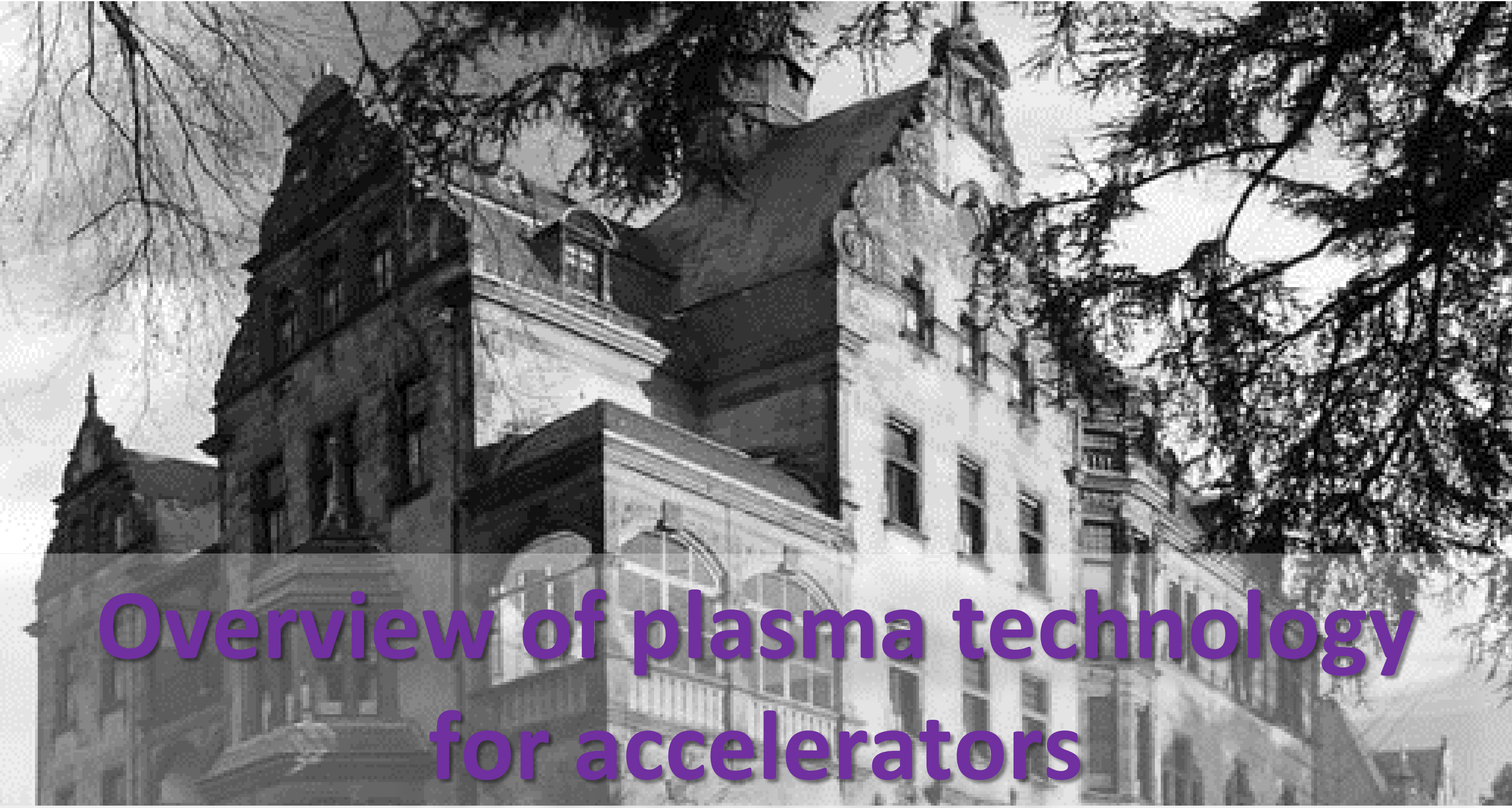


Overview of plasma technology for accelerators

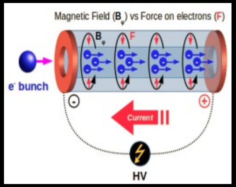
Brigitte Cros

Laboratoire de Physique des Gaz et des Plasmas
CNRS Université Paris-Saclay, Orsay, France

Plasma technologies can be used to design several types of accelerator components

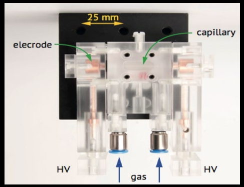
Source of electrons:

Driven by laser wakefields in plasmas cells or jets



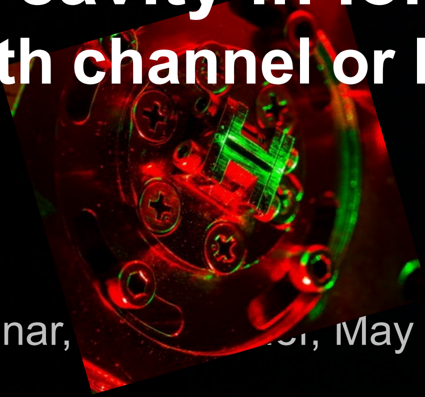
Electron lens:

Focusing force associated to azimuthal magnetic field in discharge plasma

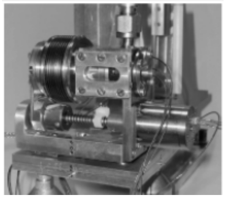


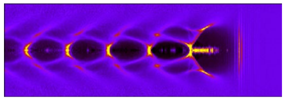
Accelerating cavity in long plasmas:

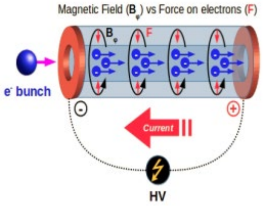
waveguides with channel or homogeneous plasma



Outline

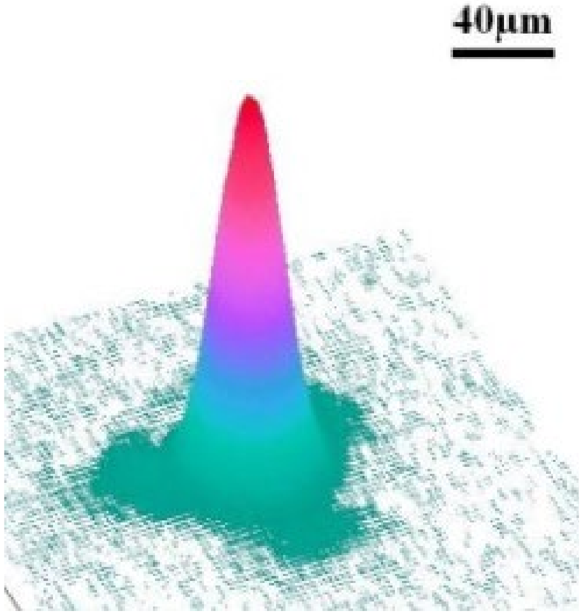






- Plasmas for laser driven compact sources of electrons in non Linear regimes
- Plasma based accelerator cavity: for laser or beam driven wakefield accelerators
- Plasmas for beam optics

Driving laser amplitude characterized by a normalized parameter



- Laser strength parameter

$\boldsymbol{a} \sim eA/mc^2$

normalized laser vector potential

- Peak value

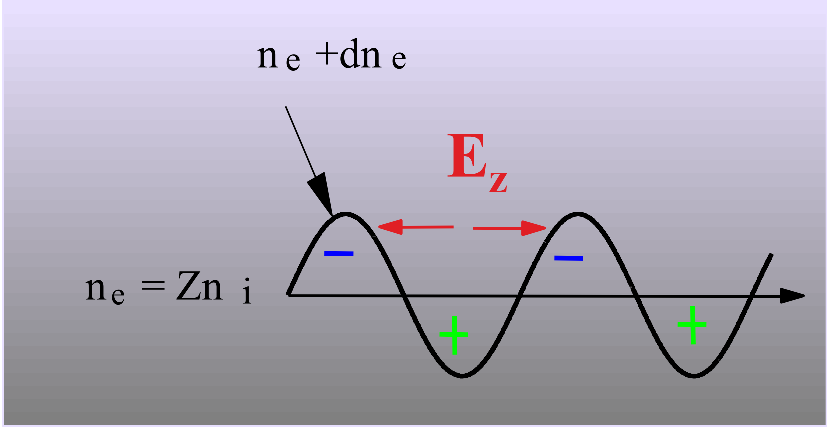
$\boldsymbol{a_0} \sim 8.5\text{x}10^{-10}\ \lambda_0[\mu\text{m}]\ I_0^{1/2}[\text{Wcm}^{-2}]$

- Quasilinear regime or weakly relativistic regime

$\boldsymbol{a_0} \sim 1$

Large longitudinal electric field associated to a plasma wave

Accelerating fields > 10 GV/m for LWFA



- Space charge field and plasma wave

  wavelength

  $\lambda_p[\mu m] \sim 33\ (n_e[10^{18} cm^{-3}])^{-1/2}$

$$E_z\ [GV/m] \sim 96\ \ (n_e\ [10^{18}\ cm^{-3}])^{1/2}\ dn_e/n_e$$

$$E_z\ [GV/m] = 1.35\ 10^{-18}\ I_{max}[Wcm^{-2}](\lambda[\mu m])^2/\tau[ps]$$

LWFA density regimes

- Energy gain in LWFA

Linear Regime ($a_0 \simeq 1$):

