Design of a 10 MeV normal conducting CW proton linac based on equidistant multi-gap CH cavities*

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Abstract: Continuous wave (CW) high current proton linacs have wide applications as the front end of high power proton machines. The low energy part of such a linac is the most difficult and there is currently no widely accepted solution. Based on the analysis of the focusing properties of the CW low energy proton linac, a 10 MeV low energy normal conducting proton linac based on equidistant seven-gap Cross-bar H-type (CH) cavities is proposed. The linac is composed of ten 7-gap CH cavities and the transverse focusing is maintained by quadrupole doublets located between the cavities. The total length of the linac is less than 6 meters and the average acceleration gradient is about 1.2 MeV/m. The electromagnetic properties of the cavities are investigated by Microwave Studio. At the nominal acceleration gradient the maximum surface electric field in the cavities is less than 1.3 times the Kilpatrick limit, and the Ohmic loss of each cavity is less than 35 kW. Multi-particle beam dynamics simulations are performed with Tracewin code, and the results show that the beam dynamics of the linac are quite stable, the linac has the capability to accelerate up to 30 mA beam with acceptable dynamics behavior.

Key words: continue wave linac, equidistant multi-gap CH cavity, high current linac

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1 Introduction

Rising concern about the greenhouse effect and the limited conservation of fossil fuels creates pressure for a severe reduction in the use of fossil fuels [1]. One possible way to allow the production of energy that is essential to the growth of developing countries, which account for the majority of humankind, without catastrophically increasing greenhouse gas emissions might be to rely increasingly on nuclear fission energy, based on its negligible contribution to the greenhouse effect [2]. China has increased its investment in nuclear power in the past two decades and this trend is predicted to be continued in the following several decades. However, nuclear power plants based on light-water reactors produce nuclear waste, which will need more than one million years to decay to the reference radio toxicity level of uranium ore [3]. Thus, it is becoming increasingly urgent to find a consensual solution to transmute long-lived radioactive waste in order to keep nuclear energy sustainable. An Accelerator Driven System (ADS), coupling a proton accelerator, a spallation target, and a sub-critical reactor, is a very promising technology for nuclear waste transmutation [4].

The proton beams delivered to the spallation target should have an energy of more than 600 MeV in order to optimize the number of neutrons produced per MeV of incident energy. The total beam power should exceed 10 MW, possibly more with high beam availability. It is clear that the requirements for both beam power and beam availability are all beyond the capability of existing accelerators. The development of superconducting techniques, especially middle beta cavities, makes it possible to build a superconducting linear accelerator from several tens of MeV [5–7]. Although high frequency (>300 MHz) low beta structures, motivated by the acceleration of high intensity proton beams, have attracted interest at the Argonne National Laboratory, the Los Alamos National Laboratory, and at other accelerator labs since the 1990s [8], and even though China has achieved great progress in low beta superconducting structures since 2010, the integrated properties of low filling ratio means that the acceleration gradient of a low energy superconducting linac has no obvious advantage compared with a normal conducting one and the beam current is limited to only about 20-30 mA [9]. A study of ADS organized by Chinese Academy of Sciences (CAS) was proposed and participated in by several institutes of the CAS,

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concentrating on designing and developing a total superconducting 15 MW continuous wave (CW) proton linac, except for the radio frequency quadrupole (RFQ) accelerators. At the same time, under the support of the National Natural Science Foundation of China, the exploration of the possibility to design and build a low energy CW normal conducting proton linac with an energy between 10 to 20 MeV as the front end of the ADS driver linac is also under way. In this paper, a scheme based on equidistant multi-gap Cross-bar H-type (CH) cavities is presented.

