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Electromagnetic design and beam dynamics simulation of a new superconducting accelerating structure for extremely low β protons*

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Abstract: For the application of high intensity continuous wave (CW) proton beam acceleration, a new superconducting accelerating structure for extremely low β protons working in TE210 mode has been proposed at Peking University. The cavity consists of eight electrodes and eight accelerating gaps. The cavity's longitudinal length is 368.5 mm, and its transverse dimension is 416 mm. The RF frequency is 162.5 MHz, and the designed proton input energy is 200 keV. A peak field optimization has been performed for the lower surface field. The accelerating gaps are adjusted by phase sweeping based on KONUS beam dynamics. The first four gaps are operated at negative synchronous RF phase to provide longitudinal focusing. The subsequent gaps are 0° sections which can minimize the transverse defocusing effect. Solenoids are placed outside the cavity to provide transverse focusing. Numerical calculation shows that the transverse defocusing of the KONUS phase is about three times smaller than that of the conventional negative synchronous RF phase. The beam dynamics of a 10 mA CW proton beam is simulated by the TraceWin code. The simulation results show that the beam's transverse size is under effective control, while the increase in the longitudinal direction is slightly large. Both the TraceWin simulation and the numerical calculation show that the cavity has a relatively high effective accelerating gradient of 2.6 MV/m. On the whole, our results show that this new accelerating structure may be a possible candidate for superconducting operation at such a low energy range.

Key words: superconducting, TE210 mode, low energy, KONUS beam dynamics

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1 Introduction

The radio frequency quadrupole (RFQ) has been applied with great success to a variety of ion accelerators as a low energy front end [1–4]. Also, the crossbar H mode (CH) cavity, which is a multi-gap drift tube accelerating structure, has been demonstrated to be possible for superconducting operation [5–8]. By combining the advantages of the RFQ and the CH cavity, a new accelerating structure working in TE210 mode, which is designed to operate in a superconducting state and to allow the acceleration of an intense proton beam with extremely low β at relatively high effective accelerating gradient, is proposed at Peking University. As can be seen from Fig. 1, the four vanes connected to the cavity wall are cut by elliptical cylinders, which results in longer electrical length to reduce the cavity's transverse dimension. The electrodes are connected by two stems with the vanes of the same electrical potential. The cavity consists of eight electrodes and eight accelerating gaps, including the gap between the first electrode and the cavity end plate, which is called the minend gap. Also, the electrodes are perpendicular to one another, so there is no quadrupole asymmetry effect, which may have an impact on the transverse beam envelope. The RF frequency of the cavity is 162.5 MHz, and the designed proton input energy is 200 keV. The cavity's longitudinal length is 368.5 mm, and its transverse diameter is 416 mm. By this arrangement, the TE110 mode, which may cause the problem of strong mixing between the quadrupole modes, is short circuited along the whole cavity. Overall, the cavity is topologically equivalent to a coaxial transmission line, terminated by a short at both ends. The magnetic field bunches up and down along the cut-vanes, while the electric field is mainly concentrated in the inter-electrode capacitance area. Besides, the use of KONUS beam dynamics results in long lens-free sections, making the design of a superconducting multi-gap structure in the low energy range possible.

This paper describes the structure and the operating

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principles of the cavity. A peak field optimization has been performed for the lower surface field. The adjustment of the accelerating gaps based on KONUS beam dynamics is presented. Also, the transverse momentum change of the proton has been calculated. Finally, the beam dynamics of a 10 mA CW proton beam is simulated by TraceWin code [9].

2 EM optimization and KONUS adjustment

The peak electromagnetic field is an important issue for this superconducting structure. In order to prevent field emission and magneto-thermal breakdown, the conventional electromagnetic field restriction is 35 MV/m and 70 mT, respectively.

For this cavity, the magnetic field bunches up and down along the cut-vanes, and the location of the peak magnetic field, are as marked in Fig. 1(b). By increasing the thickness of the vanes, the surface current at the joint will be reduced remarkably, keeping the peak magnetic field far below 70 mT. When the thickness of the vanes is 40 mm, a peak magnetic field of 41.4 mT is obtained.

