Filamentation 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)

AAC 2024– WG3

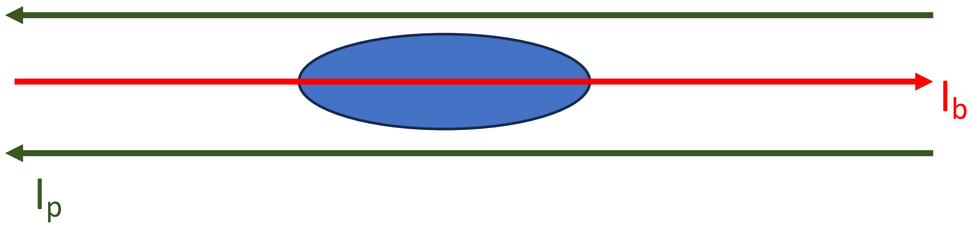
22.07.2024

livio.verra@lnf.infn.it

Current Filamentation Instability (CFI)

Plasma preserves **current** neutrality

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



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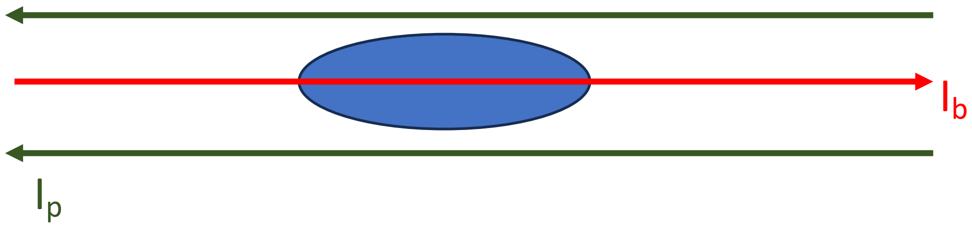
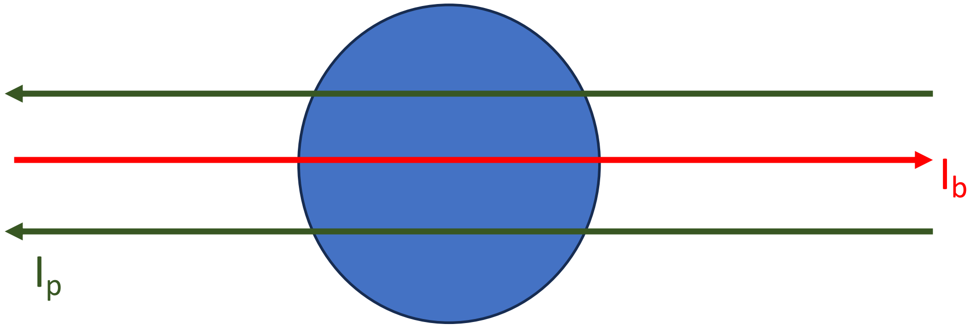


When the bunch is wider than the plasma skin depth $\delta = \frac{c}{\omega_{pe}}$

→ the return current flows within the bunch



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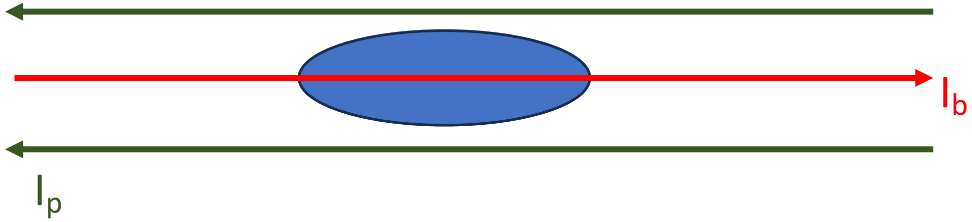

- Currents generate magnetic fields
- Opposite currents repel each other
- Perturbation or anisotropy in the transverse distribution causes unbalanced B field
  → instability
  → growth of current filaments → self-pinching
  → growth of B-field and magnetic energy

- **Transverse modulation → Wavenumber** $\overrightarrow{\boldsymbol{k}_{\perp}} \perp \overrightarrow{\boldsymbol{v}_{\boldsymbol{b}}}$

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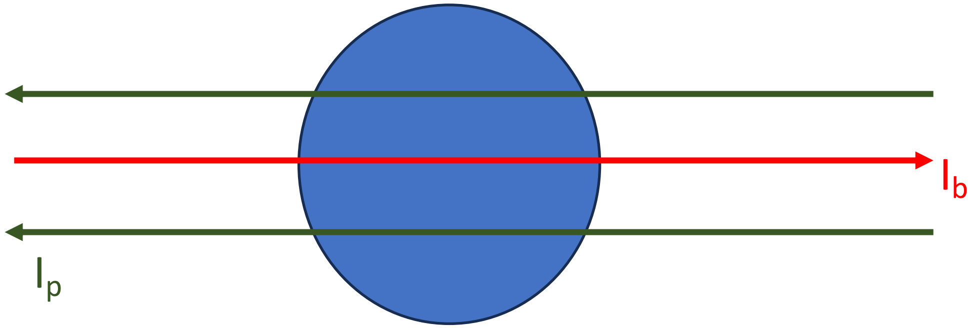
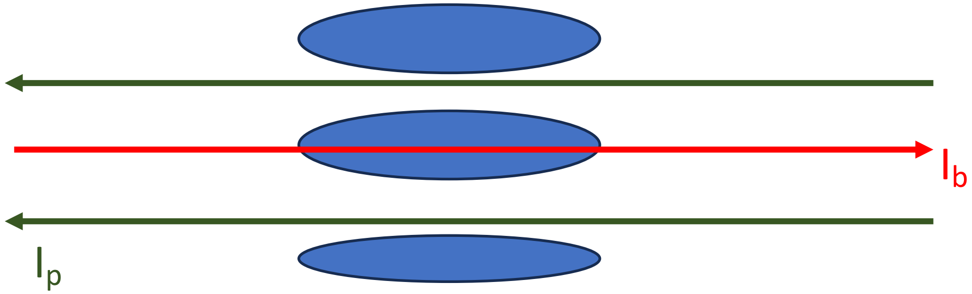


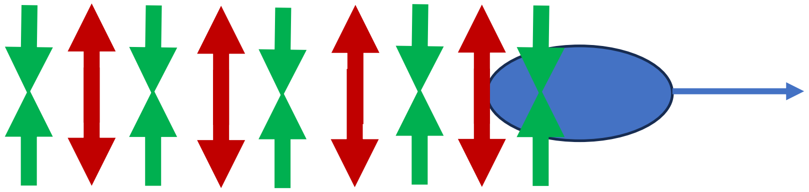


Roswell Lee and Martin Lampe, Phys. Rev. Lett. 31, 1390 (1973)

Transverse Two-Stream Instability (TTSI)

Plasma preserves **charge** neutrality

→ Bunch drives plasma wakefields



N. Kumar et al., Phys. Rev. Lett. **104**, 255003 (2010)

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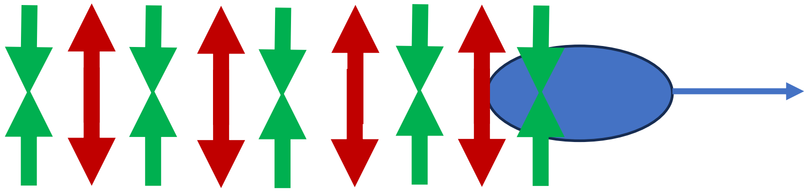
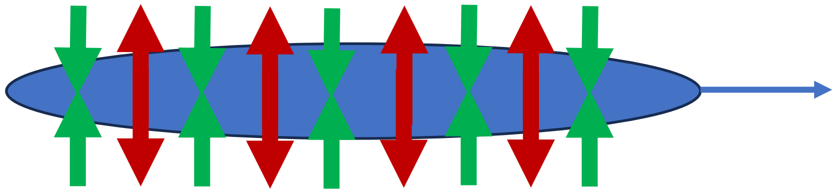


If the bunch is longer than the plasma skin depth $\delta = \frac{c}{\omega_{pe}}$

→ the transverse wakefields act back on the bunch



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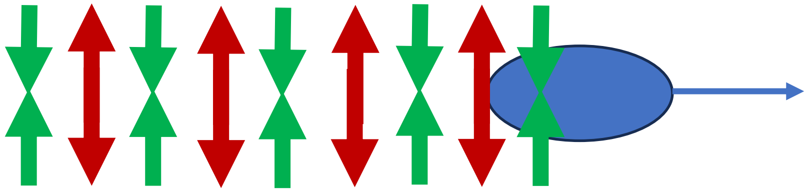

- Periodic focusing/defocusing fields
- Radial bunch and plasma density modulation
- Stronger wakefields
  → instability
  → microbunch train
  → growth of wakefields amplitude

- **Longitudinal modulation → Wavenumber $\overrightarrow{k_\parallel} \parallel \overrightarrow{v_b}$**

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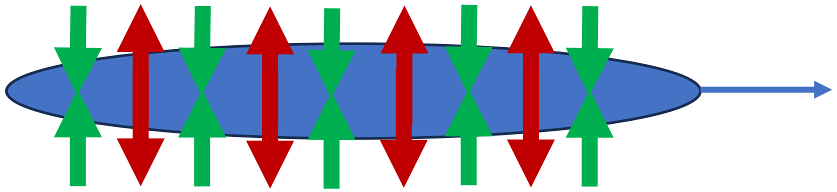
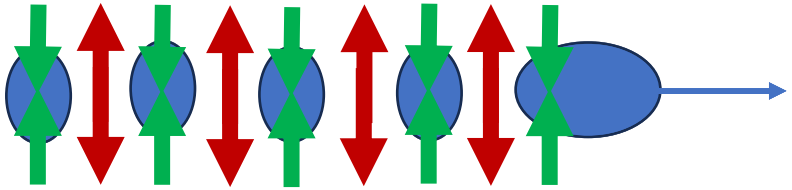




TTSI, also known as self-modulation instability (SMI)
→ use for PWFA (AWAKE)

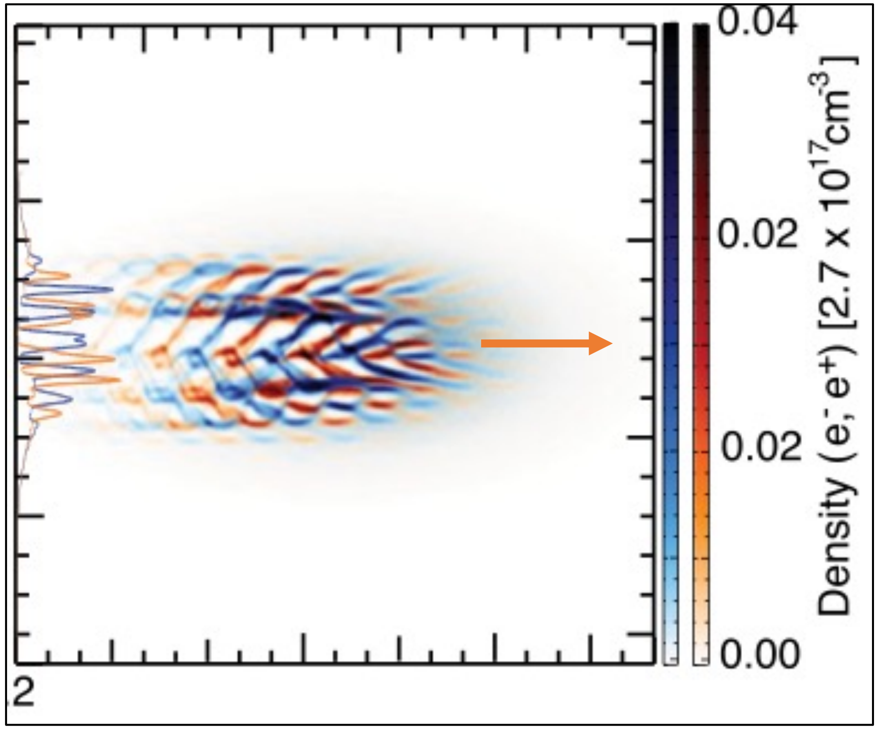
N. Kumar et al., Phys. Rev. Lett. **104**, 255003 (2010)

Oblique Two-Stream Instability (OTSI)

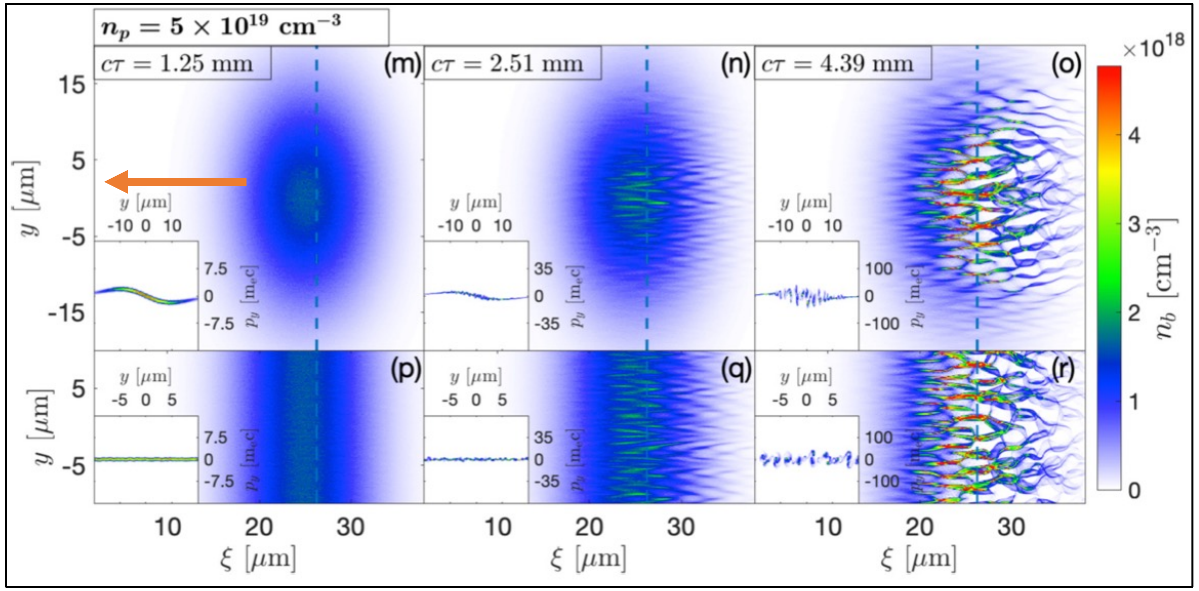
For long, wide, underdense, relativistic bunches:
instability with oblique wavenumber: $\vec{\boldsymbol{k}} = \overrightarrow{\boldsymbol{k}_\perp} + \overrightarrow{\boldsymbol{k}_\parallel}$

OTSI *can be seen as* a superposition of CFI and SMI
→ finite-length, tilted filaments

⟶ Main observable: transverse modulation into filaments



N. Sukla et al., J. Plasma Phys. **84**, 90584302 (2018)



P. San Miguel Claveria et al. Phys. Rev. Research **4**, 023085 (2022)

Motivation for Experiments

1) Plasma Wakefield Acceleration

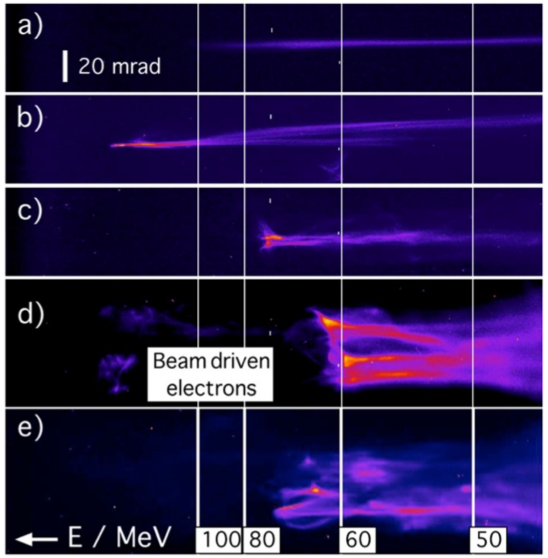
Filamentation (CFI or OTSI) splits driver and/or witness bunch in multiple filaments
→ structure of the wakefields is spoiled
→ no high-quality acceleration

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

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

→Possible deleterious effects in plasma mirrors?

