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A 90 - 160/180 MEV SPOKE LIINAC AS AN OPTION FOR THE CERN LINAC4 / SPL

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1 INTRODUCTION

Within the LINAC4 / SPL baseline layout [1], a standard Side Coupled Linac (SCL) of 34.9 metres has been chosen to cover the energy range from 90 MeV up to 180 MeV. This section, that operates at 704.4 MHz (i.e. twice the basic frequency), also corresponds to the very last stage of the LINAC4 accelerator, whose final energy is in fact limited to 160 MeV because of space available at CERN (the 90 – 160 MeV SCL section is in this case 28.1 metres long). As far as SPL is concerned, the 180 MeV SCL directly precedes the 3.5 GeV high-energy linac composed by elliptical superconducting cavities.

A very elegant and promising alternative to this scheme could be to replace this SCL section by superconducting multi-gap spoke cavities section, operating at 352.2 MHz and 4.2K (or 2K). Such a solution could allow to benefit from all the advantages of superconductivity (excellent RF-to-beam efficiency, improved transverse acceptance, high accelerating gradients) while keeping stiff enough mechanical structures, able to sustain the dynamic Lorentz detuning induced by pulsed RF operation. Besides these advantages, it could also offer the opportunity to build at CERN the first linac based on spoke-type cavity technology, and therefore to show the way to all the projects foreseeing to use such a solution (like EURISOL [2] or EUROTRANS [3]), while preparing in the most efficient way the LINAC4 to SPL future superconducting upgrade.

This note proposes a first conceptual design of a 90 MeV – 160 MeV H^- spoke linac suited to the LINAC4 needs, upgradeable to 180 MeV for the SPL.

2 PRELIMINARY DESIGN CHOICES

2.1 Initial beam specifications

The main input beam characteristics are taken at the LINAC4 / SPL CCDTL output, from [1] and [4]:

- ion type: H- with 90MeV energy and 65 mA peak current;
- beam frequency: 352.2 MHz;
- beam phase advance with current: 11°/m (transverse) and 6.3°/m (longitudinal);
- beam emittances: 0.34 π.mm.mrad norm rms (transverse) and 0.185 π.deg.MeV rms (longitudinal).

2.2 Choice of the accelerating structure

From basic considerations on transit time factors, it immediately appears that, because spoke cavities are short structures with a low number of accelerating gaps, only one cavity type is needed to cover the whole energy range 90 – 160 MeV, or even 90 – 180 MeV. This structure will operate at the basic frequency 352.2 MHz, that is straightforward given the inherent small size of spoke cavities. Concerning the number of accelerating gaps, it has been estimated than up to four-gap spoke (i.e. triple-spoke) cavities can be reasonably proposed. This limit is motivated by technological reasons linked with the cavity length and the RF power to be transmitted by the coupler, but it is also derived from the state-of-the-art of multi-spoke technology (see section 3).

Based on these hypotheses, preliminary longitudinal beam dynamics calculations performed using GenLinWin [5] in various configurations (different linac architectures, different number of gaps per cavity, different accelerating gradients, different synchronous phases law, etc.) show that the “optimal” structure is:

- a 352.2 MHz, 4-gap spoke cavity, i.e. a “triple-spoke” structure,
- with an optimal beta of around 0.49.

2.3 Choice of the focusing lattice

Two different focusing schemes have been considered as a starting point of the study: a FDO scheme, using room-temperature standard quadrupoles doublets inserted between the spoke cryomodules, and a FODO scheme, using superconducting quadrupoles located inside the cryostats. After comparison of both solutions via beam dynamics simulations, it is proposed to choose the first FDO solution using warm doublets. The main reasons are the following:

- both solutions show very safe beam behaviors, with respective linac lengths very similar (within less than 3%, see section 4);
- technologically speaking, the use of room-temperature quadrupoles seems far more comfortable than the use of superconducting ones: alignment easier in the warm part, no specific compensation of the fringe fields is required, possibility to easily insert beam diagnostics inside each doublet;
- more generally, compared to a FODO 352.2MHz solution, a FDO 352.2 MHz section seems to be a smoother solution to ensure the transition between the CCDTL section (FODO 352.2 MHz) and the high-energy section (FDO 704.4 MHz).

