MEASUREMENT OF SPACE CHARGE DYNAMICS EFFECTS IN A FODO CHANNEL

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Abstract
An experimental study of space charge-dynamic effects is in progress at Saclay. The proton-beam has a long pulse structure, high-intensity, low-energy and low-emittance. It is transported through a FODO channel. The beam transverse phase space distribution has been measured as a function of the beam current at the output of the channel. Experimental results along with analytical as well as numerical analysis are presented. Measurements for a beam mismatched at the input of the FODO channel are compared with simulation results.

1. INTRODUCTION

Intense, high-brightness beams envisioned for many advanced accelerator applications require small emittance and very low particle loss throughout the accelerating structure and transport section. The dynamics of such beams is dominated by the strong self-forces due to space-charge. Space-charge dominated beams with non-uniform charge distribution and initial mismatch are known to undergo emittance growth and halo formation.

The objective of the study undertaken at Saclay is to check theoretical predictions for the beam r.m.s. parameters and latter investigate the halo formation. As part of the ongoing study, here we report on the analysis of the transverse profile and phase-space distribution of a proton beam at the output of the 29-cell FODO channel with both :

1. a matched beam with a current ranging from weak to strong space-charge effects, and
2. an intense beam with a set of mismatch conditions.

2. EXPERIMENTAL SET-UP

The experiment has been carried out in the FODO channel at Saclay. The experimental set-up, described in detail elsewhere [1], consists of a duoplasmatron source, a matching section with a quadrupole-triplet and a quadrupole-quintuplet, a 10.2-m, 29-period FODO channel and an exit section. The source produces a pulsed proton beam of 500 keV energy, 300 μs in bunch length, at 1 Hz repetition rate. The bunch current ranges from 2.2 to 37 mA. The beam is matched to the FODO channel with the triplet and quintuplet.

Beam diagnostics are located in the matching and exit sections. Beam position, profile and emittance are measured with a pinhole/profile-harp system at the front end of the channel (input), and with a pepper-pot/phosphor-screen device with beam-image acquisition system at the exit end. Details of the phosphor screen/image acquisition system is contained in Ref. 1.

3. COMPUTER SIMULATIONS

Beam dynamics of un-bunched beams has been calculated with the 2D particle-in-cell simulation code MONET [2]. It has been specifically developed to simulate beam transport in the Saclay FODO channel and interpret experimental results. The particle dynamics is computed in a self-consistent fashion. To calculate the space-charge force, the charge distribution in the transverse plane is divided into many homogeneous elliptical rings, from which the electric fields are analytically computed at the mesh points of a two-dimensional lattice in the transverse space.

4. EQUILIBRIUM OF MATCHED BEAMS

Theoretical Background

The evolution of the beam density distribution $f(\vec{r},\vec{p},t)$ can be described by Vlasov's equation. In a continuous focusing channel, as a smooth approximation of a periodic one, the stationary solution of this equation is : $F_0(\vec{r},\vec{p}) = f_0\left(H(\vec{r},\vec{p})\right)$, where $H(\vec{r},\vec{p})$ is the Hamiltonian of the motion of the beam particles. This Hamiltonian function depends on the beam shape and current through the space-charge potential.

The evolution of the beam rms envelope R is described by the equation:

$$d^2R/dz^2 + F_c(R) - F_{sc}(\Re) - \varepsilon_R^2/R^3 = 0\,,$$

where R and ε_R stand for the beam rms-size and rms-emittance respectively in the three spatial directions and $\Re$ is a function of these three rms-sizes. $F_c(R)$ denotes the external confinement force, and $F_{sc}(\Re)$ is the space-charge force. In the case where the beam is matched ($d^2R/dz^2 = 0$), the particle distribution is stationary with $R = R_m$.

We introduce the parameter $\zeta_R = F_{sc}(\Re_m)\cdot R_m^3/\varepsilon_R^2$ which is the ratio between the space-charge force and the emittance force acting on the beam. It is related to the tune depression factor η_R by: $\zeta_R = \eta_R^{-2} - 1$. When ζ_R>>1, the beam is space-charge dominated, and if ζ_R<<1, the beam is emittance dominated. It has been shown [3] that :

- when ζ_R<<1, the iso-density curves are ellipses in the sub phase spaces. The stationary beam profile depends on the initial density distribution.
- when ζ_R>>1, as current increases, beam particles move in a potential well which is no longer harmonic but increasingly flatter in the central region of the beam and has sharp edges at the beam boundary. The phase-space distribution then becomes rectangular. If external confinement force is linear in all directions, the stationary particle distribution inside the beam is homogeneous.

Results and Discussion

A series of 9 measurements was performed with proton beams of nine different intensities ranging from 2.2 mA (ζ=.17, η=.93) to 37 mA (ζ=9.5, η=.31). The FODO channel was tuned to a phase advance per period (without space charge) $\sigma_o = 60°$. For each proton-beam current, the phase-space distribution was first measured in the matching section (at the exit of the source). Although these distributions yield emittances of slightly different values (larger at higher current), they exhibit similar patterns. The beam is then matched to the channel by adjusting the triplet and quintuplet quadrupoles with current settings determined from the phase-space data and the channel parameters by using the transport code MONET; the beam parameters σ (phase advance with space charge), η and ζ are also determined.

