STUDY OF SUPERCONDUCTING ACCELERATING STRUCTURES FOR MEGAWATT PROTON DRIVER LINAC

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Abstract

The preliminary design of megawatt level proton accelerator-driver is carrying out by collaboration between Russian scientific centers MEPhI, ITEP, Kurchatov Institute. This project was supported in 2013 by the Ministry of Science and Education of Russia. The linac general layout includes SC Spoke-cavities at middle energy range and elliptical cavity at high energy one. The usage of QWR and/or HWR at 10-30 MeV was also discussed. Due to electrodynamics models of all structures types were designed and the electrodynamics characteristics were studied. QWR, HWQ and Spoke-cavities were proposed to operate on 324 MHz and elliptical cavities on 972 MHz. The main electrodynamics simulation results will present in report. The multipactor study results will also discussed.

INTRODUCTION

The study of high-power proton linac for 1.0 GeV was performed by collaboration of MEPhI, ITEP and Kurchatov institute researchers in 2013. Such linac was developed to understand the possibility of accelerator driven system (ADS) design in Russia.

The linac will consist of an RFQ, RF focusing sections and SC modular configuration sections. A number of QWR and HWR were also studied for 20-50 MeV energy range as an alternative of RF focusing sections. The SC part of developed linac can include QWR, HWR, Spoke-cavities and elliptical cavities due to. Medium energy cavities will operate on 324 MHz and elliptical one on 972 MHz [1, 2].

The results of noted above structures models design will discuss bellow. All simulations have been performed using CST Microwave Studio [3].

QWR AND HWR CAVITIES

The aim of the QWR and HWR optimization is to increase the beam energy gain and to have optimal power consumption at the same time. The beam energy gain is defined by the time-factor and the accelerating gradient. As it follows from the time-factor T definition, its maximum value is gained when the gap length is minimized. But the gap length decrease leads to higher gap capacity and, therefore, to lower shunt impedance, which is another important optimization target. The optimal value of the accelerating gap length g to the period length d equal to 1/3 could be taken [4], since its further decrease slightly improves the time-factor and the optimal particle velocity is only by 3 % higher than the optimal geometrical velocity β_g. Another QWR feature that affects the beam energy gain is the accelerating gradient. The accelerating gradient is estimated by the ratio B_p/E_a, where B_p is the magnetic field pick value and E_a is the accelerating field amplitude. Therefore, the ratio must be minimized for higher gradients. B_p/E_a depends on the inner and outer QWR conductor radii ratio R_i/R_o. The solution of the equation $\ln(R_o / R_i) = 1$ gives the optimal value of R_i/R_o [4] and it is equal to 0.36. The QWR effective shunt impedance R_a/Q_o defines how effectively RF field energy converts to the accelerating gradient. According to the "sphere in cylinder" approach offered in [5] the ratio R_i/R_o=0.12 yields the maximum shunt impedance (see Fig. 1). High shunt impedance and relatively low accelerating gradient results in a resonator with optimal power consumption, while a low B_p/E_a parameter resonator has an extreme accelerating gradient. When simulating a 324MHz QWR the value R_i/R_o=0.3 is chosen in favour of a higher accelerating gradient. Geometrical and RF characteristics of the QWR are presented in Table 1.

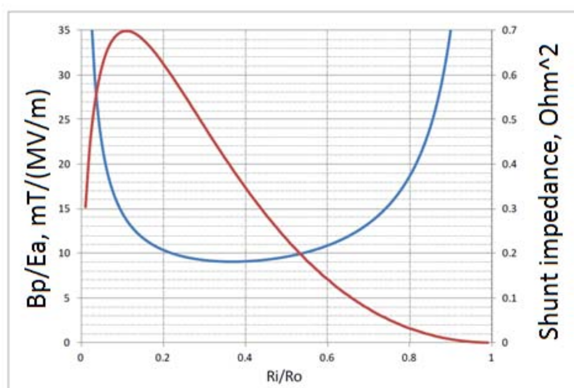

Figure 1: B_p/E_a and shunt impedance in QWR versus R_i/R_o.

The same analysis was performed for HWR also. To develop the electrodynamics model and determine the approximate geometric parameters of the HWR we assume the average value of the relative phase velocity β=0.25. The shape of the resonator should be optimized to minimize ratios B_p/E_a and E_p/E_a and get the maximum value of R_a/Q_o. Characteristics of the HWR are also presented in Table 1.

ISBN 978-3-95450-170-0

Table 1: Geometrical and RF characteristics of the QWR and HWR.

