

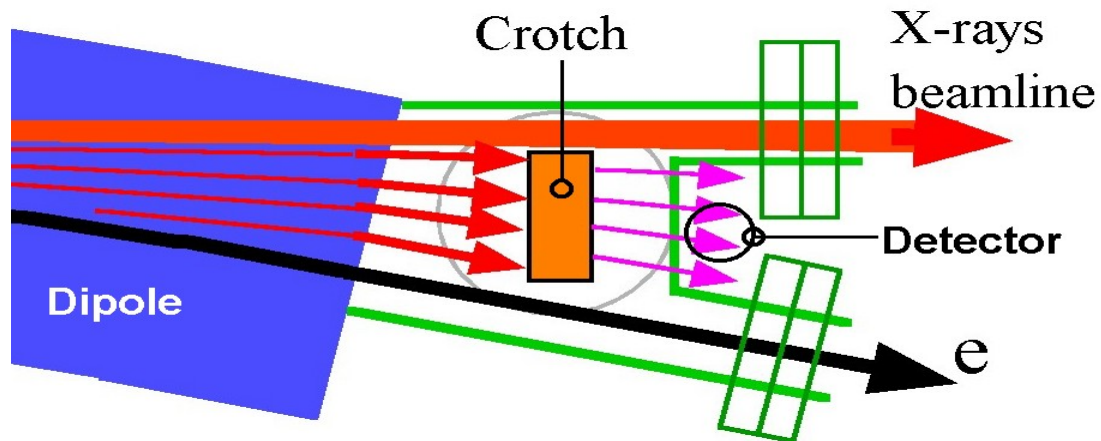
# In-Air X-Ray Detectors : A New Field of Simple and Powerful Beam Diagnostics

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**Abstract.** Crotch or beamport absorbers deal with the unused power of the synchrotron radiation generated by dipoles in electron storage rings. A tiny fraction of the very hard X-rays fully penetrate the absorber structure and enter the free air space behind it. Both at the ESRF (6GeV) and at ANKA (2.5GeV) it was shown that this tiny leakage power can be detected by a simple, compact and low-cost device consisting of a scintillator with optics & camera. Situated In-Air just behind the absorber it measures precisely the vertical electron beams size. This imaging detector is also applied for 1 $\mu$ s, 5mA single shot measurements in the ESRF transfer-line. A 2nd detector type was developed, using the same leakage X-rays, that consists of a high-Z blade in combination with a small In-Air ionization volume. It generates a direct electric signal that is used for nanometer resolution measurements of vertical beam motion in a spectrum upto 1KHz. The concept and results of both types of detector used now in various applications are reported here that show their potential for simple and powerful beam diagnostics.

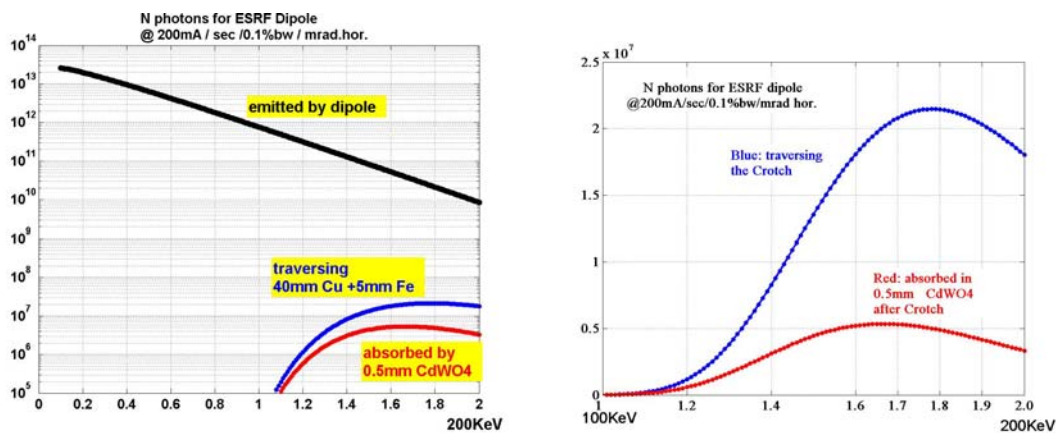
## HARD X-RAYS THAT TRAVERSE THE ABSORBERS



