# CUPID: NEW SYSTEM FOR SCINTILLATING SCREEN BASED DIAGNOSTICS

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## *Abstract*

The Facility for Antiproton and Ion Research (FAIR) with its wide range of beam parameters poses new challenges for standard beam instrumentation like precise beam imaging. To cover the various foreseen applications for standard scintillating screen based diagnostics, a new technical solution was required.

CUPID (Control Unit for Profile and Image Data) is a new system for scintillating screen imaging, which is based on the data acquisition framework for FAIR. It includes digital image acquisition, remote control of the optical system (focus and iris; camera setup and power) and a graphical user interface (GUI). CUPID is also designed to work with different imaging devices like GigE cameras or video cameras using frame grabber cards. In this paper we report on the first results with this novel system during routine beam operation.

For imaging applications in the high radiation environment of the heavy ion synchrotrons radiation-hard cameras are required. One possible candidate for such cameras at FAIR is the CCIR MegaRAD3 from Thermo Fischer Scientific. We describe here our first results with this camera, which has been installed at the SIS18 extraction point, where a high radiation level is present.

## CUPID SYSTEM

CUPID is a new, fully FAIR-conformal system for standard scintillating screen based beam diagnostics including pneumatic drive, data acquisition, slow control of parameters like focus and iris and graphical user interface. The new system, installed and commissioned at several GSI High Energy Beam Transport Lines (see Figure 1) in the beginning of this year, is now used in standard accelerator operation.

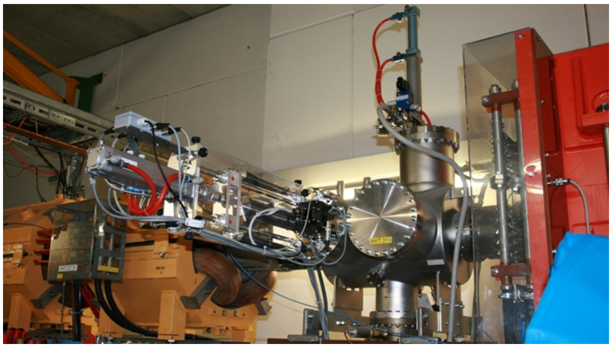

Figure 1: Scintillating Screen installation at High Energy Beam Transport Lines.

The scintillating screens with typically 120 mm diameter, made of Chromox or phosphor P43, are mounted on a pneumatic drive in vacuum. Special markers on the screen holder are used to calibrate the image and convert pixels into beam position and size in millimeters. The scintillating screens are typically (but not exclusively) mounted under 45° with respect to the beam axis and the optical axis of the camera. The camera is operated outside the vacuum chamber and views the screen through a UV-glass flange.

A LED can illuminate the scintillating screen for diagnostic purposes or recalibration of the optical system.

With the exception of the pneumatic drives, the direct hardware access (camera readout, lens control etc.) is based on FESA, the CERN Front-End Software Architecture [1]. Image acquisition, lens control and camera power are implemented as different FESA classes. Because CUPID is designed to work with different imaging hardware, a dedicated image acquisition FESA class is written for each imaging system supported. Using the inheritance mechanism in FESA a new imaging device can be easily incorporated in the system. The imaging base class contains all common code, like image manipulation (rotation, mirroring) and computations (profiles, intensity histogram, moments of the intensity distribution). It also provides the code to save raw images to disk (local or via network) as standard bitmap files. In addition, it enforces the common interface between the imaging FESA class and the CUPID GUI. The derived FESA class for the specific imaging device only implements the specific code to set up the device and acquire the images.

The decision to implement image acquisition, lens control and camera power as separate FESA classes (and thus devices) has the advantage, that single components can easily be exchanged or even removed. It is currently the responsibility of the GUI, to connect to the different FESA classes and hide this diversity from the operator. In the future FAIR control system, the paradigm proposed by the accelerator control system department is to treat all components as a single device and access it via a single FESA class. This is not contradictory to the approach used currently in the CUPID system. Using the 'association' feature of FESA, the single device paradigm can be implemented by creating a simple wrapper FESA class acting as a middle tier between the separate FESA classes now in use and the future control system.

