On-line spectrometer for FEL radiation at FERMI@ELETTRA

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Fermi@ELETTRA features / Introduction 1/2

Fermi@ELETTRA:
• Single pass-seeded FEL user facility providing photons in the spectral interval spanning from EUV to XUV
• its radiation is based on Harmonic Generation

Highlights:
•Peak brightness (photons/s/mm^2/mrad^2/0.1%BW) more than 10 orders off magnitude greater than 3rd generation sources
  • Non linear multiphoton processes
•Transform limited bandwidth
•Full transverse coherence
  • Single-Shot imaging
•Pulse length of the order of ps or less
  • Nuclear and electronic ultra-short dynamics
•Variable polarization (linear-horizontally to circular to linear-vertically)
•Energy tuneability (changing the gap of the ondulator)

Ref: FERMI@elettra: A Seeded FEL Facility for EUV and Soft X-Rays
C. J. Bocchetta et al., Proc. FEL conf. 2006

Fermi@ELETTRA features / Introduction 2/2

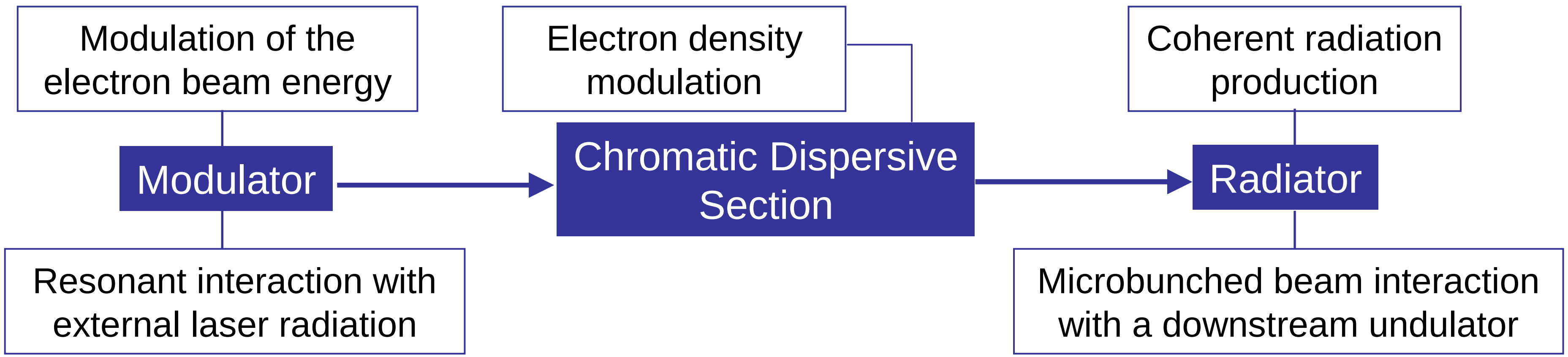
In order to full-fill the users' requests two FEL layouts are foreseen:

- FEL-1
  - Time domain experiments (pump-probe, non linear interactions)
    - Total number of photons per pulse
    - Pulse duration
- FEL-2
  - Frequency domain experiments
    - Longitudinal coherence
    - Narrow bandwidth

Approach:

Harmonic up-shifting of a "seed" radiation in a single-pass FEL amplifier employing multiple undulators

Implementation:



Fermi@ELETTRA features / Source characteristics

FEL-1

Photon range	100-40 nm (12-31 eV)
Output pulse length	<= 100 fs
Bandwidth	≈ 20 meV
Peak power	1-5 GW
Energy per pulse	0.2 mJ @ 31 eV 0.4 mJ @ 12 eV
Waist location	-7 m @ 40 nm -4.5 m @ 100 nm
Output transverse stability	50 mm rms
Pointing stability	<5 mrad rms
Waist size	300 mm rms
Divergence	50 mrad rms @ 40 nm
Repetition rate	10-50 Hz

FEL-2

Photon range	40-10 nm (31-124 eV)
Output pulse length	400 fs
Bandwidth	≈2.2 × transform-limited
Peak power	1 GW @ 10 nm
Energy per pulse	0.4 mJ @ 10 nm
Waist location	*Not available*
Output transverse stability	50 mm rms
Pointing stability	<5 mrad rms
Waist size	210 mm rms
Divergence	15 mrad rms @ 10 nm
Repetition rate	50 Hz

Necessity of an on-line spectrometer

- In FEL-1 time domain experiments, shot-to-shot repeatability is crucial.
  - In non-linear experiments shot-to-shot RMS jitter, in normalized photon number, should be 5% or less.

    With the foresee injector and accelerator parameters this goal (probably) cannot be obtained.

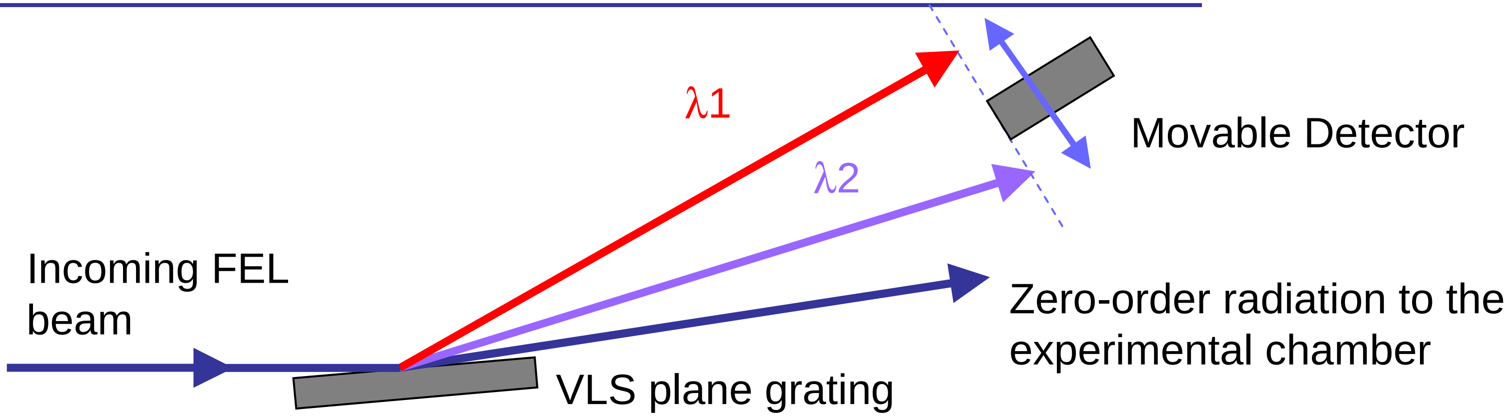
- In FEL-2 frequency domain experiments, shot-to-shot central wavelength jitter is a critical parameter.

