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WHAT IS MISSING FOR THE DESIGN AND OPERATION OF HIGH-POWER LINACS?

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Abstract

The design process, tuning, and operation of high-power linacs are discussed. The inconsistencies between the basic beam physics principles used in the design and the operation practices are considered. The missing components of the beam physics tools for the design and operations are examined, especially for negative hydrogen ion linacs. The diagnostics and online models necessary for tuning and characterization of existing states of the linac are discussed.

INTRODUCTION

The design process of a new high power linac is always a combination of two simultaneous and interacting processes [1]. The first is an engineering design where the available technologies (normal temperature or superconducting) are chosen for each section of the linac; the feasibility, availability, and cost of cavities and magnets are analysed; the limitations of the real estate are considered; and so forth. This part of the design process is mostly related to hardware choice, and it should minimize the overall cost of the new linac construction. The second part is related to the beam physics. The new linac should deliver a beam with necessary properties, and, at the same time, beam loss should be low enough to allow "hands on" maintenance of the linac equipment. Also, this low beam loss requirement will define the necessary tolerance limits for hardware and electronics influencing the final cost of the project. These two parts of the whole design process interact, and usually several iterations between them are necessary to get a good design.

The linac operation cycle can be broken onto three parts: maintenance/upgrade, commissioning/tuning, and production. In this paper I will only consider the tuning component of this cycle, and its dependency on the design and simulation model.

In my opinion, there are several deficiencies in the design and operation processes

- During the physical and engineering design, not enough attention is given to the procedures and hardware for tuning/commissioning of the linac in the operation cycle. With the increasing number of components in future projects this could be a bottleneck for the availability of future linacs.
- The model-based beam loss simulations for tolerance limits in the engineering design should use more realistic models and tuning algorithms.
- The beam loss reduction during operation should be model-based not only for the initial stage of tuning. The final empirical beam loss tuning should also be replaced with a model-based one. For this, we need benchmarked models.

It is possible that some of these problems cannot be solved for a long time, but we have keep them in mind as our goals. In this paper the examples describing these deficiencies are discussed mainly for the Oak Ridge Spallation Neutron Source (SNS) linac [2].

SNS LINAC

The SNS linac structure is shown in Fig. 1. It has both a normal temperature and a superconducting cold linac. The normal conducting part includes front end, RFQ, medium energy beam transport part (MEBT), drift tube linac (DTL), and coupled cavities linac (CCL). It accelerates beam to 186 MeV. The superconducting linac (SCL) includes 81 cavities and accelerates beam to 1 GeV.

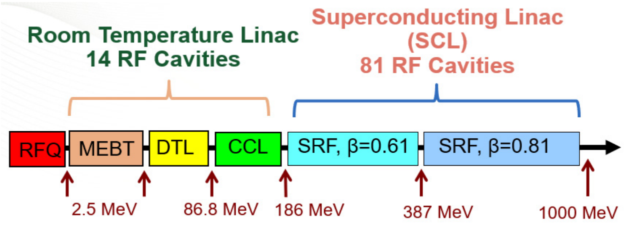

Figure 1: The SNS linac.

SNS LINAC TUNING/COMISSIONING

In this section the three examples related to the SNS linac tuning are discussed: two examples about RF set up procedures, and one about the orbit correction in CCL. The SNS linac diagnostics includes Beam Position Monitors (BPMs) which are also capable to measure the bunch phase proportional to the bunch arrival time. These BPMs are used for "time-of-flight" measurements.

SCL RF Tuning

The initial design of SCL suggested 100 us beam for superconducting cavities tuning [3]. The process was based on the RF cavity response to a beam loading with occasional "time-of-flight" measurements to avoid accumulating errors. The procedure should be repeated for all cavities one by one. At the beginning all cavities are detuned, and, as the process moves on, they will be brought to the resonant frequency. The whole tuning procedure was expected to give an uncertainty of ±20 MeV in the final beam energy which was a static error.

