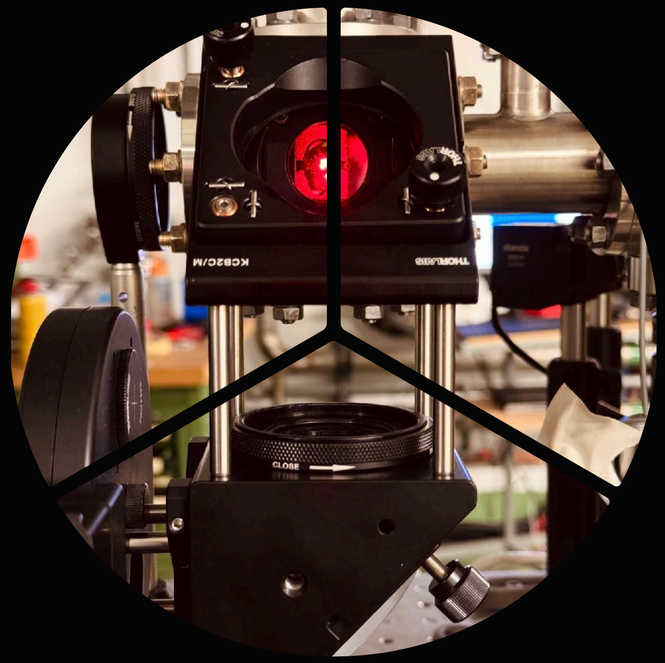
15th July., ‘25

Optical Synchrotron Radiation as a Non-Invasive Tool for Emittance Diagnostics

EuPRAXIA-DN Camp II: Science
Lisbon



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clear
AWAKE
The Cockcroft Institute of Accelerator Science and Technology

Overview

Key points…

- Plasma Accelerator: **P**roton **D**riven **W**ake**F**ield **A**cceleration- AWAKE
- Challenges in Beam quality for AWAKE to EuPRAXIA
- Beam diagnostics-Emittance via **O**ptical **S**ynchrotron **R**adiation
- OSR for EuPRAXIA
- Conclusion

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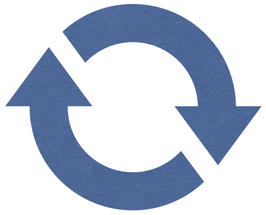
Plasma Accelerators

a transformative step —> HEP, photon science, and medical applications.

Conventional Accelerator

- Large
- Expensive
- More Energy
- few 10s MeV/m



LHC: 27 km Vs Inner ring road of Paris ~ 30 km

Plasma Accelerator

- Ionized medium —> High E-field

$E_z \sim \omega_p \sim \sqrt{n_e}$

- GeV/m gradient
- Compact
- Less carbon footprint

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Plasma Accelerator: AWAKE

At a glance...

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AWAKE

At a glance...

Proton-driven plasma wakefield acceleration

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At a glance...

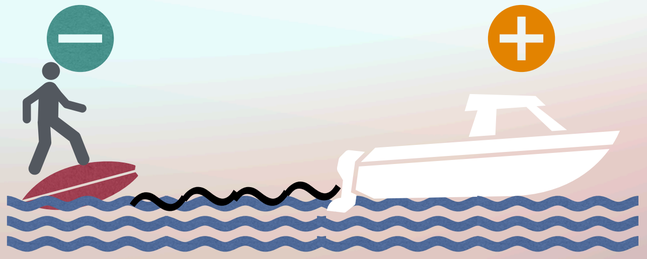
Proton-driven plasma wakefield acceleration

Protons
(from CERN SPS, 400 GeV)

Rubidium vapor
/ plasma wake

Laser (short
intense pulse)

Electrons



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AWAKE

At a glance...

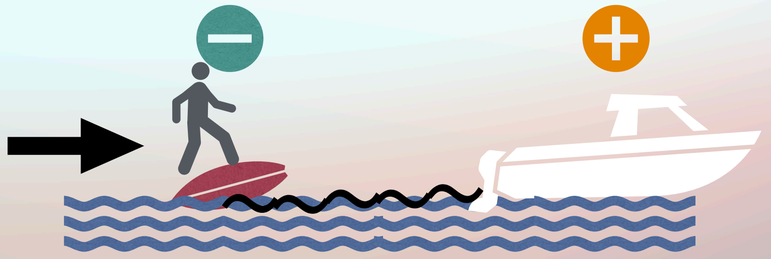
Proton-driven plasma wakefield acceleration

Protons (from CERN SPS, 400 GeV) → energy source

Rubidium vapor / plasma wake → transformer to an E-field (a few GV/m)

Laser (short intense pulse) → Rb vapor ionization to seed an instability of p+

Electrons → to probe a wake fields



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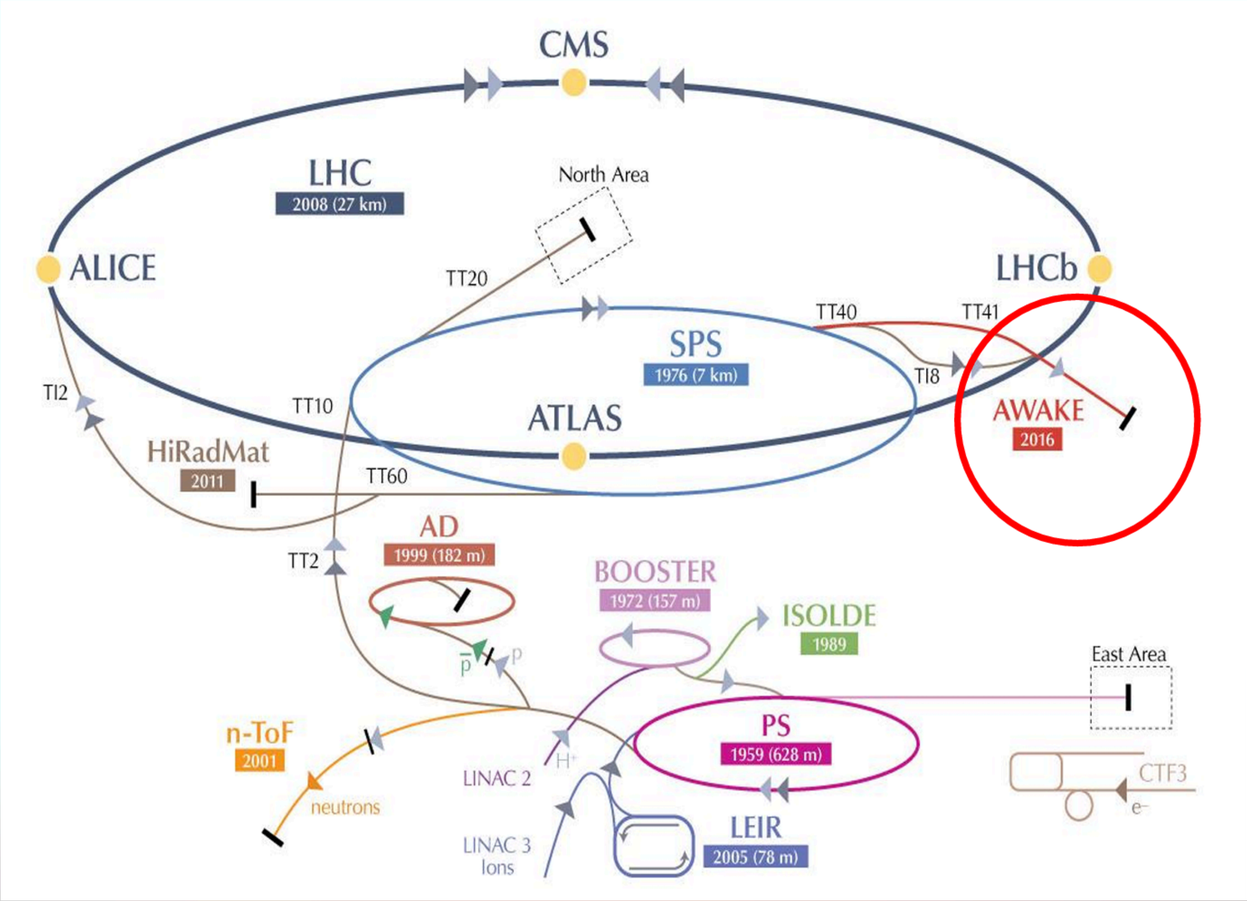
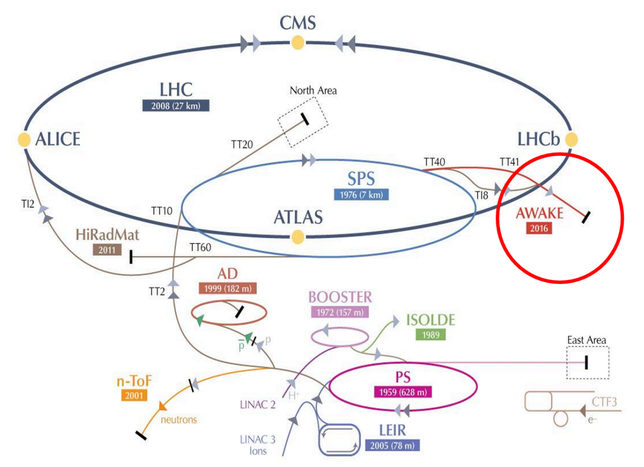
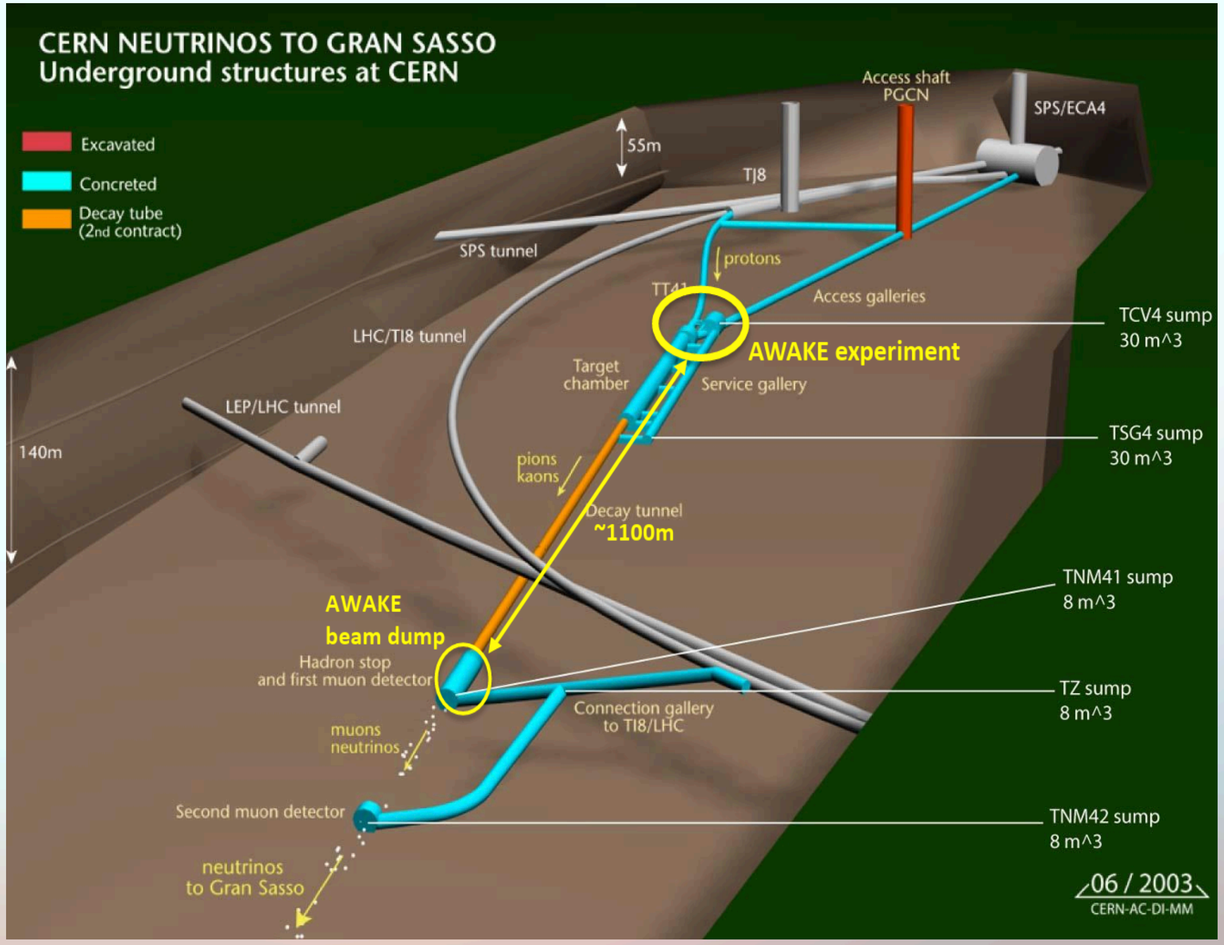
AWAKE at CERN



[Mikhail]

