767. WE-Heraeus-Seminar
Science and Applications of Plasma–Based Accelerators
Physikzentrum Bad Honnef - 15 May - 18 May 2022

Electron Beam Diagnostics

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Outline

- Scientific Scenario
- Critical Issues
- Diagnostics before and after plasma acceleration module
  - Techniques used (experience with PWFA)
  - Possible novel solutions
- Conclusions

Scientific Scenario

- ***Multi GeV*** acceleration ***in cm scale*** plasma modules
- Acceleration of high brightness electron beams and their transport up to the final application, preserving the high quality of the 6D phase space
- Characteristic scale length of the accelerating field, i.e. the plasma wake, is the plasma wavelength, λ_p ==> **Bunch length << λ_p <=> tens of fs down to <u>fs scale</u>**

focusing/injection **LWFA/PWFA** **capture/extraction** **Application, *e.g.* FEL, Linear collider**

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- **Injection and matching** to plasma accelerating module (**PWFA case**)
  - the beam has to be focused to the matching transverse size to prevent envelope oscillations that may cause emittance growth
    - **Blow-out regime**

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$$\beta_{matching} = \frac{\sqrt{2\gamma}}{k_p}$$

$$\alpha_{matching} = 0$$

Typical numbers

$$k_p = \frac{2\pi}{\lambda_p}$$

$$\lambda_p(\mu m) \approx 3.3\ 10^4 n_p^{-1/2}(cm^{-3})$$

$$\gamma = 1000$$

$$n_p = 10^{16}\ cm^{-3}$$

$$\varepsilon_n = 1\ mm\ mrad$$

Matching condition

$$\sigma_{matching} = \sqrt{\frac{\beta_{matching}\varepsilon_n}{\gamma}} \approx \mu m$$

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Scientific Scenario

- **Extraction** from plasma accelerating module
  - plasma fields are stronger than in conventional accelerators

$$\boxed{G[MT/m] \equiv \frac{F_r}{ecr} \approx 3n_p[10^{17}cm^{-3}]}$$

F_r : transverse focusing force

    - beams experience huge transverse size variation when propagating from the plasma outer surface to the conventional focusing optics

$$\boxed{\sigma_x \sim \ \mu m} \qquad \boxed{\sigma_{x'} \sim \ mrad}$$

    - the particle transverse motion becomes extremely sensitive to energy spread
  - the beam angular divergence has to be reduced and the transverse spot size increased to limit the chromatic induced emittance degradation in vacuum

$$\boxed{\varepsilon_n^2 =<\gamma>^2 (\sigma_E^2\sigma_x^2\sigma_{x'}^2 + \varepsilon^2) \approx <\gamma>^2 (\sigma_E^2\sigma_{x'}^4 s^2 + \varepsilon^2)}$$

*M. Migliorati et al., PRST AB **16**, 011302 (2013)*

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Motivation

- Diagnostics is essential for the development of plasma-based accelerators
  - At the **injection point**
    - Transverse diagnostics to guarantee the matching conditions at the plasma
    - Longitudinal diagnostics
      - to measure the witness beam duration
      - to check, in case of PWFA, the proper time distance between driver and witness beams
      - to evaluate the arrival time jitter (ATJ) of the witness beam with respect to the driver
  - At the **extraction region** to guide and validate both efficiency and quality of the plasma-based acceleration technique
    - 6D diagnostics to evaluate the brightness of the plasma-accelerated beam
- Applications, in particular those needing high brightness beams, are mandatory for the validation of the plasma-based acceleration method
  - SASE FEL radiation represents the best non-invasive, and online, diagnostics

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Critical Issues

Injection point (in PWFA technique)

- Overestimation of the transverse beam size due to
  - overlapping of driver and witness beams
  - lack of resolution of the conventional measurement methods
- Evaluation of temporal jitter between driver and witness bunches

Extraction region

- critical 6D beam characterization due to
  - low stability —> plasma instability issues, ATJ at the plasma entrance, …
  - high energy spread **—> efforts to reduce it**
  - high divergence —> fast capture
  - driver removal, either laser or particle beam

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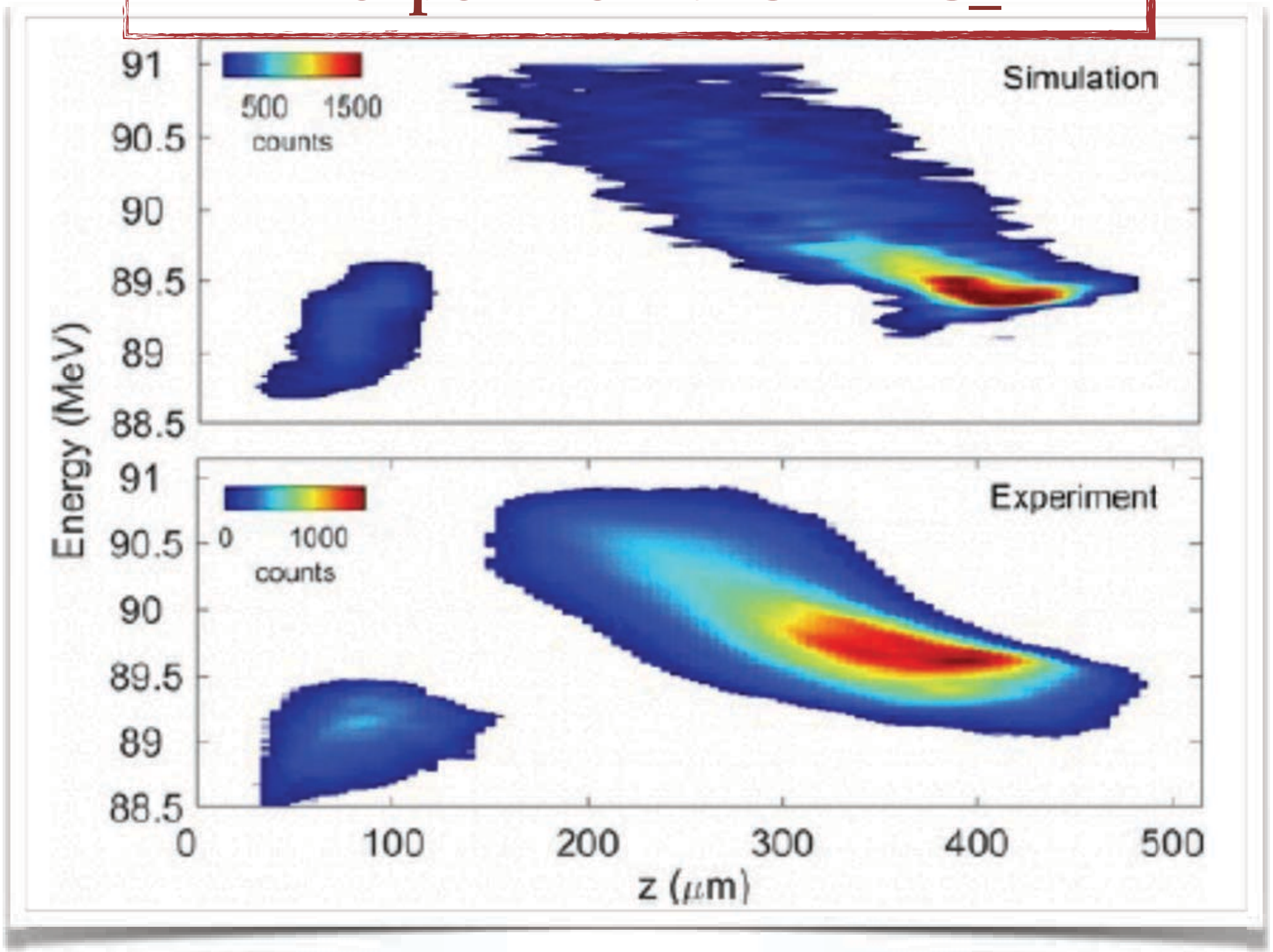
Electron Beam Parameters at Injection

PWFA Experience

- ps/sub-ps time distance between driver and witness bunches with ~10s of fs jitter
- few 10s of fs, 30 pC witness and 100s of fs, 200 pC driver bunch duration
- µm scale witness transverse beam size

PWFA experiment at SPARC_LAB



Two **bunches configuration** produced directly at the cathode via the **laser comb technique**, and then manipulated in the first S-band section using RF compression (i.e. **velocity bunching**)

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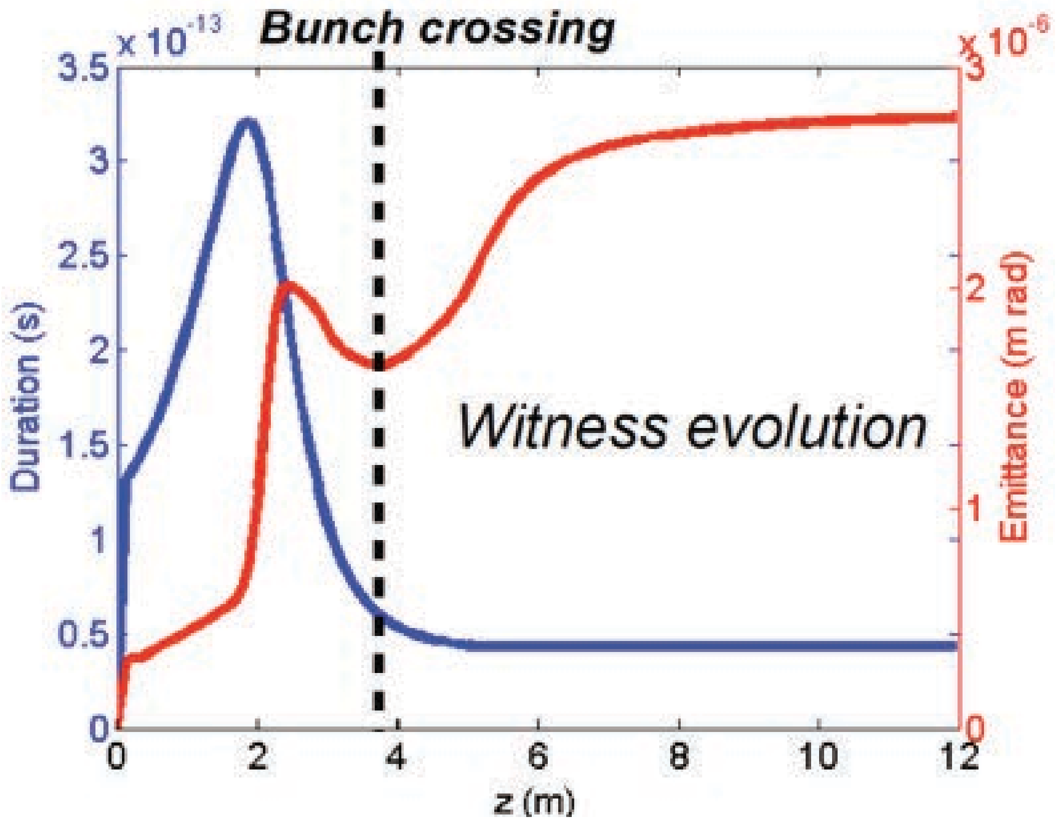
Transverse Beam Size at the IP

- Driver and witness are measured at the same point
  - They cannot be distinguished one from each other
  - The driver has much more charge than the witness, typically a factor 10
  - During the compression, based on the velocity bunching technique, the witness passes through the driver
    - Driver acts as nonlinear lens => emittance growth
    - Driver field is opposed to RF => lower compression

Courtesy of R. Pompili



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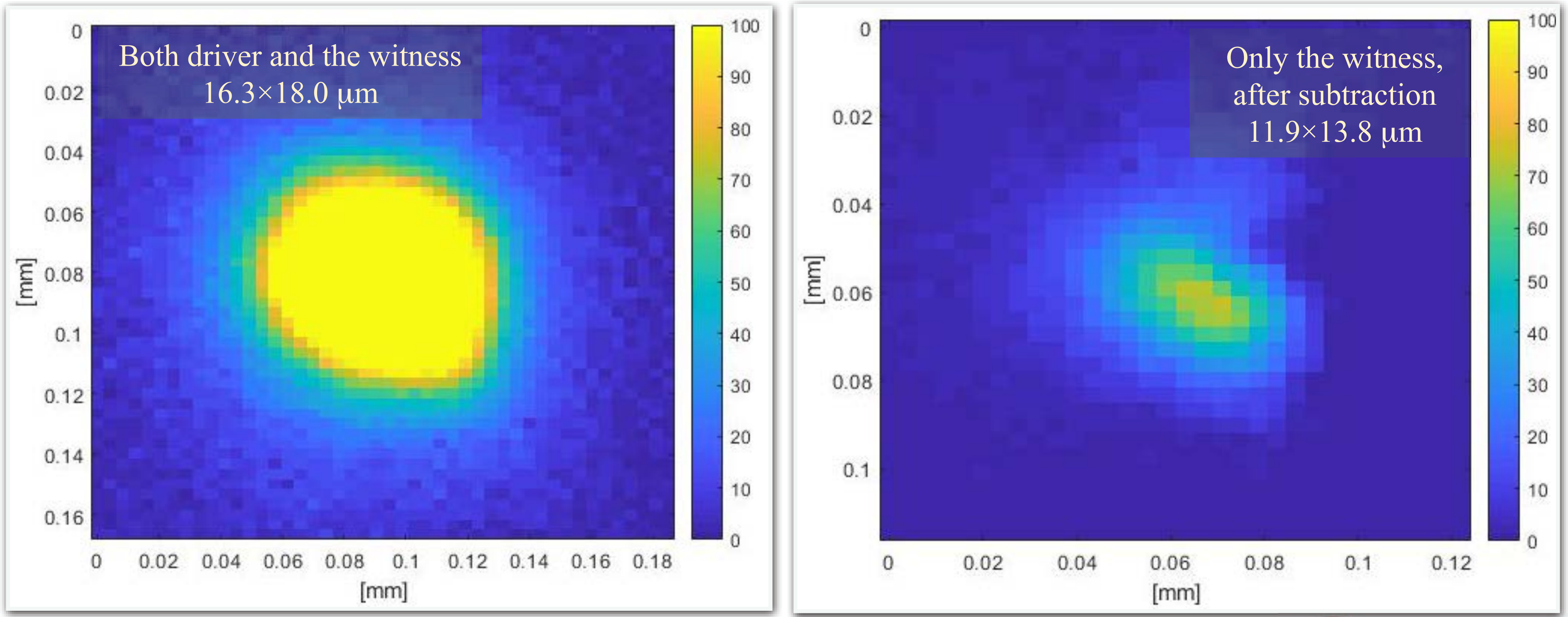
Transverse Beam Size at the IP

