OPTICAL TRANSVERSE BEAM PROFILE MEASUREMENTS FOR HIGH POWER PROTON BEAMS

P. Ausset, S. Bousson, D. Gardès, A.C. Mueller, B. Pottin, I.P.N., 91406, Orsay, France,
R. Gobin, CEA Saclay, 91191, Gif sur Yvette, France,
G. Belyaev, I. Roudskoy, ITEP, Moscow, Russia

Abstract

High Power Proton Accelerator (H.P.P.A.) projects are being proposed in fundamental and applied physics research: radioactive beam production, neutron sources, neutrino factories and transmutation. The front end design of these accelerators is based on a high intensity ion source (several mA up to 100 mA), followed by a Radio Frequency Quadrupole (R.F.Q.) to accelerate protons at several MeV. Finally the beam energy is increased up to 10 MeV or more by a Drift Tube Linac (D.T.L.).

Among the parameters needed to be measured for beam control, monitoring and halo formation prevention, the transverse beam profiles are the most difficult to obtain. The large expected specific energy deposition in any interceptive monitor can lead to the destruction of the sensor and in addition to an appreciable amount of radiation production. Therefore traditional multi-wires chambers and wire scanners are not usable under too high duty factor pulsed-beam operation and obviously continuous beam operation.

A very attractive phenomenon is the production of visible light by the proton beam-background or additional gas interaction. Transverse beam profiles of the "S.I.L.H.I." E.C.R. proton source (95 keV, 100 mA) have been measured. However, several difficulties emerge to explain the difference shape between the transverse beam profiles deduced from the elementary observation of the emitted light by a C.C.D. camera, a grid profiler (low duty cycle operation) and a residual gas profiler, respectively. More sophisticated measurements using the Doppler effect have been brought into operation to determine the energy and the spatial extension of the different components of the beam (H^+, H_2^+, H_3^+).

1 INTRODUCTION

The I.P.H.I. (high intensity proton injector) project (C.E.A. / C.N.R.S. collaboration), which could be the front end of a High Energy Proton Accelerator (H.P.P.A.) is based on a E.C.R. proton source "S.I.L.H.I." (95 keV, current ≈ 100 mA.) under operation at the present time. After travelling along the Low Energy Beam Transport line (L.E.B.T.), a Radio Frequency Quadrupole (R.F.Q.) will accelerate protons at 5 MeV. Finally the beam energy will be increased up to 10 MeV by a drift tube LINAC (D.T.L.). I.P.H.I. is able to work under pulsed mode operation for machine commissioning and experimental operation and under C.W. operation. The beam average power reaches 10 kW at the entrance of the R.F.Q. and 500 kW at the exit. A safe operation of H.P.P.A. strongly requires an accurate measurement of the transverse beam profiles for beam monitoring, halo formation prevention and minimisation of beam losses.

The wire scanner, traditionally used for transverse profiles measurements can not withstand the high average power pulsed beam and C.W. operation mode of H.P.P.A.. The large quantity of beam energy deposited in any possible intrusive sensor, specially in the low energy sections of H.P.P.A., forces the use of non interceptive beam diagnostics.

2 DIRECT OPTICAL BEAM PROFILE MEASUREMENTS

In the L.E.B.T. the moderately relativistic protons interact strongly with the atoms of the residual gas which is mainly hydrogen (pressure: 2.10^{-5} hPa). A blue light, visible by the human eye, is emitted by the de-excitation of these atoms. This light was first sensed with an intensified C.C.D. camera working in the 200 nm-820nm range.

2.1 Fluorescence Beam Profile Measurements (F.B.P.M.) Under C.W. and Pulsed Mode Operation

Our experiments were carried under C.W. and pulsed mode operation in a "diagnostics box", located after the two solenoids focusing the beam in the L.E.B.T. line. We were able to inject inside this box other gases such as N, Ne, Ar, Kr, Xe in addition to the residual gas.

Two intensified 16 bit C.C.D. cameras were installed perpendicularly to the axis of the beam, in order to measure vertical and horizontal beam profiles. Specific software performing the subtraction of the background signal (without beam) to improve the signal/noise ratio, the calculation of vertical and horizontal projection* and peak fitting convolution** were used. It has been found:

- The proton beam is cylindrical along the L.E.B.T.
- The intensity of the emitted light depends on the nature of the gas and increases proportionally to the pressure of the gas.
- Profiles obtained by F.B.P.M. have the same geometrical shape (Fig1) for all gases at the same pressure (after normalisation with respect to the amplitudes of the profiles). The same result is obtained for a classical grid profiler working under pulsed mode operation.

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*Princeton Winview. **Microcal Origin 6.0 software

- Under pulsed mode operation, the widths of the profiles measured by F.B.P.M. are larger than the ones measured by a grid profiler (Fig 2). The width decreases as the pressure increases.

