CEA Studies on Halo Formation

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Abstract. Beginning with the TRISPAL project, halo formation has been extensively studied at CEA last 10 years. Effect of mismatching, non-linear forces, resonances, longitudinal-transverse coupling, intrabeam scattering, and interaction with the residual gas have been explored. They have been studied theoretically from both analytical models and dedicated simulation codes and, for some of them, experimentally from proton beam profile measurements over a high dynamic range in a 26 periods FODO channel. Our knowledge, strongly improved through collaborations with our worldwide colleagues, has been applied to the design of several linac projects, whose last are SPIRAL2 and RX2. The goal of this presentation is to summarise the contribution of the CEA teams to the understanding of the halo formation.

INTRODUCTION

About 10 years ago, a great interest for Halo production in high intensity proton linac arises at CEA with the TRISPAL Project aiming to produce Tritium using a 40 mA, 600 MeV, cw proton accelerator. At that time, a large program of halo studies (experimental as well as theoretical) began. At the end of the TRISPAL project (1998), the interest was kept alive with the arrival of new projects where CEA was involved : ASH, aiming to produce energy and destroy nuclear waste by coupling a reactor with an accelerator, CONCERT, proposing a multipurpose installation, ESS, the European Spallation Source, and the last one, SPIRAL2, a cw Deuteron-Heavy ions linac for nuclear physics studies. For all these projects, beam loss control is crucial to avoid large activation of the machine. Many suspected sources of halo have then been studied theoretically and some even experimentally. A short summary of these studies with relevant references is presented here.

Experimental Setup

Two machines have been used for diagnostics development and experimental measurements.

◆ **ELSA** is an electron RF accelerator located at Bruyères-le-châtel. It was essentially used to develop profile measurement diagnostics with a high dynamics range. Two methods based on RTO (Optical Transition Ray) or scintillating screens observed by an intensified camera were used [1]. They allowed to reach beam profile measurements over up to 7 decades.

Because of the specificity of the tails of a beam created in a RF photo-injector it was difficult to extrapolate the measurements made on ELSA to long linacs.

◆ The **FODO experiment** took place in Saclay on the former Saturne DTL injector [2]. It is a 52 Quadrupole FODO channel. The beam profiles as well as beam transverse phase-space distributions have been measured in front of and behind the channel. Unfortunately, no diagnostic was possible in the channel. A strong effort was made on the measurements of initial beam characteristics and on the matching of the beam (comparison between simulations and experiments). Some experimental results are presented here.

THERORETICAL STUDIES

Equilibrium

We spent first some time studying the equilibrium for transverse distributions in a focusing channel. We have learned that a beam tends always to an equilibrium in an infinitely long channel. The equilibriums are characterised by a distribution function which only depends on the motion Hamiltonian. We have proven that, whatever the equilibrium, the profile of a space-charge dominated beam tends to the profile of an opposite charge distribution whose space-charge would produce the focusing force (for example, an homogenous distribution producing a linear space-charge force ⇨ the beam profile tends to an homogenous profile in linear forces). In these conditions, particle trajectories in phase-space look like rectangles (whatever the external force) instead of ellipses in linear external force, for example.

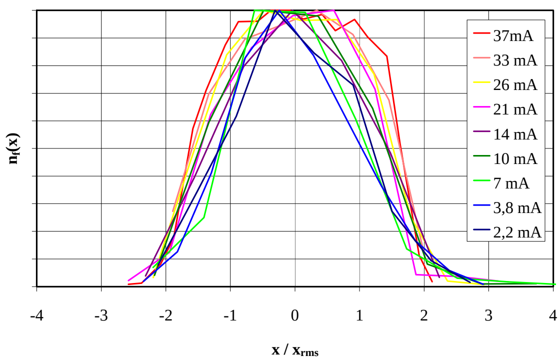

Figure 1 : Experimental normalised beam profiles for different currents

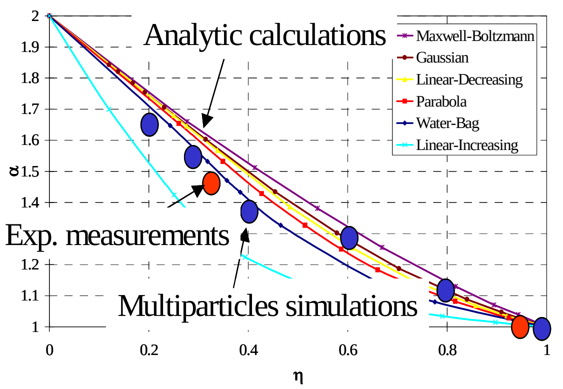

Figure 2 : Comparison between experience, analytic model and simulations of the beam "shape parameter" in phase-space as a function of tune depression.

Experimental measurements of beam transverse profiles at the FODO channel exit (Figure 1) and phase-space distributions (Figure 2) for different tune-depression confirmed the theoretical model [3]. The phase-space "shape parameter" α used in Figure 2 and defined in [3] is 1 for tune depression $\eta = 1$ and goes to 2 (same amplitude for both particles) when $\eta \to 0$.

