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

AWAKE Collaboration Meeting

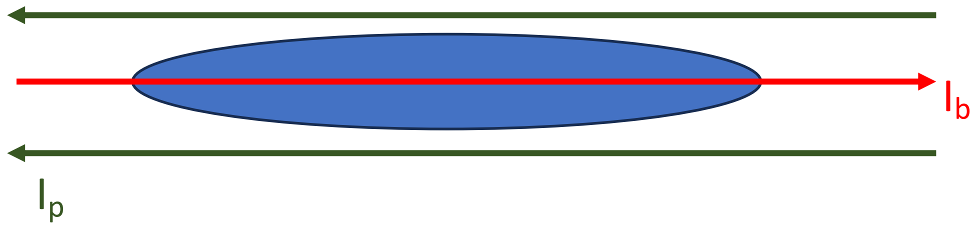
04.10.2023

livio.verra@lnf.infn.it

Current Filamentation Instability (CFI)

Plasma preserves the current neutrality

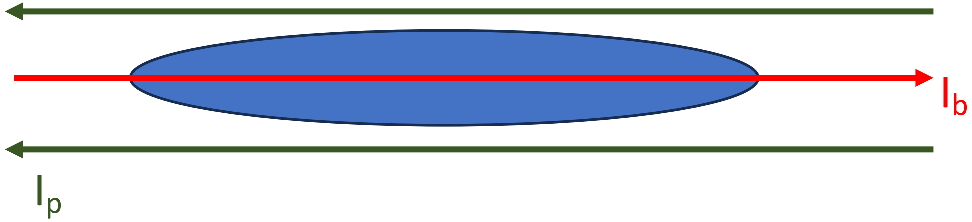
→ return current of plasma electrons to compensate for the bunch current



Current Filamentation Instability (CFI)

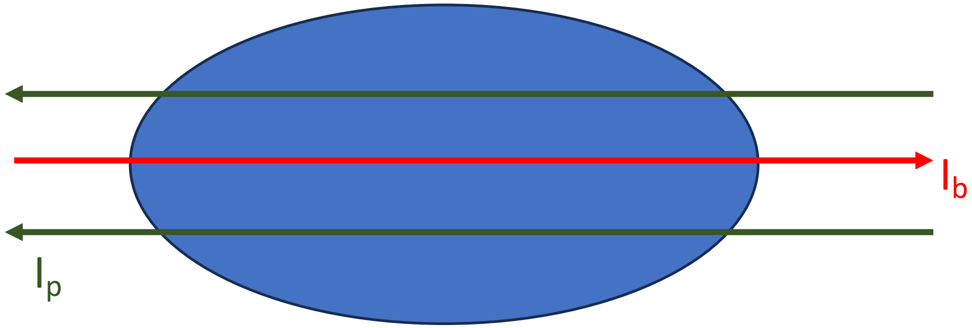
Plasma preserves the current neutrality

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



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

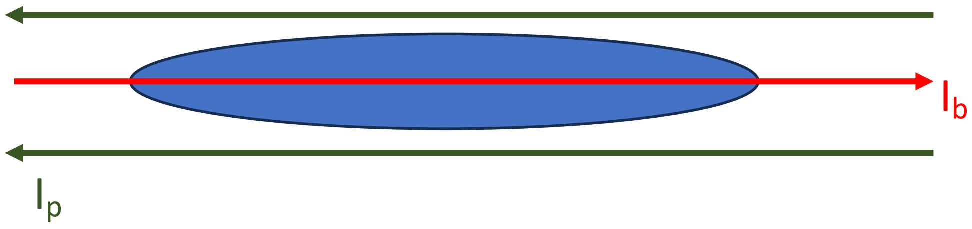
→ the return current flows within the bunch



Current Filamentation Instability (CFI)

Plasma preserves the current neutrality

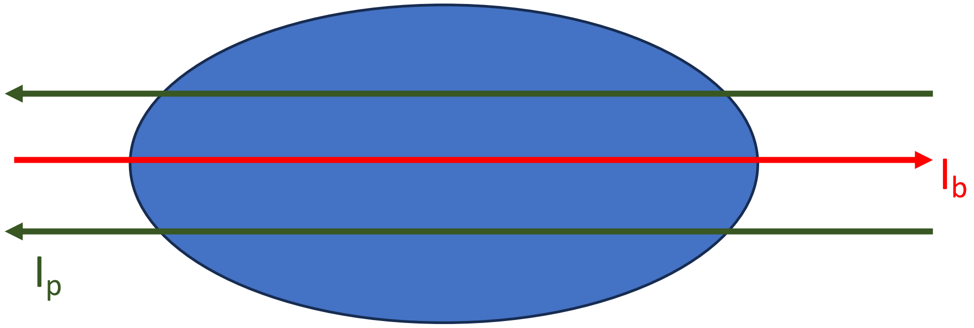
→ return current of plasma electrons to compensate for the bunch current

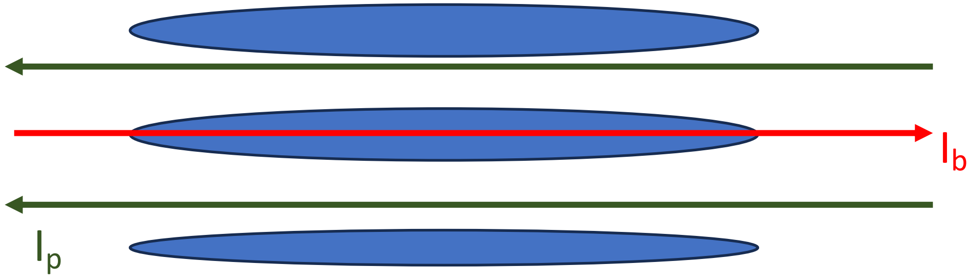


- Currents generate magnetic fields
- Opposite currents repel each other
- Perturbation or anisotropy in the transverse distribution causes unbalanced B field
  → instability
  → growth of current filaments → self-pinching
  → growth of B field and magnetic energy

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

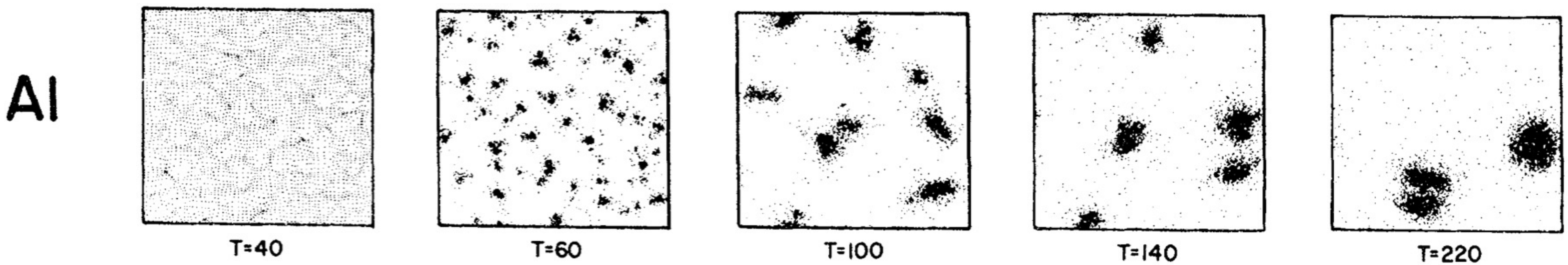
→ the return current flows within the bunch





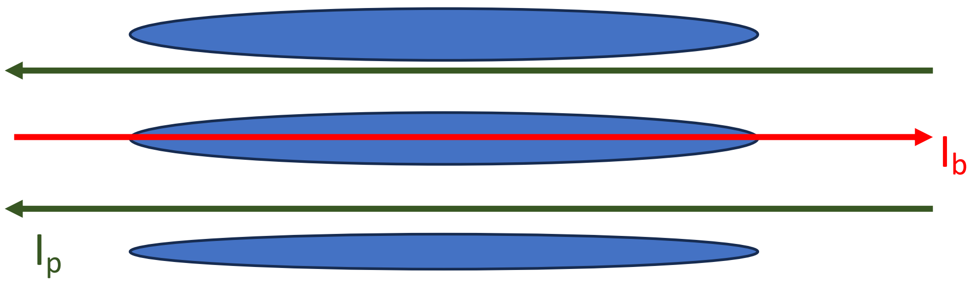
Roswell Lee and Martin Lampe, Phys. Rev. Lett. 31, 1390 (1973)

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

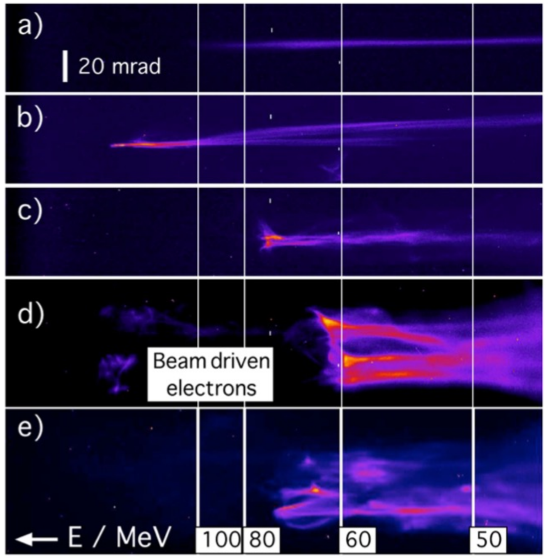
CFI splits driver and/or witness bunch in multiple filaments

→ 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

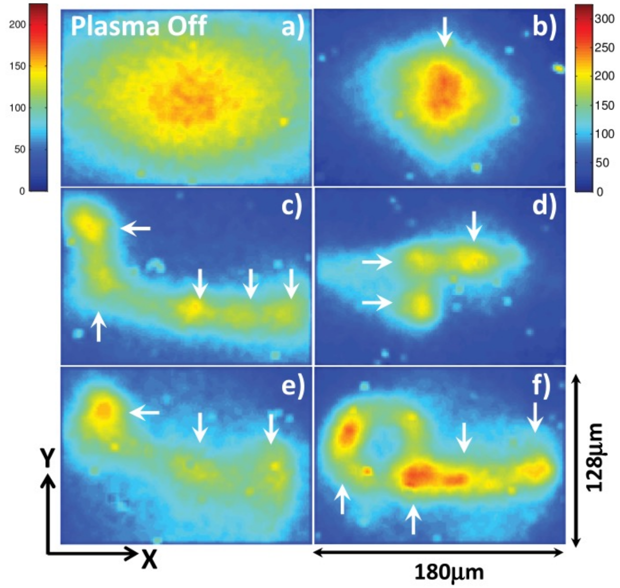
LWFA



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

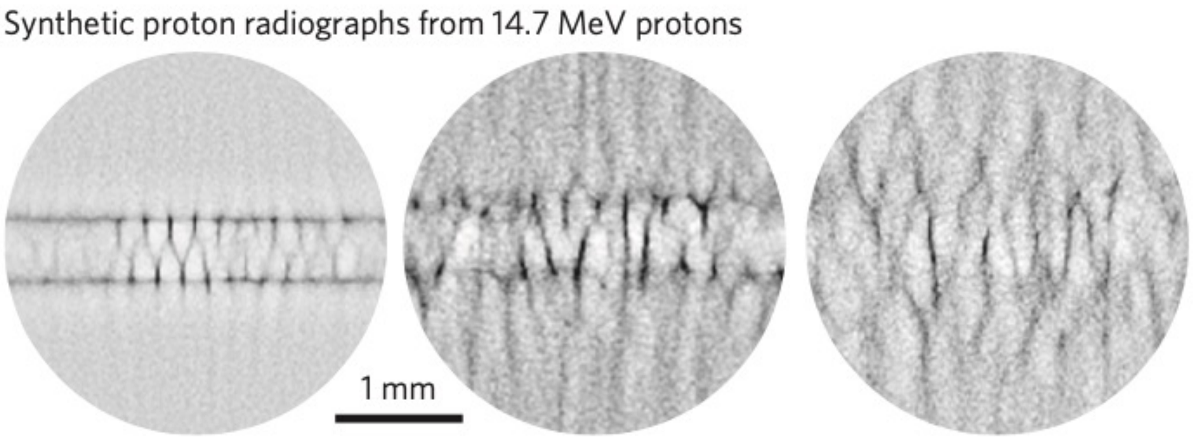
→Define a maximum ratio $\frac{\sigma_r}{\delta}$

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

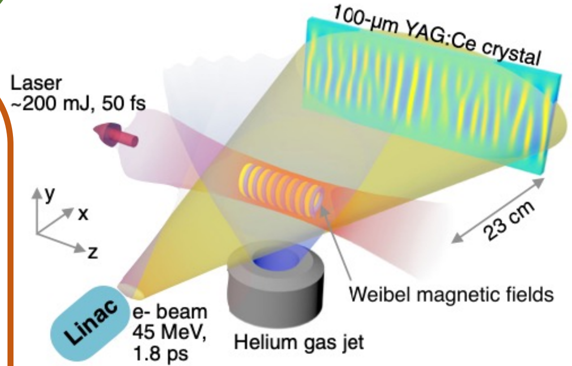
2) Laboratory Astrophysics

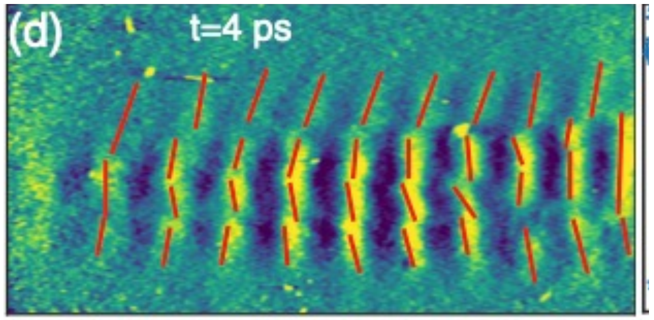
CFI generates and amplifies magnetic field
→ fraction of the bunch kinetic energy is converted into magnetic energy

→ Directly measure on the drive bunch
(until now, experiments with probe beams)



