Laboratory Astrophysics and Plasma Wakefield Acceleration:

Experimental Study of Magnetic Field Generation by Current Filamentation Instability of a Relativistic Proton Bunch in Plasma

---

L. Verra, C. Amoedo, N. Torrado, A. Clairembaud, J. Mezger, F. Pannell, J. Pucek, N. van Gils, M. Bergamaschi, G. Zevi Della Porta, N. Lopes, A. Sublet, M. Turner, E. Gschwendtner, P. Muggli

(and the AWAKE Collaboration)

EAAC 2023 – WG1

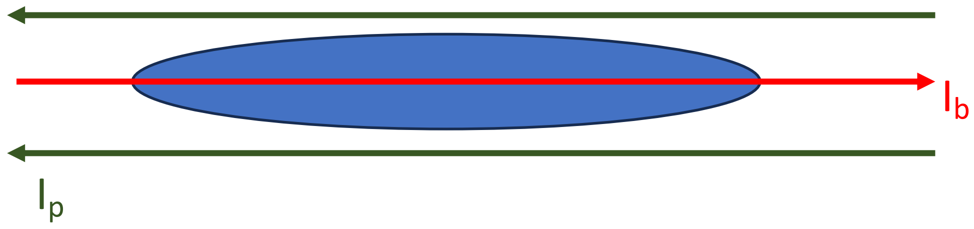
20.09.2023

livio.verra@lnf.infn.it

Current Filamentation Instability (CFI)

Plasma preserves the current neutrality

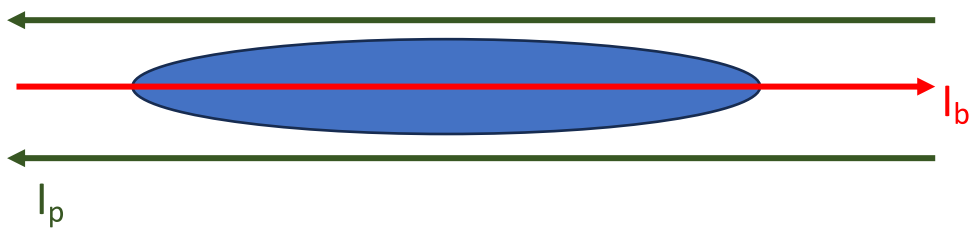
→ return current of plasma electrons to compensate for the bunch current



Current Filamentation Instability (CFI)

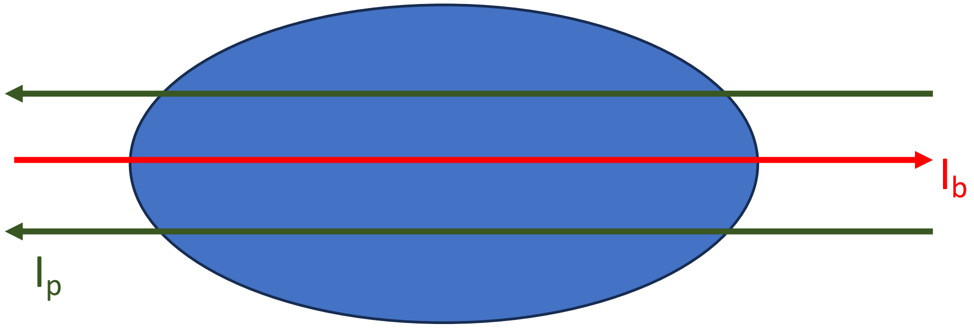
Plasma preserves the current neutrality

→ return current of plasma electrons to compensate for the bunch current



If the bunch is wider than the plasma skin depth $\delta = \frac{c}{\omega_{pe}}$

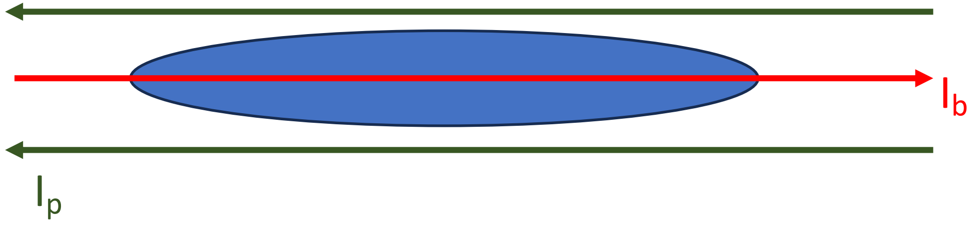
→ the return current flows within the bunch



Current Filamentation Instability (CFI)