In order to full-fill the users' requests, the monitoring of each FEL pulse is fundamental.

⬇

We present the design of a single-shot online EUV and soft X-ray spectrometer for the FERMI@ELETTRA FEL-1 / FEL-2 facility.

The instrument / Optical layout / Principle's scheme 1/2

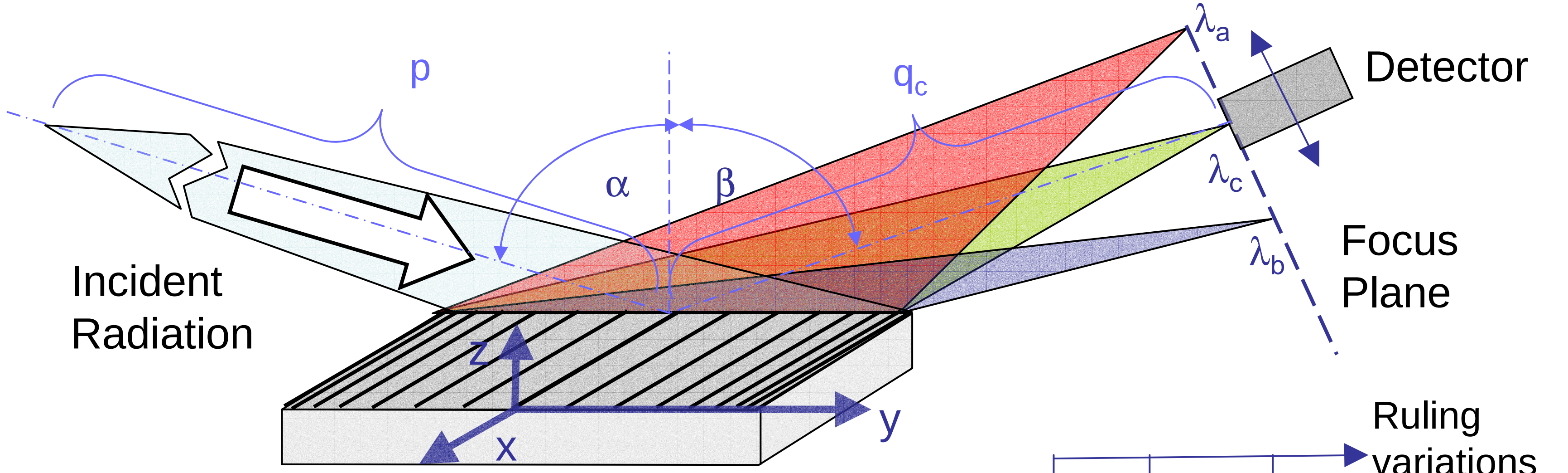


- A fraction of the incoming beam radiation is redirected on the first diffraction order of a grazing incidence flat field variable line spaced (VLS) grating.

- The length of the spectral curve is normally larger than the detector size, the latter is mounted on a linear stage and moved in the desired position to acquire the spectral interval of interest.
- The radiation diffracted at the zero-order propagates unperturbed to the experimental chamber.
- The beam deviation is constant.

The instrument / Optical layout / Principle's scheme 2/2

The polynomial law of variation of the groove density (σ) along the grating surface is selected in order to give the focusing of the spectrally dispersed radiation on an almost flat surface, where a plane detector can acquire the spectrum.



$$\sigma(y) = \sigma_0 + \sigma_1 y + \sigma_2 y^2 + \sigma_3 y^3$$

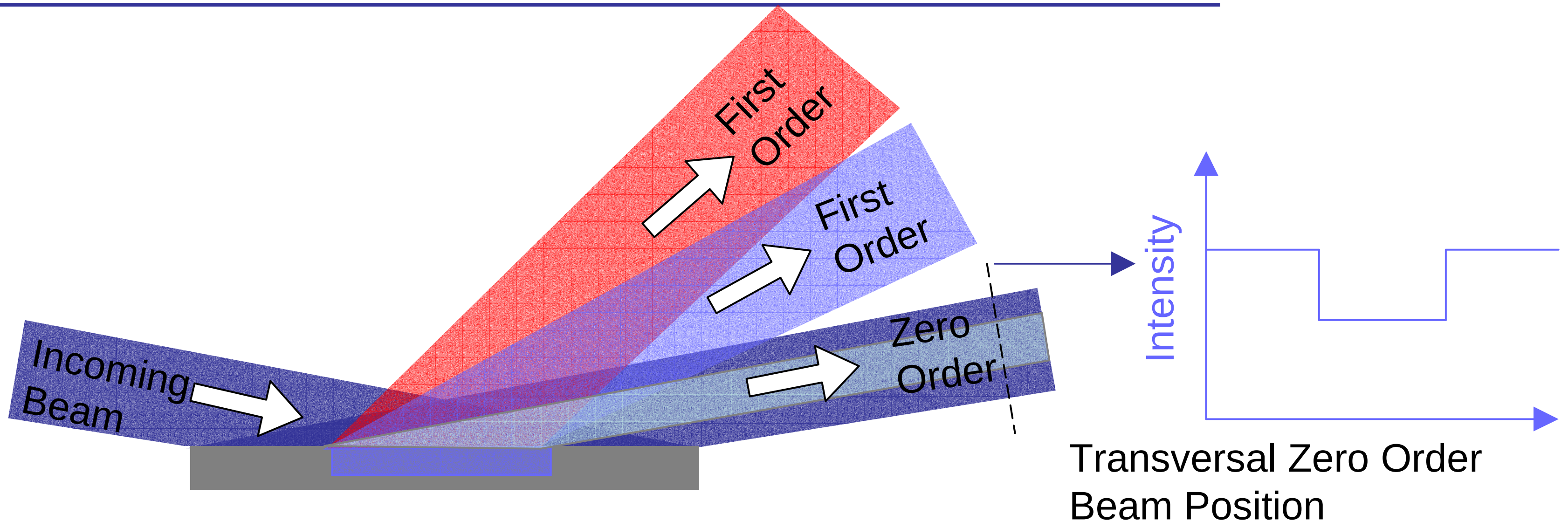
Grating equation: $\sin\alpha - \sin\beta = m\lambda\sigma_0$

