MEASUREMENTS OF INITIAL BEAM CONDITIONS FOR HALO FORMATION STUDIES

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Abstract

An experimental study of halo formation for a low-energy, high-brightness proton beam transported through a periodic FODO channel is in progress at Saclay. Since beam halo evolution sensitively depends on the initial beam conditions, in particular the emittance, precise measurements of this parameter have been performed at the front end of the FODO channel. They were made using two different techniques described here: the hole-profile method and the pepper-pot method. Measured data are presented and compared. The proton beam contains additional H_2^+ and H_3^+ ions which are troublesome for halo observation. To eliminate these undesirable species, a Wien filter has been designed and installed behind the proton source at the beginning of the transport line. The setup is described and its performances are presented.

1 INTRODUCTION

High-intensity proton-linac technology has made so much progress over these last years that numerous accelerator-driven facilities are now proposed for nuclear waste management, tritium production, material sciences and other applications. However, beam losses are a main concern in the design of a high-current accelerator. Beam losses, at high energies (above 100 MeV), are required to be less than 0.1 nA/m to avoid large induced activation and radiation damage in the structures and to allow hands-on maintenance of the machine [1]. Particle losses result from a halo, surrounding the beam core, which can extend radially at several core radii beyond the beam center. Important work has been undertaken in several laboratories to study halo-formation processes and to find means to further control them. Beam losses in a long periodic channel are believed to be mainly caused by mismatch and misalignment in the transport of a space-charge dominated beam. Losses in a high-intensity linac may, also, originate from longitudinal tails of a poorly bunched beam.

We have undertaken an experimental program to study the halo developed by an intense proton beam, with high optical qualities, along its transport through a long periodic focusing channel. This work is based on a proposal which consists of using the 29-periods FODO channel of the Saturne 20-MeV DTL linac (not powered with RF) as a transport line for the proton beam of the injector Amalthée [2].

We present here the first phase of the experiment which deals with accurate characterization of the beam delivered by Amalthée. Beam emittance and brightness are measured using two different techniques: the hole-profile method and the pepper-pot method. The experimental apparatus are described and measurement results are shown. To perform emittance and halo measurements over a large dynamic range (10^5) and with acceptable background, H_2^+ and H_3^+ ions must be eliminated from the proton beam. For this purpose, a Wien filter has been recently installed. The design and performances of this system are described.

2 EXPERIMENTAL PROCEDURES

2.1 Experimental set-up

The experimental set-up is composed of the proton source Amalthée, a low-energy matching section (LEMS), the 29-periods (58 quadrupoles) FODO channel and an exit section designed for halo measurements. The source produces, for the purpose of our experiment, a pulsed proton beam of energy up to 500 keV, intensity up to 50 mA and pulse duration up to 700 μs, at a maximum repetition rate of 1 Hz; normalized emittance is expected to be less than 1π mm.mrad. Numerical simulations have shown that these characteristics are suitable to allow beam instabilities to grow and halo to develop or stay under control [2].

The LEMS has been modified in order to perform accurate measurements of the initial conditions for the beam entering the FODO channel. The experimental arrangement, described elsewhere [3], includes diagnostic equipments for beam current, position, profile and transverse emittance. Beam current is monitored by Faraday cups and current transformers. Beam position and profile are measured using scintillating screens coupled to video cameras and multiwire profile monitors. Transverse emittance is determined by means of two experimental techniques: the pepper-pot method (PPM) and the hole-profile method (HPM). They are used for cross-checking the emittance data, since this parameter is particularly important for our studies.

2.2 Emittance measurement methods

In the hole-profile technique, presented in detail in

Refs. 3 and 4, the associated electronics is capable of sampling the beam during a minimum snapshot of 5 µs anywhere within the beam bunch, with, however, a limited dynamic range. This measuring technique is time consuming (an emittance measurement takes about 30 mn) and may suffer from beam fluctuations. However, the data accuracy is expected to be about 1%.

The pepper-pot method, also presented in Refs. 3 and 4, is based on a fast and powerful imaging technique which yields full information on the beam hyperemittance in only one beam shot. Moreover, it allows to measure density distributions with a dynamic range of at least 5 decades.

Earlier measurements, performed with a chromium-doped-alumina (Al_2O_3:Cr) scintillator [3,4], suffered from very poor spatial resolution and too long light persistence to yield accurate and time-resolved emittance data. Thereby, new scintillators have been developed. They consist of P46 ($Y_3(Al,Ga)_5O_{12}$;Ce) and P47 (Y_2SiO_5;Ce) phosphor crystal powders deposited on stainless-steel plates. They are made in our laboratory using a decanting technique. With their high sensitivity, fast response (~100 ns) and spatial resolution of the order of the particle size (~10 µm), these scintillators allow measurements with improved accuracy (Fig. 1) and time-resolved analysis of the profile and emittance data, within the beam bunch. However, they do not suffer high energy-density deposition.

