Diagnostics

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On behalf of EuPRAXIA@SPARC_LAB team

Contributions from

- Alessandro Cianchi, Livio Verra (deputy), Paola Bolognesi (CNR), Jacopo Chiarinelli (CNR), Francesco Demurtas, Giovanni Franzini, Federico Galdenzi (Tor Vergata), Mario Galletti (Tor Vergata), Andrea Ghigo, Anna Giribono, Valerio Lollo, Stefano Pioli, Danilo Quartullo, Angelo Stella, Giulia Latini, Cristina Vaccarezza, Fabio Villa

General remarks

- Big impulse to keep the diagnostics as **compact** as possible
- Conventional or in-house developed solutions for most of the measurement parameters
- **TRL** of every device is shown in this presentation [1]
- Status of **TDR readiness** is highlighted for every device/measurement type
- Main issues and **risk mitigation** strategies will be also presented

[1] https://it.wikipedia.org/wiki/Technology_Readiness_Level

Electrons Diagnostics

Parameters to measure (electrons)

Charge	1 pc – 500 pC
Beam size	1 mm – 1 um
Trajectory	20 um – 1 um
Emittance	> 0.5 mm-mrad
Energy	80 MeV – 1.2 GeV
Energy spread	1 over 10000
Bunch duration	> 3 fs

Integrated Current Transformer

Commercially available integrating current transformers (ICT Bergoz Instrumentation) will be used between accelerating structures to allow non-destructive measurements.
Bunch charge can be measured with a few pC accuracy in the full range of 500pC bunch by bunch

Turbo Toroids will be added just after the RF photocathode and before and after the plasma section, where higher resolution is needed at a lower charge (<10pC).

These devices are virtually insensitive to dark currents and optimized to work in the lower charge range.

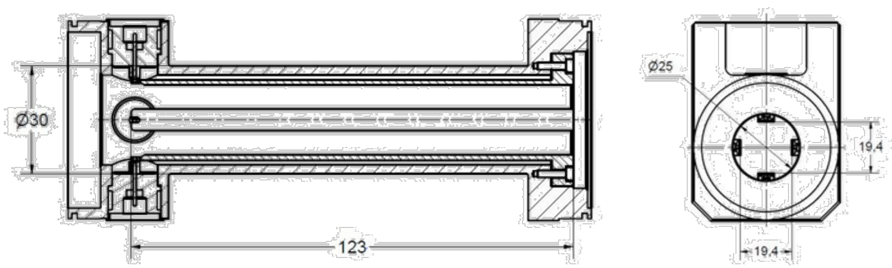
Definition 100%
TRL: 8
Writing readiness: 90%

A.Stella

Beam Position Monitors

Beam Position Monitors (BPMs) of the strip-line type will be used to measure the beam alignment on the magnetic axis. A dedicated strip-line pickup has been designed to satisfy the following main requirements:

- Transfer impedance suitable to allow single bunch measurements at a charge as low as 10pC while maintaining an RMS resolution of 10 um in the range 50-500pC over 25% of the beam aperture.
- BPMs have been required to be installed inside quadrupole magnets to save longitudinal space,
- Compatibility with existing (and already tested) commercial detection electronics centered at 500MHz



Vacuum pipe diameter d	mm	25
BPM total length	mm	155
Stripline distance r	mm	19
Strip coverage angle	degree	37
Strip length l	mm	123
Strip Char Impedance Z0	Ohm	50
Max Transfer Impedance	Ohm	2.55
Strip distance from chamber d	mm	1.5
1st lobe BW	MHz	1219.5

Stripline BPM parameters

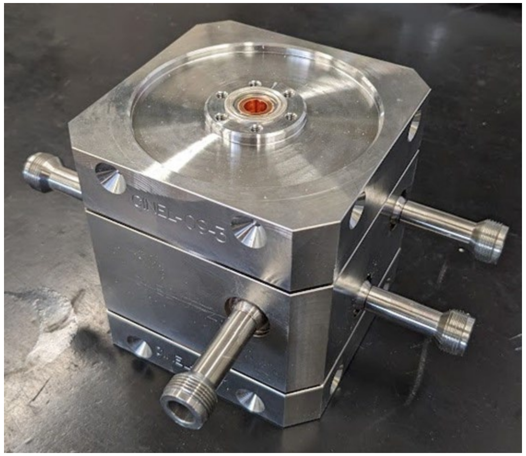
Definition 100%
TRL: 7
Writing readiness: 90%

A.Stella

Cavity Beam Position Monitors

Cavity BPM (cBPM) are foreseen to be installed between the undulator sections and before and after the plasma acceleration module, where the required precision for beam position measurements is 1 μm.

- The chosen design is the PSI model “BPM8”, designed at PSI.
- The readout electronics is represented by the “LIBERA Cavity BPM” by Instrumentation Technologies.



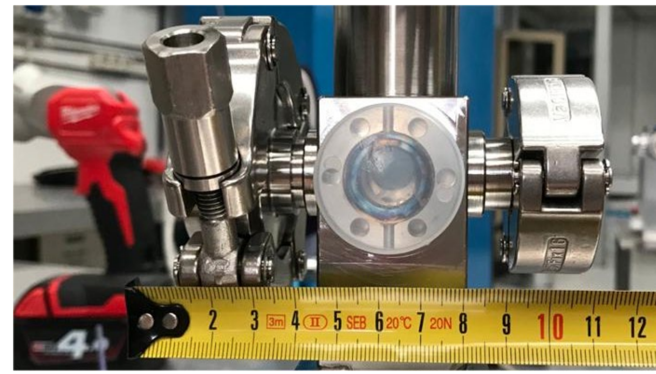
Parameter	Value
General	
Material	Stainless Steel 316LN
Beam Acceptance [mm]	8
Total length [mm]	100
Position Cavity Resonator	
Length [mm]	12
Q_L [mm]	1000
TM_{110} frequency [GHz]	4.9266
TM_{010} frequency [GHz]	3.150
Position Signal Sensitivity [V/(mm nC)]	4.3
Angle Signal Sensitivity [μm/mrad]	6.3
Reference Cavity Resonator	
Length [mm]	14
Q_L [mm]	1000
TM_{010} frequency [GHz]	4.9266
Reference Signal Sensitivity [V/nC]	58

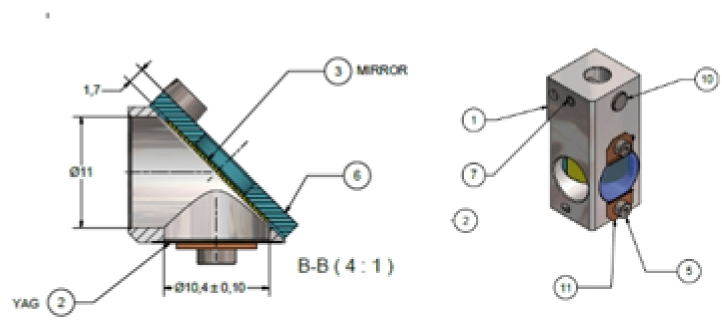
Definition 100%
TRL:7
Writing readiness: 90%