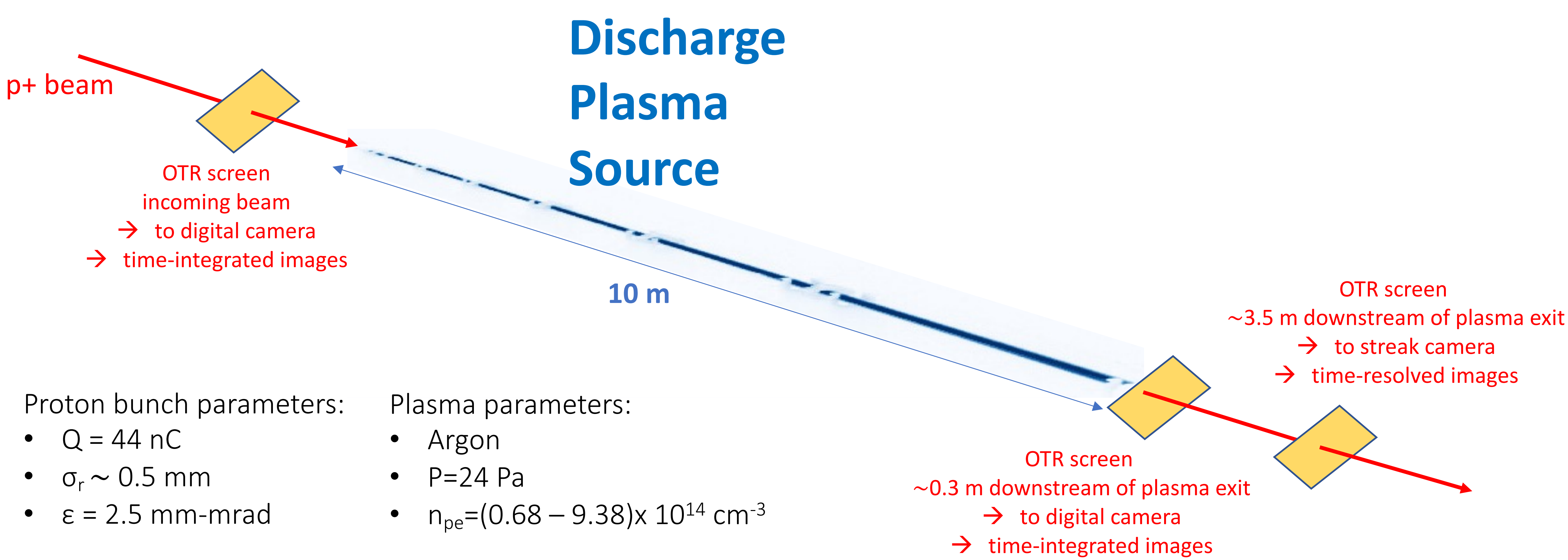
C. M. Huntington et al., Nature Physics **11**, 173–176 (2015)





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

Experimental Setup



Proton bunch parameters:

- Q = 44 nC
- $\sigma_r \sim 0.5$ mm
- ε = 2.5 mm-mrad

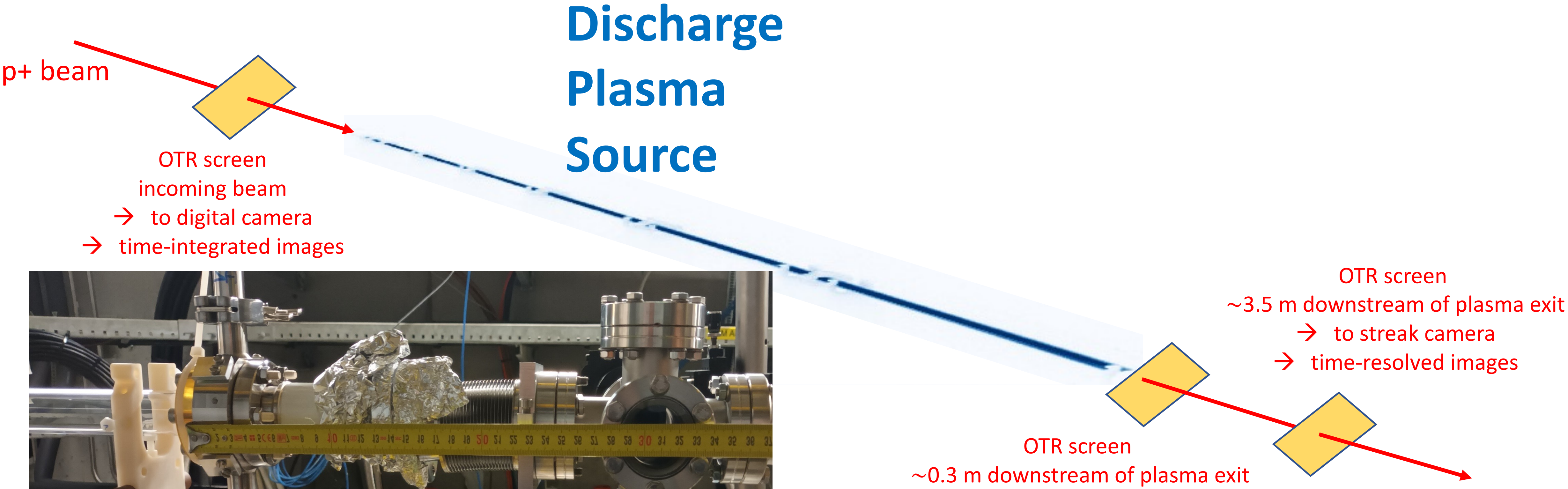
Plasma parameters:

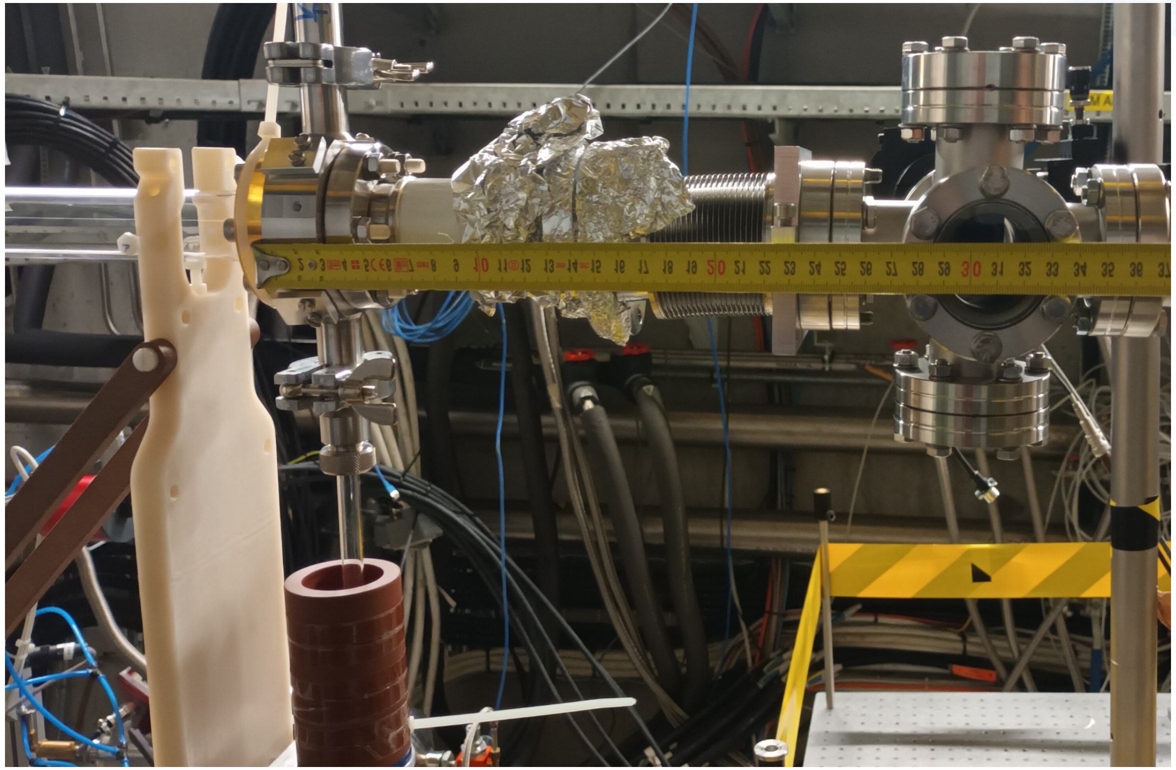
- Argon
- P=24 Pa
- $n_{pe}=(0.68 - 9.38) \times 10^{14}$ cm^{-3}

→we can vary the ratio initial size – skin depth

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

Experimental Setup

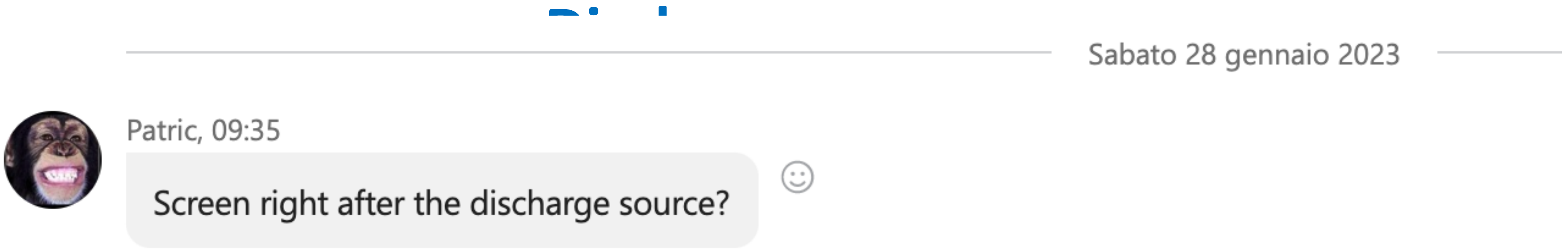




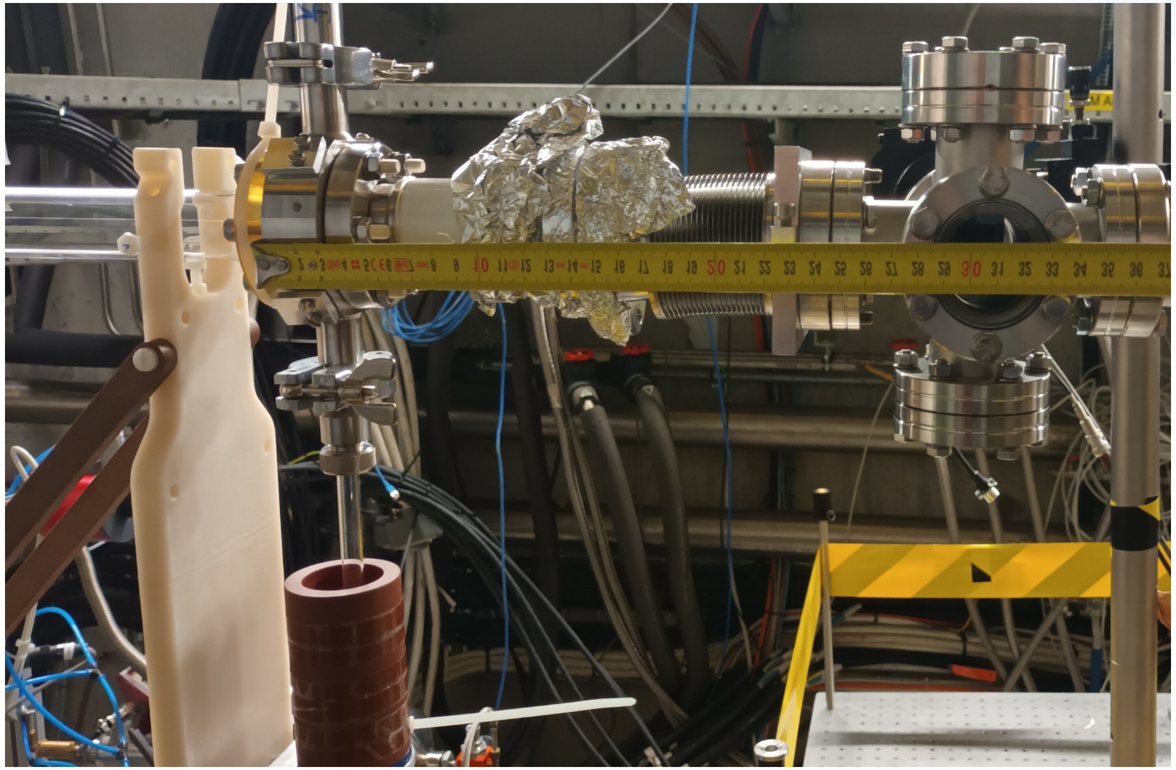
Expected filaments with small size, large emittance
→ large divergence when leaving the plasma
→ screen as close as possible to exit

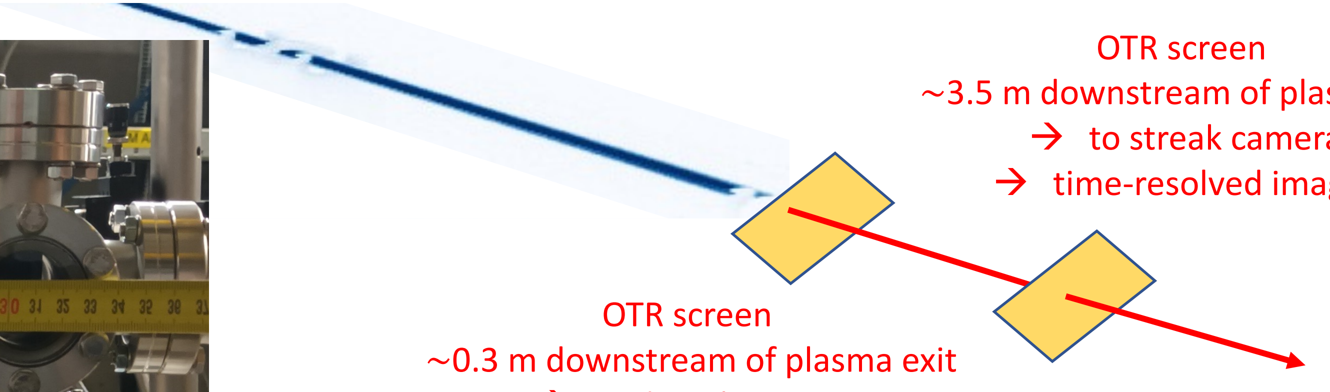
Experimental Setup

p+ bea



→ time-integrated images





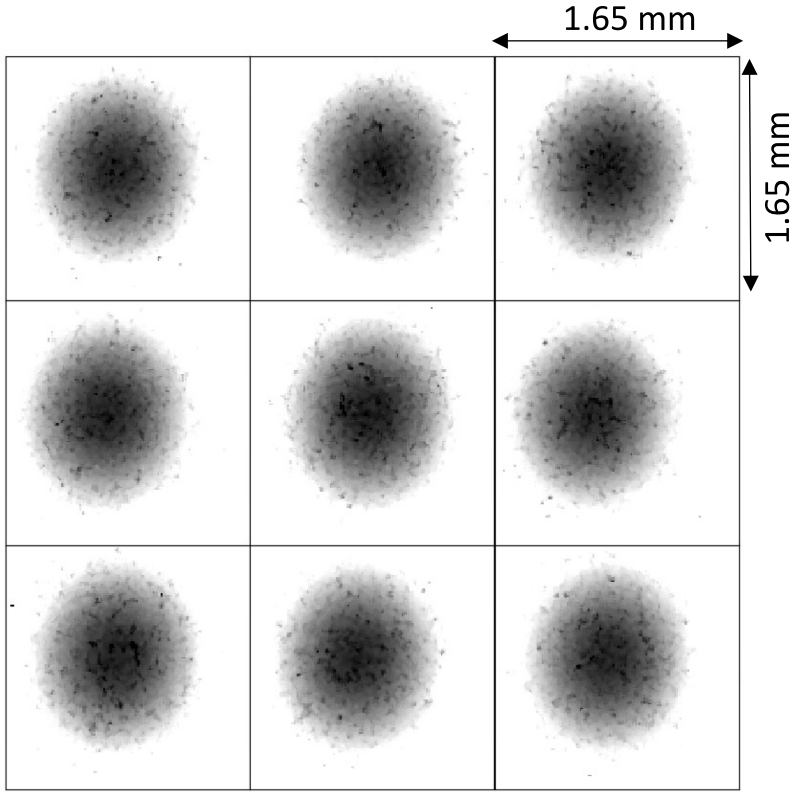
OTR screen
~3.5 m downstream of plasma exit
→ to streak camera
→ time-resolved images