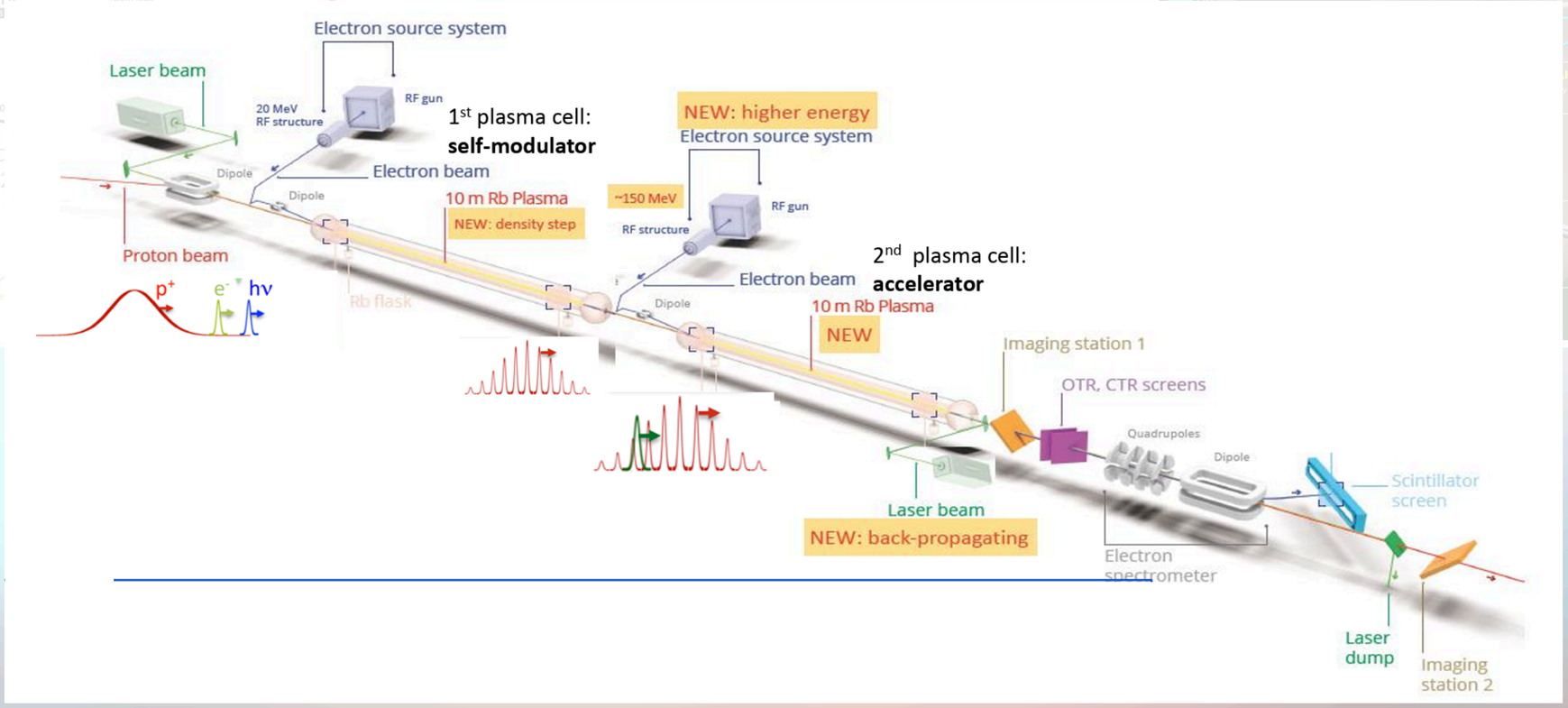
AWAKE at CERN





Mikhail

AWAKE at CERN



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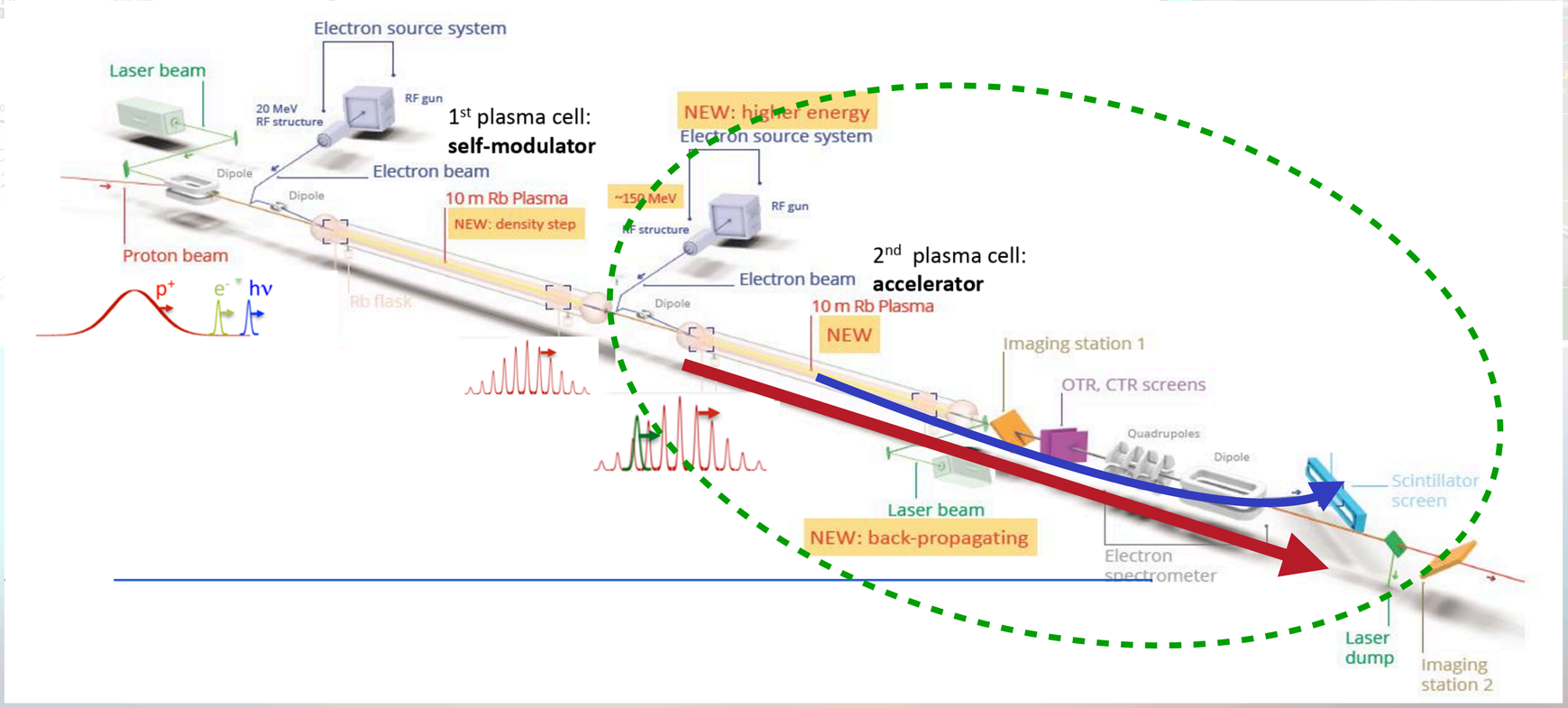
AWAKE at CERN



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AWAKE Beam Parameters & Challenges

Beam Quality is the Bottleneck

Parameter	Proton line	Electron line
Beam energy	400 GeV	150 MeV
Charge	48 nC	100-200 pC
Bunch length	6-12 cm	60 μm
Energy spread	0.03%	0.2%
Norm. emittance	3.5 mm mrad	2 mm mrad

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- Injection jitter *(t and s of the e⁻ beam w.r.t plasma wake)*
- Emittance growth during plasma *(spread in phase space)*
- Measuring e⁻ beam properties at plasma exit

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- Injection jitter *(t and s of the e- beam w.r.t plasma wake)*
- Emittance growth during plasma *(spread in phase space)*
- Measuring e- beam properties at plasma exit

FEL: beam quality challenge—>high energy spread, high divergence…

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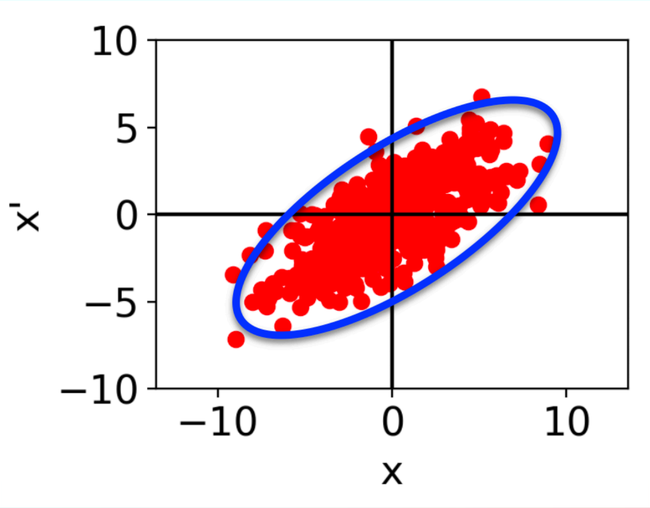
Emittance & Beam Quality

Why Diagnostics Matter for AWAKE



CDS

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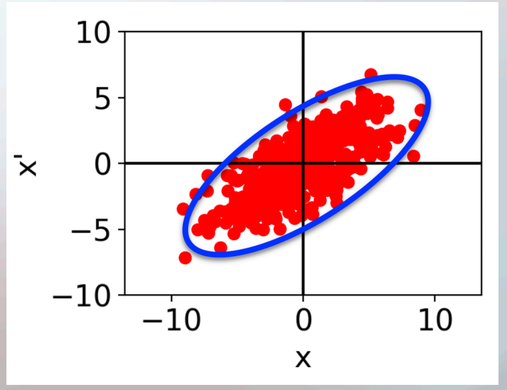
Emittance & Beam Quality

Why Diagnostics Matter for AWAKE

Precise knowledge of the witness e⁻ **beam quality**:
Accurate characterization of emittance, divergence ⟶ validating beam transport, stability

Emittances tells us about the beam **focusability**, **brightness**, **transport**, and is critical for FELs and staging.



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Emittance & Beam Quality

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EuPRAXIA → delivering high-quality electron beams → beam characterization

- tight focusing
- small transverse dimensions

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Diagnostic Constraints

Space, Background, and Integration Constraints

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Diagnostic Constraints

Space, Background, and Integration Constraints

Compact beamlines

Non-invasiveness, Single-shot

High beam quality targets

Multi-user facility: high-rep-rate demands real-time feedback

Polarization- and energy-sensitive

Sub-mm resolution

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Beam diagnostics → Emittance

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Emittance- A Key Parameter

Why Emittance Matters?

Emittance ~ how '**collimated**' the beam is!
...in a way it controls the divergence and beam size.

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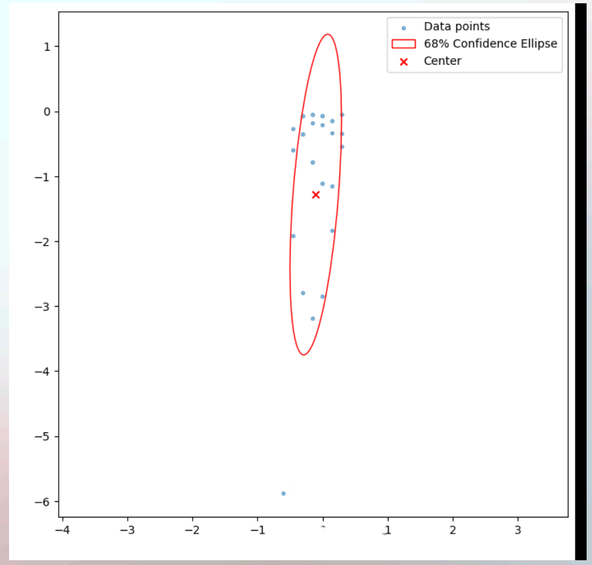
Emittance- A Key Parameter

Why Emittance Matters?

Emittance ~ how '**collimated**' the beam is!
...in a way it controls the divergence and beam size.

