Electron Injection Schemes in Laser-Plasma Accelerators

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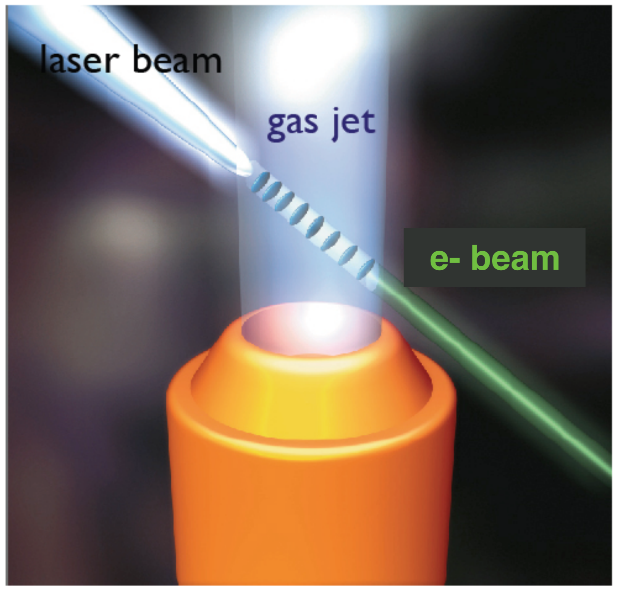
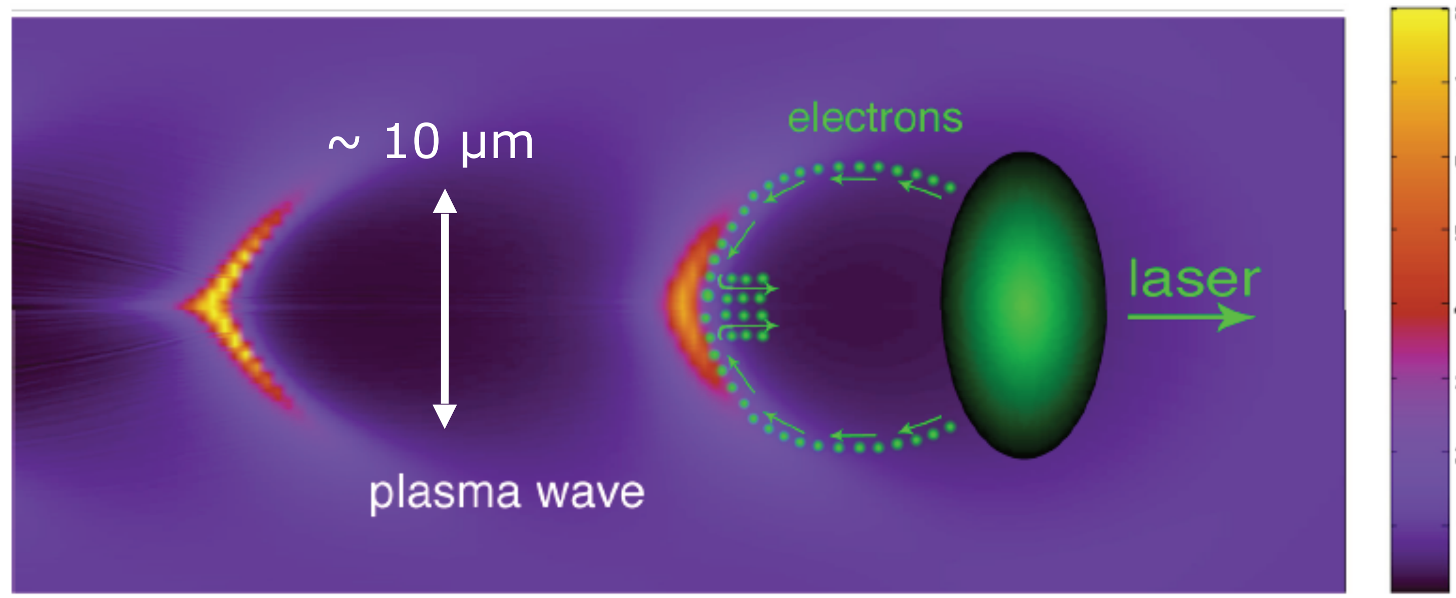
A. Lifschitz, V. Malka

The injection issue in laser plasma accelerators





Requirements for the injection beam :

- Few MeV energy
- Few femtosecond duration
- ~ µm transverse size
- ~ µm normalized transverse emittance
- Femtosecond synchronisation and µm pointing precision

A typology of injection schemes

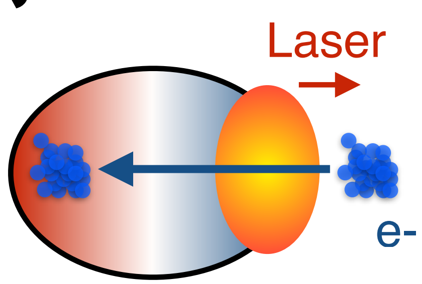
Self injection

Injection is triggered by the driver dynamics.

Controlled injection

Injection is triggered by an external mean.

Longitudinal injection



Longitudinal self-injection

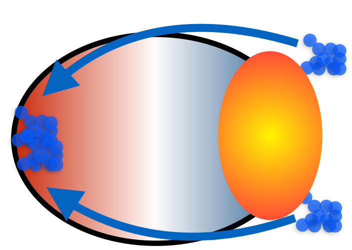
Ionization injection

Electrons are released directly inside the bubble.

Optical injection (long. or trans.)

An additional laser beam is used to heat electrons and trigger the injection.

Transverse injection



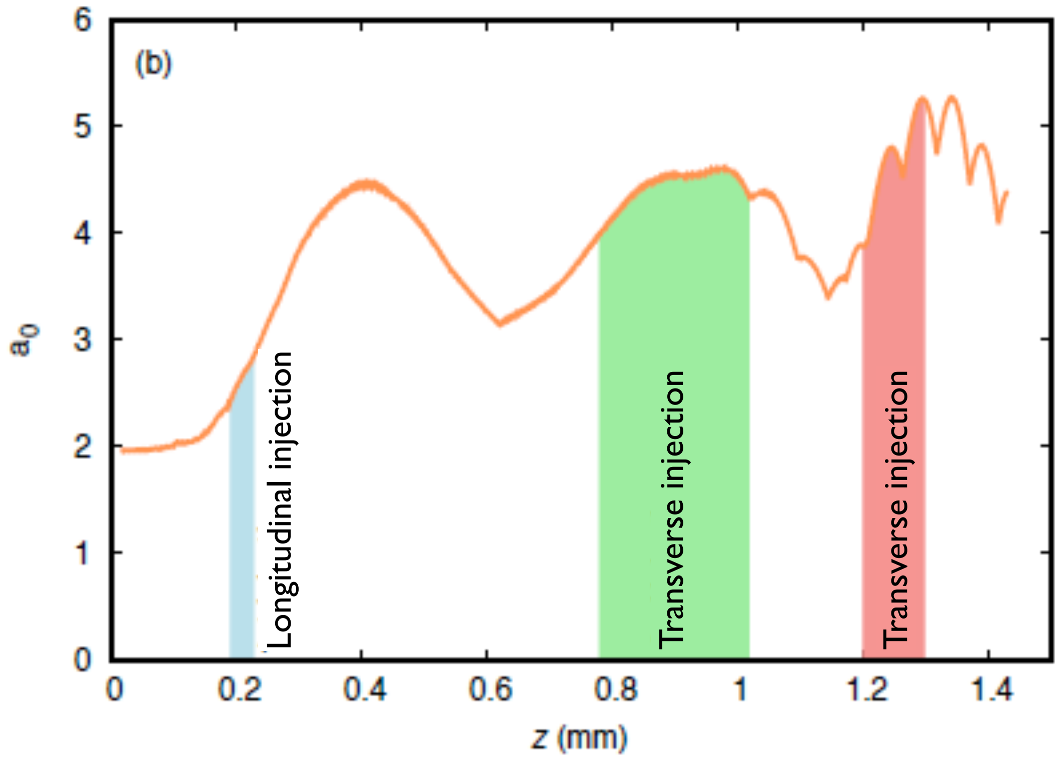
Transverse self-injection

Density gradient / shock front injection

The injection is trigger by the bubble expansion.

Longitudinal and transverse self-injection

Evolution of the laser amplitude due to self-focusing

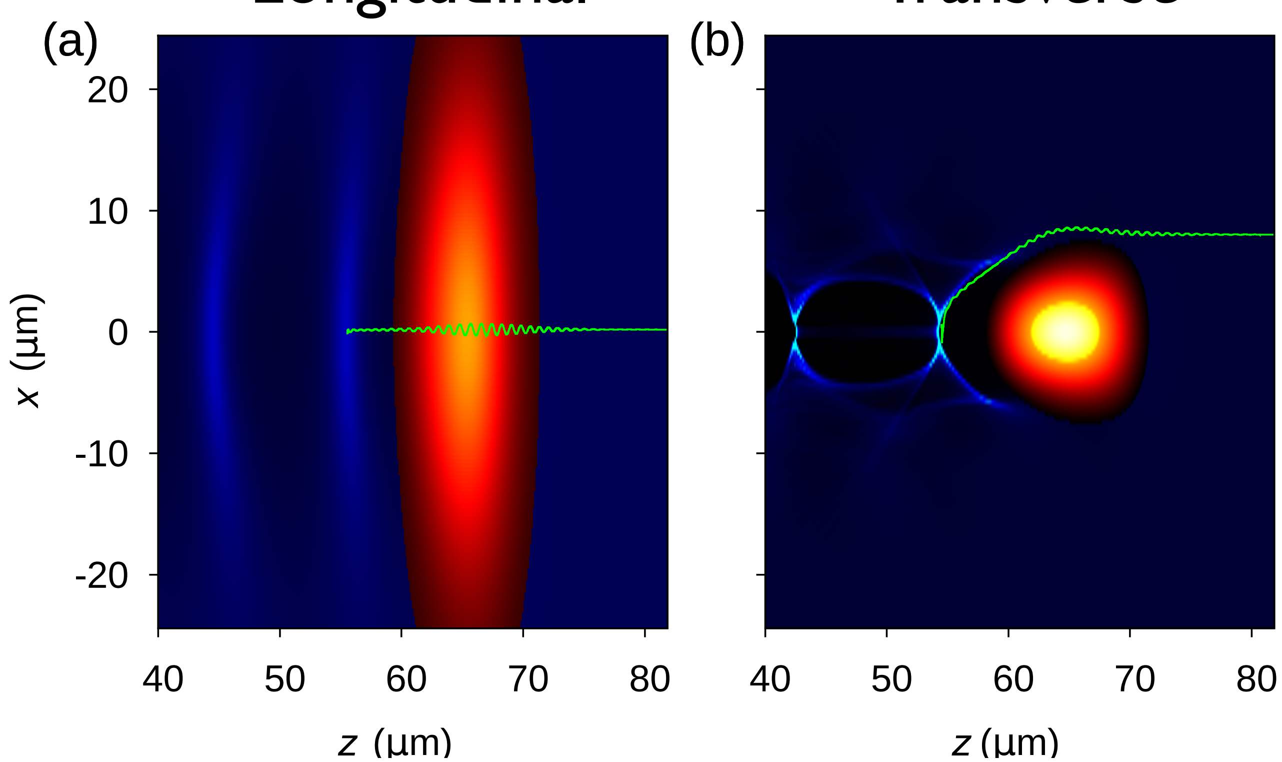


Longitudinal self-injection :

- large laser waist,
- fast increase of the laser intensity → increase of cavity length → injection.

Longitudinal

Transverse



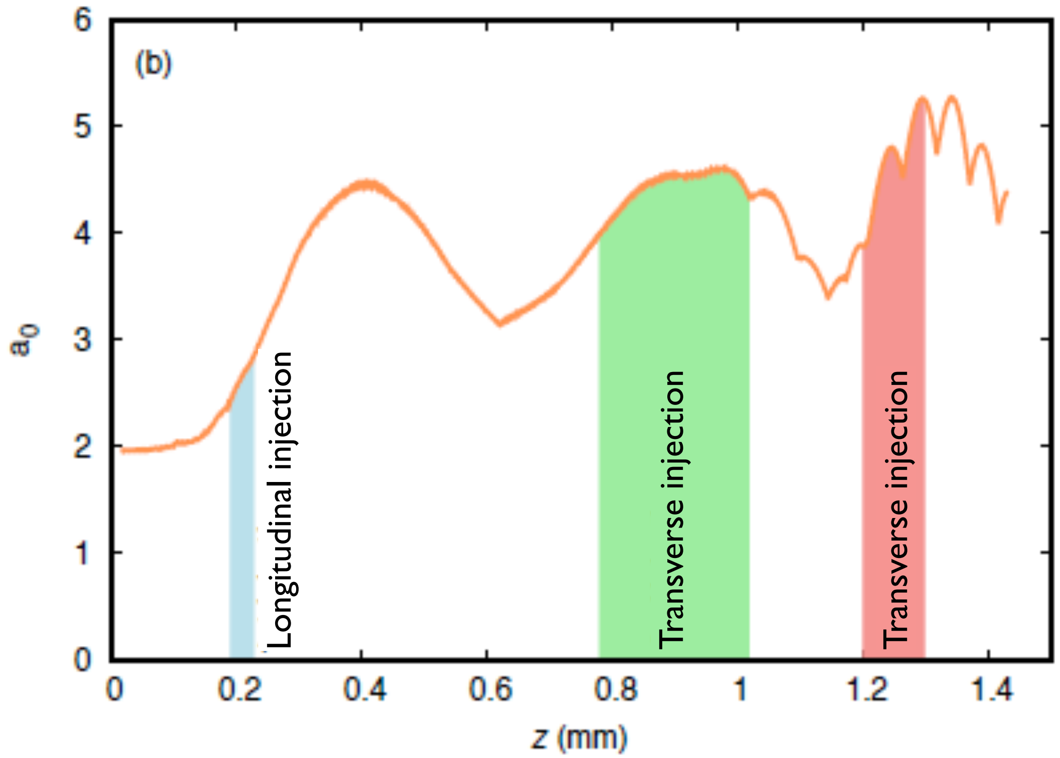
Transverse self-injection :