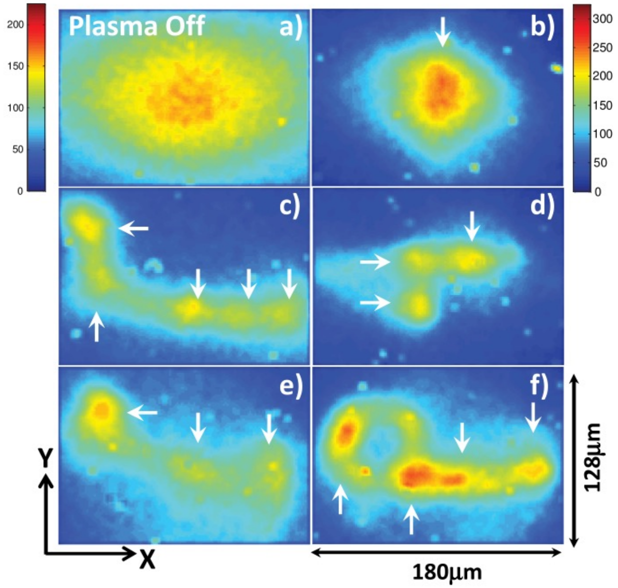
LWFA



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)

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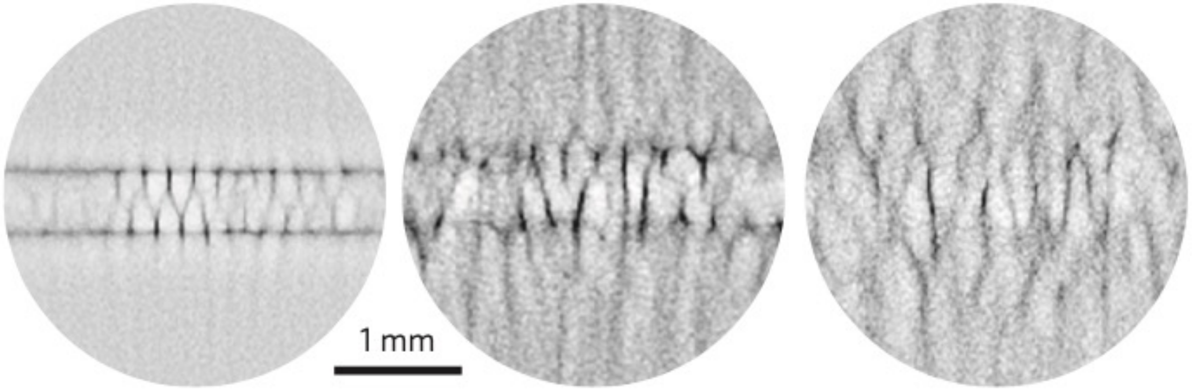
2) Laboratory Astrophysics

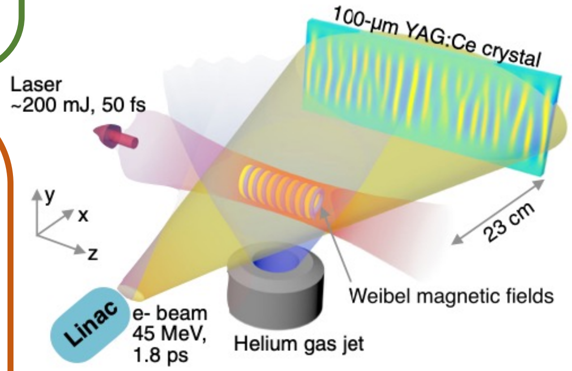
Filamentation generates and amplifies magnetic field
→ fraction of the bunch kinetic energy is converted into magnetic energy
Plausible candidate for:

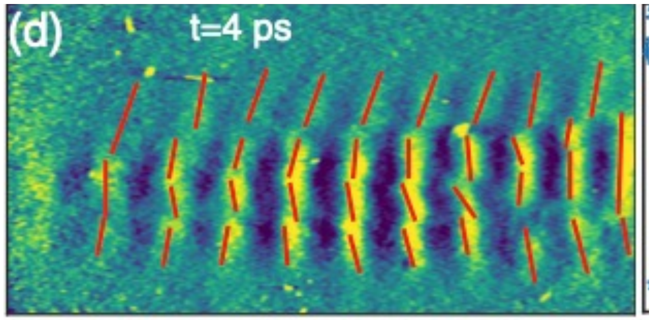
- magnetization of astrophysical media, magnetic fields enhancement, collisionless shocks

Synthetic proton radiographs from 14.7 MeV protons



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



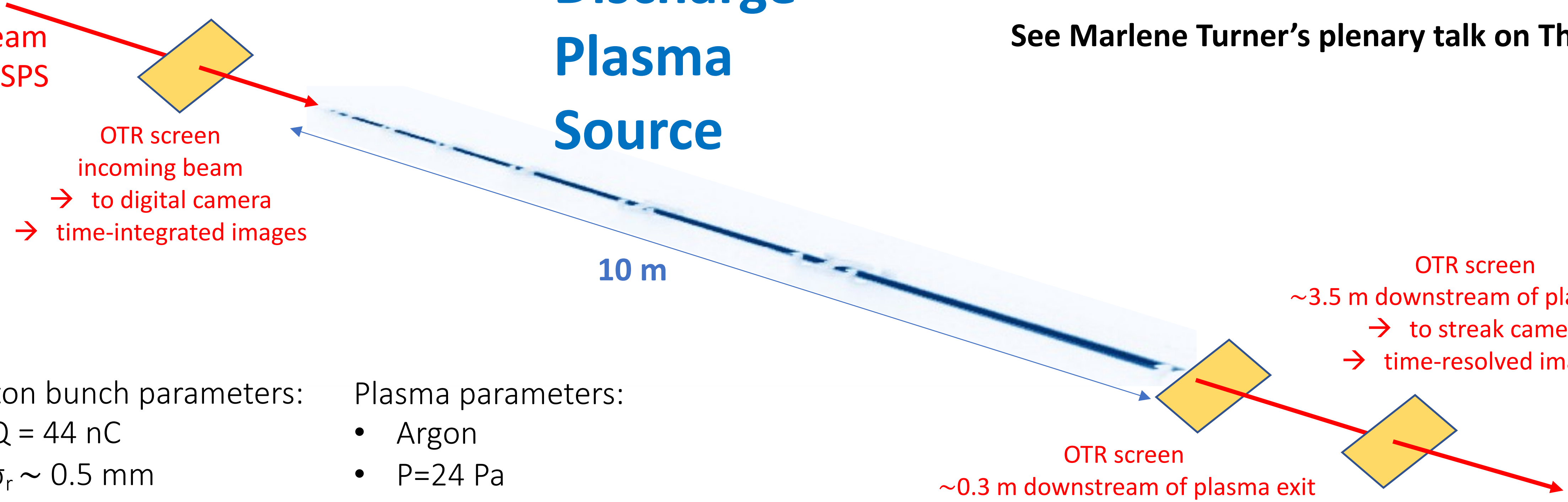


Chaojie Zhang et al., Phys. Rev. Lett. 125, 255001 (2020)

[J. Niemiec et al., The Astrophysical Journal **684**, 1174 (2008)]
[M. V. Medvedev et al.,The Astrophysical Journal **666**, 339 (2007)]
[M. V. Medvedev et al., Astrophys. Space Sci. **322**, 147–150 (2009)]
[M. V. Medvedev and A. Loeb, The Astrophysical Journal **526**, 697 (1999)]

Experimental Setup - AWAKE

See Marlene Turner's plenary talk on Thursday!



Proton bunch parameters:

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

Plasma parameters:

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

→we can vary the ratio initial size – skin depth

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

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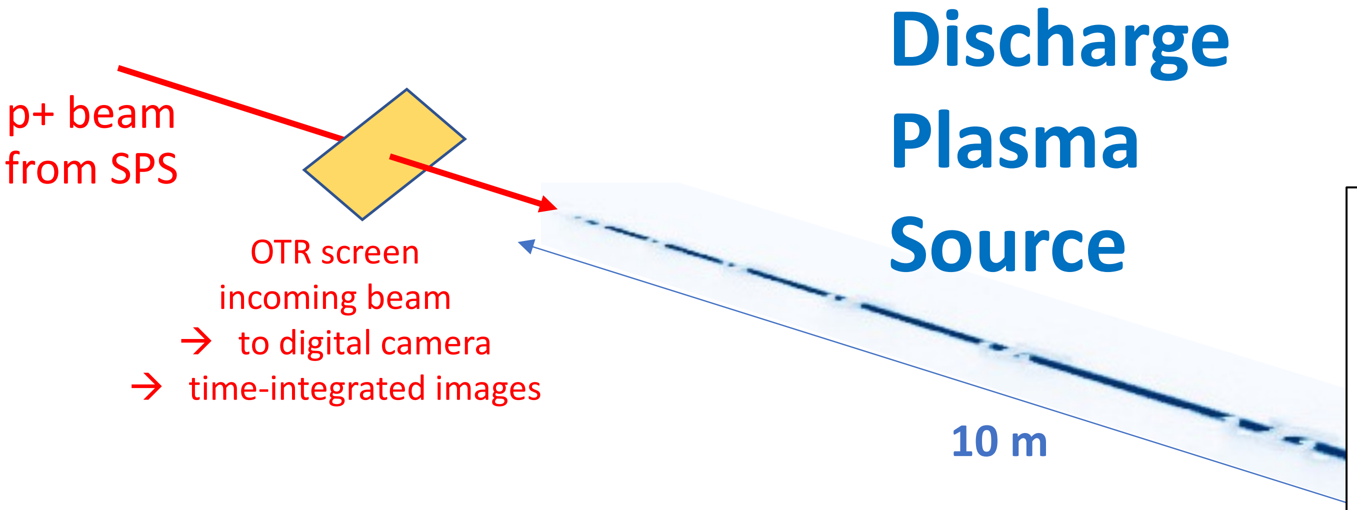
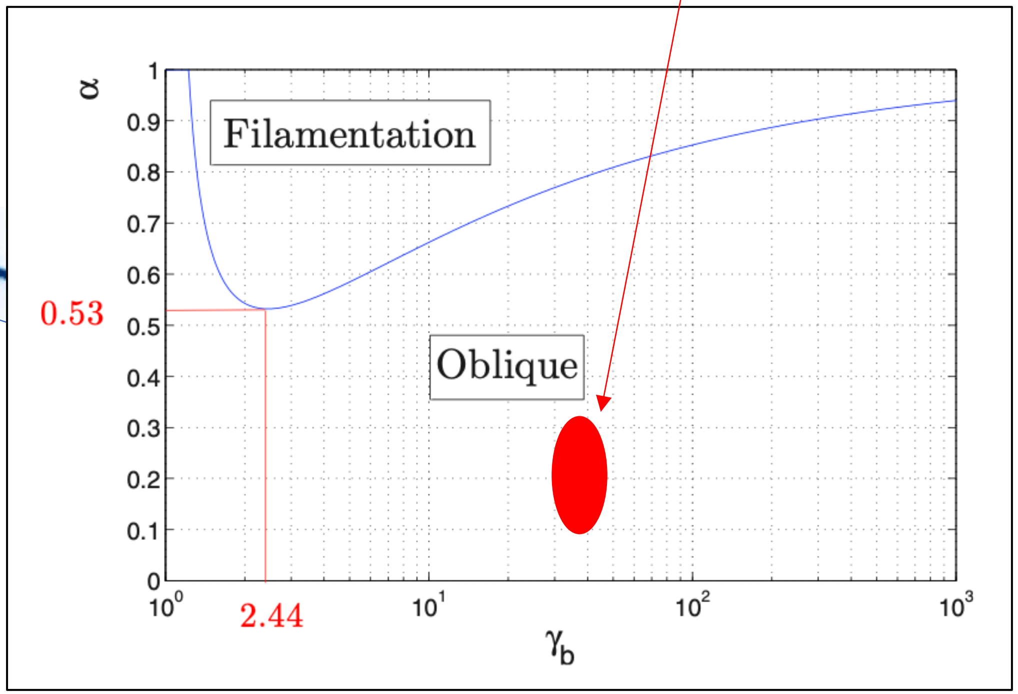


Parameters place the experiment in the OTSI regime



A. Bret, L. Gremillet, and M. E. Dieckmann, PoP **17**, 120501 (2010).

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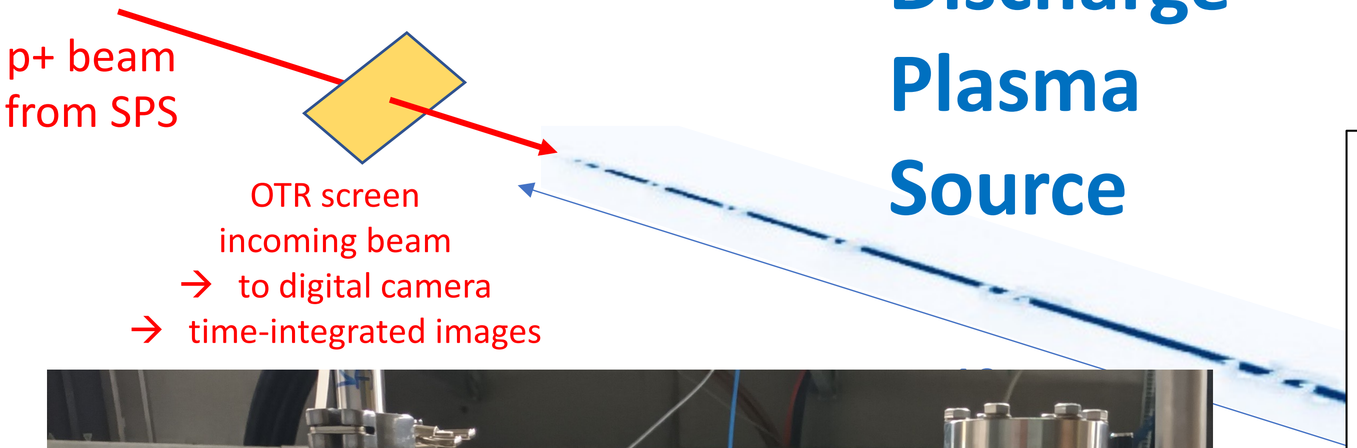
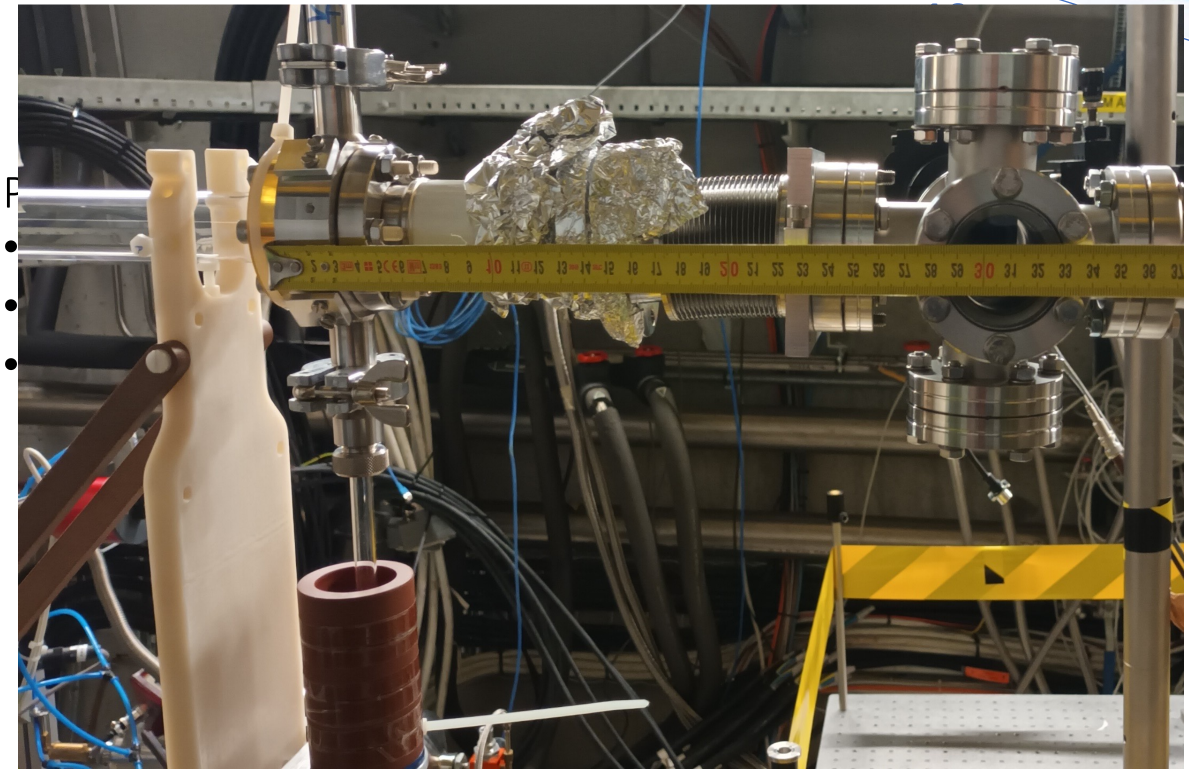
Discharge Plasma Source





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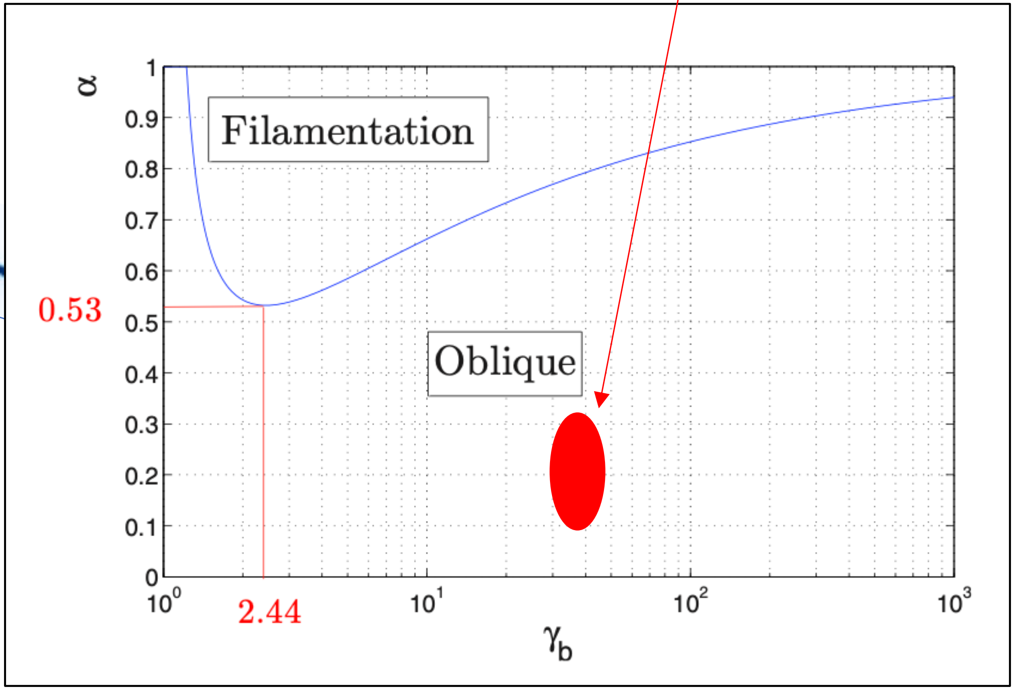