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

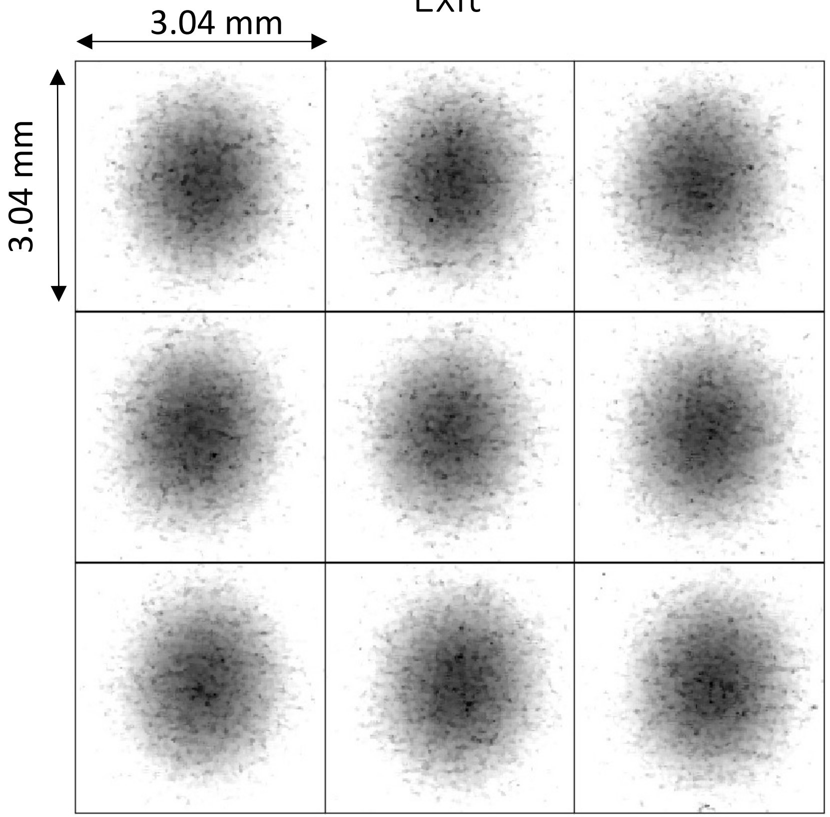
Plasma OFF – no gas

Entrance



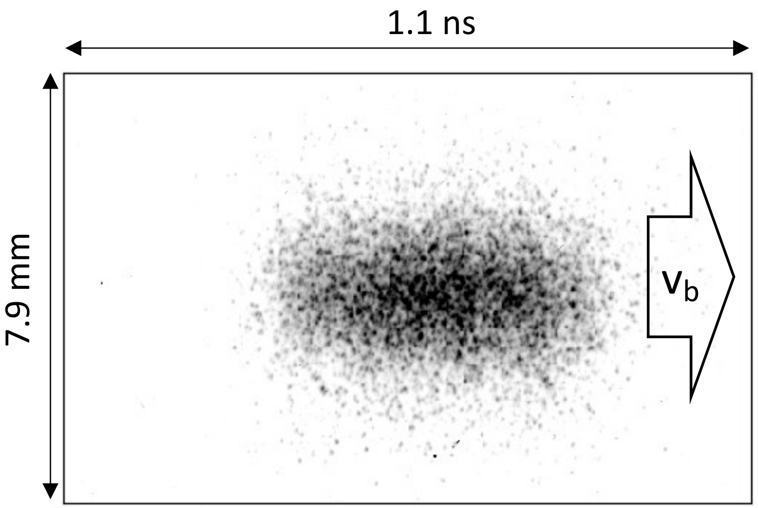
σ_x=0.48 mm
σ_y= 0.53 mm
} σ_{r0}=0.5 mm

