NON-DESTRUCTIVE VERTICAL HALO MONITOR ON THE ESRF'S 6GeV ELECTRON BEAM

B.K. Scheidt, ESRF, Grenoble, France

Abstract

The population density along the electron's beam vertical profile at far distance from the central core (i.e. the far-away tails or "Halo") is now quantitatively measurable by the use of bending magnet X-rays. An available beam-port is equipped with two specific adapted absorbers, an Aluminium UHV window, an X-ray light blocker, an X-ray imager, and a few motorizations. The simple and inexpensive set-up (resembling much that of an X-ray pinhole camera system for emittance measurements in Light Sources, but much shorter in length) allows to record images of the electron density profile over the 0.5 to 6mm distance range from the core. Results, obtained under various manipulations on the electron beam to vary either Touchek or residual Gas scattering and thereby the Halo levels, will be presented, to fully demonstrate that this Halo monitor is exploring those realms of the beam where other diagnostics can not reach ...

NON-DESTRUCTIVE MEASUREMENTS OF VERTICAL BEAM HALO

The European Synchrotron Radiation Facility runs a 6GeV electron beam at nominally 200mA and with a vertical emittance typically below 10pm.rad. The typical (natural) lifetime of the beam is above 50hrs, and the ESRF presently only uses 'slow' top-ups at intervals up to 12hrs. The small vertical emittance implies that the vertical size of the electron beam is in a range of roughly 13 to 50um [fwhm] depending on the local vertical Beta value which varies from >45m in some dipole sections to <3m in the straight sections reserved for Insertion Devices. [1]

However, it is known that a non-negligible beam population exists at many millimetres vertical distance from the beam-centre. [2, 3]

This is easily verified by using a vertical scraper and measuring the signal from a down-stream Beam Loss Detector (BLD). The progressive insertion of such a scraper jaw at 10mm above the beam-centre shows the so induced electron beam-losses thanks to the high sensitivity of such BLD. But this method is destructive to the beam and not useable for assessing the Halo population while serving normal users operation.

A prototype of a non-destructive Halo monitor based on imaging the X-rays from an available bending magnet beam-port was successfully operated to demonstrate the principle and the strait forwardness of a practical implementation. [4]

Since the above mentioned prototype device shared this beam-port with other (incompatible) usages we decided to build a dedicated Halo monitor on one of the still un-occupied bending magnet beam-ports, and to optimize both the associated X-ray absorbers and the distances between the main components in this new set-up that are illustrated in Fig.1 and Fig.2.

Long-distance X-rays Projection with Specific Central Absorbers to Attenuate Those Coming from the Intense Beam Core

The ESRF dipoles (0.86T, Ec=20KeV) provide an angular X-ray fan of 6.25degrees that is absorbed mainly in the crotch-absorber indicated at point 1 in Fig.1. Such crotch-absorber lets through about 15mrad of horizontal beam fan from its bending magnet, and normally this beam goes through a Front-End first and then further down-stream to a User's beam-line.

But in our case for this Halo beam-port there is neither Front-End nor beam-line, instead a second horizontal absorber (2) limits the horizontal fan of the X-rays to about 1.6mrad. About 10cm further down-stream is the third absorber (3), positioned vertically such that it takes fully the X-rays beam. However, its upper edge is only 0.7mm above the vertical heart of the beam.

The X-rays that are emitted from electrons that are >0.7mm above the centre of the electron beam will pass over this vertical absorber, and their first (and only) obstacle is a 2mm thick Aluminium window (5cm behind the vertical absorber) before hitting a scintillator screen. This scintillator screen is part of a sensitive X-ray imager that includes focussing optics and CMOS camera and covers a field of view 6.9x5.2mm (hor. x vert.).[5]

The total path length of X-rays is about 4.2m from their source-point in the dipole to the screen.

The X-rays emitted from the centre of the electron beam will hit that 28mm thick Copper vertical absorber. This small absorber is water cooled and evacuates about 240W of heat-load coming from the 1.6mrad wide X-ray beam fan. It protects the Aluminium window behind it that is not cooled.

