Study of medium beta elliptical cavities for CADS*

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Abstract: The China Accelerator-Driven Sub-critical System (CADS) is a high intensity proton facility to dispose of nuclear waste and generate electric power. CADS is based on a 1.5 GeV, 10 mA CW superconducting (SC) linac as a driver. The high energy section of the linac is composed of two families of SC elliptical cavities which are designed with geometrical beta 0.63 and 0.82. In this paper, the 650 MHz β=0.63 SC elliptical cavity is studied, including cavity optimization, multipacting, high order modes (HOMs) and generator RF power calculation.

Keywords: high current, medium beta, ADS, superconducting cavity, HOMs

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1 Introduction

China is striving to develop nuclear energy, and 58 million kilowatts of the nuclear power will be reached in 2020. The nuclear waste will accumulate to 10400 tons [1]. The demands of nuclear energy will grow further with economic development. The disposal of nuclear waste and the shortage of nuclear fuel are therefore increasingly serious in China. An Accelerator-Driven Sub-critical System (ADS) is the optimal way to dispose of nuclear waste and solve the problems of nuclear fuel shortage. The China Accelerator-Driven Sub-critical System (CADS) is being promoted and constructed by the Chinese Academy of Sciences (CAS), as a long-term energy strategy for China.

CADS is composed of a superconducting (SC) linac, a spallation target and a nuclear reactor operating in subcritical mode. The schematic of the configuration of the SC linac is shown in Fig. 1. There are two different injectors operating in parallel, which act as a spare for each other to satisfy the strict requirement on stability in the low energy section. The injector is followed by two kinds of cavities, the spoke cavity and the elliptical cavity, which are designed to accelerate protons to 1.5 GeV.

This paper is mainly concerned with the radio-frequency (RF) properties, multipacting, damping of HOMs and required generator power of the 650 MHz β=0.63 elliptical cavity which accelerates protons from 180 MeV to 360 MeV.

Fig. 1. (color online) Layout of the CADS linac.

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2 Cavity RF design

The elliptical cavity can be parameterized with the geometrical parameters shown in Fig. 2. The shape of the elliptical cavity is optimized for ideal electromagnetic and mechanical properties by tuning the geometrical parameters. The optimum design of an elliptical cavity is the consequence of a series of compromises among RF properties, mechanics, multipacting and HOMs damping requirements.

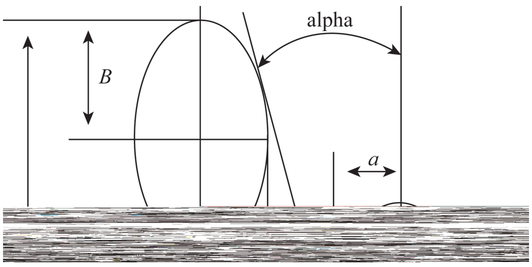

Fig. 2. Geometrical parameters of elliptical cavity.

The following must be taken into consideration for the cavity design:

1) HOMs damping is primarily of concern in high-current SC elliptical cavity design. A larger cavity aperture reduces the interaction between the cavity and beam, and also improves the cell-to-cell coupling to reduce potential for trapped HOMs and beam instability. The geometry is optimized to tune the frequency of the monopole HOMs away from the fundamental machine line, which could reduce power dissipation.

2) The accelerating efficiency improves by increasing the numbers of cells per cavity, which can raise the active accelerating length per meter for the whole accelerator. On the other hand, more cells per cavity not only make the transit time factor (TTF) drop faster, as illustrated in Fig. 3, but also makes it difficult to extract and damp the HOMs. Five cells per cavity is a compromise between the accelerating efficiency, the particle acceptance of TTF and HOMs damping.