The standard camera installed is the IDS uEye UI-5240SE-M [2], which is a digital GigE camera equipped with the radiation tested e2v CMOS sensor [3] with 1280 by 1024 pixel. A camera internal area-of-interest limits the image to

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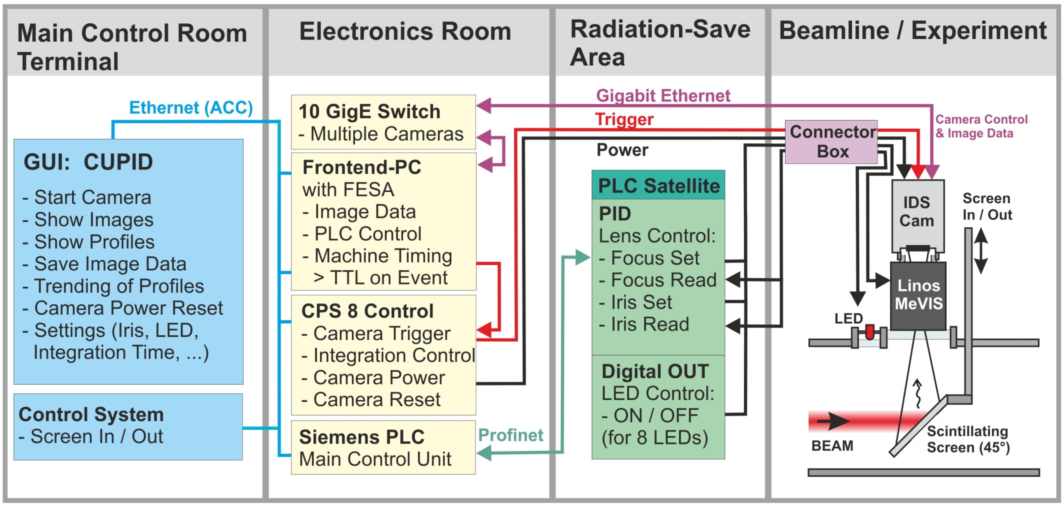


Figure 2: CUPID: overview of electronic devices and communication scheme.

the size of the scintillating screen and reduces the amount of data transferred already in the camera. Grouped according to their location,the cameras are connected via a HP Procurve 10 Gigabit Ethernet switch to a Kontron PCI 761 Industrial PC. The PC is equipped with an additional 10 Gigabit network adapter to provide a private network for the camera readout. The PC also runs the FESA classes and provides the link via the accelerator network to the GUI. The performance of the system reached more than 15 frames per second at full resolution with one active camera and a single connected client. Besides the IDS uEye camera, the Allied Vision Technology GC650 GigE camera has also been integrated in the CUPID system. It has been used in machine experiments with an image intensifier. Currently, a FESA class is under development to acquire images from an IDS FALCONquattro frame grabber card to be used with a radiation hardened camera from Thermo Fischer Scientific (see next section).

Power supply and remote reset for up to eight digital cameras are realized by the in-house developed Camera Power Supply controller CPS8. The CPS8 is based on an Arduino single-board microcontroller [4] and controlled via Ethernet. By sending simple ASCII commands the controlling FESA class sets the power of any attached camera. It can also obtain the power status of each connected camera. In addition, the CPS8 distributes hardware triggers to the cameras either from an external input or self-generated.

The standard installation for CUPID uses a Linos MeVis-Cm lens with 16 mm focal length, motorized iris and lens control with potentiometers to read back actual positions [5]. A Siemens PLC (main unit and satellites) handles control of focus and iris motors, read and set by a PID controller (FM355C). In addition, digital outputs (SM322) of the PLC control the LED to illuminate the phosphor P43 target (ProxiVision) respectively Chromox (BCE Ceramics) for calibration issues. A dedicated FESA class using the CERN IEPLC [6] library provides access to the PLC from the CUPID GUI.

Conforming to FAIR requirements, the GUI (see Figure 3) is written in Java. It displays the acquired image (corrected for camera orientation), the profiles, the intensity histogram as well as integral data like total brightness, centre of intensity in the reference coordinate system and full-width-half-maximum of the profiles. The GUI is also responsible for the conversion of pixels into millimetres. The corresponding conversion factors are stored with the FESA class and sent to the GUI with each profile or image. Because the scintillating screen is tilted 45° with respect to the camera's optical axis, the image suffers from perspective distortion. This means that the $x$ and $y$ positions in mm are a function of both, $x_p$ and $y_p$ the pixels positions. Because profiles are obtained by integrating the image pixels along the y (or x) axis, for the profile display the position in mm ($x$ and $y$ respectively) are assumed to be dependent only on the corresponding pixel coordinate ($x_p$ and $y_p$):

