LOSS CONTROL AND RELIABILITY ISSUES IN HIGH INTENSITY LINACS

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Abstract

New projects like IFMIF or the new generation of Spallation Neutron Source require high power beams with high availability and reliability. To achieve these results one needs low beam losses and a good control beam dynamics.

This paper focuses on the important characteristics and critical beam dynamics design issues for the high intensity linacs. In particular the techniques used for the loss control at the design stage, with the emphasis on the physical phenomena like emittance growth and halo. The reliability issue will be addressed with practical examples from the low energy and high current IFMIF-EVEDA project and comparing this case with higher energy projects.

INTRODUCTION

The emittance growth and the halo control is an issue in the new high intensity Linac like IFMIF [1] and ESS [2], for that the design is very important to mitigate the beam losses.

In this way is it possible to keep induced radioactivity to a low level and to retain hands-on maintenance of the accelerator with personal safety and environmental protection for ground, water and air.

A low emittance also guarantee a good beam quality for the experimental setup that is an issue for high energy accelerators, on the other hand the final emittance is not so important for low energy accelerators with an high power target to heat up.

To guarantee hands-on maintenance the level of beam loss must be in average below 1W/m, but this figure is valid only at high energy instead for a low energy the safe level of beam losses can be relaxed.

A low level of beam losses is also necessary to protect machine part from beam related break, like radiation structural damage and thermal damage of superconducting components.

EMITTANCE GROWTH AND HALO CONTROL

Transverse Emittance Control

The transverse emittance is created in the accelerator source and is mainly due to fact that the beam is created in a magnetic fields, in this way by the conservation of angular moment, the beam at the source exit present an emittance different from zero. After the beam creation, the source extraction electrodes, the level of neutralization in the low energy beam transport, the magnets aberrations and last but not least the space charge, increase the transverse emittance. More in general all the non linear self E.M. fields and external E.M. fields increase the transverse emittance.

In the RFQ (Radio Frequency Quadrupoles) accelerator the transverse emittance is almost constant, the only zone where the emittance can increase is in the "coupling gap section", these abrupt interruptions in the electrodes are presents in very long, respect to the wavelength, RFQ.

In the MEBT (Medium Energy Beam Transport) Transport, from the RFQ to the following Linac, DTL (Drift Tube Linac) or SC (Super Conducting) cavities, the transverse emittance typically increase, this is due to the fast change in the phase advance per meter, from a very short focusing period (inside the RFQ) to a more long focusing lattice, like inside the DTL, or still more longer focusing period inside the SC cavities. To avoid the problem is it necessary to reduce the period length in the following linac, by increasing the final period in the RFQ reducing the focusing force and/or rising the final RFQ energy.

In the DTL part of the linac the transverse emittance is constant, due to the regular focusing lattice design.

In the SC part of the linac the transverse emittance should be conserved, but this is more challenging due to the longer focusing period.

Another small source of transverse emittance growth is the change in the RF frequency along the linac, due to non linear effects of the E.M. Bessel components that double by doubling the frequency, for the same beam size.

Longitudinal Emittance Creation and Control

The longitudinal emittance is formed in the RFQ and the final value can be control by using a longer shaper section with a right numbers of longitudinal phase advance rotations. In the case of high intensity RFQ the longitudinal space charge phenomena can increase quite fast the emittance due to the presence of baffles in the phase space that also induce fast longitudinal losses. In this way a long shaper section in a high intensity RFQ get more losses, i.e. low longitudinal capture, than low final longitudinal emittance.

The part of the beam that is not captured longitudinally can be scraped out at the end of the gentle buncher by reducing the RFQ small aperture "a", in this way that part of the beam is removed at low energy and induce only a small activation of the structure.

The longitudinal emittance can be transported, from the end of the shaper, up to the end of the RFQ without increase, due to the regular longitudinal focusing scheme, if is avoided a fast change in the synchronous phase inside the RFQ.

In the MEBT section the longitudinal emittance can increase due to the difficult of keep a longitudinal focusing scheme, with the bunchers, to inject in the matched longitudinal acceptance of the following linac.