2 Why equidistant multi-gap CH cavities?

Although the acceleration gradient of a CW machine is quite low, usually just around 1 MV/m, only 1/3 or 1/4 that of a pulsed machine, and the peak power is decreased dramatically so that it can be properly cooled down, it is still hard to imagine building a long drift tube linac (DTL) tank, as used in a pulsed one. This is partly because the very large average power creates a lot of challenges in the design of the RF system, such as the amplifiers, power couplers and so on. A long tank with more than 20 gaps will also decrease the RF stability of the cavity because of the very small gaps between neighboring modes. Furthermore, the decreased accelerating gradient not only decreases the dissipated power but also decreases the longitudinal focusing and transverse defocusing strength of the RF field. As a result, it is possible to have a longer transverse focusing period than in a pulsed machine. It is natural to apply a series of cavities with multi-gaps and without transverse focusing elements, with the transverse focusing maintained by magnetic quadrupole lenses between the cavities, and the number of gaps within each cavity determined by the longitudinal and transverse focusing requirements. In this way, the longitudinal focusing and transverse focusing will be more balanced, which is very important for high current beams. We have simulated the behavior of a 3 MeV, 20 mA proton beam with 3σ truncated Gaussian distribution transporting through a periodic focusing channel. The focusing channel consists of 74 cells. Each cell is composed of a magnetic quadrupole doublet and an RF gap. During simulation we set the RF phase of the RF gaps at $-90°$, so that they only work as bunchers without accelerating the particles. The widely used Tracewin code [10] with 2D Particle-In-Cell (PIC) space charge routine is used for simulation. Four different cases are simulated: Case-Ⅰ, the transverse and longitudinal phase advance per period is 67° and 75°; Case-Ⅱ, the transverse and longitudinal phase advance is 24° and 27°, i.e. the ratio of the transverse and longitudinal focusing strength is the same as Case-Ⅰ, only the focusing strength is decreased; Case-Ⅲ and Case-Ⅳ are unbalanced focusing cases and the transverse and longitudinal phase advances per period are 24° and 75°, respectively, for Case-Ⅲ and 67° and 27°, respectively, for Case-Ⅳ. The normalized rms emittance evolutions for the four cases are shown in Fig. 1 and they reveal that if the transverse and longitudinal focusing is balanced (Case-Ⅰ and Case-Ⅱ), then the emittances growth is well controlled (less than 10%) in both transverse and longitudinal planes, even for the very weak focusing Case-Ⅱ; if the transverse and longitudinal focusing is unbalanced (Case-Ⅲ and Case-Ⅳ), then the emittance of the weak focusing plane increases significantly (transverse of Case-Ⅲ and longitudinal of Case-Ⅳ). Further study shows the nonlinear space charge force plays an important role in the emittance growth [9]. Another advantage of this design is that, since there are no transverse focusing elements in the drift tubes, the radial dimension of the drift tubes can be decreased and slim drift tubes can be used, which will increase the effective shunt impedance greatly. Because the cavity only contains several gaps (usually less than 10), the total power per cavity is also limited. This will also decrease the difficulties in the design and fabrication of the power coupler.

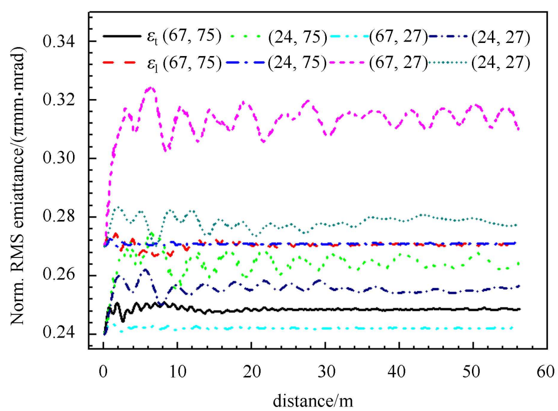

Fig. 1. (color online) Evolution of normalized RMS emittances of a 20 mA proton beam transport through a focusing channel.

