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EuPRAXIA
Preparatory Phase

Beam diagnostics at plasma entrance for EuPRAXIA@SPARC_LAB

F. Demurtas

On behalf of the EuPRAXIA@SPARC_LAB group

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Outline

- **Plasma-entrance diagnostic layout and requirements**
- **Transverse diagnostic strategy**
- **Beam instrumentation:**
  - **YAG scintillating screen**
  - **Microwire scanner**
  - **OTR screen**
- **Summary and conclusions**

EuPRAXIA@SPARC_LAB diagnostics

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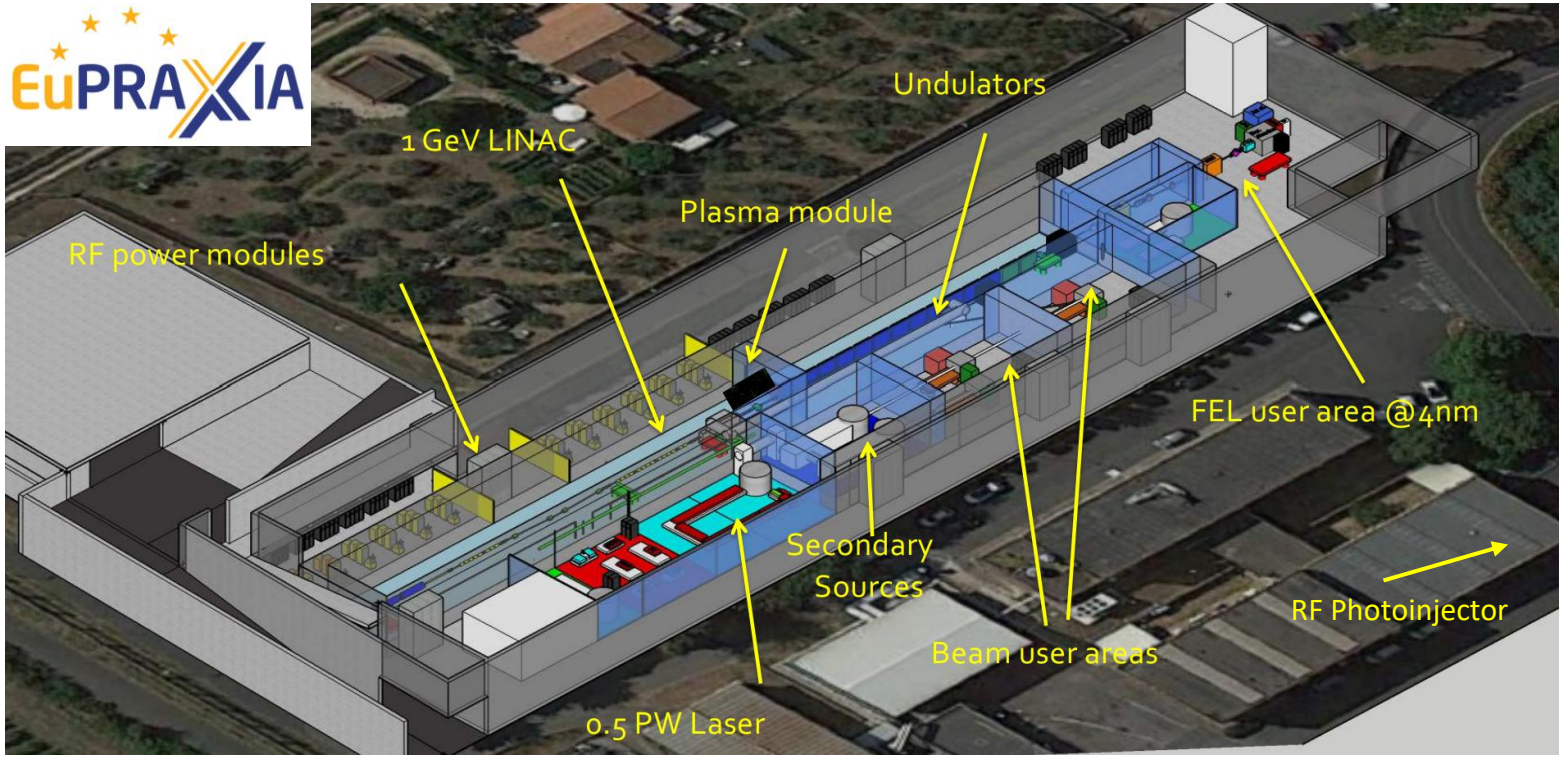

- **EuPRAXIA@SPARC_LAB** is designed as **the first user-facility** based on a Free-Electron Laser driven by a **plasma-accelerated beam [Ref. 1]**

- **Diagnostic needs:**

  Precise characterization of the driver and witness before the plasma, and of the accelerated witness downstream, before the undulator

Before plasma:

- Driver ($200\ pC$)+Witness ($30\ pC$)
- $E \simeq 500\ MeV$

Plasma entrance:

- Witness transversely matched to the plasma focusing channel

Post-plasma:

- Driver-witness separation
- Accelerated witness ($1\ GeV$) characterization

Talk scope – Plasma-entrance diagnostics

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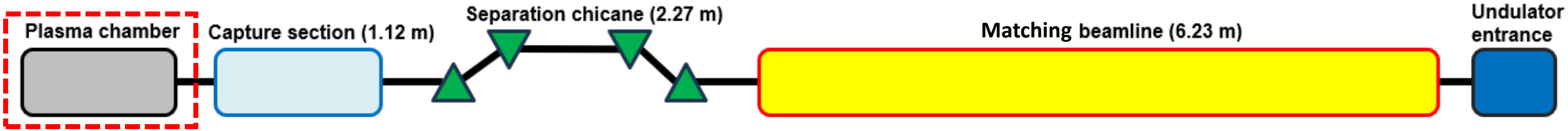
- The diagnostic system around the plasma interaction covers both the plasma chamber and the downstream beamline. In this talk, **the focus is on transverse beam diagnostics at the plasma entrance**

- **Beamline layout:**



Before plasma acceleration :

- **Beam size measurement**

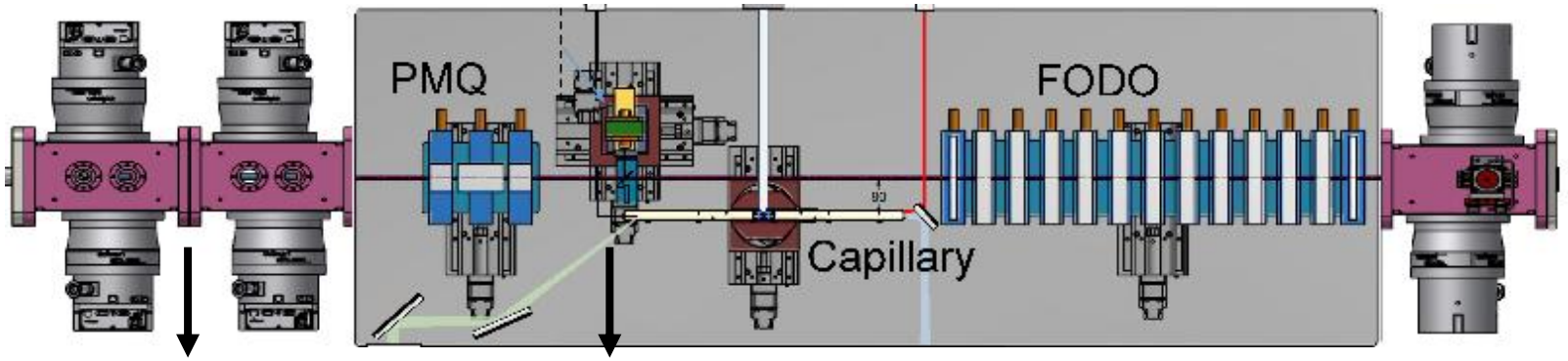
After plasma acceleration:

- Longitudinal phase space
- Transverse phase space

- **Talk goals:**
  - Define the diagnostic requirements at the plasma entrance for the driver–witness system
  - Discuss the complementary use and limitations of YAG, microwire scanner and OTR imaging for few-µm beams
  - Assess the main resolution and robustness limits and the strategy for reconstructing the witness waist

Plasma chamber diagnostic layout

- Diagnostics are installed inside the plasma interaction chamber, between the PMQ and the plasma capillary



External Diagnostic section:
Electro-optical sampling

Internal diagnostic section:
Wire Scanner + OTR screen + YAG

- **Ideal matched conditions at plasma entrance [Ref. 2]:**
  - $\alpha_{twiss} = 0 \Rightarrow$ Beam injected at waist
  - $\beta_{twiss} = \sqrt{\frac{2m_e c^2 \varepsilon_0}{\rho_e e^2}}\gamma \Rightarrow$ Matching to the plasma focusing force

→ Matched conditions minimize envelope oscillations and allow stable transverse transport through the plasma.

- **Diagnostic implications:** Matched conditions require a few-µm witness beam size

$\sigma_x, \sigma_y \sim few\ \mu m$ → $\sim \mu m$-level spatial resolution

Diagnostic requirements at plasma entrance

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- The expected driver and witness parameters define the performance requirements of the plasma-entrance diagnostics

- **Expected beam parameters:**

Beam parameter	Driver	Witness
E [MeV]	~ 563.8	~ 562.5
Q [pC]	~ 200	~ 30
ε_n [μm]	~ 1.6	~ 0.7
$\sigma_{x,y}$ [μm]	~ 9	$\sim 3-4$
σ_t [fs]	~ 151	~ 18
D-W separation [ps]	0.5	

- The witness dynamics is not independent of the driver: during velocity bunching the two bunches overlap, so removing the driver modifies the witness evolution and therefore its final transverse distribution *[Ref. 3]*

- In the laser-comb scheme, driver and witness are generated by separate time-delayed photocathode-laser pulses; removing one laser pulse prevents generation of the corresponding electron bunch *[Ref. 4]*

- **Witness measurement strategy:**

$$I_W(x,y) = I_{D+W}(x,y) - I_D(x,y)$$

1. Measure driver + witness

2. Suppress the witness laser pulse and measure driver only

3. Subtract the driver reference to retrieve the witness distribution

Plasma-entrance transverse diagnostics strategy

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- The plasma-entrance monitor combines three complementary transverse diagnostics, covering the evolution from large commissioning beams to the few-µm matched witness waist

Scintillating YAG screen

- Fast direct imaging
- **Main limitations:** Scintillator resolution and possible screen damage at high charge density
- **Large-beam regime:** commissioning and initial tuning, typically **tens to hundreds of µm**

Microwire scanner

- Reference measurement for sub-10 µm beams
- **Main limitations:** Intercepting, slower scan; wire robustness / heating
- **Small-beam regime:** high-resolution reference measurement for **sub-10 µm beams**, down to the few-µm matched witness waist

Optical Transition Radiation screen

- Direct optical image and waist localization
- **Main limitations:** Intrinsic OTR Point-Spread Funtion (PSF) dominates below $\sim 4\ \mu m$ at 500 MeV
- **Intermediate regime:** OTR PSF becomes increasingly relevant in the few-µm regime

- Therefore, the diagnostic strategy is not based on a single “best” device, but on a staged use of complementary tools depending on beam size, resolution requirement and robustness

YAG screen

- A scintillating YAG screen provides a strong and easy-to-image signal, making it well suited for commissioning and for relatively large beam sizes

➢ **Why it is useful:**

- Direct single-shot beam image
- High light yield

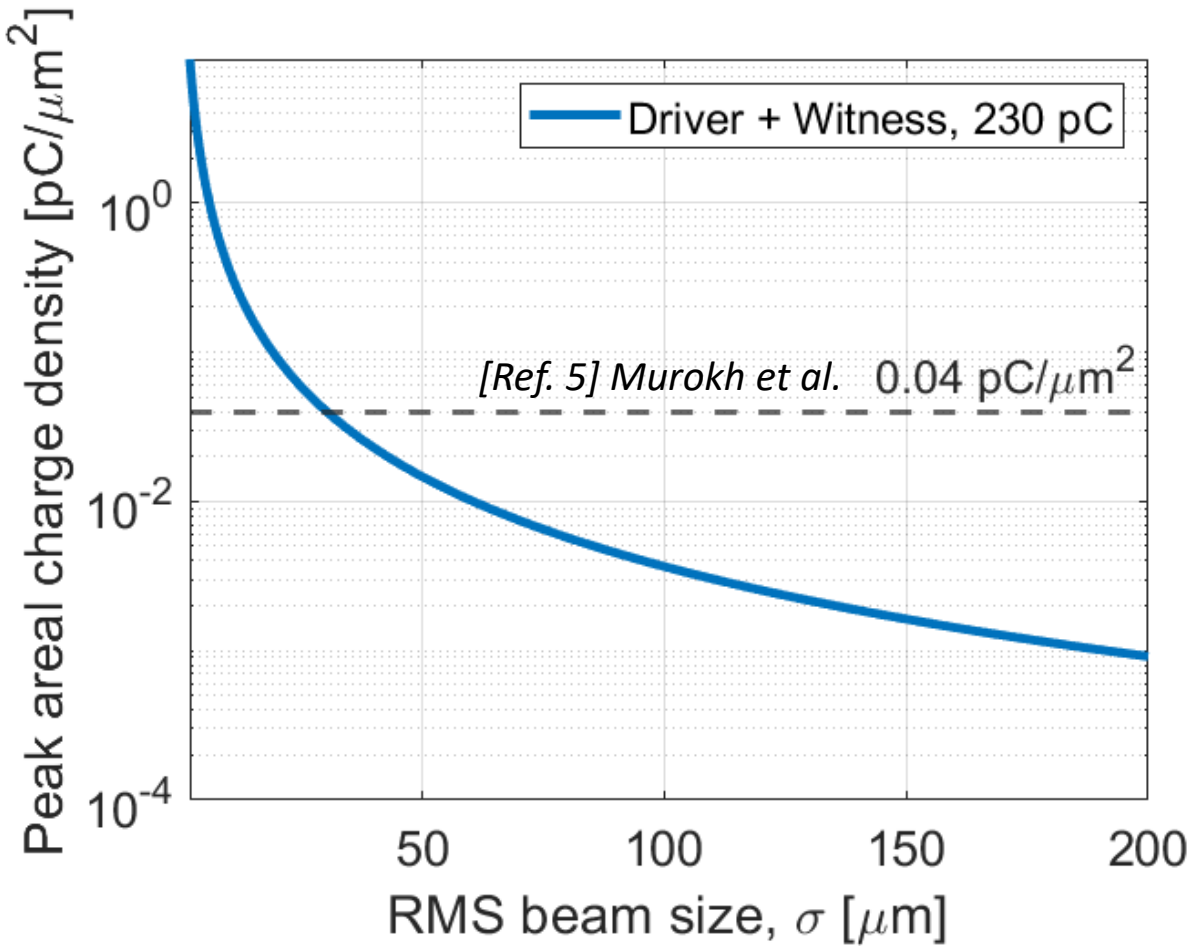
➢ **Main limitations:**

- Finite scintillator spatial resolution
- Light spreading in polycrystalline/powder screens
- This introduces an intrinsic spatial-resolution floor
- Saturation and possible damage at high areal charge density