- A set of images of **driver and witness together** is **acquired**
- Taking advantage of the laser comb technique, used to generate the driver/witness beam, the **witness beam** can be easily **stopped**, allowing for the **acquisition of** a set of images for the **driver alone**
- A **subtraction procedure** is then applied to subtract the driver from the whole image
  - A **high number of shots** is needed in order **to minimize the reconstruction error** => typically average of 100 shots
- The **subtracted image** represents the image of the **witness bunch**

OTR-based measurement



Both driver and the witness
16.3×18.0 µm

Only the witness,
after subtraction
11.9×13.8 µm

Courtesy of V. Shpakov

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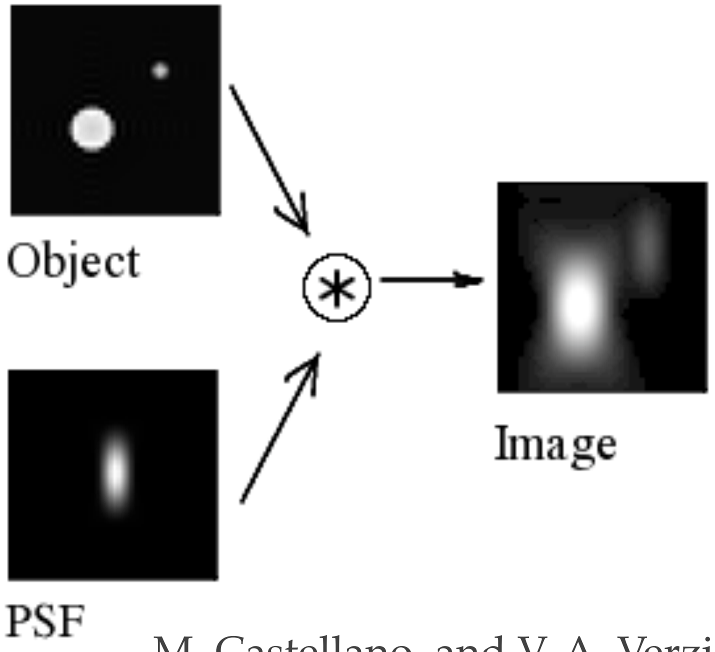
Measuring μm Scale Beam Spot

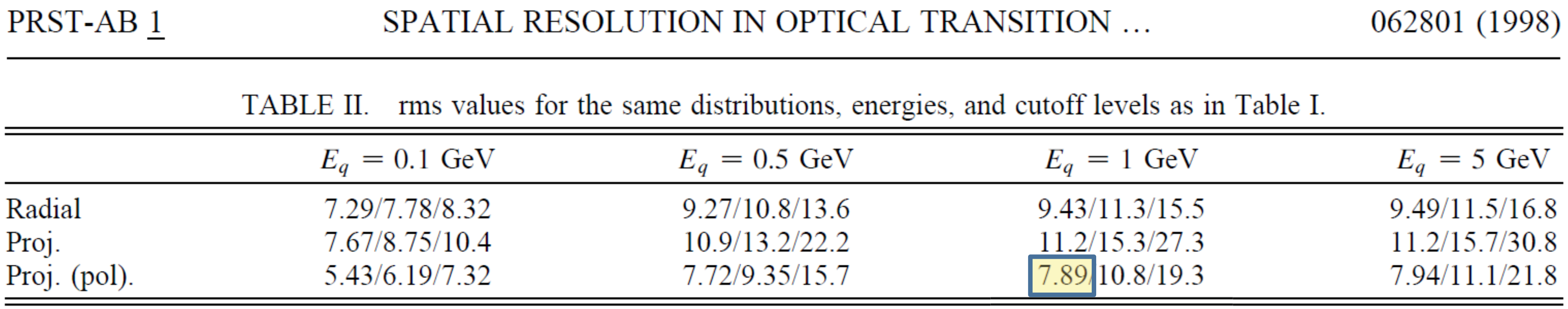
- The characterization of **μm/sub-μm beams** requires the development of diagnostics with **spatial resolution of the same order of magnitude**
- **Screens** are the most used 2D beam profile monitors
  - **YAG:Ce => Spatial resolution limited by grains, thickness, …**
    - **Swiss FEL**: the spatial resolution is 8 μm with a smallest measured beam size of 15 μm
    - **UCLA Pegasus laboratory**: a 20 μm YAG:Ce crystal with an in-vacuum infinity-corrected microscope objective coupled to a CCD camera => beam sizes down to 5 μm have been measured
  - Optical Transition Radiation (**OTR**) **=> Spatial resolution only limited by camera sensor and optics**
    - **ATF2 at KEK**: a vertical beam size of 750 nm has been measured

S. Borrelli et al., *Generation and measurement of sub-micrometer relativistic electron beams*, Communications Physics 1.1 (2018): 1-8

Resolution Limit of OTR-based Imaging



- At low beam size the OTR PSF (Point Spread Function) starts to give a contribution



PRST-AB 1 SPATIAL RESOLUTION IN OPTICAL TRANSITION … 062801 (1998)

TABLE II. rms values for the same distributions, energies, and cutoff levels as in Table I.

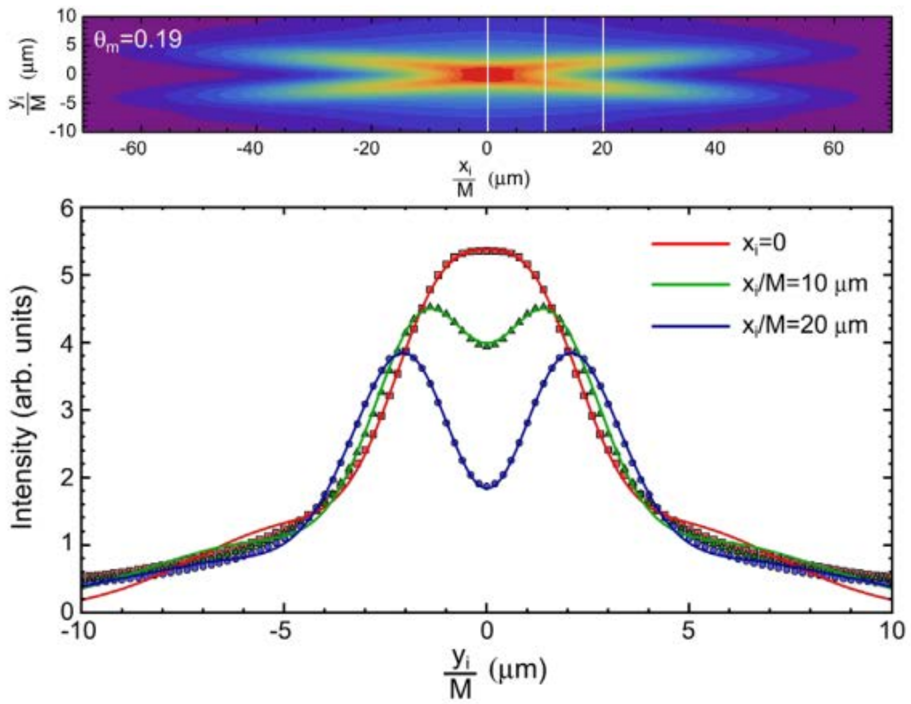
	$E_q = 0.1$ GeV	$E_q = 0.5$ GeV	$E_q = 1$ GeV	$E_q = 5$ GeV
Radial	7.29/7.78/8.32	9.27/10.8/13.6	9.43/11.3/15.5	9.49/11.5/16.8
Proj.	7.67/8.75/10.4	10.9/13.2/22.2	11.2/15.3/27.3	11.2/15.7/30.8
Proj. (pol).	5.43/6.19/7.32	7.72/9.35/15.7	7.89/10.8/19.3	7.94/11.1/21.8

About 4 μm

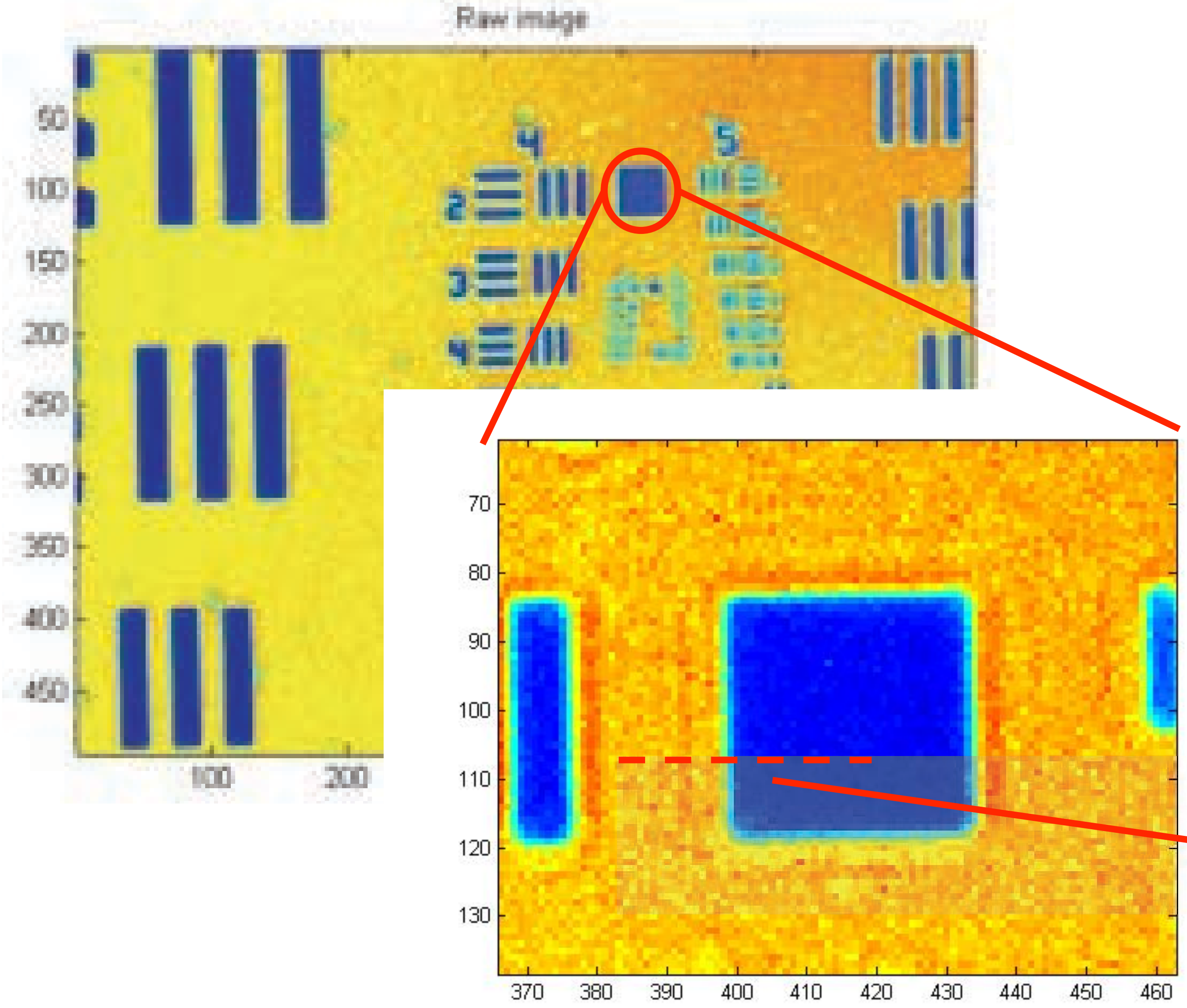
M. Castellano, and V. A. Verzilov, *Spatial resolution in optical transition radiation beam diagnostics*, Physical Review Special Topics-Accelerators and Beams 1.6 (1998): 062801.

- PSF deconvolution

L. G. Sukhikh, G. Kube, and A. P. Potylitsyn, *Simulation of transition radiation based beam imaging from tilted targets*, Physical Review Accelerators and Beams 20.3 (2017): 032802.



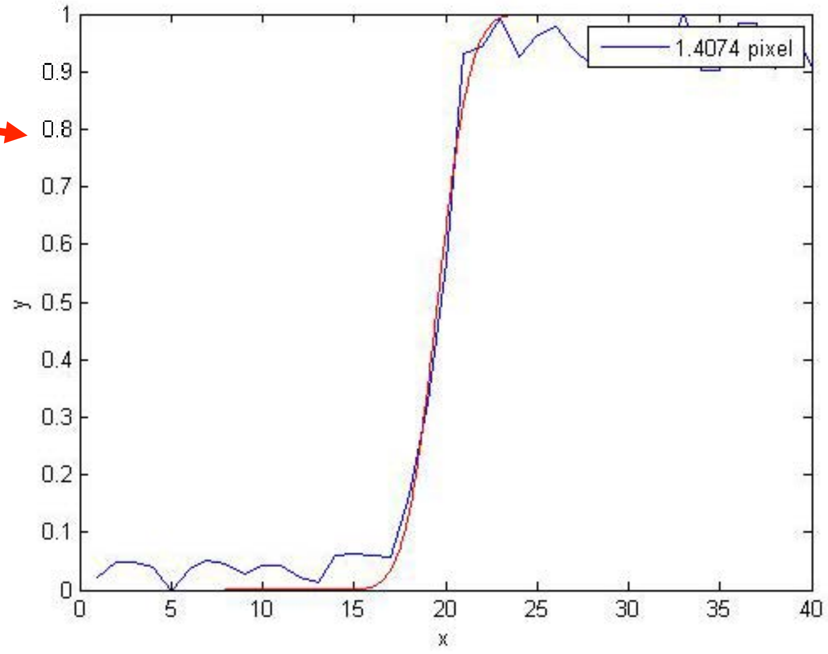
Measuring μm Scale Beam Spot



- At the plasma entrance the beam is foreseen to be in the order of 1-2 μm rms

It is a great challenge to achieve this resolution with optic but…

…even in this case it is useless!