Mismatch

Mismatch is known as the main source of halo observed in the PIC simulations. It has been studied by many accelerator physicists worldwide. This halo is the result of the contribution of 2 phenomenons :

- a filamentation due to non linear forces,
- a parametric resonance of particle trajectories with the core oscillation.

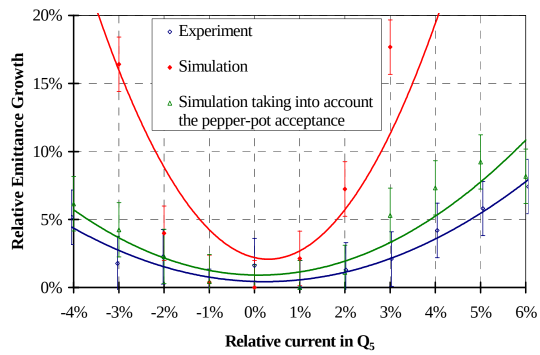

Figure 3 : Emittance growth through the FODO channel by mismatching the beam with an upstream quadrupole

Using Poincaré plots, we have shown that the half integer resonance between particles and core motions is always excited when the beam is mismatched [4]. This resonance is responsible for large amplitude particle oscillations. As many resonances can be excited, chaotic motion is observed in phase-space when these resonances are overlapping. Depending on the working point (coupling resonances can be also excited), the impact of the mismatch is more or less important. To find safe working point, we had to calculate the 3 mismatched mode frequencies of bunched beam in a continuous focusing channel with no approximation in the case where the forces along x and y are the same [5]. Measurements of emittance growth in the FODO channel as a function of the beam mismatch have been compared to simulations (Figure 3). By taking into account the acceptance of the emittance measurement, the agreement is quite good.

Coupling resonances

In the CEA-CNRS-INFN collaboration for the ASH design (1999) an emittance exchange has been observed when the longitudinal and transverse phase advances were the same. Following I. Hofmann advices, we have studied the effect of the coupling resonance in these conditions with the help of S. Nath from LANL. Some results of these studies are presented in this workshop in a dedicated talk [6]. We have seen that for reasonable average tune depression η the time needed for a maximum emittance exchange depends linearly on a space charge factor ($1/(1-\eta)$). The resonance width seems to be almost insensitive to the initial beam distribution. Emittance exchange is not necessarily accompanied by halo production.

Intrabeam scattering

PIC codes usually do not simulate properly intrabeam scattering. In the Vlasov equation dealing with the motion of particles without collision, the collision process must be modelled by adding a collision term. The denser the beam, the lower the two-body collision influences on the beam dynamics. Space-charge routines of PIC codes generally smooth the space-charge forces. This smoothing suppresses or reduces the low range collisions in the beam compared to a simple particle-particle interaction (PPI) routine. Nevertheless, the remaining collision process in the PIC code is generally far from reality.

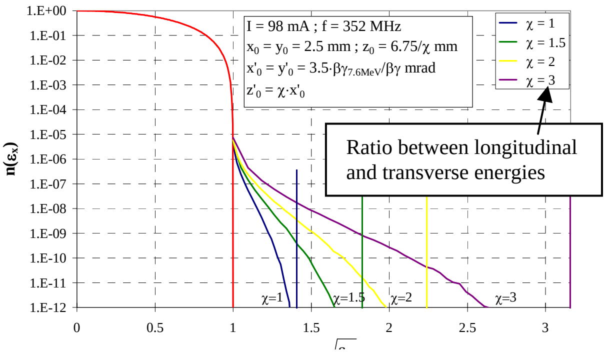

Figure 4 : Beam profile and tails from intrabeam scattering at the end of a 1GeV linac

We have developed a model to estimate the contribution of the two-body intrabeam scattering to halo formation. The extend of the induced halo depends on the beam equipartitioning factor (ratio between longitudinal and transverse average energies), but its level is low ($<10^{-8}$ m^{-1}) for 100 mA proton beams [7], (Figure 4).

Interaction with residual gas

The beam interaction with residual gas is usually not taken into account in PIC simulations. Many kinds of interactions can happen. For the moment, we have studied only 3 of them :

◆ The **stripping of H^- ions**, electron exchange of H^- ions with residual gas atoms, is probably the major source of losses in linacs like SNS or ESS in the normal conducting sections (even if it is not really a source of halo). The loss rate knowing the residual gas pressure and composition, or the vacuum needed to keep beam losses lower than a given limit can easily be estimated from the reaction cross section. For ESS linac losses around 1W/m have been estimated at the end of the room-temperature linac [8] (Figure 5).