Areal charge density: $\rho \simeq \frac{Q}{2\pi\sigma_x\sigma_y}$

$\rho(\text{Driver}) \simeq 0.39\ \text{pC}/\mu\text{m}^2$

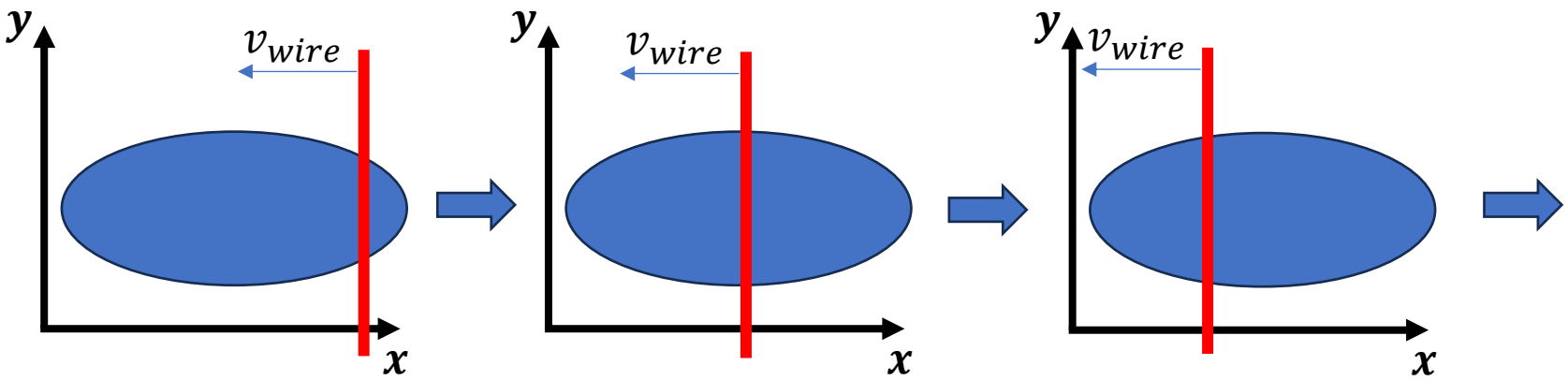
$\rho(\text{Witness}) \simeq 0.30\ \text{pC}/\mu\text{m}^2$

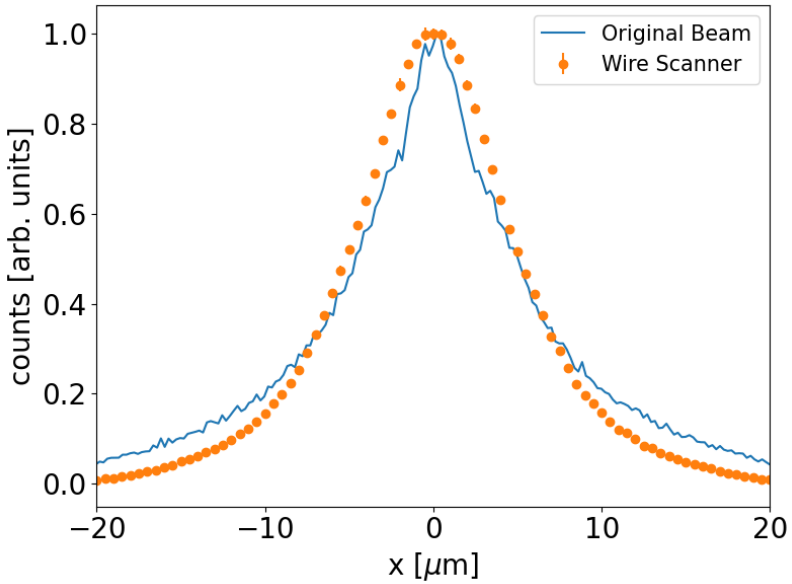


- At small beam sizes, the YAG response can become non-linear and the measured profile can be broadened or distorted *[Ref. 5, 6]*

Wire Scanners – Working Principle

- **Beam-wire interaction:**
  - A micrometric wire is moved transversely across the beam
  - Beam-wire interaction generates scattered electrons and a shower of secondary particles
- **Signal Reconstruction:**
  - The secondary signal is detected by Beam Loss Monitors (BLMs)
  - The BLM signal is correlated with the wire position to reconstruct the transverse beam profile





- **Multi-shot measurement:** one profile point is acquired at each beam pulse.
- **Two-bunch operation:** the BLM signal contains both driver and witness contributions; the witness profile is retrieved by subtracting a driver-only reference scan.

Wire scanner – Spatial resolution

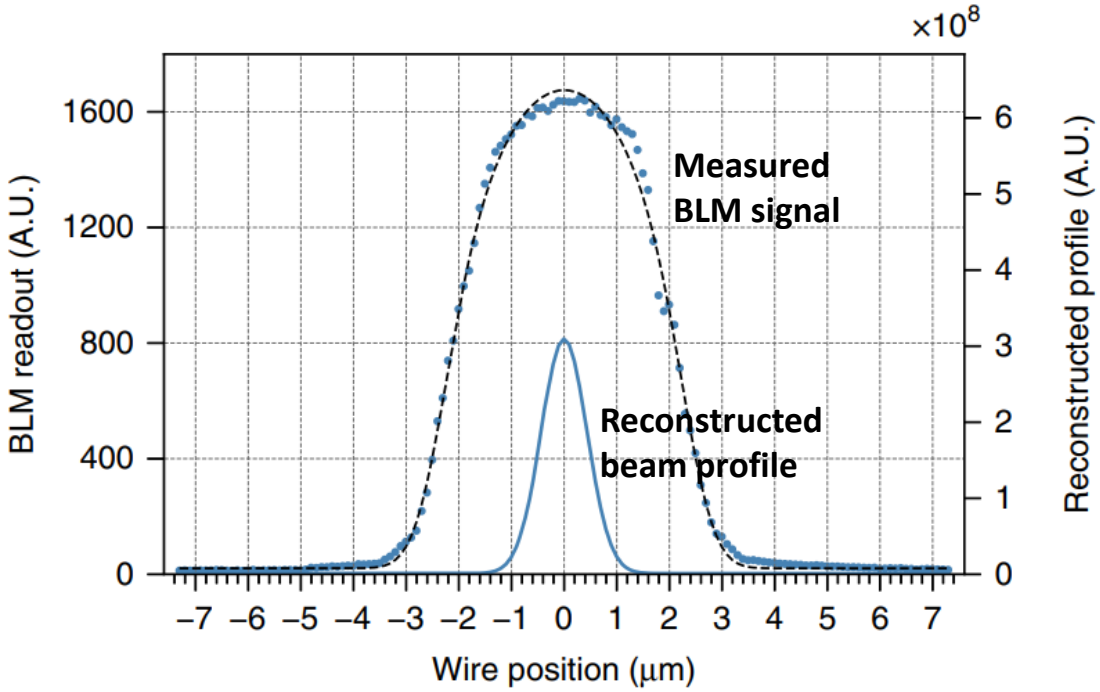
- The measured wire-scanner profile is the convolution of the transverse beam distribution with the finite wire response

Finite wire response: $S_{meas}(x) = \rho_{beam}(x) * R_{wire}(x)$

The finite wire diameter broadens the measured profile.

