BEAM INTENSITY STABILITY OF A 250 MEV SC CYCLOTRON EQUIPPED WITH AN INTERNAL COLD-CATHODE ION SOURCE

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Abstract

In PSI’s new proton therapy facility [1], the new Gantry-2 will apply the protons with fast 3D pencil beam scanning. During the scan, the beam intensity is controlled with a vertical deflection plate in the center of the new 250 MeV SC cyclotron built by Varian/ACCEL. To deliver a radiation dose with sufficient accuracy with this method, the specification of the short term (ms) stability of the beam intensity is crucial and much more demanding than for standard spot scanning. The SC cyclotron is equipped with an internal ”cold cathode” ion source. We have investigated the beam properties for different settings of the source, the plasma conditions and cyclotron parameters. Dedicated control system applications and fast diagnostics of the beam and ion source were used in a systematic approach that successfully improved the beam stability.

INTRODUCTION

Implications of fast pencil beam scanning

During the commissioning of the new SC cyclotron [2], the typical stability (σ) of the beam intensity was often worse than 40 %. This is not a problem for the spot scanning technique employed at PSI’s Gantry-1 and at the Varian/ACCEL gantry employing spot scanning, since in these gantries the dose is applied with a “step and shoot” method, where the pencil beam is aimed at a certain voxel until the voxel-dose has been applied. This technique is successfully applied in tumors and tissues that do not move during the treatment. For a cancer treatment involving moving tumors or moving surrounding tissue (e.g. due to breathing) these motions must be taken into consideration to avoid over- or under dosage. Different strategies can be employed and one of the techniques to be used at PSI’s new Gantry-2 [3] will be a fast rescanning of the tumor. This is done by a transversal fast movement (1-2 cm/ms) of the ~7 mm FWHM pencil beam over the tumor, with a controlled simultaneous continuous variation of the beam intensity. In order to reach the best possible dose accuracy, an acceptance test has been defined that tests whether the beam intensity stability satisfies $\sigma < 2\ \%$ in 0.1 ms.

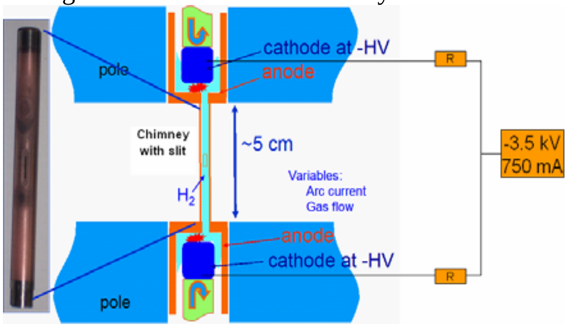


Figure 1. Schematic view of the cold cathode source in the cyclotron center.

To reach this high stability requirement, a systematic investigation has been performed to improve the beam intensity stability at PSI.

Cold cathode source

The SC cyclotron is equipped with an internal ”cold cathode” ion source, developed at NSCL [4], mounted in the cyclotron center, see fig. 1. It consists of an upper and lower part, connected by a chimney. In each part a negative high voltage is applied to a cathode to create an arc to the grounded anode. The source is flushed with a regulated flow of few cm^3/min. H_2 gas. The free electrons in the chimney are trapped between the two cathodes, and ionize the gas. The protons will leave the chimney though a narrow slit at the median plane and are pulled towards the puller on the first HF Dee. The high voltage supply operates in a current stabilized mode, allowing the arc current to be set until a maximum of 750 mA for the two cathodes. Series resistors with approximately the same resistance as the ohmic plasma resistance give sufficient DC-stability of the beam intensity and avoid cross talk between the upper and lower arc.

Forringer [4] showed that the emittance of the proton beam from the ion source increases with arc current. Although not proven experimentally, he showed by model calculations that this may be due to a changing shape of the plasma boundary.

