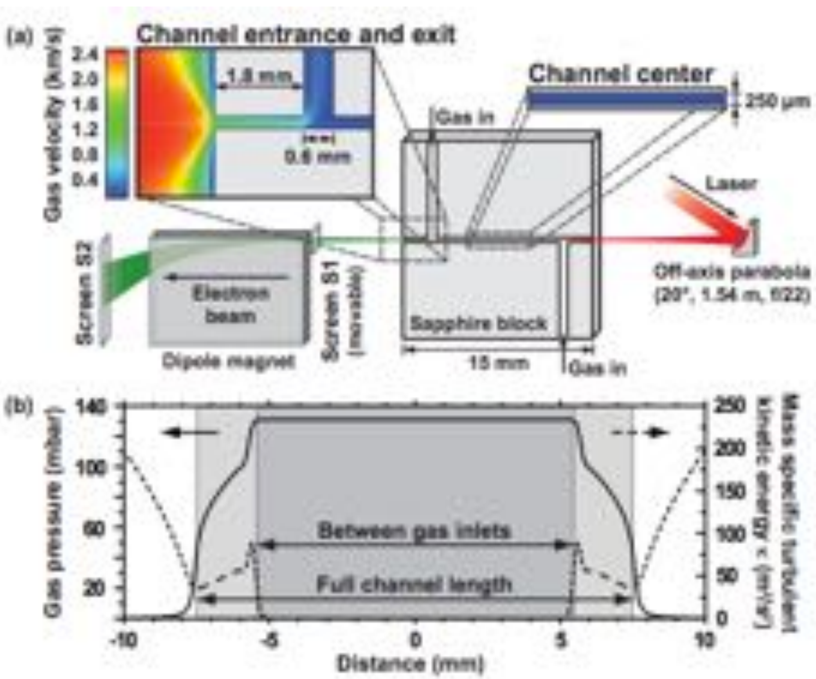
$$\text{For 4 GeV gain:} \quad \left(n_{\rm cr}/n_e\right) \approx 4000, \quad L_{\rm dp} \approx 25\,\text{cm}$$

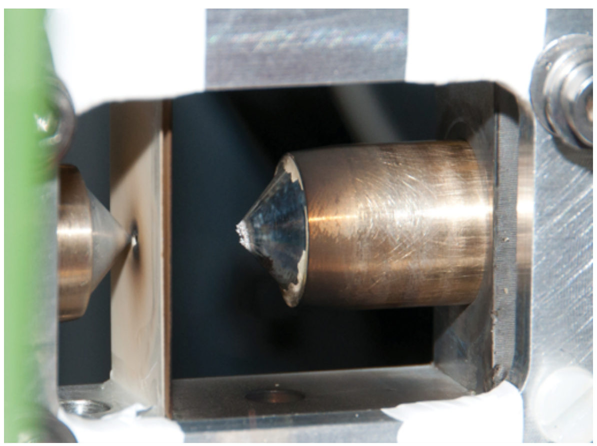
For a spot size $w_0 \approx \lambda_p = (2\pi c/\omega_p) \approx 30(60)\mu\text{m for } 1(4)\,\text{GeV}$

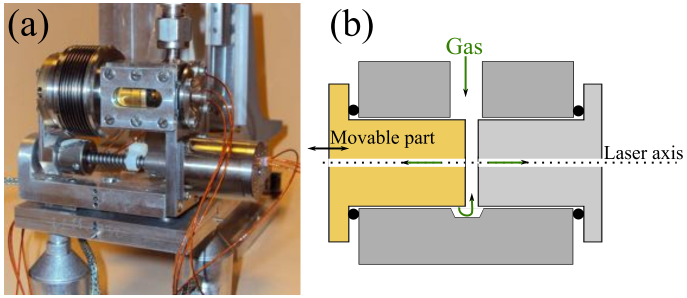
$$\text{Rayleigh range:} \quad z_R \approx \pi w_0^2/\lambda_0 \approx 3(12)\ \text{mm}$$

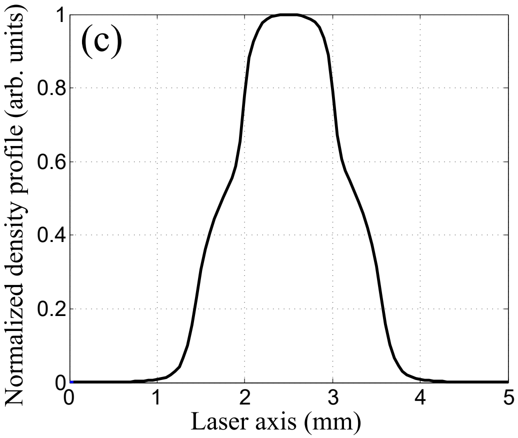
Need guiding over 10 (20) z_R

Gas cells for long stages









Osterhoff, J, Phys. Rev. Lett. 101, 085002 (2008).

B. B. Pollock, et al, Phys. Rev. Lett. 107, 045001 (2011).

T.L. Audet, et al. NIM A, (2016)

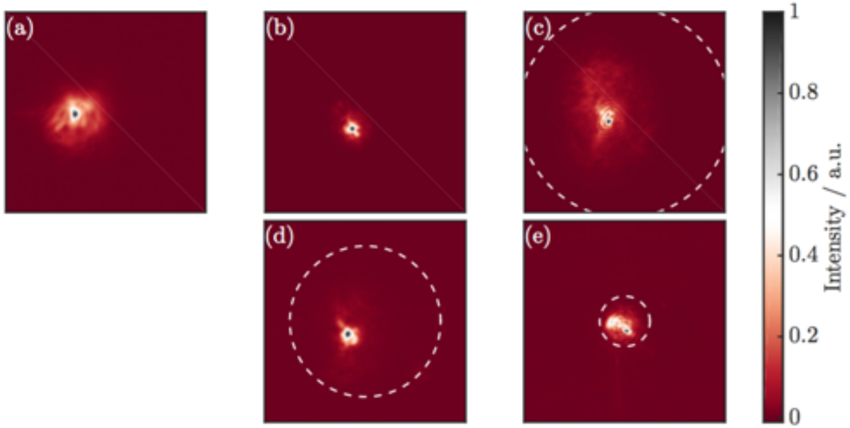
Self-focussing

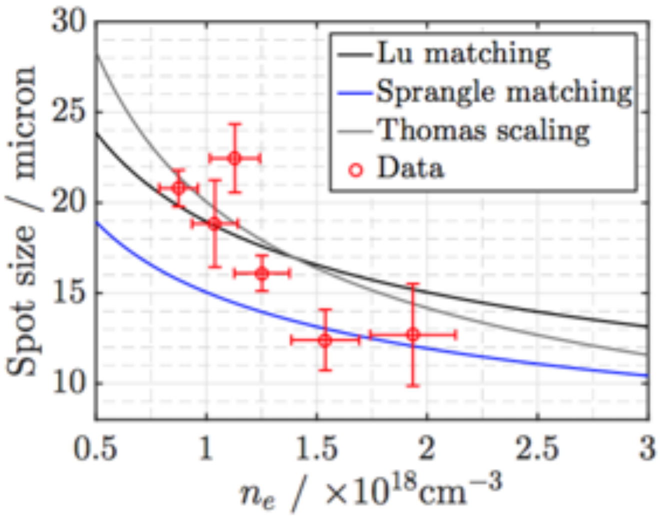
Self-focussing: $P_{sf} > P_{cr} \approx 17(n_{cr}/n_e)\,\mathrm{GW}$

For 1 GeV: $w_0 \approx 30\,\mu\mathrm{m}, \quad P_{sf} \approx 17\,\mathrm{TW}, \quad a_0 \approx 1$

For 4 GeV: $w_0 \approx 60\,\mu\mathrm{m}, \quad P_{sf} \approx 68\,\mathrm{TW}, \quad a_0 \approx 1$

Long scale self-focussing:

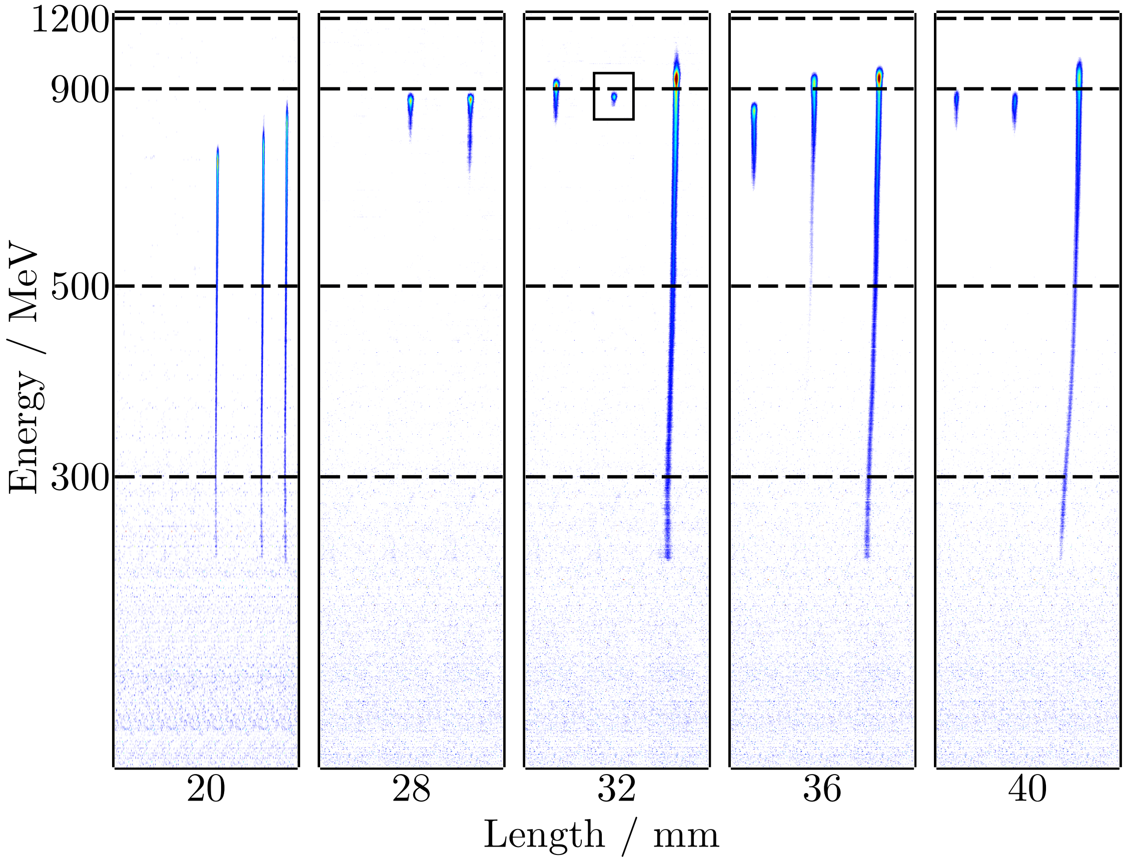




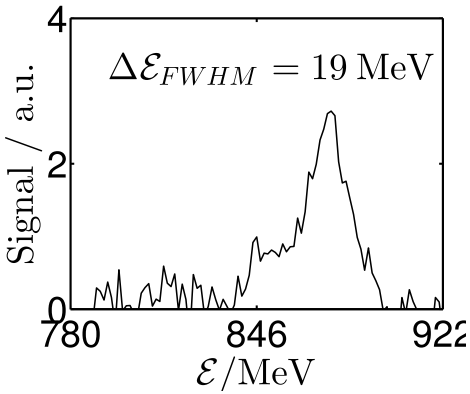
Poder, K., et al. Plas. Phys. Cont. Fusion (2017).

Non-linear regime

Injection is easier in the non-linear regime:



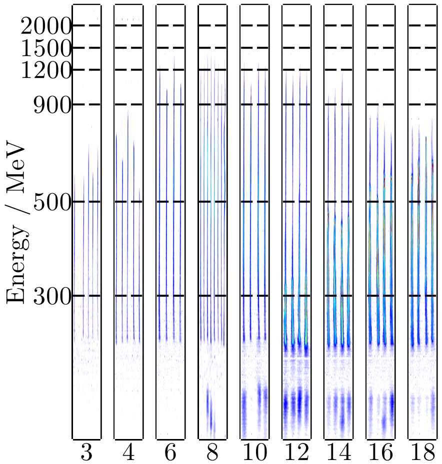
Energy on target
9.5 ± 0.2 J
Density
1.8×10^{18} cm^{-3}

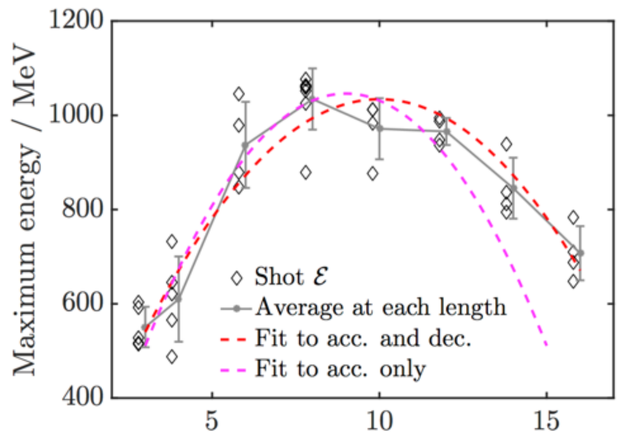


However laser parameters must be well controlled

Non-linear regime

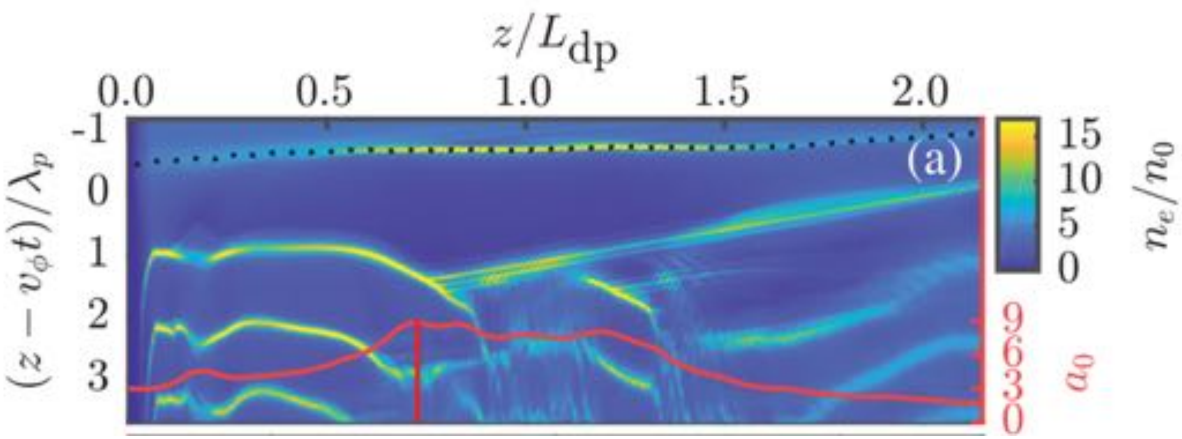
Field strengths can be very high:





a_0	n_e $10^{18}\,\mathrm{cm}^{-3}$	E_{peak} GV/m	
		Acc only	All
1.5	1.6	113 ± 4	124 ± 15
1.1	2.3	362 ± 27	349 ± 39
1.0	2.6	339 ± 49	336 ± 62
1.5	2.6	299 ± 15	284 ± 24
1.0	3.2	570 ± 190	540 ± 200

But power amplification means wakefield is always evolving:

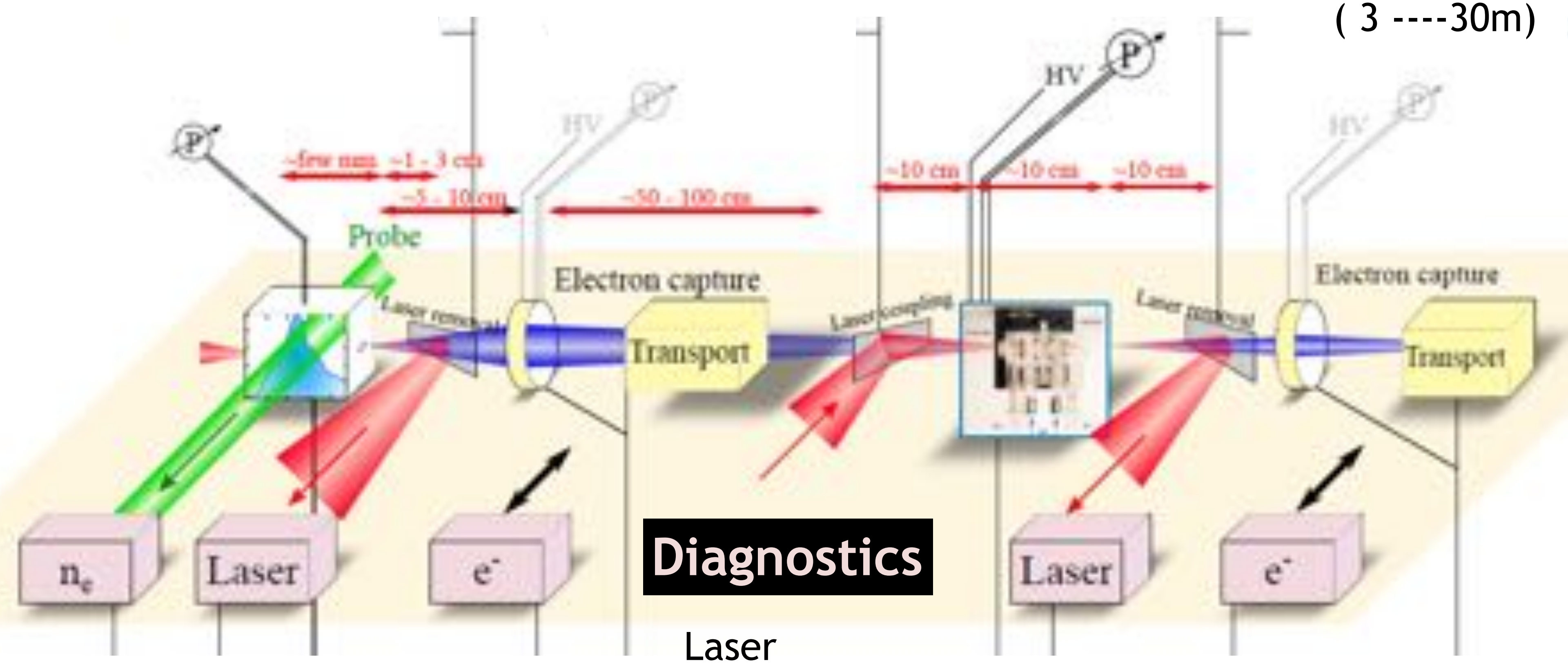


Poder, K. et al. In preparation.

M. J. V. Streeter, et al., Phys. Rev. Lett. 120, 254801 (2018).

Plasma Guiding

(3 ----30m)



Plasma Density Cavity (Ep)

Laser Energy Spectrum pointing

Electron parameters

Laser Energy Spectrum pointing

Plasma Density Cavity (Ep)

Laser Energy Spectrum pointing

Electron parameters

Self-focussing

But self-focussing has a number of disadvantages:

dependent on beam quality:

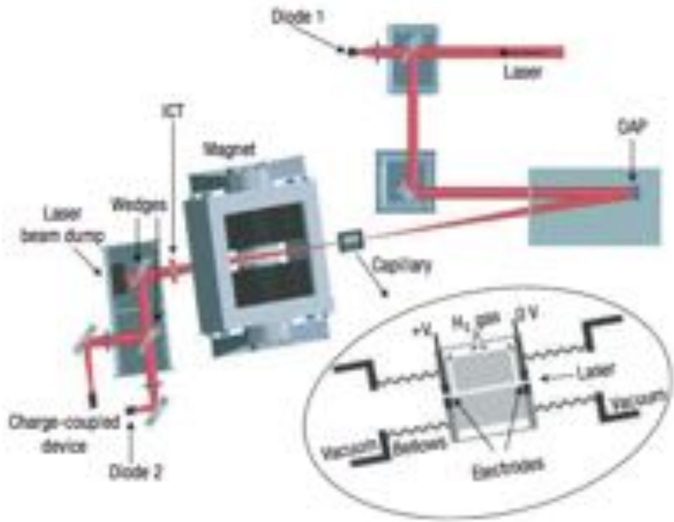
- ➡ poor encircled energy requires higher powers
- ➡ poor beam quality affects pointing
- ➡ poor beam quality affects reproducibility

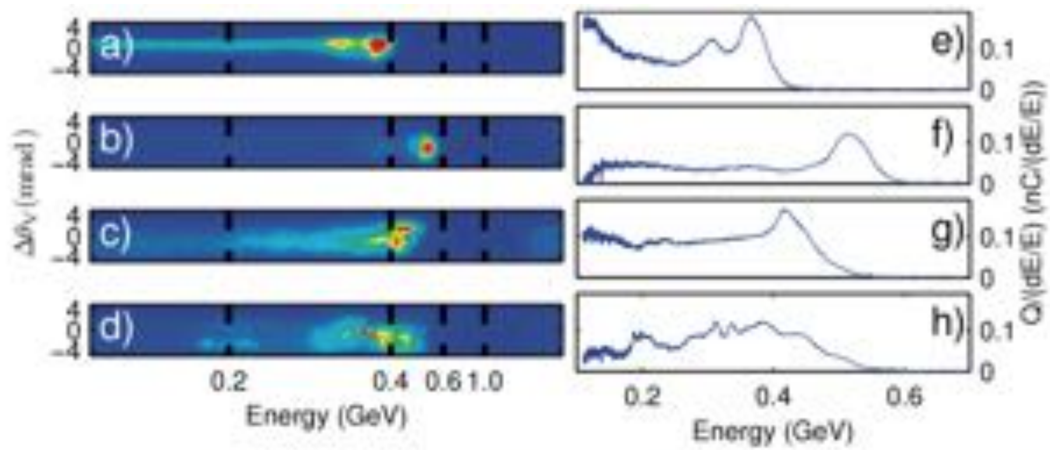
Desirable to control laser propagation with guiding channel

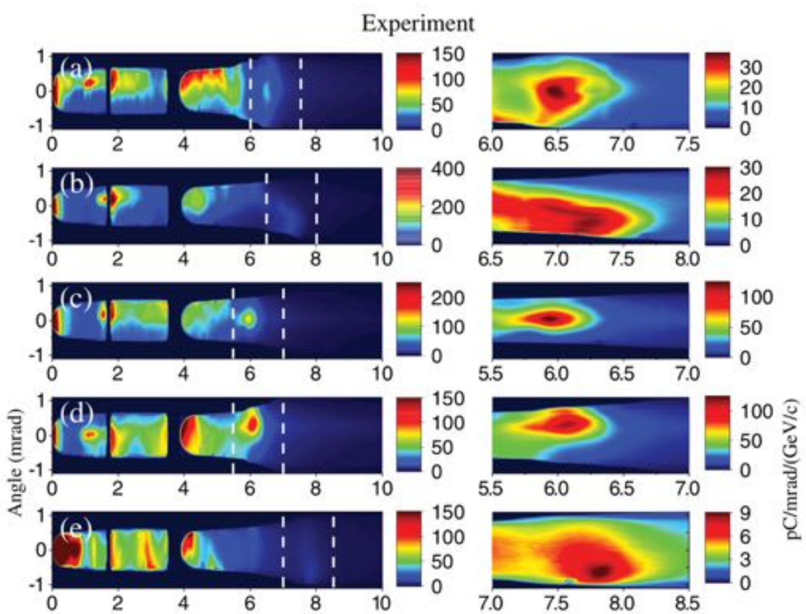
guiding channel can:

- ➡ trap and guide more laser energy
- ➡ directs pointing and minimises variability
- ➡ reduces guided spot size, reducing power requirements