3) The following RF properties are required:

a) Maximize the R/Q of the accelerating mode to minimize the cavity wall dissipation.

b) Minimize the $E_{\rm pk}/E_{\rm acc}$ and $B_{\rm pc}/E_{\rm acc}$ to avoid field emission and quench at lower gradients to get a higher accelerating gradient.

c) Large cell-to-cell coupling to improve field flatness and reduce potential for trapped HOMs.

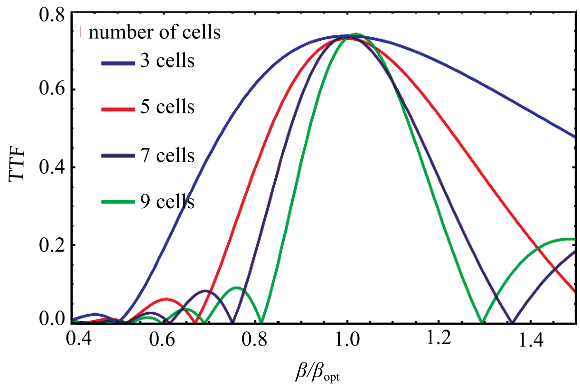

Fig. 3. (color online) TTF versus a ratio of beam velocity β to the optimum $\beta_{\rm opt}$.

A 650 MHz β=0.63 superconducting cavity was designed and studied using Superfish [2] and the 3D CST Studio Suite code [3]. The achieved cavity RF parameters are listed in Table 1. The geometry parameters are shown in Table 2. Figure 4 depicts the final β=0.63 five-cell cavity design by the 3D CST Studio Suite code.

Table 1. RF parameters of the 650 MHz β=0.63 elliptical cavity.

parameter	unit	value
$\beta_{\rm g}$		0.63
frequency	MHz	650
equator diameter	mm	394.4
iris aperture	mm	90
beam pipe aperture	mm	96
cell-to-cell coupling	%	0.9
$R/Q(\beta_{\rm g})$	Ω	333.5
G	Ω	192.7
$E_{\rm peak}/E_{\rm acc}(\beta_{\rm g})$		2.34
$B_{\rm peak}/E_{\rm acc}(\beta_{\rm g})$	mT/(MV/m)	4.63

Table 2. Geometrical parameters of the 650 MHz β=0.63 elliptical cavity.

parameter	unit	center cell	end cell
L	mm	72.5	75.2
iriis	mm	90	96
D	mm	394.4	394.4
A	mm	53	52
B	mm	58	58
a	mm	16	15
b	mm	31	29
α	(°)	3	4.7

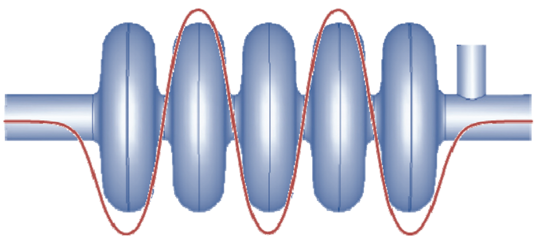

Fig. 4. (color online) Final β=0.63 five-cell cavity design.

3 Multipacting simulation

Multipacting restricts SC cavity performance and accelerating gradient enhancement since a great number of electrons reach resonance and absorb RF power. It also leads to the temperature of the SC cavity rising and eventually to thermal breakdown. It is crucial to optimize the shape of the cavity to eliminate unexpected multipacting barriers. Multipac 2.1 [4] code was used to simulate the multipacting of the 5-cell media beta elliptical cavity. Figure 5 shows the enhanced counter function. The results indicate that the multipacting barrier can be processed for a good cavity surface.

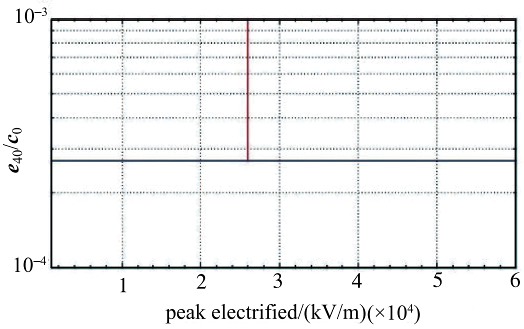

Fig. 5. Enhanced counter function: ratio of the number of particles after the 40$^{\text{th}}$ impact to the initial number of particles.

