RF CAVITY DESIGN FOR A LOW-COST 1 MeV PROTON SOURCE

D. Soriano Guillen*, R. Seviour, University of Huddersfield, Huddersfield, UK.
S. Hunt, Alceli Ltd, MediCity Scotland, Newhouse, UK.

Abstract

In this paper we present the design for a low-cost RF cavity capable of accelerating protons from 100 keV to 1 MeV. The system is designed to meet the specifications from the proposed Alceli LTD medical proton therapy linac, to deliver a 1 nA proton beam current with a 1 kHz repetition rate.

We present a design of an RF normal conducting (NC) re-entrant Cu cavity operating at 40 MHz consisting of a coupled two cavity system, both driven by a single Marx generator. The choice of such a low operating frequency for the cavity system enables us to use a relatively low-cost cost Marx Generator as the RF source. Marx generators work in a similar fashion to a Cockcroft-Walton accelerator (without the expensive components), creating a high-voltage pulse by charging a number of capacitors relatively slowly in parallel, then rapidly discharging in series, via spark gaps. Marx generators can deliver 2.5 GW, 1 ns pulses, with rise times of 200 ps, and (relatively) low jitter.

INTRODUCTION

The use of protons for cancer treatment was first proposed in the 1940's, and put into practise on an experimental scale in the 1950's, with the first dedicated hospital based facility was built, at Loma Linda USA in the 1990s. Since then, more than 60 facilities have come on line or are under construction, and more than 100 000 patients have been treated.

Proton therapy (PT) is the use of protons (rather than X-ray or gamma radiation) for the radiological treatment of cancer. There are strong advantages over other types of treatment for certain cancers, such as brain tumours, where current 5 year survival rates are very low ($\sim$ 20%). PT can also reduce or eliminate the need for chemotherapy with its associated devastating side-effects, and in some cases (such as eye cancers and prostate cancer) provide a cure without the loss of function (loss of sight, impotence) caused by surgery. The advantages of proton therapy have been known for a long time, but it is still not widely used, in part due to the previously high cost of building the large and complex particle accelerators necessary. The market for PT machines now has an annual value of $\$1B$ (for 10-15 machines a year), which is rapidly rising, with only 70 machines currently deployed, and with a minimum of 800 new machines needed over the next 20 years.

Alceli Ltd are in the process of designing a relatively cheap commercial, 200 MeV, 1 kHz rep-rate, 1 nA average, 200 MHz LINAC for PT. In this paper we focus on the the 1 MeV proton source RF cavity design. The system consists of an off-the-shelf pulsed ion Source [1], with electrostatic acceleration system to 100 keV. Given the frequency, rep-rate and beam current we have been investigating the use of an RF acceleration scheme based around a Marx generator and RF cavity to take the beam from 100 keV to 1 MeV. The use of a Marx generator with RF Cavity offers the potential to be substantial cheaper than conventional options such as an RFQ. The Marx generator [2] is basically a voltage multiplier working on the principle of charging a set of capacitors in parallel, then discharging in series, creating a high-voltage pulse from a low-voltage supply. The basic circuit is similar to a Cockcroft-Walton Accelerator (without the expensive diodes), using a spark gap to control the breakdown voltage. Modern Marx generators are commercial available, see for example APELC [3], capable of generating, low-jitter, 100's of MW peak power, 10's MHz pulses with rep-rates in excess of 1 kHz [4]. The key issue that has limited the application of Marx generators to particle accelerator technologies is the relatively low max. frequency and rep-rates. Although for the Alceli system the Marx generator is a feasible option. In this paper we focus on the design and optimisation of the RF cavities, the basic design is focused around a NC reentrant Cu cavity operating at 40 MHz.

* dario.soriano.guillen@gmail.com

DESIGN

In order to design the cavity and optimise performance the well known numerical simulation code SuperFish [5] was used. SuperFish solves the differential form of Maxwell's equations, with an irregular triangular mesh, to calculate 2D and axisymmetric static and RF EM fields, via a direct, non iterative method. In addition to producing the EM field solutions for an RF cavity SuperFish also determines the RF cavity's Figures of Merit (FoM) and resonant frequency.

The incoming energy of the proton beam into the cavity from the ion source was 100 keV. As the proton beam energy is well below the relativistic regime (β=0.0146), we developed our own non-relativistic particle tracking algorithm around a uniform discretization of the EM fields determined by SuperFish. The difference between our tracking algorithm and the established formula [6] for energy gain (Eq.1) was found to be less than 0.1 %.

$$\Delta E = \int_0^L E_z \cos(\omega t(z) + \phi) dz \qquad (1)$$

The calculations from the longitudinal electric field to compute the energy gain have been only done for the ideal particle, i.e. the synchronous particle is receiving maximum acceleration by choosing the optimal phase at entrance, ϕ, with respect to the field. Ongoing work will consider beam dynamics for longitudinal stability.

Cavity geometry

Several designs were considered in order to optimise the performance of the cavity. These designs differed in the outer wall curvature and the reentrant cone shape (see Fig. 1). The cavity dimensions are bigger than conventional RF cavities due to the low frequency chosen. Table 1 summarises the approximate values of the dimensions for the models compared in next section (differences due to frequency tuning). Cavity length is represented by L, R2 is the outer radius, g is the acceleration gap length and R1 is the nose cone height. A slight inclination, α, has been given to the nose cone wall to avoid multipacting phenomena.

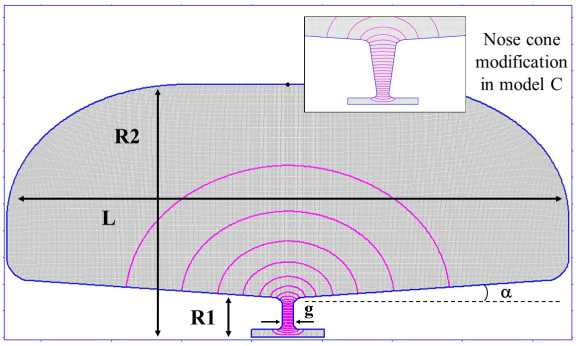

Figure 1: Cavity geometry and parameters used for frequency tuning and FoM optimization.

Previous study in HFSS of the beampipe length that should be included in the 2D model was done [7]. The electric field leaks into the beampipe affecting the incoming beam. Simulations show that 8 cm is enough to find values below 5 % of the maximum longitudinal electric field (E_z).

Table 1: Cavity dimensions

f (MHz)	R2 (m)	R1 (cm)	L (m)	g (cm)	α (°)
40 MHz	1.1	12-15	1.5 - 2	3	5

The proposed structure comprises a double 40 MHz cavity. Three different designs are considered and labelled F, O and C in Table 2 and 3. The first two differ in the outer wall shape (F being more rounded), and C resembles O but the nose cone gap is linearly widen to reduce capacitive effects between parallel conductors (zoom in Fig. 1).

RESULTS

Tables 2 and 3 show the results from SuperFish simulations of the 1st and 2nd cavities of these models. From the values obtained, the most remarkable aspects are the lower power dissipation of models C1 and C2 compared with the others. Also, both shunt impedances and r/Q are higher for this last model giving a greater acceleration efficiency.

The Kilpatrick factor (also known as 'bravery' factor) is the ratio of the maximum surface field over the Kilpatrick limit. Previous tests presented in [8] for 88 MHz MuCool

Table 2: First Cavity Model Comparison

Parameter	F1	O1	C1
Frequency (MHz)	40	40	40
Stored Energy (J)	4.58	4.25	3.11
Power dissipation (kW)	27.18	27.73	15.96
Shunt Impedance (MOhm/m)	60.3	59.07	78.9
ZTT (MOhm/m)	17.4	17.0	24.33
Q (-)	42402	41552	49033
Geometry Factor (Ohm)	69.96	68.56	80.9
r/Q (Ohm)	72.63	72.6	112.65
E_0 (MV/m)	8	8	8
Max. surface E (MV/m)	19.2	19.3	19.6
Kilpatrick Factor	2.32	2.33	2.37
Transit Time Factor (-)	0.54	0.54	0.55
Final Energy (keV)	389	389	397

Table 3: Second Cavity Model Comparison

Parameter	F2	O2	C2
Frequency (MHz)	40	40	40
Stored Energy (J)	8.53	8.53	5.67
Power dissipation (kW)	50.6	51.6	29.1
Shunt Impedance (MOhm/m)	51.8	50.74	78.97
ZTT (MOhm/m)	35.8	35.1	55.33
Q (-)	42402	41552	49033
Geometry Factor (Ohm)	69.96	68.5	80.9
r/Q (Ohm)	174.3	174.3	256.2
E_0 (MV/m)	10.9	10.9	10.8
Surface E_{peak} (MV/m)	26.3	25.3	26.2
Kilpatrick Factor	3.18	3.06	3.17
Transit Time Factor (-)	0.83	0.83	0.84
Final Energy (keV)	1000	1000	1001

CERN cavities showed values of 2.4 Kilpatrick with maximum fields of 26 MV/m. Considering this, 1st cavities show acceptable values and slightly higher (above 3) for the 2nd cavities. A good cavity surface conditioning is required to avoid any chance of getting RF breakdown [6].

Thus, taking everything into account, models C1 and C2 were chosen to take forward to 3D simulations. The energy gain curve for these two cavities is shown in Fig. 2.

COUPLER

The power coupler has been designed and simulated in the commercially available software COMSOL Multiphysics platform, which uses Finite Element Method to solve Maxwell's equations on an irregular mesh [9]. The coupler consists in a coaxial waveguide shorted on the cavity wall by a loop antenna (Fig. 3). This creates a inductive coupling from the loop to the fundamental magnetic field mode at the cavity.

The characteristic impedance of the coaxial waveguide is assumed to be 50 Ω. Optimal coupling was achieved by simulating in COMSOL various penetrations and orientations

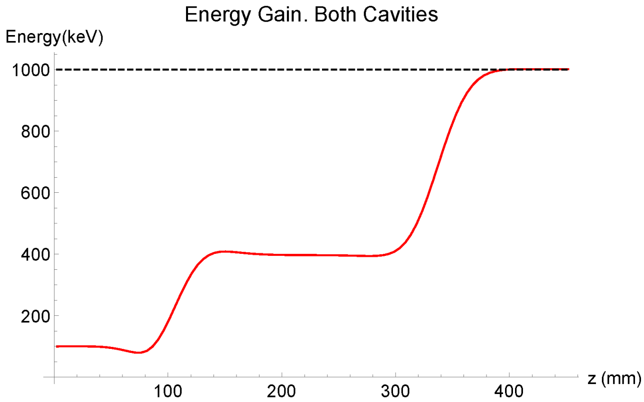

Figure 2: Energy gain curve from cavities C1 and C2. The length indicated ignores the drift sections in between cavities.

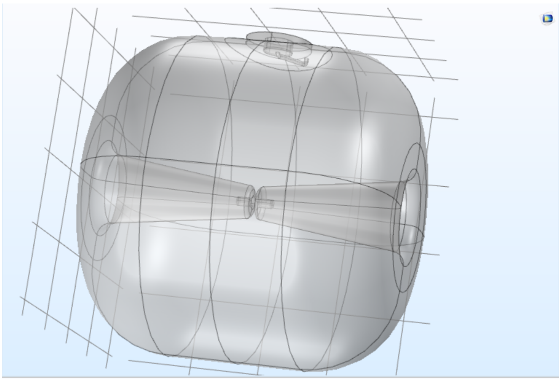

Figure 3: 3D model of the reentrant cavity and RF input coaxial coupler designed in COMSOL. The loop shorted on the outer wall generates the inductive coupling.

of the loop coupler to minimize reflections at the operating frequency, i.e. obtain a S_{11} parameter of at least −30 dB (less than 0.1 % reflected). Simulations showed this optimal coupling occurs for a loop penetration of 4 cm and orientation of 48 ° from the beam path line. The resonant frequency shifted down due to the presence of the coupler itself, but tuners must be added in the future to address this and other variations. The results from the simulations of optimal coupling are shown in Fig. 4. A minimum value of −49.5 dB was found at a frequency of 39.3525 MHz with a bandwidth of around 8 kHz.

CONCLUSIONS

In summary, an RF cavity design for a 1-MeV proton injector of a PT linac has been presented. The structure consists of a double 40 MHz NC cavity driven by a Marx Generator. Three different models are compared from their FoM in SuperFish simulations aiming to minimise power dissipation, maximum surface field, and best possible efficiency. For the chosen model, a power coupler from a coaxial line into a loop antenna was designed. The optimization gave a −49.5 dB reflection coefficient at 39.3525 MHz.

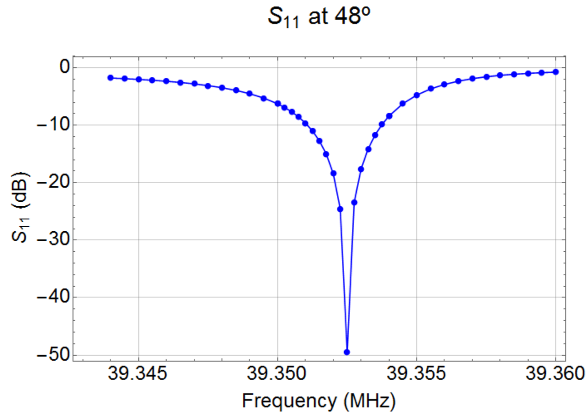

Figure 4: Plot of the S_{11} parameter simulated for the coaxial coupler. A minimum of −49.5 dB is found at 39.3525 MHz.

Future work will address thermal simulations and cooling, frequency tuners and particle longitudinal dynamics.

ACKNOWLEDGEMENT

Mr. Soriano Guillen would like to thank Fundación Mutua Madrileña for the economic support to take part in this research.

REFERENCES

[1] http://www.dreebit.com/en/. (accessed 09/05/2017)

[2] E. Marx, "Versuche uber die Prufung von Isolatoren mit Spanningsstoben". Elektrotechnische Zeitschrift (in German). 25: 652-654. ISSN 0424-0200. OCLC 5797229, 1924.

[3] http://www.apelc.com/pdfs/15.pdf (accessed 09/05/2017)

[4] R. J. Focia, C. A. Frost, "A compact low jitter 1 kHz pulse repetition rate gas-switched pulse generator system", Proc. IEEE Pulsed Power Conf., pp. 1341-1344, Jun. 2005.

[5] K. Halbach and F. Holsinger, "SUPERFISH - A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry", Particle Accelerators 213-222, 1976.

[6] T. Wangler, *RF Linear Accelerators*. Wiley-VCH, 2008.

[7] http://www.ansys.com/products/electronics/ansys-hfss (accessed 09/05/2017)

[8] R.Garoby, F. Gerigk, J. Marques, C. Rossi and M. Vretenar, “High gradient tests of an 88-MHz RF cavity for muon cooling”, in *Proc. 10th European Particle Accelerator Conf. (EPAC’06)*, Edinburgh, UK, June 2006, paper TUPCH143, pp. 1352–1354.

[9] https://www.comsol.com/. (accessed 09/05/2017)