Capillaries for long stages







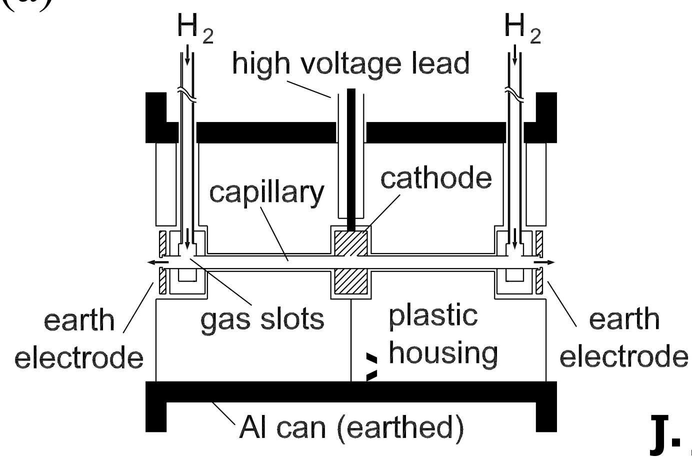
Gonsalves, A J, et al. ***Phys. Rev. Lett.*** **98, 025002 (2007).**

Ibbotson, et al. New J. Phys. 12, 045008 (2010).

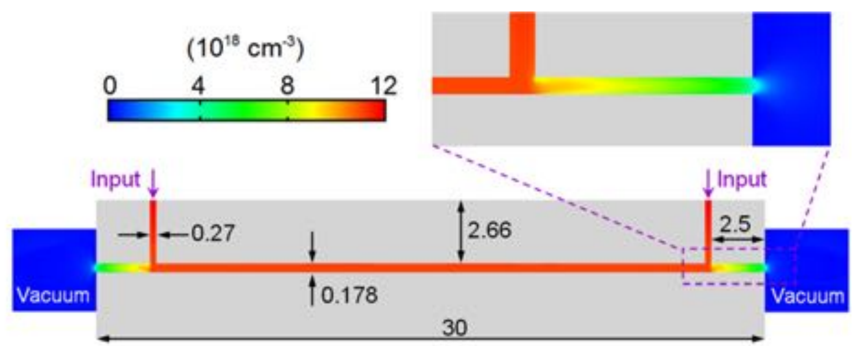
A. J. Gonsalves, ***Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide*****, Phys. Rev. Lett. 122, 84801 (2019).**

Guiding options

(a)



(b)



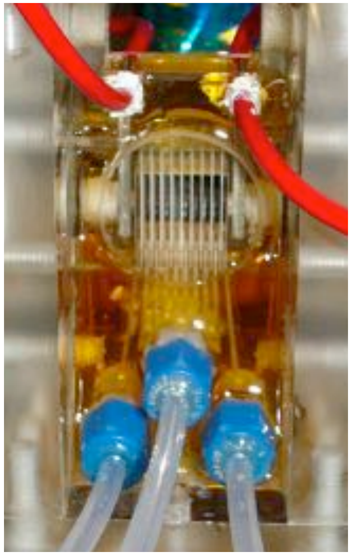
J. Ju and B. Cros. J. Appl. Phys., 112:113102, 2012.

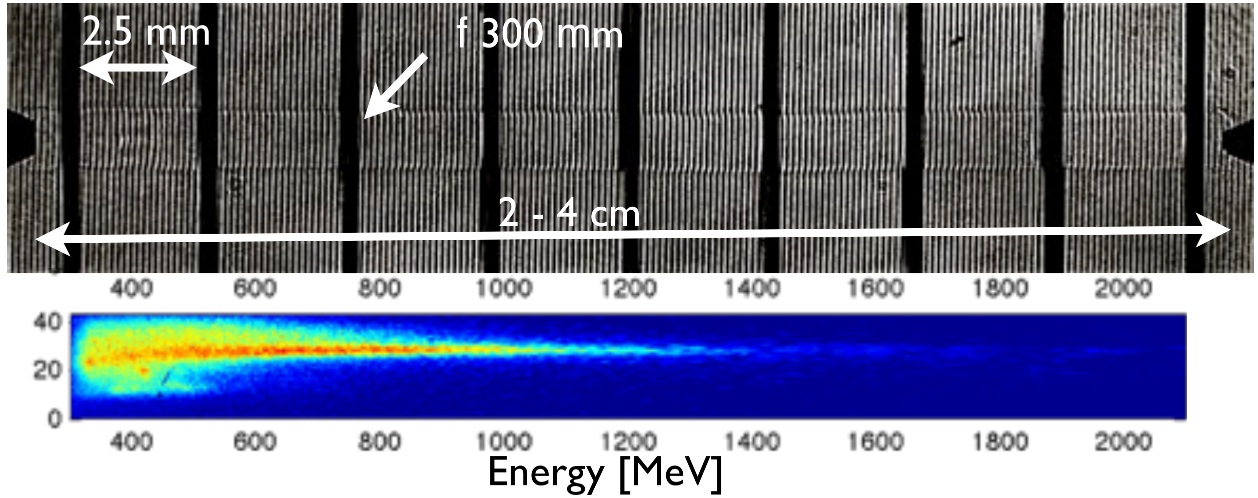
Other guiding structures have been proposed and need investigating:

Advantages:
- ➡ longer lifetimes
- ➡ easy diagnostic access

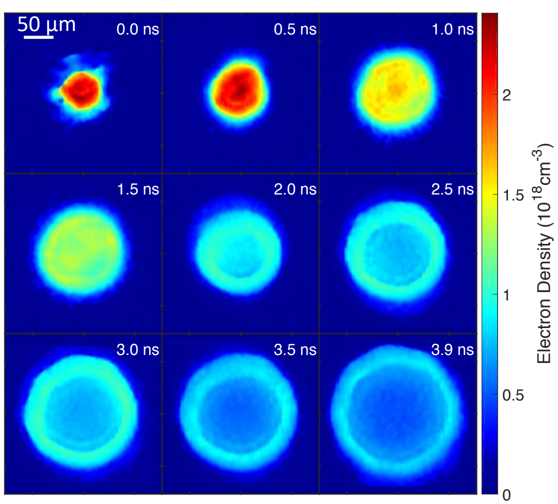
Disadvantages:
- ➡ not clear on reproducibility
- ➡ easy diagnostic access

Other long stage concepts

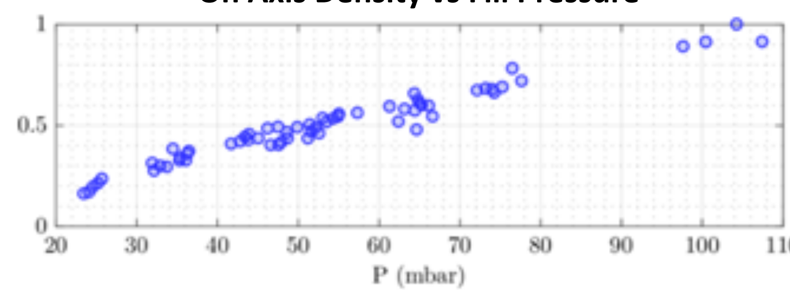




R. Bendoyro, at al., IEEE Trans. Plasma Science, 36, 1729 (2008)



- On Axis Density vs Fill Pressure



Plasma Parameters

- Plasma waveguides formed in H_2
- Low On-Axis densities ~ 10^{17} cm^{-3}
- Matched Spot Sizes ~ 10's microns