- **Baseline cylindrical wire: Tungsten (W)**, $d = 5\ \mu m$
  - **RMS Geometric resolution:** $\sigma_{geo} = \frac{d}{4} = 1.25\ \mu m$
  - **Small wire diameter** → better spatial resolution, but reduced robustness and signal

- **Beam-size reconstruction:**
  Although the 5 µm wire has a geometric resolution of 1.25 µm, the underlying sub-µm beam size can be reconstructed by fitting the convolution with the known wire response, assuming a Gaussian beam profile



[Ref. 7] S. Borrelli et al., "Generation and measurement of sub-micrometer relativistic electron beams," Communications Physics 1, 52 (2018).

- For the EuPRAXIA few-µm witness, the 5 µm tungsten wire gives $\sigma_{\mathrm{geo}} = 1.25\ \mu m$; additional practical limitations include positioning accuracy, sampling, and wire robustness/heating

Wire Scanners – Material and Motion

- **Continuous wire motion** minimizes vibration excitation and ensures a reproducible wire position at each beam pulse

- Since the measurement is **multi-shot**, the wire velocity determines the spatial sampling of the reconstructed profile. Requiring about **eleven samples** over a **5σ scan** gives these maximum velocities

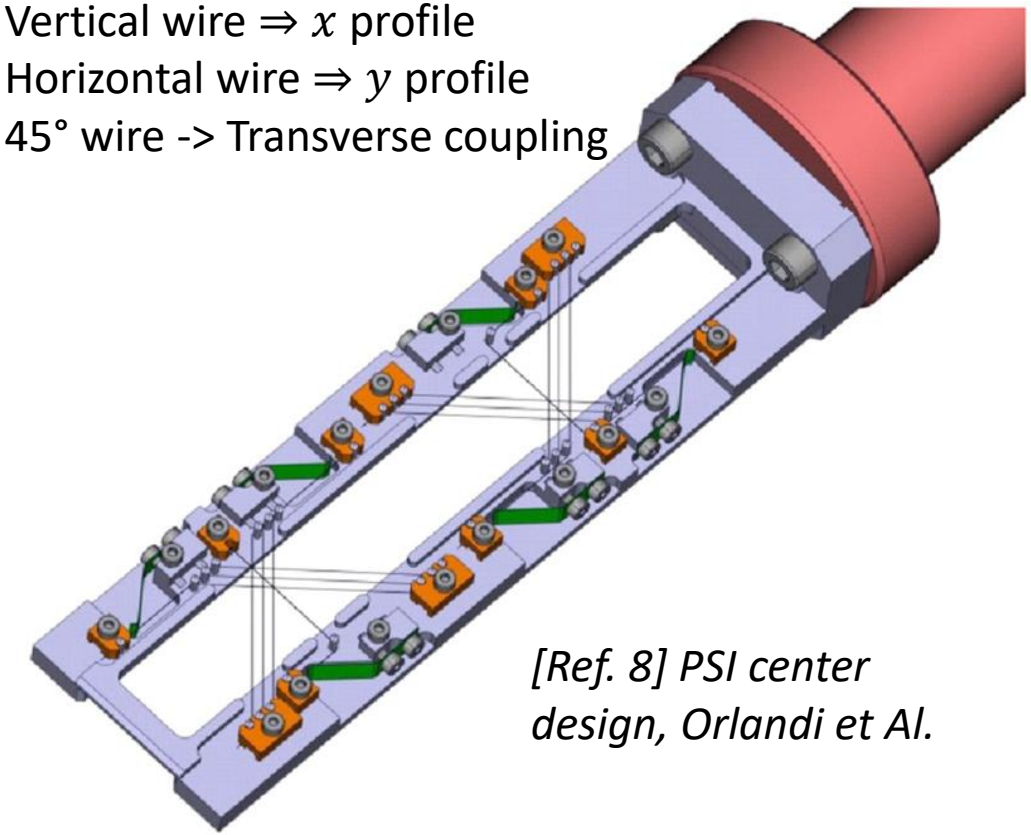
$$v_{scan_{max}} = \frac{5\sigma_{x,y}}{N_{scan}} f_{rep}$$

$$\sigma_{x,y} \approx 9\ \mu m, N = 11\ shots$$

$$v_{scan}(f_{rep} = 10\ Hz) \sim 41\ \mu m/s$$

$$v_{scan}(f_{rep} = 100\ Hz) \sim 410\ \mu m/s$$

Vertical wire ⇒ x profile
Horizontal wire ⇒ y profile
45° wire -> Transverse coupling



[Ref. 8] PSI center design, Orlandi et Al.

- Previous experimental studies showed wire vibrations below the geometrical resolution over the relevant operating range, except for a narrow mechanical resonance around **0.5–0.6 mm/s** [*Ref. 8,9*].

Wire scanner – Thermal model

- **Once the wire size and operating velocity are fixed, the remaining question is whether such a thin wire can withstand the energy deposited by the driver and witness *[Ref. 10]***

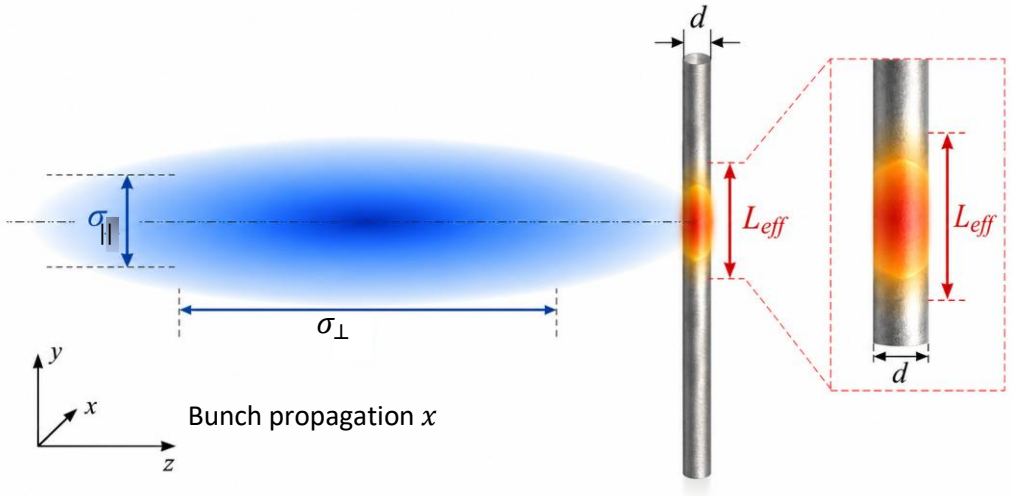
- **Beam interception:**
  - **Driver and witness are modeled as Gaussian transverse distributions**
  - The wire is assumed to be centered on the beam, corresponding to the maximum-heating condition

$$f_{hit} = \mathrm{erf}\left(\frac{d}{2\sqrt{2}\sigma_{\perp}}\right) \Rightarrow N_{hit} = f_{hit} N_e$$