MODEL OF EFFECTS ON STABILITY

Based on the observations of Forringer, we have assumed that variations of the beam intensity mainly effect the beam size and not the amplitude of the maximum current density. So, an intensity variation would then mainly result in a fluctuation of the width of the beam from the source (see fig 2a). The emittance of this beam is cut by various slits and fields, so that only a small fraction of the emittance is accelerated and extracted from the cyclotron. If the accepted part of the emittance is not at the maximum but rather at the slope or tail of the distribution, one will be very sensitive to intensity variations (fig. 2b).

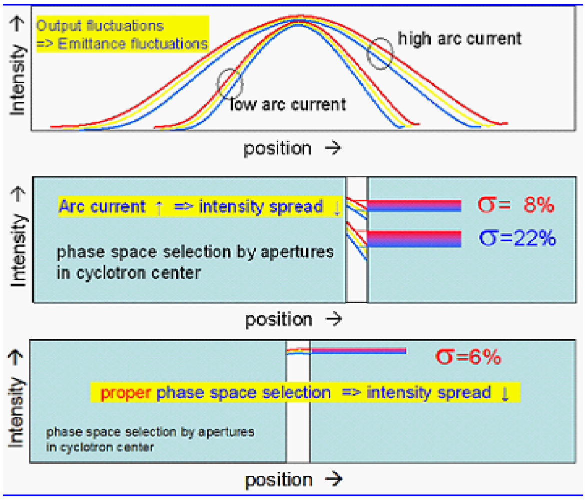


Figure 2 a): intensity fluctuations result mainly in beam width fluctuations. b) and c): the acceptance of the cyclotron (schematically shown as a slit aperture) selects a small part of the emittance and the intensity variations are strongly dependent on the arc current and on the part of the emittance selected. Listed intensity spreads (σ) are typical experimental results to indicate the sensitivities.

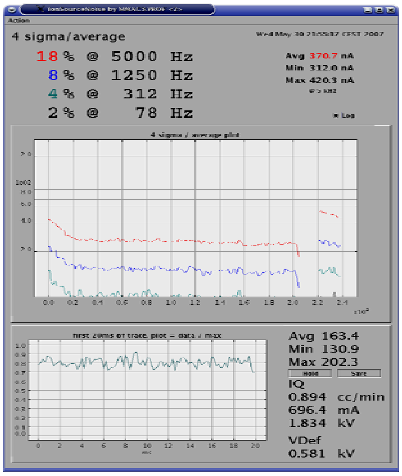
An increase of the arc current then leads to a broadening of the beam and to a reduction of the intensity spread within the acceptance, since an emittance fraction relatively closer to the maximum (fig 2b) is selected. Apart from arc current, other parameters that act on plasma conditions could have similar effects. When, in addition to that, also the selected emittance part can be chosen more close to the maximum of the current density, the variations can be minimized (fig. 2c). This model has been used to understand and improve the intensity stability.

METHODS AND MATERIALS

We have investigated the effects of "plasma related" parameters (arc current, gas flow, gas type) as well as "acceptance related" parameters, such as source position, HF voltage and beam position with respect to slit apertures inside the cyclotron.

The beam intensity has been measured with a parallel plate ion chamber filled with N_2. The current averaged over ~12 μs, is read out by VME electronics at a sample rate of 5 kHz. Assuming that the fluctuations are "white noise", the specification of 2 % at 0.1 ms, corresponds to σ≈5.6 % for the 12 μs samples as measurement result.

In a dedicated control system application (fig. 3) the beam intensity is saved in series of 1024 samples (each of 12 μs), that were sampled at 5 kHz. The data is analyzed by calculating the standard deviations of the full set, as well as of binned data sets, effectively yielding measurements at sample rates of 5 kHz, 1.25 kHz, 312 Hz and 78 Hz. When the intensity variations are due to white noise, these numbers differ a factor 2. Deviations from the factor 2 indicate the presence of specific noise sources (e.g.100 Hz).