Exit



σ_x=0.81 mm
σ_y= 0.87 mm
} σ_r=0.84 mm

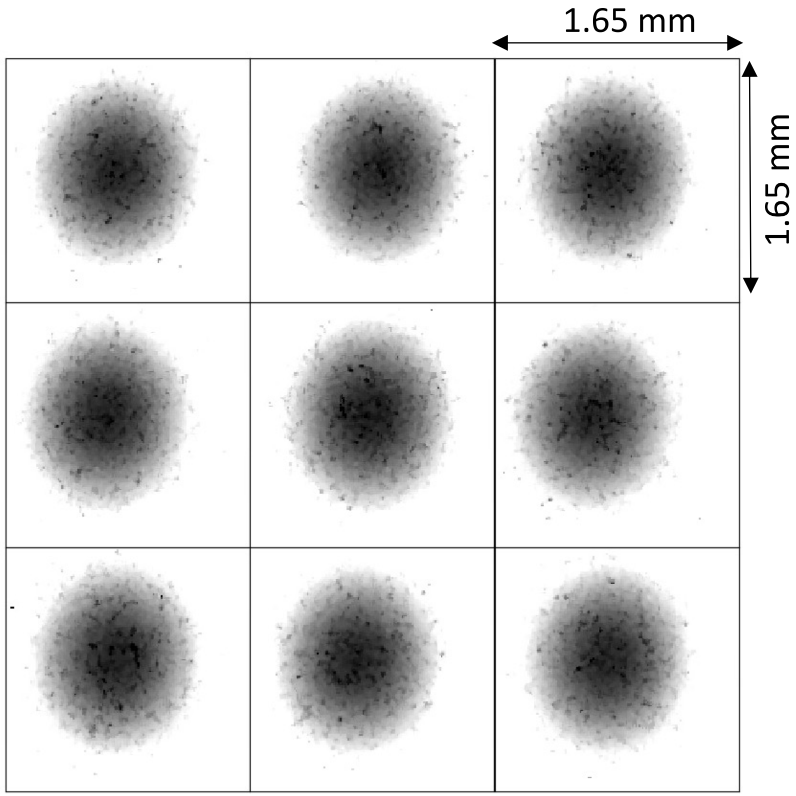
Streak camera
ns-scale images



σ_t = 170 ps

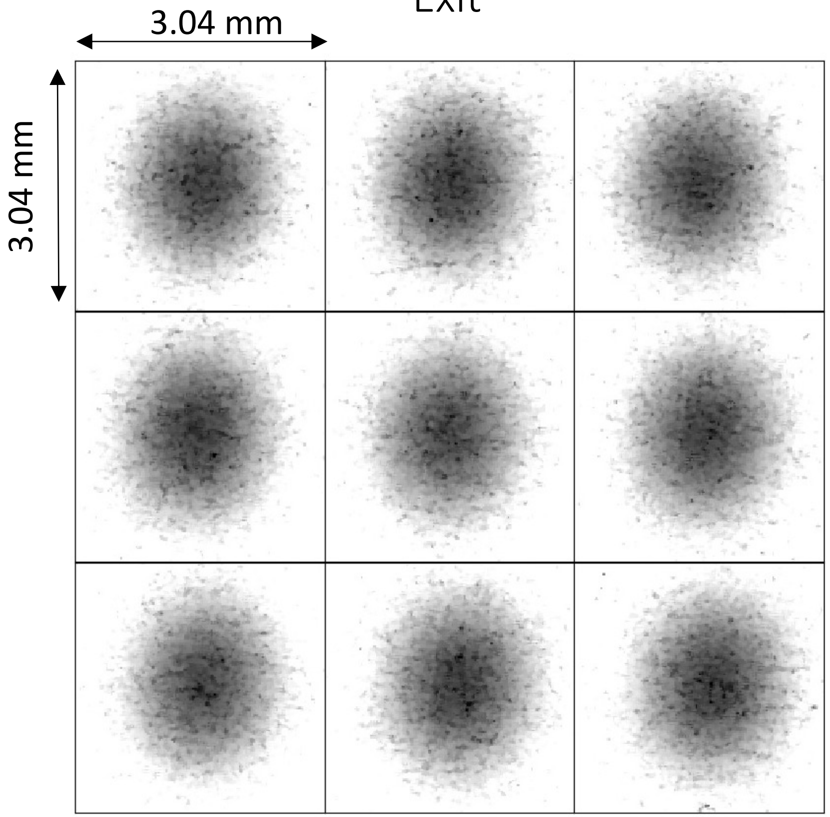
Plasma OFF – no gas

Entrance



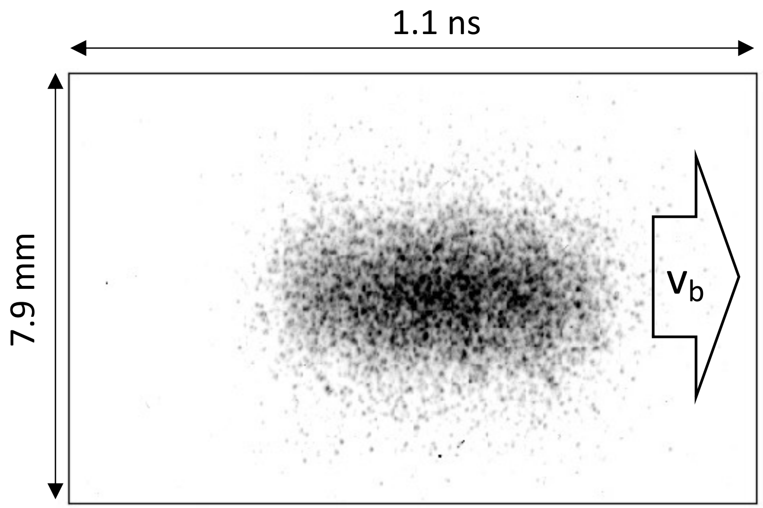
σ_x=0.48 mm
σ_y= 0.53 mm
σ_{r0}=0.5 mm

Exit



σ_x=0.81 mm
σ_y= 0.87 mm
σ_r=0.84 mm

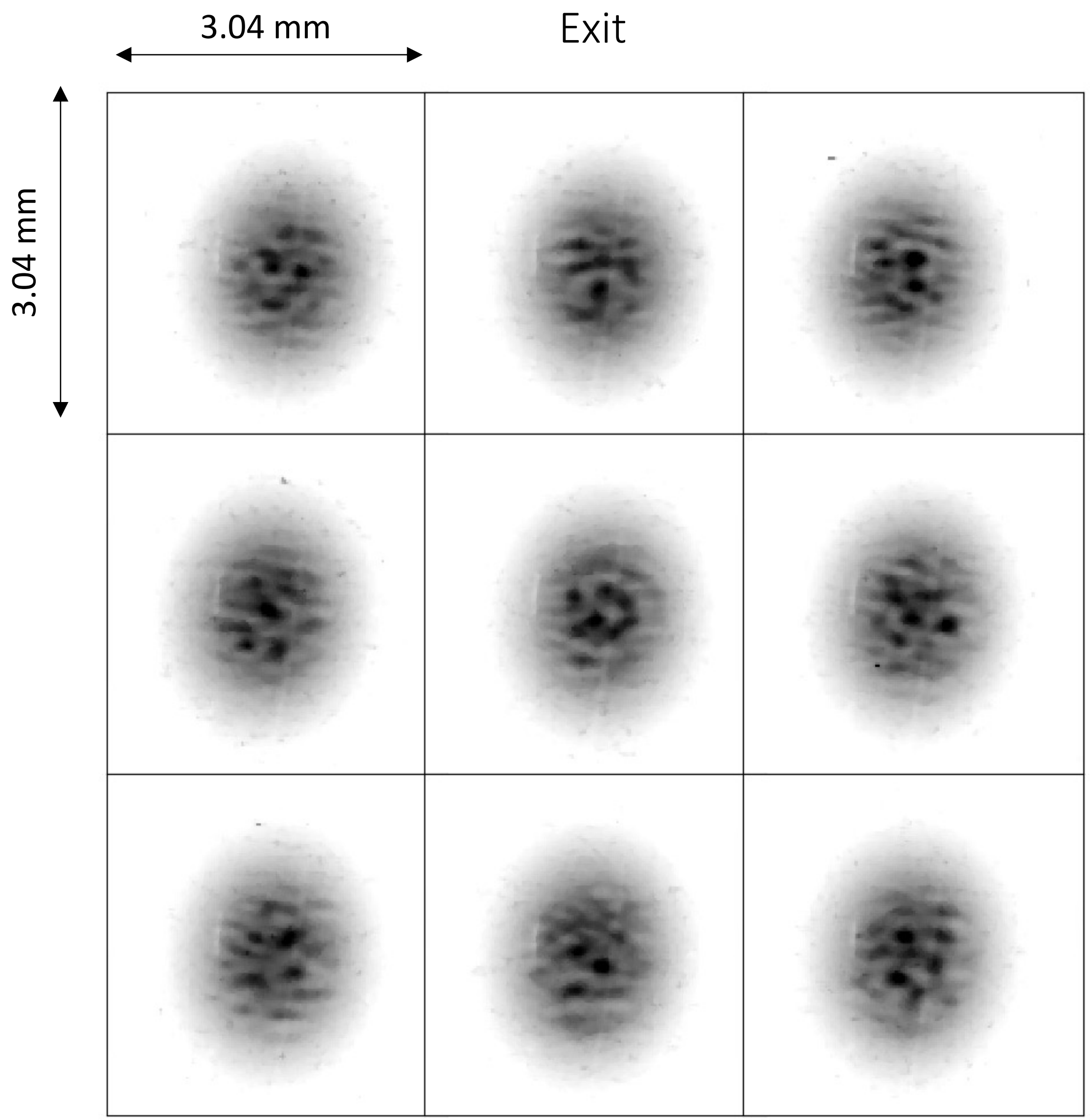
Streak camera
ns-scale images



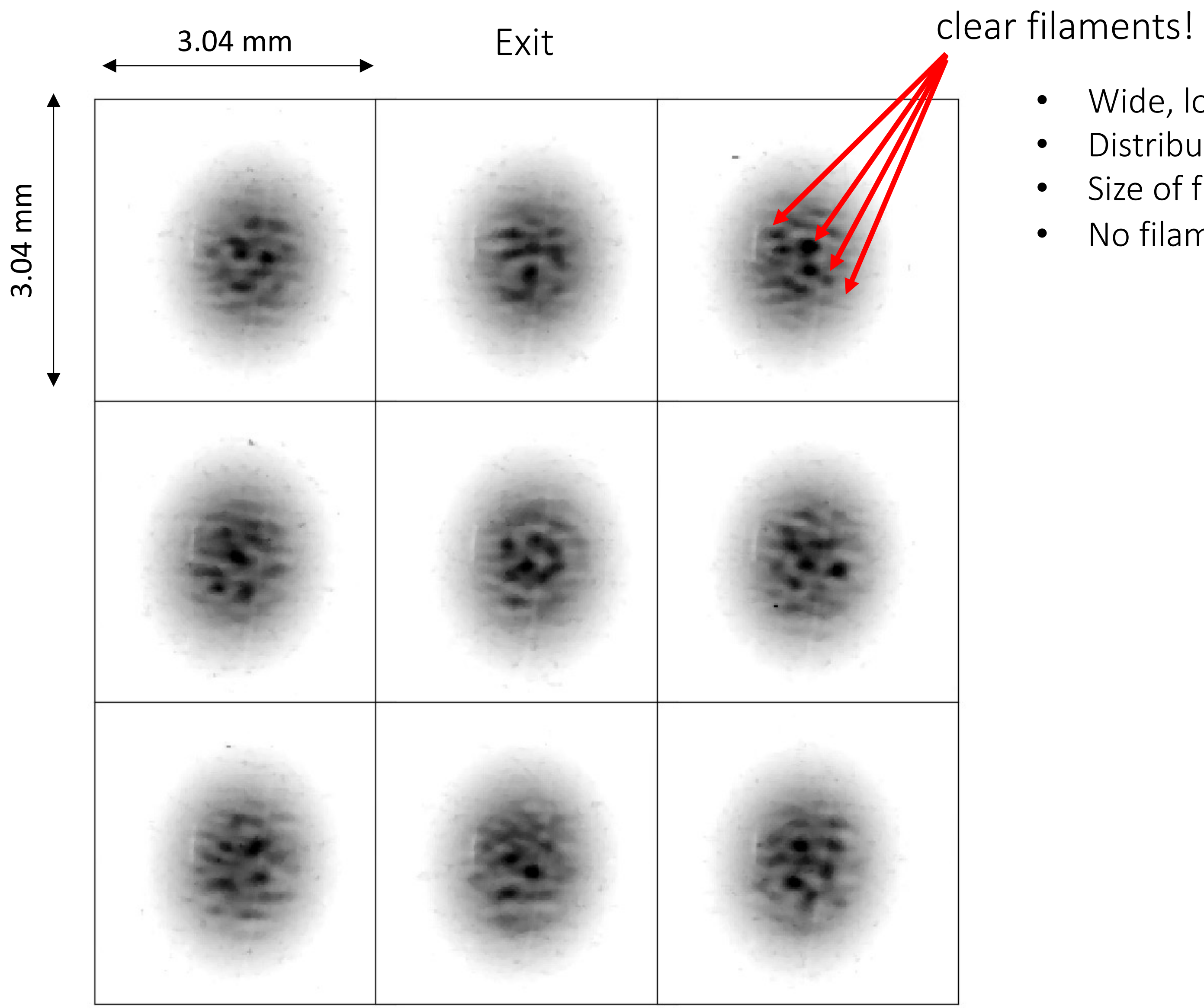
σ_t = 170 ps

No distinguishable features in the transverse or longitudinal distribution

Plasma ON – n_{pe} = 9.38e14/cc → $\sigma_r/(c/\omega_{pe})$ = 3.2 at plasma entrance

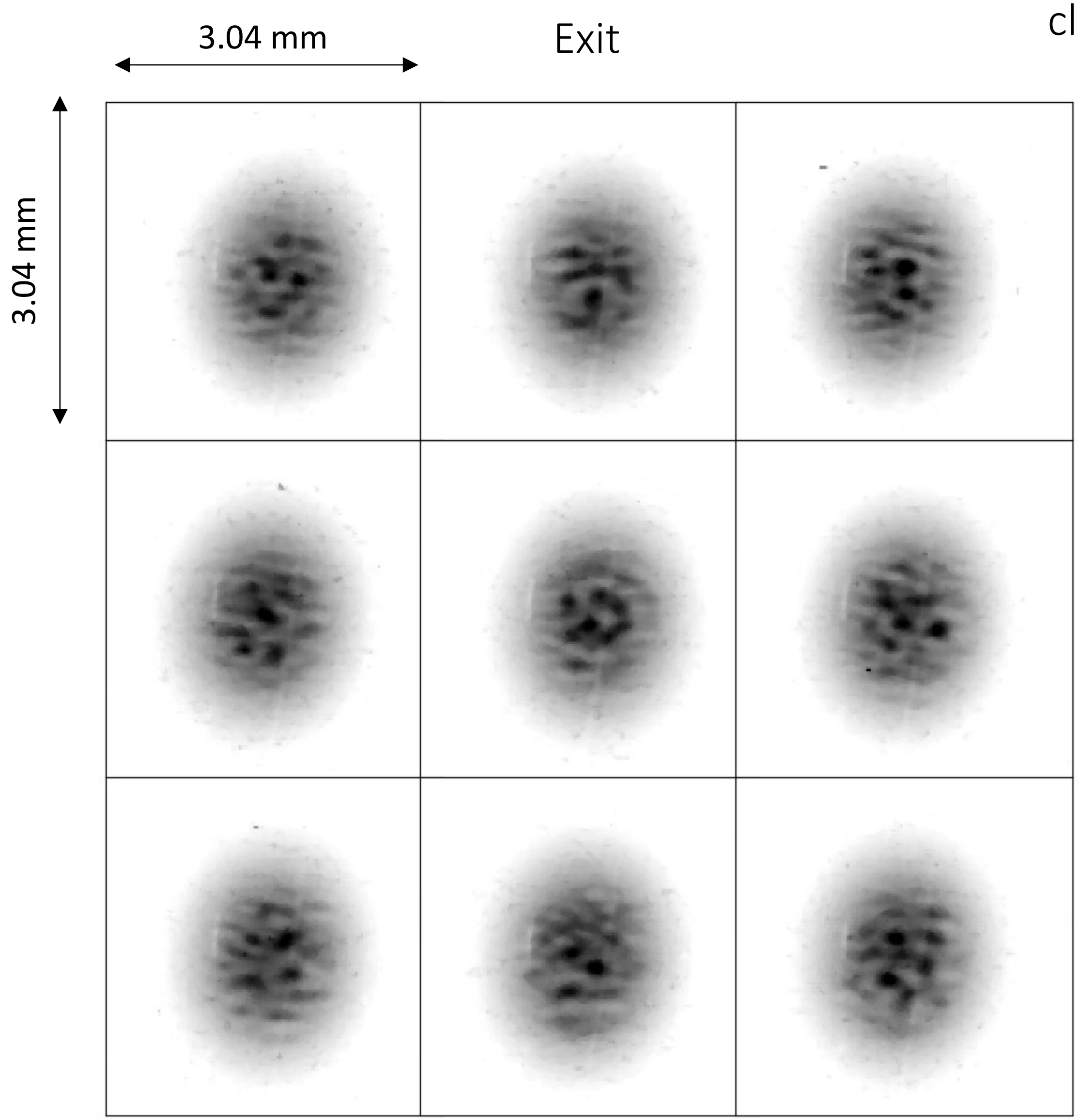


Plasma ON – n_{pe} = 9.38e14/cc → $\sigma_r/(c/\omega_{pe})$ = 3.2 at plasma entrance



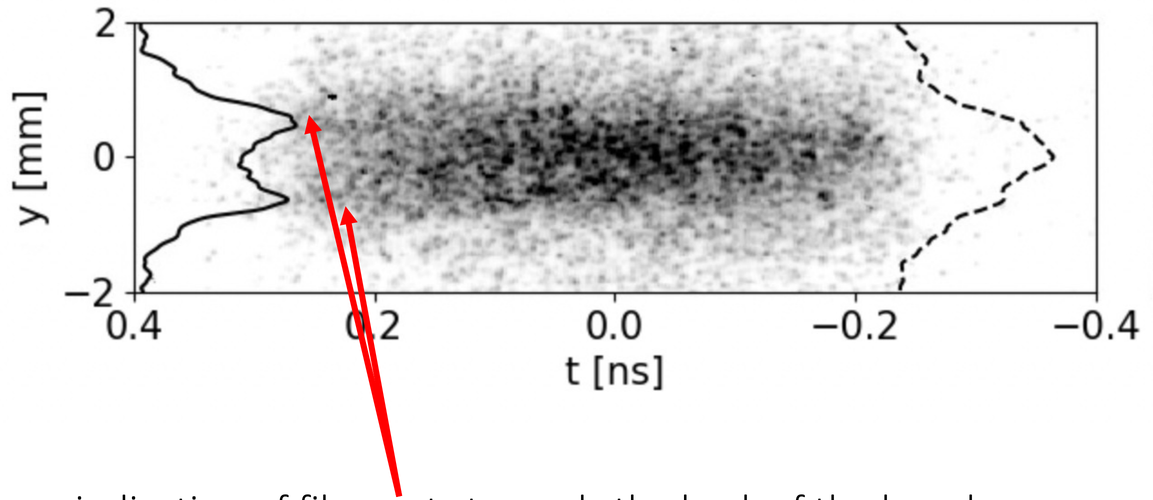
- Wide, long, relativistic proton bunch undergoes CFI
- Distribution of filaments changes from event to event
- Size of filaments $\sim \delta$
- No filaments at $r > \sigma_r$ → bunch density and growth rate too low

Plasma ON – n_{pe} = 9.38e14/cc → $\sigma_r/(c/\omega_{pe})$ = 3.2 at plasma entrance



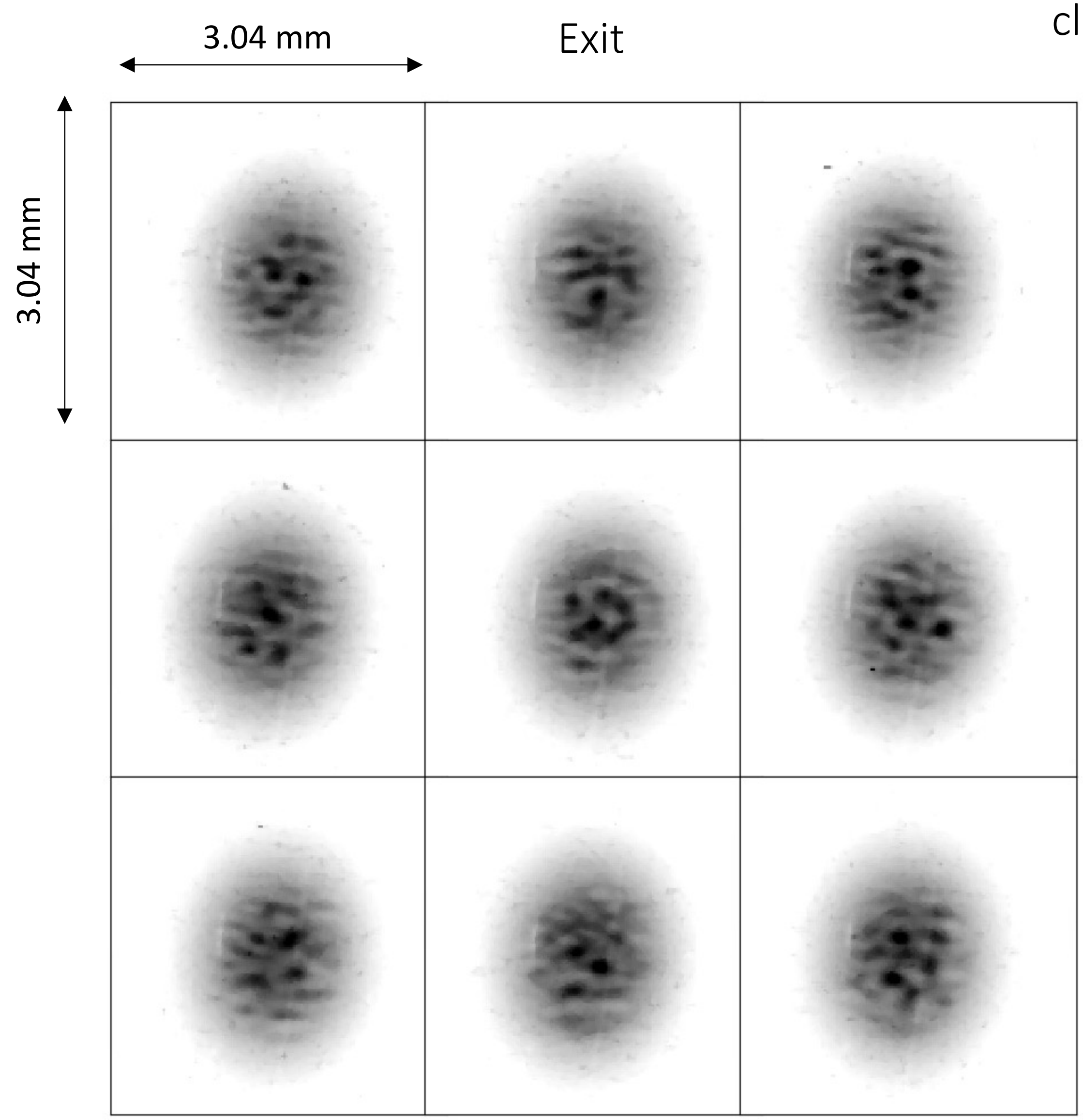
clear filaments!

- Wide, long, relativistic proton bunch undergoes CFI
- Distribution of filaments changes from event to event
- Size of filaments ~ δ
- No filaments at $r > \sigma_r$ → bunch density and growth rate too low



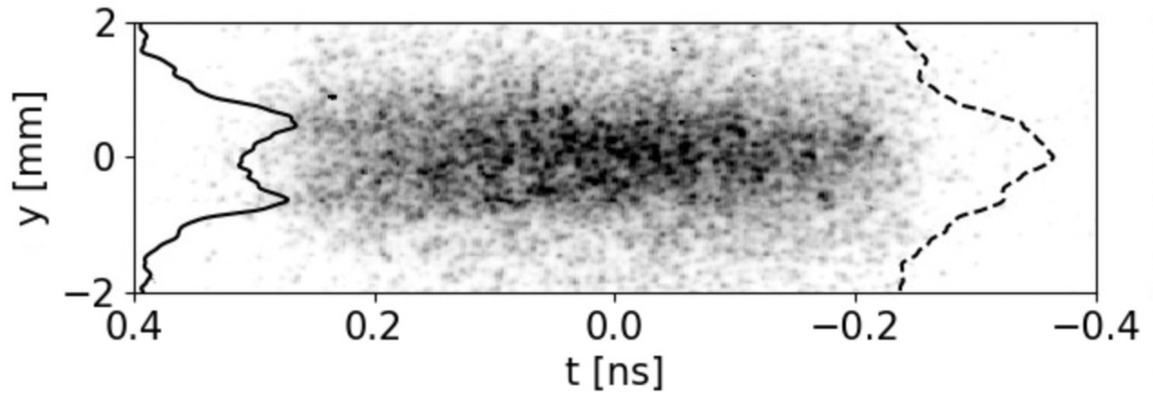
indication of filaments towards the back of the bunch
caveat: 1) screen far away from plasma exit
2) streak camera captures only the central slice

Plasma ON – n_{pe} = 9.38e14/cc → $\sigma_r/(c/\omega_{pe})$ = 3.2 at plasma entrance



clear filaments!