$$\left.\begin{matrix}\sigma_0 \\ \alpha \\ p \\ q_c\end{matrix}\right\} \sigma_1 \longrightarrow q(\lambda)|_{\sigma 1}$$

focal curve
(spectral defocusing is zero)

σ_2 and σ_3 are selected to minimize coma and spherical aberrations at the wavelength λ_c

The instrument / Optical layout / Working scheme



To assure maximum photon flux to the experimental chamber and minimum wave front aberration, only the central part of the optic is ruled: the remaining part is finished as a mirror.

Advantages:

- The reflection coefficient of the beam which propagates unperturbed is maximized (the reflectivity of a mirror is slightly higher than the efficiency of a grating at the 0^{th} order);
- The optical performance of the spectrometer (e.g. aberrations, depth of focus) are improved;
- The manufacturing cost of the VLS grating is reduced.

The instrument / FEL-1 / Incidence angle

The main parameters driving the choice of the incidence angle are:

• Energy density on the optics (Maintain the energy density under the damage threshold of the coating)

Any incidence angle higher than 86° gives energy densities below 0.1 mJ/cm^2.

• Requirements on reflectivity

Incidence angles higher than 88° have to be selected to obtain reflectivity higher than 90% in the 10-100 nm region (gold and carbon coating).

• Maximum size of the optics

Giving a maximum length of the optics (given by the provider), the incidence angle has to be selected to keep the losses as low as possible.

Percentage of photon flux collected by the optical element. The coated area is 300 mm × 22 mm. The ruled area is 30 mm × 22 mm. The incidence angle 88°.

Wavelength (nm)	Flux collected by the total area (%)	Flux collected by the ruled area (% of the total)
40	100	28
60	99	20
80	94	15
100	86	12

The instrument / FEL-1 / Spectrometer design

The optical element is assumed to be 28 m far from the source at an incidence angle of 88°: the correspondent deviation angle of the FEL beam is 4°. The whole spectral region of operation is the 13-100 nm interval, which includes the FEL-1 main spectral region down to the 2nd and 3rd harmonics. The spectral interval is covered by two gratings:

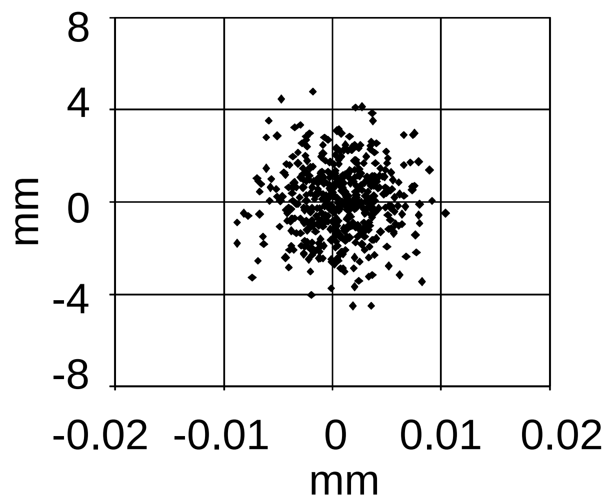
- G600 - 600 g/mm - 40-100 nm
  - Size of reflecting area 300 mm × 22 mm
  - Size of ruled area 30 mm × 22 mm
  - Incidence angle 88°
  - Entrance arm 28 m
  - Exit arm @ 40 nm 2 m

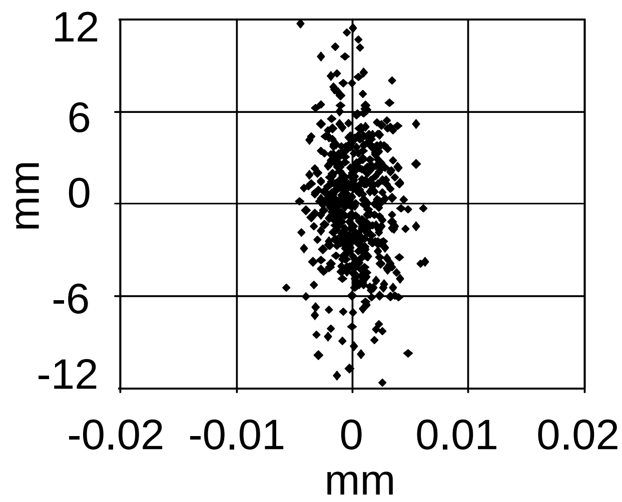
- G1800 - 1800 g/mm - 13-40 nm
  - Size of reflecting area 200 mm × 10 mm
  - Size of ruled area 15 mm × 10 mm
  - Incidence angle 88°
  - Entrance arm 28 m
  - Exit arm @ 13 nm 2 m

The instrument / FEL-1 / FP Aberrations

Grating aberrations on the focal curve. The aberrations are defined as the spot size in the spectral direction with 80% of the rays. The aberrations are lower than 10 μm.