Action

4 sigma/average

18 % @ 5000 Hz
8 % @ 1250 Hz
4 % @ 312 Hz
2 % @ 78 Hz

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Avg 370.7 nA
Min 312.0 nA
Max 420.3 nA
@5 kHz

Avg 163.4
Min 130.9
Max 202.3

IQ
0.894 cc/min
696.4 mA
1.834 kV

VDef
0.581 kV

Figure 3. Control system application for fast monitoring of the beam intensity fluctuations. The lower plot indicates the beam intensity during 20 ms, the upper plot shows stability values at different binnings during the last three minutes.

In this paper the measured stabilities are referred to as "4σ/A" (%), which is 4 times the standard deviation measured at 12 μs band width, sampled at 5 kHz, divided by the average intensity value over 1024 consecutive samples (so the spec. corresponds to: 4σ/A<24 %).

RESULTS

Effects of phase space selection

Due to cascading tolerances and developing service procedures, the chimney slit was not always placed at the same azimuth or at median plane height after a source service. An optimal azimuth yielded almost a factor 2 improvement of the stability. From the edges of the copper evaporation on the chimney, we could deduce the vertical offsets, but also tests were made with a chimney with a deliberate offset in the slit position. A clear correlation between the offset and the observed intensity fluctuations could be observed (fig. 4).

Figure 5 shows the effect of the HF voltage on the beam intensity, as well as on the beam stability. In the cyclotron, moveable phase slits are mounted at ~215 mm radius. The beam position at these slits is strongly dependent on the HF voltage and they select the beam that is accelerated to extraction. Their effect yields the presence of a clear maximum of the beam intensity at the

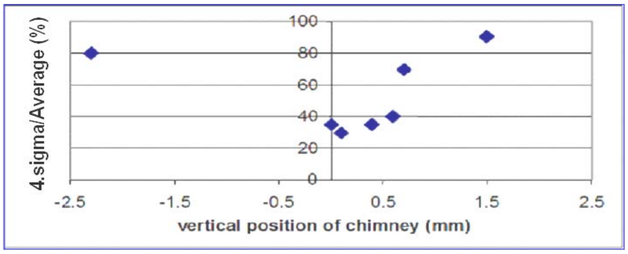

Figure 4. Influence of the chimney-slit position on beam stability.

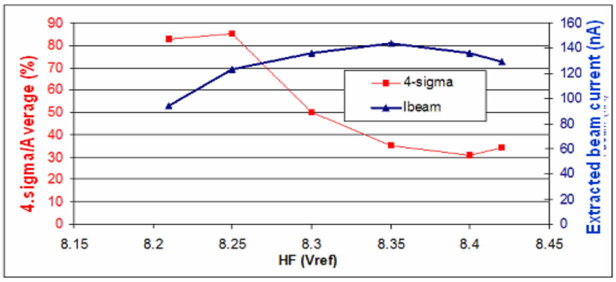

Figure 5. Effect of HF voltage on beam intensity and stability.

HF-reference value 8.35V. Near this maximum, also the fluctuations were minimal (4σ/A =30 %). Figure 6 shows the effect of the phase slit position for different HF reference voltages, where above mentioned effects are clearly seen.

Effects of plasma properties

The arc current has a strong effect on the beam intensity as well as on the stability. Figure 7 shows that the stability can improve by a factor four by increasing the arc current. Although we observed that also the gas flow had some influence on the stability, it showed a broad optimum working range around the setting for normal stable operation. By combining all above mentioned optimizations, a stability 4σ/A <25 % could be reached.

Since the amount of electrons in the plasma plays such an important role, also another gas (He) was added to the hydrogen, to increase the amount of electrons with respect to the amount of protons. When adding ~5 % He, the stability improved a factor two, with a slightly increasing beam intensity (fig. 8). At the maximum arc current, the stability was improved further to 4σ/A =18 %.