4 High Order Modes (HOMs)

HOMs excited by the beam need to be analysed in detail in the SC cavity. HOMs not only adversely impact on the beam and degrade the beam quality, even leading to beam loss and beam breakup, but they also interact with the cavity wall, inducing additional power dissipation and even thermal breakdown. Therefore, finding the HOMs is crucial in SC elliptical cavity design.

The effect of HOMs on beam instability in the proton linac is much lower than that in the electron linac due to the relatively high proton mass compared to that of the electron. In the case of CADS, HOMs simulation shows that the effect of longitude (mainly monopole modes) and transverse parasitic mode (mainly dipole modes) is not a big concern. The effective transverse emittance increase induced by HOMs is lower than the tolerable limit even for external Q=10^8 and beam current =100 mA [5]. If the frequency of HOMs is far away from the machine line and R/Q are small, the longitudinal beam instability induced by HOMs has little effect [6]. Therefore, the frequency of HOMs is sufficiently far away from the mechanical resonance frequency, even when variation of HOMs frequency due to imperfect manufacture is considered.

The power dissipation induced by TM-monopoles in the cavity wall is much larger than that induced by multipoles such as dipoles and quadrupoles. Hence the calculation of the power dissipation by HOMs mainly concerns TM-monopoles [7]. If the voltage of HOMs excited by the beam in the SC cavity reached an equilibrium state in continuous wave (CW) operation, the actual power dissipated by mode n in the cavity wall can be directly calculated by the following formula, which does consider the beam noise:

$$P_{\mathrm{c},n}=\frac{|V_n|^2}{(R/Q)_n(\beta)Q_{0,n}}. \tag{1}$$

Here, V_n is the longitudinal cavity voltage of mode n of the HOMs excited by the beam.

Figure 6 shows the actual power dissipation induced by HOMs in the medium-beta elliptical cavity walls in the parameter space of Q_{ex} and frequency. From Fig. 6(a) we can conclude that at resonance the dissipated power increases exponentially with Q_{ex} and reaches

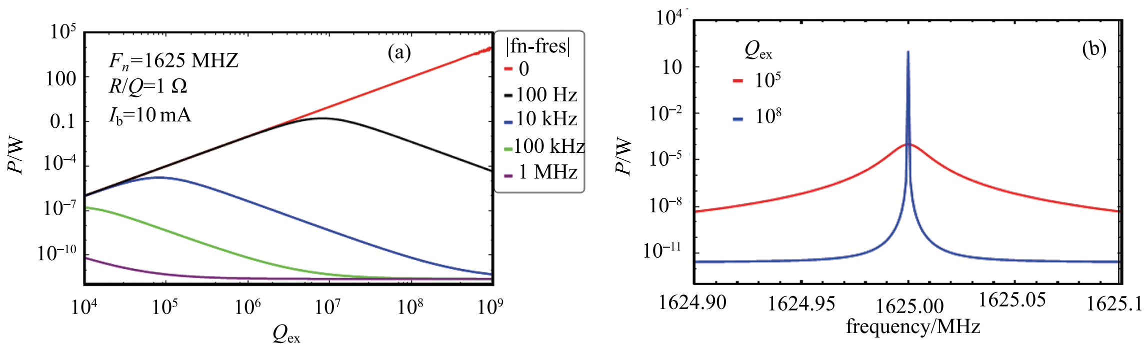

Fig. 6. (color online) HOM power dissipation in cavity wall versus (a) Q_{ex} and (b) frequency.