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

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

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

- Sets rougly plasma density

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

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

LWFA interaction lengths

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

- Dephasing length

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

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

- For a spot size

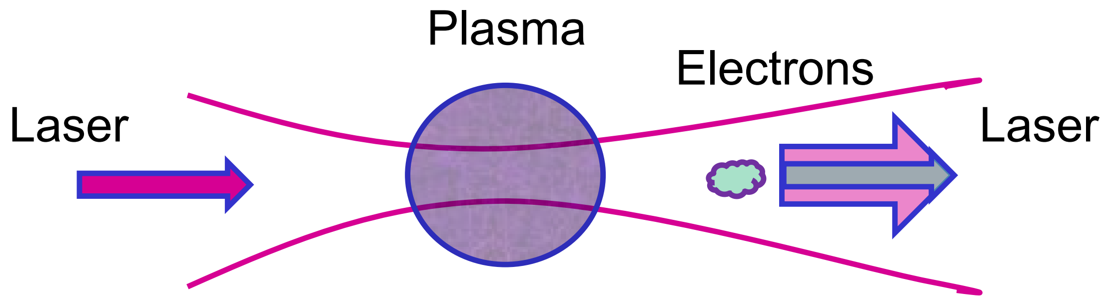
$$w_0 \approx \lambda_p = \left(\frac{2\pi c}{\omega_p}\right) \approx 30(60)\mu\mathrm{m}\ \text{for}\ 1(4)\mathrm{GeV}$$

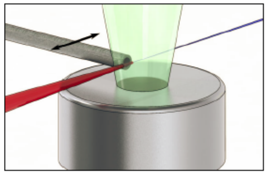
Rayleigh range: $z_R \approx \pi w_0^2/\lambda_0 \approx 3(12)\ \mathrm{mm}$

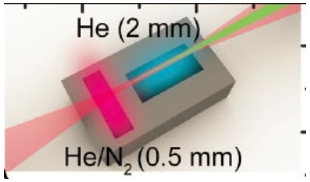
Need guiding over 10 (20) z_R

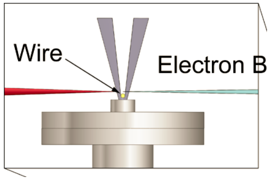
Plasma based electron sources rely on NL laser wakefield acceleration

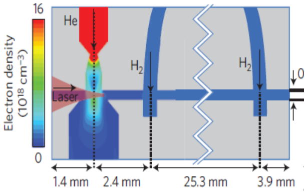
- Non linear interaction of an intense laser with gas responsible for gas ionisation, electron acceleration







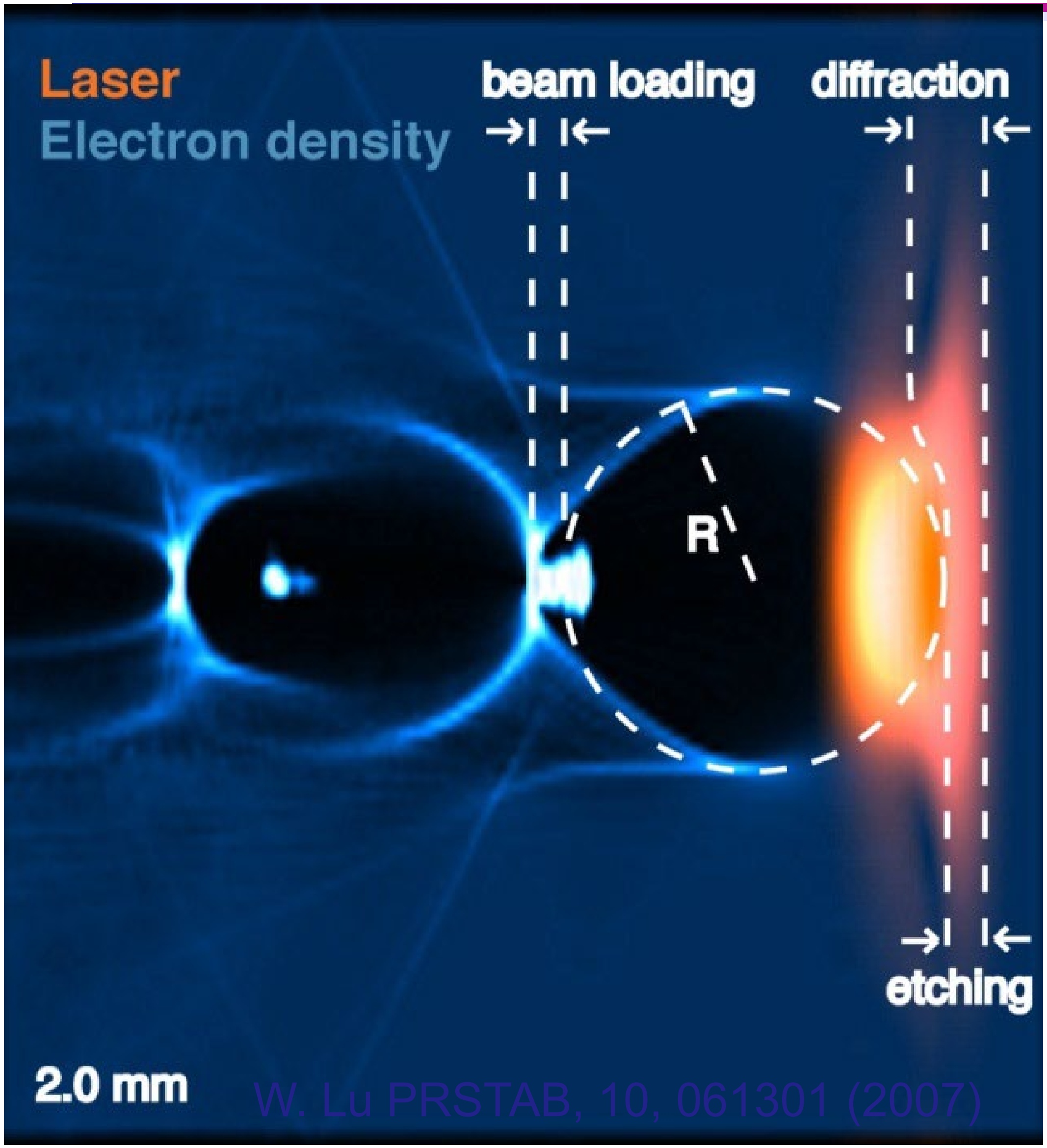




Intense laser
creates a plasma I > I ionization
drives plasma waves, $\omega_p \tau \sim 1$
traps plasma electrons $a_0 > 2$
accelerate electrons

Plasma created from background gas distribution (jet, cell, capillary,….)

Self injection of electrons in a plasma cavity is the most simple LWFA-ES



W. Lu PRSTAB, 10, 061301 (2007)

$a_0 > 2$

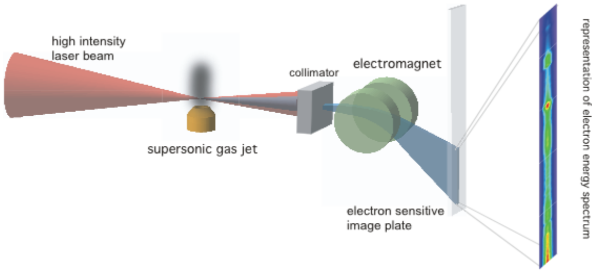
- Pulse compression and self-focussing
- Electrons are expelled from high laser intensity area and leave behind a cavity (bubble filled with ions)
- Electrons self-injected at the back of the bubble and accelerated
- Injected electrons modify the back of the bubble (beam loading)

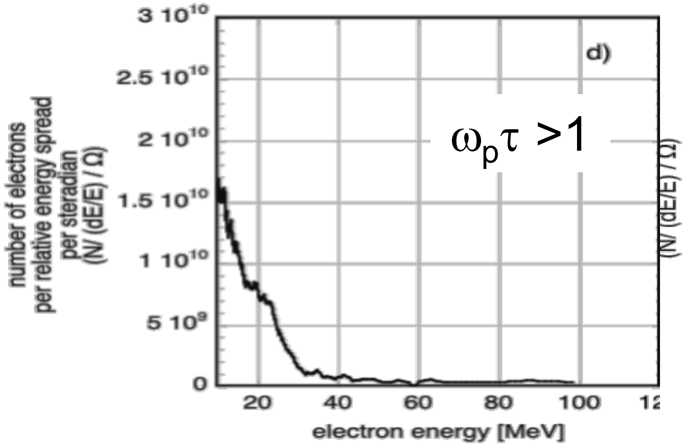
Lu (2007), Pukhov (2002)