**FIGURE 1.** Topview of the position of the In-Air X-ray detector just behind the crotch absorber.

Only 10% of the synchrotron light generated by the ESRF dipole ( $B=0.86T$ ,  $E=6GeV$ ) is accepted for possible passage into an X-ray beamline's front-end. The other 90% are dissipated directly by a crotch absorber (fig.1). However,  $\sim 2ppm$  of this power (i.e. 300uW/mRad hor. angle) is not absorbed and traverses the complete

structure to enter the free air behind. This leakage power is carried by the high energetic photons >150KeV. The dipole's spectral flux emission characteristics (fig.2) show their decreasing intensity with increasing energy. Their 40mm path through the ESRF copper crotch absorber and 5mm through the steel vacuum chamber causes a strong attenuation of several orders of magnitude. Nevertheless, the fraction that enters the free air is still of an intensity of  $\sim 2E7$  photons per second, per mrad horizontal angle in a 0.1% bandwidth at 200mA current. The curves in the right graph of fig.2 with a linear scale show a sort of bandpass shape that is determined at the left-side by the increasing copper attenuation to lower energy photons, and on the right side by the slope of decreasing dipole flux for higher energy photons. The peak response is at  $\sim 170KeV$ . At this energy the photon beam divergence has a perfect gaussian distribution of a value of about 42 $\mu$ rad fwhm.



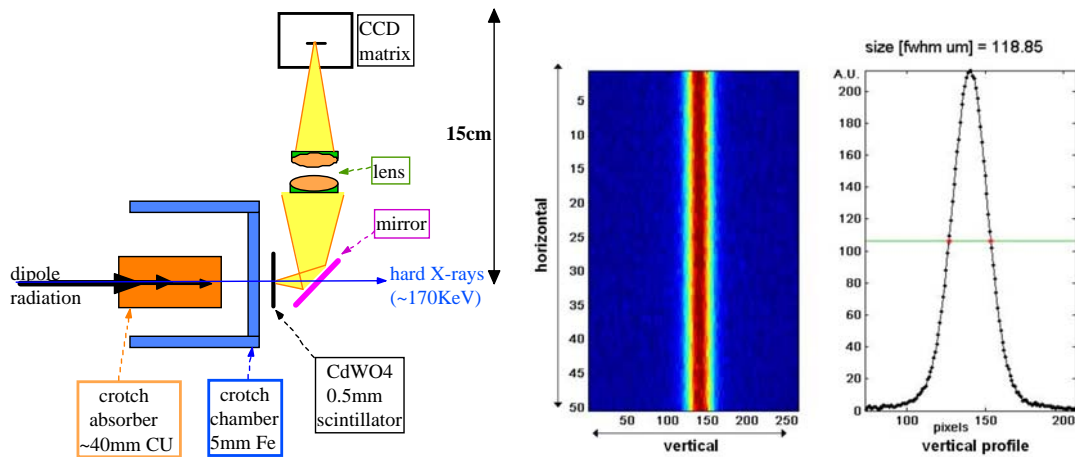
**FIGURE 2.** The spectrum of the X-rays emitted by the ESRF dipole, entering the air and absorbed in the CdWO4 scintillator, with (at left) a linear scale showing the energy peak at  $\sim 170KeV$ .

## OPTICAL SYSTEM : THE X-RAYS IMAGED BY SCINTILLATOR SCREEN WITH OPTICS & CAMERA

Cadmium Tungstenate (CdWO4) is a high-Z crystal of nearly 8gr/cm3 density. [1] Thanks to its mechanical hardness it can be manufactured and polished to a thickness below 0.5mm. It is transparent to visible light and has a good light yield for the hard X-rays with a short decay time of  $\sim 1\mu$ s. The lower (red) curve in fig.2 shows the X-ray spectrum absorbed by a 0.5mm thick CdWO4 screen out of the spectrum that traverses the crotch. The fig.3 shows the detector with the scintillator screen directly behind the crotch chamber. The light emitted by the screen is deflected upwards by an Aluminium mirror just 7mm behind to an achromat pair that collects and focuses an image on the CCD matrix. The entire detector is mounted together and adjusted optically in laboratory before installation. The optical resolution of the system is assessed in laboratory and estimated at  $\sim 10\mu$ m.

For the first prototype versions the optics had a strong light collection with an effective F-number of  $\sim 4$ , with the achromat pair of resp.  $f_1=50mm$ ,  $f_2=75mm$ . This yielded a 4.4 $\mu$ m pixel size at the screen source point with the analog (CCIR standard) Sony ST-30 (1/3" format) CCD camera [2, 3]. This initial optical system allowed to

work with CCD measurement times as low as 0.5millisec. For the definitive version a miniature (approx. a cubic inch volume) IEEE-1394 standard camera is used with 640x480 pixels of 7.4um [4]. For the foreseen applications longer CCD measurement times can be accepted (typ. 5-50millisec) and therefore the optics has been reduced in diameter (F=15 with 4mm aperture and with f1=60mm, f2=80mm). This yields a 5.55um pixel size at the screen source and a viewing range of 3.6x2.7mm. This was also very helpful in optimizing the Lead shielding, that is necessary to protect against damage (to camera) and degradation (lens blackening), and in reducing the overall size & weight of the detector. The entire assembly has to be very small and compact since the space behind the crotch-chamber and the flanges just a few cm further downstream is extremely limited. The scintillator screen and the Aluminium mirror have never shown any sign of degradation.