The architecture of the linac is therefore based on the lattice shown in Figure 1. Distances have been chosen as realistic as possible, and are mainly extrapolated from past engineering studies, and especially from the layout of the SPIRAL-2 high-beta cryomodule [6], the first prototype of which is currently under fabrication. L_{mag} is the quadrupole magnetic length; L_{diag} is the inter-quad length, that can be used for beam diagnostic; L_{valv} is the length between quadrupole and cryostat wall; L_{cav} is the wall-to-wall cavity length; $L_{intercav}$ is the wall-to-wall inter-cav length inside the cryostat, that can be used to insert the cold tuning systems; L_{trans} is the length of the 4K/300K transition. The optimization of the linac architecture is done with the following values: $L_{mag} = 200$ mm, $L_{diag} = 130$ mm, $L_{valv} = 150$ mm, $L_{intercav} = 340$ mm and $L_{trans} = 220$ mm, that leads to a warm part length $L_{300K} = 830$ mm, and to a cryomodule length $L_{4K} = N \times (L_{cav} + 340\text{ mm}) + 100$ mm, where N is the number of cavities per cryostat.

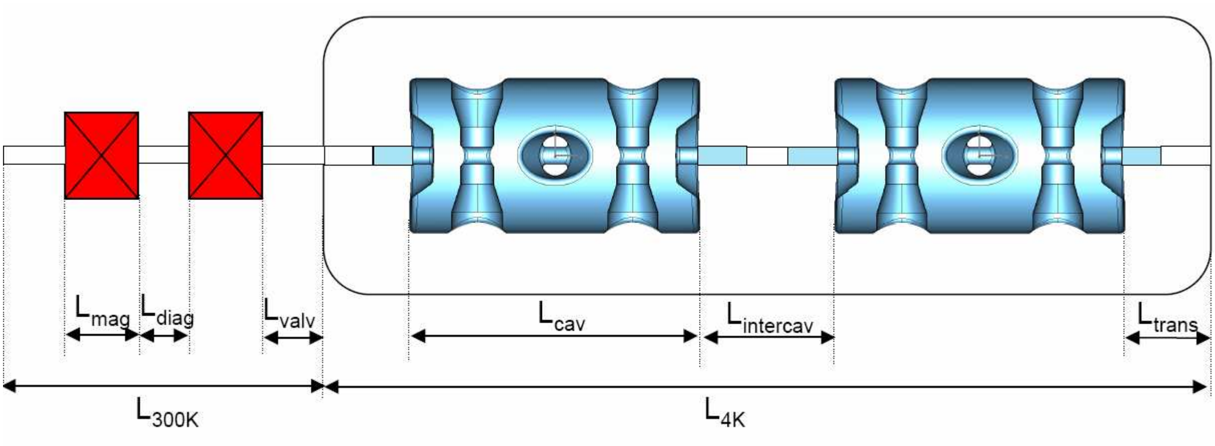

Figure 1: Spoke linac lattice layout

3 TRIPLE-SPOKE CAVITY DESIGN

The accelerating gradient Eacc already includes the transit time factor, is always given at the optimal beta, and is normalized to the accelerating length Lacc, given by:

$L_{acc} = n_{gaps} \times \beta_{optimal}\lambda/2$

3.1 Spoke cavities state-of-the-art

Spoke-type cavities have been studied for more than 15 years but only 10 prototypes exist nowadays! First prototype was studied and tested end of 90's by J.R. Delayen in Argonne National Laboratory (ANL) [7,8]. The main goal of this study was to find alternative superconducting structures to the Alvarez and Slotted Iris ones, developed end of 80's for protons accelerator and whose accelerating gradients were limited, respectively to, 3 and 5 MV/m [9]. This 855 MHz, single-spoke cavity showed, during its first and only test performed, very promising results: Eacc max = 4.3 MV/m at 4.2 K.

Figure 2: First Spoke-type cavity (beta 0.28, 855 MHz) developed at ANL

The second spoke-type prototype was manufactured only 10 years later [10], still in Argonne, by K.W. Shepard and his team in the frame of the RIA project [11]. This second "birth" was strongly linked to the growing interest of many laboratories in developing the so-called superconducting "low and medium beta" resonators within the frame of high power protons and/or ions accelerators projects.

From 2000 to 2005, 9 cavities have been fabricated by 3 laboratories. The ultimate RF performances obtained at 4.2 K are summarized Table 1. One has to note that only 4 laboratories are involved, in 2006, in developing and, above all, prototyping spoke-type cavities, i.e. IPN Orsay (France), ANL and Fermilab (USA), and Forschungszentrum Jülich (Germany).

Table 1: RF performances at 4.2 K of the existing spoke cavities around the world.

