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Study on Design of Superconducting Proton Linac for Accelerator Driven Subcritical Nuclear Power System*

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Abstract: As a prior option of the next generation of energy source, the accelerator driven subcritical nuclear power system (ADS) can use efficiently the uranium and thorium resource, transmute the high-level long-lived radioactive wastes and raise nuclear safety. The ADS accelerator should provide the proton beam with tens megawatts. The superconducting linac (SCL) is a good selection of ADS accelerator because of its high efficiency and low beam loss rate. It is constitute by a series of the superconducting accelerating cavities. The cavity geometry is determined by means of the electromagnetic field computation. The SCL main parameters are determined by the particle dynamics computation.

Key words: ADS, Superconducting linac, Beam loss rate

INTRODUCTION

The rapid development of the national economy asks for sufficient energy supply. It is more pressing for China, whose economy increases at a rate of about 8% per year. Now our electrical supply mainly comes from coal burning. It gives us the serious troubles in transportation and environment. The coal is a precious chemical material and its deposits in the world are limited. So to burn coal is a great waste.

Nuclear energy is an effective, clean and safe energy resource. But now, there are some shortages in commercial nuclear fission energy system: the resource utilization is very low and a great amount of high-level long-lived radioactive wastes exists in spent fuel. Recently the accelerator driven

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subcritical nuclear power system (ADS) attracts interest of the international nuclear community. In ADS the high power proton beam from an accelerator bombards a heavy target in the subcritical reactor and produces a large amount of spallation neutrons to keep the chain fission reaction. The extra neutrons can transmute radioactive wastes and breed nuclear fuel. The ADS can utilize efficiently the uranium and thorium resource, supply electric energy without production of a great amount of radioactive wastes and raise the safety of the system [1]. Many countries have carried out lots of research works.

1 SUPERCONDUCTING LINAC

The ADS accelerator should provide the beam power of several ten megawatts, which is tens of times higher than that of the highest one in the world at present. It needs low beam loss, high efficiency and high reliability. The superconducting linac (SCL) is a good selection of ADS accelerator because of its many advantages [2, 3]:

(1) Negligible wall powers losses, which increase the power efficiency and saves the cost of operation.

(2) Higher accelerating gradient, which reduces the accelerator length and saves the cost of construction.

(3) Larger beam hole, which reduces the beam loss rate.

(4) Fewer cells per accelerating cavity, which extends the velocity acceptance.

The SCL is constituted by a series of the multicell elliptical superconducting accelerating cavities. In accelerating process the proton velocity increases gradually. We define the physical β value as the ratio of the proton velocity to the light velocity and geometric β value β_0 as $\beta_0=2L/\lambda$, where L is the accelerating cell length and λ the radio frequency (RF) wavelength.

For an accelerating cavity with N identical cells, the proton energy gain is:

$$\Delta W=qNLE_{\mathrm{a}}T_{\mathrm{cav}}\cos(\phi_0),\ \ E_{\mathrm{a}}=E_0T_0,\ \ T_{\mathrm{cav}}=\beta\sin(\pi\lambda\beta_0/\beta)T_{\mathrm{s}}/[\beta_0\sin(\pi\gamma)] \quad (1)$$

where q is the proton charge, E_a the accelerating gradient, T_{cav} the relative transit time factor of the cavity, ϕ_0 the phase of the RF field when the beam bunch centroid is at the cavity center, E_0 the amplitude of the axial average accelerating field, T_0 the transit time factor of the inner cell for β_0, and γ the accelerating gap factor given by

$$T_0=\sin(\pi\gamma)/(\pi\gamma) \tag{2}$$

and T_s is the synchronism factor given by

$$T_s=\begin{cases}\dfrac{2}{N}\left[\dfrac{1}{2}+\sum_{i=1}^{m}\tau_i\cos(i\Delta\phi)\right], & m=\dfrac{N-1}{2}, \quad N=1,\ 3,\ 5,\cdots \\ \dfrac{2}{N}\sum_{i=1}^{m}\tau_i\cos\left[\left(i-\dfrac{1}{2}\right)\Delta\phi\right], & m=\dfrac{N}{2}, \quad N=2,\ 4,\ 6,\cdots\end{cases} \tag{3}$$

$$\Delta\phi=(\beta_0/\beta-1)\pi \tag{4}$$

When $i=m$, $\tau_i=T_0'/T_0$, otherwise $\tau_i=1$. T_0' is the transit time factor of the end cell for β_0. T_0 and T_0' can be given in the cell geometry computation. When $\beta=\beta_0$, $T_{cav}=T_s=1$. Fig. 1 shows the variations of T_{cav} with β. Evidently, the larger N is, the smaller the velocity acceptance is.

