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Deliverable:

Design report of optical transition/diffraction radiation combined measurement station including initial beam tests.

Executive summary:

The ATF2 demonstrates the possibility to generate a very low-emittance beam (pm) with small beam size (nm) for the next generation large-scale particle physics facilities such as the Compact Linear Collider (CLIC) or the International Linear Collider (ILC). This kind of beam needs sensitive instruments for high resolution measurements. This report presents the setup and the first results of the diffraction radiation (DR) and transition radiation (TR) emittance station recently installed and tested at ATF2 by CERN, RHUL and KEK teams as part of the E-JADE programme. This instrumental set-up is designed to allow non-invasive beam size measurements down to tens of microns via DR and high-resolution measurements for sub-micron beam size via TR.

This instrument have been successfully installed, commissioned and tested during the last ATF2 operation year. The set-up will be upgraded next year to optimize the sensitivity to a smaller beam size moving from the observation wavelength in the visible range to the far-UV (180-200nm).

These studies are also important in the context of the E-JADE Tasks 2.5 (Beam Instrumentation and control).

1. INTRODUCTION

To measure the very small beam, at nanometre scale, produced at ATF2, high-resolution instrumentation is fundamental. Next generation large-scale particle physics facilities such as the Compact Linear Collider (CLIC) or the International Linear Collider (ILC) will benefit from the development of this kind of instrumentation, in particular non-invasive techniques mandatory for the high-current beam in a collider.

The set-up installed at ATF2, developed by CERN and RHUL as part of WP2, consists of a transition/diffraction radiation combined measurement station:

- A high-resolution Optical Transition Radiation (OTR) monitor operating with wavelengths in the visible range that allows the measurement of sub-micron beam sizes.
- A Diffraction Radiation (DR) monitor operating, at present, with wavelengths in the visible range to perform non-interceptive measurements of tenths of micrometres transverse beam size. The optical line will be upgraded to observe the far-UV (180-200nm) to optimize the sensitivity to smaller beam size in the next ATF2 operational year.

2. OPTICAL TRANSITION RADIATON MONITOR

Transition radiation (TR) is generated when a charged particle crosses the interface between two media. Polarisation currents are formed on the surface resulting in the emission of photons (Potylitsyn, 1998). These photons are emitted along the path of the charged particle beam known as Forward Transition Radiation (FTR) and in the direction of spectral reflection known as Backward Transition Radiation (BTR). The two dimensional beam profile, tilt angle and position may be measured in a single shot using the BTR, primarily in the optical spectral range.

The use of OTR monitors in high intensity future accelerators is restricted to low current pilot beams because the high current beam can destroy the OTR target.

The spatial resolution of the OTR monitors decreases with increasing beam energy. The resolution of traditional OTR monitors is defined by the root-mean-square of the so-called Point Spread Function (PSF) (M. Castellano, 1998). In the optical spectral range, the PSF is defined as the OTR generated by a single electron and propagated through the optical system to the detector. Predominantly at these wavelengths the resolution is limited due to broadening caused by diffraction and aberration effects of the optical system (P. Karataev A. A., 2011), (K. Kruchinin, 2014). Recently, the resolution of conventional OTR monitors has been significantly improved. The OTR PSF differs from the conventional PSF of an optical system (P. Karataev A. A., 2011). The vertical polarisation component of the OTR PSF exhibits a two-lobe structure from which the visibility can be used to monitor the vertical beam size with sub-micrometre resolution. Furthermore, provided the beam is flat as is the case for linear colliders, the horizontal beam size may be directly obtained from the horizontal projection of the OTR distribution. This was demonstrated at ATF2 in 2014 (K. Kruchinin, 2014).

The new OTR system installed at ATF2, as can be seen in Fig. 1 scheme, consists of an in-vacuum lens, a polarizer, chromatic filters and a sCMOS camera. The in-vacuum lens has been chosen to be as close as possible to the target to minimize spherical aberration of the system that were limiting the minimum measurable beam size in the previous experiment performed at ATF2.