Labs	Spoke-type	Geometrical /Optimal betas*	Eacc max @ 4.2 K [MV/m]	Epk [MV/m]	Bpk [mT]	Voltage gain [MV]	Limitation	Ref
IPN Orsay†	Single	0.15/0.20	4.77	32	69	0.81	Quench	[12]
	Single	0.35/0.36	8.15	38	104	2.49	Power	[13,14]
ANL‡	Single	0.29/0.29	8.46	40	106	2.21	Quench	[15,16]
	Single	0.40/0.40	7.57	46	123	2.63	Quench	[17,18]
	Double	0.40/0.40	8.60	40	79	4.40	Quench	[19]
	Triple	0.50/0.50	7.65	28	88	6.65	Quench	[20]
	Triple	0.63/0.63	8.61	34	104	9.40	Quench	[21]
LANL§	Single	0.175/0.21	7.50	38	99	1.34	Quench	[22,23]

As shown in Table 1, a third of the cavities reached 8.5 MV/m and all results are well concentred around 8 MV/m (we exclude the beta 0.15 spoke cavity of Orsay whose bad result seems to be related to a big defect at the surface). Taking as a reference the SNS project whose nominal design operating gradients are ~2/3 of the ultimate RF performances [24], it comes that 6 MV/m seems a quite safe value for the multi-gap spoke gap. This value is going to be used as the nominal design operating gradient for LINAC4.

3.2 Beta 0.49 triple-spoke cavity design

The cavity has been studied with MicroWave Studio software. We took the ANL beta 0.50 Triple-spoke cavity geometry as a reference for designing our model. For instance, we used also elliptical shapes for the spoke bars but, as illustrated Figure 3, we chose a complete different option to design the end-cups. Of course, our cavity is not fully optimized but its RF parameters allow fulfilling the LINAC4 requirements as demonstrated in Section 4. The main RF parameters are summarized Table 2.

** Spoke cavities are often named using the geometrical beta which may differs from the optimal beta value. For example, our beta 0.15 spoke cavity has an optimal beta of 0.20.
† Institut de Physique Nucléaire d'Orsay (France)
‡ Argonne National Laboratory (USA)
§ Los Alamos National Laboratory (USA)

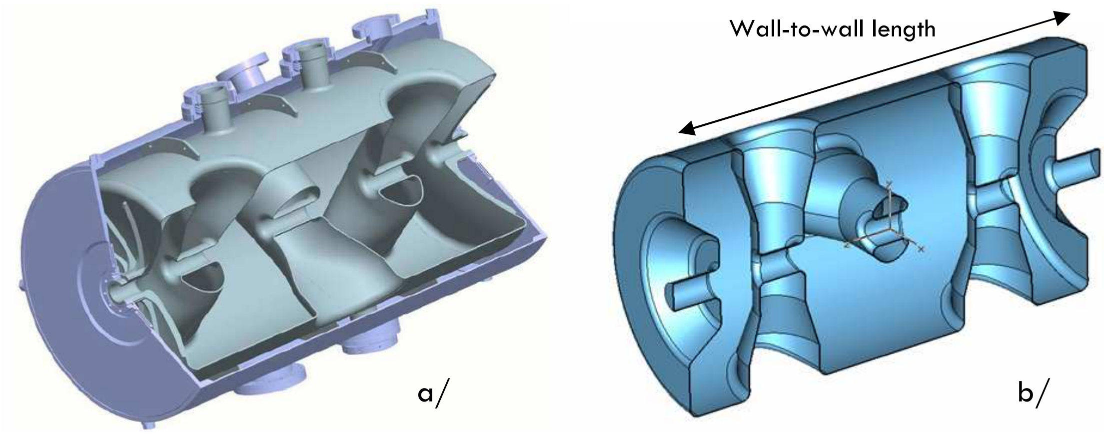

Figure 3: Two Triple-Spoke cavity designs: a/ ANL and b/ IPN Orsay

Table 2: RF parameters of the β0.49 Triple-Spoke cavity

		Comments
Frequency [MHz]	352.08	
Cavity diameter [mm]	459	
Wall-to-wall length [mm]	808	
Accelerating length Lacc [mm]	834	
Beam tube aperture [mm]	50	
Geometrical factor G [Ω]	133	
r/Q [Ω]	579	$=(Eacc.Lacc)^2/\omega U$
Optimal beta β_{opt}	0.49	
For Eacc=1 MV/m		Calculated @ β_{opt}
Epk [MV/m]	4.42	
Bpk [mT]	10.37	
U [J]	0.543	