- Wide, long, relativistic proton bunch undergoes CFI
- Distribution of filaments changes from event to event
- Size of filaments $\sim \delta$
- No filaments at $r > \sigma_r$ → bunch density and growth rate too low



indication of filaments towards the back of the bunch
caveat: 1) screen far away from plasma exit
2) streak camera captures only the central slice

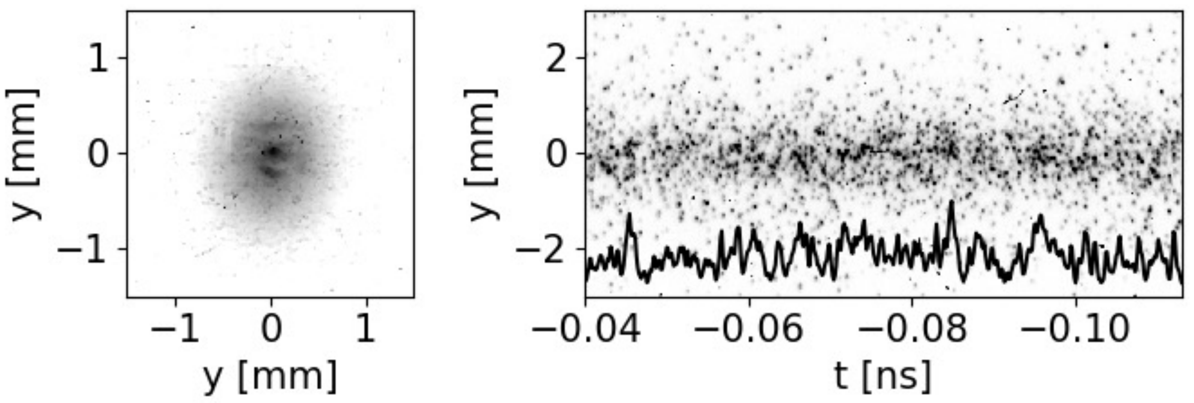
- Evolution along the bunch (convective instability)
- Moderate growth rate → early stage of CFI

Plasma ON – n_{pe} = 2.25e14/cc → $\sigma_r/(c/\omega_{pe})$ = 1.5 at plasma entrance

At the threshold, the system alternates between:

- multiple filaments (CFI)
  → no self-modulation instability

[already shown in L. Verra et al. (AWAKE Coll.), Phys. Plasmas 30, 083104 (2023)]



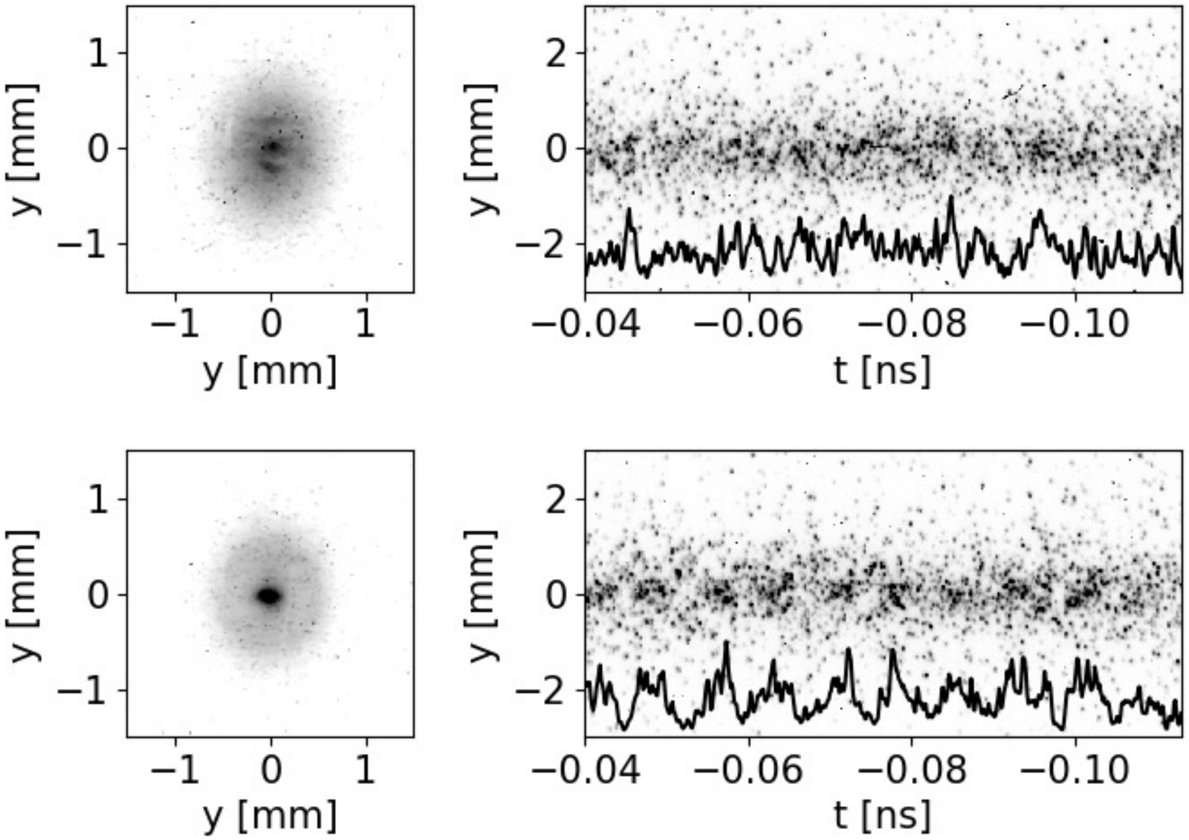
Plasma ON – n_{pe} = 2.25e14/cc → $\sigma_r/(c/\omega_{pe})$ = 1.5 at plasma entrance

At the threshold, the system alternates between:

- multiple filaments (CFI)
  → no self-modulation instability

[already shown in L. Verra et al. (AWAKE Coll.), Phys. Plasmas 30, 083104 (2023)]

- focusing to single "filament"
  → self-modulation instability



(For lower n_{pe}, the bunch undergoes SMI)

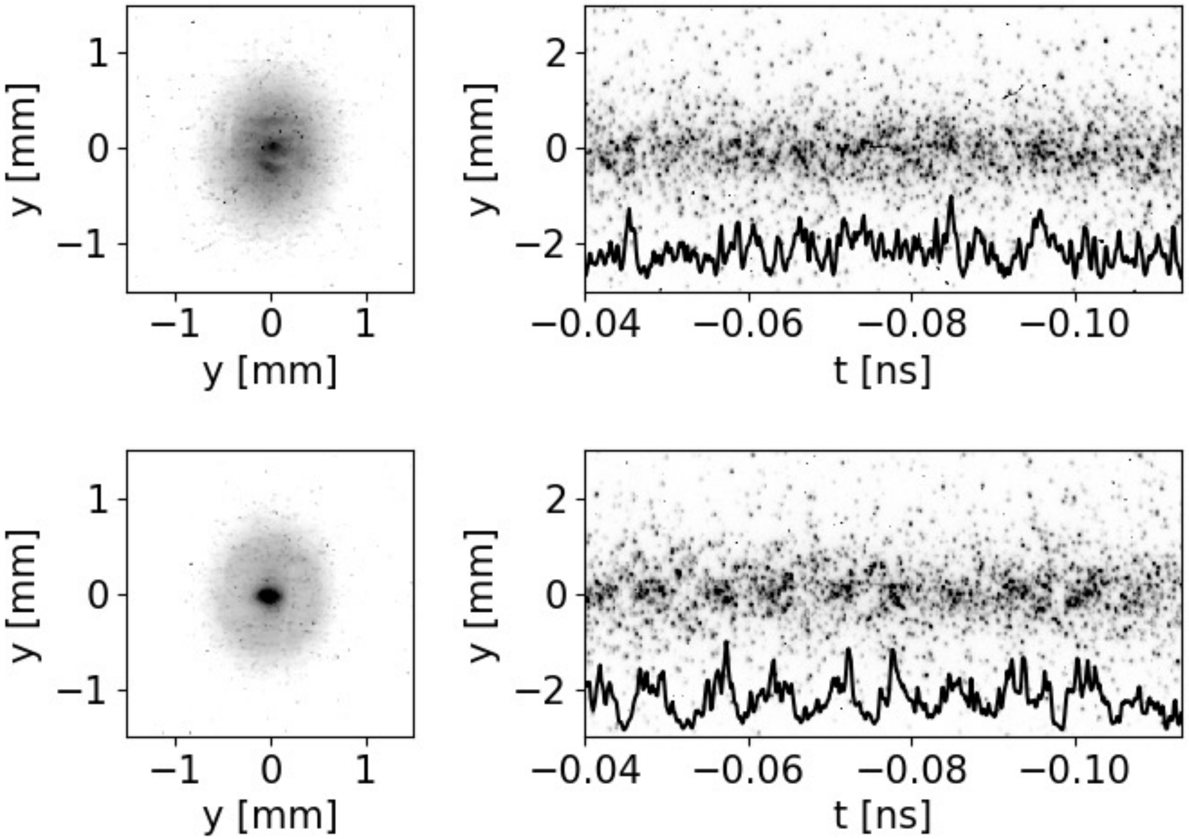
Plasma ON – n_{pe} = 2.25e14/cc → $\sigma_r/(c/\omega_{pe}) = 1.5$ at plasma entrance

At the threshold, the system alternates between:

- multiple filaments (CFI)
  → no self-modulation instability

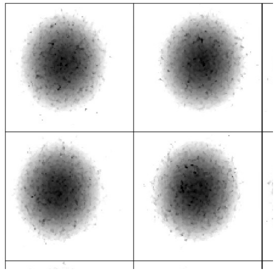
[already shown in L. Verra et al. (AWAKE Coll.), Phys. Plasmas 30, 083104 (2023)]

- focusing to single "filament"
  → self-modulation instability



(For lower n_{pe}, the bunch undergoes SMI)

Reminder: no observable differences in the incoming bunch distribution



Magnetic field generation

- Plasma return current overall compensates for the bunch current and magnetic field
- CFI → non-zero fields at scales ~ skin depth

- <u>We calculate return current to compute magnetic fields</u>

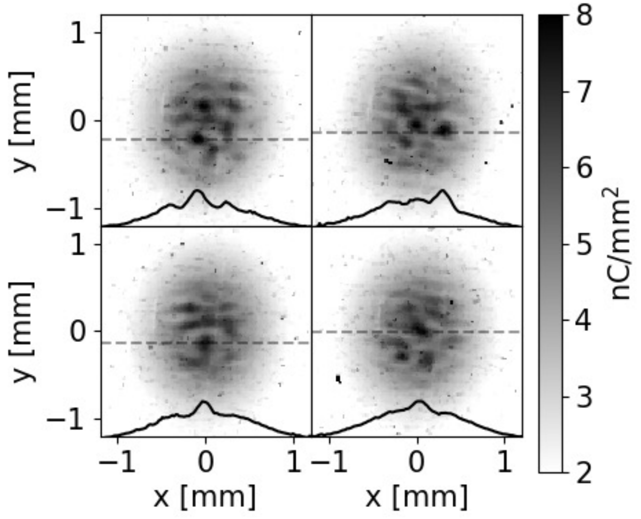
Magnetic field generation

- Plasma return current overall compensates for the bunch current and magnetic field
- CFI → non-zero fields at scales ~ skin depth

- <u>We calculate return current to compute magnetic fields</u>

- Early stage of CFI → Filaments are confined within the Gaussian distribution

Bunch Charge Density Profile



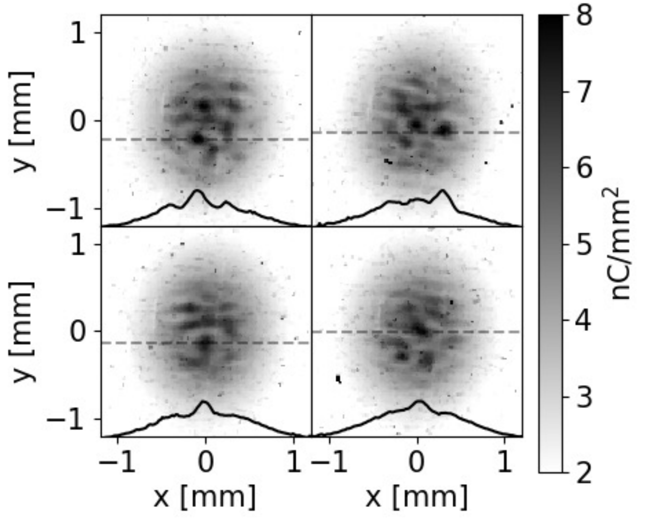
Magnetic field generation

- Plasma return current overall compensates for the bunch current and magnetic field
- CFI → non-zero fields at scales ~ skin depth

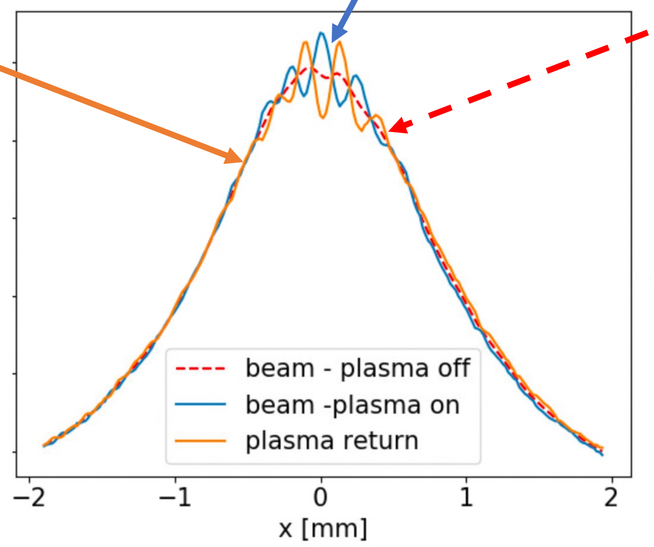
- <u>We calculate return current to compute magnetic fields</u>

- Early stage of CFI → Filaments are confined within the Gaussian distribution
- Return current obtained as the "complementary" of the bunch current with respect to the <u>smooth Gaussian distribution</u>

Bunch Charge Density Profile



Horizontal projections



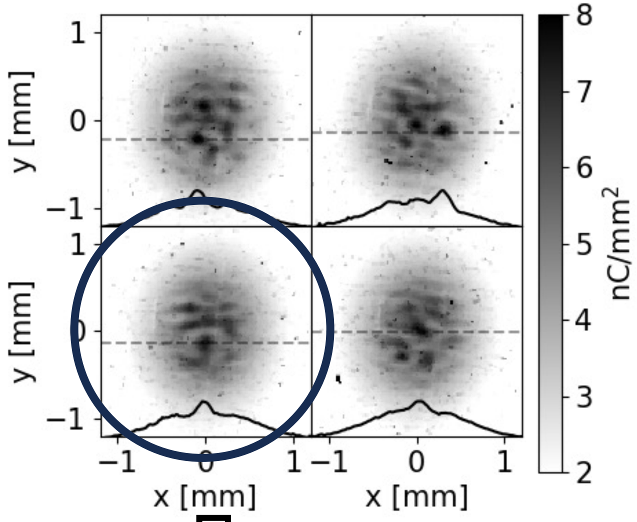
Magnetic field generation

- Plasma return current overall compensates for the bunch current and magnetic field
- CFI → non-zero fields at scales ~ skin depth

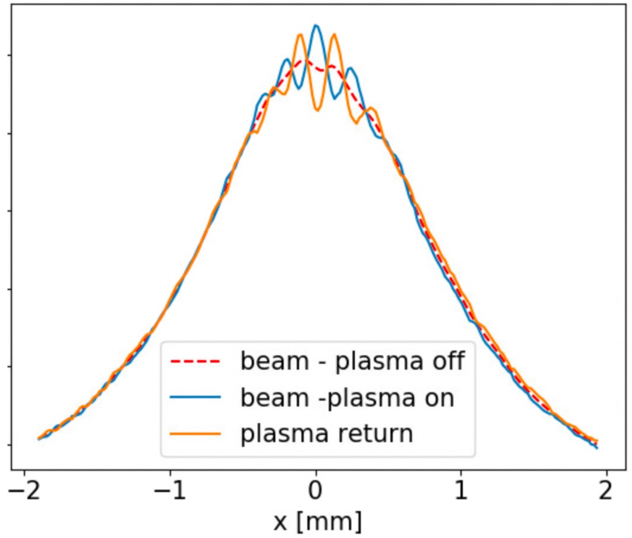
- **We calculate return current to compute magnetic fields**