100 W/Ω at $Q_{\rm ex}$ $=10^8$, but drops quickly with $Q_{\rm ex}$ when the frequency is far away from the machine line. Fig.6 (b) illustrates the dissipated power as a function of frequency among the machine line with different $Q_{\rm ex}$. The bandwidth of the dissipated power at resonance with $Q_{\rm ex}=10^8$ is much smaller than that with $Q_{\rm ex}=10^5$. The probability of HOMs at resonance with $Q_{\rm ex}=10^8$ are much smaller than that with 10^5.

Frequency, $Q_{\rm ex}$ and R/Q of each HOM can be simulated with the 3D CST Studio Suite code. Table 3 depicts the frequency and $Q_{\rm ex}$ of TM-s, and Fig. 7 shows the maximum R/Q from 180 MeV to 360 MeV of TM-monopoles. The R/Q of monopole modes, except for the fundamental modes, is very small compared to the accelerating mode and the $Q_{\rm ex}$ of most monopole modes is about $\sim 10^8$. The theoretical dissipated power of monopole modes is about $\sim 10^{-10}$ without considering beam noise and variation of HOMs frequencies in actual operation.

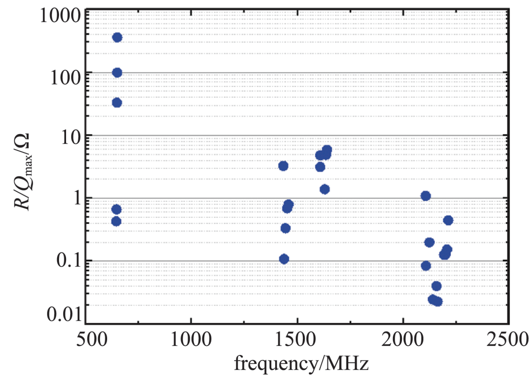

Fig. 7. (color online) Maximum $(R/Q)(\beta)$ value in the used velocity range for all monopole modes up to 2.5 GHz.

Table 3. Frequency and $Q_{\rm ex}$ of TM-monopoles in the elliptical cavity.

mode	frequency/MHz	off resonance/MHz	$Q_{\rm ex}$	mode	frequency/MHz	off resonance/MHz	$Q_{\rm ex}$
TM020,1/5π	1432.95	29.55	7.30E+08	TM011,1/5π	1606.90	18.10	1.65E+07
TM020,2/5π	1436.52	25.98	2.86E+08	TM011,2/5π	1606.97	18.03	4.92E+07
TM020,3/5π	1442.81	19.69	2.53E+08	TM011,3/5π	1628.56	3.56	1.28E+09
TM020,4/5π	1450.60	11.90	3.69E+08	TM011,4/5π	1634.21	9.21	1.10E+09
TM020,5/5π	1457.31	5.19	1.13E+09	TM011,5/5π	1638.85	13.85	3.20E+09
TM021,1/5π	2104.32	8.18	3.56E+05	TM012,1/5π	2160.58	48.08	1.84E+09
TM021,2/5π	2105.81	6.69	4.21E+05	TM012,2/5π	2190.58	78.08	1.78E+02
TM021,3/5π	2121.64	9.14	3.07E+06	TM012,3/5π	2197.24	77.76	6.16E+04
TM021,4/5π	2138.55	26.05	1.60E+02	TM012,4/5π	2205.00	70.00	6.11E+12
TM021,5/5π	2155.22	42.72	6.32E+07	TM012,5/5π	2211.01	63.99	4.33E+02

5 Required generator power

The 650 MHz β=0.63 SC cavity is designed to operate in an accelerating gradient ($E_{\rm acc}$) of 15 MV/m. The optimum external Q needs to be considered to minimize the generator power of the input power coupler. In fact, the practical requirement on power needs to consider the effect of frequency detuning and the accelerating gradient upgrading in the cavity design. The generator power is determined by the following equations [8] for a given accelerator field.

$$P_{\rm g}=\frac{V_{\rm c}^2}{R_{\rm sh}}\frac{1}{4\beta}\{(1+\beta+b)^2+[1+\beta\tan\psi-b\tan\phi]^2\} \quad (2)$$

and

$$b=\frac{R_{\rm sh}i_0\cos\phi}{V_{\rm c}},$$

$$\tan\psi=-2\frac{Q_0}{1+\beta}\frac{\Delta\omega}{\omega}.$$

Here, $R_{\rm sh}$ is the shunt impedance, $V_{\rm c}$ is the voltage in the cavity, i_0 is the beam dc current, ϕ is the detuning angle and ψ is the beam phase.