In particular a RMS phase spread of more than 10 deg, can put part of the beam in the non linear zone of RF fields, due to the longitudinal sinus behaviours of E.M. fields.

After the MEBT in a DTL section the longitudinal emittance can be kept constant by changing in a smooth way the synchronous phase. This can also be done in a SC cavities linac, but is more challenging due to the longer longitudinal focusing period.

Particular care must be put in the frequency jump linac sections, due to the change of the longitudinal phase space acceptance. If the frequency jump is made by keeping a constant longitudinal acceptance, the longitudinal emittance is constant.

More in general if part of the beam goes out of the longitudinal acceptance that part of the beam can be loose quite fast after few periods or in the next linac section.

Halo Formation

The beam halo is an important characteristic of high-intensity beams. By visual inspection of simulated particle distributions, we can intuitively identify halo as the tails present in the phase space. However is important to obtain a more quantitative value of this phenomenon. In the article of C. K. Allen and T. P. Wangler [3], has been investigated parameters based on moments of the particle distribution that provide a quantitative description of halo.

The halo parameter *H* contains additional information as to the beam state, since it is possible to have emittance growth without halo growth and big halo growth with very small RMS emittance growth.

As with emittance, the halo parameter is invariant under linear forces. Thus, halo growth is necessarily the result of nonlinearities.

If the halo is formed in the low energy part of the linac these can induce losses in the high energy part of the linac.

The transverse halo in the RFQ is almost constant if the RMS beam size is almost constant along the RFQ.

The longitudinal halo in the RFQ, after the shaper, is also almost constant. In the RFQ shaper the rapid formation of the longitudinal emittance creates baffles and tails, that the halo parameter report, but at the end of the longitudinal capture process the beam distribution is almost regularized, if the not captured particles are scraped out.

Another source of halo can be the MEBT section if the beam is going mismatched in the following linac section, DTL or SC cavities.

HIGH INTENSITY LINAC DESIGN ISSUE

Beam Losses

The first concerned of a high-average-current high-energy facility is radiation hazard due to beam loss. There are two types of beam losses: continuous beam loss of normal operations, like the missing longitudinal capture of particles in the RFQ, and incidental beam losses in which part or the entire beam is lost as an example in the case of a SC cavity failure.

The radiation dose produced by small but continuous beam loss accumulates over time and is the main concern for radiation safety, at high energy this is described by the limit of 1W/m that corresponds, at above 1 GeV, to approximately $2*10^{11}$ n/s produced by Spallation on a metallic (W) target orthogonal to the beam with about 1 mA.

At example for 1MW beams the losses must be below 10^{-6} for meter, which means in the simulation the necessity of follow more than 10^{6} macroparticles along the linac.

At low energy, below 100 MeV, the neutron production is much less abundant, by several orders of magnitude, and allowed losses that must be scaled with the lower neutron production.

In the nominal IFMIF case, we lose, with an input beam distribution waterbag, more than 350 W from the RFQ, with neutron production on copper largely below 10^{10} n/s, i.e. in the IFMIF RFQ the level of losses are more than 30 W/m.

Phase Advance Design

The phase advance per period *L* is defined as:

$$\sigma_u = \int_s^{s+L} \frac{\varepsilon_u}{\left\langle u^2 \right\rangle} ds \quad u \equiv x, y, z$$

where ε is the not normalized RMS emittance and $<u^2>$ is the squared RMS beam size, the phase advance can be defined for every plane of beam motion X, Y as transverse plane and Z as longitudinal, or along the beam, plane. In a high intensity linac the phase advance is one of the most important parameter to check for avoid problems, like emittance growth and beam losses. As example keeping constant the phase advance along the linac means that the ratio of emittance on beam size stays constant, i.e. in a perfect matching condition. In the presence of space charge the phase advance (σ) is less than the tune without space charge (σ_0), due to the larger beam size. The ratio of this tune is defined as "tune depression", and should not keep below 0.4 to avoid very large beam size due to the nonlinear and chaotic space charge effects [4]. Anyhow for a low energy and high intensity Linac, like in the IFMIF case, can be possible to transport the beam with a tune depression of about 0.2, without beam losses but with emittance growth.

