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SUPERCONDUCTING SPOKE LINAC DESIGN AS AN ALTERNATIVE OPTION FOR THE CERN LINAC4 HIGH ENERGY PART

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Abstract

A standard normal-conducting Side Coupled Linac (SCL) has been chosen as a mainline solution for the CERN LINAC4/SPL to accelerate the beam from 90-160/180 MeV. This type of structure is well known and operates at twice the basic frequency (704.4 MHz). Two alternative superconducting solutions with elliptical and triple-spoke cavities have been studied for this energy range.

The present note summarizes the beam dynamics calculations in the superconducting triple-spoke linac section analyzing advantages/disadvantages.

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1. Introduction

A standard normal-conducting Side Coupled Linac (SCL) has been chosen at twice the basic frequency (2x352.2 MHz) as a mainline for the CERN Linac4/SPL [1] to accelerate the beam from 90 MeV up to its final energy of 160 MeV within 27.8 m in case of Linac4 and in case where Linac4 serves as an injector into the SPL the output energy is 180 MeV and the corresponding length is 34.4 m. This type of structure is well known and has been successfully used in many projects worldwide including the TERA project at CERN. Transition to a higher frequency provides higher shunt impedance and reduced dimensions with respect to the previous structures.

Two superconducting structures with elliptical and spoke loaded cavities are being considered as alternative options for the CERN Linac4 high energy section (90-160 MeV). This note summarizes the beam dynamics design of a linac section based on superconducting triple-spoke cavities operating at 352.2 MHz and 4.2 K.

2. Triple-spoke cavities developed at FZJ

A superconducting triple-spoke (four gaps) cavity (Fig.1) operating at 352.2 MHz has been developed at the Research Centre of Julich (FZJ, Germany) [2] in the framework of the European project of a High Intensity Pulsed Proton Injector (HIPPI). This type of structure is a spoke loaded TEM-mode cavity [3], where adjacent spokes are of opposite polarity and the cell length is $\beta\lambda/2$. In such a cavity transverse dimensions scale as ~0.5λ, that for a given transverse dimensions allows to operate at half the frequency of the TM-mode structure.

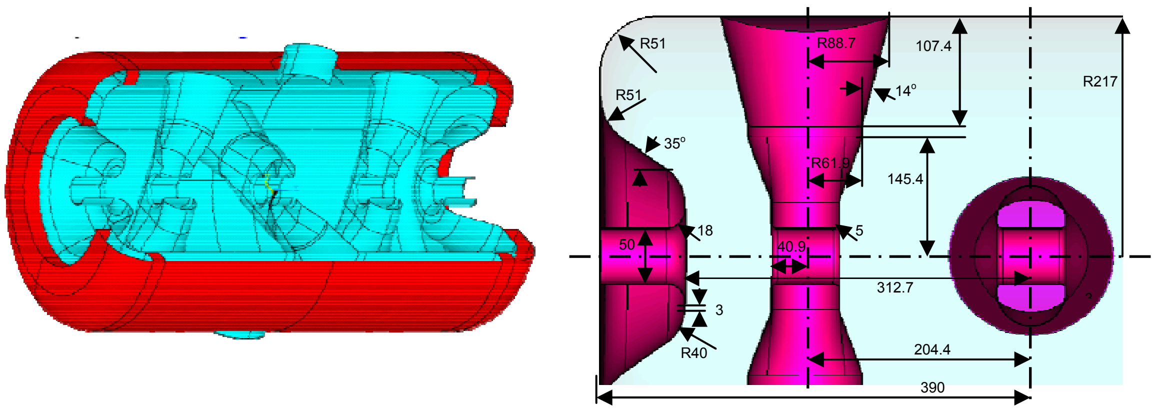

Fig. 1. Triple-spoke cavity at FZJ: artistic view (right), half cavity geometry (left), dimensions in mm

Operation at 352.2 MHz versus 704.4 MHz entails several advantages with respect to TM-mode structures, such as larger longitudinal acceptance, high operation temperature of 4.2 K, less number of cells for a given cavity length and consequently a larger velocity acceptance and voltage gain. The large velocity acceptance allows to cover the energy range of 90-160 MeV (up to 180 MeV) with just one type of cavity with β_g=0.48.

The main parameters of the triple-spoke cavity developed at FZJ are summarized in Table 1 and the field pattern on axis normalized to the maximum field is shown in Fig. 2.

