START TO END ERROR STUDY FOR THE SPIRAL2 LINAC

R. Duperrier, D. Uriot
CEN Saclay 91191 Gif sur Yvette, France.

Abstract

The possibility of a high intensity accelerator at GANIL, producing secondary beams of unprecedented intensity, is considered. The proposed CW driver for the SPIRAL2 project aims to accelerate a 5 mA deuteron beam up to 20 A.MeV and a 1 mA ion beam for q/A = 1/3 up to 14.5 A.MeV [1]. The error sensitivity study which has been performed for this linac in order to define the tolerances for the construction is presented. The correction scheme and the expected losses are described. The Extreme Value Theory is used to estimate the expected beam losses.

INTRODUCTION

Once the reference design for the accelerator with perfect elements respects the requirements, it is necessary to evaluate the effects of errors. This evaluation permits to define tolerances for the construction of the SPIRAL2 linac and to test its robustness. This evaluation may be compared to a risk measurement. To cure the errors, a tuning scheme based on correctors and diagnostics has to be designed taking into account the diagnostics imperfections (misalignments, ...). Only the 5mA deuteron beam case will be studied as it is assumed to be the more critical (space charge, radioprotection issues).

SENSITIVITY OF THE LINAC TO ELEMENT ERRORS

Before detailing the different types of error, it is important to remark that two families of errors have to be coped for:

- static errors: the effect of these errors is detected and corrected. The strategy of the correction scheme is established to correct these errors (see below).
- dynamic errors: these errors are not corrected. They are induced by the vibrations of the RF field or mechanical vibrations from the environment. The effect of uncorrected errors is simulated by adding them after the correction of the static errors. The amplitudes of this defect is set to one order of magnitude lower than the static errors.

Depending on the linac section, errors with different amplitudes have been used. These amplitudes are typically 0.1 mm for displacements, 1 degree for the RF phase and 1% for the electromagnetic fields. The reference [3] details these amplitudes for each linac section. For an error of amplitude A, the value has a uniform probability to be between $-A$ and $+A$.

Correction scheme

A correction scheme has been studied in order to be also capable to match the beam in the different part of the linac. The beam center trajectory is controlled by using steerers which kick the beam in both planes. The transverse beam matching is adjusted with quadrupoles coupled with beam profilers or an emittance measurement. Only data coming from diagnostics are used to tune the elements. A detailled description of the correction scheme for each section is given in reference [3]. For the whole deuteron linac, 17 profilers, 1 emittance measurement and 22 Beam Position Monitors have been used. Expected diagnostic errors are included. The longitudinal plane is not corrected. The figure 1 shows the losses and emittance growths for the whole linac without error as reference. The emittance growths are relevant observables to set the tolerances if an upgrade to 100 MeV/uis required. All errors are merged and amplified to 200%. It corresponds, for instance, to displacement of 0.2 mm. The transport of the beam through the RFQ is computed with the code TOUTATIS [2], the rest of the linac is simulated with TraceWin/PARTRAN [2]. The space charge is calculated with 3D routines. Several elements are simulated using a 3D field map: the LEBT quadrupoles, the RFQ and the quarter wave resonators. The Monte Carlo computations have been performed with $\sim$10 PCs using a client/server architecture for the data management according to a multiparameters scheme rather than a parallel scheme which is less optimal.

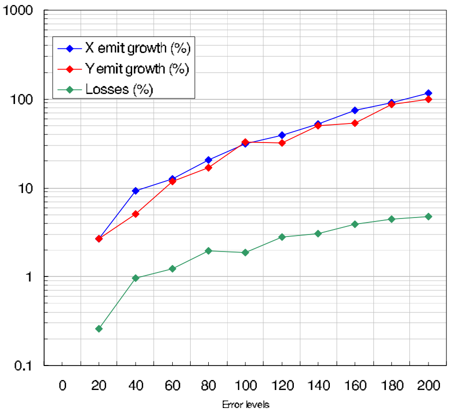

Figure 1: The deuteron losses and emittance growths in the whole linac in respect to the error level.

This first scanning shows that SPIRAL2 requirements are respected if the amplitudes of errors are lower than 140% if we consider mean values. A safer approach would be to choose an amplitude equal to 100% as a good compromise to minimize constraint for a possible upgrade to 100 MeV/u. The following section shows detailed results of the 100% amplitude error level study.