Low emittance is key for:

- High-brightness beams
- Efficient transport
- FEL gain
- Staging between plasma sections



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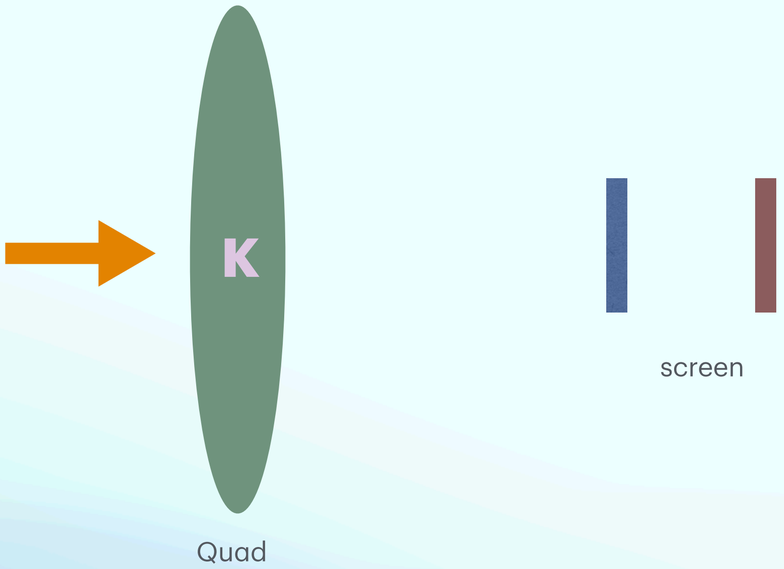
Emittance Measurement

Quad Scanning method & its limitations



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Emittance Measurement

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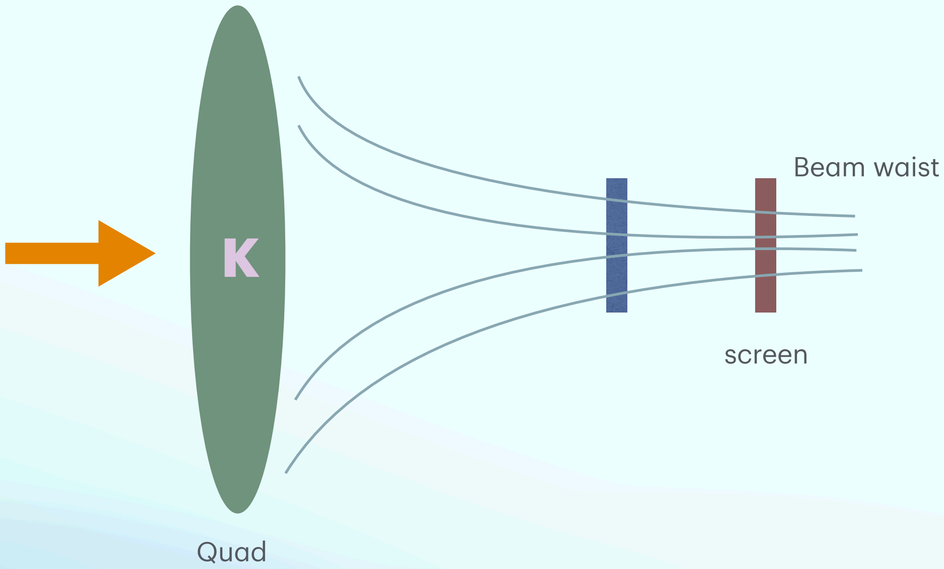

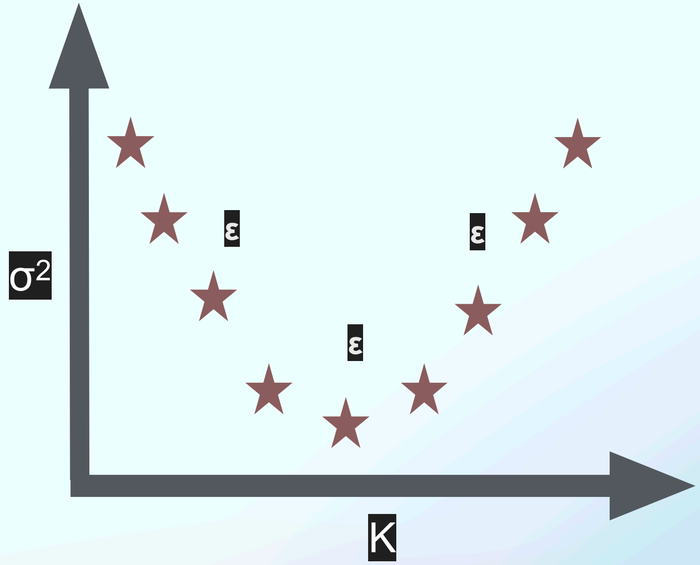

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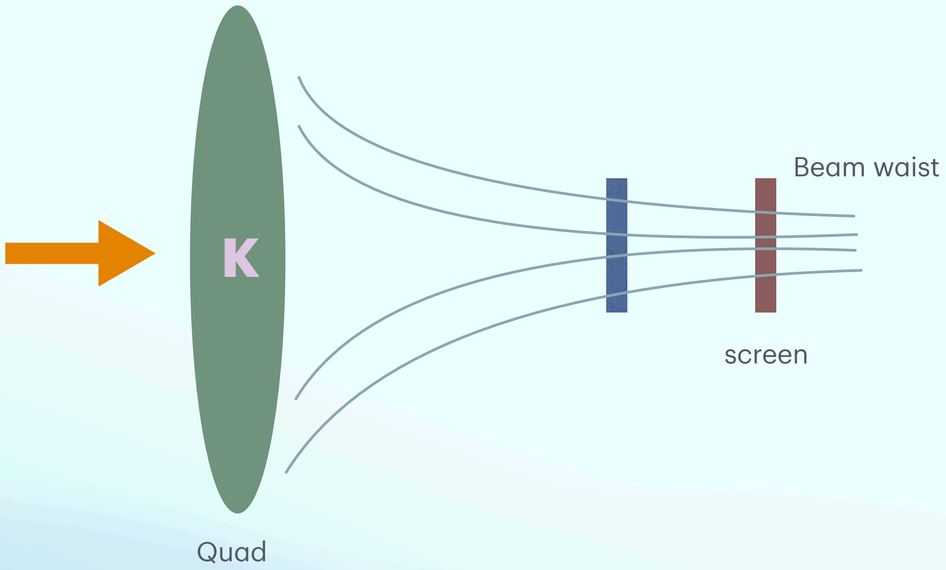

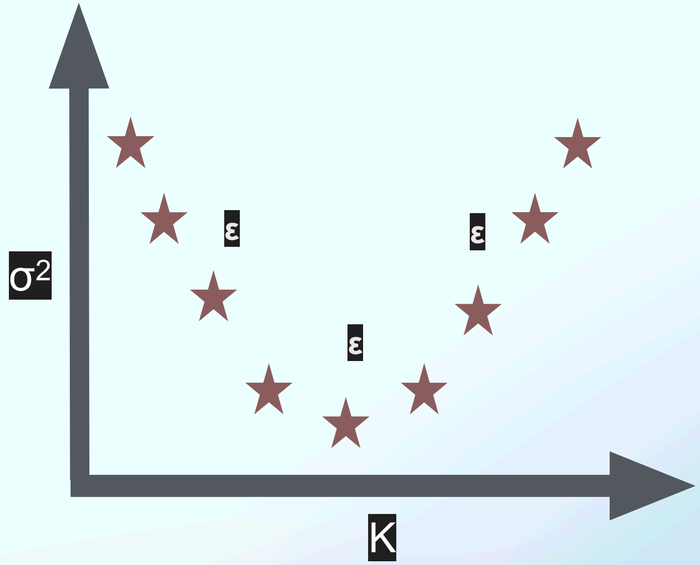

! **Multiple measurements** (beam stability issue), **Invasiveness**, **Energy spread** (plasma accelerator ~>1%)

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Emittance Measurement

Pepper-pot & Corresponding Optical Mapping

- **Single shot** (over multi-shot Quad scans)
- **Phase space mapping**

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Emittance Measurement

Pepper-pot & Corresponding Optical Mapping

- **Single shot** (over multi-shot Quad scans)
- **Phase space mapping**

But!

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Emittance Measurement

Pepper-pot & Corresponding Optical Mapping

- **Single shot** (over multi-shot Quad scans)
- **Phase space mapping**

But!

- Lower energy-limitation of Slit/pinhole scans & pepper-pot
  —> Possible solution: ***Optical version***

- Non-/minimally invasive optical radiation sources can be used (Transition & Synchrotron Radiation)

- Increase in Divergence resol. with energy

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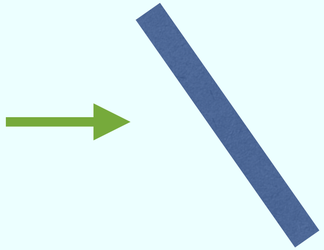
Emittance Measurement

OTR & OSR



Optical Transition Radiation (OTR)

Optical Synchrotron Radiation (OSR)

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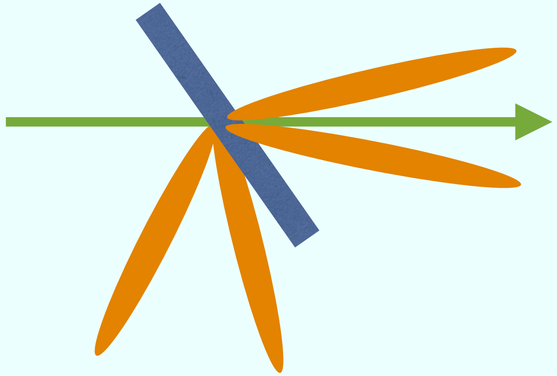
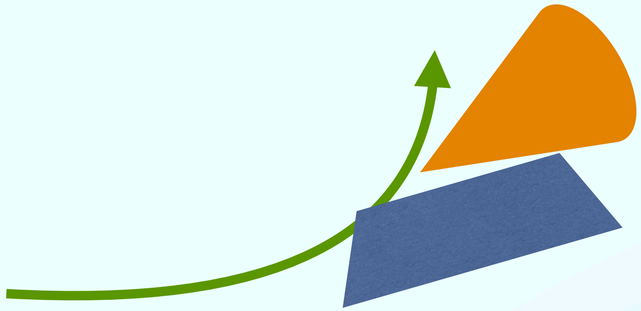
Emittance Measurement

OTR & OSR



Optical Transition Radiation (OTR)



Optical Synchrotron Radiation (OSR)

shorter wavelength
produced at interfaces

intense
broad spectrum
rel. beam + mag. fiel

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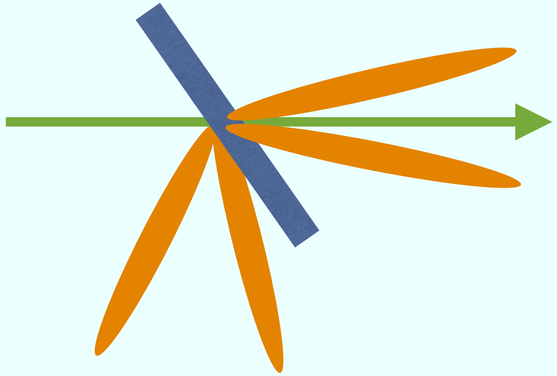
Emittance Measurement

OTR & OSR



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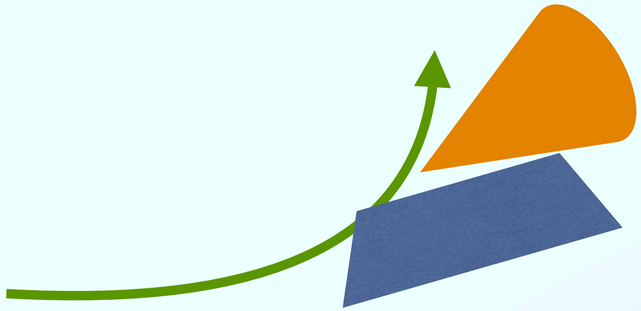

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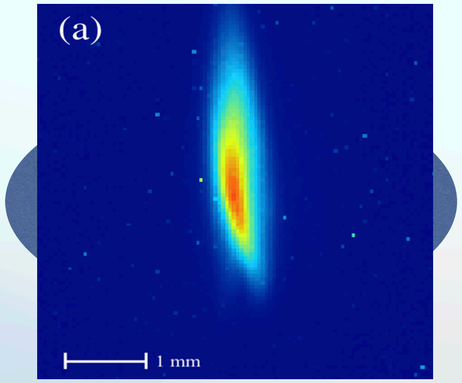
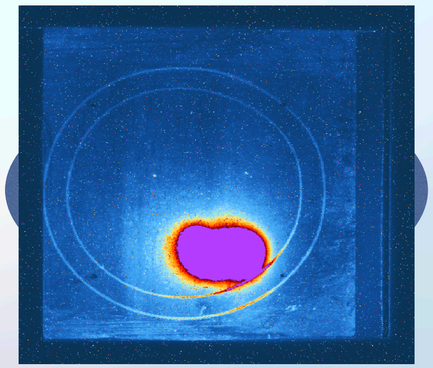


[Michele]



Beam diagnostics → Emittance

With OSR

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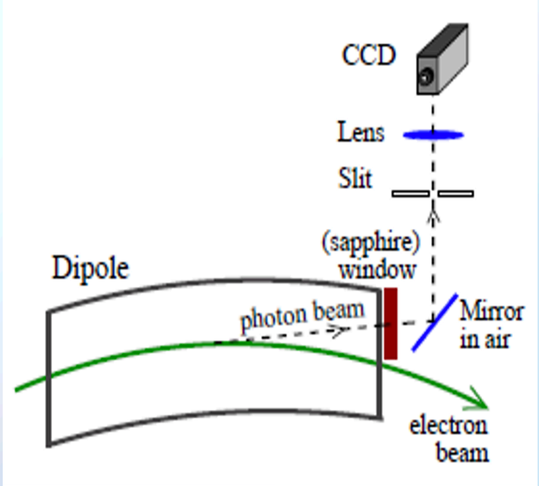
OSR

A subset of SR, that falls in the visible to near-IR range.

Synchrotron radiation (SR) is emitted when relartivistic charged particles (e.g. electrons) are bent by the magnetic fields. —> highly collimated and polarized.



credit

OSR

Why SR/OSR can be the Game-Changer

Synchrotron radiation (SR) is emitted when relartivistic charged particles (e.g. electrons) are bent by the magnetic fields. —> highly collimated and polarized.