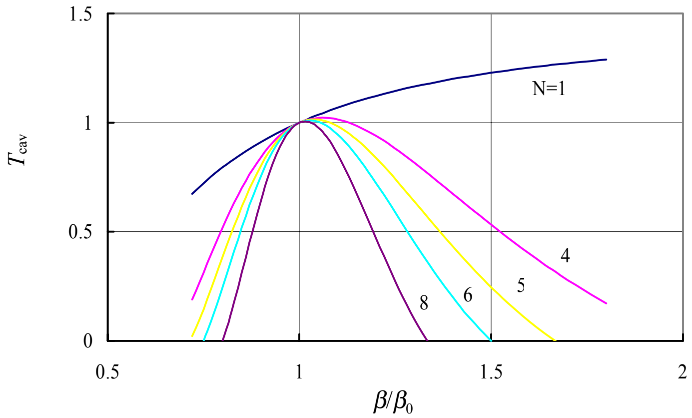

Fig. 1 The variations of T_{CAV} with β (N=1, 4, 5, 6, 8)

2 CELL AND CAVITY GEOMETRY COMPUTATION

We consider an elliptical SCL as the high-energy part (>100 MeV) of a 1 GeV, 30 mA ADS accelerator (its low energy part, a radio frequency quadrupole (RFQ) and a low velocity SCL, will be not discussed here). For convenience of manufacture, the SCL is divided into three sections with different geometric β value. Every section is of a periodic focussing structure. Every focussing period includes a cryomodule and a focussing quadrupole doublet. The superconducting accelerating cavities are laid in the cryomodules for maintaining necessary low temperature. In the same section all the components and their relative positions in the period are the same.

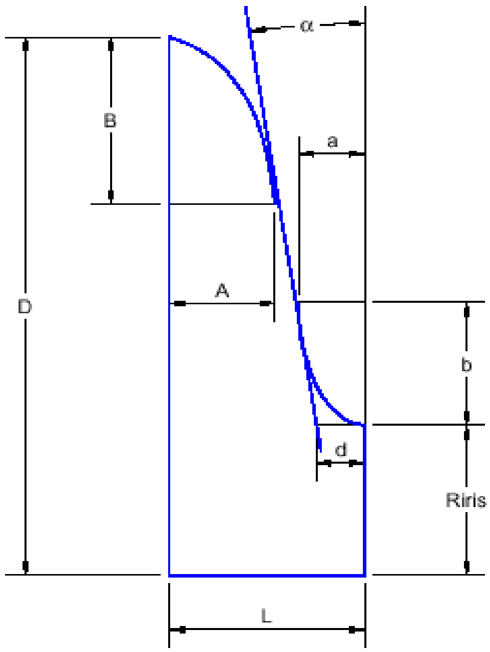

Fig. 2 The cell geometry

We adopt the 5-cell superconducting cavities. A larger N reduces the velocity acceptance and a smaller N reduces the energy gain per cavity. The cell geometric parameters (see Fig. 2) determine its electromagnetic performance[4]. The cell radius D is used for the RF frequency tuning. The beam hole radius R_{iris} should be higher than 30 times of beam size. It determines the cavity-coupling factor. The $r=b/a$, $R=B/A$ and d allows to find the local minimums for the peak surface electric field and peak surface magnetic field on the cavity walls. The wall angle inclination α influences the mechanical behavior.

In order to determine a cell geometry that has the necessary electromagnetic performances we first compute the distribution of the RF electromagnetic field in the cell and the cell performance parameters for the trial initial cell geometry by means of the RF electromagnetic field software SUPERFISH [5]. Then we modify the cell geometry and compute again until the satisfied results are obtained.

To determine a cavity geometry a separate iterative procedure is need for the end cells because their geometry is different from that of the inner cells.