Plasma preserves the current neutrality

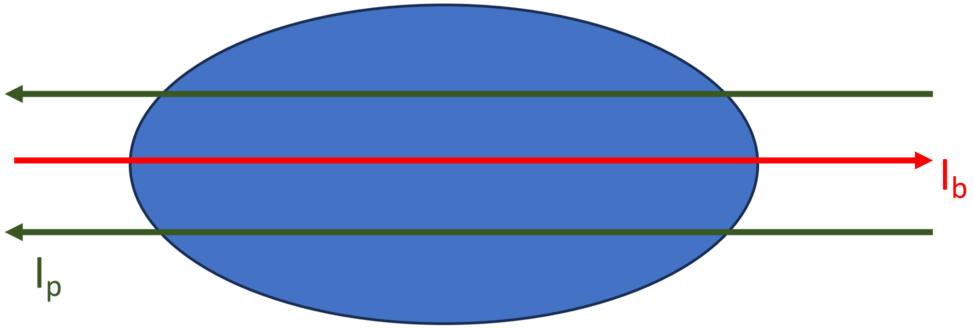
→ return current of plasma electrons to compensate for the bunch current

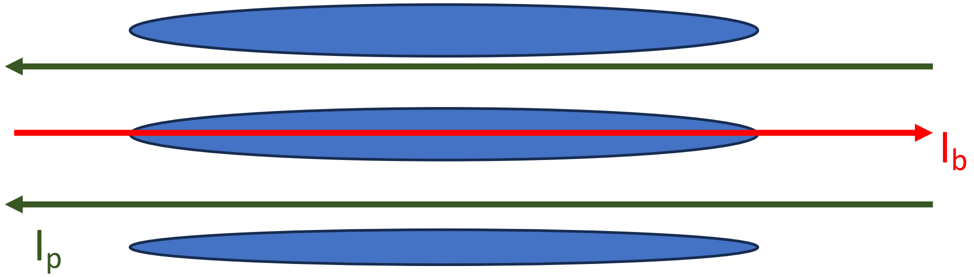


- Currents generate magnetic fields
- Opposite currents repel each other
- Perturbation or anisotropy in the transverse distribution causes unbalanced B field
  → instability
  → growth of current filaments → self-pinching
  → growth of B field and magnetic energy

If the bunch is wider than the plasma skin depth $\delta = \frac{c}{\omega_{pe}}$

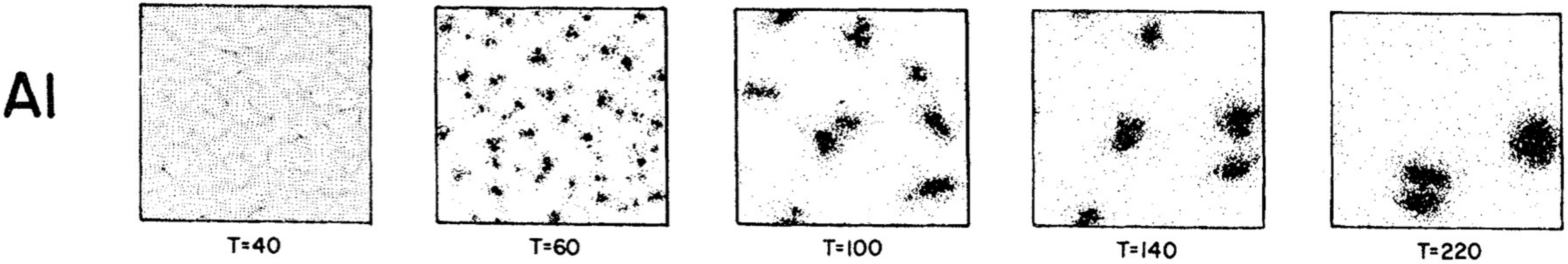
→ the return current flows within the bunch





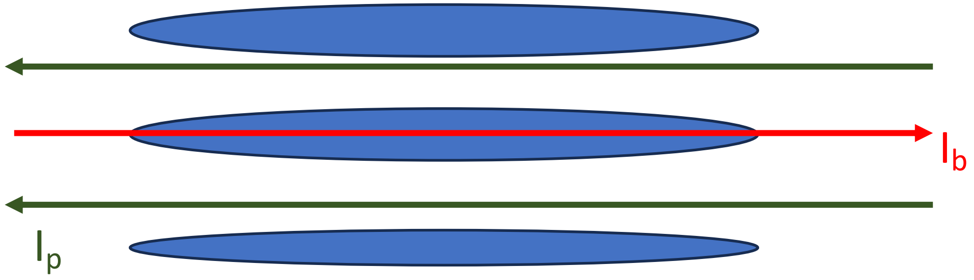
Roswell Lee and Martin Lampe, Phys. Rev. Lett. 31, 1390 (1973)

Current Filamentation Instability (CFI)



(simulations of electron beam streaming through plasma)

- Currents generate magnetic fields
- Opposite currents repel each other
- Perturbation or anisotropy in the transverse distribution causes unbalanced B field
  → instability
  → growth of current filaments → self-pinching
  → growth of B field and magnetic energy



Roswell Lee and Martin Lampe, Phys. Rev. Lett. 31, 1390 (1973)

