REVIEW OF INSTABILITY MECHANISMS IN ION LINACS

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Abstract

An important issue for the new high power class ion linac projects is the preservation of the beam quality through the acceleration in the linac. An extremely low fraction of the beam (from 10^{-4} down to 10^{-7}) is sufficient to complicate the hands on maintenance in such accelerator. This paper reviews the instability mechanisms in Ion Linacs. Basics rules for the definition of their architecture and the results applied to existing machines and projects are covered.

INTRODUCTION

High power ion linacs have become increasingly attractive in recent years. Among the possible applications are heavy ion drivers for thermonuclear energy [1] or rare ion beam production [2, 3], transmutation of radioactive wastes [4], neutrino physics [5] and the spallation sources of neutrons for matter research [6, 7, 8]. High intensity charged particle beams can develop extended low density halos. The existence of halos can have serious consequences for the hands on maintenance. Beam dynamics for such accelerators requires an exhaustive research of the different mechanisms that may induce beam loss from 10^{-4} down to 10^{-7}. The control of these mechanisms is the main guideline for the design of high power linacs. Among the different sources of beam loss, instabilities induced by the coupling of the beam and the accelerator working points are a major concern. This paper reviews the instability mechanisms in Ion Linacs. Basics rules for the definition of their architecture and the results applied to existing machines and projects are covered.

SPACE CHARGE NON LINEARITIES

As a particle beam is a charge and current distribution, it acts as a source term in Maxwell equations and generates self fields or space charge fields. The effect of space charge is essentially a low energy issue for two reasons: transversally, the self magnetic force tends to compensate the repulsive self electric force when the ions become relativistic and, longitudinally, the bunch length increases with the energy which corresponds to a reduction of the beam charge density. It is worth noting that beam waists may affect this statement at high energy. In essence, self fields are a strong function of the particle distribution and only an uniform beam density may produce linear fields but this case is only valuable for theoretical investigations. The non linear nature of self fields induces a spread of the tune shift. One importance consequence is that if each particle isn't located in phase space on an isohamiltonian curve which is matched to its own energy, a filamentation will occur and provoke and emittance growth (see figure 1). After a relaxation time which corresponds to a few focusing period when the space charge is important [11], a new equilibrium is reached and the emittance remains constant until a new mismatch is applied to the beam. This mechanism is applicable to the longitudinal focusing force of the cavities or any non linear force. Even if this phenomena could induce an emittance growth, it doesn't correspond to an instability mechanism. In this paper, a beam loss mechanism will be assumed to be an instability when the solution of the equation of the motion for the particles or the beam envelop corresponds to an exponential like behavior. It is worth noting that the impact on the motion of the instability changes significantly the initial conditions and the necessary conditions for the instability may vanish. The exponential like behavior is then transitional.

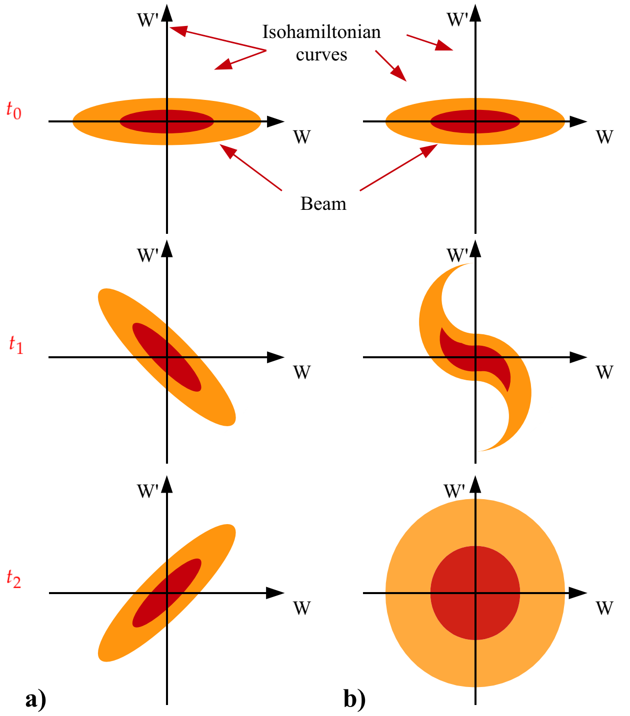

Figure 1: Evolution in phase space of a mismatched beam in case of a linear (a) or a non linear (b) force.