- laser waist ~ laser pulse length
- ~ cavity radius,
- normalized laser amplitude >4 ($I > 3.10^{19}$ Wcm^{-2})

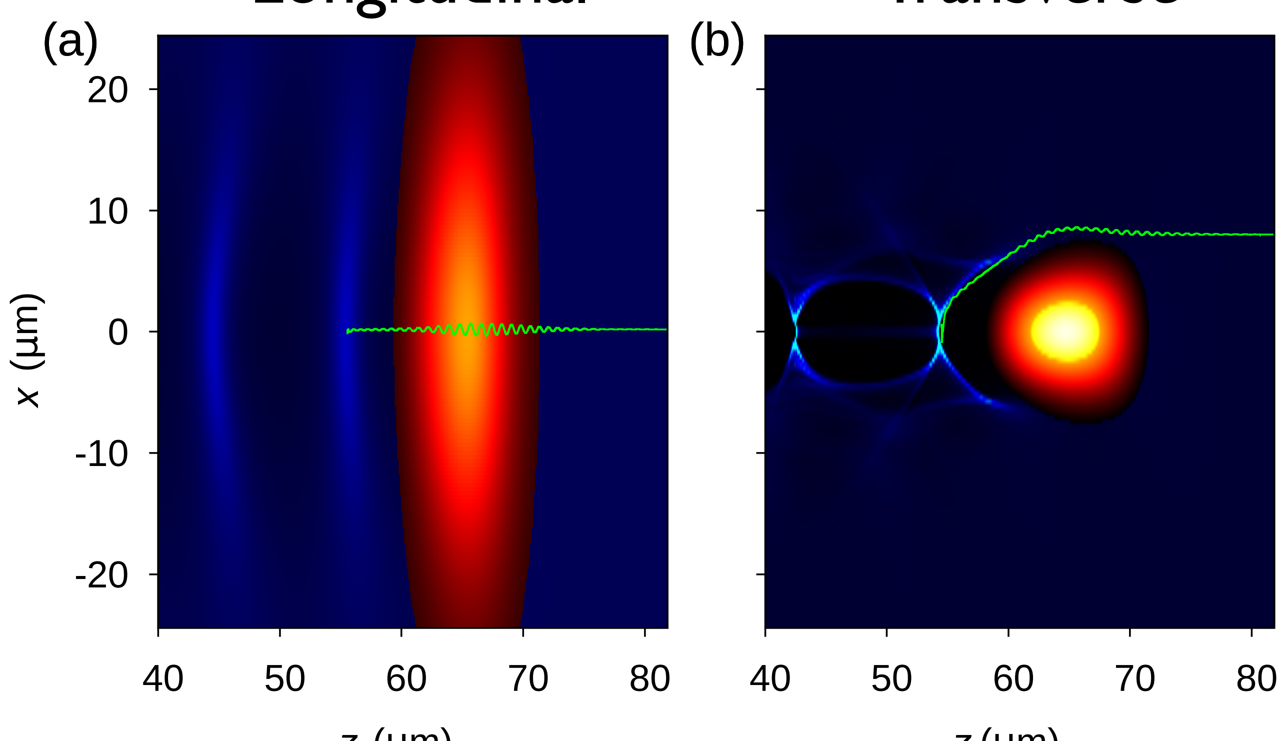
Nature Communications **4**, 1501 (2013)

Longitudinal and transverse self-injection

Evolution of the laser amplitude due to self-focusing

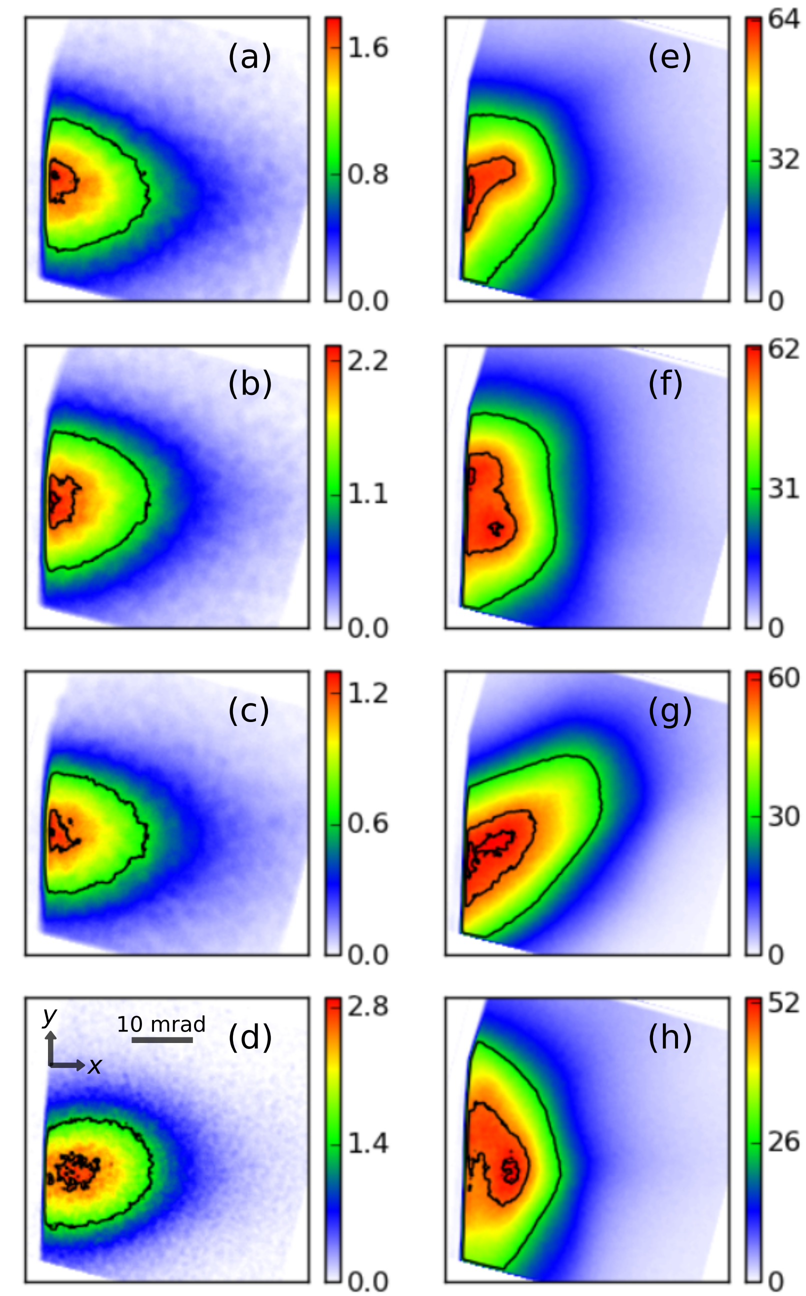


Longitudinal / Transverse



Measured X-ray beams

Longitudinal / Transverse



Transverse injection is unstable
(is very sensitive to laser fluctuations)

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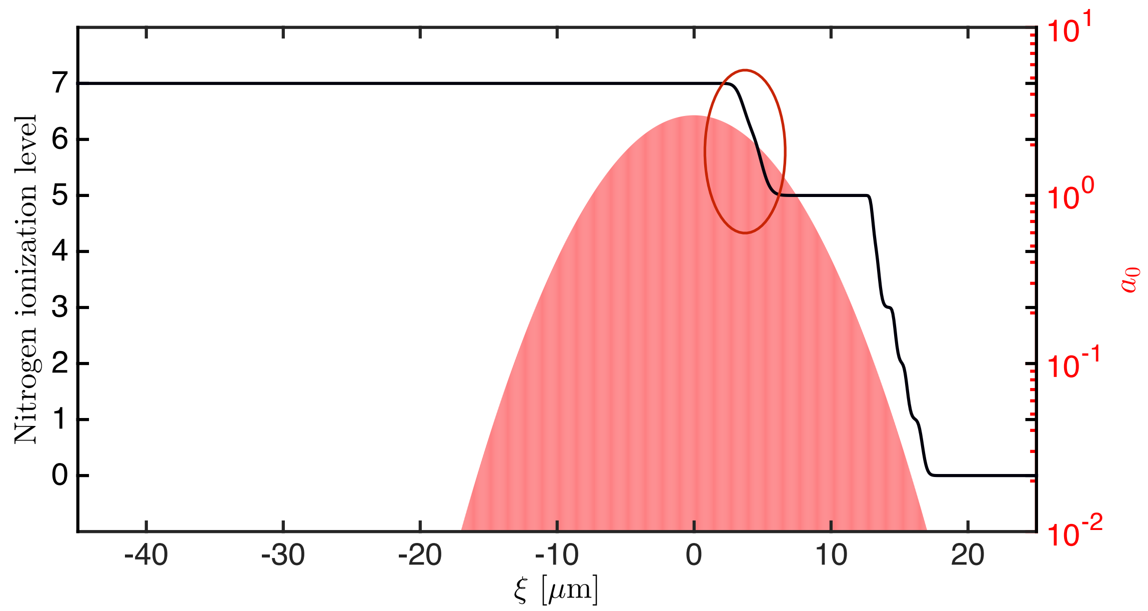
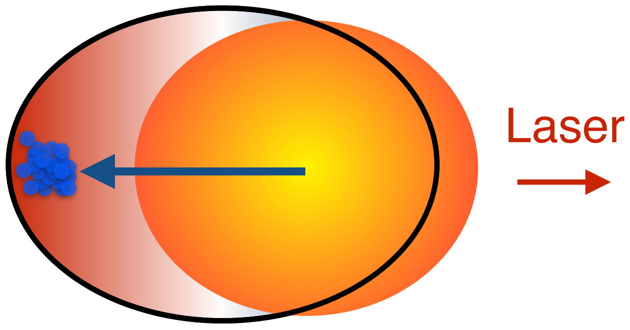
Ionization Injection

Ionization injection in a mixture He / N_2



N^{5+} and N^{6+} are ionized when the laser intensity is max.

➡ Electrons released at rest close to the center of the plasma cavity gain enough energy to be trapped, as they slip toward the back of the cavity.



Chen et al. Phys. Plasmas **19**, 033101 (2012)

Ionization Injection

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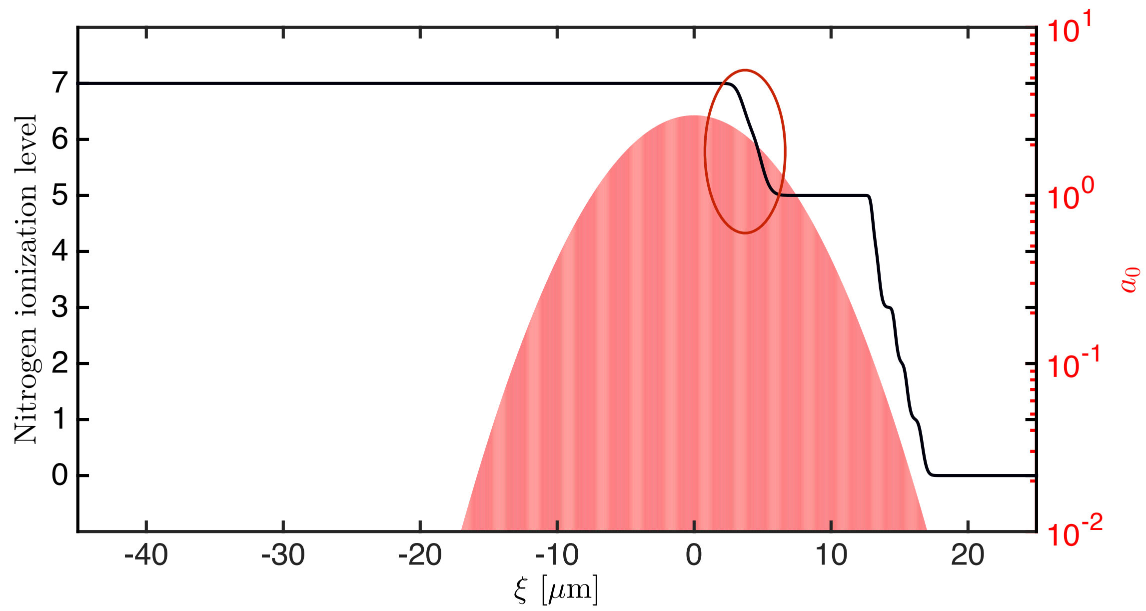

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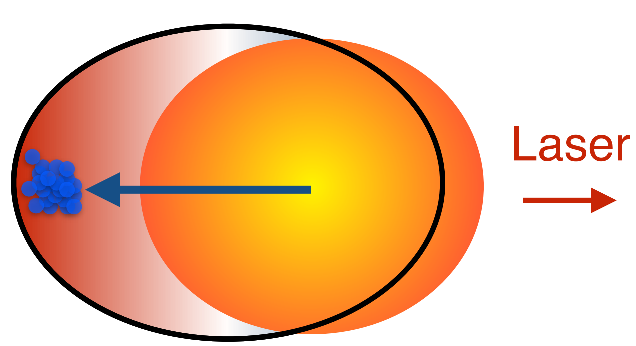