Table 1. Main parameters of the triple-spoke cavity

Frequency	352.9	MHz
Geometric beta	0.48	
R aperture	25	mm
R cavity	217	mm
L cavity	780	mm
$G=Q*R_s$	92	Ω
E peak	35.34	MV/m
B peak	80	mT
Voltage gain	7.28	MV

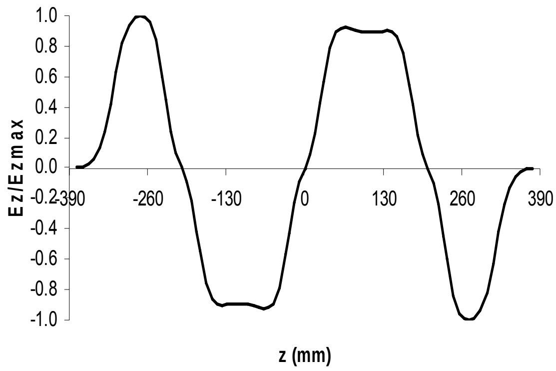

Fig. 2. Electric field pattern on axis

3. Spoke linac design

3.1. Linac architecture

Possible layouts of the linac focusing period have been analyzed, considering different transverse focusing schemes (FODO or FDO) with 'warm' or 'cold' quadrupoles and different number of cavities per cryomodule. The focusing period length has been chosen such as to provide a zero current longitudinal phase advance per period that would satisfy the condition $0.5k_{0t}<k_{0z}<0.8k_{0t}$. This choice avoids space-charge induced emittance exchange between longitudinal and transverse planes. Imposing the condition of stable motion on the transverse phase advance per period (k_{0t}<90 deg) we find that the longitudinal phase advance per period should be less than 72 deg. The choice of the distances in the layout has been based on the experience and discussions with our colleague from IPN Orsay [4]. The architecture of the superconducting linac period discussed in this note comprises of 'warm' quadrupoles with FDO focusing scheme and two triple-spoke cavities per cryomodule (Fig.3). Each cavity is assumed to be powered independently.

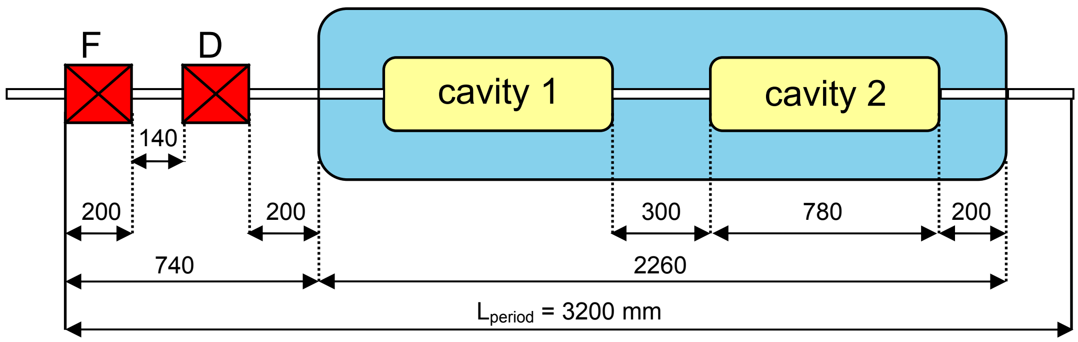

Fig. 3. The layout of the focusing period (dimensions in mm)

3.2. Beam dynamics

To calculate the effective voltage, transit-time factor and synchronous phase in each cavity, field integration on axis for a test particle has been done using following expressions:

$$\Delta W = q\int E(0,z)\cos(2\pi z/\beta\lambda + \phi)dz = V_0 T\cos(\phi_s),$$

$$W = W_0 + \Delta W,$$

$$\phi = \phi_0 + \Delta\phi,$$

$$T = \Delta W_{\max}/V_0,$$

$$V_{eff} = V_0 T,$$

where ΔW is the energy gain, $E(0,z)$ is the electric field on axis as from Fig. 2, V_0 is the nominal voltage across the cavity, ϕ_s is the synchronous phase of the cavity and the transit-time factor T is calculated at the maximum energy gain per cavity $\Delta W_{\max}$ i.e. when $\cos(\phi_s) = 1$.