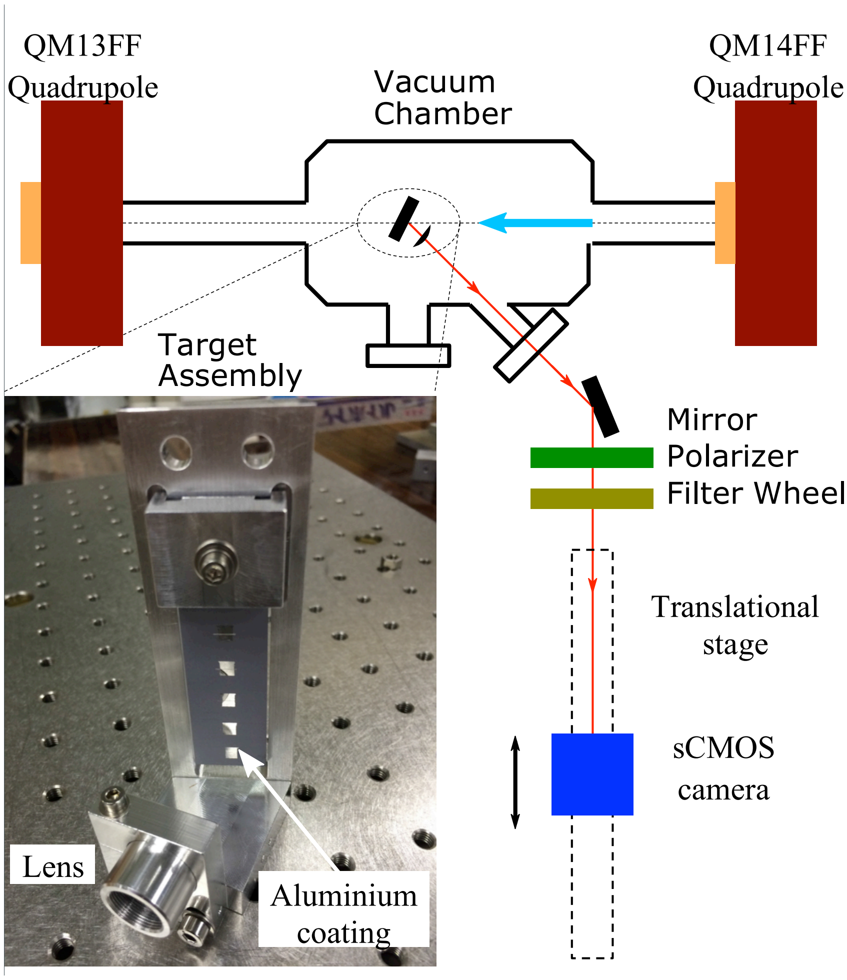


Fig. 1: OTR optical line scheme with target picture

The vertical beam size measurements with this new set-up were performed varying the strength of a quadrupole to move the beam waist longitudinally across the target, to be able to observe different beam sizes on the target. Fig. 2 shows the 2D plot of the two-lobe PSF for different strengths of the quadrupole QM14FF in the beam line just before the OTR monitor. Considering the vertical projection of the 2D OTR images (Fig. 3), the ratio between the two peak maxima and the minimum in between the two peaks is related to the vertical beam size.