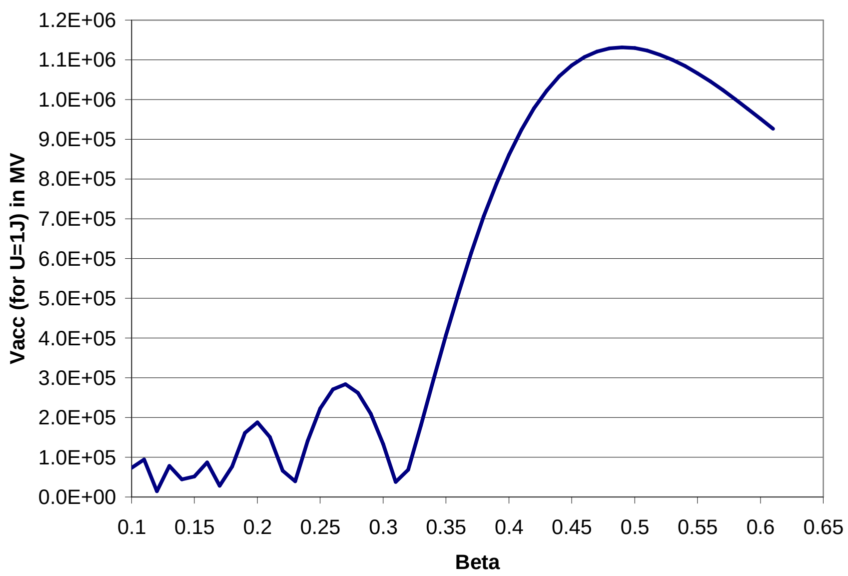

Figure 4: Voltage gain Vacc = f($\beta_{particle}$) for 1 Joule of energy content. NB: Transit Time Factor is included.

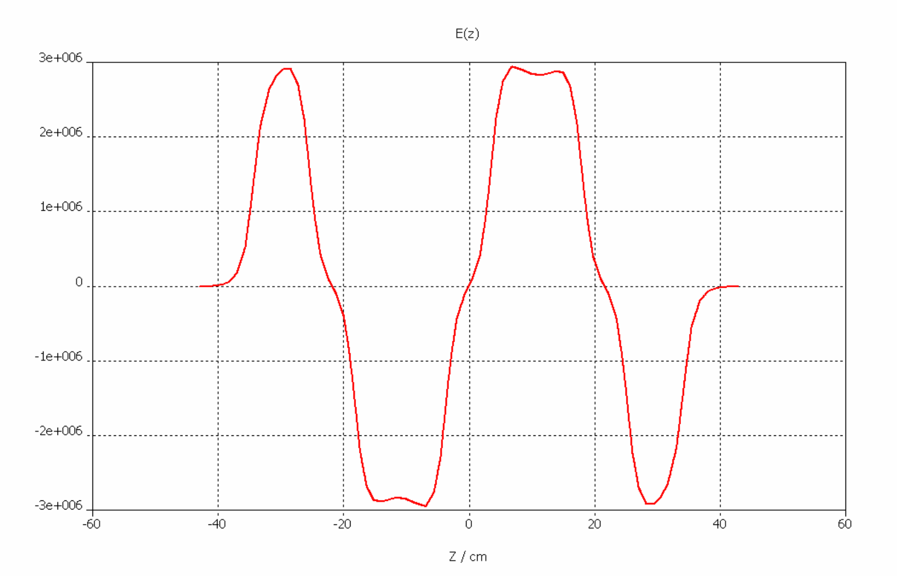

Figure 5: Accelerating field profile on z axis (for 1 Joule).

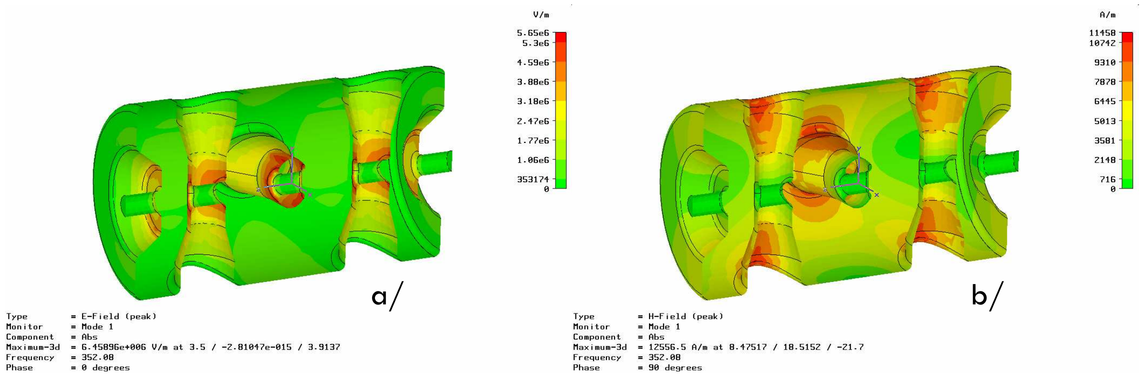

Figure 6: 3D representations of a/ electric and b/ magnetic fields.