$$\begin{aligned} x &= m_x(x_p - x_0) \\ y &= m_y(y_p - y_0) \end{aligned}$$

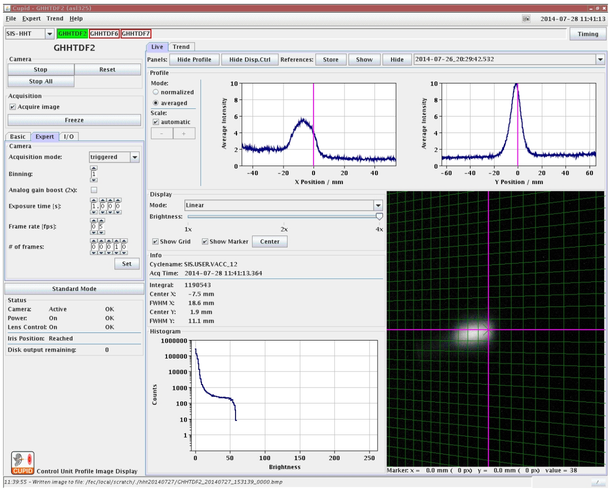
Here $m_x$ and $m_y$ are the average scaling factors in mm per pixel in x and y. The error due to perspective distortion is less than 5 mm at the edges of the scintillating screen with 120 mm diameter.

The GUI provides the possibility to overlay a grid with 5 mm line spacing over the image. In addition, the coordinates of any pixel under the mouse cursor are displayed not only in pixels but also in mm. For the grid and the cursor display, the conversion is calculated according to (for the x-axis):

$$\begin{aligned} x'_p &= x_p - x_0 \\ y'_p &= y_p - y_0 \\ m &= m_x + m_{xx}x'_p + m_{xy}y'_p \\ x &= mx'_p \end{aligned}$$

Thus for each pixel coordinate a scaling factor $m$ in x is calculated, which depends on the pixels x and y coordinate.

$m_{xx}$ is the change of the scaling factor in x with the pixel's x coordinate $x_p$ (i.e. $\Delta m_x/\Delta x_p$) and $m_{xy}$ is the change with $y_p$ (i.e. $\Delta m_x/\Delta y_p$). Depending on the orientation of the scintillating screen, in general either $m_{xx}$ or $m_{xy}$ is zero. The conversion for the y axis is performed accordingly. However, it should be noted, that this more elaborate calibration noticeably improves the accuracy of the beam position only at the outer regions of the scintillating screen.



2014-07-28 11:41:13

2014-07-26_20:29:42.532

☑ Acquire image

Camera

Acquisition mode: triggered

Binning: 1

Analog gain boost (2x): ☐

Exposure time [s]: 1.000

Frame rate [fps]: 05

# of frames: 00010

Status

Camera: Active OK

Power: On OK

Lens Control: On OK

Iris Position: Reached

Disk output remaining: 0

○ normalized

● averaged

☑ automatic

Mode: Linear

Brightness:

☑ Show Grid ☑ Show Marker

Info

Cyclename: SIS.USER.VACC_12

Acq Time: 2014-07-28 11:41:13.364

Integral: 1190543

Center X: -7.5 mm

FWHM X: 18.6 mm

Center Y: 1.9 mm

FWHM Y: 11.1 mm

Marker: x = 0.0 mm ( 0 px) y = 0.0 mm ( 0 px) value = 38

11:39:55 - Written image to file: /fec/local/scratch/./hht20140727/GHHTDF2_20140727_153139_0000.bmp

Figure 3: CUPID GUI with an image of $7\times10^9$ protons at 4 GeV on Chromox screen.

For basic operation the camera controls are reduced to changing the opening of the iris and switching on or off the illuminating LED. An expert mode provides more detailed control like changing the exposure time, the binning of the image or requesting the raw images to be automatically saved to disk by the FESA class. It also allows to change the acquisition mode. The CUPID system provides three acquisition modes, which may either be realised in hardware or in software by the FESA class. The two most important ones are 'free run' and 'triggered'. In 'free run' the camera continuously acquires images with the specified exposure time and frame rate. The acquired images are displayed in the GUI as they arrive in real time. In the 'triggered' mode, the image acquisition is triggered by a machine event of the accelerator (for example at beam extraction). At the time of the trigger, a single image is acquired by the FESA class and displayed by the GUI. An extension of the 'triggered' mode is the 'sequence' mode, which acquires a predefined number of images with the specified frame rate after a trigger is received.

The CUPID system is currently running successfully at 16 different points in the GSI high energy beam transport lines. In daily operation it was used to image several beams from protons up to uranium with various beam energies and intensities. The generally positive feedback by the operating team highlights the simple usage of the GUI and the advanced features of the new system. The work experience gathered so far confirms CUPID as the standard for scintillating screen based beam instrumentation at GSI and FAIR.

## RAD-HARDENED CAMERA TESTS

Technological advances in solid state camera design provide a wider choice of equipment for beam instrumentation. However, our previous experience with CCD based cameras has shown that their performance degrades during operation due to the background radiation ($\gamma$, neutrons, etc.) produced by the heavy ion beam (see Figure 4). Any semiconductor device operating in a radiation field can undergo degradation due to radiation damage effects. Energetic particles incident on the semiconductor bulk lose their energy to ionising and non-ionising processes as they travel through a given material. The ionising processes involve electron-hole pair production and subsequent energy deposition (dose) effects. The non-ionizing processes result mainly in displacement damage effects, i.e. displaced atoms in the detector bulk and hence defects in the semiconductor lattice like vacancies and interstitials. More details can be found in [7].