Resonances of the Structures Lattice

The magnitude of lattice tune σ_0 must be below 90° to avoid emittance growth and halo formation [5], [6]. In general this condition expresses the necessity of a short period means that the distance between focusing elements cannot be very large. In the longitudinal plane this rule imposes as consequence a not so large energy gain per meter. A low cost linac design typically requires the opposite: large energy gain per meter and low as possible number and force of focusing elements, so this rule on phase advance is very expensive.

Equipartitioning

The exchange of "thermodynamics" energy between the X, Y and Z beam motion plane is a problem that can induce emittance exchange and halo formation [7]. To avoid the problem the beam must be "Equipartitioned" means that:

$$\varepsilon_{n,x} \cdot k_x = \varepsilon_{n,y} \cdot k_y = \varepsilon_{n,z} \cdot k_z$$

where ε is the RMS normalized emittance and *k* is the phase advance per meter.

In a RFQ this condition requires a particular attention to avoid that the created longitudinal emittance, typically a factor two larger than the transverse emittance, produces an increase in the transverse emittance.

RELIABILITY ISSUE

The Reliability of a high intensity linac accelerator start from the early design phase and continue up to a long statistical story of years of machine runs. In the design phase is very important to evaluate the failure mode and the effects analysis of every components of the system like RF, cryogenics, conventional facility and so on, its aim is to identify all the possible failure modes of components, analyze their effects on the system performance, and suggest solutions and improvements. In the risk analysis, it is important to include also severity ranking for the failures and possibly their frequency.

As an example a long run of beam source and RFQ, before the final installation, is crucial to evaluate a long term trustworthiness of the system.

The main source of trouble in the beam source can be the reduced consumption of components like the gas use or the cathode. Another problem of ion source and also in the RFQ can be the sparking rate, means the rapid electrical discharge in electrodes zone, with beam losses and equipments damages. All this kind of problems must be addressed in the design phase, for example by using a lower surface electrical field.

A flexible linac lattice with additional optics transport solutions can be a beam dynamics design that contributes a beam transport with faulty elements.

Moreover a larger longitudinal acceptance could even handle the instantaneous failure of one cavity.

The design phase can be the most effective way in improving reliability and availability of the system by derating and redundancy/spares.

The solution of derating allows putting less stress on the components and in general guaranteeing a longer lifetime and hence a higher reliability.

The Redundancy can be applied to key elements of the system that may induce its failure, for example a new linac project can consider the use of two beam source and of a reliable RF system, with possibly redundant or with graceful fault as an example a multistage solid state amplifier.

Although this approach improves the system reliability, it increases the number of components and hence the failure rate, requiring a more complex organization of the system logistic.

A very important aspect in the reliability is the accurate record keeping of problems that interfere with beam delivery. These records should be started at the beginning of the commissioning stage and should be maintained for all the life of the accelerator.

IFMIF RFQ DESIGN ISSUE

The RFQ of IFMIF-EVEDA project [1] is characterized by very challenging specifications, with 125 mA of deuteron CW accelerated up to 5 MeV. The objectives of EVEDA (Engineering Validation Engineering Design Activities) are to produce the detailed design of the entire IFMIF facility, as well as to build and test a number of prototypes, including the high-intensity CW deuteron RFQ that will be design and build in Italy by INFN and then assembled and operated at Rokkasho in Japan.