Parameter	QWR	HWR
f, MHz	324	324
β_g	0.25	0.25
E_p/E_a	6	2.3
B_p/E_a, mT/(MV/m)	10	5.1
R_a/Q_o, Ohm	608	140
Cavity height, mm	266	338
Central conductor length, mm	184	-
R_i, mm	30	60
R_o, mm	100	320
g, mm	39	60
d, mm	117	150

SPOKE-CAVITIES

Main geometrical parameters used for RF design and optimization of spoke cavities are shown in Figure 2. The main goal of the RF design is to provide a lower heat load and a higher accelerating gradient, which are determined by a higher R_a/Q_0. Also peak surface fields should be minimized.

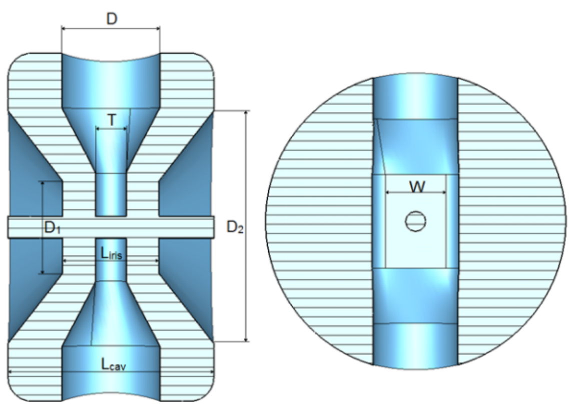

Figure 2: Cross-section of the spoke cavity with the geometrical parameters.

Accelerating electric field E_a is defined as:

$$E_a = \Delta W(\beta_0)/\beta_0\lambda\,. \quad (1)$$

where $\Delta W(\beta_0)$ is the energy gain at the optimal velocity and λ is the free-space wavelength of the accelerating mode. In our case β=0.2 and the operating frequency is f=324 MHz. The length from iris to iris is $2/3\beta\lambda$. The diameter of the cavity is of order of $\lambda/2$. To achieve a lower peak electric field the spoke width W and gap ratio T/L_{iris} were optimized. Simulation results are presenter in Figure 3.

The diameter of the spoke base D is optimized to get a lower B_p/E_a. The variation of B_p/E_a and R_a/Q_o is depicted in Figure 4. Also parameters D_1 and D_2 should be optimized. The diameter of small bottom D_2 is more sensitive to B_p/E_a, while the diameter of large bottom D_1 is more sencitive to B_p/E_a. Moreover blend edges will help to decrease the peak surface fields. The Geometric and RF properties of the spoke cavity are given in Table 2.

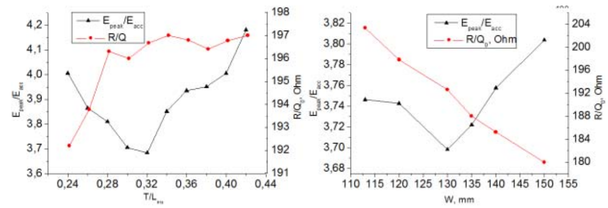

Figure 3: E_p/E_a (black) and R_a/Q_o (red) versus T/L_{iris} and W.

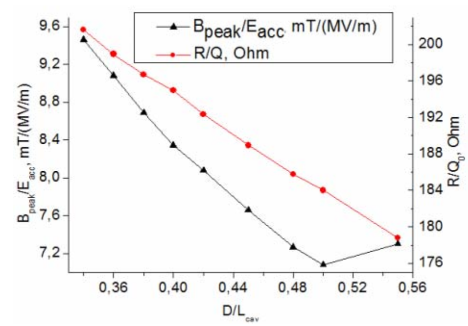

Figure 4: B_p/E_a (black) and R_a/Q_o (red) versus $D/L_{cav.}$

Table 2: Geometric and RF properties of the spoke cavity.

Parameter	Value
f, MHz	324
β_g	0.2
E_p/E_a	3.86
B_p/E_a, mT/(MW/m)	6.76
R_a/Q_o, Ohm	192
L_{iris}, mm	123.4
R_{cav}, mm	225
L_{cav}, mm	263.4

ELLIPTICAL CAVITIES

Multi-cell cavities based on modified disk-loaded waveguide shape are widely used for particle acceleration in 0.5-1.0c velocity range. Cavities with TESLA-shape design are the only known choice for superconducting accelerators dedicated for fault free operation. Wide experience gained by laboratories

First question presented by the cavity development is the cell number. It is known that multicell cavities require less power couplers and give rise to active length because of drift tubes number reduction. Contrariwise cavities of just a few cells typically show better performance because of easier quality control on material and production [6]. Usually cavities of 5 to 9 cells are used, but 7 to 9 cell ones are common for electron while 5 to 6 cells - for proton accelerators. SNS project using 5 cell cavities is the example of good performance facility. The beam dynamics simulation also shows that 5 cell cavities are optimal for high rate of the energy gain and 100 % current transmission [1]. This 5-cell design was chosen as basis for this study (Fig. 5).