One of the biggest challenges for CW normal conducting linacs comes from how to decrease the dissipated power density on the cavity surface, so that after proper design of the cooling channel, the power can be removed out of the cavity. The CH structure matches this requirement perfectly because of its high effective shunt impedance compared with the widely used Alvarez type drift tube linac (DTL) structure [11]. Even compared with multi-tank DTL (MTDTL) structures, which are characterized by short DTL tanks with 4 to 10 gaps, and drift tubes free of transverse focusing elements, so that the effective shunt impedance is much higher than that of the traditional DTL structure, the effective shunt impedance of the CH structure is still more than two times higher. Of course, what is really important in relation to cooling is the power density, and the effective shunt impedance gives some idea about the total power dissipation. By adopting slim drift tubes, the capacitance of the acceleration gaps is decreased, so the MTDTL has a larger transverse dimension compared with that of the CH structure. For example, as Table 1 shows, the radius of a 325 MHz MTDTL cavity with geometry beta 0.087 is around 340 mm, while for a CH structure with same frequency and geometry beta, the cavity radius is only about 161 mm. Our simulation results show that not only the total dissipated power of the CH structure is less than that of the MTDTL one but also the maximum surface electric and magnetic fields are smaller than those of the MTDTL structure. This means that the power is more uniformly distributed within the CH structure and this makes it easier to cool down. By adopting an equidistant structure, the geometries of drift tubes and gaps within a single cavity are identical, and the field distribution can be adjusted by the two end cells. This not only eases the fabrication and installation of the drift tubes but also decreases the number of movable devices for field tuning, which would be very helpful for stable working of a cavity in CW mode. Based on the reasons mentioned above, it is natural to choose equidistant multi-gap CH cavities as the acceleration structure for a low energy high current CW normal conducting proton linac.

Table 1. Comparison of the main parameters of MTDTL and CH structures.

parameters	DTL	CH
frequency/MHz	325.0	325.0
cavity radius/mm	340.0	161.0
aperture radius/mm	10	10
cell length/mm	80	40
cell numbers	5	5
gap length/mm	18	18
1 MV/m gradient 1 m structure		
power/(kW/m)	35.02	15.96
max surface electric field/(MV/m)	13.46	8.35
max surface magnetic field/(A/m)	4610.73	4269.76

3 Cavity properties and lattice layout

The first parameter which needs to be decided for the cavity design is the number of cells in each cavity. This number is decided by the expected acceleration gradient of the linac. Since this is a high current proton machine, the requirements for stable beam dynamics have to be satisfied. One of the most important requirements for stable beam dynamics is that the zero current phase advances per period in three directions should be kept below 90°. In our case, the focusing period is composed of one cavity and the quadruples between cavities. If we want to achieve an effective average acceleration gradient of about 1 MV/m, which is comparable with that obtained by the low beta superconducting linac for the China ADS injectors under development [12], then we should determine the number of cells per cavity. We found that under this condition, a seven cell cavity is perfect and the corresponding maximum surface electric field is less than 1.3 times the Kilpatrick field, which is thought to be a safe number in CW RFQ design. Fig. 2 shows the cavity geometry with cell length 43 mm, the corresponding geometry beta is 0.093. The cavity is composed of a cylindrical vacuum chamber, which is loaded by bars alternatively oriented in the x and y directions. The bars are all identical and are composed of a cylinder connected to the outer cylinder cavity on one side and to a cone on the other side. The cone is smoothly connected to another cylinder with small radius, which is connected to the drift tube on the other side. The drift tubes are located at the axis of the cavity. On the two sides of the cavity, two larger cylinders with radius of 80 mm are intruded into the cavity with length of 120 to 130 mm to obtain an approximately uniform longitudinal field distribution along the axis, as Fig. 2 shows. There are ten cavities applied to accelerate the beam from 3 MeV to 10 MeV, and only the period length and the gap width are changed in the different cavities. The main parameters of the cavities are shown in Table 2. The period length is increased almost linearly from 37 mm to 65 mm and the minimum drift tube length in the first cavity is 20 mm, which is equal to the inner drift tube diameter. This ensures that the field in the drift tubes can be well shielded. The field levels in each cavity are determined by the requirements of the longitudinal phase advances, which means the maximum zero current phase advance per period is less than 90° and the phase advance per meter changes smoothly.

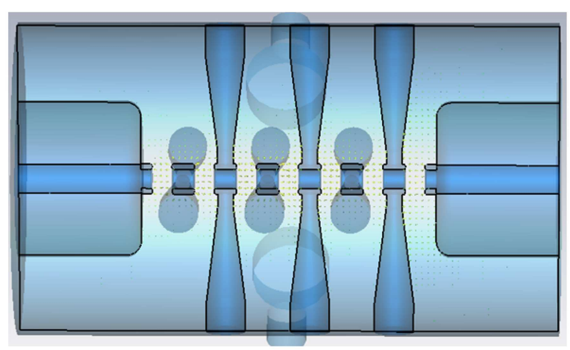

Fig. 2. (color online) Geometry of the CH cavity.

