REVIEW OF BEAM DYNAMICS ISSUES IN MW CLASS 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 theory and the codes for the design and simulation of MW 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. This point and the natural role of integrator that plays the beam dynamics in the construction of a machine make that the link between the beam dynamics team and the system engineering has to be strong. This paper reviews the theory and the codes for the design and simulation of MW ion linacs.

MW ION LINAC LAYOUTS

In modern MW ion linac, the beam is first generated by a Electron Cyclotron Resonance ion source for positive ions and volume or surface source for negative ions. Such sources have demonstrated routine operation with currents higher than 100 mA a good reliability for pulse length about one ms. When the pulse length is increased, the peak current with negatively charged ion source drops down rapidly to a few mA. The high voltage extraction system of these sources provides a primary acceleration from a few tens up to one hundred keV. For these ion sources, the beam pulse rise time of 1 to 2 ms may be reduced below 100 ns using a fast chopper in the Low Energy Beam Transport (LEBT) line which is mainly made for the transport and steering from the source up to the Radio Frequency Quadrupole (RFQ) cavity. A particular feature of the RFQ is that it focuses transversally and longitudinally the beam while it is bunched and accelerated with a very high efficiency up to a few MeV. Around a few MeV, a new type ofresonator will be used to enhance the acceleration efficiency. A Medium Energy Beam Transport line provides the focusing and steering for the transition between these structures and may include a fast chopper to define the microstructure of the pulse which may be required.

Beyond a few MeV, various normal conducting (NC) or superconducting (SC) structures may be used depending on the specifications to cover this medium energy range. From a few MeV up to a few tens of MeV, structures which provide very compact lattices are preferred to enhance acceleration while preserving beam brilliance. It turns out that the filling factor (ratio between the accelerating length and the total length) is lower in the beginning of this range than at its end. This compacity may be obtained with Drift Tube Linacs or linacs based on NC or SC quarter and half wave resonator like. Around one hundred MeV, normal conducting like CCL [7] or superconducting with spoke resonators systems [8] permit to reach filling factor close to 80%. Above 150 MeV, there is a consensus to use SC elliptical cavities which have benefit from the intensive R&D for the Tesla project [9]. To transport, steer and match the beam to the experiment requirements, a High Energy Beam Transport system performs the transition between the linac exit and the target. This system may be spitted in subsystems to distribute the beam to several targets eventually simultaneously [10].

BEAM PHYSICS

Space Charge

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

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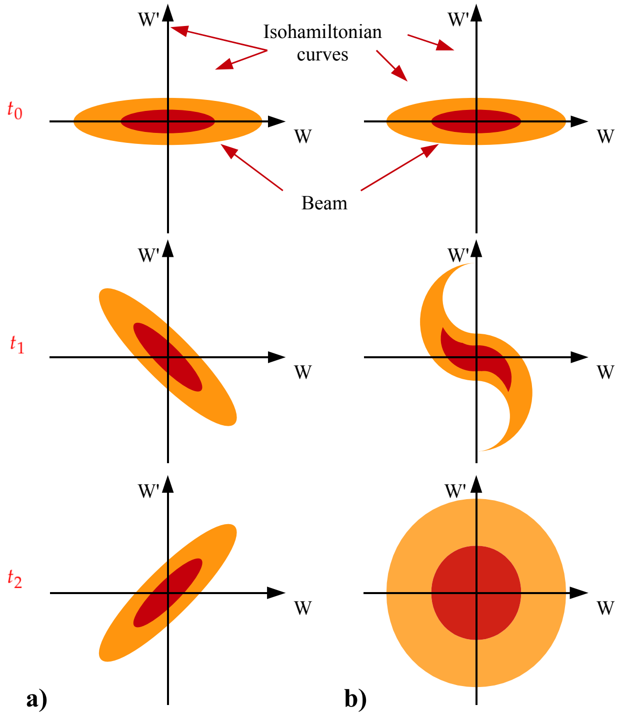

Figure 1: Evolution in phase space of a mismatched beam in case of a linear (a) or a non linear (b) force.

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 is reason why it is mandatory to smooth phase advance per meter evolution and to minimize the number of transitions in the accelerator because a perfect matching is impossible for all practical cases. This mechanism is applicable to the longitudinal focusing force of the cavities or any non linear force.

More than a filamentation, a mismatched beam can be unstable if the channel working point is not properly set. Struckmeier and Reiser have shown that when space charge couples two plans and the beam envelops are slightly mismatched, envelop instabilities occur when the phase advance per focusing period without space charge is greater than 90° [12].