- **Energy deposition:**
  - Only collisional energy losses are considered in the thin-target approximation

$$\Delta E_e = S_{coll}\rho_w d_{wire} \Rightarrow E_{dep} = N_{hit}\Delta E_e$$

- **Temperature rise:**



$$L_{eff} = \sqrt{2\pi}\sigma_{||} \Rightarrow V_{\mathrm{heat}} = \overbrace{\pi\left(\frac{d}{2}\right)^2}^{A_{wire}} L_{\mathrm{eff}}$$

$$\Delta \mathrm{T} = \frac{E_{dep}}{\rho V_{heat} c_p}$$

Wire Scanners – Thermal Assessment

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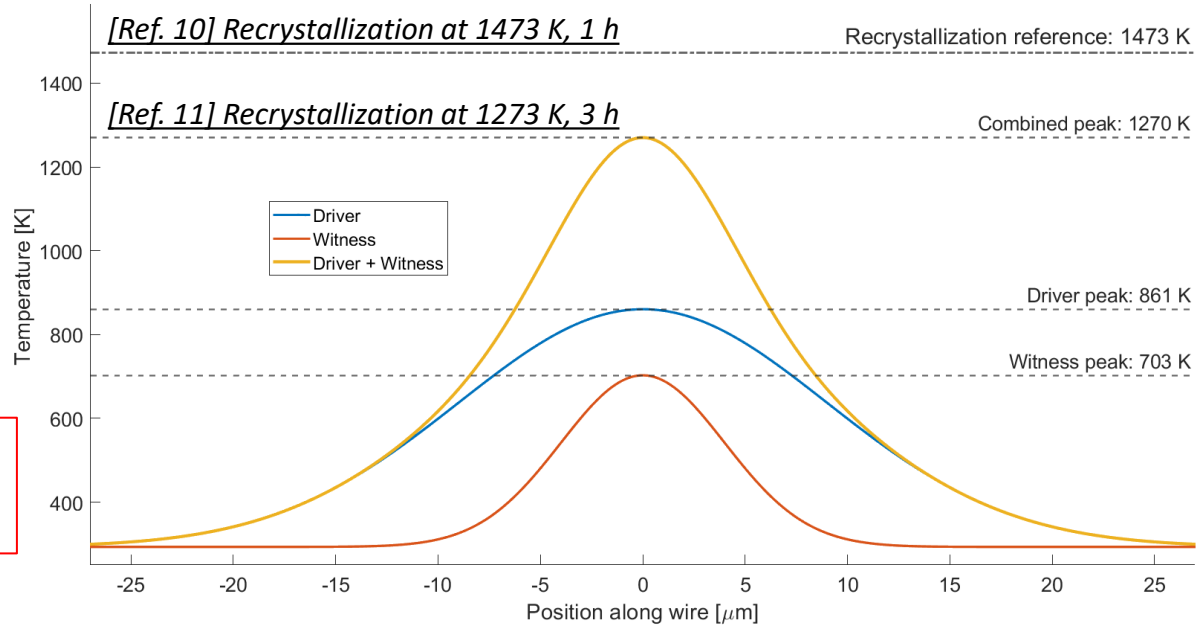
- The thermal model was applied to the nominal driver–witness ($Q = 200 + 30\ pC$, $\mathrm{E} \approx 560\ MeV$) parameters to evaluate the single-shot temperature rise of the $5\ \mu m$ tungsten wire

Parameter	Driver	Witness
Intercepted beam fraction [%]	21.88	46.80
RMS Beam size, $\sigma_{x,y}$ $[\mu m]$	~ 9	$\sim 3-4$
Peak ΔT $[K]$	567.35	409.56



➢ At the nominal working point, the combined driver–witness interaction produces a peak wire temperature of $\approx\ 1270\ K$

- **Cooling between consecutive shots:**
  - 1D heat diffusion along the wire; radiative losses neglected *[Ref.12]*
  - α_W: Thermal diffusivity

$$\Delta T(t) = \Delta T0 \frac{\sigma_{||}}{\sqrt{\sigma_{||}^2 + 2\alpha_W t}}$$

$$\Delta T(10\ Hz) \approx 1.9\ K$$
$$\Delta T(100\ Hz) \approx 5.9\ K$$

Residual heating ≪ single-shot rise $(\sim \mathbf{977\ K})$

- However, the nominal peak temperature (~1270 K) reaches a temperature at which recrystallization has been reported in pure tungsten wire under prolonged annealing [11], motivating further thermal assessment and a complementary diagnostic

OTR – Spatial resolution

- In OTR imaging, the measured beam profile is broadened by the finite single-electron response of the OTR optical system

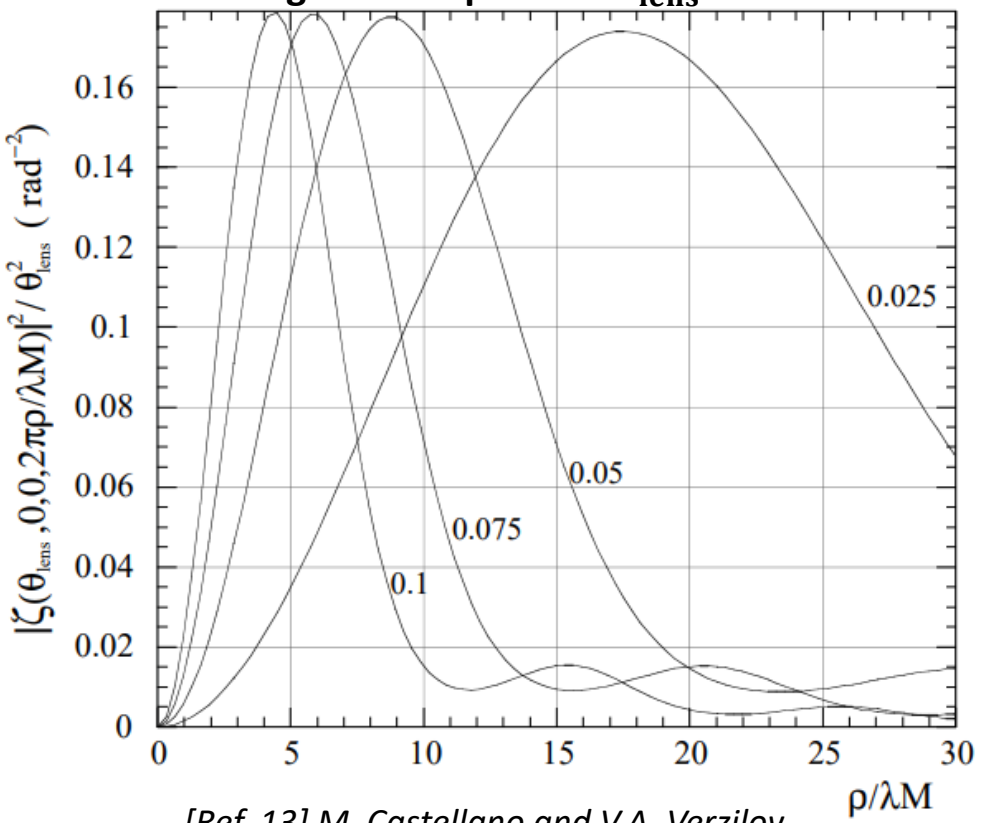
$$I_{meas}(x,y) = \rho_{beam}(x,y) * PSF_{OTR}(x,y)$$