Laser Parameters

- Low-energy required: 10-70 mJ @ 50 fs
- Formed with Lens or Axicon

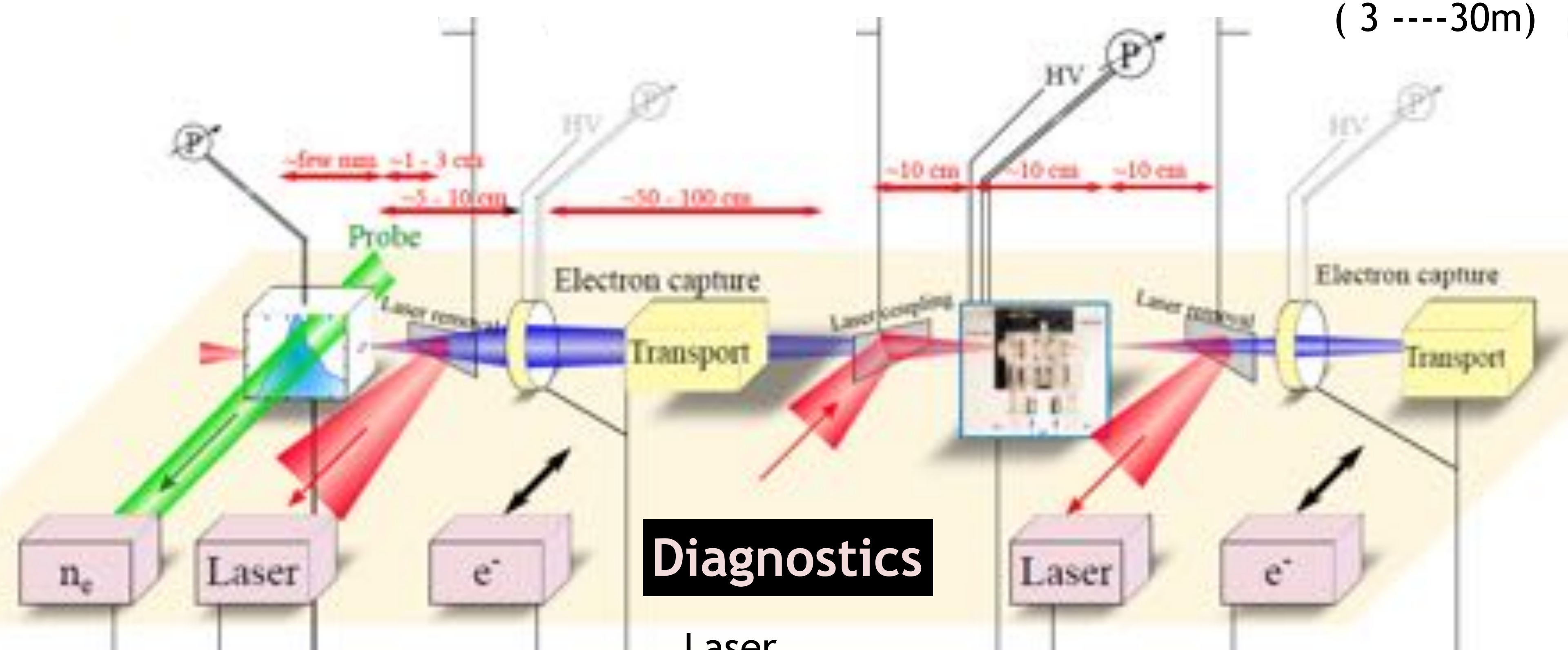
R. J. Shalloo, et. al. , Phys. Rev. E, 97 053203 (2018)

Plasma target characteristics have been compared

Target type	Length mm	n_e value cm^{-3}	n_e tailoring	n_e stability	rep rate	life time
Gas jet	< 20 self-foc.	10^{18}	multiple jets	turbulent flow	10 Hz	> 24 h
Gas cell	> 1 self-foc.	10^{17} - 10^{19}	machining	gas feed dependent	10 Hz	laser quality dependent
Plasma channel HE	< 30 guiding	$(1-5) \times 10^{18}$ parabolic	similar to gas jet	laser quality dependent	10 Hz	>24h
Plasma channel discharge	$10-90$ guiding	5×10^{17} - 10^{19} parabolic	multiple gas feed	discharge dependent	10 Hz	laser quality dependent
Cap tube	10-1000 guiding	$(0-5) \times 10^{17}$ homogeneous	multiple gas feed	gas feed static	10 Hz	laser quality dependent

Plasma Guiding

(3 ----30m)



Plasma Density Cavity (Ep)

Laser Energy Spectrum pointing

Electron parameters

Laser Energy Spectrum pointing

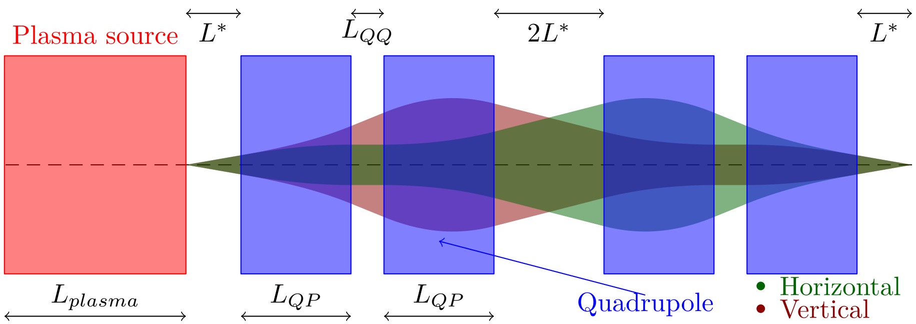
Plasma Density Cavity (Ep)

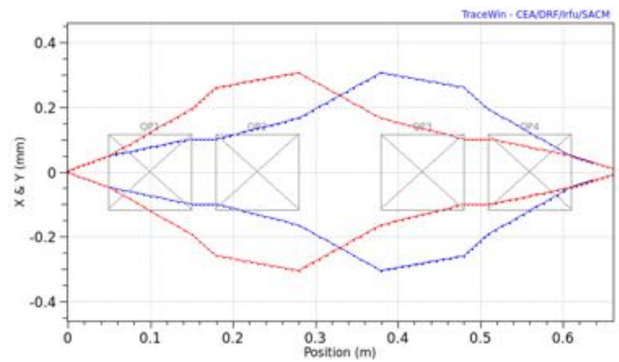
Laser Energy Spectrum pointing

Electron parameters

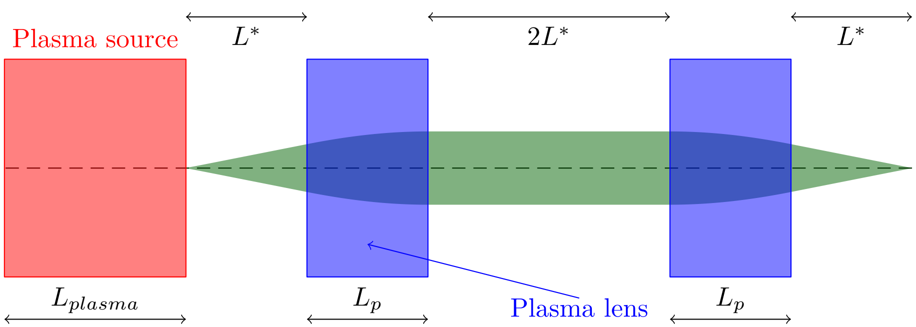
Coupling of electron beams

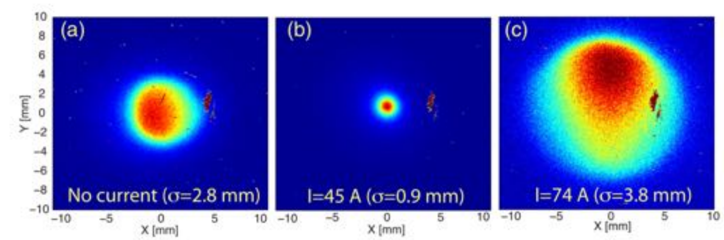
Magnetic structures: low overhead once aligned, but long distances