Courtesy of V. Shpakov, A. Cianchi

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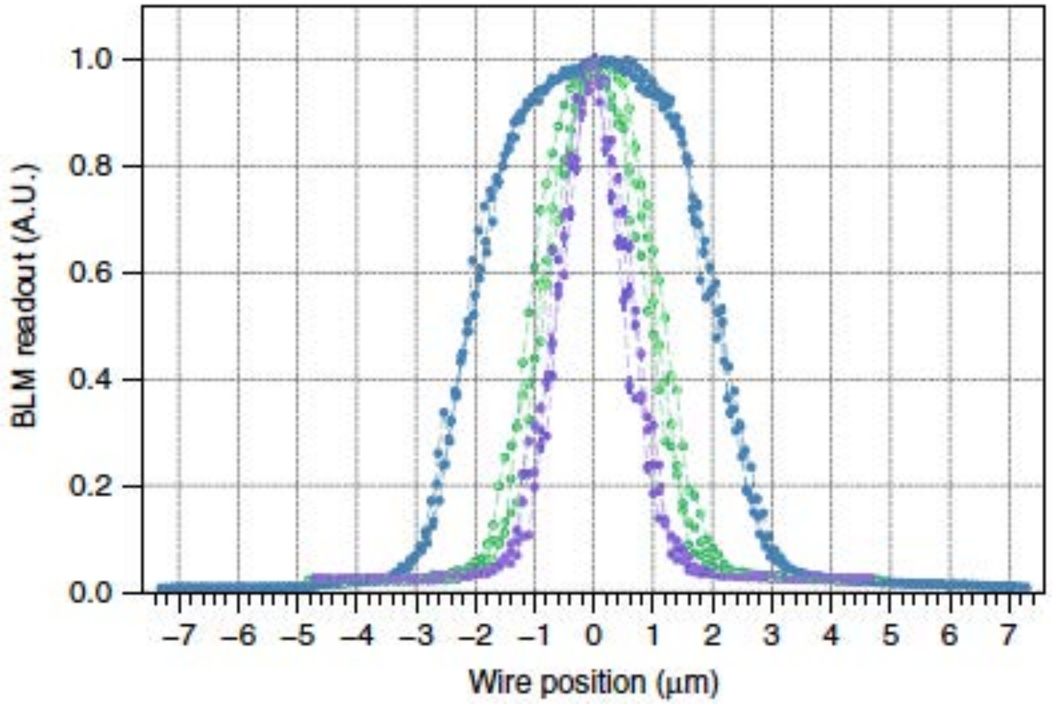
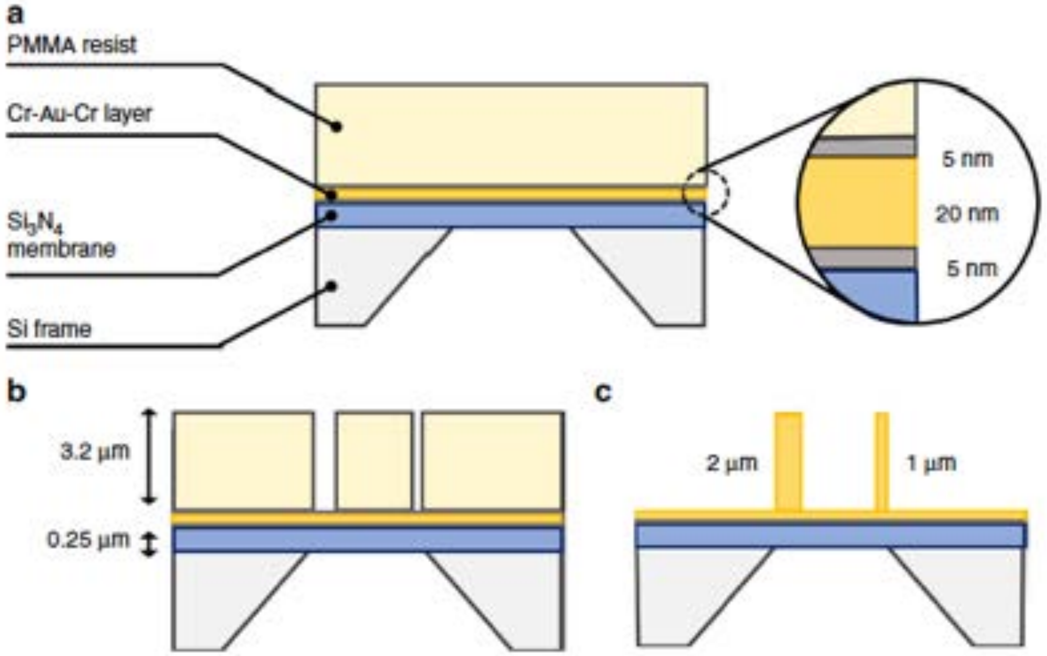
Self-Standing Wire Scanner

Courtesy of A. Cianchi

- A thin metallic wire (free-standing gold wire) scans the beam transversally
    - The generated particle shower (**loss signal**) is **detected** downstream => **reconstruction of the beam transverse profile**
- **Sub-um resolution** requires the reduction of the wire width
    - **nano-fabrication techniques to produce a 1 µm wide** metallic stripe on a membrane by electron-beam lithography and electroplating
        - **Smallest transverse beam size measured <500 nm (rms)**





Drawbacks

- 1D, multi-shots, measurement
- Resolution limited by the encoder readout, the wire diameter and vibrations

S. Borrelli et al., *Generation and measurement of sub-micrometer relativistic electron beams*, Communications Physics 1.1 (2018): 1-8

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Driver-Witness Temporal Characterization

- **Coherent Radiation** based diagnostics allows for **fs scale resolution**, are **non-invasive**, but suffers frequency domain problems, i.e. knowledge of frequency spectrum, and **phase reconstruction methods** (e.g. Kramers-Kroenig technique)

- The **Electro-Optics techniques** are **limited** in **temporal resolution** (~40 fs) but
  - are "**non-destructive**"
  - allow for **on line measurement of driver-witness time separation** (in case of PWFA)
  - allow **direct measurement of ATJ**

- **RF-based transverse deflecting structure (TDS)** is a very **well known and established diagnostic** device
  - **fs-scale** resolution is achievable operating at **higher frequencies** (e.g. X band)
  - **Combined with a dispersive system**, allows to measure not only **absolute bunch length and temporal profile, slice emittance,** but also **energy and slice energy spread**
    - It is **self-calibrating,** but **intercepting and multi-shots**
  - **Novel schemes** allow for **3D characterization of the phase space** using tomographic methods, relying on **variable polarization of the deflecting field => PolariX TDS**

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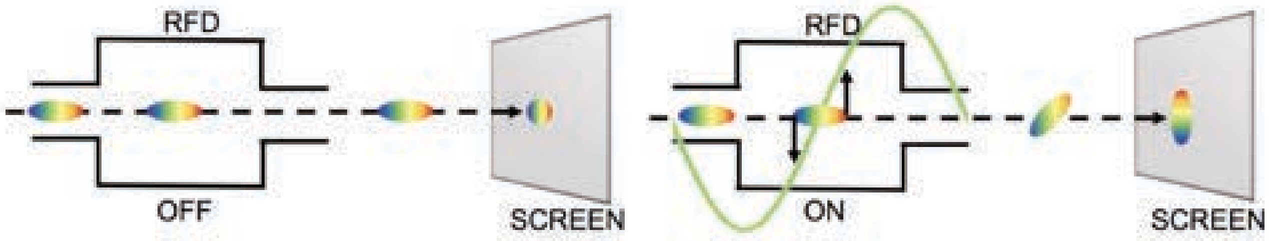
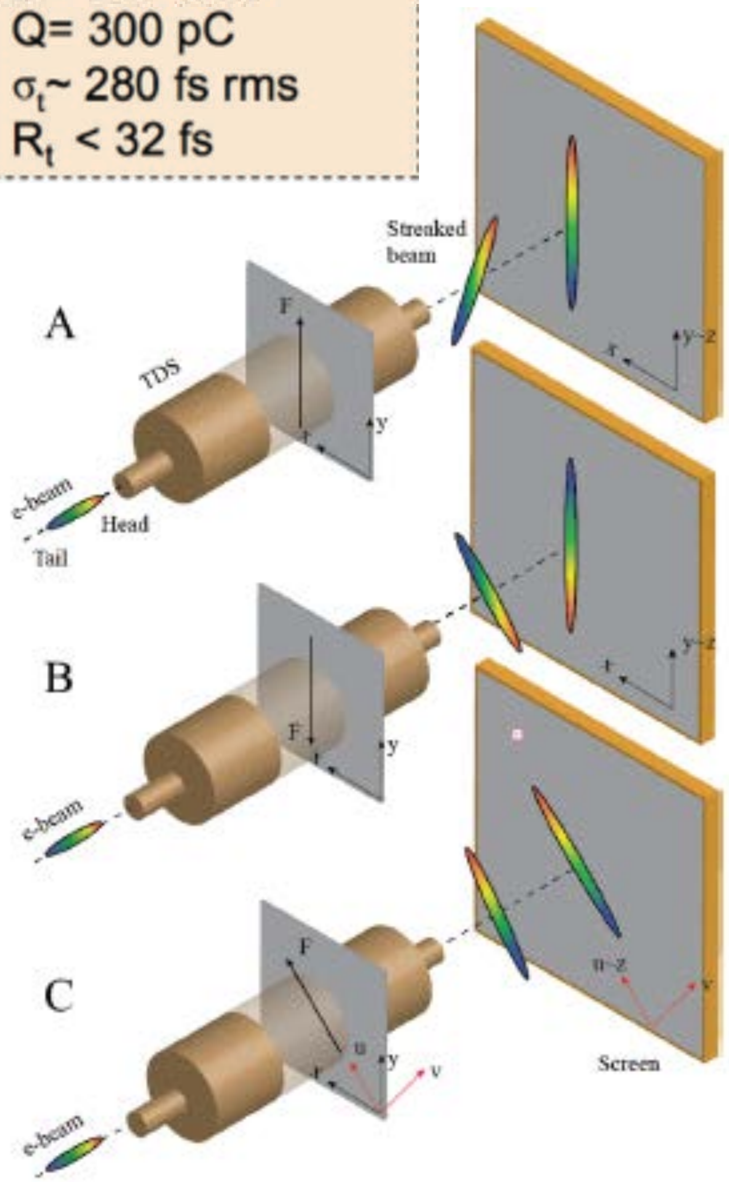
PolariX TDS

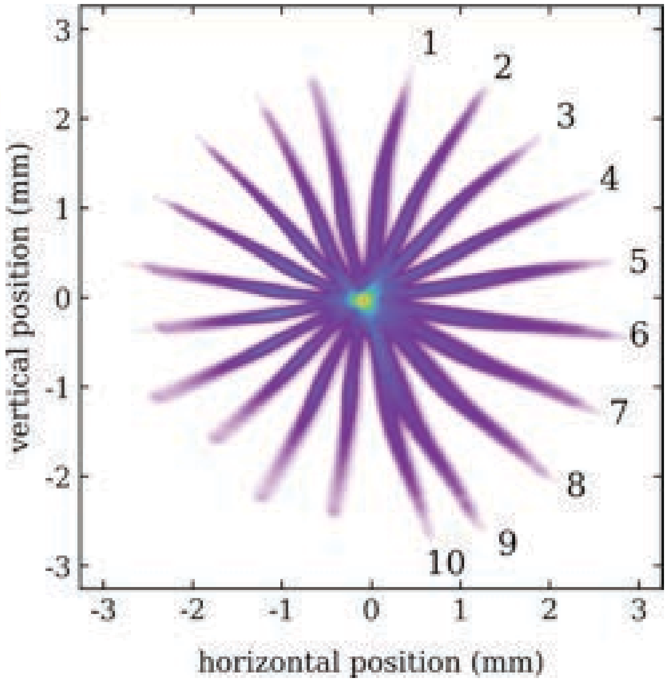
PolariX TDS is a variable **Polari**zation **X**-band **T**ransverse **D**eflecting **S**tructure

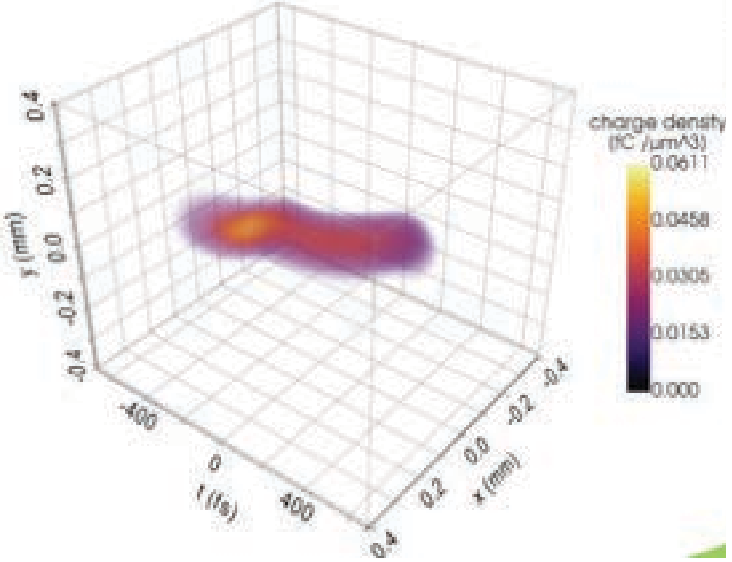


E= 680 MeV
Q= 300 pC
σ_t~ 280 fs rms
R_t < 32 fs

Standard Design







- TDS design allows to change the direction of the streaking field on an arbitrary transverse plane
- Modular structure because based on celle => depending on the energy, the TDS length varies
- Identification of correlations, tilts of the beam distribution in 3D