During the commissioning of the SNS SCL this approach was modified to avoid uncontrollable spraying of superconducting structures with 100 us beam. In addition to that, the process of bringing the detuned cavity to the

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resonant frequency takes 10-15 minutes including the bureaucratic overhead, and the total tuning time would be about two 8-hour shifts. Eventually the following modification to the SCL tuning procedure and linac hardware were implemented:

- All SCL cavities are on the resonance frequency all time. To avoid beam acceleration, initially all cavities are at 59 Hz repetition rate of RF pulses. The beam repetition rate for tuning is 1 Hz. The cavities are tuned one by one by switching to 60 Hz and performing "time-of-flight" energy measurements with all available BPMs.
- To avoid the beam loading of the cavities an attenuation system has been installed in MEBT to reduce the beam peak current by 80% or more.
- To reduce the beam loading even further, the Low Energy Beam Transport (LEBT) chopper at the RFQ entrance is used to provide only 1-5 us of beam.
- The SNS ring is used to calibrate the beam final energy with accuracy about 100 keV.
- The tuning process is automated. Now it takes about 45 minutes to tune all RF cavities in SCL.
- In the case of a cavity failure, the SCL can be retuned based on the model without any additional measurements. The cavities' phases will be changed to return the final beam energy to the initial value.

The fast tuning/retuning technique for new superconducting linacs becomes more important for high availability, because they have hundreds of cavities. The model-based retuning is especially significant for user facilities that need a fast reconfiguration for different experiments.

Warm Linac RF Setup

The SNS normal temperature linac includes 10 long RF structures: 6 DTL and 4 CCL cavities. To setup design values of amplitudes and phases for such type of cavities, the Delta-T procedure was developed at Los Alamos National Lab [4]. This procedure uses only a narrow phase range around the design value (~10°), because it is based on a linear model. A more general approach called "Phase scan signature matching" was developed at Fermilab [5]. At SNS both these algorithms were implemented in the high level tuning applications. The scheme describing these methods is shown in Fig. 2. To tune the cavity's amplitude and phase they use a phase scan of this cavity and data from two BPMs in the next cavity. The downstream cavity should be in the "off resonance" state.

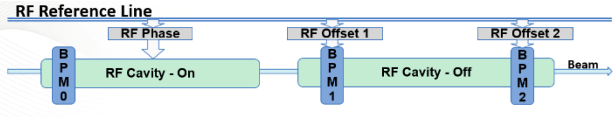

Figure 2: Warm linac RF tuning: DTL and CCL cavities.

During the SNS normal conducting linac commissioning and operations, it was found that tuning applications always needed an expert presence and "try and miss" iterations, because the working region around the design RF amplitude and phase is very narrow. The BPM 1 and 2 (see Fig. 2) should be calibrated for the "time-of-flight" bunch phase measurements. Later another tuning method was developed which uses only one BPM inside the tuning cavity (BPM0 in Fig. 2). We were lucky to have these inner BPMs at the right positions in the cavities with just a few accelerating RF gaps after the cavity entrance. This configuration allows to perform the cavity phase scan from -180° to +180° without BPM's signal interruptions for all cavity amplitudes. An example of a resultant BPM's phase as a function of the cavity's phase is shown in Fig. 3.

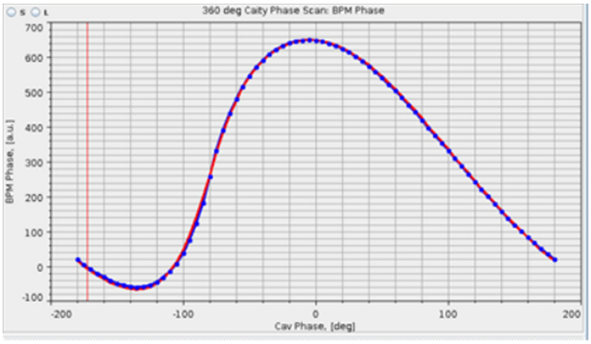

Figure 3: DTL3 phase scan. Blue points are BPM phases. Red line is the model calculation. The vertical red line is a cavity phase working point.