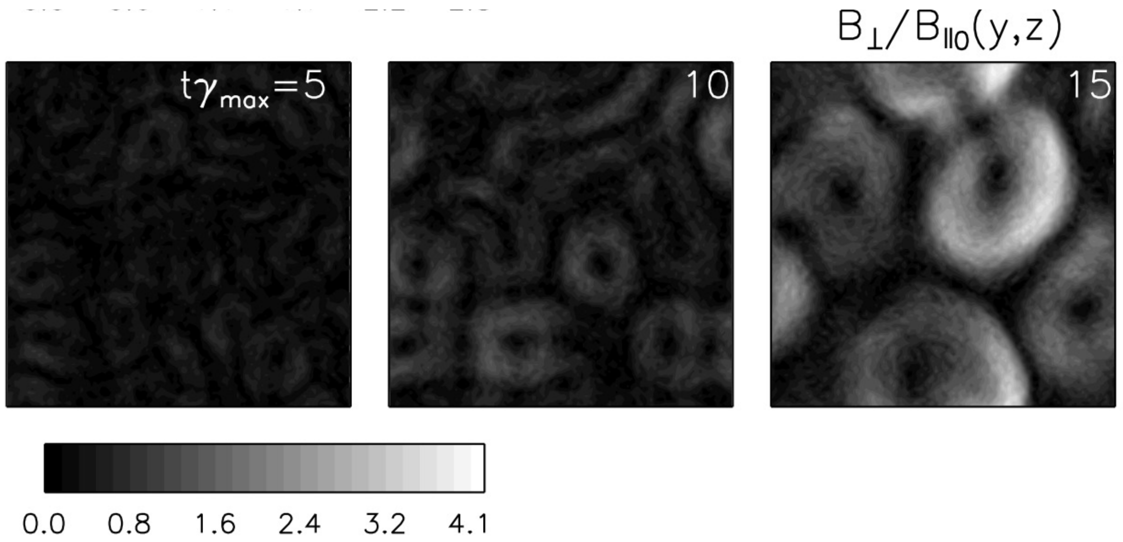
CFI in space

Plausible candidate for:

- magnetization of astrophysical media
  [J. Niemiec et al., The Astrophysical Journal **684**, 1174 (2008)]

- magnetic fields enhancement
  → long duration afterglow of gamma-ray bursts
  [M. V. Medvedev et al.,The Astrophysical Journal **666**, 339 (2007)]
  [M. V. Medvedev et al., Astrophys. Space Sci. **322**, 147–150 (2009)]

  → collisionless shocks
  [M. V. Medvedev and A. Loeb, The Astrophysical Journal **526**, 697 (1999)]



Also important for hot electron propagation in inertial confinement fusion targets:
[M. Tabak et al., Physics of Plasmas 1, 1626 (1994)]

Motivation for Experiments

1) Plasma Wakefield Acceleration

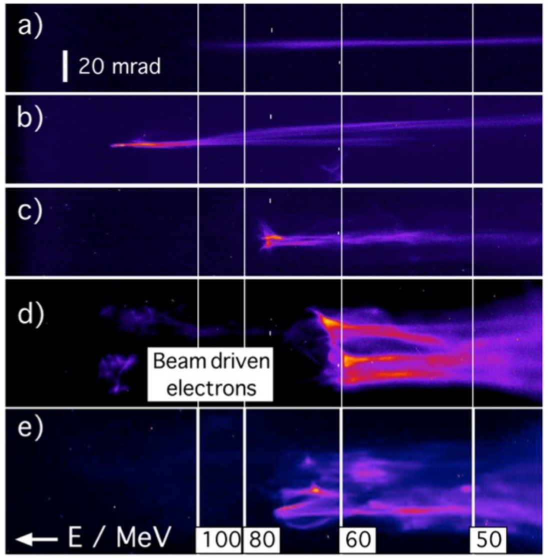
CFI splits driver and/or witness bunch in multiple filaments

