EXPERIMENTAL RESULTS ON BEAM HALO

G. Haouat, Commissariat à l'Energie Atomique, BP-12, 91680 Bruyères-le-Châtel, France.

Abstract

The increasing interest for high-intensity, high-energy linear accelerators has induced the scientific community to consider a phenomenon whose effects are worrying: the beam losses. Lost particles can, indeed, produce enough radioactivation in the accelerator structures to considerably complicate operation and maintenance of the machine. They originate in a low-density halo which can extend far from the beam core. Theoretical and experimental studies have been undertaken in order to understand the physics of halo production and to develop methods to limit and control beam losses. The present work reviews efforts and advances in beam-halo and emittance-growth experiments. Experimental techniques, used in different laboratories, are described and measurement results are presented and commented. Experiments on the transport of space-charge dominated beams through periodic focusing channels are considered with particular emphasis.

1 INTRODUCTION

Advances achieved this last decade in the physics and technology of high-intensity, high-power linear accelerators have brought the scientific community to consider their use in a variety of applications. In many projects, examined in recent review papers, large proton (or H^-) linacs are proposed as drivers of intense spallation-neutron sources for transmutation of radioactive nuclear wastes [1], safe production of tritium [2], burning of defense and commercial plutonium inventories [3], energy production in hybrid reactors [3] and for basic research [4]. In these accelerators, with up to 200 mA CW beam current and 200 MW beam power, beam losses are a major concern, since they will cause unacceptably large activation of the structures. Therefore, accelerator designs have to account for this worrying phenomenon. For example, to ensure hands-on maintenance of a 100-mA linac, estimates of the allowed relative losses range from $\sim 10^{-6}$/m at 10 MeV to $\sim 10^{-9}$/m at 1 GeV [5].

Beam losses are attributed to the particular behavior of a small fraction of beam particles surrounding a dense core and called the halo. The term "halo" has been proposed for the first time at the outset of the seventies by LAMPF physicists to designate tails in the beam transverse distribution they observed in the early experiments on the 1-mA, 800-MeV proton beam [6].

The projects of new accelerators, with beam currents 100 times (or more) larger than at LAMPF, have led up to a major challenge: understanding the mechanisms involved in beam-halo production in order to elaborate methods to limit and control beam spill. The efforts include essentially theoretical studies with model developments and extensive numerical simulations. Several scenarios for the formation and development of halos have been proposed:

- Incoherent effects of space-charge and focusing forces on a matched beam which can, via resonant interactions [7] and/or chaotic processes [5,8], expel particles from the beam core toward the periphery.
- Transverse mismatch and misalignment effects on a space-charge dominated beam [9].
- Incomplete longitudinal capture and longitudinal mismatch [10].
- Longitudinal and transverse space-charge waves generated in a beam bunch which can, during their relaxation toward an equilibrium state, generate particle ejection [8].
- Effects of the transverse-longitudinal coupling force which can, via space-charge forces and non-linear accelerating RF fields, communicate transverse energy to some particles [11].
- Coulomb elastic scattering of beam particles on residual gas which modify particle trajectories [12].

This non-exhaustive list of mechanisms calls for a question: what is the criterion for defining the halo? Brown and Reiser [13] define the "halo" as the ensemble of non-thermalized particles of a beam having betatron oscillation amplitudes larger than the maximum extent of the beam core. They make the difference between the halo and the "tail", which is the part of the thermal equilibrium distribution that extends beyond the beam core. Tail and halo particles are, however, unfavorable with regard to beam loss.

The halo appears to experimentalists essentially in the transverse plane, as a collection of particles, of any origin and behavior, which lie in the low-density region of the beam transverse distribution far from the core, beyond a given number n of rms core radii (say $n \approx 3$). It is so tenuous that its observation is difficult. Halo can be more precisely defined as the ensemble of particles having radial position greater than $n\sigma_r$ or trajectory slope greater than $n\sigma_{r'}$, σ_r and $\sigma_{r'}$ being the second order moments of the phase-space beam distribution. The halo formed around the dense core results in emittance growth, a quantity which is accessible to measurement.