- Why OSR as a Diagnostic Tool?
  Key Characteristics like:
  - Non-invasiveness
  - High-resolution
  - Wide spectral range (SR is broadband)
  - Can be used to measure various beam parameters (e.g. emittance)

Characteristics	OSR capability
Spatial Resolution	High (when optics and cam resol permits), useful for short bunches
Spectral Content	Broad, continuous
Intensity	Scales with beam energy, charge
Angular Distribution	Energy and wavelength dependent
Polarization	Angle-resolved pol diagnostics; σ and π components

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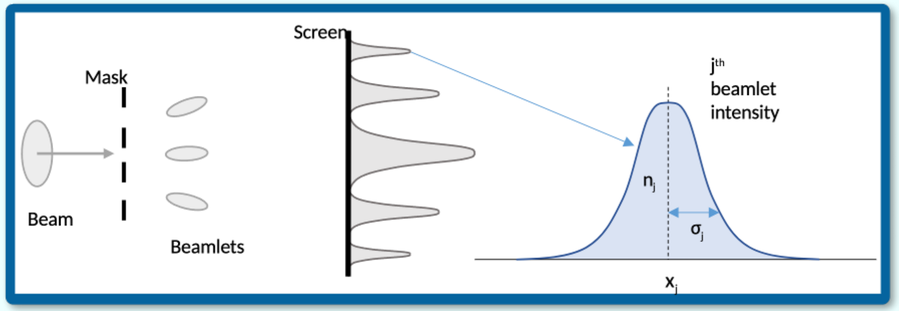
OSR with MicroLens Array

Emittance measurement



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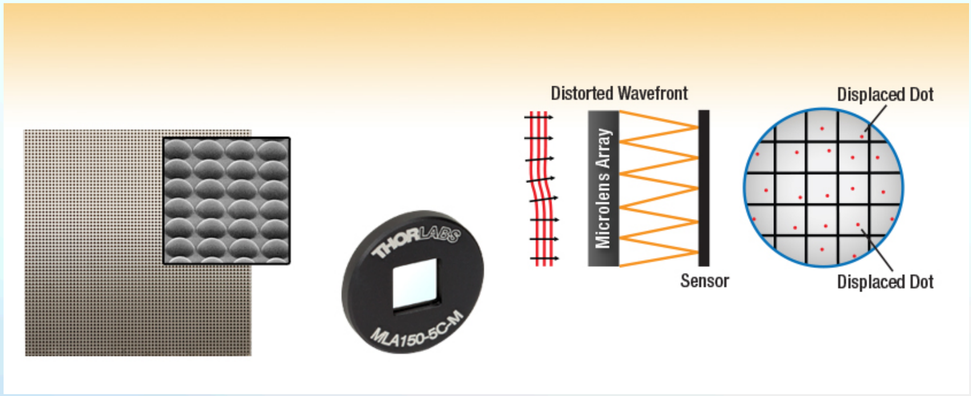

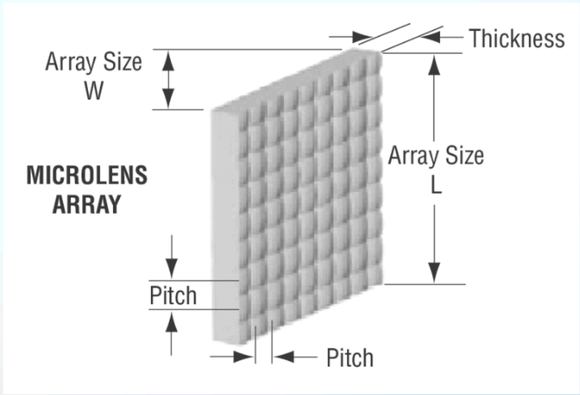

Thorlabs

MLA, with 150μm pitch

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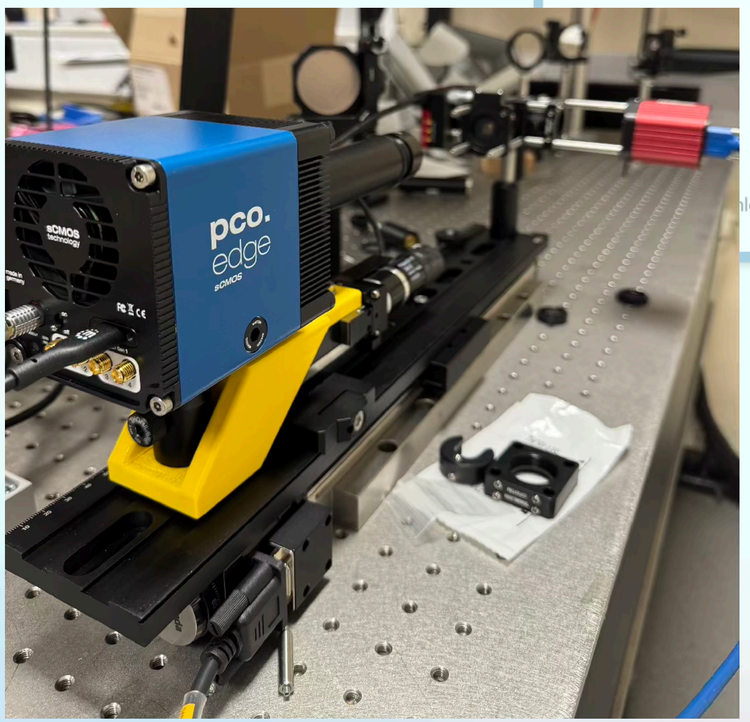
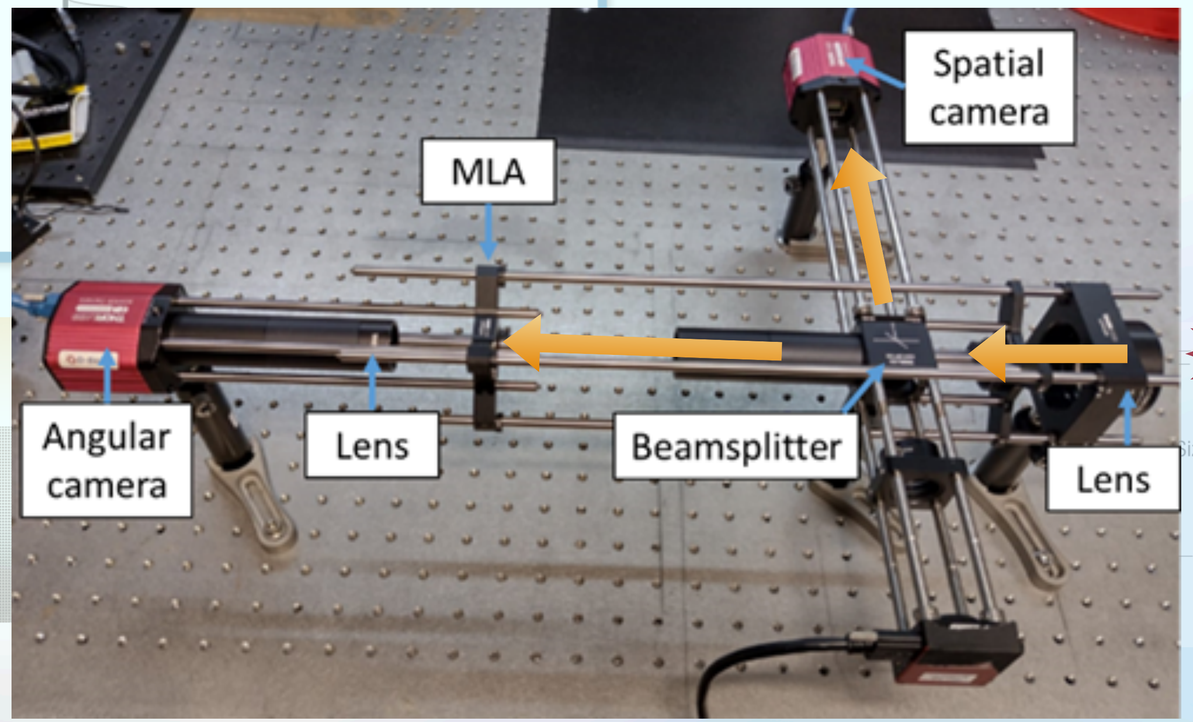
OSR Setup

Emittance measurement





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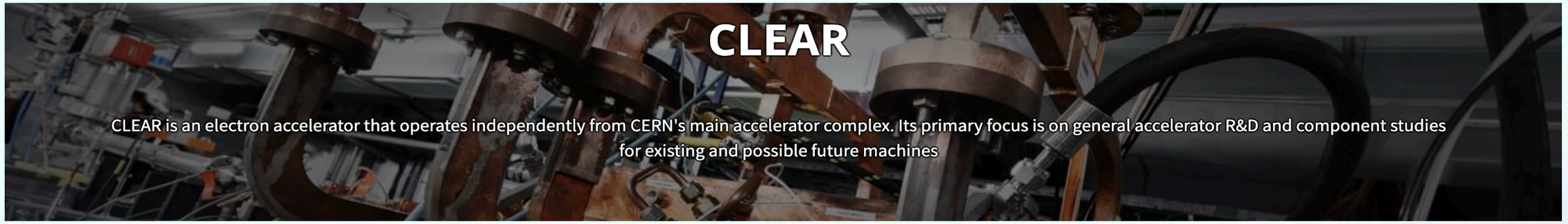
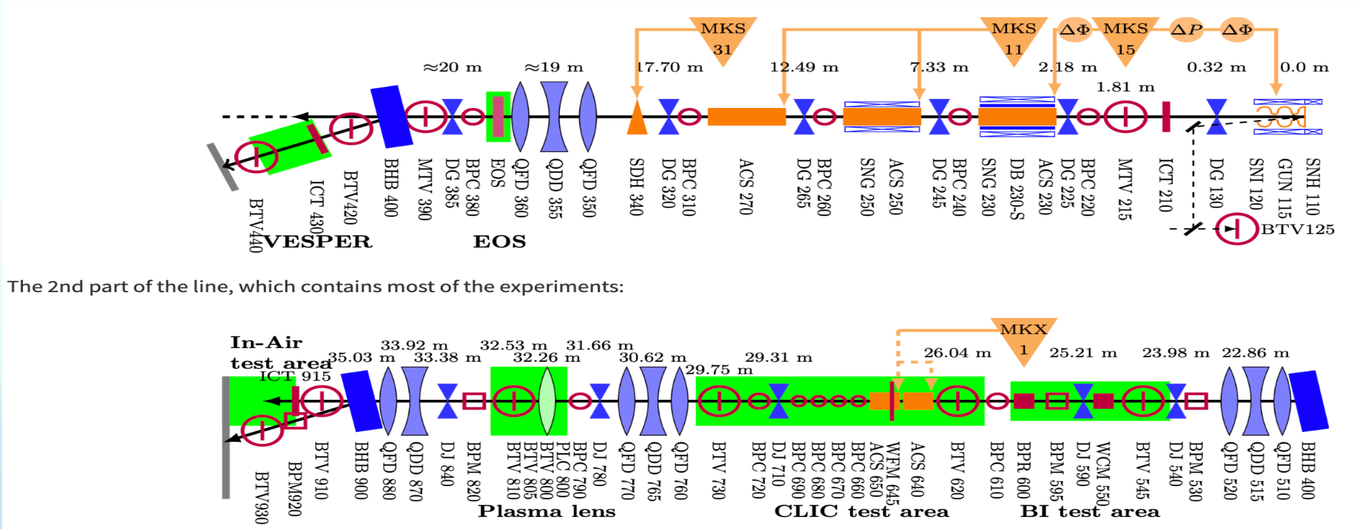
PoC Measurements

@CLEAR ('24 & '25)