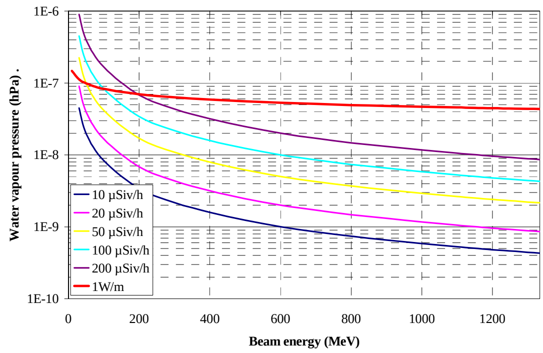

Figure 5 : H_2O maximum pressure needed to stay below a given rate of H^- stripping beam losses

◆ The **space-charge compensation** plays an important role in the beam transport at low energy. The beam ionises a part of the residual gas, trapping species with opposite charge and expulsing those with same sign. The average space-charge force acting on the beam is then reduced. This phenomenon, occurring mainly at low energy, should be completely understood to predict the correct matching of the beam to the linac. Its time evolution should be modelled and, why not, compensated to avoid strong mismatch of a pulsed beam front end. A 10 µs time constant is actually small (rise time for a 100 mA beam neutralization at 10^{-5} hPa), but represents 1% of a 1ms pulse, much more than what one can afford to lose! Studies are started at Saclay [9].

◆ The **elastic scattering** of the beam on the residual gas can give large angles to some particles. Once scattered, the particles can either be lost after a fourth of betatron period (called direct loss) or populate the beam halo. The fraction of direct losses and of halo particle can be estimated from the scattering cross section [10]. In a Nitrogen 10^{-6} hPa gas pressure, a beam with 0.2 π.mm.mrad normalised transverse emittance and an average rms size of 3 mm would accumulate a 1.3 10^{-6} beam fraction out of 4 RMS size from 5 MeV to 1 GeV in a 340 m linac (see figure 6). This is not a lot (only 13 W from a 10 MW beam at 1 GeV) but can contribute to large local losses in case of errors or reduction of the acceptance.

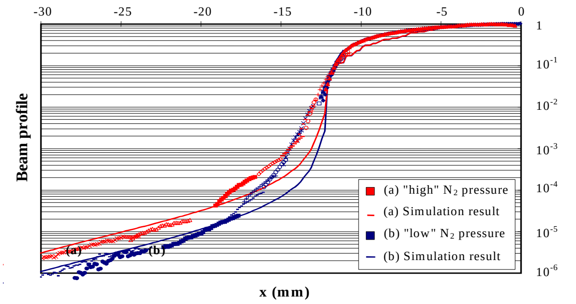

Figure 6 : Experimental and simulated beam profile and tails at the end of a drift for 2 Nitrogen gas pressures

Error studies

Errors on quadrupoles, and on cavities can cause localised losses. These errors are responsible of beam c.o.g motion (transverse and longitudinal) and mismatch. As these are statistical errors, a statistical treatment is thus the most appropriate. Having chosen the amplitude and the distribution law of each error, beam transport is simulated through many (1000, for example) linacs with different sets of errors. The different results are used to define the probability to find a particle at a given position.

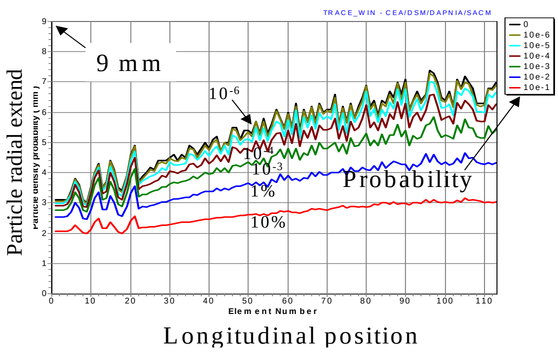

Figure 7 : Probability to find a particle to above given radial extend in the IPHI DTL including errors.

At the same time, a correction strategy with diagnostics and corrections can be included in the calculation. Some effects can be compensated by the correction scheme (misalignment, …), some cannot (fast vibrations, …). These error studies are very design-dependent and must be done once the design is done, at the end of a design process. They have been done in Saclay for IPHI (see figure 7), IFMIF, ESS and SPIRAL2 projects [11].

Conclusion

A small CEA team has worked for 10 years on halo formation. Its work has always been supported by projects of high intensity proton or H^- beam. A large effort has been put on effects that are not simulated by PIC codes. In the same time, codes like TraceWin (envelope code), PARTRAN and TOUTATIS (PIC codes) have been developed and used to design and simulate the linacs. Our strategy is to use the increasing power of computers to put more linac physics in our codes. Our participation to strong collaborations has been a great help to understand the physics of these kinds of accelerators. We would like to thank our colleagues from LANL, ORNL, RAL, INFN, CERN, FZJ as well as physicists of other labs we met in the conferences, workshops and through their books (M. Reiser, R. Gluckstern, I. Hoffman, R. Ryne, Ji Qiang, K. Crandall, and many others …).

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