In the present paper, we survey recent and prominent experimental studies of beam halo formation and emittance growth. The experimental techniques developed in different laboratories are described. Periodic focusing channels are considered with special emphasis since they constitute excellent tools for studying the development of instabilities in space-charged dominated beams. Measurement results and proposed interpretations are presented.

0-7803-4376-X/98/$10.00 © 1998 IEEE

2 EMITTANCE GROWTH AND FIELD ENERGY

Emittance growth of low-energy, intense ion beams, induced by space-charge effects through the nonlinear field energy [14], has been investigated in two laboratories. Palkovic [15] reports on emittance measurements in a drifting, decompensated proton beam, at energies between 19 and 45 keV and currents between 9 and 39 mA. They were made at three different positions along the beam axis using a moving-slit emittance probe. Analysis of the results, which are in good agreement with simulations, shows that almost all of the emittance growth is due to a halo containing ~10% of the beam particles. These halo particles are found to be located near the edge of the distribution in phase space.

In a study of the influence of partial space-charge compensation on the transverse emittance of space-charge dominated beams, the University of Frankfurt group observes a severe emittance growth in a 10-keV, 2.5-mA, He^+ beam transported through a magnetic transfer line [16]. Emittance measurements were performed at different locations in the beam line with an electric sweep scanner. They attribute this emittance growth to charge-redistribution and beam-instability effects dominating lens aberrations. This group observes also halo formation in He^+ and Ar^+ beams caused by solenoids, Gabor plasma lenses and radio-frequency quadrupoles [17].

3 HEAVY-ION BEAM TRANSPORT IN A FODO CHANNEL

Heavy-ion drivers for inertial confinement fusion depend crucially on the capability to produce high-intensity, high-quality beams. Emittance growth and beam loss are the primary issues in designing the various components of a heavy-ion fusion accelerator. Of particular concern are the low-energy, multi-beam, electrostatic-focusing induction linacs and the beam-combining devices [18]. Since no comprehensive self-consistent analytical theory for high-current dynamics in such accelerators is so far available, experimental and simulation works are needed to clarify design issues.

3.1 The Lawrence Berkeley Laboratory experiments

As part of the Heavy Ion Fusion Program at Lawrence Berkeley Laboratory [18], a Single Beam Transport Experiment (SBTE) and a Multiple Beam Experiment (MBE) have been set up, more than 10 years ago, to investigate the stability limits for a highly space-charge dominated ion beam in a long alternating-gradient transport channel. Experiments, surveyed here, have been performed on the SBTE [19-22]. The experimental apparatus is composed of an ion gun, a matching section and a transport section, with 82 electrostatic quadrupoles arranged in a FODO lattice, and diagnostic instrumentation. The ranges of beam parameters are: Cs^+ beam, kinetic energy 120-160 keV, beam current 0.7-23 mA, normalized beam emittance 0.08-5 π mm.mrad. Beam emittance is measured at four locations in the FODO channel with the conventional two-slit scan method [19].

Halo formation has been demonstrated in several experiments. In a first one [20], a well-matched beam is provided for injection in the FODO channel. The single-particle betatron phase advance per period without space charge σ_0 is varied in the range 45°-150° to determine the stability limits for the space-charge depressed phase advance σ. The beam transport is defined as stable if both the emittance and current remain unchanged from the entrance to the exit of the channel, and unstable if either the emittance grows or the current decreases because of collective effects. Data analysis indicates that beam transport is always stable below $\sigma_0 = 90°$, within the limits of current and emittance accessible to measurement. It is unstable above $\sigma_0 = 90°$ if sufficiently high current is injected, leading to emittance growth and beam loss. Stable transport conditions can seemingly be met in this region, at low beam currents (See Fig. 4 in Ref. 20).