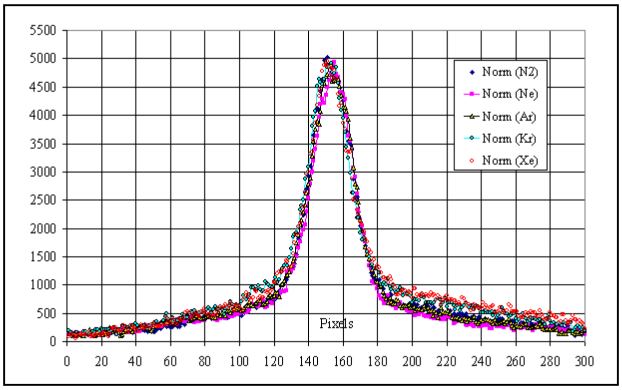

Figure 1: F.P.B.M. for different gases N_2, Ne, Ar, Kr, Xe at the same pressure.

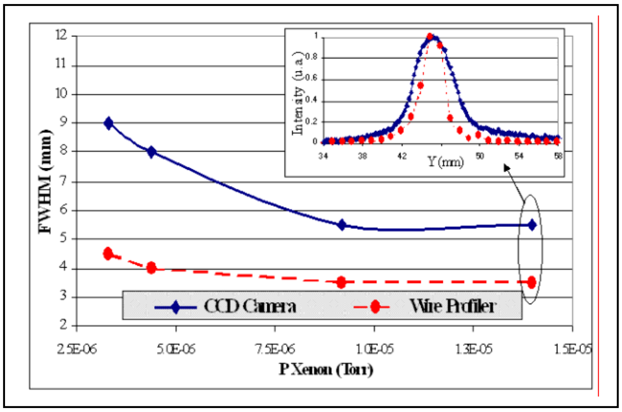

Figure 2: Evolution of the widths of the profiles measured by a grid profiler and by F.W.H.M. with the pressure of the gas (Xenon).

2.2 Spectroscopic Measurements

We replaced the horizontal C.C.D. camera by a Photo-multiplier coupled to a scanning monochromator in order to analyse the emitted light spectrum. As expected we found again the well-known lines of the Balmer series : H_α = 656.2 nm, H_β = 486.1 nm H_γ = 434 nm. Previously [1], precise measurements were made and showed that the amplitude of each line is proportional to the intensity of the proton beam.

The light spectrum of the other gases (N, Ar, Kr, Xe, Ne) were also recorded. Experiments were carried out with a laser absorption on specific lines of Ar (λ = 811.5 nm) and Kr (811.3 nm) with the aim of measuring the transverse profiles of the beam.[1,3]

3 SHIFTED DOPPLER FLUORESCENCE BEAM PROFILE MEASUREMENTS (S.D.F.B.P.M.)

The existence of a « halo » surrounding the « core » of the beam measured by F.B.P.M. suggests that the light produced by the excited atoms of the gas does not result only from the incoming protons, but also from second step processes involved in the production of this light.

Trying to explain the intensity and the spatial extension of the light produced in the vessel needs to consider several major physical processes which may contribute to the production of this light and to the broadening of the measured profiles:

- Possible delayed decay of excited atoms of specific gas present in the vacuum vessel (Nitrogen is well known for this phenomenon).
- Back scattered protons may also excite other atoms of the gas which lead to the production of light
- Inelastic collisions may produce electrons able to excite in their turn atoms of gas.
- Dissociation of molecules of H_2^+ and H_3^+ unfortunately produced by the source S.I.L.H.I. in addition to the protons may occur and create excited atoms which become source of light.

As we want to discriminate only the light produced by the incoming protons delivered by the source at 95 keV, and accelerated back-stream by the R.F.Q., we turn around to their high electronic capture cross section :

A part of these protons captures in flight an electron and may give birth to excited hydrogen atoms. The typical Doppler shift effect (1) of these very specific atoms in the frequency (or wavelength) domain will allow us to select their light produced by de-excitation among the overall light in the vessel :

$$\boxed{\Delta\lambda \approx \lambda_0 \cdot \beta \cdot \cos\theta} \qquad (1)$$

where $\Delta\lambda$ is the Doppler shift, λ_0 the wavelength of the line under consideration, β the classical ratio of the velocity of the proton to the velocity of light and θ the angle of observation with respect to the axis of the beam.

3.1 Experimental Set Up

The C.C.D. Camera was installed in the focal plane of an imaging spectrograph* equipped with a 900 gr/nm grating. The resolution was better than 0.1 nm at 500 nm. The experimental configuration was chosen to shift sufficiently (≈ 8 nm) the H_α line of the Balmer series of hydrogen.

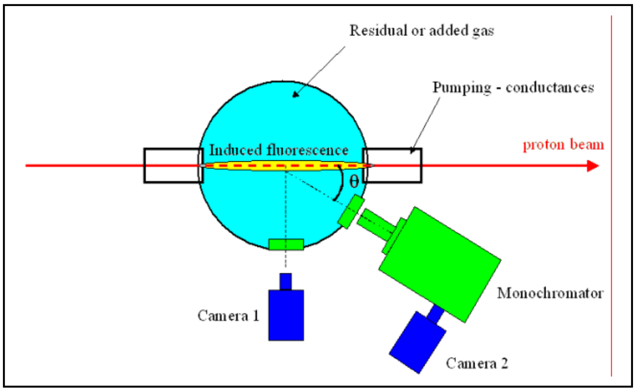

Figure 3: Scheme of the S.D.F.B.P.M. experimental set up.

