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Beam Shape and Halo Monitor Study

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Abstract

The Beam Shape and Halo Monitor, designed by Masaki Hori, is the main diagnostic tool for the 3 MeV test stand scheduled in 2008. This detector will be able to measure the transverse halo generated in the RFQ and the Chopper-line and to detect and measure the longitudinal halo composed of the incompletely chopped bunches.
Its principle of functioning is the following: H- ions hit a carbon foil and generate secondary electrons with the same spatial distribution than the incoming beam and a current depending on an emission coefficient given by the carbon foil. These electrons are accelerated towards a phosphor screen by an electric field applied between accelerating grids. Once the electrons reach the phosphor screen, they generate light which is transmitted to a CCD camera via optic fibers [1]. It is expected to give a time resolution of 1-2ns and a spatial resolution of 1mm.
The first test of the BSHM done with a Laser has shown a spatial resolution bigger than 1cm and the time resolution bigger than 2ns[2].
The purpose of this study is to understand what are the processes which deteriorate the resolution and to show the benefits brought by adding a pre-accelerating grid in the detector.

Geneva, Switzerland
10/10/2006

I Secondary electron emission

Here we summarize the physics of the secondary electron emission process from a carbon foil for both Laser and H- ion beam impact.
The electron beam is characterized by its transverse and longitudinal dimensions, its current, and its energy spread.

1) With Laser.

In the first test done by Masaki Hori, the electron beam has been created by a Laser impact on the carbon foil.

Lasers properties : Wave length : 214-264nm
Pulse length : 700ps
Energy : 10µJ/pulse
Diameter : 2mm

240nm wave length corresponds to a photon energy of:

$$E = \frac{hc}{\lambda} = 5.17eV$$

The work function of carbon is approximately equal to 4.5eV [3]. It means that if the photon energy is bigger than this value, an electron can be extracted from the carbon foil by photoemission. These electrons can be emitted in all directions with different energies and the dimensions of the beam are the same as the Laser (700ps and 2mm diameter).
Laser energy could also be related to the electron beam current.

2) With H- particles beam.

Each H- ion will enter the carbon foil and create an electric field due to its charge. This electric field will give sufficient energy to electrons of carbon atoms in order to strip them. Emitted electrons have a bigger initial energy range than in case of the Laser creation. The energy is mainly between 0 and 20eV but some electrons can have up to 50 or 100eV. If we assume that the ratio between the coming H- current and the emitted electron current is between 0.3 and 1, then a 65mA H- beam should produce an electron beam current from 20 to 65mA.
As the carbon foil of the detector has an angle of 45° with respect to the H- trajectory, so the transverse electron beam dimensions are multiplied by $2^{1/2}$.

The first tests done with laser showed the necessity to improve the detector in order to reach the specification resolution.

II Detector Hardware

There are two different configurations for the detector. The baseline configuration as presently implemented in the detector and an improved configuration, with a pre-acceleration grid. The main purpose of the simulations we have done is to highlight the possible advantages of adding this grid.

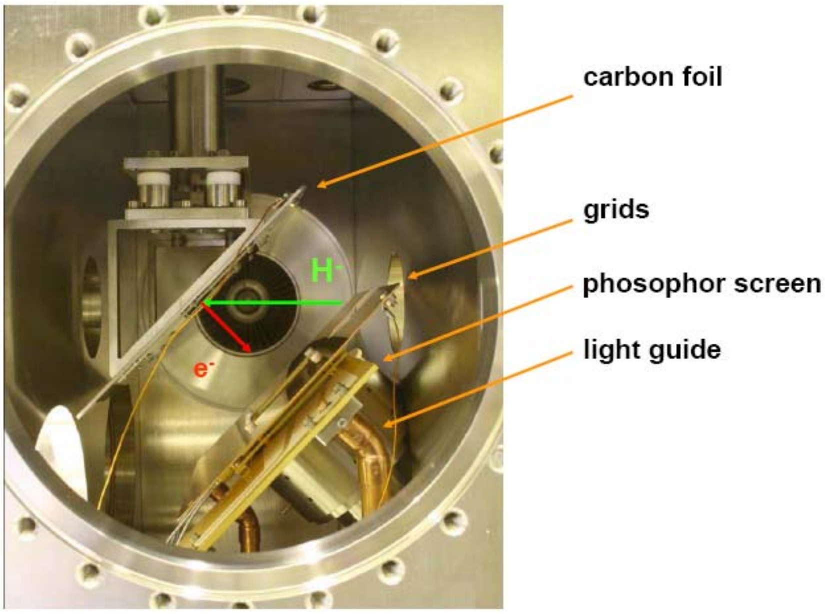
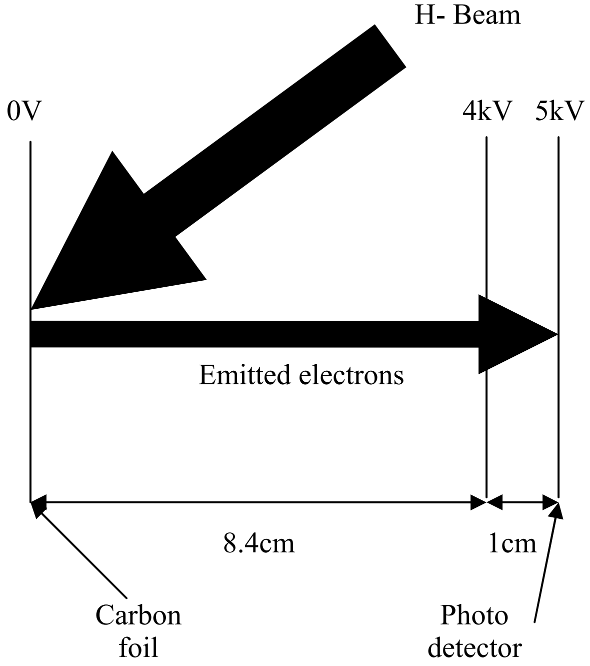


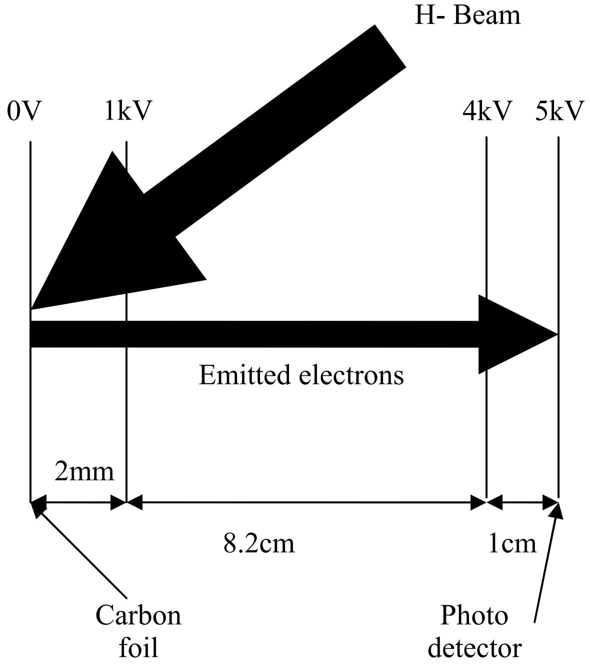
Figure1 :BSHM side view



Baseline configuration

H- beam impacts on the carbon foil and generates electron cloud which is first accelerated with a 4kV voltage over 8.4cm and 1kV over 1cm before it reaches the photo-detector.

Figure2: BSHM baseline configuration



Improved configuration

H- beam impacts on the carbon foil and generates electron cloud which is first accelerated with a 1kV voltage over 2mm, then 3kV over 8.2cm and finally 1kV over the last 1cm before it reaches the photo-detector.

Figure3: BSHM with pre-accelerating grid

III Simulation of electron beam transport with Matlab

(No space charge)

A map of the field between the carbon foil and the collector has been generated with Superfish [4] to simulate the dynamics of the electron transport. The model built is as close to the BSHM hardware as possible.

Model specification

18 cm long plates, distance between the plates 8.5 cm.

Upper plate voltage 0V.

Lower plate voltage 5000V.

Box at 0 potential.

Field lines are quite straight in the central region between the plates for the detector area of 4x4 cm.

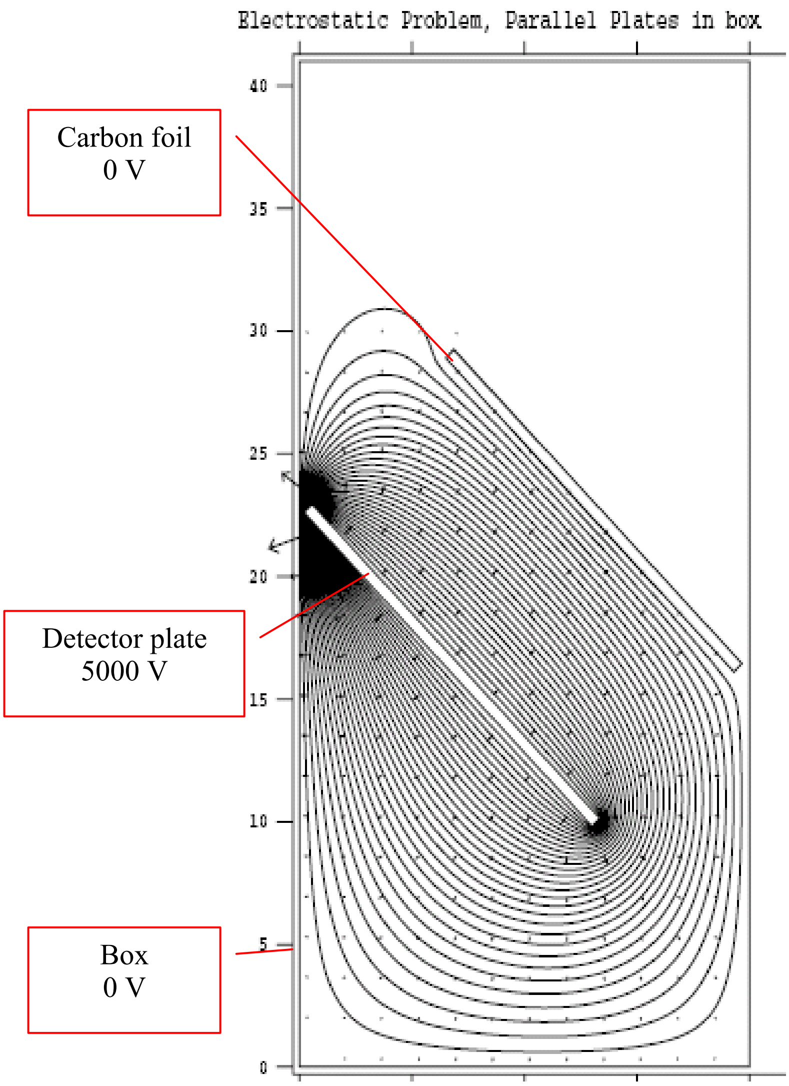


Figure4: Equipotential field line of Superfish BSHM model

We have taken the field map to make a simulation in Matlab of the electron beam dynamics. The purpose of these first simulations is to show the effect of the initial electrons speed and of the fringe field.

- **First case : Effect of velocity spread.**

We have considered three electrons emitted in the middle of the plate with three extreme directions. These particles are representative of three extreme cases we can observe. One with a 20eV energy and a speed perpendicular to the foil, and two with a 20eV energy and a speed parallel to the foil in both directions. The trajectories of these 3 electrons in the BSHM are shown in figure5.

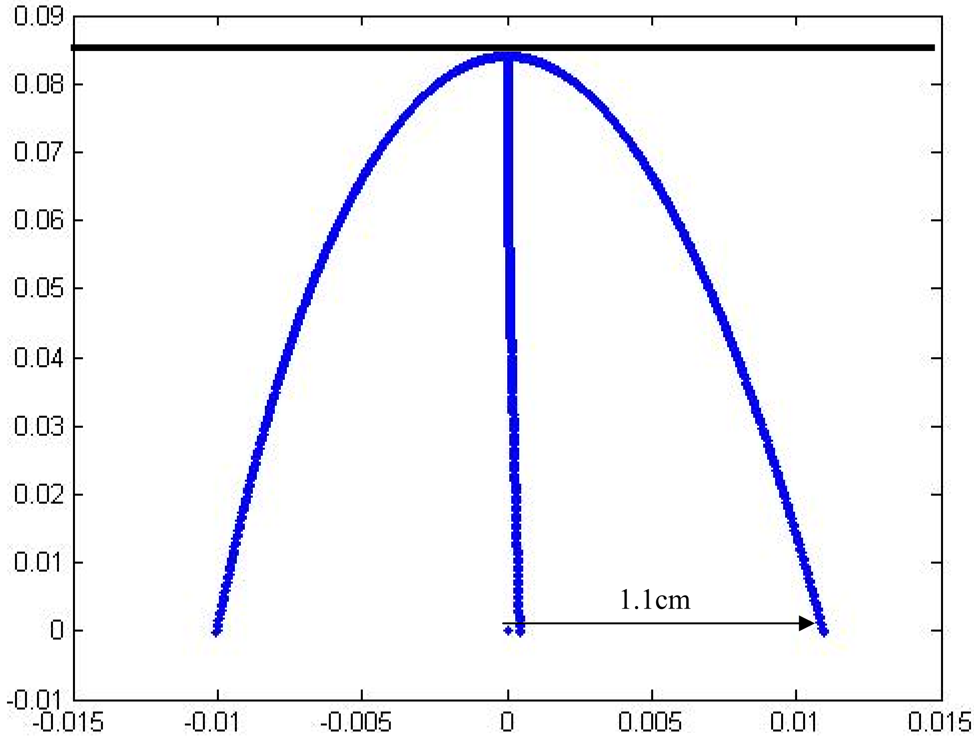


Figure5: Trajectories of particular electrons

The fastest particle is the one with the perpendicular speed. It reaches the plate after 3.84 ns. The two other take 4.1ns to reach the detector. The biggest transverse displacement is equal to 1.1cm.
These results show that the differences in initial speed of the emitted electrons leads to a 0.26 ns time spread and 1.1cm transverse spread.

ΔX in	ΔX out	Δt in	Δt out
0	1.1 cm	0	0.26ns

Table1: Effect of the initial velocity spread

- **Second case : Effect of velocity spread combined with fringe field.**

The same simulation than for the first case has been done, but with a larger number of electrons emitted in different points of the carbon foil.
We have generated randomly 200 electrons with a energy range from 0 to 20eV and a random initial speed angle between -90° and 90°. These particles are emitted in a range of +/- 3cm around the center of the plate.

The extreme values are summarized here:

Minimum travel time: 3.87ns
Maximum travel time: 4.44ns
Maximum transverse displacement: 1.23cm

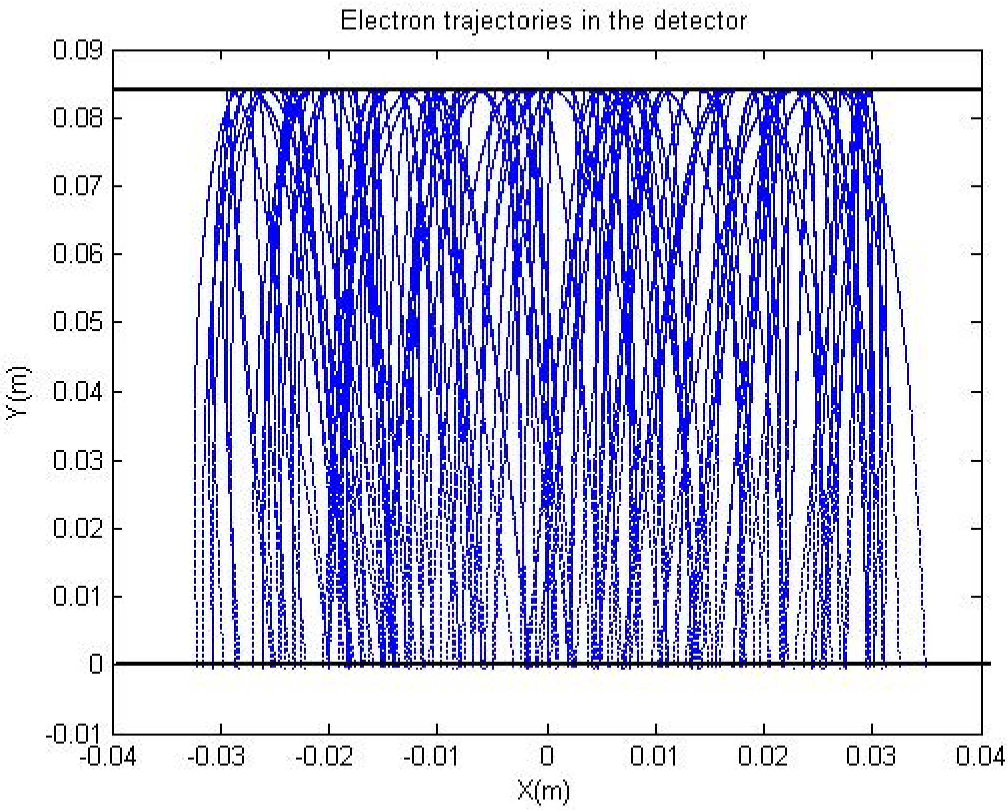


Figure6: Trajectories of 200 electrons in BSHM

That means that the differences of initial electron speed and the field lines which are not fully perpendicular to the carbon foil leads to a 0.57ns time spread and a 1.23cm transverse spread.

ΔX in	ΔX out	Δt in	Δt out
+/- 3cm	+/- 3.5cm	0	0.57ns

Table2: Effect of fringe field and energy spread

By looking at extreme cases we can learn that:

- The biggest displacement appears for an electron emitted far from the center, where the field lines are the more distorted (-2.72 cm for an initial range of +/- 3cm), and with a 17eV energy and a speed almost parallel to the carbon foil (-83°).
- The slowest electron, as also been emitted on the side of the initial range (2.4cm) and see distorted field lines. It has also been emitted with a very small speed (its initial energy is 0.0046eV).
- The fastest electron, has been emitted close to the center of the carbon foil (0.35cm), where the field lines are the more straight, and with a high speed, with respect to others, (initial energy of 15eV) almost perpendicular to the foil (initial angle of 10°).

This first stage of study shows us that the initial electron velocity and the fringe field are not enough to explain the degradation of the time and space resolution. But they have a non negligible influence.

IV Simulation of electron beam transport with PathManager (including space charge)

Path [5] was used to simulate electron beam transport with space charge, which is important at such a low energy. We have simulated 3 cases : the baseline configuration, the improved configuration with the pre-accelerating grid, and the improved configuration combined with a 1kGauss magnetic field.
We want to see the effects of the pre-accelerating grid on the time and position resolution. We have also made a case with a constant longitudinal magnetic field obtained with existing permanent magnet designed for the detector, which should improve the space resolution. In the following graphs are represented the two main quantities which bring us the interesting information:

- The final beam radius on the phosphor screen (space resolution)
- The Phase spread (time resolution)

For the three detector configurations, we have taken the same electron beam parameters. We have just varied the beam current from 0 to 65mA.
Electron beam parameters:

Radius : 7mm (circular).
Phase length : 60° @ 352.2MHz (corresponding to H-beam length).
Energy : from 0 to 20eV in all directions.
Current : from 0 to 65mA

1) Radius of the electron beam: Space resolution.

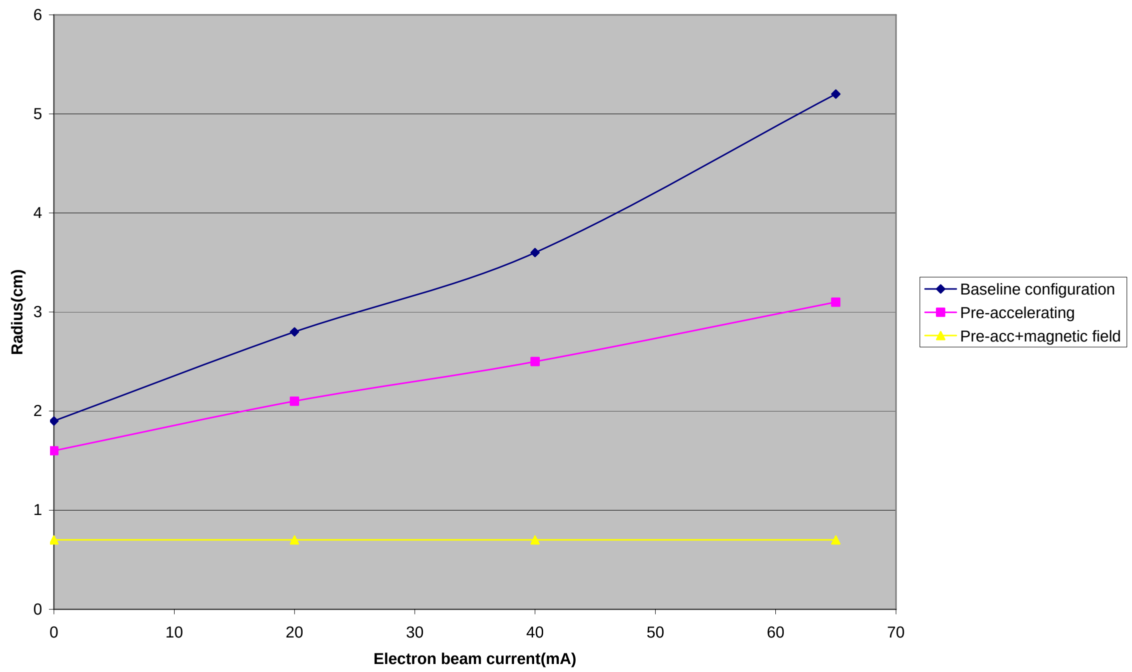


Figure7: Final beam radius on the photo detector

With no current, we can see the influence of the initial emittance of the beam. Adding the pre-accelerating grid doesn't change a lot the final radius. By increasing the current until 65mA, we have the effect of the space charge. In this case, the grid effect becomes more important decreasing the final radius from 5.2cm to 3.1cm. The grid has, with space charge, a good influence on the transverse expansion. In fact, space charge is decreasing with velocity, so the earlier energy is given to particles, the earlier the space charge effect decreases. By adding a longitudinal constant magnetic field of 1kGauss to the modified detector, we manage to constrain the beam radius in a cylinder of 7mm radius and the envelope of the beam is constant along the whole detector. In fact, considering that the transverse energy of electrons is not bigger than 20 eV, a

1kGauss longitudinal magnetic field confines them in a quasi linear trajectory. Their radius of curvature around the magnetic field is :

$$\rho = \frac{p}{qB} = 0.15mm$$

In order to improve the space resolution, adding the pre-accelerating grid and a magnetic field, ensures that we keep the size of the initial electron cloud created by the H- beam. We conserve the spatial information has shown by the multiparticle code Path.

2) Phase spread: Time resolution.

The phase spread of the electron beam gives us information about time resolution. Working at 352.2MHz, a period corresponds to 2.84ns.

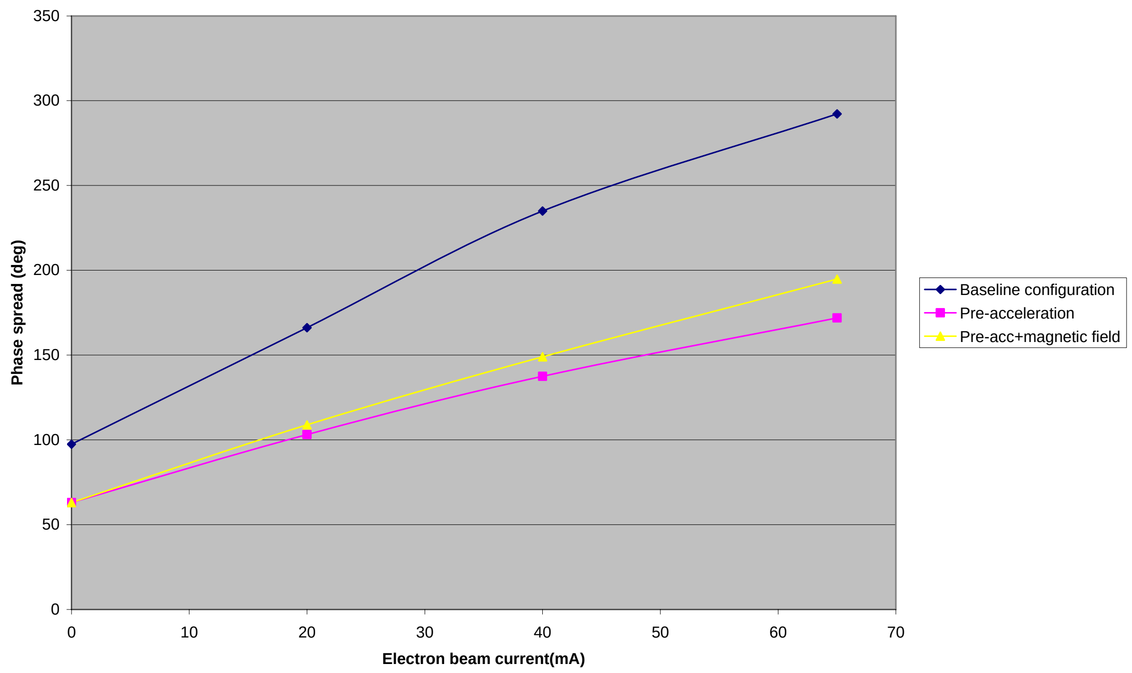


Figure8: Phase spread on the photo detector

As for the transverse directions, the space charge has an effect on the longitudinal size of the beam. The benefits of pre-acceleration are the same as for the transverse plane, due to the higher acceleration of the electrons.
As for the radius evolution, with no current (no space charge), we only observe the effects of the initial energy spread of electrons. Without pre-accelerating grid, the longitudinal length increases from 60° to 100°. With the pre-acceleration grid it stays around 60°. With the grid we suppress the noise entailed by the initial energy spread coming from the process of electron generation.
With 65mA, we manage to keep with the pre-accelerating grid, the longitudinal length under 180° which goes up to 300° with the “basic” detector configuration. That means reducing time resolution from 2.37ns to 1.35ns.
In order to have a clear signal of 1ns between two adjacent bunches (for the electronics) , we must add the pre-accelerating grid. In fact, if we have a current of 65mA with the basic version of the detector, it remains only 0.5ns between two bunches signals (without considering the H- incoming beam angle of 45°).

Adding the magnetic field, as we expected, the longitudinal size becomes bigger. As we keep the transverse size constant, the space charge field applied in the longitudinal direction becomes higher (for 65mA, 0.2ns longer).

V Table of results

All the values of the simulations are summarized in the following tables:
Input electron beam parameters:

Radius: 7mm (circular).
Phase length: 60°, 0.47ns @ 352.2MHz (corresponding to H-beam length on the detector).
Energy: from 0 to 20eV in all directions.

Final electron beam radius	No current	20mA	40mA	65mA
Baseline detector	1.9cm	2.8cm	3.6cm	5.2cm
With pre-accelerating grid	1.6cm	2.1cm	2.5cm	3.1cm
Pre-accelerating grid and magnetic field	**0.7cm**	**0.7cm**	**0.7cm**	**0.7cm**

Table3: Electron beam size on photo detector

Final electron beam length	No current	20mA	40mA	65mA
Baseline detector	100° 0.77ns	166° 1.31ns	235° 1.85ns	292° 2.30ns
With pre-accelerating grid	**60° 0.47ns**	**103° 0.81ns**	**137° 1.08ns**	**172° 1.36ns**
Pre-accelerating grid and magnetic field	**60° 0.47ns**	109° 0.86ns	149° 1.18ns	195° 1.54ns

Table4: Electron beam length on the photo detector

VI Conclusion

This study shows the benefits of adding a pre-acceleration grid both for space and time resolution. It really becomes necessary if the current of the generated electron beam is above 20mA. As for adding the 1kG magnetic field, it ensures a very good space resolution, but adds more time spread. The choice of adding this field depends really on the H- beam electron emission coefficient. For 0.3 to 0.7 this field has no inconvenience, but for a factor equal to 1, we will not be able to observe a 1ns white signal between two bunches. That means that the detector will not distinguish two different bunches.
More details about the initial electron energy spread and about the emission coefficient are now required and test with H+ beam will be lead in Orsay at the beginning of 2007.

References

[1] M. Hori, K. Hanke, CERN, “Design and construction of a Beam Shape and Halo Monitor for the CERN-SPL”, AB-Note-2005-033 OP.
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[4] Los Alamos Accelerator Code Group, “Poisson / Superfish Reference Manual”, Los Alamos National Laboratory report LA-UR-87-126.
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