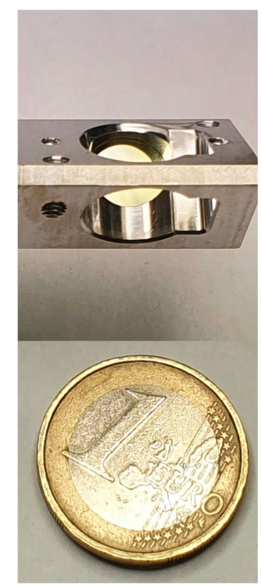
G. Franzini

View Screens

- In house design
- Tested already in SPARC
- Very compact design
- Modular system to host different kind of screens





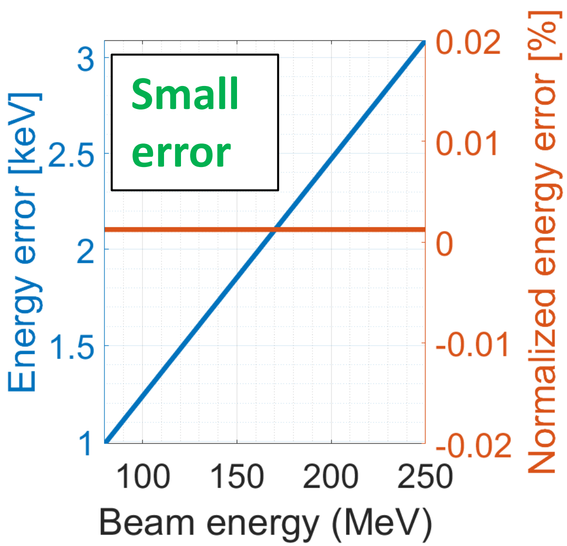


Definition 100%
TRL: 8
Writing readiness: 90%

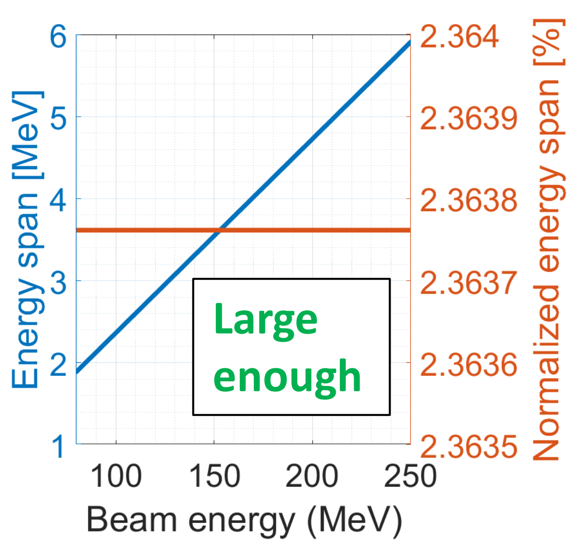
Energy measurements with spectrometers

Design of beam-energy measurements with the first spectrometer along the beam line.
Dipole parameters: $B_{\max} = 1.7$ T, $\varphi_0 = 24°$, $L_0 = 232$ mm.
CCD parameters: pixel size $3.5\ \mu\text{m}$, sensor size 6.6 mm × 4.1 mm, magnification of 3.

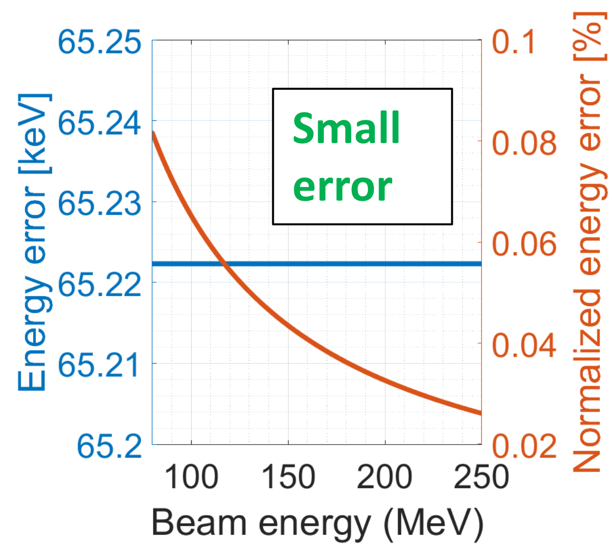
Energy error due to CCD pixel resolution (10 μm)



Energy span covered by horiz. field of view (20 mm)

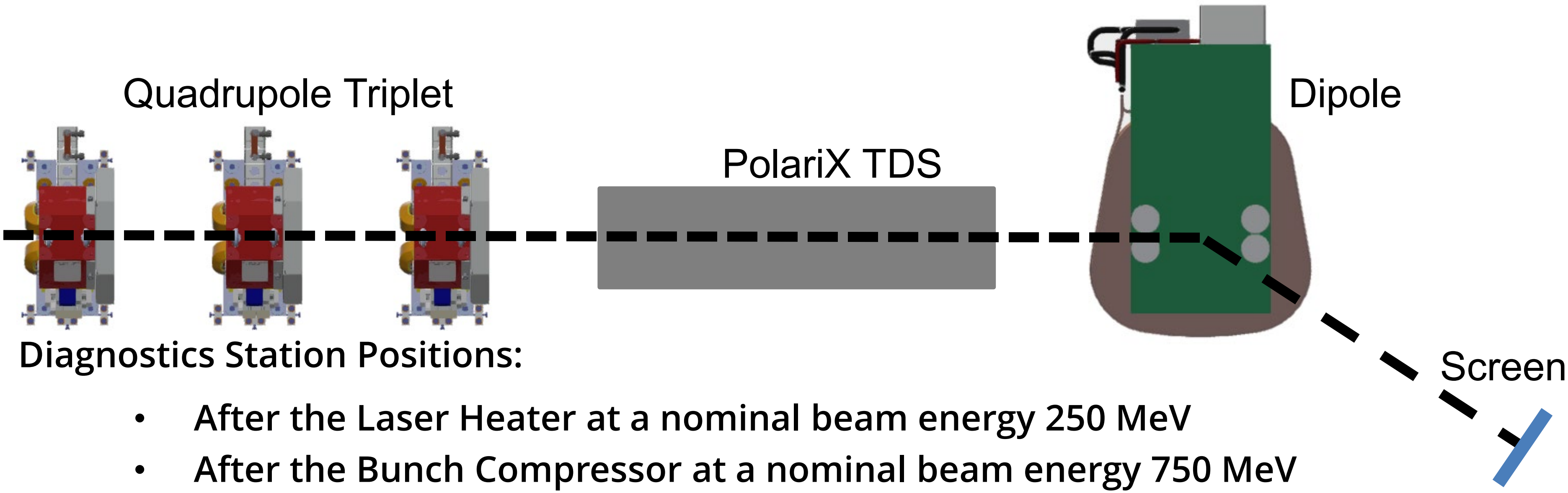


Energy error due to B field inhomogeneity (3.9 G)



Definition 33%
TRL: 7
Writing readiness: 30%

Emittance Measurement



Diagnostics Station Positions:

- After the Laser Heater at a nominal beam energy 250 MeV
- After the Bunch Compressor at a nominal beam energy 750 MeV
- Before the Undulator at a nominal beam energy 1 GeV