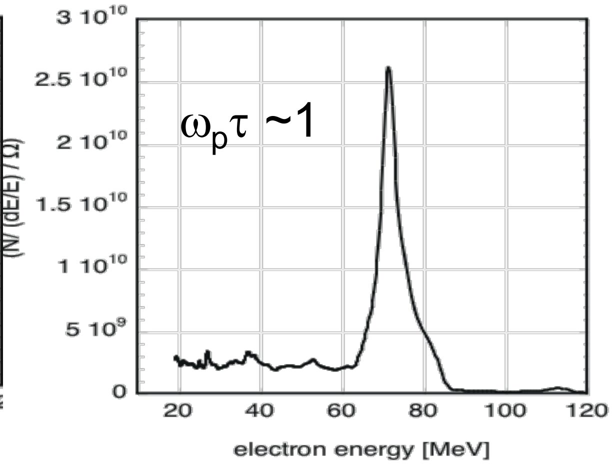
LWFA self-injection with short pulses ($\omega_p \tau \sim 1$) in gas jets

- Self injection of electrons heated during the interaction of laser pulse and plasma wave,
- Large energy spread (exponential distribution) due to continous injection
- Out of resonance operation: reduced efficiency

- Typical parameters for operation in **gaz jets** Ti:sapph laser:
- Electron density $n_e \sim 10^{19}$ cm^{-3}
- Pulse duration 40fs
- Peak intensity 2×10^{18}W/cm²







nature

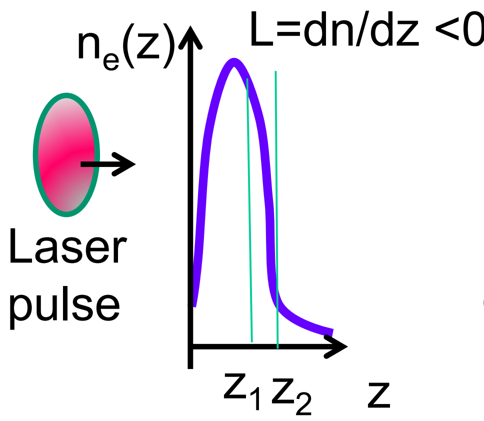
Dream beam

The dawn of compact particle accelerators

NATURE | VOL 431 | 30 SEPTEMBER 2004

- Self-injection mechanism can lead to peaked spectra, with small energy spread (a few %) and small charge (pC)
- Other mechanisms can be used leading to more complex plasma designs

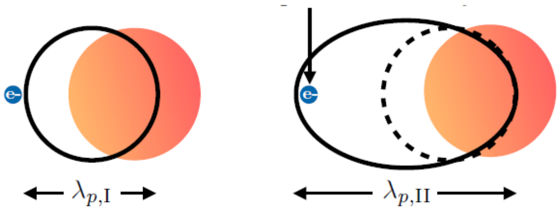
Injection with negative density gradient



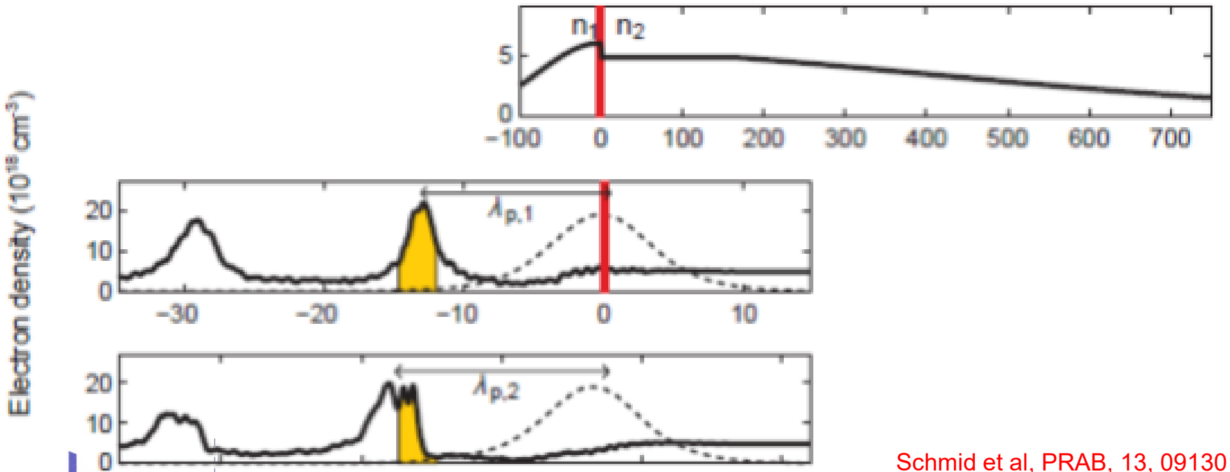
$\lambda_p(z)$ ~33 $[n(z)]^{-1/2}$

$\lambda_p(z_2) > \lambda_p(z_1)$

the plasma wavelength increases with decreasing density



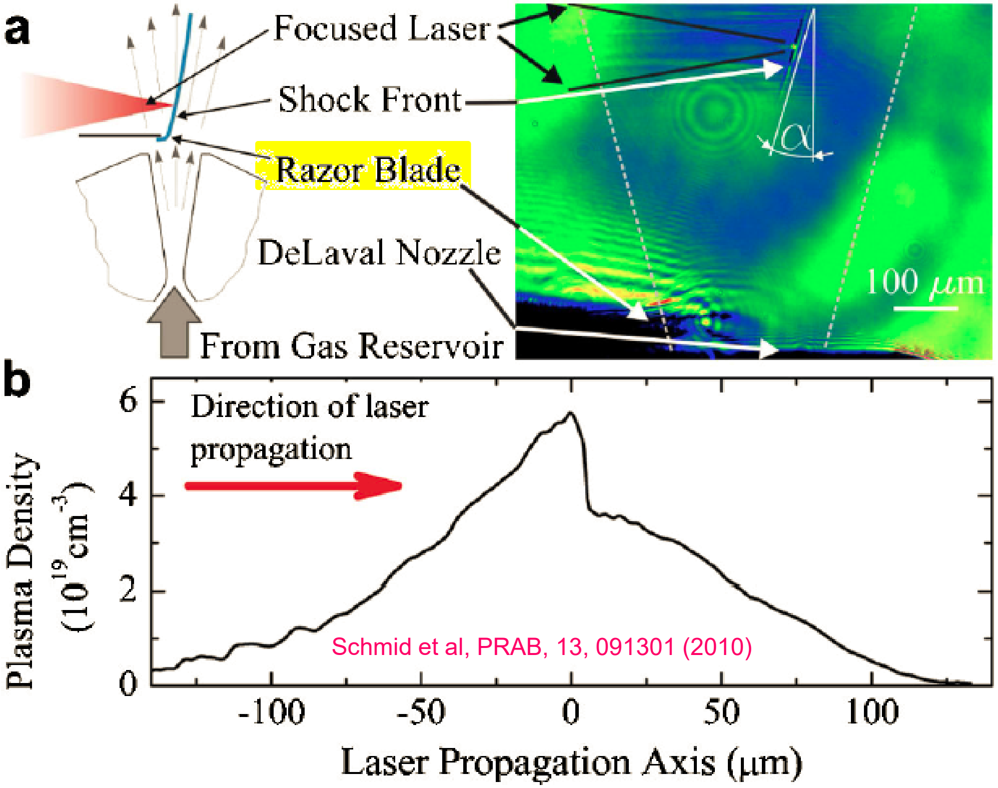
- The back of the wake slows down as the laser propagates down the gradient
- This reduces the trapping threshold
- Trapping can be confined to a small region in the gradient area



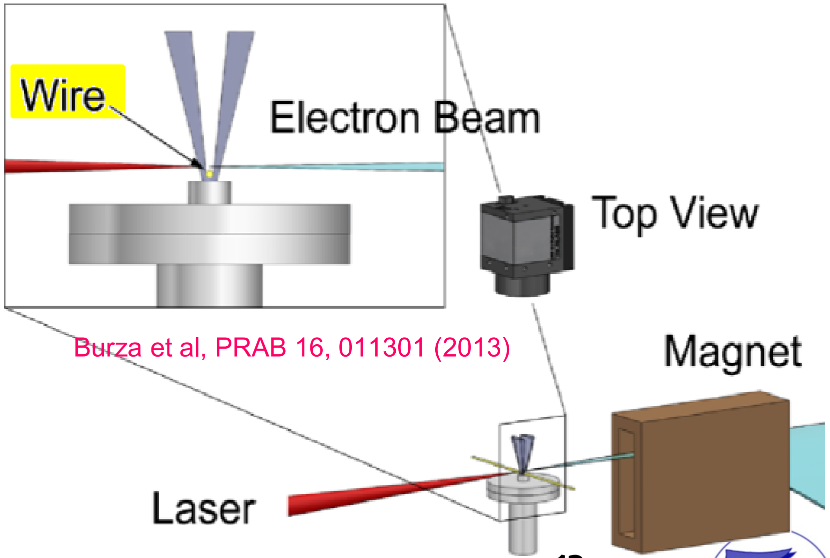
Schmid et al, PRAB, 13, 091301 (2010)

A sudden change in plasma density : practical aspects

- An object placed in the gas flow creates a shock associated to change of gas density over a short distance
- Laser ionisation occurs over a short time scale: the plasma profile follows gas profile