CLEAR

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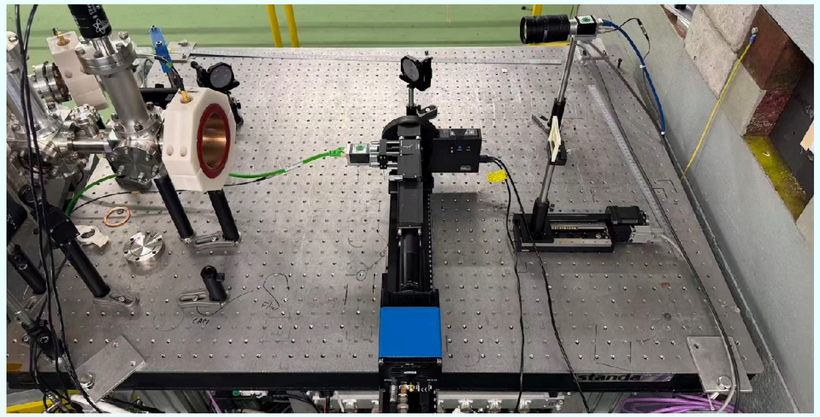
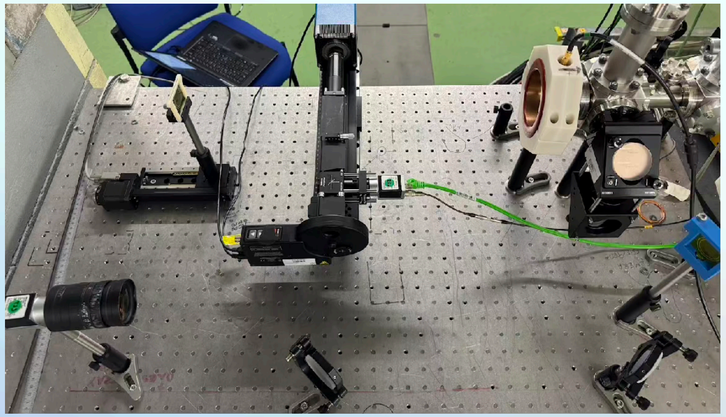
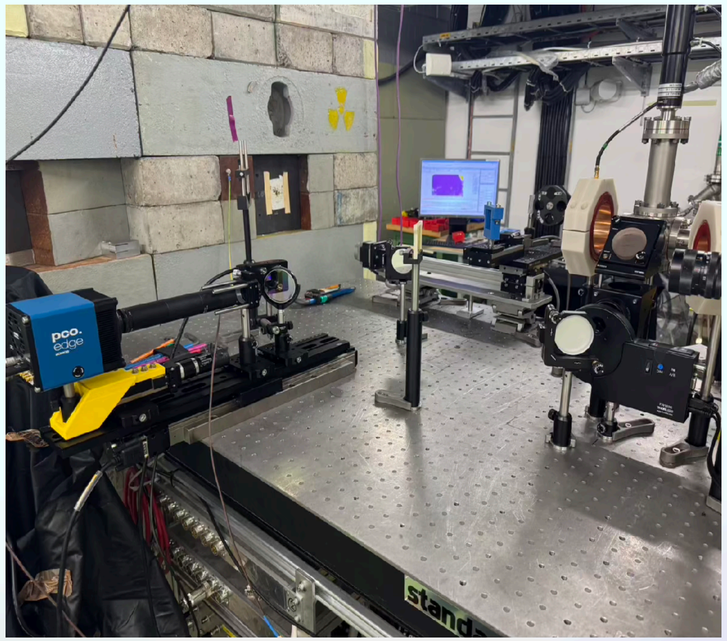
@CLEAR ('24 & '25)







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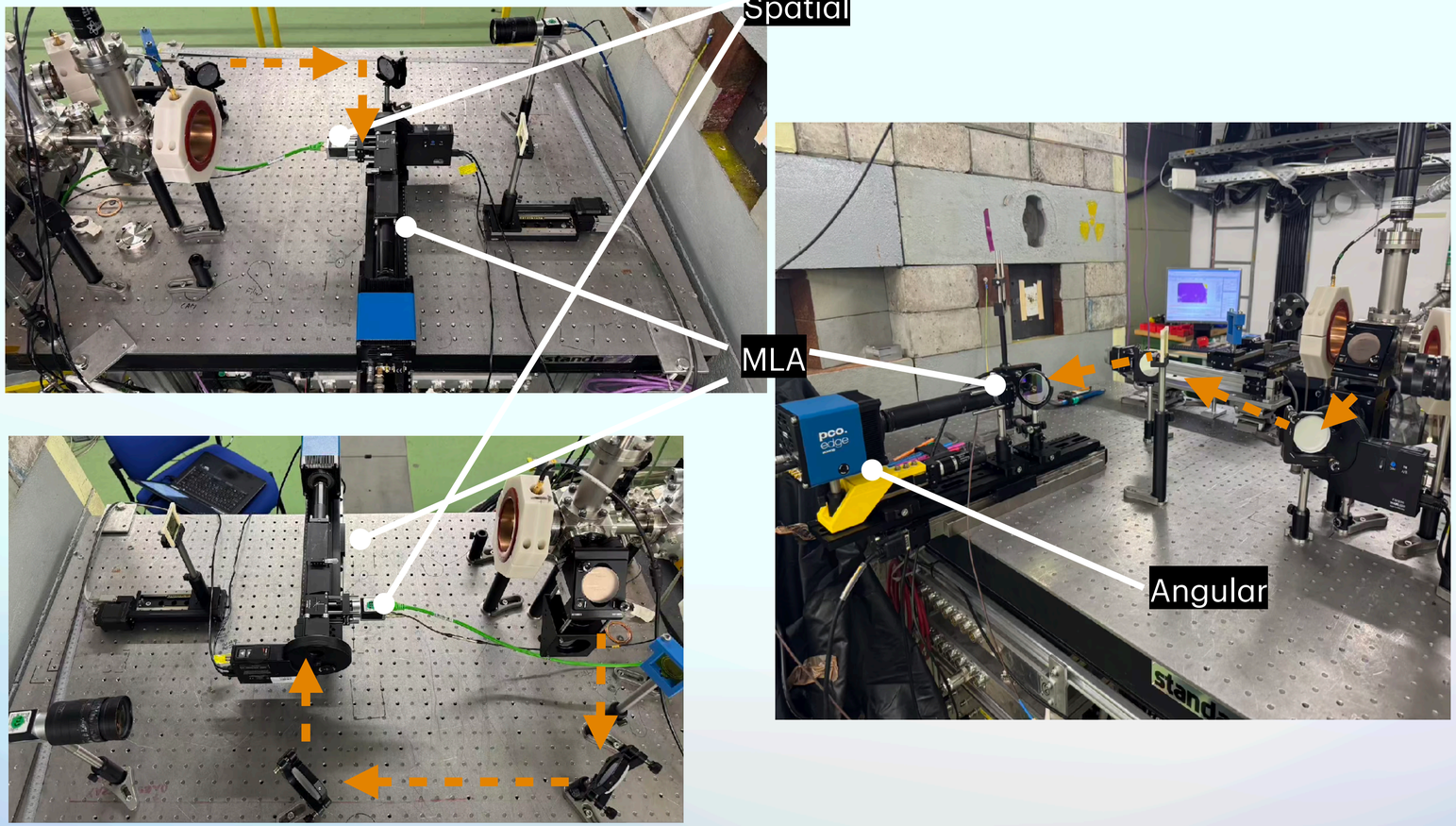
PoC Measurements

@CLEAR ('24 & '25)



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PoC Measurements

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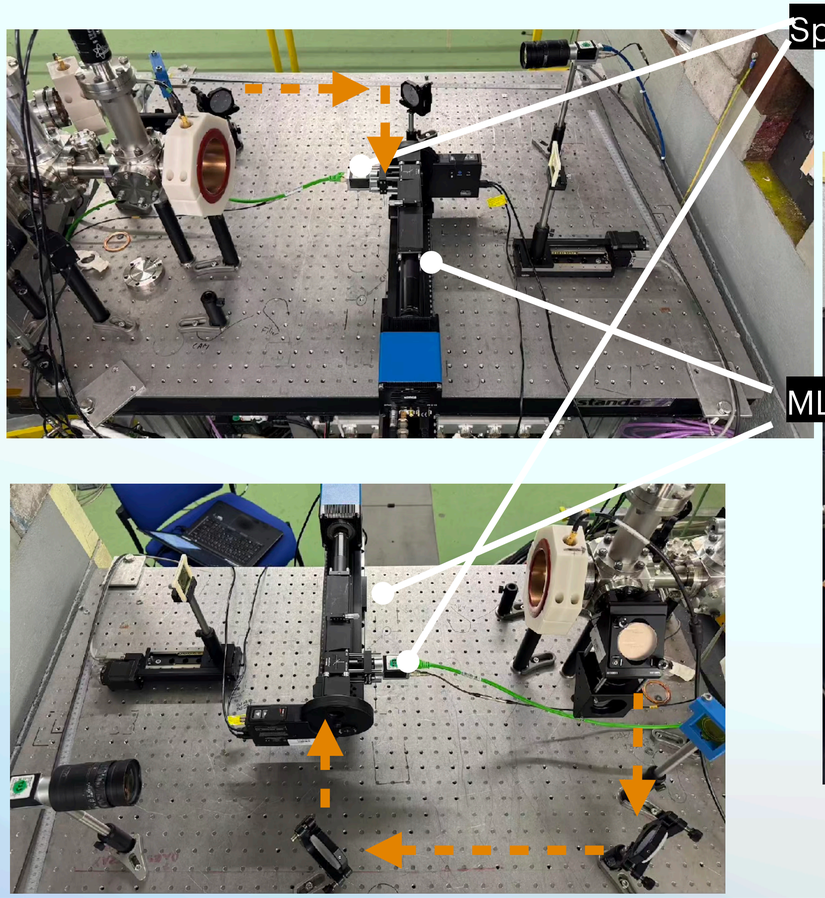

Parameters	Values
E (MeV)	198 ± 5
Q (nC)	0.1 - 2
ΔE	1.5-2 %

Benchmarked Emittance	Values
ε_x (mm.mrad)	16 ± 2.6
ε_y (mm.mrad)	4.5 ± 0.7

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PoC Measurements

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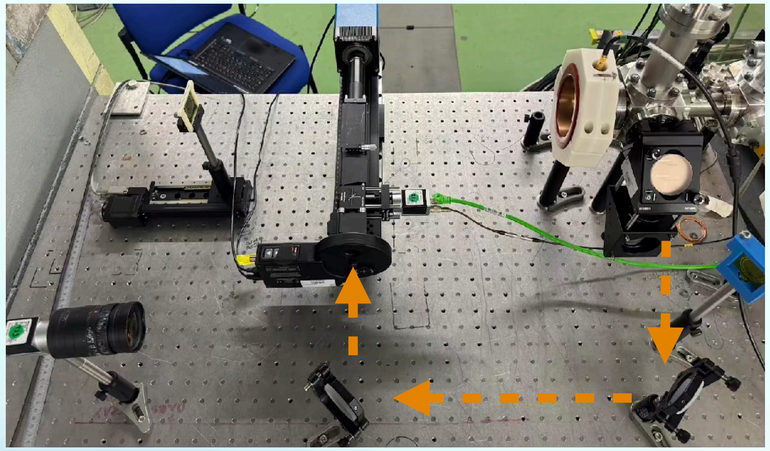