DETAILED RESULTS FOR THE ERROR STUDY AT 100%

Distributions of centers

To get a good estimate of the center position in phase space plane, 10,000 macroparticles per run are largely sufficient. The most important quantity to reach convergence for the standard deviation is the total number of generated linacs. 1000 different linacs with all combined errors on each element have been used.

Except for the LEBT, the rms centre position is kept lower than 1 mm especially in the quarter wave resonators where it is well controlled and kept lower than 0.5mm. We notice that the rms jitter centroid position at the target is about 0.9mm. It is mainly due to the dynamic errors (vibrations) and BPM accuracy.

Regardless of the cavity field fluctuations, the tolerance on field amplitude and phase errors would lead to an rms energy fluctuation of 55 keV and phase fluctuation of 11 deg. at the linac exit (see figure 2).

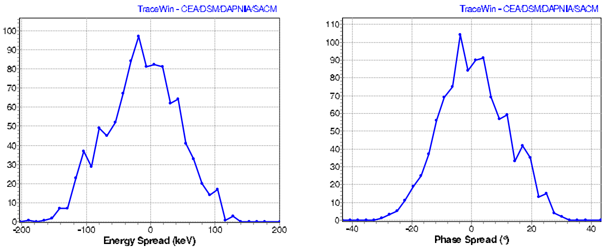

Figure 2: Energy and phase distributions at linac exit (1000 simulations).

Application of the Extreme Value Theory for the loss estimate

To study more precisely the deposited beam power in the linac, the 10,000 macroparticles are not enough to estimate losses lower than 1 W for each linac. Thus, the number of particles per run has been increased to 1,000,000 in order to reach the required resolution and the number of run has been decreased to 341. This set of simulations provides data which can be used to build statistical models describing the extreme events. Extreme value theory (EVT) provides a firm theoretical foundation to perform such a goal (Fisher and Tipett (1928) and Gnedenko (1943)). In many field of modern science, EVT is well established [4]. This paper won't detailed this theory. See the reference [4] which reviews the basics and illustrates EVT with examples of application. To model the tails of our deposited beam power in the SPIRAL2 linac, we will apply the following method:

Table 1: Average an peak losses repartition according to linac section (ndy means "not designed yet").

	Loss. (W)	Length (m)	Loss. (W/m)	Peak loss. (W)
LEBT	0.2	8.9	0.0	0.1
LEBT scrapers	46.9	ndy		33.9
RFQ	0.3	5.1	0.1	0.1
MEBT	1.	7	0.1	0.7
MEBT scraper	317.2	ndy		317.2
SCL1 (warm)	1.	10.2	0.1	0.6
SCL2 (warm)	0.2	7.0	0.0	0.0
SCL1 (cold)	0.3	3.6	0.1	0.1
SCL2 (cold)	0.5	7.0	0.1	0.2
HEBT	2.4	33.1	0.1	0.9

- first, scan the mean deposited power for each element of the accelerator to detect the most critical components.
- second, fit the data with the Generalized Extreme Value (GEV) distribution.
- Third, estimate confidence intervals for value of interest with the bootstrap method.

Figure 3 shows the mean losses repartition along the structure for the 341 linacs and the corresponding dissipated power. The repartition along the linac parts is summarized in the table 1. For an amplitude of 100% of the errors, the mean deposited power are always lower than the requirements. The selection of the most critical components assumes that the higher average deposited power the higher the beam loss power for a given probability.

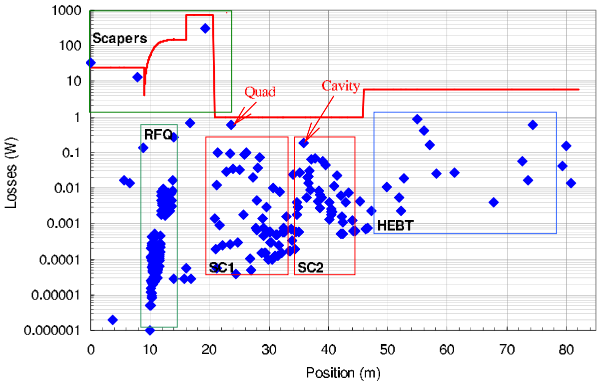

Figure 3: Average loss repartition along the structure (the red line is the acceptable limit). The most critical components are pointed with red arrows.