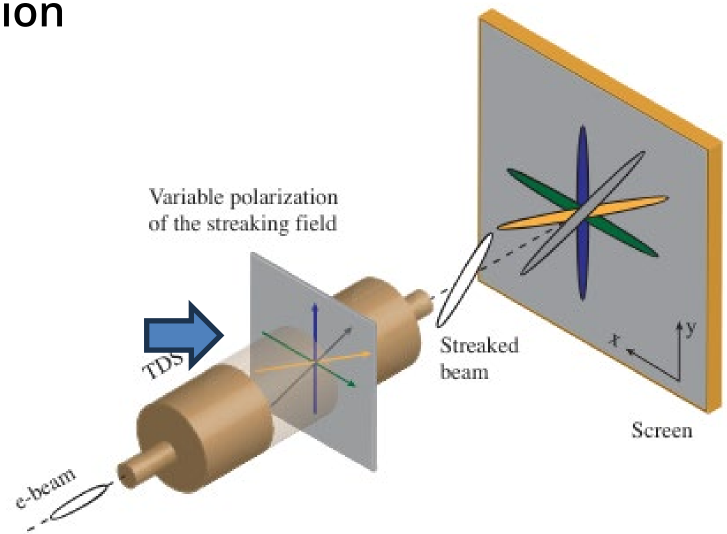
Parameters	Before Undulator
Beam Energy	1 GeV
Drift Quadrupole-Screen	4.84 m
Resolution	0.3 mm mrad

Definition 33%
TRL: 8
Writing readiness: 10%

F. Demurtas

PolariX Transverse Deflecting Structure

- The **PolariX** is a Transverse Deflecting Structure with the feature of changing the beam streaking direction



P. González Caminal *et al.* Phys. Rev. Accel. Beams **27**, 032801(2024)

B. Marchetti et al., Scientific Reports **11**, 3560 (2021)

Allows to perform tomography of the beam to retrieve the 3D beam distribution

Allows to measure the slice emittance on different transverse planes by using the same TDS device

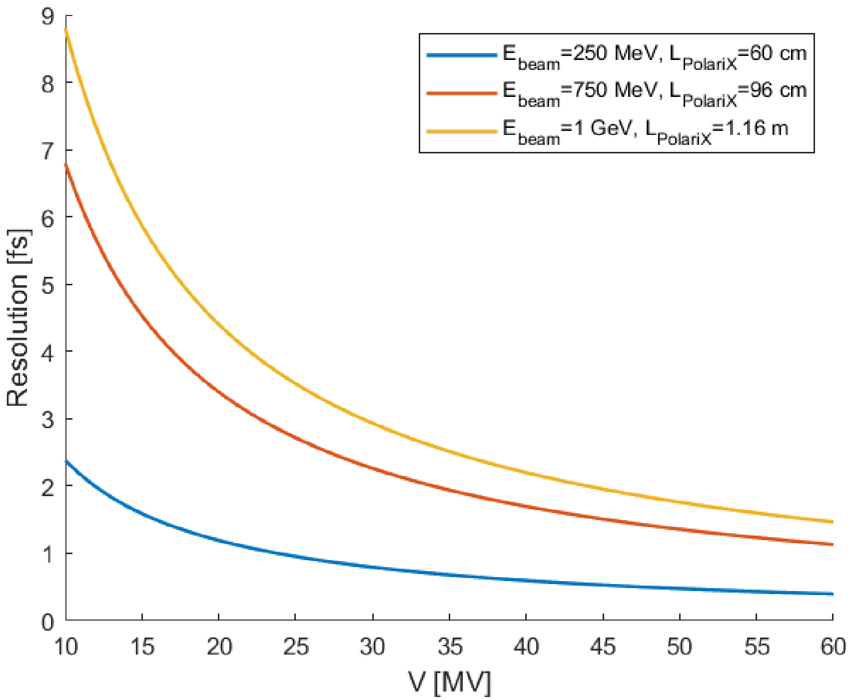
Combined with a quadrupole scan and a dipole spectrometer allows to measure the full 6D beam distribution

F. Demurtas

TDS Resolution

- After the Laser Heater: L=0.60 m
- After the Bunch Compressor: L=0.96 m
- Before the Undulator: L=1.16 m

$$R_t = \sqrt{\frac{\epsilon_y}{\beta_y^{PX\ center}}} \frac{1}{|sin\Delta\mu|} \frac{E}{eV_0 k_{rf} c}$$



Parameters	Before Undulator
Nominal Energy	1 GeV
Drift TDS-Screen	3.42 m
TDS Length	1.16 m
Voltage	40 MV
Resolution	3 fs

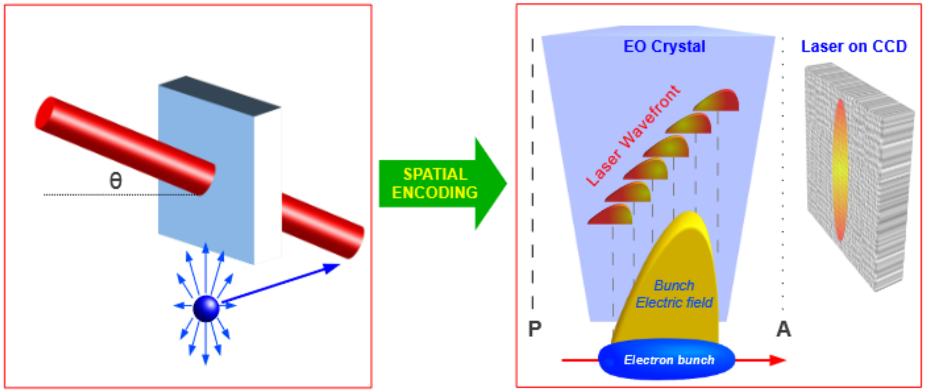
Definition 75%
TRL: 7
Writing readiness: 70%

F. Demurtas

Electro-Optical Sampling

- The Electro-Optical Sampling is a non-intercepting and single-shot device used for measuring the beam longitudinal properties of the driver and witness beam

Spatial Decoding Scheme:



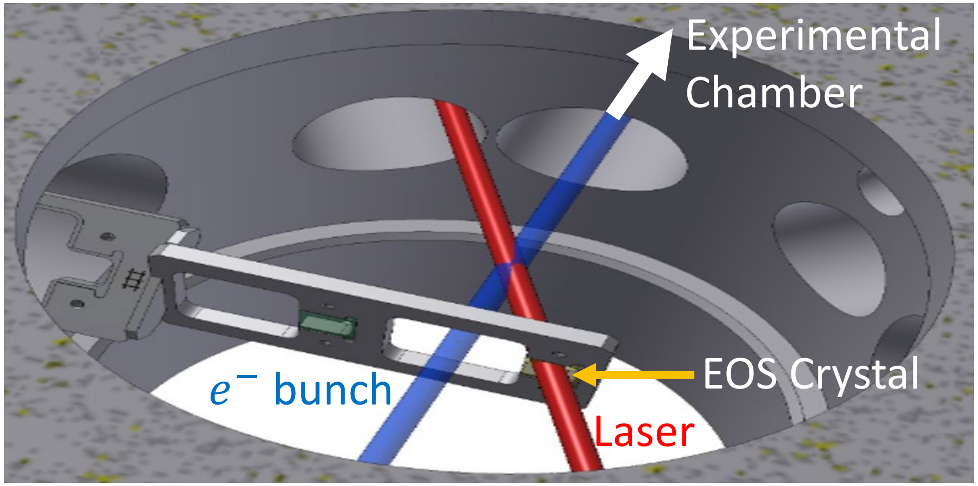
R. Pompili et al., Scientific Reports **6**, 35000 (2016)

