2D WIRE GRID INTEGRATED WITH FARADAY CUP FOR LOW ENERGY H- BEAM ANALYSIS AT SIEMENS NOVEL ELECTROSTATIC ACCELERATOR

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Abstract

A wire grid with 21 wires each vertically and horizontally with a spacing of 1 mm has been developed for beam analysis at Siemens' novel electrostatic accelerator. The wire grid is integrated in a Faraday Cup and profile measurements can therefore be combined with current measurements. The grid is used to analyse the 10 keV H^- beam coming from the ion source and the obtained beam parameters will be used as input for simulations of the beam transport in the accelerator. All 42 wires can be read out simultaneously with a multi-channel precision electrometer and the data can be fitted instantly with LabVIEW code that was developed for this purpose. This paper reports on some details of the mechanical design and the data analysis procedure in LabVIEW as well as some results of first measurements at the novel accelerator.

INTRODUCTION

Siemens is currently building a prototype for a novel electrostatic accelerator [1] for industrial applications such as radioisotope production for medical imaging. The novel accelerator makes use of a modified form of the Cockcroft-Walton accelerator principle. It integrates capacitors, grading electrodes and beam tubes resulting in a simple as well as very compact machine which offers many advantages in an industrial environment.

The novel accelerator consists of two sets of concentric hemispherical metallic shells with the highest potential being in its centre. The accelerator will therefore be operated in tandem mode with a carbon stripper foil in its centre and a H^- negative ion source as injector. In order to contribute to the compactness of the machine, a bespoke H^- volume cusp ion source has been designed for the system (see [2]). The ion source produces H^- ions in a hydrogen plasma, which is contained in a magnetic field. The plasma is ignited, maintained and heated by a discharge current between a heated tungsten filament cathode and the walls of the source volume itself. It is fueled by a constant inflow of hydrogen from a pipe and pumped by a vacuum system on the extraction side of the source. In order to provide an ideal environment for the formation of H^-, the plasma chamber is divided into two major regions by a magnetic filter field. The first area is the one on the cathode side of the source where the discharge takes place. It serves for heating the plasma and Ro-vibrationally exciting H_2 molecules. The second area is on the extraction side and has a much lower electron temperature, which is ideal for the formation of H^- ions through dissociative attachment of electrons. H^- extracted from plasmas usually forms non space charge compensated beams with a Bennett profile

$$j(x,y) = I_{beam} \cdot \frac{1}{\pi b_x b_y} \frac{1}{\left(1 + \frac{x^2}{b_x^2} + \frac{y^2}{b_y^2}\right)^2} \tag{1}$$

As soon as space charge compensation begins these beams develop a Gaussian profile

$$j(x,y) = I_{beam} \cdot \frac{1}{2\pi\sigma_x\sigma_y} e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} \tag{2}$$

It is not clear which one of the two profiles is to be expected for our ion source and therefore the beam instrumentation has to be able to deal with both of them.

In order to contribute to the compactness of the proposed accelerator the ion source will directly inject into the DC structure without any LEBT or beam instrumentation inbetween. Therefore the beam coming from the ion source needs to be well characterised, stable, reliably repeatable and matched to the beam transport in the DC structure. For this reason temporal instrumentation has been developed and used to characterise the beam extracted from the ion source with repeatable ion source operating parameters prior to the installation of the cascade accelerator structure. The obtained results serve as a basis for beam transport simulations in the accelerating structure.

The presented system consists of a Faraday Cup with a magnetic suppression of electrons at its entrance as well as a secondary electron suppression field. Integrated in the cup is a wire grid for horizontal and vertical beam profile measurements. As the beam is expected to be round it might seem possible to measure the beam diameter with just one set of wires. However, in order to measure the beam position as well, and include its effect into the signal reconstruction process, a second set of wires is necessary. The whole cup sits on rods and the distance to the ion source is therefore variable. This enables measurements at different positions and hence makes a measurement of the beam divergence possible.

ISBN 978-3-95450-127-4

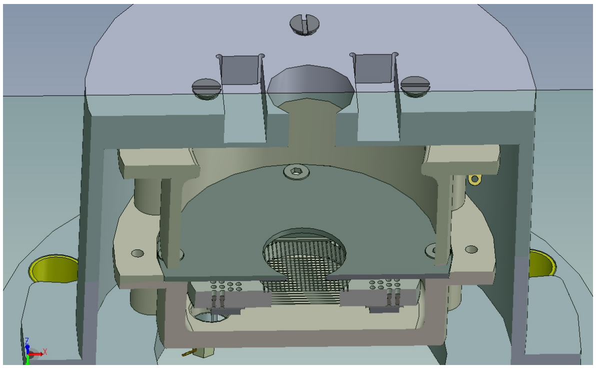

Figure 1: The Faraday Cup with the integrated Wire Grid.

HARDWARE DESIGN

The expected beam diameter from the ion source is in the range of 1-20 mm.

The Faraday Cup has permanent magnets at its 20 mm entrance aperture which create an orthogonal magnetic field in order to deflect electrons with their 1000 times higher q/m ratio. This ensures that electrons extracted from the ion source do not contribute to the measurement. The H^- ions then hit the collector electrode at the back of the cup where the current is measured. The suppression electrode in front of this electrode can be biased up to 1000 V in order to suppress secondary electrons incident from the H^- ions hitting the cup, however measurements have shown that a suppressor voltage of 500 V is sufficient (see Fig. 2.

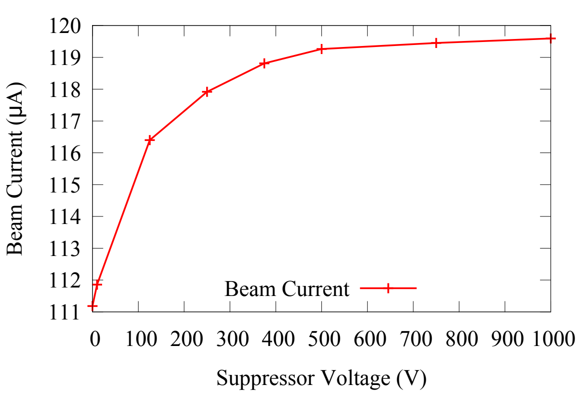

Figure 2: Relation between the applied suppressor voltage and the measured beam current. Without suppression one secondary electron for every ten H^- leaves the cup and falsifies the measurement. 500 V are sufficient to suppress most of this effect.

On the inside of the beam collector electrode sits a piece of ceramic that holds the 42 stainless steel wires, 21 horizontally and 21 vertically (see Fig. 3). All wires are electrically isolated and individually connected to a 50 way vacuum connector at the back of the cup. The individual wires are spaced vertically by 1 mm and have a width of 0.2 mm each. The vertical and horizontal set of wires are spaced by the ceramic ring which has an effective thickness of 4 mm. The collector electrode has an aperture of 20 mm which ensures that the beamlet incident on the grid is no wider then 20 mm, which is important for the accuracy of the analysis procedure. The collector electrode could potentially be biased for suppression of secondaries.

Due to the filigree design the assembly of the wires has proven rather challenging. Both the set on the top and on the back of the ceramic piece have to be assembled wire by wire, fixing each wire with tiny grub screws on each side and fixing its electrical connection with another grub screw. During the assembly process the ceramic piece broke and the design had to be improved to make assembly easier. For the new design the wires have been etched as one large harp from a sheet of steel. Therefore they are rather bands than wires and can be laid on top of the ceramic as one large piece. The wires can then be fastened with the grub screws and afterwards disconnected from each other by cutting the sides of the harp.

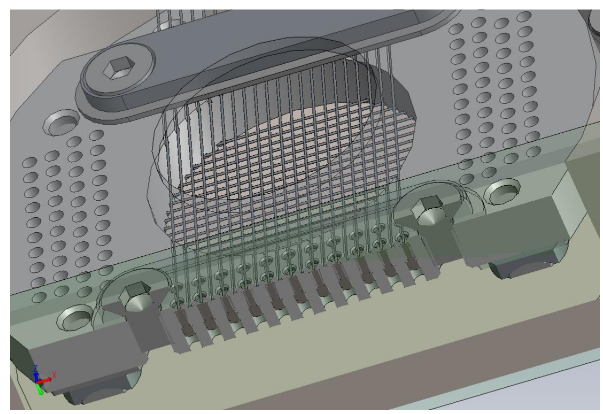

Figure 3: The Wire Grid with its ceramic assembly and grub screws for every single wire.

Each individual wire of the grid is connected to a separate channel of a 64-way high precision electrometer. All wires can be read out at the same time by the electrometer. The electrometer itself is implemented into a LabVIEW environment via a serial interface. Measurements can be triggered from the LabVIEW user interface and results can be viewed on the screen instantly.

ANALYSIS PROCEDURE

The beam profile can be reconstructed by fitting the experimental data to the expected current density distribution function. Each electrometer channel measures the integrated current on the surface area of the connected wire, i.e. a long very narrow rectangle.

Gaussian Profile

Taking the current density distribution from Equation 2 we can do the integration in the y-dimension over a narrow wire with width d_{wire} and infinite length to calculate the measured current I_{meas}:

ISBN 978-3-95450-127-4

$$\frac{I_{meas}(x)}{d_{wire}} = I_{beam} \cdot \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \tag{3}$$

This is a 1D Gaussian distribution. However, our wires are not of infinite length and parts of the wire will be shadowed by the circular aperture and therefore not contribute to the measurement. With (z_y) being the displacement of the whole distribution in the y dimension and r the radius of the aperture, the y integration needs to be performed along the length $2y$ with $y^2 = r^2 - x^2$:

$$\frac{I_{meas}(x)}{d_{wire}} = I_{beam} \cdot \int_{-\sqrt{r^2-x^2}-z_y}^{\sqrt{r^2-x^2}-z_y} \frac{e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}}}{2\pi\sigma_x\sigma_y}\, dy \tag{4}$$

$$= I_{beam} \cdot \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \cdot C \tag{5}$$

This is the 1D Gaussian distribution in x from Equation 3 multiplied with a correction factor C which accounts for the finite length of the wire:

$$\frac{1}{2}\left(\mathrm{Erf}\left[\frac{\sqrt{r^2-x^2}-z_y}{\sqrt{2}\sigma_y}\right] + \mathrm{Erf}\left[\frac{\sqrt{r^2-x^2}+z_y}{\sqrt{2}\sigma_y}\right]\right) \tag{6}$$

With $\mathrm{Erf}(x)$ being the error function. This factor between 0 and 1 depends on σ_y, z_y and x but not on the fit parameters σ_x and z_x. A Gaussian fit in x can be done once the factors have been calculated using the numbers from the y-distribution. For the fit of the y-distribution from the y-wires' data there will be a correction factor depending on σ_x and z_x. Therefore an iterative procedure needs to be carried out until convergence:

1. Measure data with x and y wires
2. Do Gauss fit on the y data, determining σ_y and z_y
3. Use σ_y, z_y to correct x data (Equation 5)
4. Do Gauss fit on corrected x data yielding σ_x and z_x
5. Use σ_x, z_x to correct y data
6. Do Gauss fit on corrected y data yielding σ_y and z_y
7. Go to step 3

Bennett Profile

For the Bennett profile in Equation 1 integration along an infinitely long wire in the y-dimension yields:

$$\frac{I_{meas}(x)}{d_{wire}} = \frac{I_{beam}}{b_x} \cdot \frac{1}{2} \cdot \frac{1}{\left(\sqrt{1+\frac{x^2}{b_x^2}}\right)^3} \tag{7}$$

However, according to the argument in the treatment of the Gaussian profile, the limited length of our wires lead to a smaller current actually measured on the wire:

$$\frac{I_{meas}(x)}{d_{wire}} = \frac{I_{beam}}{\pi b_x b_y} \cdot \int_{-\sqrt{r^2-x^2}-z_y}^{\sqrt{r^2-x^2}-z_y} \frac{1}{\left(1+\frac{x^2}{b_x^2}+\frac{y^2}{b_y^2}\right)^2}\, dy \tag{8}$$

$$= \frac{I_{beam}}{b_x} \cdot \frac{1}{2} \cdot \frac{1}{\left(\sqrt{1+\frac{x^2}{b_x^2}}\right)^3} \cdot C \tag{9}$$

this is the distribution from Equation 7 multiplied with a correction factor C to take account of the finite length of the wires:

$$\frac{1}{\pi}\left[\frac{\frac{y}{b_y}\cdot\sqrt{1+\frac{x^2}{b_x^2}}}{1+\frac{x^2}{b_x^2}+\frac{y^2}{b_y^2}} + \tan^{-1}\left(\frac{\frac{y}{b_y}}{\sqrt{1+\frac{x^2}{b_x^2}}}\right)\right]\Bigg|_{y=-\sqrt{r^2-x^2}-z_y}^{y=\sqrt{r^2-x^2}-z_y} \tag{10}$$

Again an iterative procedure needs to be carried out fitting the x and y profiles until the numbers converge. The correction and fit procedure for both the Bennett and Gauss distributions has been implemented into LabVIEW and can be carried out simultaneously for both of them along with the actual measurement. The fit residues can then be compared to see whether the beam looks more Gaussian or Bennett like.

The approach we have chosen relies on an elliptical beam profile and on a matching between the axes of the ellipse and the vertical and horizontal wires. The reconstruction would not be correct for an ellipse which is tilted towards the coordinate system given by the wires. However, as we expect the beam to be round, this does not play a role in our considerations.

FIRST RESULTS

In order to test the analysis software module of the control software a simulation environment has been implemented in the control system. This software component creates dummy data for each channel of the electrometer, adds a certain noise level to the dummy data and then feeds it into the analysis module. The tests of the analysis software have shown that the procedure is capable of reconstructing the correct beam distribution parameters within ten iterations for beams with diameters of the order of 20 mm or less at reasonable noise levels. The larger the beam diameter is, the higher are the corrections of Equations 6 and 10 and therefore the higher the number of iterations required. In this case the procedure is also much more sensitive to noise and more likely to diverge. The residue of the fit makes it possible to decide whether the distribution looks more like a Gaussian or like a Bennett profile, however as Fig. 6 shows this effect goes down with noise levels. This implies that at high noise levels it is impossible to distinguish between a Gaussian shaped and a Bennett shaped beam.

ISBN 978-3-95450-127-4

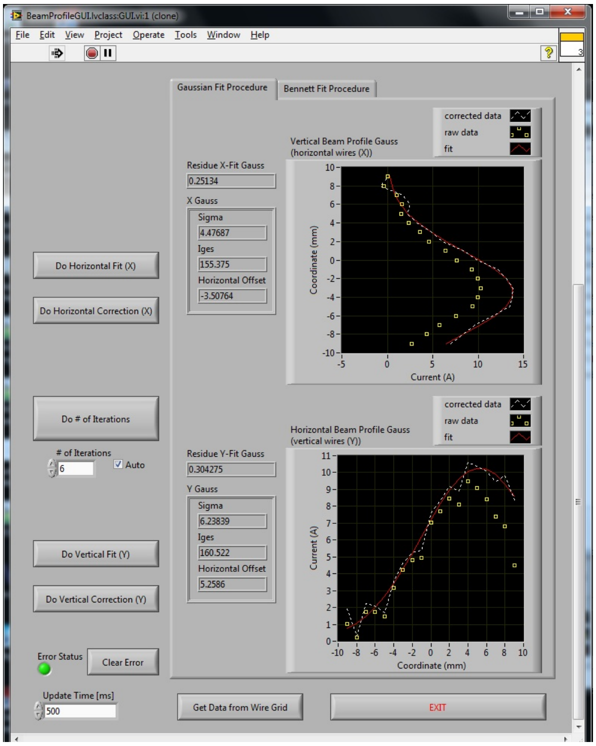

Figure 4: The analysis software reconstructing simulated data.

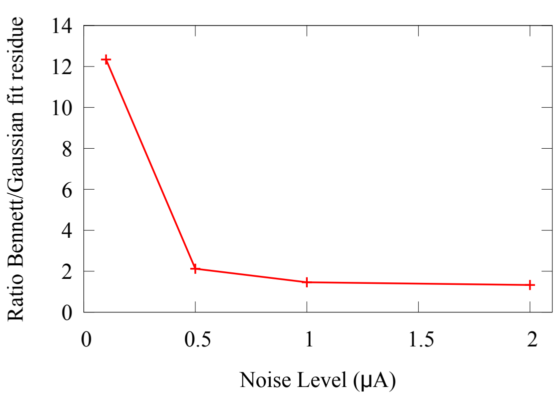

Figure 5: Ratio of the residue from Bennett and Gaussian fits from simulated Gaussian beam data with $\sigma = 8$ mm, displacement $z = 5$ mm and beam current $I_{beam} = 150\ \mu$A. At low noise levels it is easy to tell that the data comes from a Gaussian beam as the residue from the Bennett fit is far higher.

Unfortunately a broken ceramic wire holder has so far prevented real measurements. The ceramic component and the way of assembling the wires have been redesigned and the assembly of the new parts is under way. First measurements will take place immediately after this conference. These will aim to confirm the round beam shape as well as to demonstrate that small beam diameters of a few mm can be achieved. Another objective will be to reach sufficiently low noise levels to be able to reliably distinguish between Gaussian and Bennett shaped beams. This will enable us to investigate how the space charge compensation of the beam evolves. Later on a full characterisation of the extracted beam will be carried out. This will focus on how the different ion source operating parameters affect the beam diameter and divergence and the data will then serve as input for beam simulations for the subsequent DC accelerator. These simulation studies will aim to find the ion source settings which are matched to the unchangeable beam transport in the machine.

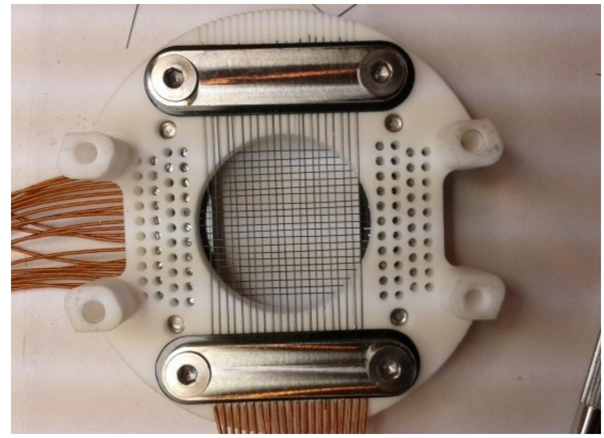

Figure 6: A photo of the ceramic piece holding the wires. The tiny threads for the grub screws are rather fragile and assembly using simple wire is difficult as wires start bending when the screws are fastened. The future design therefore uses the bands of a harp etched from a sheet of steel.

CONCLUSION AND OUTLOOK

A versatile beam instrument has been presented which is suitable to characterise the novel accelerator's ion source in order to provide data for beam simulations in the subsequent machine as well as for the actual operation of the accelerator. The analysis procedure allows for the use of a circular aperture which is very practicable in conjunction with the circular beam coming in through the Faraday Cup outer aperture. The analysis software has been successfully tested and validated with dummy data sets. Up to a certain noise level it is able to distinguish between a Gaussian and Bennett beam profile. Problems with the assembly of the ceramic wire holder have made a redesign of this component necessary and hence prevented measurements with real beams. However the assembly of the new component is underway. Measurements with beam are expected to take place within the next couple of weeks and a full characterisation of the ion source will then be carried out.

REFERENCES

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ISBN 978-3-95450-127-4