BEAM DYNAMICS OF SPL: ISSUES AND SOLUTIONS

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Abstract

SPL is a superconducting H- LINAC under study at CERN. The SPL is designed to accelerate the 160 MeV beam of LINAC4 to 4-5 GeV, and is composed of two families of 704.4 MHz elliptical cavities with geometrical betas of 0.65 and 1.0 respectively. Two families of cryo-modules are considered: the low-beta cryo-module houses 6 low-beta cavities and 4 quadrupoles, whereas the high-beta one houses 8 cavities and 2 quadrupoles. The regular focusing structure of the machine is interrupted at the transition between low beta and high beta structure and at 1.4 and 2.5 GeV for extracting medium energy beam. The accelerator is designed for max. 60 mA peak current (40 mA average) and max. 4% duty cycle, implying a very accurate control of beam losses. In particular the choice of the diagnostics and correction system, the maximum quadrupole gradient to avoid Lorentz stripping and the effect of the RF power delivery system on the beam quality are discussed in this paper.

INTRODUCTION

SPL, Superconducting Proton Linac [1], is a CERN multi user facility with the aim to produce at 5 GeV a high power proton beam suitable for a neutrino factory. Fixed target experiments are foreseen at lower energies, like ISOLDE at 1.4 GeV or Eurisol at 2.5 GeV.

LINAC4 [2] accelerates H- ions from 45 keV to 160 MeV in a sequence of normal conducting structures at 352.2 MHz and injects the beam into SPL: the H- are then accelerated from 160 MeV to 5 GeV by about 240 5 cells elliptical cavities (704.4 MHz) whose geometric β in the low energy part is equal to 0.65 and 1.0 above (see Figure 1). The nominal accelerating gradients are 19 and 25 MV/m respectively. The transition energy between the two families is set between 700 and 800 MeV, optimized in order to have the best beam dynamics and the most efficient acceleration [3]. At the moment two current scenarios are under study: while the final power is the same (4 MW), the peak current can be 32 or 64 mA, the latter being the highest among high power linac projects in the world running or under study (see Table 1).

A large community participates to the SPL design, including members of high power proton linac projects and of various Universities, companies and Institutes, all generally involved in electron and proton linac studies or in the technology of SC cavities.

SPL BEAM DYNAMICS

General Criteria

SPL beam dynamics was designed according to the following three general beam dynamics criteria:

Table 1: High Power Linac Projects in the World

Param.	Unit	SPL LC	SPL HC	SNS	ESS	Project X
ion		H-	H-	H-	p	H-
Energy	[GeV]	5	5	1	2.5	3
Beam power	[MW]	4	4	1.4	5	3
Rep. rate	[Hz]	50	50	60	20	CW
Av. pulse current	[mA]	20	40	26	50	1
P. pulse current	[mA]	32	64	38	50	10
Source current	[mA]	40	80	47	60	≤ 10 dc
Chopping ratio	[%]	62	62	68	/	10
Beam pulse	[ms]	0.8	0.4	1	2	100
Duty cycle	[%]	4	2	6	4	10

- The phase advance per period for zero current does not exceed 90 degrees in all planes to avoid beam envelope instabilities.
- The longitudinal phase advance is always smaller than the transverse. The ratio between the two is far from the peaks of Hofmann plots [4], avoiding resonances.
- The matching between the two cavity families is achieved by means of a smooth transition of the phase advance per meter.

Consequently:

- Maintaining the cavity voltage at its maximum except at the beginning of the low β and high β sections where the resulting phase advance would exceed 90 degrees, the longitudinal phase advance is reduced along the acceleration as the beam energy increases.
- Accordingly, the transverse phase advance is reduced in order to maintain the ratio. This is obtained by lowering the focalization. As the geometrical emittance decreases in the acceleration, the resulting average beam size remains almost constant along the linac.