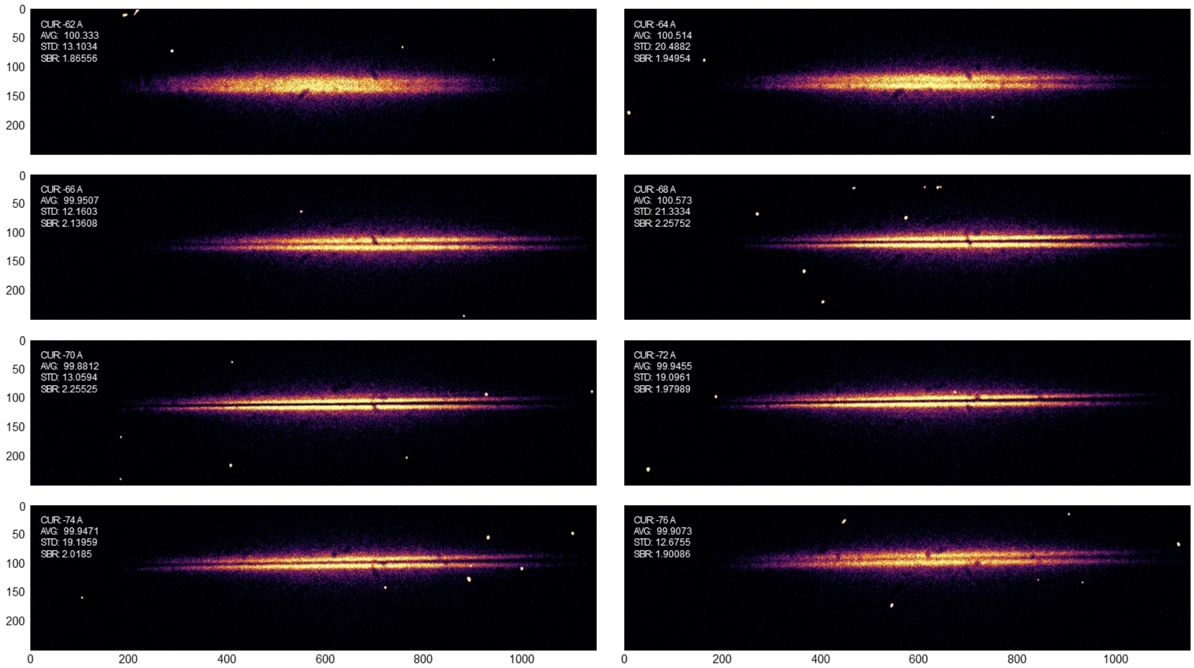


Fig. 2: Images of the vertical polarization of the OTR signal at different strengths of the QM14FF quadrupole

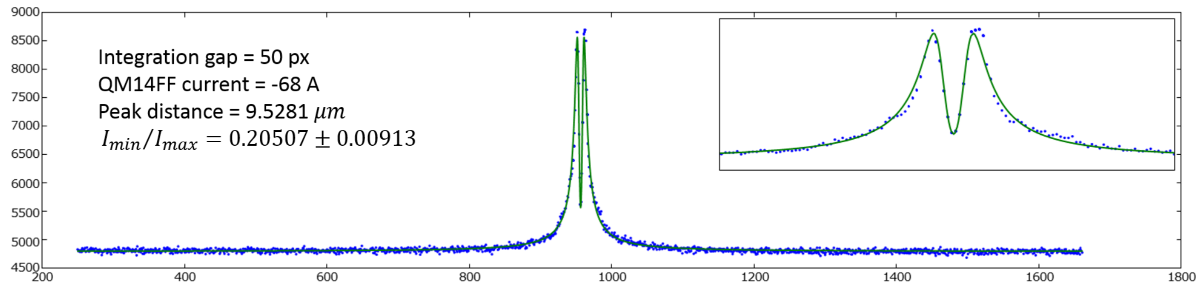


Fig. 3: Example of OTR vertical projection. Data point (blue) obtained by integrating 50 pixel around the center of mass of the image. The parameters of the distribution are obtained from the fit.

The results of the vertical beam size measurement and the vertical emittance obtained during the ATF2 last year operation are shown in the Fig. 4. The vertical emittance is calculated from the squared vertical beam size and the quadrupole strength using a thin-lens approximation. It can be noticed that the minimum beam size measured is around 600nm. More detailed studies with a new grated target will be performed in the next ATF2 operational year.