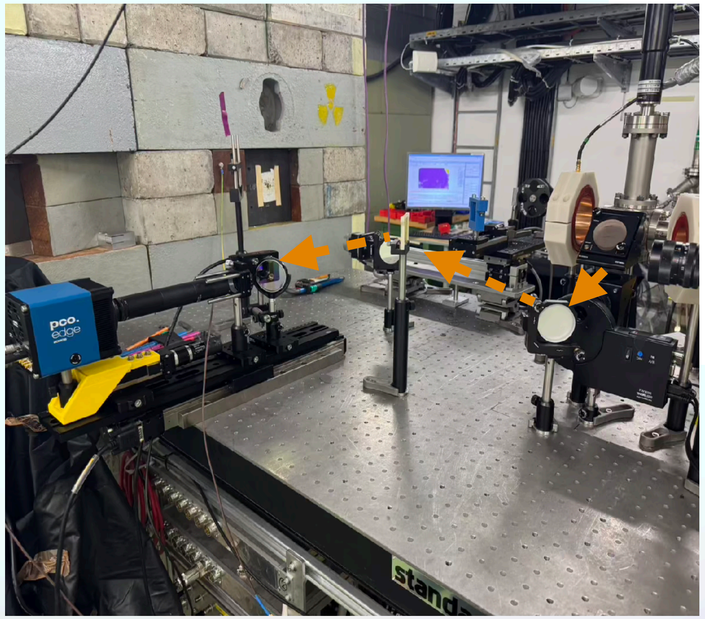

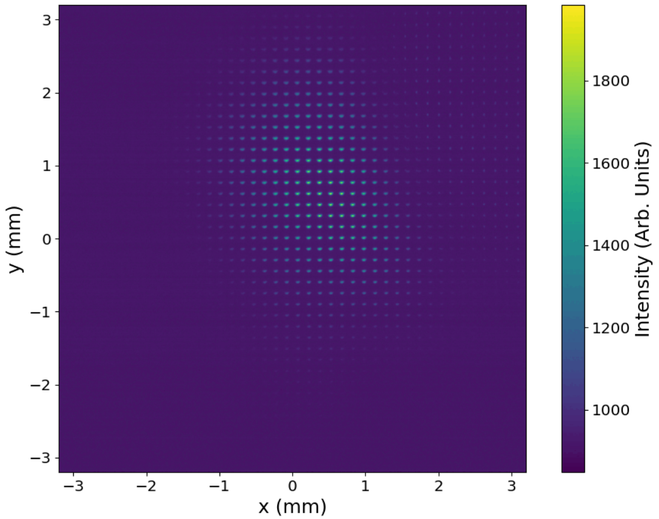

ΔE	1.5-2 %

Joe

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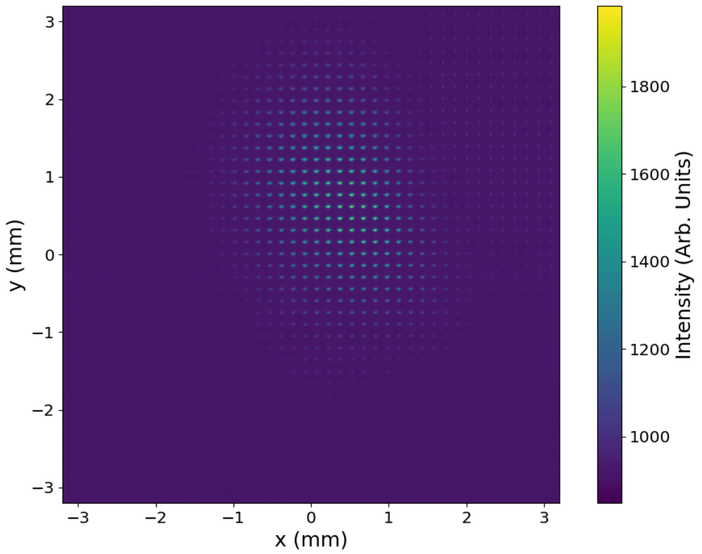
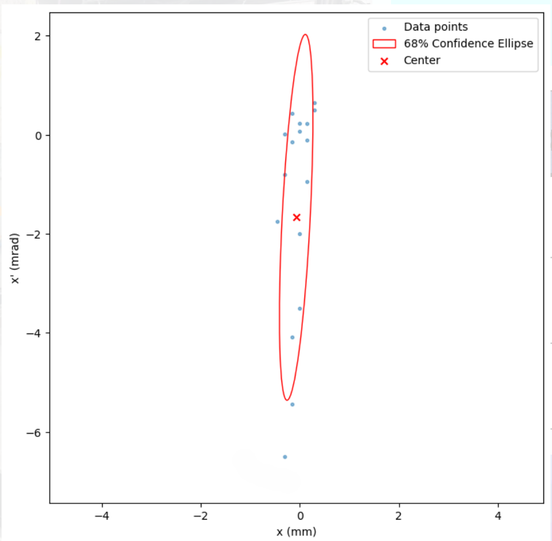
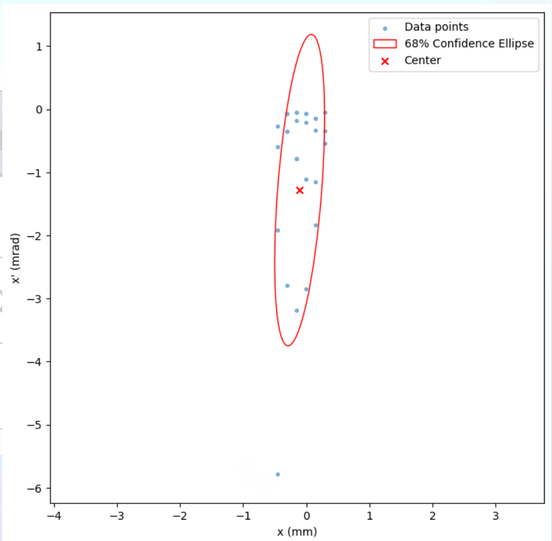
PoC Measurements & Analysis

@CLEAR ('24 & '25)







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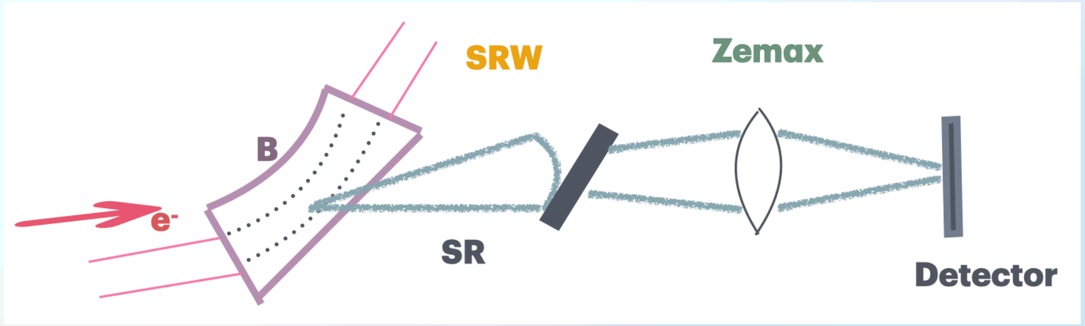
OSR Simulation

SRW & Zemax



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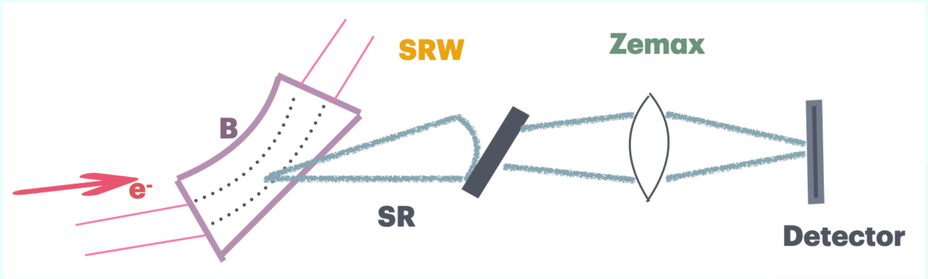
OSR Simulation

SRW & Zemax



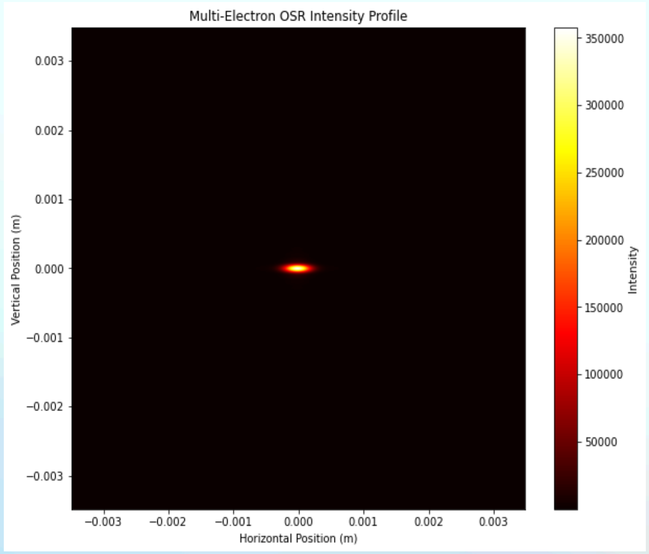
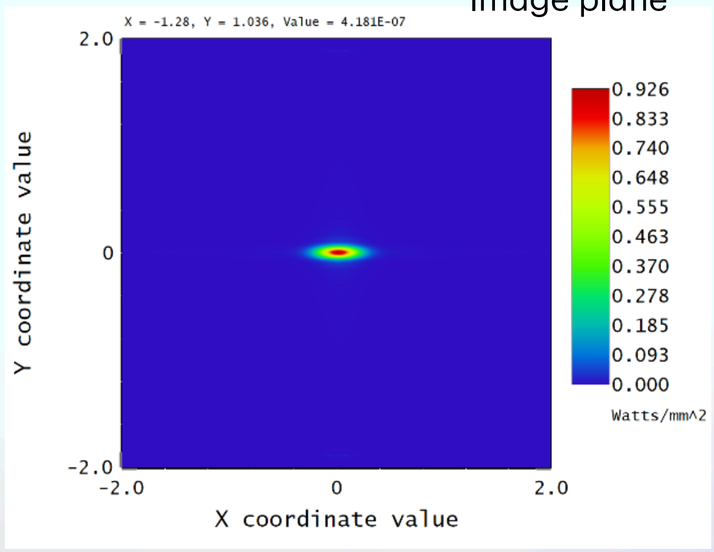
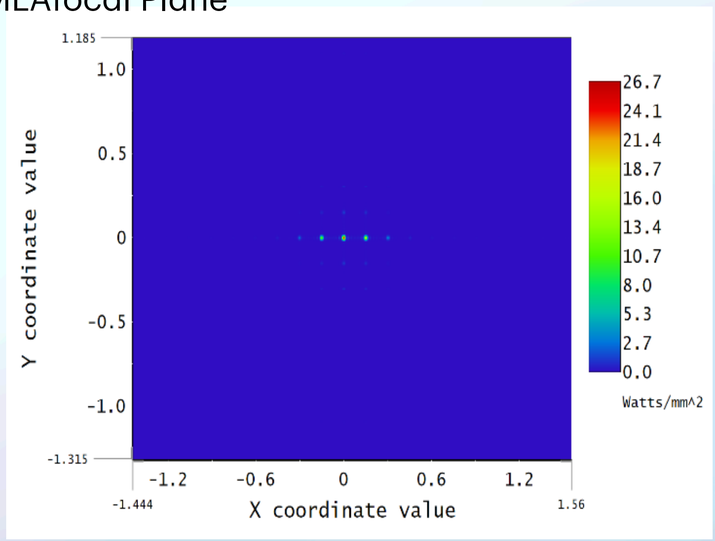


Image plane



MLAfocal Plane



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Lessons from AWAKE & CLEAR

From PoC to Diagnostic Backbone

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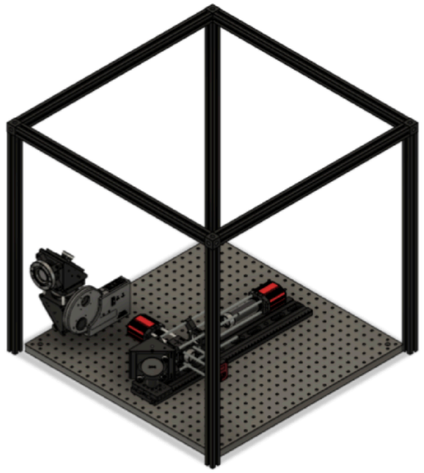
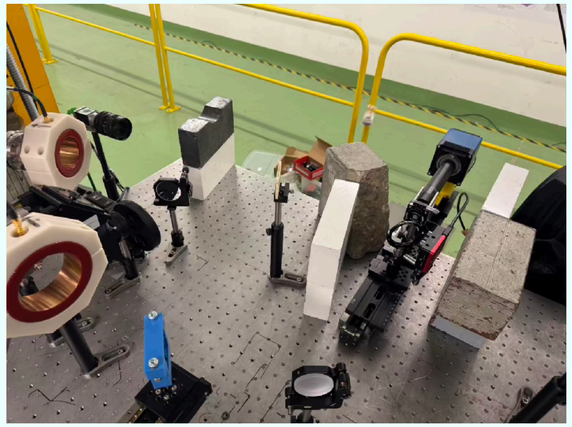
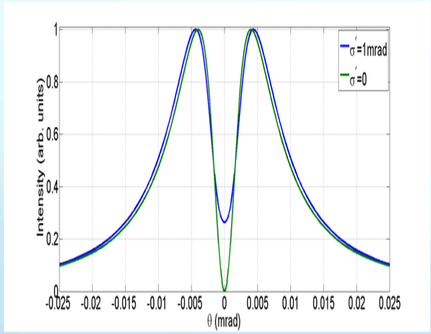
Lessons from AWAKE & CLEAR

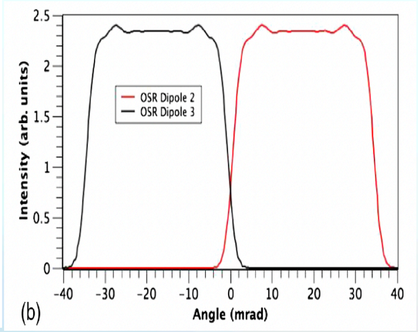
From PoC to Diagnostic Backbone



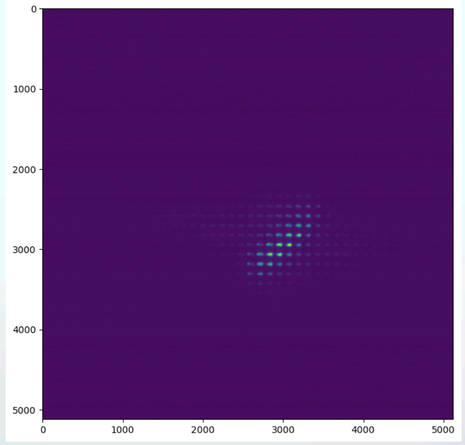




[Credit1]



[Credit2]



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OSR Experience to Future Science & EuPRAXIA

Translating Diagnostics into Scientific Capability

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OSR Experience to Future Science & EuPRAXIA

Translating Diagnostics into Scientific Capability

precise **beam commissioning** and **optimization**

Modular and scalable diagnostic

High-resolution, real-time monitoring

Non-invasiveness

Compact footprint

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Translating Diagnostics into Scientific Capability

precise **beam commissioning** and **optimization**

- transverse beam profiles and angular distributions —> to adjust quad strengths
- tracking of twiss params evolution over propagation
- identifying asymmetries due to misalignments

Modular and scalable diagnostic

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OSR Experience to Future Science & EuPRAXIA

Translating Diagnostics into Scientific Capability

precise **beam commissioning** and **optimization**

- transverse beam profiles and angular distributions —> to adjust quad strengths
- **a feasibility study: only one dipole downstream, distances from the plasma stage…**
- identifying asymmetries due to misalignments

Modular and scalable diagnostic

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OSR Experience to Future Science & EuPRAXIA

Translating Diagnostics into Scientific Capability

precise **beam commissioning** and **optimization**

- transverse beam profiles and angular distributions —> to adjust quad strengths
- **a feasibility study: only one dipole downstream, distances from the plasma stage…**
- identifying asymmetries due to misalignments

Modular and scalable diagnostic → universality across accelerator types- both LPAs and beam-driven setups

High-resolution, real-time monitoring → can provide micron-scale spatial resolution in favorable conditions

Non-invasiveness → non-invasive, shot-to-shot monitoring— ideal for high rep.-rate, high-gradient machines & FEL

Compact footprint → OSR setups can fit into space-tight beamlines in EuPRAXIA

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To Wrap up!