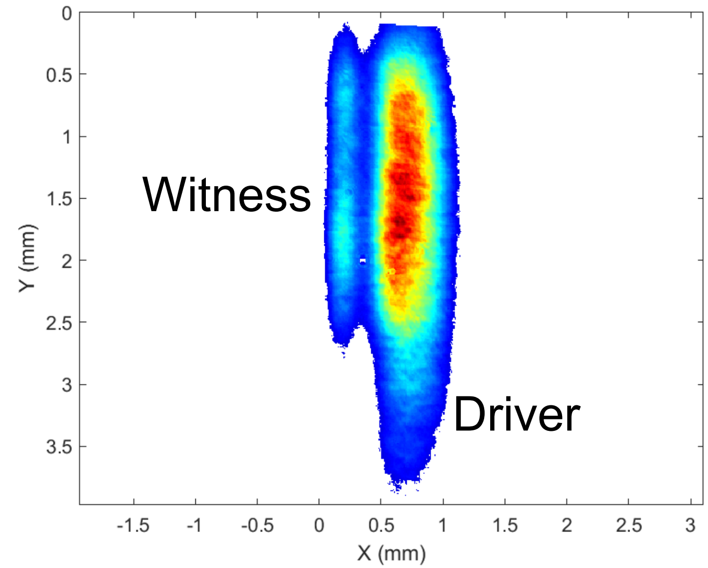
- The probe laser crosses the crystal with an angle $\theta = 30\ deg$, therefore different points across the transverse profile of the laser pass through the crystal at different times and acquire a different polarization

F. Demurtas

Electro-Optical Sampling

- EOS position: entrance of the experimental chamber





- Resolution of a few fs on the beam arrival time
- Resolution of tens of fs on the longitudinal beam distribution

Definition 100%
TRL: 7
Writing readiness: 70%

F. Demurtas

Coherent Diffraction Radiation Monitor

- Online, non-invasive diagnostic of bunch duration
- Diffraction radiation emitted when a charged bunch travels close to the edge of a discontinuity between two media
- Radiation spectrum:

$$I_{tot}(\omega) = I_{sp}(\omega)[N + N(N-1)F(\omega)]$$

Single-bunch spectrum

Number of electrons in the bunch

Form factor:

$$F(\omega) = \left| \int_{-\infty}^{\infty} S(z)\, e^{\frac{i\omega}{c}z} dz \right|^2$$

E. Chiadroni, PhD thesis

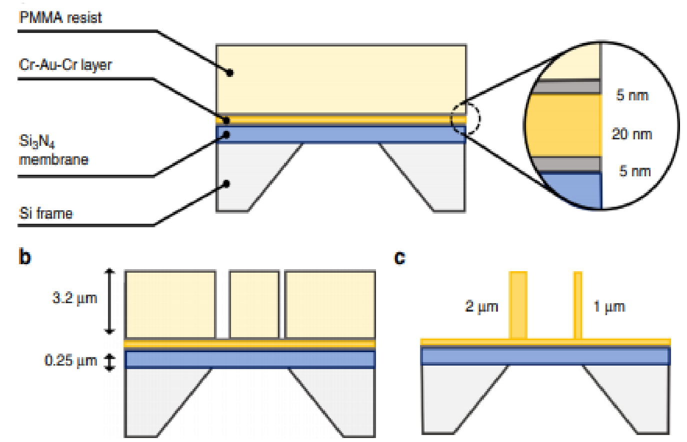
Measurement of the coherent emission spectrum is a measurement of the form factor
Info on the longitudinal bunch distribution from the signal's amplitude (Pyrodetector)

Definition 80%
TRL: 7
Writing readiness: 70%

L. Verra

Micro wire scanner

- Problem: measure the beam size at the plasma entrance (about 1 um rms)
- The microwire scanner developed at PSI and Fermi is the most feasible solution.
- It is a 1-D diagnostic, multi-shot for its nature as a wire scanner.
- Tested so far up to 200 pC
- Laser wire scanner is another device that is in developing and could be also another alternative.
- Main problems related with the integration in the plasma chamber
- It is the central topic for electron diagnostics in PACRI proposal
- Ongoing simulation studies with EuPRAXIA parameters

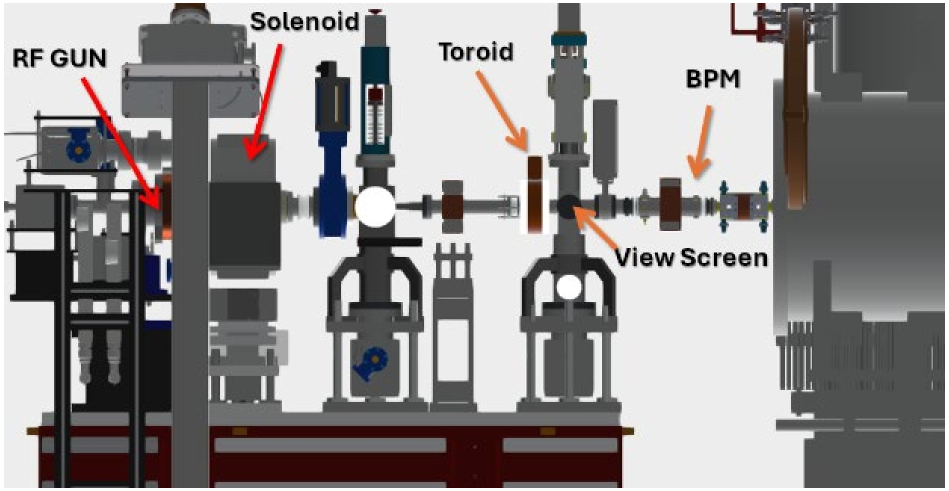


Borrelli, Simona, et al. "Generation and measurement of sub-micrometer relativistic electron beams." *Communications Physics* 1.1 (2018): 1-8.

Risk mitigation: measure the beam size before the final focus and transport the beam parameters

Definition 20%
TRL: 5
Writing readiness: 0%

Layout integration



- Layout integration almost completed
- Integration in the plasma chamber is the hot topic of the following months.

- One open problem related to space occupancy
- Still to be put in the TDR

Definition 80%
Writing readiness: 10%

Electron diagnostics situation

	Definition	status TDR	TRL
Integrated current transformer	100%	90%	8
Beam position monitors	100%	90%	7
Cavity BPM	100%	90%	7
View screens	100%	90%	8
Emittance measurements	33%	10%	8
Energy measurements with magnetic spectrometers	33%	30%	8
Transverse deflecting structure	75%	70%	7
Electro Optical Sampling	100%	70%	7
Coherent radiation monitor	80%	70%	7
Plasma entrance diagnostics .	20%	0%	5
Layout integration	80%	10%	N/A

Open problems in electron diagnostics

- Beam size at plasma entrance with microwire scanner
  - Problem: to realize the design and the prototype, to test the prototype
  - Risk mitigation: measure the beam size before the last magnetic focusing system
- Space allocation for Polarix after the undulator
  - Problem: find a place for the Polarix (1 meter)
  - Risk: no longitudinal phase space diagnostics after undulator (lasing/no lasing!)