→ structure of the wakefields is spoiled
→ no high-quality acceleration

→Define a maximum ratio $\frac{\sigma_r}{\delta}$

→ Maximum σ_r, given n_{pe}, to effectively drive wakefields

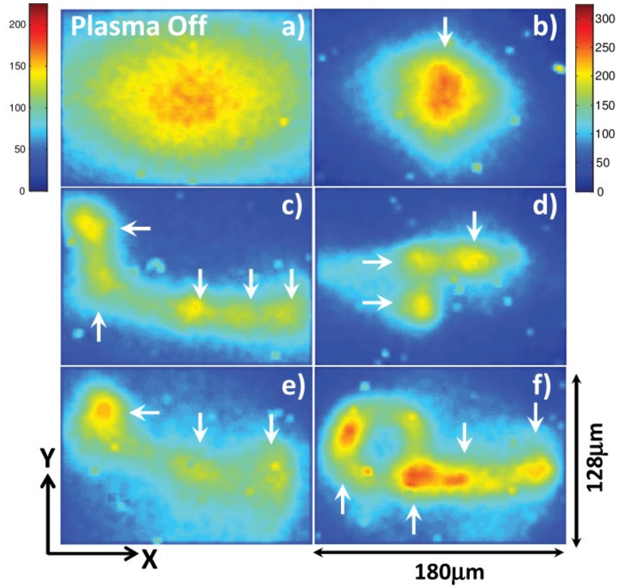
LWFA



C. M. Huntington et al.,
Phys. Rev. Lett. 106, 105001 (2011)

M. Tatarakis, et al.,
Phys. Rev. Lett. 90, 175001 (2003)

PWFA



B. Allen et al.,
Phys. Rev. Lett. **109**, 185007 (2012)

Motivation for Experiments

1) Plasma Wakefield Acceleration

CFI splits driver and/or witness bunch in multiple filaments

→ structure of the wakefields is spoiled
→ no high-quality acceleration

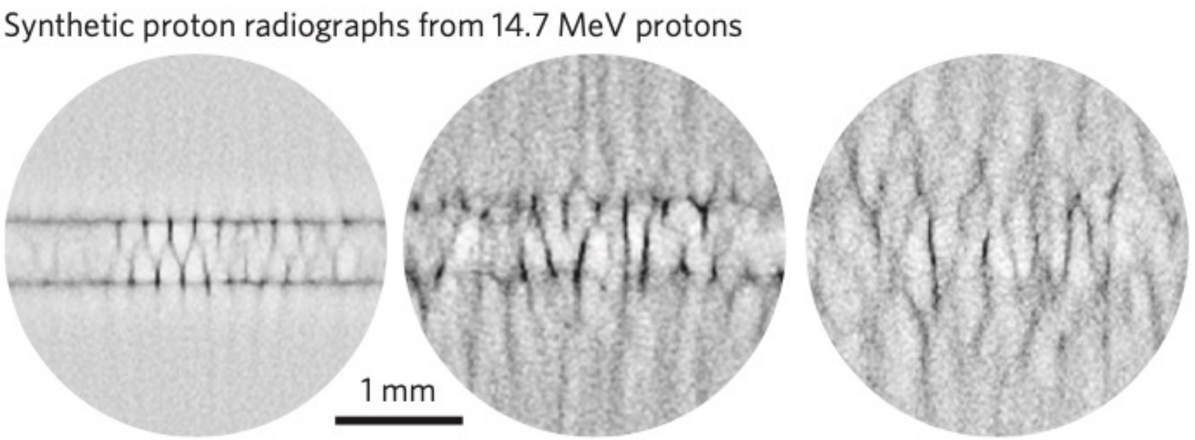
→Define a maximum ratio $\frac{\sigma_r}{\delta}$

→ **Maximum σ_r**, given n_{pe}, to effectively drive wakefields

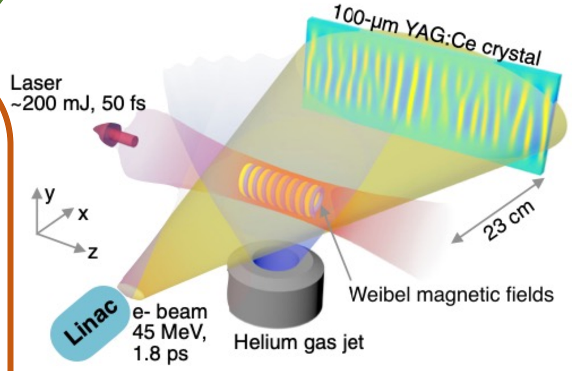
2) Laboratory Astrophysics

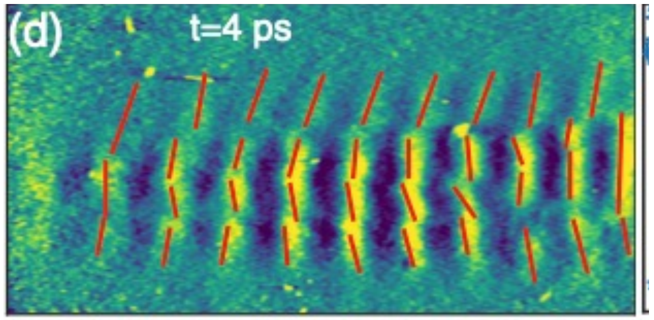
CFI generates and amplifies magnetic field
→ fraction of the bunch kinetic energy is converted into magnetic energy

→ Directly show in experiments
(until now, experiments with probe beams)