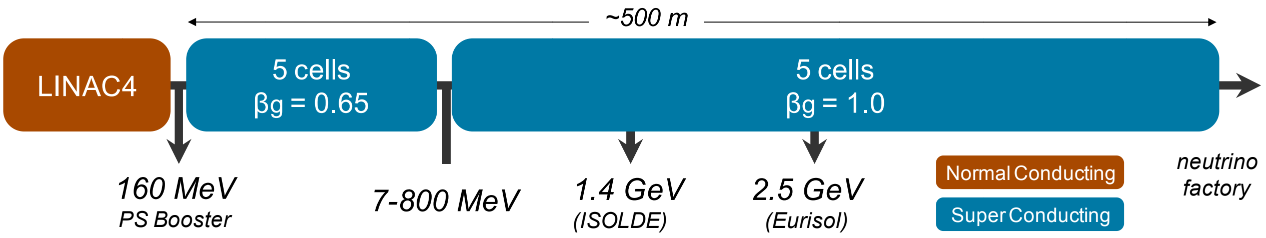

Figure 1: SPL conceptual layout (longitudinally to scale).

The CEA code GenLinWin is used to generate and to optimize the structures whereas TraceWin [5] is used to simulate the particles running through the entire linac starting from the output of the Linac4 to SPL transfer line.

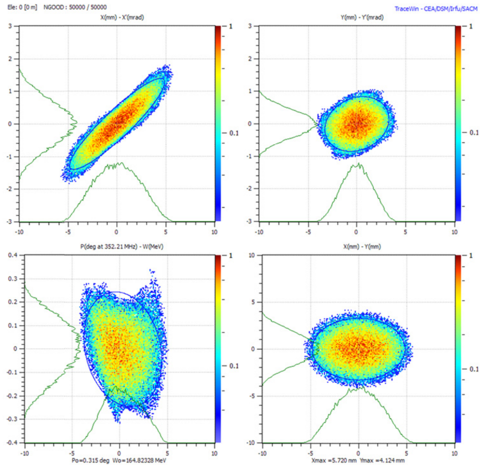

Figure 2: SPL input distribution (50k macroparticles).

Lattice Comparison

The transverse phase advance per period can be adjusted with either a doublet (FD0, the baseline solution) or a FODO lattice (layouts in Figure 3). In the thin lens approximation, the ratio (at the same gradient) between the phase advance of the FD and the F0D0 lattice is $2\sqrt{LD/(L+D)}$ (L being the distance between the center of the D magnet to the end of the period and D the distance between the centers of the quads). For SPL lattices this ratio is ~0.5. Therefore the gradients needed for the F0D0 layout are half of the ones of the FD layout.

Initially, a magnetic length of 450 mm and a bore radius of 50 mm are taken as reference for the quadrupoles. Each quadrupole will have an extra coil to perform a steering correction in one plane, and a BPM will be installed at each lattice period.

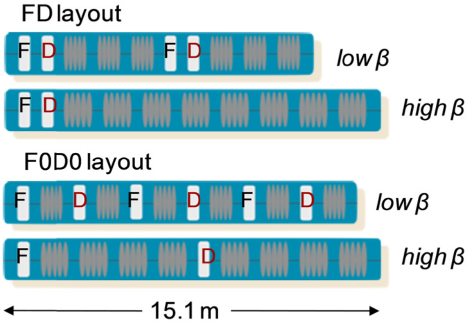

Figure 3: Lattice comparison.

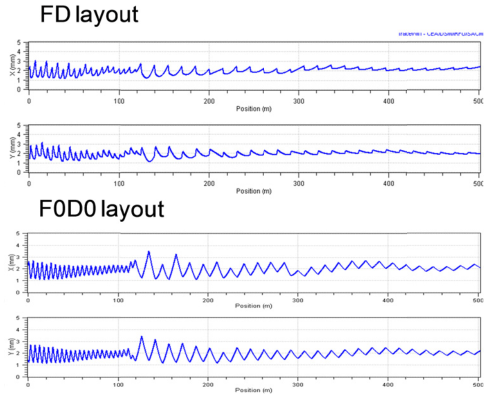

Figure 4: Transverse envelopes for both layouts.

Both lattices (details in Table 2) perform very well regarding the final beam dynamics parameters (see Figure 4 and Table 3). Nevertheless statistical runs on the machines indicate that the F0D0 layout is slightly more robust against the quadrupole misalignments, as shown in Figure 5.

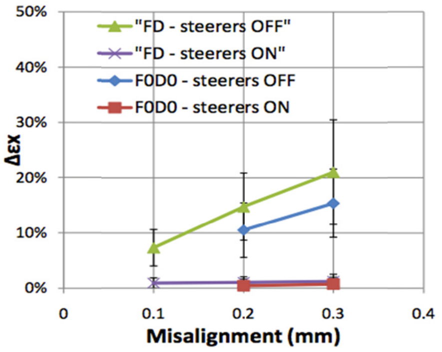

Figure 5: Transverse emittance increase as function of the quadrupole misalignment, for the two layouts with and w/o correction.

