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DESIGN OF HIGH EFFICIENCY HIGH POWER CW LINACS FOR ENVIRONMENTAL AND INDUSTRIAL APPLICATIONS*

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Abstract

We have designed three high average power normal conducting rf linacs for environmental and industrial applications: 2 MeV, 1 MW; 10 MeV, 10 MW; and 10 MeV, 1 MW. Their rf to beam efficiencies are 96.7%, 97.2%, and 79.6%, respectively. These linacs comprise of 1.3 GHz rf modules. Each rf module has about 1 m long rf accelerating structure fed by one rf source. The accelerating structures consist of standing wave π-mode cavities which are individually fed using distributed coupling. The coupling coefficient of these over-coupled cavities is chosen to maximize rf to beam energy transfer. The thermomechanical simulations of the rf cavities have resulted in acceptable temperature and stress distributions with practical water cooling. The beam focusing is provided by solenoids running along the length of the linac. The magnetic field of the focusing solenoids is optimized to reduce total beam halo loss to less than a kW. In this paper, we will present the design and simulation results of 2 MeV, 1 MW linac

INTRODUCTION

We made conceptual designs of three extremely high efficiency 1.3 GHz rf linacs capable of providing continuous electron beams of up to 10 megawatt power for energy and environmental applications [1]. The optimal design parameters, like the type of cavities, operating frequency, aperture size, and linac length were finalized after a rigorous efficiency analysis [2]. Each linac comprises of a 100 kV injector, several rf modules consisting of high efficiency accelerating structures fed by high average power klystrons or inductive output tubes (IOT's), and focusing solenoids for the beam transport with minimum halo loss. The performance parameters of these linacs are shown in Table 1.

Table 1: Design Performance Parameters of the Linacs

	2 MeV 1 MW	10 MeV 10 MW	10 MeV 1 MW
Output beam energy [MeV]	1.79	9.71	10.1
Beam energy spread	1.3%	1.2%	1.4%
Beam power [MW]	1.001	9.72	0.892
RF input power [MW]	1.035	10.00	1.120
RF to beam efficiency	96.7%	97.2%	79.6%
Linac length [m]	4.4	14.2	14.2
RF power loss per length [kW/m]	7.7	19.7	16.1
Solenoid losses [kW]	0.77	5.6	10.4

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Here, we discuss the design and simulation of the first of these linacs, i.e., 2 MeV, 1 MW case. The other two cases are presented in detail in Ref. [1].

CONCEPTUAL LAYOUT

The schematic of the linac is shown in Fig. 1. A 100 keV, 682 mA beam is injected into the first of the three accelerating structures. Each accelerating structure is fed by a klystron that provides continuous wave (CW) rf power of 345 kW at 1.3 GHz frequency.

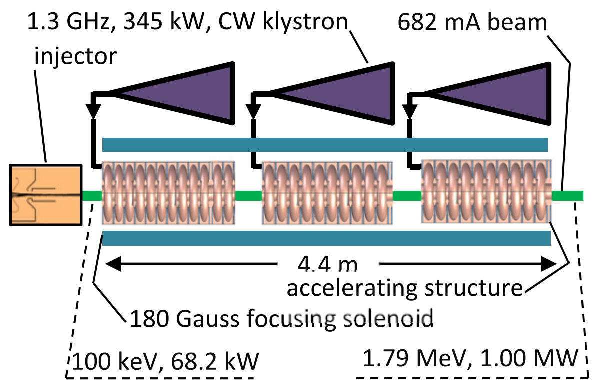

Figure 1: Conceptual layout of 2 MeV, 1 MW linac showing injector, focusing solenoid, and the three rf modules.

DESIGN OF THE ACCELERATING STRUCTURE

We used nose-cone cavities because of their higher shunt impedance and lower higher order mode loss factor ratio [2]. Particularly, we chose π -mode cavities because they could be fed with rf power using distributed coupling [3]. This is an innovative method of individually feeding small aperture and high shunt impedance cavities.

The beam impedance of 2 MeV, 1 MW linac is 4 MΩ. The efficiency analysis [2] of a 4 MΩ linac shows that for an efficiency of 90 to 98% and beam aperture radius of 15 to 30 mm, the minimum linac length is achieved at L-band. With these considerations, we chose the operating frequency of the linac as 1.3 GHz, the beam aperture radius as 25 mm, and the linac length as 3 m. The rf to beam efficiency of this design is 96.8% for a 10° long bunch. The corresponding optimal rf coupling coefficient of the cavities is 32.9. The shunt impedance per unit length of this cavity is 42.6 MΩ/m and the higher order mode loss factor ratio is 6.22×10^{-5}.