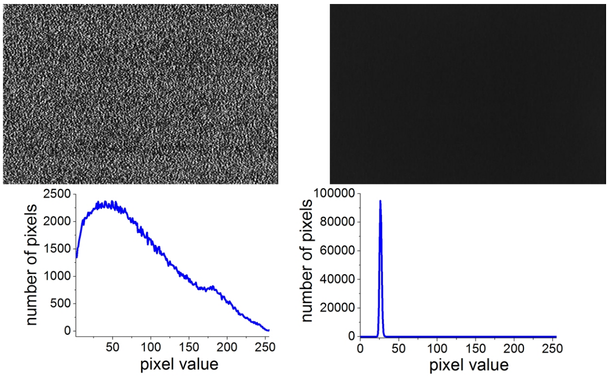


Figure 4: Dark image of the standard CCD camera Sony XC-ES30 (upper left) and new radiation-hardened solid-state CID camera MegaRad3 (upper right) after few weeks of irradiation with its corresponding histograms of pixel brightness below (bottom right, bottom left, respectively).

In the GSI SIS18 extraction point a great variety of particles with energy of up to few GeV/u is present. At this location, where a high radiation level is observed, the CCIR MegaRad3 (8726DX7) radiation-hardened solid-state CID (Charge Injection Device)-based camera [8] was installed in 2013. According to the manufacturer [9] this device is tolerant to gammas, neutrons, high energy electrons and proton radiation to at least 3 MRad. Only in tests up to 14 MRad a noticeable degradation in the image quality has been reported by the manufacturer.

In our tests, the camera has been placed near the SIS18 extraction. The camera is continuously running since November 2013. The accumulated dose impinging on the camera has been monitored by thermoluminescent dosimeters placed next to the camera. During this test, we found the image quality to be nearly the same after eight months of exposure to neutrons (accumulated dose: 55 Sv) and $\gamma$ (accumulated dose: 33 Sv) radiation. As shown in Figure 4 and Figure 5, no significant change in camera performance like loss of contrast and resolution was observed. A standard

CCD camera at the same position was out of order due to irradiation within two weeks of operation. The dark image of a standard CCD camera at a position with lower radiation level is shown in Figure 4.

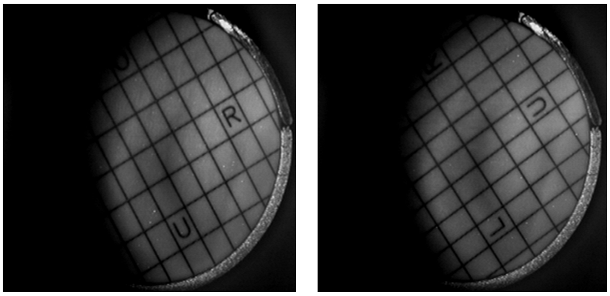


Figure 5: Original pictures of scintillating screen target with progressive level of accumulated dose. No loss of contrast was observed. Left: before test, right: after 8 months beam operation at SIS18.

Our first test with this radiation-hardened solid-state CID-based camera is very promising. This device exhibits a significant improvement for operation in a radiation rich environment as compared to the CCD and CMOS-based cameras. The performed tests show that the camera is not sensitive to radiation damage on the level observed at GSI. This makes this camera suitable for use in precise and reliable profile monitors of high energy heavy ion beams in the vicinity of beam extraction points, targets or beam dumps as well as other higher radiation environments expected at FAIR.

## SUMMARY

The Facility for Antiproton and Ion Research (FAIR) poses new challenges for standard beam instrumentation like precise beam imaging over a wide range of beam parameters, radiation hardness, etc. CUPID, a new, fully FAIR-conformal system for standard scintillating screen based diagnostics was developed, commissioned and employed in routine beam operation at GSI. CUPID includes digital imaging, a remote controllable optical system, mechanical drive and easy to use GUI. Based on FESA it is expected to seamlessly integrate into the future control system of FAIR.

In addition, we reported on our first experiences with a radiation hardened CID-based camera. The camera is working in the SIS18 extraction point at a high radiation level. After 10 months of operation no deterioration or loss in the camera features were observed. This device exhibits a significant improvement for operation in radiation rich environments as compared to standard CCD-based cameras.

CUPID and the radiation hardened camera are the first beam instrumentation devices for FAIR used in routine operation with beams from proton to uranium. Results and feedback from the operating team promises a successful operation at FAIR.

## ACKNOWLEDGEMENT

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