Summary & Outlook: OSR at the Frontier

OSR

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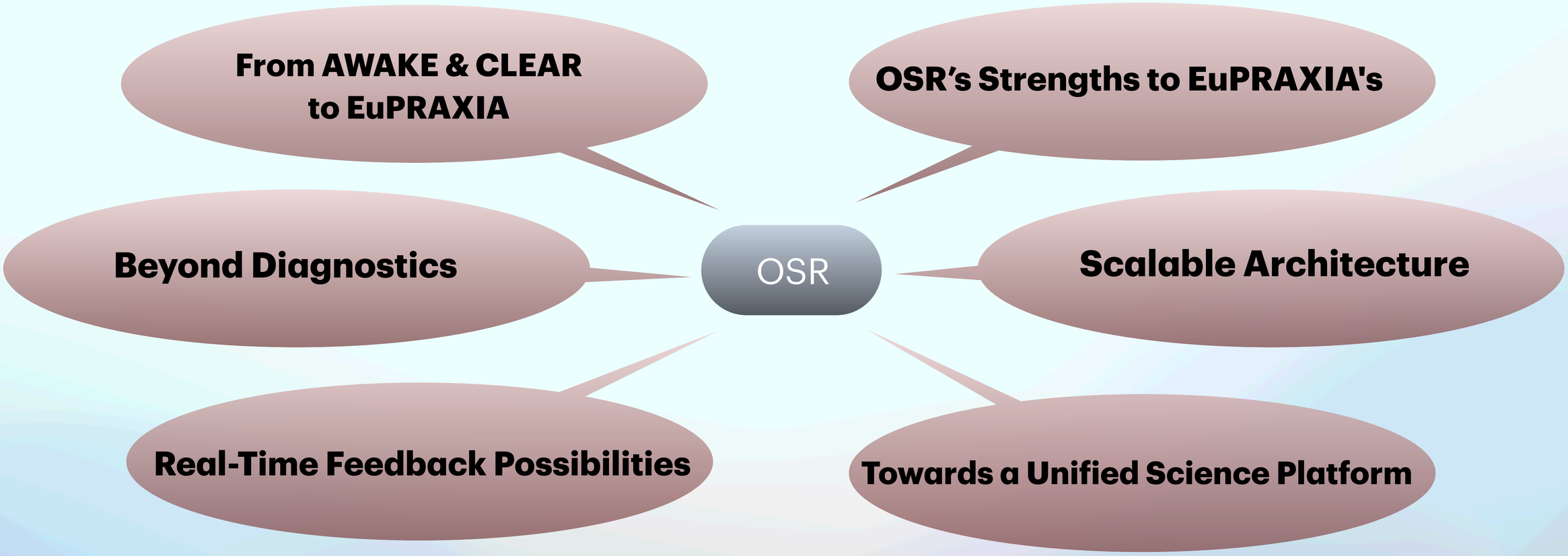
To Wrap up!

Summary & Outlook: OSR at the Frontier



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To Wrap up!

Summary & Outlook: OSR at the Frontier

From AWAKE & CLEAR to EuPRAXIA
High Emittance diagnostic value: requires a dipole and suitable/relevant location.

OSR's Strengths to EuPRAXIA's
Compact, robust, non-invasive diagnostics suited for beam-driven & laser-driven regimes

Beyond Diagnostics
shot-tagging, jitter monitoring, and real-time beam feedback: FEL-support.

OSR

Scalable Architecture
OSR systems can be **modularly deployed** across beamlines with dipoles.

Real-Time Feedback Possibilities
OSR-based measurements feed directly into **adaptive beam tuning**

Towards a Unified Science Platform
OSR is the bridge connecting beam physics and user science in EuPRAXIA

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Backup

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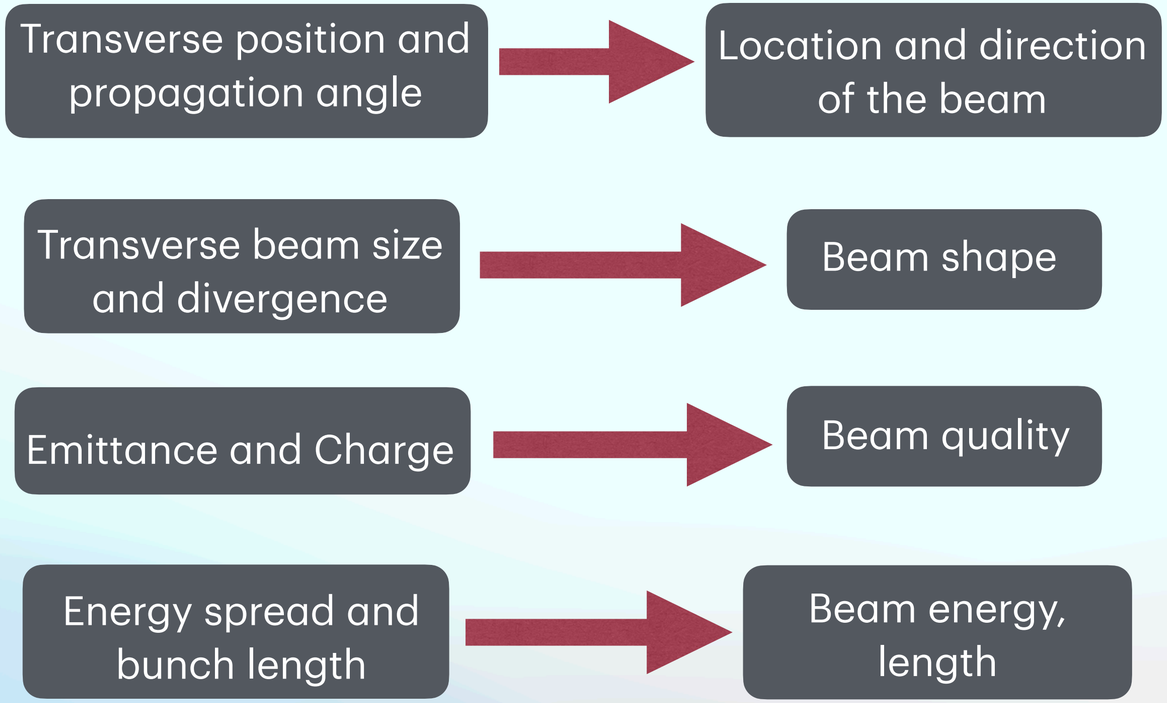
Beam diagnostics

Diagnostics in Accelerators (context):



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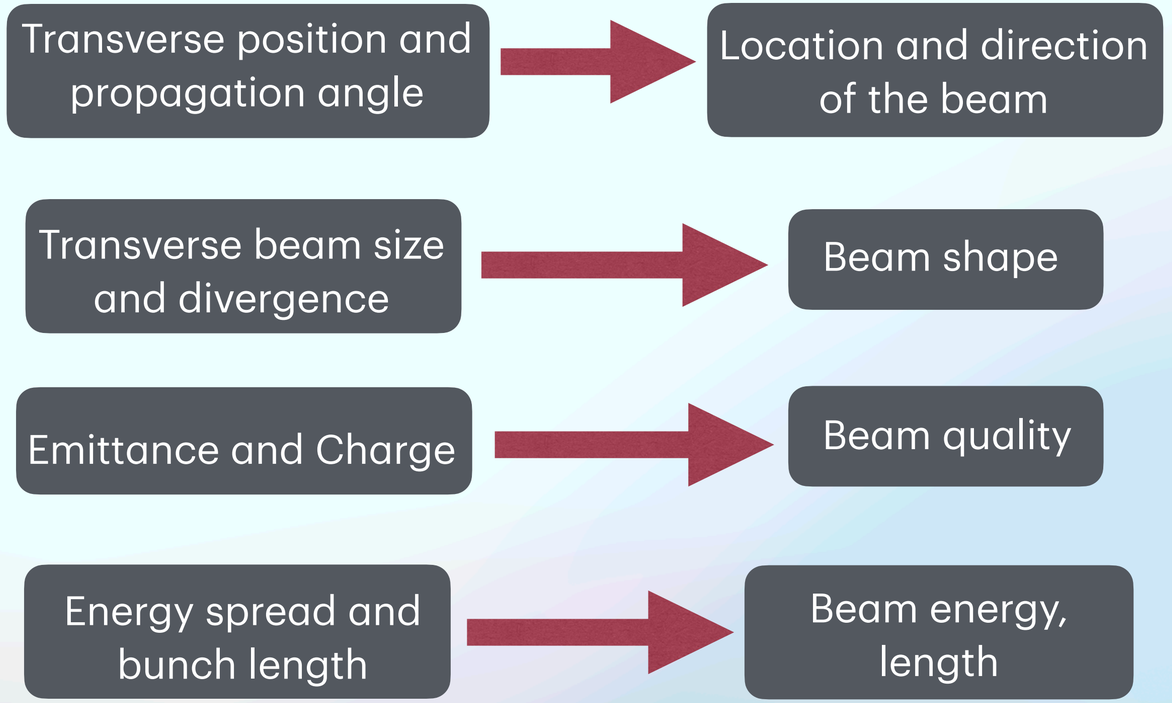
Beam diagnostics

Diagnostics in Accelerators (context):

- <u>Different techniques to measure:</u>
  - Beam Profile Monitors
  - Wire Scanners
  - Beam Position Monitors (BPM)
  - via Optical Transition Radiation (OTR)
  - via Optical Synchrotron Radiation (OSR)
  - Gas jet beam profile monitor



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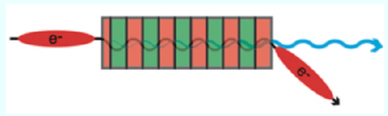
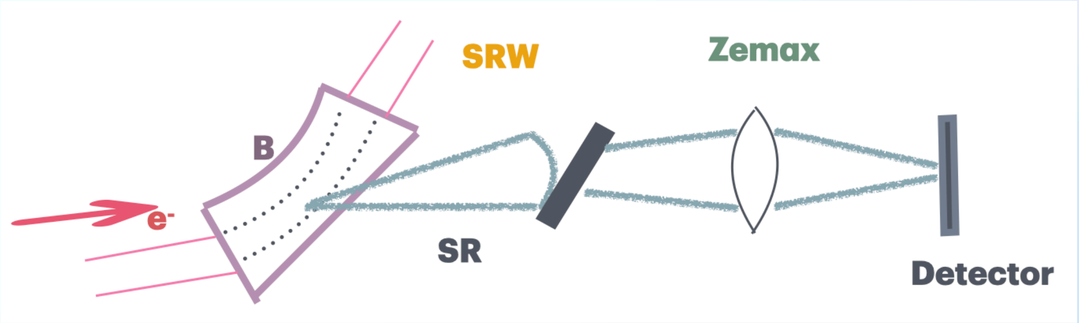
OSR Simulation



SRW & Zemax

https://github.com/ochubar/SRW

- **SRW** is a comprehensive software toolkit developed *(by O. Chubar & P. Elleaume, @ESRF)* for simulating the emission, propagation, and interaction of SR with materials.
  Fast computation of SR emitted by relativistic electrons in mag. field of arb. configuration
- SR **wavefront propagation**
- Simulation of experiments involving SR
- Python-based API
- Accurate **Field computation**



- **Zemax** is used to simulate the optical path for OSR collection and imaging
- Helpful with **ray tracing**, **PoP** and **spot size analysis**

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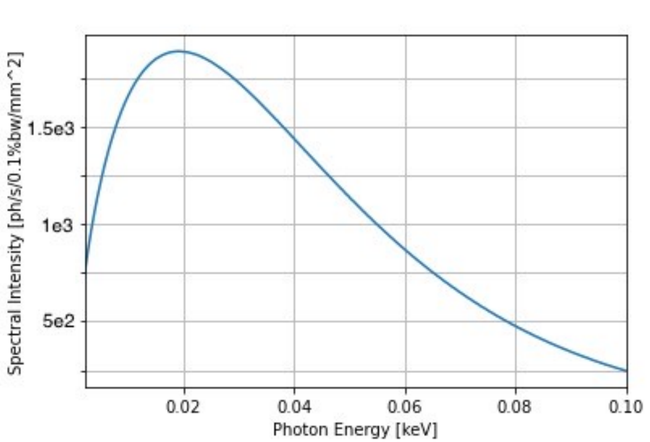
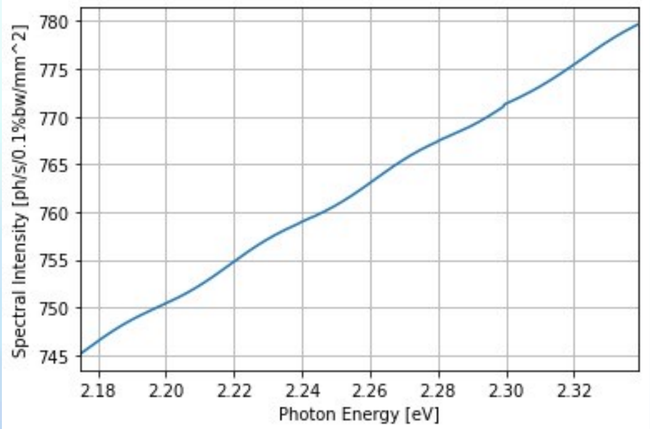
OSR Simulation