plasma structures: strong focussing gradients



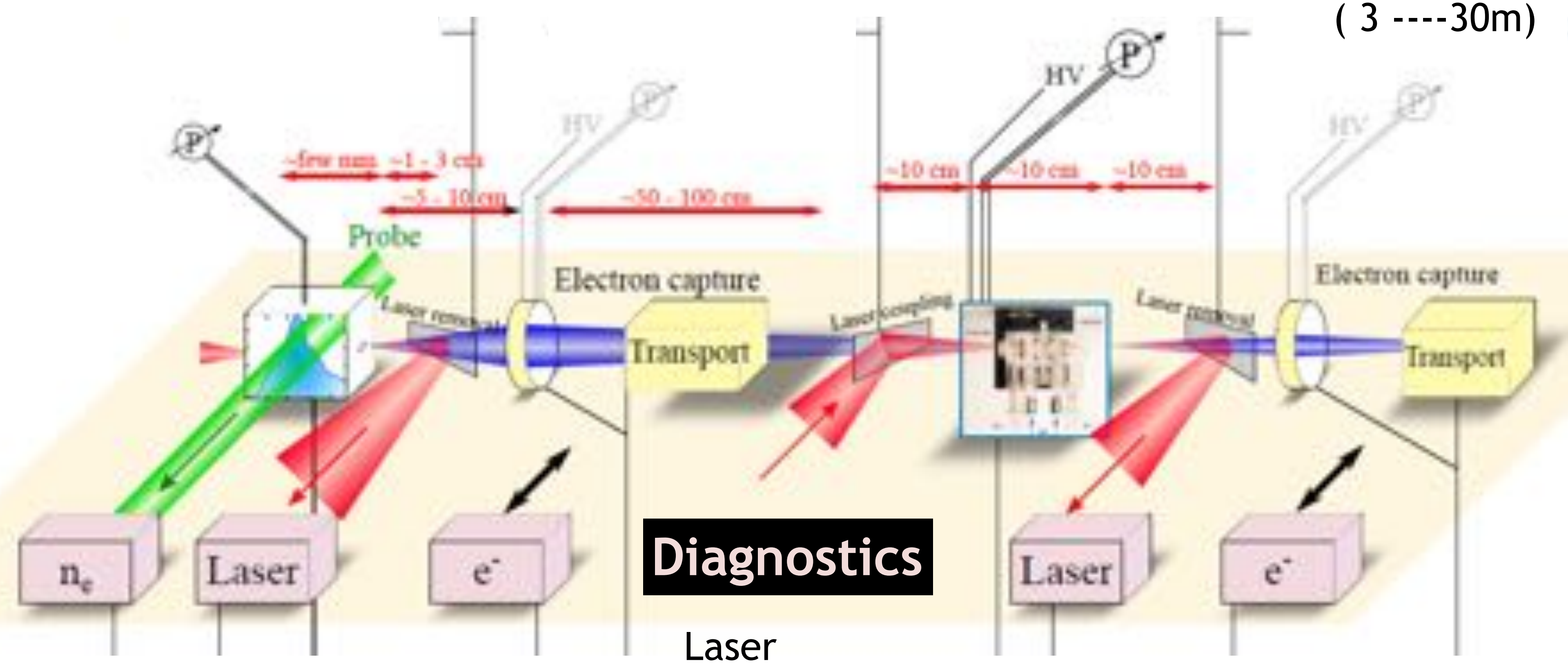


J. Van Tilborg, et al, Phys. Rev. Lett. 115, 184802 (2015).

C. A. Lindstrøm, et al. Phys. Rev. Lett. 121, 194801 (2018)

Plasma Guiding

(3 ----30m)



Plasma Density Cavity (Ep)

Laser Energy Spectrum pointing

Electron parameters

Laser Energy Spectrum pointing

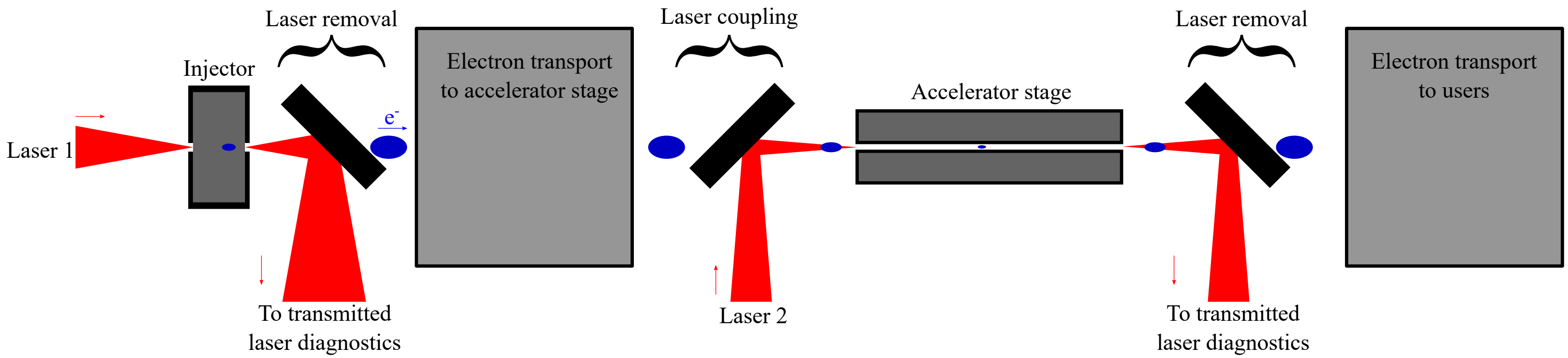
Plasma Density Cavity (Ep)

Laser Energy Spectrum pointing

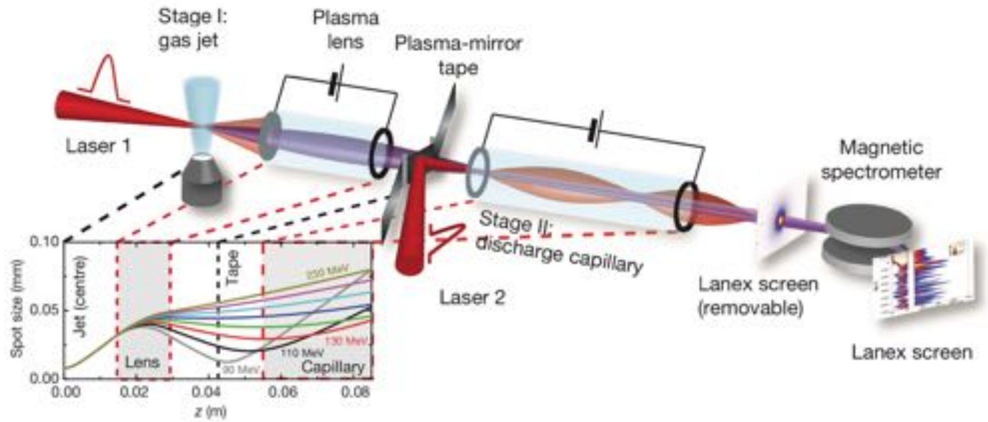
Electron parameters

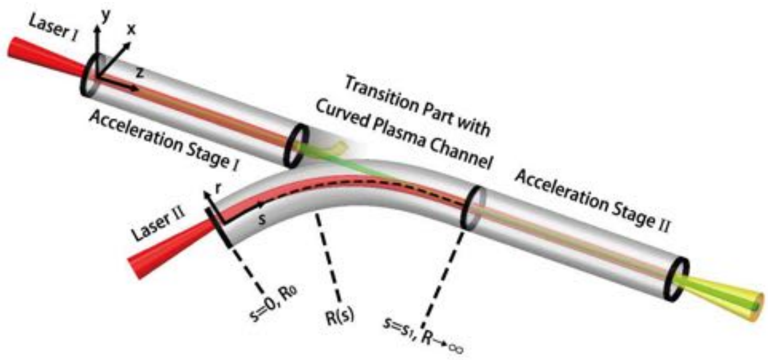
Coupling of laser beams

Most investigated option is plasma mirrors:



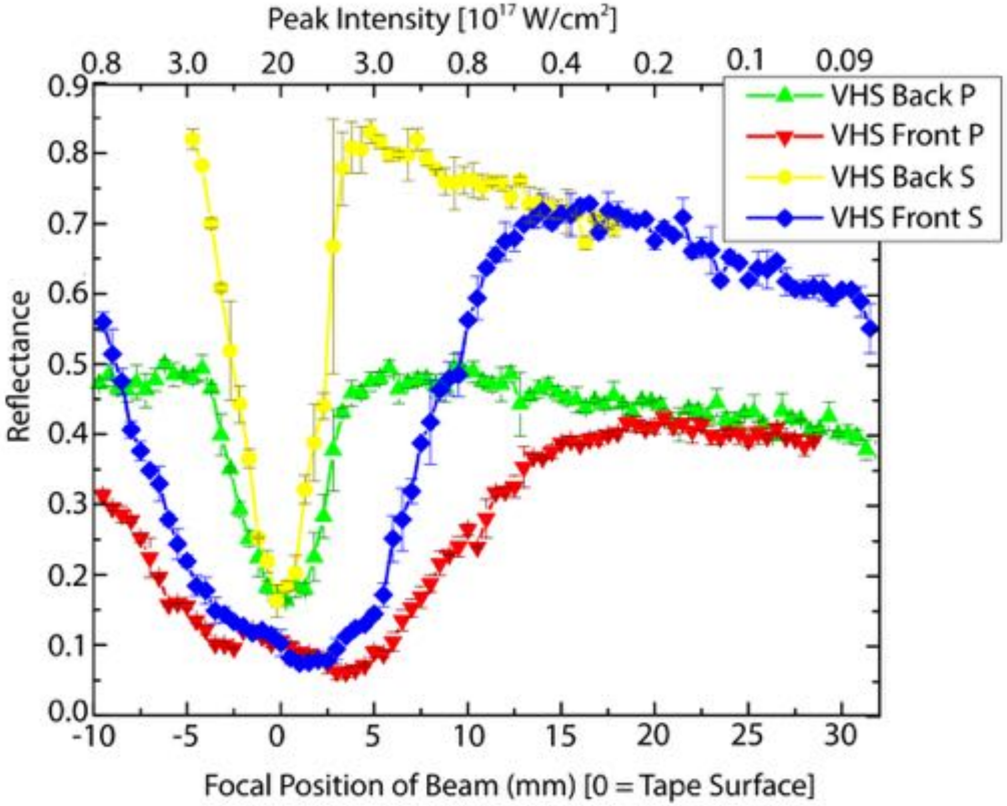
Most likely tape drives, could be liquid crystal mirrors



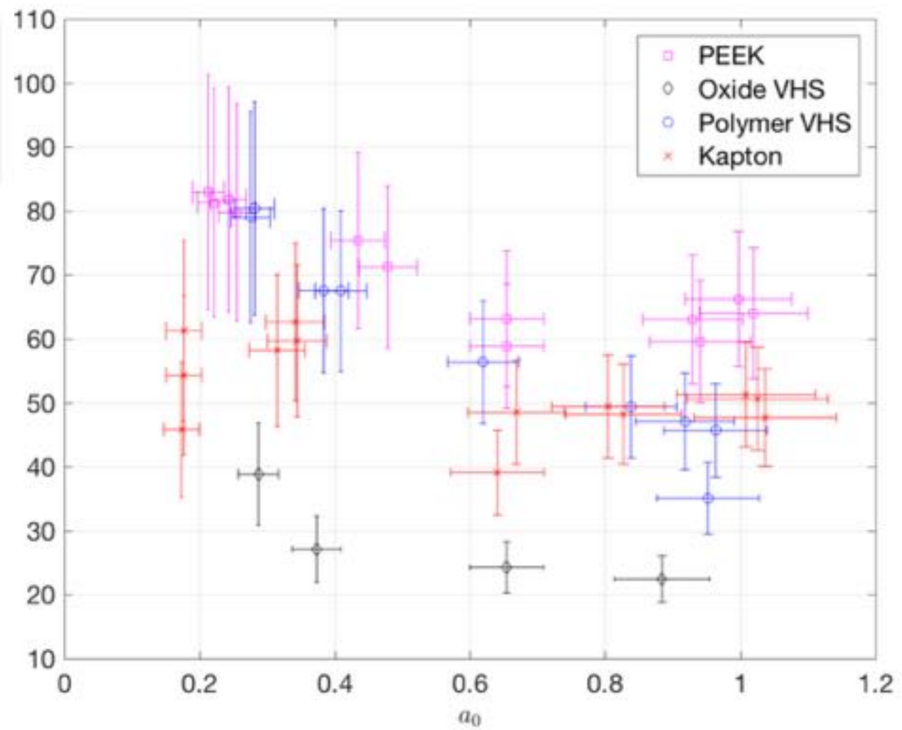


Other options include perforated mirrors

Reflectivity measurements:

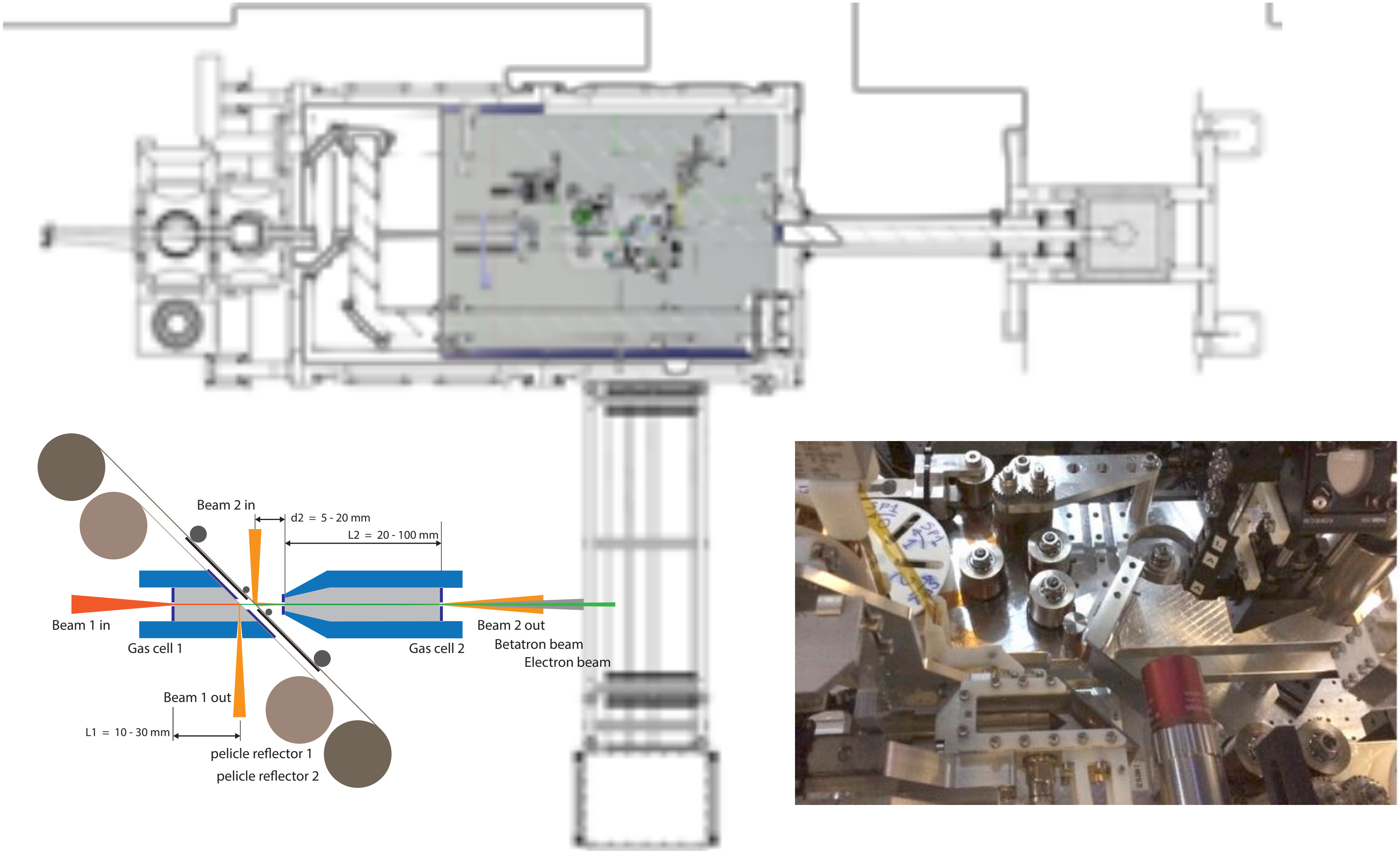


B. H. Shaw et al, Phys. Plasmas 23, 4954242 (2016).



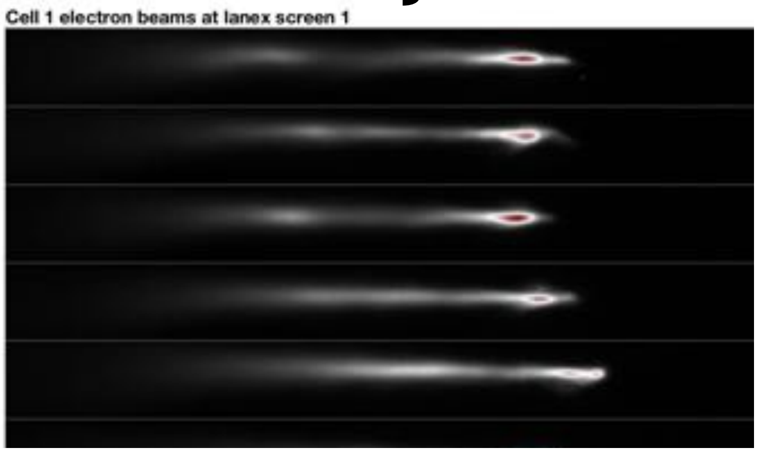
J-N. Gruse, In preparation (2018).