In order to provide acceleration in whole energy range needed for ADS systems three phase velocity cavities were considered, namely 0.6, 0.7 and 0.8c. Operating frequency of all three cavities operated on π mode were

ISBN 978-3-95450-170-0

tuned to 972.6 MHz. Field flatness better than 99.3% was reached by end cells modification. Cavity electrodynamical characteristics are summarized in Table 3. Cavity for 0.6*c* has maximal surface field overvoltage factor due to lower period length. Surface magnetic field does not limit cavity performance because much lower than known limits.

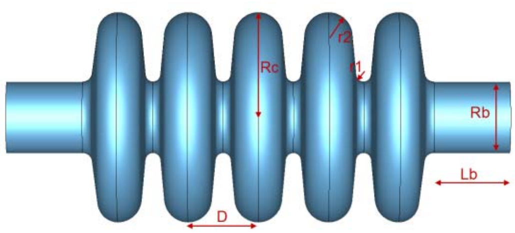

Figure 5: Five cell elliptical accelerating cavity.

Table 3: Electrodynamical parameters of elliptical cavity.

Parameter	β=0.6	β=0.7	β=0.8
coupling, %	3.53	2.35	1.57
$r_{sh\ eff}$, MOhm/m	5.39	7.79	10.44
r_{sh}, MOhm	12.5	16.24	20.84
Q	$1.17{\cdot}10^{10}$	$1.23{\cdot}10^{10}$	$1.79{\cdot}10^{10}$
E_{max}/E_{acc}	3.92	3.06	2.38
H_{max}/E_{acc}	0.0012	0.0011	0.001

Dispersion curves on fundamental mode being close to each other are presented in Figure 6.

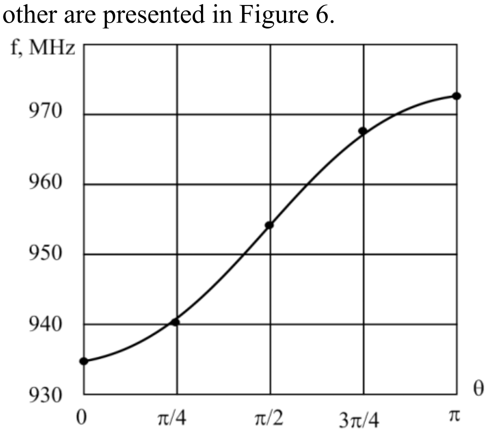

Figure 6: Dispersion curve for five cell elliptical accelerating cavity.

MULTIPACTOR SIMULATIONS

The results of calculation multipactor for elliptic superconducting accelerating cavities with phase velocity β_{ph}=0.6, 0.7, 0.8 are shown in Figure 7. As it could be seen from figure structures for β_{ph}=0.6 and 0.7 show very close accelerating field strength ranges with stable trajectories of 1st and 2nd order observed. They are equal to 0.86–3.1 MeV/m and 1.05–3.8 MeV/m correspondingly. But the structure for β_{ph}=0.8 features stable trajectories maintain up to 6 MeV/m. Electrons hitting surface have an energy of 180 eV at 4 MeV/m.

Geometry modification with flattened equator area or small hump added is known remedy for this kind of trajectories suppression [7]. But this solution demands special research on modified cavity electrodynamical parameters to be done.

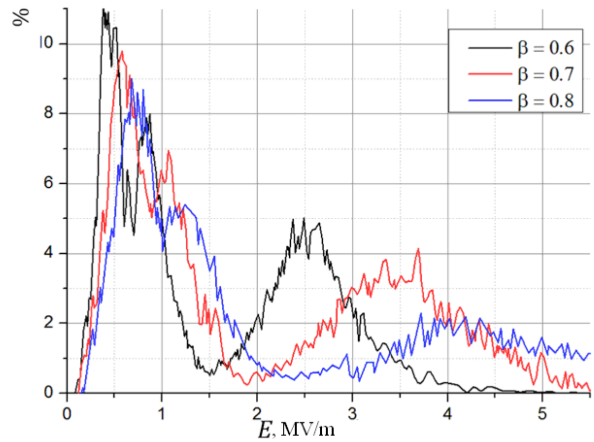

Figure 7: Particle number growth rate vs. field strength dependence

CONCLUSION

Results of electrodynamics models development and study and cavities design for superconducting part of 1 GeV linac were discussed. The tuned models of 324 MHz QWR, HWR and Spoke-cavities and 972 MHz 5 cell elliptical cavities were presented.

ACKNOWLEDGMENT

This work is supported in part by the Ministry of Science and Education of Russian Federation under contract No. 14.516.11.0084.

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