4 SPOKE LINAC DESIGN

4.1 Beam dynamics considerations

Beam dynamics rules commonly used in high-intensity linac design have been taken into account in this study. The main constraints, which aim at avoiding any emittance growth and halo formation, are the following.

- The synchronous phase is chosen to provide enough longitudinal acceptance along the spoke linac. It varies from – 20° at 90 MeV up to –15° at 160 MeV. This is a quite safe choice, given that the rms size of the bunch at the CCDTL output is lower than +/- 3°. One could think to even start with a –15° synchronous phase to reach –11° at the high-energy end, under the condition that this gives enough margins to manage the longitudinal errors induced by the RF systems.

- The zero-current phase advances per lattice are always kept below 90° to ensure stability, that is straightforward in the present case. Moreover, the longitudinal phase advances are always kept lower than 80% the transverse ones, but higher than half their values, so as to avoid any resonant collective instabilities that could imply emittance exchange between both planes.

- The phase advances per meter are kept continuous through the linac to decrease the sensitivity to current variations. In particular, these values have been adjusted at the spoke linac input to provide a good matching with the preceding CCDTL structure, leading to a limitation of the accelerating gradients in the first spoke lattice(s), as illustrated in Figure 7.

4.2 Optimized linac architecture

The optimization procedures converge towards a FDO spoke linac using 2 cavities per cryomodule. Its total length is 25.8 metres, and it is composed of 8 cryomodules. Its architecture and operation characteristics are given in Table 3. The quadrupoles gradients have been kept around 10 T/m for technical reasons, and spoke cavities are operated with an accelerating gradient (at optimal beta) of 6 MV/m maximum. This is a very safe value as explained in section 3, since this gradient corresponds to peak fields values in the cavity of respectively E_{pk}=26.5 MV/m and B_{pk}=62 mT.

An interesting characteristic of this solution is precisely that it uses moderate accelerating gradients. Increasing these gradients from 6 MV/m up to 8 MV/m, which doesn't seem unrealistic at all given the state-of-the-art, could allow to easily boost the linac final energy from 160 MeV to 180 MeV, and consequently, to match the future SPL needs while keeping exactly the same accelerator structure and length.

Table 3: Layout of the 90-160/180 MeV FDO spoke linac for LINAC4/SPL

	6 MV/m operation	**8 MV/m operation**
Cavity optimal beta	0.49	
Cavity number of gaps	4	
Cavity aperture	50 mm	
Number of cavities per module	2	
Number of cryomodules	8	
Cryomodule length	2.40 m	
Lattice length	3.23 m	
Total linac length	25.8 m	
Final energy	160.2 MeV	180.7 MeV
Synchronous phase	-20° up to -15°	-20° up to –14°
Maximum B_{pk} in cavities	62 mT	83 mT
RF peak power per cavity*	188 - 315 kW	211 – 421 kW
Quadrupole gradients	9.0 - 10.1 T/m	9.2 – 10.6 T/m

* This is the required beam RF power within the pulse; the associated mean RF power is lower, by a factor of 1/(RF duty cycle).