In a combined experimental and simulation study, the effects on transverse beam dynamics of charge induced on focusing electrodes are analyzed [21]. For misaligned highly space-charge-dominated beams ($\sigma/\sigma_0 \sim 0.1$), a large oscillation of the rms emittance appears, in a beat pattern, along the FODO channel, and can result in beam instability.

In another experiment, emittance growth in mismatched intense beams is investigated [22]. It is found that in the transport of a mismatched beam in both horizontal and vertical directions, with mismatches of the same amplitude but of opposite sign, the emittance grows by as much as a factor of four over that of the matched beam. Observation of the phase space shows a very extensive, but low-level, halo which has formed around the beam core and contains 2 to 3% of the beam particles.

3.2 The experiments at GSI

An experimental program has been undertaken at GSI to explore stability thresholds and instability modes of a high-current ion beam in a transport channel of a few periods [23]. Computer simulation studies have shown, indeed, that many space-charge effects should be observable in such a transport channel [24].

The experimental set-up consists of a 190-keV Ar^+ beam injected, through a matching section, into a six-period magnetic-quadrupole FODO channel. Injected beam current can be varied from 0.1 to 6 mA, and unnormalized emittance from 2 to 30 π mm.mrad. Emittance measurements are made with a conventional slit-collector system positioned at the entrance and exit of the channel. Measurements can be performed on unneutralized and partially space-charge compensated beams.

Analysis of the data shows an enormous deterioration of beam emittance depending on the tune σ_0 and the beam current [23]. Emittance growth is observed, not only above $\sigma_0 = 90°$, where envelope instabilities develop as predicted by theory and computer simulations, but also below $\sigma_0 = 90°$. Emittance growth occurs at high intensities even when the beam passes through only one FODO period. The source of this emittance increase is attributed to homogenization of the particle distribution at least in cases where no instabilities occur [25].

4 THE MARYLAND TRANSPORT EXPERIMENT

The University of Maryland has carried on, for more than 15 years, an active research program on the fundamental physics of space-charge-dominated beams. A remarkable feature of this program is the tight connection between experiment, theory and simulation.

The Maryland Transport Experiment (MTE) has been originally designed to study the causes of emittance growth and instabilities that limit beam current and brightness in a periodic-focusing transport channel. The experimental set-up consists of a thermionic gun delivering a 5-keV electron beam, a transport channel with 36 periodically spaced solenoids and a two-solenoid matching section between the gun and the channel [26]. The full 240-mA solid beam produced by the gun can be masked to form a 5-beamlet configuration of 44 mA total current. Beam emittance is measured at the end of the channel using a slit/pinhole device. A movable phosphor screen is used to observe the beam profile anywhere along the channel.

In earlier experiments made with the solid beam and only 12 lenses [27], it is shown that beam transport with essentially no particle losses and with very little emittance growth (~30%) can be achieved over a range of $40° \leq \sigma_0 \leq 110°$ at large tune depression of $\sigma/\sigma_0 \sim 0.1$. On the other end, the rapid current drop above $\sigma_0 = 110°$ is due to halo formation which results in beam loss to the wall of the tube. It has been proposed that this beam loss could result from envelope instabilities.

Subsequent experiments in the full 36-lens channel indicate considerable beam loss occurring in the longer system, which is explained by misalignment effects and injection errors. Simulations performed with the expected misalignment from mechanical tolerances reproduce an emittance growth comparable to the measured one. Further measurements with the realigned system show a dramatic improvement of beam transmission efficiency [28].

Recent experiments have been conducted on the MTE with a 44-mA beam, divided into five separate beamlets, to study the effects on the transverse dynamics in intense beams of nonuniformity as well as mismatch and misalignment [29]. This beamlet combination is also of interest for investigating merging of several beams for heavy-ion-fusion purpose. The use of a movable fluorescent screen in these experiments is of great importance since it allows to examine beam-profile evolution as the beam propagates down the transport channel.

Experimental observations of a nonuniform, matched beam indicate charge homogenization in the transverse space and emittance growth, which occur not only in a focusing channel, but also in a drift space [30]. These trends are theoretically predicted to be due to conversion of free energy, associated with a nonuniform rms-matched charge distribution, into random transverse kinetic energy. There is, however, no evidence of halo formation and misalignment is believed to contribute negligibly to emittance growth.