The 28mm thickness of the Copper absorber is enough to fully take the heat-load but totally insufficient to stop all the X-rays. Therefore a 7mm thick Tungsten blade is positioned behind the window to further attenuate these X-rays coming from the core of the electron beam. This 7mm thickness was chosen so that the intensity of the traversing X-rays (28mm Cu, 2mm Al and 7mm W), coming from the central beam-core, will produce a light signal on the imager system of roughly comparable intensity to that of the Halo signal (created by X-Rays traversing only 2mm Al).

ISBN 978-3-95450-141-0

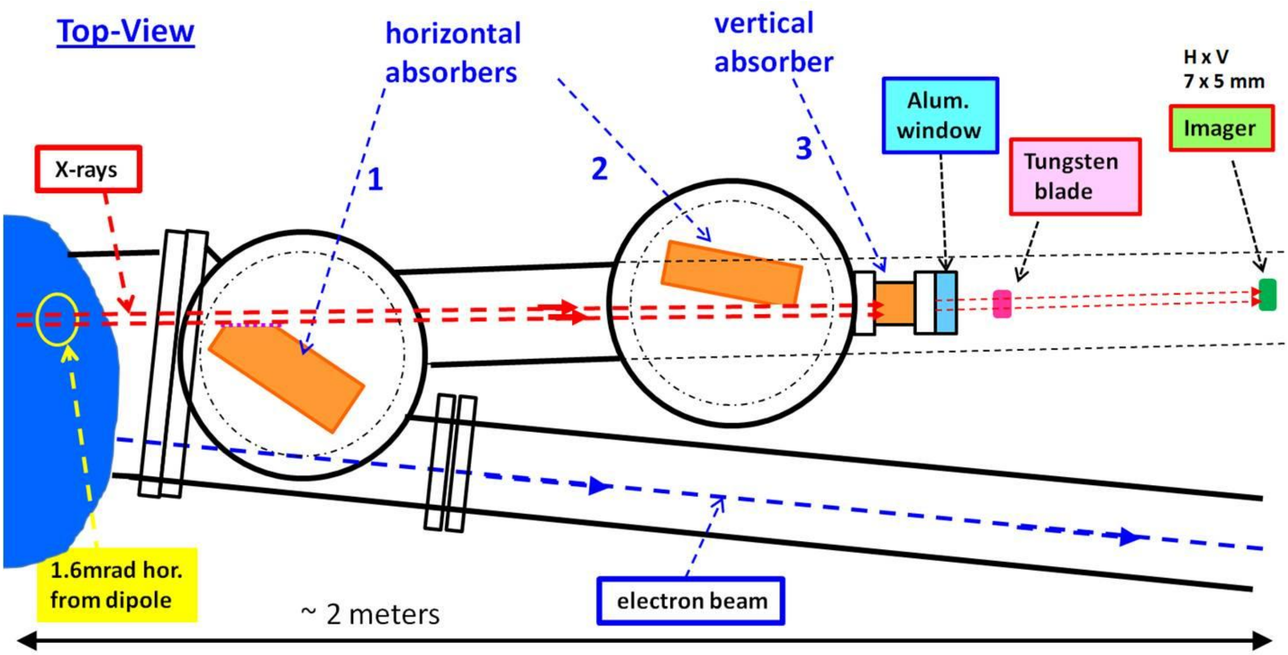


Figure 1: Top-view of the set-up with the dipole at far left and the (red) X-rays going to the right towards detector.