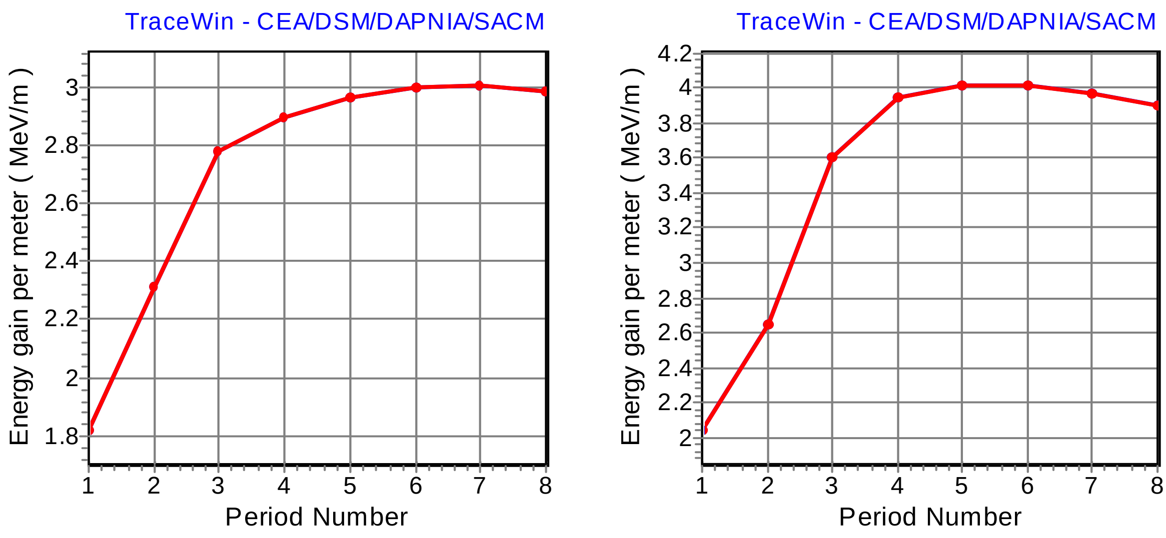

Figure 7: Real estate gradient for 6MV/m (left) and 8 MV/m (right) operations

NB: the optimized linac using a FODO lattice leads to the same total number of cavities (16), and to a total linac length very similar, as already mentioned (25.2 m). The obtained FODO and FDO lattices are compared in Figure 8.

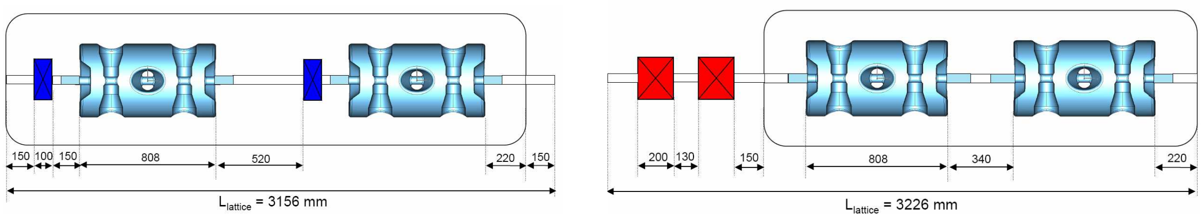

Figure 8: Optimized FODO (left) and FDO (right) spoke lattices

4.3 Beam dynamics simulations

Beam dynamics simulations have been performed using the TraceWin / Partran codes package, developed in CEA Saclay [5]. The calculations include space charge effects (PicNic 3D routine), and multi-particle simulations have been checked using different particle distributions. In every case, the transmission is 100%, no significant emittance growth is observed, and the halo parameter stays stable.

The results presented here after have been obtained using a particle distribution derived from the LINAC4 end-to-end simulations at the CCDTL output [4]. The input* and output beam distributions are shown in Figure 10. Beam envelopes at $\sqrt{8}\,\sigma$ are shown in Figure 9, phase advances in Figure 11, and halo parameters in Figure 12.

Table 4: Beam dynamics results for the 90 – 160/180 MeV FDO spoke linac (no errors)

	6 MV/m operation	**8 MV/m operation**
Beam losses	< 1.E-5	< 1.E-5
Rms norm X emittance growth	- 0.3 %	- 0.6 %
Rms norm Y emittance growth	+ 1.2 %	+ 1.2 %
Rms norm Z emittance growth	+ 6.2 %	+ 5.9 %
Aperture to rms beam size ratio	≥ 10	≥ 10