On the contrary, for a nonuniform mismatched beam, experiment and simulation reveal a strong halo at the channel end [29]. This can be seen on images from the movable fluorescent screen. Comparison of these images to those produced by the numerical simulations shows excellent qualitative agreement in the beam profile throughout the channel **(**See, for example, Fig. 3 in Ref. 29**)**. On the other hand, the measured beam emittance is much smaller (about half) than that predicted by theory and simulation. This difference is attributed to the lack of sensitivity of the profile and emittance detectors for the very diffuse halo surrounding the mismatched beam core [29].

Analysis of measurement and simulation results indicates that *i)* most of the energy associated with the mismatch goes into the halo, *ii)* the halo is responsible for most of the emittance growth predicted by theory and *iii)* the beam core thermalizes much faster than the surrounding halo [31]. It has also been found that many of the particles that form the halo are determined by their position in the initial distribution.

5 THE BRUYERES-SACLAY HALO PROGRAM

The Bruyères-Saclay halo program is associated with the TRISPAL project of a high-intensity, high-power proton linac [2]. Its objective is the study of halo-producing mechanisms in two different scenarios: the generation and transport of a very intense, very bright electron beam [32] and the transport of a high-current proton beam through a periodic magnetic-quadrupole FODO channel [33]. For these purposes, sophisticated experimental techniques have been developed for measuring transverse profile and emittance of the beams over a large dynamic range, and for analyzing the very low density regions constituting the halo. They are described below and measurement results are presented.

5.1 Measurement techniques

Beam transverse distribution is measured using either of two experimental procedures, established on the corona observation: the hole-drilled screen method and the neutral-density filter method. They both ensure a correct measurement of the low-density outer part of the beam profile. They are based on an imaging technique in which the light emitted from a charged-particle/photon conversion screen, is analyzed by an intensified video camera. The converter is an optical-transition-radiation screen in the electron experiments and a phosphor screen in the proton experiments.

In the hole-drilled screen method, a hole is bored in the center of the conversion screen. The beam being slightly off-center with respect to the hole in the disk, the beam core is first observed. The beam is then steered toward the hole through which most of the core particles pass. Then, the halo can be properly observed by increasing amplification of the light intensifier. This method is very powerful since background light originating from the core is eliminated [32].

Another way to observe the beam corona is to use the neutral-density filter method in which the light corresponding to the beam, and provided by a conversion screen without hole, is attenuated only for the core by a circular filter. Images of the halo and the attenuated core are then observed on the same picture [34].

Beam emittance is measured using the quad-scan technique for the electron beam, and the pepper-pot or pinhole/profile-harp techniques for the proton beam.

5.2 *Transverse dynamics in an electron photo-injector*

In an experiment, performed at Bruyères-le-Châtel, on the electron beam from the ELSA photo-injector, the effect of focusing strength of the photo-injector anode coil on the beam transverse dynamics has been analyzed for various electron-bunch charges [35]. The focusing anode coil is of particular importance since it counteracts the space-charge defocusing force, which is important at low electron energy.

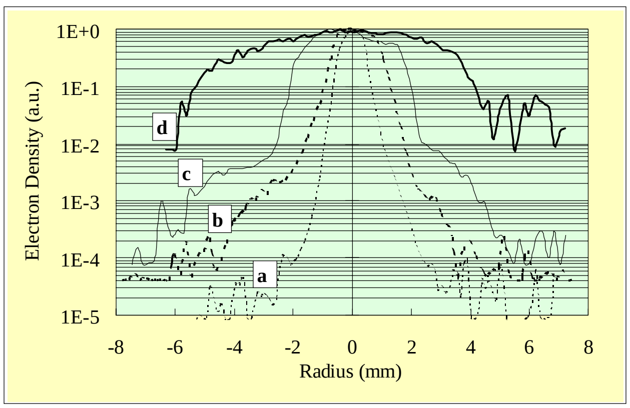

Figure 1: *Density distributions of a 16.5-MeV electron beam for four settings of the parameters Q (Bunch charge), B (Anode-coil current) which are:*