Finally, the phase-space distribution is measured in the exit section on the matched beam after it's transported through the FODO channel. In Fig.1 displayed are the contour plots of *x,x'* for two different beam-current.

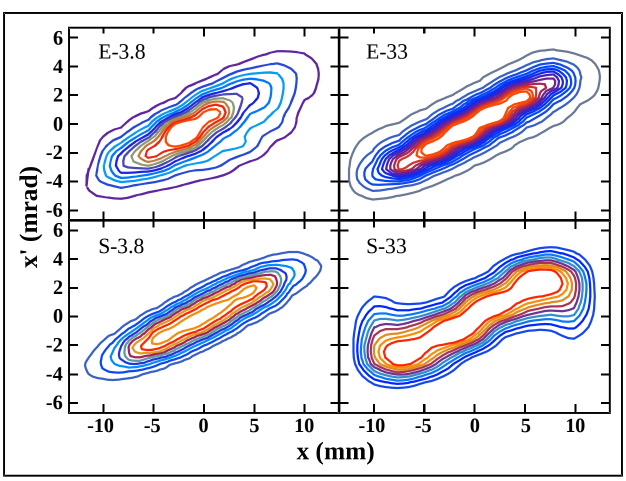

Figure 1: *Comparison of Experimental (above) and Simulated (below) phase-space contour plots for beam currents of 3.8mA (left) and 33 mA (right).*

Also shown in this figure are the corresponding simulation results obtained by using the phase-space distributions measured in the matching section as input parameters for the code MONET. It appears clearly that the measured equal-density contours are much closer to rectangular shapes for the 33-mA data than are the contours for the 3.8-mA data, a result which is consistent with the theory. The qualitative agreement between experiment and simulation is very good.

Figure 2 shows the transverse profiles at the end of the channel. Only three beam currents are shown for simplicity though measurements were done with nine different currents.

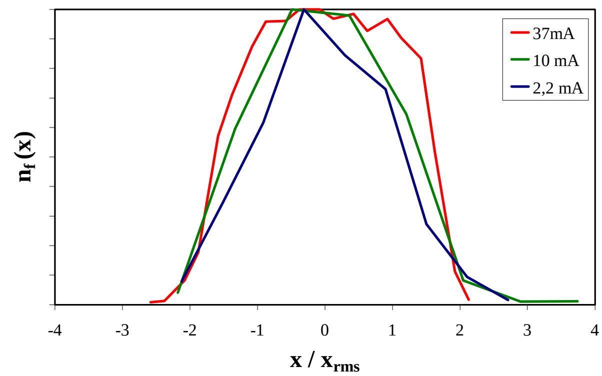

Figure 2: *Measured beam profiles at the exit of the FODO channel.*

It is apparent that, at low beam current, the output beam profile is very similar to the initial one, but as beam intensity increases, the output profile becomes progressively closer to a square shape, implying that the proton density in the beam becomes almost uniform.

5. MISMATCHED BEAM EMITTANCE GROWTH

Theoretical Background

In the phase-space, the particles follow trajectories for which $H(\vec{r},\vec{p}) = C^{ste}$. Let's consider the case of a beam in a continuous focusing channel. A beam in equilibrium in this channel has its iso-density curves in the phase-space (contour-plot) that coincide with the curves given by the equation : $H(\vec{r},\vec{p}) = E_k(\vec{p}) + E_{ext}(\vec{r},[\vec{p}]) + E_{sc}(\vec{r},[\vec{p}]) = C^{ste}$, where E_k, E_{ext}, E_{sc} represent the kinetic, external and space charge energy respectively. The symbol $[\vec{p}]$ means that, most of the time, the dependence on p can be neglected.

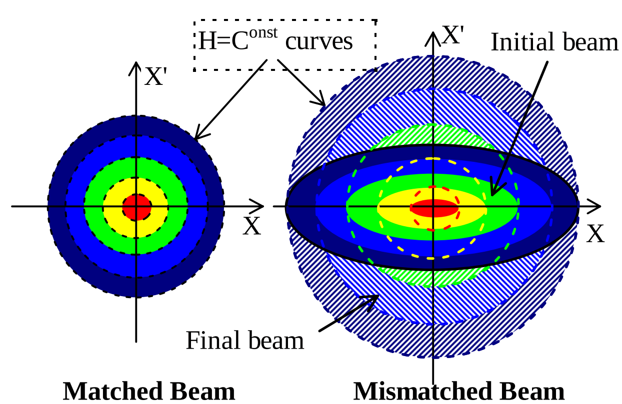

Figure 3:Matched and mismatched beam evolution with time

We define a beam to be 'mismatched' when it is not in equilibrium in the channel. It should be noted that this definition is more rigorous than the conventional definition of 'RMS-mismatch'. An RMS-mismatched beam is never matched, but rigorously speaking, an 'RMS matched' beam can be mismatched ! The phase-space distribution of a mismatched beam changes with time (or from period to period), while that of a matched beam stays unchanged. When the forces are non linear as with space-charge forces, the particles do not turn in the phase-space with the same angular velocity. After a while, they fill the phase-space completely until an equilibrium state is reached (Fig. 3). This auto-matching mechanism or redistribution of charges toward an equilibrium results in an overall emittance growth and tail formation for the case of strong non-linearity.