= longitudinal injection

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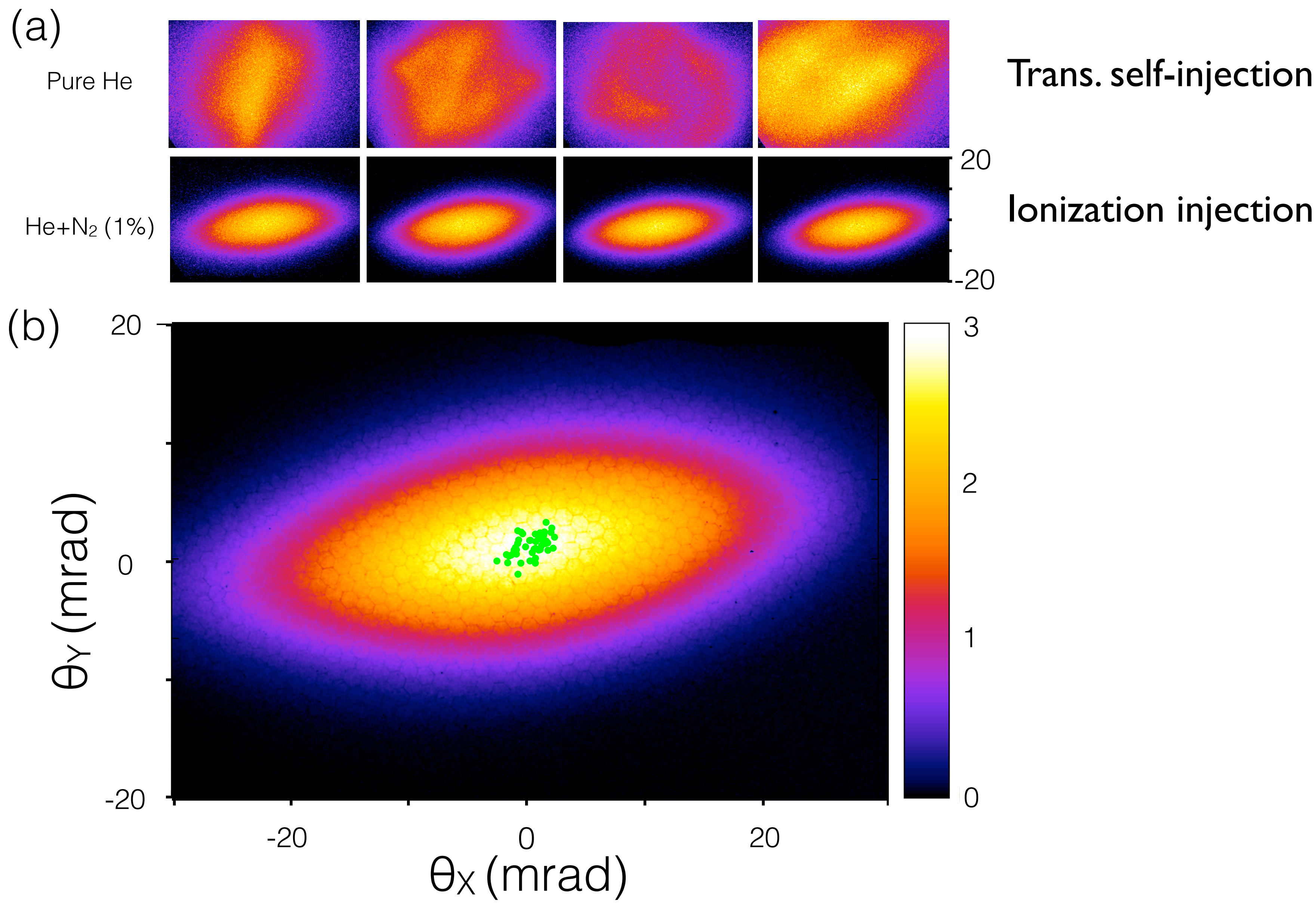
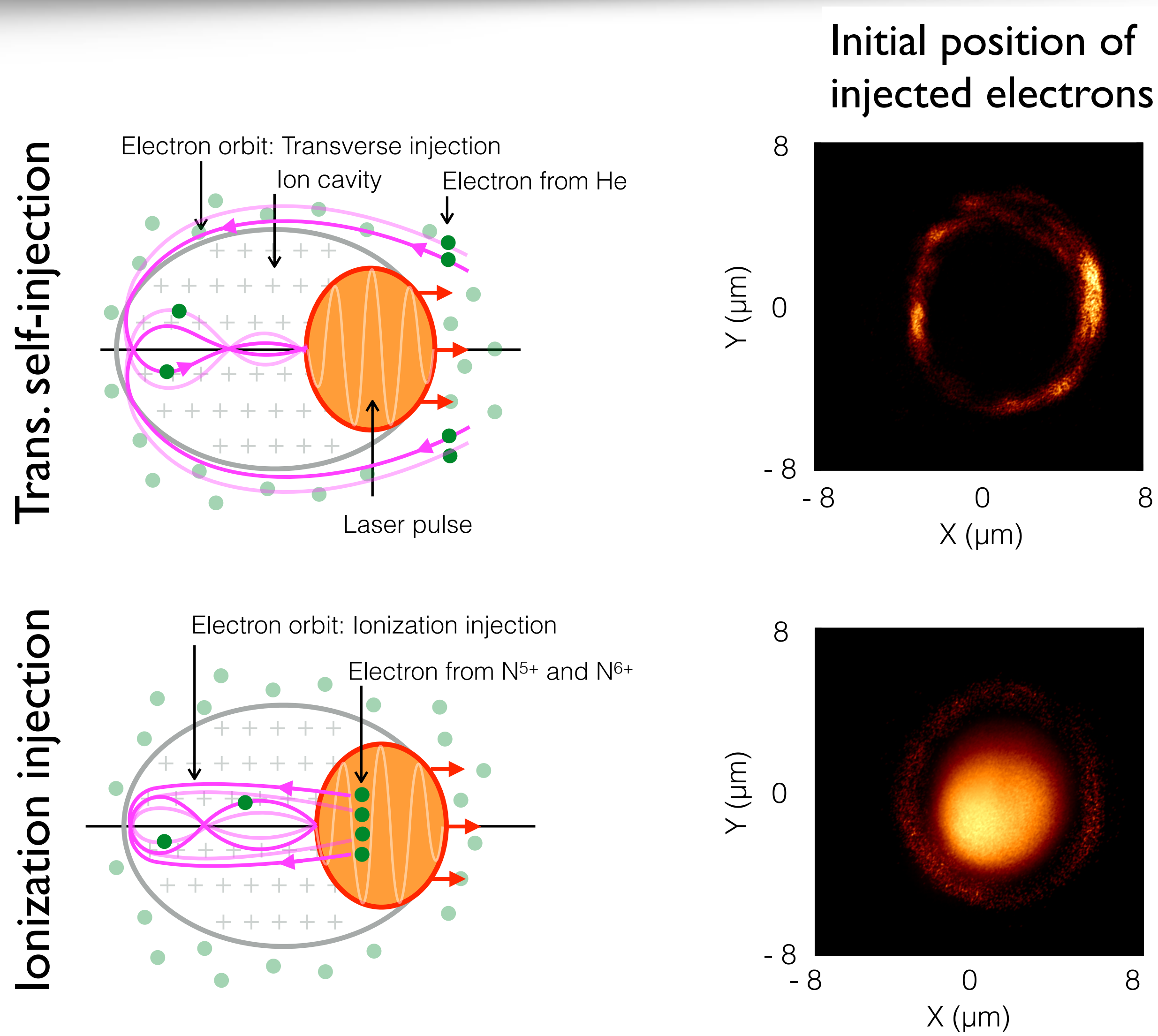
Stability of Ionization Injection

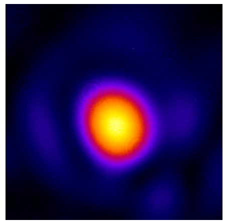
Consecutive experimental
X-ray beams



Stability of Ionization Injection



3D PIC simulations with measured focal spot.

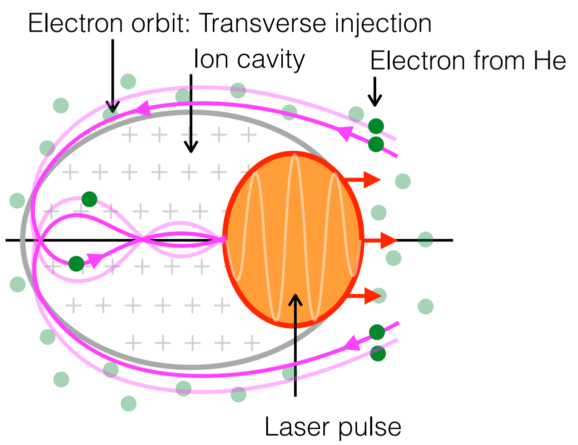


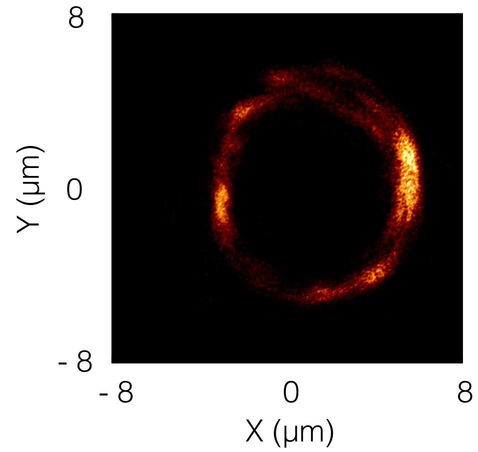
Stability of Ionization Injection

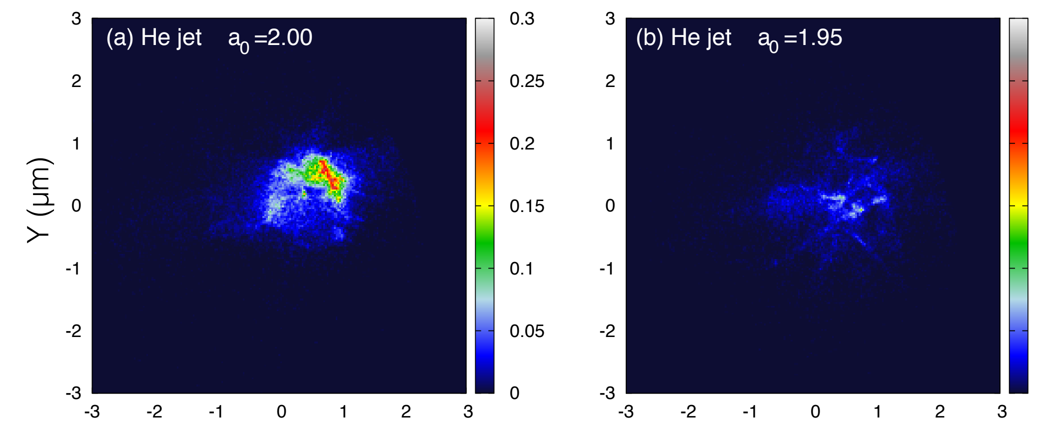
Initial position of injected electrons

Electron beams at the exit of the accelerator for a_0 = 2.0 and a_0 = 1.95.