**FIGURE 3.** (left) schematic side-view of the imaging detector with scintillator, optics and camera. (right) typical image with a vertical profile plot, showing ~119um projected beamsize.

## Calculation of the Vertical Electron Beam Size

The 170KeV X-rays travel 1.9meter before hitting the screen where they project a stripe-line image (see image in fig.3). Horizontally this line covers the full-recorded image width because of the horizontal fan of dipole light, and obviously no data of interest can be obtained in this horizontal plane. In the vertical plane however, the relation between the height (h) of the projected image on the screen, and the size of the source-point (i.e. electron beam) can be established in simple and precise terms (see fig.4). Because of the very narrow divergence of the 170KeV photon beam (42urad fwhm, and of gaussian distribution) the projected vertical beam size (h) is only 115um fwhm compared to the vertical electron beam size of 86um fwhm at typical ESRF emittance of 35pm.rad. The precision of this deconvolution depends on the precision with which the distance (S) and the exact photon beam divergence ( $\alpha_v$ ) can be determined. It can be shown that the uncertainty on both is small and that therefore the precision of the electron beamsize measurement is estimated at better than 2%.

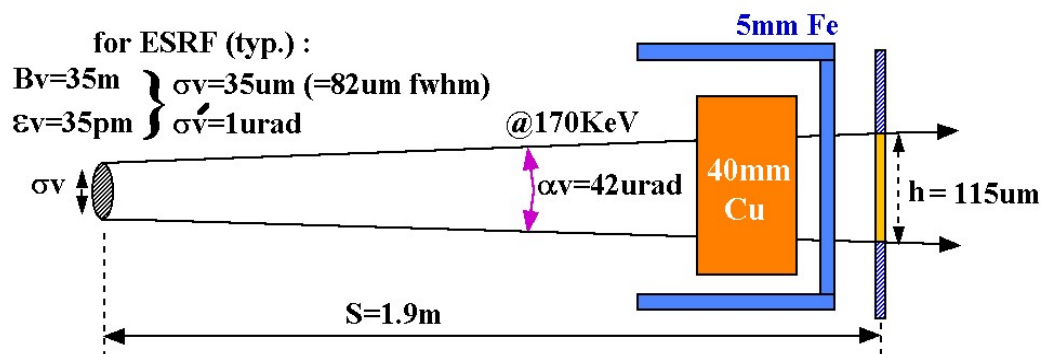


FIGURE 4. Relation of the electron beamsize (source-point) to the projected image size on the screen.

### Results and Prospects in 2006 for the ESRF Storage Ring

A first prototype (with a simple and insufficient Lead shielding) was installed in Jan-2005 and yielded results for only 2 days of operation. The location of the detector directly behind the crotch implies a strong exposition to radiation caused by particles that are generated inevitably by the interaction of 13KW of high energetic synchrotron light with the crotch absorber. Throughout 2005 various prototypes were developed and tested with the aim of making the system compatible with both this hostile environment and the physical space limitations. This implied a reduction of the optical diameter, a reduction of the camera-size, and an optimization of the lead shielding with an additional mirror to create a chicane structure. The mechanical fixation of the detector and the choice of the camera standard (IEEE-1394 under Linux control) are also now definitive.

A number of comparative measurements of the ESRF emittance were carried-out with this In-Air Imaging Device, and two independent emittance measurement system based on X-ray pinhole cameras [5].