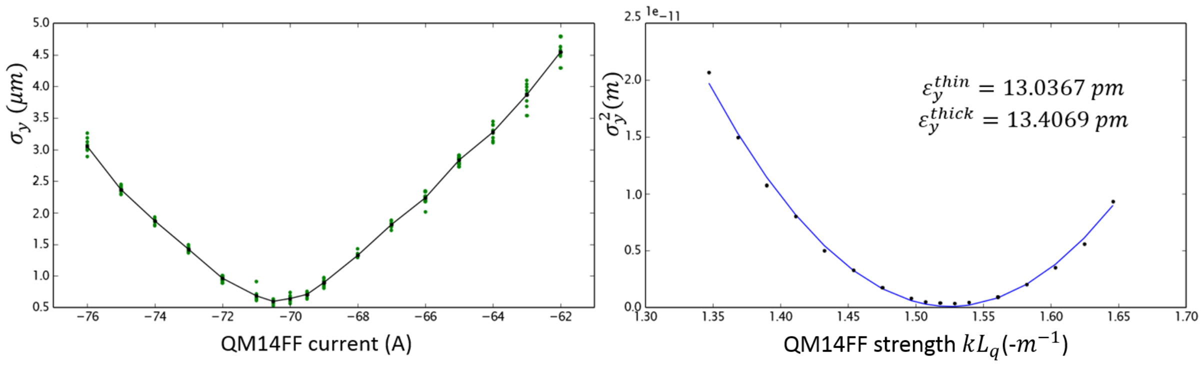


Fig. 4: Results of the beam size measurements as function of the quadrupole current (left), squared beam size as function of the quadrupole strength and fitted emittance (right).

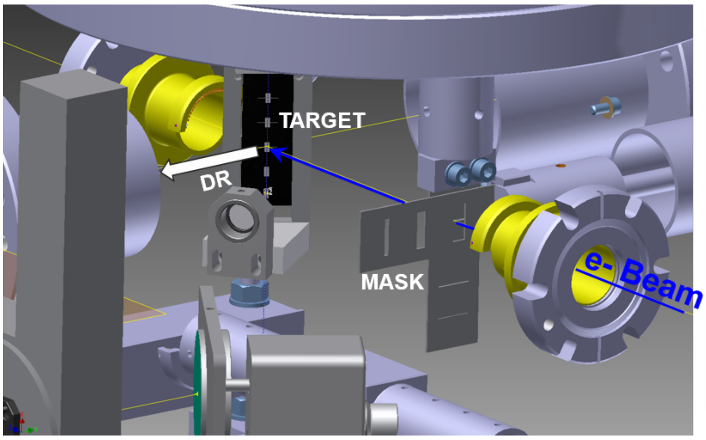
3. DIFFRACTION RADIATION MONITOR

Diffraction radiation (DR) is the instantaneous emission of photons when a relativistic charged particle moves in the vicinity of a medium. The electric field of the charged particle polarizes the target atoms which then oscillate, emitting radiation with a very broad spectrum known as DR. Much like TR, DR is also emitted in two directions from the target: in the direction of the moving charge known as Forward Diffraction Radiation (FDR) and in the direction of specular reflection known as Backward Diffraction Radiation (BDR). BDR is measured for non-invasive beam diagnostics since it is emitted away from the charged particle given a suitable target tilt angle. The spatial-spectral properties of DR are sensitive to a range of electron beam parameters. Furthermore, the energy loss due to DR is so small that the electron beam parameters are unchanged (i.e. remain nearly same as the initial parameters). Therefore DR can be used to develop non-invasive diagnostic tools.