Up to the present there is not an operating linac with triple-spoke cavities in the world and we lack sufficient experimental data and experience on how reliably and routinely can be achieved and maintained a certain electric field gradient in such cavities. Proceeding from aforesaid facts, we have simulated two similar linac sections based on the same focusing lattice but with a different voltage gain (or electric field gradient) across the cavity. The voltage across the cavity is $V_0 = 7.28$ MV (E_0=8.9 MV/m*) in the first version and $V_0 = 6$ MV (E_0=7.34 MV/m*) in the second version. Beam dynamics design has been done fulfilling the following requirements:

- continuity of the phase advance per meter between the sections
- zero current phase advance per period k_{0t}< 90 deg to avoid instabilities
- phase advance ratio of $0.5<k_z/k_t<0.8$ to avoid emittance exchange
- provide sufficient phase advance (focusing) to limit the emittance growth

Multi-particle simulation code TraceWin (CEA, Saclay) [5] with a 3D space-charge routine has been used for beam dynamics calculations. Input beam parameters and main results of simulations are summarized in Table 2 and 3 respectively. Table 3 includes corresponding parameters of the mainline SCL section for sake of comparison. More details on beam dynamics can be found in Appendix.

Table 2. Input beam parameters

no. of particles	50000	generated
distribution	Gaussian	truncated at 3σ
ε_t rms, normalized	0.34	π mm-mrad
ε_z rms @ 352.2 MHz	0.185	π deg-MeV
peak current	65	mA

* the electric field gradient E_0 is normalized to the effective length of L_{eff}=Nβλ/2=817.6 mm, where N is the number of gaps

Table 3. Results of simulations

	Spoke Version 1	Spoke Version 2	SCL	
frequency	352.2	352.2	704.4	MHz
V_0	7.28	6	-	MV
synchronous phase	-20	-20	-20	deg
W_{out}	163.9	159.8	163.4	MeV
no. of cavities/tanks	14	16	20	
no. of cryomodules	7	8	-	
total length	22.4	25.6	28.7	m
ε_x growth	2.2	2.3	2.3	%
ε_y growth	3.5	3.5	4.7	%
ε_z growth	4.4	5.3	3.1	%
$r_{beam, max}/r_{aperture}$	0.315	0.319	0.505	
transmission	100	100	100	%

The main advantages of the superconducting triple-spoke linac section with respect to the SCL are a shorter length, a larger transverse and longitudinal (due to a lower operation RF frequency and a higher electric field) acceptance and low RF power consumption/RF losses. Nevertheless, from the beam dynamics point of view there are no strong arguments in favor/against either of the structures as they are both satisfactory as far as beam quality is concerned. Other issues such as availability and reliability of the technology, construction and operation costs as well as sensitivity to errors have to be considered in making a choice.

4. Conclusion

A linac section with superconducting triple-spoke cavities operating at 352.2 MHz and 4.2 K has been studied as an alternative option for the CERN Linac4/SPL front-end. It provides a number of good properties and the advantages of the superconducting technology. However, from the beam dynamics point of view there is no particular advantage/disadvantage in choosing one structure or the other except relatively smaller transverse and longitudinal acceptance in case of the SCL that is nevertheless sufficient.

The results of beam dynamics simulations suggest that the choice has to be based on the analysis of construction and operation costs, sensitivity to errors and taking into account that reliable routine operation is an important concern for the Linac4. The SCL is still considered as the mainline structure for the CERN Linac4 project.