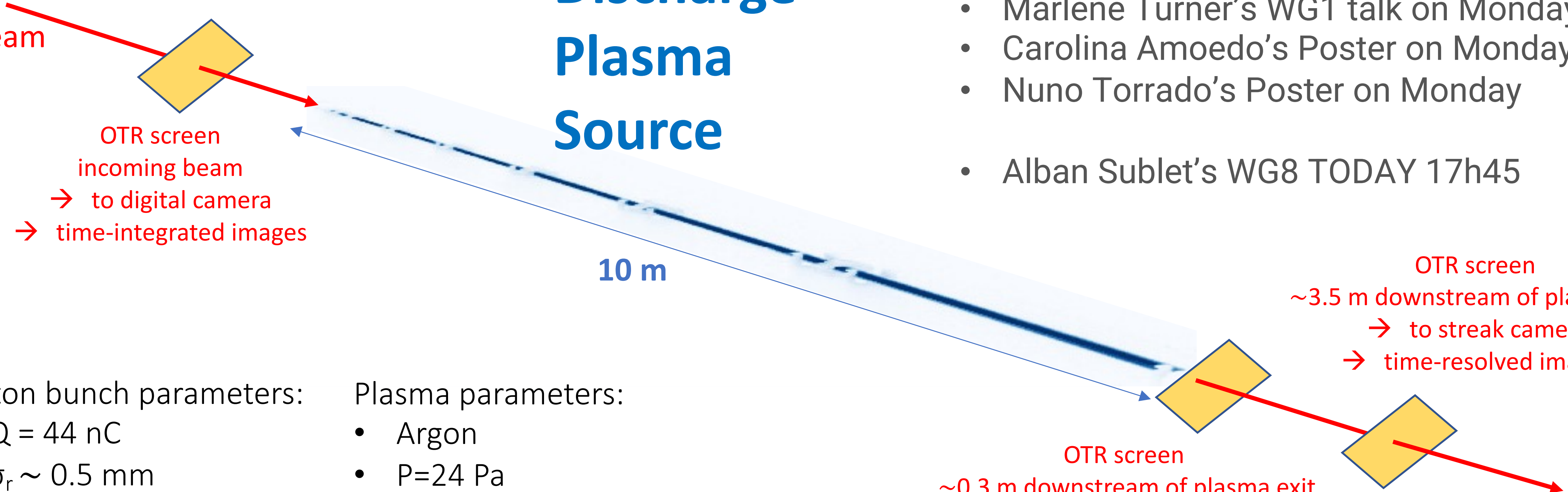
C. M. Huntington et al., Nature Physics **11**, 173–176 (2015)





Chaojie Zhang et al., Phys. Rev. Lett. 125, 255001 (2020)

Experimental Setup



- Edda Gschwendtner's plenary talk on Tuesday
- Marlene Turner's WG1 talk on Monday
- Carolina Amoedo's Poster on Monday
- Nuno Torrado's Poster on Monday

- Alban Sublet's WG8 TODAY 17h45

Proton bunch parameters:
- Q = 44 nC
- $\sigma_r \sim 0.5$ mm
- $\varepsilon = 2.5$ mm-mrad

Plasma parameters:
- Argon
- P=24 Pa
- $n_{pe}=(0.68 - 9.38) \times 10^{14}$ cm^{-3}

→we can vary the ratio initial size – skin depth

$$\frac{\sigma_r}{\delta} = 0.9 - 3.2$$

Experimental Setup

- Edda Gschwendtner's plenary talk on Tuesday
- Marlene Turner's WG1 talk on Monday
- Carolina Amoedo's Poster on Monday