An accelerating structure was comprised of ten such cavities and each of these cavities was fed them using distributed coupling method. This involved splitting the rf power using a 3-dB coupler and then using each of the

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two ports to feed a sub group of five cavities. We designed and simulated this ten-cavity accelerating structure using Ansys® Electronic Desktop [4]. Figure 2 shows the longitudinal cross section of this accelerating structure without the 3-dB splitter. The total shunt impedance of this structure, including the feeding network, is 46.4 MΩ. When fed with an input power of 345 kW, the total accelerating voltage for this 1.35 m long structure (including 10 cm long beam pipes on each end) is 0.696 MV. Due to a small power loss in the feeding manifold, the rf to beam efficiency is calculated to drop by 0.06%. The optimal beam current for 10° bunch length (form factor of 0.985) is 487 mA. Using three such rf modules after the 100 keV injector will yield a beam of energy 2.09 MeV and power 1 MW. However, the actual beam energy will be less than 2.09 MeV due to lower shunt impedance of the first lower-than-the-speed-of-light accelerating structure. Moreover, the form factor of the bunch would also drop as the bunch grows longitudinally while being accelerated along the linac. The beam dynamics simulations, which are presented next, take into account the effect of both of these phenomena: lower initial shunt impedance and reduction of bunch form factor. To maintain the same beam loading for which the rf structures have been designed, we had to increase the beam current from 487 to 682 mA.

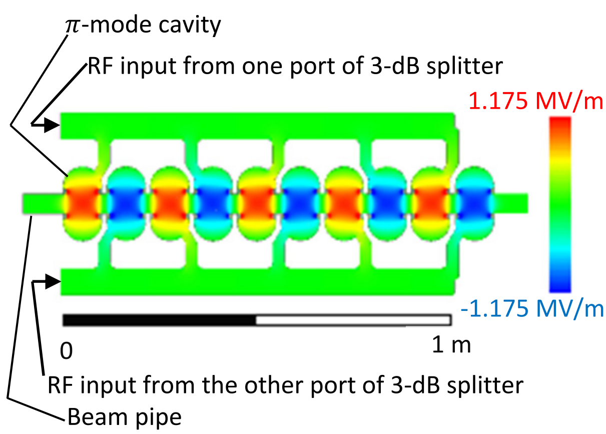

Figure 2: Accelerating field in a speed-of-light rf structure at the phase of maximum amplitude and 345 kW input power.

THERMAL ANALYSIS

We used Ansys® Thermal Analysis [5] to obtain the steady state temperature and stress distributions on the cavity surface for nominal water cooling. We imported the power flux from HFSS simulations into the thermal analysis software as heat flux. We assumed that water at 25°C flows at a rate of 5 gallons/minute through each of the eight cooling pipes that run along the length of the structure and are symmetrically located around it. The convection coefficient was estimated to be 23 kW/m^2/°C. The steady state temperature distribution of this model is shown in Fig. 3. Here, due to symmetry, we have simulated only a one-eighth wedge of the longitudinal half of an accelerating rf cavity with two halves of cooling pipes.

Once the temperature distribution was found, a static structural analysis was performed to find the stress and deformation distribution. The maximum equivalent stress occurs near the nose-cone and was found to be 11.7 MPa. which is less than the copper yield point of ~30 MPa.

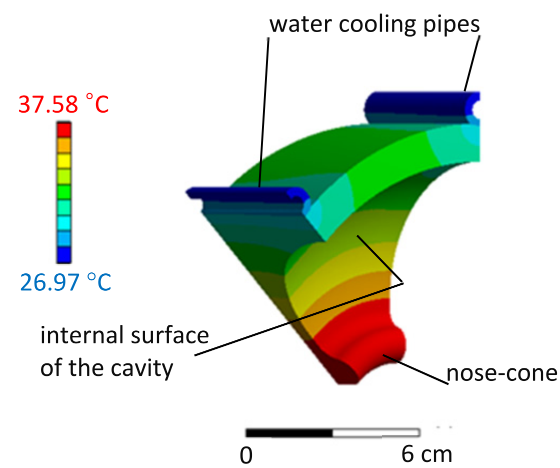

Figure 3: Temperature distribution on a one-eighth wedge of the longitudinal half of an accelerating cavity in 2 MeV, 1 MW linac.

BEAM DYNAMICS SIMULATIONS

The main concern in a high average power linac is the beam loss to the walls of the accelerating structure. This lost beam generates ionizing radiation and can also potentially damage the rf cavities, collimators, and other beam line components. Hence, the major goal of our beam dynamic simulations and beam transport design is to keep this loss within an acceptable level which we set as 1 kW for the whole linac. Figure 4(a) shows the longitudinal electric field (E, blue) of the accelerating cavities and the longitudinal magnetic field (B, red) of the focusing solenoids. The electric field correspond to 345 kW of rf power injected into each of the three accelerating structures. The first set of twelve peaks in the electric field plot corresponds to the low-electron-beta cavities of the first accelerating structure which we have optimized according to the average speed of the bunch. Each remaining set of ten peaks in the electric field plot corresponds to a speed-of-light accelerating structure as shown in Fig. 2. The first peaked curve of the magnetic field corresponds to a magnetic lens which is followed by the main focusing solenoid that runs along the whole linac. These fields were used for beam dynamics studies in ASTRA [6, 7].