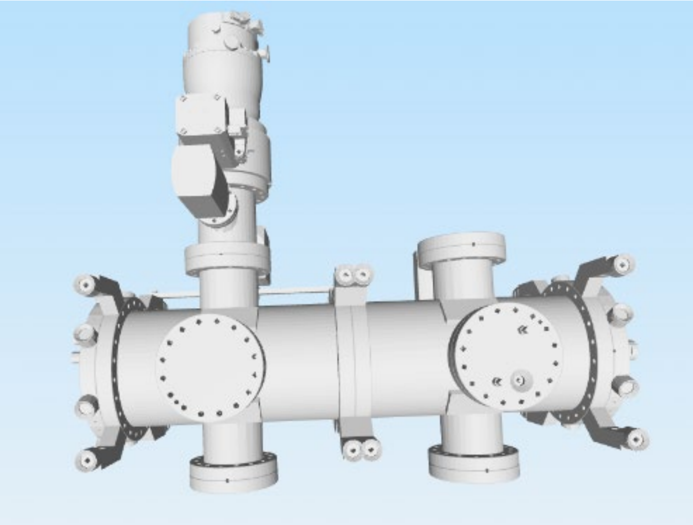
Photons Diagnostics

Parameters to measure (Photons)

	AQUA	ARIA
Photon Number	10^6-5*10^{12}	$10^6 – 10^{14}$
Pulse duration	~1 - ~100 fs	~1 - ~100 fs
Central wavelength	4-15nm	50-150nm
Spectrum	.01-3%	.01-3%
Polarization	H V Circ	H V Circ

Gas Monitor Detector

- Properties like beam position and intensity of the FEL radiation will be established and monitored on a shot-by-shot base and non-invasively, thanks to the installation of three Gas Monitor Detectors
- (GMD) along each beamline.
- GMD are the standard state-of-the art technology used for the characterization and monitoring of FEL radiation, from EUV to X-Ray .
- Their functioning is based on the photoionization of a rare gas and analysis of electrons/ions released in the process.
- The GMD originally developed at Hamburg for FLASH SASE FEL has nowadays reached an optimized design and can be made available from DESY with customizable specifications



Definition 80%
TRL: 7
Writing readiness:80%

Scintillating screens

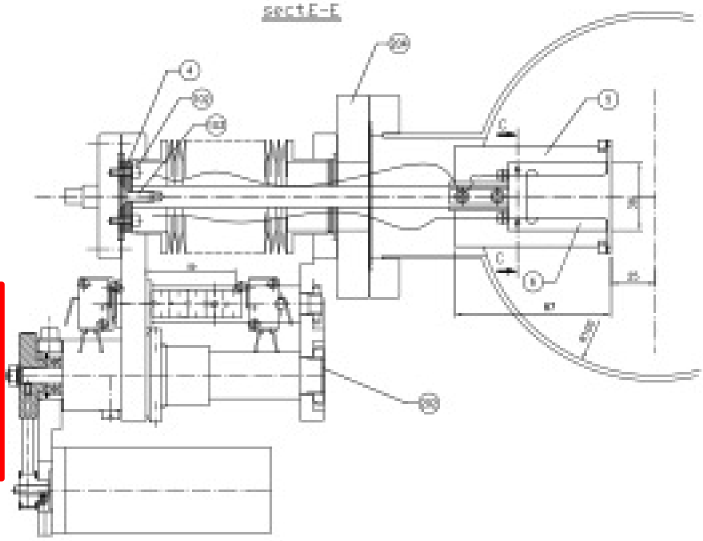
- Same chamber and screens as the electron diagnostics
  - Good light emission, standard in other FEL beamlines
  - Modularity
- Below the screen we will also insert a mirror for laser alignment of the beamline (with viewport on the opposite side of the camera one)
- Technical readiness: draft, calculation for light response and damage are ongoing

Definition 80%
TRL: 8
Writing readiness: 10%

F. Villa

Plate Beam Position Monitors

- 4 movable blades intercept the tails of the beam
  - Also act as a collimator
  - Blades also have a wire for a transverse scan of the dimension
  - System already employed in DAFNE Light beamlines
- Technical readiness: we have the CAD of DAFNE Light pBPMs, needs adjustment for the vacuum chamber. Calculation for resolution and expected photocurrent in our operation conditions are ongoing

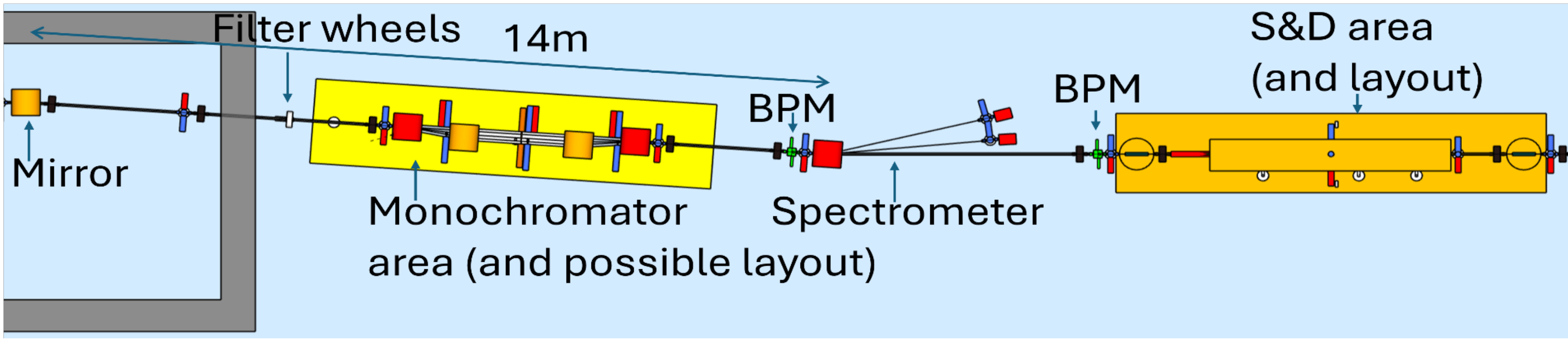


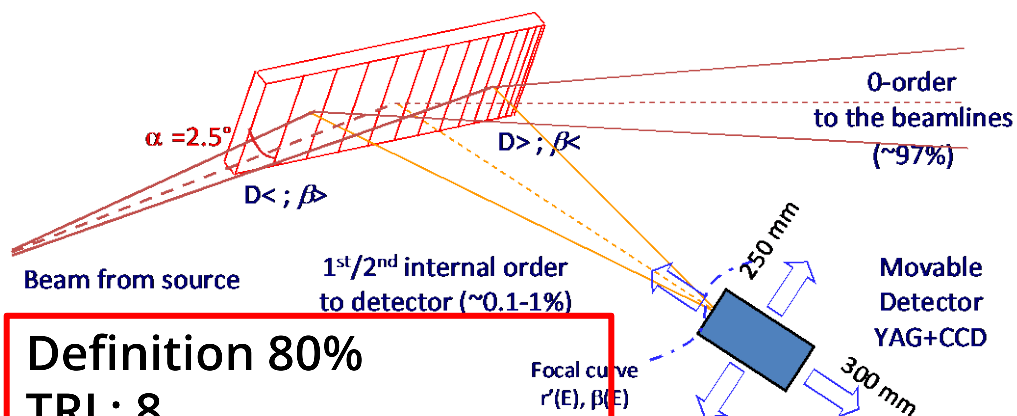
Definition 80%
TRL: 8
Writing readiness: 70%

F. Villa

Grating spectrometer

1. Shot to shot diagnostic must be implemented
2. Spectrometers before exp. Chamber and possibly after exp. Chamber
3. Non invasive diagnostic (trans. 97%) ; 1% of FEL goes to diagnostics





VLS (Variable Line Spacing Gratings): simultaneous focusing and diffraction of the beam. Higher order of diffraction goes to detector with small % loss on the main beam (0-order).