The RF power needed for the 650 MHz β=0.63 SC cavity versus the external Q at $E_{\rm acc}$= 15 MV/m is illustrated in Fig. 8. If a conservative detuning of 25 Hz is assumed, we can get an optimum external Q ranging from 2.9×10^6 to 3.3×10^6 with moderate generator power of 120 kW. Figure 9 and Fig. 10 depict the minimum generator power and the optimum eternal Q versus the accelerating gradient. The optimum generator power would be 150 kW which could make the accelerating gradient reach 20 MV/m.

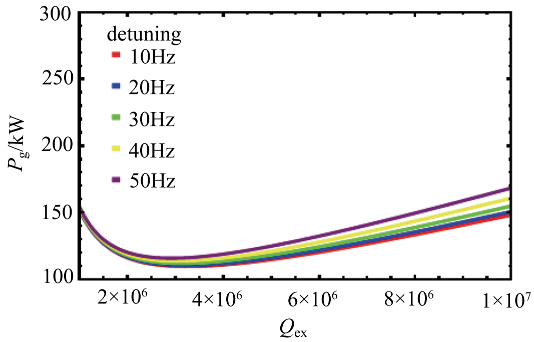

Fig. 8. (color online) RF power versus external Q at accelerating gradient $E_{\rm acc}$= 15 MV/m.

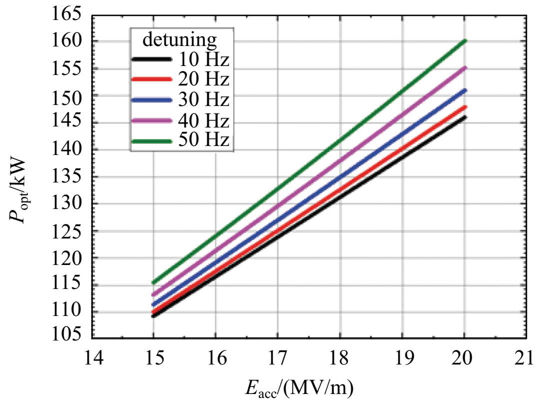

Fig. 9. (color online) Minimum generator power versus accelerating gradient E_{acc}.

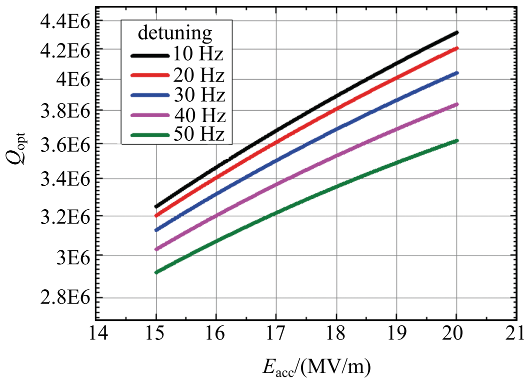

Fig. 10. (color online) Optimum external Q versus accelerating gradient E_{acc}.