Wavelength (nm)	Aberrations No slope error (μm)	Aberrations 2 μrad rms slope error (μm)
40	9	12
60	7	10
80	6	10
100	6	9

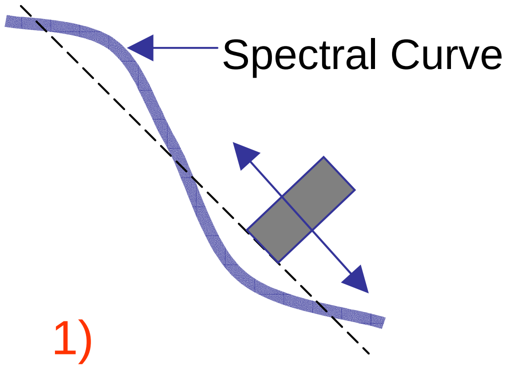




Slope errors on the plane optical element have to be less than 2 μrad rms, preferably in the range 0.5-1 μrad rms: values routinely obtainable for plane optical elements.

The instrument / FEL-1 / Detector 1/2

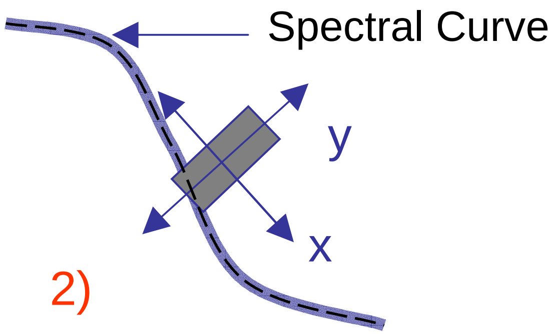
Fixed the FEL wavelength → the spatial width of the FEL spectrum is definitely lower than 1 mm → a relatively small detector is then required.
The total length of the spectral focal curve (40-100 nm region) is about 250 mm → the detector has to be moved along the curve and centered on the spectral region to be acquired.



1)

Detector mounted on a single motorized linear stage and connected to the spectrometer by a bellow:

- simplest mechanical solution ☺;
- a single straight line can not fit the focal curve with the necessary accuracy in the whole spectral region of interest ☹.

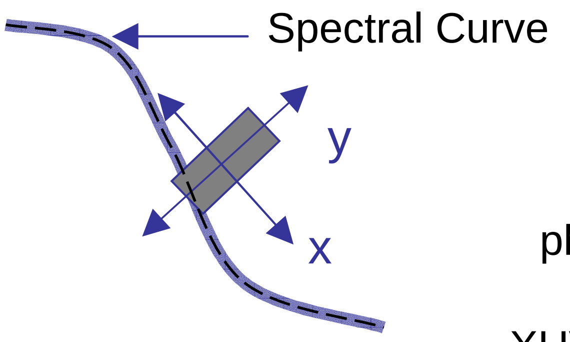


2)

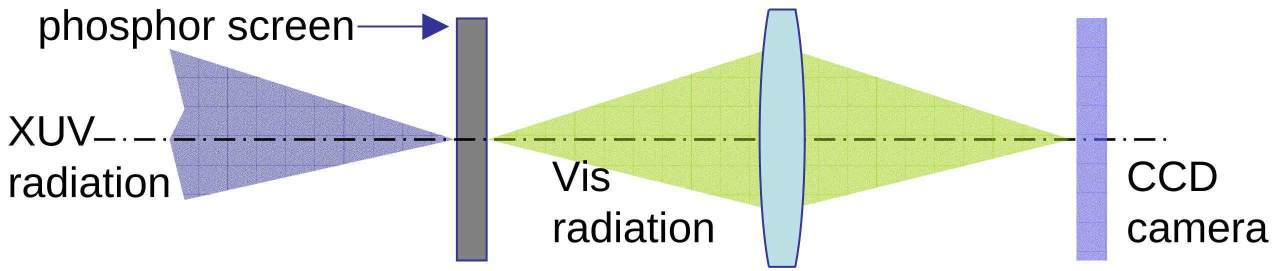
Detector mounted on two orthogonal motorized linear stages:

- more expensive and complex ☹;
- offers the maximum flexibility for fitting the focal curves of different gratings ☺.

The instrument / FEL-1 / Detector 2/2



x → fits the spectral curve and brings the desired wavelength on the detector center
y → change the grating-detector distance to the optimum value for the spectral focusing



As detector we propose a phosphor screen optically coupled to a CCD camera.

- More robust and safer than a UV-sensitive CCD or than a MCP intensifier with photocathode directly placed on the focal plane.
- The resolution is limited by the properties of the phosphor and not by the pixel size of the camera
- A pulse with very short time duration could easily saturate the response of a MCP → the phosphor decay time is considerably longer than the duration of the FEL pulse → the signal is spread in time, reducing the non-linearity problems.

As example, the TPB (tetraphenyl-butadiene) phosphor can be easily deposited on a glass plate, it has excellent spatial resolution (several micrometers) and high quantum efficiency.

The instrument / FEL-1 / Detector features

Supposing to have a spectral resolving element of 10 µm (at the phosphor level). The FEL-1 spectrum is sampled at FWHM by 14 to 55 pixels, so the line profile can be reconstructed with high accuracy. The ultimate resolution of the spectrometer is then almost limited by the pixel size.

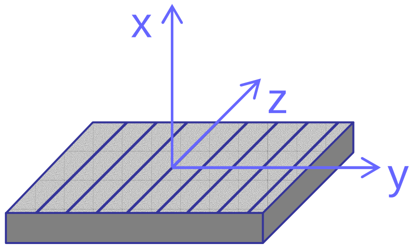
Phosphor screen	TPB, 25 mm diameter
CCD camera	1000 pixel $\times$ 1000 pixel
Pixel size (on the phosphor screen)	10 mm
Useful area (on the phosphor screen)	10 mm $\times$ 10 mm

The instrument / FEL-1 / Analysis of tolerances

Detector positioning: supposing an uncertainty of 0.1 mm, routinely achieved by common translators

- x → 0.018 nm at 40 nm and 0.029 nm at 100 nm.
- y → no appreciable effects on the optical performance (the depth of focus of the optical system is quite large)

Grating positioning: in order to have the spectral displacement below 0.1 mm, the aberrations below 20 μm and the spatial displacement below 1 mm



Translation x	0.05 mm
Translation y	0.2 mm
Rotation x	5 mrad
Rotation y	1 mrad
Rotation z	30 mrad

Grating groove spacing → increase of the aberrations to more than 10 μm.