The main IFMIF RFQ parameters are reported in Fig. 1

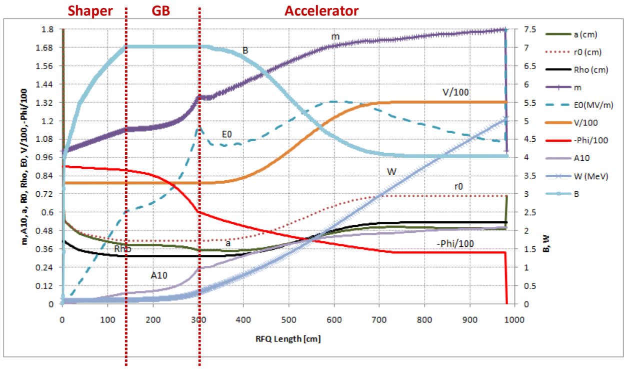

Figure 1: Main IFMIF RFQ parameters along the structure.

In the IFMIF RFQ there is no coupling cell, so the electrodes are almost continuous.

The beam evolution inside the IFMIF RFQ is show in Fig. 2. In red are reported the losses, more concentrate in the low energy part. The input distribution is Gaussian like, to increase the ratio RMS over total emittance. The total transmission in this case is 94%, in the case of a WaterBag distribution as RFQ beam input the transmission is about 99%.

The emittance and Halo along the IFMIF RFQ is reported in Fig. 3. Apart from the longitudinal emittance formation process in the shaper, there is no Halo or emittance growth in IFMIF RFQ, this is due to the accurate choice of the phase advance parameters.

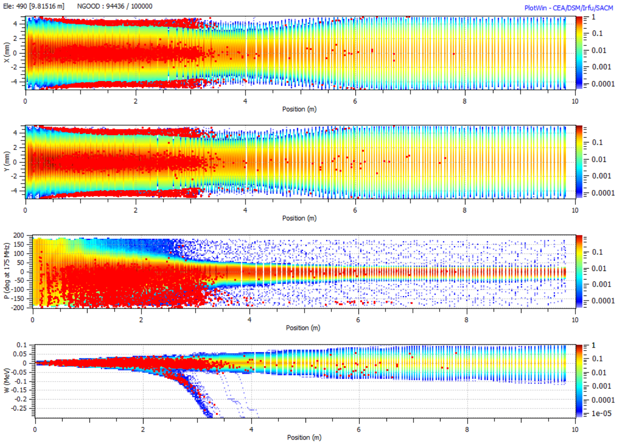

Figure 2: IFMIF RFQ beam envelopes along the structure.

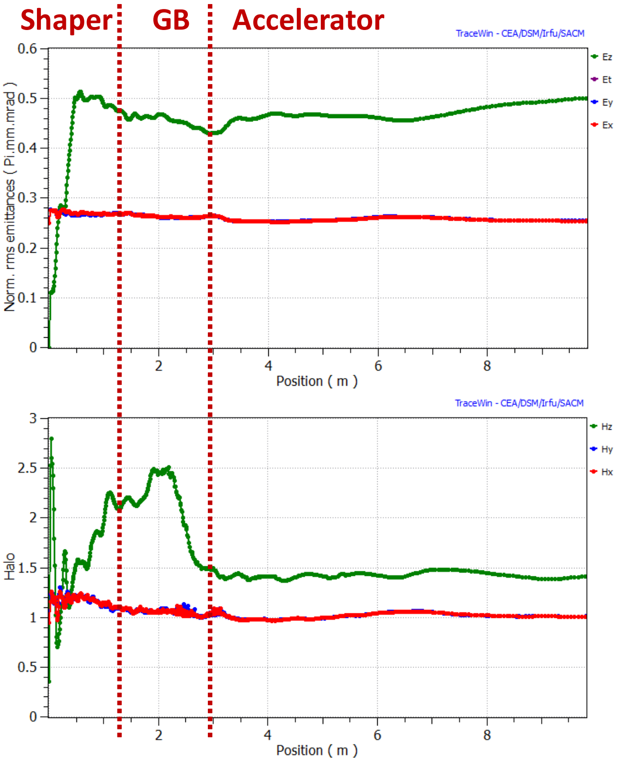

Figure 3: RMS Emittance and Halo along the IFMIF RFQ.