Space Charge Neutralization

The low energy beam can be transported in a neutralization regime using the charge of the ionized residual gas. This regime occurs naturally when the beam propagates through a residual gas. Gas ionization takes place inside the beam and produces electrons and positive ions. The plasma focusing process is very useful and mandatory for peak current above 50 mA. This restricts electrostatic focusing systems to lower currents. In a first approach, the space charge neutralization transient has to be evaluated with the formula $\tau_n = 1/\sigma N_{gas}\beta c$ with σ is the ionization cross section, $N_{gas} = P/kT$ and β the reduced beam velocity. Experimentally, it has been observed that the rise time is closer to $3\tau_n$ which corresponds to a few tens of microseconds for H_2 residual gas pressure around 10^{-5} hPa and a proton beam of 100 keV. It is interesting to notice that in case the residual gas pressure is a few orders of magnitude lower, $3\tau_n$ tends to be non negligible for a ms pulse length accelerator. It turns out that this transient has to be cleaned to avoid the propagation of a mismatched beam into the next section.The LEBT chopper with a rise time about 100 ns can be used to perform such cleaning [3]. When the beam is bunched, it acts as a periodic focusing channel in time for the neutralizing particles [13] and the phase advance of this motion has to be estimated to know if the space charge neutralization can occur. The bunch frequency f_b has to be greater than the following limit:

$$f_b > \sqrt{\frac{r_e \cdot c}{2e \cdot m_p} \cdot \frac{I_b}{\beta R^2}} \qquad (1)$$

where m_p is the proton mass in a.m.u., r_e the classical radius of the electron, I_b the beam current and R its radius. It can be also shown that even if the space charge neutralization can't exceed a maximum value which is simply the ratio of the bunch length divided by the distance between bunches [14]. One consequence is that in case the medium and high energy part of the linac is insensitive to a mismatch in the low energy part, the space charge neutralization is mainly a front end issue.

Inside the beam, the time dependent neutralization is not necessarily homogeneous in space. These conditions contribute to produce a non-linear residual space charge force at the equilibrium that induces an emittance growth and may lead to particle losses. The equilibrium state of particle distributions are strongly correlated to the electromagnetic (EM) background, it induces that PIC simulations have to include all sources of EM fields [15, 16]. It has been experimentally shown that significant enhancement of the beam emittance at the exit of a proton LEBT can be obtained by adding heavy molecule gas like krypton [17]. This phenomena can be reproduced with PIC simulations [15] which show that an increased electron production rate induce a more linear residual space charge due to a contribution of heavy ions in the beam at the equilibrium.

Recombination and Stripping

In the LEBT, the main source of residual gas is the ion source. To minimize diffusion process which would develop beam halo [11] and particle loss due to the recombination of positive beam ion or the gas stripping of negatively beam ion, a particular care with the pumping system must be taken to ensure the beam transmission and that its brilliance is preserved. For a 100 keV proton line length of a few meters, it corresponds to a total pressure lower than 10^{-4} hPa. Gas stripping is less a concern at higher energy because the cross section decreases rapidly and the average pressure is very low in the superconducting part.

For the negatively charged ions, an other stripping process has to be coped for. When the ions becomes relativistic and go through the magnets, the bended trajectory of one satellite electron and the ion core may sufficiently differ to provoke a detachment [18]. In case of mono charged ion like H^-, the produced neutral is no longer focused and hits the vacuum chamber. In the ion rest frame, the stripping force is effected by an electric field which is proportional to the magnetic field in the lab frame. One way to cure this effect is to minimize the amplitude of fields in all magnets.

An another source of electron stripping for negatively charged ion is the black body radiation (BBR): in the ion rest frame, higher the speed of the beam ions larger the energy spectrum of the BBR photon. A part of the photons can be sufficiently energetic to cause the electron dissociation. This physical process may be one of the major source of beam loss for multi GeV H^- linacs [19]. To reduce the photon intensity, it may be envisaged to cool down the vacuum chamber.

Parametric Resonances

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:

$$\frac{d^2x}{d\tau^2} + \pi^2 \left[A + 2qsin(2\pi\tau)\right] x = 0 \qquad (2)$$

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 [20]. 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 if the temperatures in each plane are different [21]. The difficulty for the beam physicist is to track the sources of coupling and to be capable to highlight their impact through the Mathieu equation or a similar mathematical model.

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 [22], it is shown that the equation of the motion in this case may be reduced to the canonical form of the Mathieu equation 2 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

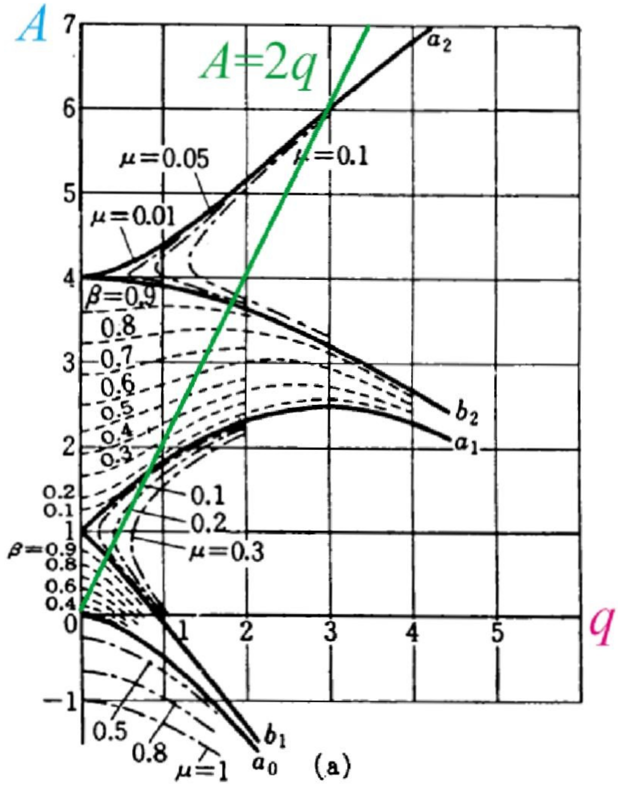

Figure 2: Diagram of the Mathieu equation (when the motion is unstable, $\mu > 0$ and the envelop goes like $e^{\pi\mu\tau}$).