The two designs in comparison have their advantages and disadvantages, namely for the FD lattice:

- Pro: flexible for cryo-sectioning. 4 cavities at low β and 8 at high β are installed between the quads, which therefore can be both warm and cold.
- Contra: alignment sensitivity.

And for the F0D0 lattice:

- Pro: weaker quadrupoles to achieve the same focusing (advisable for the magnetic stripping issue).
- Contra: a higher total number of quadrupoles. The design of the cryo-module is more complicated, especially at low energy.

Magnetic Stripping and Quadrupole Magnetic Length

When an H- ion moves in a magnetic field B it experiences a Lorentz force that bends its trajectory and also tends to strip its electrons. This phenomenon may occur in both the dipoles of the transfer lines and the quadrupoles of the linac. The stripping probability is independent of the beam transverse distribution in case of a constant field, whereas in a quadrupole magnet the linear increase of the magnetic field B with its distance from the center has to be considered. This means that for a given distribution, the probability for particles traveling around the magnetic centre of the quadrupole is very low and it increases with the distance from the axis, as shown in Figure 6. Most of the particles are located around the quadrupole centre, whereas particles very far from the center can be found only if the distribution is characterized by high halo, which may turn out to be the case for SPL due to the high current accelerated. Moreover, if the beam is off-centered, the high density part becomes closer to the higher B region and the total number of stripped particles increases.

To quantify the amount of stripped particles one has to combine the stripping probability with the probability of a particle being at a certain distance from the centre. The result will depend on the type of the distribution (Gaussian, Double Exponential, etc…), on the width σ of the distribution itself and on the displacement r_0 from the centre. Two σ value scenarios are analyzed:

- $\sigma = 1.7$ mm corresponding to the nominal case with full centring correction ($r_0 < 1$ mm);
- $\sigma = 2.5$ mm corresponding to the nominal case without any correction ($r_0 < 10$ mm).

The minimum magnetic length required to have losses below 0.1 W/m increases with the energy, as shown in Figure 7 (a safety factor 10 below the radio-protection limit of 1 W/m is needed to allow for other sources of losses, like the intra-beam stripping). If both the magnetic length and the type of lattice are kept constant for the whole linac, the magnetic length is indicated by the minimum value at 5 GeV, which means overdesigning the magnets at low energy. If one switches from an FD lattice at low energy to a F0D0 lattice at high energy (Figure 8), the magnetic length is optimized with the added benefits of a better steering correction at low energy and higher cryo-segmentation effectiveness at high energy.

The Low Energy Branching Issue

As said in the introduction, branch-offs are needed at 1.4 and 2.5 GeV for the low energy experiments. Due to the magnetic stripping issue and the consequent limit on the dipole field, each branching requires a minimum drift space of 13.6 m and 21 m respectively in the periodic structure of the linac, the former one being about 1 high β lattice period length (15.1 m) and the latter 1.5. Since a re-matching involving two periods before and after must be performed in these regions, the change in the focusing lattice mentioned before can be performed here.

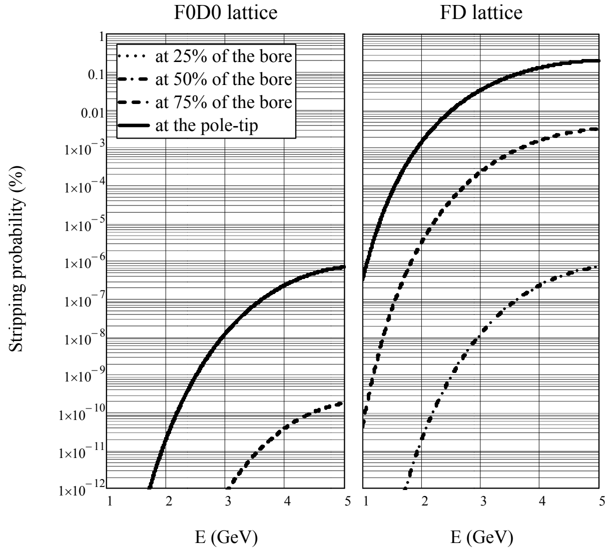

Figure 6: Stripping probability for the nominal SPL quadrupole (50 mm bore radius, 450 mm long) as function of the energy for the FD and F0D0 layouts.