Because the designed proton input energy is very low, the gap between the first two electrodes is short, which may result in a high peak electric field in the first gap, as shown in Fig. 1(a). A proton energy gain of 1 MeV is set as the cavity's design goal, which means that the proton will be accelerated from 200 keV to 1.2 MeV in a total length of about 370 mm, which results in an accelerating gradient of about 2.7 MV/m. So an electromagnetic peak field optimization is performed mainly to reduce the cavity's peak electric field under this design objective. By simulating the influence of the structural parameters in the inter-electrode capacitance area on the cavity's peak field, the peak electric field is reduced to 28.3 MV/m, which gives a sufficient margin with respect to the limit of 35 MV/m. Figure 2(a) shows the structural parameters in the inter-electrode capacitance area that may have an influence on the peak electric field. The dependence of peak electric field on vane height h_0 is shown in Fig. 2(b) as an example during one step of the optimization.

The structural parameters of the cavity after EM optimization are listed in the following table, in which H is the inside radius, L is the total length, b is the thickness of the vane and l_i refers to the length of the corresponding gap.

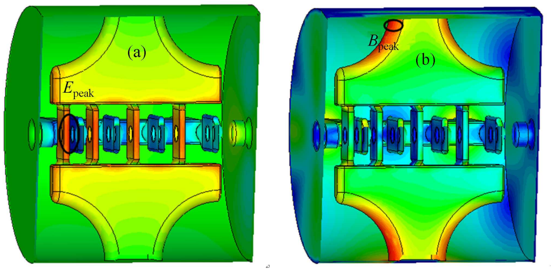

Fig. 1. (color online) CST MWS pictures of the surface fields of the cavity: (a) surface electric field (b) surface magnetic field.

Table 1. Cavity structural parameters after EM optimization.

H/mm	L/mm	b/mm	h_0/H	h_b/H	h_1/H	w/mm
208	368.5	40	0.76	0.38	0.05	50
l_1/mm	l_2/mm	l_3/mm	l_4/mm	l_5/mm	l_6/mm	l_7/mm
20	29	31.5	37	38.5	39.5	51.3

The low energy proton can sustain acceleration throughout the cavity, making the velocity change significantly, so the variation of the proton velocity must be specifically considered. In this case, the energy gain of a charged particle passing through the cavity is:

$$\Delta U = q\sum_{i=1}^{N} E_z(i)\cos\left(\frac{\omega}{c}\sum_{j=1}^{i-1}\frac{\Delta z}{\beta(j)} - \phi\right)\Delta z, \tag{1}$$

where q is the charge of the particle, $E_z(i)$ is the profile

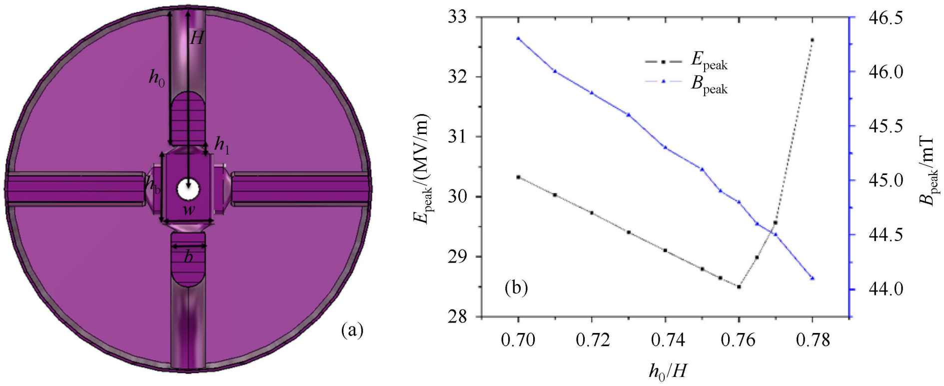

Fig. 2. (color online) Structural parameters in the inter-electrode capacitance area that may have an influence on the peak electric field. (b) Peak electric field dependence on vane height h_0 is shown as an example during one step of the optimization.