5. Acknowledgements

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6. References

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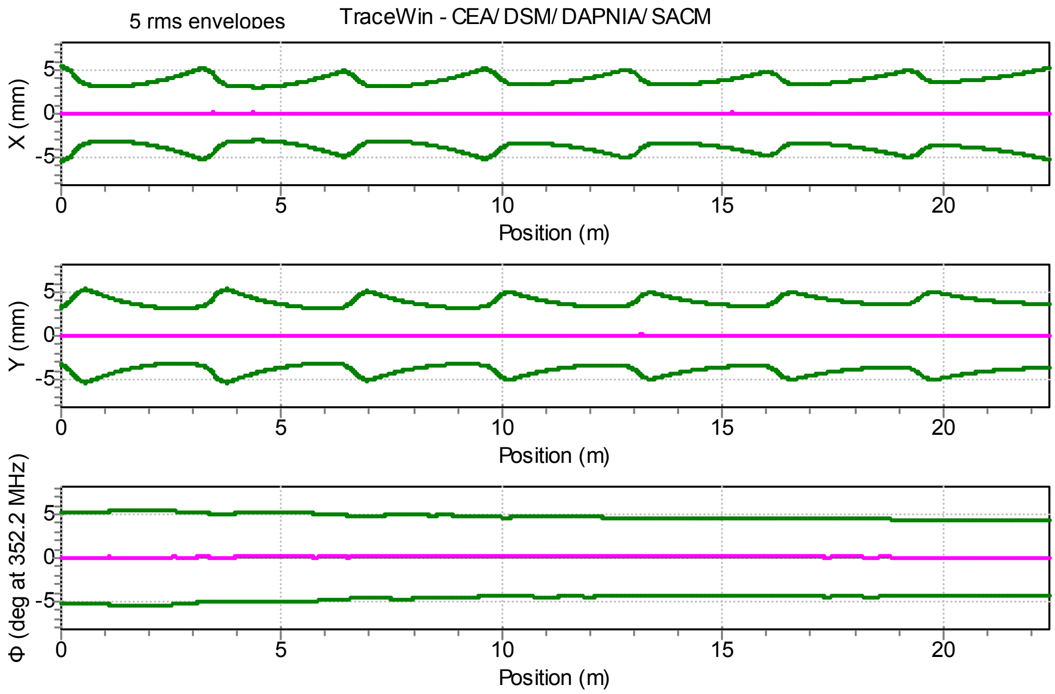
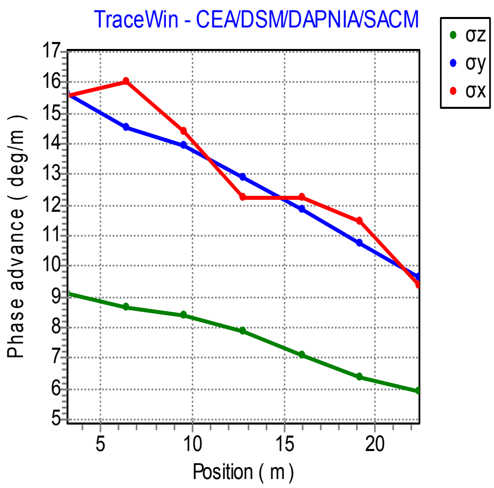
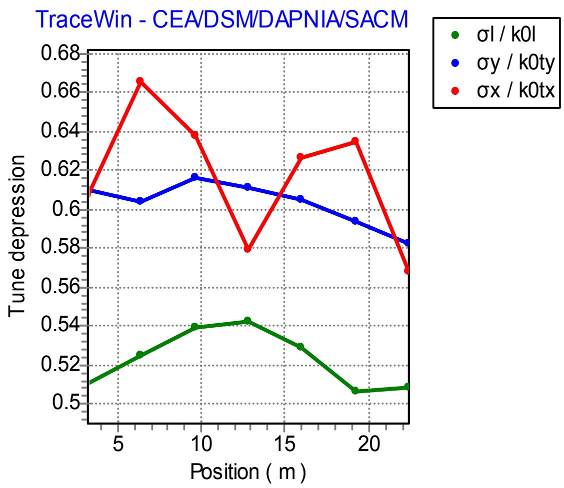
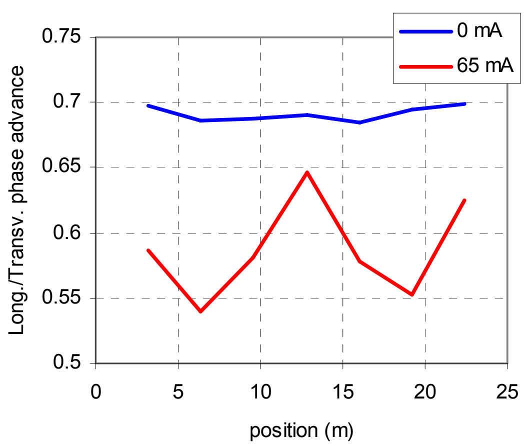
7. Appendix

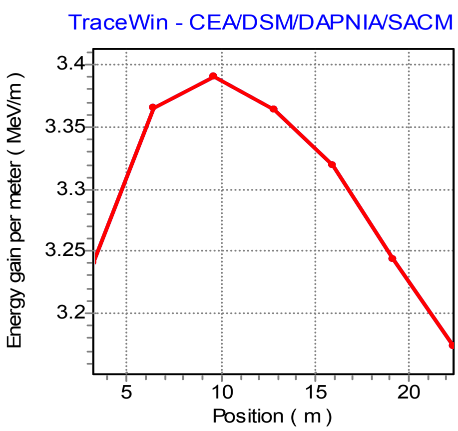
7.1. Beam dynamics in triple-spoke linac version 1











7.2. Beam dynamics in triple-spoke linac version 2