Comparing this data with the model calculation we know how far we are from the cavity design parameters. This method uses only one BPM, so there is no need for the timing calibration. It is also faster than initial methods, and it was easily automated allowing to tune RF in the whole warm linac in 22 minutes. Unfortunately, the initial design did not provide us with the inner BPM in the first DTL cavity, so for this case we still use the phase scan matching method. This example shows the importance to have the right diagnostics at the right places during the design stage.

CCL Orbit Correction

The SNS coupled cavity linac has 48 quadrupole magnets and only 10 BPMs to measure the beam transverse positions. The initial design included more BPMs, but during the cost optimization some BPMs were removed from the CCL lattice. During the commissioning it was found that a standard orbit correction application can easily make BPMs readings close to zero, but beam loss was still too high. To see the real orbit quadrupole gradient scans were performed, and they showed that the orbit between BPMs has ± 3 mm deviation from the quad centres. The quad gradient scans procedure cannot be a part of the routine orbit correction, because it is disruptive and too slow.

The situation was resolved by the development of a more comprehensive model for the beam center motion in the CCL. The new model includes possible transverse offsets of quadrupoles and BPMs from the beam pipe center. The unknown offset parameters were found after several quadrupole gradient scans, and then they were narrowed down by analysis of several hundreds of trajectories in CCL for different quadrupole and dipole corrector fields combinations. The values of the vertical offsets of the quadrupoles are shown in Fig. 4. The maximal offsets shown in Fig. 4 (±1 mm) are too big to be real, but they work very well for the new orbit correction algorithm. The new algorithm includes three steps. First, we use beam positions measured by BPMs to figure out the beam position and angles at the CCL entrance. Next we use the inverted transport matrices generated from the magnet fields and offsets to calculate the beam trajectory is in the whole CCL. In the third step, we apply the standard orbit correction algorithm for all significant points in the CCL lattice using the simulated trajectory. After correction, the orbit deviation from the center usually is less than 1 mm. This case demonstrates that deficiencies during the design will result in some additional studies and developments needed to provide a reliable and fast beam loss tuning.

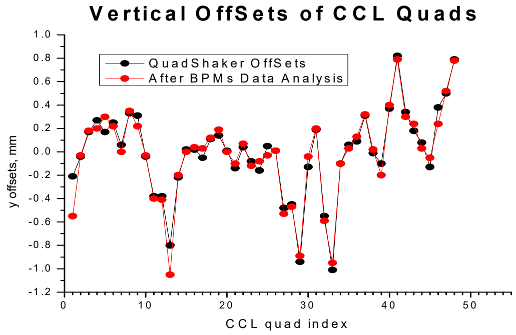

Figure 4: The vertical offsets of the CCL quads used in the model for the specialized orbit correction application.

OPTIMAL TOLERANCE DESIGN PROBLEM

Tolerance limits in the engineering design have a significant impact on the final price tag of the project. The usual procedure to check the acceptable tolerance on beam related parameters includes multiple "end-to-end" simulations with randomly distributed parameters errors. The main goal of the simulations is to estimate if beam losses are on the acceptable level. To get beam loss estimation, the linac model for simulations should be a Particle-In-Cell (PIC) code. In this section of the paper we discuss manly the RF system errors. The usual numbers for cavities tolerances are 1% in the amplitude and 1° for the phase.

The parameter errors are divided onto two different parts: static and dynamic. The distinction between them is very clear for the mechanical alignment errors in lattice components like magnets, RF cavities, apertures etc. If we apply the significant alignment errors to the model, beam loss will show up in the simulations due to the orbit distortion. Then these losses will be eliminated or significantly reduced by the orbit correction with the dipole correctors included in the engineering design. The dynamic errors usually are not compensated in hadron linacs. The source of the static errors is the positioning of the lattice elements during the construction, and for the dynamic errors that could be, for instance, mechanical vibrations. Tolerance limits will be different for static and dynamic errors in the case of the alignment errors. For the RF parameters tolerances, the situation is not so clear.