Parameter	Nominal value	Tolerance
σ_1	-0.6087	± 0.0005
σ_2	0.00044	± 0.00004
σ_3	0	$\pm 3.0 \cdot 10^{-6}$

The instrument / FEL-1 / G1800

Mechanical constraints limit the use of the G600 grating to the range 40 - 100 nm. Shorter wavelengths are diffracted at angles too close to the 0-th order and the exit flange for the diffracted radiation can not be accommodated on the spectrometer vacuum tank without overlapping with the 0-th order beam.

If needed, a second grating (G1800) can be used for wavelengths from 40 nm down to 13 nm (3rd harmonic of 40 nm).
The detector is unchanged.
The grating tolerance are nearly the same

Central groove density	1800 g/mm
Parameters for groove space variation	$\sigma_1 = -1.828 \pm 0.0005\ mm^{-2}$ $\sigma_2 = 0.0013 \pm 0.0007\ mm^{-3}$ $\sigma_3 = 0 \pm 10^{-5}\ mm^{-4}$
Coating	Au or C
Incidence angle	88°

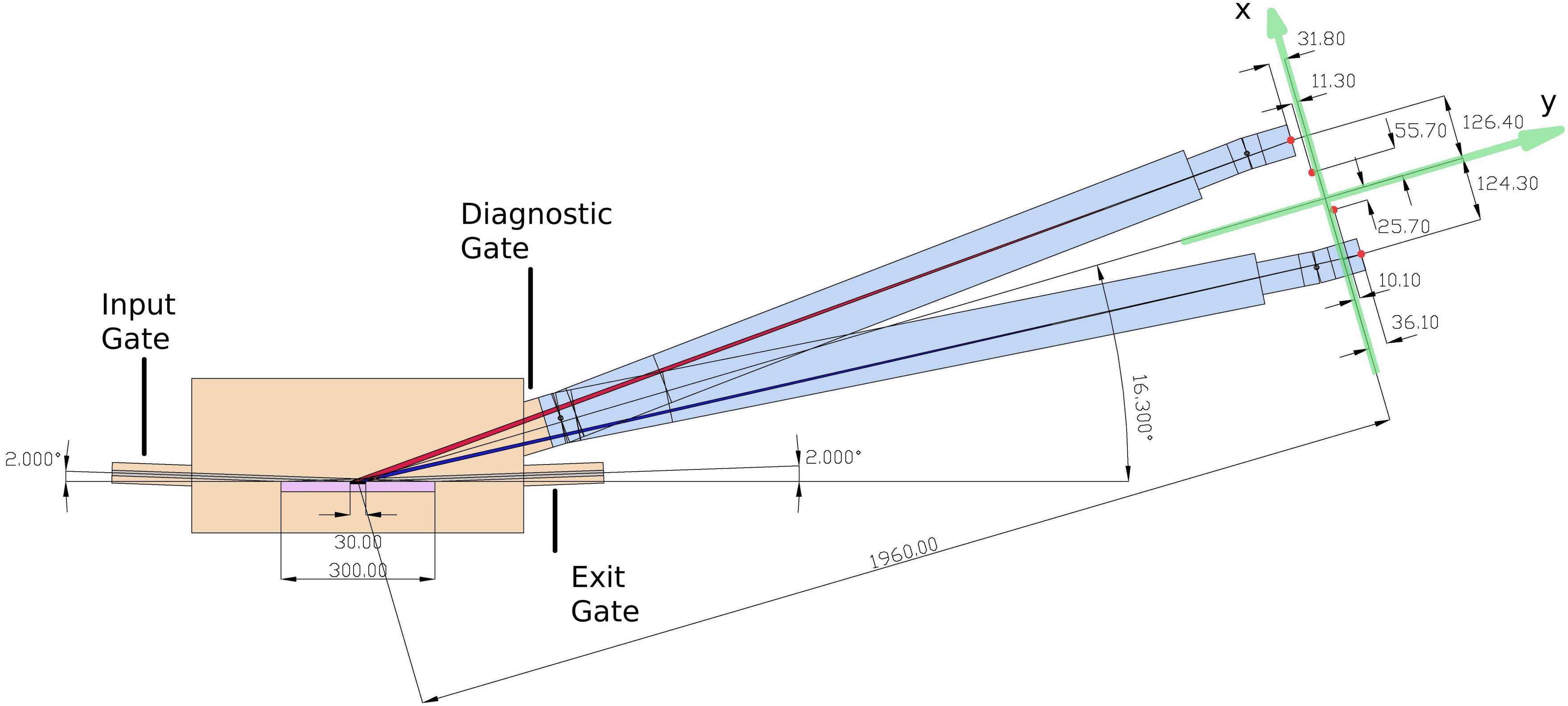
The instrument / FEL-1 / Mechanical assembly: Int.

The spectrometer has three interchangeable optical elements mounted on a turret: a mirror, if the user is not interested in acquiring the spectrum and needs the maximum throughput, and two gratings.