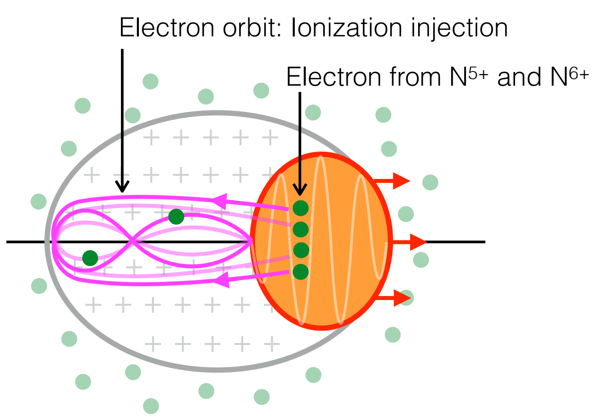
Trans. self-injection

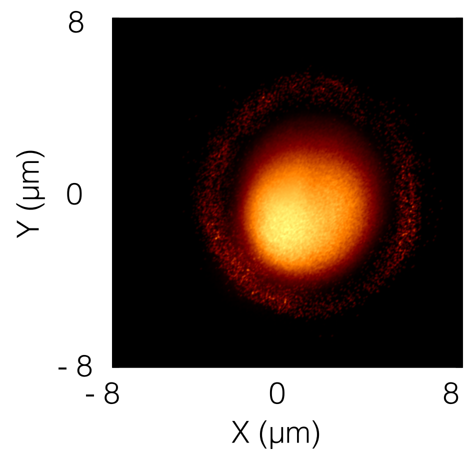


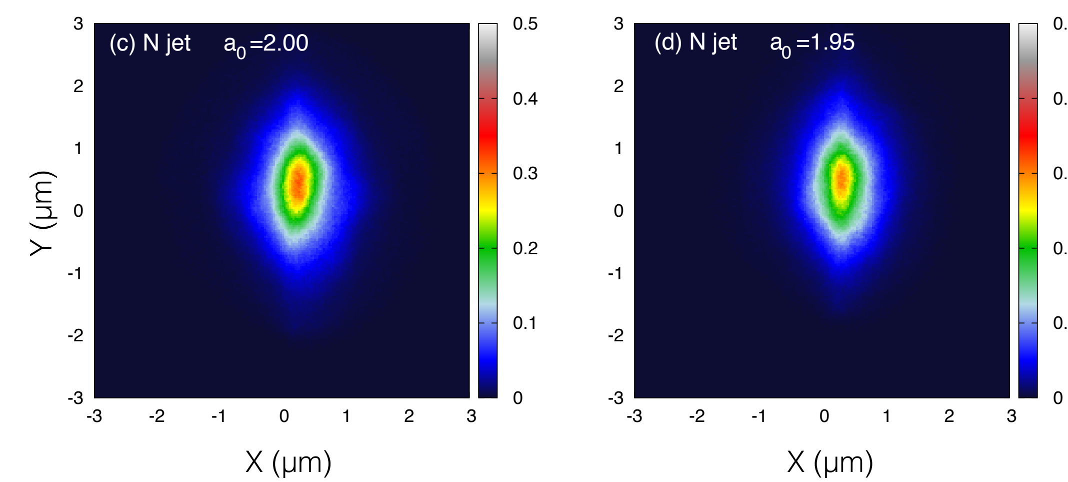




Ionization injection







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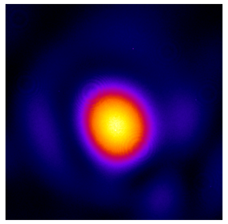
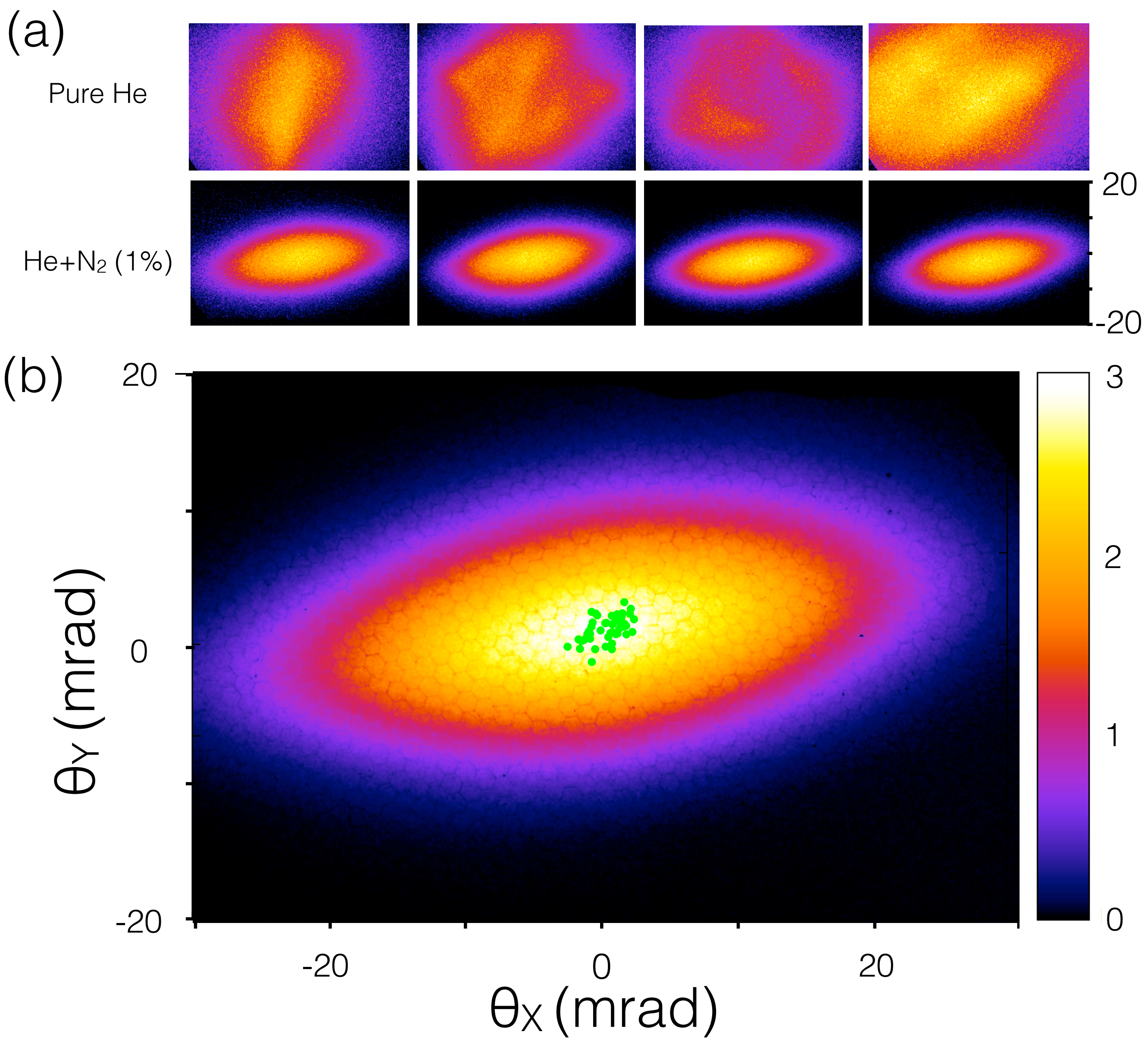


Transverse self-injection :
Electron trajectories are close to the bubble sheath → injection depends strongly on the bubble shape and hence on laser fluctuations.

Ionization injection (longitudinal injection) :
Electrons remain close to the optical axis → stable injection

Stability of Ionization Injection

Consecutive experimental X-ray beams



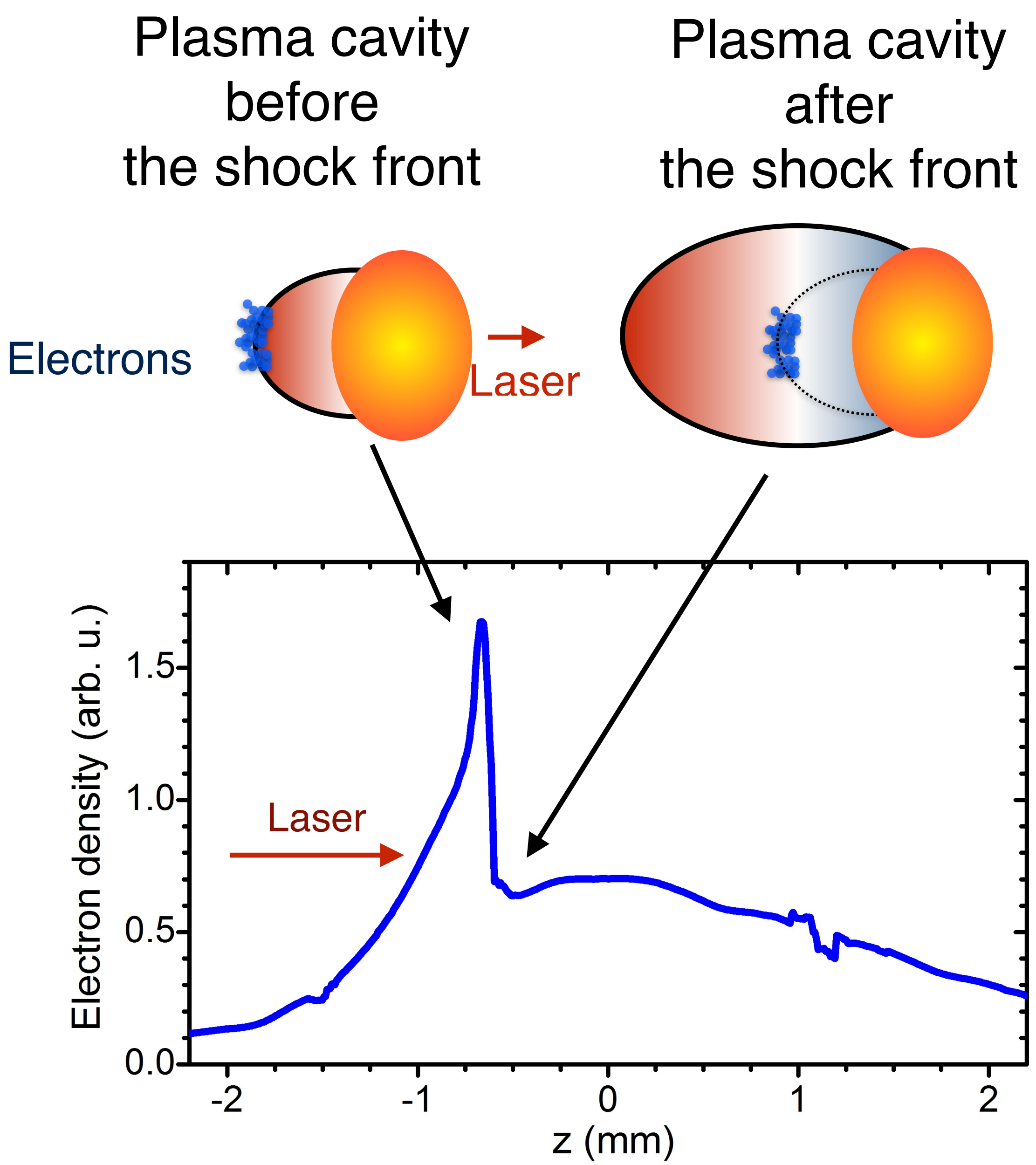
Pros and cons of ionization injection

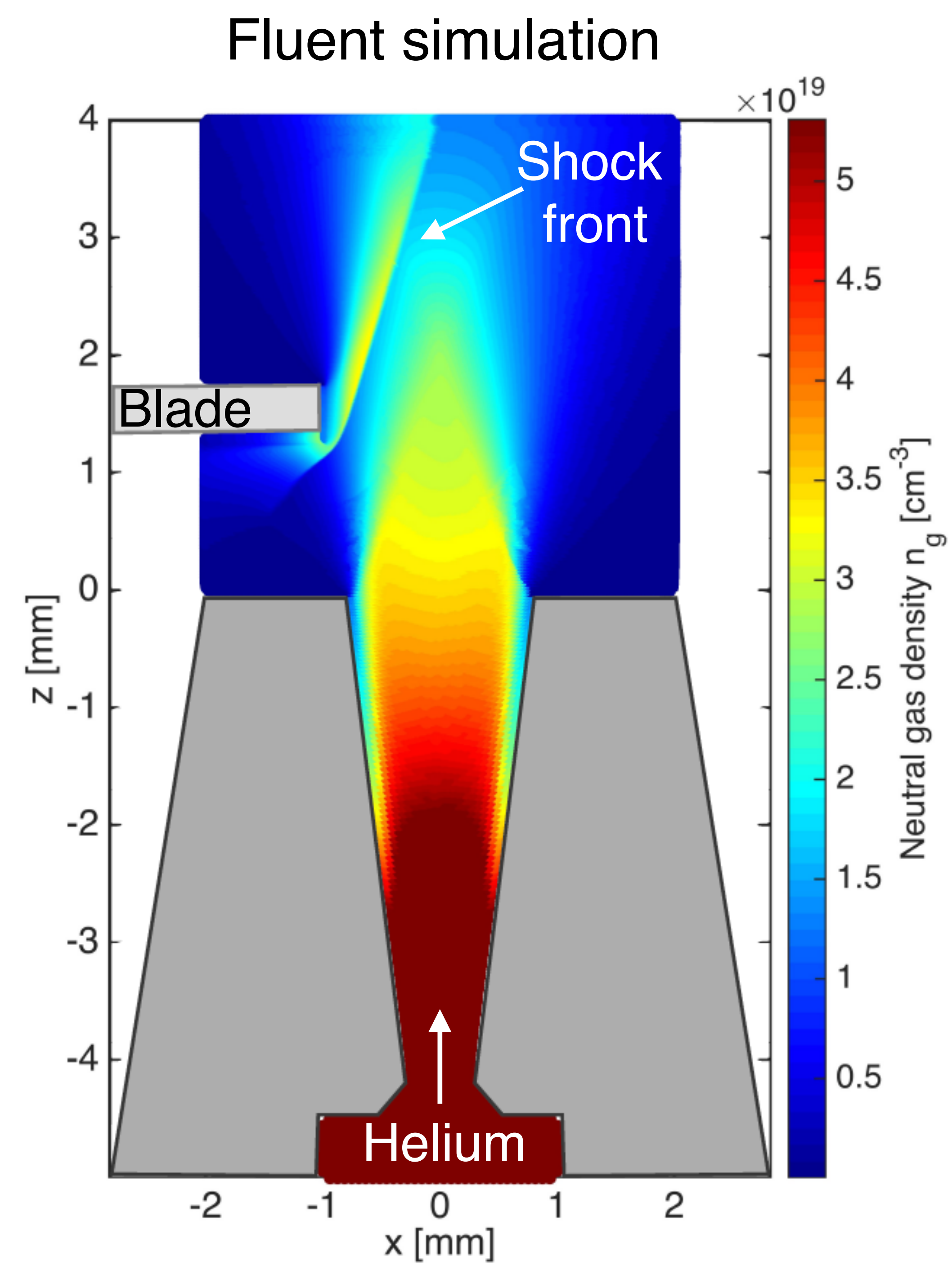
- Possibly high charge (>100 pC)
- Stable
- Large energy spread

Tricks to reduce the energy spread

- 2 or more lasers pulses
- 2 stages (injection+ acceleration)
- low power laser
- …