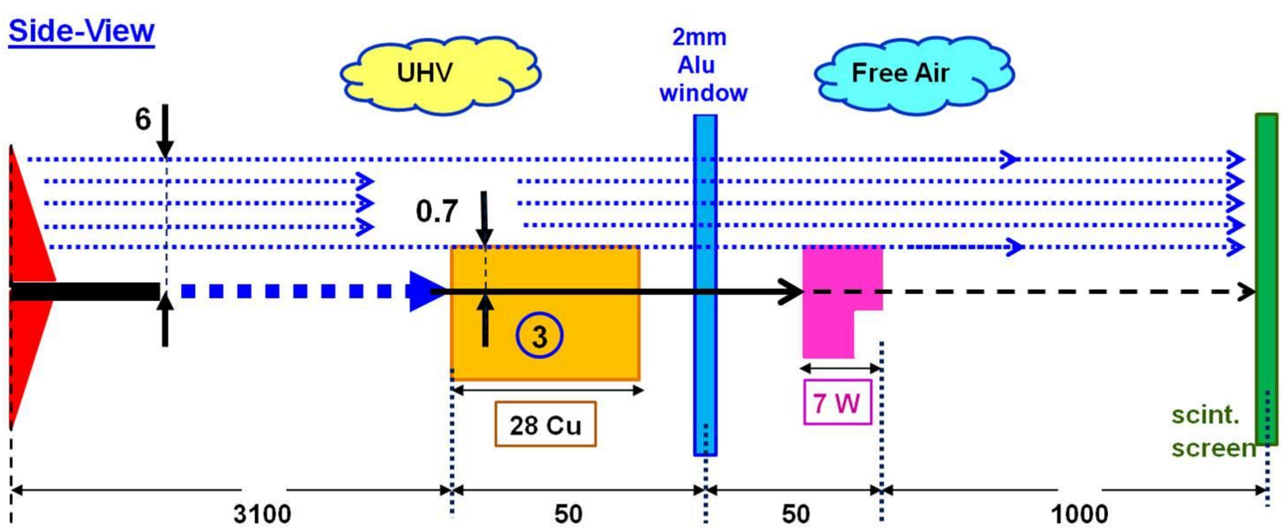


Figure 2: Side-view with emphasis on the down-stream parts with the 28mm Copper vertical absorber, the aluminium UHV window, the 7mm Tungsten light-blocker, and the detector. The latter 2 devices are equipped with hor. and vert. remote control translation stages.

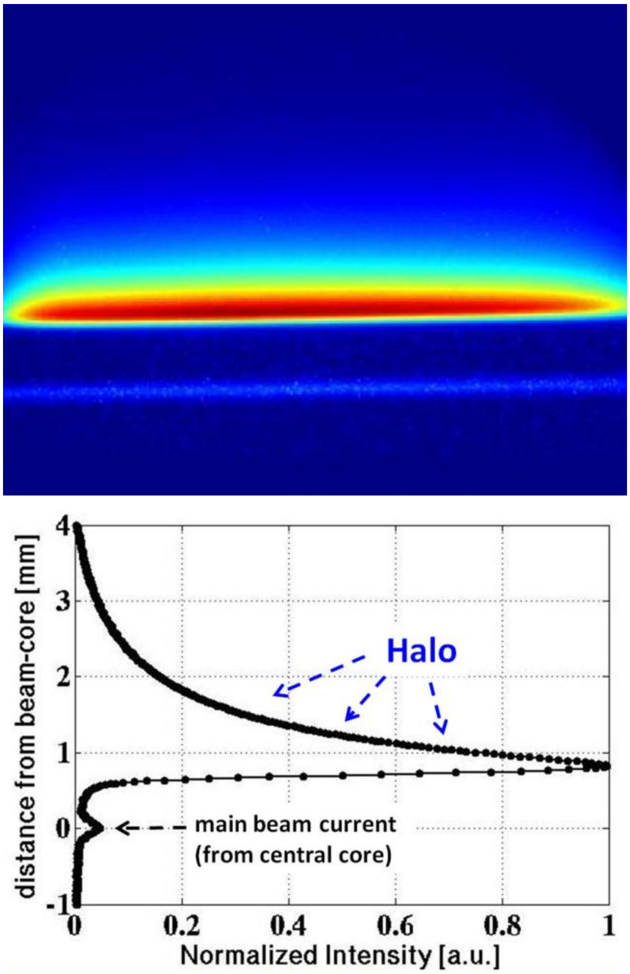
The Fig.3a shows a typical image obtained under normal operation conditions of our electron beam. Horizontally the image provides no information on the electron beam, it simply represents the (1.6mrad) width of the fan of the dipole radiation. Nevertheless, the width of this fan is proportional to the signal strength and thus to sensitivity and overall resolution of the system.