a) Q = 0.5 nC, B = 16.0 A; b) Q = 0.9 nC, B = 17.5 A

a) Q = 1.8 nC, B = 19.0 A; b) Q = 2.8 nC, B = 19.7 A

The results show different beam behaviors as illustrated on Fig. 1: *i)* At low charge and coil current, the density profile decreases rapidly from the center of the beam toward the outside (curve a), *ii)* At mid current, the density profile seems to be composed of two different shapes, as if two beams, with different transport properties, were traveling together. The more dense beam could be called the "core", the other one, the "halo". Curves b and c of Fig. 1 exhibit this particular pattern, *iii)* At high current, the core and the halo seem to be completely mixed (curve d).

Processing of the density profiles yields an estimate of the fraction of the beam that extends beyond a given distance from the beam center. Beam radii enclosing 90%, 99%, 99.9% and 99.99% of the particles have been deduced for each measurement. Variations of the beam radius enclosing 99% of the particles in the bunch-charge/coil-current space are displayed in Fig. 2 as a 3D contour plot labeled as "EXPERIMENT".

The experiment has been simulated using the code PARMELA. Because of the limited numerical capabilities of the code, contour plots could not be obtained for beam radii enclosing more than 99% of the particles. Data corresponding to this value are presented as "PARMELA" in Fig. 2. Comparison of contour plots for measured data and simulation results shows good qualitative agreement, in spite of some discrepancies in the magnitude of beam radii [35]. In particular, the valley in the contour plot is nicely reproduced by the simulation.

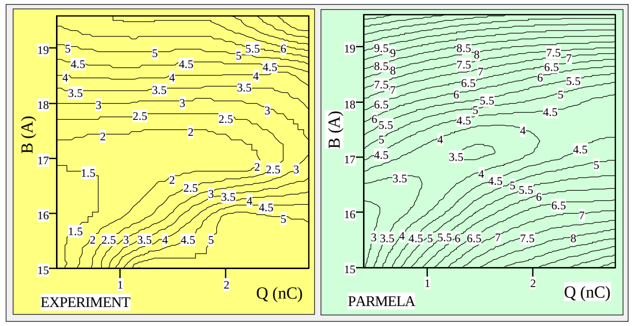

Figure 2: *Contour plot of the 99% beam-radius variations with charge Q and anode-coil current B for a 16.5-MeV electron beam..*

Experiment and simulation indicate that the anode-coil current should be higher if the objective is to optimize the transport of the beam core only, and relatively lower if the objective is to optimize the transport of the whole beam, core and halo.

5.3 *The FODO experiment at Saclay*

An experimental study of halo formation in a space-charge-dominated proton beam transported through a periodic FODO channel is in progress at Saclay. It is based on a proposal consisting of using the 29-periods magnetic-quadrupole FODO channel of the Saturne 20-MeV Alvarez linac (not powered with RF) as a transport line for the proton beam of the injector Amalthée (See Ref. 33). Because of the Alvarez-linac structure, the period length of the FODO channel is not constant, but increases gradually from the entrance to the exit.

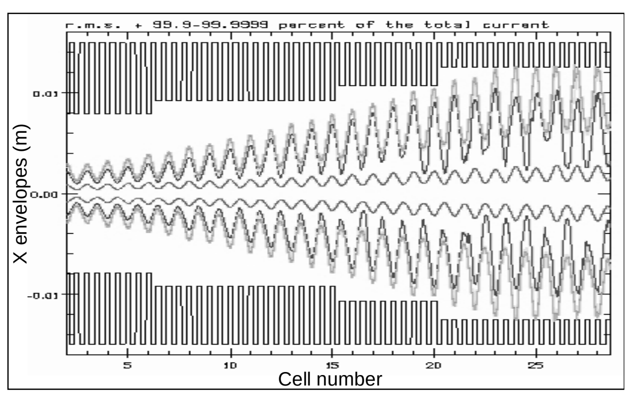

Figure 3: *Beam envelopes in the x-direction along the FODO channel from the RENOIR-code simulation for σ_o = 100° and I = 30 mA. The most inward envelope correspond to the rms beam radius and the most outward envelope to 99.9999% of the particles.*