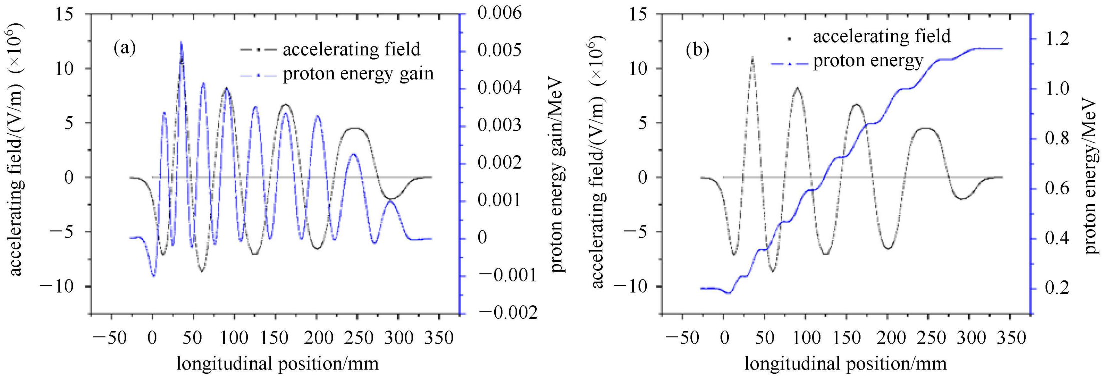

Fig. 3. (color online) The proton can undergo sustained acceleration throughout the cavity. (a) Proton energy gain at different longitudinal positions with respect to the accelerating field. (b) Proton energy at different longitudinal positions with respect to the accelerating field.

of the accelerating field in position z_i, $\beta(i)$ is the particle's velocity in position z_i, ω is the angular frequency of the electromagnetic field, and $-\phi$ is the phase of the field when the particle enters the cavity (z=0).

Unlike conventional linacs operated at negative synchronous RF phase, the accelerating gaps of this cavity are adjusted by phase sweeping based on KONUS (Kombinierte Null Grad Struktur) beam dynamics. KONUS is a modified beam dynamics concept which allows the magnetic quadrupoles or solenoids necessary for the transverse focusing of the beam to be placed outside the cavity. A detailed description of KONUS beam dynamics can be found in Ref. [5]. KONUS beam dynamics has been applied in GSI, where it has been in operation since 1991 [10].

To make the cavity meet the KONUS beam dynamics requirements, the first four gaps are operated at negative synchronous RF phase to provide longitudinal focusing. The subsequent gaps are 0° sections which can minimize the transverse defocusing effect.

In the case of KONUS beam dynamics, numerical calculation shows that the proton's output energy is 1.16 MeV, which basically meets the design goal for energy gain. It can be seen that the cavity has relatively high accelerating efficiency. Figure 3 shows the energy gain of the proton along the axial direction with respect to the accelerating field.

3 Transverse defocusing

The radial force that a charged particle suffers in the paraxial electromagnetic field [11] is:

$$F_r=-\frac{\pi qeTE_0\sin\varphi_{\rm s}}{\lambda\beta\gamma^2}r, \tag{2}$$

with $\varphi_{\rm s}$ being the synchronous phase. For conventional linacs operating at negative synchronous RF phase, the accelerated particle suffers a defocusing force. By applying KONUS beam dynamics, the overall gap RF defocusing effect is reduced. Next we will calculate the proton's transverse momentum change with both KONUS phase and conventional synchronous negative RF phase when it passes through the cavity, to compare the transverse defocusing effect in both cases. The transverse momentum change of a proton passing through in the x direction is:

$$\begin{aligned}\Delta p_x &= q\int E_x(z)\cos(\omega t-\varphi){\rm d}t\\ &\quad -q\mu_0\int\beta(z)cH_y(z)\cos\left(\omega t-\varphi+\frac{\pi}{2}\right){\rm d}t.\end{aligned} \tag{3}$$

Similarly, the transverse momentum change of a proton passing through in the y direction is:

$$\begin{aligned}\Delta p_y &= q\int E_y(z)\cos(\omega t-\varphi){\rm d}t\\ &\quad +q\mu_0\int\beta(z)cH_x(z)\cos\left(\omega t-\varphi+\frac{\pi}{2}\right){\rm d}t,\end{aligned} \tag{4}$$

where

$${\rm d}t={\rm d}\left(\frac{z}{\beta(z)c}\right)=\frac{{\rm d}z}{\beta(z)c}-\frac{z}{c}\cdot\frac{1}{\beta(z)^2}\cdot{\rm d}\beta.$$

Based on the method described above, some numerical calculation is performed to obtain the proton's transverse momentum change in the different cases, and the results are listed in Table 2.

Table 2. Transverse momentum change with different synchronous RF phase.

Syn. phase	$\Delta p_x/q$	$\Delta p_y/q$
KONUS	1.1×10^{-3}	1.1×10^{-3}
Conventional	2.9×10^{-3}	2.9×10^{-3}

The calculation shows that the transverse defocusing strength with the KONUS phase is about three times smaller than that with a conventional negative synchronous RF phase of −30°.

