# SPACE-CHARGE NEUTRALIZATION EXPERIMENT WITH A LOW-ENERGY PROTON BEAM

P.Y. Beauvais, J.M. Lagniel. CEA-Saclay, DSM-GECA, LNS,
N. Pichoff, G. Haouat, P. Chaix, CEA/DRIF/DPTA, Bruyères-le-Châtel.

### Abstract

The mechanism of space-charge neutralization of a low-energy proton beam is investigated both experimentally and theoretically. In the experiment, the transverse profile of a 500 keV proton beam delivered by a duoplasmatron source is accurately measured at the end of a 3 m long drift space. Profile measurements are performed by an imaging technique using a scintillating screen and an intensified CCD camera. Measurement results done with different beam intensities (between 0.5 and 15 mA) and various residual-gas pressures are described. They show that, at high beam current an increase of the gas pressure results in a reduction of the beam spot, which indicates an increase of the value of the neutralization coefficient. On the other hand, the behavior is the opposite at low beam current: the beam size increases with the gas pressure. An interpretation of these experimental results is proposed.

### Introduction

Beam losses result from the existence of a diffuse halo which can extend far away from the dense beam core. Halo formation originates from different processes including space-charge effects [1] and Coulomb scattering on the residual gas [2]. In the first process, mismatch and misalignment in the transport of an intense beam in a long periodic channel, as well in a linac, are believed to be important sources of halo. To check these predictions, an experimental program has been initiated, aiming at the investigation of halo formation and development in the transport of an intense low-energy proton beam through a periodic focusing FODO channel [3]. Accurate measurements of beam emittance and brightness performed at the channel entrance indicate that the initial beam conditions are suitable for further halo development through the FODO channel [4].

The low-energy proton beam may however be partially neutralized in the residual gas of the transport channel, which would increase the tune depression and mismatch the beam to the FODO channel. Interpretation of the halo measurements would then be questionable.

Therefore, an experimental study of the space charge neutralization has been undertaken to provide compensation coefficients at various beam intensities for a low-energy proton beam. This study will be also useful for the design and simulation of the low energy part of a high-intensity linac such as the one studied for the TRISPAL project [5].

### Experimental procedure

Space-charge neutralization measurements have been performed in the matching section between the proton source Amalthée and the FODO channel of our halo experimental set-up at Saclay.

#### Measurement method

The basic idea for measuring the space-charge neutralization rate is the following.

- A proton beam propagates freely in a residual gas toward a screen. We first measure its transverse size while the only force acting on it is the space-charge force.
- A pepper-pot is then placed on the beam path at the beginning of the drift space. The beamlets passing through the pepper-pot holes do not feel the full-beam space-charge force. The envelope of the beamlet spots corresponds to the full-beam transverse profile without space-charge effect. The pepper-pot can be replaced by a single-hole moved across the beam; a technique which yields more accurate beam profile measurement.
- The neutralization rate is recovered from a simulation which gives an equivalent beam current adjusted to reach the measured beam size.

#### Experimental set-up

The measurements are performed with a pulsed (500 µs, 1 Hz) proton beam at 500 keV with up to 50 mA peak current, delivered by the Amalthée duoplasmatron source. In the experiment (see **Fig. 1**), the beam is collimated by a $\phi$10 mm diaphragm (D) located at the source exit. It propagates through a drift space toward a scintillating screen (S) 2.8 m downstream. The pepper-pot (PP) and single-hole (SH) plates are located very close to the diaphragm. The SH plate with a $0.2\times0.2$ mm$^2$ sampling hole is moved in the horizontal direction across the beam by a stepping motor (0.2 mm step). Both beam-profile and beamlet-spot images are observed with an intensified CCD camera.

Fast responses of both light intensifier and scintillator (a P46 phosphor ($Y_3$ (Al,Ga)$_5$ $O_{12}$; Ce) crystal powder deposited on a stainless-steel plate) allow to take beam-profile images during a 5 µs snapshot anywhere within the beam pulse. This good time resolution is very useful for analyzing the temporal evolution of the neutralization rate in the pulse.

Residual gas pressure and composition can be adjusted by modifying pumping conditions and injecting nitrogen gas at a given flow in the vacuum chamber.

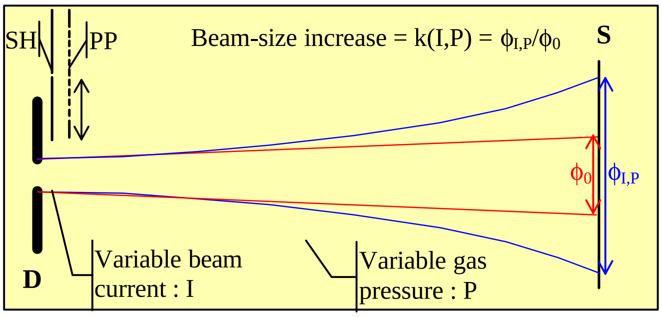


**Fig. 1** : Schematic layout of the experimental set-up for space-charge neutralization measurement.

### Measurement results

• In a first run, measurements were taken using the PP plate with a beam current of ~10 mA behind the diaphragm D. **Fig. 2** shows the beam profiles with and without the PP plate in the beam path.