This section discusses the following topics related to the tolerance of RF parameters

- The SNS experience with the RF parameters vs. the design values.
- The recent development in the TraceWin code [6] related to the RF tolerances and the tuning procedure simulations.
- The deficiencies in the PIC codes related to beam loss calculations.

SNS RF Settings vs. Design. Static Errors.

Using SNS as an example we consider three types of situations. The first is a MEBT buncher phase setting procedure where we do not have the capability to distinguish between two possible setpoints. The second is the SCL cavities' field gradients where we do not have a choice, because they are defined by the maximal achievable value. And the third case is for synchronous phases of the SCL cavities that are set to get the local minimum of beam loss.

To setup non-accelerating phases of RF bunchers in the SNS MEBT (see Fig. 1) we use the RF phase scans for different RF amplitudes and the phase signals from downstream BPMs. If the RF phase is the non-accelerating one, the phases from the BPMs will be the same for all RF buncher amplitudes. The result of such scans for one of the BPMs is shown in Fig. 5. The MEBT attenuation system was used for these measurements, so there were no space charge effects. This figure clearly demonstrates the stationary RF phase point with accuracy around 1°. The problem is that different BPMs give different set-points in the range of ±4°. The possible reason for that is a non-symmetrical longitudinal shape of the bunch, and its transformation along the MEBT. At this moment, we have no means to verify which value is the correct one, and settings found for different BPMs can be used as a stating point for final beam loss tuning. So, this ±4° spread could be considered as a legitimate static error of the MEBT RF.

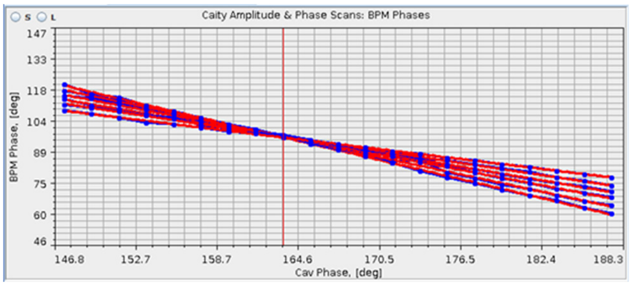

Figure 5: The MEBT buncher #2 phase scans for different amplitudes. Blue points are BPM phases, and red lines are linear fits for different RF amplitudes.

Another example of unexpected deviations from the design parameters is the field gradients of the SCL cavities. Figure 6 shows the measured SNS SCL cavity field gradients and the design values for the medium and high beta sections of the superconducting linac. As we can see, for most cavities in the medium beta region the gradients are above the design by 20-40%, and for the high beta they are lower than the design by approximately the same amount. To get the final linac energy near the design we had to keep gradients as high as possible. Figure 6 describes the SNS situation several years ago, but even at that time the linac delivered 1 MW beam with acceptable losses.

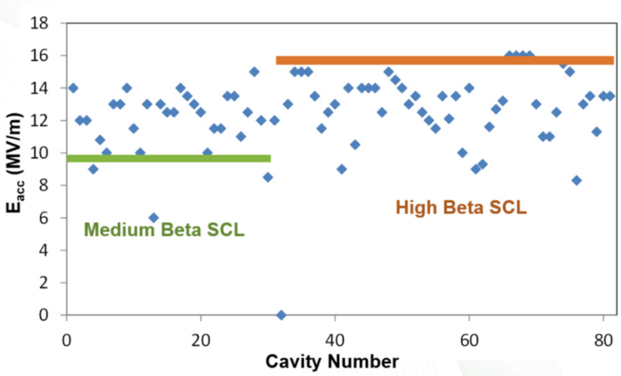

Figure 6: The real field gradients of the SNS SCL cavities. The lines are the design values.