The Phase space at IFMIF RFQ exit is show in Fig. 4. Is it possible to see the absence of no longitudinal captured particles, in the range from 0.1 MeV to 5 MeV, means that a particles or is captured and go to 5 MeV or rest at the initial energy.

In the stability chart for the IFMIF RFQ in Fig. 5, is reported the ratio of longitudinal phase advance over transverse phase advance respect to the tune depression, the graph show that the accelerator section is well equipartitioned.

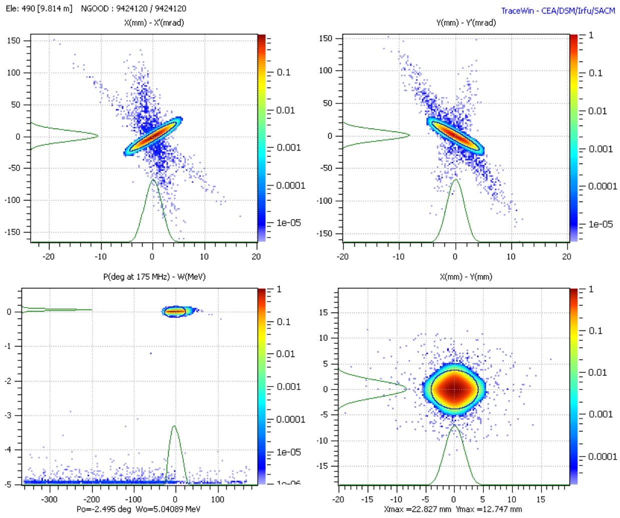

Figure 4: Phase Space at IFMIF RFQ output with 10^7 macroparticles, i.e. <0.1W for macroparticle.

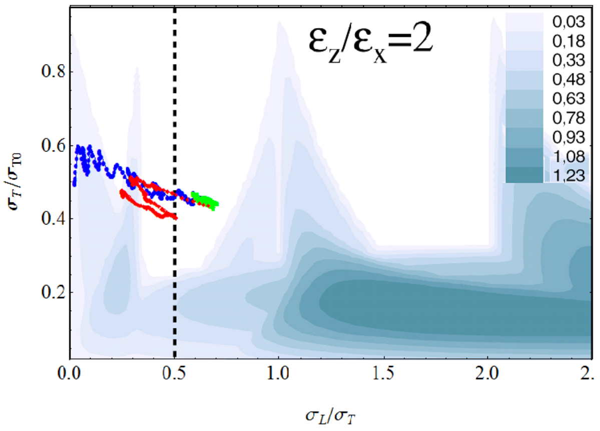

Figure 5: Stability chart, with overlapped the phase advance ratios for Shaper (BLU), G. Buncher (GREEN), and Accelerator (RED).

SPES DTL STUDY DESIGN ISSUE

A 2008 proposed SPES driver is composed by an Alvarez DTL for proton, in the range of energy from 5 to 100 MeV. It transports a high intensity beam of 50 mA of peak, for an average current of 1.5 mA. The high rep rate (50 Hz) is necessary for the correct mechanical behaviour of the target [8].

This accelerating structure is the same proposed for DTL of LINAC4 at CERN. A prototype of this structure has been constructed in Italy with the joint effort of CERN and LNL. The beam focusing in SPES DTL is guaranteed by permanent quadrupoles magnets with alternated polarity (FFDD scheme) hosted in the accelerating tubes. The beam dynamics design was aimed at keeping the transverse and longitudinal phase advances continuous.

In Fig. 6 is showed the beam envelopes along the DTL.

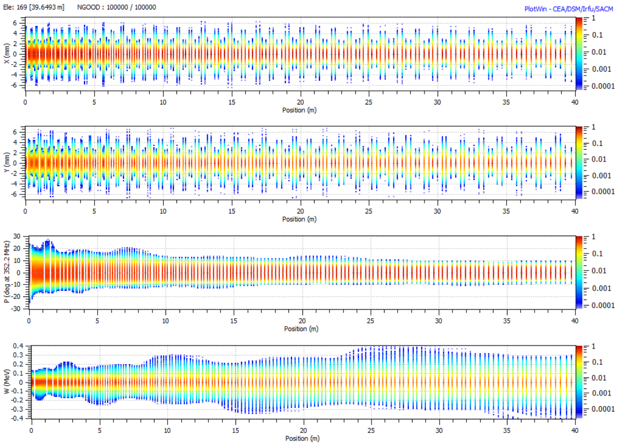

Figure 6: Envelopes plot along the SPES DTL.