- **Origin of the resolution limit:**
  - OTR has a characteristic angular distribution
  - A finite optical acceptance collects only part of the emitted radiation
  - The resulting single-electron image has a finite spatial extent

- **Larger angular acceptance → narrower OTR PSF → better spatial resolution**

$$\sigma_{\mathrm{beam}} \sim \sigma_{\mathrm{PSF}} \Rightarrow \text{resolution–limited imaging}$$

Single-electron OTR response for different lens angular acceptances θ_{lens}



[Ref. 13] M. Castellano and V.A. Verzilov

- When the beam size becomes comparable to the OTR PSF, the measured profile is significantly broadened by the instrumental response and cannot be interpreted directly as the beam size

OTR – Estimated PSF broadening

- **Simplified PSF model**
  - The OTR PSF core is approximated by an equivalent Gaussian with the same FWHM

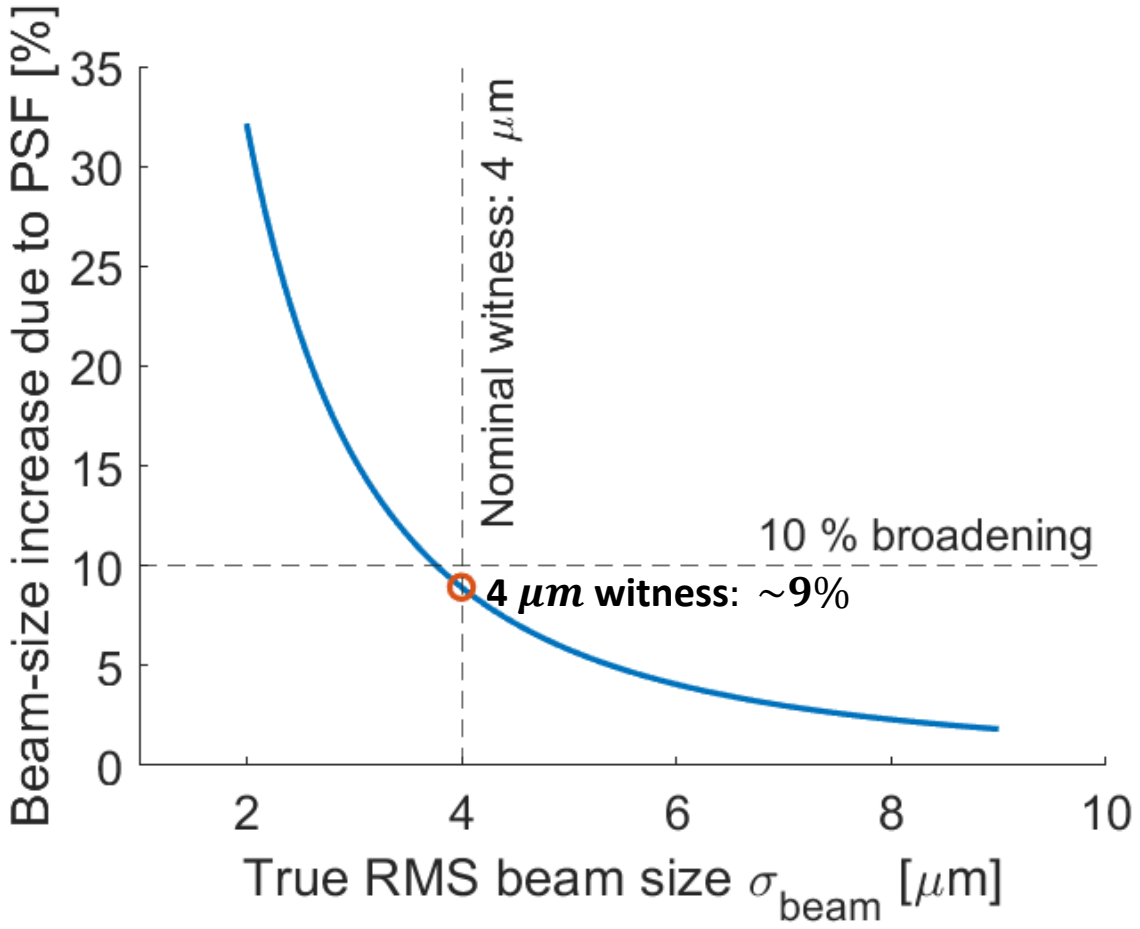
$$FWHM_{PSF}(\theta_{\text{lens}} = 0.10\ \text{rad}) \simeq 6.78\lambda$$ *[Ref. 13] M. Castellano and V.A. Verzilov*

$$\Rightarrow \sigma_{\text{PSF}} = \frac{\text{FWHM}_{\text{PSF}}}{2.355} \Rightarrow \boxed{\sigma_{\text{meas}} = \sqrt{\sigma_{\text{beam}}^2 + \sigma_{\text{PSF}}^2}}$$

- **Considered case**:

$$E \simeq 500\ \text{MeV}$$
$$\theta_{\text{lens}} = 0.10\ \text{rad}$$
$$\lambda = 600\ \text{nm}$$

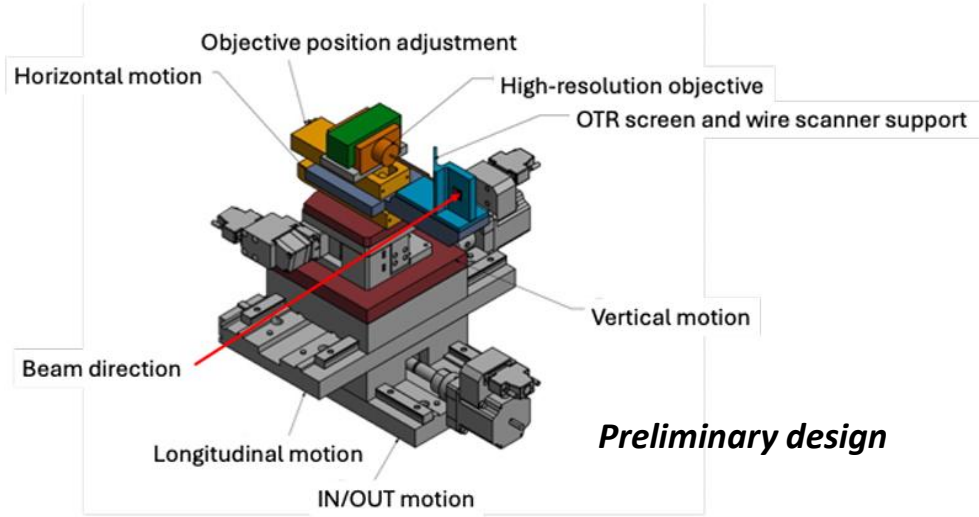
$$\text{FWHM}_{\text{PSF}} \simeq 4.07\ \mu\text{m}$$
$$\sigma_{PSF} \simeq 1.73\ \mu m$$