Experiment and simulation results

The beam (with a current of 38 mA) is matched to the channel using the triplet and the quintuplet as described in section 4. In order to mismatch it, we change the magnet-current in the last quadrupole (Q5) around its matched value. The beam transverse emittance is measured at the exit of the channel for each current setting in Q5. Fig. 4, shows the measured horizontal output emittance evolution with the magnet-current in Q5. A parabola was fitted to exhibit the position of minimum emittance. The matched beam undergoes the minimum emittance growth, while mismatch induces emittance growth.
The quantitative difference between the experiment (in blue) and the simulation results (in red) stems from an undetected flaw in experimental measurement: The pepper-pot phase-space acceptance used during measurement was smaller than the full beam distribution. The acceptance was only large enough to measure the phase space distribution of the main core (~95 %) of the beam and the tails in the x' direction were truncated. In order to reconstitute the situation during actual measurement, a final emittance (in green) was calculated from the simulated distribution wherein the particles outside the estimated acceptance of the measurement representing a few percent of the total particles were suppressed. The corrected emittance values of simulation is then found to be very close to the measured ones.

The results of the experiment suggest that mismatch (1) induces a small core-emittance growth, and (2) results in a large tail emittance growth possibly leading to halo formation. Further comprehensive measurements are needed to shed light on the formation, growth and behavior of halo under varied beam-dynamical conditions.

The transverse envelopes and emittance-evolution of the 34.5 mA mismatched (Q5 value 5% greater than the matched one) beam in the channel are shown in Fig. 5. It exhibits how an initially mismatched beam matches itself to the channel with concomitant emittance increase.

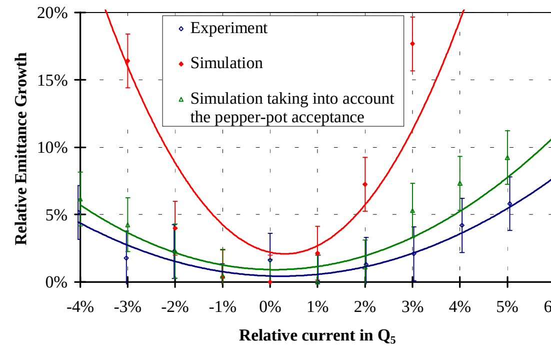

Figure 4 : Emittance growth versus beam mismatch.

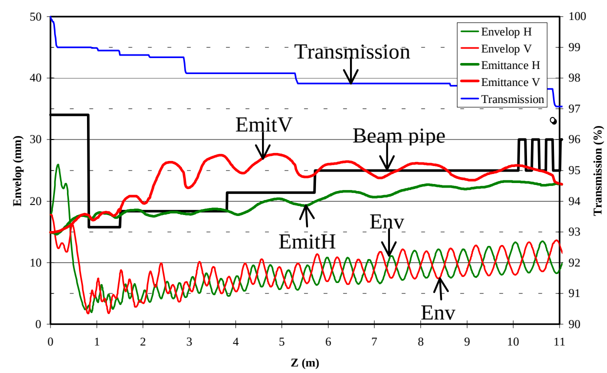

Figure 5: Transverse beam envelope and emittance evolution of a 34.5 mA mismatched beam in the FODO channel.

6 CONCLUSION

The behavior of a proton beam transported through a quadrupole FODO channel has been investigated in light of the space-charge-induced self-force effects. Experimentally measured transverse real- and phase-space distributions for a beam matched to the channel, and tuned at σ_o= 60° agree fairly well with the numerical simulation results. It also shows that the beam reaches a stationary equilibrium state consistent with a more homogeneous distribution as the space-charge force increases. An initially mismatched beam matches itself, through redistribution of charges mediated by nonlinear space-charge forces, toward a matched equilibrium distribution.

7 REFERENCES

[1] G. Haouat, N. Pichoff, P.Y. Beauvais and R. Ferdinand, Proc. of the 5th Europ. Part. Accl. Conf., EPAC96 (1996) p.1206.

[2] N. Pichoff, "Etude théorique et expérimentale du halo d'un faisceau intense de particules chargées dans un accélérateur," Ph.D. thesis, Université Paris XI-Orsay, France, 1997.

[3] N. Pichoff, G. Haouat, P.Y. Beauvais, J.M. Lagniel, R. Ferdinand, S. Nath, S. Joly, " Transverse profile equilibrium in a space-charge dominated beam," Proc. of the 1st Asian. Part. Accl. Conf., APAC98 (1998).