The structure of the focusing lattice is straightforward; the focusing period is composed of one cavity and two quadrupoles, as Fig. 3 shows. The cavity is set to work at a synchronous phase from −35° at the first cavity to smoothly increase to −30° at the last cavity so that the beam can be properly focused longitudinally,

Table 2. Parameters of the cavities.

cell length/mm	diameter/mm	cavity length/mm	Eff. voltage/MV	Acce. Grad./(MeV/m)	K_p	power/kW
37	301	490	0.56	0.93	1.1	18.3
40	312	510	0.68	1.12	1.2	24.3
43	320	530	0.76	1.24	1.3	27.3
46	326	550	0.80	1.15	1.3	25.8
50	324	570	0.81	1.22	1.3	26.2
53	333	590	0.84	1.24	1.3	26.8
56	335	610	0.86	1.22	1.3	26.7
59	340	620	0.90	1.26	1.2	29.2
62	341	640	0.94	1.27	1.2	31.0
65	344	670	0.99	1.28	1.3	33.7

Notes: K_p (kilpatrick factor) and acceleration gradient are calculated from the total cavity length.

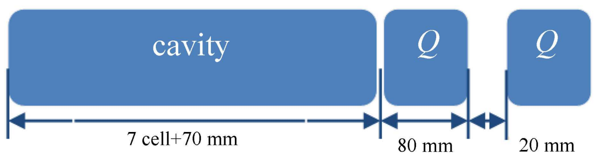

Fig. 3. (color online) Layout of the focusing structure.

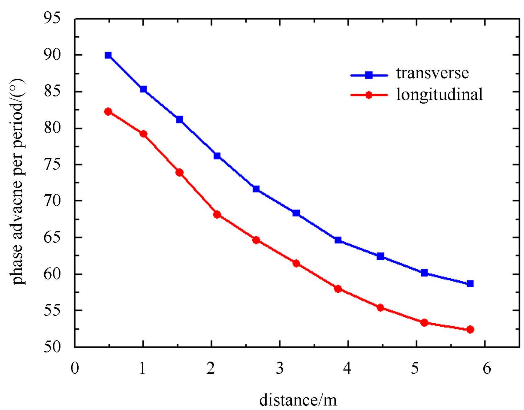

Fig. 4. (color online) Phase advance per period along the linac.

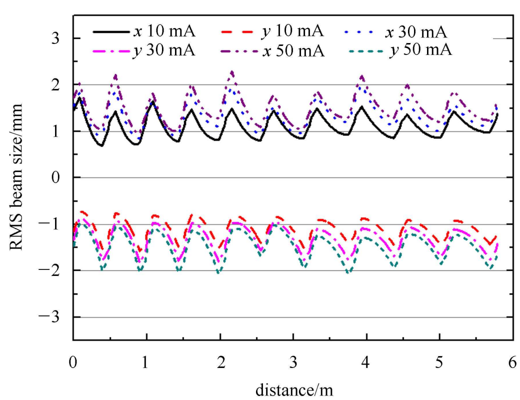

Fig. 5. (color online) Envelopes along the linac.

and the transverse focusing is performed by the quadrupole doublet. Each quadrupole lens has an effective length of 80 mm and they are separated by a 20 mm drift space. The maximum gradient of the quadrupole lens is about 35 T/m. The zero current phase advances in the longitudinal and transverse directions are shown in Fig. 4. With these settings, the total length of the linac is about 5.8 meters and the average acceleration gradient is about 1.2 MeV/m.

4 Beam dynamics simulation results and discussion

In order to check the dynamic stability and the current limits, multi-particle simulations were performed

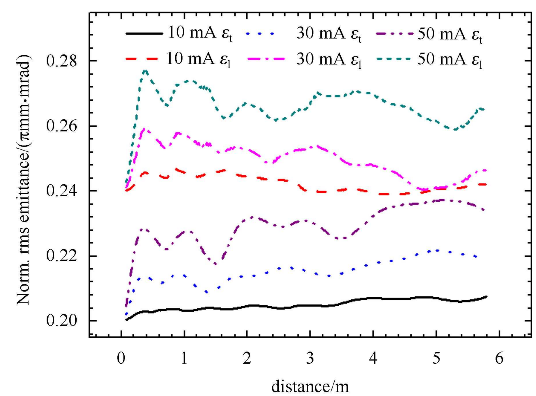

Fig. 6. (color online) Normalized RMS emittances along the linac.