3 DETERMINATION OF MAIN PARAMETERS OF SCL

The determination of main parameters of SCL is a key task of the design work[6]. For saving the cost of construction and operation, we hope to use as few cavities and low power as possible. The proton energy gain per cavity relates to the physical β value, geometric β value, accelerating gradient and cavity geometry. The RF power required per cavity, which is approximately equal to the product of the beam current times the proton energy gain per cavity, cannot exceed RF coupler capability 350 kW. We adopt the constant gain mode except the first four cavities. To maintain constant energy gain ΔW per cavity in a section, the accelerating gradient E_a can be chosen to compensate for the variations of the relative transit time factor of the cavity T_{cav} with the physical β. But the surface electric field cannot be higher than 25 MV/m to avoid multipacting. We must carefully select the main parameters of SCL within these permitted limits. It should be performed together with the cavity geometry computation.

4 PARTICLE DYNAMICS COMPUTATION

In order to determine the parameters of all the cavities and quadrupoles it is necessary to do particle trace computation by particle dynamics software

PARMILA[7]. First we get the positions and momentum of hundreds or thousands ‘macroparticles’ by random sampling from the position and momentum distribution in the proton beam at SCL input. The ‘macroparticle’ has the same charge-mass-ratio as the proton but its charge and mass are very much larger than proton. Then the orbits of these ‘macroparticles’ in the SCL electromagnetic field are computed and the changes of the beam parameters along the beam direction are determined. We hope to accelerate the proton beam to given energy with allowable beam loss rate using as few components and low power as possible. If the results are not satisfied we will adjust some parameters and compute again. Our main results are listed in Table 1.

Table 1 Main parameters of SCL

Section	1	2	3
Geometric β	0.5	0.62	0.76
Output Energy /MeV	217	412	1000
Beam Current /mA	30	30	30
Working Frequency /MHz	704	704	704
Section Length /m	80.0	74.1	163.8
Number of Cavities	40	39	84
Cavity Length /cm	52	66	80
Accelerating Gradient/MV • m^{-1}	6.6～8.8	8.7～9.8	10～11
Energy Gain per Cavity /MeV	2～3	5	7
Cavity Radius /cm	18.6	18.7	18.9
Beam Hole Radius /cm	5	5	5
Ratio of Peak Surface Electric Field to Accelerating Gradient	2.85	2.58	2.08
Synchronous Phase/deg	−30	−30	−30
Focussing Period Length /m	4.0	5.7	7.8
Cryomodules Number	20	13	21
Cavities per Cryomodule	2	3	4
Cavities per Klystron	2	3	2
Beam Power /MW	3.51	5.85	17.64

5 FURTHER WORKS

(1) We will do some structural mechanics computation of the cavities and some study about influences of the nonlinear electromagnetic fields (including the nonlinear space charge effect) to the motion of protons.

(2) In recent years a superconducting cavity laboratory will be built for research and development of the superconducting linacs.

REFERENCES

1 Rubia C, Rubio J A. A Tentative Programme Towards a Full Scale Energy Amplifier. CERN/LHC/96-11(EET)

2 Prome M. Major Projects for the Use of High Power Linacs. Proc. Inter. Linac Conf., 1996. 9

3 Chan K C D, et al. Review of Superconducting RF Technology for High-Power Proton Linacs. Proc. 9th Workshop on RF Superconductivity, 1999

4 Pierini P, et al. Cavity Design Tools and Applications to the TRASCO Project. Proc. Euro. Part. Accel. Conf., 2000

5 Halbach K, Holsinger R F. Particle Accelerators, 1976, 7: 213

6 Wangler T P, et al. Beam Dynamics Design and Simulation Studies of the APT Superconducting Linac. Proc. Part. Accel. Conf., 1999

7 Boicourt G P. PARMILA – An Overview. AIP Conf. Proc., 1988, 177: 1

加速器驱动次临界核能系统超导质子直线加速器设计研究

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摘　要：加速器驱动次临界核能系统（ADS）是下一代能源的首选方向。它能有效地利用铀和钍资源，嬗变长寿命高放射性废物和提高核安全水平。ADS 加速器应能提供几十兆瓦质子束。超导直线加速器（SCL）效率高，束流损失少，是 ADS 加速器的最佳选择。它由一系列超导加速腔组成。利用电磁场计算确定腔的形状，利用粒子动力学计算确定 SCL 的主要参数。

关键词：ADS　超导直线加速器　束流损失