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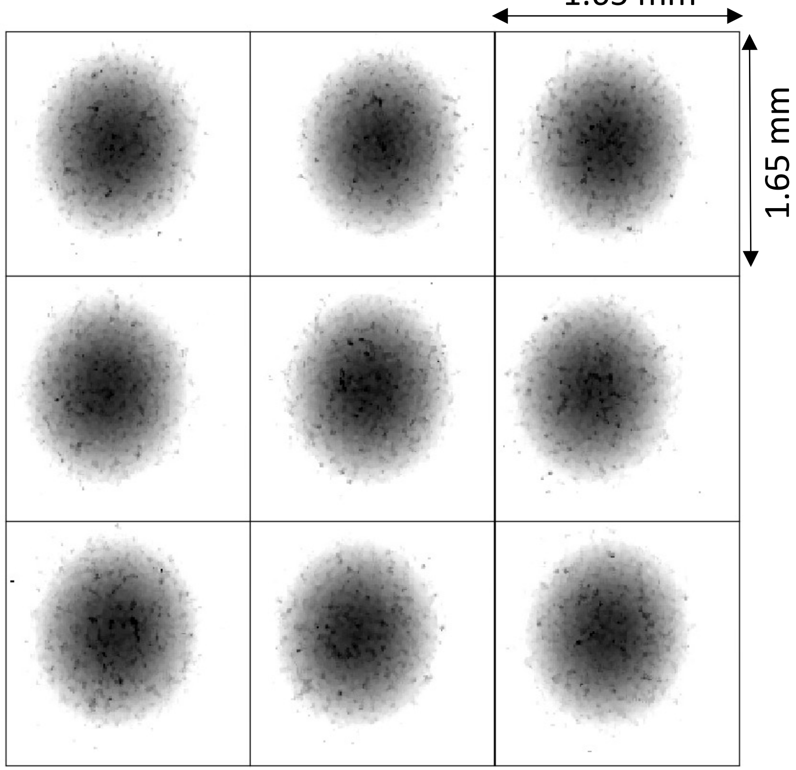
Expected filaments with small size, large emittance
→ large divergence when leaving the plasma
→ screen as close as possible to exit

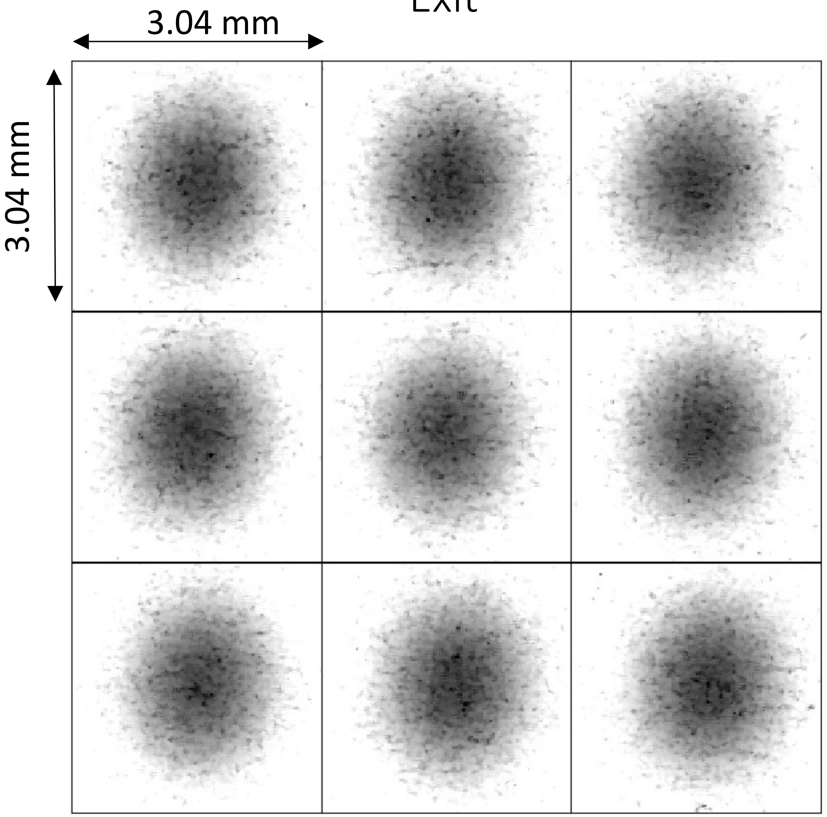
Plasma OFF – no gas

Entrance



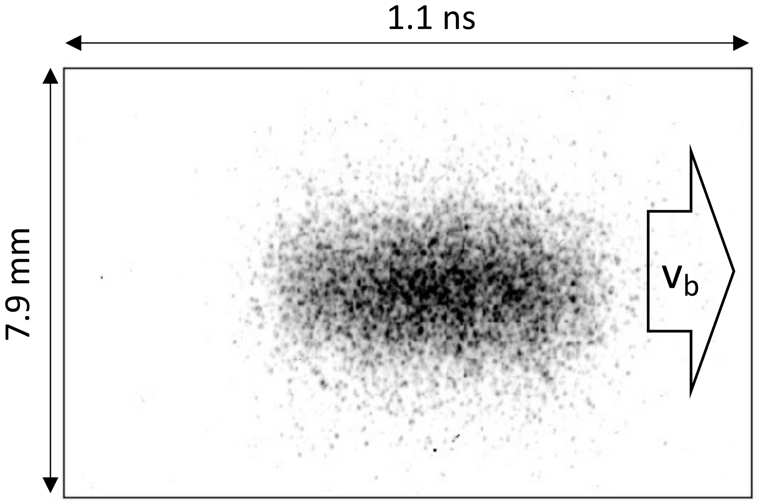
σ_x=0.48 mm
σ_y= 0.53 mm
} σ_{r0}=0.5 mm

Exit



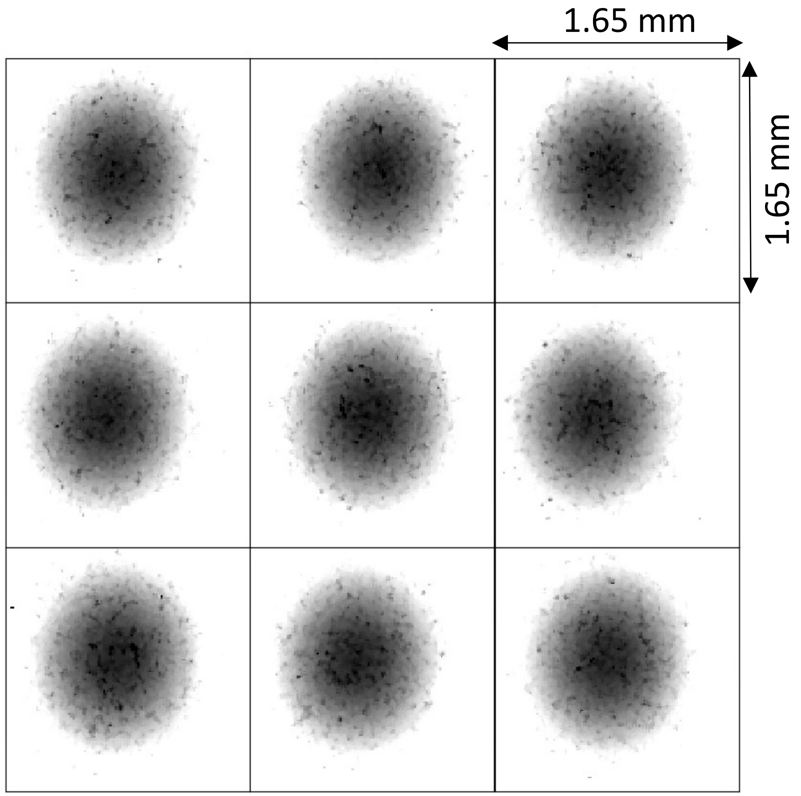
σ_x=0.81 mm
σ_y= 0.87 mm
} σ_r=0.84 mm

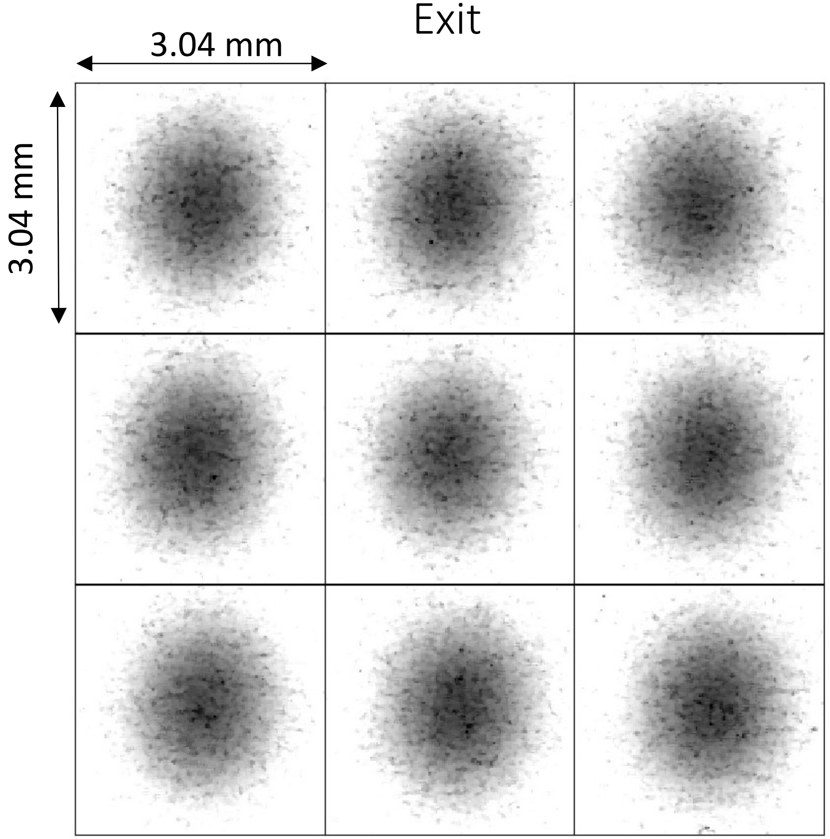
Streak camera
ns-scale images

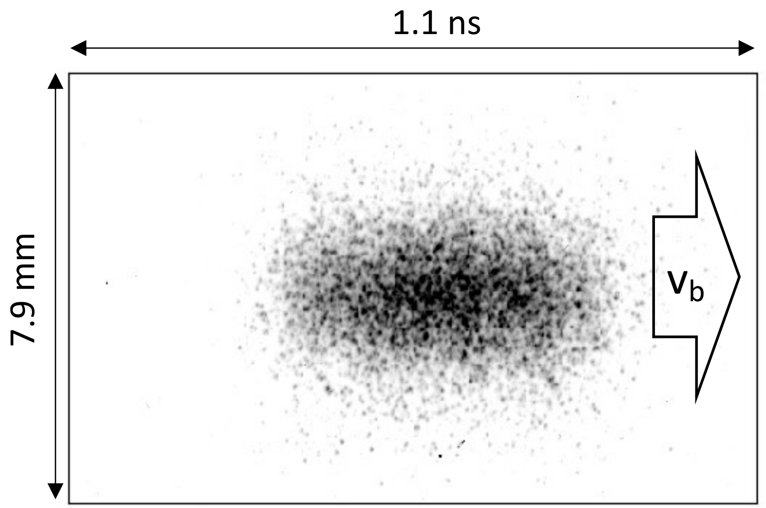


σ_t = 170 ps

Plasma OFF – no gas







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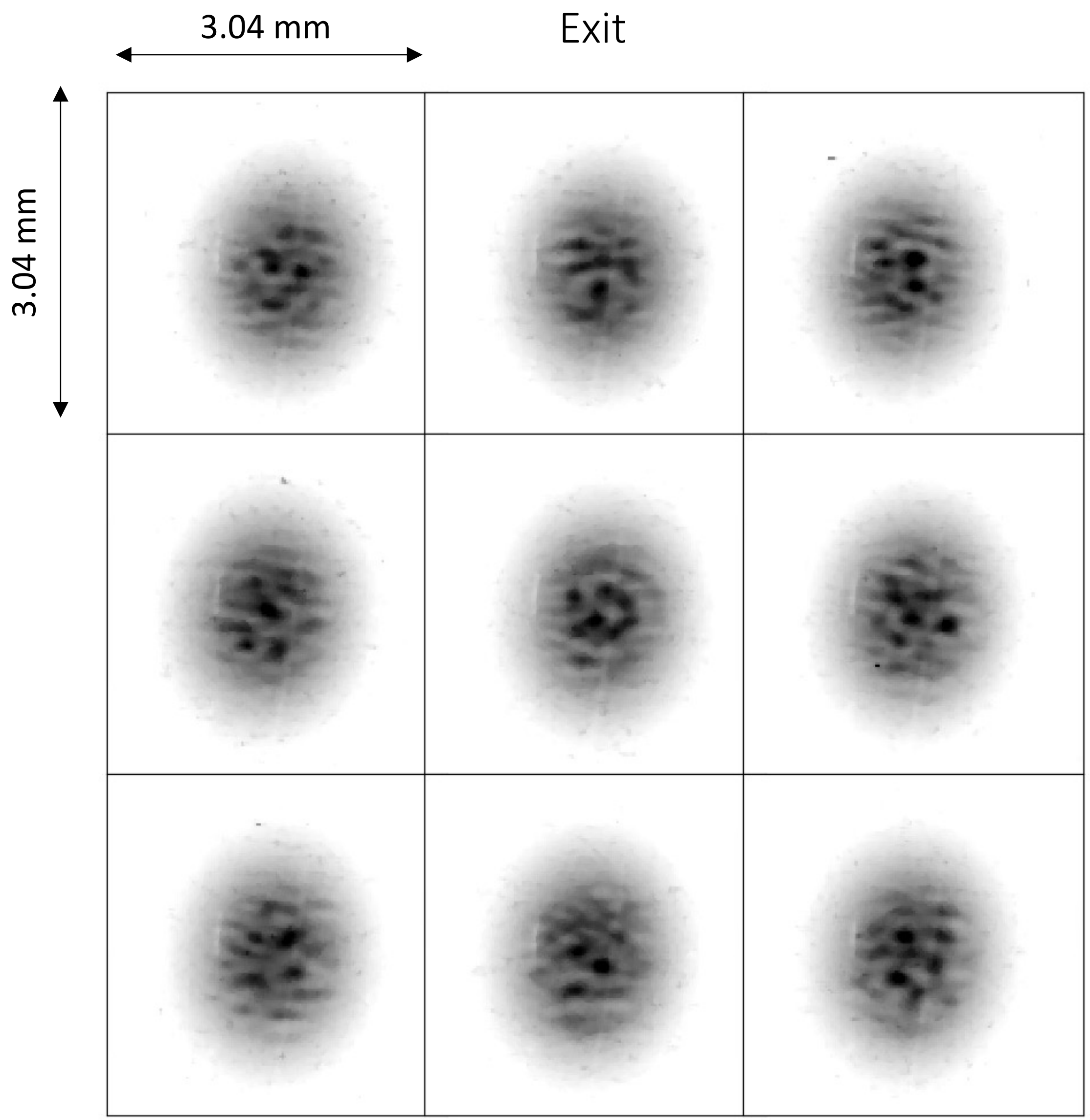
No distinguishable features in the transverse or longitudinal distribution

Plasma ON – n_{pe} = 9.38e14/cc → σ_r/δ = 3.2 at plasma entrance



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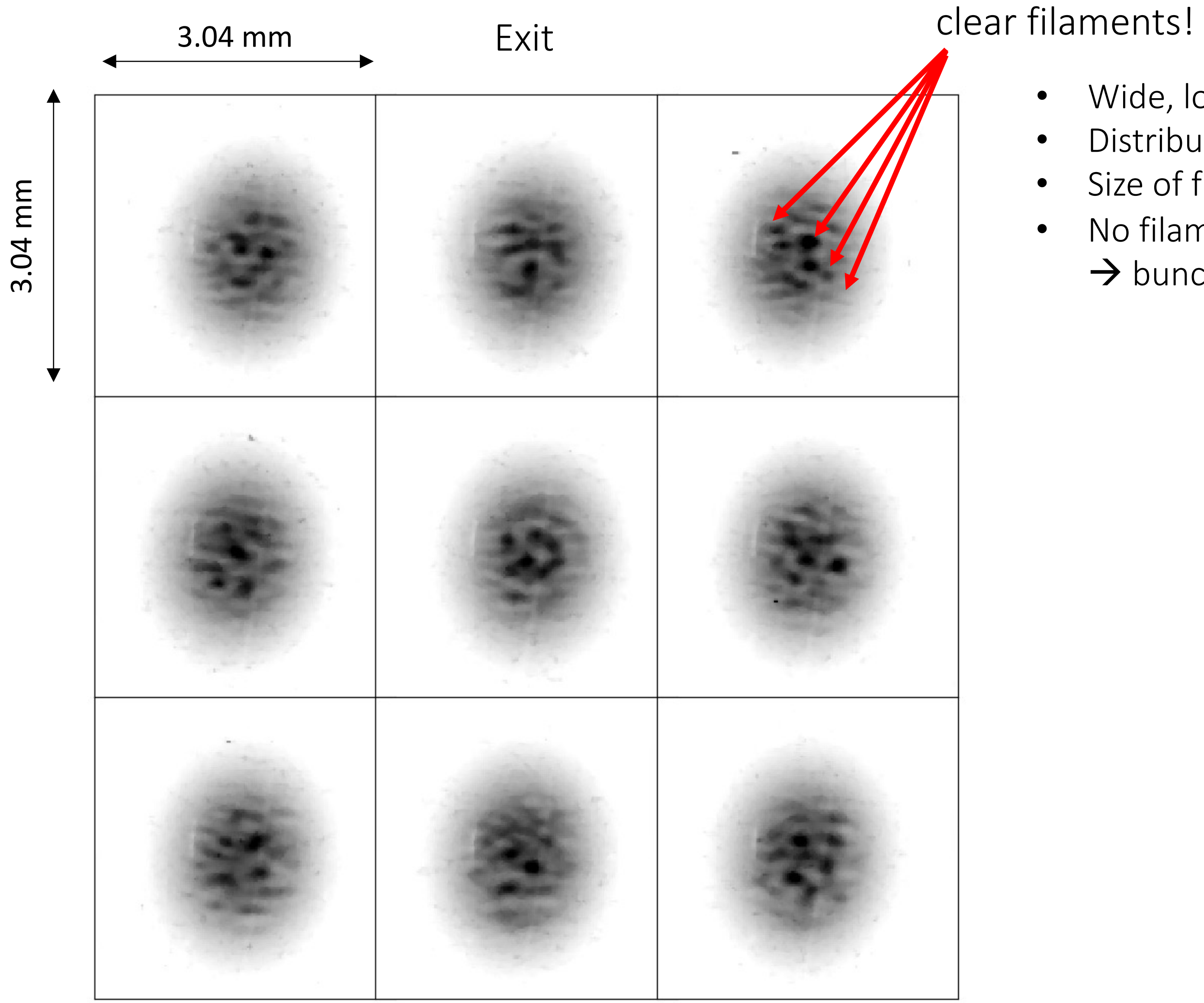