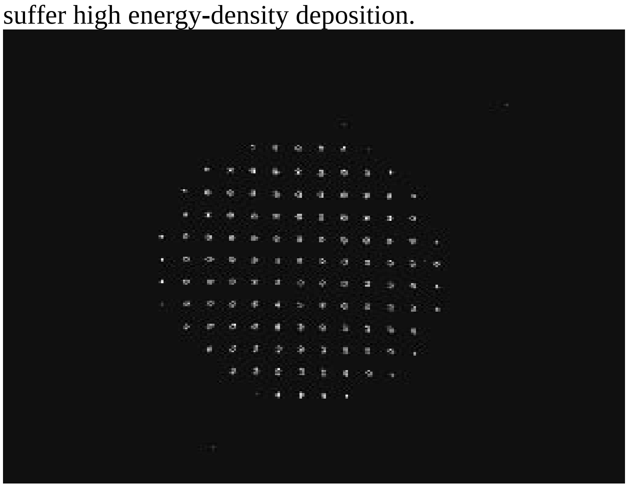

Figure 1: PPM image of a 500 keV, 3 mA proton beam on a P46 phosphor screen.

A data-processing program has been developed which gives the beam phase-space distribution and intensity-emittance characteristic curve. It includes corrections for the pepper-pot plate thickness, the finite size of the holes, the inclination angle of the scintillating screen on the beam axis and the spatial resolution of the screen and video camera.

3 MEASUREMENT RESULTS

Comparison of the two emittance-measurement methods was done with a beam collimated by a 4-mm diaphragm placed at the source exit to limit the beam profile on the PPM scintillator. Beam focusing downstream the source is, indeed, not possible because separation of the beam ion species produces an unacceptable background on the scintillator.

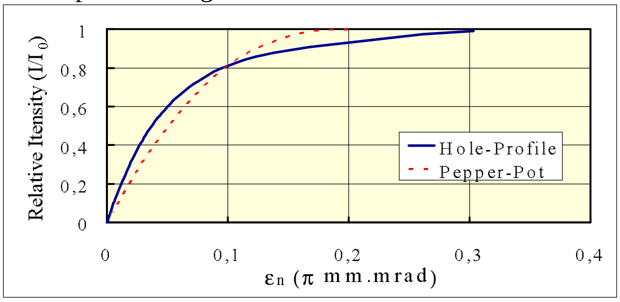

Figure 2: Comparison of HPM and PPM intensity-emittance curves for a 500-keV, 3-mA proton beam.

In both methods, measurements were taken on a 500-keV, 3-mA proton beam, 300 µs after the pulse start during a 5-µs snapshot. The intensity-emittance curves are displayed in Fig. 2; in fact, the vertical axis represents the ratio I/I_0, I_0 being the full-beam intensity (I_0 = 3 mA). The curves show a satisfactory overall agreement. The slight discrepancies, particularly noticeable at high intensity, could be attributed to differences in the data-processing techniques, in particular background subtraction, or to the different locations of the sampling plates (just at the source exit for the HPM and 1.8 m farther for the PPM), the space charge acting differently on the beam.

Emittance and brightness measurements were performed on a proton beam of 500-keV energy and intensity ranging from 5 to 50 mA. They were made to analyse the effect on the beam properties of various parameters of the duoplasmatron source, which are the gas pressure, the magnetic field, the discharge current, the Pierce voltage and the focusing voltage. The results, partly presented in Ref. 4, show that the emittance is minimized for the lowest gas pressure compatible with a good running of the discharge and for a reduced magnetic field. The emittance, for 90% of beam particles, is not very sensitive to the Pierce and focusing voltages (~ 10%); however, bad voltage tuning has a strong effect on the beam-core density and induces aberrations. Measurements also show that the emittance varies at the beginning of the pulse and then remains quite constant beyond 50 µs, with a lower value than in the transient. The best result obtained up to now gives $\varepsilon_n^{90\%}$ = 0.51 π mm.mrad for a 40 mA beam through a Φ = 26 mm collimator, indicating that the initial beam conditions are satisfactory for carrying on the transport experiment in the FODO channel.

Abundance of ion species in the beam has been measured at intensities ranging from 10 to 50 mA and for various source conditions [4]. It turns out that the H^+ abundance grows with intensity; nevertheless, it remains ~ 12% of H_2^+ and H_3^+ ions at 50 mA. Simulations show a partial transmission of these parasitic particles through the FODO channel, which would considerably hinder the interpretation of further halo observations. This is why a Wien mass separator has been designed and recently installed close to the exit of the proton source.