- Alban Sublet's WG8 TODAY 17h45

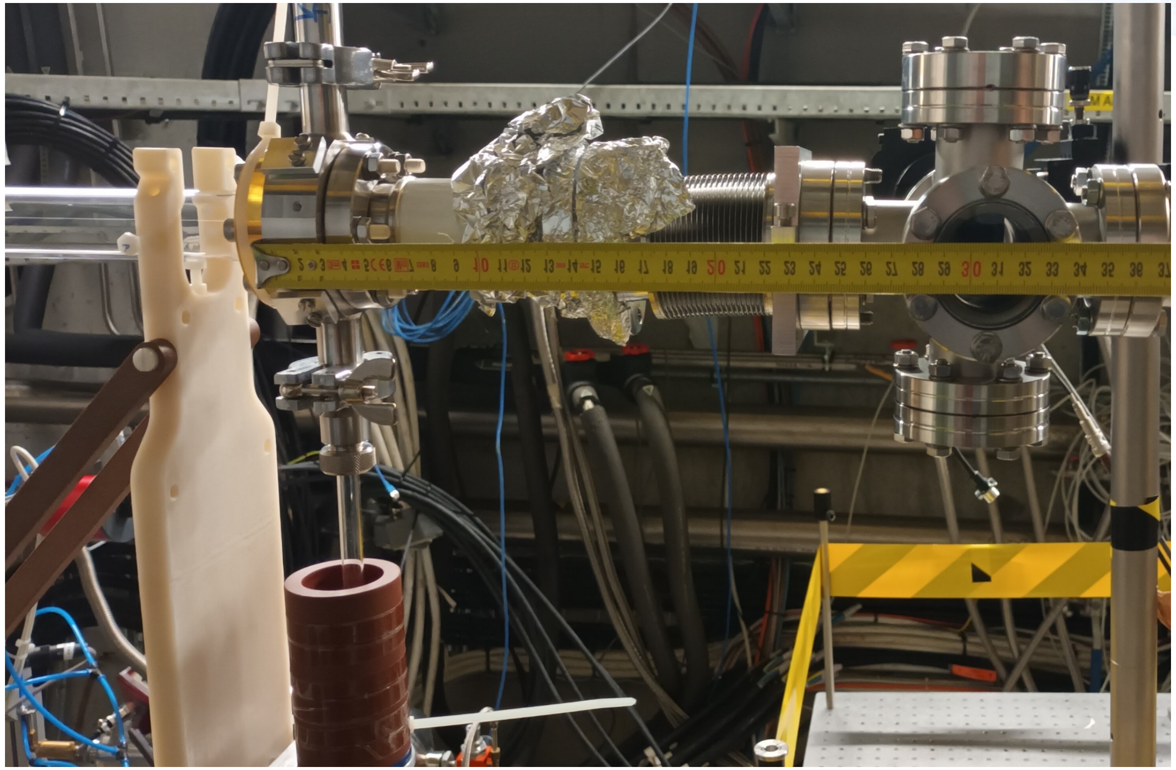
p+ beam

OTR screen
incoming beam
→ to digital camera
→ time-integrated images

Discharge Plasma Source

OTR screen
~3.5 m downstream of plasma exit
→ to streak camera
→ time-resolved images

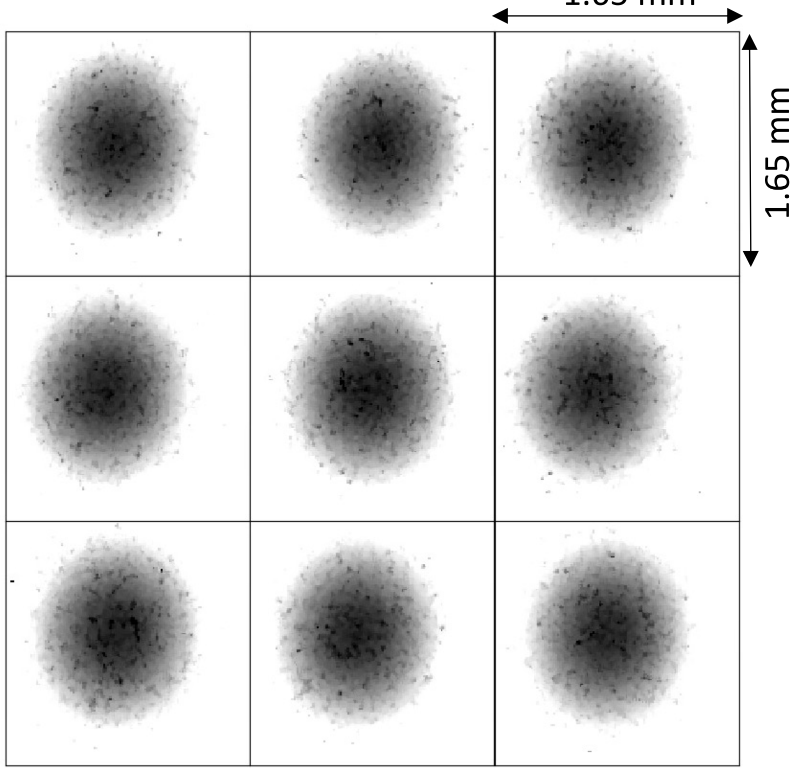
OTR screen
~0.3 m downstream of plasma exit
→ to digital camera
→ time-integrated images



Expected filaments with small size, large emittance
→ large divergence when leaving the plasma
→ screen as close as possible to exit