The next example shows the synchronous phases of the SCL cavities during the SNS production run in 2014 (see Fig. 7). These synchronous phases provide a low beam loss tune in SCL despite their significant deviation from the design value of -18°. They were a result of the empirical beam loss tuning after initially setting all of them to the design values. At this moment, we do not understand the reason why the low loss tune needs this behaviour of the synchronous phases along SCL.

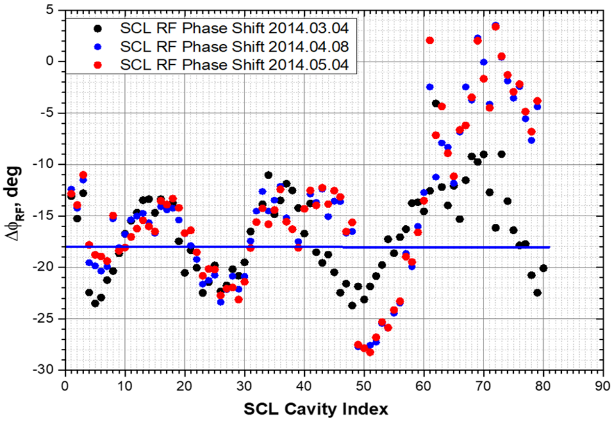

Figure 7: The measured synchronous phases of the SCL cavities for the low beam loss tune. The blue line is the design value.

All the discussed examples show that the realistic static tolerances for RF amplitudes and phases could be much higher than the 1%, 1° standard limits. For dynamics errors, the SNS experience gives 1.5% and 2° values for the SCL RF system which are close to the standard.

RF Static Errors Treatment in Simulations

The big deviations of the RF parameters from the design values in the operational high power linac with acceptable beam loss shows that our usual treatment of the static errors in the RF system must be reconsidered. As an example of this approach we have a recent modification of the TraceWin code related to this topic [6]. In [6] the longitudinal beam dynamics simulation method has been improved by including more "close-to-real" models for cavities tuning procedure. A specific command has been implemented in TraceWin code to simulate this tuning process. The new method was tested with the MYRRHA linac [7] model. The application of this new method to the simulations reduced the estimation of total beam loss by factor 60.

Despite some logical inconsistencies and unrealistic expectation of the BPM positions accuracy (±1 mm) in [6], this more realistic approach to the static errors treatment should be welcomed by the community and should encourage more studies in this direction.

Code Deficiencies in Beam Loss Simulations for H^- Linacs

We can look at the paper [6] results from another angle. If the change of the static error interpretation method in the model significantly reduced expected beam loss, can we trust these simulations with respect to the beam halo description? We are going to consider this issue in the next section. Here the simulation of the recently discovered Intra-Beam-Stripping (IBSt) mechanism of beam loss in H^- linacs [8, 9] is discussed.

The IBSt induced beam losses are important for all high-power H^- linacs, and they were not considered in any design of existing H^- linacs. At this moment, there is only one code that includes the model for such type of beam loss calculations – TRACK [10]. TRACK is a PIC code, so it is more computationally expensive to use than envelope codes. IBSt induced beam losses are defined by the bunch core, so it should be easily implemented into envelope codes. For now, these losses are usually calculated by using postprocessing scripts analysing the RMS beam sizes along the linac. Incorporating this mechanism into the modern envelope and PIC codes would benefit the community.

OPERATIONS : MODEL BASED BEAM LOSS TUNING

As we mentioned before, the operation cycle includes tuning the accelerator parameters to provide necessary beam properties and the acceptable level of beam loss. Usually the initial tuning is performed by using the online model right in the control room or with precalculated data. The final tuning of high power linacs is always an empirical beam loss reduction by slightly tweaking parameters known to be effective from previous experience. Unfortunately, at this moment we do not have reliable and benchmarked PIC codes capable of beam loss prediction on necessary level of 10^{-4} or less. Also, this type of simulation should include not only the code itself, but also a realistic initial distribution of the bunch particles. At SNS there are plans for studies related to these topics.