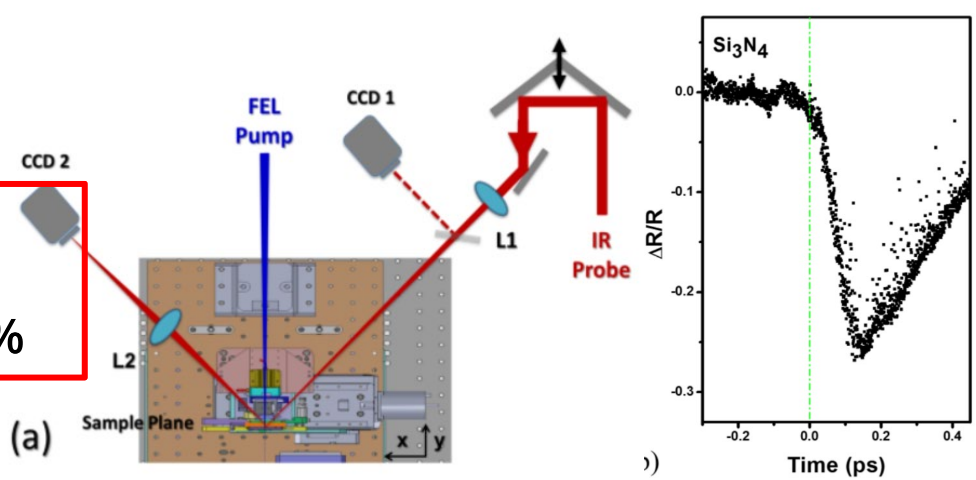
Definition 80%
TRL: 8
Writing readiness: 10%

F. Galdenzi

Arrival time monitor

- Transient reflectivity measure after the experimental chamber
  - Probed with synchronization laser
  - In INFRA-TECH-2024 “Optibeam” proposal there is a 18 month position for postdoc position dedicated to study the best materials for VUV-water window spectral range
- Can be installed in a second phase of the machine realization
- Technical readiness: draft, calculations and materials studies still need to be started (E. Principi worked on similar devices in FERMI and now he’s collaborating with us)

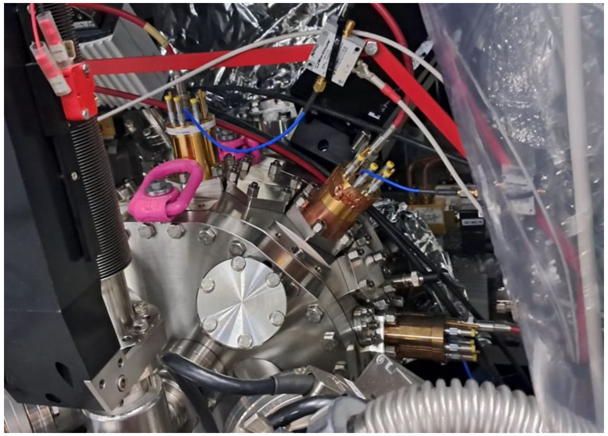
Definition 33%
TRL: 4
Writing readiness: 10%



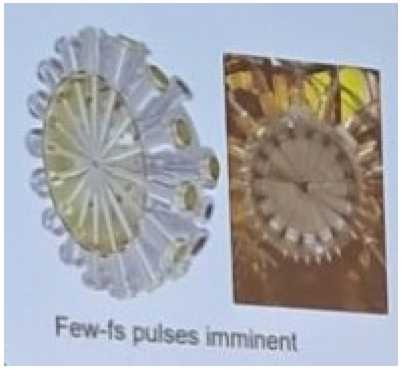
FERMI setup and measurement Optics expr., 22(11), pag. 12869, {2014}

Full temporal and polarization characterization

- Radial Time of Flight measure from gas ionization
  - Complex apparatus that can give many information in a single-shot non intercepting way (can be implemented in a second phase of the machine realization)
  - 1st phase: ToF only to measure polarization (modular, not all ToF are required)
  - 2nd phase: adding THz pulse to streak the ionization and have also measure of time of arrival and time length (this requires AI for having results in reasonable amount of time)
- TRL: 7 for polarization (es: PETRAIII), 3-4 for time
- Writing readiness: draft
- Technical readiness: draft, calculations still need to be done. Contact with DESY diagnostic group (leading group for the longitudinal measure) for possible collaboration



PETRAIII pol measure device



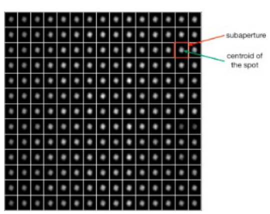
FLASH2 and EuXFEL device

PSI device

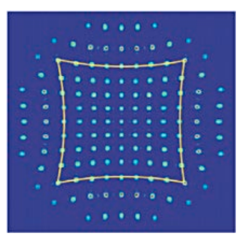
F. Villa

Wavefront Sensor

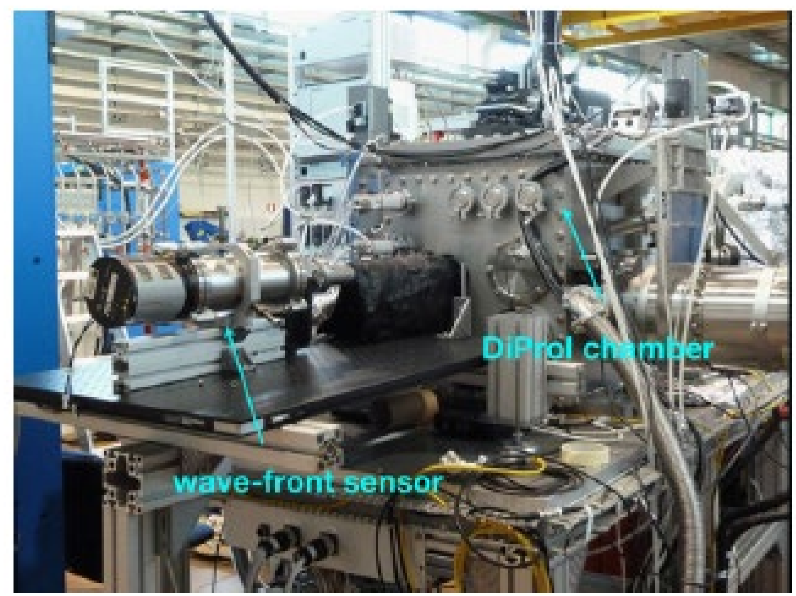
- Commercial system (e.g. ImageOptics)
  - Measure of front tilts due to mirror/gratins
  - Reconstruction of focal spot dimension of the K-B mirror system
- Technical readiness: draft, calculation to choose best item parameters needs to be done