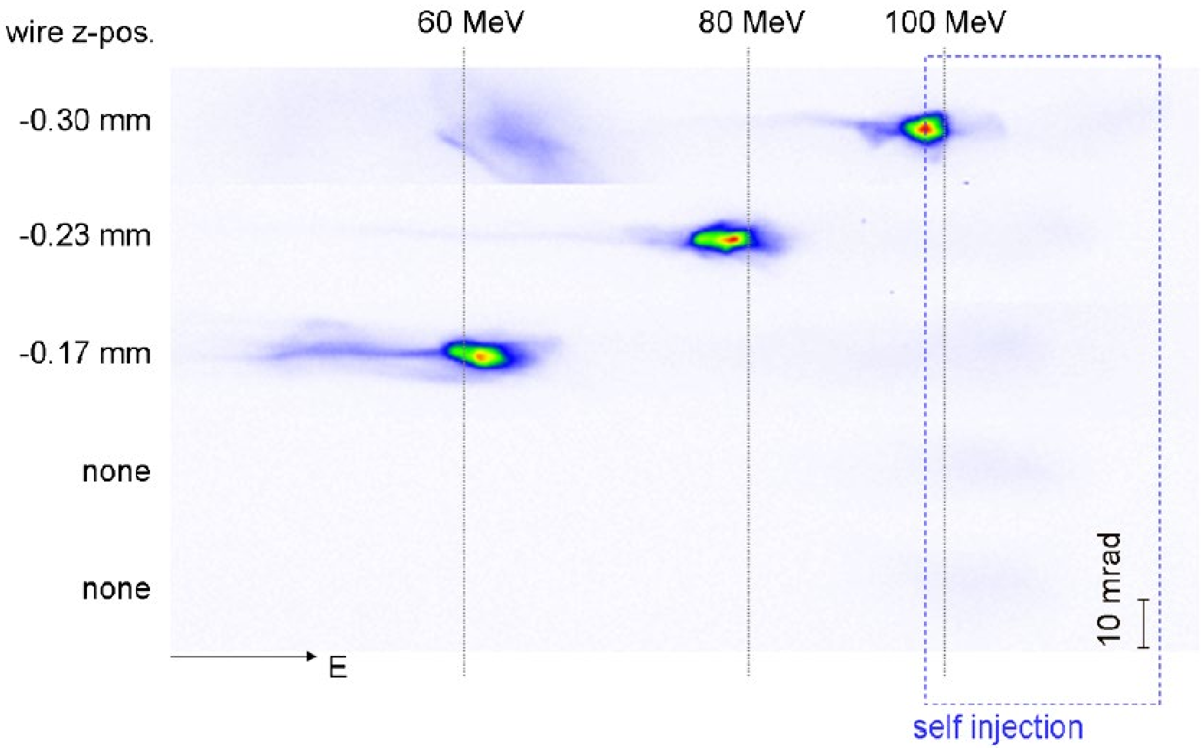
Schmid et al, PRAB, 13, 091301 (2010)



Burza et al, PRAB 16, 011301 (2013)

Density gradient injection in gas jet improves beam quality

M. Burza et al. PRSTAB (2013)

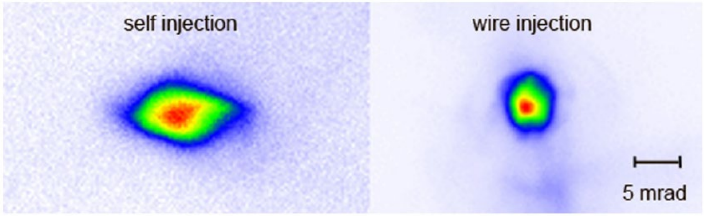


-Density 6 to 3 10^{18} / cc

Injection can happen at lower background plasma density

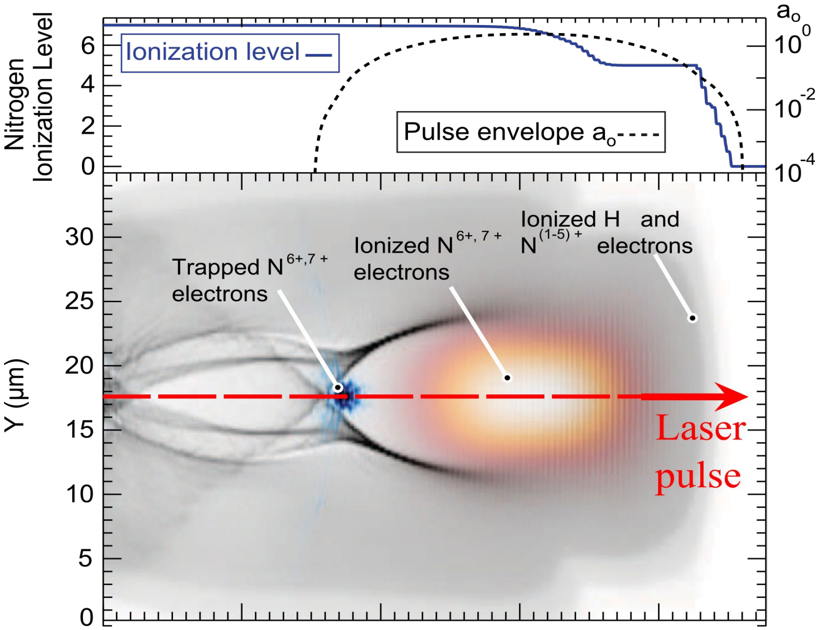
- reduces divergence by 25%

Increases charge 10 times compared to SE



- $E = 100$ MeV
- $\frac{\sigma_E}{E} = 4\ \%\ (\text{fwhm})$
- $Q \sim 43$ pC

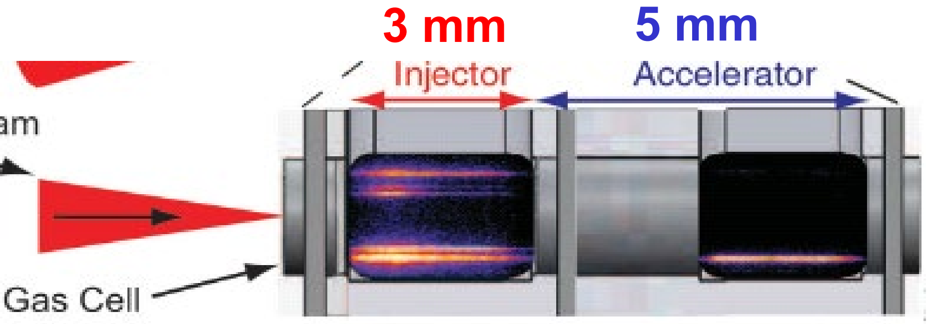
The combination of several mechanisms improves the ES quality



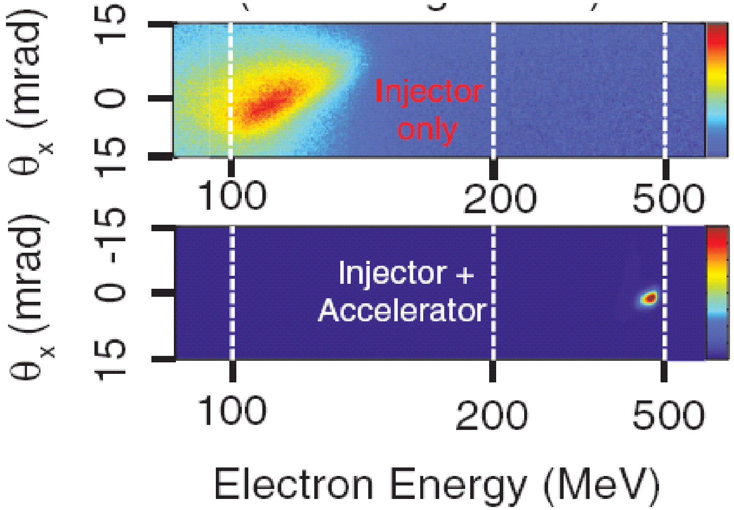
A. Pak *et al.*, PRL – **104**, 025003 (2010)

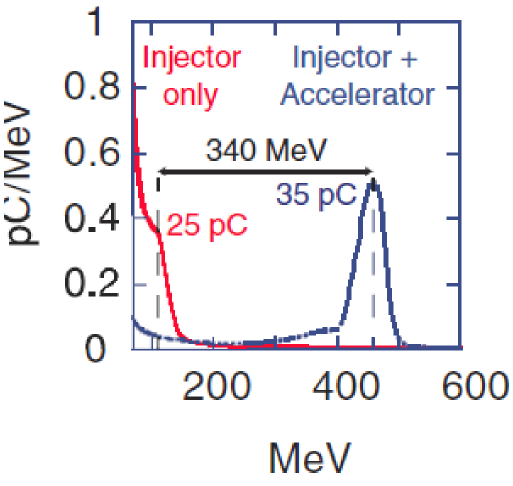
- Ionisation induced injection for increased accelerated charge
- Steep density gradient to stop injection process
- Use of gas cell for improved flow stability