4 TraceWin simulation

The numerical calculation results above show that the overall gap RF defocusing effect with the KONUS phase is indeed reduced. But the calculation does not take the space charge force into consideration, and also assumes that the proton's direction of motion remains unchanged throughout the cavity. Also, the transverse and longitudinal action that a passing beam suffers is a cumulative effect. So next the TraceWin code will be used to analyze the beam dynamics of a 10 mA CW proton beam.

The simulation is performed mainly to check whether the defocusing in both transverse and longitudinal direction can be controlled effectively. For ease of simulation, the phase ellipse in every phase space is set to be standard. The lattice structure consists of six elements, which are shown in Fig. 4(a) for reference. Apart from two solenoids and the cavity, three drift lengths are included. The basic parameters of the simulation are listed in Table 3.

Table 3. Basic parameters of the cavity simulation.

parameter	value
input energy of the proton	200 keV
output energy of the proton	1.16 MeV
frequency	162.5 MHz
radius of the beam pipe	14 mm
input $x_{\max}$	4 mm
input $x'_{\max}$	5 mrad
input transverse norm. rms emittance	0.083 πmm·mrad
output $x_{\max}$	3.2 mm
output $x'_{\max}$	2.61 mrad
output transverse norm. rms emittance	0.083 πmm·mrad
input $z_{\max}$	2.1 mm
input $z'_{\max}$	0.5 mrad
input longitudinal norm. rms emittance	0.0044 πmm·mrad
output $z_{\max}$	7.2 mm
output $z'_{\max}$	26.1 mrad
output longitudinal norm. rms emittance	0.0045 πmm·mrad

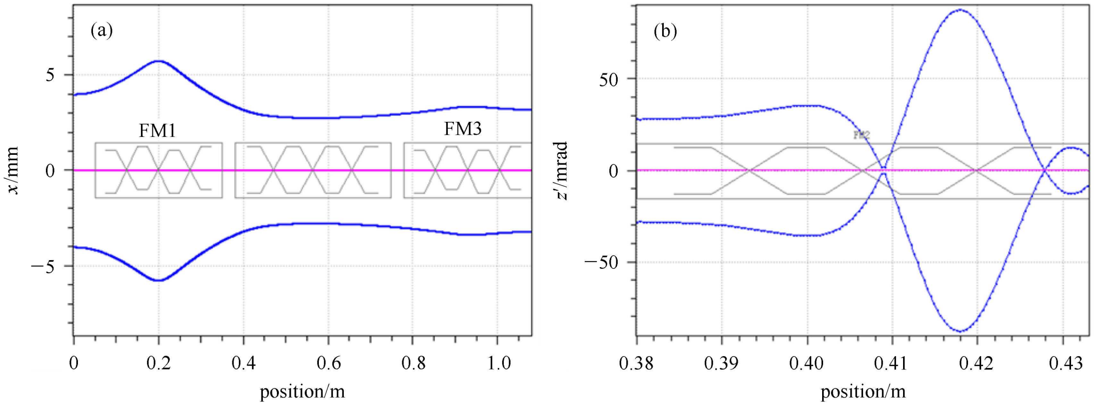

Fig. 4. (color online) (a) Envelope variation in the x direction along the KONUS structure. (b) Specific envelope variation in the z direction when the beam passes the minend gap.

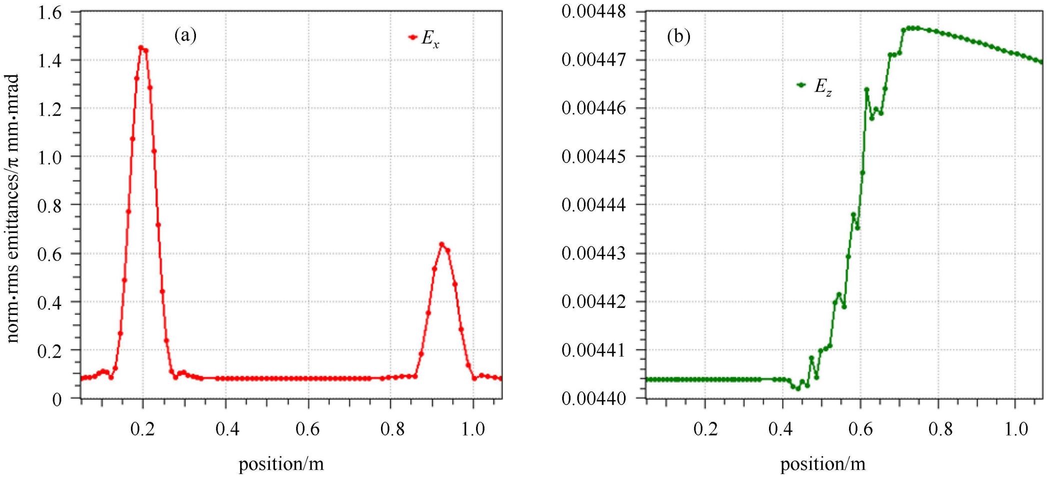

Fig. 5. (color online) Evolution of the normalized rms emittance in (a) the transverse direction and (b) the longitudinal direction.