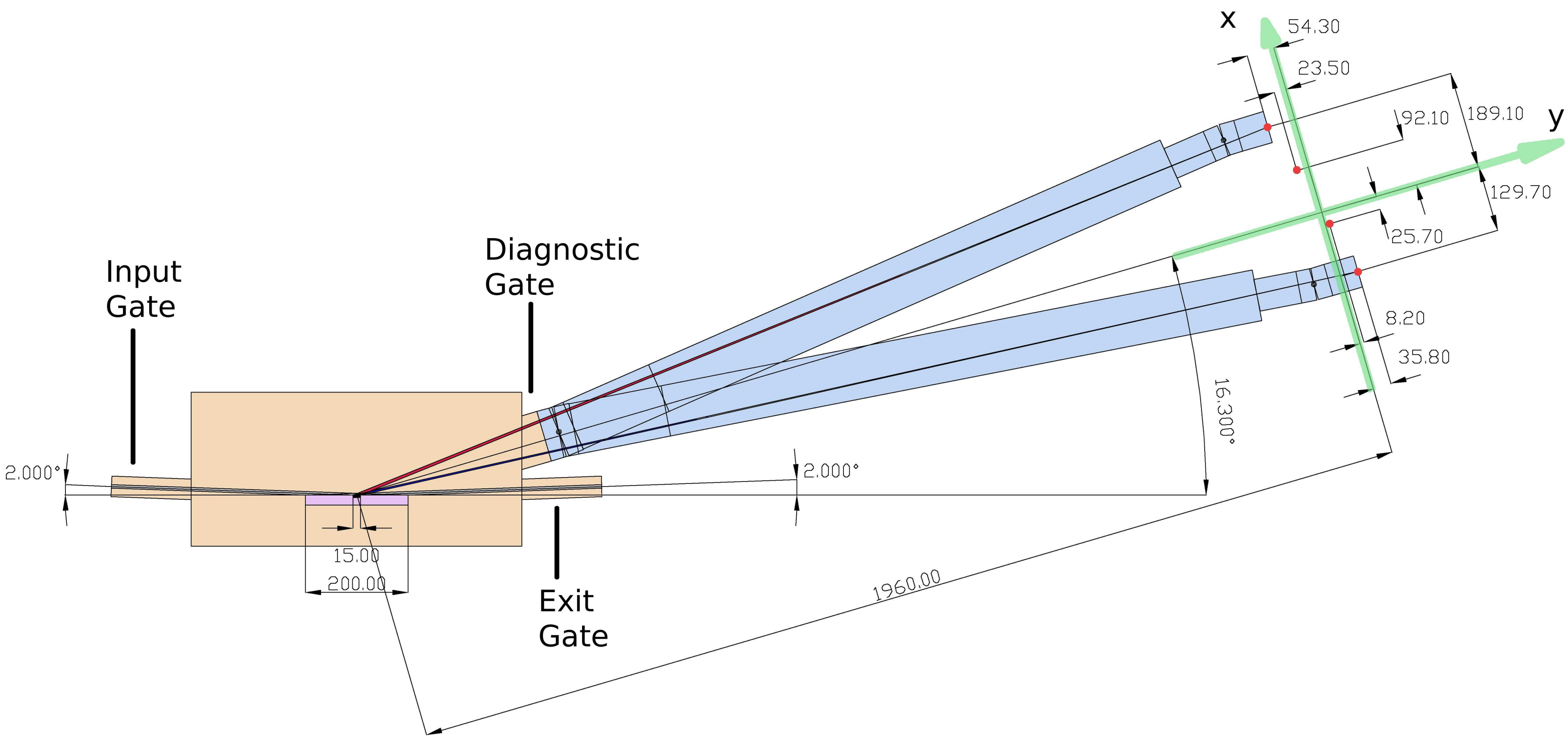
Note that the three optical elements (mirror + 2 gratings) can be ruled on the same plane substrate. This would simplify the mechanical mounting and the alignment procedure.

The spectrometer can be used also to measure the intensity of the FEL pulse: integrating the counts on the detector over the whole spectrum.

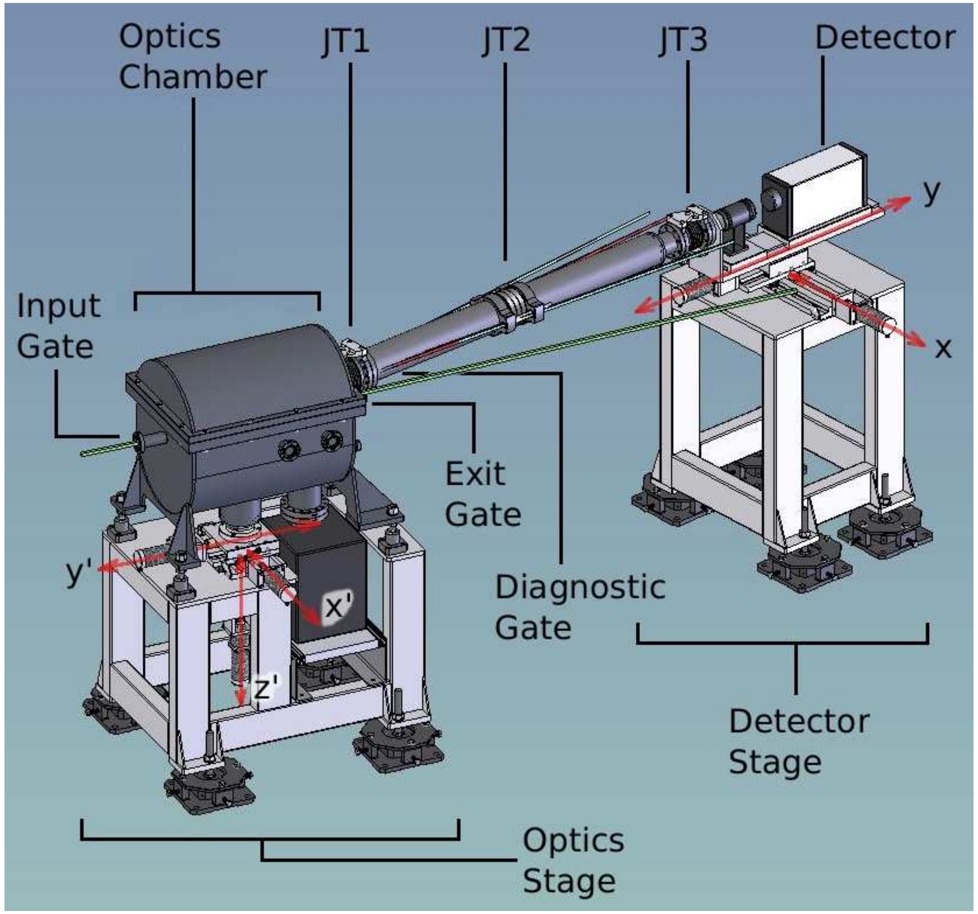
The instrument / FEL-1 / G600 Mechanical assembly