Analysis of the experimental results shows that the "PP-in" beam size is systematically smaller than the "PP-out" beam size, whatever residual gas pressure (up to $5.10^{-5}$ hPa) and sampling instant in the pulse. This behavior indicates clearly that the proton beam is not totally space-charge compensated.

Nevertheless, these measurements are not entirely conclusive since the "PP-in" beam size is determined with up to 40% uncertainty due to large spacing of the PP holes.

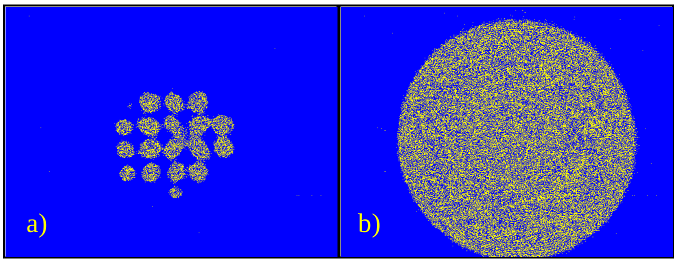


**Fig. 2**: Beam transverse-profile images with (a-left) and without (b-right) pepper-pot plate in the beam path.

• During a second run, the SH plate is used to accurately measure both beam size ($\phi_0$) without space-charge and beam transverse emittance at the diaphragm location. Beam profiles (with and without SH plate) and emittances were measured for 8 beam currents ranging from 0.8 to 15.0 mA and four sets of residual gases and pressures, $P_1$ ($2\ 10^{-6}$ hPa $H_2$), $P_2$ ($1.2\ 10^{-5}$ hPa $H_2$), $P_3$ ($1.2\ 10^{-5}$ hPa $H_2$+ $2.6\ 10^{-5}$ hPa $N_2$) and $P_4$ ($1.2\ 10^{-5}$ hPa $H_2$+ $5.8\ 10^{-5}$ hPa $N_2$). Pressures given here are mean values on the drift space. All measurements were done 350 μs after the pulse start.

For each measurement, data processing consists in determining the beam-size growth k defined as the ratio of beam diameters with and without space-charge effect :

$$k(I, P) = \phi_{I,P} / \phi_0 ,$$

where I is the beam current, P the residual gas pressure, $\phi_0$ the beam diameter on the screen without space charge and $\phi_{I,P}$ the beam diameter with space charge.

Analysis of the data shows that below 6 mA the beam size increases with the gas pressure, remains almost constant around 6 mA, and decreases at higher currents. This behavior is illustrated in **Fig. 3** where the curves for the two extreme pressure sets $P_1$ and $P_4$ are displayed. This indicates that at high-current the beam is more space-charge compensated in a high-pressure gas, as mentioned above. On the contrary, a low-current beam seems to be "undercompensated" when the pressure is high.

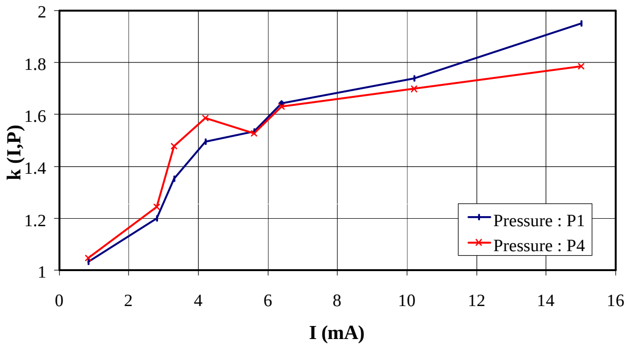


**Fig. 3**: Beam-size growth k as a function of beam current, for the pressure sets $P_1$ and $P_4$.

The rate of beam size growth with residual gas pressure is defined by :

$$\nu(I) = \langle dk(I, P)/dP \rangle ,$$

with I the beam current, P the residual gas pressure and <> is an average over the pressures.

The parameter ν has only a qualitative meaning since a precise determination of both gas pressure and composition along the drift is not possible. Nevertheless, **Fig. 4** shows a clear variation of this parameter with the beam current. A negative value of ν indicates that space-charge compensation increases with the pressure, since a positive ν indicates that the beam spread is larger than the one expected from the space-charge effect.