In the range of optical wavelengths the use of diffraction radiation (ODR) as a high-resolution non-invasive diagnostic tool for transverse beam size measurement has been widely investigated, for example at the ATF2 at KEK (P. Karataev S. A., 2004). The visibility of the ODR pattern was measured at ATF, compared with the simulated data and the beam size was determined. The resolution of this system was limited by the diffraction limit, system configuration (e.g. precision of the slit geometry and alignment) and non-optimal measurement system, as well as by the residual contribution from Synchrotron Radiation (SR) (P. Karataev S. A., 2004). To go beyond these limitations a new measurement station with a mask that can block the SR was installed this winter at ATF2. This system has been designed to let the possibility, with a small upgrade, to operate in UV spectral range (down to 180-200nm) to achieve better sensitivity for small beam sizes (10 micrometre).

The new system is shown in the Fig. 5: a set of slits with different widths is present on the silicon target. Each slit is surrounded by a rectangular aluminium coating to improve the reflectivity, and thereby the intensity of the diffraction light emitted during the interaction with the beam. In the schematic picture the already mentioned mask can be seen upstream of the target. The mask consists of two different parts: the first is made of silicon, with horizontally oriented slits of different sizes able to move vertically close to the target, and the second is made of aluminium with vertically oriented slits able to move horizontally.

The optics consists of two optical lines able to observe the same DR light source thanks to an optical beam-splitter. One of the two lines observes the DR angular distribution through an intensified CCD camera set in the back focal plane of the lens. Optical chromatic filters are also installed to probe different wavelengths. The second optical line consists of an imaging system with an achromatic lens and a sCMOS camera on a linear stage that allows to find the focusing position for the detector.



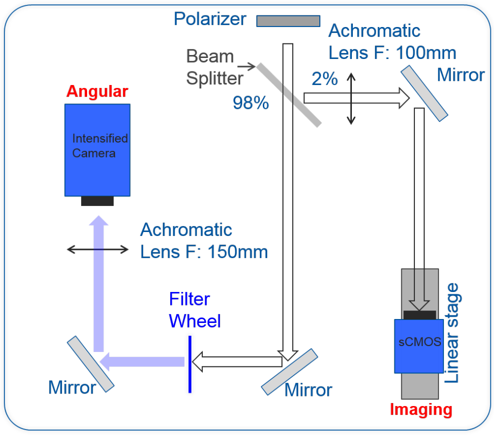


Fig. 5: Diffraction Radiation monitor instrument details: in vacuum set-up (left) and optical line (right).

In Fig. 6 and 7, the very first results of the DR monitor obtained are shown. In Fig. 6 it is possible to see 2D images of the DR angular pattern for different beam sizes and the corresponding vertical projections that contain the information on the beam size.

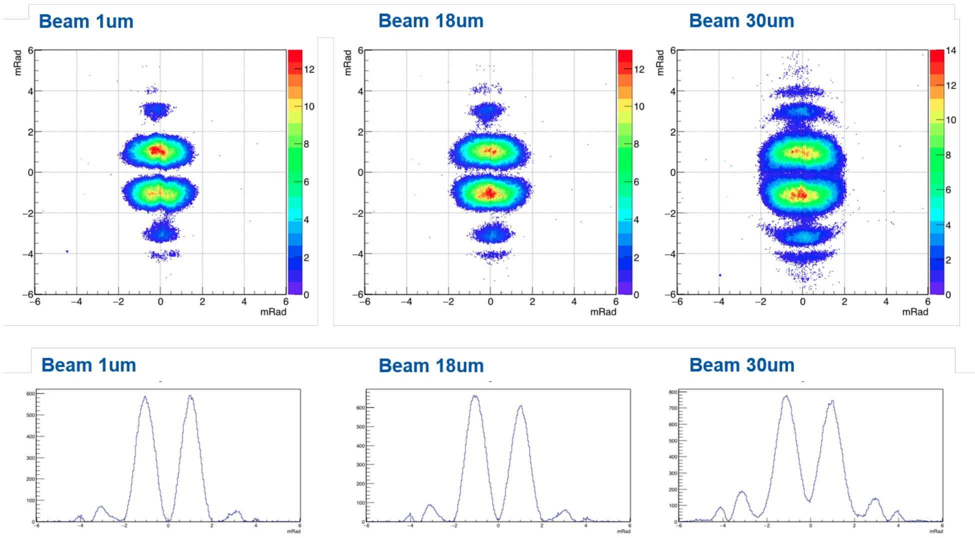


Fig. 6: First Diffraction Radiation images for different beam sizes.