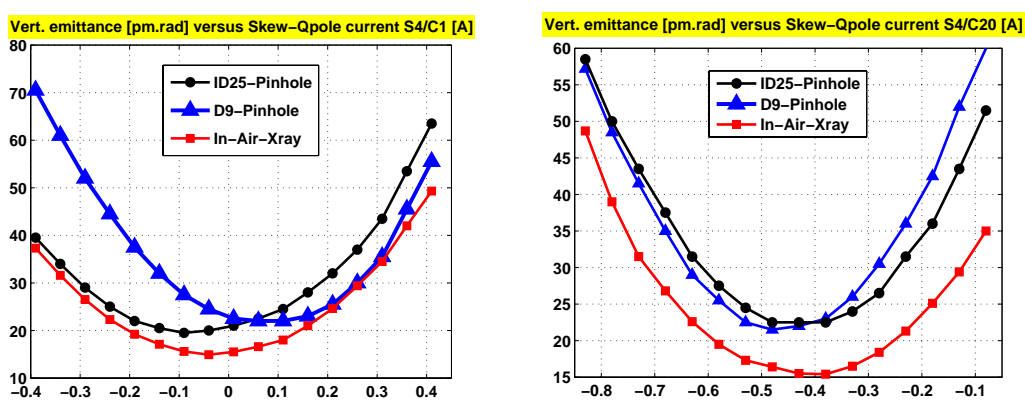
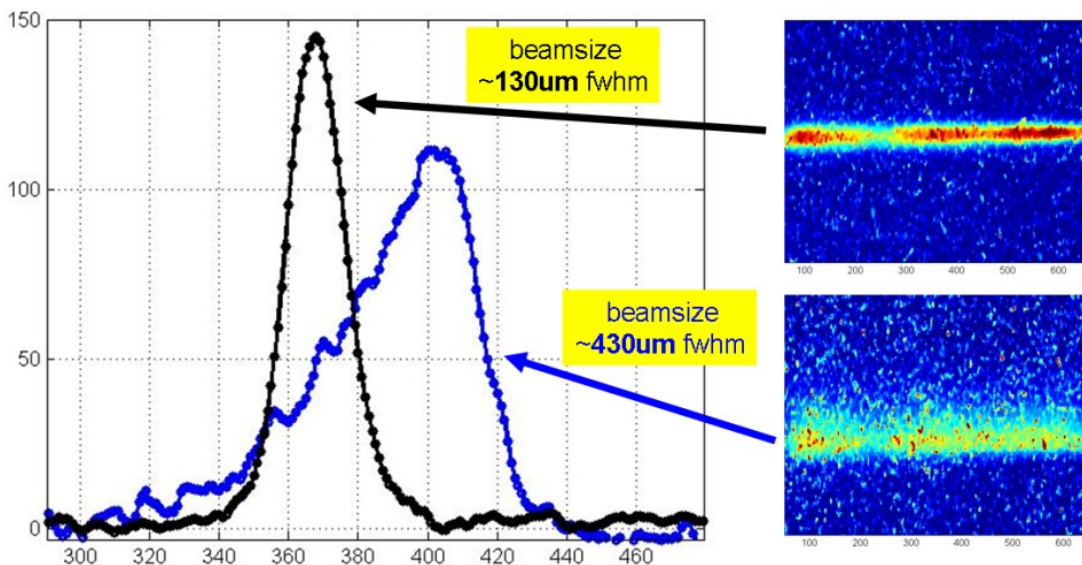


FIGURE 5. Comparative vertical emittance measurements of the In-Air Imaging Device with two independent X-ray Pinhole camera systems, for a varying current in a Skew-Quadrupole.

The current in a single skew-quadrupole (that serve to reduce & control the hor. to vert. coupling) was varied over a certain range and at each point the resulting vertical emittance measurements of the three devices were recorded. The figure 5 shows the results for two different skew-quadrupole current scanings. The In-Air Device shows its capacity to measure precisely the vertical emittance. It is to be noted that the apparent discrepancy between the three measurement results (with each device at a very different physical location in the ESRF ring) is logical with the applied method.

### Tests in the ESRF injector complex

The vacuum chamber of the dipoles of both the TL-2 transferline and the Booster (200MeV-6GeV) presents about 10mm of steel before the X-rays enter the free air. An In-Air imaging detector of the same nature as described above was used to detect & image the leakage of hard X-rays at both parts of the injector complex. Clean and high quality images were obtained from the Booster at the last third of its 50millisec acceleration cycle with electron energies above 4GeV. An even more challenging test was the detection of the In-Air X-ray signal from a single passage of a 5mA, 1us electron beam in TL-2. Although the images are much more noisy (see fig.6), the vertical profile results are exploitable for beamsiz measurements and are in good agreement with results of other diagnostics [6] at this same location.



**FIGURE 6.** Measurements of the vertical beamsize in the TL-2 transferline on a single 5mA, 1uS pulse for two different settings of Quadrupole settings.

### Vertical Beamsiz Measurements At ANKA (2.5GeV)

The ANKA synchrotron light source operates with 16 dipoles of 1.5T and an electron energy of 2.5GeV. A few beamports are presently equipped with a Copper beamport absorber of 8mm thickness, at ~1.5m from the associated source-point, with

free access (In-Air) just behind. The calculation of the transmitted flux & power shows that  $\sim 3\mu\text{W}/\text{mrad}$  hor. angle is traversing the absorber and available for detection. The peak energy of the transmitted & detected signal in 0.5mm CdWO<sub>4</sub> is at 80KeV. Although the total power available is a factor  $\sim 100$  lower than at the ESRF, the application of an analogue CCD camera (Watec-WAT-120N) with measurement times from 20millisec upto 10sec allowed to obtain high quality images (see fig.7).