Vertically the narrow stripe in the lower part represents the intensity of the beam-core, it is relatively weak since taken with 75mA beam current (16 bunch mode) in the Ring.

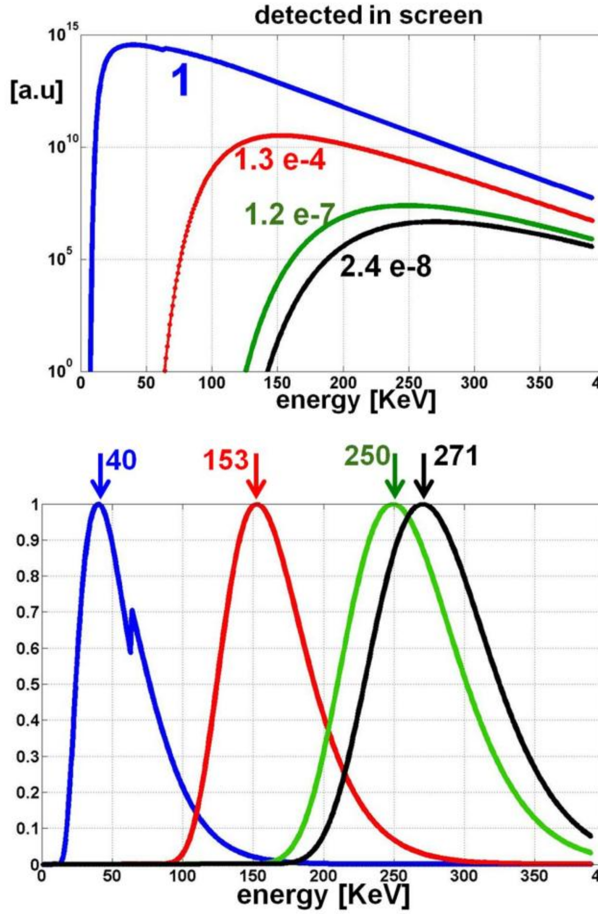
The bright zone in the middle is the contribution of the Halo. This image was taken with that 7mm thick Tungsten light blocker positioned exactly as indicated in the side-view here above in Fig.2 : its top-edge vertically at the same level as the top-edge of the Copper absorber i.e. 0.7mm above the beam-centre. It should be noted that the vertical position of the Tungsten light blocker can be remotely adjusted.

The Fig.3b shows the profile of that image along the vertical axis in which both the (strong) Halo contribution and the (small) contribution coming from the central main beam are easily resolved.

ISBN 978-3-95450-141-0



Figures 3a & 3b: Halo-monitor image covering a 6.9x5.2mm field of view (top), and the profile (bottom) along the vertical axis showing the Halo level (big peak) and the main beam current (small peak).



Figures 4a & 4b: Energy spectra of the X-rays (detected by 1mm of Prelude scintillator) for the 4 different cases of beam paths and absorption in the system.

The Characteristics of the X-rays Traversing Four Different Paths of Material Attenuation

As said before, the X-rays emitted from the Halo part of the electron beam (i.e. between 0.7 and 5mm above beam-core) will traverse much less material then those from the central beam-core. Knowing precisely the spectral characteristics of synchrotron light from the 0.86T bending magnet and the absorption characteristics of the used scintillator (1mm thick Prelude) we can calculate the detected signal. The Fig.4a and 4b show the energy spectra of 4 distinct cases and the relative numbers of detected signal. These 4 cases correspond to :

- 2mm Al (blue curve) only, peak-energy=40KeV, relative intensity=1
- 28mm Cu plus 2mm Al, (red curve) peak-energy=153KeV, relative intensity=1.3E-4
- 28mm Cu plus 2mm Al plus 5mm W (green curve) peak-energy=250KeV, relative intensity=1.2E-7
- 28mm Cu plus 2mm Al plus 7mm W (black curve) peak-energy=271KeV, relative intensity=2.4E-8

Since the Tungsten blade is on a remote control vertical translation stage it can be positioned as shown in Fig.2 (at level with the Copper absorber) but it can also be completed lowered (corresponding to the red curve case) or be put so that the X-rays from the central beam-core go through 5mm of Tungsten (instead of 7mm). This arrangement allows us to verify (in different steps) the theoretical values of detected signal with the reality of the measured values. It also allows to cross-check the linearity of the X-ray imager system that now uses a CMOS camera. In these sensitivity calibrations & verifications we make use of the camera offering an effective exposure time range of about 4 decades (600mS to 0.06mS) and a gain range of 10 (20dB).