The experimental set-up is composed of the proton source, a low-energy matching section with diagnostic equipment, the FODO channel and a diagnostic chamber at the end of the channel. The source produces a proton beam of 300 to 750 keV energy, 5 to 50 mA intensity, in 0.5-ms bunches.

Beam-halo formation appreciably 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 using both the pepper-pot mask with fluorescent screen and the pinhole/profile-harp system [36].

The emittance data have been introduced in the Particle-in-Cell code RENOIR [8], based on a self consistent model, to simulate beam transport through the FODO channel. The simulation yields beam distribution over a wide dynamic range including core and halo particles, and allows to find transport conditions for an rms-matched beam (Fig. 3). Using these transport conditions, emittance and halo measurements will be performed soon at the end of the FODO channel. However, a coherent interpretation of halo measurements implies to consider not only halo formation from space-charge effects but also halo production by beam-particle Coulomb scattering on the residual gas [37], and neutralization effects on the propagating beam [38].

6 CONCLUSION

Progresses in the reviewed experimental studies of halo formation and emittance growth contribute greatly to improve our understanding of the fundamental physics of space-charge-dominated beams. Close coordination between experimental works and numerical simulations, based on theoretical models, is essential and stimulates advances in each of the domains. However, the studies apply essentially to the transverse dynamics of intense beams.

Efforts remain to be done to experimentally study halo formation induced by the longitudinal effects, including incomplete capture, mismatch and longitudinal/transverse coupling. These effects are believed to be important sources of halo. Also, the effects of transverse and longitudinal space-charge waves have to be considered.

7 ACKNOWLEDGEMENTS

I express my sincere gratitude to N. Pichoff for support and great help in preparing this paper, and to A. Piquemal who kindly provided useful information and results from the code RENOIR.

REFERENCES

[1] M. Mizumoto, "Accelerators for nuclear wiste transmutation", LINAC 94, p.317.

[2] M. Promé, "Major projects for the use of high power linacs", LINAC 96, p.9.

[3] G. Lawrence, "Transmutation and energy production with high power accelerators", PAC 95, p.35.

[4] H. Klein, "Spallation Neutron Sources", LINAC 94, p.322.

[5] J.M. Lagniel, "Halos and chaos in space-charge dominated beams", EPAC 96, p.163.

[6] R. A. Jameson, "Beam halo from collective-core/single-particle interactions" Los Alamos Report LA-UR-93-1209, March 1993.

[7] R. L. Gluckstern, LINAC 94, p.333; Phys. Rev. Letters, **73**, 1247 (1994).

[8] J.M. Lagniel, A. Piquemal, "On the dynamics of space-charge dominated beams", LINAC 94, p.529.

[9] D. Kehne, M. Reiser and H. Rudd, Proc. 1991 Part. Acc. Conf., San Francisco, CA, p.248 (1991); A. Cucchetti, M. Reiser and T. Wangler, *ibid*. p.251.

[10] R. Garnett, E. Gray, L. Rybarcyk and T. Wangler "Simulation studies of the LAMPF proton linac", PAC95, p.3185.

[11] M. Pabst and K. Bongardt, "Halo simulation in a realistic proton linac", LINAC 96 p.27.

[12] J.M. de Conto, "Emittance growth and beam halo due to incoherent random phenomenons", EPAC94, p.1362.

[13] N. Brown and M. Reiser, Phys. Plasmas **2**, 965 (1995).

[14] T. Wangler, K. Crandall, R. Mills and M. Reiser, IEEE Trans. Nucl. Sci. NS **32**, 2196 (1985).