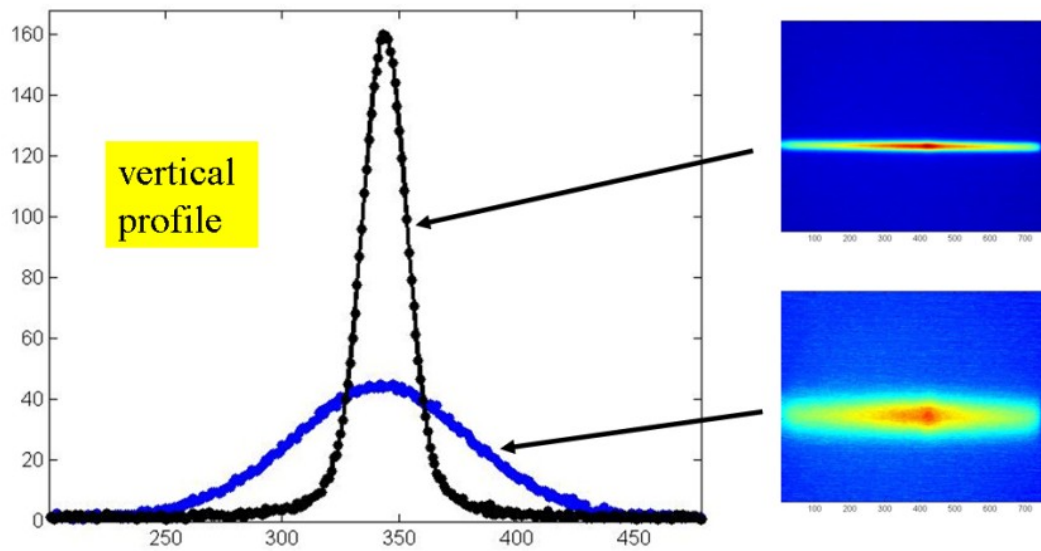


FIGURE 7. Typical results (images & vertical profiles) at ANKA for 2 different quadrupole currents.

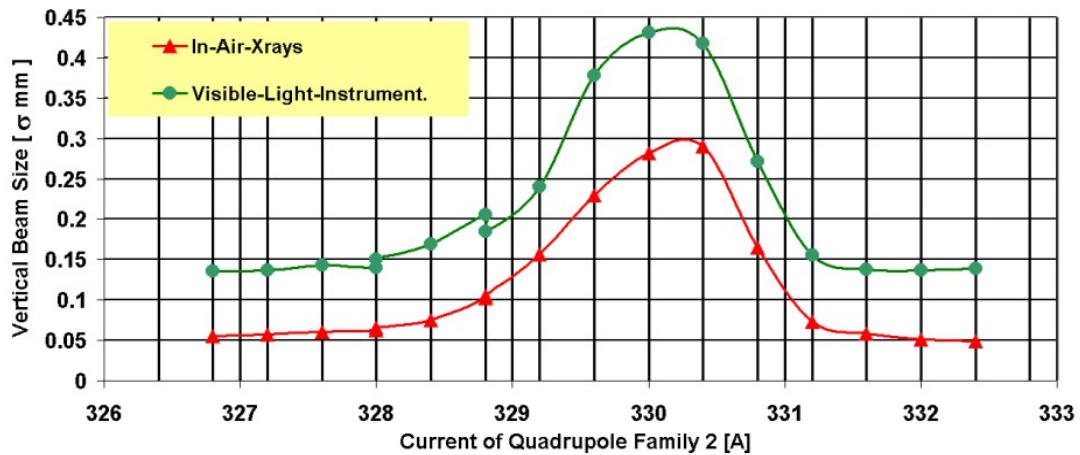
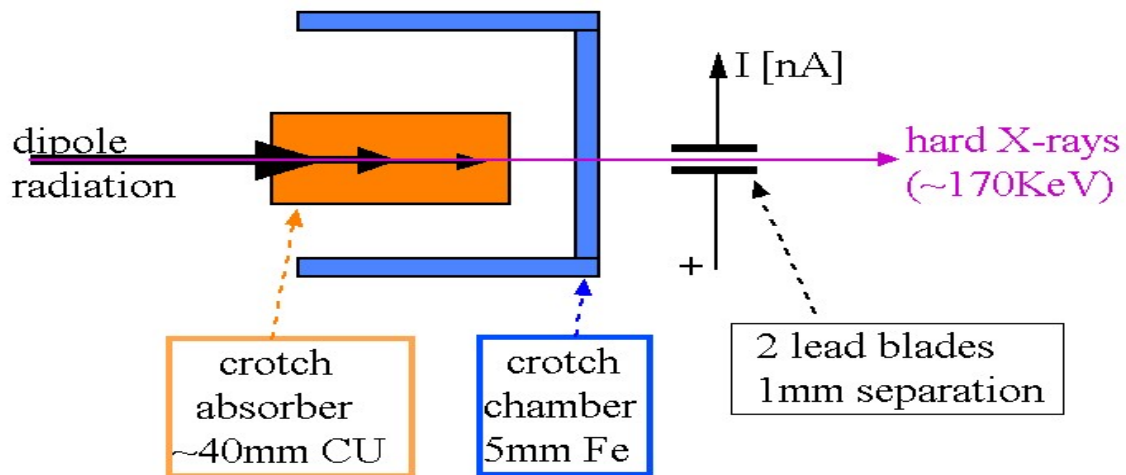