Such verifications have allowed assessing the errors of the above reported detection sensitivity values to be within 30%.

In the explanation of the concept and with the illustration of Fig.2 it was so far simplistically presented that the X-rays do not diverge (at all). However, while the vertical divergence of the X-ray beam at energies shown in Fig.4b is small, their real values do impose some limitations on the system :

The spatial resolution at the X-ray imager (at 4.2m) is approx. 300um (fwhm) for the divergence of about

ISBN 978-3-95450-141-0

75urad (fwhm) of the "soft" spectra shown by the blue curve (peaking at 40KeV).

The second limitation is on how close to the beam-core this system is able to operate. The height offset of 0.7mm of the vertical absorber is determined also by this vertical divergence of the X-rays : Those coming from the intense beam-core will at 225urad angle still have a relative intensity of 1E-9. In order to enable the system to detect real Halo levels down to below 1E-8 with respect to the central beam-core intensity, and limiting false contributions to <10% we have decided to put this value at 0.7mm which represents roughly 225urad at 3.1m.

The real Halo levels during Users' mode are in the range of 1E-6 (113nA / 75mA) as is shown in Fig.5 which is a measurement at 75mA in 16 bunch mode. Using the above reported sensitivity factors for the different energies of the X-rays we can indeed express the Halo level directly in current (e.g. nA). With Halo level is meant here the integrated value in the distance range of 0.7 to 4mm (from centre).

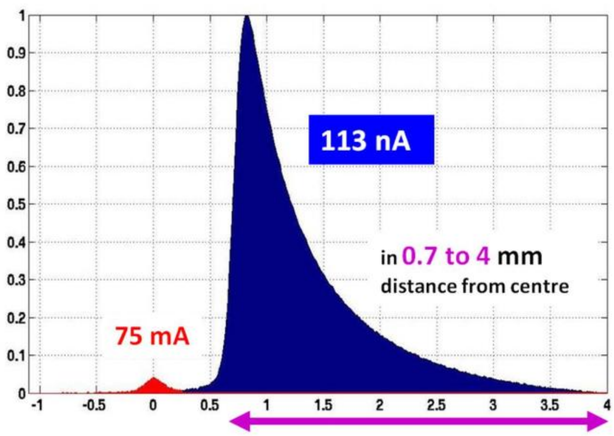


Figure 5: Profile with the main current contribution in red and the (integrated) Halo level expressed in nano-amps.

VERIFICATIONS BY SCRAPING THE ELECTRON BEAM

Since the difference in Halo level and that of the beam-core is of many magnitudes (~1E6) it could be suspected that the signal obtained on the X-ray imager is not really constituted by X-rays emitted from the electrons in these far away tails of the electron beam but instead due to some combined artefacts like scattering, reflection, leakage etc.

In fact in the earlier moments of commissioning and aligning the system some phantom signals were observed in the image that clearly seemed to come from the surface of one of the up-stream horizontal absorbers. Some of the surfaces here are unavoidably at grazing incidence angles and therefore prone to scattered propagation. We have managed to locate the origin points of these and be able to re-align the system (horizontally) thereby avoiding such scattered X-rays reaching the scintillator screen.

An efficient way of verifying that the observed signal in the image is indeed entirely coming from the electron's beam and without any phantom contributions is to remove the electron's beam tails by a scraper. One of the available scraper jaws in our Ring was used during some time dedicated to drive it in a sequence of steps close to the beam-centre and to record the Halo-monitors' images at the same time. A typical sequence is driving the scraper from 10mm to 1mm and then back out to 10mm with 0.5mm steps and staying at each step only a few seconds. The loss of the total beam current is only fractional (i.e. <0.1%) by such measurement sequence.