The RMS emittance and Halo, along the SPES DTL is reported in Fig. 7, we can observe a small longitudinal RMS emittance growth.

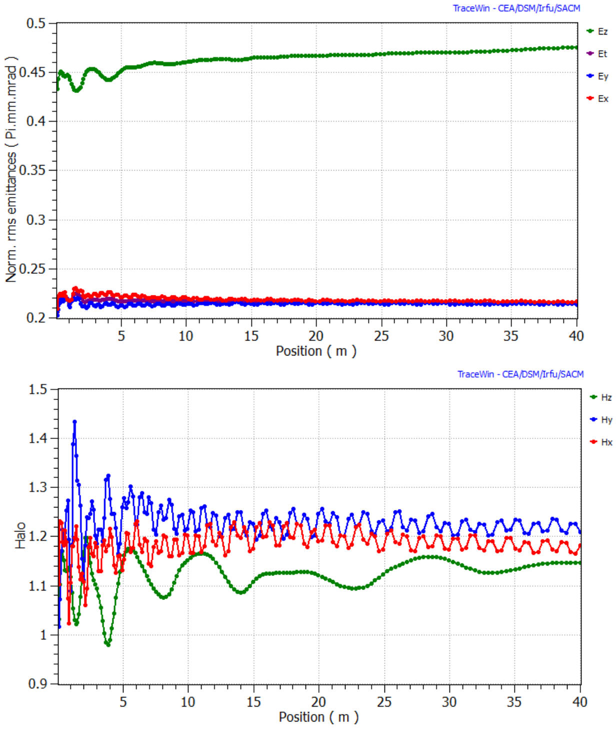

Figure 7: RMS Emittance and Halo along the SPES DTL

In the Fig. 8 is reported the stability chart for the SPES DTL, also in this case the phase advance chooses is made to conserve the equipartitioning.

CONCLUSION

The beam losses control and reliability can be done only by a “good” design.

In the high energy linac for avoid beam losses is very important to mitigate beam halo formation at low energy (SOURCE RFQ and DTL).

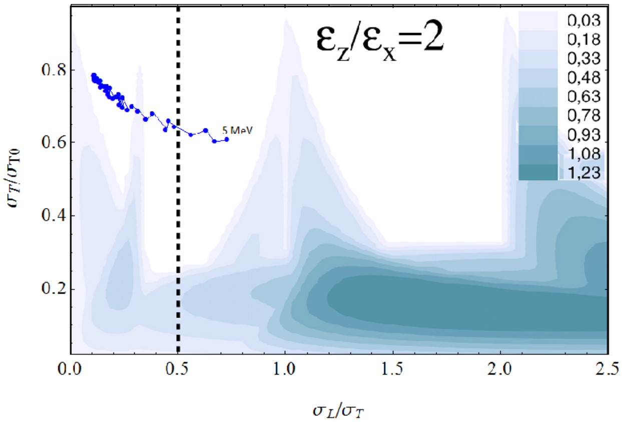

Figure 8: Stability chart, with overlapped the phase advance ratios for SPES DTL.

It is necessary to look at Equipartitioning in the RFQ and DTL and at the longitudinal emittance formation.

For a Low Energy Linac is not a problem the emittance growth it is necessary the use of large cavity bore, means bore/rms>10 and carefully design the matching between the linac sections to avoid losses.

For the Beam Reliability issues are necessary the redundancies of hardware and a flexible lattice design.

A large longitudinal acceptance cans also accommodate a cavity failure.

All the simulation here reported has been made by using the CEA programs "TraceWin" and "Toutatis" [9].

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