FIGURE 8. Measurements results of the vertical beamsize with the In-Air-Xray-Imaging Device at ANKA in comparison to that of an existing visible synchrotron light device.

The compact detector allowed the measurement of the vertical electron beamsize instantly after its quick installation, using for its mechanical attachment & alignment (by eye) only two M6 screws. The comparison of the results (with a varying quadrupole current to traverse a regime with beamsize blow-up, see fig.8) of this In-Air device with an existing instrument based on imaging the extracted visible synchrotron light showed a strong discrepancy that can be entirely attributed to the various imperfections of the latter. [7]

## ELECTRIC DETECTOR : THE X-RAYS CONVERTED TO CURRENT BY A HIGH-Z BLADE & IN-AIR IONIZATION

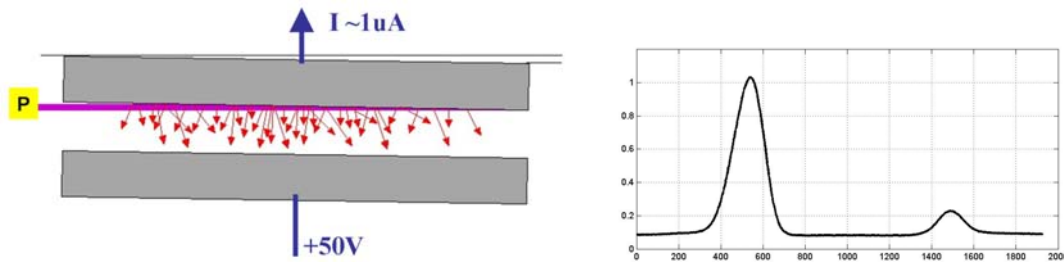


**FIGURE 9.** Side-view of the position of the In-Air Xray ‘blade-monitor’, behind the crotch absorber.

The X-rays that traverse the absorber represent a signal strength of  $\sim 300 \mu\text{W}/\text{mRad}$  hor. angle that can be detected more directly by the use of a high-Z blade in combination with a small In-Air ionization volume. A schematic side-view (fig.9) shows the detector, consisting of 2 parallel plates (or blades) separated by a small distance (typ. 1mm) in air, with the beam. One of the blades is connected to a DC bias voltage (typ. 50V), while the other blade is connected via a short coaxial cable to a high impedance electric measurement device (typ. 1Mohm input oscilloscope). The dimensions of the blades are 23x23mm. They are mechanically fixed to an electric isolator that itself is mounted to a miniature mechanical assembly allowing for the angle orientation in 2 planes and a vertical translation. This assembly is a commercial product with 3 DC motors for remote control of these 2 angles and the vertical position of the detector.

The correct 2-plane-orientation and vertical position of the blade surface with respect to the X-ray beam is crucial. The first alignment aim is to have the beam (horizontally large i.e. exceeding the 23mm detector width, while vertically  $\sim 100 \mu\text{m}$ ) intercepted by the full area of the blade surface. The interaction of the high energy X-rays with the high-Z material causes, at the surface, a shower generation of secondary particles that themselves cause an ionization of the air molecules in the small volume between the 2 blades. This conductive state together with the applied DC bias voltage now allows to measure a small voltage by the 1Mohm instrument. The physics of the X-rays with the high-Z material, the subsequent particle generation, their exact nature, and their consequence of electric ionization in air are matters outside the scope of this paper and not further described here.

The blades of a first prototype were both made of Lead; Tungsten and Gold (coating) have been used since with the advantage of better surface flatness quality. In the final version the use of a single ‘interceptive’ blade made of Nickel with Gold coating is envisaged with the 2<sup>nd</sup> blade (with the bias voltage) made out of Aluminium. The signal yield is of roughly equal strength for each of the materials tested so far : ~1uA for our 23x23mm detector at 200mA ESRF beam current. The X-ray beam power intercepted here is ~3mW, or ~10E11 photons/sec. The 1uA currents amounts to ~10E13 electrons/sec so the actual ‘conversion gain’ is roughly a factor 100.