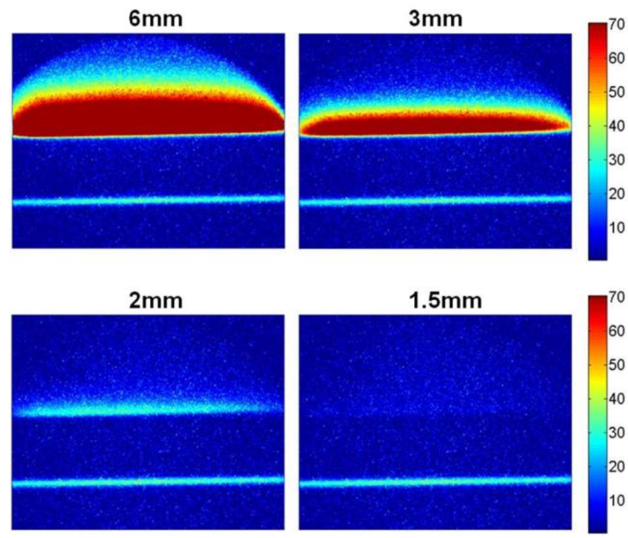


Figure 6: Images for 4 vertical scraper positions.

The 4 images in Fig.6 show only a part of such sequence i.e. the Halo images with the scraper at 6, 3, 2 and 1.5mm. In the lower part of each image one can observe that the main current (central beam-core) is not affected while the Halo signal disappears. This measurement was done with the Tungsten blade raised to 1.5mm height (instead of 0.7mm), this allowed reducing the amplitude of the Halo signal and thus increasing the camera's gain and so to get more signal of that main current. The Fig.7 shows the profile plots of such measurement.

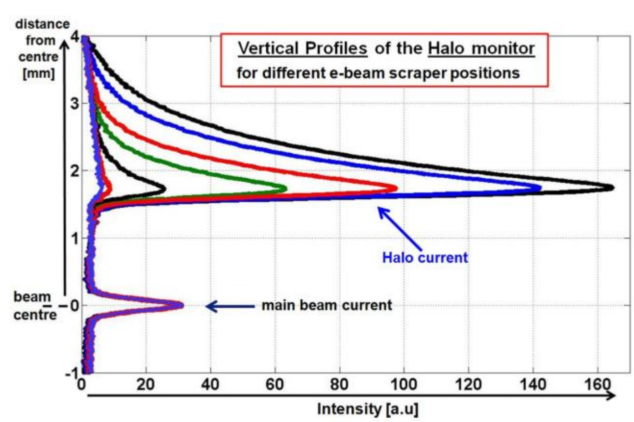


Figure 7: Profiles of the Halo for different positions of the vertical beam scraper (in Cell 5).

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MANIPULATIONS WITH THE BEAM AND THE INSERTION DEVICES

The Halo monitor essentially measures the rate of electrons suddenly leaving the central dense beam-core and subsequently describing oscillations at large distances from that centre before then damping down and re-integrating this beam-core again. During this damping time (~7ms for our lattice) they occupy this Halo zone and thus contribute (via X-ray synchrotron radiation) to the signal of the here described device.

The two main reasons of this scattering is by energy exchange between 2 electrons (known as Touchek scattering) and by the deflection of the electron by a residual gas molecule of a non-perfect vacuum in the chamber. The Touchek scattering is very much favoured by the density of the electron bunches, while scattering due to gas is proportional to the vacuum pressure.

During normal User's operation we observe that the Halo monitor is extremely sensitive to the slightest increase of the vacuum pressure. When comparing these recordings with that of our set of local Beam Loss Monitors at the occurrence of such tiny gas outburst we see in addition to the good correlation that the signal-to-noise ratio of the Halo monitor is superior to that of the BLDs.

The Touchek scattering varies with beam charge per bunch and with the beam-size. The latter can be easily manipulated (blown-up) by adding some white-noise oscillation to the beam in the vertical plane by the use of a so-called shaker.