- Wide, long, relativistic proton bunch undergoes OTSI
- Distribution of filaments changes from event to event
- Size of filaments $\sim \delta$
- No filaments at $r \sim 0.5\ mm < \sigma_r$
  → bunch density and growth rate too low

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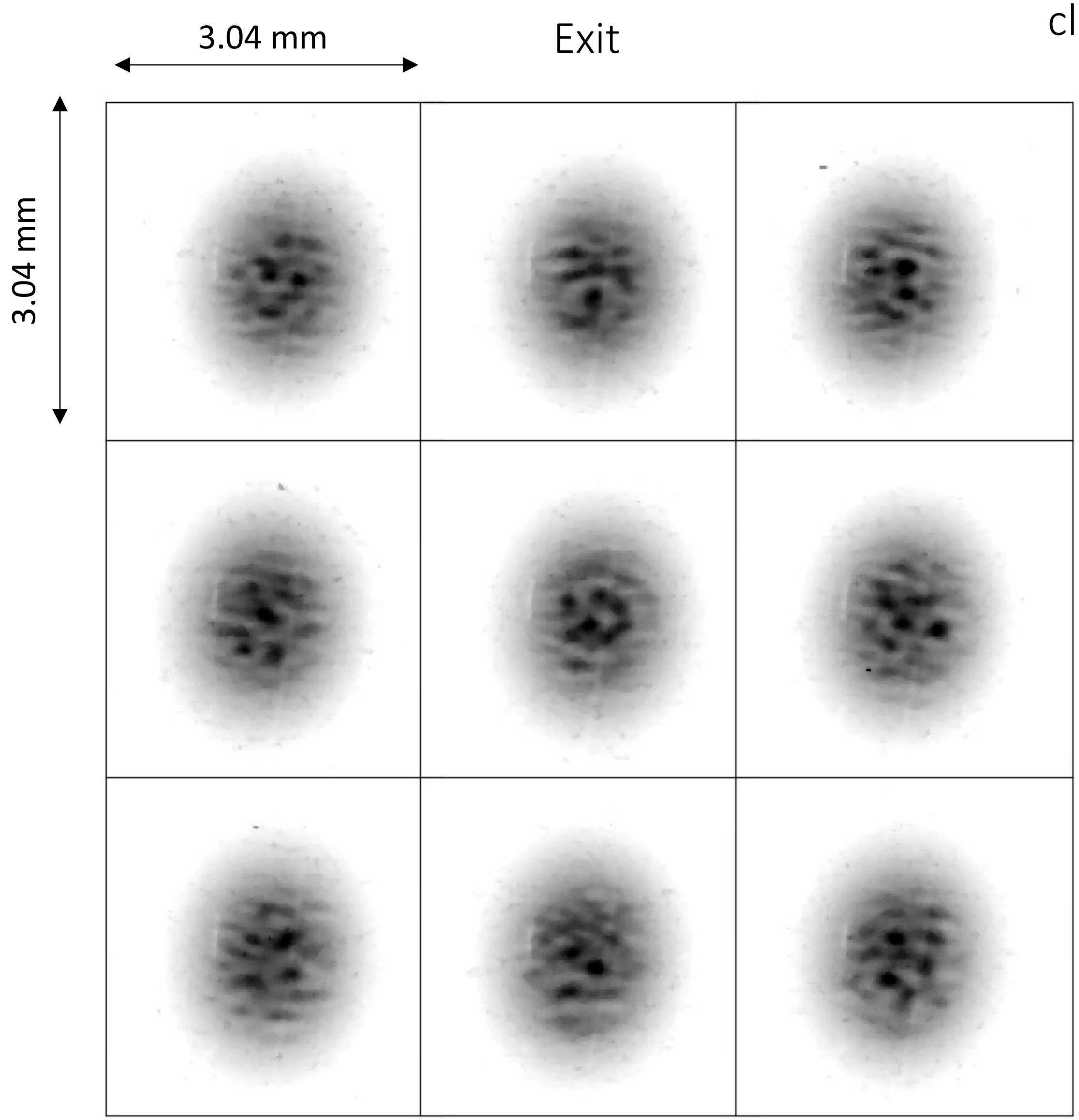

clear filaments!

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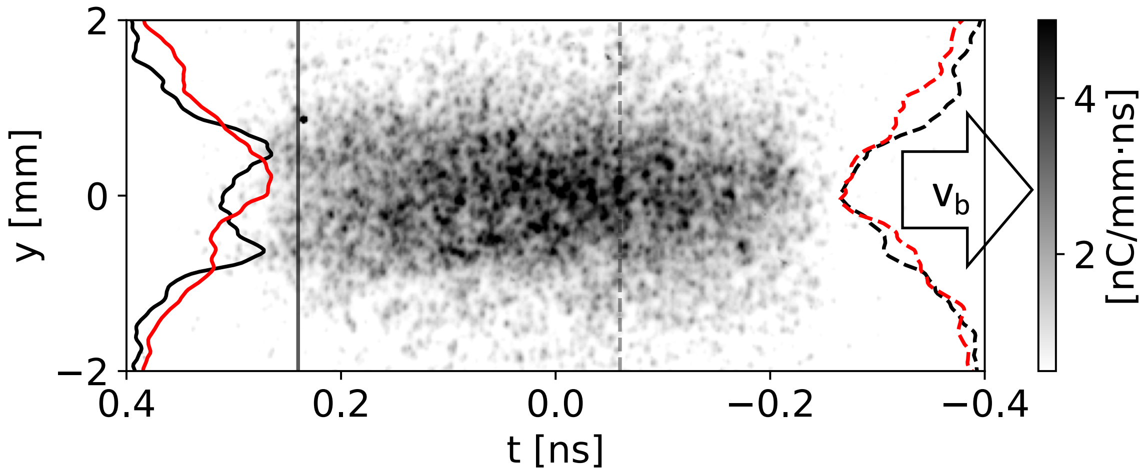

indication of filaments late along the bunch
caveat: 1) screen far away from plasma exit
2) streak camera captures only the central slice

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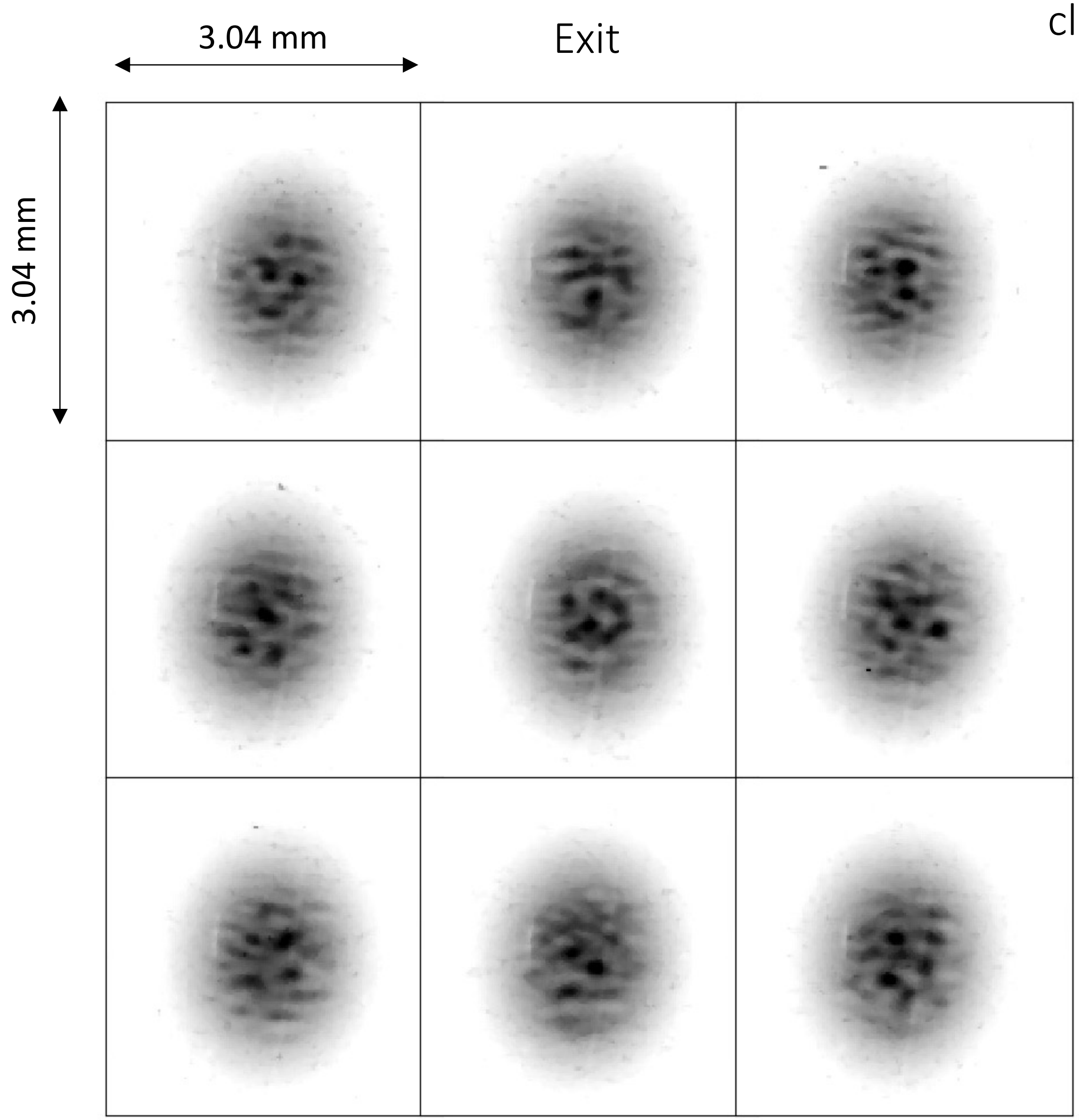

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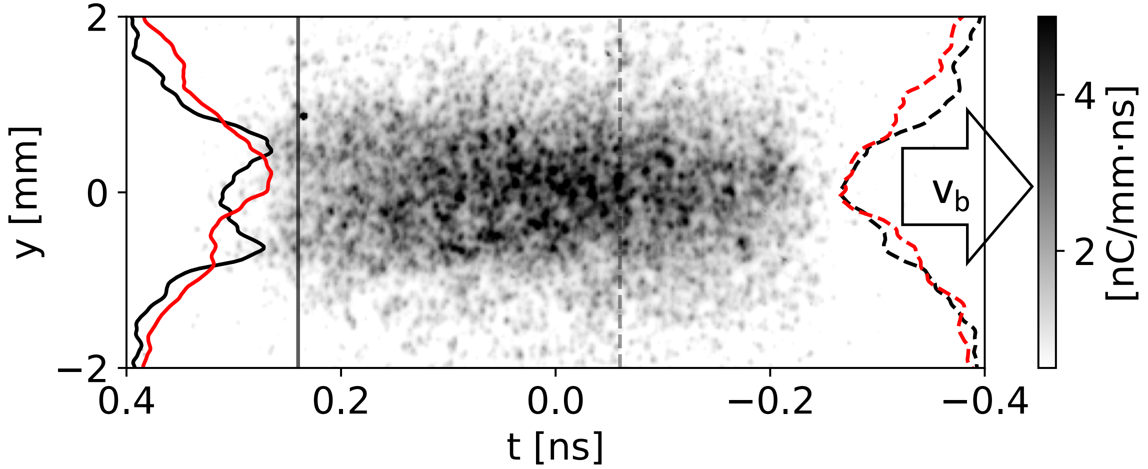

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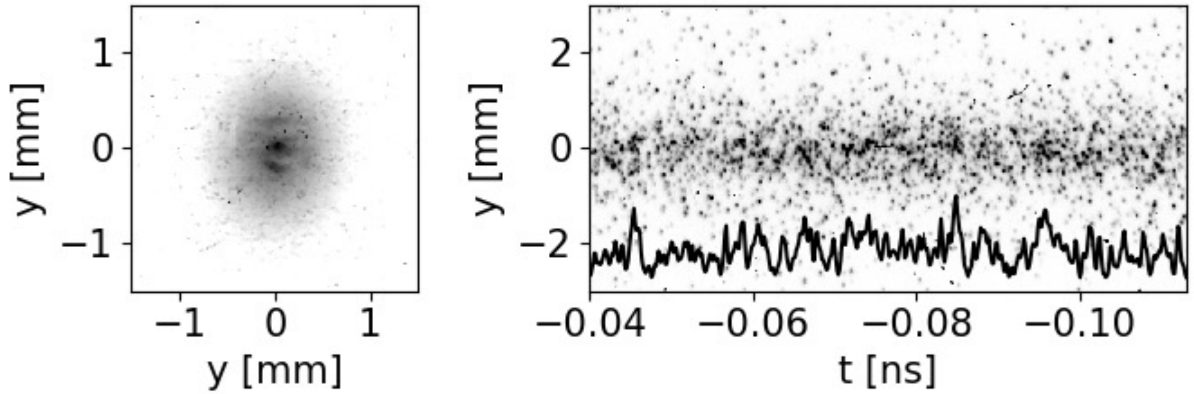
- Evolution along the bunch (convective instability)
- Moderate growth rate → early stage of filamentation

Plasma ON – n_{pe} = 2.25e14/cc → σ_r/δ = 1.5 at plasma entrance

At the threshold, the system alternates between:

ps-scale time-resolved images



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

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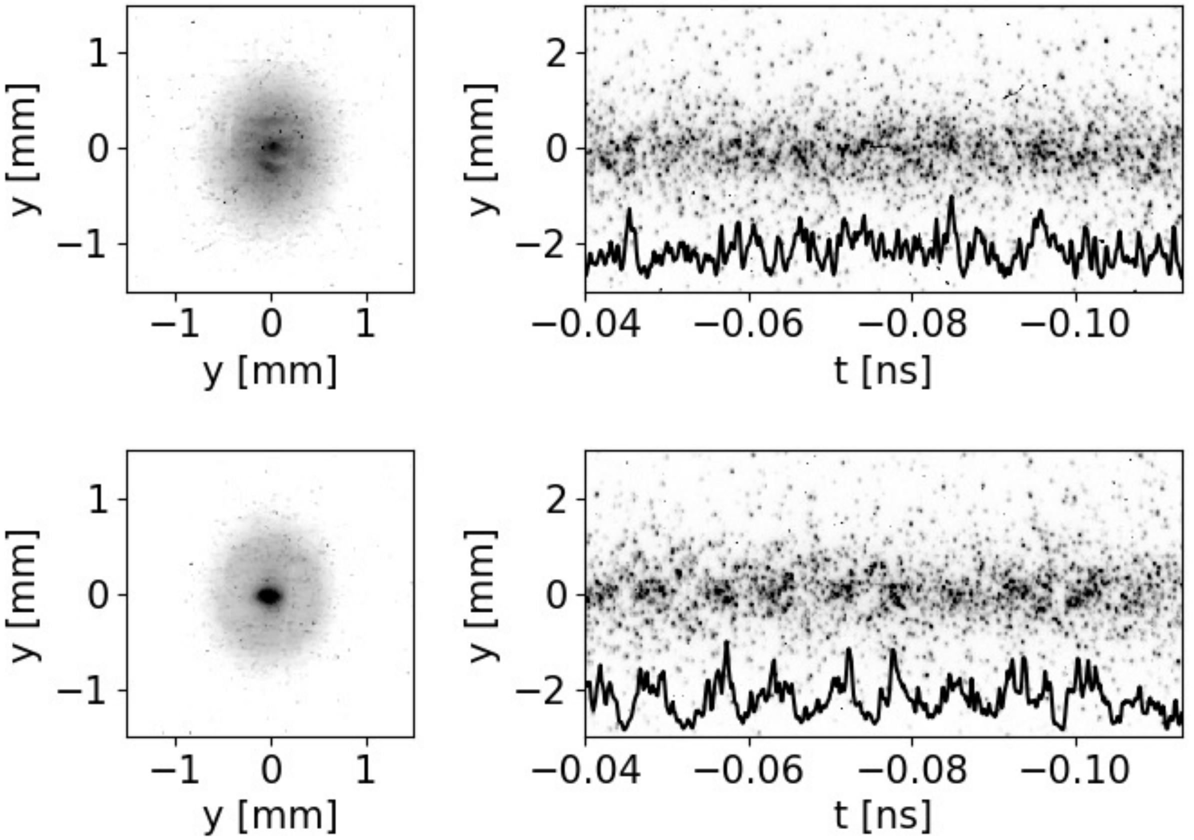

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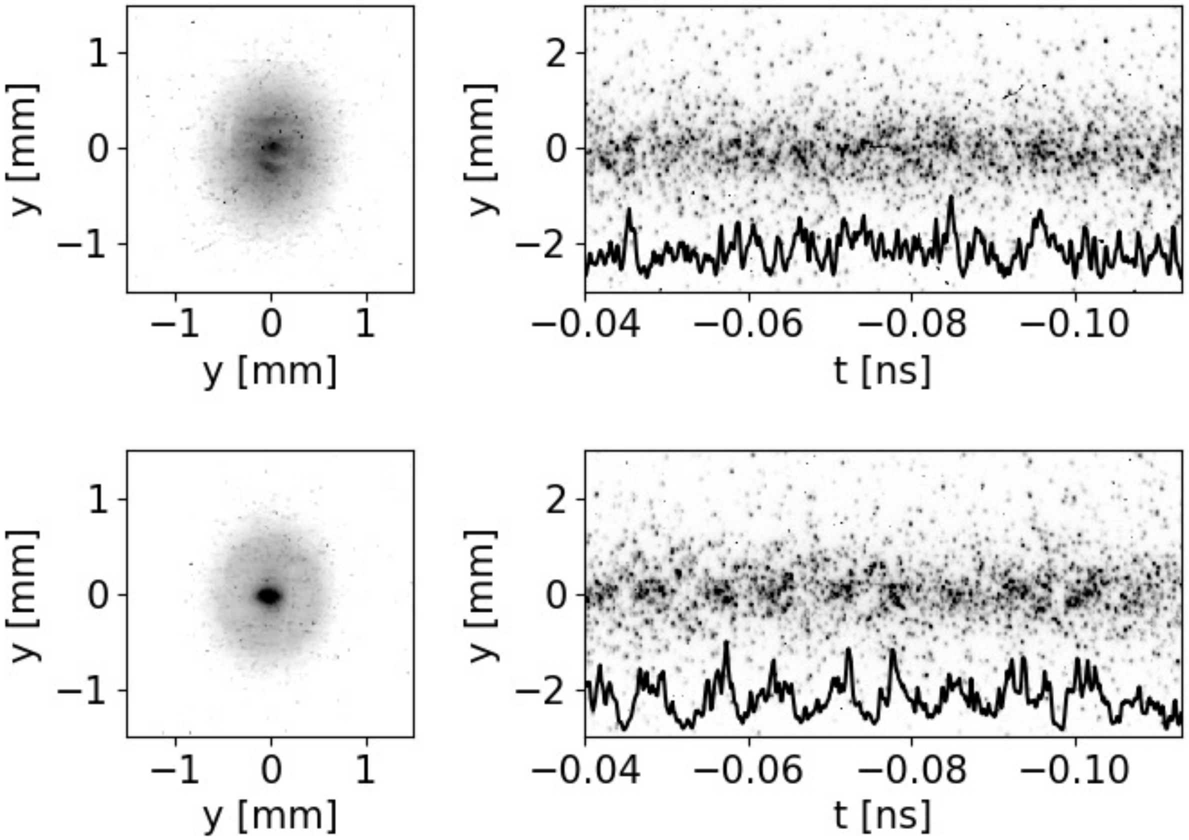

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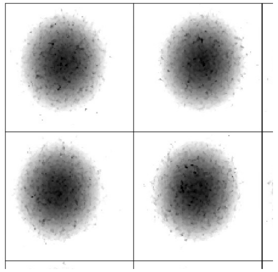
Reminder: no observable differences in the incoming bunch distribution



Magnetic field generation

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

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

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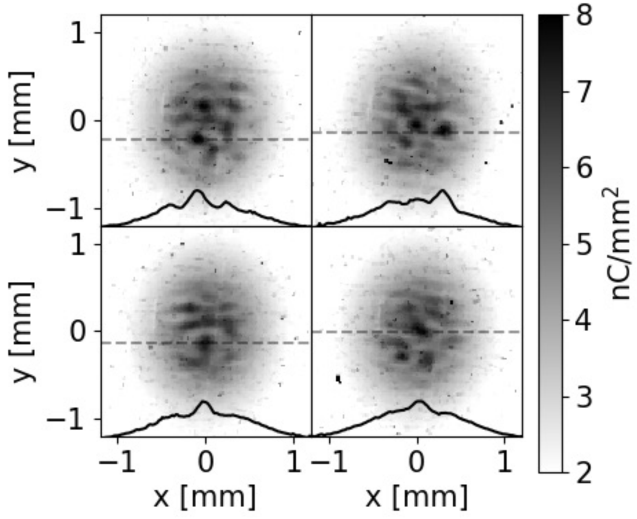
Bunch Charge Density Profile



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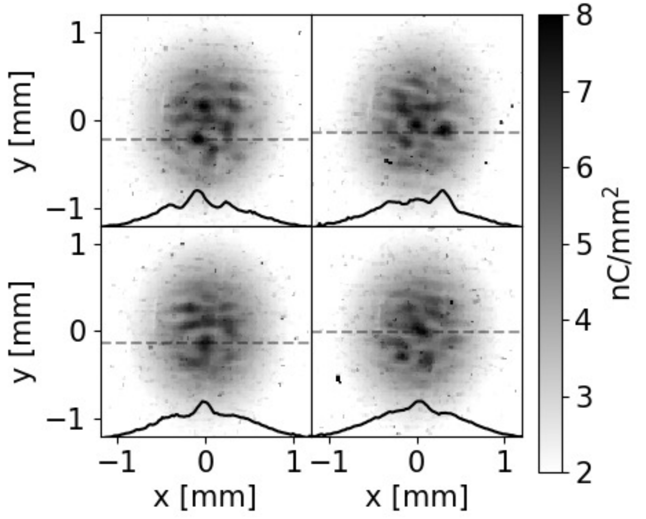
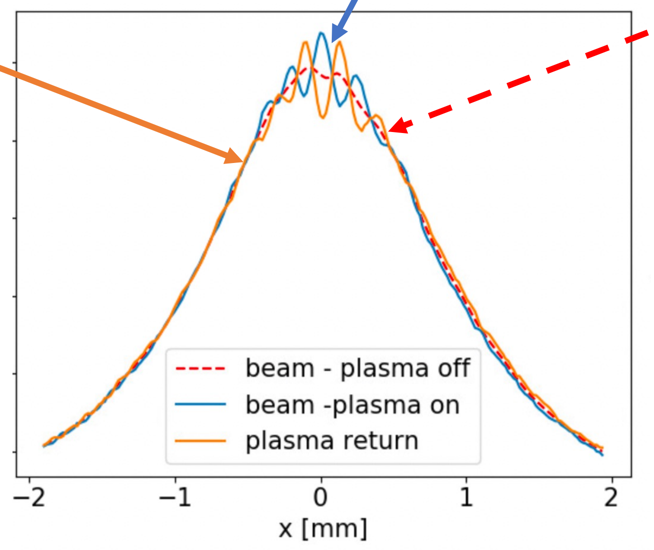


Horizontal projections



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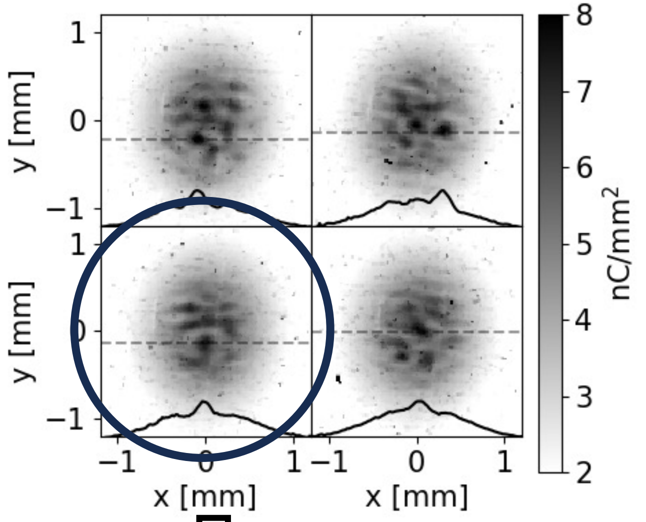

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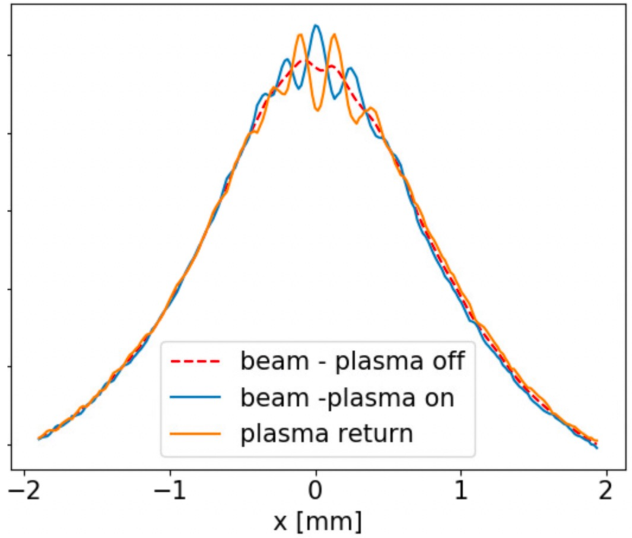
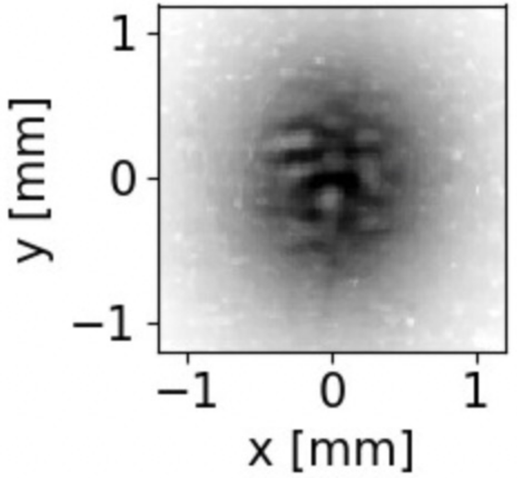


Plasma Return Current



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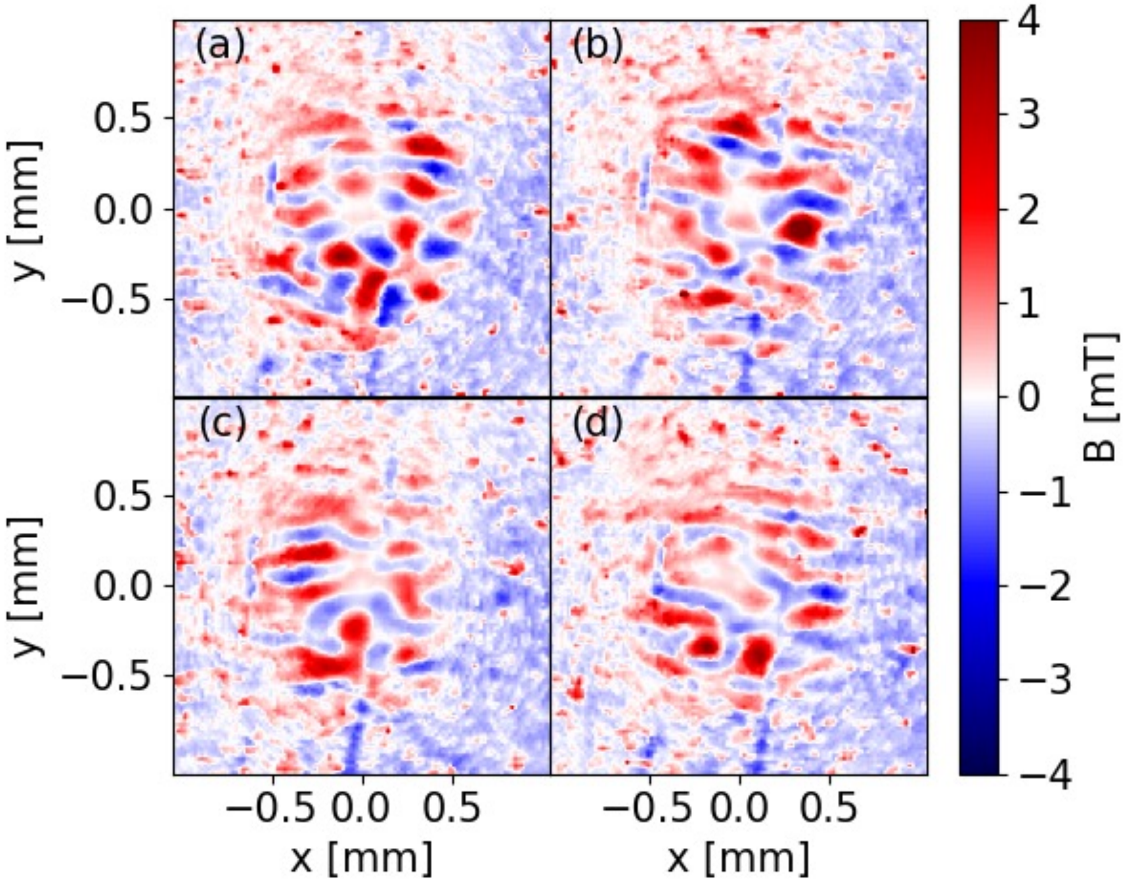

(note: $B_{max,\ bunch}$ ~ 40 mT, I_{bunch} ~50 A)

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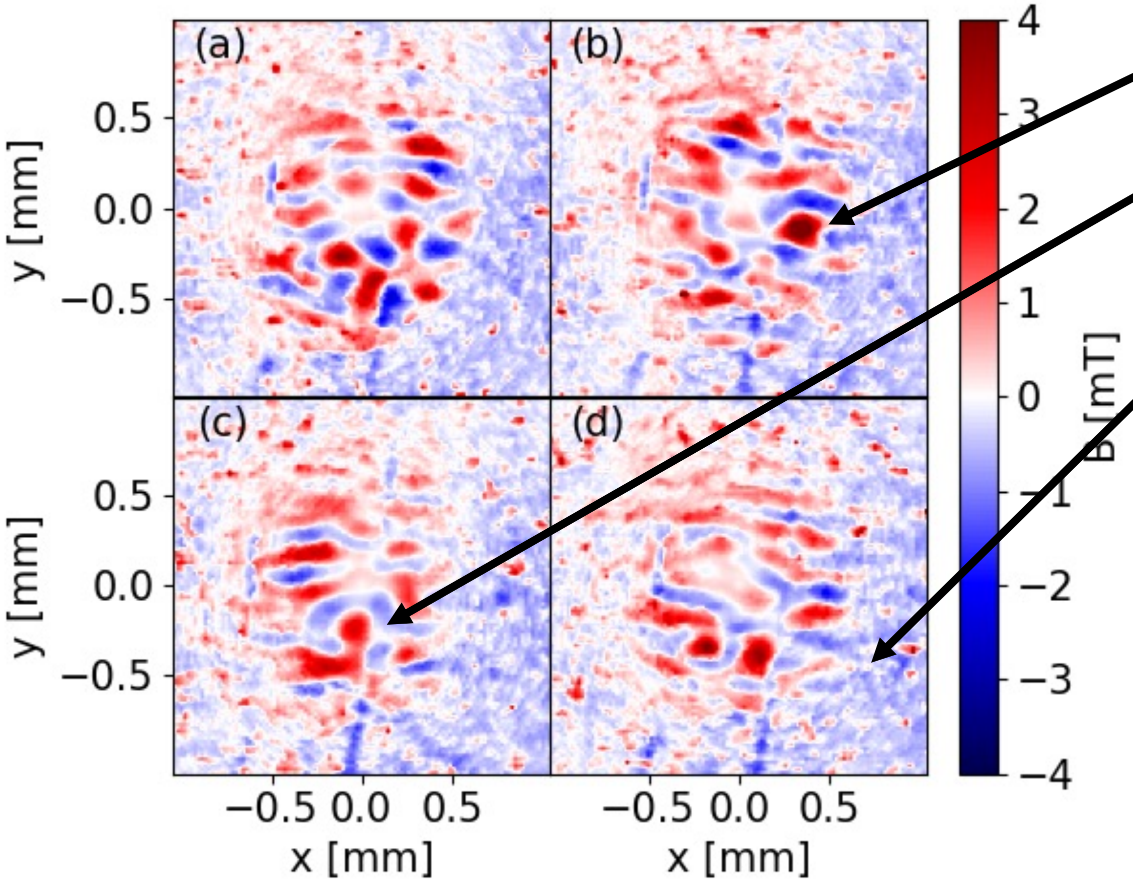

- non-zero magnetic field, confined within filaments
- sign reverses in between filaments (where the return current flows)
- on average zero outside of the bunch

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

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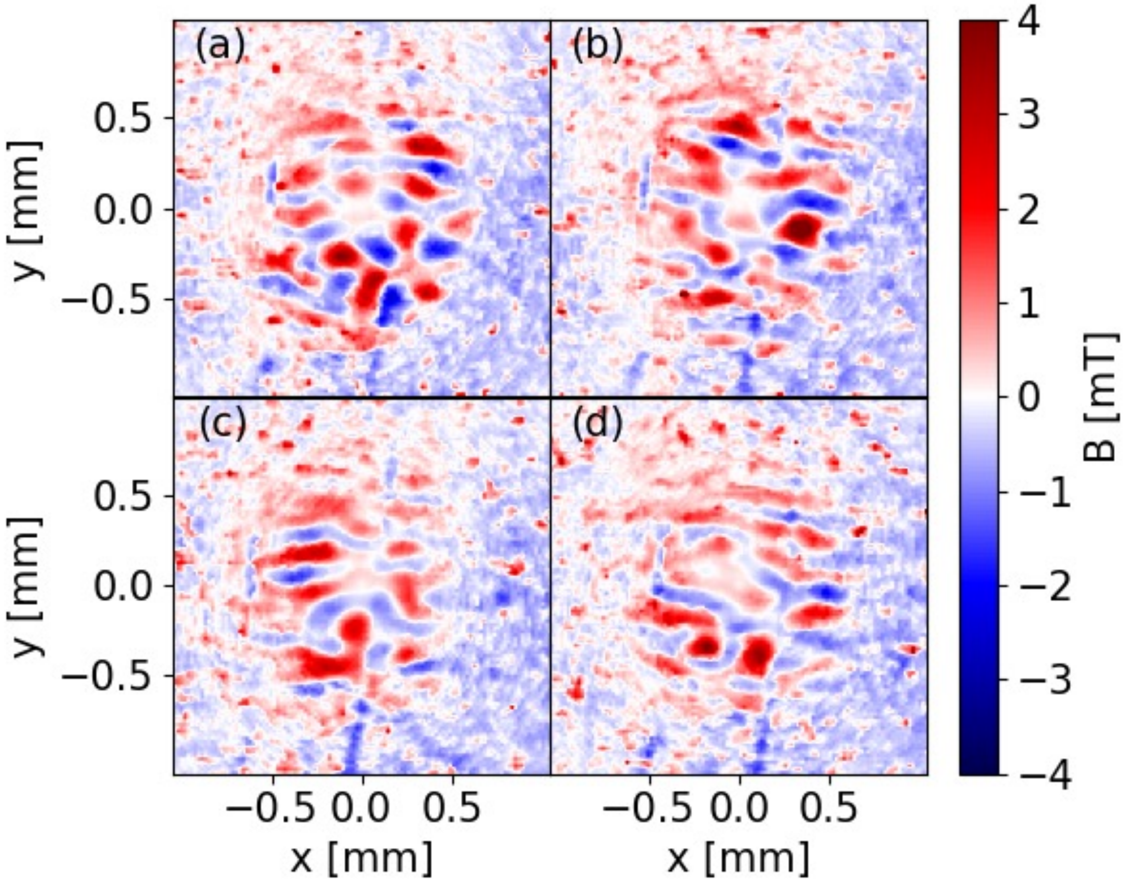

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$$E = \int dV \frac{< B^2 >}{2\mu_0}$$

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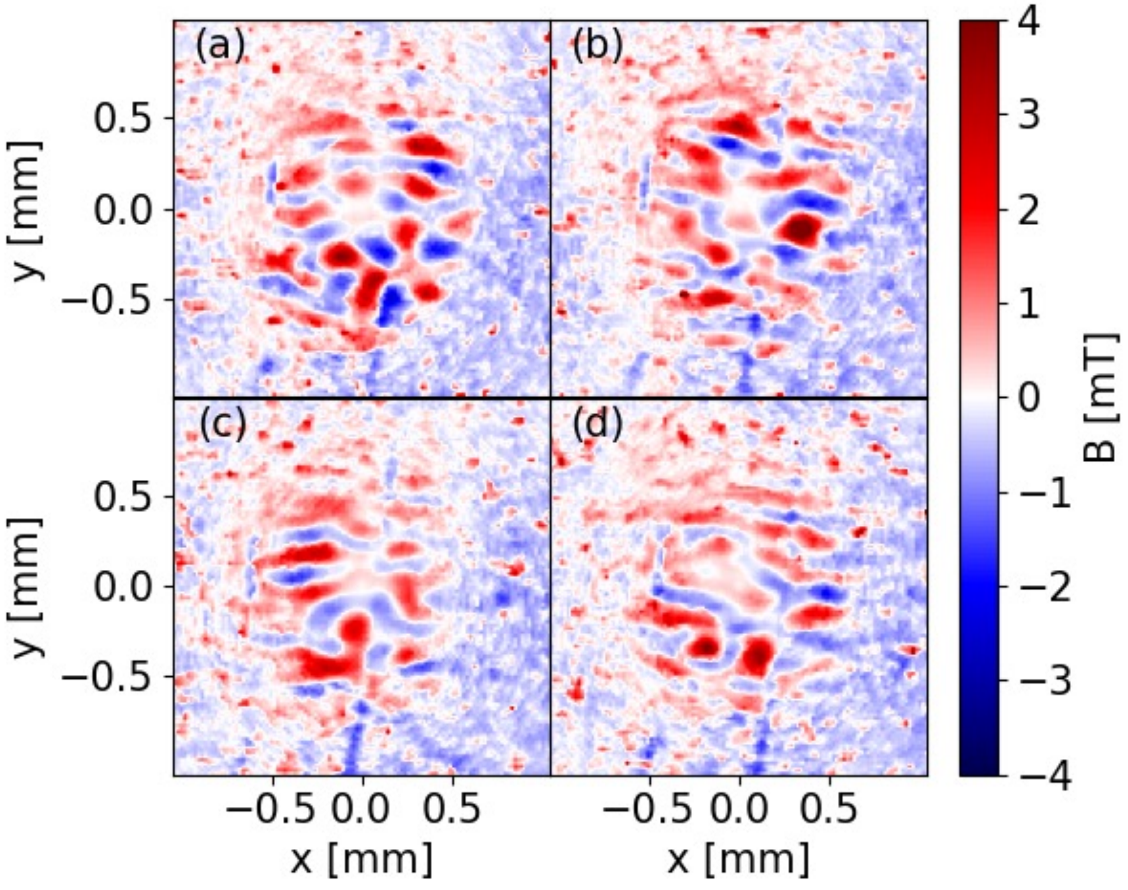

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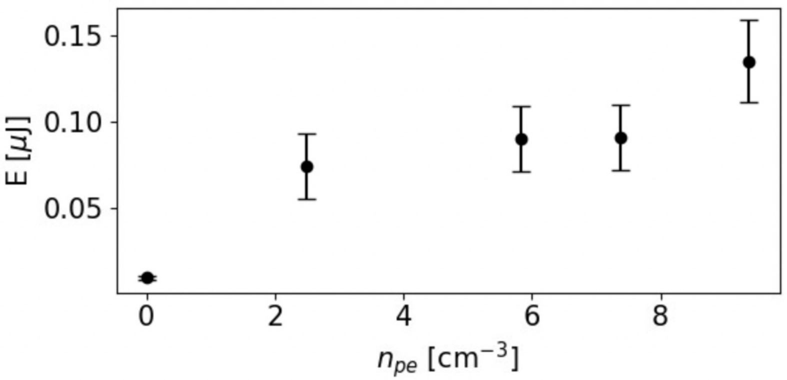
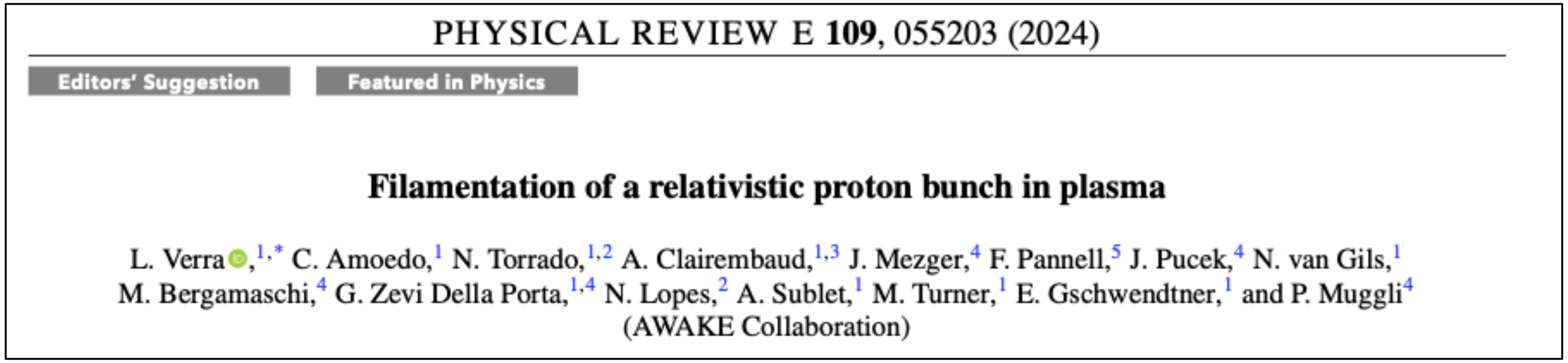


- Increase with n_{pe}
- Small amount of energy (bunch energy ~ 20 kJ):
  → early stage of the instability
  → moderate growth rate

Conclusions

- We consistently observe Filamentation 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 OTSI and SMI
- We show that occurrence of Filamentation generates magnetic fields
  - the amount of magnetic energy increases with n_{pe}
- Results published in Physical Review E

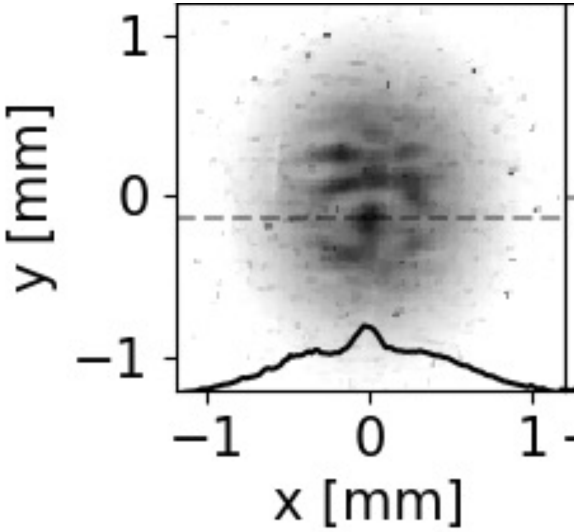


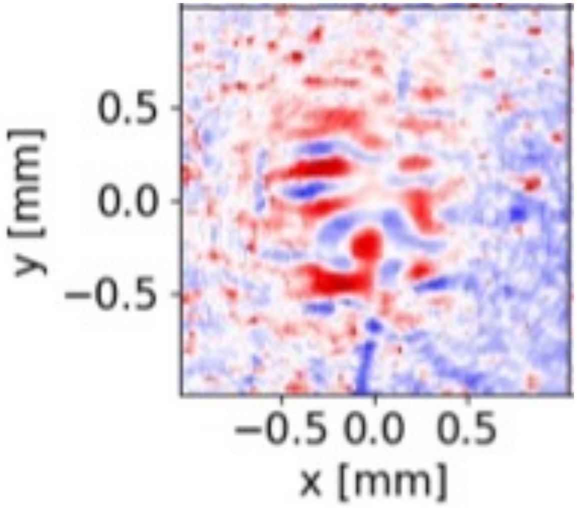
PHYSICAL REVIEW E **109**, 055203 (2024)

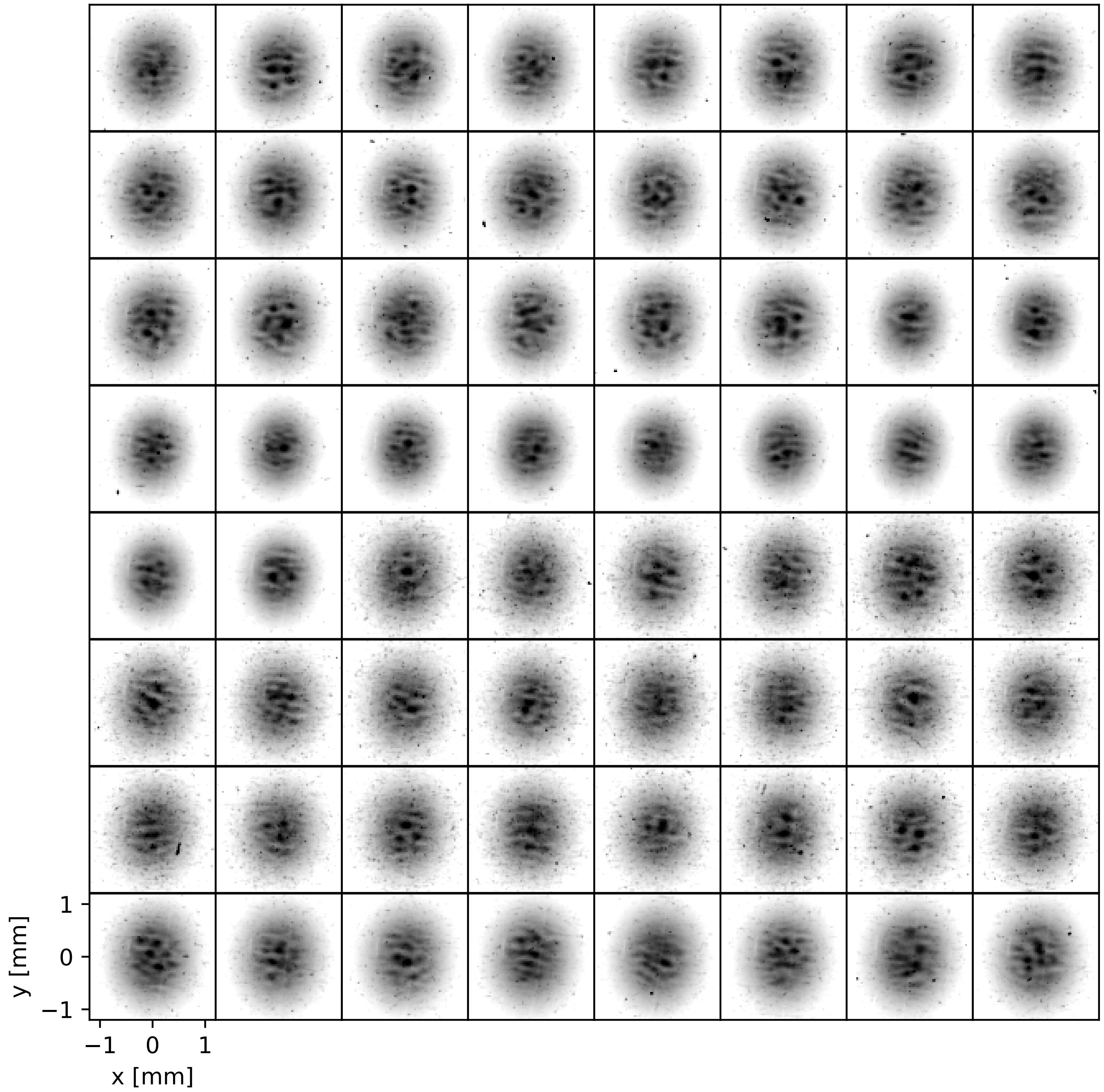
Editors' Suggestion   Featured in Physics

Filamentation of a relativistic proton bunch in plasma

L. Verra,[1,*] C. Amoedo,[1] N. Torrado,[1,2] A. Clairembaud,[1,3] J. Mezger,[4] F. Pannell,[5] J. Pucek,[4] N. van Gils,[1] M. Bergamaschi,[4] G. Zevi Della Porta,[1,4] N. Lopes,[2] A. Sublet,[1] M. Turner,[1] E. Gschwendtner,[1] and P. Muggli[4]
(AWAKE Collaboration)





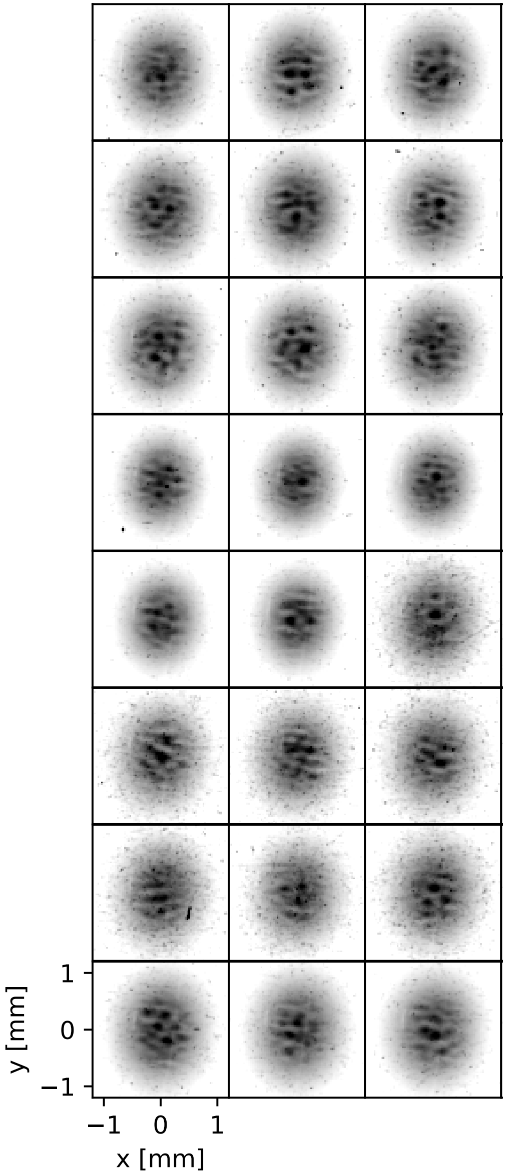


Thank you!

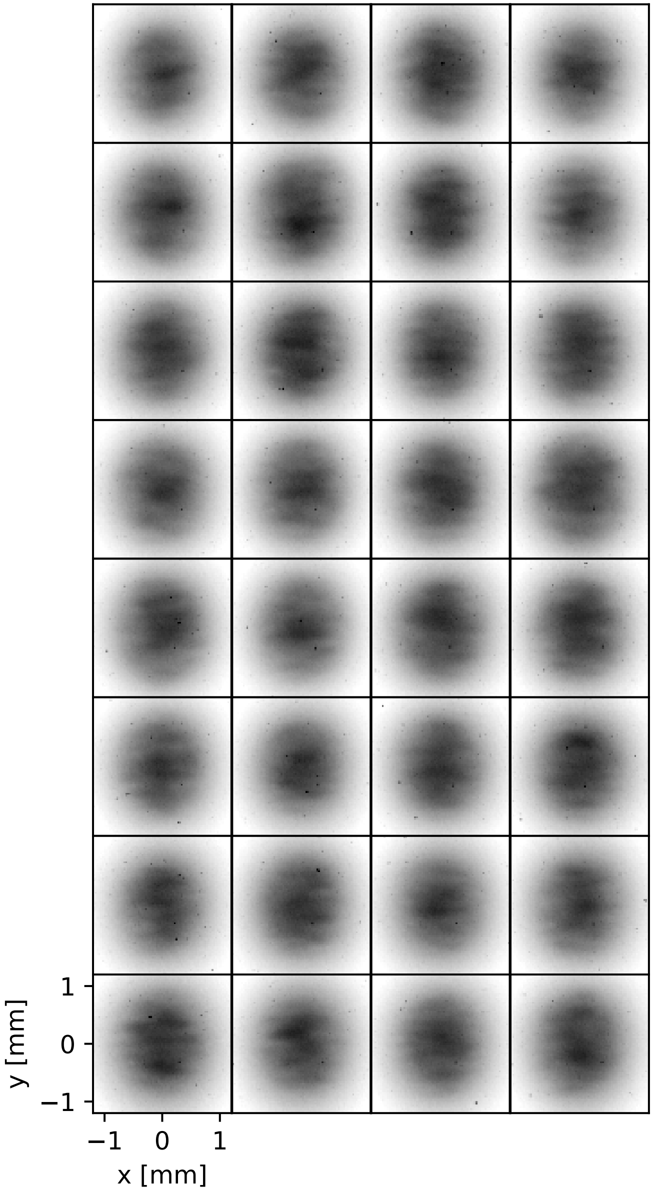
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Backup slides

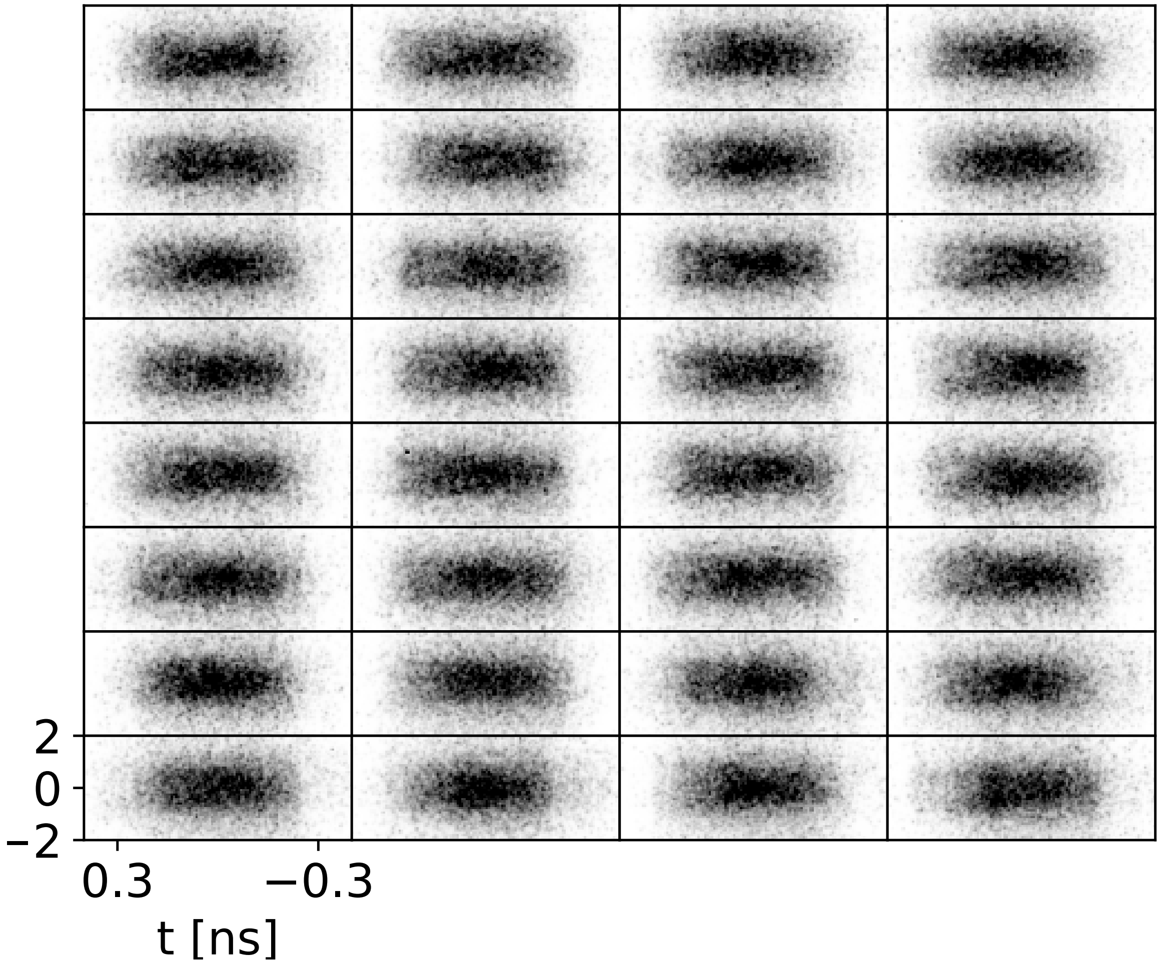
CLOSE screen

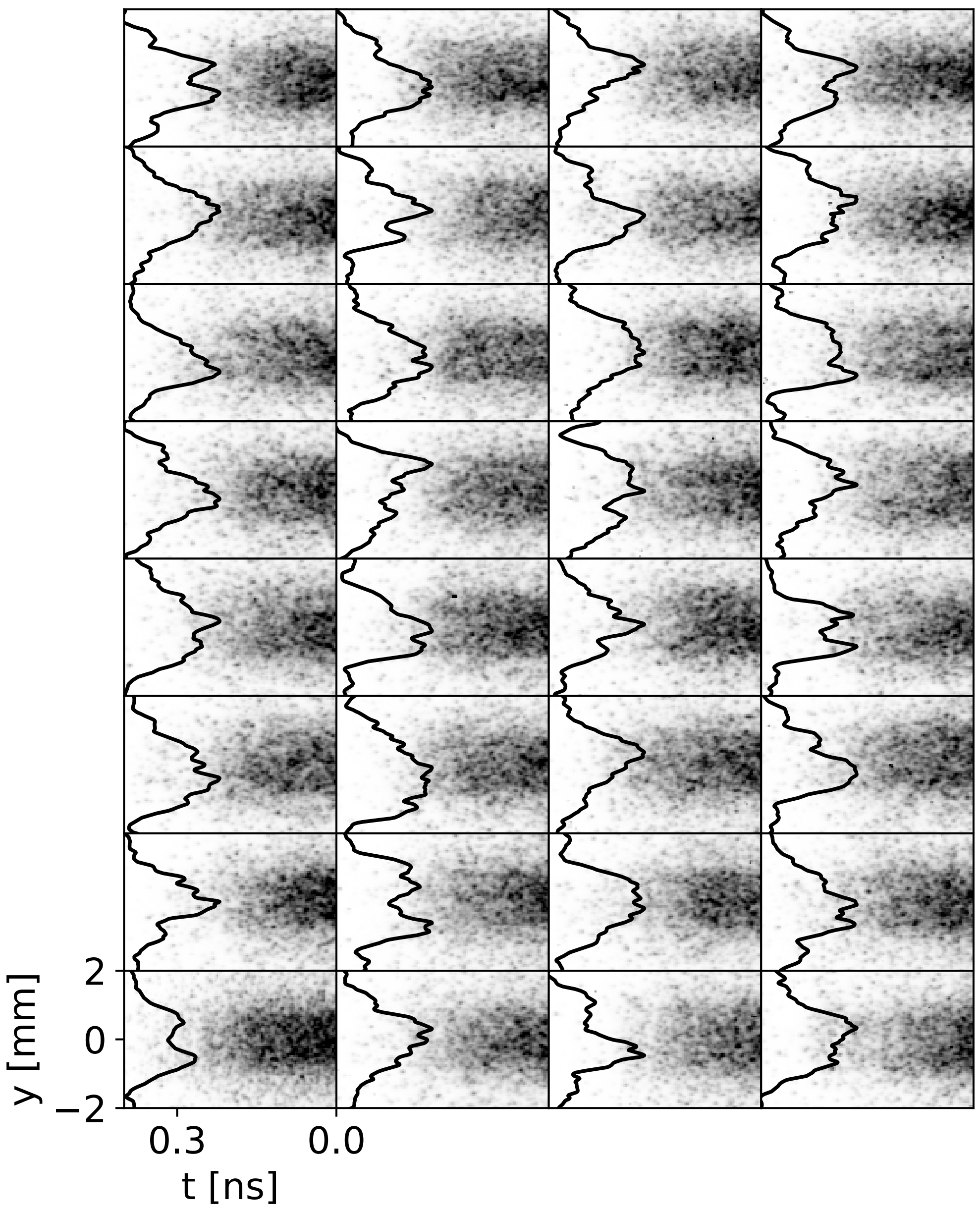


FAR screen

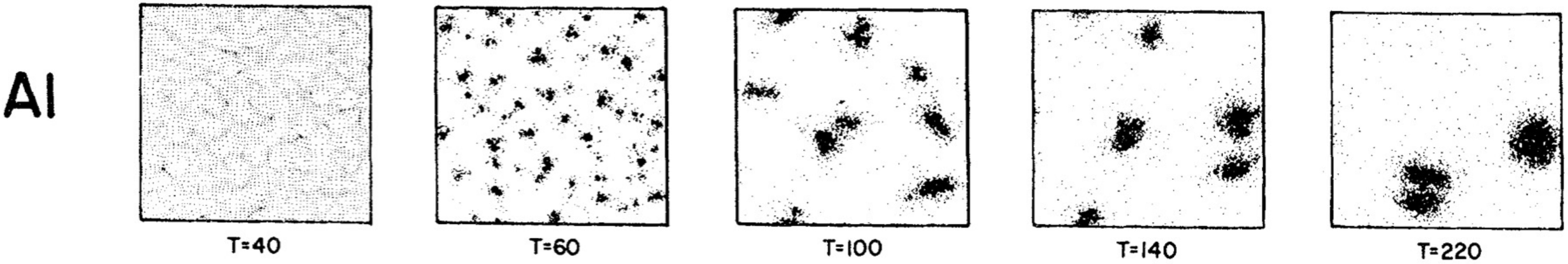


Time-resolved from FAR screen



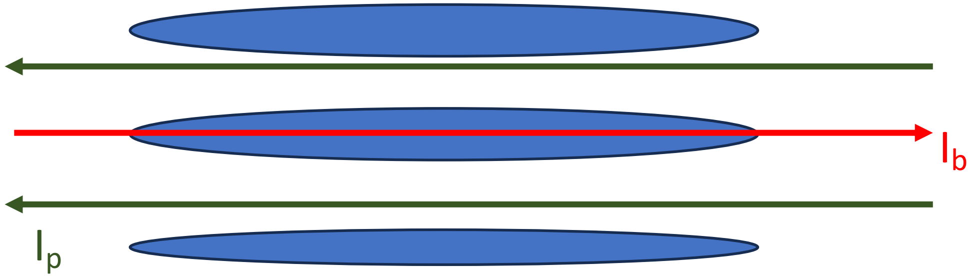

y [mm]
2
0
−2
0.3
0.0
t [ns]

Filamentation Instability



(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)

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

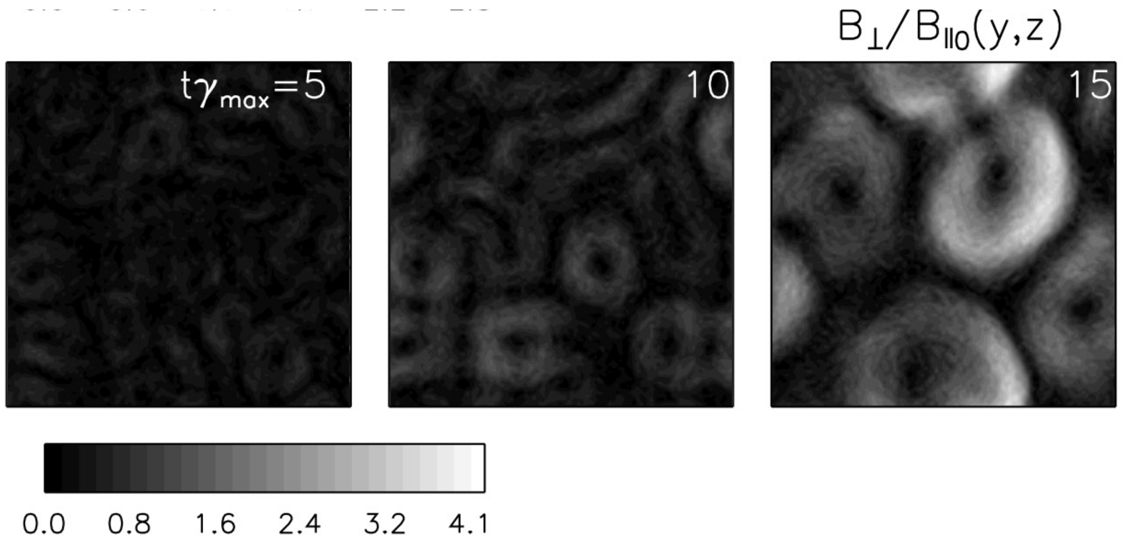
Filamentation in space

Plausible candidate for:

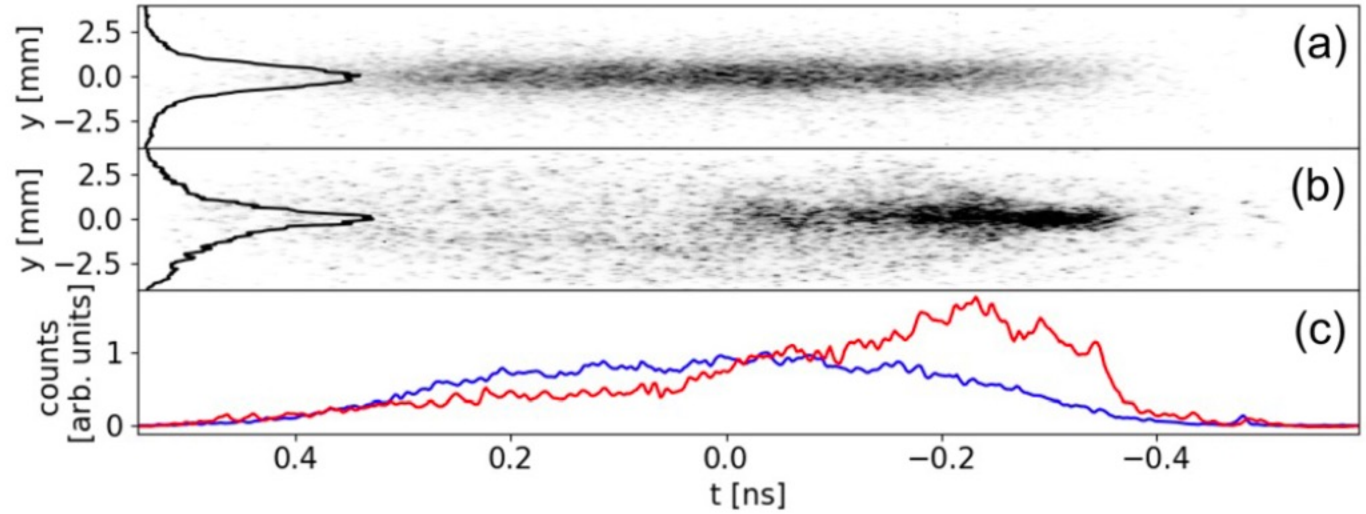
- magnetization of astrophysical media
  [J. Niemiec et al., The Astrophysical Journal **684**, 1174 (2008)]

- 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)]