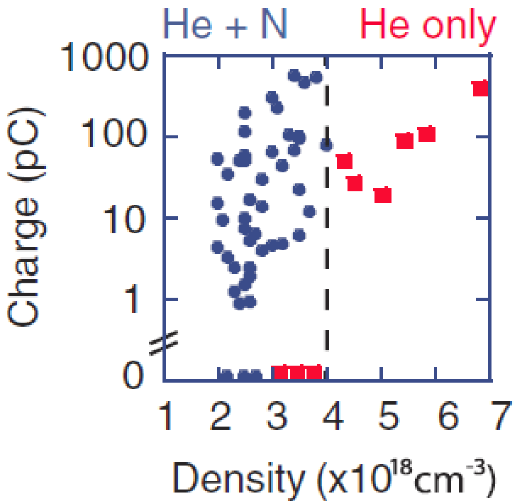
First test of ionisation injection in a double gas cell



- Laser 40TW, $n_e=3\times10^{18}\text{cm}^{-3}$
- 0.5% Nitrogen in the injector:
- Lower density accelerator He:
  Means longer dephasing length
  ie longer acceleration length





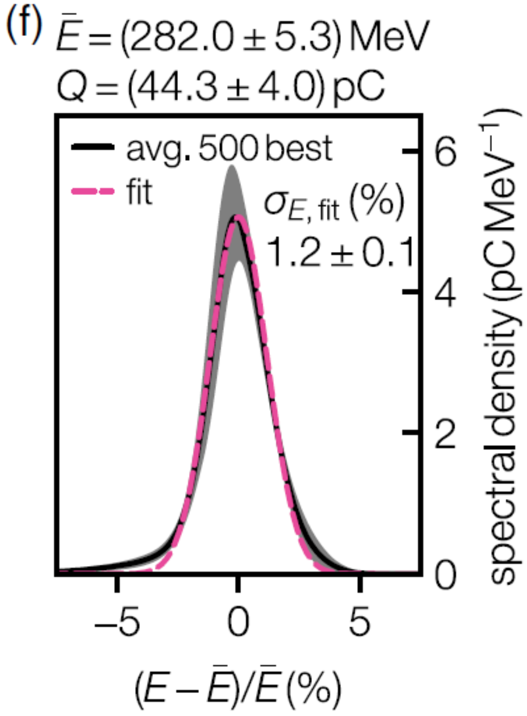


1.4 pC/MeV, Energy Spread FWHM 5%
2.3 mrad divergence

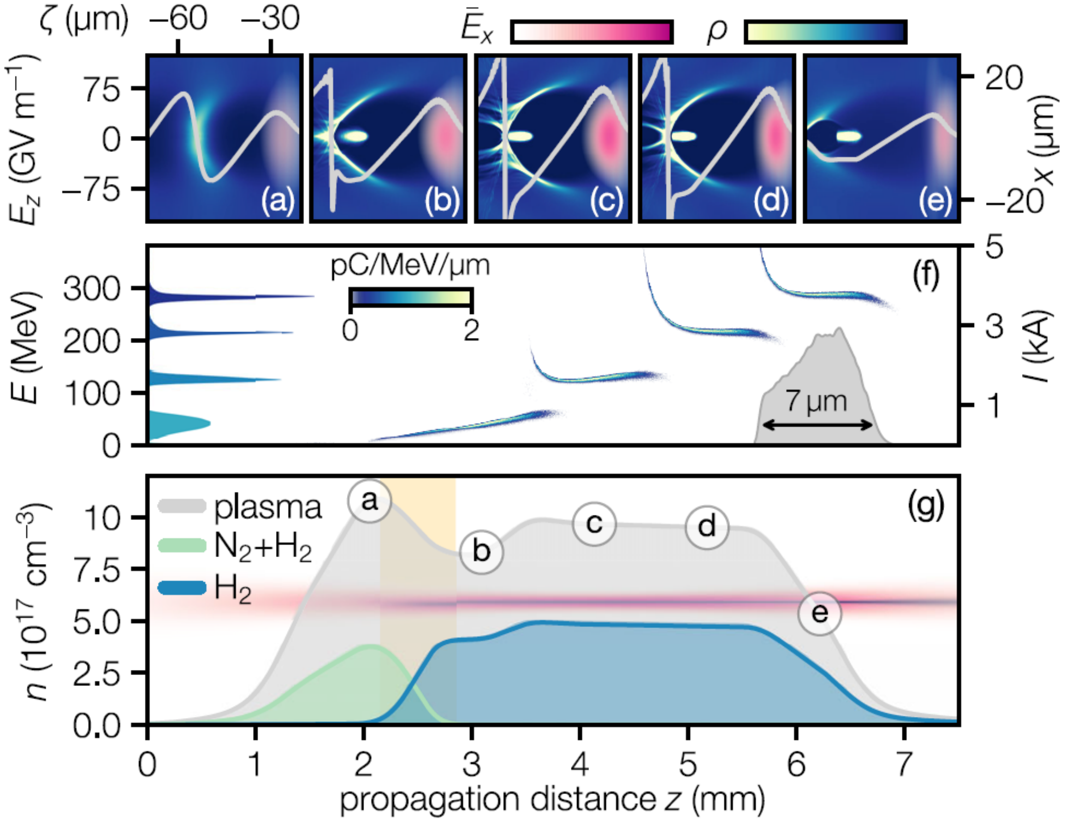
Pollock et al., Phys Rev. Lett 2011 (LLNL)

Density tailoring to control injection and acceleration processes

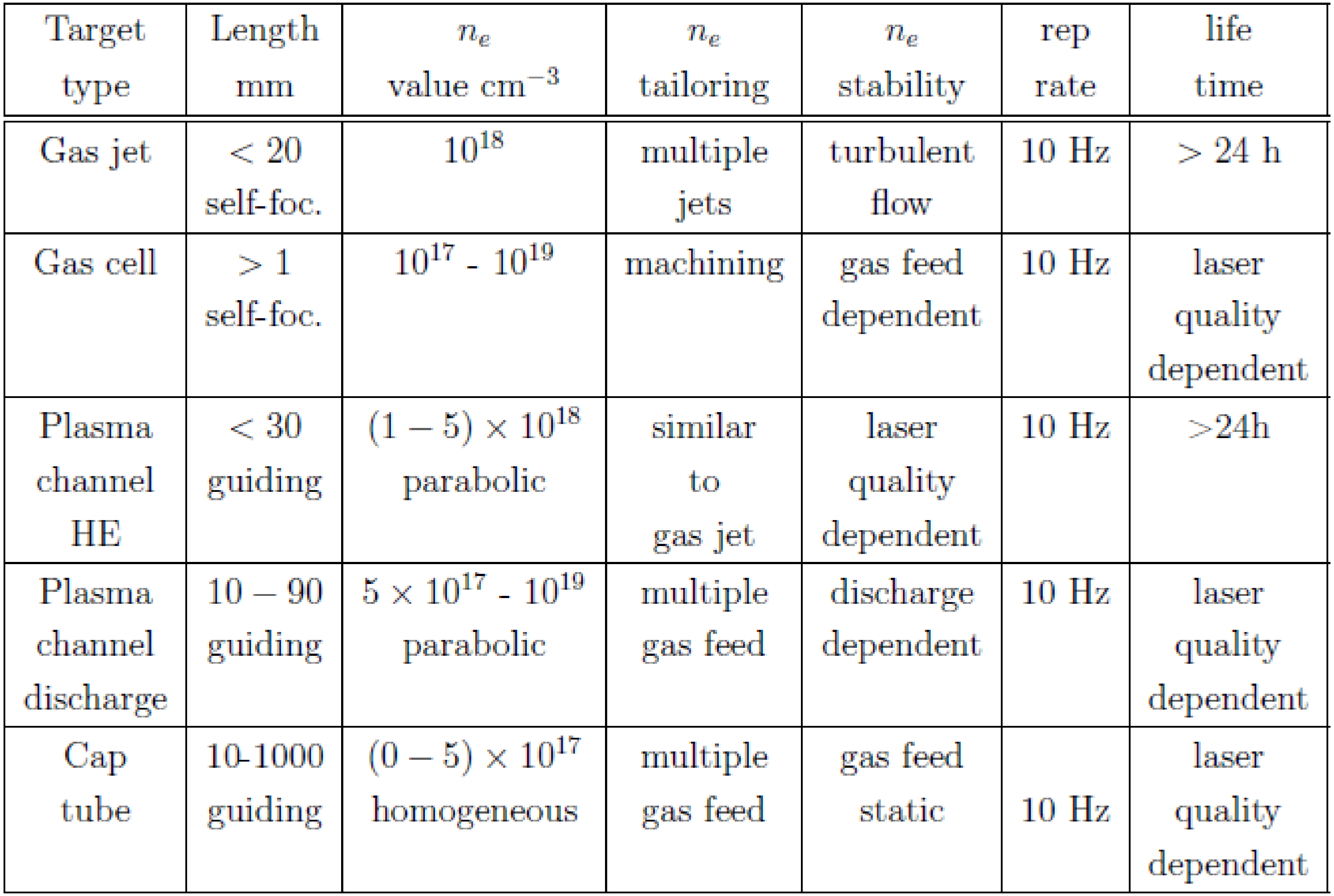
- Achieved consistently after machine learning optimisation
- Good agreement with simulations: strong basis for accelerator design



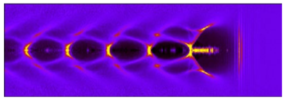
M. Kirchen, PRL 126, 174801 (2021)



Overview of plasma target capability

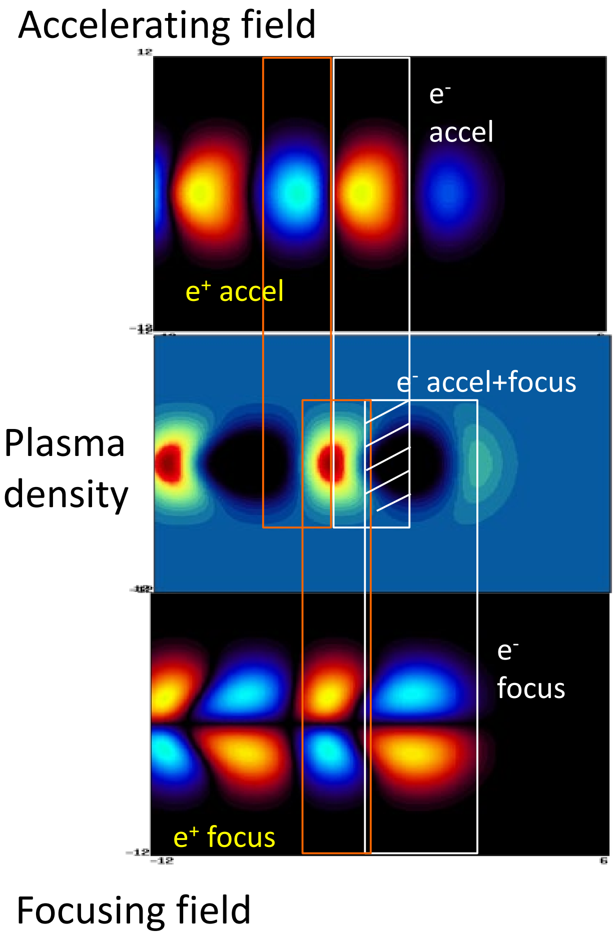


Target type	Length mm	n_e value cm^{-3}	n_e tailoring	n_e stability	rep rate	life time
Gas jet	< 20 self-foc.	10^{18}	multiple jets	turbulent flow	10 Hz	> 24 h
Gas cell	> 1 self-foc.	10^{17} - 10^{19}	machining	gas feed dependent	10 Hz	laser quality dependent
Plasma channel HE	< 30 guiding	$(1-5)\times 10^{18}$ 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 based accelerator cavity: for laser or beam driven wakefield accelerators

Plasma cavities for accelerator



Source C. Schroeder

- Quasi-linear regime of acceleration or moderately NL regime to avoid trapping electrons from plasmas (source of noise and perturbation)
- Acceleration and focussing are achieved within the plasma cavity
- Plasma cavity can be driven by laser or particle beams
- Laser driven schemes require some form of guiding (discussed in Howard Milchberg talk)

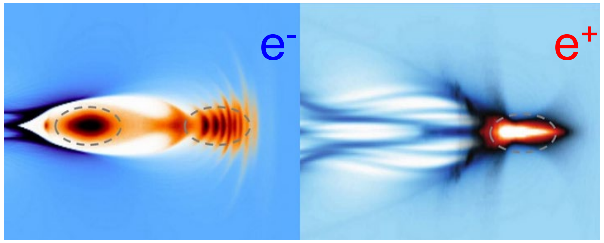
Plasma source for particle beam driven wakefield acceleration

- The driver determines plasma characteristics
  - **high-energy driver,** a long plasma is needed, m-scale
  - no guiding need for e^- , uniform transverse density
  - transverse structure for e^+ acceleration: hollow channel, etc (driven by e^- bunch)
  - longitudinal structure for self-modulation (SM)
  - **Low-energy driver**, hybrid LWFA/PWFA : Plasma source uses LWFA solutions

Source P. Muggli

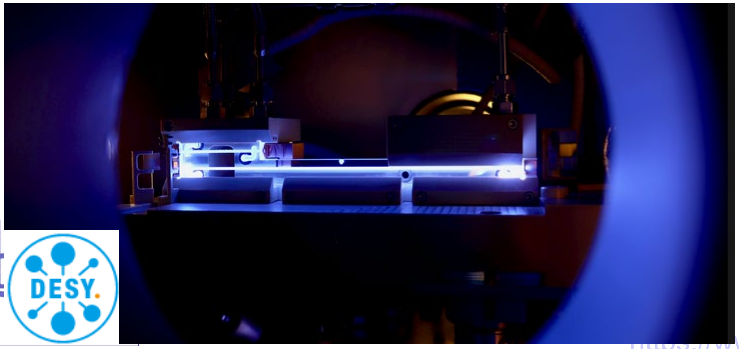
Short electron bunch driver scheme

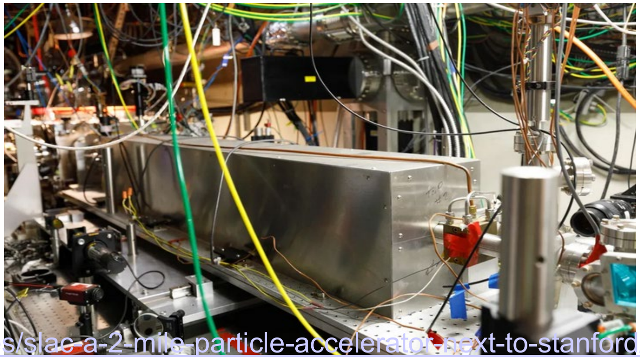
- Range of plasma parameters
  - ✧ $k_{pe}\sigma_z \sim k_{pe}\sigma_r \sim 1$ or $\sigma_z \sim \sigma_r \sim c/\omega_{pe}$
  - ✧Applications may require multiple plasmas (staging), ~100J energy per drive bunch
  - ✧m-scale plasma (FEL, collider), $n_{e0} \sim 10^{17}\text{cm}^{-3}$, $r_p >> c/\omega_{pe} \sim 17\mu\text{m}$



- Several options for plasma creation
  - ✧**Bunch, self-field-ionized** alkali metal vapor ⬄ limited by head erosion
  - ✧**Laser-ionized** (alkali metal, hydrogen, etc.) ⬄ complex ⬄ limit for staging
  - ✧**Capillary discharge** ⬄ walls, pulsed power, repetition

Source P. Muggli





FACET
SLAC

https://www.cnet.com/pictures/slac-a-2-mile-particle-accelerator-next-to-stanford/

Long p^+ bunch driver scheme

- Range of plasma parameters

- ✧ σ_z~10cm>>σ_r , $k_{pe}\sigma_r$~1 or σ_r~c/ω_{pe}.
  - ✧Requires self-modulation (SM) for GV/m wakefields amplitude
  - ✧**10-1000m-scale plasma** (HEP),
  - ✧n_{e0}~10^{15}cm^{-3}, r_p>>c/ω_{pe}~168µm
  - ✧Large energy per bunch: ~10-100kJ
  - ✧SM requires very good **density uniformity**:

$\Delta n_e/n_{e0} << (\pi/2)(c/\omega_{pe})/\sigma_r \Leftrightarrow \Delta n_e/n_{e0} < 1\%$

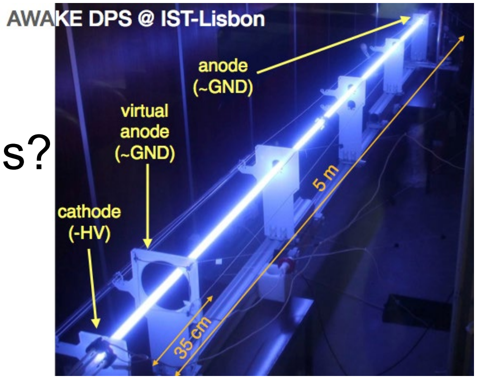
Source P. Muggli

Long p^+ bunch driver scheme

- Several plasma options explored

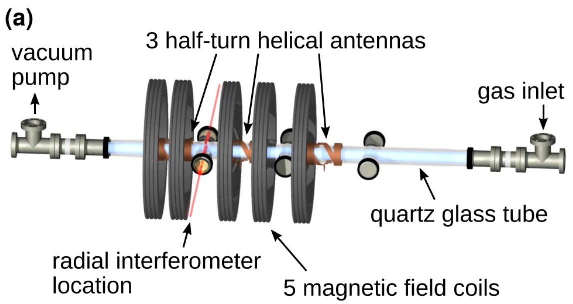
Source P. Muggli

- ✧**Laser-ionized alkali vapor** ⬄ $\Delta n_e/n_{e0}<1\%$
  - ✧Limited in length by laser ionization
- ✧**Discharge source**
  - ✧$\Delta n_e/n_{e0}$?
  - ✧Multiple electrodes/discharges?


AWAKE DPS @ IST-Lisbon

- ✧**Helicon source**
  - ✧Modular
  - ✧$\Delta n_e/n_{e0}$?
  - ✧RF-power (~kW/m)

B. Buttenschoen, PPFC 60, 075005 (2018).



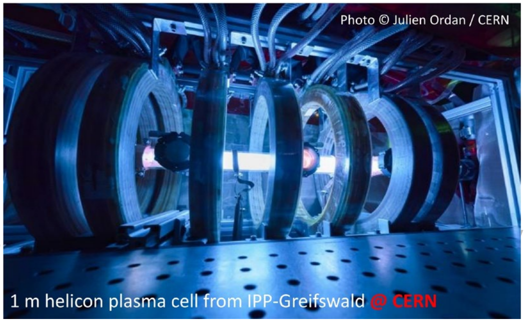
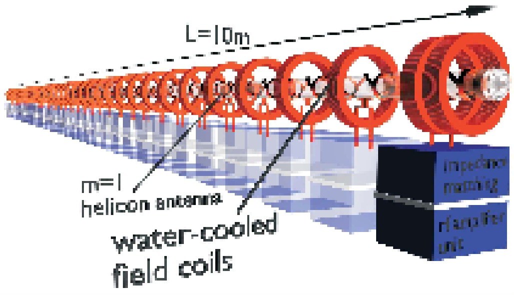
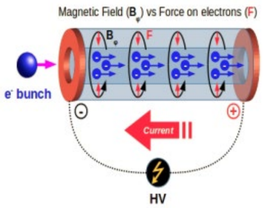


Photo © Julien Ordan / CERN

1 m helicon plasma cell from IPP-Greifswald @ CERN





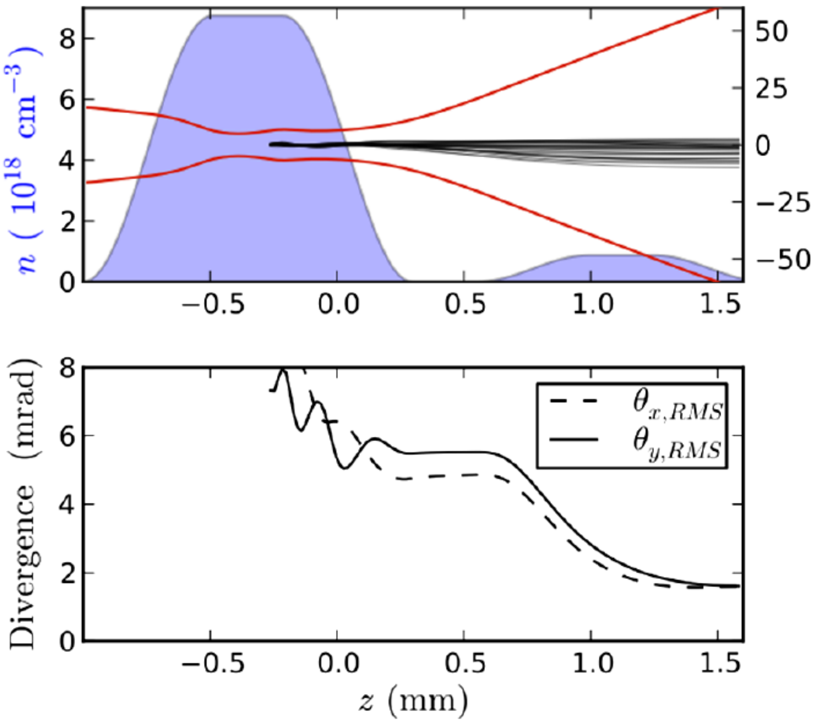
- Plasmas for beam optics

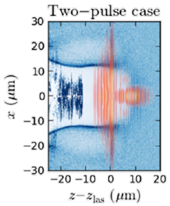
Laser driven plasma lens to reduce divergence of LWFA ES

plasma

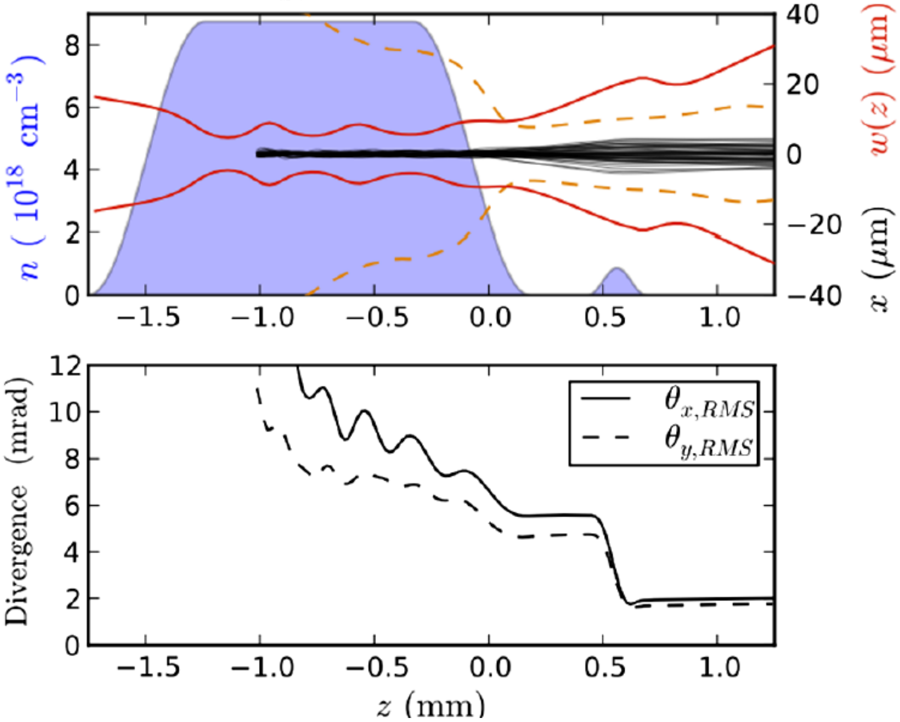
Drift space

plasma





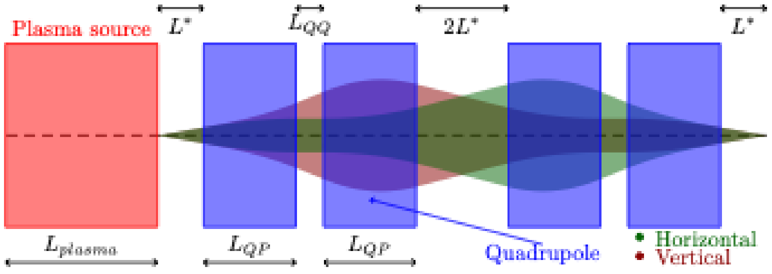
2 pulse case for e beams >200 MeV

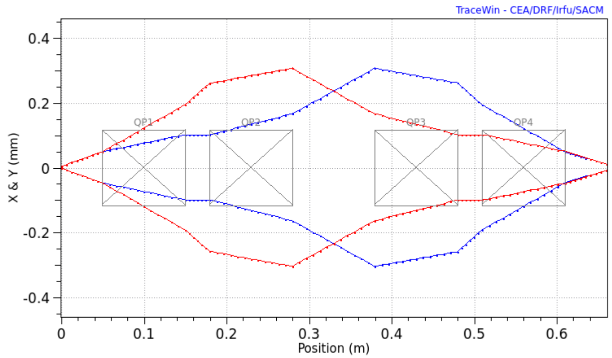


R. Lehe, et al. PRSTAB 17, 121301 (2014)

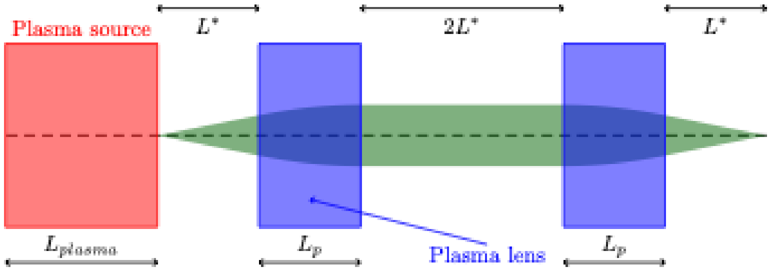
Coupling of electron beams

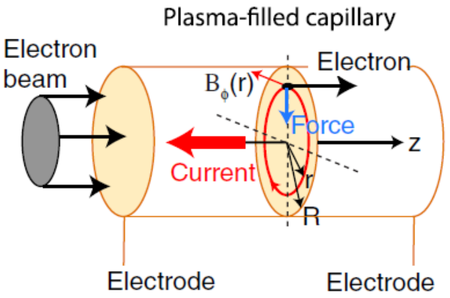
Magnetic structures: low overhead once aligned, but long distances





Plasma structures: strong focusing gradients



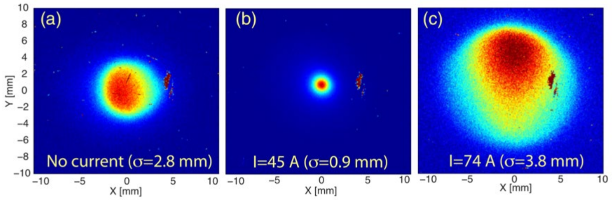


$n_{beam} < n_{plasma}$

$n_{plasma} \sim 10^{18}/cc$

Compact: tunable field gradients in excess of 3000 T/m, enabling cm-scale focal lengths for GeV-level beam energies

Radially symetric focusing of electrons in a plasma lens



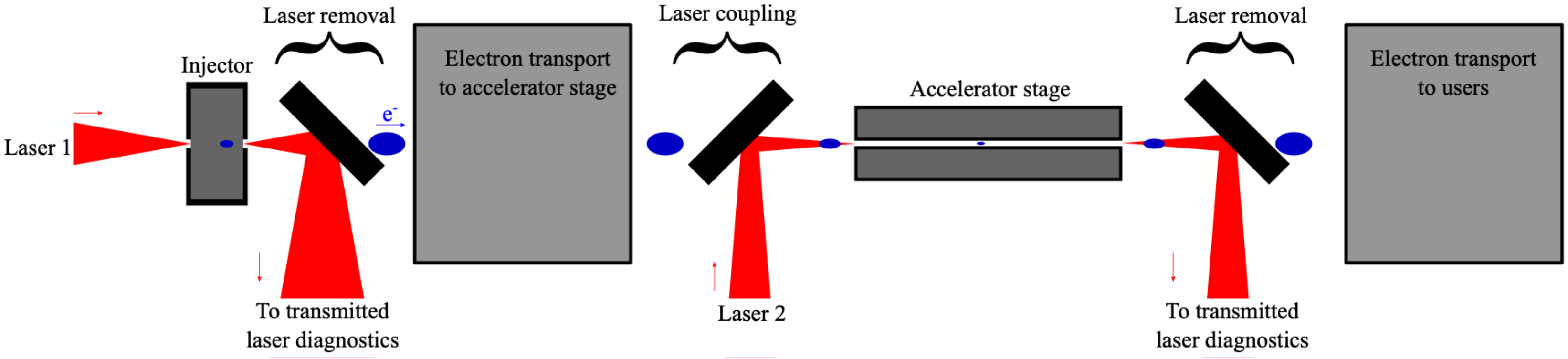
J. Van Tilborg, et al, Phys. Rev. Lett. 115, 184802 (2015).

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

Horizon 2020

Coupling of laser beams

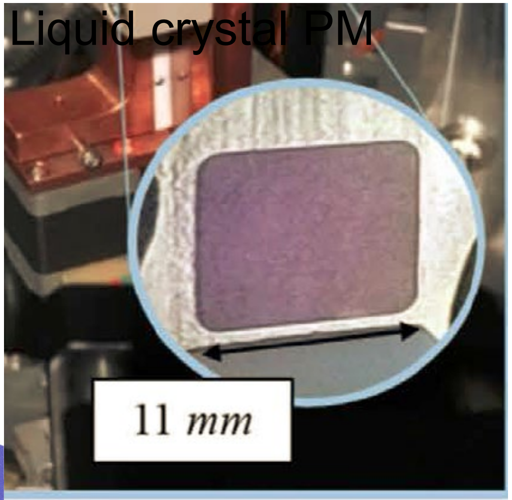
Most investigated option is plasma mirrors:

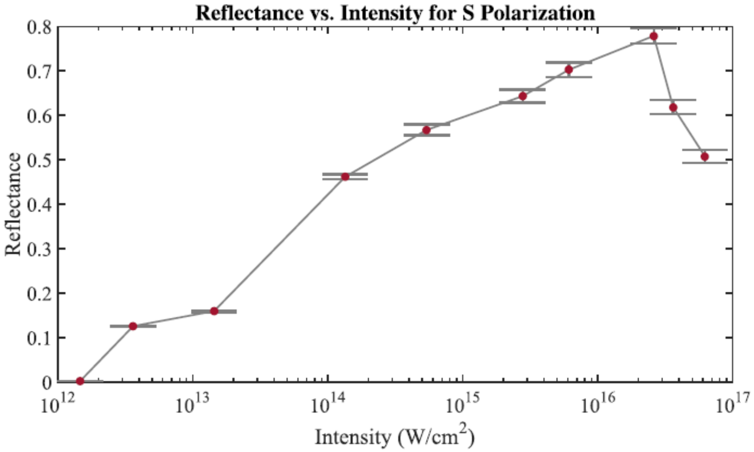


Tape drives, liquid crystal mirrors

Poole 2016, Scientific Report 6:32041 |

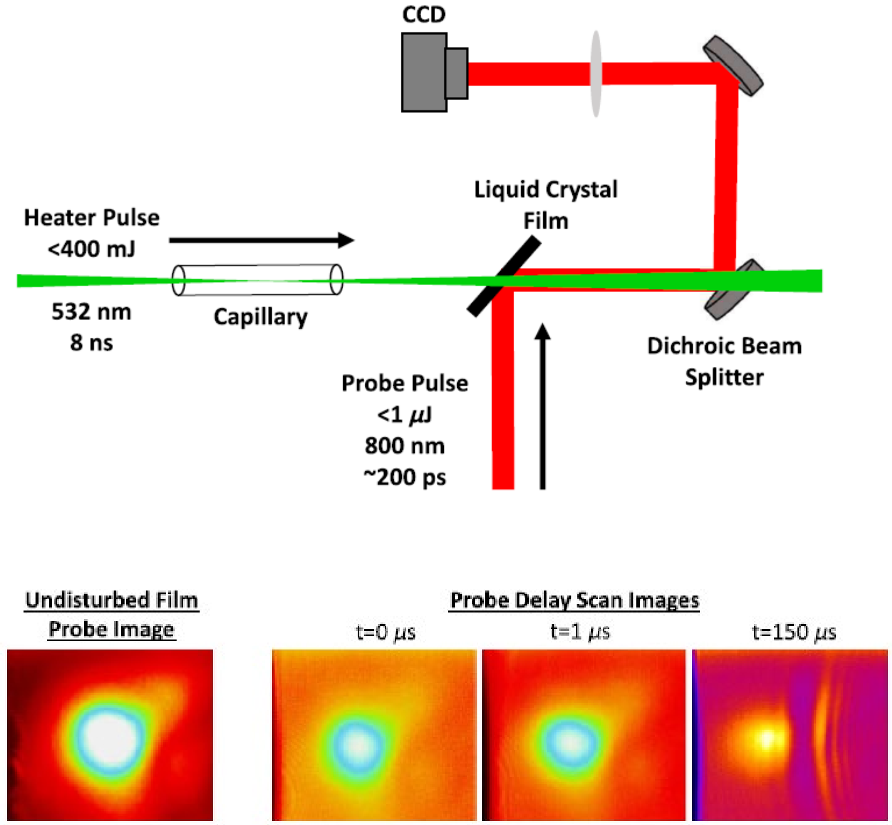
Liquid crystal PM

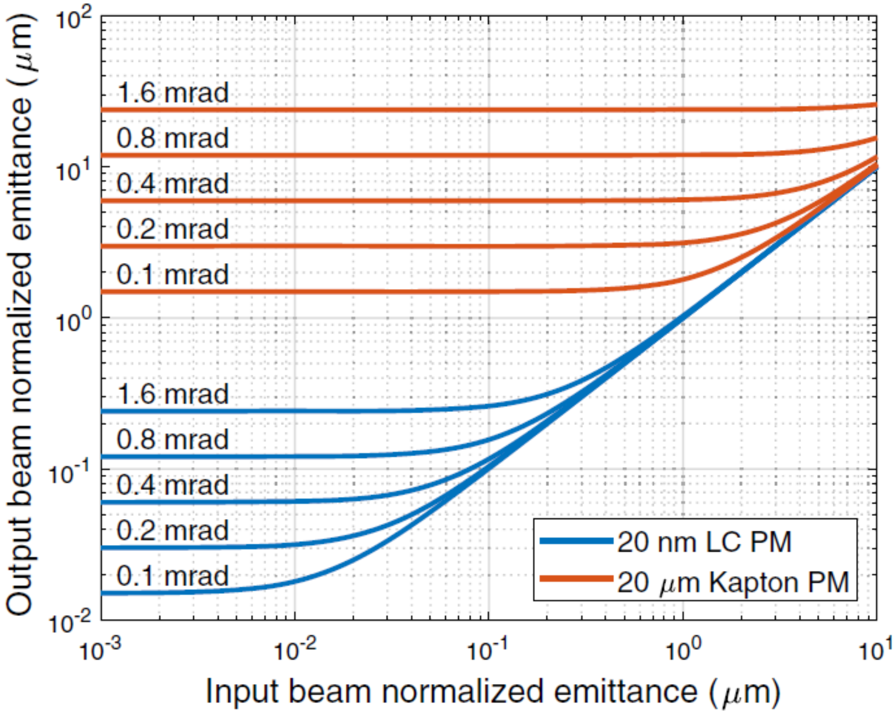




Thin film plasma mirrors for accelerators: tape drive / Liquid crystal

- LC 1000 time thinner than TD preserve 1µm emittance





Zingale, PRAB, 24, 121301 (2021))

Summary

- Plasma technology for accelerators comes in several forms for plasma **confinement and tailoring** (jet, cell, capillary, pipes, films)
- Plasma **density** value and distribution are set by the function of each accelerator component, injector, accelerating cavity, laser or beam coupling between stages(10^{15} to 10^{19} or even 10^{21} /cc for mirrors)
- Plasma **stability** (density distribution in space and time) has a strong impact on electron beam properties
- Future developments are expected on **scaling plasma sources** to large sizes, high repetition rate, and on energy management