**FIGURE 10.** Side-view (left) of the detector shown in a position of full beam interception over full blade surface, (right) signal output while vertically scanning the device through the beam

The initial alignment & angle orientation of the detector is done by scanning the detector vertically through the beam and (time-)recording the signal output (fig.10). This signal output shows here two responses, separated by ~1mm, coming obviously from each of the 2 blades, with the signal yield from the lower blade clearly smaller because of non-optimum angle orientation along the longitudinal direction. The optimization of the 2 plane orientation of the blade is done by repeating this scanning/recording so to obtain the maximum signal output (of the ‘interceptive’ blade). After that the detector is put and left in a vertical position at ~1/2 this maximum signal, i.e. on the steep slope. In this way the detector is now a vertical position monitor with a sensitivity of ~10mV/um without any amplification of the crude detector signal.

### **Results of DC and AC vertical beam position monitoring**

The rigidity of the fixation of the detector assembly to the vacuum chamber is crucial to avoid mechanical vibrations in the tens of nanometer region that the detector is potentially capable of resolving. Tests performed with 10min. measurement times show a total absence of unknown lines in the freq. spectrum of the recorded signal.

The detector positioned on the slope of a ~100um gaussian profile implies a limited range & linearity for use as a beam position monitor. This dislinearity is acceptably small (<10%) for beam displacements of +/- 20um. At the ESRF the scheme [8] of slow & fast Closed Orbit correction & feedback results in an overall beam stability well within that range. Successive 1000sec recordings (fig.11) of the vertical beam stability show the apparent effect of the slow orbit correction scheme (acting at 30sec intervals). The real resolution of the device for DC motion (estimated at <50nm with 1sec measurement time) can simply not be verified with the beam itself that has a residual & uncompressible DC motion above this value.