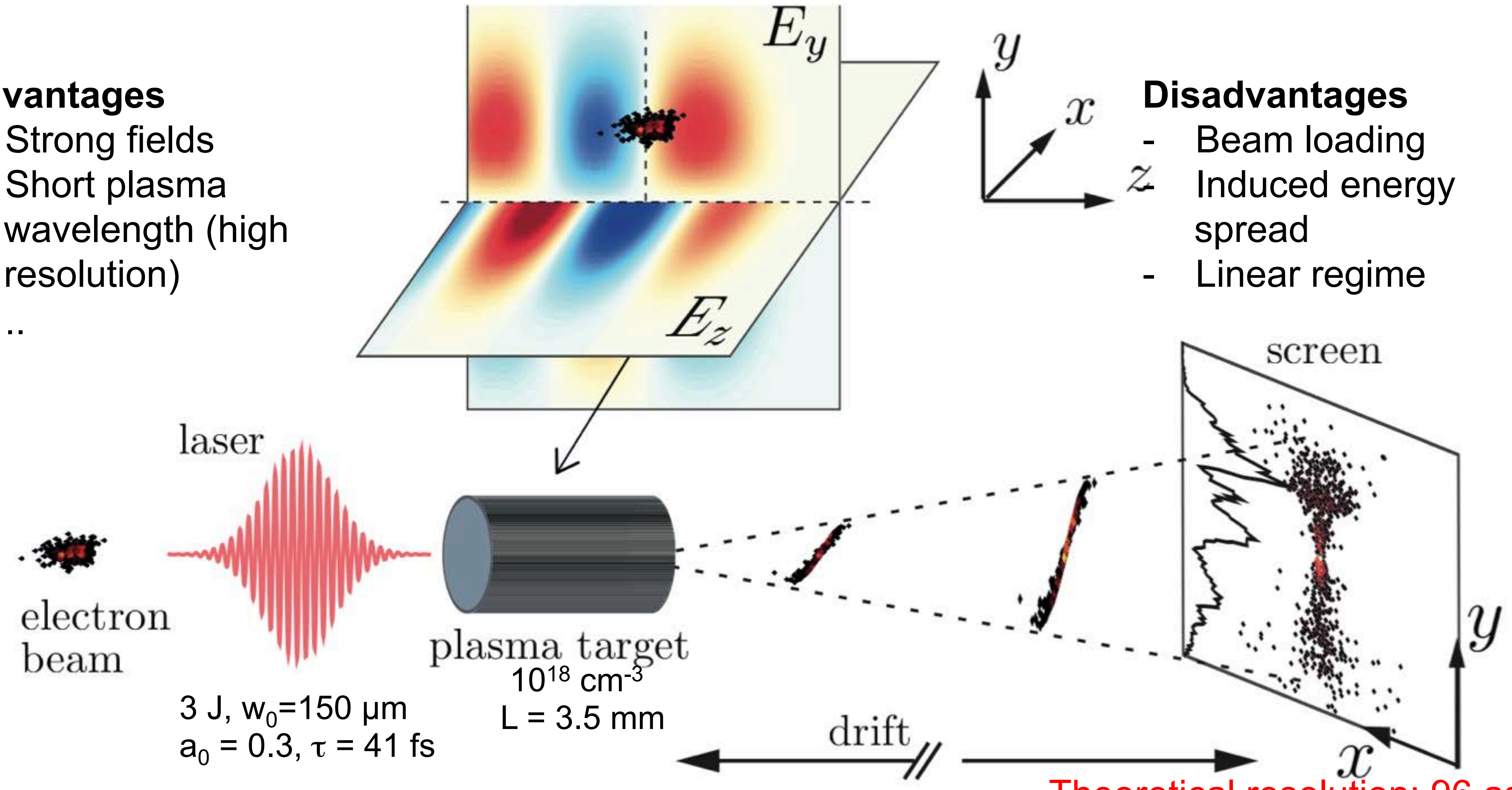
B. Marchetti et al., *Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure*, Scientific Reports (2021) 11:3560

Plasma-based Deflecting Structure

Plasma-driven ultrashort bunch diagnostic
Irene Dornmair

Laser drives linear wakefields => injecting the electron beam off-axis in y, it experiences a streaking field

PIC simulations



Advantages
- Strong fields
- Short plasma wavelength (high resolution)
- ..

Disadvantages
- Beam loading
- Induced energy spread
- Linear regime

3 J, w_0=150 µm
a_0 = 0.3, τ = 41 fs

10^{18} cm^{-3}
L = 3.5 mm

Theoretical resolution: 96 as

I. Dornmair et al., *Plasma-driven ultrashort bunch diagnostics*, Phys. Rev. AB (2016) 19, 062801

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Electron Beam Parameters at Extraction

PWFA Experience

- Typical electron beam parameters at **extraction area**
    - few 10s of fs (down to fs) scale witness bunch duration
    - <1% energy spread
    - ~mm-mrad normalized emittance (but mrad scale angular divergence)
    - low stability —> plasma instability issues, ATJ at the plasma entrance, …

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Normalized Projected Emittance

Conventional techniques

- **Multi-shot quadrupole scan technique**
    - shot-to-shot instability
        - stabilization of plasma discharge with laser ignition
    - the large energy spread, in the % range, and the large divergence, in the mrad scale, prevent from the preservation of the normalized emittance in a drift => the result is strongly dependent on the measurement position

$$\boxed{\varepsilon_n^2 =<\gamma>^2 (\sigma_E^2\sigma_x^2\sigma_{x'}^2+\varepsilon^2) \approx <\gamma>^2 (\sigma_E^2\sigma_{x'}^4 s^2+\varepsilon^2)}$$

-
    -
        - mitigation of the energy spread
            - assisted beam-loading technique
        - fast capture of the beam

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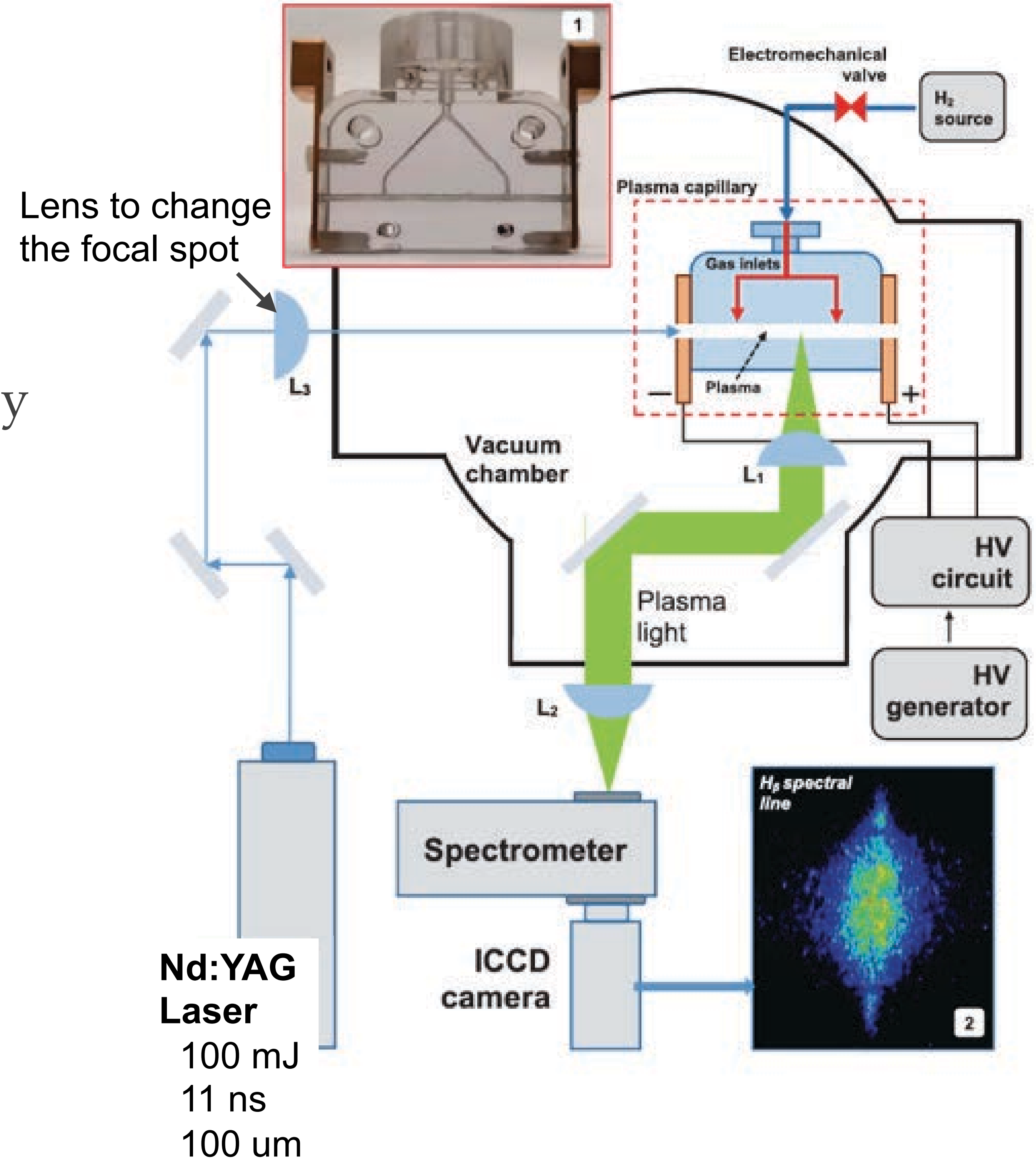
Gas-filled Capillary-Discharge Stabilization

Courtesy of A. Biagioni

- **Discharge ignition depends on the operating conditions**, since the breakdown voltage depends on the molecules distribution inside the capillary (pressure and length)
- Discharge timing jitter is affected by the **voltage** and the **gas pressure** in the capillary
- To **decrease the time jitter** (and so the shot-to-shot instability) **a laser pulse** can be used **to ignite the discharge**



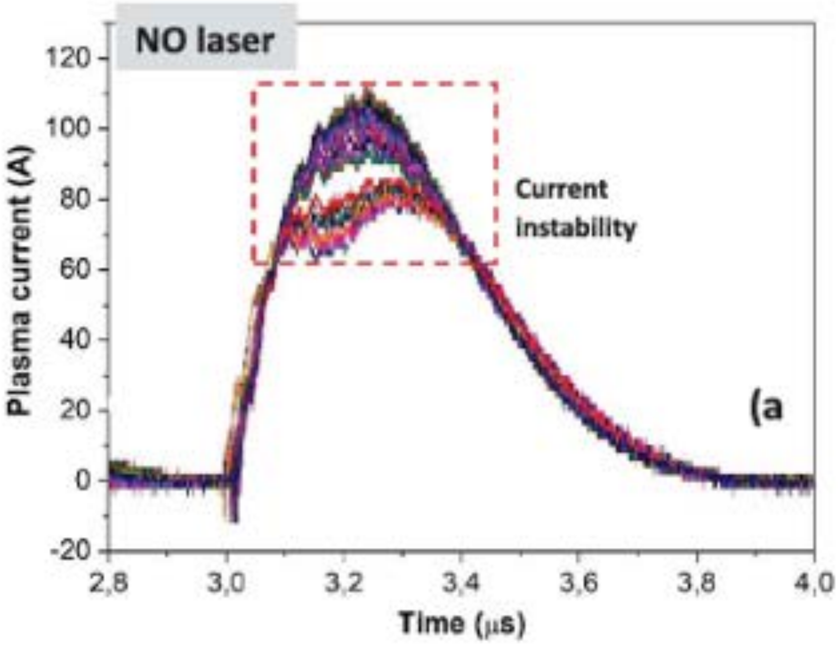
Lens to change the focal spot

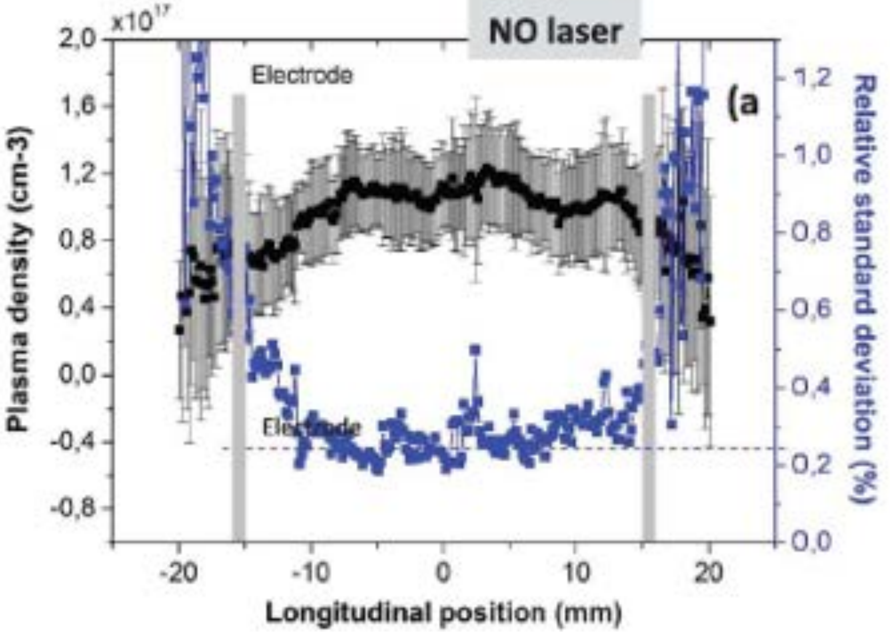
Nd:YAG Laser
100 mJ
11 ns
100 um

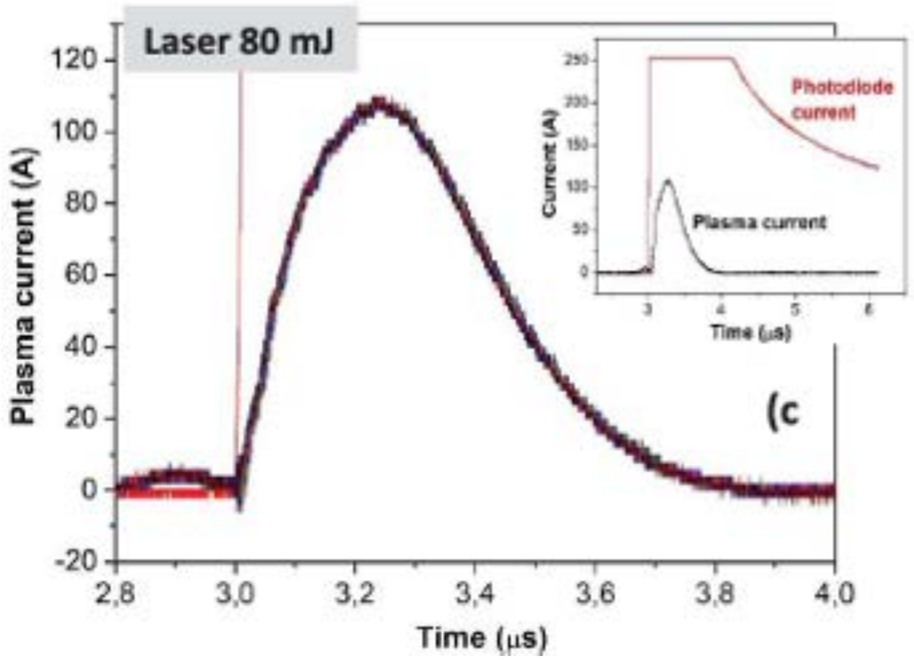
Gas-filled capillary-discharge Stabilization