For beam dynamics simulations, we assume that a 100 keV, 682 mA beam is injected in the linac. At the entrance of the linac, the bunches are assumed to be Gaussian in all dimensions. Here, quoting the rms values, the energy spread is 10%, bunch length is 10°, transverse radius is 5.2 mm, and the 95% normalized transverse

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emittance is 45 mm-mrad. The results of beam dynamics simulations are shown in Figs. 4(b) and 5.

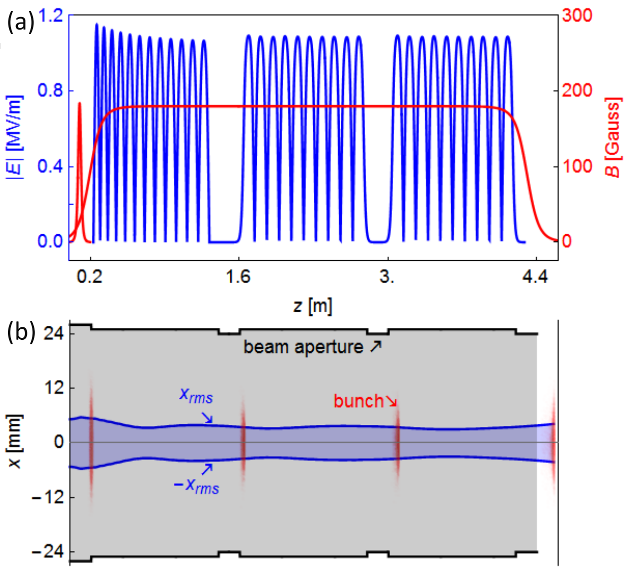

Figure 4: Beam dynamics simulations of 2 MeV, 1 MW linac. (a) Accelerating electric and focusing solenoid fields. (b) Transverses size of the beam along the linac. Beam aperture, as setup in ASTRA, is also shown.

In Fig. 4(b), we have also shown the physical space bunch distribution (red) at the entrance and exit of each accelerating structure. The transverse and longitudinal phase space bunch distributions at the end of the linac are shown in Fig. 5. At the end of the linac about 82% of the total particles remain inside the rf-bucket that is within $\pm 180°$ of the reference particle, and only these particles are taken into account in Fig. 5. The transverse rms size of the bunch is 4.18 mm and the 95% transverse normalized rms emittance is 53.7 mm-mrad. Furthermore, about 84% of the total particles in the rf-bucket are in the range of $-30°$ to $+15°$ with respect to the reference particle and only these were used to calculate the mean energy ($\overline{U}$) as well as the rms values of the longitudinal size (z_{rms}) and energy spread (U_{rms}). The longitudinal size is 9.14° and the energy spread is 1.4%. The total power lost due to beam halo is less than a kW as verified by multiple simulations with different initial seeds for bunch generation.

CONCLUSION

We have presented the design of a 1.8 MeV, 1 MW, CW normal conducting rf linac operating at 1.3 GHz. This linac comprises of three rf modules, each has a 1.4 m long accelerating structure fed by a 345 kW, CW klystron. The accelerating structures are standing wave π-mode cavities which are individually fed using distributed coupling [3]. The rf to beam efficiency of this linac is 96.7%. The thermal analysis of the rf cavities has yielded acceptable temperature and stress distributions with practical water cooling. The beam is transported using a solenoid with a field of about 200 Gauss. This field will keep the beam halo losses below 1 kW while the Ohmic losses in the solenoid are estimated to be below 1 kW.

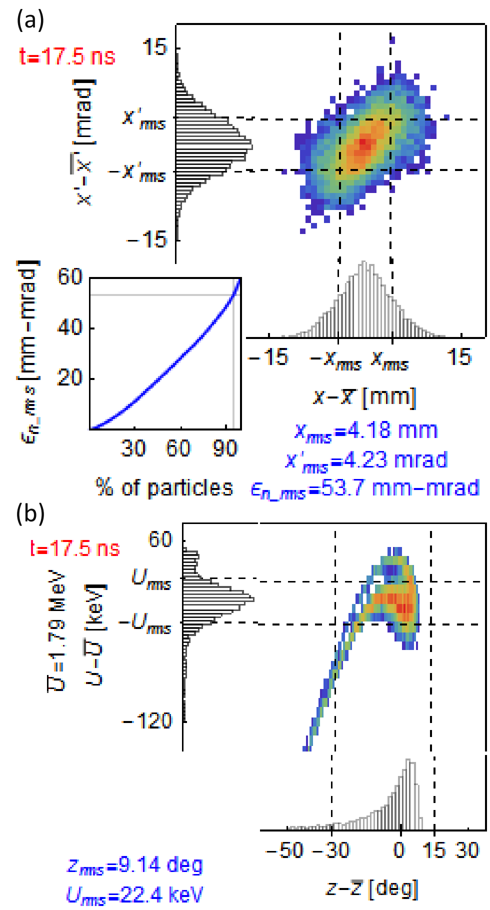

Figure 5: (a) Transverse and (b) longitudinal phase space at the exit of 2 MeV, 1 MW linac.

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