- Early stage of CFI → Filaments are confined within the Gaussian distribution
- Return current obtained as the "complementary" of the bunch current with respect to the smooth Gaussian distribution

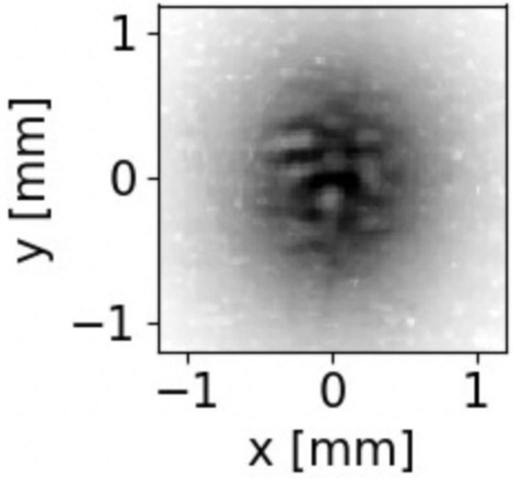
Bunch Charge Density Profile



Horizontal projections



Plasma Return Current

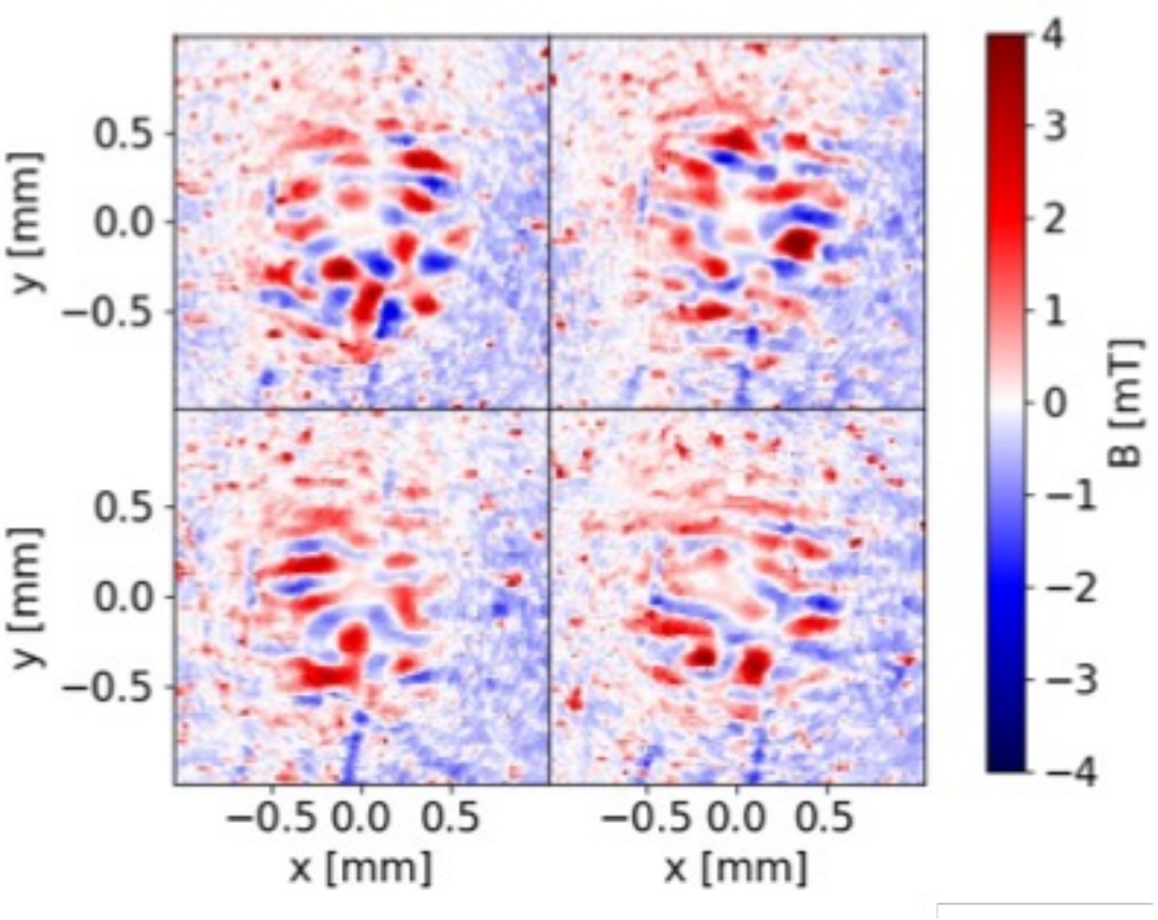


Magnetic field generation

- 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

Magnetic field generation

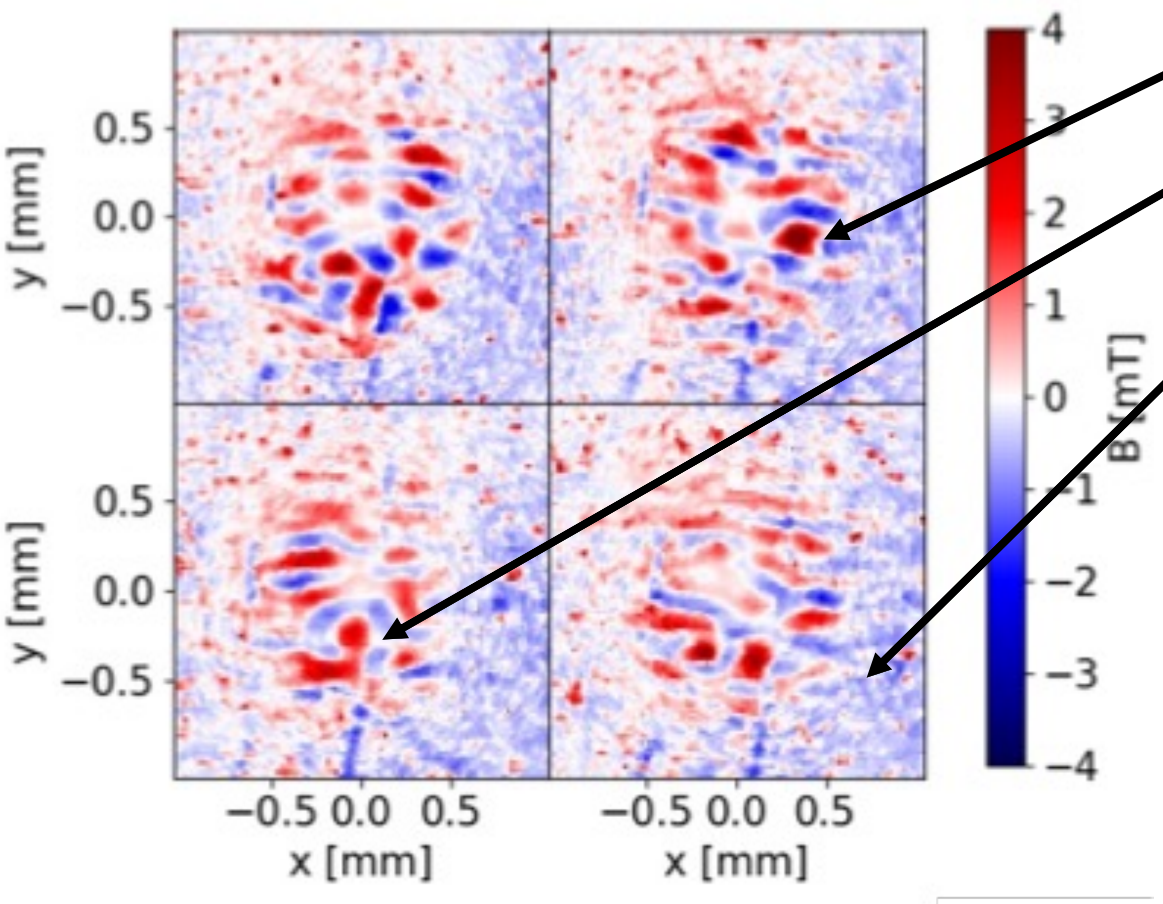
- We calculate the transverse magnetic field generated by each current with Ampère's law
  → the sum of the two contributions provides the overall magnetic field



(note: $B_{max,\ bunch}$ ~ 40 mT, I_{bunch} ~50 A)

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

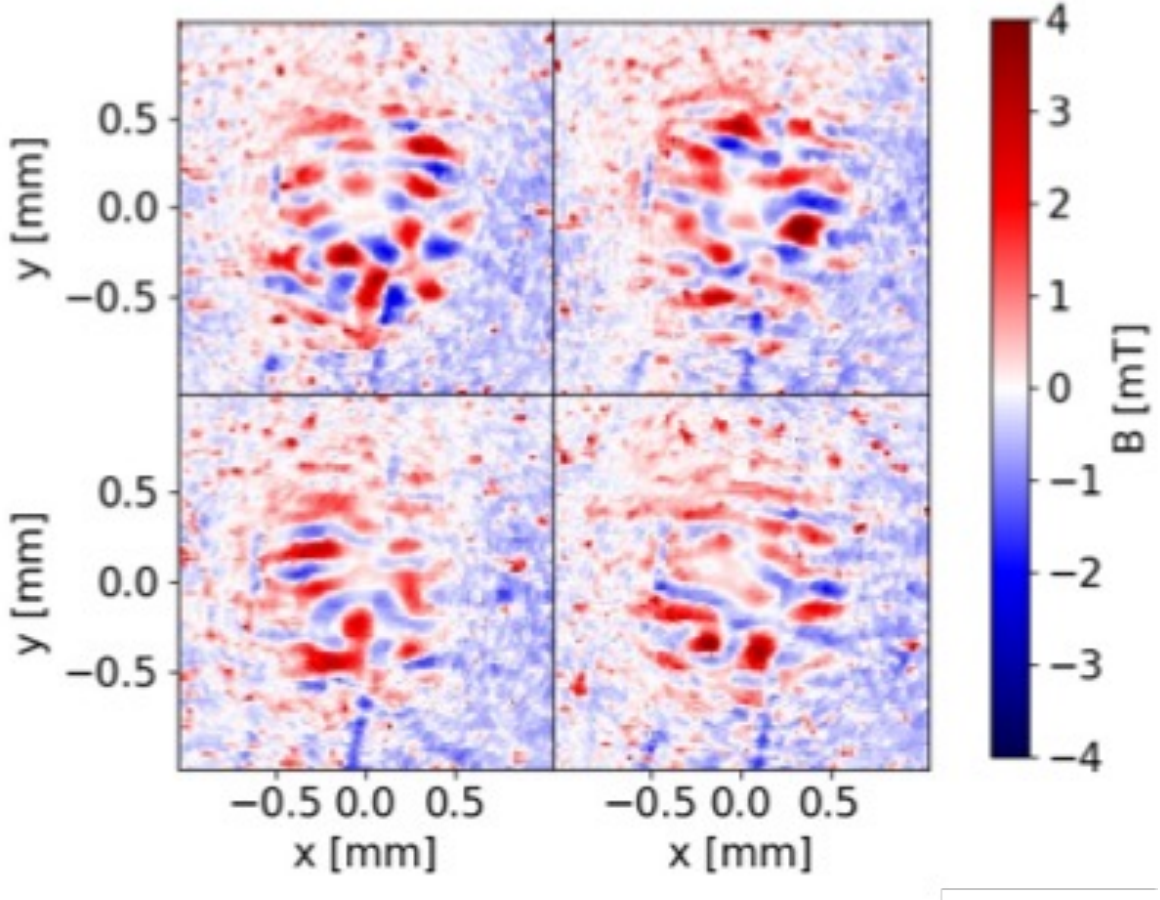


- non-zero magnetic field, confined within filaments
- sign reverses in between filaments (where the return current flow)
- on average zero outside of the bunch

(note: $B_{max,\ bunch}$ ~ 40 mT, I_{bunch} ~50 A)

Magnetic field generation

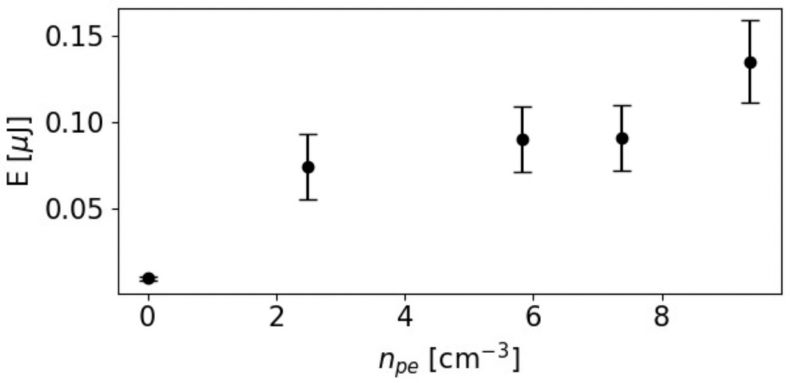
- We calculate the transverse magnetic field generated by each current with Ampère's law
  → the sum of the two contributions provides the overall magnetic field



Magnetic energy within the bunch:

$$E = \int dV \frac{< B^2 >}{2\mu_0}$$

V = bunch volume

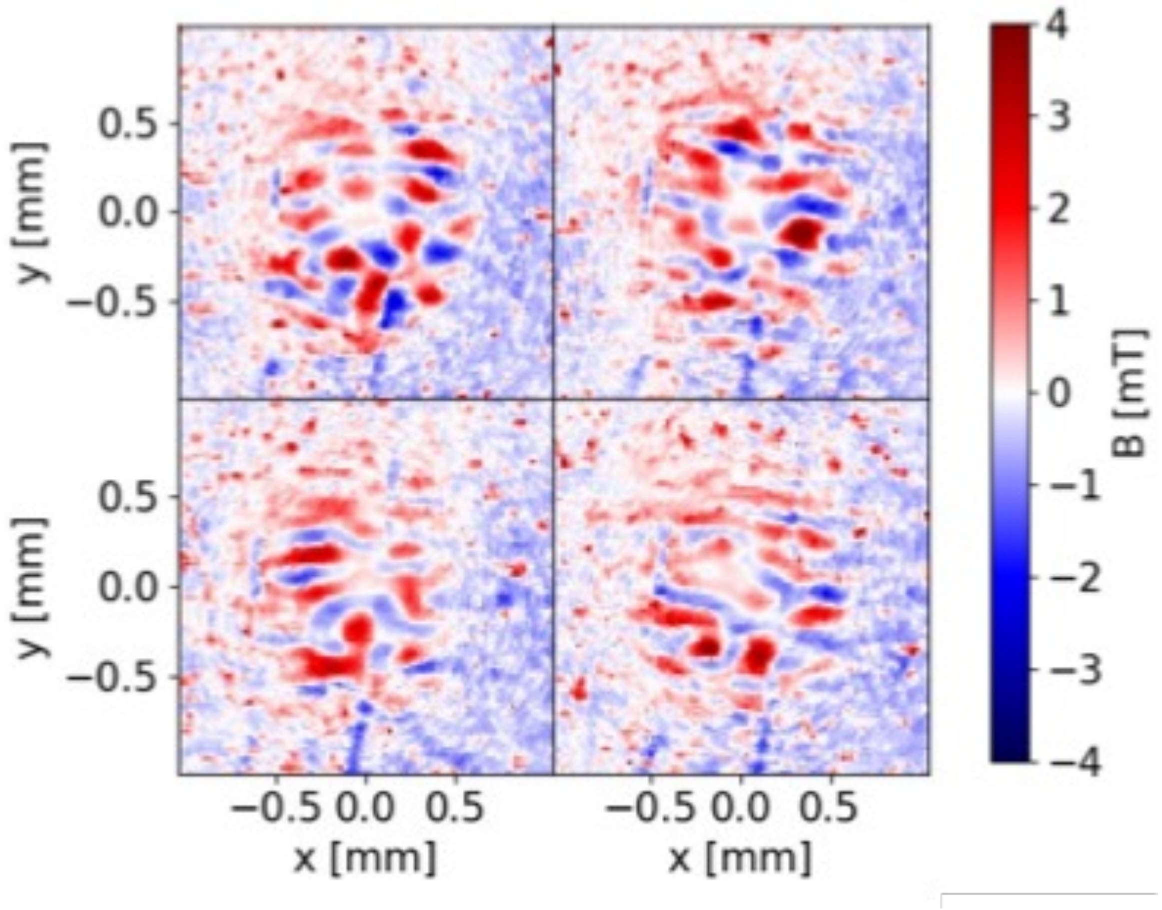


- Increase with n_{pe}
- Small amount of energy (bunch energy ~ 20 kJ):
  - → early stage of the instability
  - → moderate growth rate