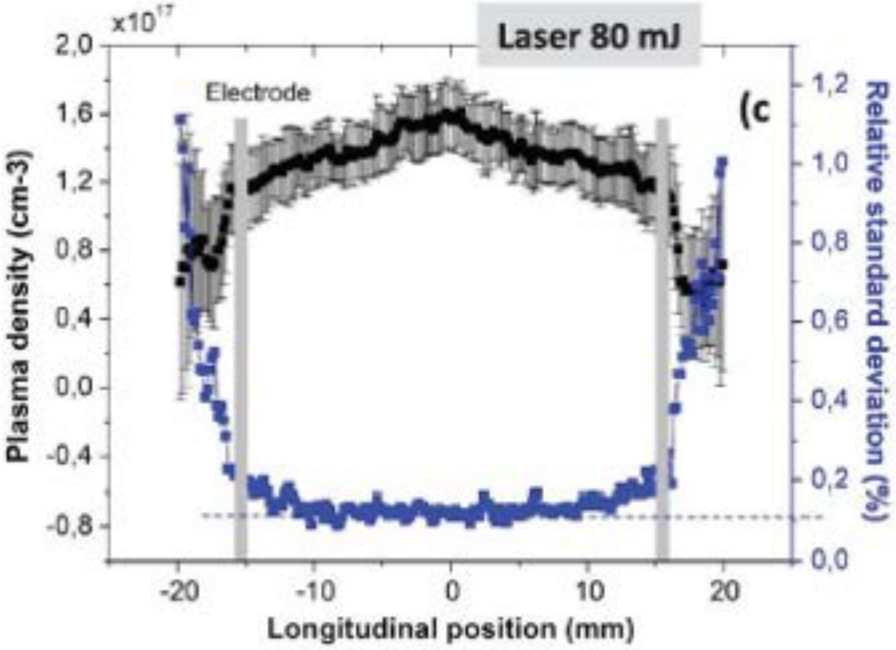
Courtesy of A. Biagioni

- Plasma density instability reduced **from 25% to 11%** at 5kV
- Instability of **5%** when operating **at 8 kV** (evaluated from Stark measurement)









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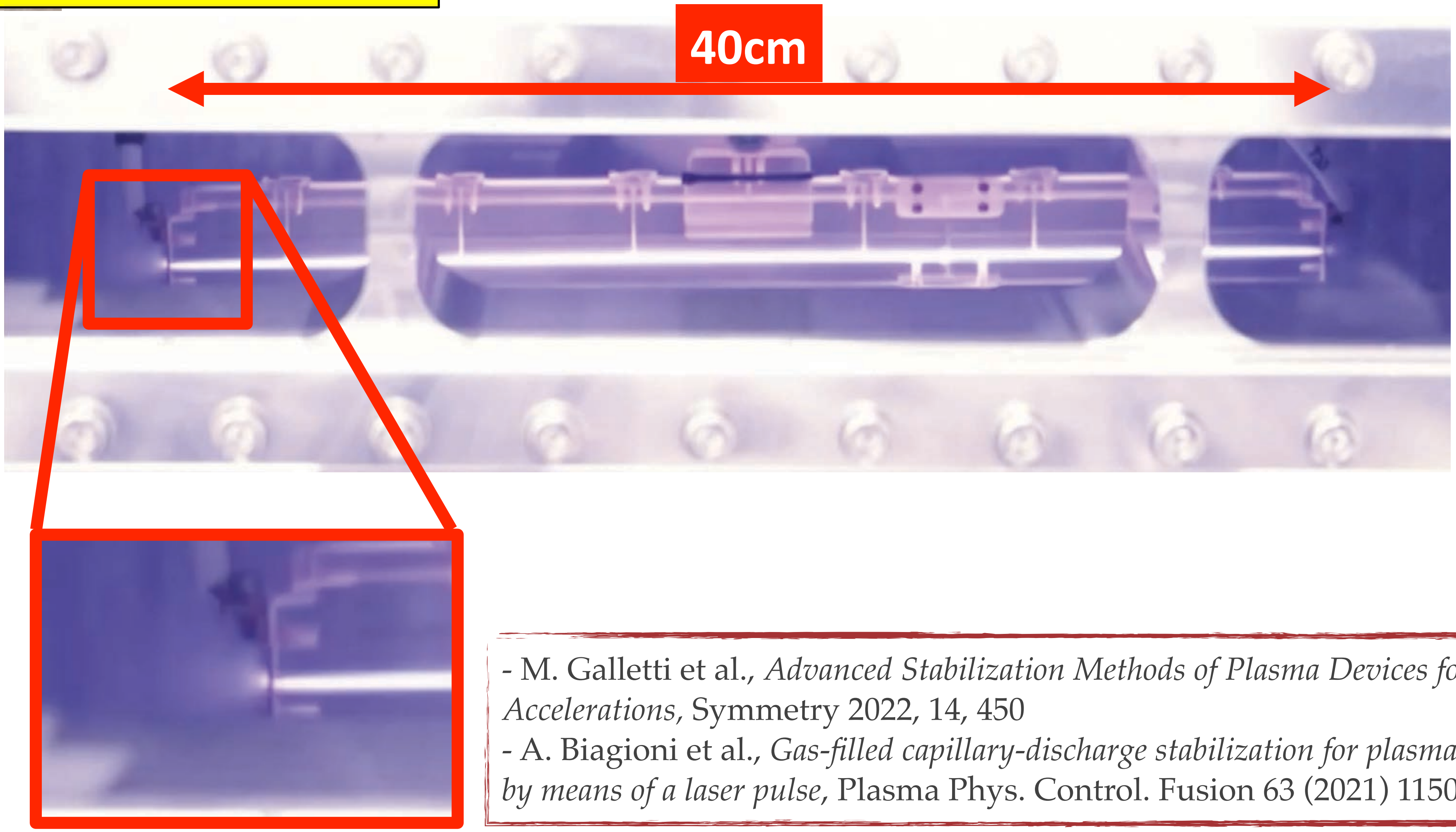
40 cm Long Gas-filled Capillary Discharge

Courtesy of A. Biagioni

This stabilization technique enables the development of very long capillaries

Last result in the Plasma_Lab: First EuPRAXIA plasma source to reach 1.1 GeV (1.5 GV/m) - **40 cm long**



- M. Galletti et al., *Advanced Stabilization Methods of Plasma Devices for Plasma-Based Accelerations*, Symmetry 2022, 14, 450
- A. Biagioni et al., *Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse*, Plasma Phys. Control. Fusion 63 (2021) 115013

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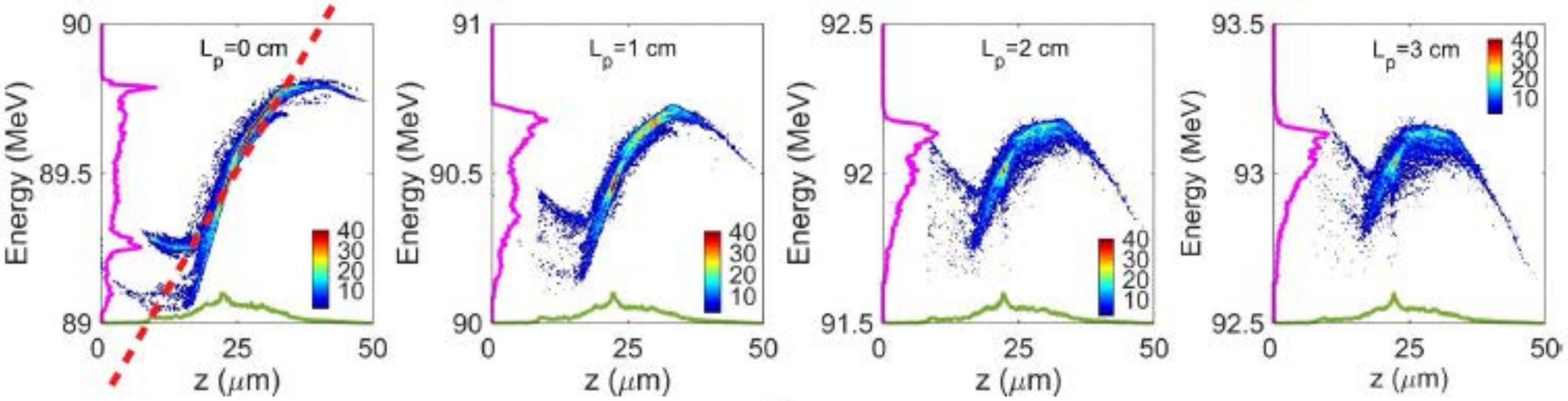
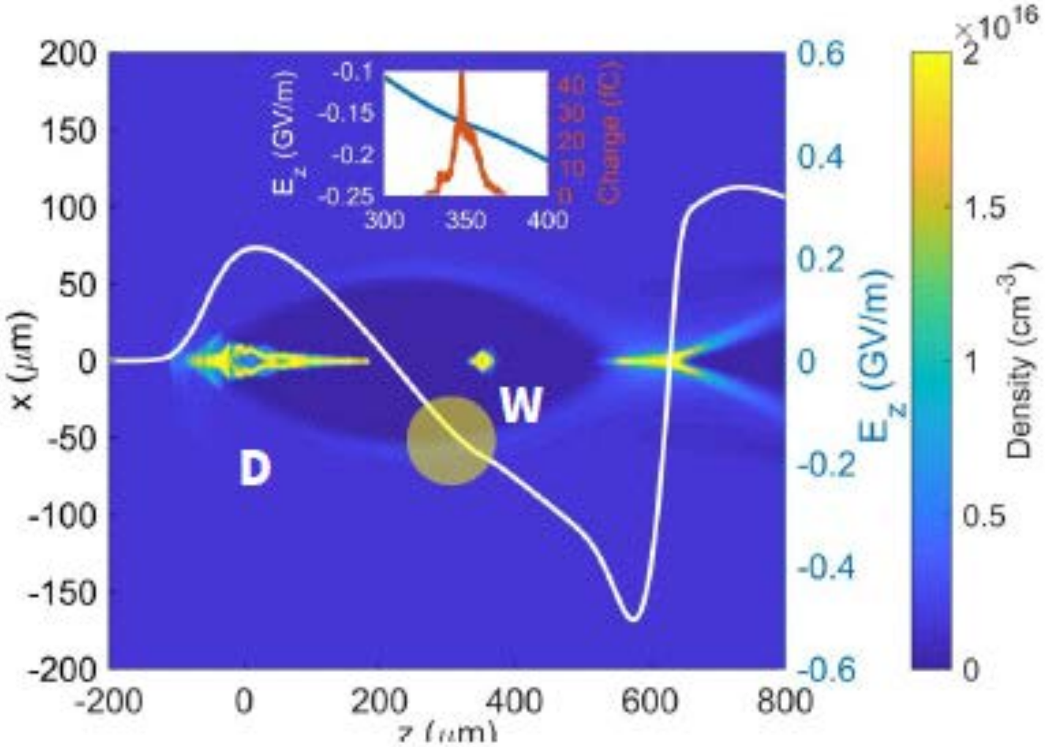
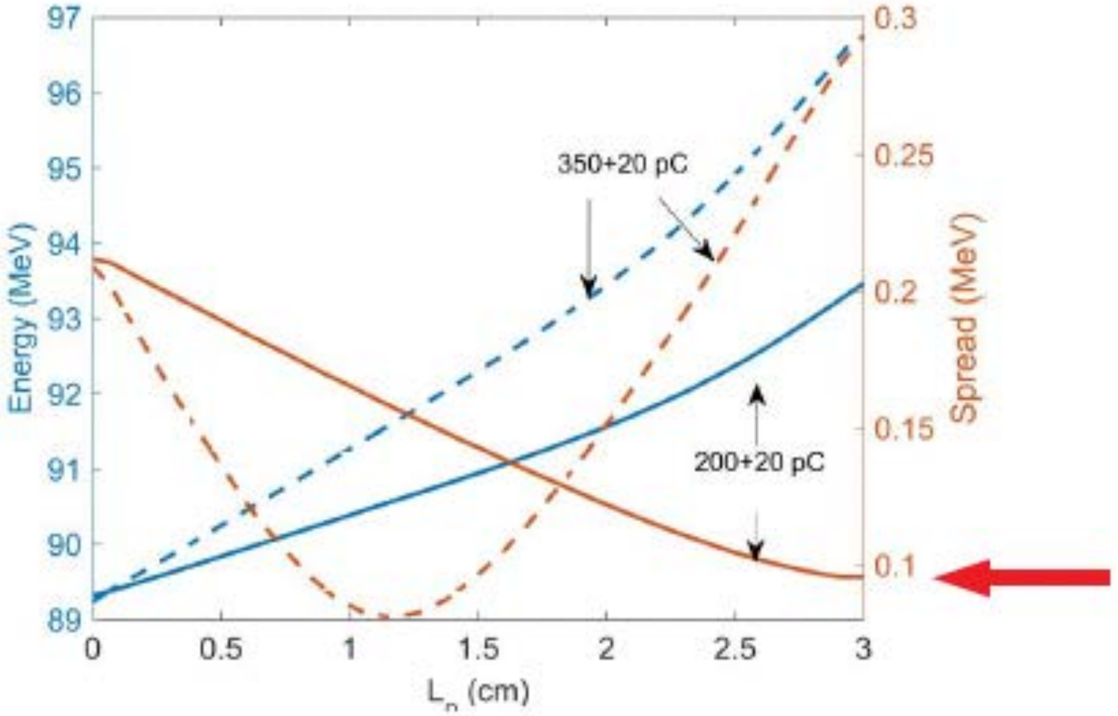
Assisted beam-loading technique