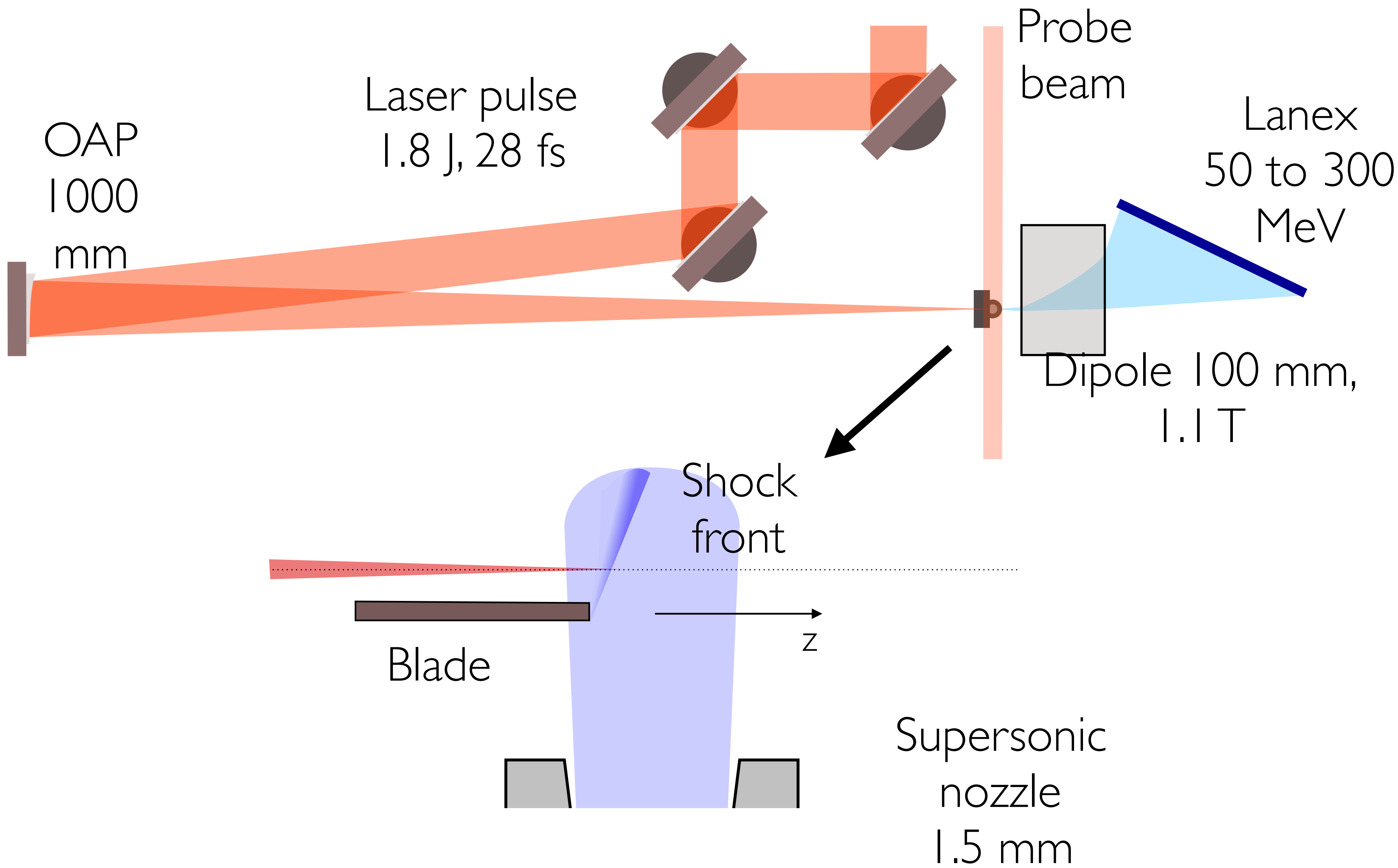
Shock Front Injection





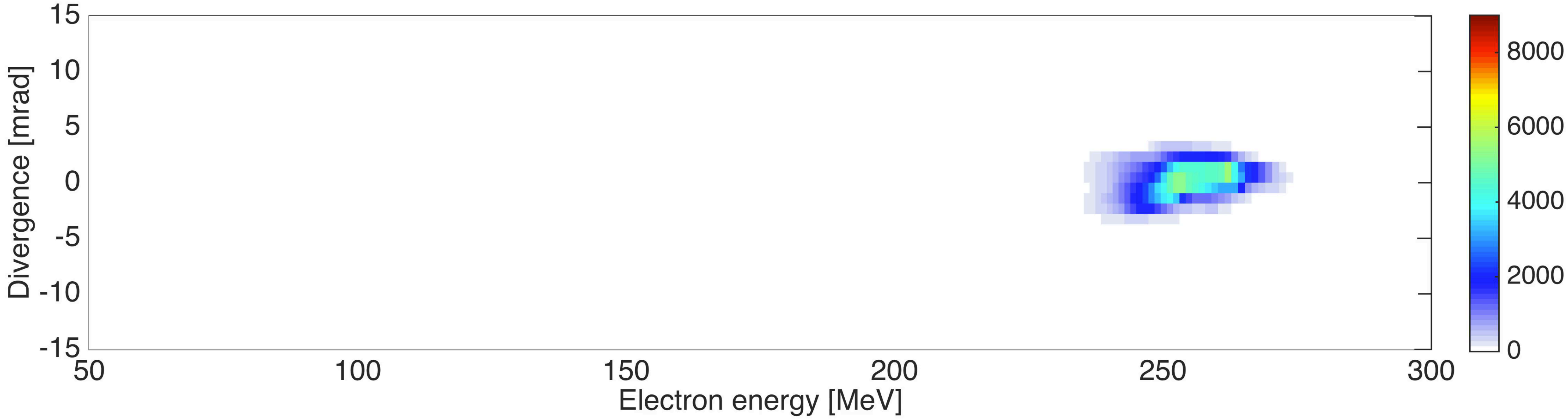
Buck et al. PRL **10** 185006 (2013)

Experimental Setup



Stability of shock front injection

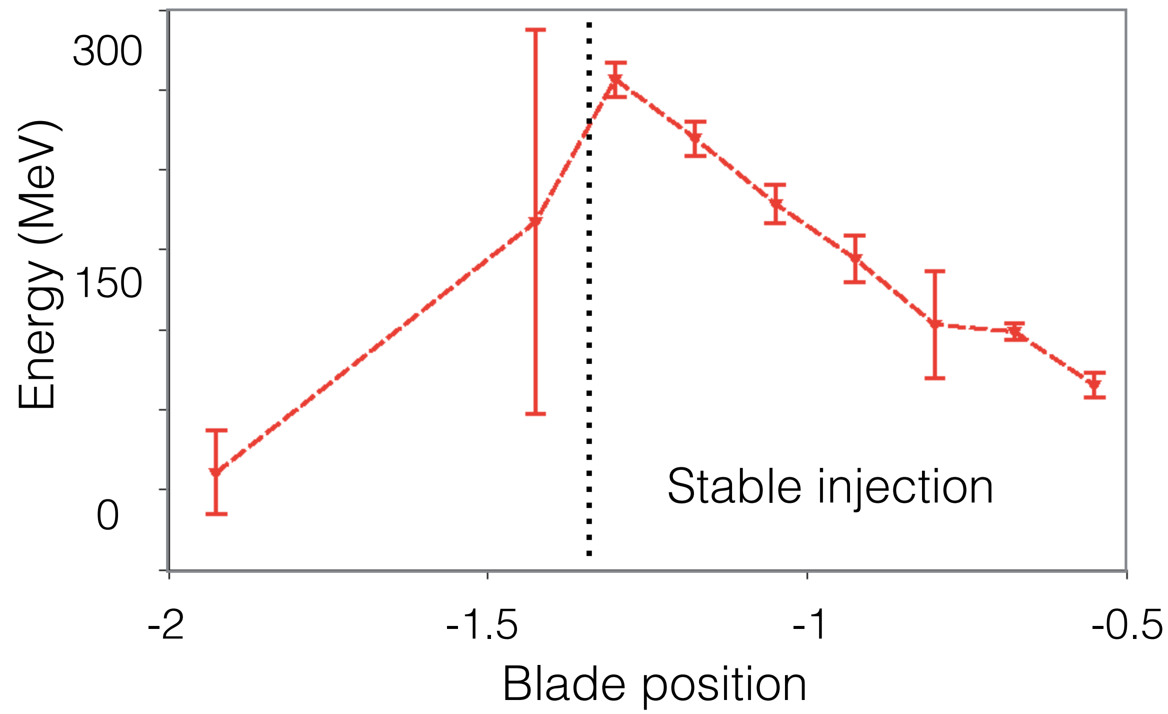
10 consecutive shots (n_e = 7.5 x 10^{18} cm^{-3})

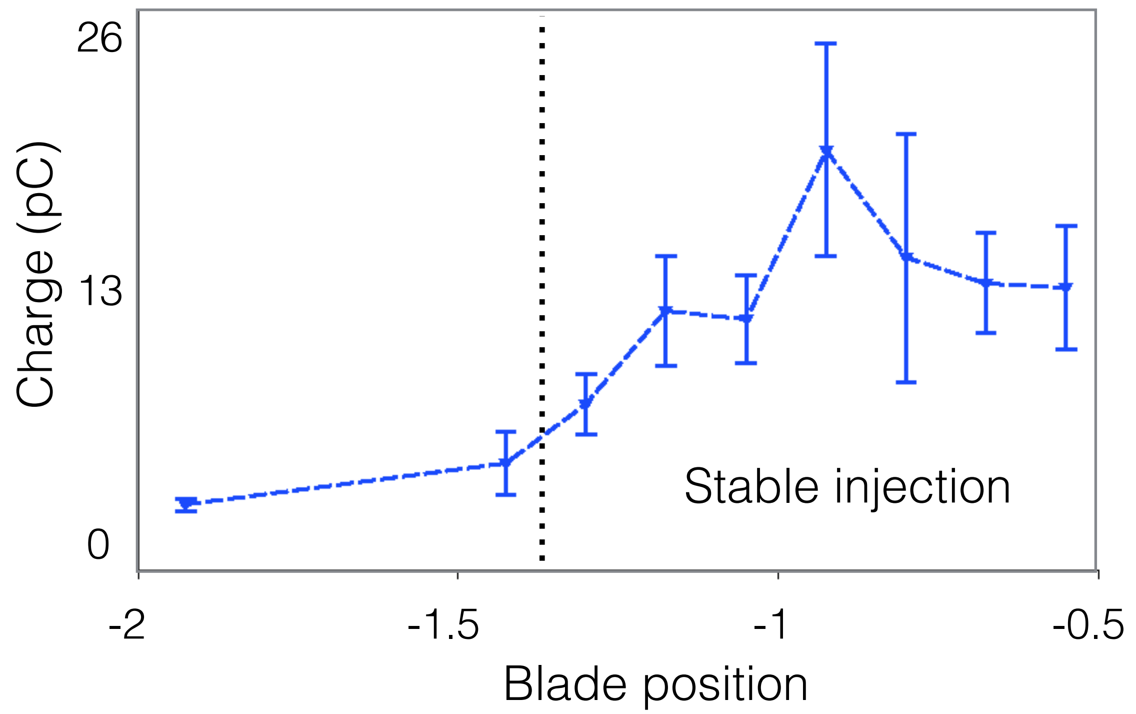


- Peak energy E = 260 ± 4 MeV
- ΔE = 20 MeV (10 MeV for best shots)
- ΔE / E = 6 ± 1%
- Divergence = 2 ± 0.3 mrad

Collaboration with S.W. Chou and L.Veisz MPQ

Tunability





Tunable energy from 75 to 275 MeV
ΔE=20 MeV (10 MeV for best shots)

Charge ~10 to15 pC

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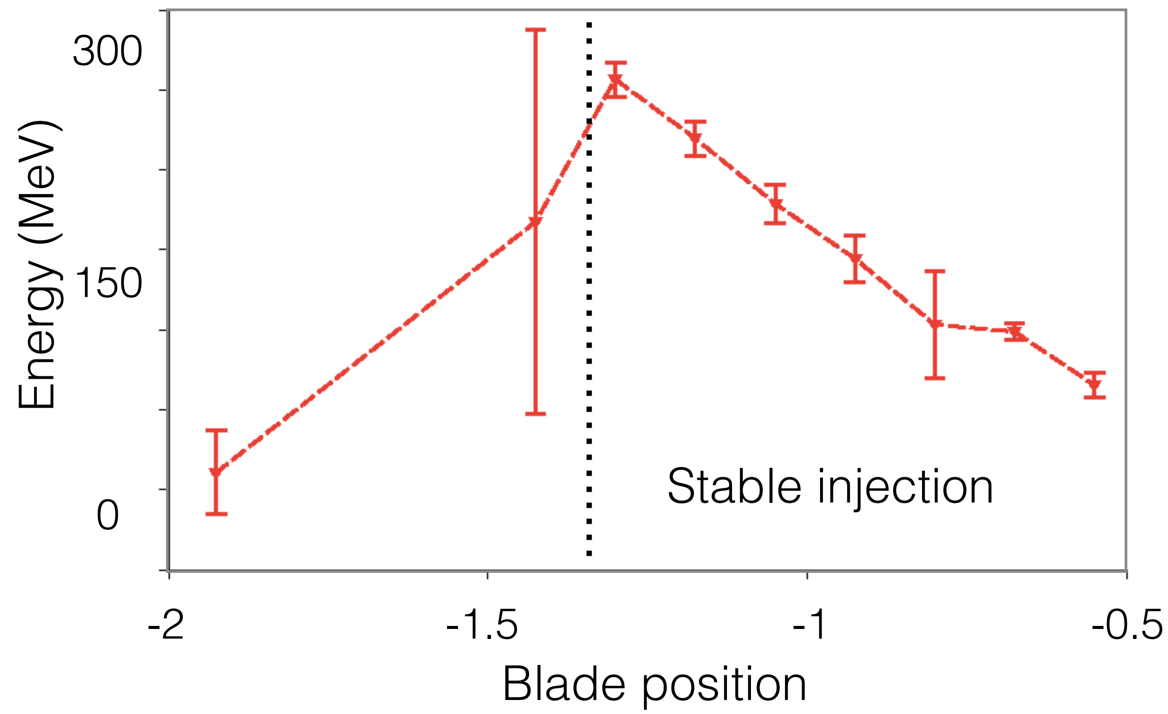
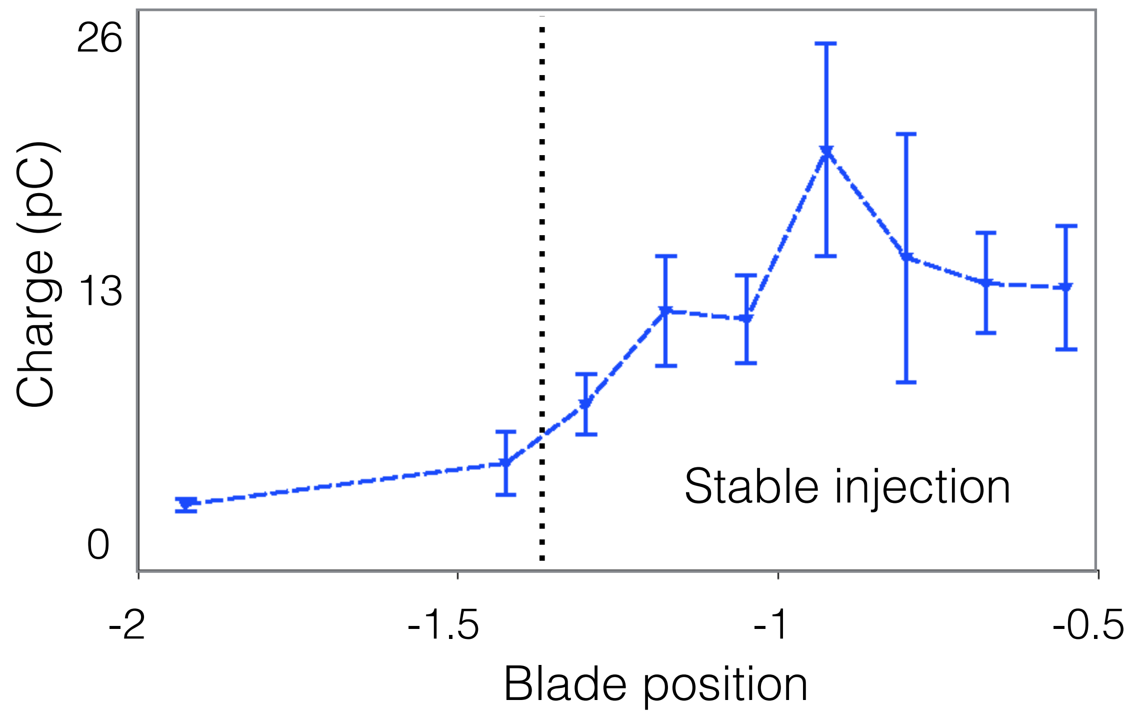