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PARAMETRIC RESONANCES

In practice, perfect matching of the beam envelope is difficult to achieve. Relevant matching parameters as the emittance, the current of the focusing gradients can not be perfectly known. Due to the periodic nature of the focusing channel in real linacs, parametric resonances can be excited. Struckmeier and Reiser have shown that because space charge couples the two transverse plans and when the beam envelopes are slightly mismatched, envelop instabilities occur when the phase advance per focusing period without space charge is greater than 90° and the intensity is sufficiently high [12].

The study of the beam instability mechanism can be also performed by modeling the single particle motion. Particle motion in an accelerator may be often reduced to a pendulum oscillation and the acting force is mostly periodic. It turns out that the equation of the motion is similar to the Hill equation. When the force may be well approximated by the two first harmonics, Hill's equation is simplified and becomes the so-called Mathieu equation:

$$\frac{d^2x}{d\tau^2} + \pi^2 \left[A + 2q sin(2\pi\tau)\right] x = 0 \tag{1}$$

where τ is a reduced variable for the time and A and q two important parameters to determine the stable or unstable nature of the motion [13]. Once these two parameters are given, the Mathieu diagram in figure 2 may be used to qualify the stability of the working point.

When the acting periodic force couples two plans, emittances can be exchanged. It has been observed that if the products of the emittance and the wave number for each plane are equal, the emittance exchange vanishes [14, 15]. The difficulty for the beam physicist is to track the sources of coupling and to be capable to highlight their impact eventually through the Mathieu equation or an other mathematical formalism.

In a linac, the radial component of EM field in cavities induces a coupling between the transverse planes and the longitudinal plane. Indeed, this EM force is a function of the phase of the particle. In [16], it is shown that the equation of the motion in this case may be reduced to the canonical form of the Mathieu equation 1 with $A = 4\sigma_t^2/\sigma_l^2$ and $q = \Delta\Phi cot(\Phi_s)$, σ_t and σ_l being respectively the transverse and longitudinal phase advance per focusing period, $\Delta\Phi$ the bunch width and Φ_s the synchronous phase. With the help of the diagram in figure 2, it is worth noting that values of σ_t greater than σ_l are preferred to keep the beam in a stable region, nevertheless second order resonance is sufficiently weak to be crossed without any significant impact. When this limitation is combined with the restriction $\sigma_{0t} < 90°$ linked to the stability of the envelope, it turns out that $\sigma_{0l} < \sigma_{0t} < 90°$ which corresponds to a reduced accelerating efficiency and short focusing periods at low energy.

Space charge is also a source of parametric resonances. The space charge driven resonances may involve core-core with possible emittance exchange as well particle-core process (related to halo genesis) [17]. Gluckstern developed a model for the particle-core interaction [18]. This single particle-core interaction can be illustrated with a simple approach based on the transport of a particle in an mismatched uniform cylindrical beam assuming a constant focusing channel. The equation of the motion can be linearized for small mismatches and corresponds then to:

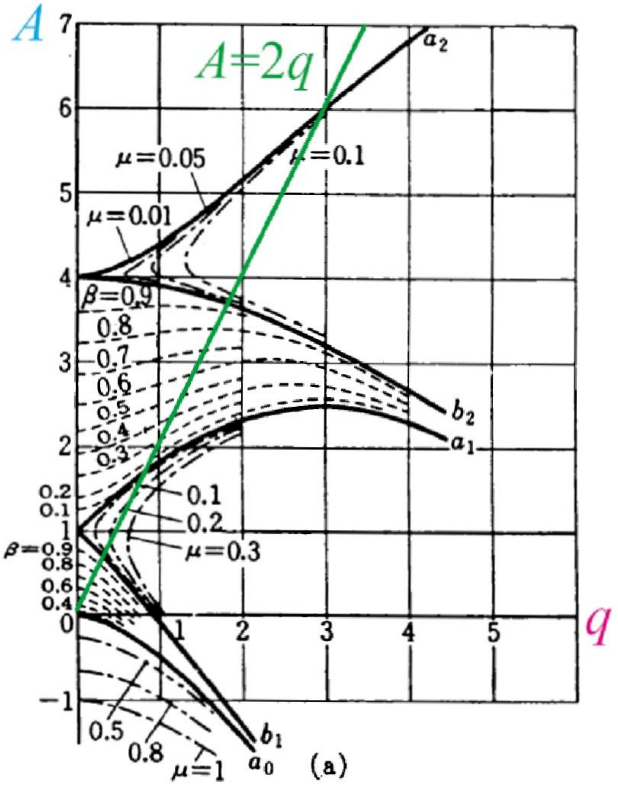

Figure 2: Diagram of the Mathieu equation (when the motion is unstable, $\mu > 0$ and the envelope goes like $e^{\pi\mu\tau}$).

$$r'' + k_{ra}^2 \left(1 + \delta cos(k_m z)\right) r = 0 \tag{2}$$

with k_{ra} the wave number of the matched beam with space charge, k_m the wave number of the mismatched mode, $\delta = 2M(1/\eta^2 - 1)$, η the tune depression and M the mismatch factor. This differential equation can be transformed in the canonical form 1. It turns out that $A = 2\eta^2/(1 + \eta^2)$ and $q = 2M(1 - \eta^2)/(1 + \eta^2)$. For most of the cases, the motion is stable, only very large mismatch associated with very low tune depression can exhibit an instability. To investigate the anisotropy effects in ellipsoidal bunches to go beyond this previous simplified halo model, the reference [19] details a study of the stability of solutions of linearized Vlasov equation. It is shown how stop bands similar to the unstable regions of the figure 2 can arise in the plane $(\eta, k_z/k_x)$ for different transverse/longitudinal emittances ratio and different modes of oscillations which are solutions of the perturbed hamiltonian. In this approach, each mode corresponds to an particular order of a polynomial that represents the space charge potential perturbation (non uniform beam). One consequence is that if working points are properly selected in passband regions, emittance exchange is absent whatever the ratio of the product emittance/wave number between coupled planes.

HIGH ORDER MODES

A beam passing through a cavity deposits a fraction of its energy and can excite modes. The effects of pulsed mode operation on transverse and longitudinal beam breakup instability have been studied for proton beam in a consistent manner [20]. Numerical simulation indicates that cumulative transverse beam breakup instabilities are not a concern for the SNS linac, primarily due to the heavy mass of ion beam and the HOM frequency spread resulting from manufacturing tolerances. As little as ± 0.1 MHz HOM frequency spread stabilizes all the instabilities from both transverse and longitudinal HOMs. Nevertheless, new more ambitious project like ESS and SPL (higher peak current and longer pulse length) needs to reevaluate this issue with studies tailored to their own parameters. Indeed, a recent study at CERN [21] promote the idea that, due to the excitation starting from noise, many HOMs at any frequency can get excited to non-negligible levels and the average cryogenic load as function of Q_{ext} has to be estimated. The reference [21] shows that one order of magnitude for the current or the HOM frequency spread is sufficient to induce an instability. In reference [22], it is shown that, for the SPL case, the energy and phase jitter, created by the RF system, yield an effective longitudinal emittance growth significantly more important compare to HOM impact. The damping of the TM_{010} modes via the power coupler was calculated and found to be sufficient for the case of unchopped beams. For chopped beams significant effective longitudinal emittance growth was observed for the case of HOMs coinciding with machine lines, which are created by the chopping. A Q_{ext} of 10^5 is recommended for this case.