Bunch 6D Initial Distribution Studies

To test a new RFQ for the SNS accelerator, a functional copy of the SNS Front End with the H- Ion Source, LEBT, RFQ, and MEBT has been built at SNS. From the beginning this installation was dedicated for beam physics studies, and it is called the Beam Test Facility (BTF). The first accomplished study on BTF was the measurements of the 6D phase space distribution of the particles in the H- bunches from the RFQ [11]. The data analysis is still in progress. The knowledge of the 6D distribution is a necessary step in the experimental benchmark of any PIC code. The next step is a study of halo development for different optics.

Plans for FODO Lattice at SNS BTF

In addition to the existing beam line of BTF, there is a plan to install a FODO lattice with the necessary diagnostics for beam halo formation studies [11]. The combination of known 6D distribution at the entrance of this FODO line, and halo measurements at the exit, will give us a useful instrument for a full benchmark of PIC models.

Backtracking Feature of Codes

The 6D phase space measurement is an ultimate solution for the initial distribution problem, but even right now many linacs have an emittance measuring station somewhere in the lattice. The data from these measurements could be used for the bunch generation in PIC codes assuming zero correlation between planes. Beam diagnostics also can include Bunch Shape Monitors (BSM), but usually they are at different locations. If BSMs are upstream of the transverse emittance stations (the case at SNS), and we want to combine the data, then we need the ability of the code to track the bunch backwards in the lattice. This feature of the code can serve many purposes, but not many codes have it. From the theoretical point of view there is no obstacle for the backward tracking, because all our equations of motion are time reversable.

CONCLUSION

Briefly summarizing the arguments about the missing components in design and operations of the high power linacs, I want to highlight the following

- In the design process, more attention should be paid to the tuning procedures of the linacs including hardware and algorithms.
- To estimate tolerance in engineering design the realistic models and algorithms for beam loss calculations are needed.
- The same realistic models are needed for beam loss tuning during the operations.

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APPENDIX

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REFERENCES

[1] P. Ostroumov, F. Gerigk, “Superconducting Hadron Linacs,” *Rev. Accel. Sci. Tech.*, vol. 6, pp. 171-196, 2013.

[2] S. Henderson *et al*., “The Spallation Neutron Source accelerator system design”, *Nucl Instrum Meth A*, vol. 763, pp. 610-673, 2014.

[3] J. Stovall *et.al.*, “Superconducting linac for the SNS”, in *Proc. LINAC’00*, Monterey, CA, USA, Aug. 2000, p. 605.

[4] K.R.Crandall, "The Delta-T Tuneup Procedure for the LAMPF 805-MHz Linac", LANL Report LA-6374-MS, June 1976.

[5] T.L. Owens, M.B. Popovic, E.S. McCrory, C.W. Schmidt, and L.J. Allen, “Phase Scan Signature Matching for Linac Tuning”, *Particle Accelerators*, vol. 48, pp. 169-179, 1994.

[6] D. Uriot, “Improvement of the RF field phase & amplitude errors simulation in TraceWin code,” in *Proc. IPAC’18*, Vancouver, Canada, April 2018, paper THPAF017.

[7] D. Vandeplassche *et al*., “The MYRRHA Linear Accelerator”, in *Proc. IPAC’11*, San Sebastian, Spain, Sep. 2011, pp. 2718-2720.

[8] V. Lebedev *et al*., “Intrabeam Stripping in H-Linacs”, in *Proc.* LINAC’10, Tsukuba, Japan, September, 2012, pp. 929-931.

[9] A. Shishlo *et al*., *Phys.* Rev. *Lett*., vol 108, p. 114801, 2012.

[10] V. Aseev *et al*., “TRACK : The new beam dynamics code”, in *Proc. PAC’05*, Knoxville, Tennessee, USA, 2005, pp. 2053-2055.

[11] A. Aleksandrov *et al*., “6D Beam Measurement, Challenges and Possibilities”, in *Proc. IPAC’18*, Vancouver, Canada, April 2018, paper THXGBE1.