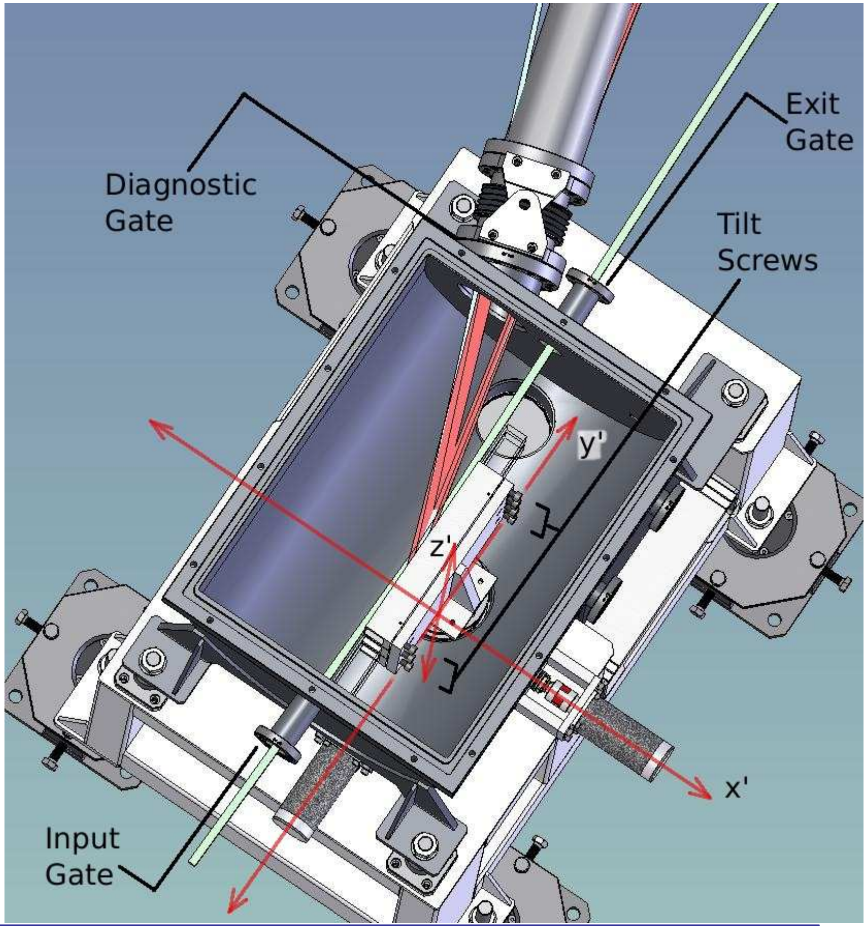


The instrument / FEL-1 / G1800 Mechanical assembly

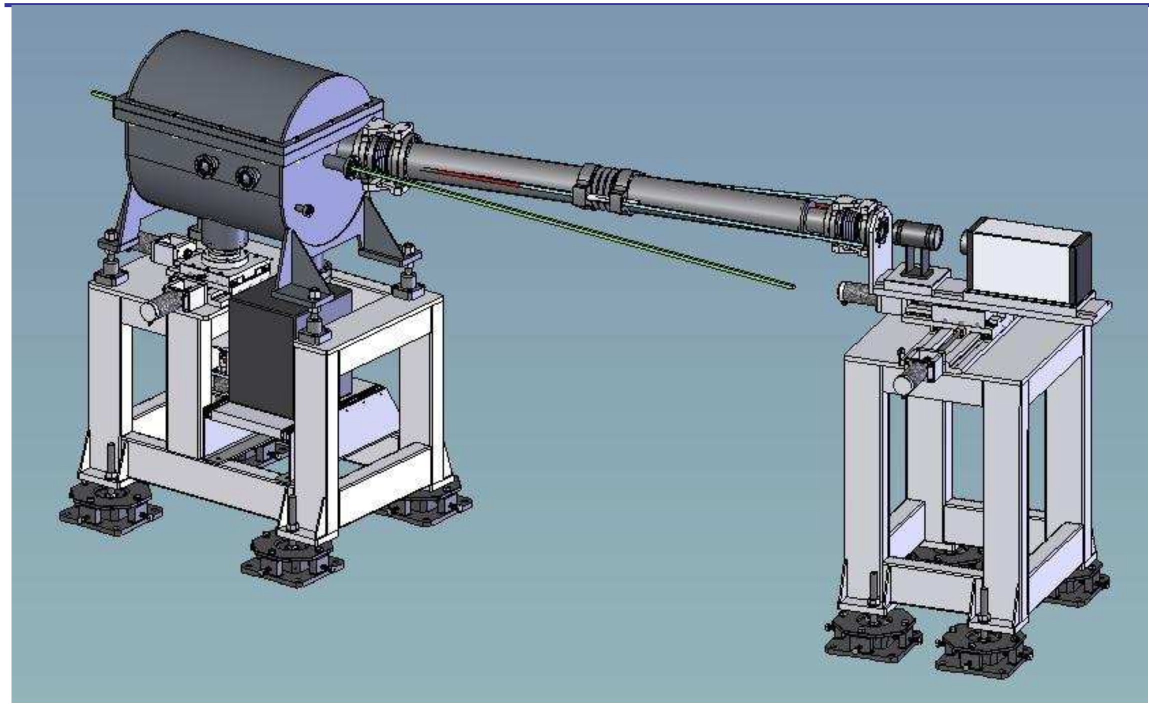


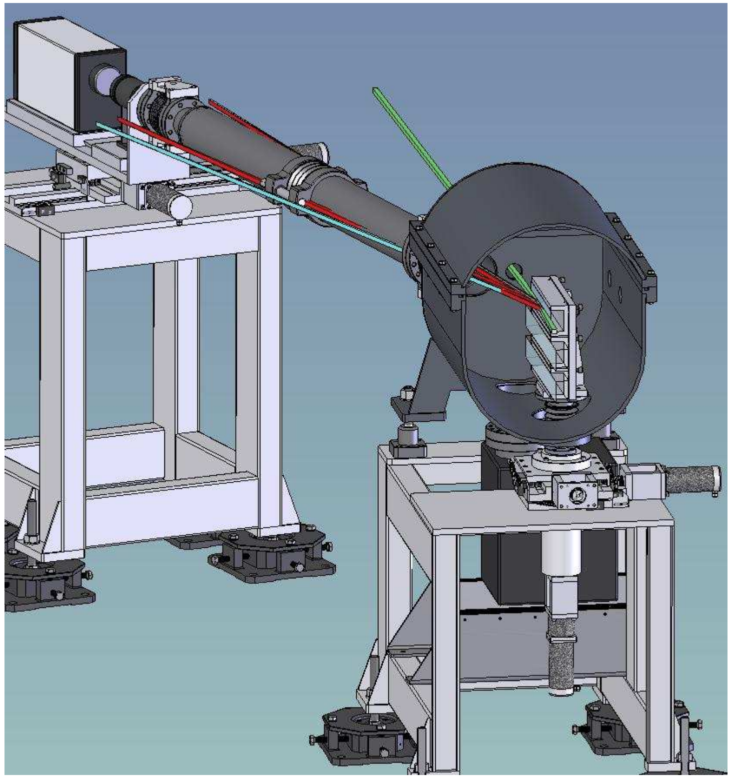
The instrument / FEL-1 / Mechanical assembly 1/2





The instrument / FEL-1 / Mechanical assembly 2/2



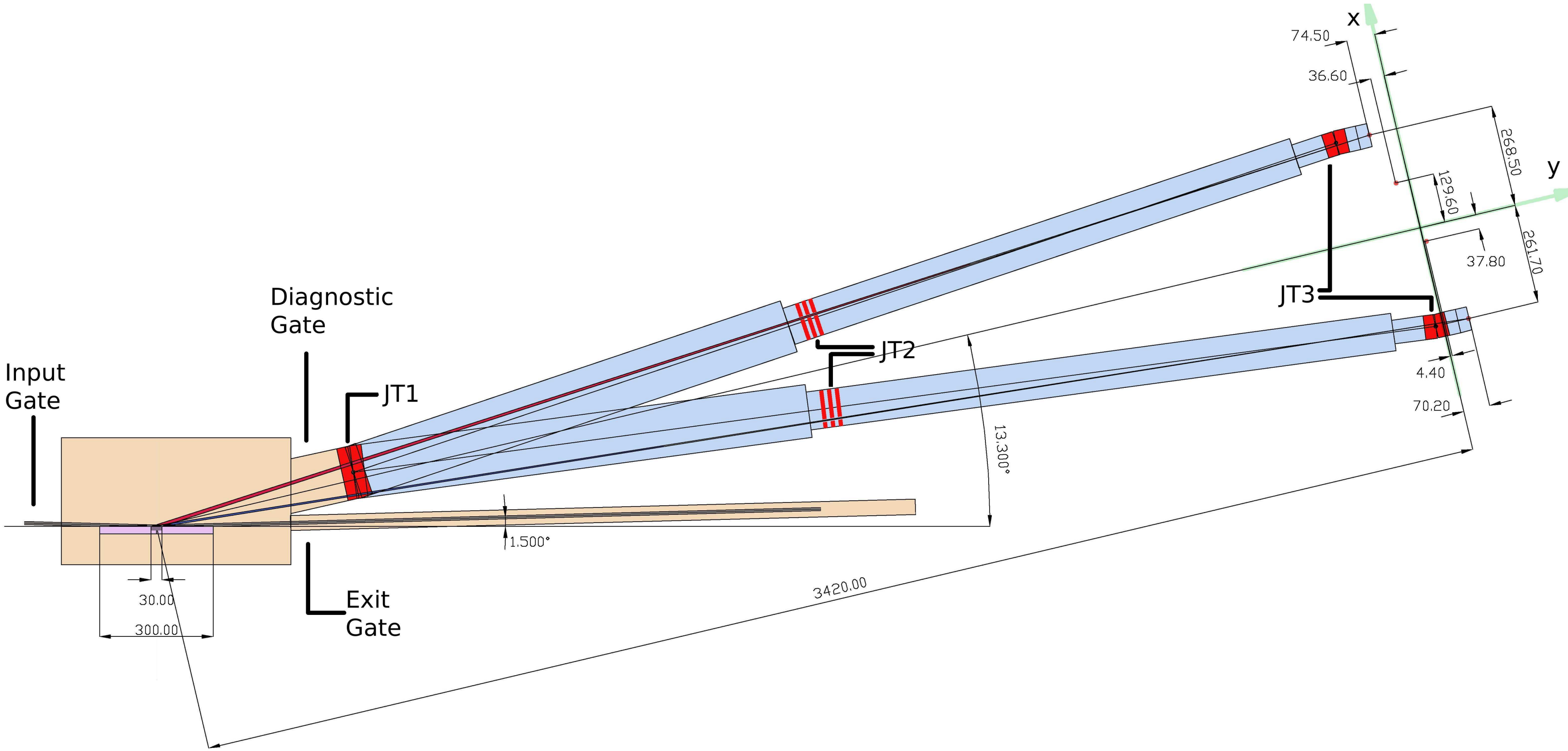


The instrument / FEL-2 / General characteristics

Following the same driving parameters of the FEL-1 spectrometer the following main optical parameters have been selected:

• Incident angle → 88.5° (energy density is lower than 1 mJ/cm^2 for any angle above 87.5°)
• Optical coating → Au (reflectivity higher than 90% at 88.5° in the whole 8-40 nm spectral region and decreasing to 70% for wavelengths in the 3.3-8 nm region)

The instrument / FEL-2 / Mechanical assembly



Conclusions

The acquisition of the FEL spectrum is essential both during the development and characterization of the source, and for the definition of the experimental conditions for the users, that have to know the spectrum at each FEL shot.

Since FERMI@ELETTRA is operated at low repetition rate (10-50 Hz), the spectrum has to be obtained in single-shot operation.

It has been presented the design and performances of a single-shot online EUV and soft X-ray spectrometer for the FERMI@ELETTRA FEL-1-2 facility.

END

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