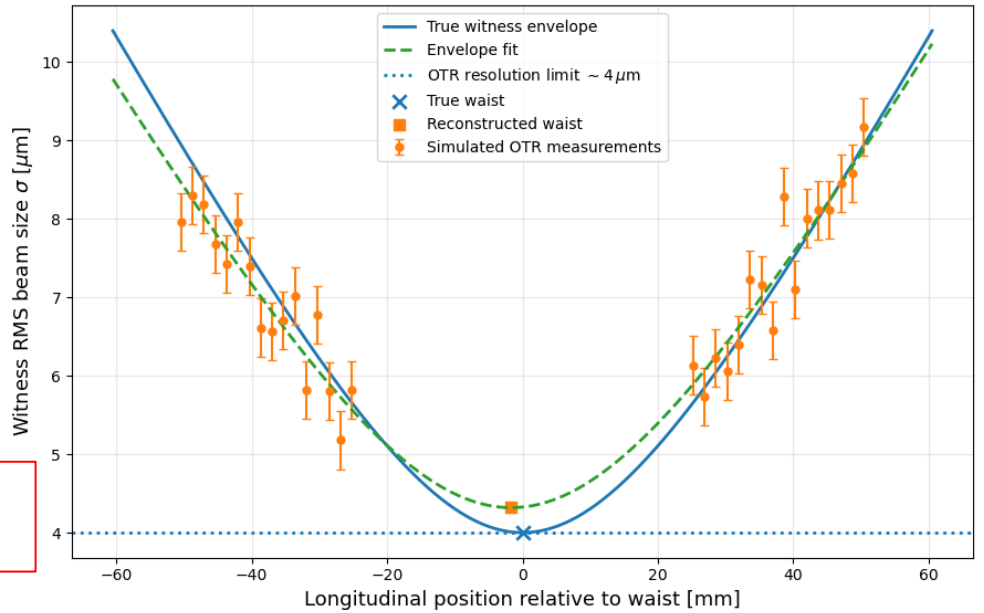
- For the 4 µm witness, the equivalent OTR PSF produces about 9% beam-size broadening
- Below ~4 µm, direct OTR imaging becomes increasingly sensitive to the PSF, motivating an indirect waist reconstruction

OTR screen – Indirect waist reconstruction

- The OTR screen and wire scanner are mounted on **a movable support that can be translated longitudinally** across the expected waist region
- This allows the transverse beam size to be sampled at several longitudinal positions without requiring a direct measurement exactly at the waist
- **Motivation:**
  - The expected witness waist is in the few-µm regime
  - Direct OTR beam-size measurements become increasingly sensitive to the PSF near the waist
  - Measurements away from the minimum are less affected and can constrain the envelope
- **Indirect waist reconstruction**
  - Measure the beam size at several positions around the waist
  - Fit the transverse envelope to reconstruct waist size and position



Preliminary design



$$\sigma_{waist} = 4.0 \pm 0.3\ \mu m$$
Reconstruction uncertainty $\approx 7.8\%$

Summary, conclusions and open points

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1. **Plasma-entrance measurement strategy:**
   - Driver and witness cannot be treated as independent beams because their dynamics is coupled during velocity bunching
   - The witness transverse distribution can therefore be reconstructed from driver+witness and driver-only measurements.

2. **Complementary transverse diagnostics**
   - **YAG:** fast and robust imaging for commissioning and large beams; scintillator response and high charge density limit its use in the few-µm regime
   - **Microwire scanner:** a 5 µm W wire provides $\sigma_{\mathrm{geo}} \approx 1.25\ \mu m$, suitable for few-µm beams; nominal thermal modelling gives $T_{\mathrm{peak}} \sim 1270\ K$, requiring further robustness assessment
   - **OTR:** direct imaging avoids wire heating, but the intrinsic PSF becomes increasingly relevant in the few-µm regime

Thank you for your attention

Email: Francesco.Demurtas@lnf.infn.it

References

[1] Ferrario, M., et al. "EuPRAXIA@ SPARC_LAB Design study towards a compact FEL facility at LNF." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 909 (2018): 134-138.

[2] Verra, Livio, E. Gschwendtner, and P. Muggli. "Study of external electron beam injection into proton driven plasma wakefields for AWAKE Run2." *Journal of Physics: Conference Series*. Vol. 1596. No. 1. IOP Publishing, 2020.

[3] Falcoz, F. "EuPRAXIA Conceptual Design Report." *The European Physical Journal Special Topics*.

[4] Ferrario, M., et al. "Laser comb with velocity bunching: Preliminary results at SPARC." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 637.1 (2011): S43-S46.

[5] Murokh, A., et al. "Limitations on the resolution of YAG: Ce beam profile monitor for high brightness electron beam." *The Physics of High Brightness Beams*. 2000. 564-580.

[6] Miyahara, Fusashi, et al. "Response of scintillating screens to high charge density electron beam." *Proc. IPAC* 17 (2017).

[7] Borrelli, Simona, et al. "Generation and measurement of sub-micrometer relativistic electron beams." *Communications Physics* 1.1 (2018): 52.

[8] Orlandi, G. L., et al. "Nanofabricated free-standing wire scanners for beam diagnostics with submicrometer resolution." *Physical Review Accelerators and Beams* 23.4 (2020): 042802.

References

[9] Orlandi, G. L., et al. "Design and experimental tests of free electron laser wire scanners." *Physical Review Accelerators and Beams* 19.9 (2016): 092802.

[10] Wang, Songke, et al. "Consideration of tungsten recrystallization in plasma facing components design." *Fusion Engineering and Design* 200 (2024): 114162.

[11] Zhao, P., et al. "Microstructure, mechanical behaviour and fracture of pure tungsten wire after different heat treatments." *International Journal of Refractory Metals and Hard Materials* 68 (2017): 29-40.

[12] H. S. Carslaw, J. C. Jaeger, *Conduction of Heat in Solids*, 2nd ed., Oxford University Press, 1959.

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

Acknowledgements

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EuPRAXIA Doctoral Network

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EuAPS

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OTR – Magnification limitation

- **Camera sampling and magnification:**

$$p_{obj} = \frac{p_{cam}}{M}\ , \qquad \sigma_{\mathrm{pix}} = \frac{p_{\mathrm{obj}}}{\sqrt{12}}$$