Pre-chirp to compensate wakefield slope





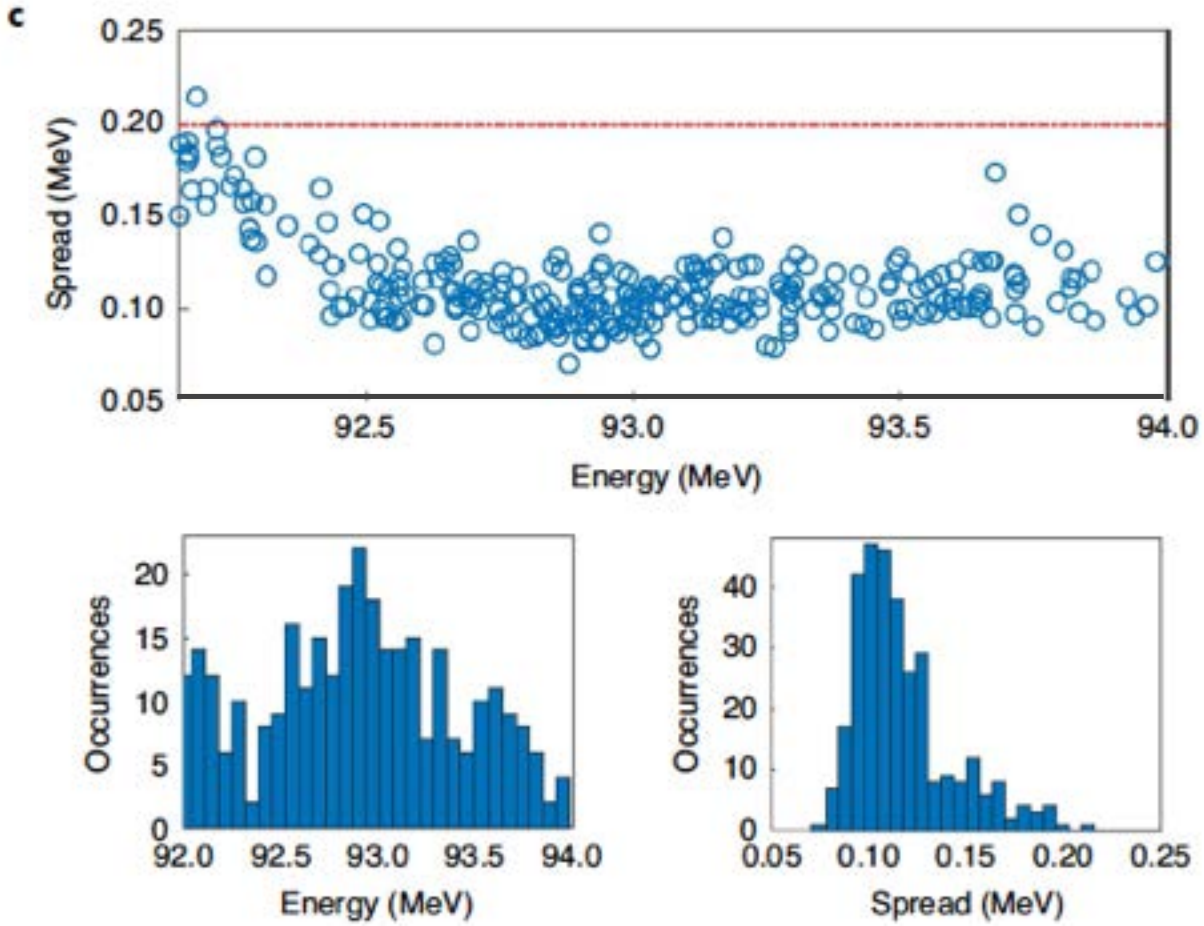


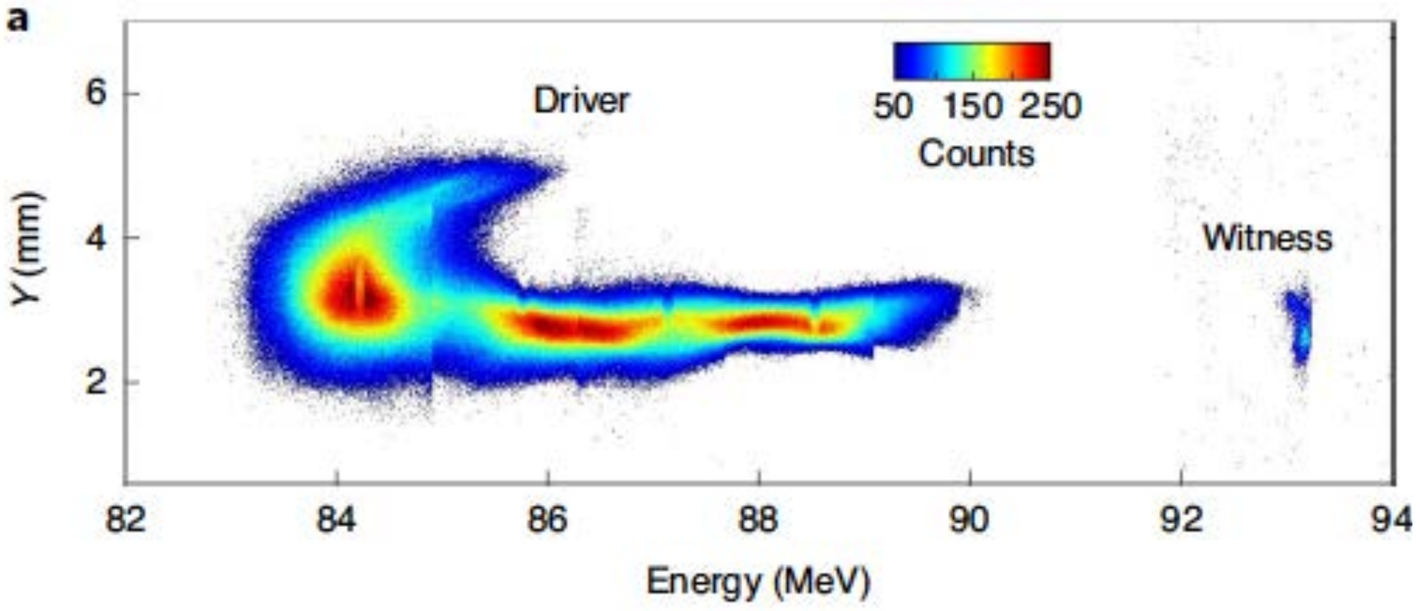
R. Pompili et al., *Energy spread minimization in a beam-driven plasma wakefield accelerator* (2021), Nature Physics, **17** (4), pp. 499-503

Energy Spread Minimization

- **Energy spread reduction in the beam driven PWFA experiment**

- 4 MeV acceleration in 3 cm plasma with 200 pC driver
  - ~133 MV/m accelerating gradient
  - 2x10^{15} cm^{-3} plasma density
  - Energy spread from 0.2% to 0.12%





Energy jitter of the witness energy is 0.5 MeV

R. Pompili et al., *Energy spread minimization in a beam-driven plasma wakefield accelerator* (2021), Nature Physics, **17** (4), pp. 499-503

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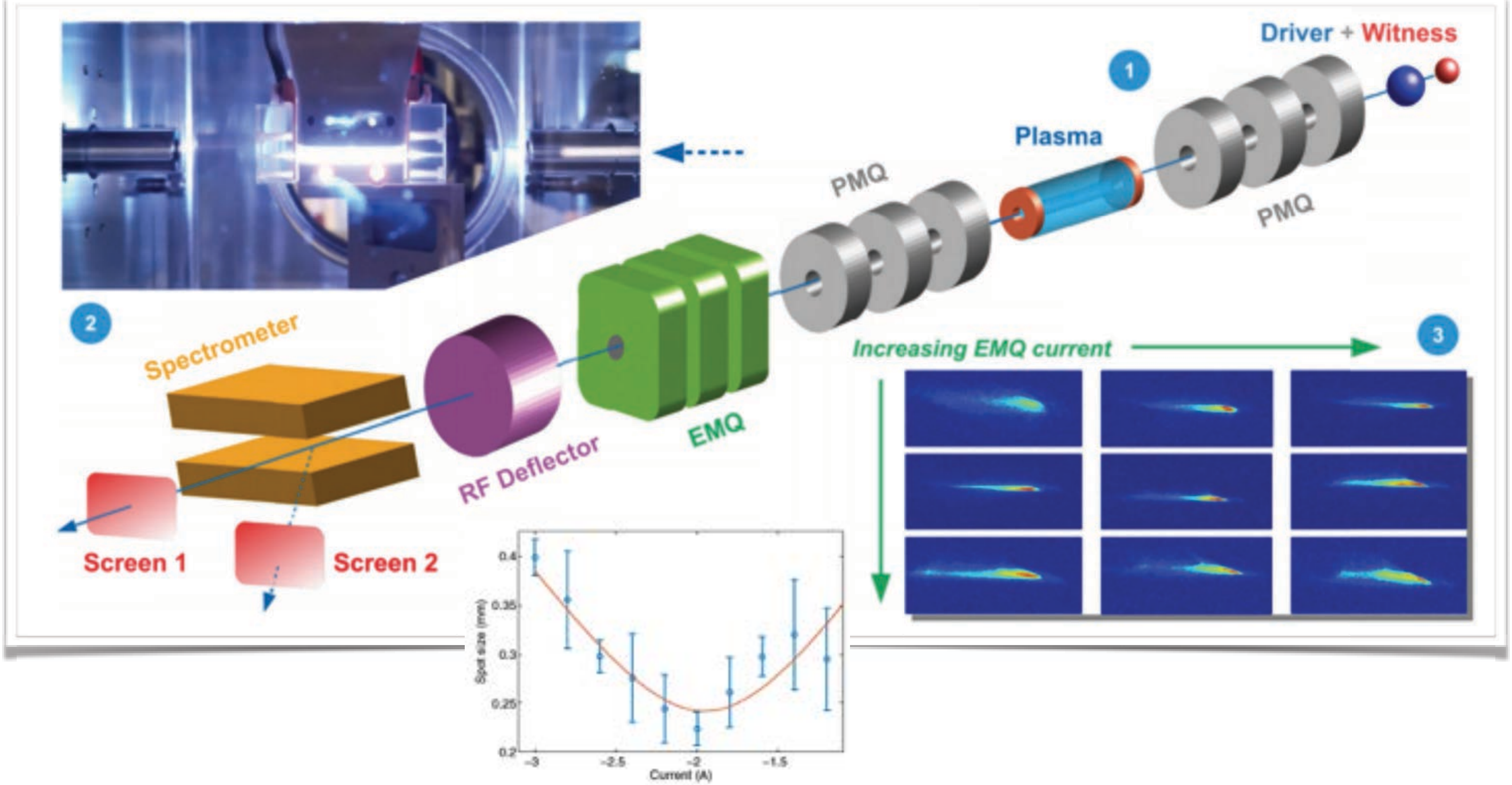
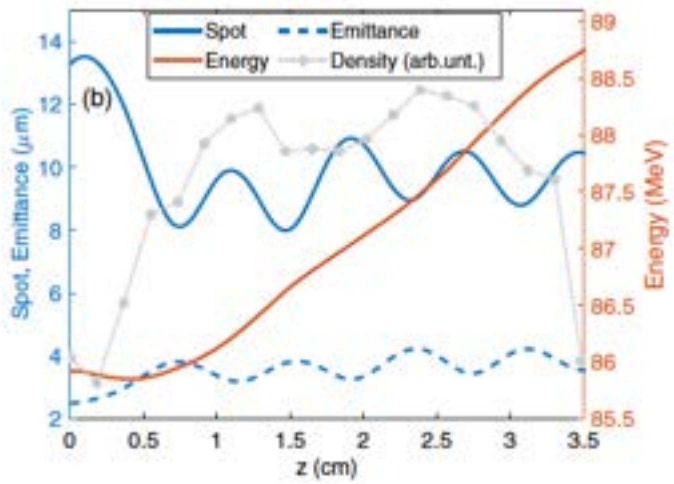
First normalized emittance measurement at SPARC_LAB

- **Multi-shot quadrupole scan technique** to measure the plasma-accelerated witness normalized emittance
    - emittance increase from 2.7 um to 3.7 um (rms) during acceleration





V. Shpakov et al., *First emittance measurement of the beam-driven plasma wakefield accelerated electron beam*,
(2021), Physical Review Accelerators and Beams, **24** (5), art. no. 051301

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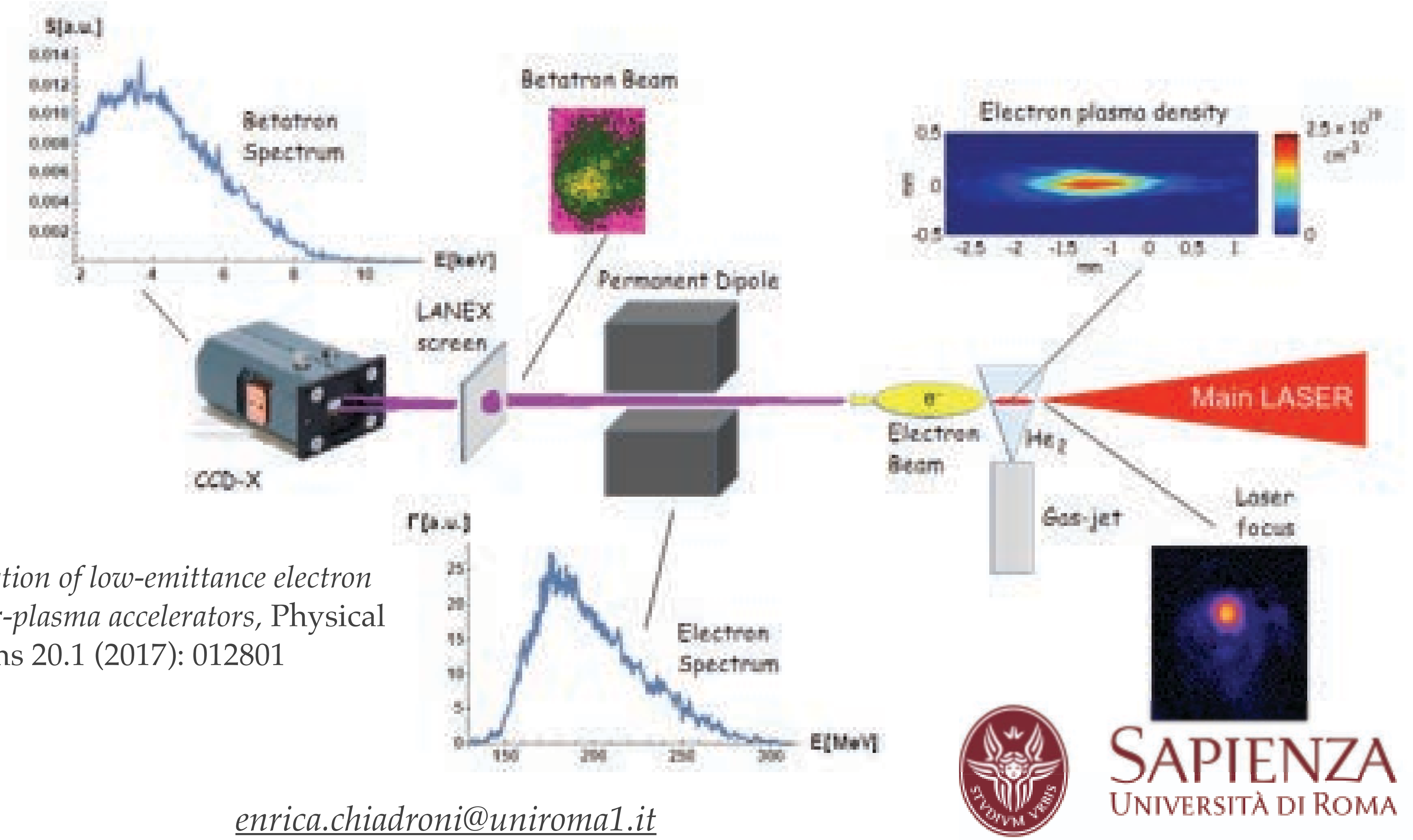
Normalized Projected Emittance