plane wavefront



Wavefront with spherical aberration



Definition 80%
TRL: 9
Writing readiness: 10%

F. Villa

A. Cianchi

Coherence

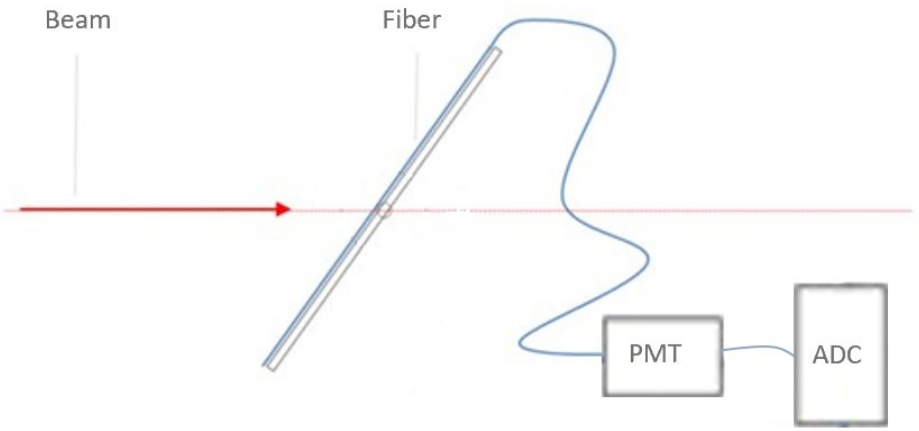
- Longitudinal coherence via a removable Michelson interferometer inside the experimental chamber
- Transverse coherence with double slit aperture using scintillating screens in the beamline
- TRL 7
- Writing readiness: draft
- Technical readiness: draft (collaboration with FERMI through Z. Ebrahimpour)

Definition 20%
TRL: 7
Writing readiness: 10%

Cherenkov BLM

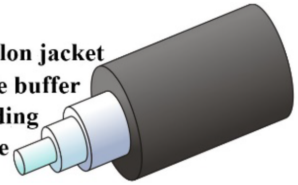
The Cherenkov effect can be utilized to construct a Beam Loss Monitor. The Cherenkov Beam Loss Monitor consists of an optical fiber positioned along the entire accelerator.

The Cherenkov photons produced by the electrons lost from the beam are collected and acquired using a photomultiplier tube (PMT) and digitized by an ADC. By calculating the time of flight of photons, it is possible to evaluate the position where a loss occurred in the beam



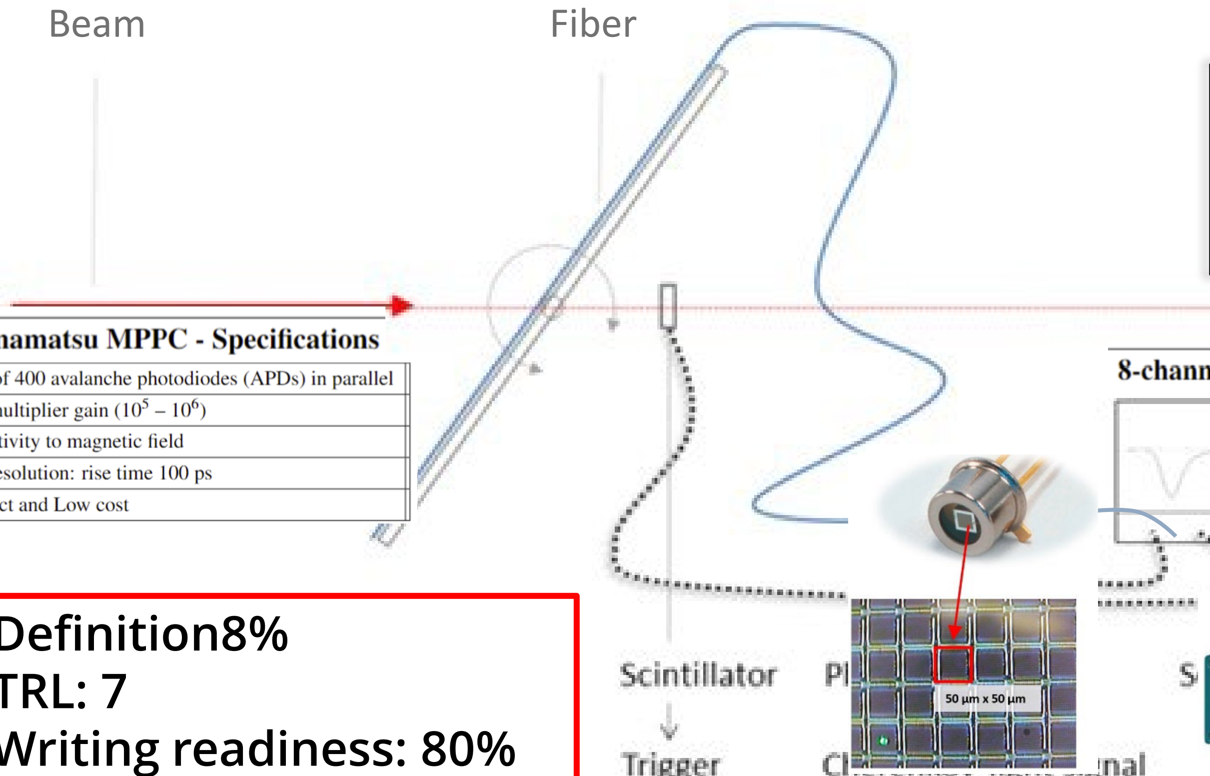
G. Latini

Cherenkov BLM (2)



high-OH silica Optical Fiber - Specifications

Parameter	Value
nylon jacket	850 μm
polyimide buffer	370 μm
fluorine silica cladding	330 μm
high-OH silica core	300 μm
core refractive index	1.479



Minimum Fiber Length

$$\Delta x = c\frac{\Delta t}{1+n} = 0.038m \sim 4cm$$

Hamamatsu MPPC - Specifications

Array of 400 avalanche photodiodes (APDs) in parallel
Photomultiplier gain ($10^5 - 10^6$)
Insensitivity to magnetic field
Time resolution: rise time 100 ps
Compact and Low cost

8-channels WaveCatcher - Specifications

Parameter	Value
sampling rate	3.2 GS/s
sample depth	12-bit
BW	0.5 GHz
memory	128 B
cost/channel	€ 400