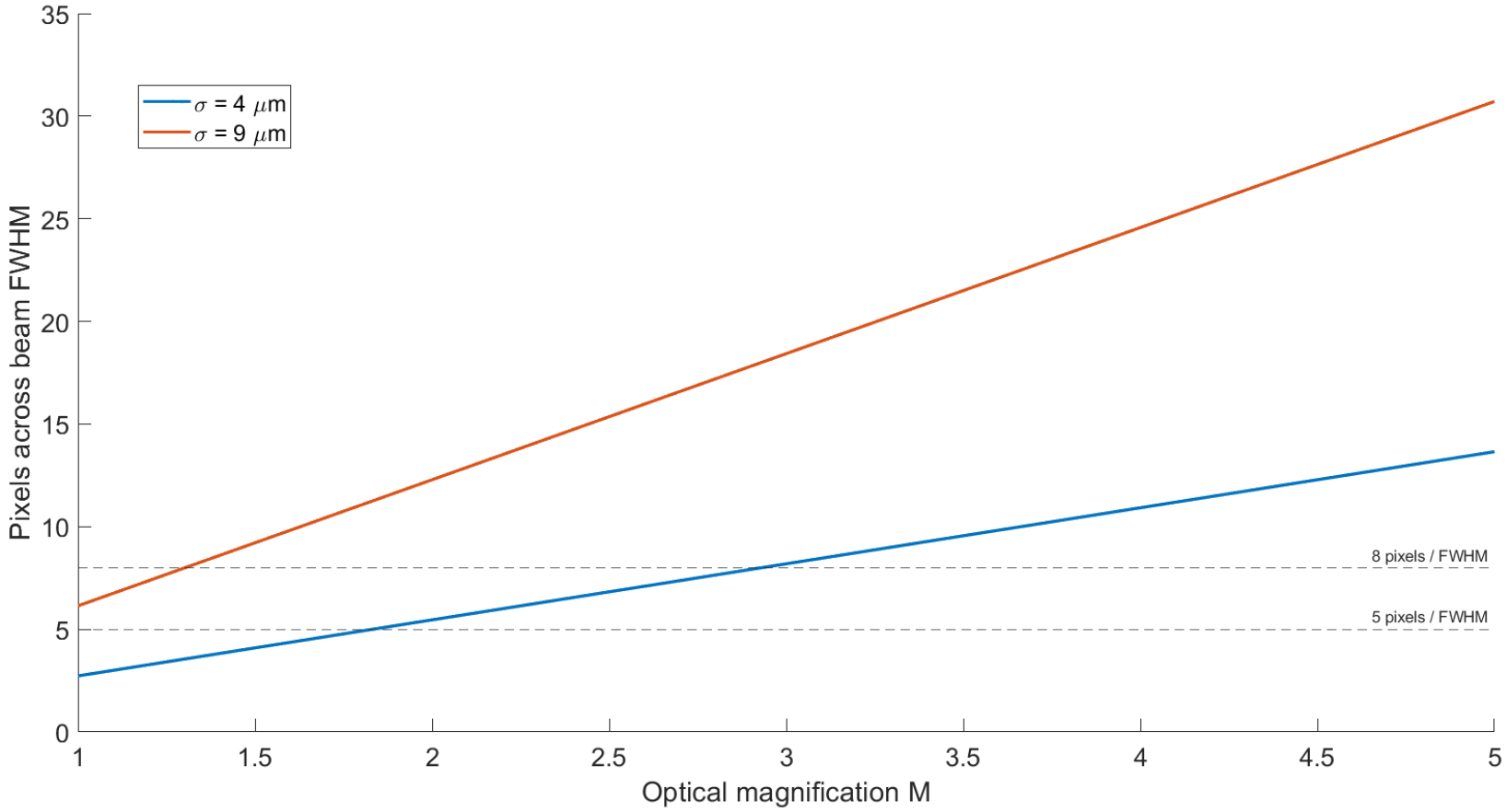
$$N_{\mathrm{pix,FWHM}} = \frac{2.355\ \sigma_{\mathrm{beam}}}{p_{\mathrm{obj}}}$$

- **Camera pixel pitch:** $p_{\mathrm{cam}} = 3.45\ \mu\mathrm{m}$
- **Smallest expected beam:** $\sigma_w = 4\ \mu m$

$$M = 3 \Rightarrow p_{\mathrm{obj}} = 1.15\ \mu\mathrm{m/pixel}$$

$$N_{\mathrm{pix,FWHM}} \simeq 8.2$$

$$\sigma_{pix} \simeq 0.33\ \mu m$$



EuPRAXIA-PP Structure

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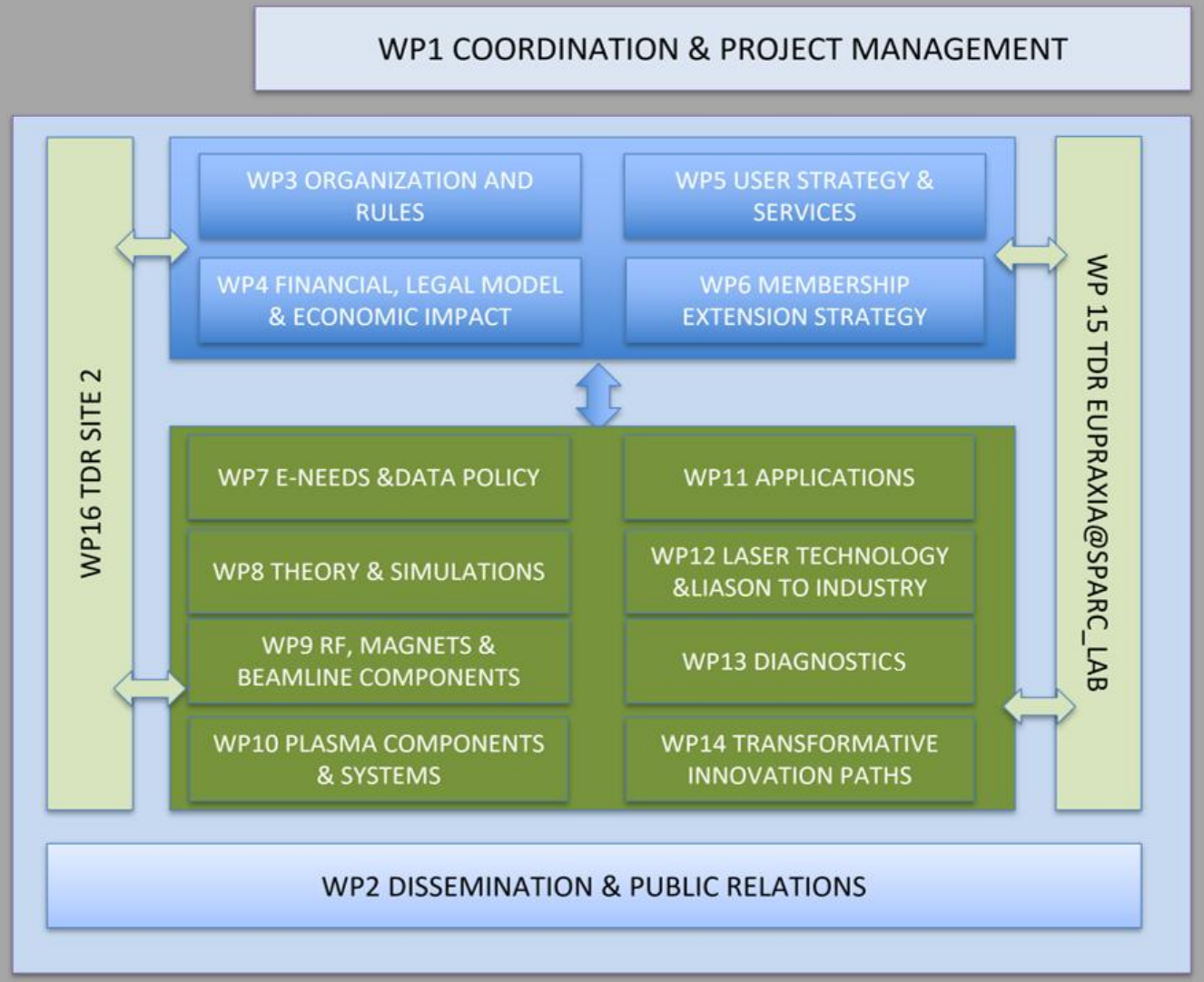

Selected Committees and Boards

GOVERNING BOARD
(decision-making body, 1 representative per institute)

Steering Committee
(coordinator plus WP leaders plus experts)

Scientific/Technical Advisory Board
(external experts in user services, RI implement-tation, ESFRI aspects and technical themes)

Board of Financial Sponsors
(connection to decision makers and funding authorities)