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If we focus on the results for the SCL, we can observe two critical elements. The first one is the first quadrupole of the first super-conducting section where a mean value of 0.61 watt is dissipated and the second one is the first cavity of the $\beta = 0.12$ section where a mean power of 0.19 Watt is recorded. We will concentrate our study on these two elements.

First quadrupole of the $\beta = 0.07$ section: Using the recorded loss distribution at the first quadrupole of the first super-conducting section, we can build a Cumulative Distribution Function (CDF) which will be our reference data to fit with the GEV function of the lost power p:

$$H_{\xi\sigma\mu}\left(p\right) = exp\left(-\left(1+\xi\frac{p-\mu}{\sigma}\right)^{-\frac{1}{\xi}}\right) \qquad (1)$$

with μ, the location parameter, σ, the scale parameter and ξ, the Jenkinson and von Mises parameter. The GEV fitted with these data is plotted in the figure 4. At this location of the linac, the requirements assume that less than 4Watt should be deposited on the pipe. With the fitted GEV, we can estimate that the probability to loose less than 4 Watt is 0.97 which is very confortable. To see how sensible is this result in respect to the achieved statistics, we can calculate a confidence interval at 95%. The bootstrap method is a helpful technique to construct such confidence interval. We resampled 1000 times the recorded losses and recomputes the expected return power level for a probability of 0.97. The figure 5 shows the empirical bootstrap distribution for the return level. The confidence interval at 95% is then $[2.3; 5.9]$ Watt. The two small red marks indicate the $\pm 2\sigma$ interval, the big red mark indicates the return level obtained with a direct estimate from the recorded losses.

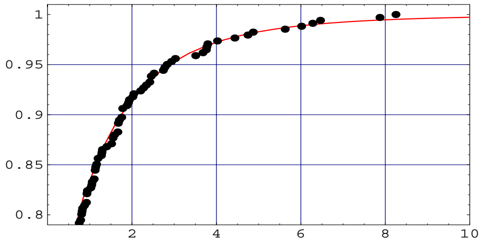

Figure 4: GEV fitted with the recorded losses for the quadrupole. The deposited power (W) forms the abscissa.

First cavity of the $\beta = 0.12$ section: With the same procedure, we can construct a GEV function fitted with the recorded losses at the cavity location. The figure 6 shows the fitted GEV with the recorded losses at the cavity location. The probability to loose less than one watt is 0.99. With the bootstrap method, we can estimate a confidence interval of $[0.44; 1.33]$ Watt (see figure 7).

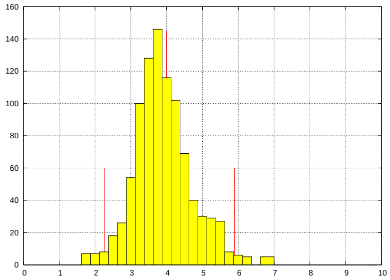

Figure 5: Empirical bootstrap distribution for the return level with a probability of 0.97.

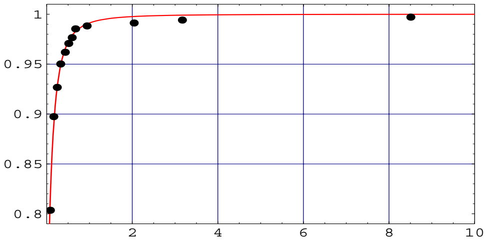

Figure 6: GEV fitted with the recorded losses for the critical cavity. The deposited power (W) forms the abscissa.

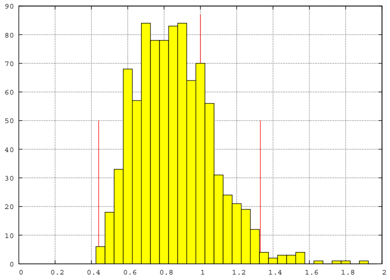

Figure 7: Empirical bootstrap distribution for the return level with a probability of 0.99.

CONCLUSION

The start-to-end error study for the SPIRAL2 linac show manageable losses with a 4σ gaussian as input distribution and the use of collimators. The probability to loose more than one watt in a superconducting cavity is lower than 10^{-2}. The element tolerances are not challenging and exist in other machines like the photon machines.

REFERENCES

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