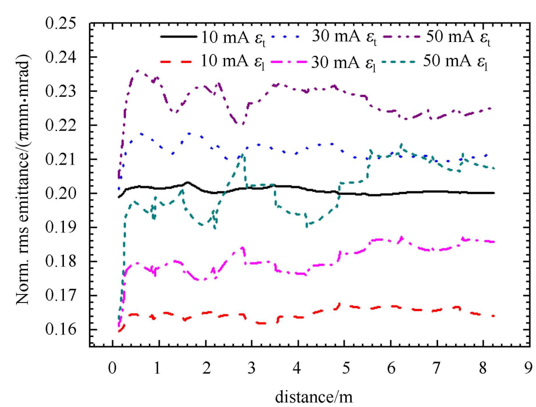

Fig. 7. (color online) Normalized RMS emittances along the superconducting spoke012 section of C-ADS Injector Scheme-Ⅰ.

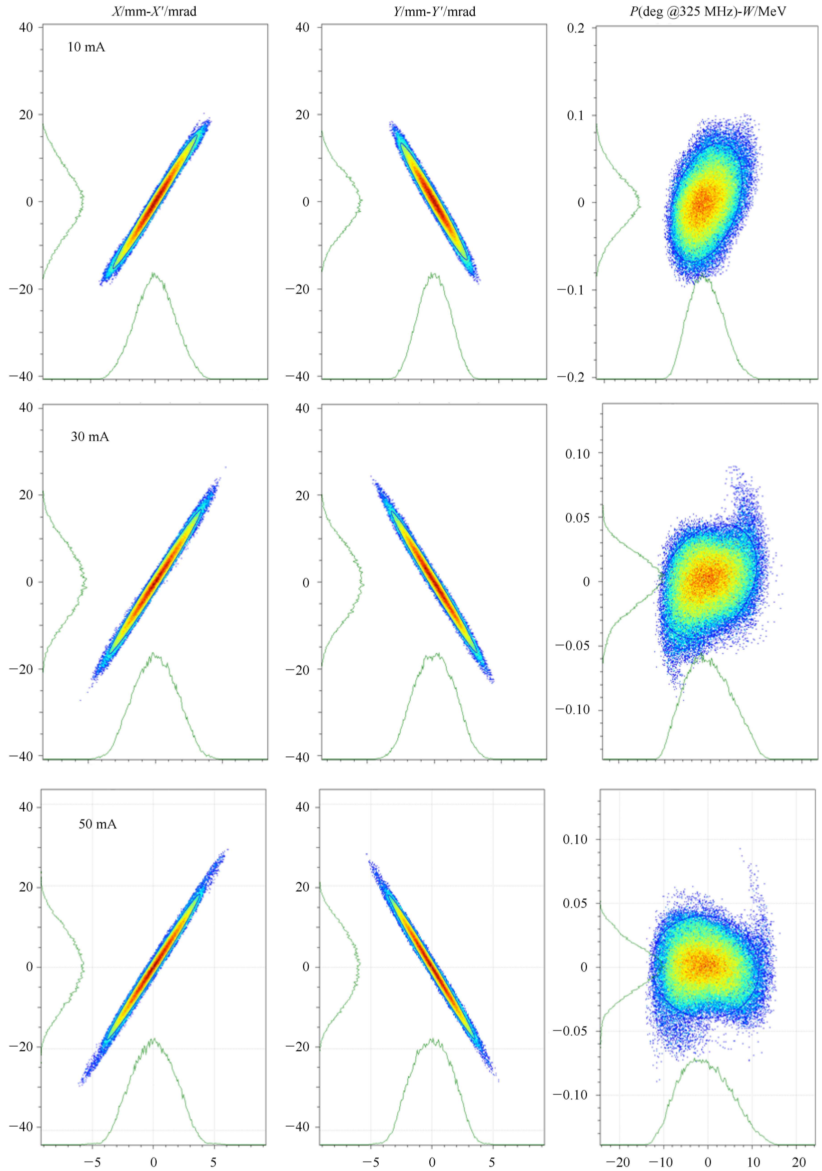

Fig. 8. (color online) Phase distributions at the exit of the linac with different beam current.