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 envelop, 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 (emittance exchange in case of non equipartition) as well particle-core process (related to halo genesis) [23]. The 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 $r'' + k_{ra}^2 (1 + \delta cos(k_m z)) r = 0$ 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 2, 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 [24] 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. One consequence is that if working points are properly selected in passband regions, equipartition is not necessary, this condition being inaccessible for most of the practical cases.

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 [25]. 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, recent studies at CERN [26] shown that one order of magnitude for the current or the HOM frequency spread is sufficient to induce an instability "from the noise" whatever the considered mode frequency.

SINGLE PARTICLE SIMULATIONS

The Longitudinal Plane

Ion linac design uses to start with single particle dynamics. Simple projections of transit time factors for different cavities can't be applied anymore to select the best arrangement of resonators. The need to include a part of the beam physics described in the previous section makes mandatory to compute accurately the synchronous particle dynamic. The parameter choice for the optimization (evolution for the synchronous phase, phase advance, restriction for the power and fields) has to anticipate the required margins to match the system acceptance to the input beam with imperfections. One important issue in case of frequency jumps is the preservation of this acceptance. The reference [27] detailed several methods to that purpose. In the medium or high energy part of the machine, a simple and robust technique to select the optimum linac may be a multilayer discretization of the parameter space that has to be explored. It can be performed with an extensive use of single particle tracking [28].

The Transverse Planes

The alignment of the accelerator components and the beam steering is a critical issue to minimize emittance dilution and beam loss. A first mechanism is the effect of non linear fields in magnets and cavities. Because very high filling factors and low beam loss are required, magnets are often short and wide opened. This may induce a non negligible multipole spectrum. Large beam position offset in resonator can excite dipolar modes that have to be included in the HOM studies. Finally, large amplitude for the beam center may lead to intersection with the accelerator wall. A special attention to the minimization the beam position offset induced by machine imperfections has then to be considered in the design of a high power linac.

MULTIPARTICLE SIMULATIONS

Once the reference design for the accelerator with perfect elements has been set up, it is necessary to evaluate the collective effects in presence of perfect or imperfect elements to define tolerances for the construction and test the robustness. Here, "imperfect element" means, for instance, that the quadrupoles would not be at the correct position or that the cavities would not be at the right phase. To correct, a strategy based on correctors and diagnostics has to be developed considering that the diagnostics are also imperfect (misalignments, measurement). To tend to "realistic" simulation, it is needed 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. The use of macroparticles to estimate beam distribution and to record the losses at the beam pipe induces a discrete cumulative distribution function (CDF) to provide a probability to deposit more than a certain fraction of beam. The consequence is that the probability to lose more than the more extreme recorded loss becomes null. To predict very extreme events, the reference [29] shows how the extreme value theory (EVT) may be used to perform such goal. The large set of input data for the EVT analysis can be obtained via large scale S2E computations. The TraceWin and Track codes are able to complete these data sets [30, 31]. Such 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 [15] or Warp [16]. The EM fields at equilibrium predicted by these codes may be included in SE2 simulations afterward [32].

OBSERVED ISSUES

The design gradient of the SNS cavity is 10.2 MV/m for geometry β 0.61 and 15.9 MV/m for geometry β 0.81, but the operational gradient may vary widely from -100 % to +80% [33]. It is necessary to smooth the longitudinal focusing by adjusting the synchronous phase of several cavities, particularly around the unpowered ones, to preserve beam gradient spread. This SNS experience feedback shows that future errors studies for intense linacs will have to include a huge gradient spread in the cavity set.

Another 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 [34]. No sign of beam degradation induced by HOMs was observed in this linac. On the other hand, unexpected longitudinal tails have been measured at the entrance of the SC section [35]. One possible origin of this longitudinal halo could be the shrinkage of the acceptance at the frequency jump. Another probable sign which would confirm this hypothesis is the observation of a reduction of beam loss when the transverse phase advance is decreased and a clear correlation with the phase and amplitude tuning of the CCL [36].

To give rise to space charge induced resonances, a recent experiment has been carried out at GSI [37]. 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.

SUMMARY

Beam dynamics in a high intense ion linac is a very rich field of physics. It requires skills in plasma physics as well as in statistical physics. Supported by activities of present and future accelerators, this domain progressed during the last decades and allows now very fine simulations based on a more mature knowledge of the beam behavior.

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