WG B – BEAM DYNAMICS IN HIGH INTENSITY LINACS

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Abstract

Loss control, emittance preservation and the performance under the influence of machine and beam errors are just a few topics of interest to all high intensity Linacs in the world, both in operation and in planning. These topics were thoroughly discussed during the parallel sessions of Working Group B, Beam Dynamics in High Intensity Linacs. The session hosted talks on the general beam dynamics for future projects, talks on comparing simulation and measurements in operational Linacs and some more general comprehensive talks on issues related to beam quality conservation under non-optimal conditions. A total of 15 talks were presented. The details of each contribution can be found in the relevant section of these proceedings. In this paper we report the results of the discussion and some concluding remarks of general interest to all projects presented in the working group.

INTRODUCTION

The talks and discussions of the "Beam dynamics in high intensity Linacs" Working Group B can be classified in 3 main topics. A series of 6 talks dedicated to the general beam dynamics for future projects. These included the European Spallation Source in Lund; the Superconducting Proton Linac at CERN; the International Fusion Materials Irradiation Facility with its Engineering Validation and Engineering Design Activity (IFMIF-EVEDA); PROJECT X at FermiLab; the Facility for Rare Isotope Beam (FRIB) at Michigan State University; SPIRAL2 at Ganil; and the Chinese Spallation Neutron Source.

A second set of four talks was dedicated to the comparison between simulations, measurements and machine tunings for operation. This session included talks from representatives of existing facilities, like JPARC in Tokai, the Spallation Neutron Source in Oak Ridge, the UNILAC in Darmstadt and the Soreq Applied Research Accelerator Facility (SARAF) in Yavne, Israel.

A third session (4 talks) was dedicated to more general beam dynamics themes, like instabilities, reliability and other high intensity issues.

FUTURE PROJECTS

Table 1 gives a brief description of future projects which were discussed in WG-B. As it can be seen from the table, the variety of particles accelerated and the final energy and power are quite diversified, yet all projects have in common a design based on well known and agreed standard recipes, discussed in books [1] [2] and implemented in the most widespread computer programs used for defining an optimised accelerator layout [3][4]. These projects have different specifications, and even different "Linac" shapes (of particular interest is the FRIB folded layout). The beam dynamics optimization is strongly linked to the choice of the RF cavity technology, to the choice of the frequencies and the location of the frequency jumps, the choice of the type of radial focusing period (FODO, FDO…) and the length of the focusing period.

Notwithstanding all these differences and peculiarities, the design philosophy is the same for all the projects, namely: a zero-current phase advance per period below 90° to avoid structure resonances, a smooth phase advance per unit length to avoid mismatches and, tunes chosen to avoid the radial - longitudinal coupling resonances in order to prevent emittance exchanges.

A typical behaviour of the phase advance per period, the phase advance per meter and the ratio of the longitudinal to transverse tune are illustrated in Fig. 1, taking as example the CERN SPL. Such choices guarantee a dynamics that is resonance free, a minimum emittance increase and a reduced sensitivity to errors.

Table 1: Main Parameters of the Future Project Presented in the Working Group

	ESS	**SPL**	**IFMIF-EVEDA**	**PROJ-X**	**FRIB**	**SPIRAL2**
Particle	p	H-	D	H-	All! Up to U	p,D, A/q=3
Power(MW)	5	4	5-1.1	3	0.4	0.2
Energy(GeV)	2.5	5	0.040-0.009	3	0.200/u	0.040 (D)
Peak current(mA)	50	64	125	1	2	1-5
Duty cycle	4%	2%	CW	CW	CW	CW
	Long pulse operation	High rep rate (50Hz)	Space charge dominated	Low current	Simultaneous acceleration of up to 5 charges	Upgrade A/q=6