As expected the sensitivity decreases for small beam sizes (from 1 to 10 micrometre), as can be seen in Fig. 7. More detailed studies are foreseen for the next year of operation, to collect more data to explore all the capabilities of the instrument.

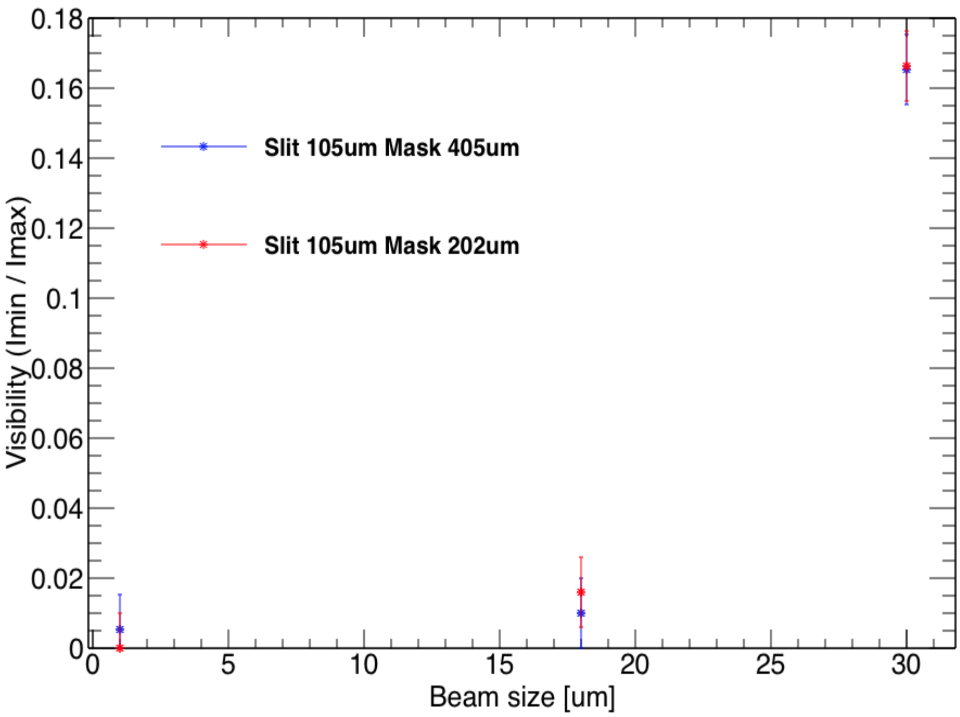


Fig. 7: First results for the Beam size sensitivity of the DR monitor:
Min/Max ratio of the vertical projection of the angular patter for different beam sizes.

4. FUTURE PROSPECTS

Further studies are required to evaluate and optimise the performance of the OTR system, in particular to understand the real limitations to the smallest measurable beam sizes. The installation of a new grated target is foreseen the next beam operation. Furthermore, as one of the limitations of the instrument is the poor signal to noise ratio a new intensified camera was installed and is ready for the next beam operation.

The sensitivity of the DR monitor to a 20 to 30 micrometres beam has been demonstrated. More detailed studies to improve the performance of the system are foreseen for the next operational year. Furthermore an improved version of the optical line has been prepared for installation in Spring 2017. This upgrade will allow observation of the DR in the far-UV wavelengths, down to 180-200nm, to optimize the sensitivity to beam sizes around 10 micrometre.

5. REFERENCES

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ANNEX: GLOSSARY

Acronym	Definition
OTR	Optical Transition Radiation
DR	Diffraction Radiation