Novel technique based on betatron radiation

- First measurement of the emittance including the correlation term
- The beam profile is retrieved not simply the average dimensions
- An expression is given for the correlation function between the betatron oscillation amplitude and the divergence of the single accelerated electrons, i.e. the angle with respect the acceleration axis, in order to obtain the distribution of the electron divergences

1 J
30 fs (FWHM)
10 μm diameter focus,
a0 ~ 4.4
n_e=(8±1)10^{18} cm^{-3}



A. Curcio et al., *Trace-space reconstruction of low-emittance electron beams through betatron radiation in laser-plasma accelerators*, Physical Review Accelerators and Beams 20.1 (2017): 012801

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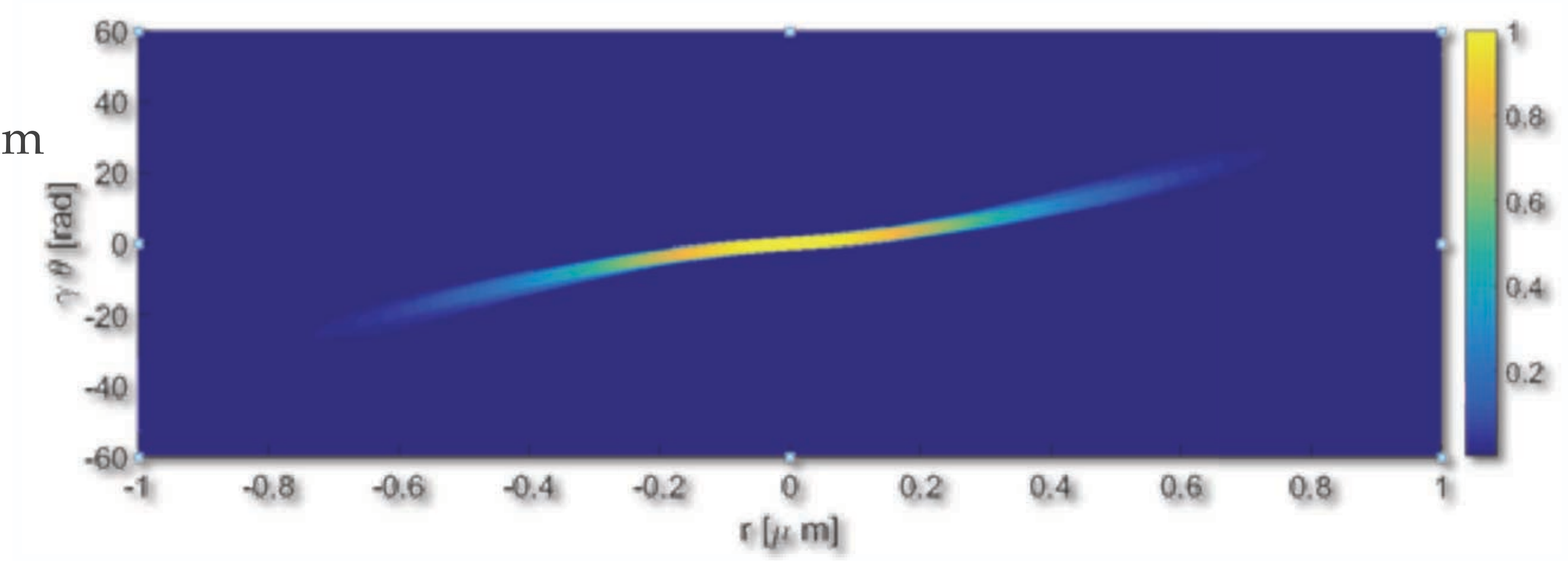
Phase Space Reconstruction

Novel technique: Emittance with the correlation term

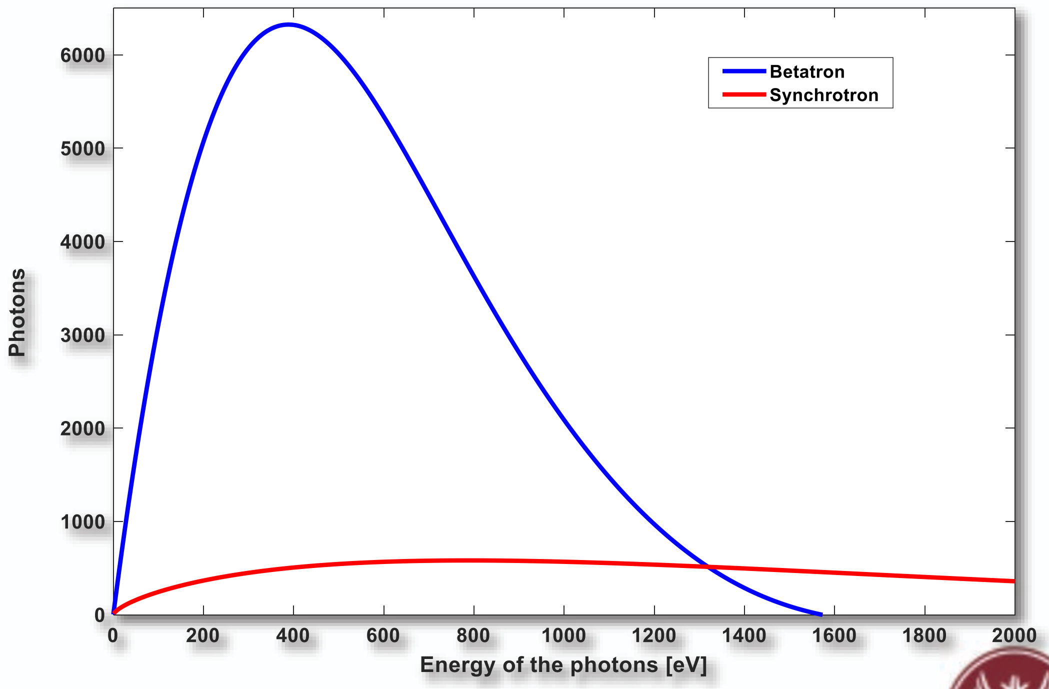
A. Curcio et al., PR AB 20.1 (2017): 012801

- Phase space reconstruction by means of betatron radiation + simultaneous measurement of electron energy spectrum
- Normalized rms emittance (correlated): 0.6 mm mrad
- Normalized rms emittance (non correlated, upper limit): 1.6 mm mrad



ISSUES

- Separation of betatron radiation from synchrotron radiation coming from bending magnet
- Separation of witness and driver radiation in case of beam driven
  - Driver has typically a factor 10 more charge



Beam charge 30 pC
Energy 1 GeV
plasma density 2 10^{16}cm^{-3}
magnet filed 1.5 T
radius of curvature 2.2 m

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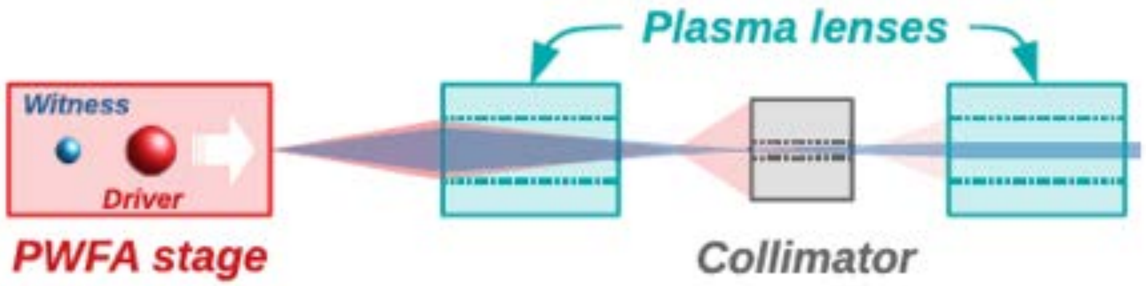
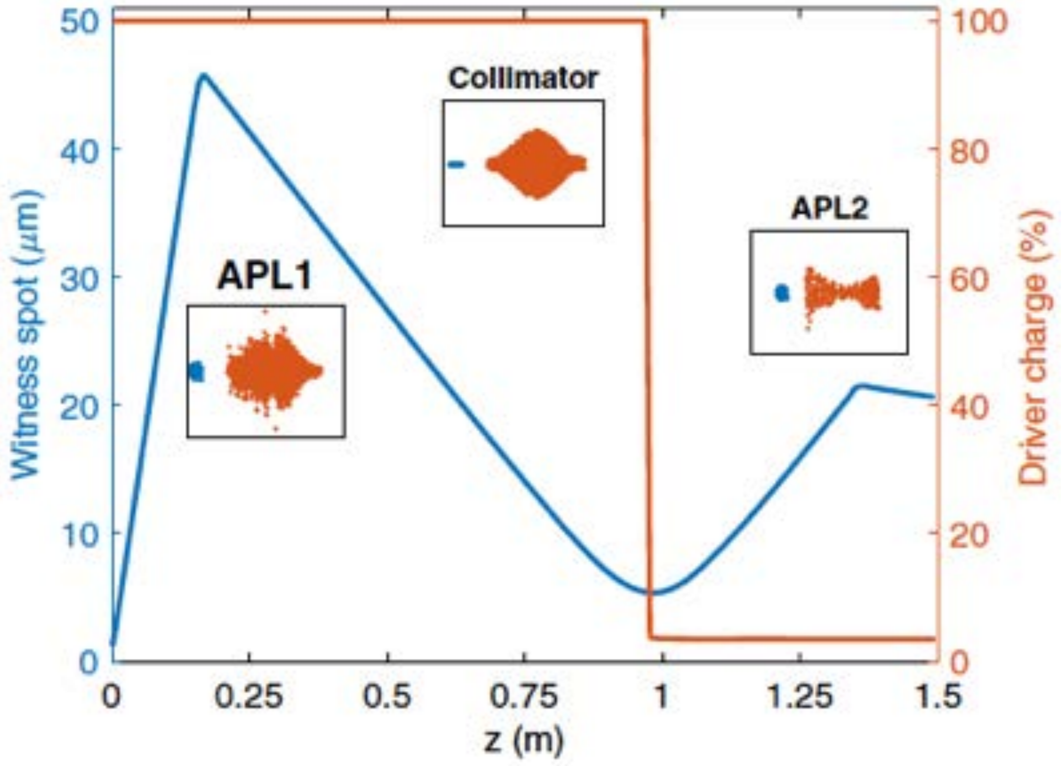
Driver Removal Issue

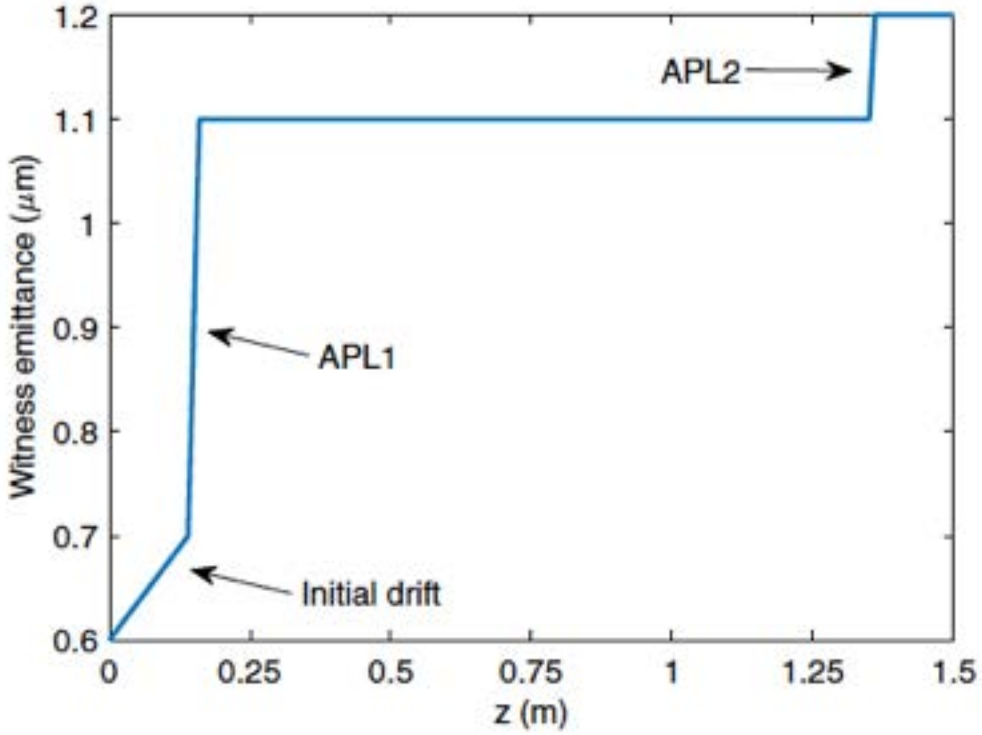
- **Extraction system based on active plasma lenses** to **remove** the high-charge and energy-depleted **driver** bunch and, at the same time, provide an **efficient capture of the witness** bunch minimizing its degradation

Advantages

- tunability
- good dumping efficiency of the driver
- compactness







R. Pompili et al., *Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments*,
Physical Review Accelerators and Beams 22 (2019): 121302