The normalized rms emittance at the exit of the lattice structure in the transverse direction remains almost unchanged compared with that of the input beam. Due to the acceleration in the longitudinal direction, the normalized rms emittance in the longitudinal direction increases by about 2%.

Figure 4(a) shows the envelope variation in the x direction along the lattice structure. The specific envelope variation of z' in the z direction in the minend gap is shown in Fig. 4(b). Also, the evolution of the normalized rms emittance in both transverse direction and longitudinal directions is shown in Fig. 5.

Both the TraceWin simulation and the numerical calculation shows that the proton's output energy is 1.16 MeV, resulting in a relatively high effective accelerating gradient of 2.6 MV/m.

On the whole, the TraceWin simulation has preliminarily shown that the beam can pass through the cavity smoothly if KONUS beam dynamics are used. This new accelerating structure may be a possible candidate for superconducting operation in a very low energy range with a relatively high effective accelerating gradient. Reducing the length of the first accelerating gap to meet the KONUS requirement, however, may raise the peak electric field. This may be resolved by changing the first accelerating gap from a 0.5 $\beta\lambda$ structure to a 1.5 $\beta\lambda$ structure, or by increasing the input energy, of which the feasibility has not been verified yet.

Also, this cavity faces great challenges in manufacturing, and its feasibility of production is being discussed.

5 Conclusion

For the application of high intensity and CW proton beam acceleration, a new superconducting accelerating structure for low energy protons, working in TE210 mode, has been proposed. By applying KONUS beam dynamics, the design of a long, lens-free multi-gap superconducting resonator becomes possible. The cavity consists of eight electrodes and eight accelerating gaps. The RF frequency of the cavity is 162.5 MHz, and the proton's input energy is 200 keV. The cavity's longitudinal length is 368.5 mm, and its transverse diameter is 416 mm. Peak field optimization has been performed for the lower surface field. The maximum electric and magnetic fields are 28.3 MV/m and 41.4 mT, respectively. A phase sweep was done to make the cavity meet the KONUS beam dynamics requirements. Numerical calculation shows that transverse defocusing strength with the KONUS phase is about three times smaller than that with a conventional negative synchronous RF phase of 30°. TraceWin code has been used to analyze the beam dynamics of a 10 mA CW proton beam. The simulation shows, on the whole, that the beam can pass through the cavity smoothly using the KONUS beam dynamics. The gap between the first electrode and the cavity end plate should be carefully designed, however, and the input phase should be chosen properly. The feasibility of changing the first accelerating gap from a $0.5\beta\lambda$ structure to a $1.5\beta\lambda$ structure or of increasing the input energy to avoid high peak electric field is being studied.

References

1 Ostroumov P N, Kolomiets A A. Phys. Rev. ST. Accel. Beams, 2002, **5**(060101): 1

2 Ostroumov P N, Mustapha B et al. Phys. Rev. ST. Accel. Beams, 2012, **15**(110101): 1

3 TANG J Y, LI Z H et al. Conceptual Physics Design on the C-ADS Accelerator. IHEP-CADS-Report

4 XIAO C, HE Y et al. Chinese Physics C, 2011, **35**(11): 1053–1058

5 Ratzinger U. Nucl. Intrum. Methods A, 1998, **415**: 229–235

6 Amberg M, Aulenbacher K et al. Proceedings of IPAC. Spain, 2011. 268–270

7 Podlech H, Ratzinger U et al. Phys. Rev. ST. Accel. Beams, 2007, **10**(080101): 1–19

8 Busch M, Dziuba F et al. Proceedings of SRF, France. 2013. 896–898

9 Uriot D. TraceWindocumentation. http://irfu.cea.fr/Sacm/logiciels/index3.php,2011

10 Ratzinger U. Proceedings of EPAC, Austria, 2000. 98–102

11 CHEN J E. Foundation of Accelerator Physics. Beijing: 1993 (in Chinese)