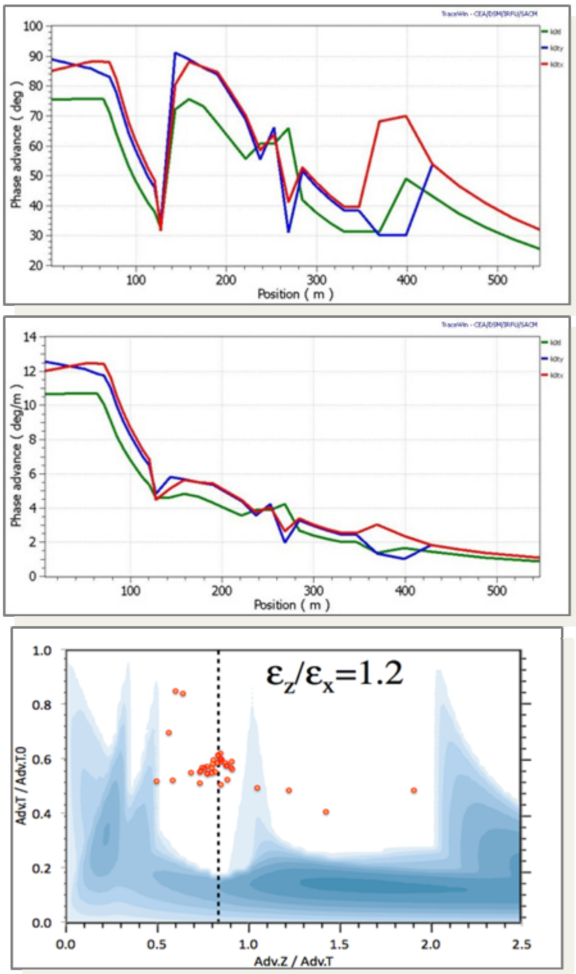

Figure 1: From top to bottom. Phase advance at zero current (deg), phase advance per meter at the nominal current and ratio of the transverse and longitudinal tunes for the CERN SPL (0.160 to 5 GeV). .

LINAC TUNINGS FOR OPERATION

In existing accelerator, the Linac tunings which operationally give the best performance and minimize the losses are often far from the design values.

A good example comes from SNS: the operating parameters of the quadrupoles in the SCL which minimize the losses are very different from the design parameters (Fig 2). A comprehensive explanation of this discrepancy is not found yet, although hints point at the phenomenon of H- intrabeam-stripping discussed later.

It must be also pointed out that the beam dynamics team of IFMIF EVEDA reported the results of statistical studies aimed at reducing the beam losses. These studies showed that a Linac with radial and transverse tunes in the parameteric resonances region is less sensitive to losses of halo particles. The IFMIF-EVEDA Linac is strongly space charge dominated and it seems that an emittance increase (core particles) can be favourable to reduce losses (halo particles).

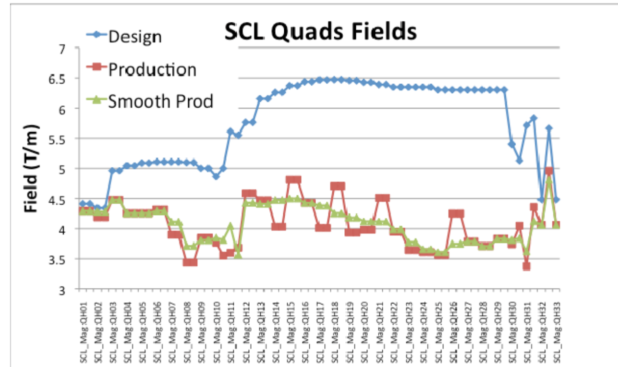

Figure 2: Comparison of the design and operational (production and production smoothed) quadrupole gradients for the SNS. The optimised operational values are about 2/3 of the nominal.

SNS, JPARC, UNILAC and SARAF Operational Experience

At SNS a good agreement is found between the dynamics of the centre of the beam and the results of the simulations. These include the orbit and the average phase and energy. As far as the envelope is concerned a good agreement is found between measurements and calculations up to the CCL and less good in the SCL itself. In the SCL region the machine fine tuning is done with Beam Loss Monitors and it is found that scrapers in the MEBT also reduce the losses all along the Linac. A longitudinal mismatch in the CCL is measured and reproduced by simulation (is this cause of halo formation?)

At JPARC an excessive emittance growth is observed in the DTL, but not in the SDTL, whereas halo formation seems to happen in the SDTL but not in the DTL. At JPARC beam dynamics simulations with the code IMPACT were very useful tools to understand these phenomena. It appears that longitudinal mismatches can be detected using radial profile monitors because of the radial – longitudinal couplings via space charge and RF defocusing.