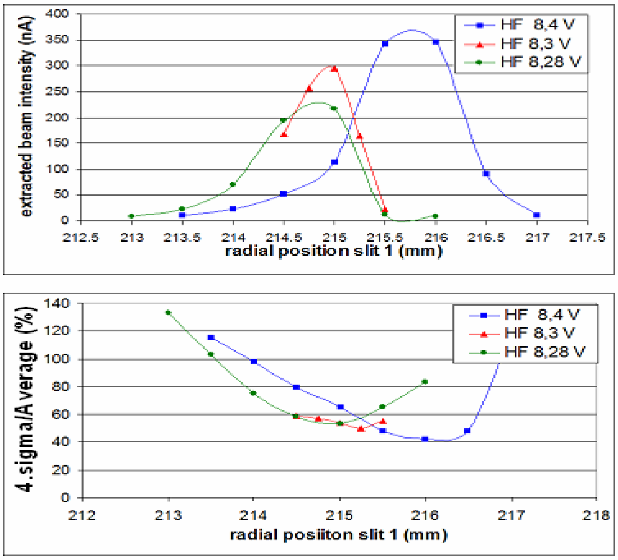

Figure 6. Effect of the position of a radial phase slit on the beam intensity and stability at different HF voltages.

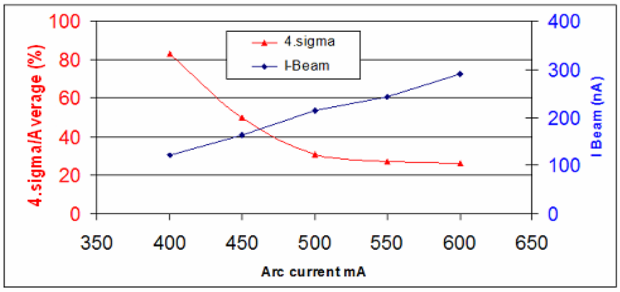

Figure 7. Extracted beam intensity and stability as a function of arc current.

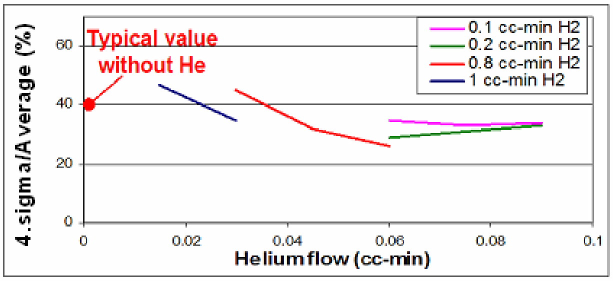

Figure 8. Addition of a small amount of helium to the gas decreases the beam fluctuations.

Slight mechanical modifications at the anode, to match the plasma shape better to the chimney's inner volume, improved the stability (only H_2) to 4σ/A <13%, with more then enough extracted beam intensity (> 1 μA). However, this also yields very high beam intensities from the source. Due to power dissipation limitations on the phase slits we cannot run with maximum arc current at the moment and the routinely obtained stability 4σ/A is 25-30%. Therefore preparations are made to decrease existing apertures in the first orbits (low beam energy), to obtain the required stability routinely.

CONCLUSIONS

A model describing the effects of various parameters on the beam intensity and its stability has successfully been demonstrated and employed to stabilize the beam intensity to the required value. A proper part of the source emittance must be selected, and the amount of electrons in the plasma must be maximized. Measures following this receipe have successfully improved the routinely obtained stability close to the specified value and after planned changes to cope with the high source output, another improvement of a factor two is expected.

REFERENCES

[1] J.M. Schippers et al., Nucl. Instr. Meth. B 261(2007) 773-776.
[2] M. Schillo et al., Proc. 16th Int Conf. Cycl. Appl., 2001, pp. 37–39.
[3] E. Pedroni et al., Z. Med. Phys. 14 (2004) 25-34
[4] E. Forringer et al., Proc. 16th Int. Conf. Cycl. Appl., 2001, 277-279, and PhD thesis (NSCL, unpublished)