Plasma devices: plasma dechirper and plasma lens

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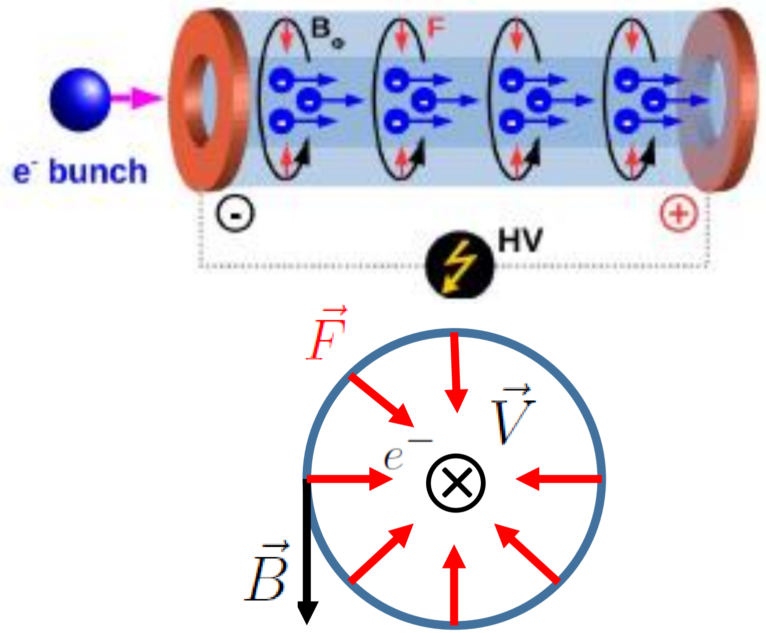
on behalf of SPARC_LAB collaboration

- ***Active plasma lens***
  - *focusing with the current magnetic filed*
  - *experimental setups*
  - *emittance preservation in APL*
- ***Plasma based dechirper***
  - *self-induced dechirping wakefield*
  - *capillary and gas jet setups*
  - *experimental results & standing questions*
- ***Conclusions***

Active plasma lens

Discharge-current inside gas-filled capillary

- ✓ *The gas is used as a conductor, to create a current*
- ✓ *An azimuthal field, created by the current, radially grows inside of the current and decrease outside of it*
- ✓ *Capillary keeps the gas and thus the current confined*



Advantages

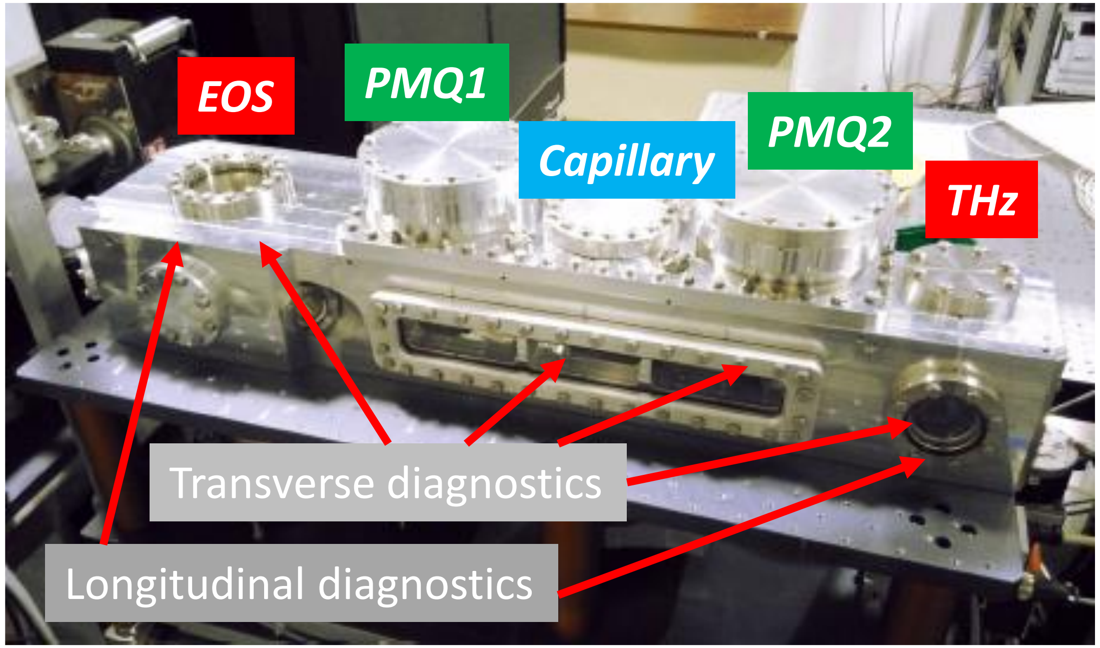
- ✓ *Cylindrical symmetry in focusing (~ solenoids)*
- ✓ *Favorable focusing strength K~ 1/γ (~ quadrupoles)*
- ✓ *Large focusing gradient ~ kT/m*
- ✓ *Tunability by adjusting the current amplitude*

$$B_\phi(r) = \frac{\mu_0}{R}\int_0^R J(r)rdr$$

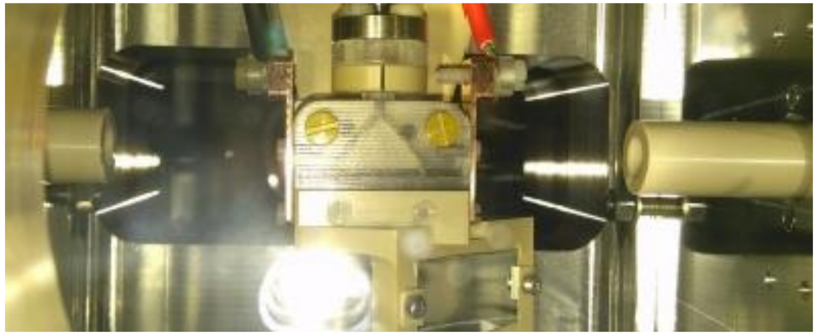
Panofsky, Wolfgang Kurt Hermann, and W. R. Baker. *"A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley."* ***Review of Scientific Instruments 21.5 (1950): 445-447.***

Experimental setup

SPARC APL setup

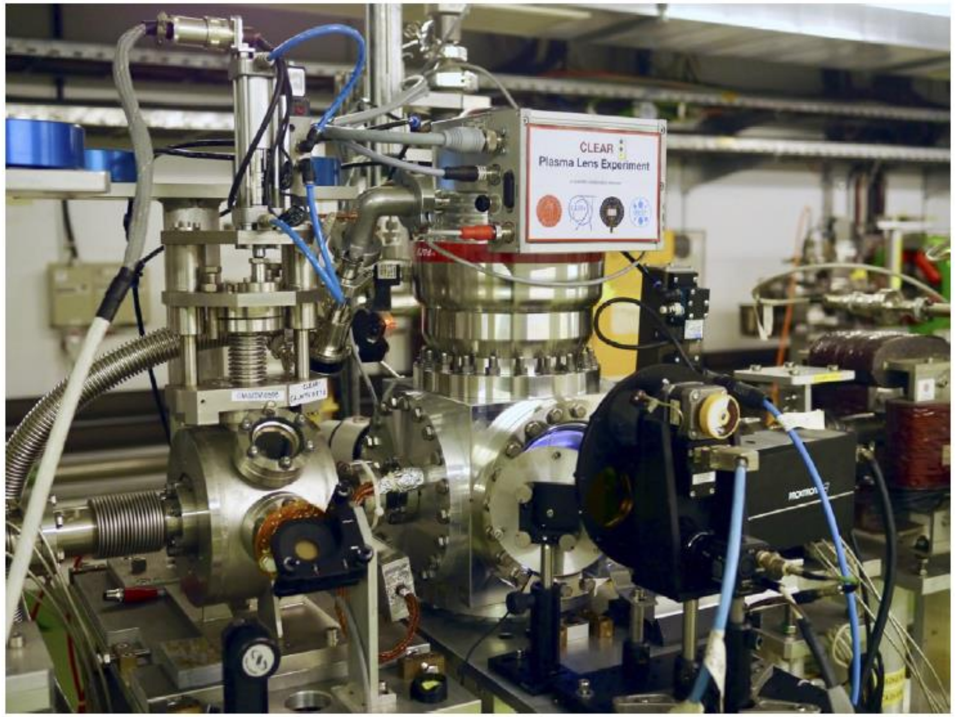


Inner view of the interaction chamber



Pompili R., et al., *Experimental characterization of active plasma lensing for electron beams*, ***App. Phys. Lett. 110 (2017): 104101.***

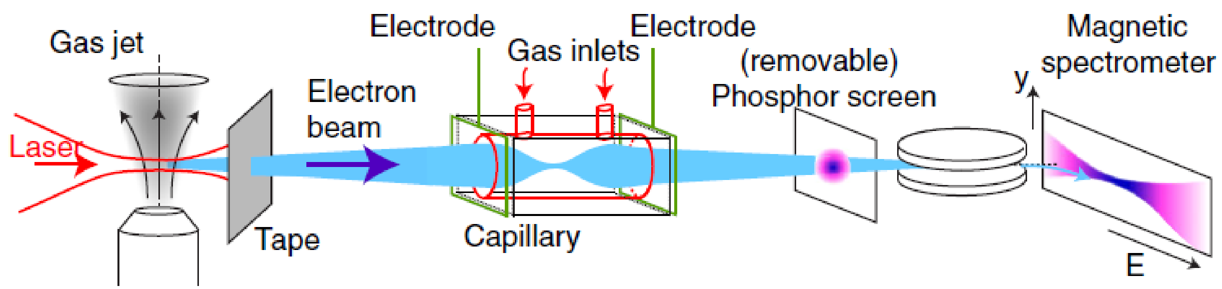
CLEAR APL setup



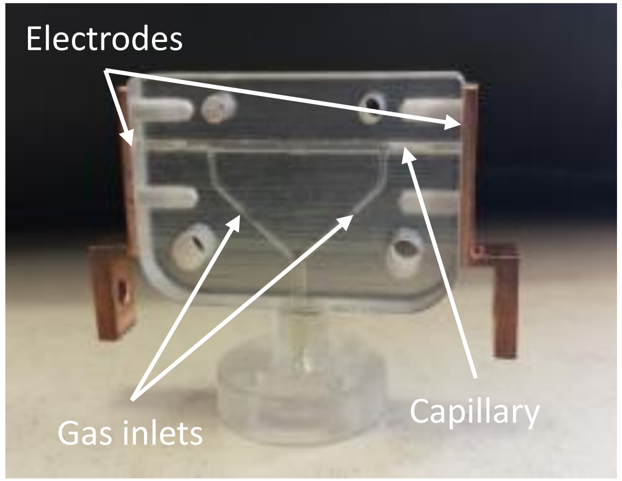
Lindstorm C.A., et al., *Overview of the CLEAR plasma lens experiment*, ***NIM A 909 (2018): 379-382.***

Plasma lens experimental setup

BELLA APL setup

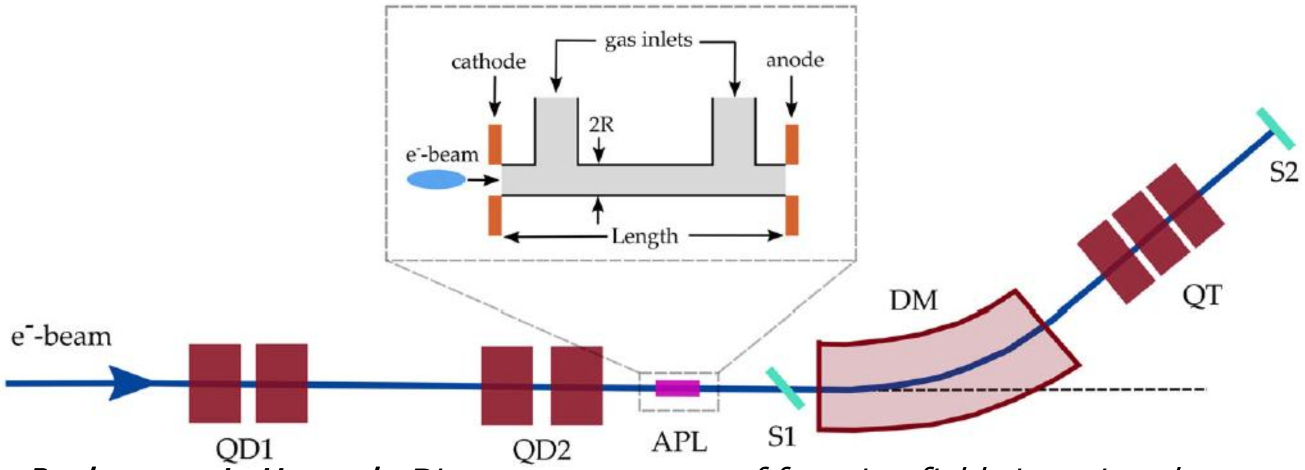


J. van Tilborg, et al., Active plasma lensing for relativistic laser-plasma – accelerated electron beams, PRL 115 (2015): 184802.



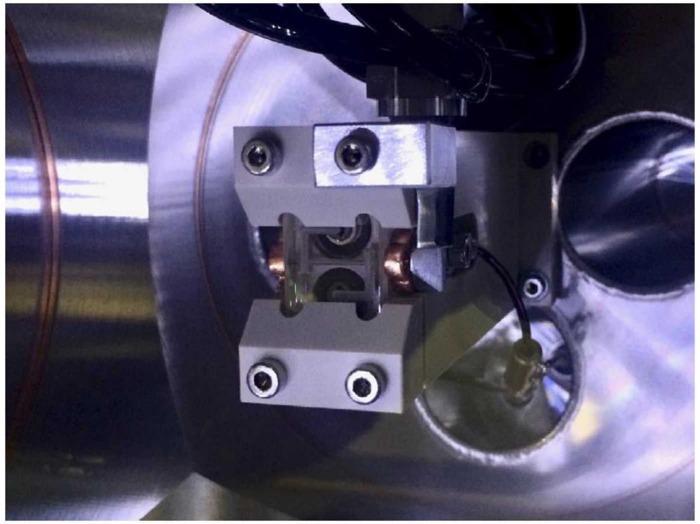
Capillary SPARC

MaMi APL setup

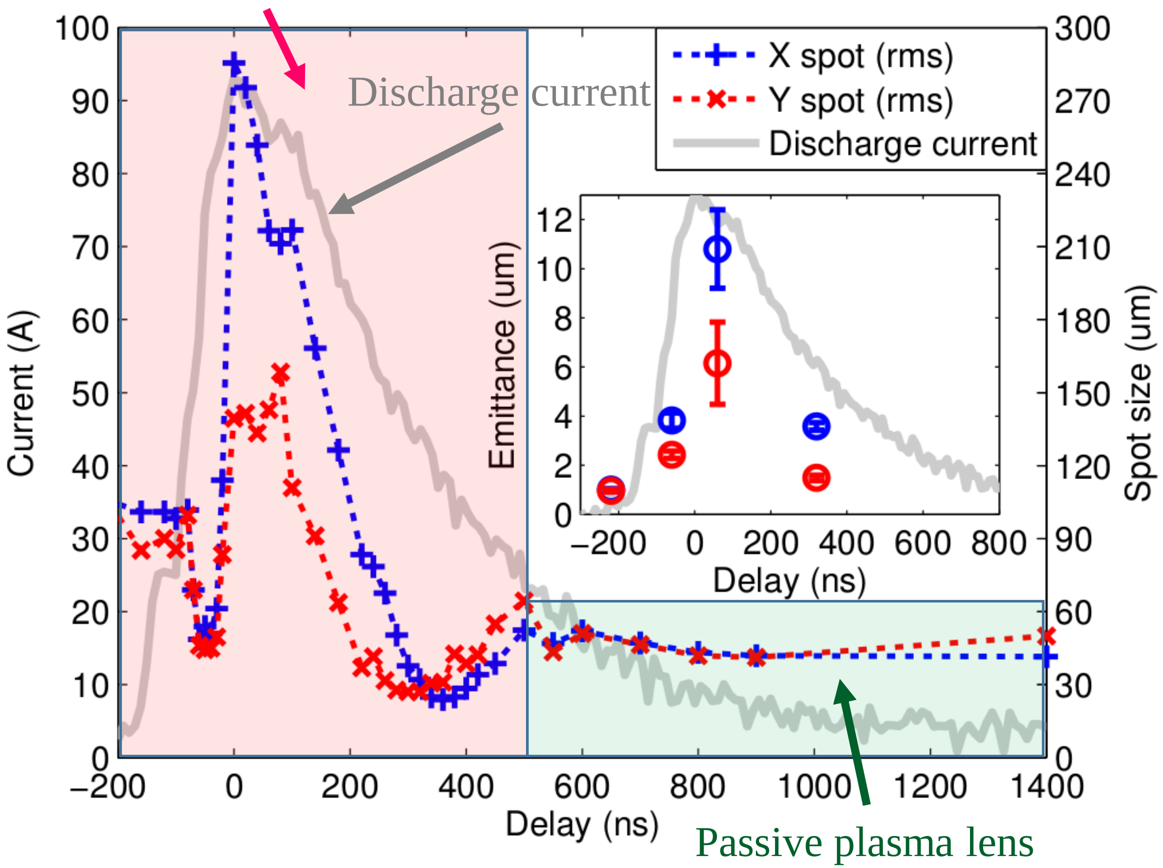


Rockemann J.-H., et al., Direct measurement of focusing fields in active plasma lenses, Phys.Rev A&B 21 (2018): 122801.

Capillary CLEAR

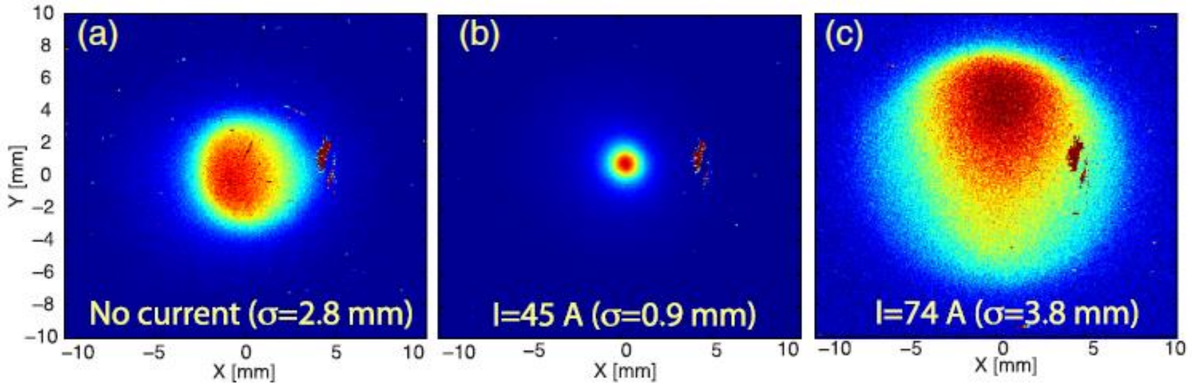


SPARC APL results



Pompili R., et al.**, Experimental characterization of active plasma lensing for electron beams, **App. Phys. Lett. 110 (2017): 104101.

BELLA APL results



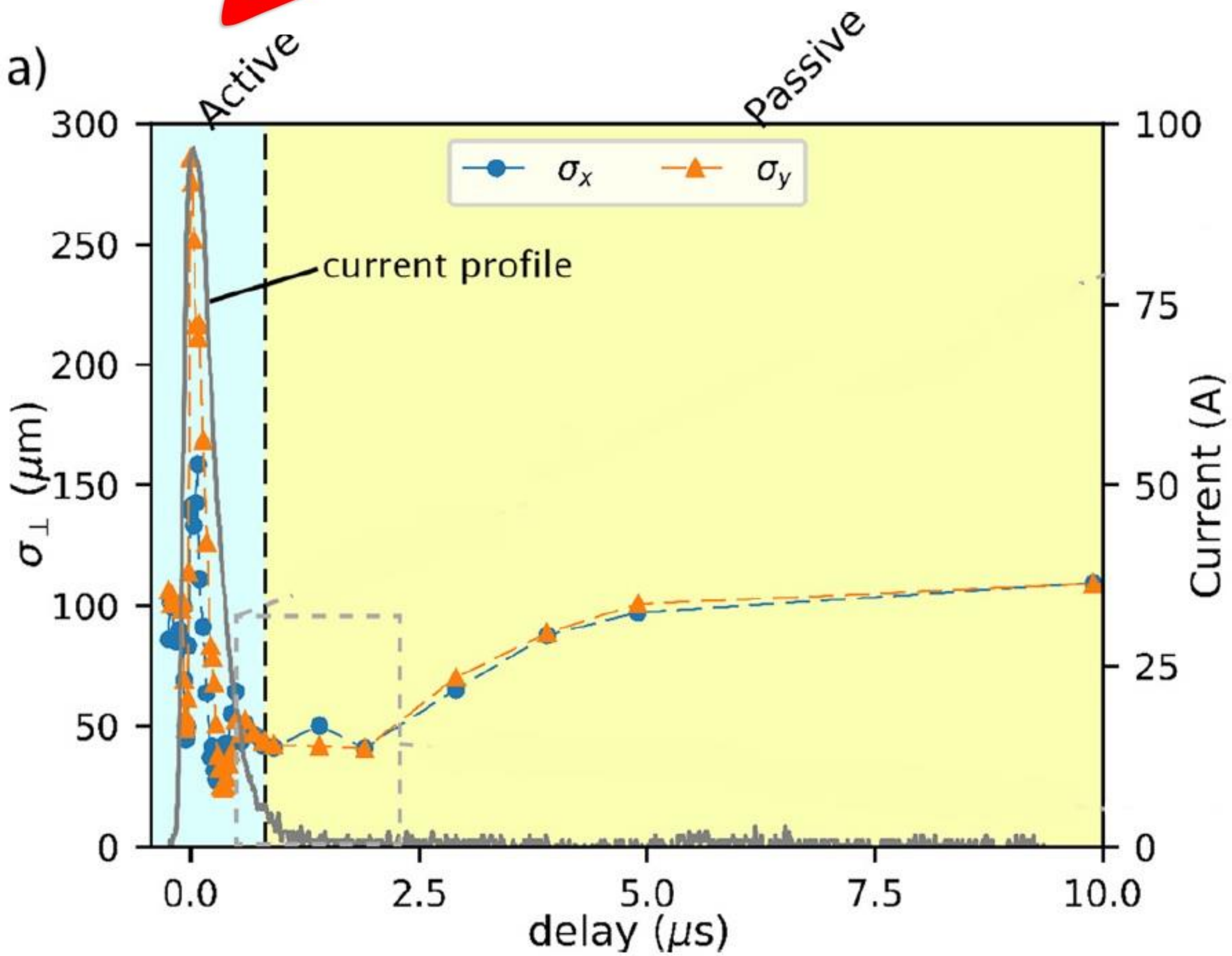
J. van Tilborg, et al.**, Active plasma lensing for relativistic laser-plasma -accelerated electron beams, **PRL 115 (2015): 184802.

The lens proved to be capable to focus the beam, however **emittance deterioration** was observed (e.g. at SPARC 1.0 to 3.6 mm•mrad)

Beam quality dependencies:

- ✓ *current distribution → non-linear focusing (aberrations at the edges)*
- ✓ *passive plasma lens effects*
- ✓ *size of the beam at the injection into the lens*

Passive plasma lens effects



Passive plasma lens regimes

$n_b \ll n_p$ $\qquad$ $n_b \gg n_p$

Interaction with plasma:

- ✓ *there are two regimes for the passive plasma lens*
- ✓ *passive plasma lens is significantly weaker then the APL (during the experiments at SPARC ~250 T/m for APL while for passive lens only 30 T/m)*
- ✓ *most of the emittance deterioration happens under condition $k_p\sigma_z$~1*

Marocchino A., et al.**, Experimental characterization of the effects induced by passive plasma lens on high brightness electron bunches, **App. Phys. Lett. 111 (2017): 184101.
Chiadroni E., et al.** Overview of plasma lens experiments and recent results at SPARC_LAB, **NIM A 909 (2017): 16-20.

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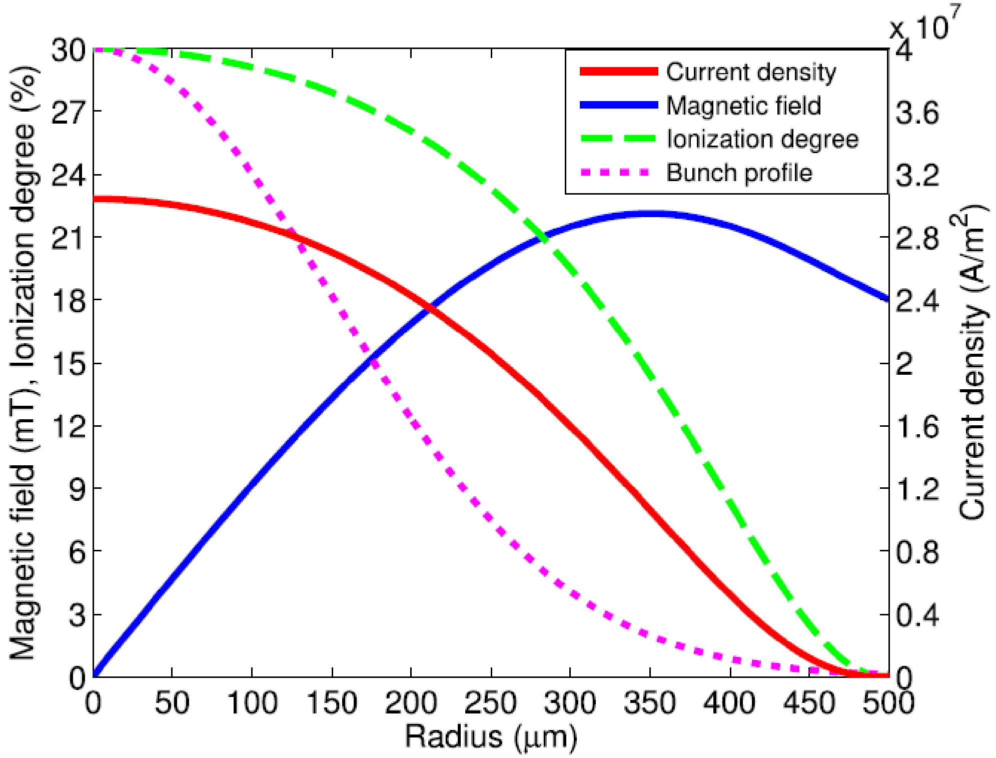
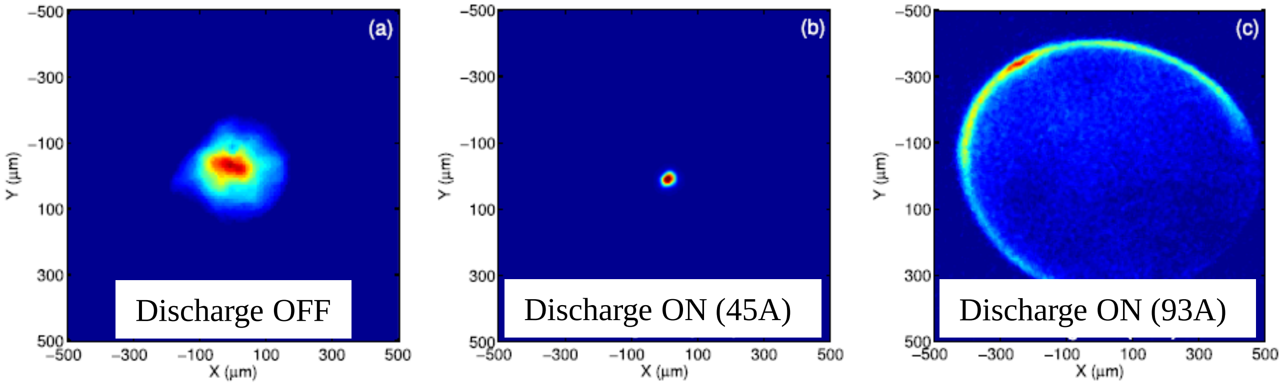
Current/magnetic field/beam distribution



*Pompili R., et al., Experimental characterization of active plasma lensing for electron beams, **App. Phys. Lett. 110 (2017): 104101.***

SPARC APL results



Non uniform distribution of the current leads to a non linear gradient of the magnetic field

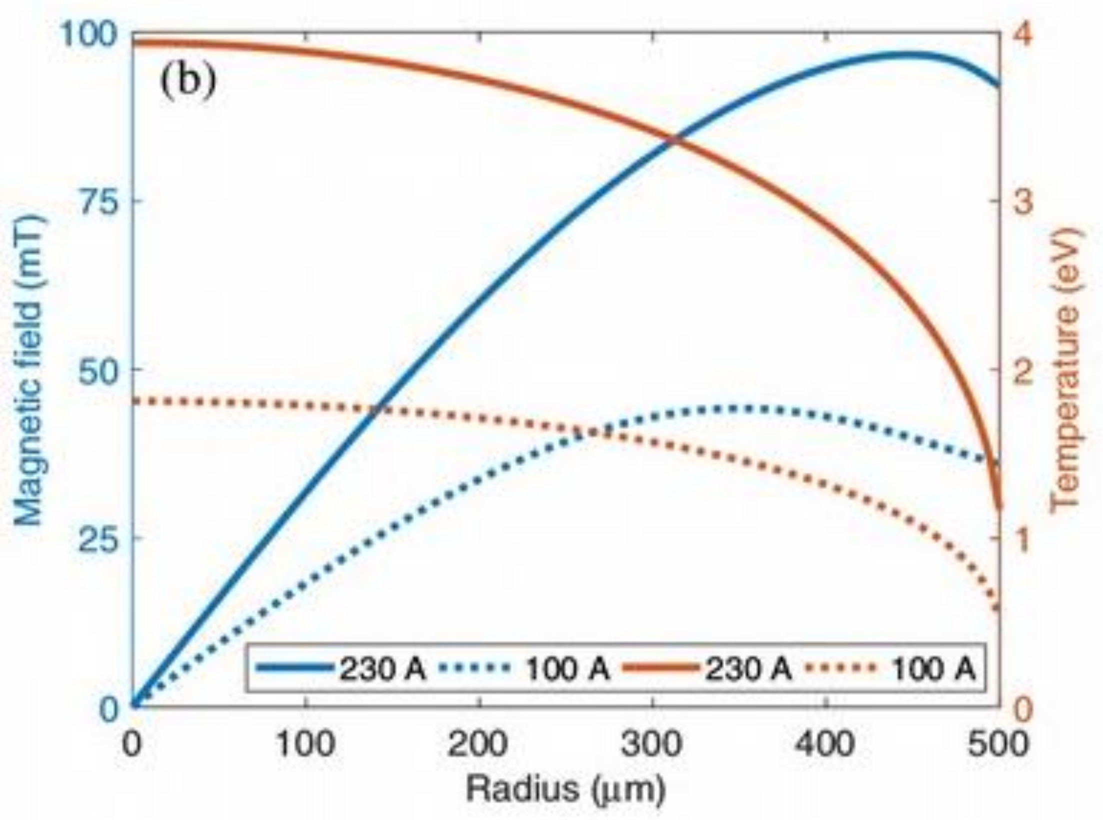
$$J(r) = \sigma E \propto T_e^{3/2}$$

$$B_\varphi(r) = \mu_0 r^{-1} \int_0^r J(r') r' dr'$$

Boborova N.A., et al.,** Simulations of a hydrogen-filled capillary discharge waveguide **Phys.Rev. E 65 (2001): 016407.
Van Tilborg J., et al.,** Nonuniform discharge currents in active plasma lenses **Phys.Rev. STAB 20 (2017): 032803.

Emittance preservation inside the APL

SPARC



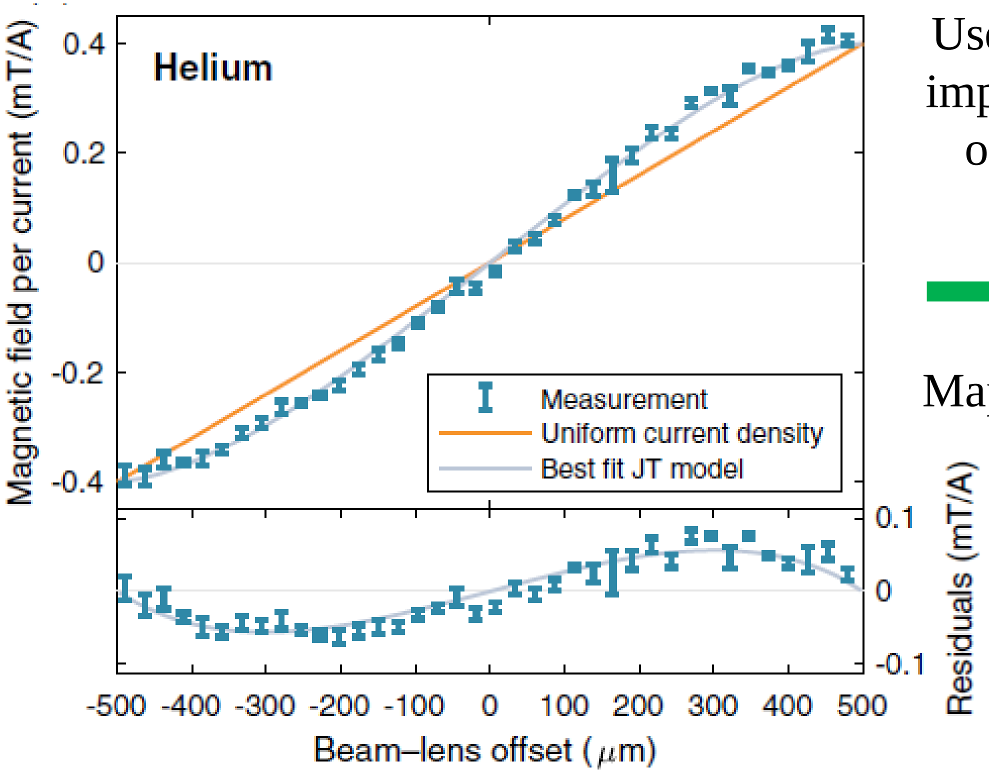
The peak current was increased from ~90 A to ~220 A, which extended a linear gradient area of the capillary

- ✓ *better ionization of the H2 led ot a better distribution of the current*
- ✓ *increased linear part of the magnetic field gradient*
- ✓ *the emittance was preserved (0.8 →0.9* mm•mrad*)*
- ✓ *improved minimum spot size (21 →17 μm)*

Pompili R., et al., *Focusing of High-brightness electron beams with active-plasma lenses*, ***PRL 121 (2018): 174801.***

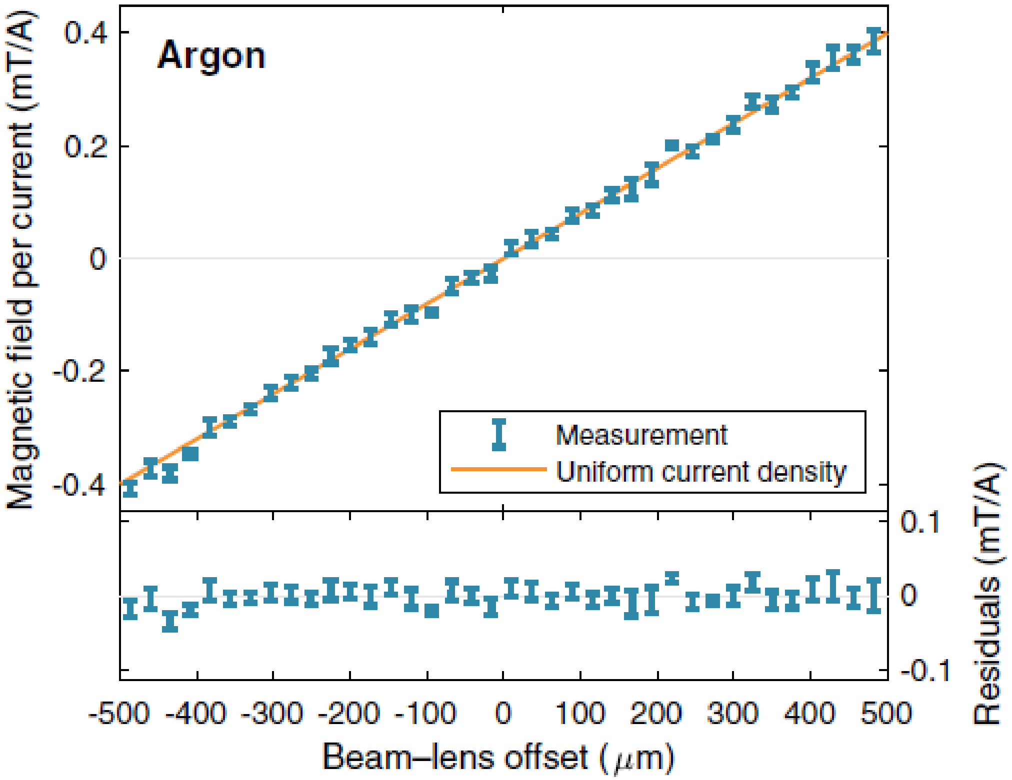
Emittance preservation inside the APL

CLEAR



Use of the heavier atoms improved the distribution of the current density

Mapping of the magnetic field was done



Lindstorm C.A., et al., *Emittance preservation in an aberration-free active plasma lens,* ***PRL 121 (2018): 194801.***

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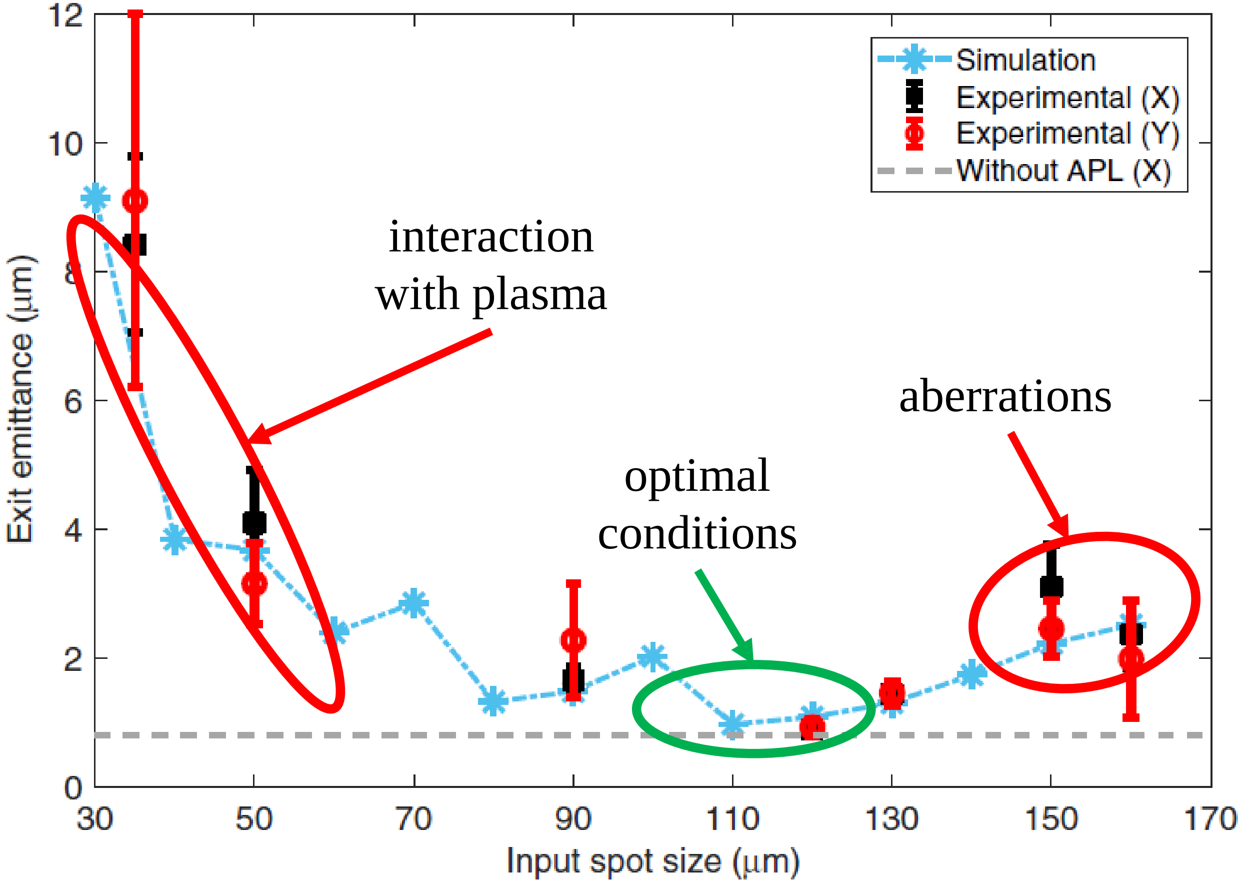


- ✓ *there was observed the dependence of the emittance on the size of the beam at the entrance to the capillary*
- ✓ *for smaller sizes (higher density) of the incoming beam the interaction with the plasma starts to affect the incoming beam quality*

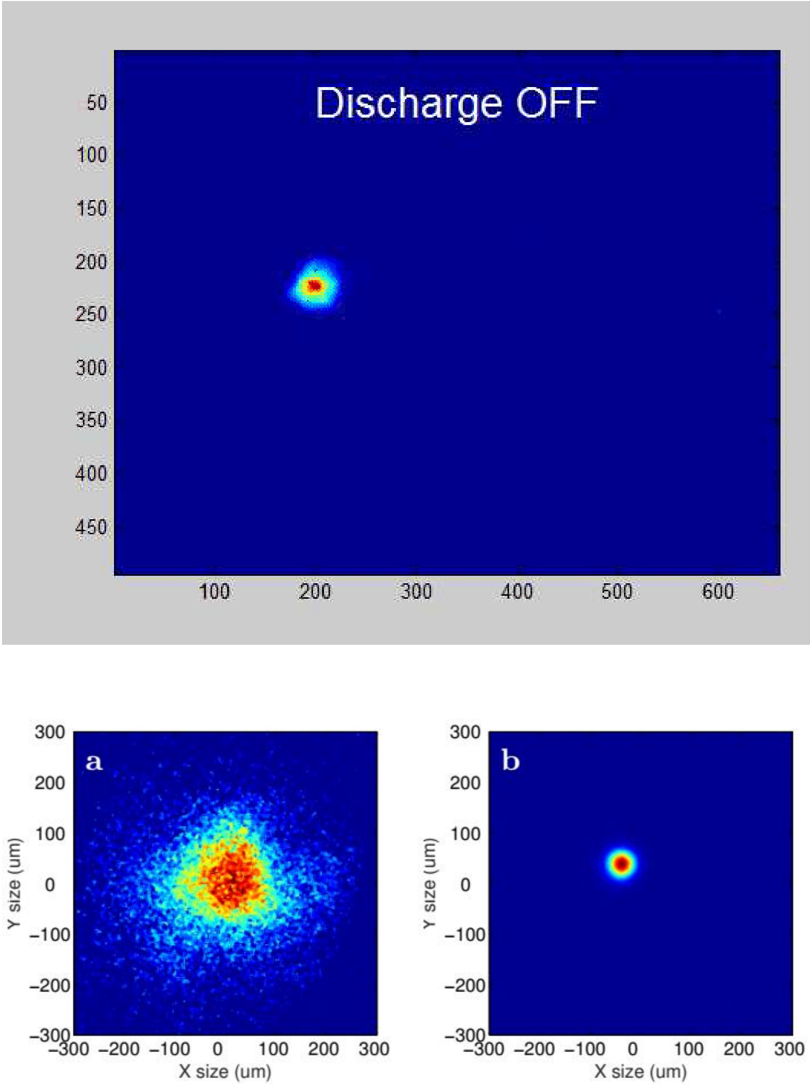
Two conflicting requirements

smaller beam size is needed to avoid aberration effects from non-linear mag. field gradient

larger incoming beam size is preferable to avoid any interaction with the plasma

***Pompili R., et al.**, Focusing of High-brightness electron beams with active-plasma lenses, **PRL 121 (2018): 174801**.*

Active plasma lens: summary



- ✓ ***it works!**, it was demonstrated the APL can preserve the quality of the beam.*
- ✓ *it highly flexible, the change of the lens strength can be easily changed from 10s to 1000s T/m*

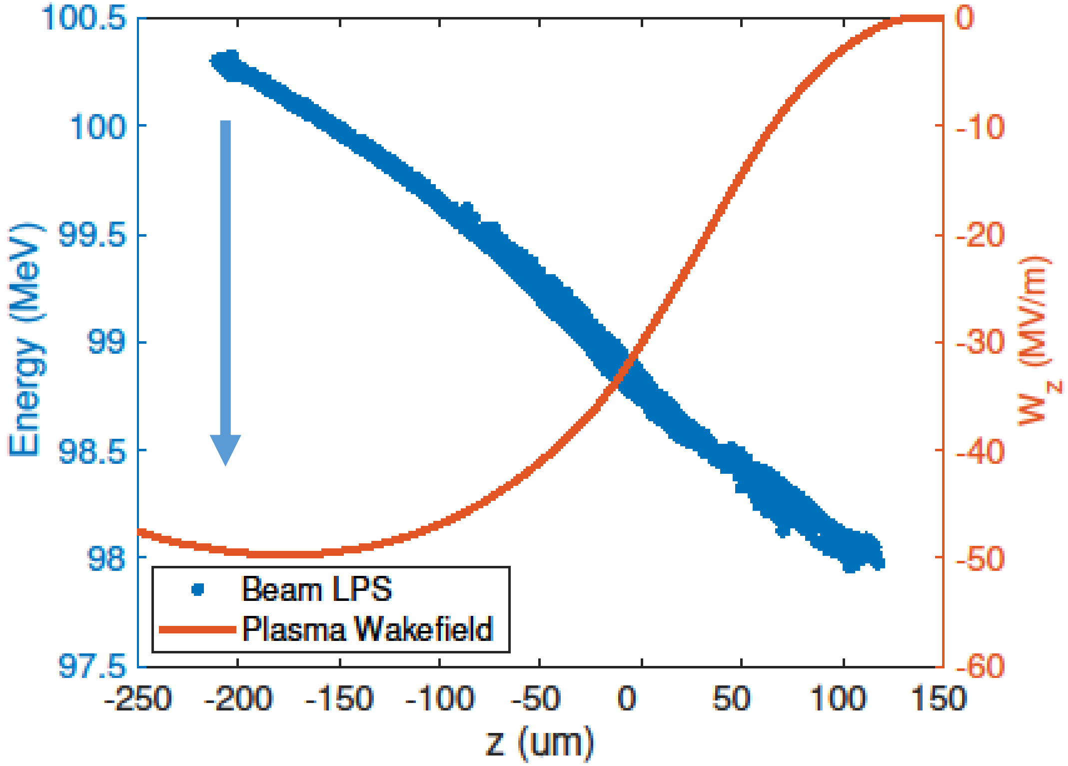
To keep in mind about APL:

- ✓ *emittance deterioration mostly caused by non-uniformity of the current density*
- ✓ *active plasma lens favors higher peak current, due to the better linearity of the resulting magnetic field/ proper choice of the gas for the plasma*
- ✓ *interaction with the plasma can cause some issues, even as severe as current profile*
- ✓ *low bunch densities ($n_b << n_p$) are preferable for preventing passive plasma lens effects*

Plasma based “dechirper”

Plasma dechirper, basic idea

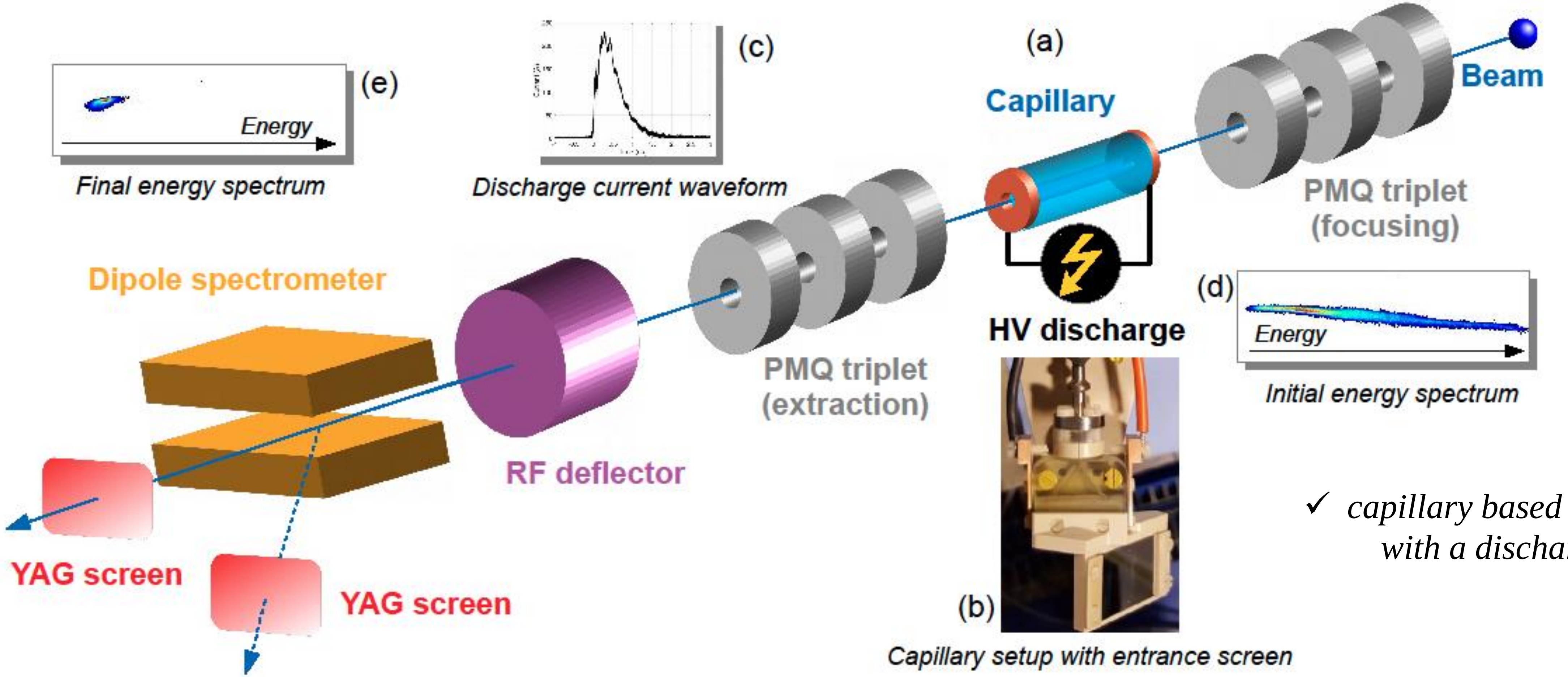
Self-wakefield created by the chirped beam



D'Arcy R., et al., *Tunable plasma-based energy dechirper,* ***PRL 122 (2019): 034801.***
Shpakov V., et al., *Longitudinal phase-space manipulation with beam driven plasma wakefields,* ***PRL 122 (2019): 114801.***
WU Y.P., et al., *Phase space dynamics of plasma wakefield dechirper for energy spread reduction,* ***PRL 122 (2019): 034801.***

- **Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.**
  - ✓ *the large gradient that plasma can sustain (~ GV/m) allows to imprint or remove large energy correlation (chirp) from the beam by means of relatively short structures (~ cm).*
- **Large flexibility of the method, by varying parameters of the system:**
  - ✓ *plasma density (large density → large wake amplitude)*
  - ✓ *beam density (large density → large wake amplitude)*
  - ✓ *length of the plasma channel (cumulative effect)*
- **Applications:**
  - ✓ *energy-chirp removal ("dechirper") for PWFA, LWFA*
  - ✓ *bunch compressors (dogleg/chicane beamlines)*

SPARC plasma dechirper setup

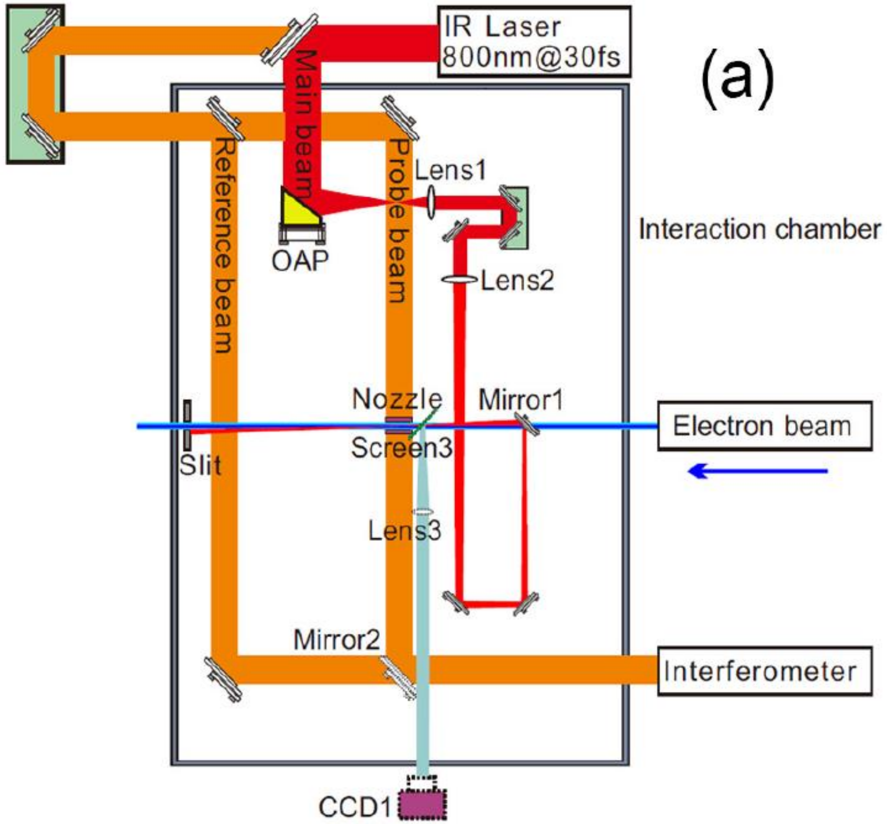


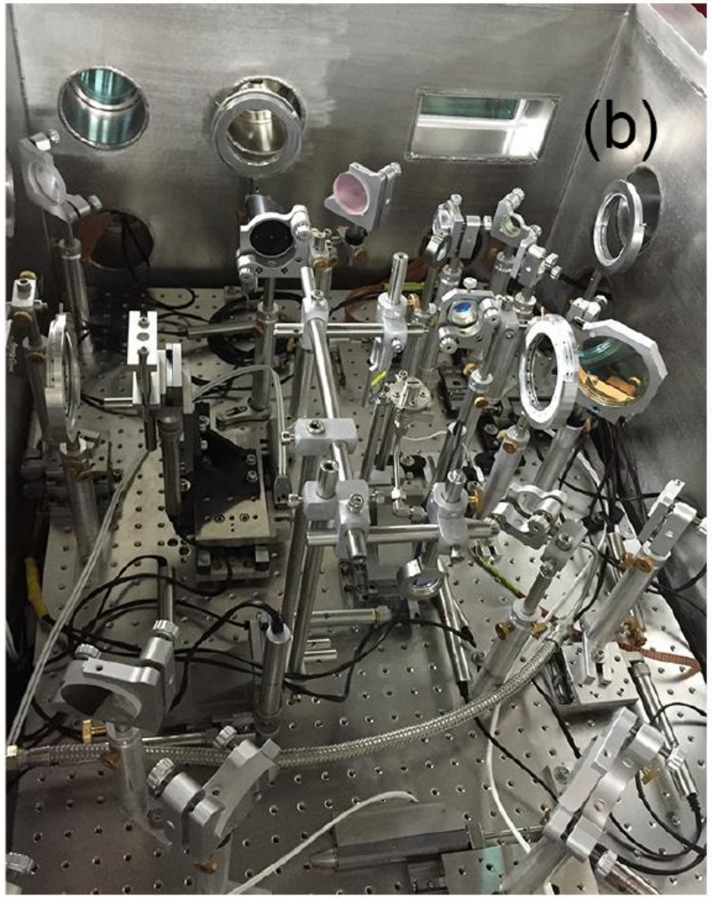
✓ *capillary based setup with a discharge*

Plasma dechirper, experimental setup

Tsinghua Univ. plasma dechirper setup

- ✓ *gas jet illuminated by the laser pulse*

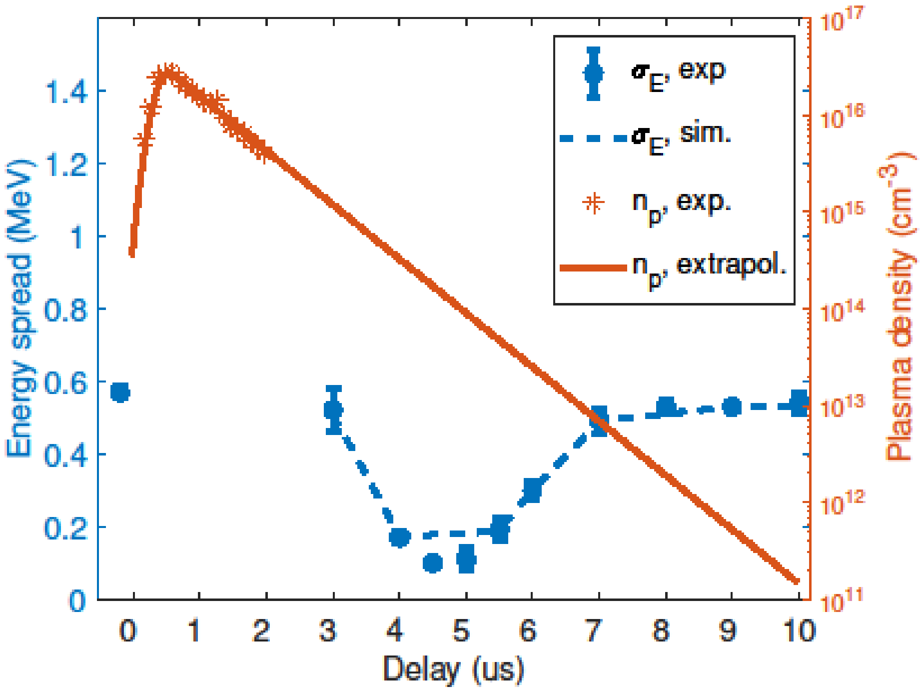




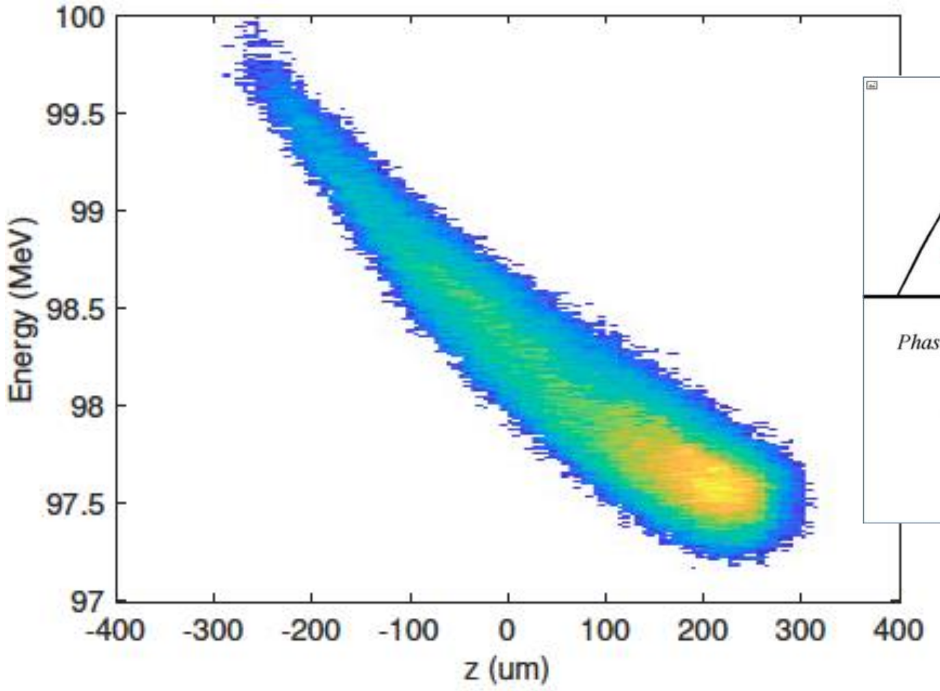
WU Y.P., et al., *Phase space dynamics of plasma wakefield dechirper for energy spread reduction,* ***PRL 122 (2019): 034801.***

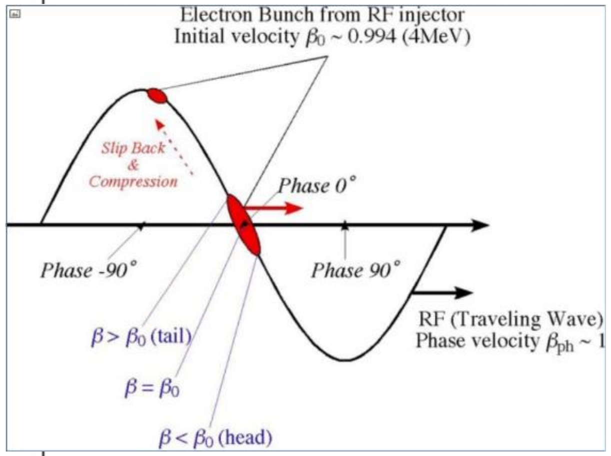
Plasma dechirper, experimental results

Energy spread (plasma density)



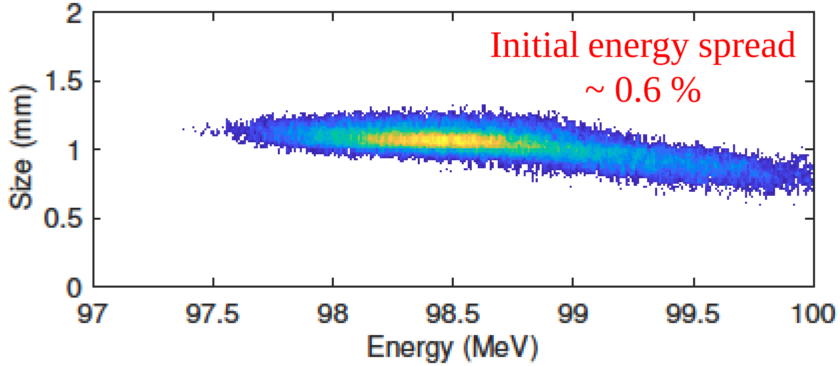
Beam LPS at the injection



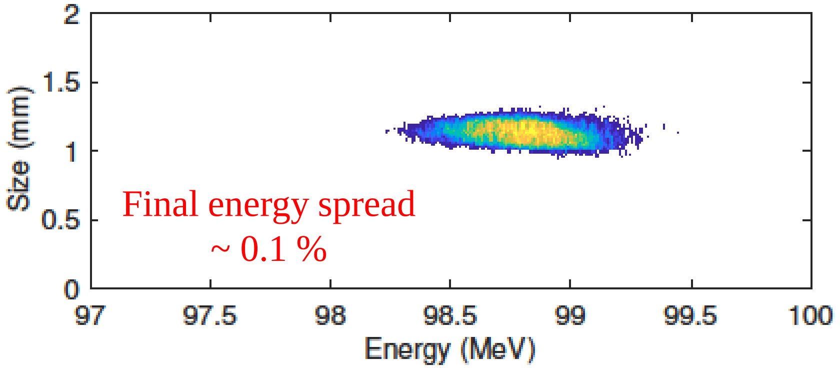


Beam parameters:

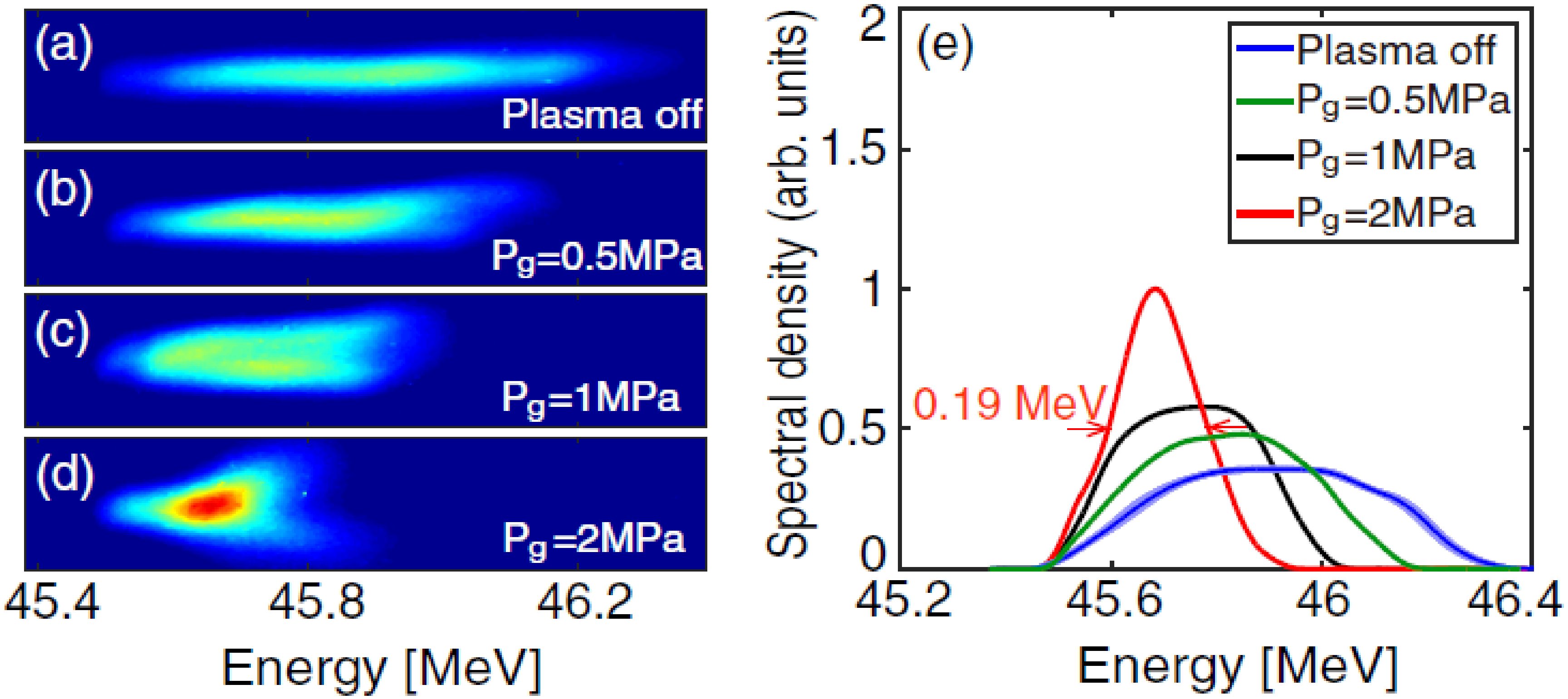
- ✓ $E=100$ MeV
- ✓ $Q=200$ pC
- ✓ $\sigma_{x,y} \approx 20(32)$ μm
- ✓ $\sigma_z = 75$ μm (250 fs)
- ✓ $\varepsilon_{x,y} \approx 1.1(1.4)$ μm



Dechirper



Plasma dechirper, experimental results



Beam parameters:

- ✓ $E = 46\ MeV$
- ✓ $Q = 40\ pC$
- ✓ $\sigma_{x,y} = 40\ \mu m$
- ✓ $\tau = 300\ fs\ (FWHM)$
- ✓ $\varepsilon_{x,y} = 1.5\ \mu m$

WU Y.P., et al., *Phase space dynamics of plasma wakefield dechirper for energy spread reduction*, ***PRL 122 (2019): 034801.***

Plasma Dechirper: summary

Conclusions on Plasma Dechirper:

- ✓ *it was demonstrated that Plasma dechirper can be used to manipulate the beam LPS*
- ✓ *the correlated energy spread was completely removed, leaving only uncorrelated part*

To keep in mind about Plasma Dechirper:

- ✓ *it can decrease the energy of the tail*
- ✓ *parameters of the Plasma Dechirper are interconnected and should be changed accordingly*

$$6 \times \sigma_z \leq \lambda_p/4 \qquad \sigma_x = \sqrt[4]{\frac{2}{\gamma}}\sqrt{\frac{\epsilon_n}{k_p}}$$

- ✓ *was not fully characterized yet (beam quality after the PD).*

Thank You