RESONANT HALO BUILD UP AND MACHINE ERRORS

In practice, linacs contain many defaults like focusing gradient errors, magnet off set. These imperfections may arise resonant collective effects. A particular scenario may push up particles to the acceptance limit, longitudinally or transversally. By scenario, it is assumed that a specific sequence of defaults may increase resonantly the amplitude of particles. To study this resonant process and to tend to "realistic" simulation, it is mandatory to perform start-to-end (S2E) transport to be capable of estimating the impact of halo produced at low energy on the beam losses at the high energy part of the accelerator. These S2E simualtions must be carried out with a large number of particles and a large number of different possible linacs to build discrete cumulative distribution function (CDF) to provide a beam loss probability. This CDF helps to put in perspective the impact of the rare resonant scenarios. To tend to more realistic estimates, a strategy based on correctors and diagnostics has to be developed considering that the diagnostics are also imperfect (misalignments, measurement).

The use of macroparticles to record the losses at the beam pipe induces a discrete CDF, and then the probability to lose more than the more extreme recorded loss becomes null. To predict very extreme events, the reference [23] shows how the extreme value theory (EVT) may be used to perform such goal.

The TraceWin and Track codes are able to perform such Monte Carlo studies [24, 25]. Relevant estimates require that the relevant physics is considered, for instance, the space charge neutralization effect. This can be performed with plasma PIC codes like Solmaxp [26] or Warp [27]. The EM fields at equilibrium predicted by these codes may be included in S2E simulations afterward [28].

RESONANCES AND EXPERIMENTAL HIGHLIGHTS

An important feedback from SNS is the confirmation that HOM dampers wouldn't be necessary for ms pulse machines with peak current of 30 mA at 60 Hz with less than one hundred cavities [31]. No sign of beam degradation induced by HOMs was observed in this linac. On the other hand, unexpected beam loss have been measured in the SC section [32]. One possible origin could be the SNS linac quadrupole magnets that have unfavorably large dodecapole components. In reference [29], it is detailed a study which shows that sixth-order weak resonances may be excited. Beam dynamic simulations are performed and shown that 60, 90 and 120° phase advance resonances at zero current in the superconducting linac could be excited. According to simulations, the weak resonance leads to beam halo and can cause linac beam loss in addition to several other possible mechanisms. A slight reduction of quadrupole strengths and transverse phase advances from 60° could avoid this weak resonance and decrease the linac beam loss.

To give rise to space charge induced resonances, a recent experiment has been carried out at GSI [34]. Measurements of transverse phase space distributions behind a periodically focusing structure reveal a resonance stop band above zero current phase advance of 90° per focusing cell. These experimental findings agree very well with results from three different beam dynamics simulation codes and the present theory (see figure 3).

SUMMARY

The inventory of different instability mechanisms and their studies provide guidelines for linac design. The present knowledge in this field points out that several rules or limitations must be respected when working points of the accelerator are defined. From beam envelop instability

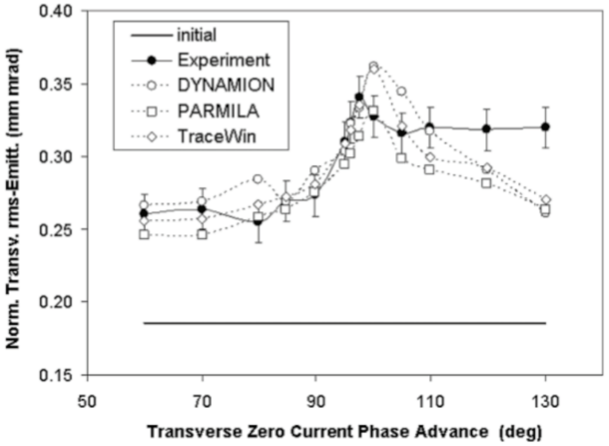

Figure 3: Mean of horizontal and vertical rms emittance as a function of the transverse zero current phase advance along the Unilac DTL.

issues, the transverse phase advance at zero current must be less than 90°. From synchrobetatron coupling, the longitudinal phase phase advance at zero current must be less than the transverse phase advance at zero current. To avoid the sextupole instability, it is required to minimize the dodecapole component of the quadrupole magnets, otherwise the linac will have to operate with a transverse phase advance at zero current lower than 60°. This means that the transverse acceptance will have to accommodate a larger beam.

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