6 Comparison with other projects

The achieved cavity RF parameters are listed in Table 4 in comparison with various cavities designed for ESS, SNS, SPL and PIP-II [9]. The RF parameters and mechanical stability are constrained by the iris aperture. The choice of the iris aperture is the consequence of compromises between HOM damping, α, RF parameters and mechanical stability. On the one hand, larger iris aperture and α improve mechanical stability in relation to cell deformations and the ability for chemical etching at the cell equator, but they decrease most of the RF parameters which are mainly constrained by iris aperture [10]. On the other hand, HOM damping is the primary concern compared with RF parameters for a medium-beta elliptical cavity in a high-current proton linac. The CADS medium-beta elliptical cavity is designed for a 10 mA CW beam. Pulsed mode can provide a much longer time for HOMs to decay compared with CW mode. However, HOMs in CW mode reach a steady state and the effect of HOMs is very small if the HOMs frequencies deviate from the mechanical resonance. Pulsed mode has more mechanical resonances than CW mode since there might be as many as three or more beam time-structures in linacs designed for different pulsed beam applications and each time-structure of a pulsed beam generates resonances [7]. Hence a stronger damping of pulsed mode is required than that of CW mode. A larger iris aperture decreases the interaction between the beam and cavity and reduces the potential for trapped HOMs.

Table 4. Parameters of different medium-beta elliptical cavities.

	unit	ESS	SNS	SPL	PIP-II(Fermilab)	PIP-II(JLAB)	CADS
geometrical beta		0.67	0.61	0.65	0.61	0.61	0.63
frequency	MHz	704.42	805	704.42	650	650	650
number of cells		6	6	5	5	5	5
beam mode		pulse	pulse	pulse	pulse	pulse	cw
$E_{peak}/E_{acc}(\beta_g)$			2.72	2.63	2.26	2.71	2.34
$B_{peak}/E_{acc}(\beta_g)$	(mT/MV/m)		5.81	5.12	4.21	4.78	4.63
$E_{peak}/E_{acc}(\beta_{opt})$		2.36					2.25
$B_{peak}/E_{acc}(\beta_{opt})$	(mT/MV/m)	4.79					4.45
G	/Ω	196.6	176	197	191	190	192.7
$R/Q(\beta_g)$	/Ω		279	275	378	296.6	333.5
$R/Q(\beta_{opt})$	/Ω	394					360
iris aperature	/mm	94	86	96	83	100	90

Based on the above considerations, the medium-beta elliptical cavity of CADS is designed compared with other medium-beta elliptical cavities from different projects. Though the RF parameters of the cavity are best in the design of PIP-II (Fermilab), with an iris aperture $R_{iris} = 83$ mm and small α, a further analysis of the cavities' mechanical stability is required. In CW mode, the power dissipation in the cavity wall induced by the accelerating mode is much more than that in pulsed mode, so it is crucial to maximize the R/Q of the accelerating mode to minimize the cavity wall dissipation. The R/Q per cell of the CADS medium-beta elliptical cavity is the largest among the medium-beta elliptical cavity designs of all the projects except for PIP-II (Fermilab). Furthermore, $E_{\rm peak}/E_{\rm acc}$ and $B_{\rm peak}/E_{\rm acc}$ of the CADS media beta elliptical cavity are the best of the designs except for PIP-II (Fermilab). The designed $E_{\rm acc}$ ($\beta_{\rm g}$) is 15 MV/m, so that $E_{\rm peak}$ is 35.1 MV/m and $B_{\rm peak}$ is 69.45 mT. The RF parameters of the CADS medium-beta elliptical cavities are reasonable, and the final design of the medium-beta elliptical cavities meets the requirements of the CADS linac.

7 Summary

A 650 MHz β=0.63 SC elliptical cavity is designed for the CADS linac, accelerating proton beams from 180 MeV to 360 MeV. The RF and geometry parameters meet the requirements for the CADS linac. The multipacting was checked by the Multipac 2.1 and no hard multipacting barriers are found in the cavity. The problems induced by HOMs are theoretically not a main concern in the β=0.63 SC elliptical cavity. The optimum external Q ranges from 2.9×10^6 to 3.3×10^6 and the moderate generator power is 120 kW at the designed gradient $E_{\rm acc}$=15 MV/m.

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