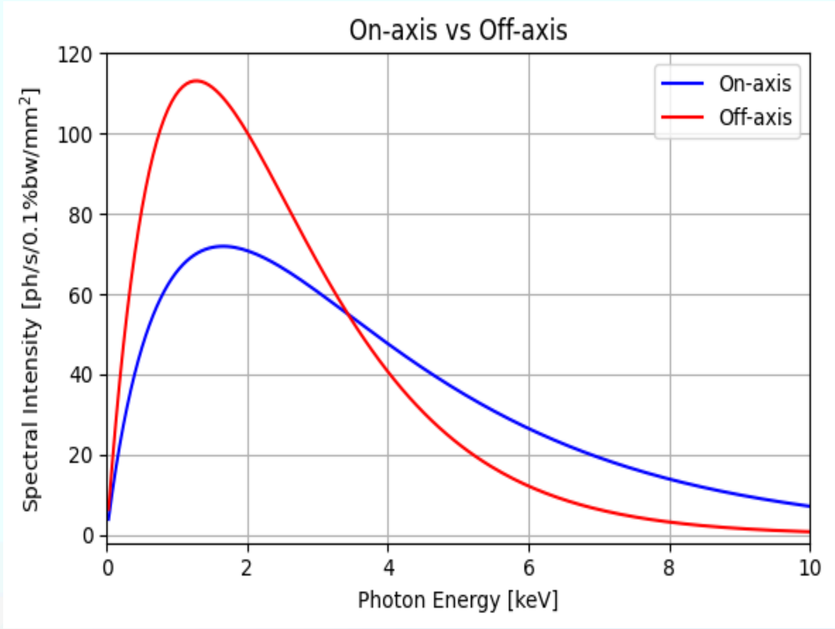
SR Spectral Intensity plot (Bandwidth feasibility): CLEAR Vs AWAKE





CLEAR

AWAKE



Visible spectrum for beam profile and position diagnostics

for 20 microns spot & 0.5 mrad div.

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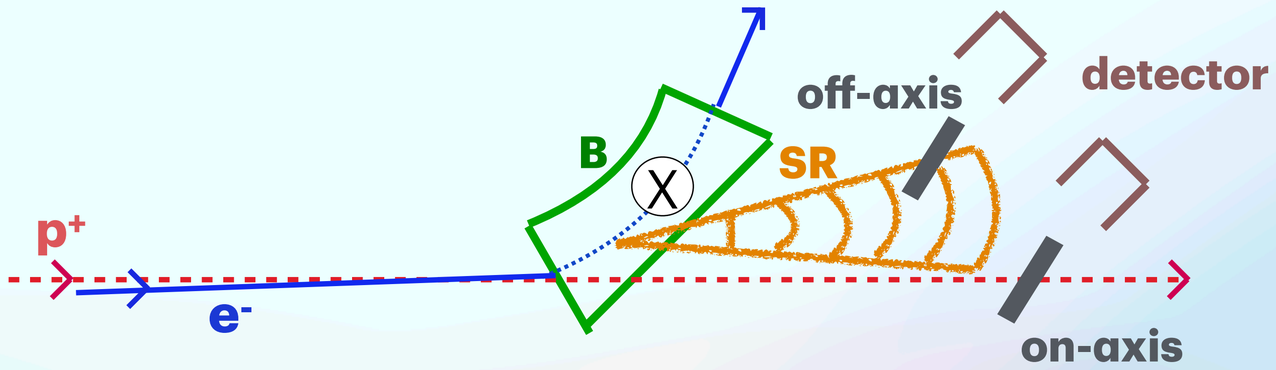
OSR Simulation

OnAxis-OffAxis

Comparison on the two different extraction methods: **On Axis Vs Off Axis** (5 mrad deflection angle)



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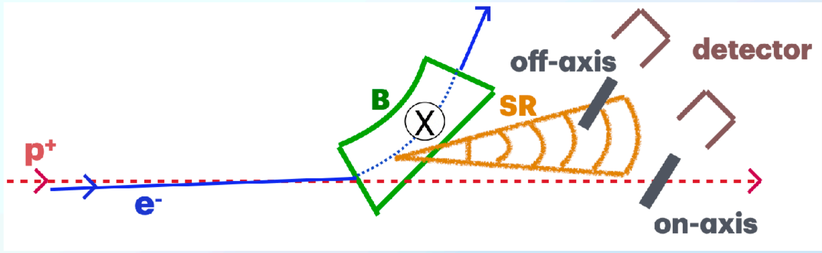
OSR Simulation

OnAxis-OffAxis

Comparison on the two different extraction methods: **On Axis Vs Off Axis** (5 mrad deflection angle)

Extraction methods	Pros	Cons
On-Axis	less dispersion expected, Easier alignment	extract radiation with mirror with a hole/half surface (halo effect)
Off-Axis	Not much trouble from proton beam	modification in the dipole, extra dispersion, OSR intensity...



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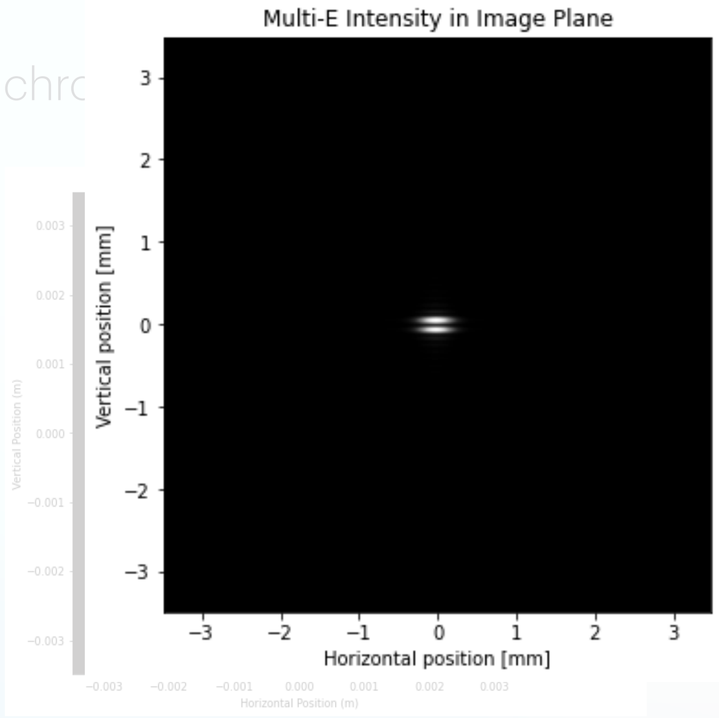
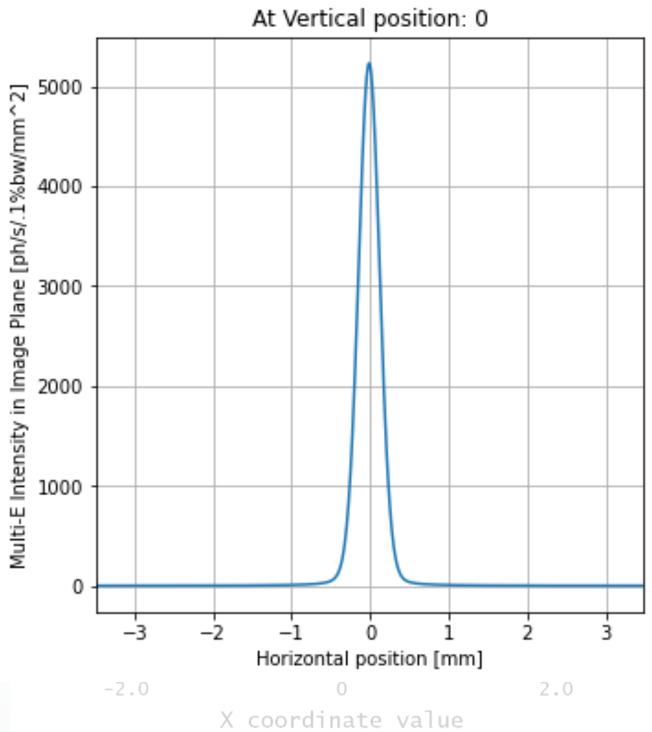
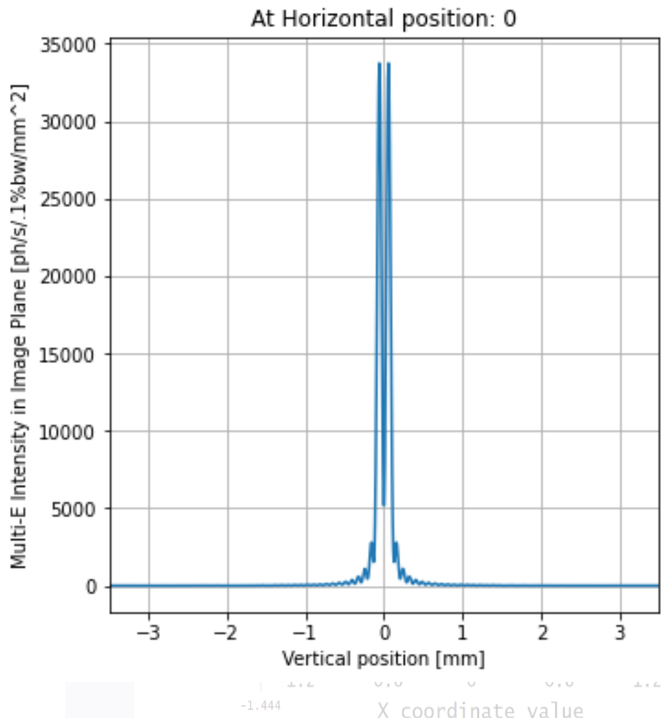
OSR Simulation: Multi-electron intensity @image-plane

End-to-end integration

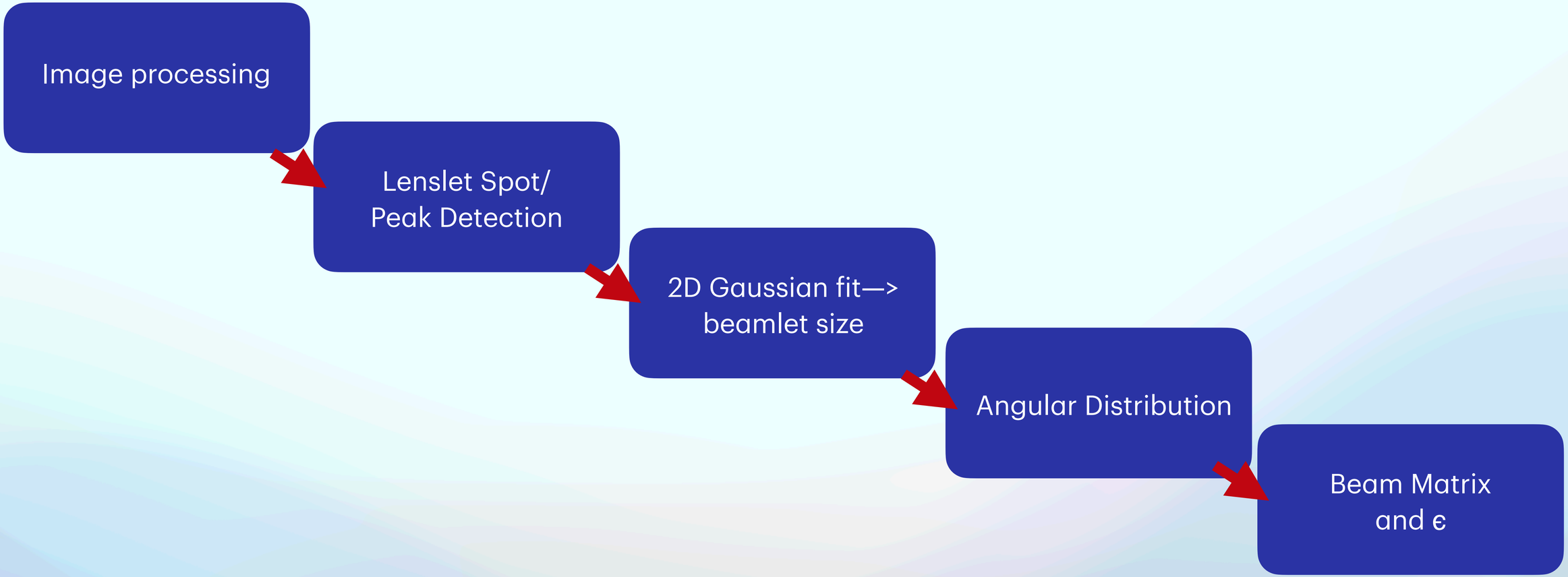






OSR Simulation

MLA Analysis: reconstruction from OSR simulated image



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