The vertical beam profiles , according to the vertical slit orientation at the entrance of the monochromator, are deduced from the image transported on the C.C.D. matrix of the camera.

In addition, due to the possible discrimination of the different components of the beam H^+, H_2^+ and H_3^+ because of their different Doppler shift wavelengths, this method potentially allows:

- The relative intensity measurement of the different species present in the beam.
- The measurements of the transverse profiles of the species, which contribute to the entire profile of the beam.
- The energy measurements of the different species and in particular their energy spread which is proportional to the width of the corresponding spectrum line.

3.2 Experimental results

Identification of the different lines of the Balmer series of hydrogen were first recorded. Their corresponding Doppler shifts were checked. Secondly, the current in the solenoids were changed in a large range to vary the size of the beam. The full width half maximum (F.W.H.M.) of the (H_α) and its corresponding Doppler shift line H^+ component profiles were measured. A remarkable result is that the size of the halo surrounding the beam remains constant whatever the focusing conditions.

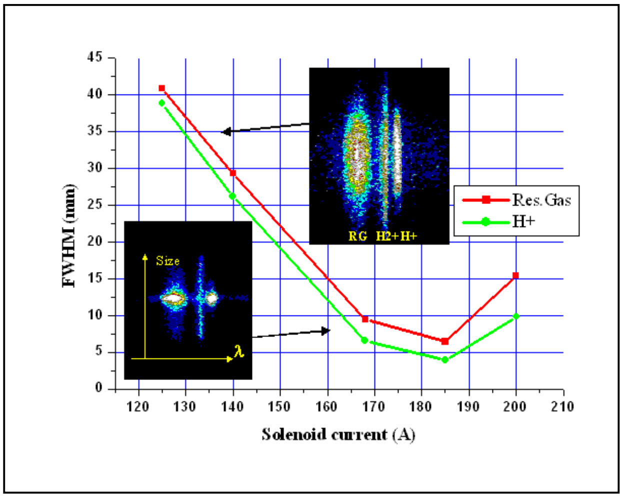

Figure 4: F.W.H.M. of the H_α (residual gas) and its corresponding Doppler shift line (proton beam : 95 keV).

The evolution of the profiles was also studied varying the nature and the pressure of the gases introduced in the vessel: N, Ar, Kr, Xe, Ne and H. Adding gas into the vessel increases the produced light: for each component H_α, H^+, H_2^+, H_3^+ the fluorescence yield increases linearly with the pressure (up to 10^{-4} hPa), except for hydrogen. The curve shows a saturation which may be attributed in a first time to an auto absorption process but this needs to be confirmed.

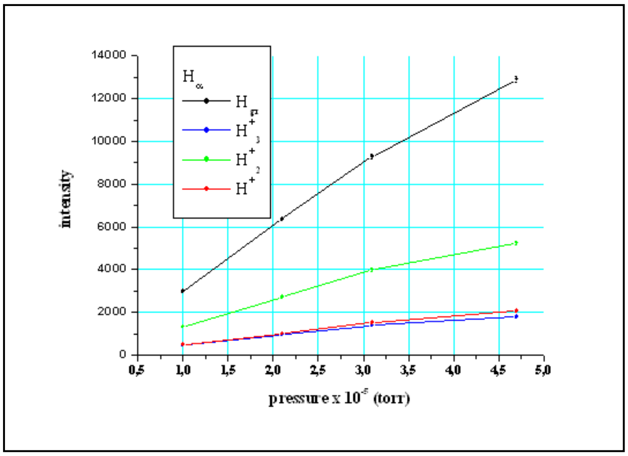

Figure 5: Evolution of the intensity of the light produced by each component H_α, H^+, H_2^+ and H_3^+ with H_2 pressure.

4 CONCLUSION

Because of their non destructive nature with respect to the beam, optical methods are very attractive for high power beam monitoring. We investigated and brought into operation some specific optical diagnostics on the high intensity source "S.I.L.H.I." (100 mA current proton, 95 keV)

- Direct fluorescence beam profile measurements under high average power beam pulsed mode and C.W. operation are valid for centroïd beam position measurement. In addition the qualitative estimate of the beam transverse profiles is possible.
- Fluorescence measurements on the Doppler shifted lines of the hydrogen Balmer series are very promising to determine the energy of the different components of the beam (H^+, H_2^+ and H_3^+). In addition, the energy spread of the beam is potentially obtainable.
- We have to carry on additional experiments in order to understand more accurately the observed beam profiles.

REFERENCES

[1] B. Pottin and al, "Optical beam profiler for high current beams" EPAC 2000, Vienne, June 2000

[2] D.Gardès and al, "Optical beam-profile monitoring developed for high intensity proton beam" presented at 14th International Symposium on Heavy Ion Inertial fusion, Moscow, May 2000. To be published in Laser and Particle Beam.

[3] B. Pottin, "Etude d'un Profileur Optique de Faisceaux Intense de Protons par Absorption Laser", These Université Paris XI, 18 Octobre 2001.