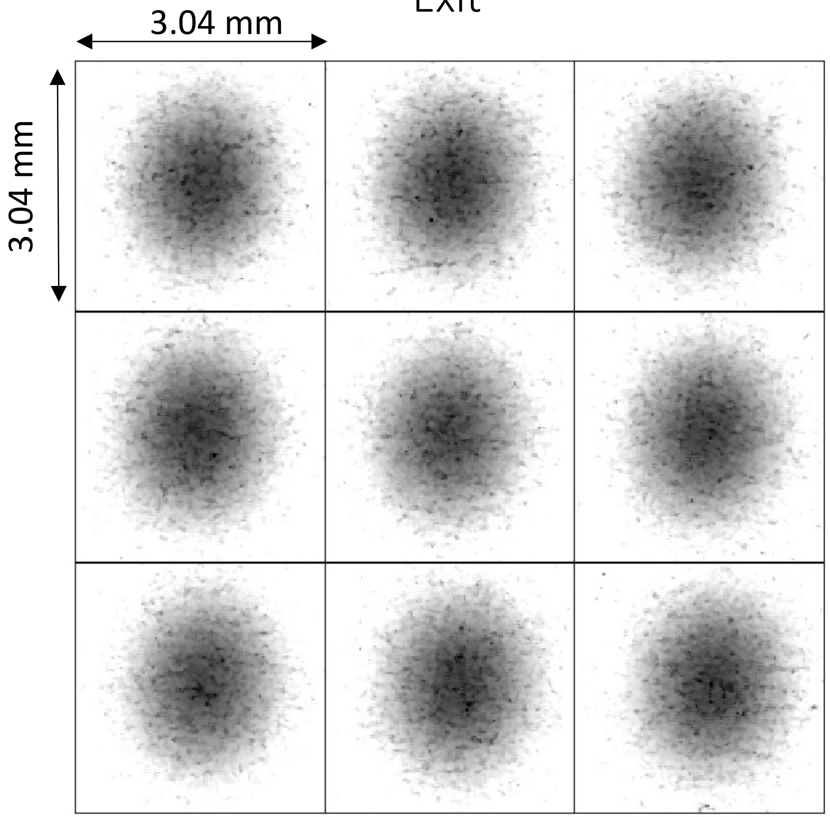
Plasma OFF – no gas

Entrance



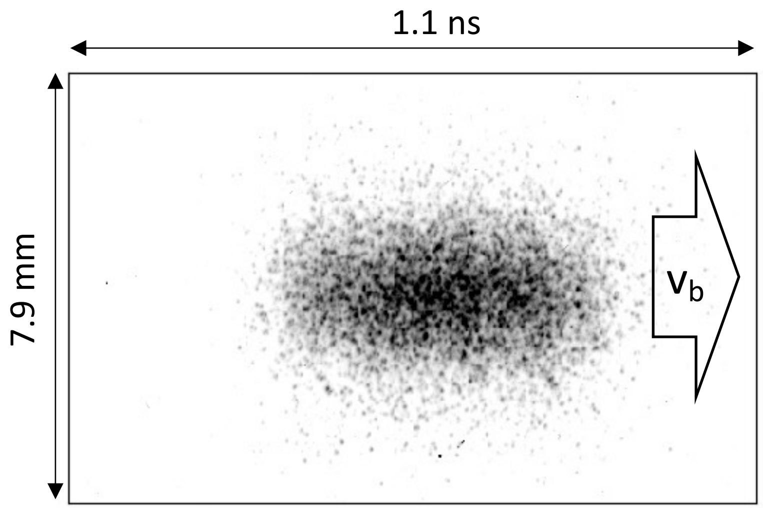
σ_x=0.48 mm
σ_y= 0.53 mm
σ_{r0}=0.5 mm

Exit



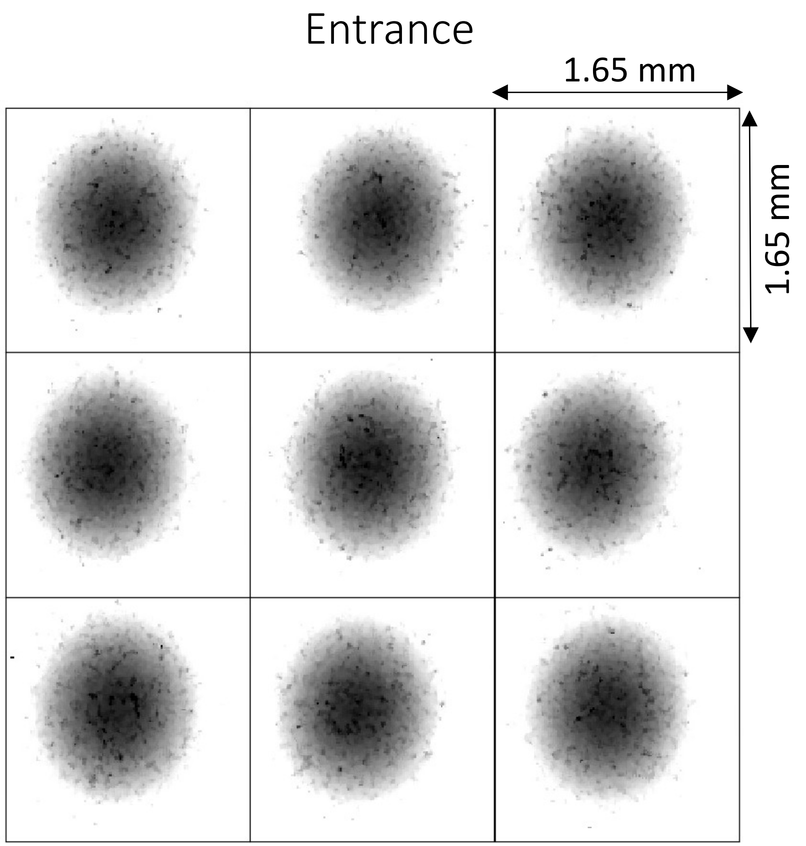
σ_x=0.81 mm
σ_y= 0.87 mm
σ_r=0.84 mm

Streak camera
ns-scale images

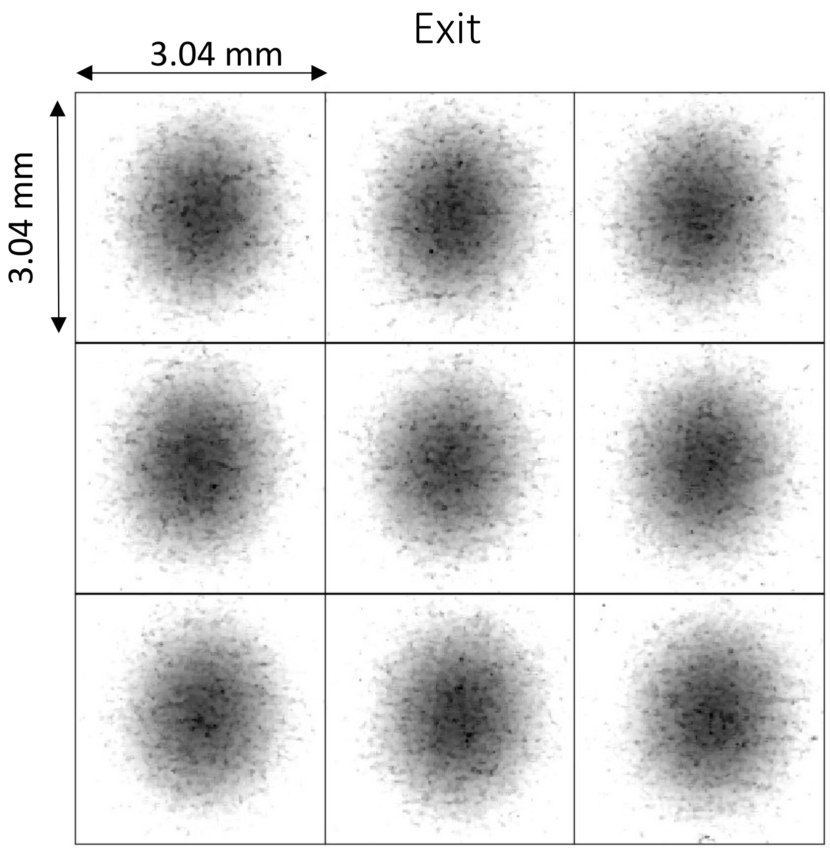


σ_t = 170 ps

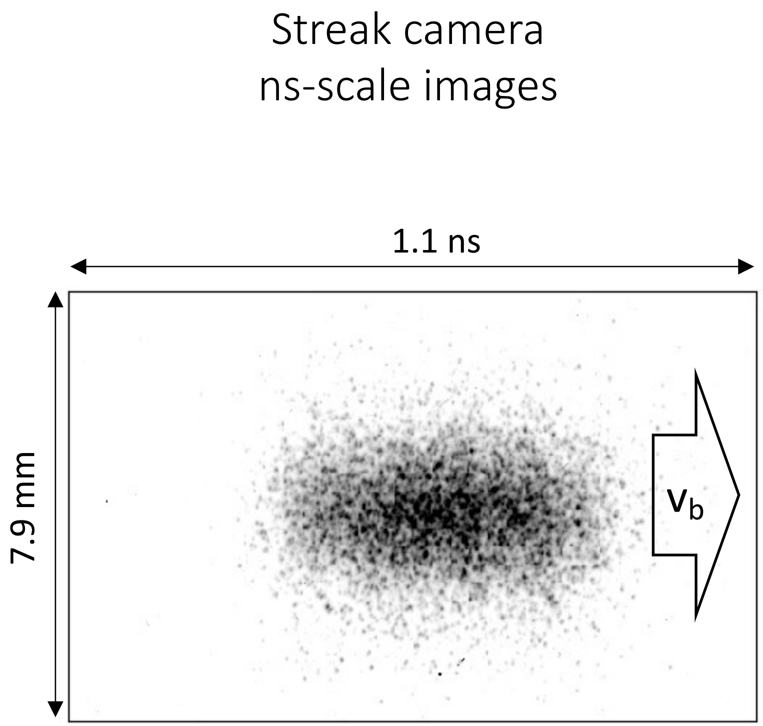
Plasma OFF – no gas



σ_x=0.48 mm
σ_y= 0.53 mm
σ_{r0}=0.5 mm



σ_x=0.81 mm
σ_y= 0.87 mm
σ_r=0.84 mm



σ_t = 170 ps

No distinguishable features in the transverse or longitudinal distribution

Magnetic field generation

- We calculate the transverse magnetic field generated by each current with Ampère's law
  → the sum of the two contributions provides the overall magnetic field

Conclusions

- We consistently observe CFI of long, relativistic proton bunch when $\frac{\sigma_r}{\delta} > 1.5$

- At the threshold $\frac{\sigma_r}{\delta} = 1.5$, the bunch-plasma system alternates between CFI and SMI

- We show that occurrence of CFI generates magnetic fields
  - the amount of magnetic energy increases with n_{pe}

Thank you for your attention!

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati