Observation of space-charge field screening in plasma, and other recent experimental results from SPARC_LAB

Livio Verra

(on behalf of SPARC_LAB Collaboration)

Advanced Accelerator Concepts Workshop 2024

25.07.2024

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INFN

Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati

Summary

0a. EuPRAXIA@SPARC_LAB
0b. SPARC_LAB Facility

I. Space-Charge Field Screening in Plasma

II. Beam Guiding in Curved Plasma-Discharge Capillary

III. Focusing – Acceleration – Capture in all-plasma compact device

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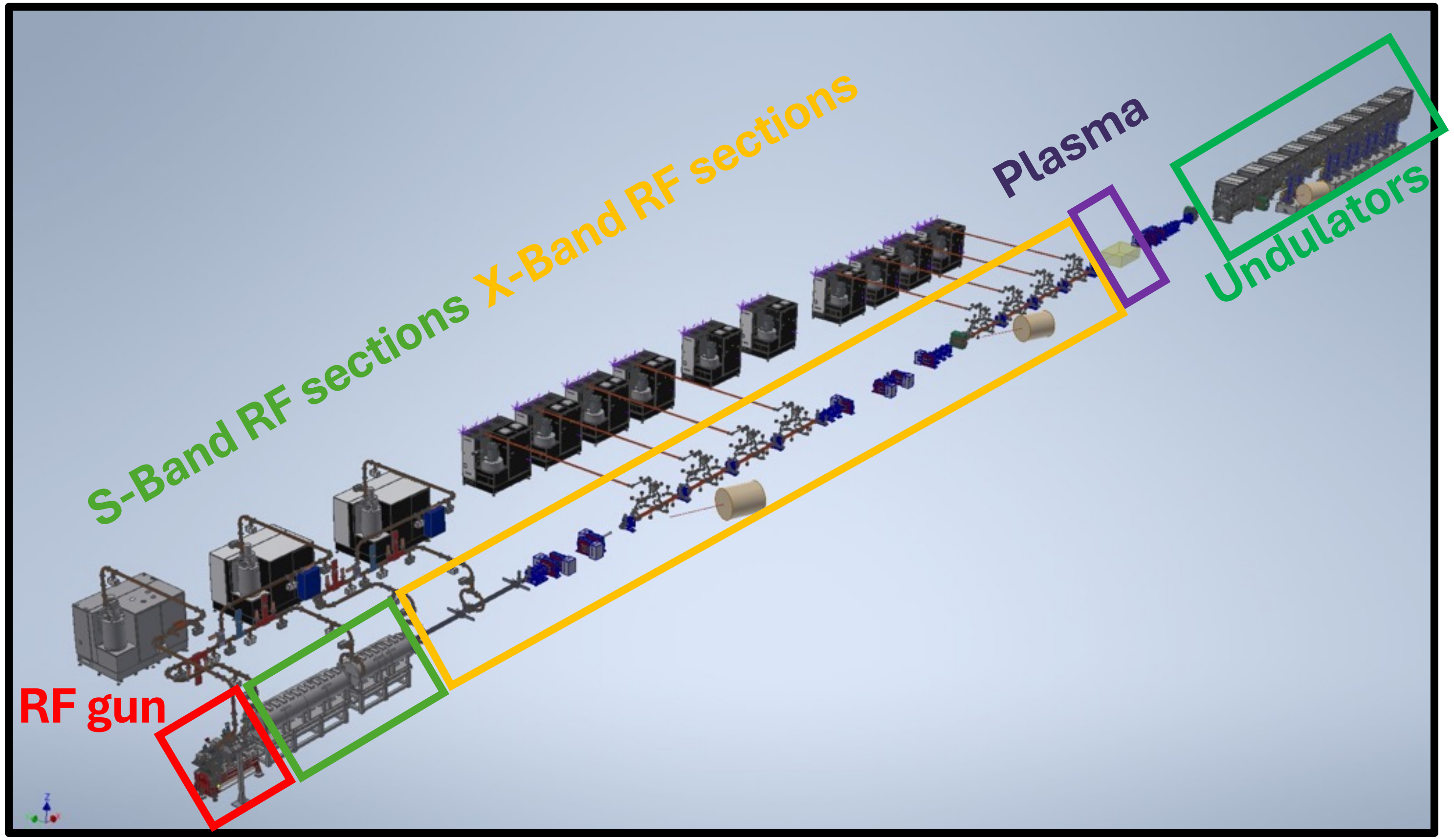
- Soft X-ray (< 4nm) FEL based on PWFA at INFN/Frascati
- 500 MeV 30 pC witness bunch boosted to 1 GeV in 60-cm-long discharge-plasma capillary



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- Installation starting ~ 2029
- Commissioning starting ~ 2030

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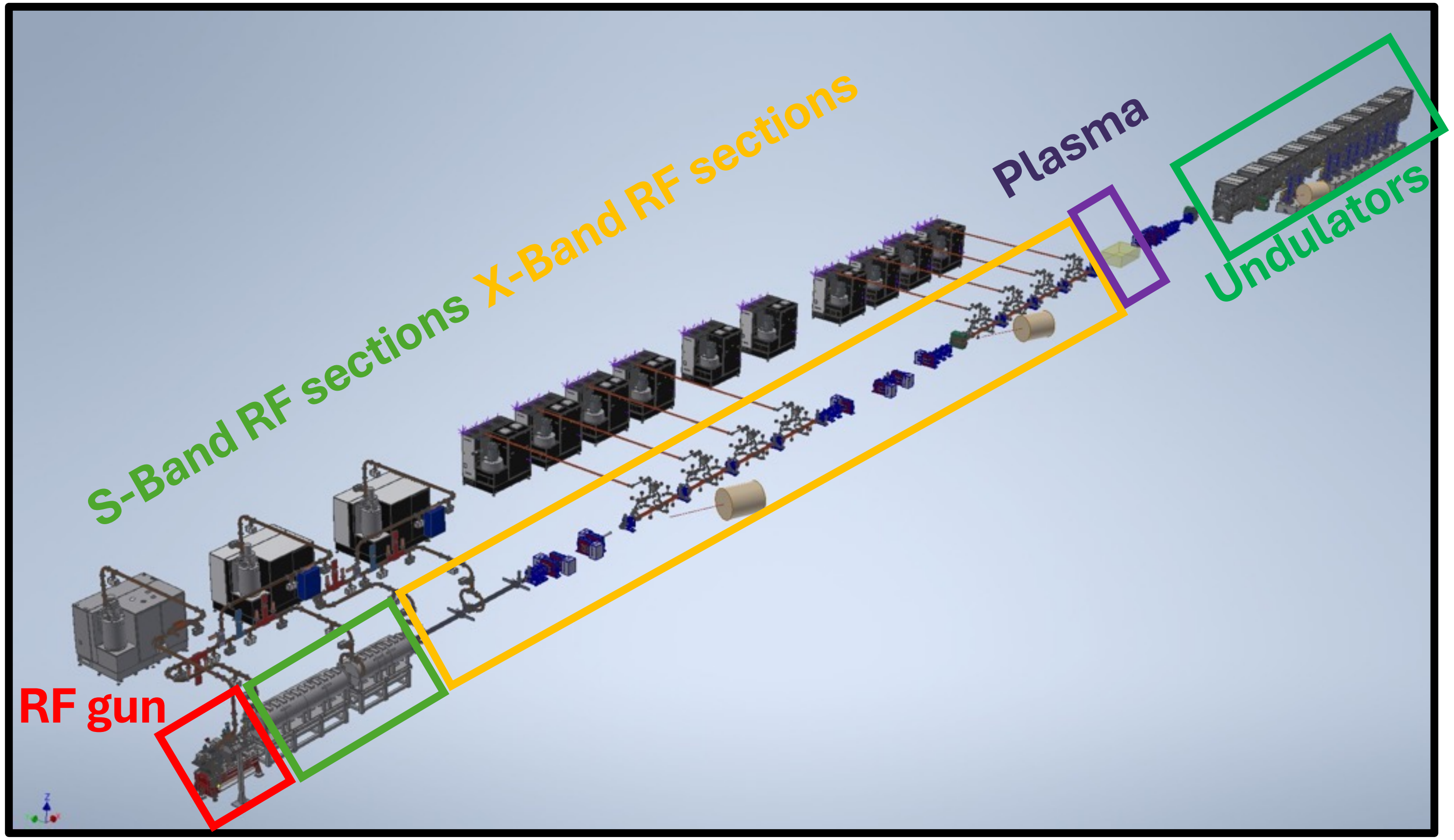

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User-oriented plasma-based FEL

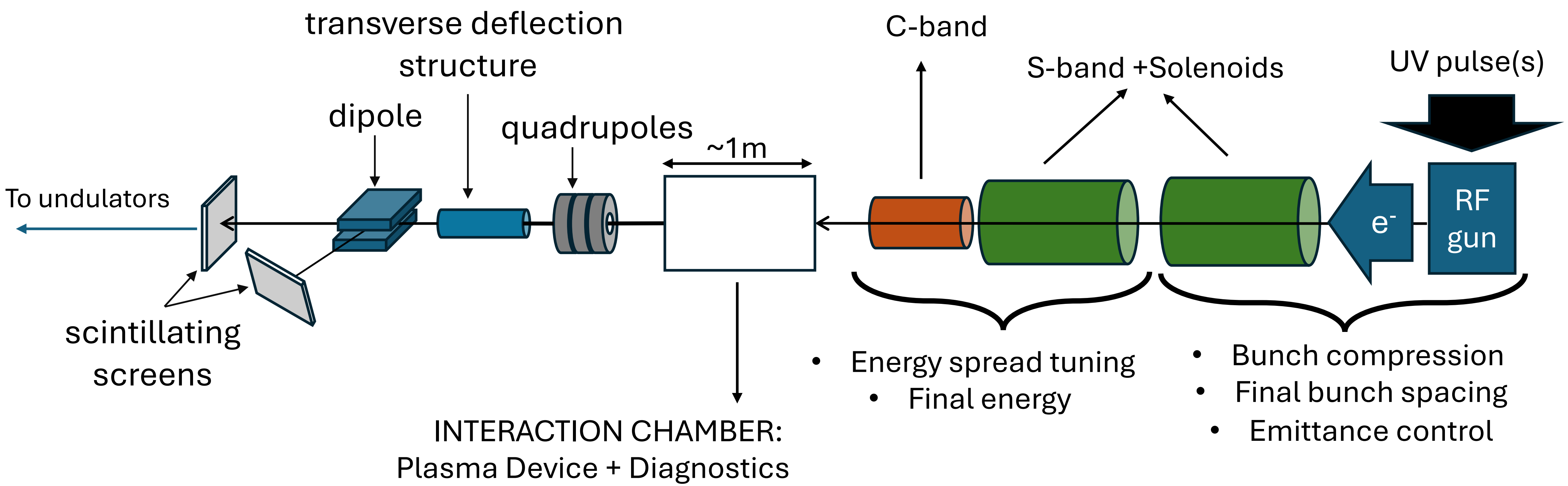
Transition from experiment to "real" accelerator

Building up from results and expertise from SPARC

0b. SPARC - Setup

- Photoinjector + Linac
  - Acceleration and bunch compression (<20 fs)
  - Velocity Bunching
- Discharge Plasma Capillary
- Diagnostics (Charge, Energy, Emittance, etc..)
- Undulators

Charge (total)	20 – 1000 pC
Energy	70 – 150 MeV
Normalized Emittance	~ 1 mm mrad
Bunch Duration (rms)	0.02 – 3 ps
Bunch Transverse size (rms)	0.1 – 0.5 mm



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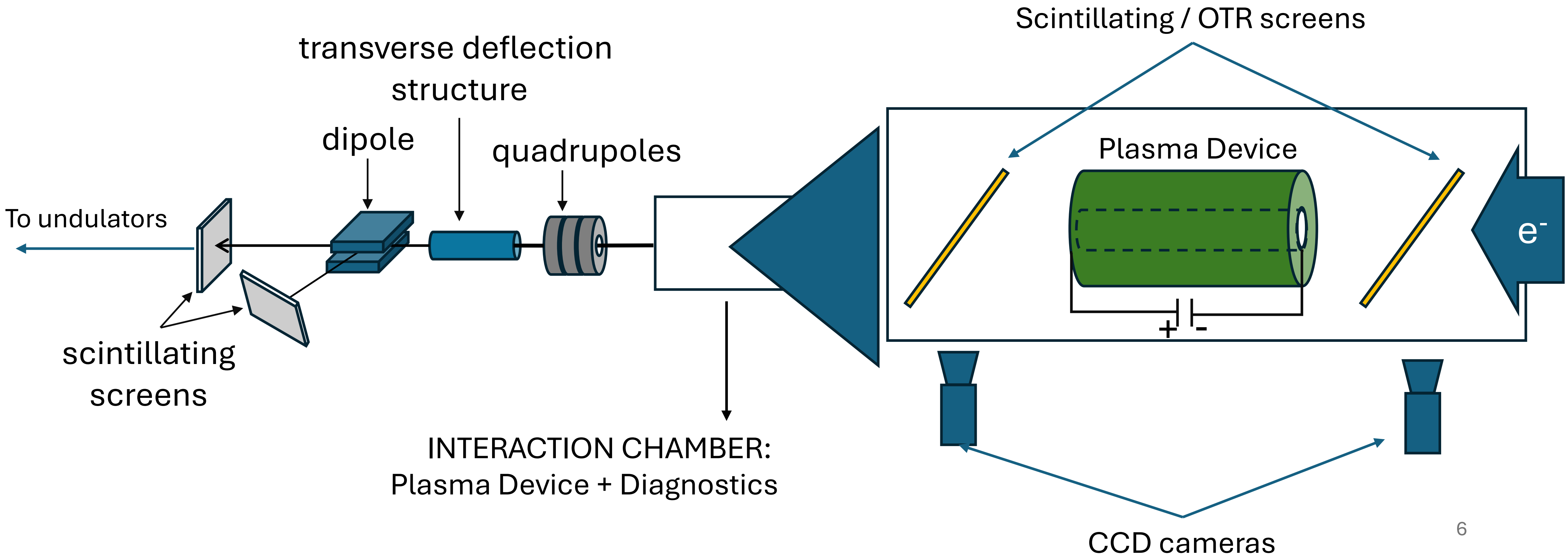
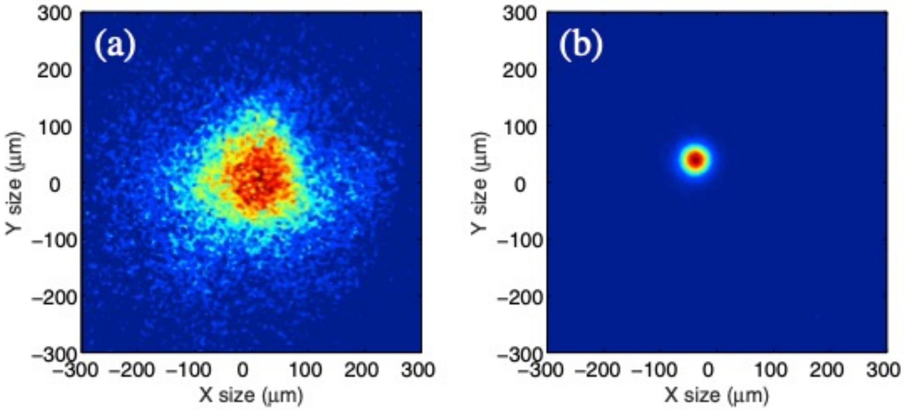


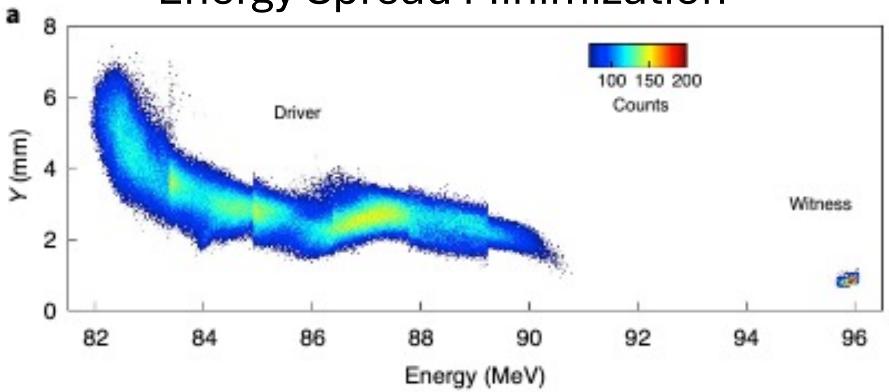
0b. SPARC – Previous Results

Active Plasma Lens



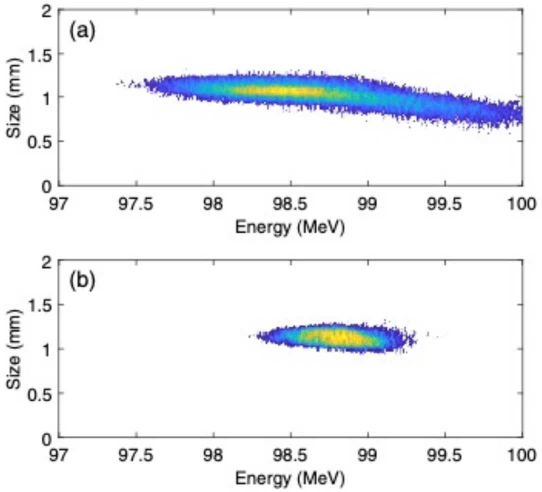
Pompili et al. PRL 121, 174801 (2018)

Energy Spread Minimization



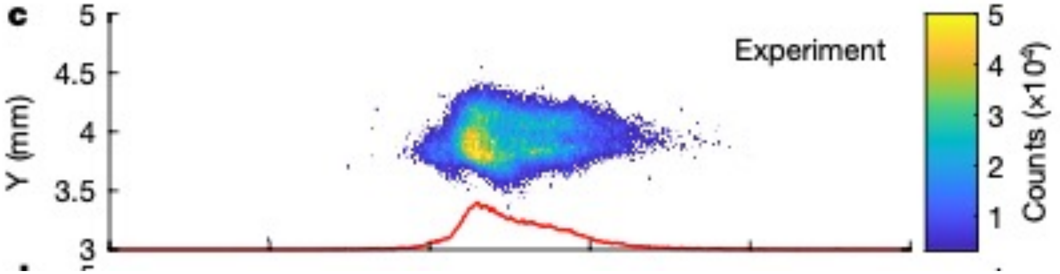
Pompili et al. Nat. Phys. 17, 499-503 (2021)

Plasma Dechirper



Shpakov et al. PRL 122, 114801 (2019)

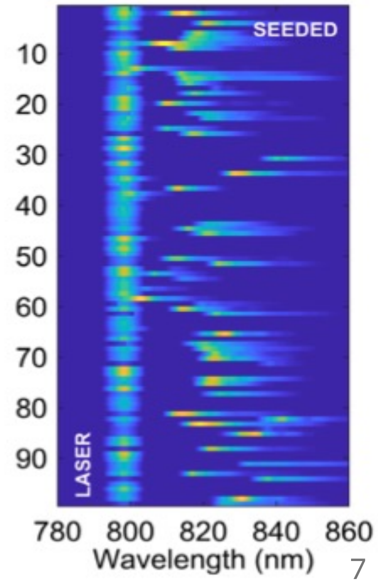
Lasing of PWFA witness bunch (SASE)



Pompili et al. Nature 605, 659-662 (2022)

Results building up expertise and paving the way towards EuPRAXIA

Lasing of PWFA witness bunch (Seeded)



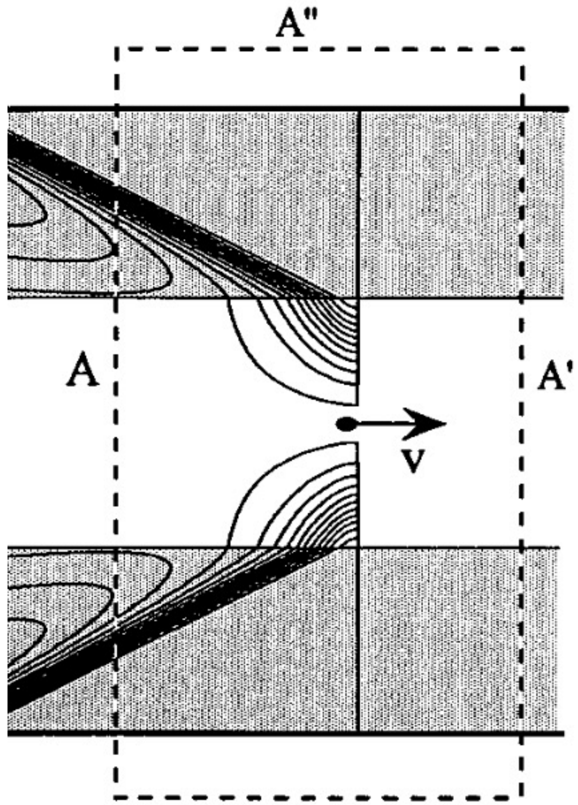
Galletti et al. PRL 129, 234801 (2022)

Summary

MOTIVATION

- Space-charge field of relativistic bunches interacts with slow-wave structures **(e.g. dielectric capillary)**
  → Cherenkov/Dielectric wakefields (DW)
  → Acting back on the drive bunch and on the witness bunch

- Beam couples with dipolar mode when traveling off-axis in a dielectric capillary
  - → Transverse deflection in the misalignment direction
  - → Head-to-tail correlation



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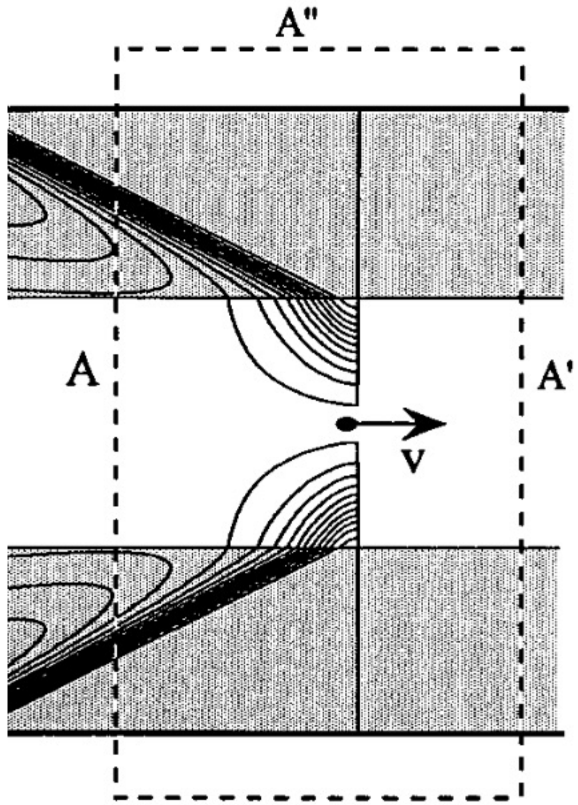
- Possible use as passive longitudinal diagnostics



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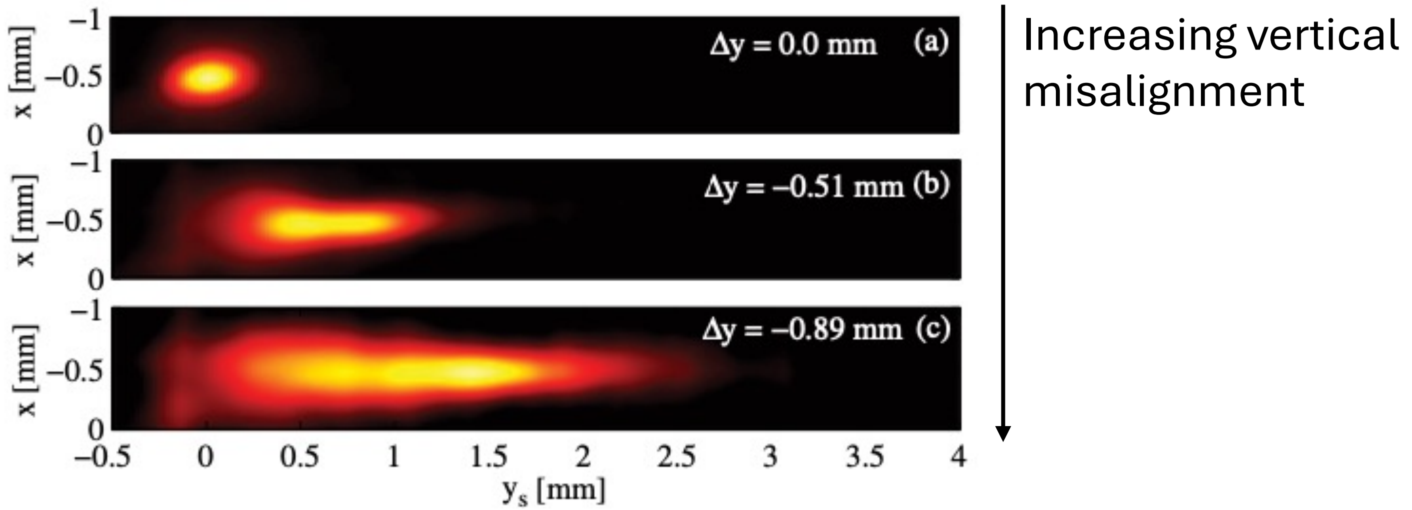

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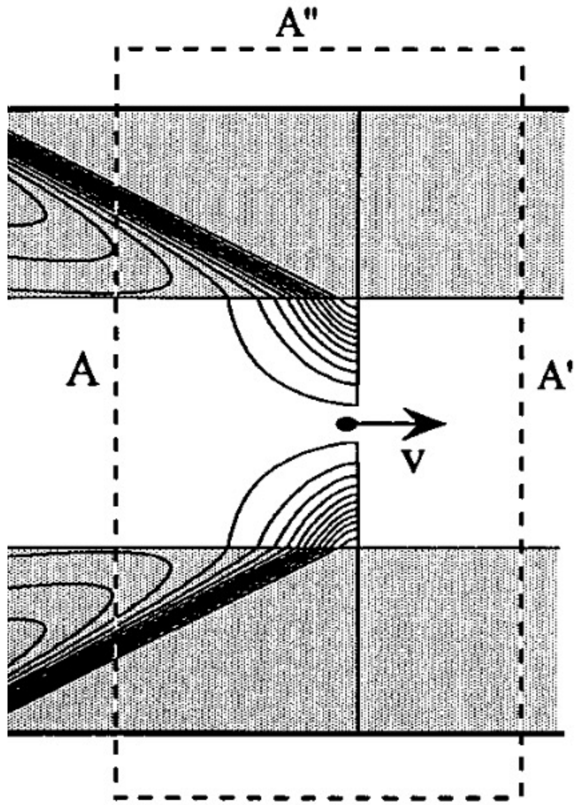

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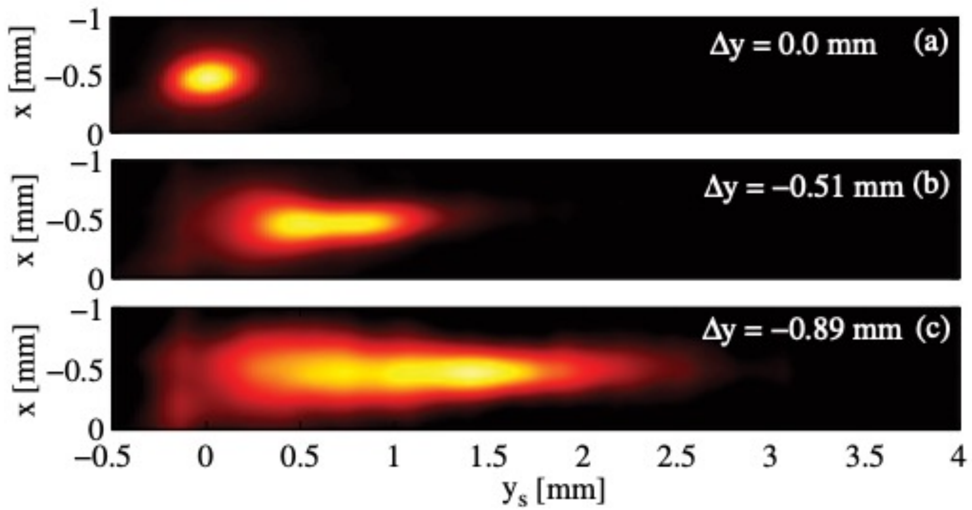


Increasing vertical misalignment

S. Bettoni, P. Craievich, A. A. Lutman, M. Pedrozzi PRAB **19**, 021304 (2016)

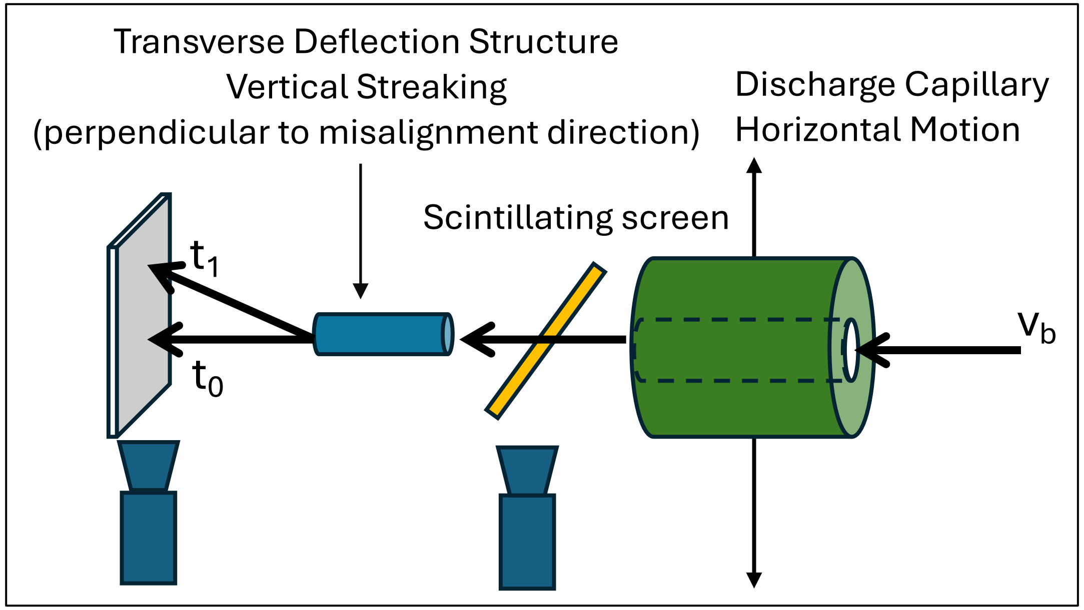
If space-charge is screened:
→ no dielectric wakefields
→ no transverse deflection

This work

I. Space-Charge Field Screening in Plasma

- Effect of DW clearly visible when beam travels off-axis in uncoated plastic capillary. L=10cm, R=1mm

Specific Setup



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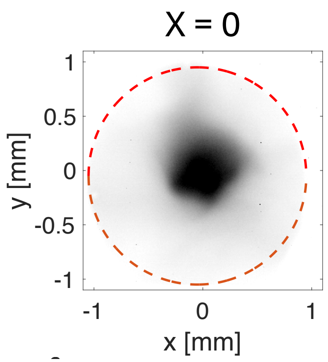

Transverse time-integrated images
→ "shadow'' of the capillary

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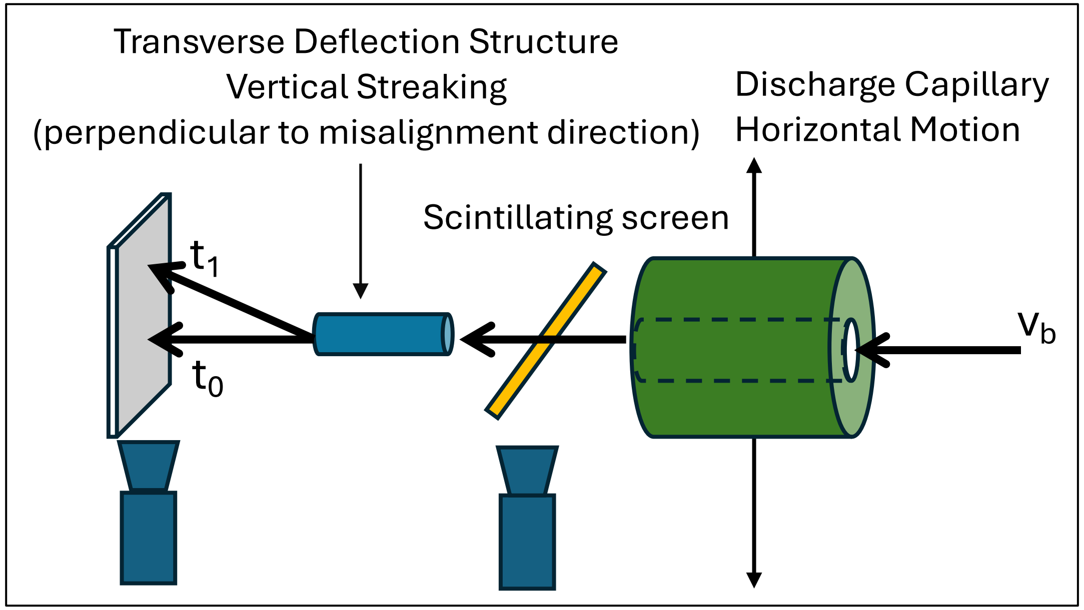

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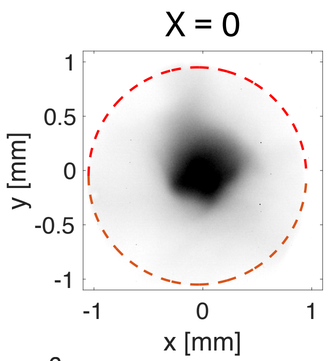

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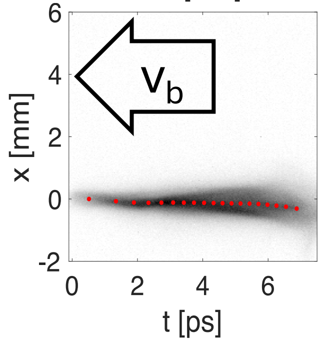

Transverse time-resolved images (using TDS)

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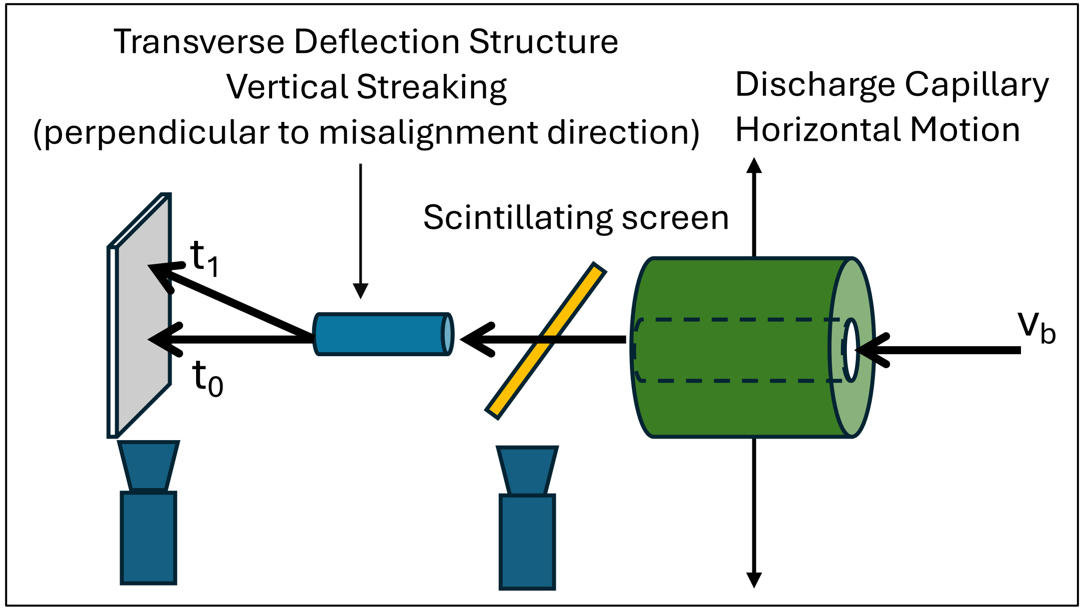

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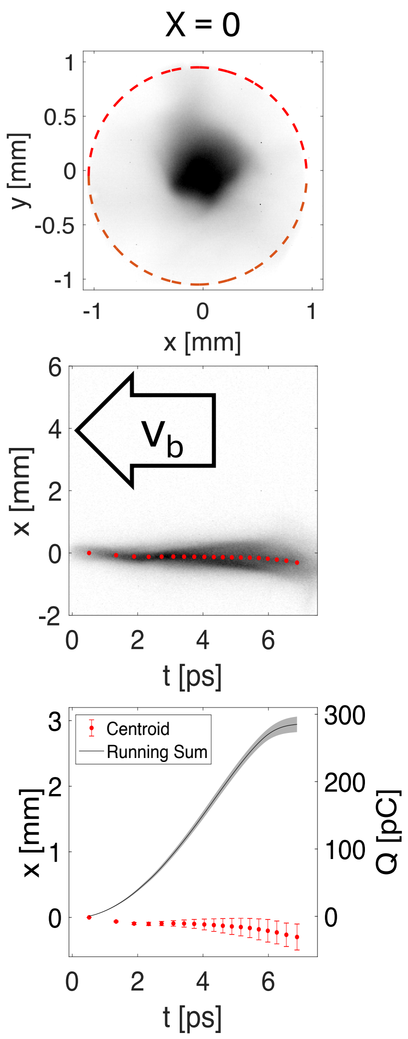

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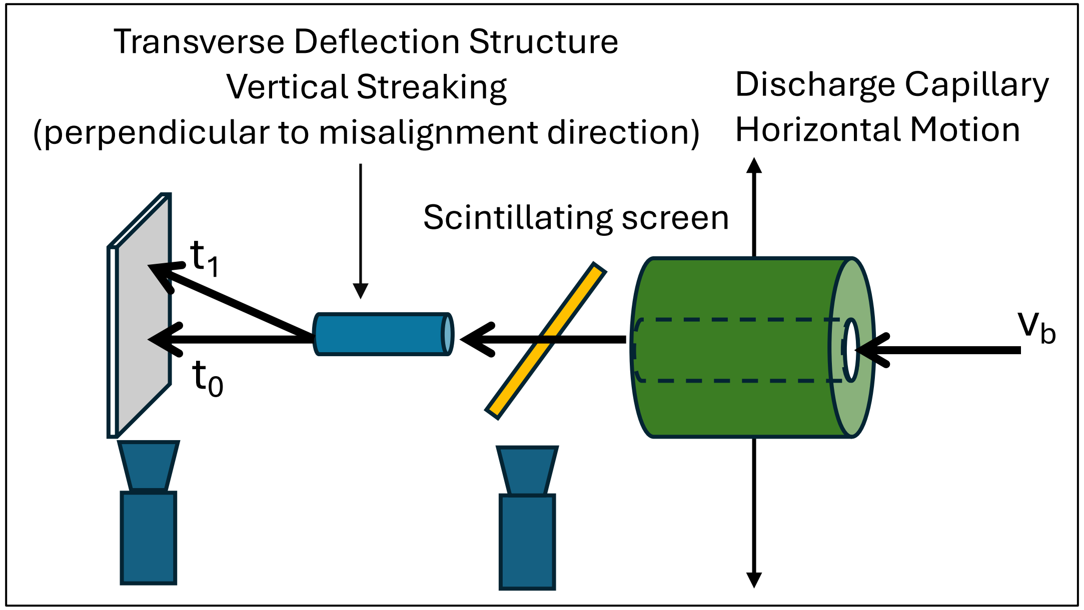
Transverse time-resolved images (using TDS)

- Centroid of longitudinal slices
- Running integral of the charge

Specific Setup



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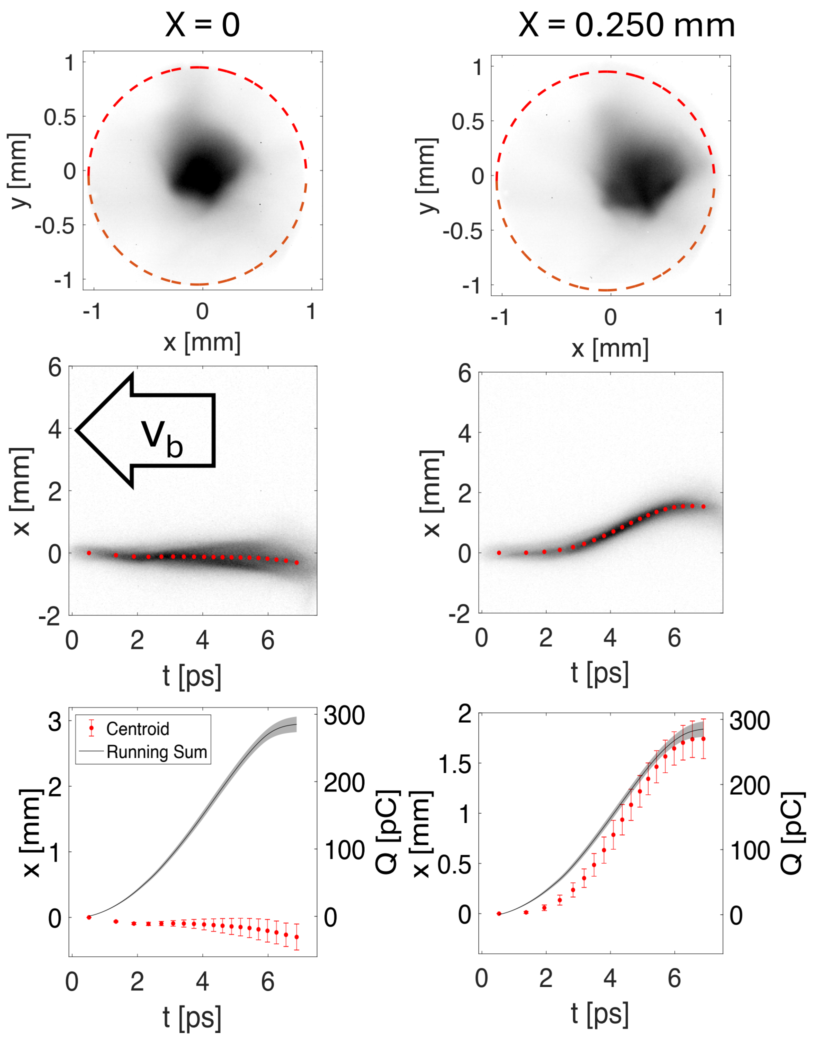

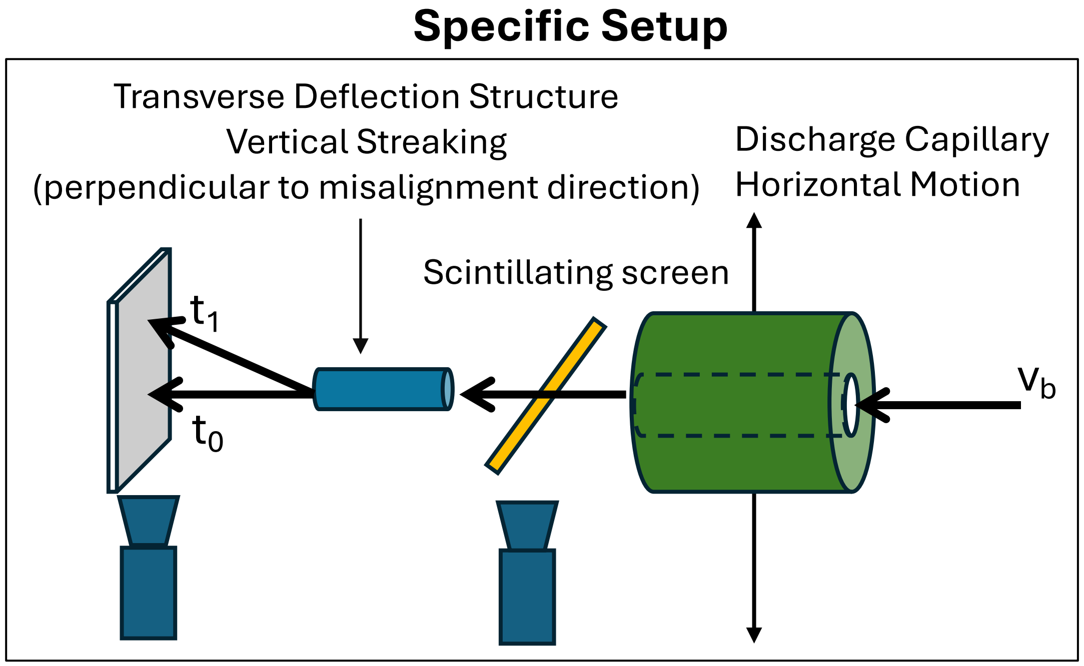

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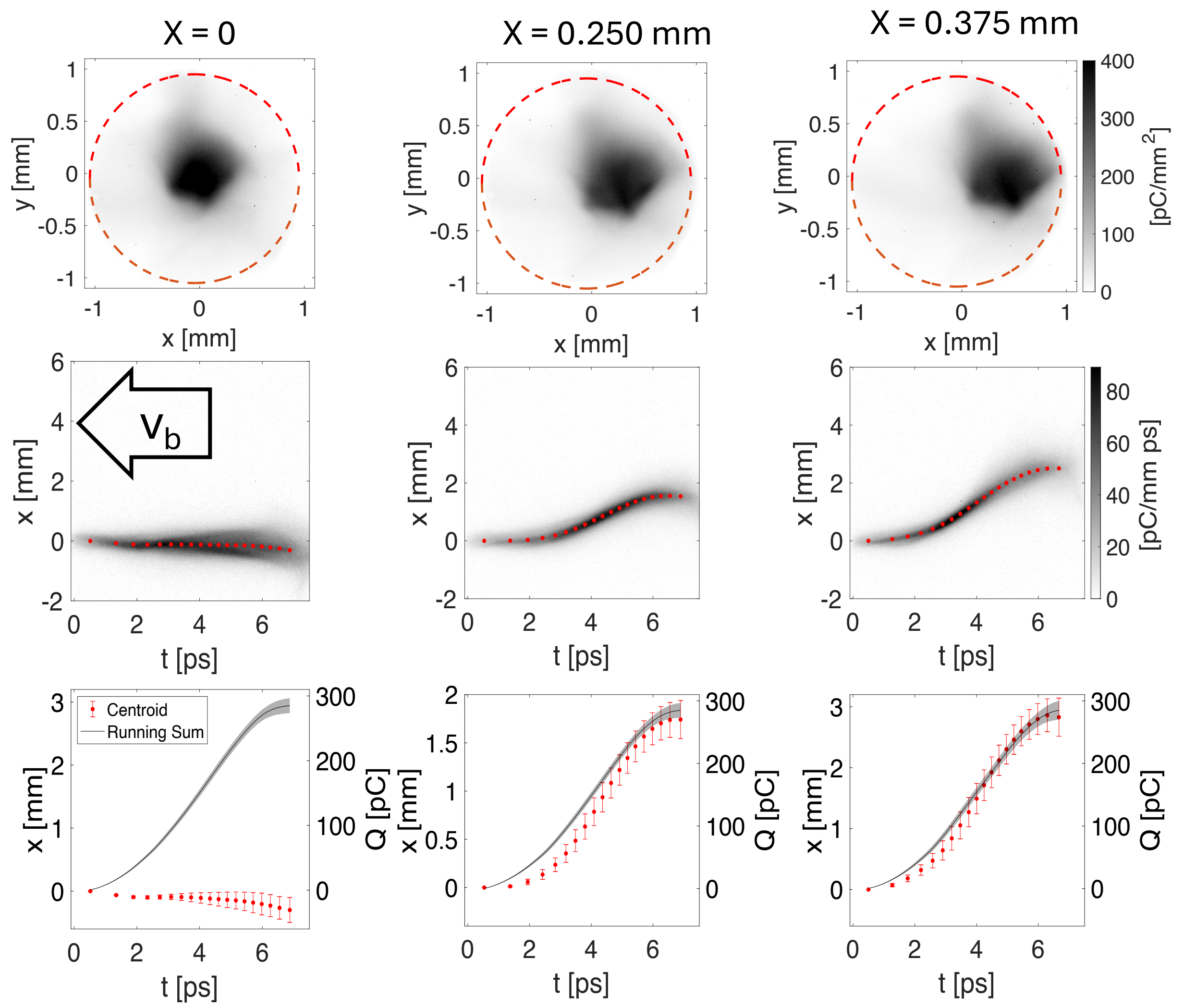

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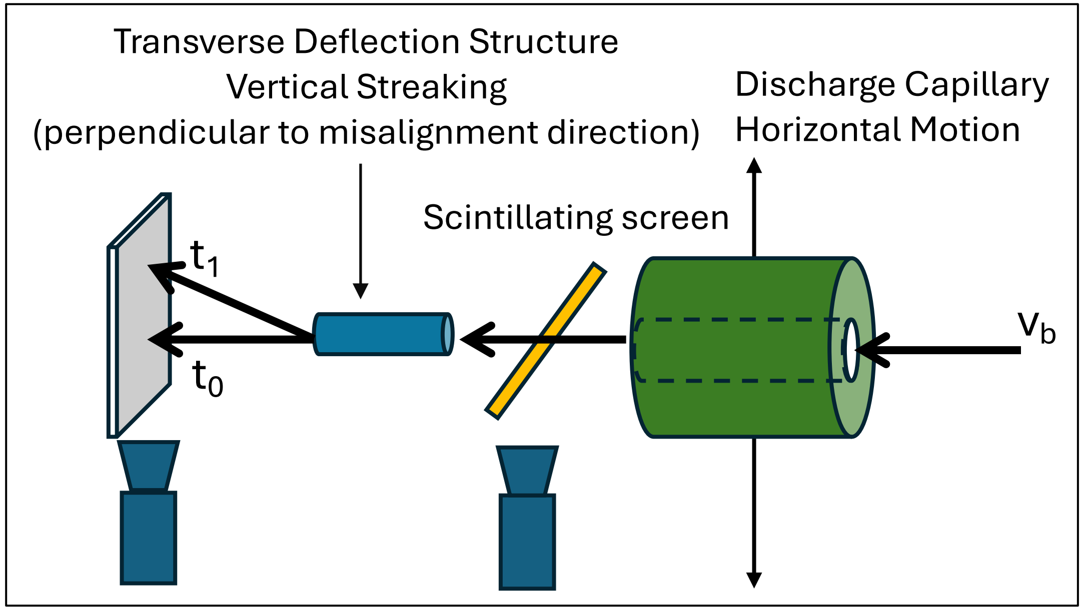

Dipolar force increases with:

- offset
- with running integral of charge

$$W_\perp(t) \propto w(x,y) \cdot \int_0^t n_b(t)dt$$

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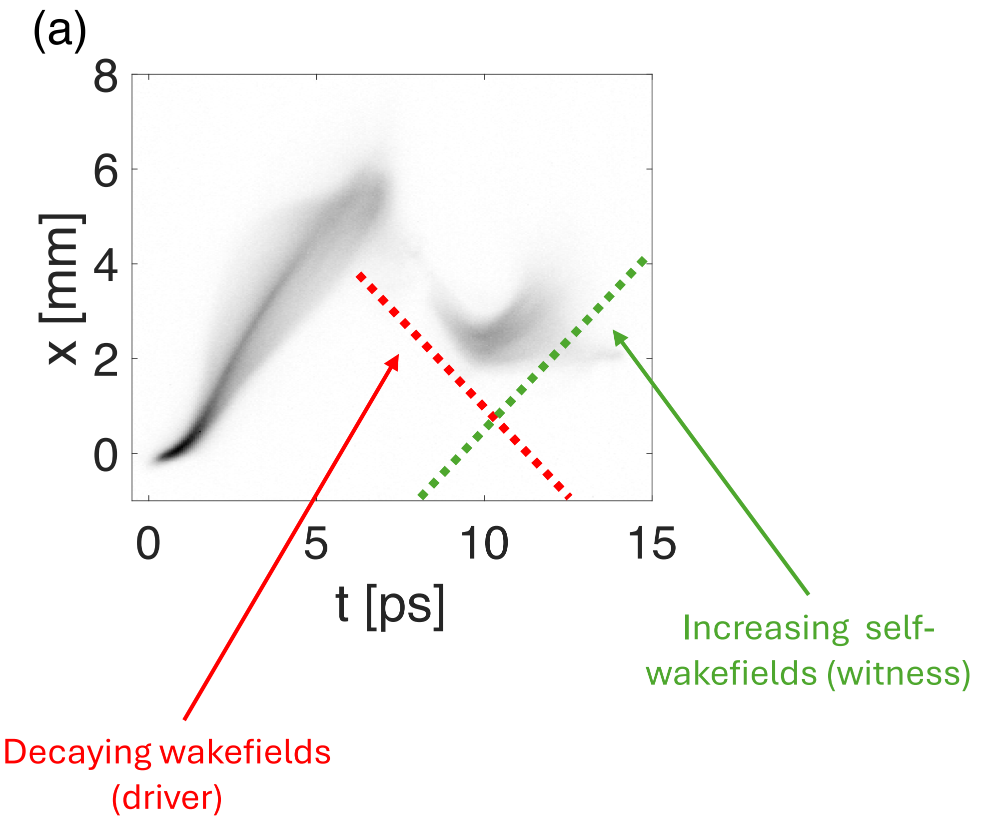
    - Dielectric wakefields decay after the drive bunch has passed (uncoated dielectric)
- Witness also affected by self-driven wakefields



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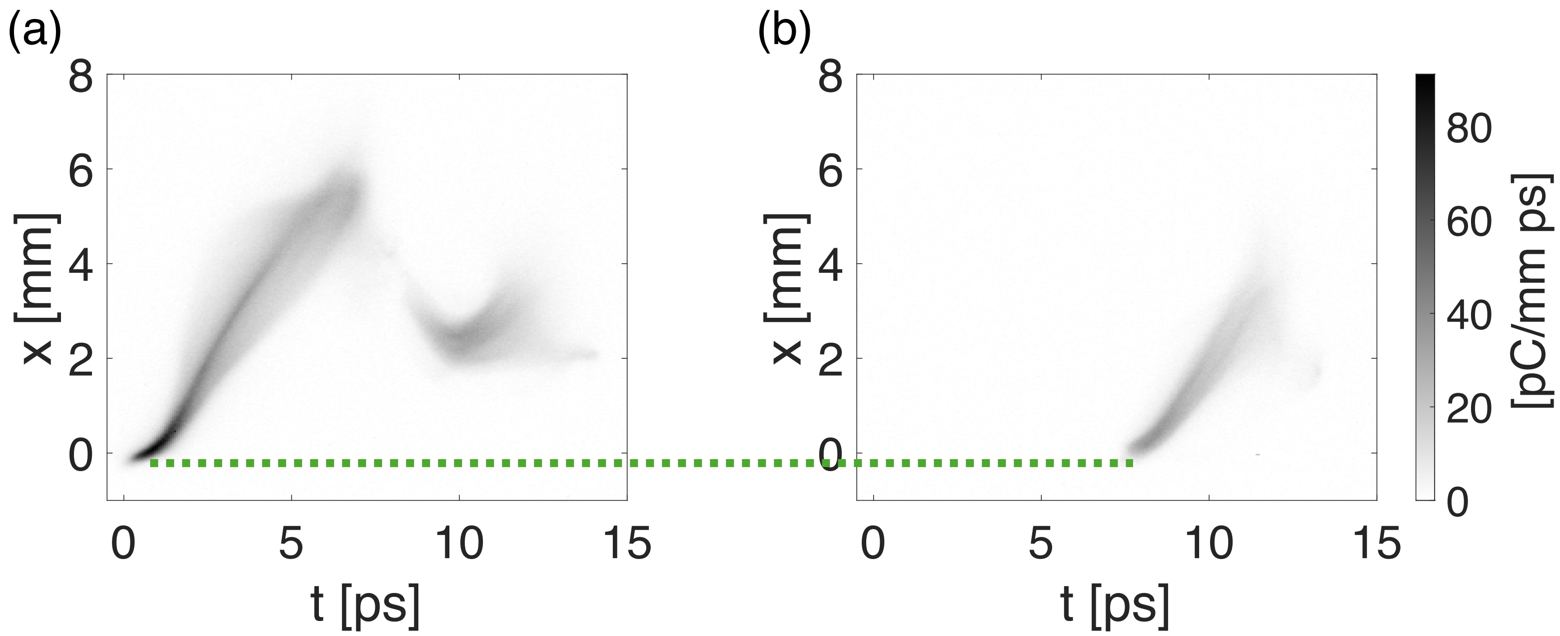

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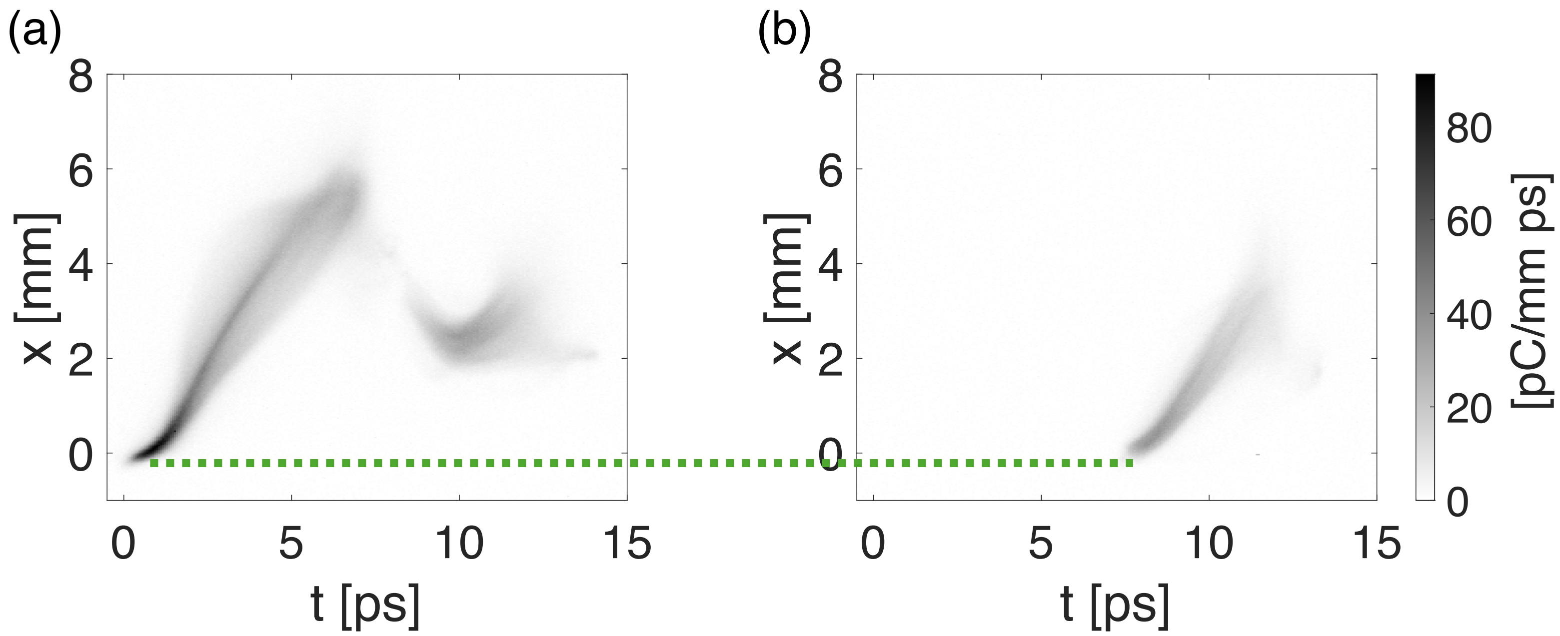

Can the plasma take care of the misalignment?

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- Space-charge field of relativistic bunches has the same properties of an electromagnetic field
- Plasma screens electromagnetic fields as $E_r \propto e^{-\frac{r}{\delta}}$ ➔ full screening at r >> plasma skin depth $\delta = c\sqrt{\frac{m_e \epsilon_0}{n_{pe} q^2}}$
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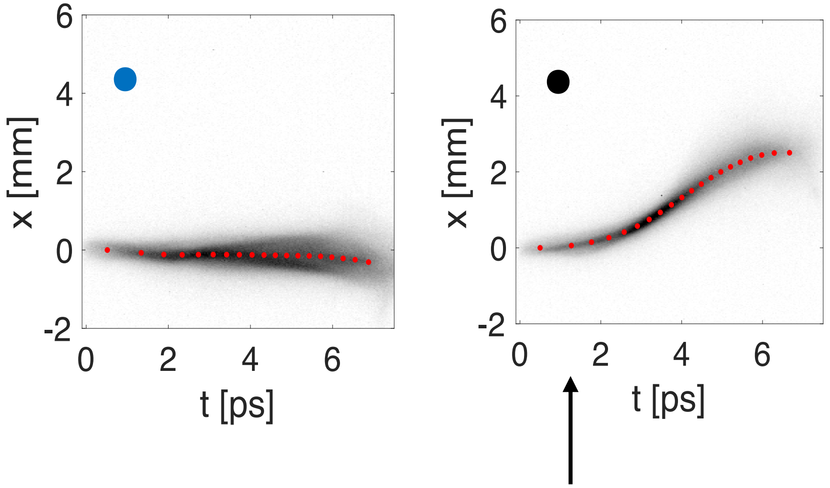
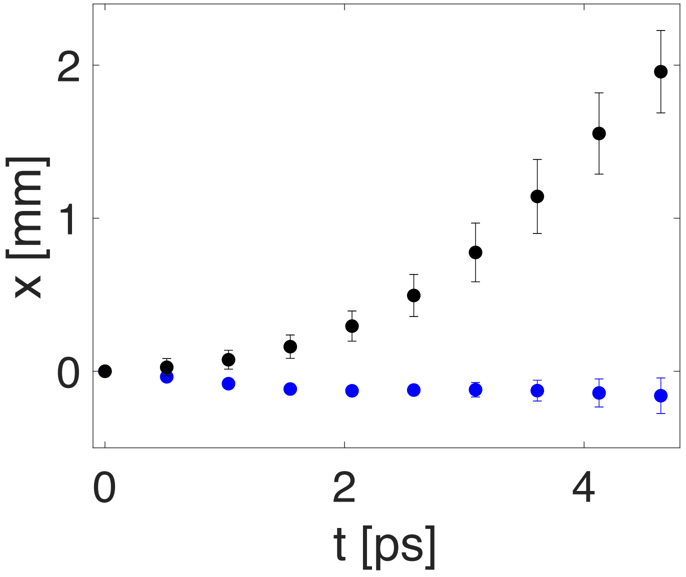
Aligned
No plasma

Misaligned
No plasma



DW effect



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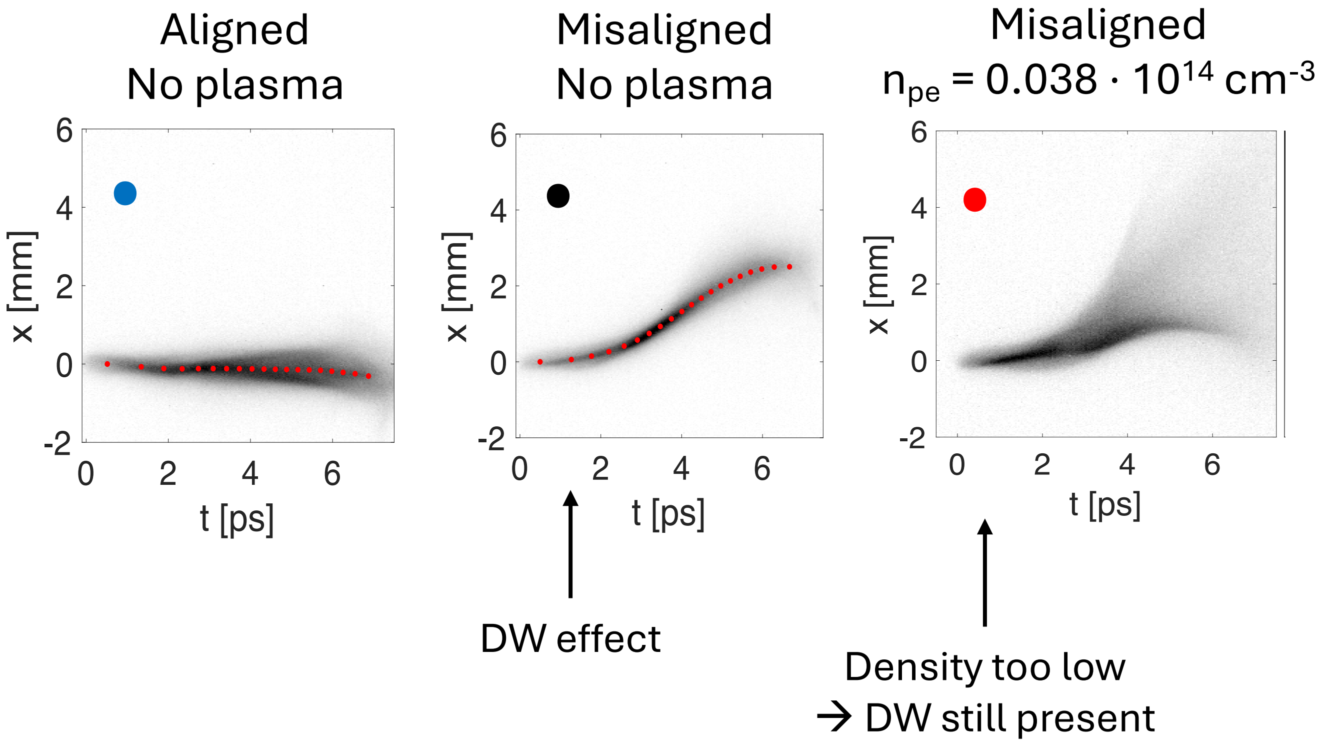

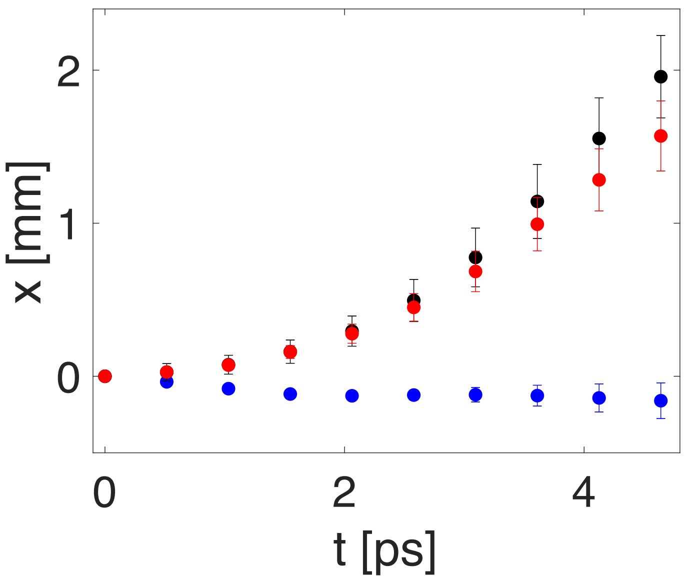

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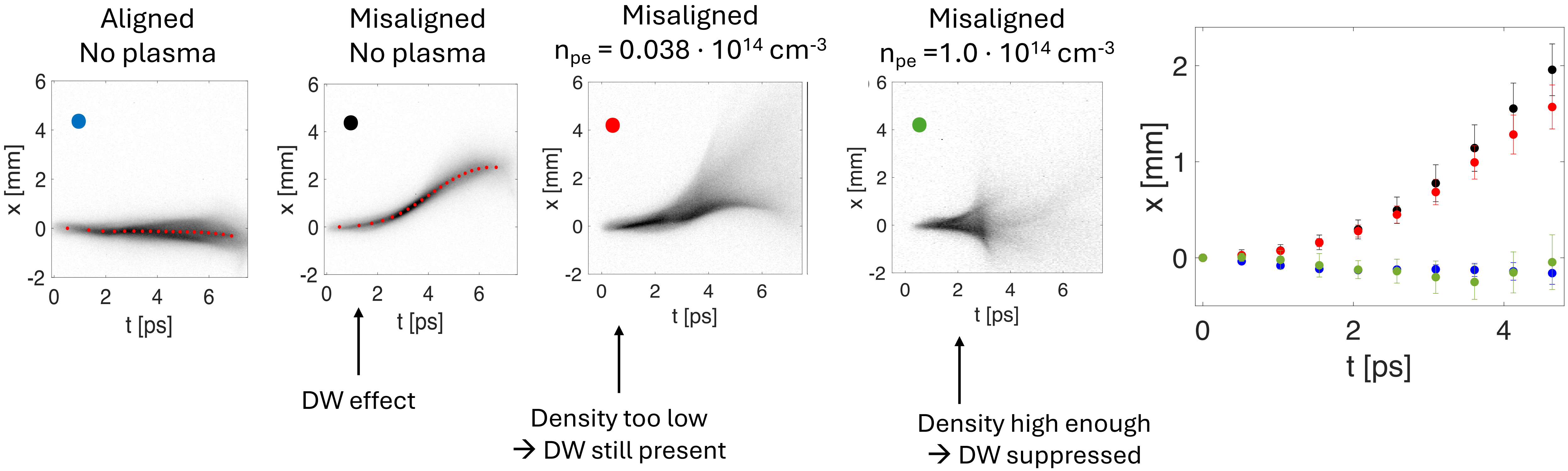

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- Both wakefields present simultaneously at low densities
- Only PW at high density → transition depends on distance from capillary surface

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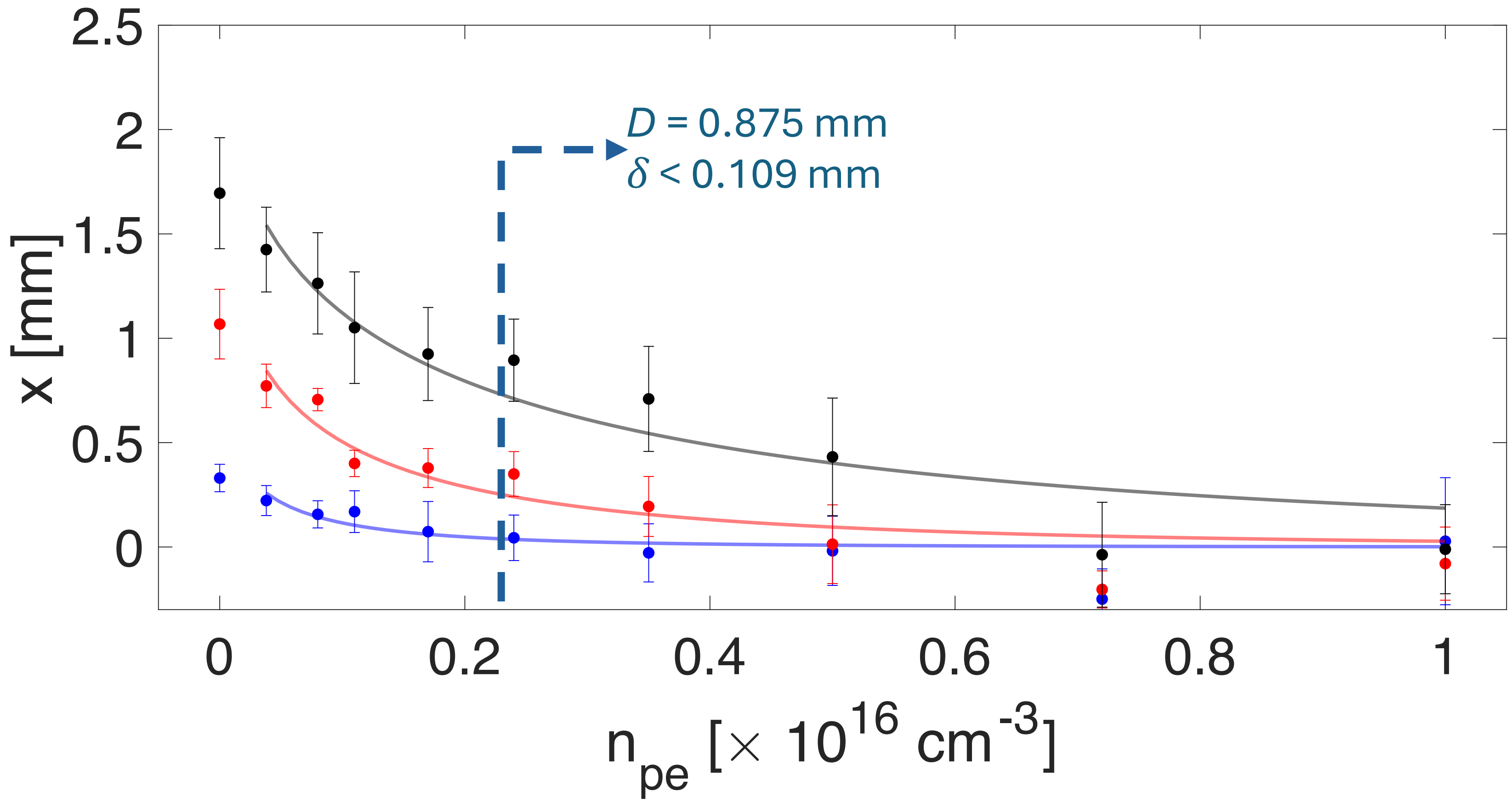

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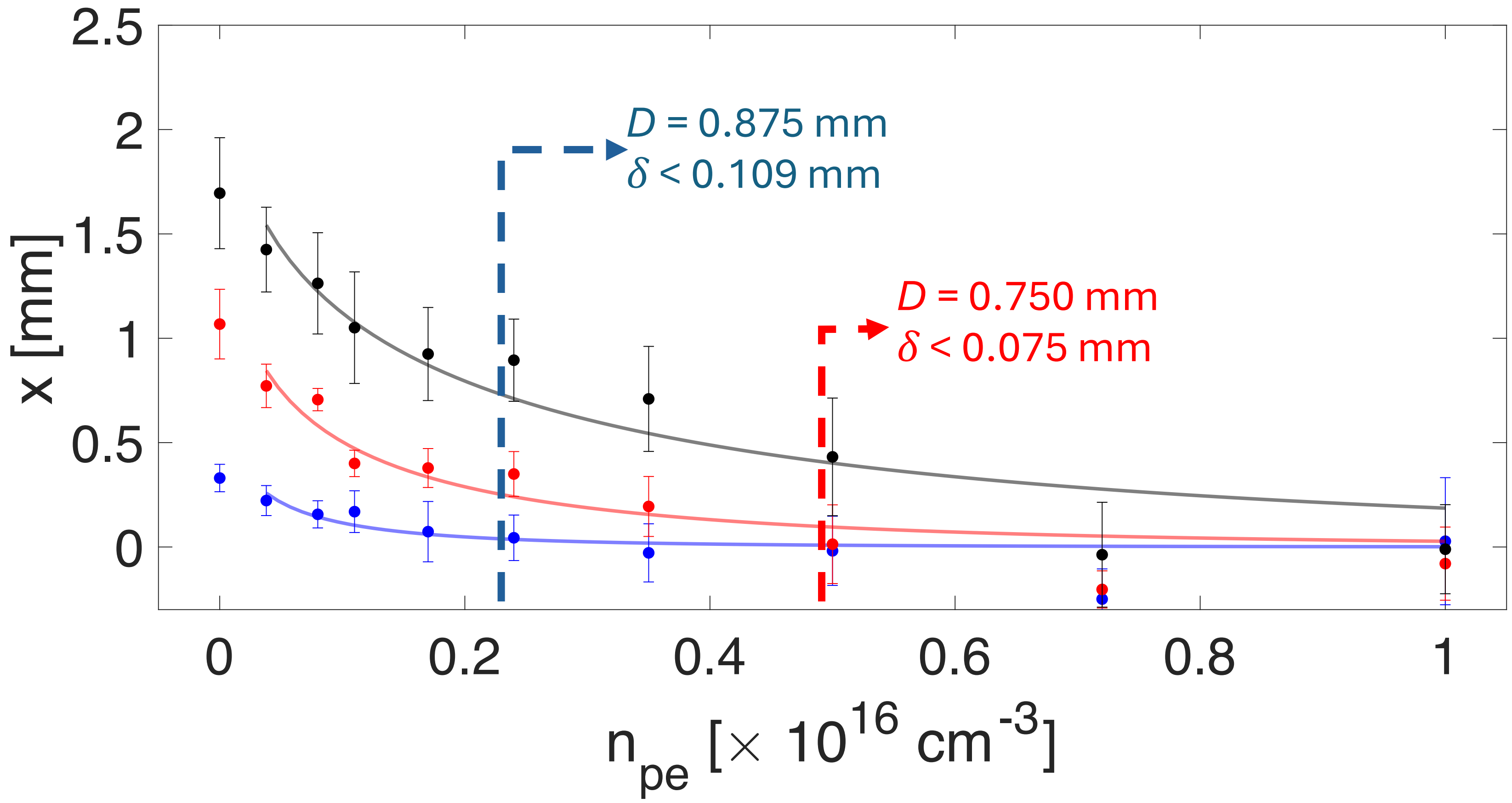

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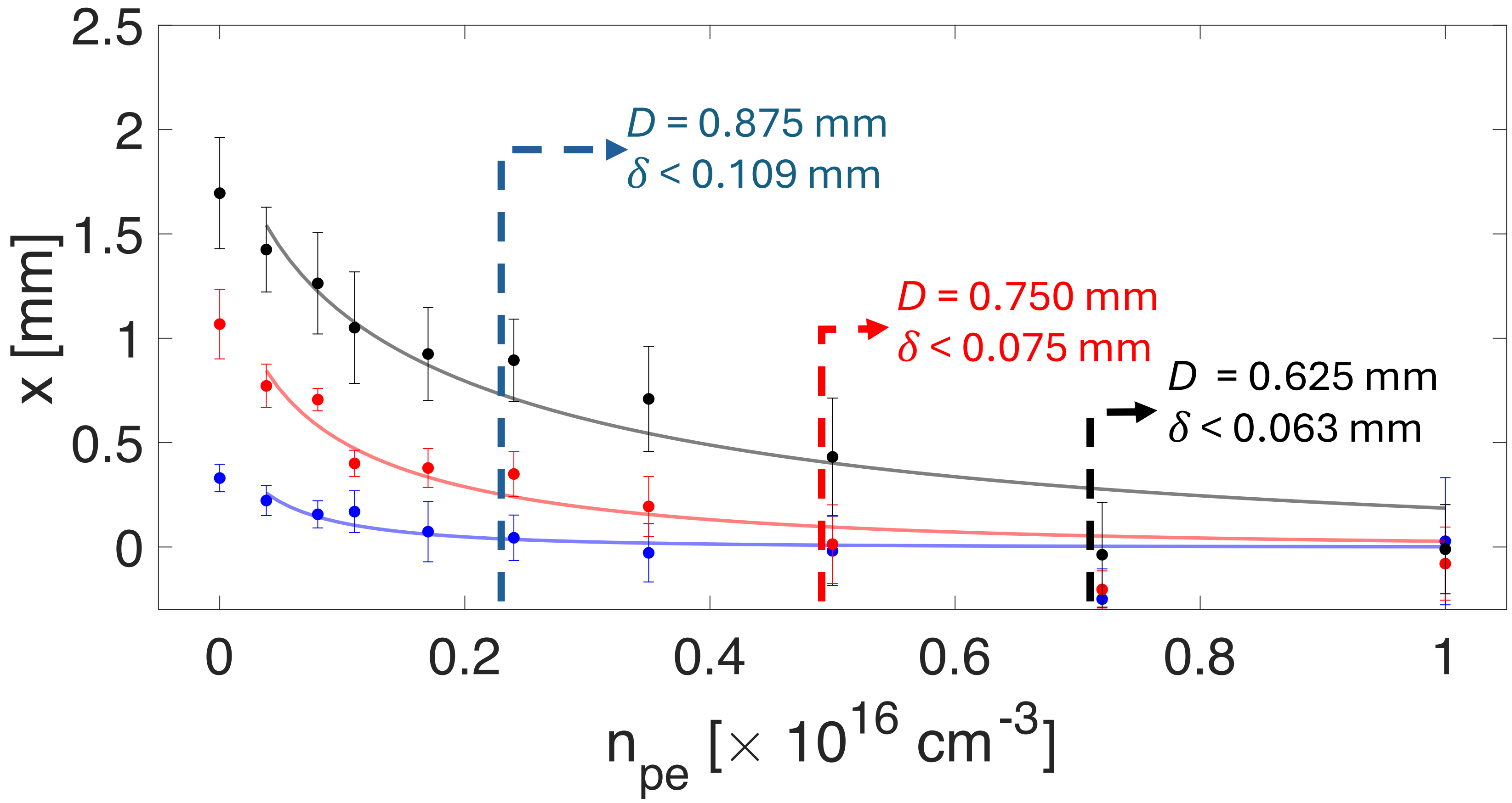

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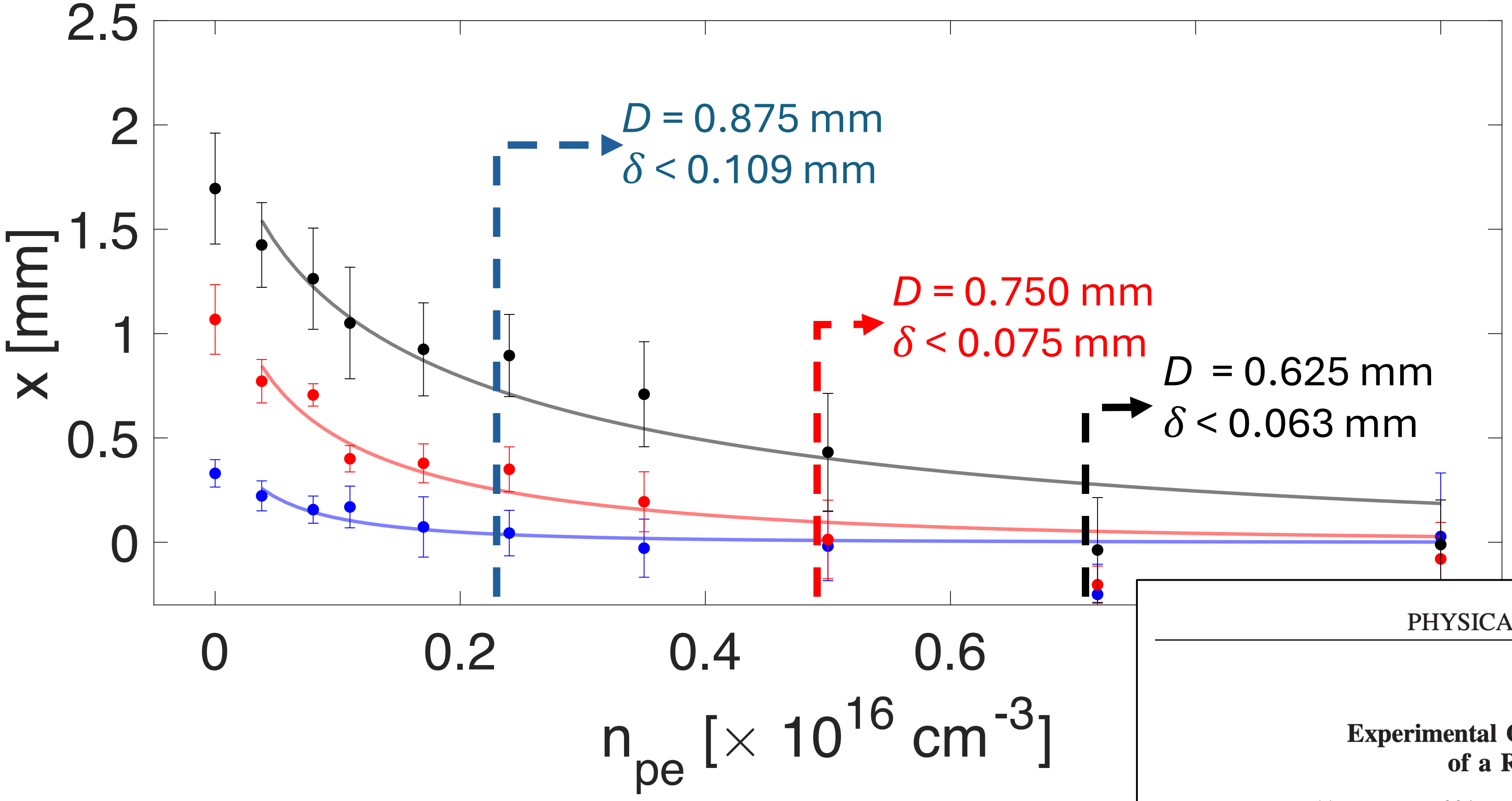
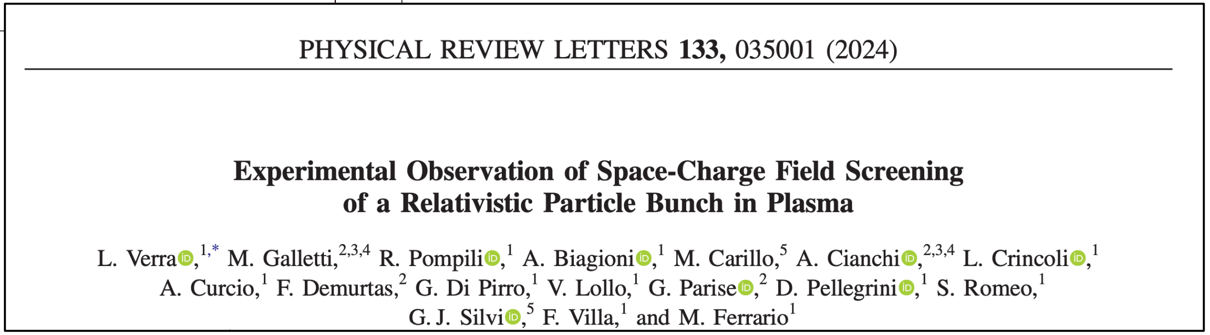


‘Basic physics’ result: plasma screening of space-charge field

Useful result for beam driven accelerators as EuPRAXIA
➔ tolerance on transverse alignment
(well within current capabilities)



PHYSICAL REVIEW LETTERS **133,** 035001 (2024)

Experimental Observation of Space-Charge Field Screening of a Relativistic Particle Bunch in Plasma

L. Verra,[1,*] M. Galletti,[2,3,4] R. Pompili,[1] A. Biagioni,[1] M. Carillo,[5] A. Cianchi,[2,3,4] L. Crincoli,[1] A. Curcio,[1] F. Demurtas,[2] G. Di Pirro,[1] V. Lollo,[1] G. Parise,[2] D. Pellegrini,[1] S. Romeo,[1] G. J. Silvi,[5] F. Villa,[1] and M. Ferrario[1]

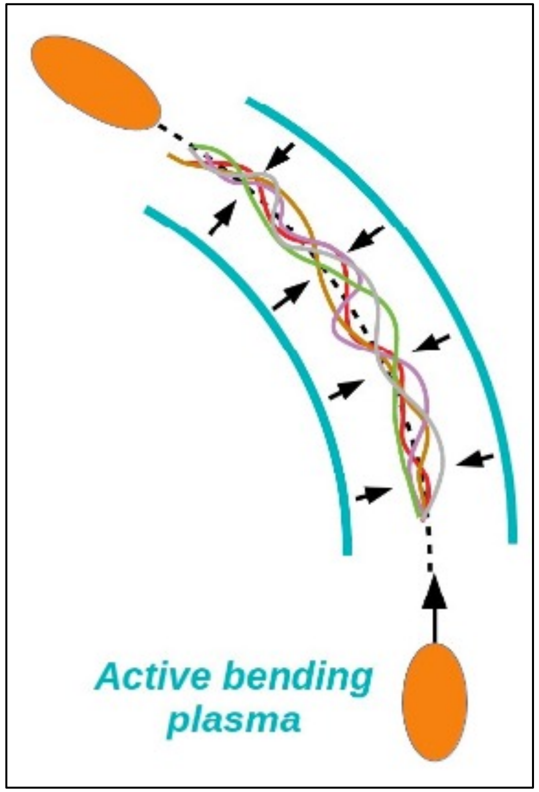
Summary

II. Guiding in Curved Plasma-Discharge Capillary

- Active Bending Plasma (ABP) acts as a curved active plasma lens

  Azimuthal magnetic field $B_\phi = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$

  → restoring force keeps bunch close to longitudinal axis



R. Pompili et al., PRL **132**, 215001 (2024)

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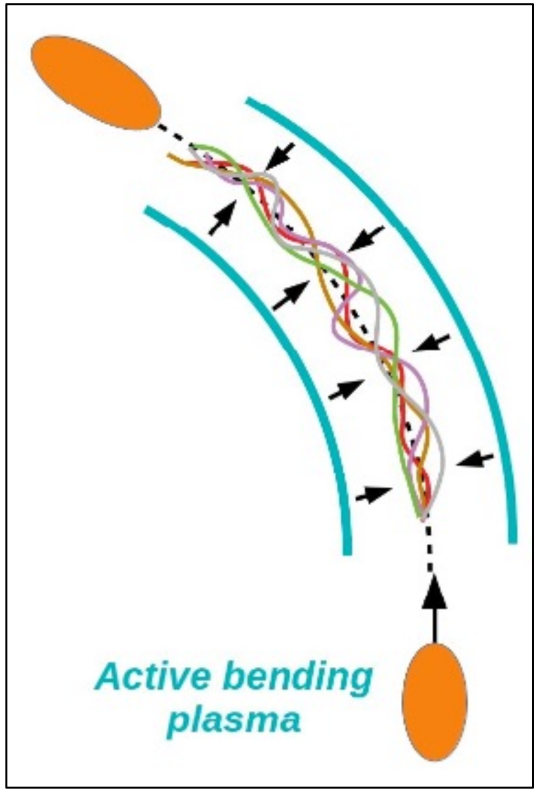

Stronger restoring force for outer particles
→ Potentially achromatic bending

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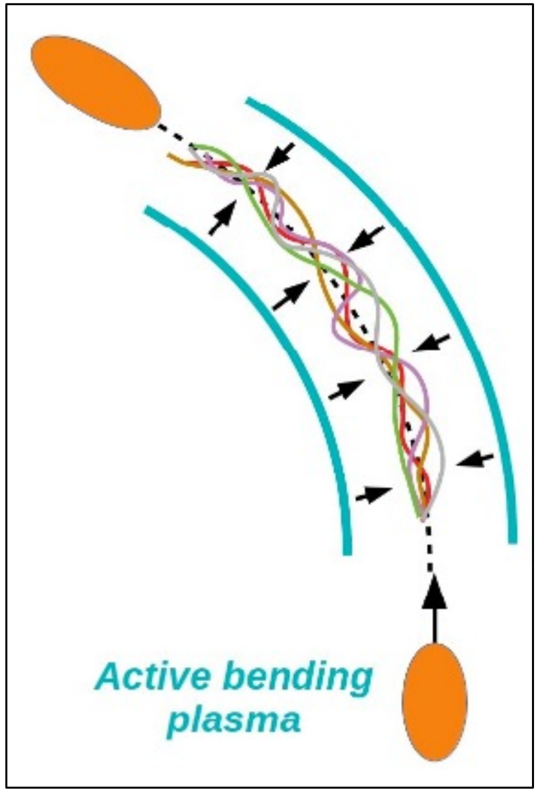

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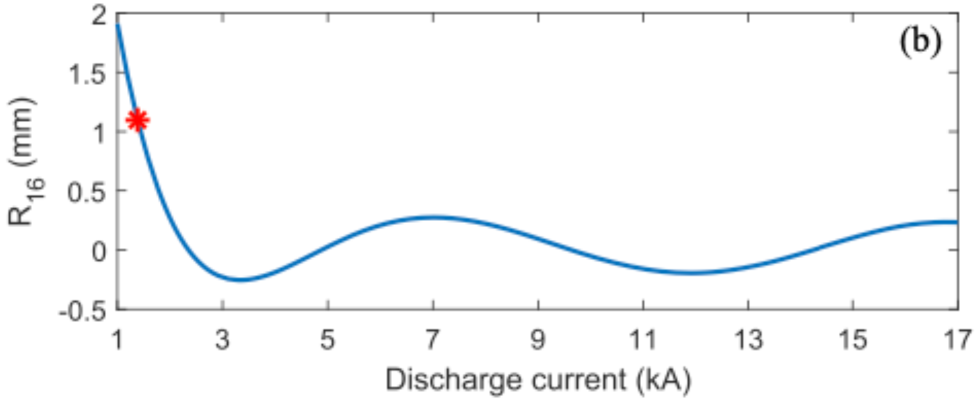

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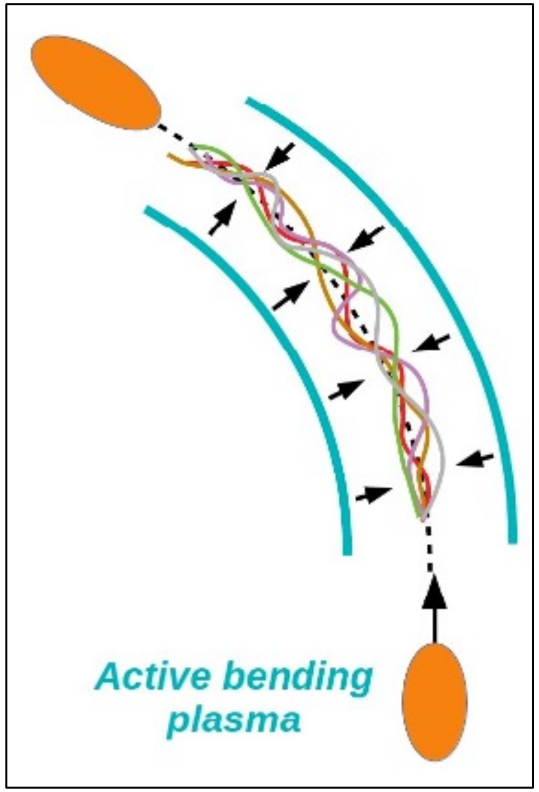
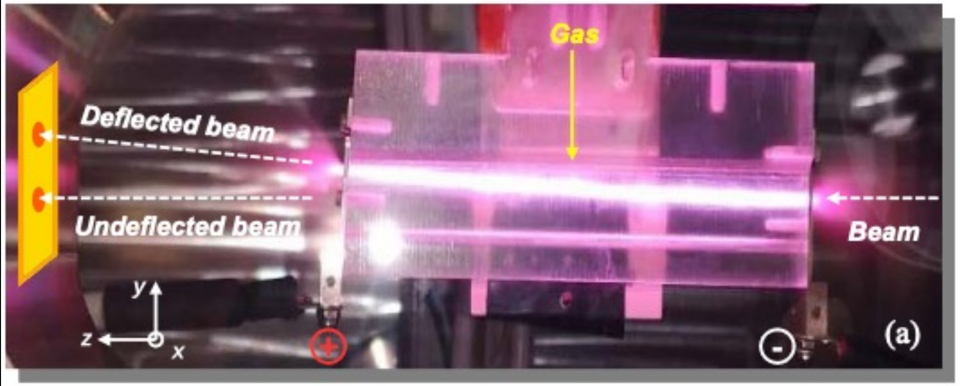
  Azimuthal magnetic field $B_\phi = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$

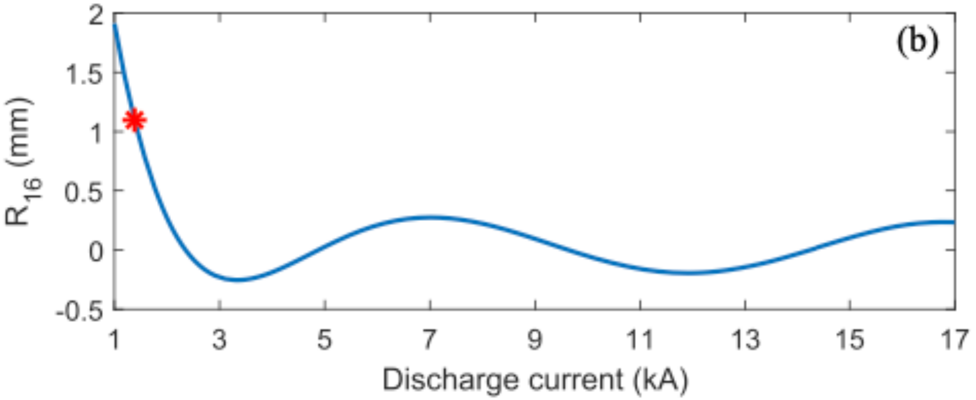
  → restoring force keeps bunch close to longitudinal axis



- 3D-printed plastic discharge capillary
- R_b = 1.6 m, L_c=10 cm
- I~1.6 kA, 20 kV
- n_{pe} ~ 2.5 x 10^{17} cm^{-3}



Stronger restoring force for outer particles
→ Potentially achromatic bending



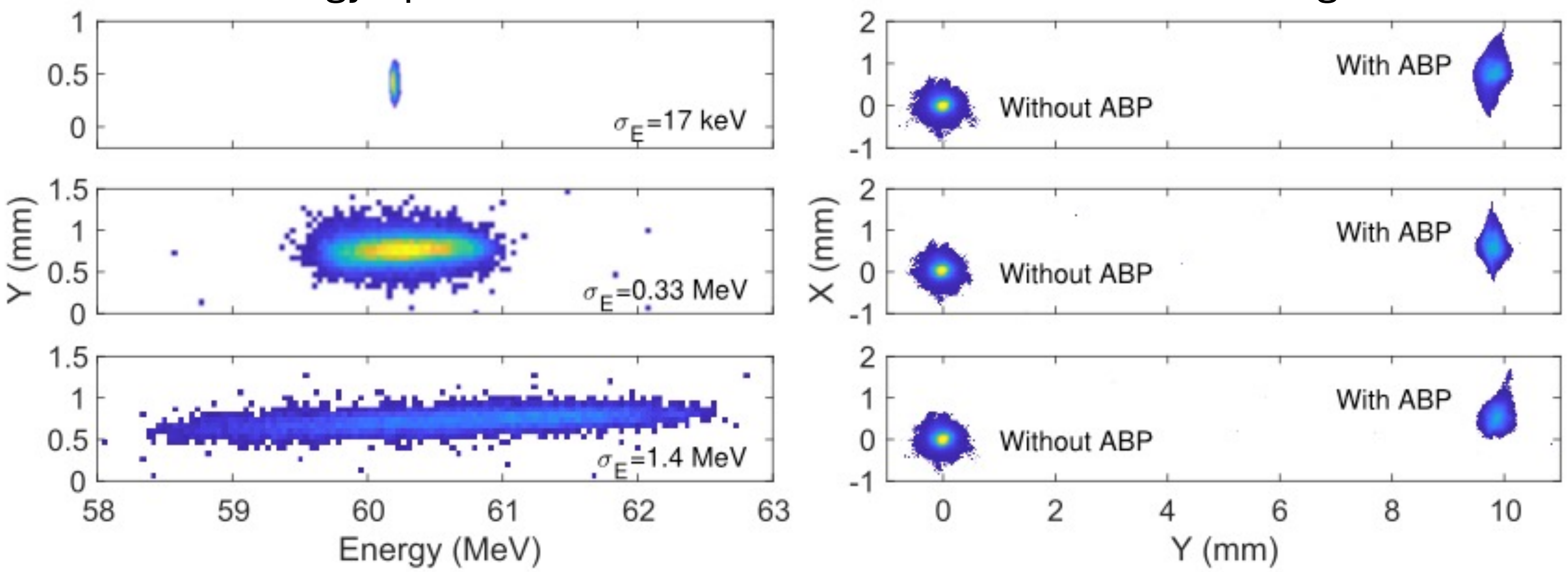
R. Pompili et al., PRL **132**, 215001 (2024)

II. Guiding in Curved Plasma-Discharge Capillary

- Demonstration of 150 MeV beam guiding:

Energy Spectrum

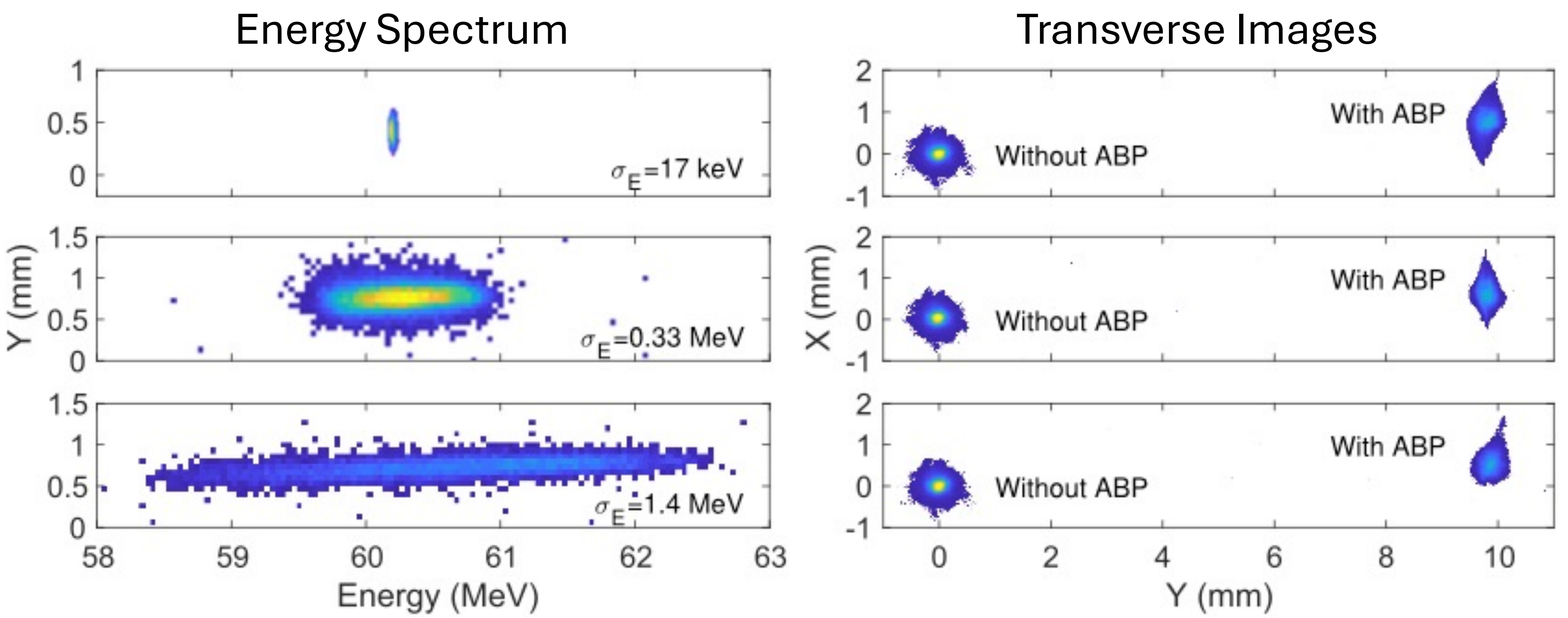
Transverse Images

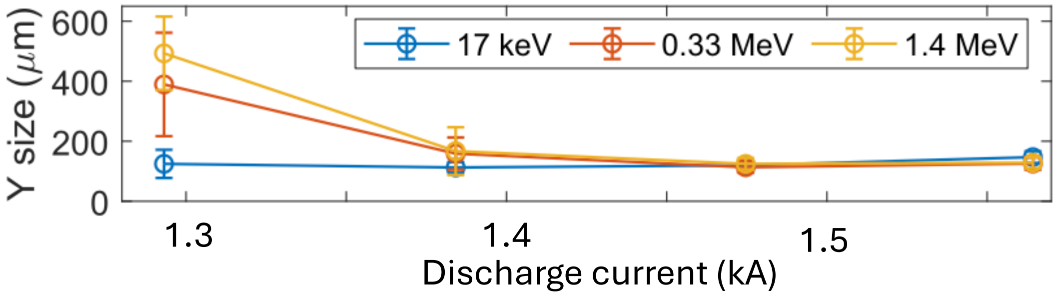


R. Pompili et al., PRL **132**, 215001 (2024)

II. Guiding in Curved Plasma-Discharge Capillary

- Demonstration of 150 MeV beam guiding:



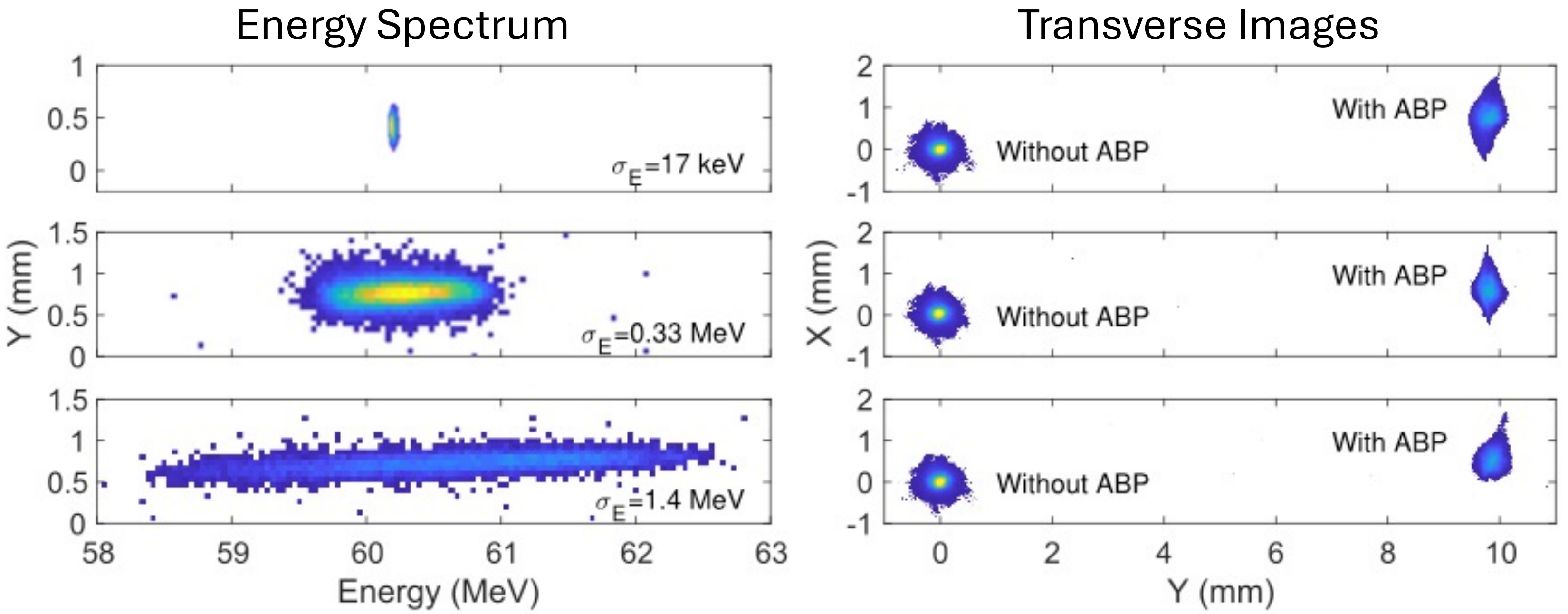


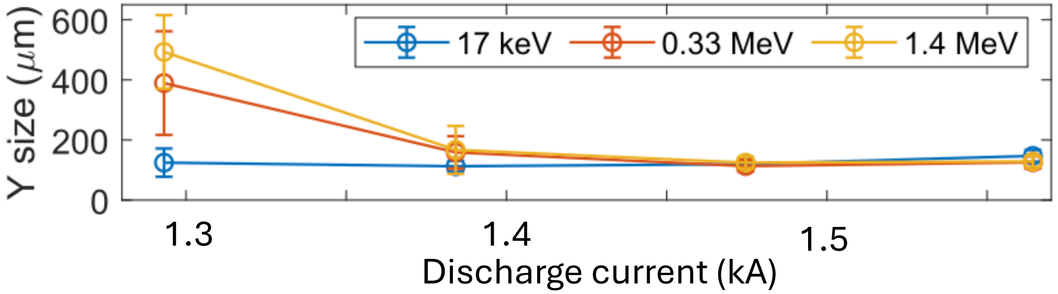
Transverse size in the bending plane essentially independent of energy spread
→ ~ achromatic bending

R. Pompili et al., PRL **132**, 215001 (2024)

II. Guiding in Curved Plasma-Discharge Capillary

- Demonstration of 150 MeV beam guiding:





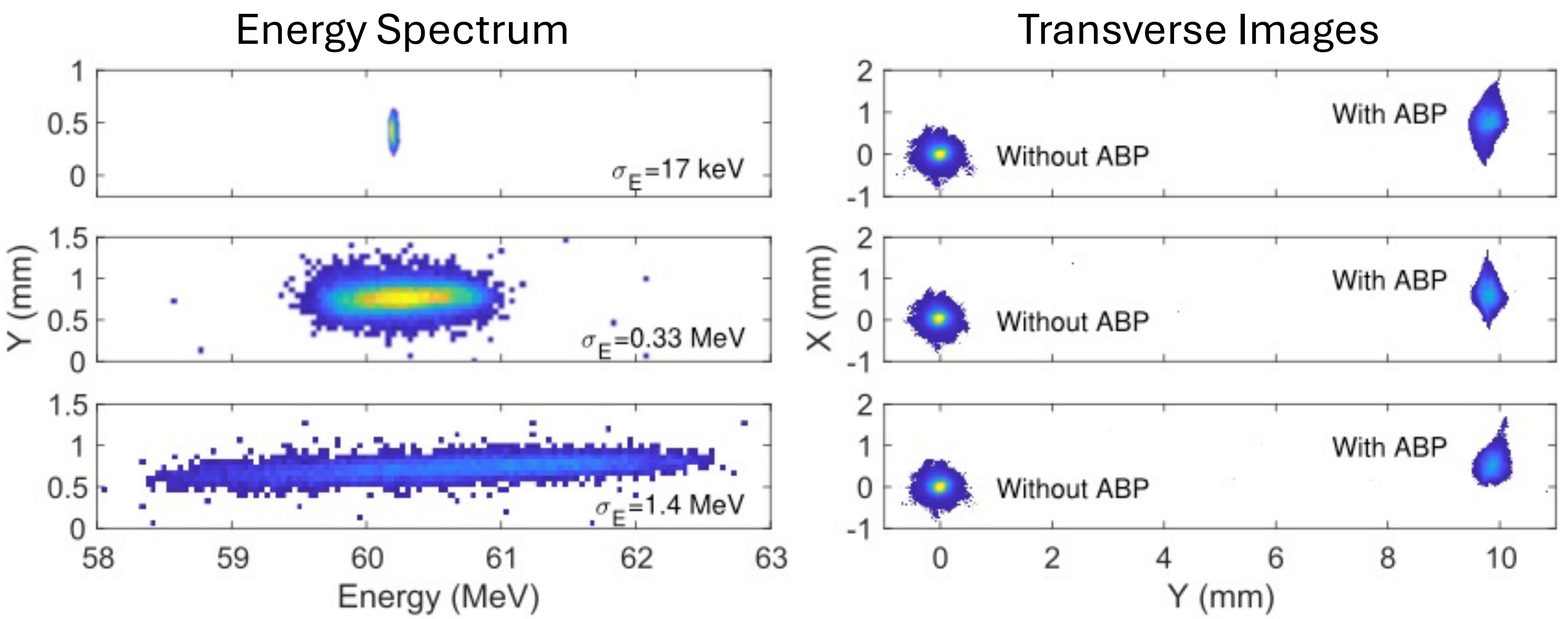
Transverse size in the bending plane essentially independent of energy spread
→ ~ achromatic bending

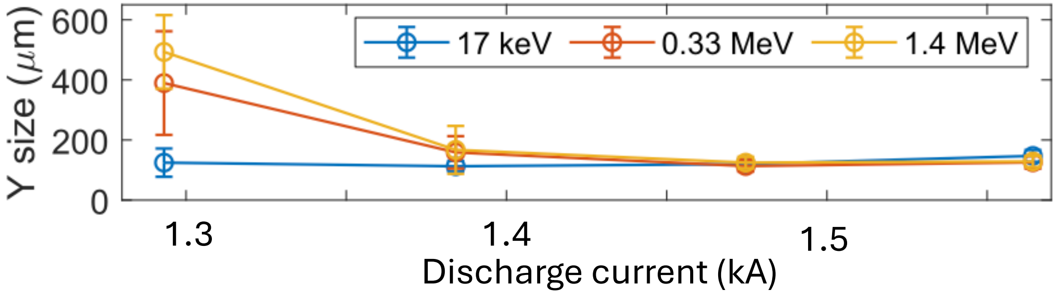
Main challenges:
- Capillary manufacturing
- Maximum current available
- Aging of the capillary
  → wider channel
  → lower current density

R. Pompili et al., PRL **132**, 215001 (2024)

II. Guiding in Curved Plasma-Discharge Capillary

- Demonstration of 150 MeV beam guiding:





Transverse size in the bending plane essentially independent of energy spread
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R. Pompili et al., PRL **132**, 215001 (2024)

Summary

0a. EuPRAXIA
0b. SPARC_LAB Facility

I. Space-Charge Field Screening in Plasma

II. Beam Guiding in Curved Plasma-Discharge Capillary

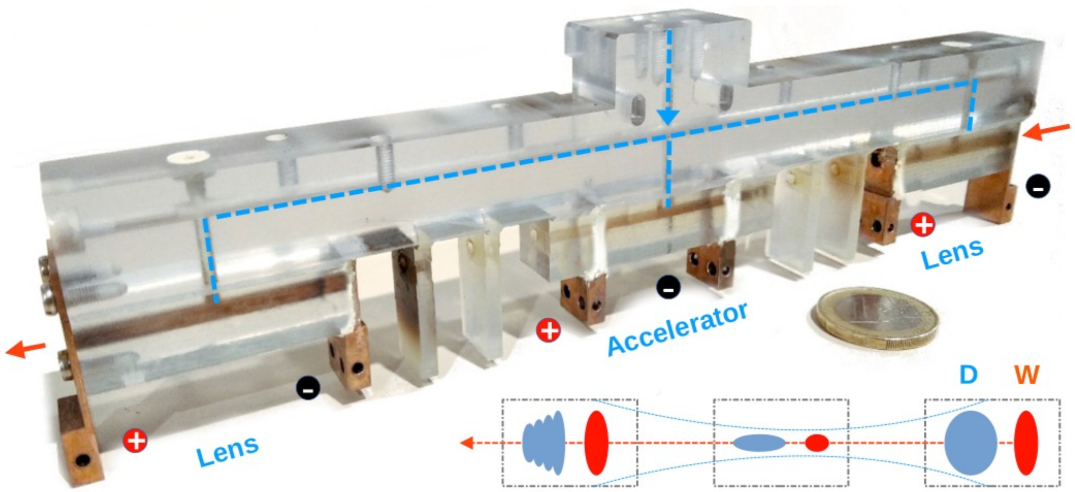
III. Focusing – Acceleration – Capture in all-plasma compact device

III. Focusing – Acceleration – Capture in All-Plasma Device

- Single device:
  - Active plasma lens for injection
  - Accelerating section
  - Active plasma lens for extraction

- Common gas injection

- Independent discharge pulse circuit for each device



R. Pompili et al., PRE **109**, 055202 (2024)

III. Focusing – Acceleration – Capture in All-Plasma Device

- Single device:
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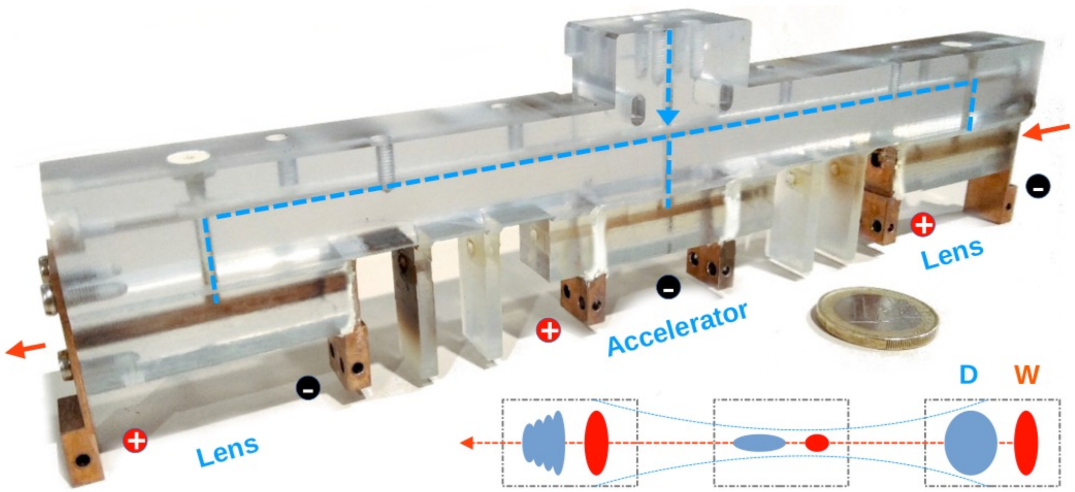
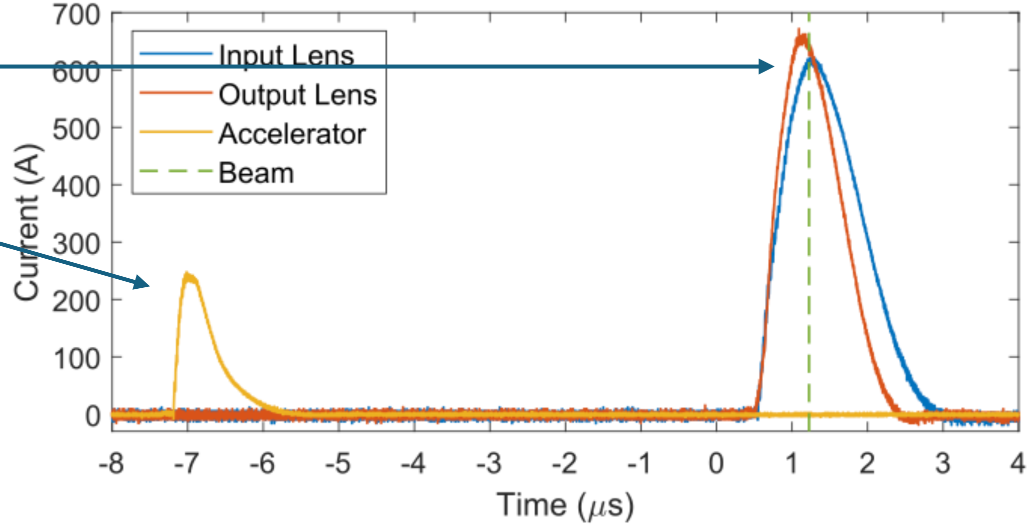
  - Accelerating section
  - Active plasma lens for extraction

- Common gas injection

- Independent discharge pulse circuit for each device

  - Bunch simultaneous with lenses' current pulse
    → Active Plasma Lens (I ~ 650 A)
  - Plasma density in the accelerator tuned with the bunch delay (I~ 250 A, ~8μs delay)





R. Pompili et al., PRE **109**, 055202 (2024)

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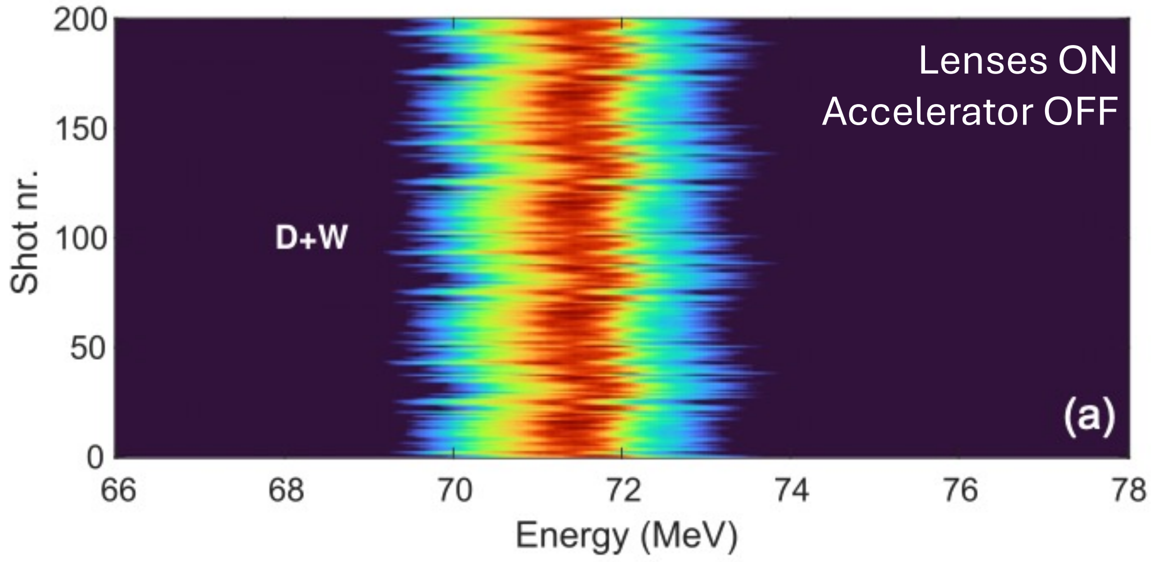

R. Pompili et al., PRE **109**, 055202 (2024)

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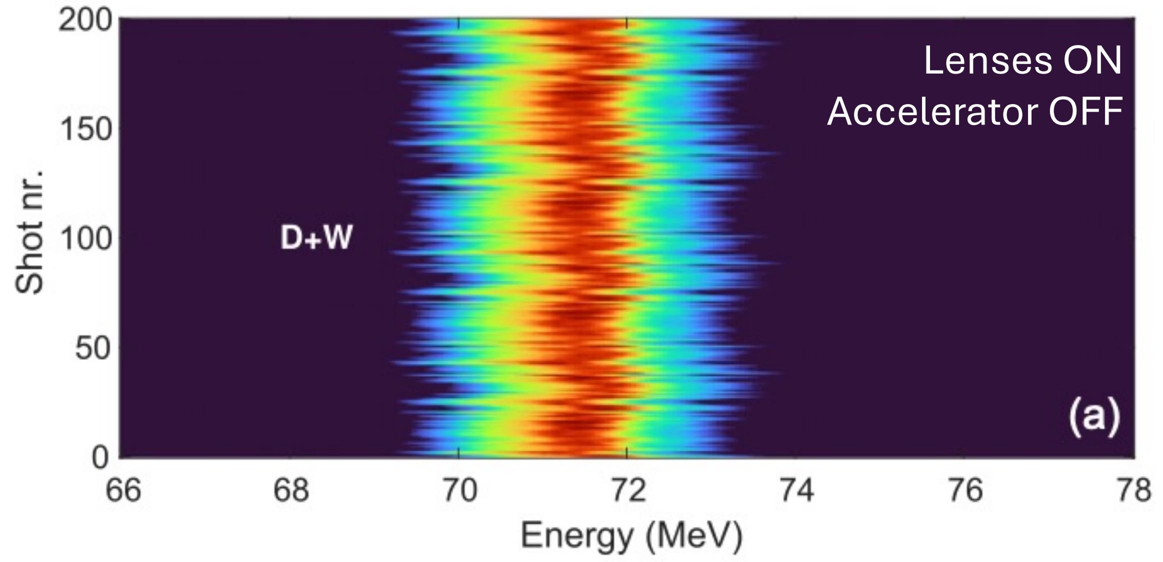
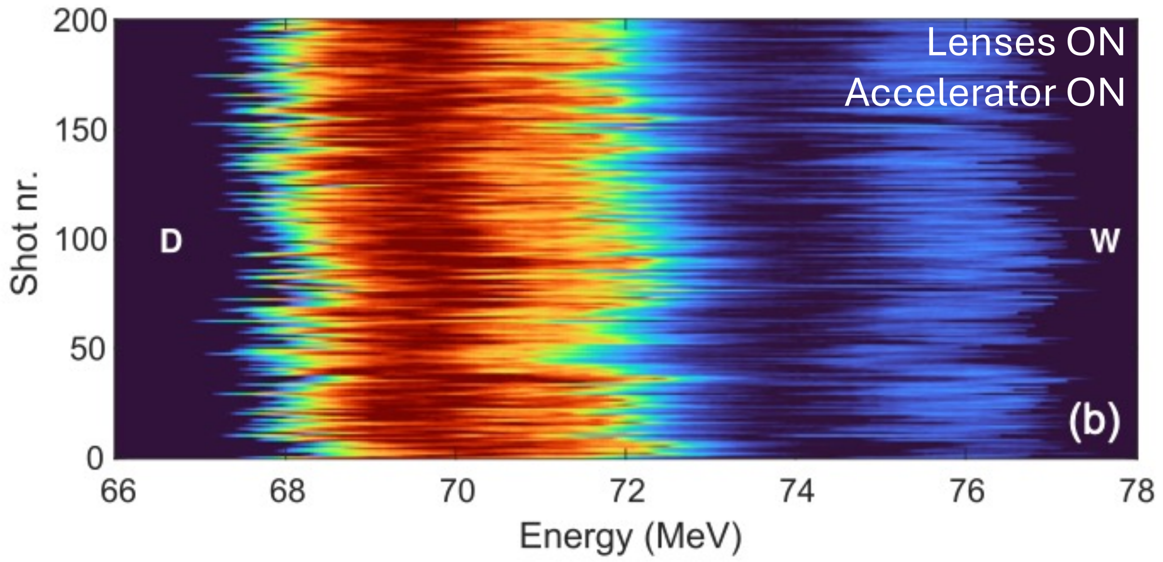
- Independent discharge pulse circuit for each device

  - Bunch simultaneous with lenses' current
    → Active Plasma Lens (I ~ 650 A)
  - Plasma density in the accelerator tuned with the bunch delay (I~ 250 A, ~8μs delay)

- Energy gain ~ 4.5 MeV → 150MV/m, $n_{pe} = 4 \times 10^{15}$ cm^{-3}

Main challenges:
- Manufacturing
- Cross-talk between sections
  → First discharge in the accelerator triggers the discharge in the lenses

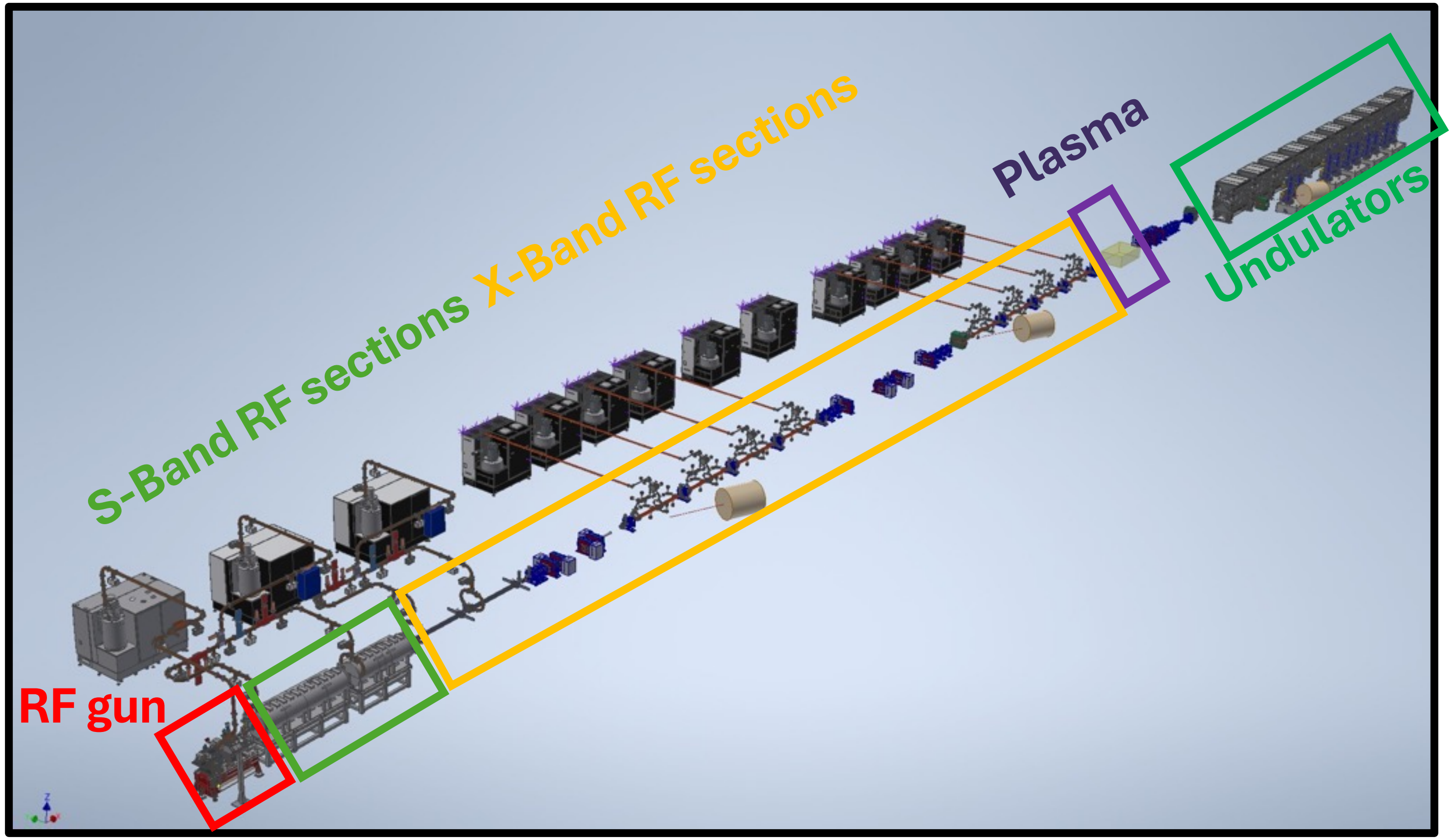




R. Pompili et al., PRE **109**, 055202 (2024)

Road to EuPRAXIA@SPARC_LAB

- Soft X-ray (< 4nm) FEL based on PWFA at INFN/Frascati
- 500 MeV 30 pC witness bunch boosted to 1 GeV in 60-cm-long discharge-plasma capillary



- Construction starting ~ end of 2025
- Installation starting ~ 2029
- Commissioning starting ~ 2030

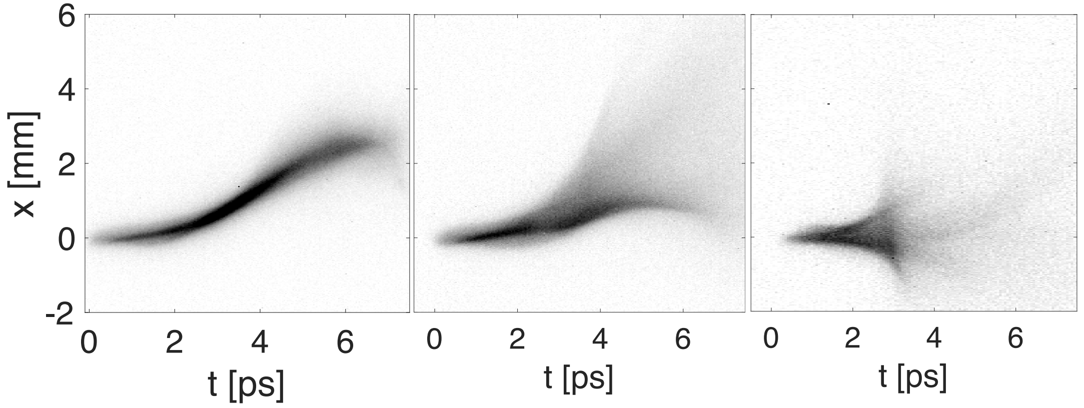
User-oriented plasma-based FEL

Transition from experiment to "real" accelerator
Building up from results and expertise from SPARC

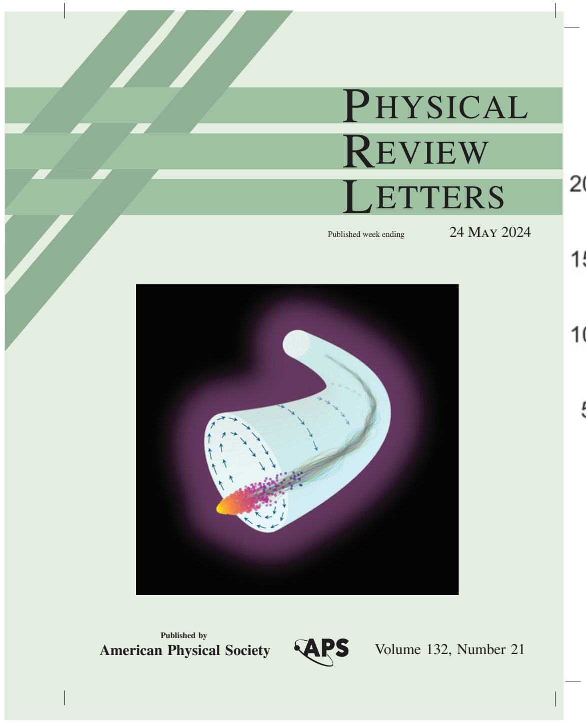
Working on some of the main issues for a future linear collider (e.g. matching-extraction, driver-witness separation, etc..)

Conclusions

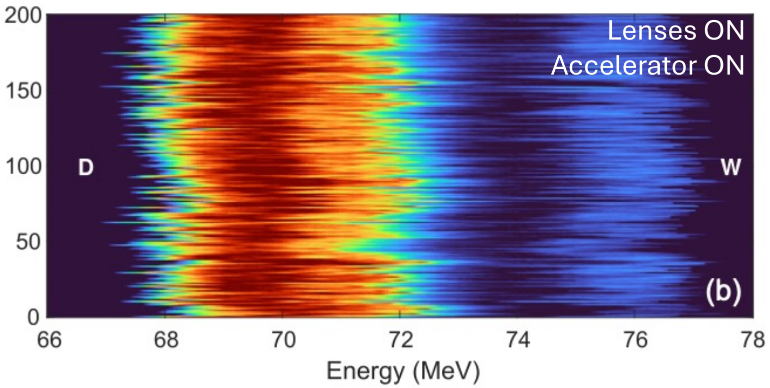
- Space-Charge Field Screening in Plasma
  → Dielectric wakefields suppressed when bunch-capillary distance >> plasma skin depth



- Beam Guiding in Curved Plasma-Discharge Capillary
  → Potentially dispersionless dipole



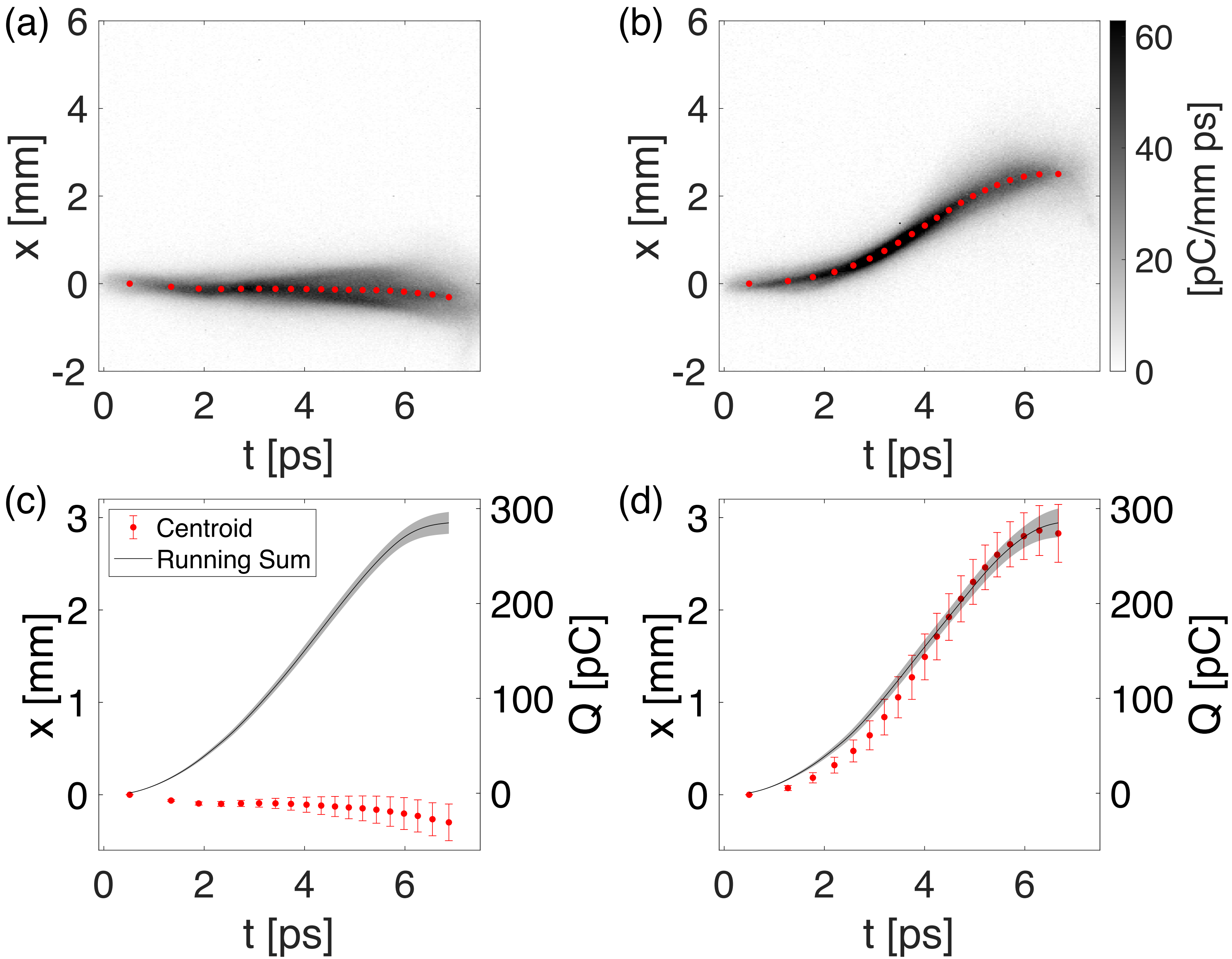
- Focusing – Acceleration – Capture in all-plasma compact device



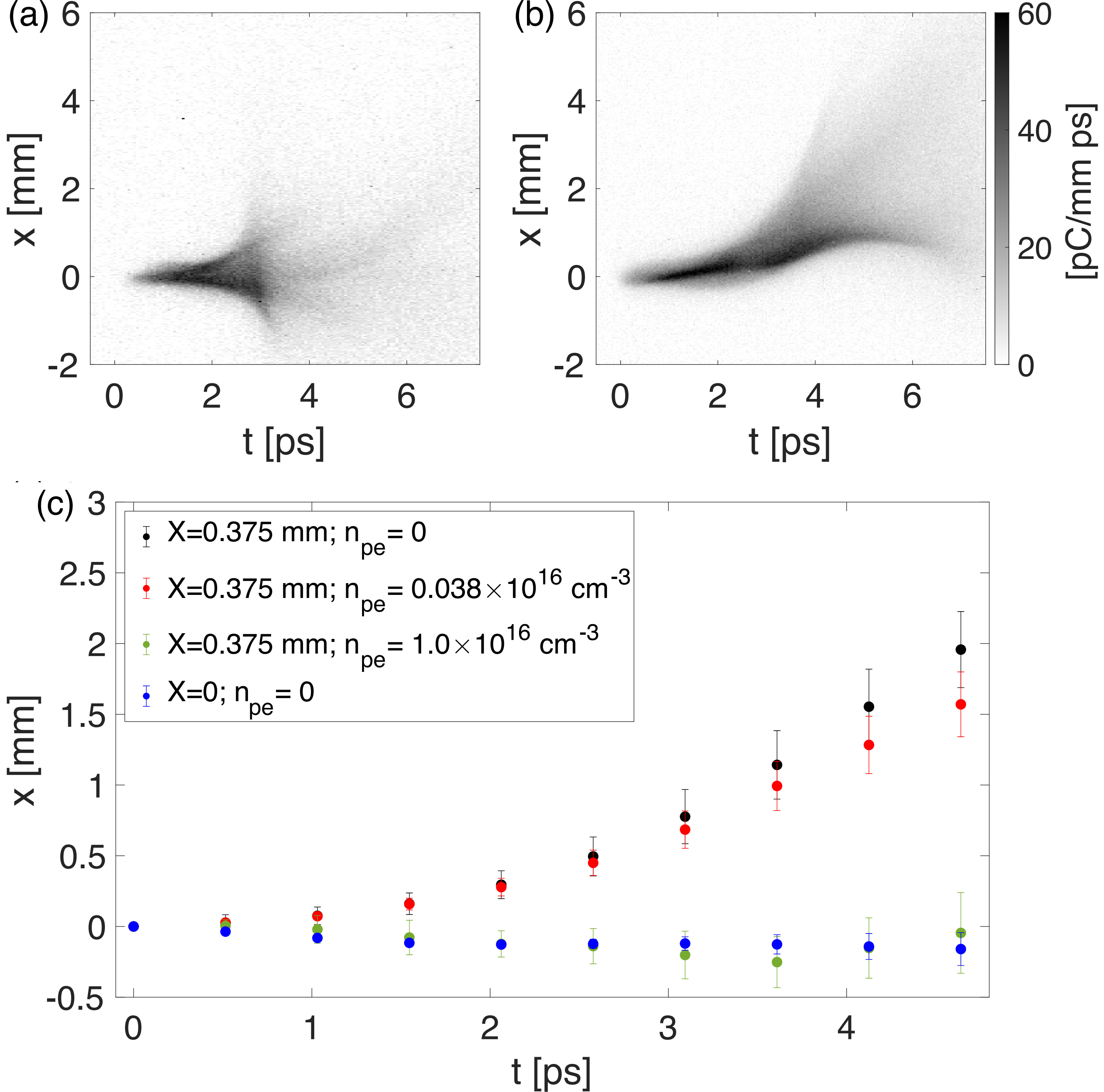
- On the way to EuPRAXIA@SPARC_LAB

Thank you!

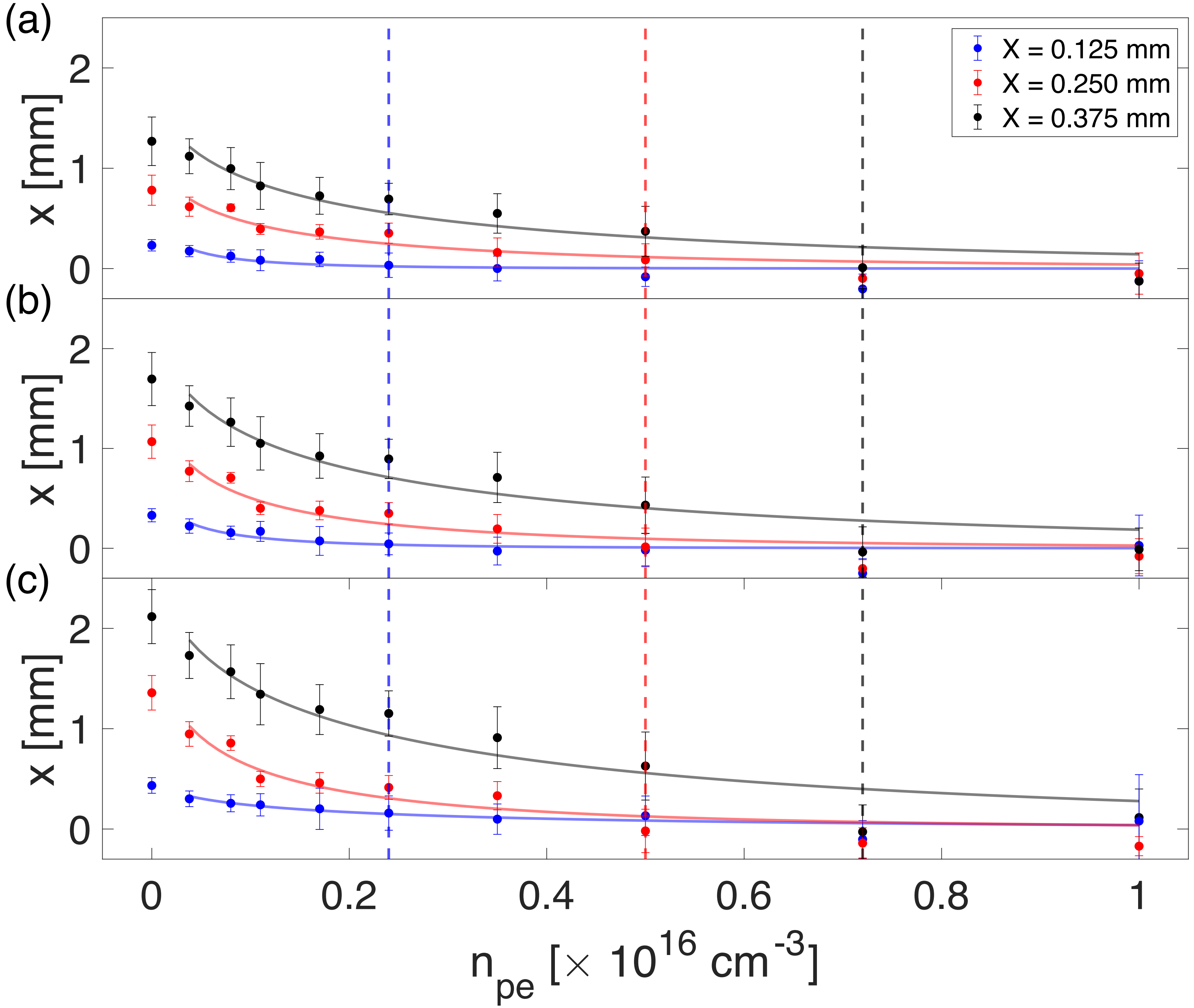
Backup slides



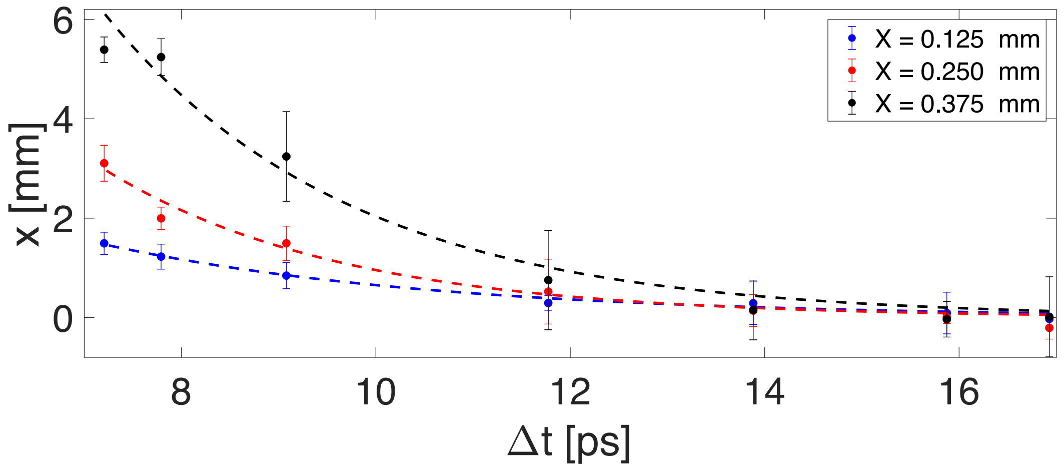
(a)
(b)
(c)
(d)
x [mm]
t [ps]
[pC/mm ps]
Q [pC]
Centroid
Running Sum



(a)
(b)
x [mm]
t [ps]
[pC/mm ps]
(c)
X=0.375 mm; n_pe = 0
X=0.375 mm; n_pe = 0.038×10^16 cm^-3
X=0.375 mm; n_pe = 1.0×10^16 cm^-3
X=0; n_pe = 0



(a)
(b)
(c)
X = 0.125 mm
X = 0.250 mm
X = 0.375 mm
x [mm]
0
1
2
0
0.2
0.4
0.6
0.8
1
n_pe [× 10^16 cm^-3]



- Effect increases with misalignment
- Exponential decay with time
- Effect negligible for Δt>14ps

EuPRAXIA

European Plasma Research Accelerator with Excellence in Applications

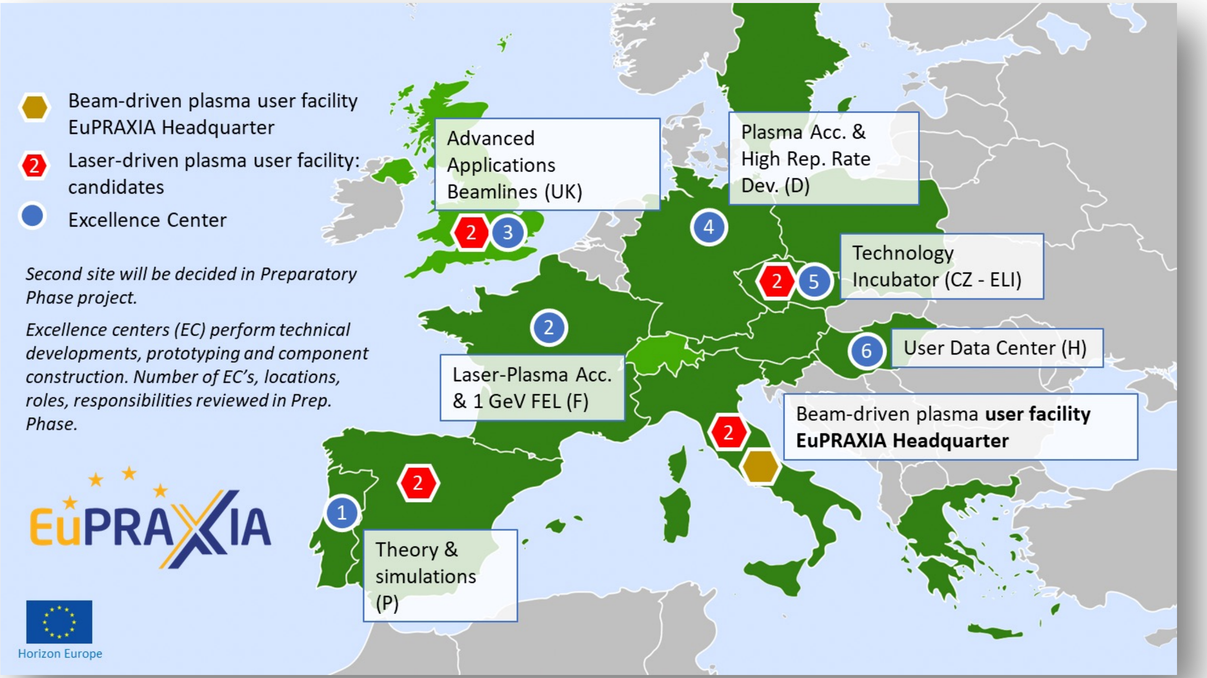
→ The first project developing user-oriented accelerators **based on plasma accelerator technology**

→ Distributed Research Infrastructure building **TWO** facilities driven by high-gradient plasma wakefield accelerator

→ > 1 GV/m accelerating field

→ Beam-driven and laser-driven facilities

→ Provide a practical path to more research facilities and ultimately to higher beam energies for the same investment in terms of size and cost

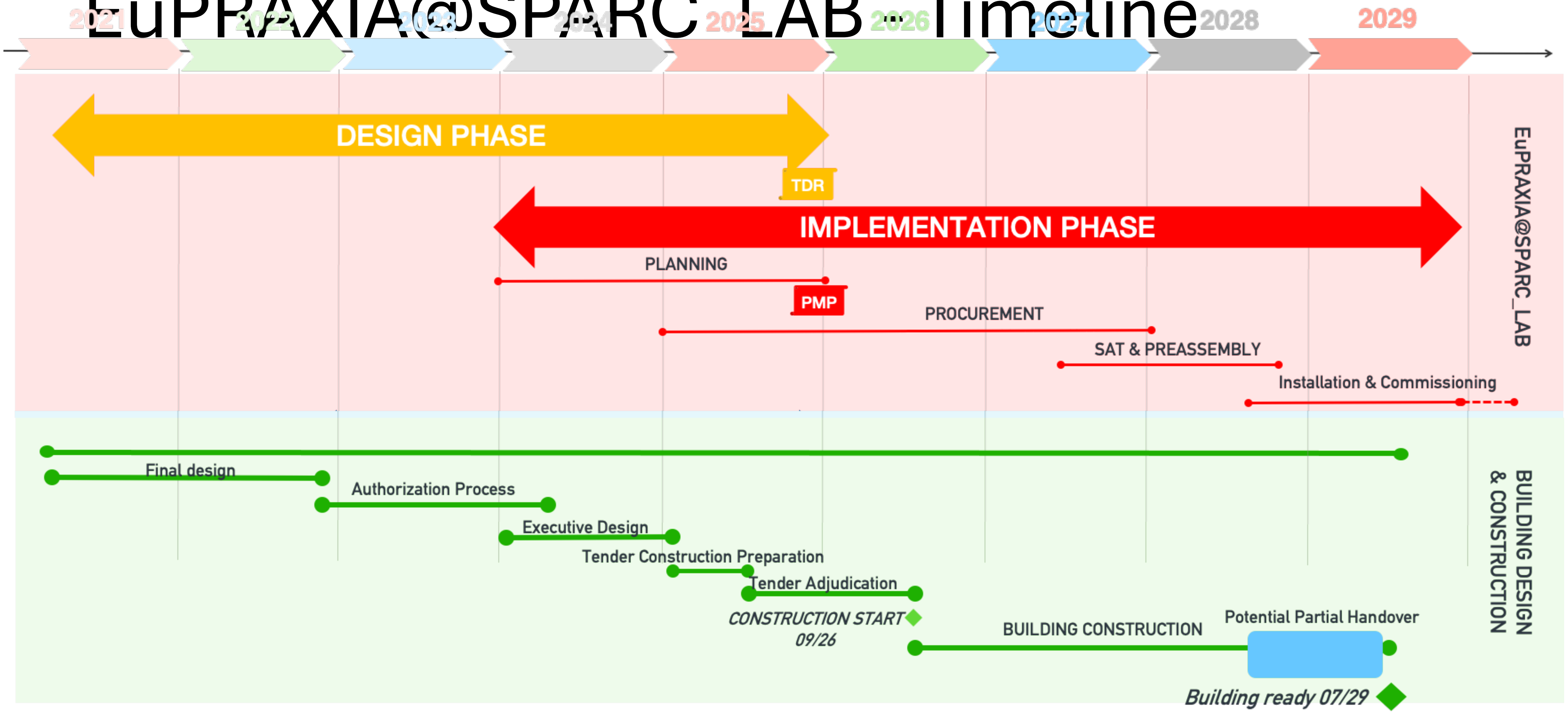


Included in 2021 European Roadmap For Research Infrastructure (ESFRI) Roadmap

EuPRAXIA@SPARC_LAB

- Soft X-ray (2-4 nm) FEL based on Plasma Wakefield Acceleration (PWFA) at Frascati
- 500 MeV, 30 pC electron bunch boosted to 1 GeV in 60-cm-long plasma

EuPRAXIA@SPARC_LAB - Timeline



EuAPS Project

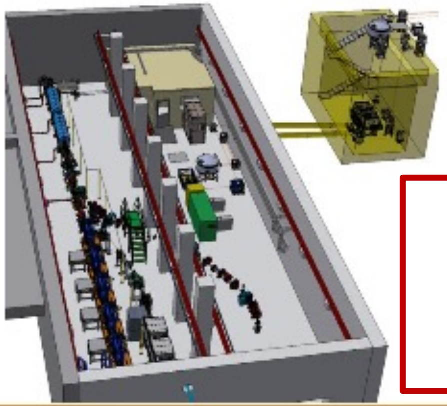
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | EuPRAXIA Advanced Photon Sources

EuPRAXIA Advanced Photon Sources (EuAPS)

- Supported by PNRR funding
- Collaboration among INFN, CNR, University of Tor Vergata
- EuPRAXIA → *laser-driven betatron radiation source @SPARC_LAB*
  → development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) laser
  → pre-cursor for user-facility

Parameter	Value	unit
Electron beam Energy	100-500	MeV
Plasma Density	10^{18}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10	keV
Number of Photons/pulse	10^{7}-10^{9}	
Repetition rate	1-5	Hz
Beam divergence	3-20	mrad

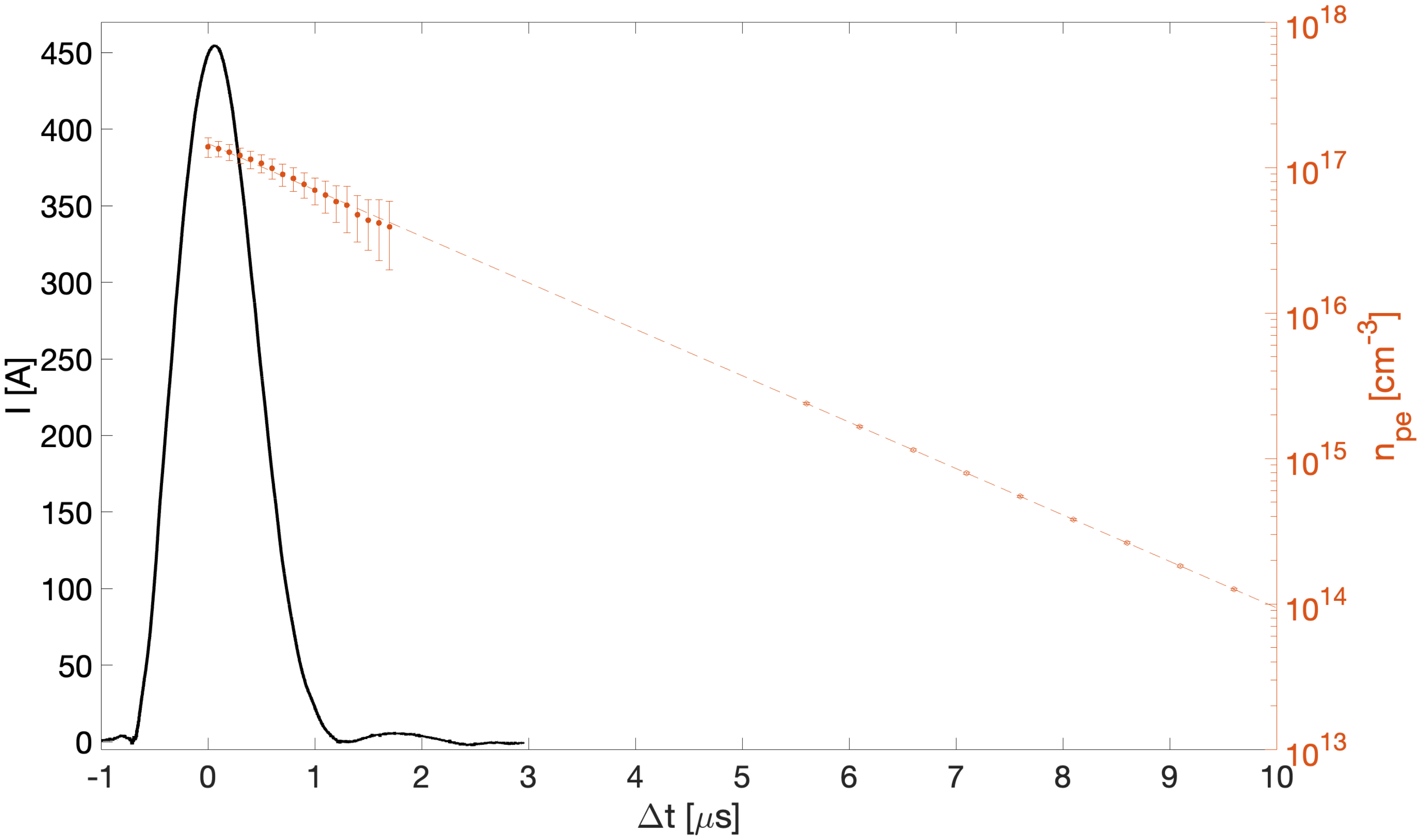
1) **Ultrafast** - laser pulse duration tens of fs useful for **time resolved experiments** (XFEL tens of fs, synchrotron tens to 100 ps).
2) **Broad energy spectrum** - important for **X-ray spectroscopy**.
3) **High brightness** - small source size and high photon flux for **fast processes**
4) **Large market** - 50 synchrotron light sources worldwide, 6 hard XFEL's and 3 soft-ray ones (many accelerators operational and some under construction).



Good example of exploiting the unique features of plasma-based accelerators!

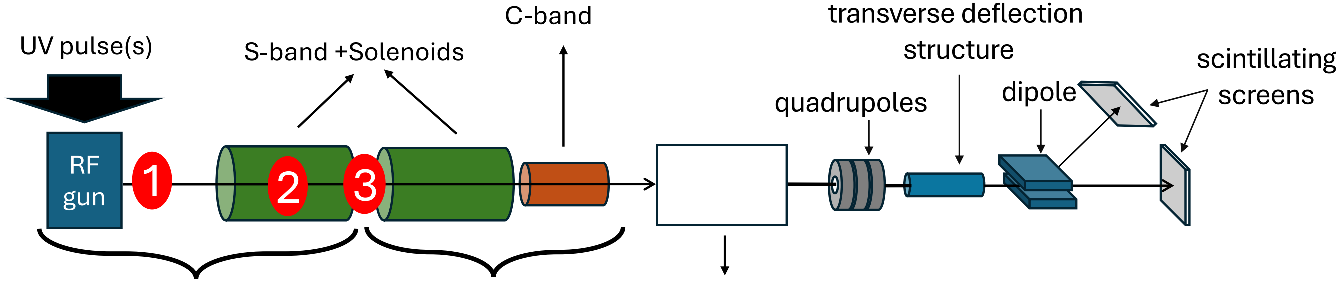
'EuPRAXIA Advanced Photon Sources PNRR_EuAPS Project', M. Ferrario et al. INFN-23-12-LNF (2023)

23



I [A]
450
400
350
300
250
200
150
100
50
0
-1
0
1
2
3
4
5
6
7
8
9
10
Δt [μs]
10^18
10^17
10^16
10^15
10^14
10^13
n_pe [cm^-3]

SPARC LINAC



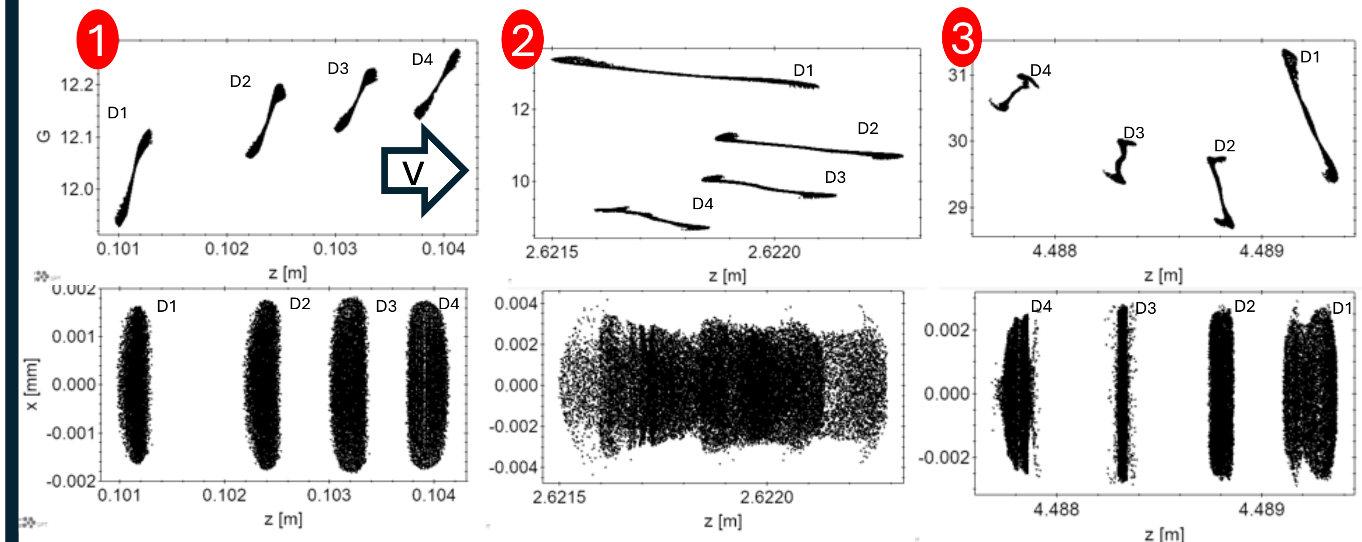
- Bunch compression
- Final bunch spacing
- Emittance control

- Energy spread tuning
- Final energy

INTERACTION CHAMBER:
Final focusing + discharge capillary + Capture System + Diagnostics

Train of compressed bunches generated via velocity bunching

L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87–106 (2001)

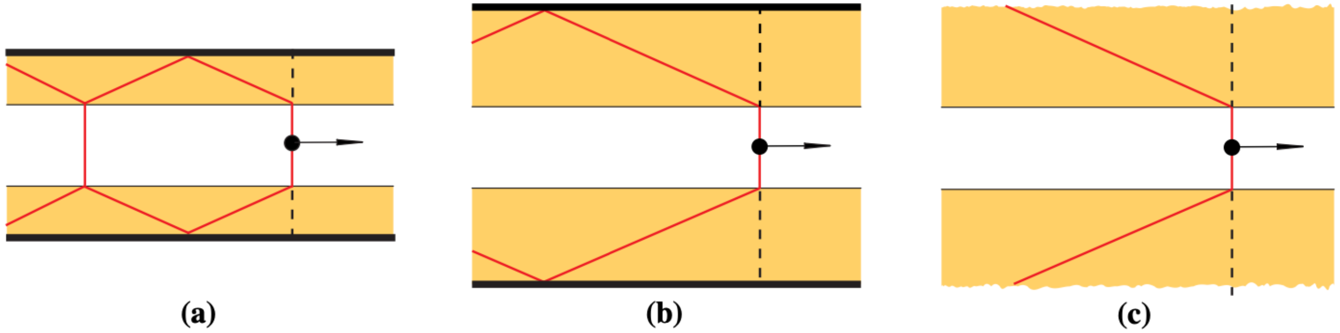


One ps-long bunch for each UV pulse

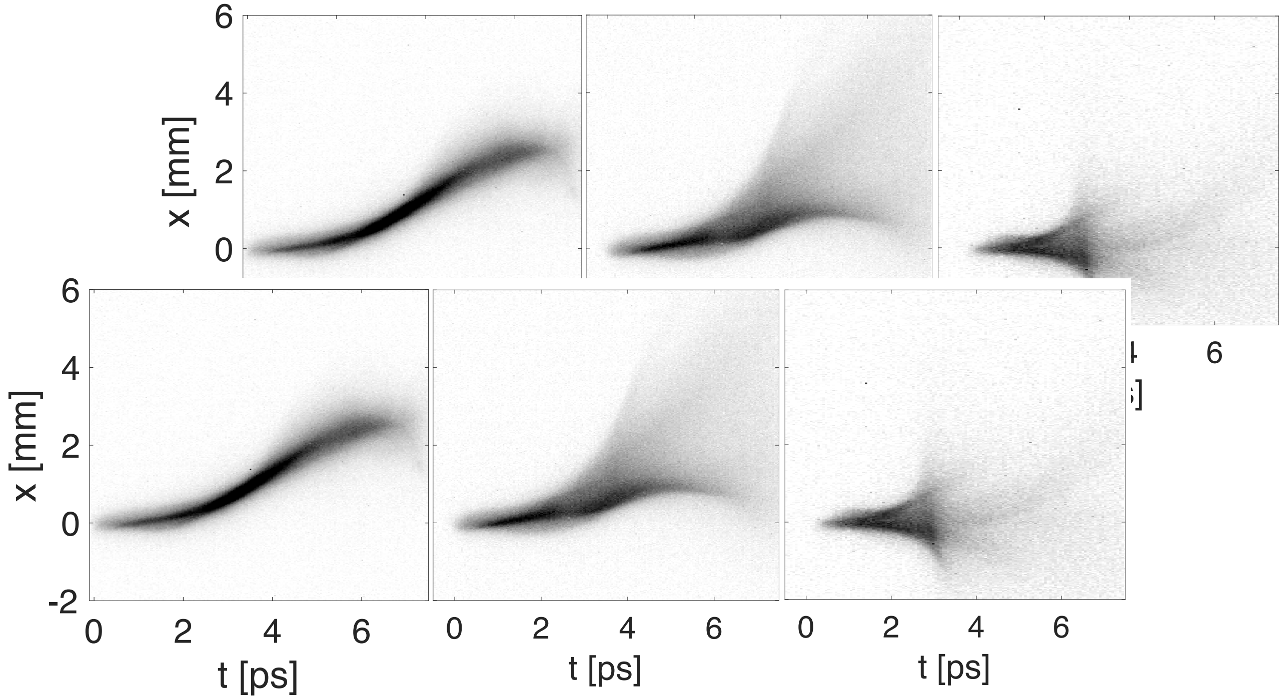
Later bunches overtakes bunches ahead
→ Bunch compression
→ Crossing of bunches

Afterwards, "rigid" acceleration to 70-150 MeV

GPT Simulations



Baturin PRL 113, 214801 (2014)


x [mm]
t [ps]
t [ps]
t [ps]