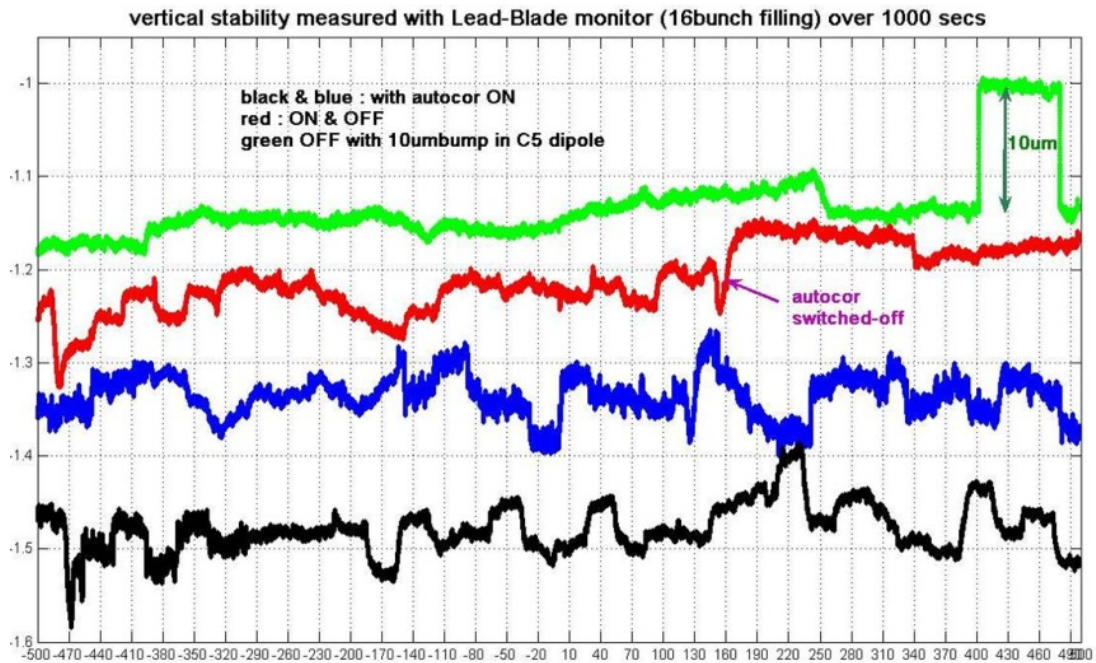


FIGURE 11. 4 traces of 1000sec recordings of vertical beam position

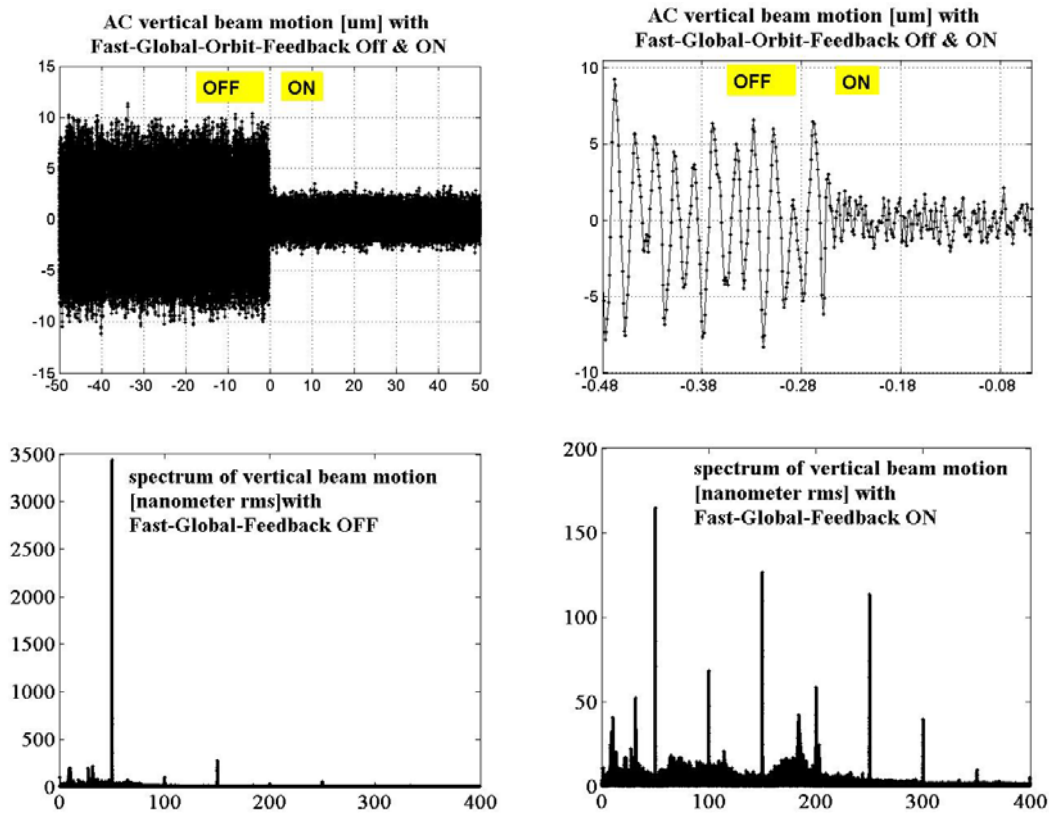


FIGURE 12. Upper graphs: recordings of AC beam motion (100sec & 80millisec) with Orbit Feedback being switched to ON; Lower graphs: frequency spectrum of the AC motion (Feedback ON & OFF)

The performance in the AC range upto 400Hz is shown in recordings with the Global Feedback active and off (fig12). Extensive tests have been carried-out to assess the resolution and to compare that with other diagnostics. The In-Air blade-monitor, that benefits of its location on a high vertical Beta of the ESRF machine lattice, demonstrates a superior resolution to both the fast-electron-BPMs (in-strait sections) and the classical X-BPM (blades in UHV).

## CONCLUSION AND FUTURE PROSPECTS

It is shown that the small leakage power, carried by the high energetic part of the synchrotron radiation, that traverses absorbers and vacuum chambers and becomes accessible in free air, can be detected efficiently, in different ways, and in various parts of different electron machines, to constitute a very powerful diagnostic of high simplicity.

Although the nature of the dipole radiation imposes that the measurement of electron beam parameters is limited to the vertical plane, the performance in terms of precision and resolution raises an exciting challenge for this field of detectors. This performance potential combines with the huge advantages of installing, aligning, operating and maintaining these devices in (accessible) free air and at negligible heatload, thereby liberating the designer of major concerns of UHV compatibility and cooling requirements so typical of other diagnostics systems.

The imaging type of detector is capable of resolving the electron beamsize to a precision and resolution at least as good as the X-ray pinhole camera systems. In contrast to the latter, its performance is not sensitive to alignment or affected by very large beamsize values. An adapted lead shielding against the very hostile radiation environment satisfies reliability requirements. Four of these devices will be installed and commissioned in 2006.

The numerous tests performed on the 'blade-monitor', in comparison to other diagnostics for vertical beam motion measurement, have shown that it is of superior performance in terms of resolution. This detector clearly benefits from the fact that it can touch the heart & center of the beam signal, while other devices have to work with the edges or tails of the beam (X-BPMs) or feel the beam indirectly by wall-current pick-ups at considerable distance from the beam itself (e-BPMs). Eight of these devices will be installed and commissioned in 2006.

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