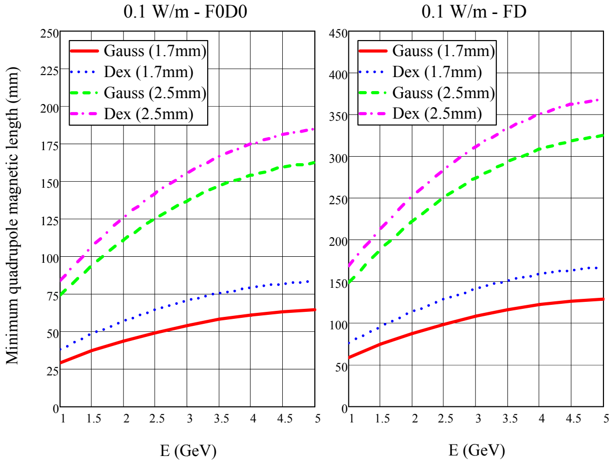

Figure 7: Minimum quadrupole magnetic length for the scenarios described in the text.

THE MIXED SOLUTION

In the FD & F0D0 mixed architecture of the highly segmented SPL (see Figure 8) there are:

- 3 cavities (low β cryo-module) with a NC doublet per period in the low energy part.
- 8 cavities (high β cryo-module) and a NC doublet in the high energy region before the 2.5 GeV.
- 2x one high β cryo-module and one single NC quadrupole after 2.5 GeV. This makes a F0D0 lattice twice the length of the F0D0 previously discussed.

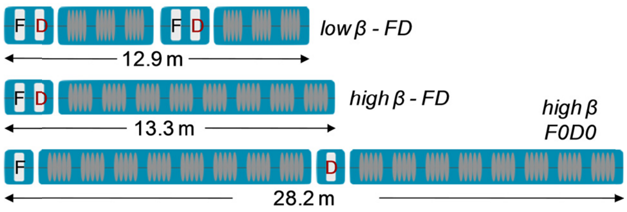

Figure 8: Lattices for the SPL mixed solution.

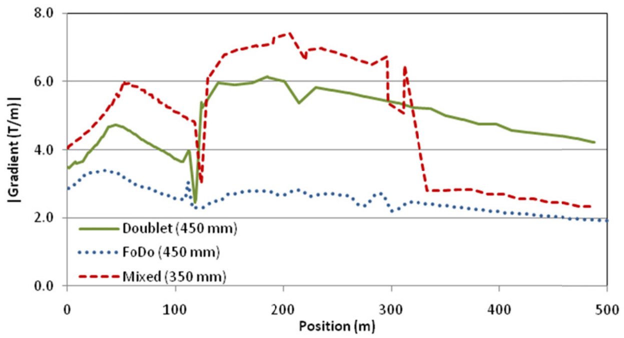

Figure 9: Gradient of the quadrupoles along the line for the 3 SPL layouts. The magnetic length used in the design is reported between brackets.

After each lattice transition the length of the focusing doubles, maximising the packing density of the cavities and therefore increasing their "real-estate gradient". Having less quadrupoles after the transition at 2.5 GeV brings the beam to the same energy within the same linac length as the unsegmented layouts in Figure 3. An optimization of the magnetic length of the quadrupoles can be done and the resulting value is 350 mm. Such a length would not be advisable for any of the previous designs. The gradients are reported in Figure 9.

Even though the matching is done carefully from low energy to high energy and also across the extraction branches, the long extraction drift spaces have an impact on the beam halo (Figure 10). Longitudinal halo is enhanced at 1.4 GeV and the transverse halo is mainly increased at the 2.5 GeV transition where there is the change of the focusing scheme from FD to F0D0. This is where the major emittance increase in transverse plane as well as the maximum beam size occurs, the rms value being 4 mm in horizontal plane, while in the rest of the machine this value stays below 3 mm. The minimum aperture to ratio value is therefore 17. Nevertheless the performances of this solution are similar to the ones of the previous designs (Table 3).