4 WIEN MASS SEPARATOR

The Wien separation system has been adopted because, contrary to a dipole magnet, it does not modify the H^+ particle trajectories and, thus, requires only minor modifications of the existing transport line.

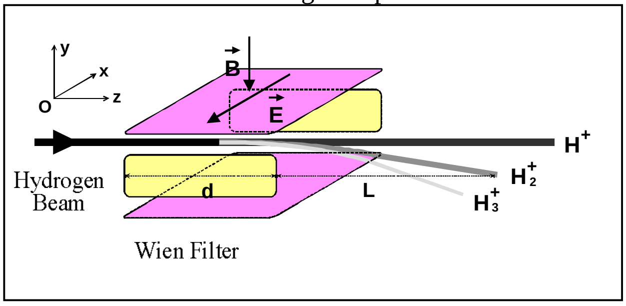

Figure 3: Schematic design of the Wien mass separator.

The Wien filter combines a magnetic field and an electric field and works as follows: when a particle of charge **q**, mass **m** and kinetic energy **W** enters the filter, it undergoes the effects of the magnetic field **B** and the electric field **E** over a distance **d** (Fig. 3). The fields **B** and **E** are perpendicular one to the other, and they are both perpendicular to the particle trajectory. When the electric and magnetic forces acting on the particle are equal but of opposite sign, that is, when the equality:

$$\frac{\mathbf{E}}{\mathbf{c}} = \mathbf{B}\sqrt{\frac{2\mathbf{W}}{\mathbf{mc}^2}}$$ (**c**: light velocity; $\mathbf{mc}^2$: particle rest mass)

is fulfilled, the particle trajectory is not deviated. Trajectories of particles with the same charge and kinetic energy but with a mass different of **m** are deflected. At a given drift distance **L**, these particles, separated from the main beam, are stopped.

The apparatus has been designed to fit with the available space in the LEMS and to satisfy geometrical constraints. Preliminary transport calculations for 500-keV-energy H^+, H_2^+ and H_3^+ ions through the system were made using a sharp-edge field model. Choosing **E** = 1 MV/m and **B** = 0.1022 T, for which the H^+ particles are not deflected, **d** = 30 cm and **L** = 70 cm, calulations indicated sufficiently good separation of the particles to carry on more precise calculations.

The code MAFIA was then used to calculate the exact electric and magnetic field distributions (including the fringe fields). Spacing, shape and dimensions of the magnet poles (magnetic field) and electrodes in the vacuum chamber (electric field) were optimized to obtain rms field inhomogeneities of less than 1% in an area of 40 x 40 mm^2 around the beam axis and over an effective length of 29.5 cm. The magnetic-field homogeneity is in fact much better. The beam maximum diameter at the level of the Wien filter is about 30 mm.

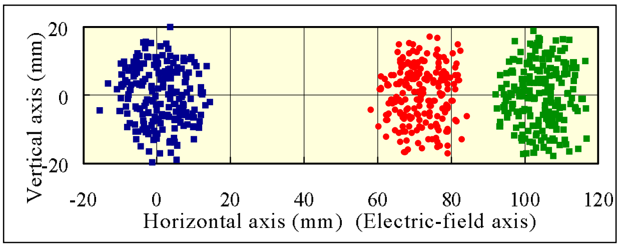

Figure 4: H^+, H_2^+ and H_3^+ ion-beam distributions.They range, respectively, from left to right.

The optimized field distributions have been used to simulate the transport of a beam containing the three ion species, with size and emittance similar to the results presented above. Space-charge effect was not taken into account. It turns out that the separation power is the same for the "real" system (Fig. 4) and for the equivalent sharp-edge field model. Analysis of the filter optical properties indicate that it is slightly focusing in the electric-field direction and behaves as a drift space in the magnetic-field direction; however, beam symmetry can be restored by using the quadrupole triplet of the LEMS. Simulations have shown a slight increase of the H^+-beam transverse emittances: below 0.5% in the electric-field direction and less than 2% in the magnetic-field direction. On the other hand, the limited field inhomogeneities and the source energy dispersion (10^{-4}) have almost no influence on the beam transport.

5 CONCLUSION

The results reported here on the initial beam conditions indicate that the halo formation studies can be carried on with measurements on the proton beam transported through the FODO channel. The newly installed Wien filter will improve beam-emittance measurements and greatly help halo observation with considerably reduced background. Tests and calibration of this system are in progress. The two emittance-measurement methods though different are complementary; both will be used in our next experiments.

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