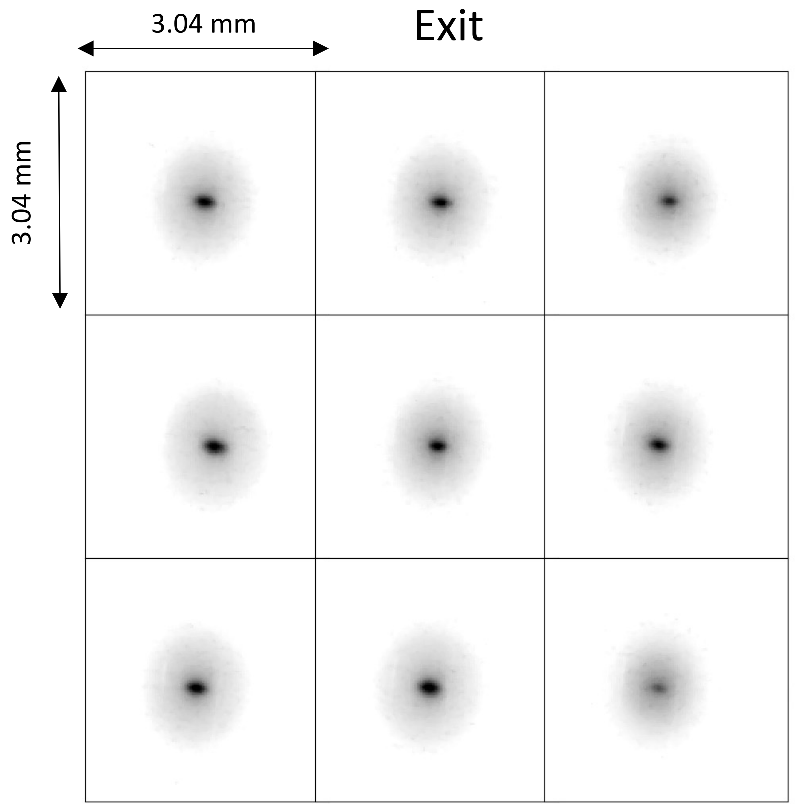


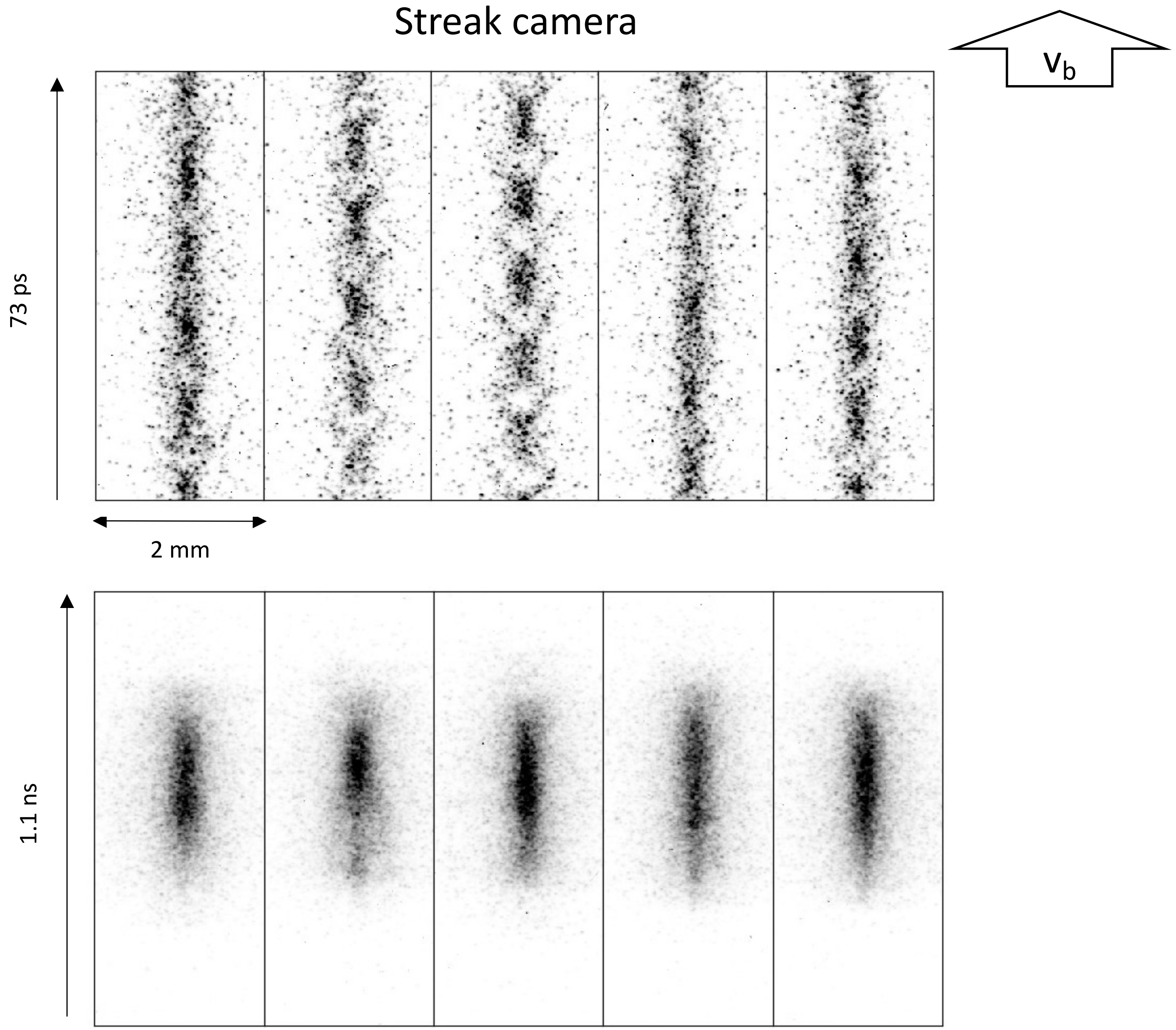
Also important for hot electron propagation in inertial confinement fusion targets:
[M. Tabak et al., Physics of Plasmas 1, 1626 (1994)]



(a)
(b)
(c)
y [mm]
y [mm]
counts [arb. units]
2.5
0.0
−2.5
2.5
0.0
−2.5
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**

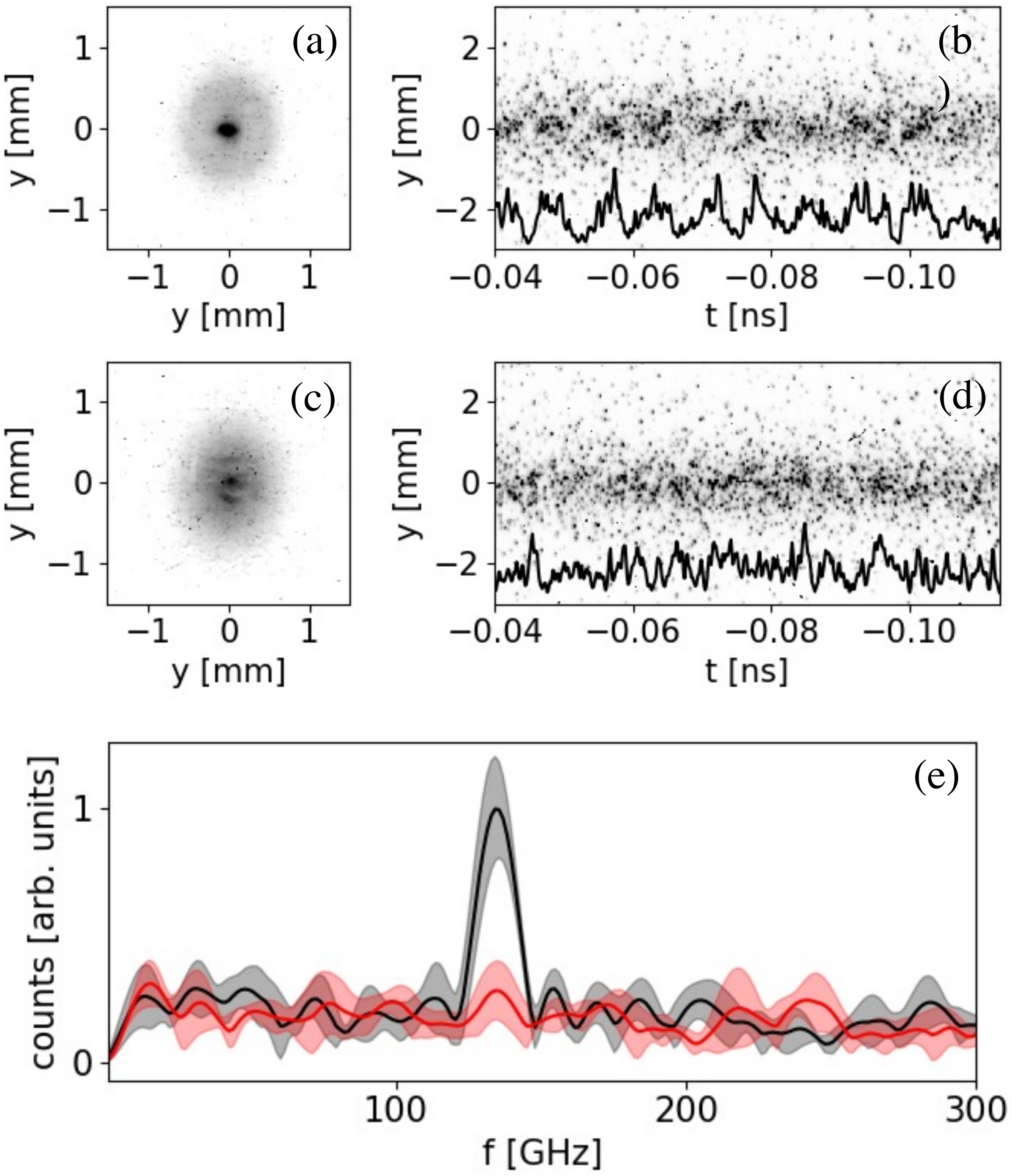
→ **microbunches on ps images**

→ **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

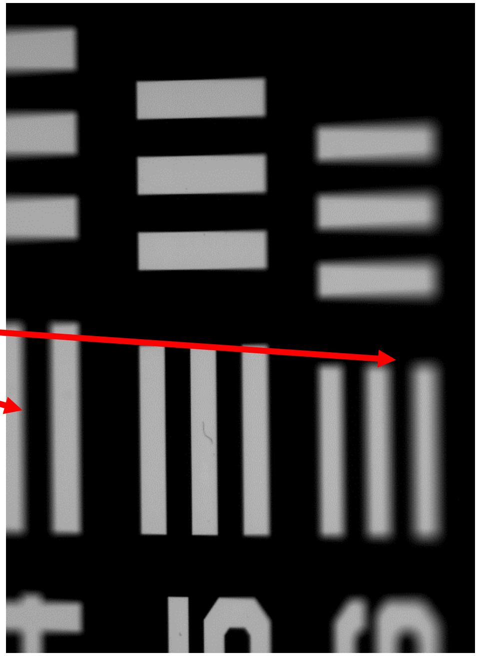
Filaments have small size, large emittance
→ large divergence when leaving the plasma

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

Screen –camera distance: 50 cm
M = 3.2

50% MTF at = 0.027 mm

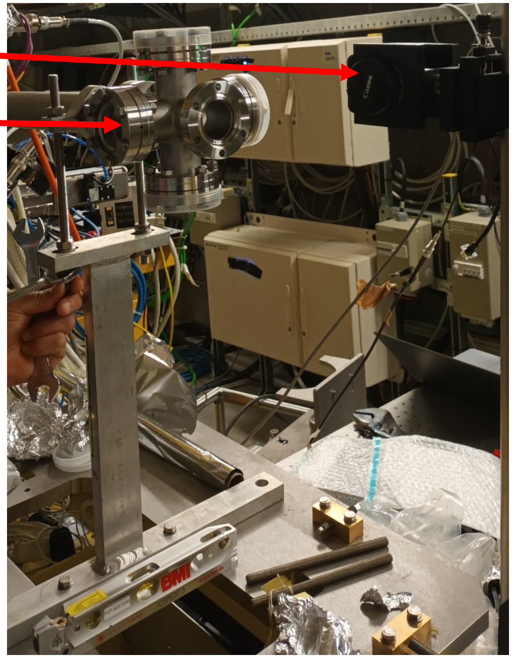
depth of field ~1.5 mm

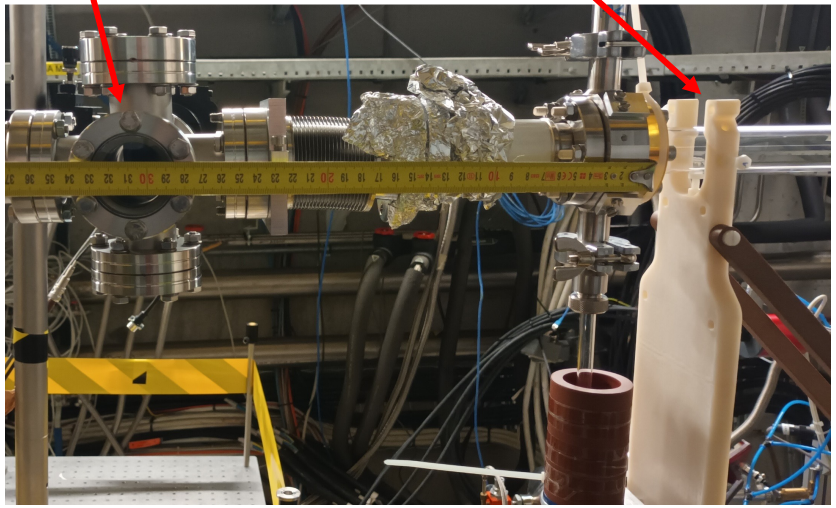


camera

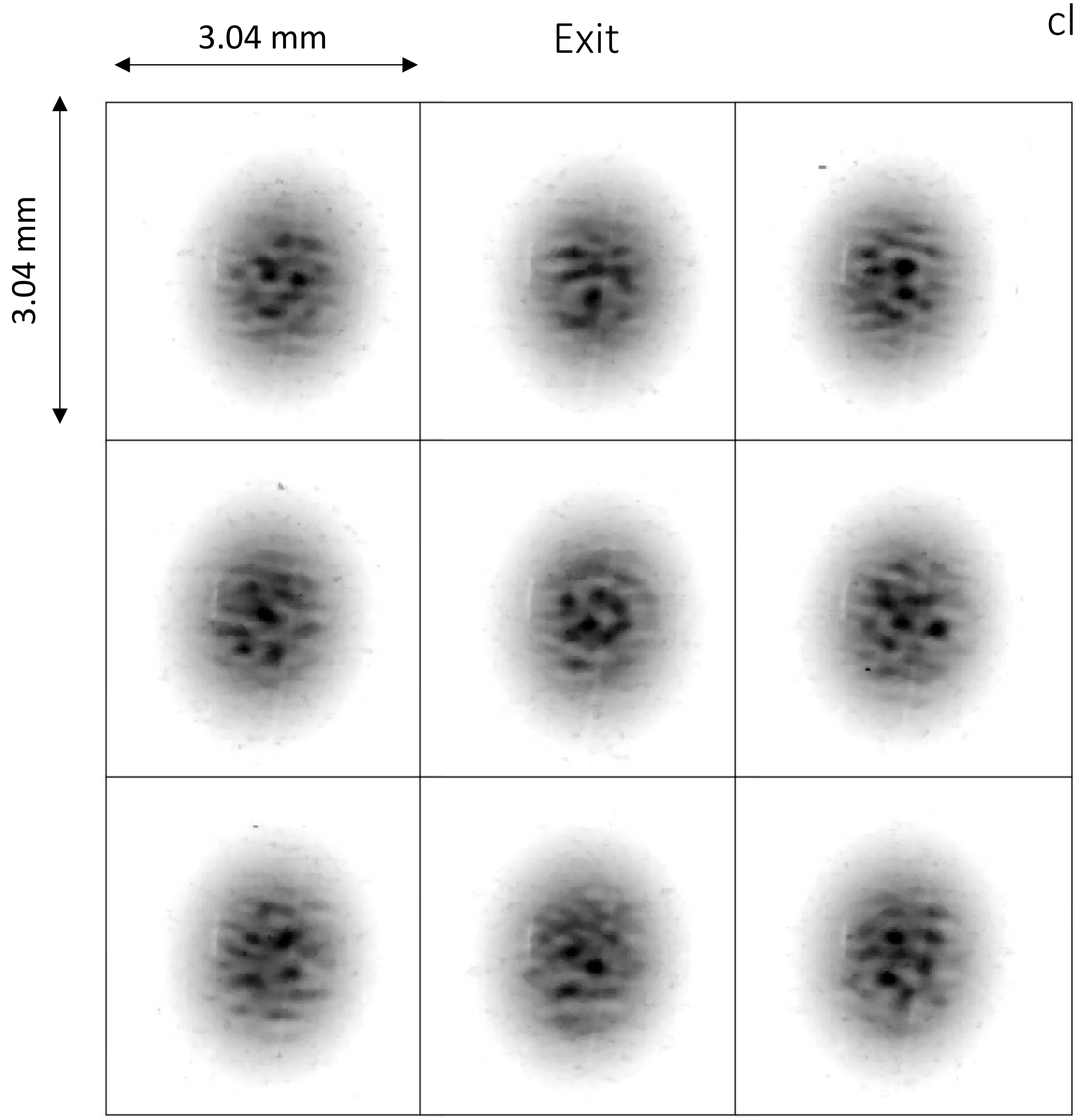
screen

DPS



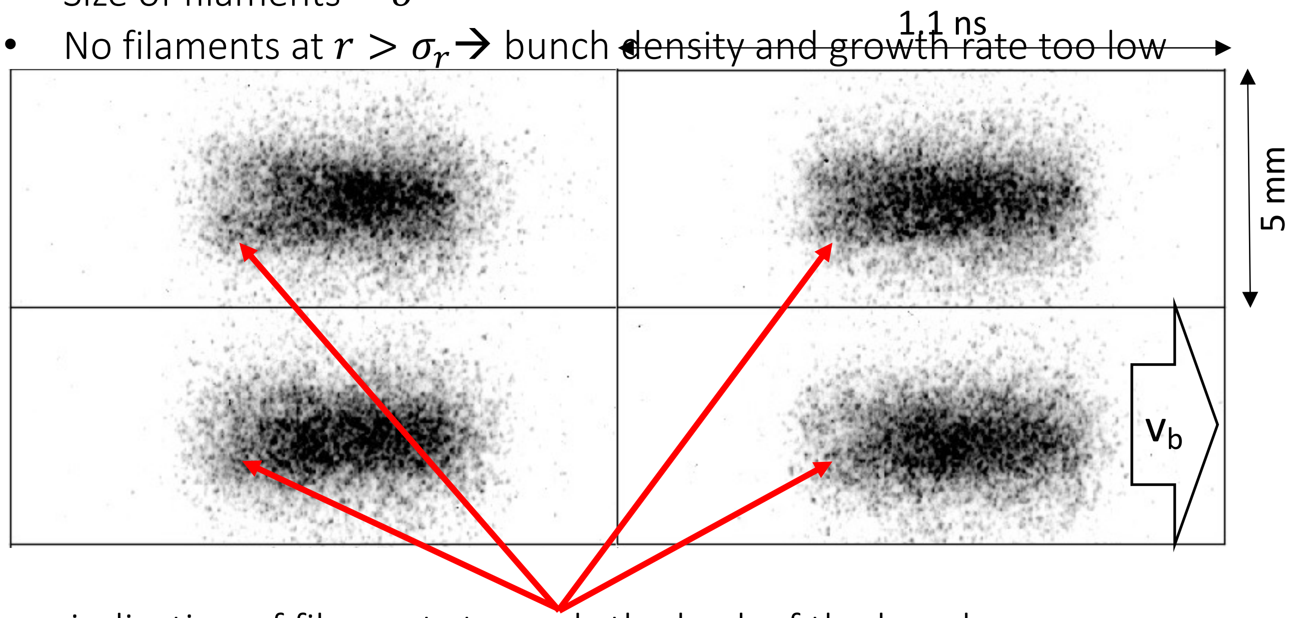


Plasma ON – n_{pe} = 9.38e14/cc → $\sigma_r/(c/\omega_{pe})$ = 3.2 at plasma entrance



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