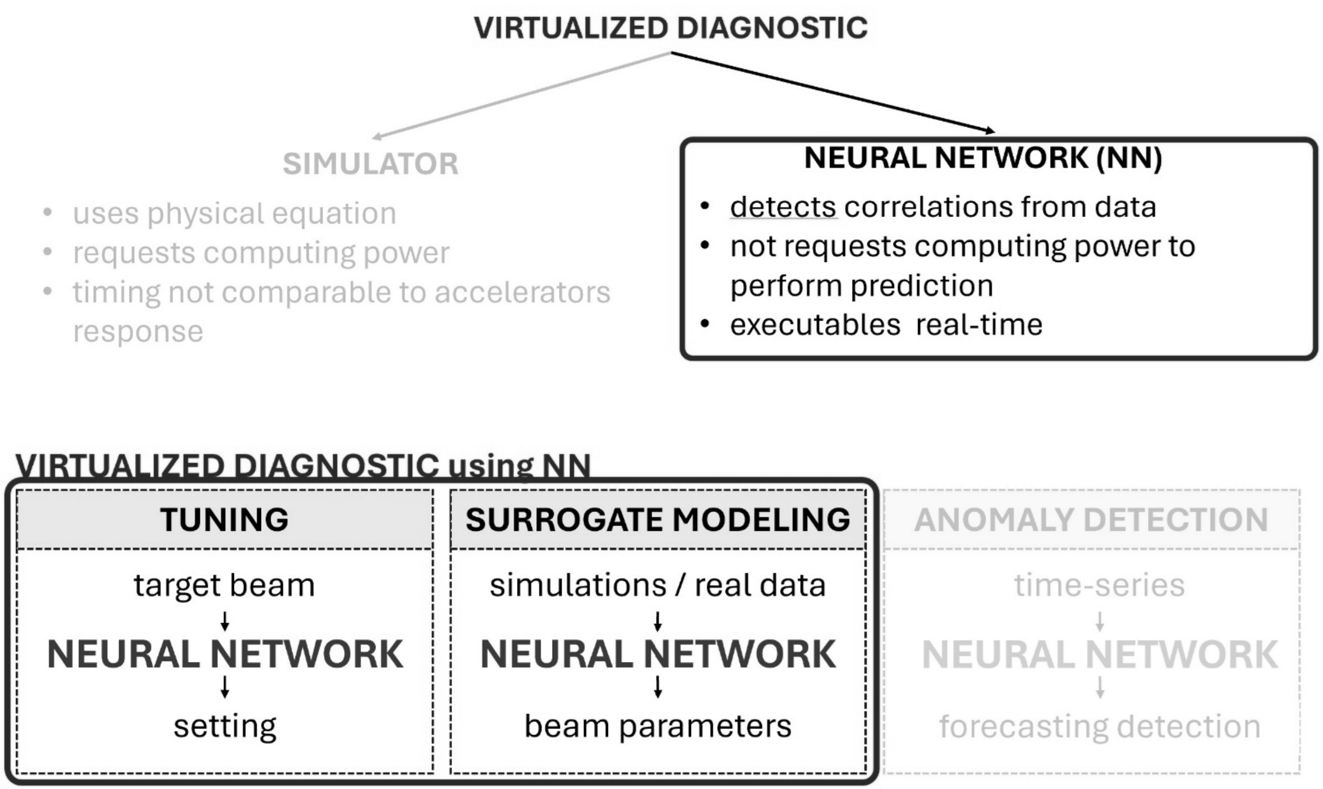
$\Delta t = 0.3125$ ns/S

Definition8%
TRL: 7
Writing readiness: 80%

G. Latini

Artificial Intelligence

Artificial Intelligence is an instrument to perform virtualized diagnostic tools capable of providing predictions on a specific assessment or classify data for defined problems. In this sense, any measurement can be quickly and easily performed without having to be executed on real diagnostic systems.

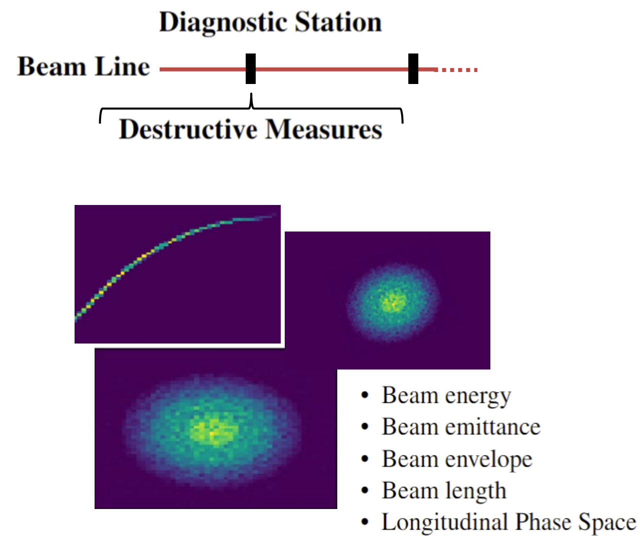


S. Pioli

Artificial Intelligence (2)

Case of study:

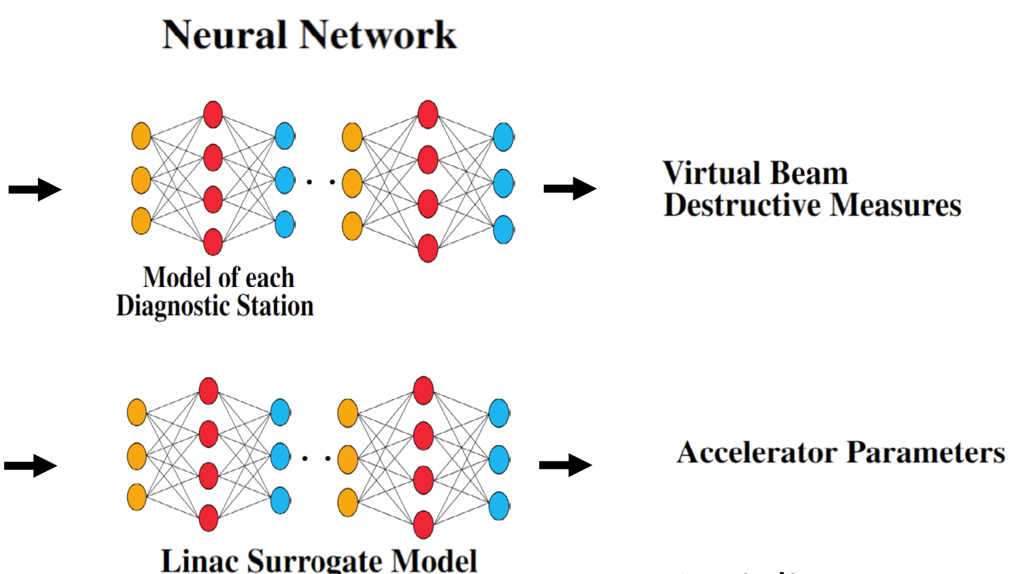
Virtualize beam measures from destructive beam diagnostics allow to improve accelerator performance and beam quality. It is also possible reverse the procedure to set the optimal beam parameters obtaining a linac surrogate model.



Accelerator Parameters

- Photo Cathode Laser pulse length
- Photo Cathode Laser spot size
- RF Gun phase
- RF Gun solenoid setpoint
- Beam charge
- RF structures phases
- RF structures accelerating field
- Solenoids setpoint
- Quadrupols setpoint
- Dipoles setpoint
- Steerers setpoint
- RF Deflector phase
- RF Deflector accelerating field

Destructive Measures



Definition 80%
TRL: 7
Writing readiness: 80%

S. Pioli

Photon diagnostics situation

Layout integration	80%	10%	N/A
Gas Monitor Detectors	80%	80%	7
Scintillating screens	80%	10%	8
Plate Beam Position Monitors	80%	70%	8
Grating spectrometer	80%	10%	8
Arrival time monitor	33%	10%	4
Full temporal and polarization characterization	20%	10%	7
Wavefront Sensor	80%	10%	9
Coherence	20%	10%	7
BLM	80%	80%	7
AI	80%	80%	7

Open problems in Photon diagnostics

- Manpower
  - technical is severe and scientific is moderate
- Risk mitigation:
  - stronger collaboration with Fermi (Principi, Ebraihmpour) for scientific collaboration and sharing of technical drawings of similar elements
- Time measurements
  - no consolidated technology for vuv- xray pulses at few fs
- Risk Mitigation
  - International workshop in Frascati (postponed in November)

Conclusions

- The Photons and Electrons diagnostics is mainly defined with reliable and tested instrumentation.
- Major problems:
  - Related to space occupancy
  - Related to manpower
  - Related to complete the design of some instrumentation
- Risk mitigation:
  - Adopt different approach
  - Increase the external collaboration