with Tracewin [10], which is a well-known high current linac design and simulation code developed by CEA Saclay, which includes functions such as automatic matching and matching parameter searching, error analysis, three dimensional electromagnetic field map elements, 2D and 3D particle in cell space charge force calculation routings, and so on. The 3σ truncated Gaussian distribution was generated by the Tracewin code with transverse and longitudinal normalized rms emittances of 0.20 and 0.24 πmm·mrad, respectively. The total number of macro particles was 100000. The cavities were represented by three dimensional field maps and the fields were calculated by Microwave Studio from CST [13]. The quadrupole lenses were represented by widely accepted hard edge ideal quadrupole lenses. Three different cases with 10 mA, 30 mA, and 50 mA beam currents were simulated.

Figure 5 shows the rms envelopes of the beam along the linac. The aperture of the linac is limited by the radius of the drift tube inner radius, which is 10 mm in our case. We can see from Fig. 5 that within all of the cavities, the rms envelopes are less than 1.5 mm. Even if we take 5 times the rms envelopes as the total envelopes, there is still enough margin for safety, even for a beam current of 50 mA. Fig. 6 shows the evolution of the normalized rms emittances along the linac. We can see that for 10 mA, the emittance growths in both transverse and longitudinal directions are well controlled, and the maximum is less than 5%. As the beam current increases, the emittances growth also increases. For the 30 mA case, the growth is still controlled within 10%, but for 50 mA, it increases to nearly 20%. For all three cases, the emittance growth mainly occurs at the very beginning of the linac, within 0.4 meters. This means that it occurs in the first period. This characteristic shows that it comes from the charge redistribution within the beam. For the real case, the beam coming from upstream will have already reached a static distribution and the emittance growth should not happen. For comparison, the normalized rms emittance evolutions along the superconducting spoke012 section of the C-ADS Injector Scheme-Ⅰ [14] are also shown in Fig. 7. We can see that for 10 mA and 30 mA, the two linacs perform almost the same, but for 50 mA, the large longitudinal emittance growth shows that it is obviously beyond the capability of the superconducting spoke012 section.

The rms envelopes and emittances are statistical properties of the beam and are good for describing the properties of the beam core. In order to fully describe the transport properties of the linac, Fig. 8 shows the phase distributions at the exit of the linac for the three cases. From Fig. 8 we can see that the transverse phase space distribution for the three different beam current cases are almost identical and there is no distortion of the phase space distribution, except for the beam halo which develops as the beam current increases; the halo particles can be collimated when necessary. However, the longitudinal phase space distributions for the three different cases are quite different. As the beam current increases, the dense part of the beam core is still an ellipse, which the rms envelopes and emittances show, but at the outside, the sparse beam halos are distorted as beam current increases. The distorted beam halo will significantly increase the total emittance. Unlike the transverse halo particles, the longitudinal ones cannot be collimated unless a dispersion section is introduced, but this will make the situation even more complicated [15] and will unavoidably introduce rms emittance growth. Thus, the longitudinal halo particles will be transported to the high energy part. In order to keep the particle loss less than 1 W/m, the halo beams have to be treated carefully and the downstream acceleration structures should have larger longitudinal acceptances. Considering that the energy gain per cavity may be larger than 10 MeV in the downstream high energy superconducting sections, the beam power will be more than 500 kW per cavity. A coupler for such high power is still under study. From both beam dynamics and a RF technical point of view, it is better to keep the beam current less than 30 mA for the CW proton machine and the CH linac can satisfy this requirement as the front end of the CW proton linac.

5 Conclusions

The physics design for a low energy (3–10 MeV) CW proton linac based on 7-gap equidistant CH cavities is presented. The beam dynamics results are quite promising and show that it is a good candidate for front end of CW high current proton linac. By adding cavities, it is possible to accelerate up to 20 MeV with good efficiency. The only question is whether the cavity can work stably under the required gradient, which needs to be resolved by experiment. At present, the cavity optimization and technical design of an equidistant 5-gap cavity is under way at another group at CIAE, and power tests are foreseen in the future.

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