Table 2: SPL Layouts

Lattice	L (m)	Periods	Cavs. pp	Quads	Cavs
FD	501	20/23	3/8	86	244
F0D0	510	24/24	2/8	96	240
Mixed	505	18/15/6	3/8/16	78	244

Table 3: Nominal SPL beam dynamics results (mm mrad norm.). In brackets the comparison with the $\mathrm{SPL}_{\mathrm{in}}$ values

	Lattice	X emit.	Y emit.	Z emit.
	$\mathrm{SPL}_{\mathrm{in}}$	0.338	0.339	0.494
SPL out	FD	0.369 (+9.2%)	0.365 (+7.7%)	0.486 (-1.7%)
	F0D0	0.359 (+6.2%)	0.356 (+5.0%)	0.546 (+10.5%)
	mixed	0.387 (+14.5%)	0.384 (+13.3%)	0.515 (+4.3%)

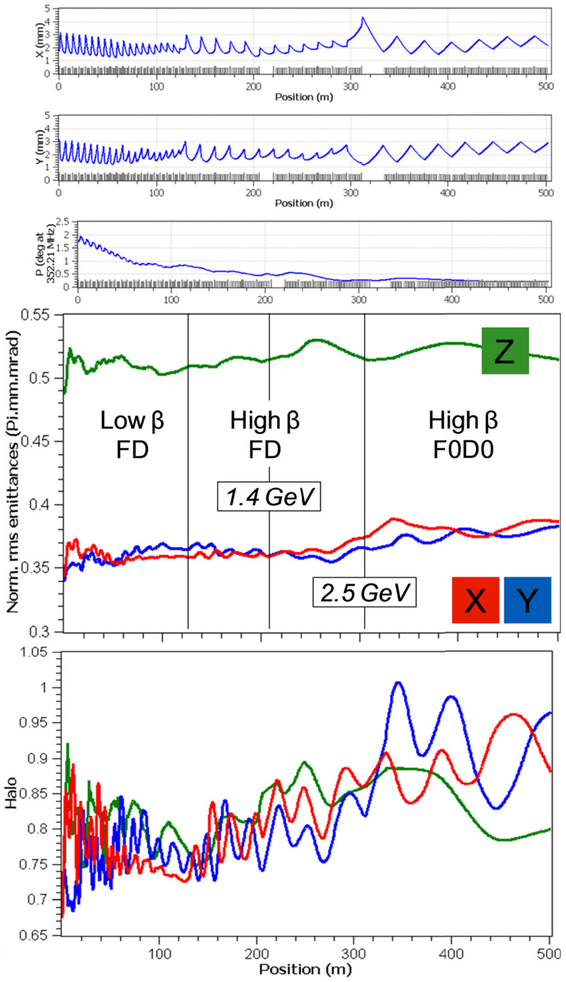

Figure 10: SPL mixed solution beam dynamics results.

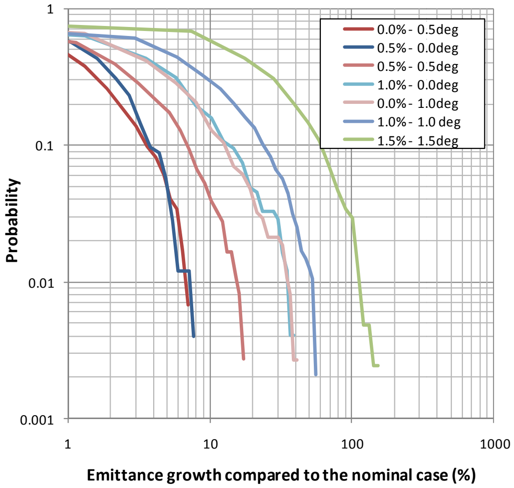

Figure 11: Cumulative probability as function of the uniform random error applied to the single cavities.

CAVITY JITTER SPECIFICATIONS

In order to test the effect of phase and amplitude jitter on the SPL longitudinal beam dynamics (common to all 3 designs), sets of 500 linacs with increasing jitter values were generated, as reported in Figure 11. If the longitudinal emittance increase has to be contained within

10%, 0.5 deg for the phase and 0.5 % for the amplitude is the specification needed for the RF controls.