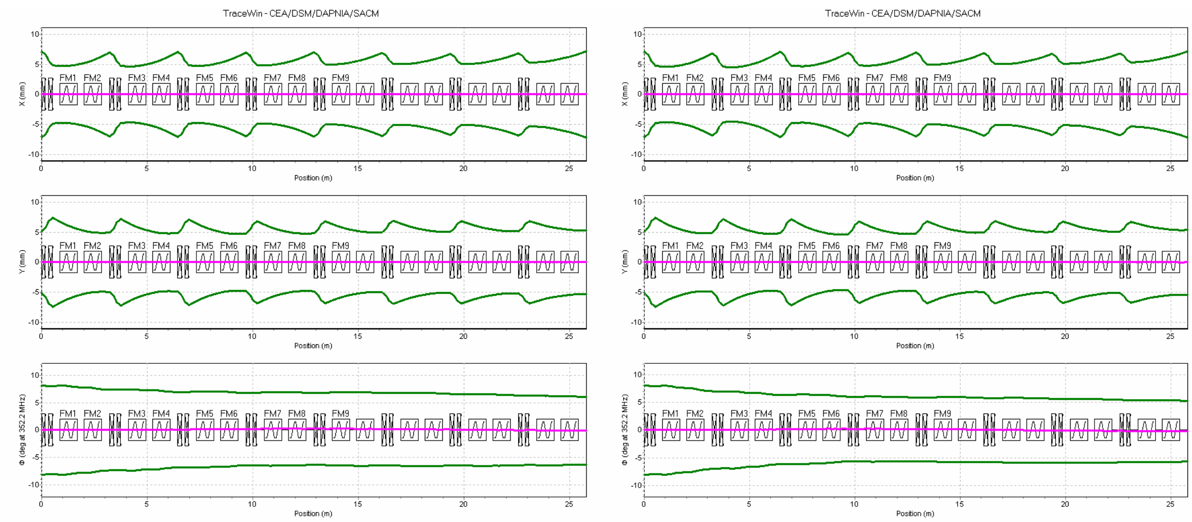

Figure 9: 99% beam envelopes ($\sqrt{8}$ times the rms size) for 6 MV/m (left) and 8 MV/m (right) operations

* The input distribution is scaled from the CCDTL output one to recover the matched Twiss parameters; a "complete" end-to-end simulation would consist in fully matching the CCDTL-spoke transition with slight adjustments of gradients and phases; this should be straightforward since the continuity of the phase advances per meter is already reached.

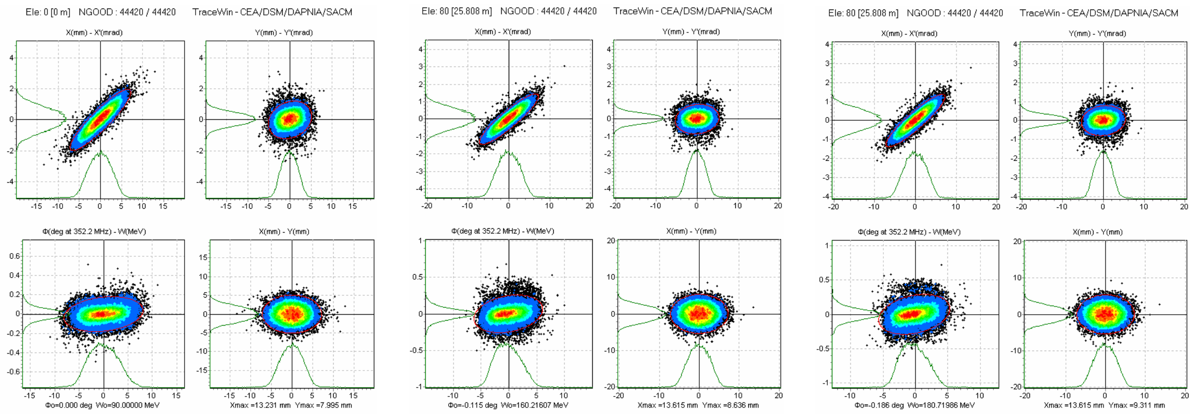

Figure 10: Beam distributions at the 90 MeV input (left), and at the high-energy output for 6 MV/m (centre) and 8 MV/m (right) operations