Coupling of laser beams

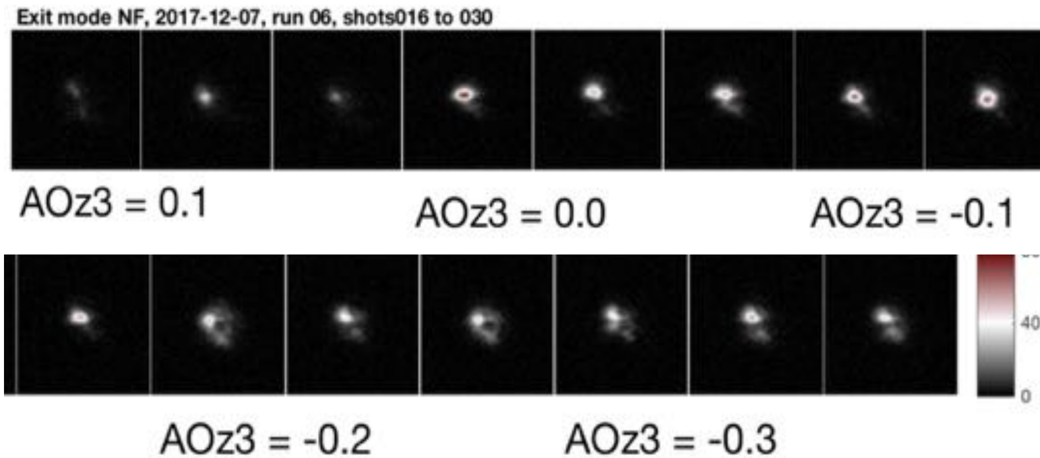


Coupling of laser beams

Reproducible 500-800 MeV beam from injection cell

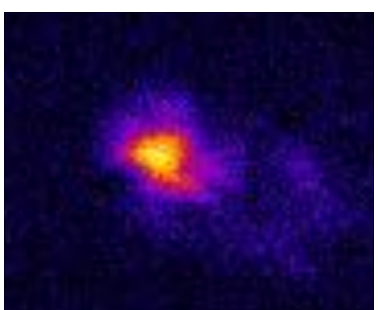


Good quality reflection from tape (>20%)

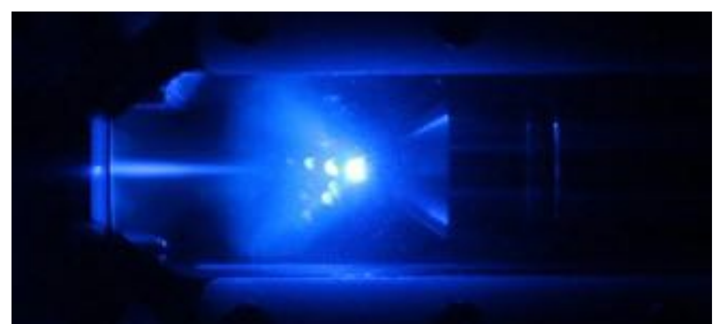


Guiding of reflected beam over 2.5 cm from:

exit mode

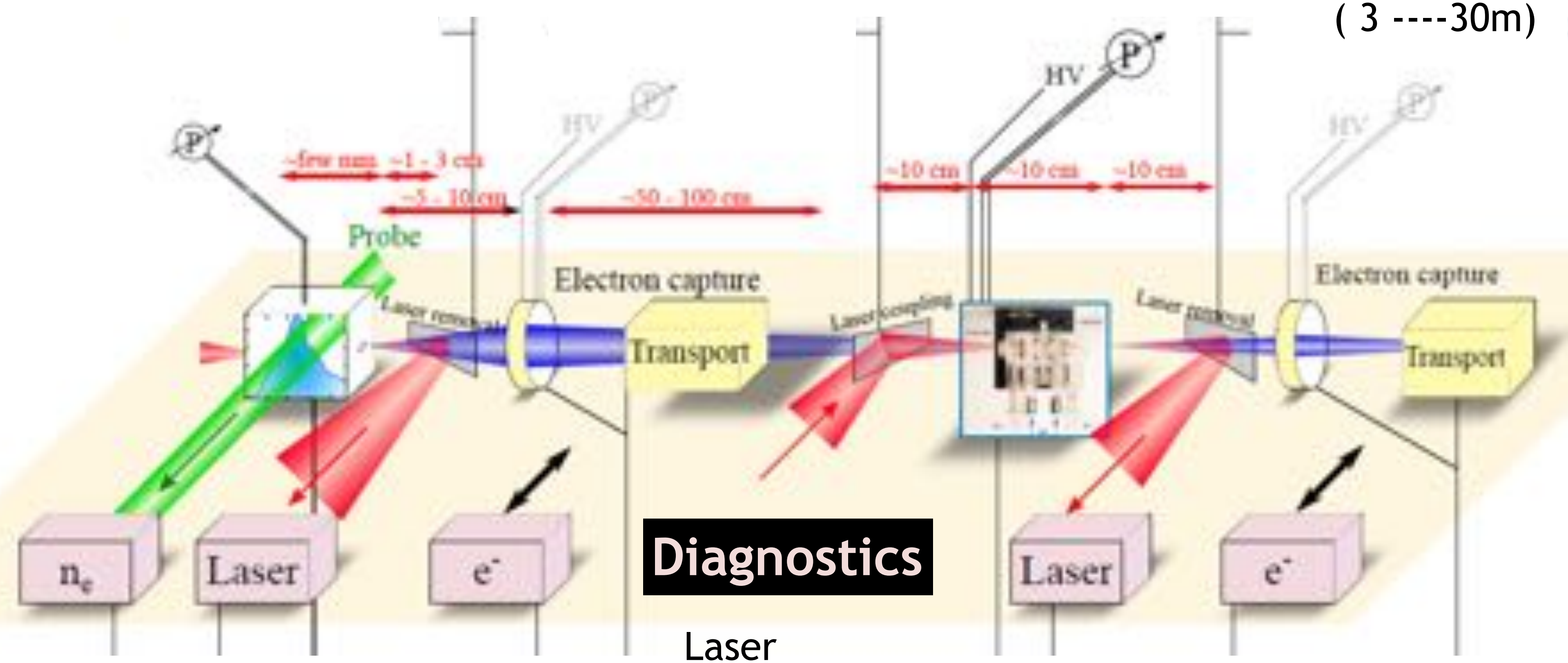


channel emission



Plasma Guiding

(3 ----30m)



Plasma Density Cavity (Ep)	Laser Energy Spectrum pointing	Electron parameters	Laser Energy Spectrum pointing	Plasma Density Cavity (Ep)	Laser Energy Spectrum pointing	Electron parameters

Summary

- Plasma Accelerator stages have been considered for EUPraxia
  - Laser driven plasma stages of density ~10^{17} cm^{-3} and metre length required
  - Compact lens systems can couple electron beams
  - Lasers can be coupled with plasma mirrors
  - ***Options for each element has been considered***

Contributors:

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