At UNILAC a very good agreement is found between experimental observations and the DYNAMION simulations, the laboratory just went through a campaign of optimization of the existing set-up with focus on the matching to the RFQ. The removal of the known injector bottleneck happened in two steps : RFQ re-machining and then RFQ redesign in 2009. End-to-end simulations were a necessary tool to drive all the improvements.

At SARAF the tuning of the RFQ was done by comparison of measurements, electromagnetic field calculations and beam dynamics (code TRACK).

H- Intrabeam-Stripping

The phenomenon of intrabeam-stripping was not considered so far in all the loss pattern calculations.

The cross section was measured by M. Chanel et al, in LEAR in 1987 [7] and recalculated recently from electron detachment data available at BNL. This unaccounted for stripping of H- might be the explanation for the high energy losses in SNS and it might be the explanation of the difference between empirically optimized settings and theoretical settings (quadrupole field reduction for a larger beam). To validate this explanation a short experiment will be run at the end of the year at the SNS: the source will be changed and protons will be run through the accelerator and the beam loss pattern recorded.

Other Points on Matching and Transfer

The importance of careful simulation of transition and matching lines, where the emittance and halo degradation are most at risk was highlighted by almost all the speakers. The low energy lines are the most sensitive to mismatch and mistune and emittance growth up to 96% depending on solenoid settings in the LEBT line were reported. In general simulations including error studies are important when dealing with high power beam in transfer lines. The identification of the highest loss location is very important for any future operation of high intensity beam.

EMITTANCE, HALO AND BEAM LOSSES

Based on operational experience and on multiparticle simulation it is now understood that the dynamics of the core and dynamics of the halo are different. In fact, halo particles experience almost zero-current phase advances whereas the core particles experience the full current. Operational experience hints that in some cases it is better to accept (some) emittance increase but to control the losses.

The standard Linac recipe is relevant for the core of the beam and probably to avoid halo formation but it is not applicable to the halo that already pre-exist in the beam, i.e. coming from the source and/or the RFQ. As a supporting evidence one can take the SNS where the introduction of scrapers at low energy reduces losses all along the Linac.

As a consequence, more information is needed on the input particle distribution. How to measure the beam distribution (including tails and correlation) out of the source and/or out of the RFQ is not straightforward. The problems are the very small space available at the low energies and the complication of a diagnostic tool with a very broad dynamic range. The difference between the operational and the theoretical settings is probably due to the fact that the loss pattern dependence on the beam input particle distribution (tail) is probably more than we have assumed so far.

The computing codes, as of today, agree on the r.m.s. values, sometimes also on the 99% envelope but seem to disagree on the halo. This statement needs verification and the question was raised whether the real fields (including errors) in the computer codes are described accurately enough to predict to the level of 10^{-6} ? The dynamics of the halo could be mastered if sufficient information on the input 6D beam distribution was available. This is beyond the reach of standard diagnostics tool implemented in existing machines.

Theoretical evidence has been shown that space charge non-linearities, depending on the beam input distributions, can cause emittance growth and halo formation and that some specific error distributions can induce resonant amplitude build up. Theoretical model of an inhomogeneous beam shows that mismatch can delay disruption due to break-up modes.

An interesting topic, not much explored so far, is the importance of higher order harmonics: it has been shown that octupole components of the beam self field and dodecapole components in the quadrupoles might reduce the acceptance of the machine.

In general halo formation is not necessarily accompanied by emittance growth and vice-versa, halo is difficult to detect also in simulations, therefore a quantification of halo by halo parameter is a quality factor for a given machine design. Finally the halo is acceptable at low energy (limit of 100 W/m is acceptable at energies below few MeV) but it must be collimated out before acceleration to high energies.

CONCLUSIONS

More information on the input beam distribution is needed to better predict loss patterns. In absence of such information the use of scrapers at low energy (before and after the RFQ) can mitigate the losses at high energy. This is an indication that a good fraction of the halo is present in the beam before the DTL.

The standard recipes shall remain as guidelines for the Linac design but need to be adjusted to give more weight to halo formation and loss control in addition to emittance growth.

Intrabeam stripping studies should be further pursued and included in the design codes.

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