(note: $B_{max,\ bunch}$ ~ 40 mT, I_{bunch} ~50 A)

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

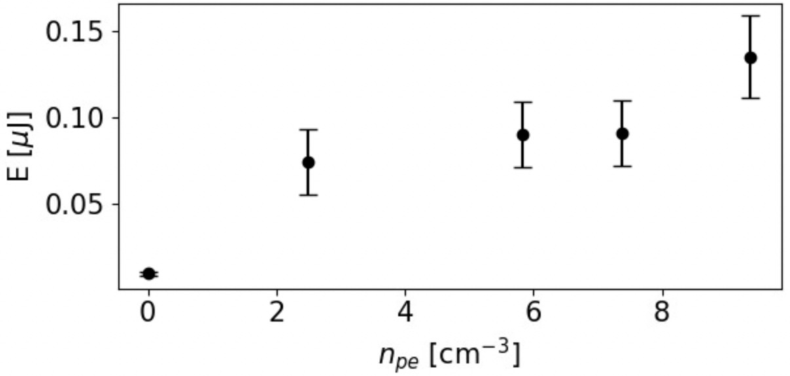


(note: $B_{max,\, bunch} \sim 40$ mT, $I_{bunch} \sim 50$ A)

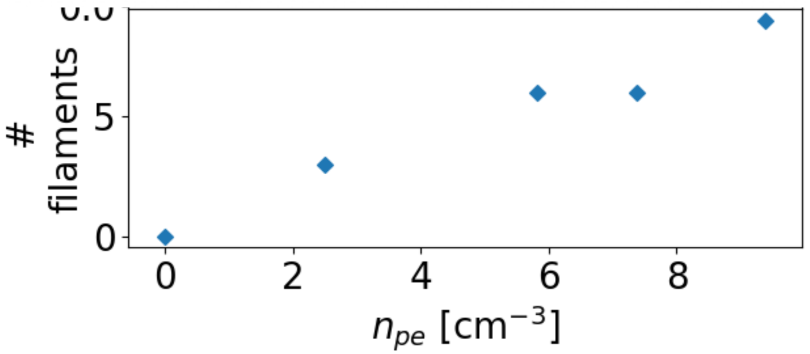
Magnetic energy within the bunch:

$$E = \int dV \frac{< B^2 >}{2\mu_0}$$

V = bunch volume



- Increase with n_{pe}
- Small amount of energy (bunch energy ~ 20 kJ):
  → early stage of the instability
  → moderate growth rate



- Energy correlated with the number of filaments within the bunch

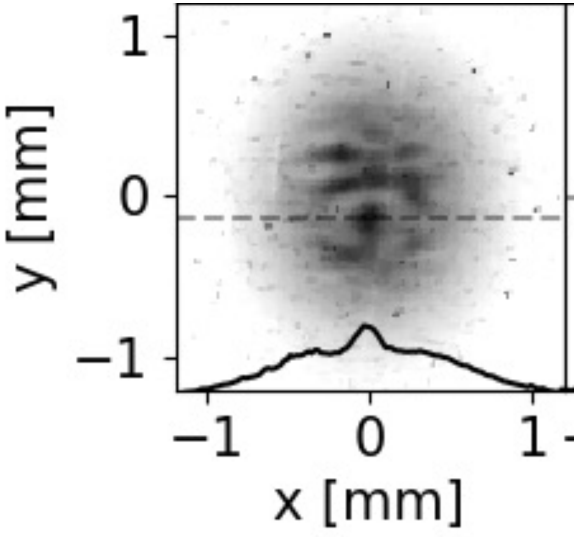
Conclusions

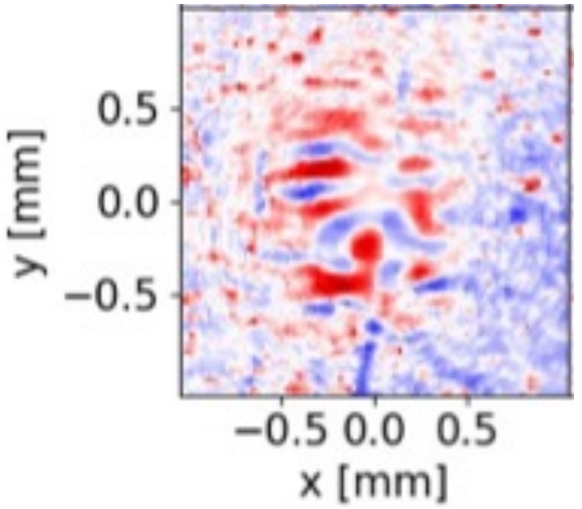
- We consistently observe CFI of long, relativistic proton bunch when $\frac{\sigma_r}{\delta} > 1.5$

- 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}

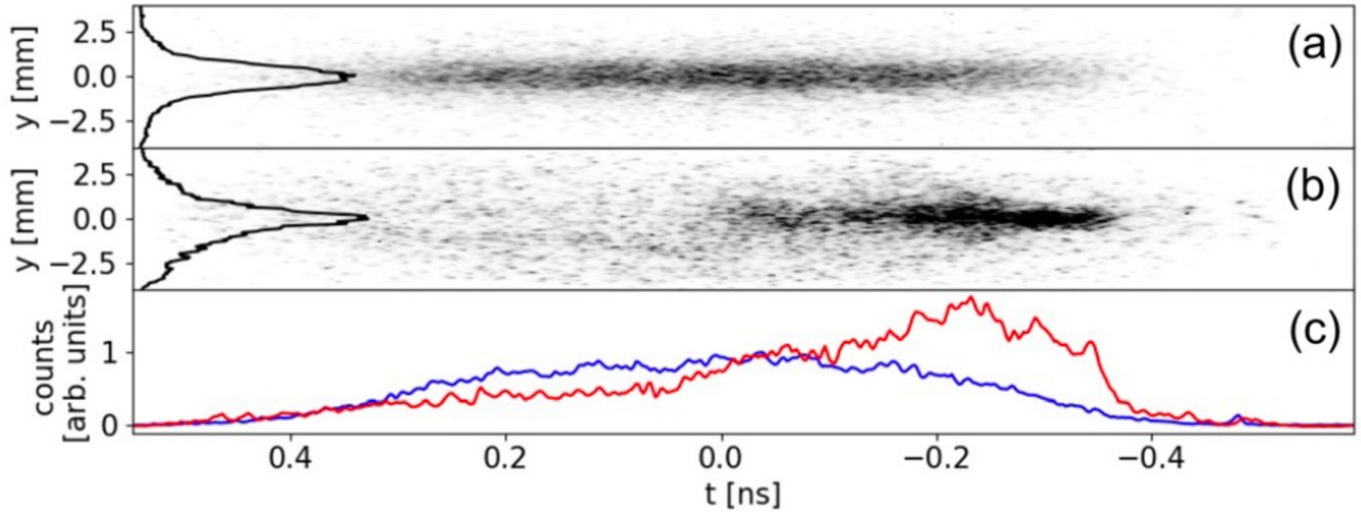
- Manuscript to circulate in the next days



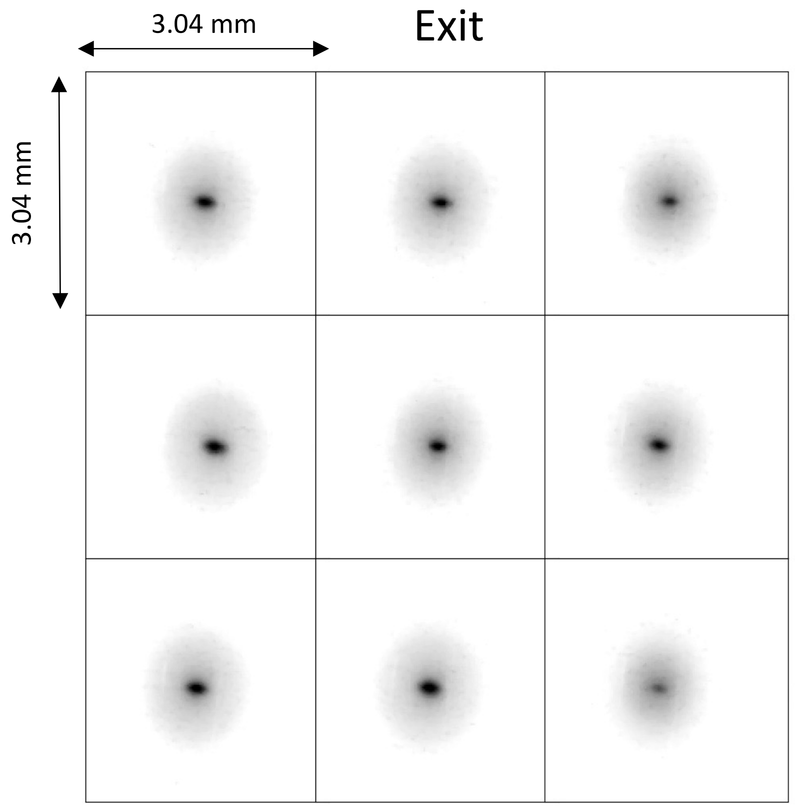


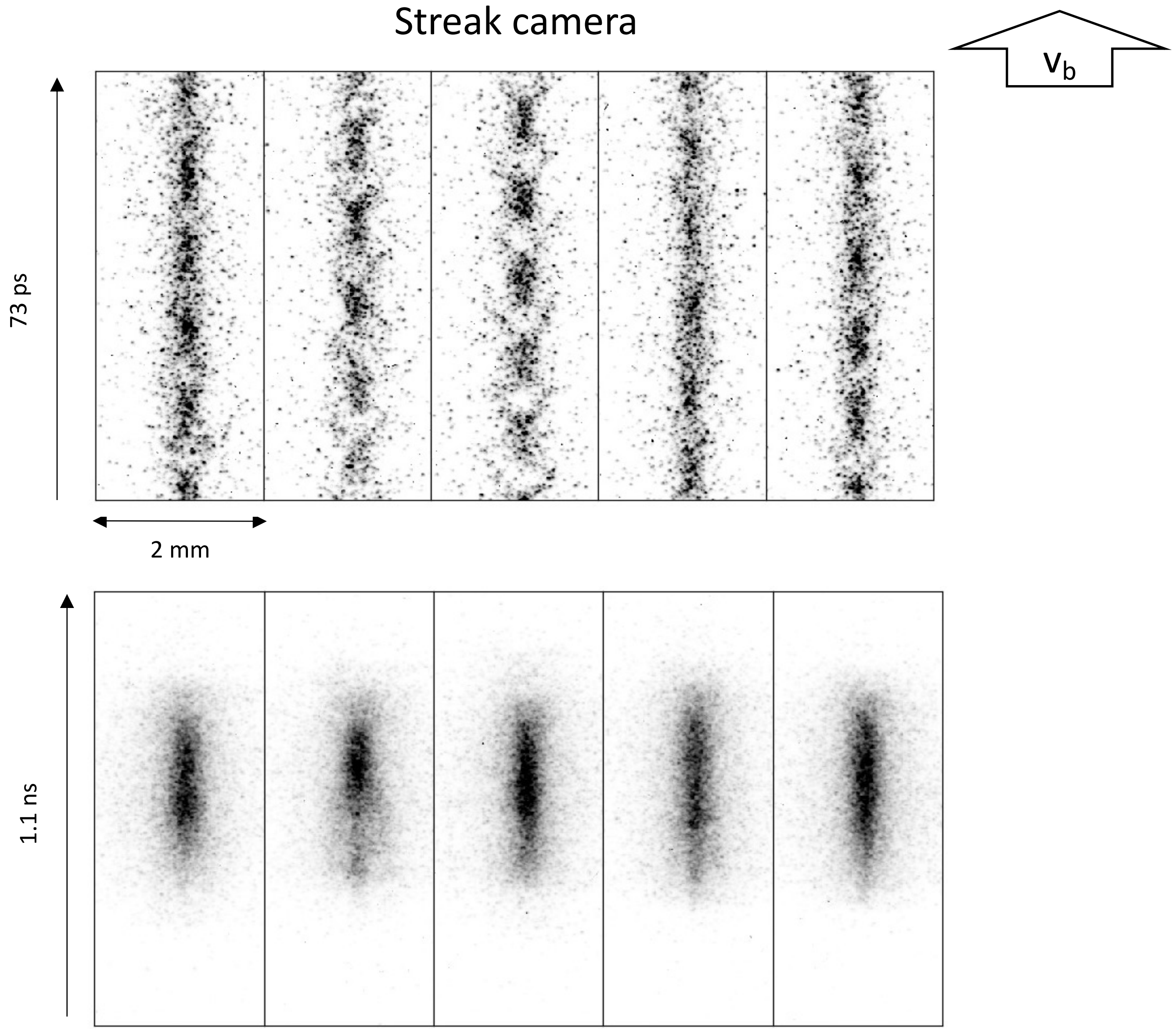
Thank you for your attention!