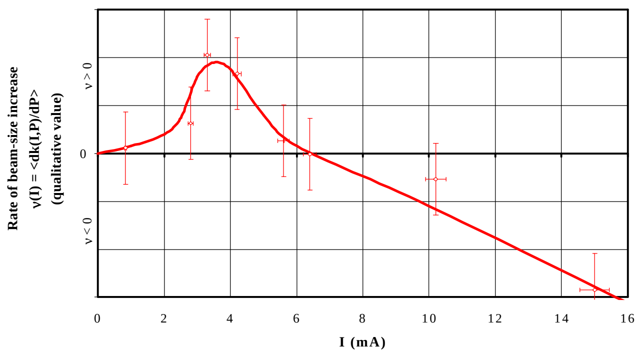


**Fig. 4**: Variation of the rate of beam size growth with residual gas pressure versus the beam current.

For each beam current, emittance measurements are processed to yield the beam-particle distribution in the phase space at the diaphragm position. The space-charge neutralization coefficient is determined as follows. Starting from the particle distribution for a given current ($I_0$), the transport to the scintillating screen is simulated taking into account the space-charge effect. For each pressure set, the space-charge force is adjusted through an "equivalent" beam current ($I_{equ}$) to give a beam size equal to the measured one. The mean space-charge neutralization coefficient $\tau$ is set by :

$$\tau = \left(I_0 - I_{equ}\right) / I_0 \ ,$$

For the low hydrogen pressure (P1), $\tau$ is always equal to 0. For the high pressure (P4), the mean neutralization coefficient range from -20% for I=3.3mA to 20% for I=15mA.

## Theoretical basis - Interpretation of the results

There are 3 species in the plasma created by ionization of the residual gas: beam particles ($p^+$), ions ($I^+$) and electrons ($e^-$), the last two being created by the ionization process. Neutral species (gas) are not taken into account because they have a negligible influence on the dynamics.

The ions are created at very low kinetic energy, while the electrons initial kinetic energy can be larger than 10 eV. Ions and electrons move under the action of a potential well $\Delta V$ generated by themselves, the beam and the vacuum chamber. Furthermore, the electrons, much lighter than the ions, undergo collisions inducing dispersion in their kinetic energy.

The combination of ionization and transverse transport of the charged particles leads to an equilibrium where the potential is $\Delta V_e > 0$. If the initial beam potential $\Delta V_0$ (without neutralization) is larger than $\Delta V_e$ (high current), the expulsion of the ions is enhanced and the electrons are trapped. This decreases the potential down to the equilibrium. If the initial potential $\Delta V_0$ is smaller than $\Delta V_e$ (low current), the reverse occurs. This means that

i) the equilibrium is stable,

ii) one observes partial neutralization [6] at high current, and the inverse effect ("undercompensation") at low current. Note that in the case of a negative beam, one can have $\Delta V_0 < 0$ and $\Delta V_e > 0$, which leads to an overcompensation [7].

An interpretation of our experimental results can be the following: for a high beam current (>6 mA), the initial uncompensated potential well $\Delta V_0$ is deeper than the stable equilibrium $\Delta V_e$, then the potential decreases and the beam becomes partially compensated. For low beam current, $\Delta V_0$ could be less than $\Delta V_e$ leading to an increase of the potential, the beam is "undercompensated".

## Conclusion

A positive potential well $\Delta V_e$ should exist at the steady state. Its shape and depth depends on the beam properties (shape, energy and current), the gas composition (differential cross section and ion mass) and the vacuum chamber size. This well would drive the beam dynamics in compensation conditions. This well should be the right parameter to study in order to understand the compensation phenomenon.

A new experiment, not presented here, has been undertaken with $H_2$ residual gas only. It shows the same behavior as with the Nitrogen gas, but with a lower beam current edge (1.5 mA rather than 6mA for Nitrogen). This can certainly be explained by the fact that the $H_2^+$ mass is lower than the $N_2^+$ one.

The proton beam used for the FODO experiment is not space-charge compensated at low pressure (< $2.10^{-6}$ hPa) allowing a good control of the tune depression in the FODO channel.

## References


[1] J.M. Lagniel, "Halos and Chaos in space-charge dominated beams", EPAC'96, Barcelona, Spain, June 10-14, 1996, to be published.

[2] N. Pichoff et al., "Halo formation from beam Coulomb scattering on residual gas", EPAC'96, Barcelona, Spain, June 10-14, 1996, to be published.

[3] J.M. Lagniel, Saclay report LNS-SM-94/06 (1994).

[4] G. Haouat et al., "Measurements of initial beam conditions for halo formation studies", EPAC'96, Barcelona, Spain, June 10-14, 1996, to be published.

[5] M. Promé, "Conceptual studies for high-power proton linac", LINAC94, Tsukuba, Japan, Aug. 21-26, 1994, p.146.

[6] J. Sherman et al.,"$H^+$ beam neutralization measurements at 870 keV beam energy", Rev. Sci. Instrum. 63 (4), April 1992, p.2776.

[7] J. Sherman et al., "$H^-$ beam neutralization measurements with a gridded-energy analyzer, a noninterceptive beam diagnostic", LINAC88, Williamsburg, VA, October 3-7, 1988.