Tunable energy from 75 to 275 MeV
ΔE=20 MeV (10 MeV for best shots)

Charge ~10 to15 pC

Stability and beam quality depends strongly on laser and plasma conditions

ΔE=5 MeV, Q=6 pC obtained in *A. Buck et al. PRL* ***110****, 185006 (2013)*

Collaboration with S.W. Chou and L.Veisz MPQ

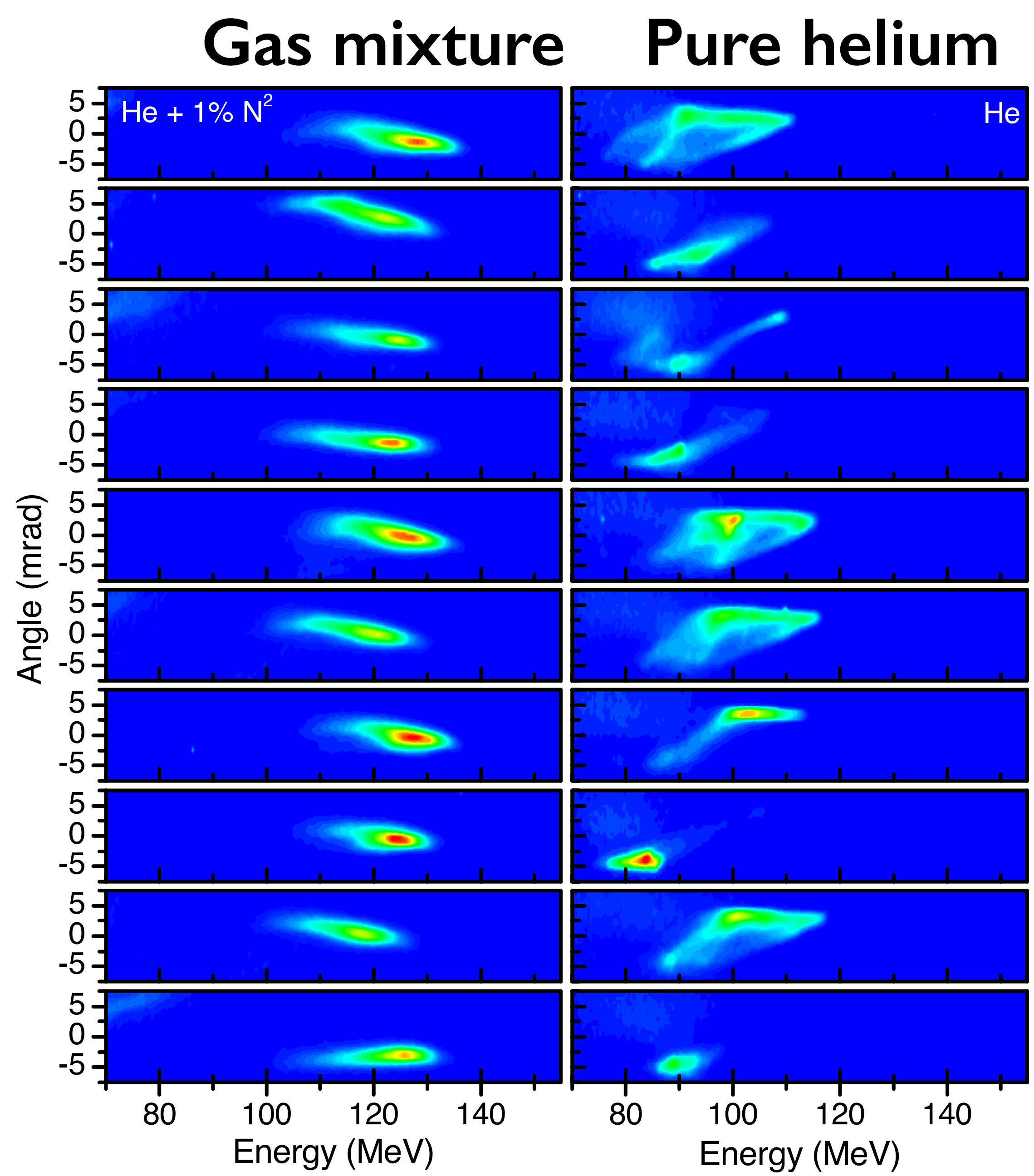
Shock Assisted Ionization Injection

RMS Stability
δE/E = 2.5%
δQ/Q = 12%

Pointing
1.5 mrad RMS
(down to 0.7)

Divergence
2.6 x 5 mrad^2

Energy spread
14 ± 2 MeV



RMS Stability
δE/E = 7%
δQ/Q = 24%

Pointing
3.2 mrad RMS

Divergence
3.2 ± 0.7 mrad

Energy spread
20 ± 10 MeV

Shock Assisted Ionization Injection

RMS Stability
δE/E = 2.5%
δQ/Q = 12%

Pointing
1.5 mrad RMS
(down to 0.7)

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2.6 x 5 mrad^2

Energy spread
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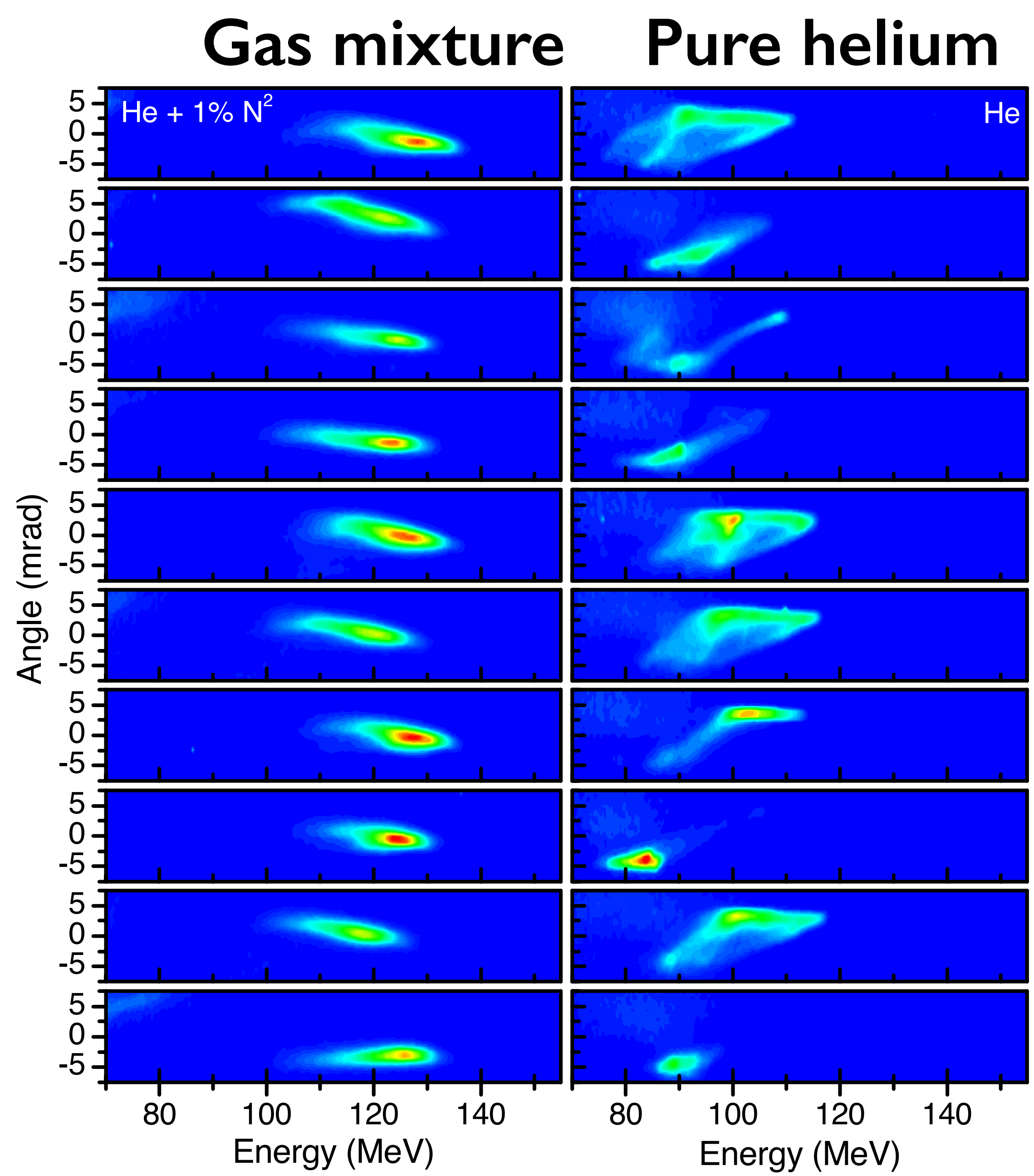

RMS Stability
δE/E = 7%
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Pointing
3.2 mrad RMS

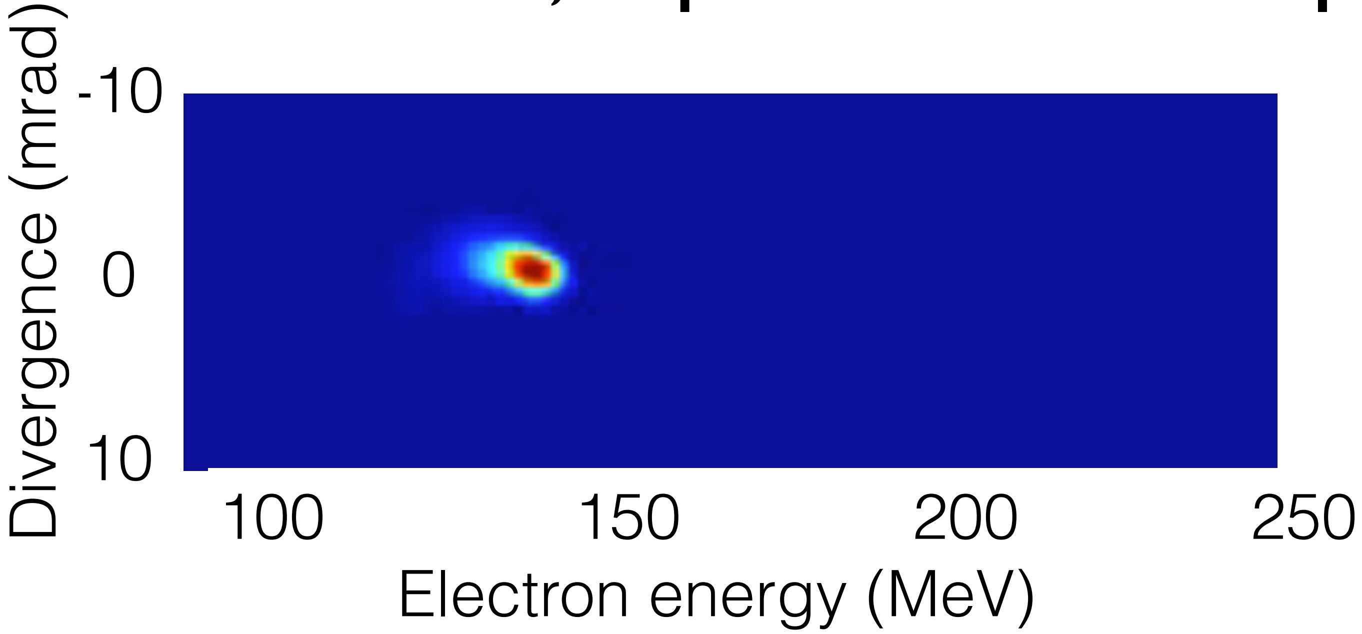
Divergence
3.2 ± 0.7 mrad

Energy spread
20 ± 10 MeV

Shock front injection in a gaz mixture gathers the advantages of ionization injection (stability) and shock front injection (control and energy spread)