In addition to these manipulations on the electron beam we have also investigated how the Halo level varies under different scraper (both horizontal and vertical) settings and this again for different beam conditions (intensity, vertical emittance). An example is shown in Fig.8.

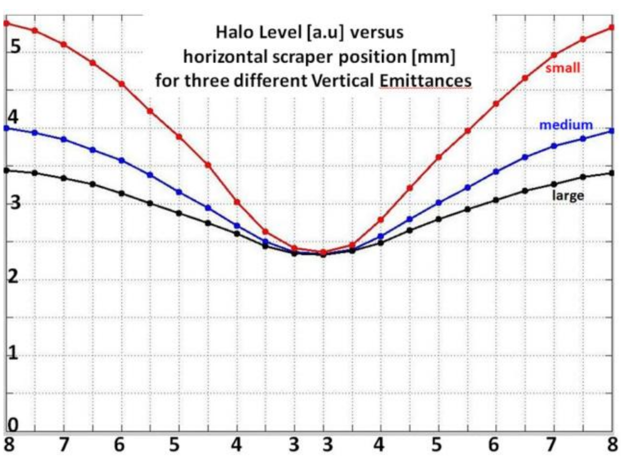

Figure 8: scraping the beam with a horizontal scraper.

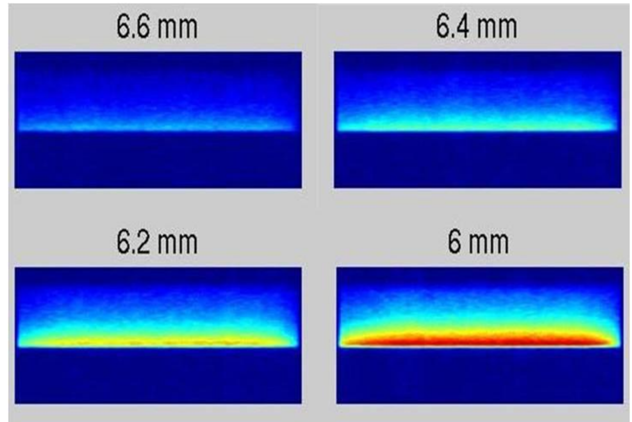

Figure 9: four differential Halo images when closing the ID15 In-Vac undulator down to its minimum of 6mm.

Finally, an interesting application is to see how the In-Vacuum undulators (12 installed in the Ring) can affect the Halo levels when their gaps are set to small values (i.e. 6mm). An illustration is shown in Fig.9 with differential images at 4 different gap settings. A differential image is obtained when subtracting the image when gap_fully_open from the image with a small gap setting.

ACKNOWLEDGMENT

The author wishes to thank N.Benoist for taking care of the mechanical designs, the installation work and for the realisation of the adequate protection and housing of the image/detector system. The help and support in the initial design concept received from B.Ogier and J-C.Biasci is also acknowledged. Thanks are also expressed to F.Ewald and J-M.Chaize for support given to the device-server aspects of various new cameras that have been used and tested.

REFERENCES

[1] F.Ewald et al., "Vertical Emittance Measurement at the ESRF", MOPD61, DIPAC'11, Hamburg, May 2011. http://accelconf.web.cern.ch/AccelConf/DIPAC2011/papers/mopd61.pdf

[2] A.Zholents, W.Decking, "Non-gaussian beam tails at the Advanced Light Source", 04-01-2000. http://escholarship.org/uc/item/54z1j750

[3] T.Mitshuhashi, "Beam Halo Observation by Coronograph", ITMM03, DIPAC'05, Lyon, May 2003. http://accelconf.web.cern.ch/AccelConf/d05/PAPERS/ITMM03.PDF

[4] B.K.Scheidt, "Recent Development of Novel Beam Diagnostics at the ESRF", TUOCB201, IPAC'13, Shanghai, May 2013. http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/tuocb201.pdf

[5] Saint-Gobain, Cerium doped Lutetium based scintillation crystal, http://www.crystals.saint-gobain.com