INTRA-BEAM STRIPPING: AN OUTSTANDING ISSUE

A problem recently arose from the SNS experience is the intra-beam stripping [6]. This phenomenon occurs when two H- are very close in space and have different velocity (relative velocity $\beta > 2\times10^{-4}$). If a Gaussian distribution for both spatial and velocity distribution is assumed and the three planes are decoupled, the resulting fractional loss can be written as

$$-\frac{1}{N}\frac{dN}{ds} \simeq \frac{N\sigma_{\text{stripping}}}{8\pi^2\sigma_x\sigma_y\sigma_s\gamma^2\beta c}\sqrt{\sigma_{v_x}^2+\sigma_{v_y}^2+\sigma_{v_z}^2}\cdot F(\theta_x,\theta_y,\theta_z)$$

where $\sigma_{\text{stripping}} \cong 3.0\times10^{-13}\text{mm}^2$, σ is the rms spatial width of the bunch, σ_v is the rms velocity width and $F(\theta_x,\theta_y,\theta_z)$ is a form factor which is =2/√3 (max) when all 3 velocity spreads are equal. The first evidence of this phenomenon is reported in [7] and its cross section reviewed in [8]. It is important to underline that the fractional loss depends proportionally to the peak current: keeping the product of the peak current and the pulse length constant (i.e. maintaining the beam power), the power loss is proportional to the peak current itself.

In Figure 12 the Fractional Loss is calculated by means of a program supplied by FNAL [9] for all the SPL beam dynamics previously described: since the transverse and longitudinal phase advances are almost the same for the 3 cases, so are the spatial widths and the velocity distributions. This means that the 3 cases are indistinguishable. The resulting Power Loss exceeds the 0.1 W/m limit in many zones and in particular in the achromatic bend transfer line from Linac4, where a strong waist in both transverse and longitudinal plane is achieved. The only way to reduce these losses is to reduce the peak current: if the Low Current scenario is chosen instead of the High Current, the power loss would be reduced by a factor 2, preserving the above limit.

CONCLUSIONS

The SPL beam dynamics was studied based initially on 2 lattices, a doublet and a F0D0. The comparison of the two layouts does not give a preference to any of the designs, but statistical runs on the machines indicate that the F0D0 layout is slightly more robust against the quadrupole misalignments. However, the doublet layout is more flexible on cryo segmentation. For these reasons a third solution based on a doublet architecture below 2.5 GeV and a long F0D0 lattice above has been recently designed. This layout has some advantages to the nominal doublet layout as it uses 12 less quadrupoles. These quadrupoles are shorter (350 mm vs. 450 mm) and they can be normal conducting, much easier to align. The 3 designs offer almost the same performances in terms of beam dynamics, whereas the mixed solution offers a higher reliability due to the higher segmentation.

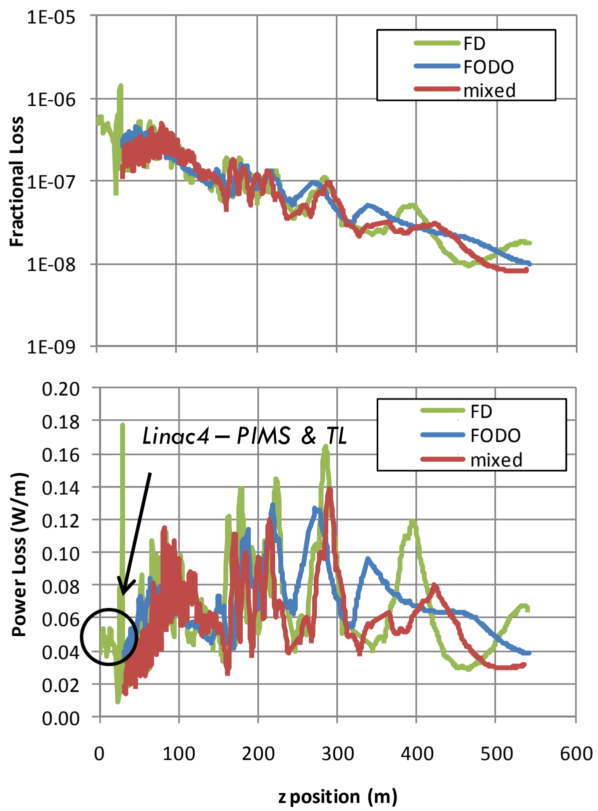

Figure 12: Fractional Loss and Power Loss calculated as function of the position along the linac for the High Current scenario. The data were generated by a program supplied by FNAL [9].

The 3 solutions were obtained keeping into account the low energy branching needed by the Project, and the losses due to magnetic stripping are below 0.1 W/m. The intra-beam stripping has been studied as well and it might be an issue for the SPL High Current scenario.

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