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Conclusions

- Plasma-accelerated beam diagnostics is very challenging, because of the scale length involved (um and fs) and the stability issue
- **Diagnostics must be well-established** to be really useful
  - Novel diagnostics are welcome, but once they are **straightforward and easy to implement**
    - Diagnostics cannot be an experiment
      - **Efforts** have to be done to make plasma acceleration equivalent to conventional one in terms of **beam quality, reliability and reproducibility**
- **Compact, single shot, reliable systems must be preferred**
  - Betatron radiation might be a good candidate to measure the beam properties at the end of the plasma and get hints on the acceleration
- **High level applications are the best diagnostics for plasma-accelerated beams**
  - **We (the whole community) are not far from that!!**

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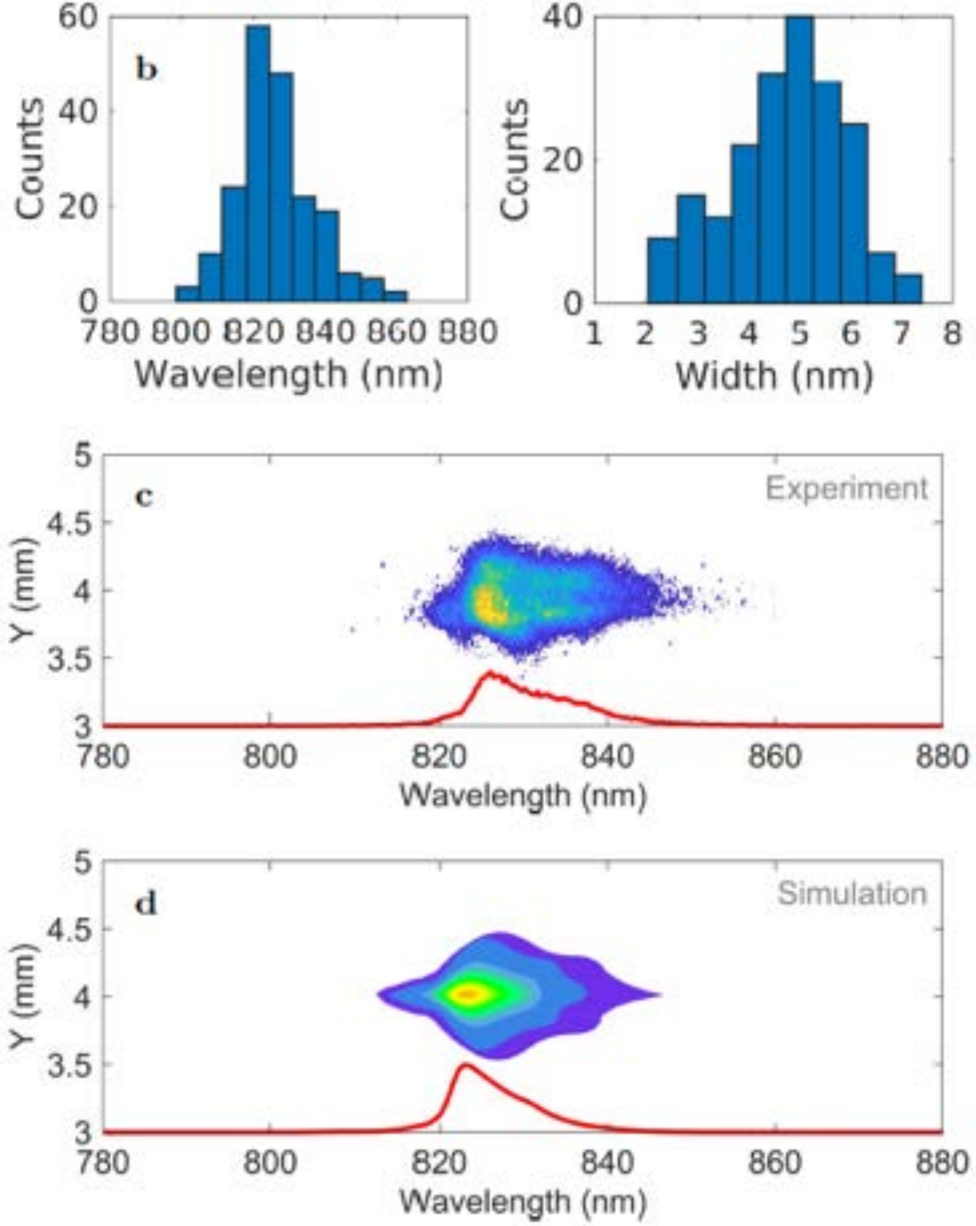
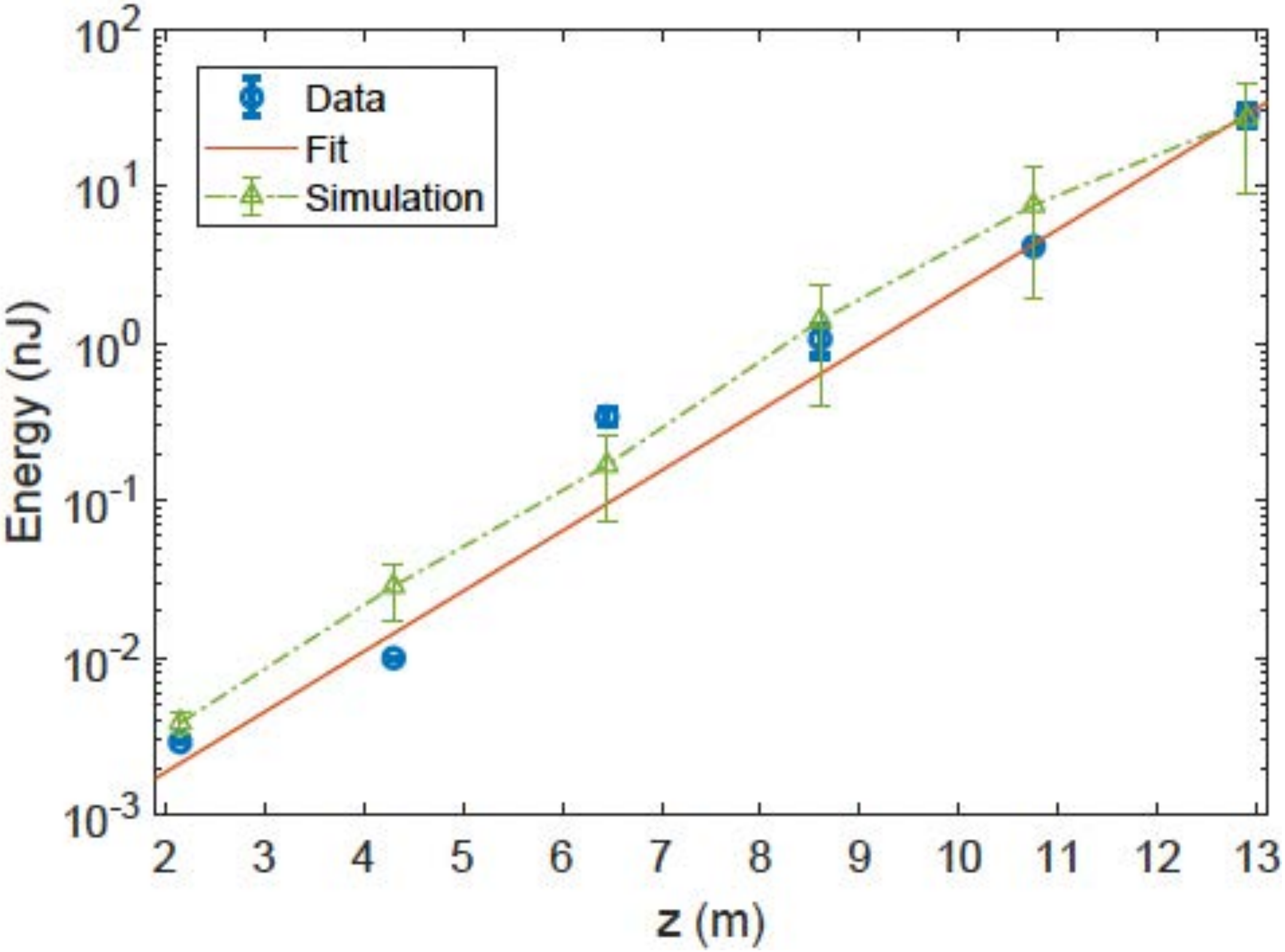
First PWFA-driven SASE FEL

First experimental observation of the gain growth of a plasma-driven SASE FEL at the SPARC_LAB Test Facility





R. Pompili et al., *First lasing of a free-electron laser with a compact beam-driven plasma accelerator,* (2021), **will be available on Nature from May 26th**

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First LWFA-driven SASE FEL

Article

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

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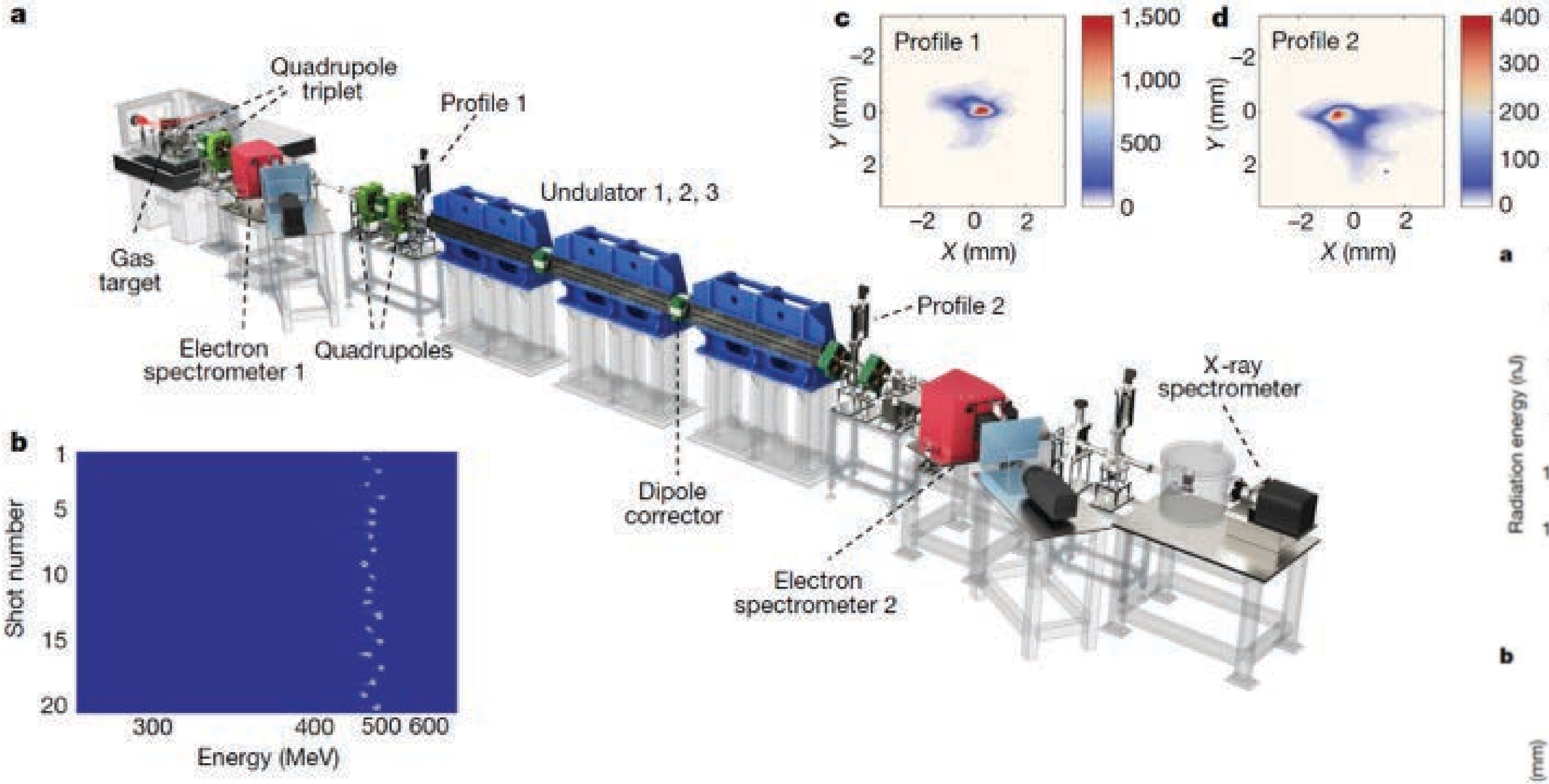

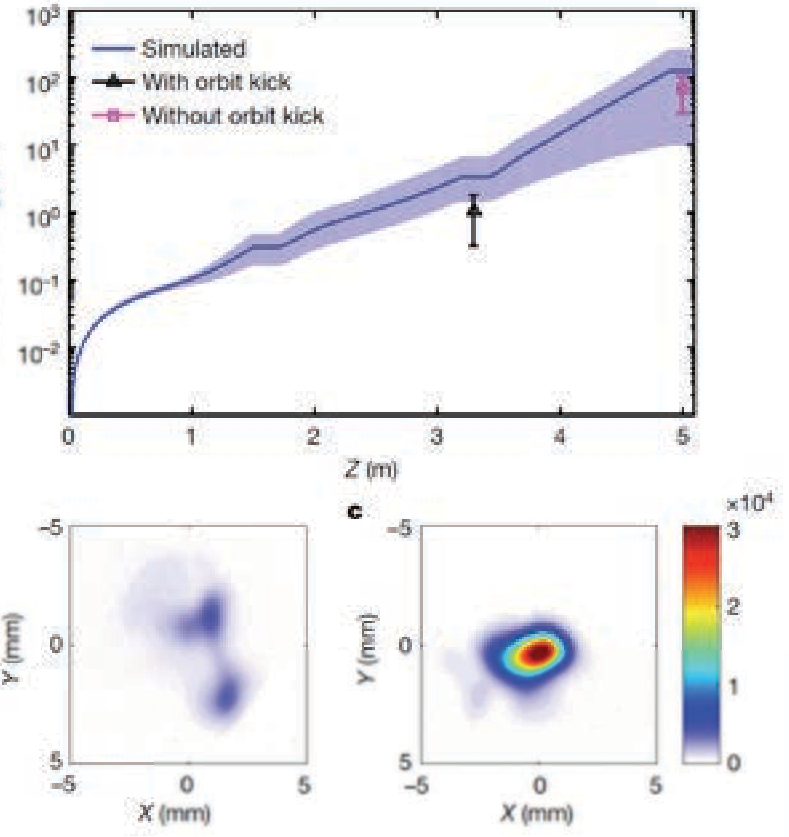

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