[15] J. Palkovic, "Emittance growth in a low-energy proton beam", PAC93, p.21.
J. Palkovic, "Gabor lens focusing and emittance growth in a low-energy proton beam", Thesis, the University of Wisconsin - Madison, 1991.

[16] P. Gross, J. Pozimski, R. Dölling, T. Weiss and H. Klein, LINAC94, p.520.

[17] G. Riehl, Pozimski and W. Barth, Proc. 1990 Lin. Acc. Conf., LA-12004-C, UC-910/UC-414, 755 (1991).

[18] P. Seidl, "Beam dynamics in heavy ion fusion", PAC95, p.3159.

[19] A. Feltens, D. Keefe, C. Kim, S. Rosenblum, M. Tiefenback and A. Warwick, Proc. 1984 Lin. Acc. Conf., Seeheim, GSI-84-11, 312 (1984).

[20] M. Tiefenback and D. Keefe, IEEE Trans. on Nucl. Sci. NS **32**, 2483 (1985).

[21] C.M. Celata, Proc. 1987 Patr. Acc. Conf., 996 (1987).

[22] M.G. Tiefenback, Proc. 1987 Patr. Acc. Conf., 1046 (1987).

[23] J. Klabunde, A. Schönlein, R. Keller, T. Kroll, P. Spädtke and J. Struckmeir, Proc. 1984 Lin. Acc. Conf., Seeheim, GSI-84-11, 315 (1984).

[24] J. Struckmeir and M. Reiser, Part. Acc. **14**, 227 (1984); J. Struckmeir, J. Klabunde and M. Reiser, Part. Acc. **15**, 47 (1984).

[25] J. Klabunde, P. Spädtke and A. Schönlein, IEEE Trans. on Nucl. Sci. NS **32**, 2462 (1985).

[26] J. Haber, D. Kehne, M. Reiser and H. Rudd, Phys. Rev. A **44**, 5194 (1991).

[27] M. Reiser, E. Chojnacki, P. Loschialpo, W. Namkung, J. Lawson, C. Prior and G. Warner, Proc. Proc. 1984 Lin. Acc. Conf., Seeheim, GSI-84-11, 309 (1984).

[28] M. Reiser, J. McAdoo, K. Low, D. Kehne and T. Shea, Proc. 1987 Patr. Acc. Conf., 1135 (1987).

[29] D. Kehne, M. Reiser and H. Rudd, AIP Conf. Proc. **253**, 47 (1991).

[30] M. Reiser, C. Chang, D. Kehne, K. Low, T. Shea, H. Rudd and J. Haber, Phys. Rev. Lett. **61**, 2933 (1988).

[31] D. Kehne, M. Reiser and H. Rudd, PAC93 p.65.

[32] G. Haouat, N. Pichoff, C. Couillaud, J. Di Crescenzo, S. Joly, S. Seguin and S. Striby, AIP Conf. Proc. **333**, 245 (1995).

[33] P.Y. Beauvais, D. Bogard, P. Chamouard, R. Ferdinand, G. Haouat, J.M. Lagniel, J.L. Lemaire, N. Pichoff and C. Ruiz, PAC95, p.3173.

[34] N. Pichoff, G. Haouat, C. Couillaud, J. Di Crescenzo, S. Joly, C. Ruiz, S. Seguin and S. Striby, DIPAC95, Travemünde, Germany, 28-31 May 1995, Conf. Proc. p.63.

[35] G. Haouat, N. Pichoff, C. Couillaud, J. P. De Brion, J. Di Crescenzo, S. Joly, A. Loulergue, C. Ruiz, S. Seguin and S. Striby, PAC95, p.3170.

[36] G. Haouat, N. Pichoff, P.Y. Beauvais and R. Ferdinand, EPAC96, p.1206.

[37] N. Pichoff, G. Haouat and P.Y. Beauvais, EPAC96, p. 1209.

[38] P.Y. Beauvais, J.M. Lagniel, N. Pichoff, G. Haouat and P. Chaix, LINAC96, p.202.