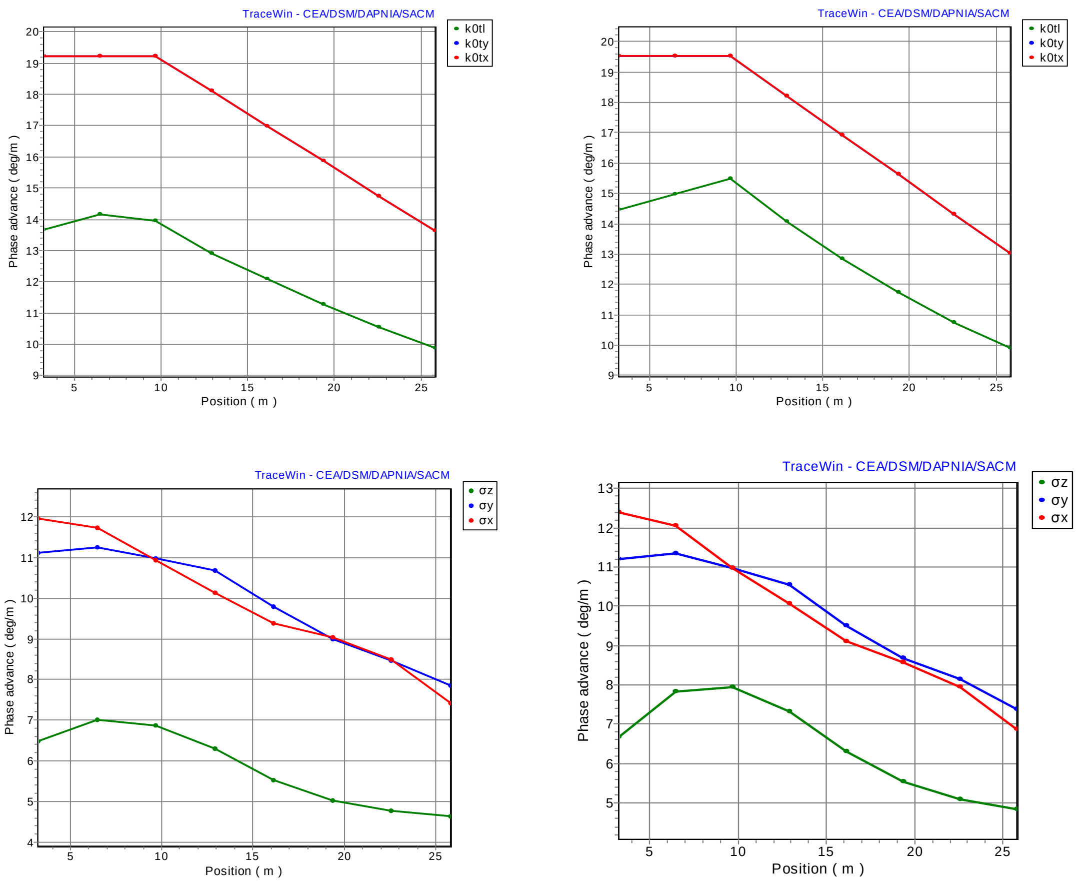

Figure 11: Evolution of phase advances per meter with zero-current (up) & with 65 mA current (down), for 6 MV/m (left) & 8 MV/m (right) operations

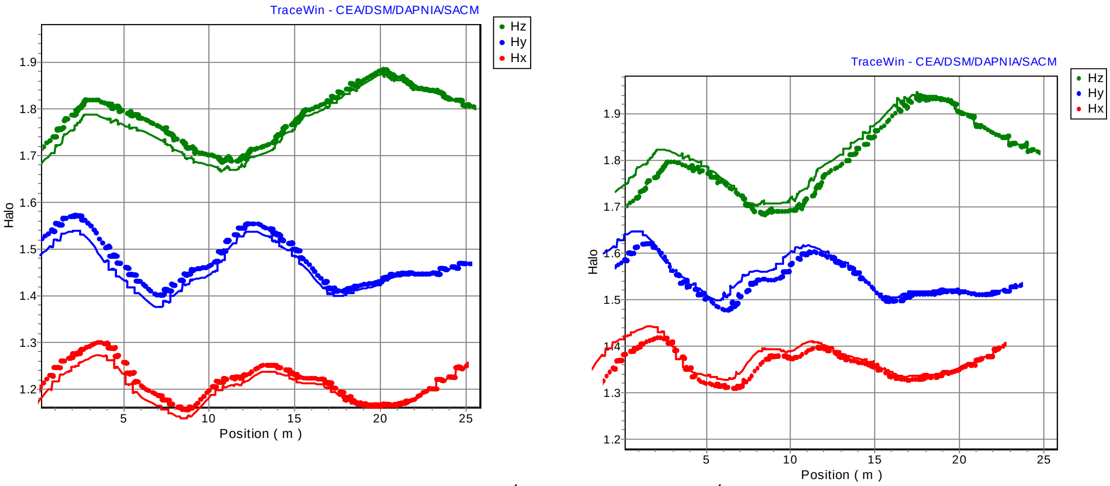

Figure 12: Halo parameters for 6 MV/m (left) & 8 MV/m (right) operations

5 CONCLUSION

A superconducting linac based on the use of 352.2 MHz triple-spoke cavities is proposed as an alternative to the room-temperature SCL for the LINAC4 / SPL project.

This linac is 25.8 metres long and is composed of 16 cavities regrouped in 8 cryostats. It uses a classical FDO focusing scheme with classical warm quadrupole doublets. For a conservative 6 MV/m operation of the cavities, the final energy meets the LINAC4 needs (160 MeV), but can also reach 180 MeV if a more ambitious 8 MV/m operation point is chosen.

This preliminary study shows that such a scheme seems very competitive compared to a solution based on a SCL: slightly better real estate gradients, lower RF power consumption, larger transverse (and longitudinal) acceptance. On the other hand, the spoke technology is not yet fully operational, and more R&D is required to validate such a solution.

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