Backup slides


(a)
(b)
(c)
y [mm]
2.5
0.0
−2.5
counts
[arb. units]
1
0
0.4
0.2
0.0
−0.2
−0.4
t [ns]

Plasma ON – n_{pe} = 0.7e14/cc → $\sigma_r/(c/\omega_{pe})$ = 0.9 at plasma entrance





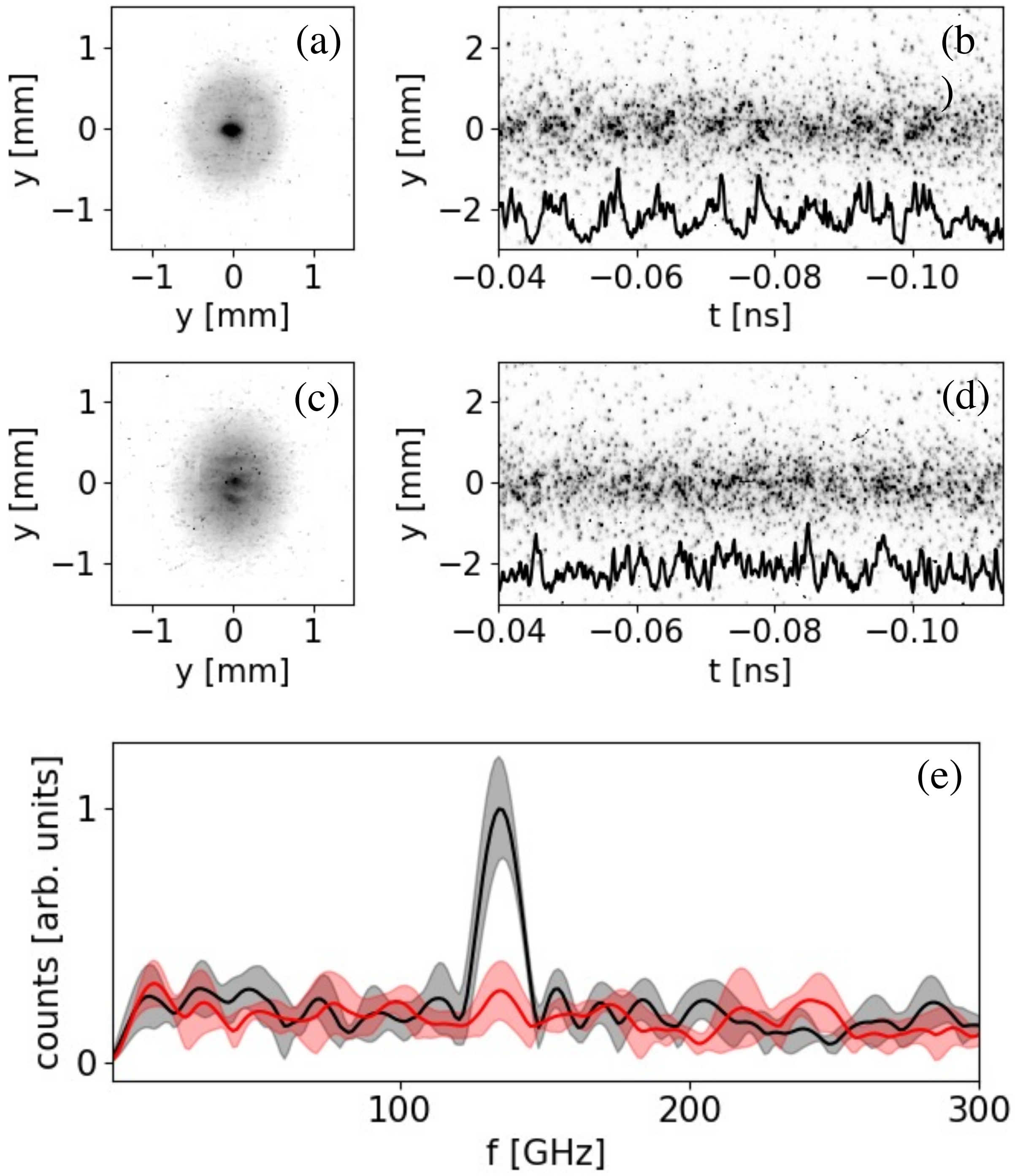
SMI on all events

→ bright core and halo on time-integrated images
→ microbunches on ps images
→ hints of growth on ns images

Oblique mode growth rate

$$\Gamma = \Gamma_e \sqrt{\frac{m_e}{m_p}} = \frac{\sqrt{3}}{2^{4/3}} (\frac{n_{b0}}{n_{pe}\gamma})^{1/3} \omega_{pe} \sqrt{\frac{m_e}{m_p}},$$

[3] A. Bret, L. Gremillet, and M. E. Dieckmann, Multidimensional electron beam-plasma instabilities in the relativistic regime, Physics of Plasmas **17**, 120501 (2010), https://pubs.aip.org/aip/pop/article-pdf/doi/10.1063/1.3514586/16019035/120501_1_online.pdf.



Screen at plasma exit

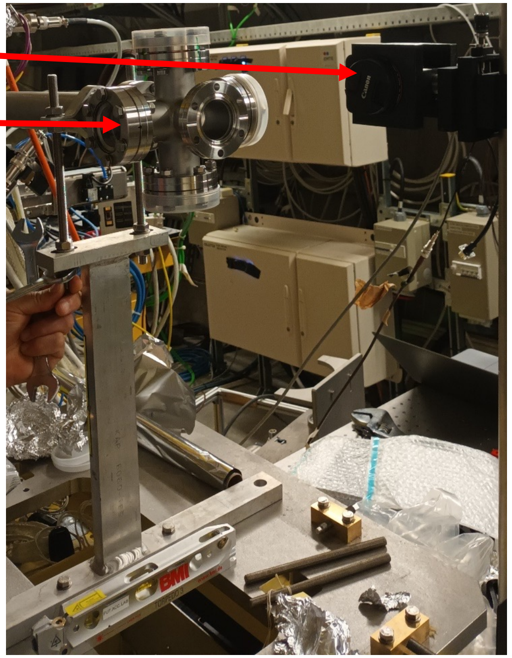
Filaments have small size, large emittance
→ large divergence when leaving the plasma

→ We installed an OTR screen as close as possible to plasma exit (not possible with vapor source because of laser pulse)

camera

screen

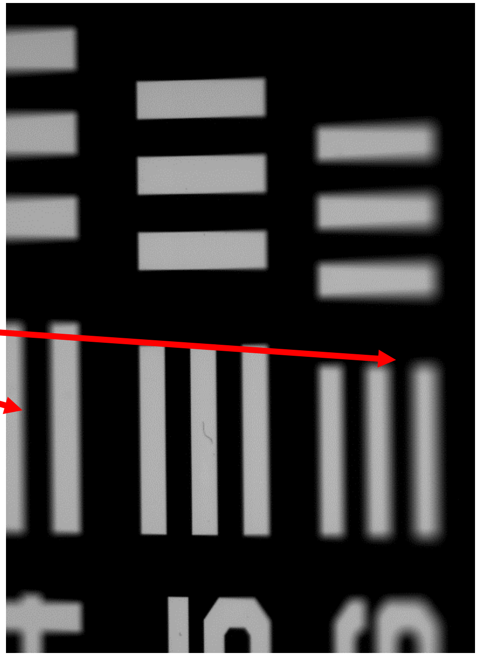
DPS

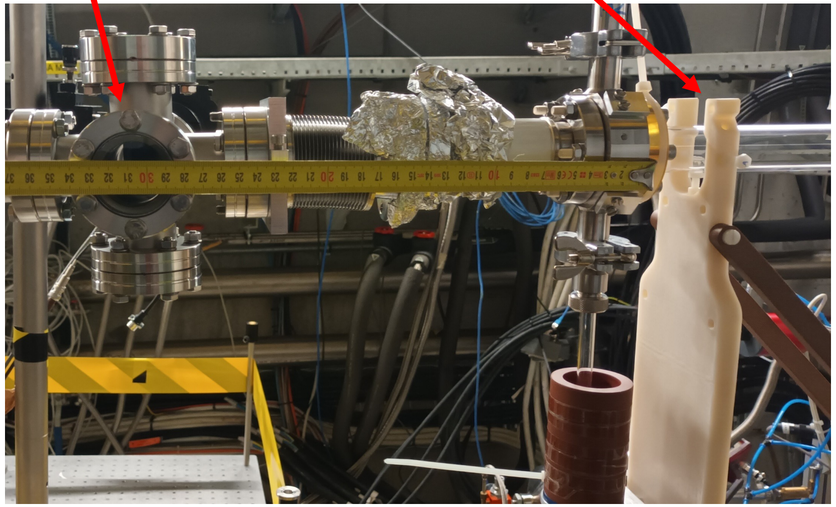


Screen –camera distance: 50 cm
M = 3.2

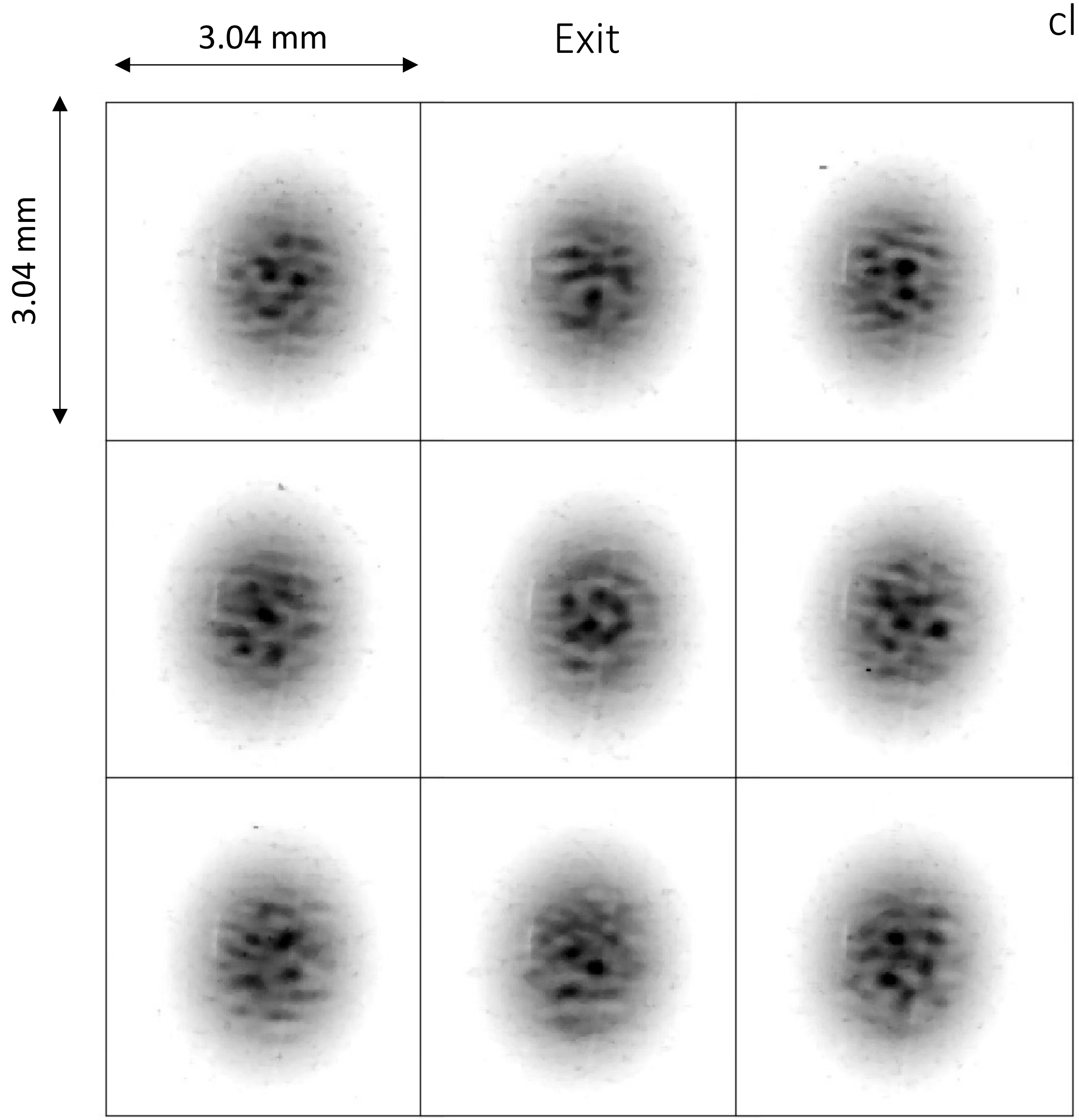
50% MTF at = 0.027 mm

depth of field ~1.5 mm



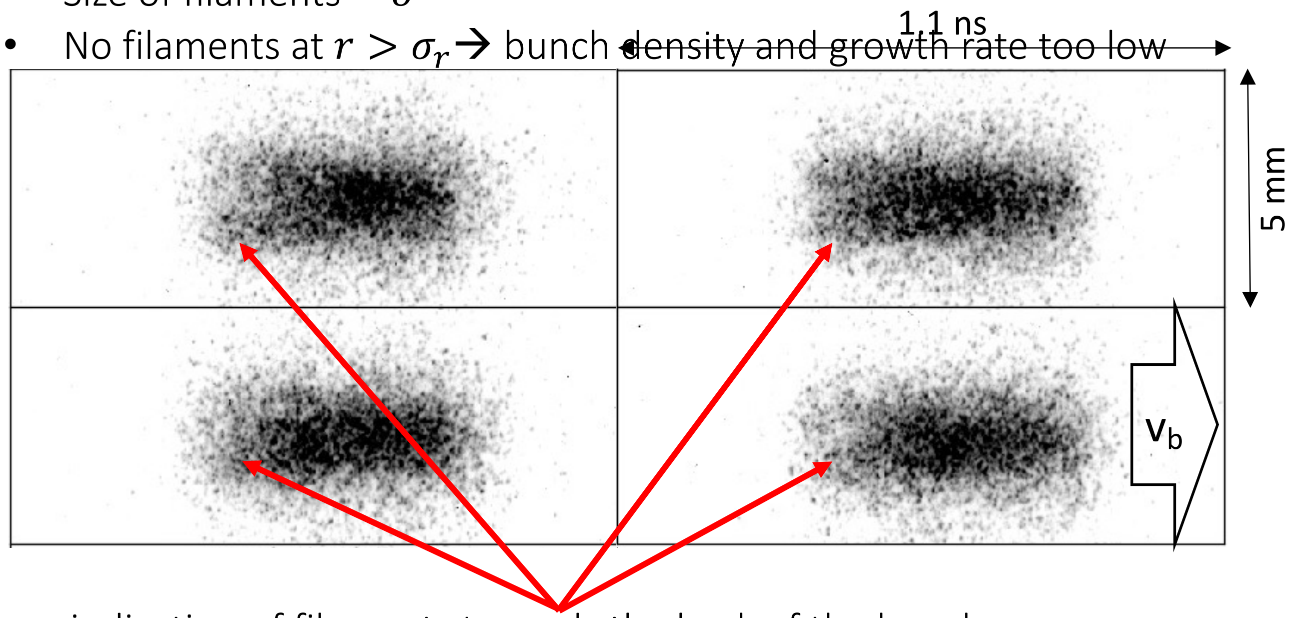


Plasma ON – n_{pe} = 9.38e14/cc → $\sigma_r/(c/\omega_{pe})$ = 3.2 at plasma entrance



clear filaments!

- Wide, long, relativistic proton bunch undergoes CFI
- Distribution of filaments changes from event to event
- Size of filaments $\sim \delta$
- No filaments at $r > \sigma_r$ → bunch density and growth rate too low



indication of filaments towards the back of the bunch
caveat: 1) screen far away from plasma exit
2) streak camera captures only the central slice

- Evolution along the bunch (convective instability)
- Moderate growth rate → early stage of CFI