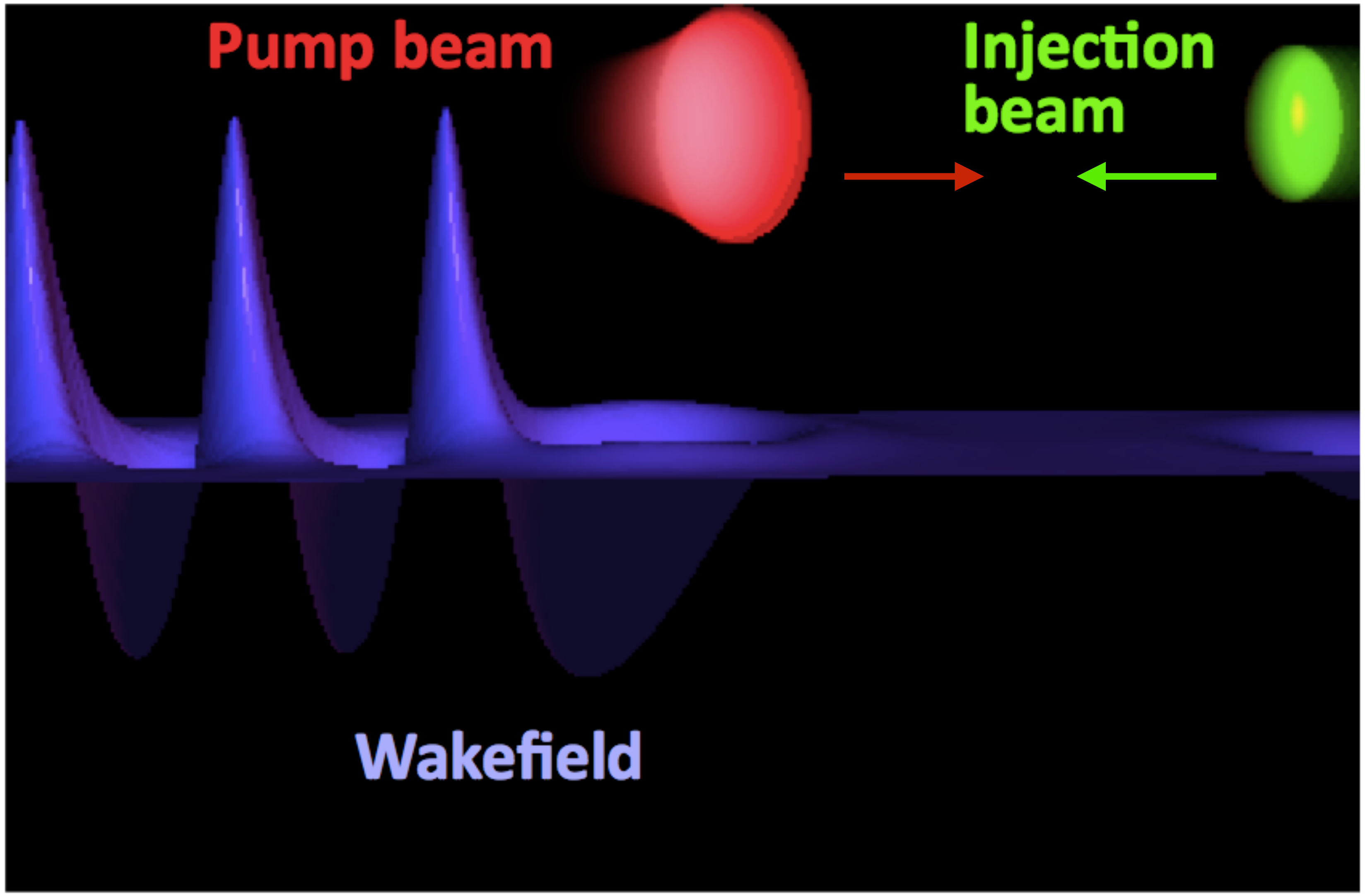
Shock Assisted Ionization Injection

50 consecutive, dispersion-corrected spectrum



Collaboration with M. Hansson and O. Lund, Lund University

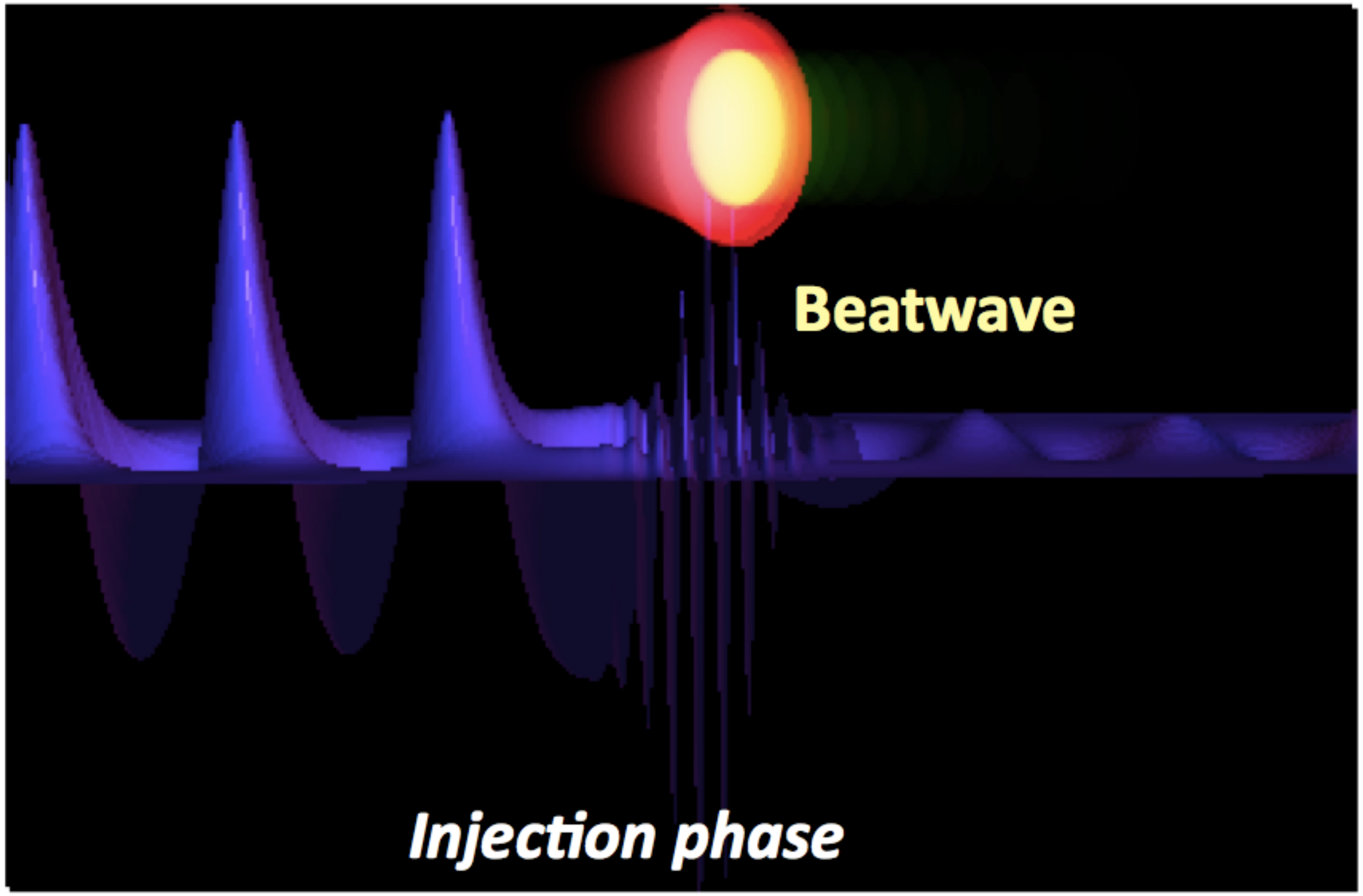
Colliding Injection



- Pump beam $\Longrightarrow$ accelerating structure.
- Injection beam $\Longrightarrow$ local injection.

J. Faure *et al.* Nature **444,** 737-739 (2006)

Colliding Injection



- Pump beam $\Longrightarrow$ accelerating structure.
- Injection beam $\Longrightarrow$ local injection.
- During the collision, some electrons are heated by the beat-wave ponderomotive force $\Longrightarrow$ they gain enough energy to be trapped.

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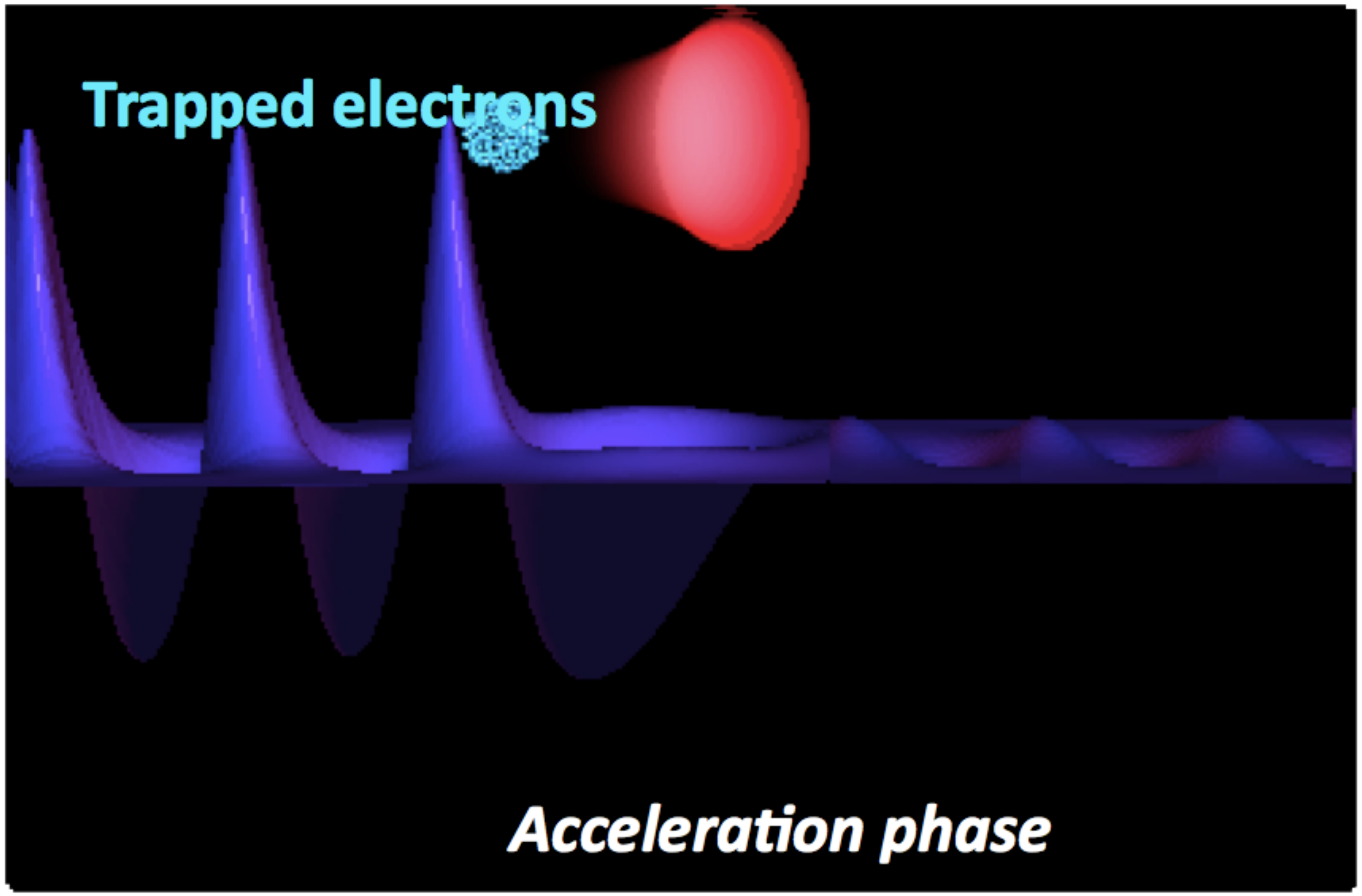
Colliding Injection



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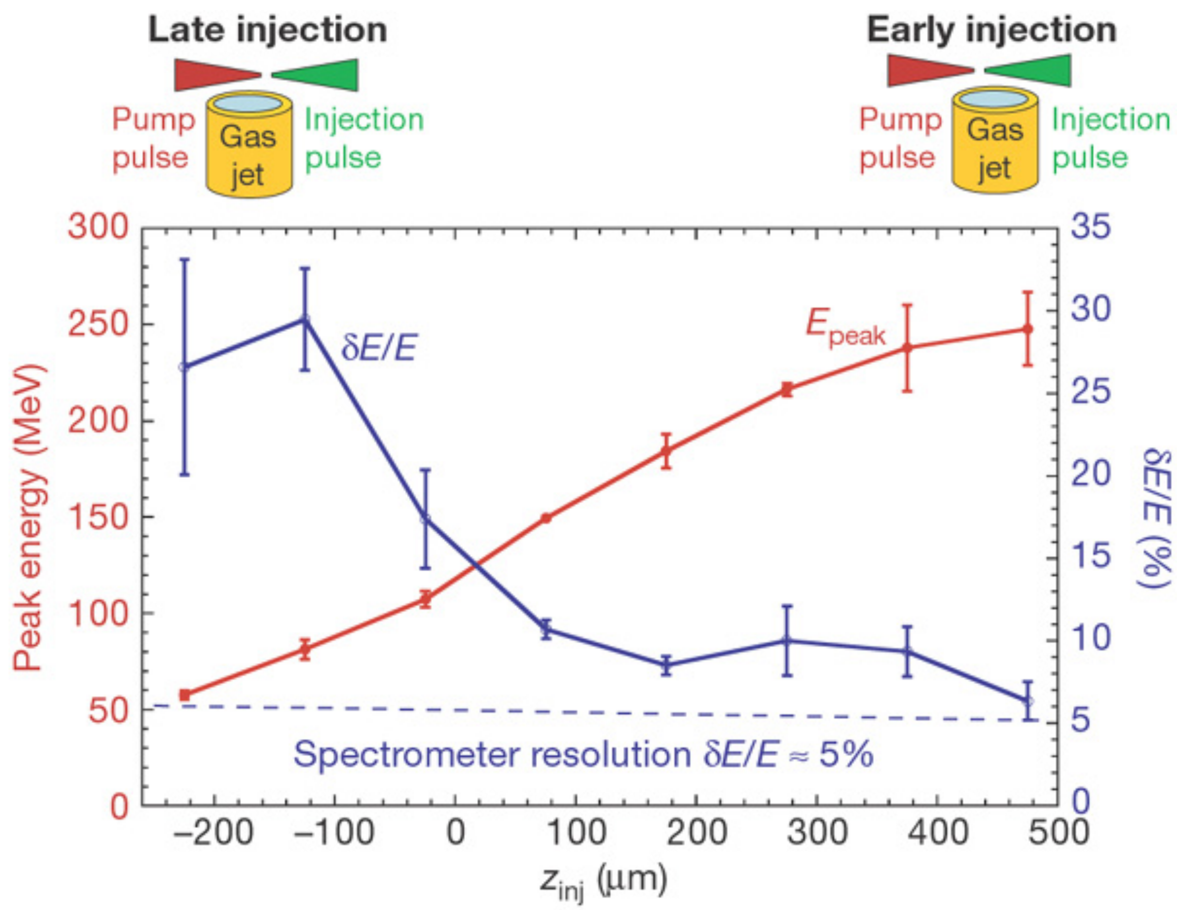
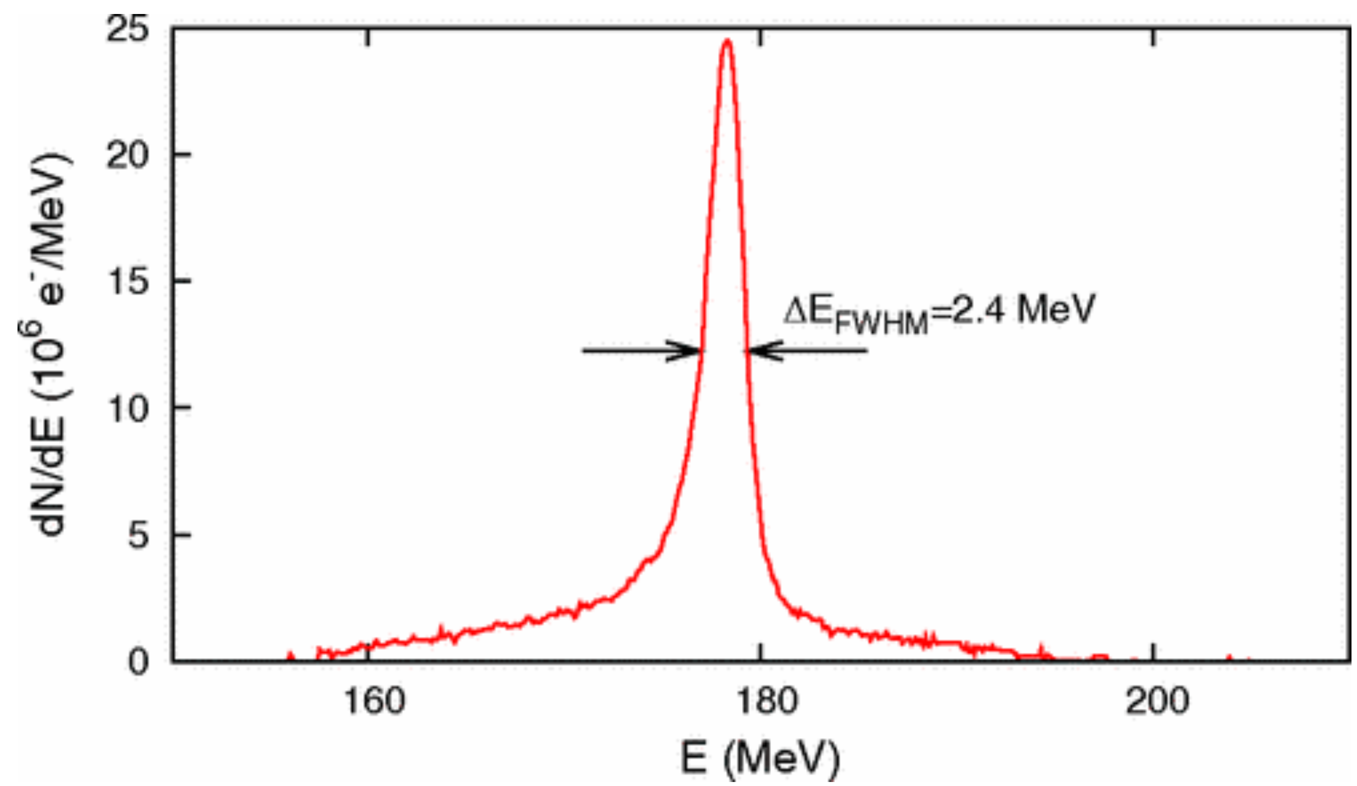
Optical Injection



Tunability

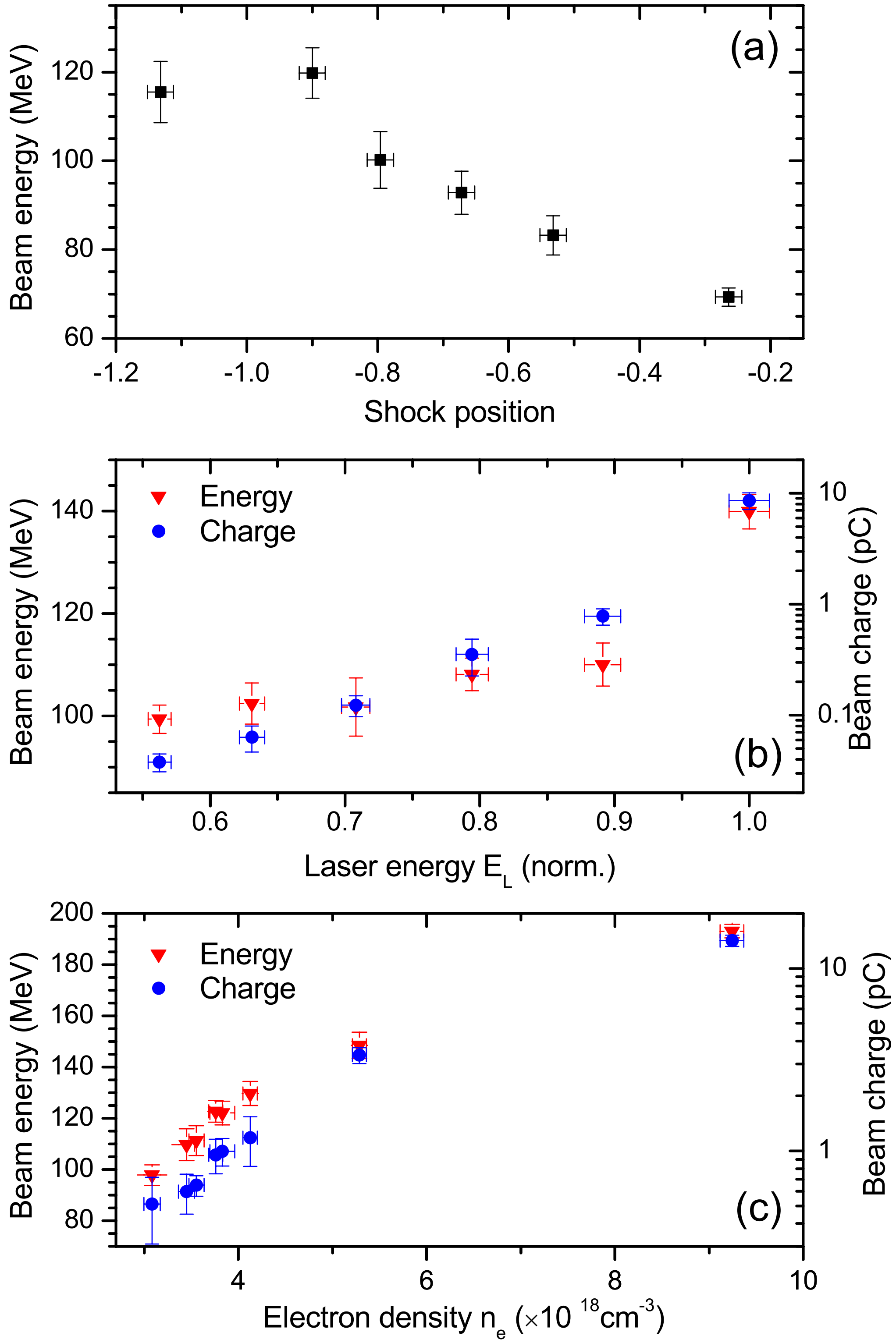
Low energy spread (~1%)

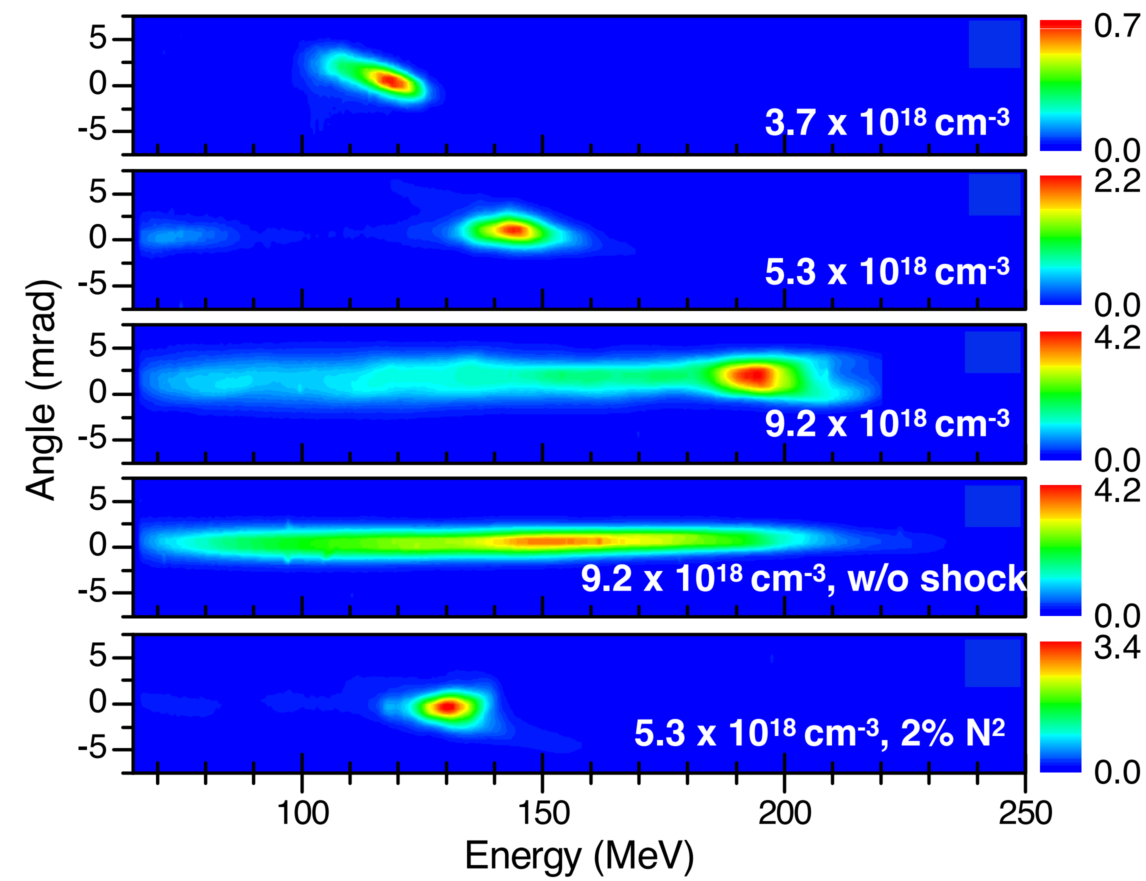


Conclusion

	Charge	ΔE/E	ΔΘ	Stabilité
Transverse self-injection	+++ ~1 nC	--	-	--
Longitudinal self-injection	-	-	++ 2 mrad	+
Shock front injection	+	+	+	+
Ionisation injection	+++ ~1 nC	--	+	-
Ctrl. ioniz. injection (shock or 2 stages)	+	+	++ 2 mrad	++ 2% energy, 10% charge
Colliding injection	+	++ ~1%	+	+

Tunability





- Works for a large range of parameters
- A second beam with a large energy spread is injected for large density

Collaboration with M. Hansson and O. Lund, Lund University