CONCEPTUAL STUDY OF HIGH POWER 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 is a good selection of ADS accelerator because of its high efficiency and low beam loss rate. Our ADS accelerator consists of a 5 MeV radio-frequency quadrupole, a 100 MeV independently phased superconducting cavity linac and a 1 GeV elliptical superconducting cavity linac. The accelerating structures and main parameters are determined and the research and development plan is considered.

1 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%. Now our electrical supply mainly comes from coal burning. It brings us serious troubles in transportation and environment. To burn coal is a great waste because coal is a precious chemical material and its deposits in the world are limited.

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 exist in spent fuel. Recently the accelerator driven subcritical nuclear power system (ADS) attracts the interest of the international nuclear community. In ADS a heavy nucleus target in the subcritical reactor is bombarded by the high power proton beam from an accelerator and a large amount of spallation neutrons are produced in order 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.

Based on the calculations of C. Rubbia and his colleagues, as a stable and reliable industrial power system, the proton beam power cannot be less than 25—30 MW [1]. To achieve this object, we have much to do in decreasing beam loss, increasing the accelerator efficiency and raising reliability.

The number of spallation neutron produced by proton bombardment depends on proton energy, beam current, target geometry and target material. Above 1.3 GeV the neutron production rate for a given power is nearly independent of the proton energy. The construction and operation cost of the accelerator mainly depends on the energy and the construction difficulty on the beam current. As a compromise, we select a 1 GeV, 30 mA proton linac. It will operate on CW mode in order to decrease the beam loss as a result of the space charge effect and transition effect due to the sudden change of beam current.

The superconducting cavity linac (SCL) is a good selection of ADS accelerator because of its many advantages [2,3]:

1. Negligible wall power 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 bore, which reduces the beam loss rate;
4. Fewer cells per accelerating cavity, which extends the velocity acceptance.

Fig. 1 shows the block diagram of our ADS accelerator, which is divided into two main parts: the low energy part up to 100 MeV and the high energy part from 100 MeV to 1000 MeV. Above 100 MeV the multicell elliptical superconducting cavities are adopted. For 5—100 MeV we use the single gap reentrant superconducting cavities because the velocity acceptance of multicell cavities is poor in low β range. An RF frequency of 352 MHz has been chosen for low energy part and 704 MHz for high energy part.

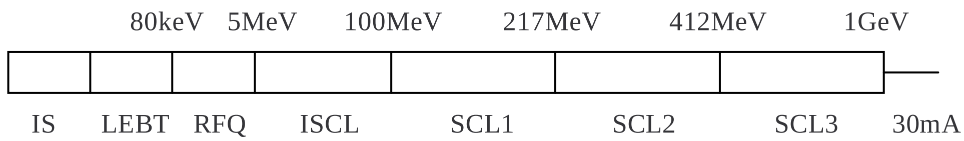

Figure 1: The block diagram of the ADS accelerator

2 LOW ENERGY PART

The low energy part consists of a microwave ion source (IS), a low energy beam transport system (LEBT), a radio frequency quadrupole (RFQ) and an independently phased superconducting cavity linac (ISCL).

We select the microwave ion source because it can guarantee the expected performances in terms of proton fraction, emittance, reproducibility, reliability and stability. In particular, it has not parts subject to consumption and can work for weeks without any maintenance.

The salient feature of the RFQ is that it bunches, focuses and accelerates charged particles by using RF fields only. It is certainly the best machine in existing accelerators today for low energy ions.

Our RFQ of four vane type consists of three sections. Each section is made up of two segments brazed together. In order to decrease the space charge effect of the low energy proton beam we adapt a higher input energy 80 keV. The list of the main parameters is shown in Table 1.

Table 1: The main parameters of RFQ

Input Energy (keV)	80
Output Energy (MeV)	5
Beam Current (mA)	30
Working Frequency (MHz)	352
Normal Transverse RMS Emittance (πmmmrad)	0.2
Normal Longitudinal RMS Emittance (πMeVdeg)	0.2
Total Length (m)	7.1
Intervane Voltage (kV)	70
Transmission	95
Synchronous Phase (deg)	-90—-30
Modulation	0.29—0.32
Average Aperture (cm)	1—1.94
Cavity RF Losses (MW)	0.58
Beam Power (MW)	0.15
Total RF Power (MW)	0.73

The extension of the superconducting RF technology to lower energy has obvious advantages for a moderate current CW proton linac. We considered an ISCL with reentrant cavities similar to Italian research program TRASCO because it has good velocity acceptance[4]. It is cylindrically symmetric and therefore theoretically dipole free. Each cavity is fed with a 15 kW single solid state amplifier. A FODO focusing structure with a period 8 $\beta\lambda$ is used. As the proton energy increases, a larger number of cavities can be installed between the quadrupoles. The list of the main parameters is shown in Table 2.

Table 2: The main parameters of ISCL

Output Energy (MeV)	100
Beam Current (mA)	30
Working frequency (MHz)	352
Total Length (m)	48
Number of Cavities	230
Cavity Length (cm)	8
Accelerating Gradient (MV/m)	~6
Beam Hole Radius (cm)	1.5
Synchronous Phase (deg)	-40
Beam Power (MW)	2.85

3 HIGH ENERGY PART

For convenience of manufacture, the SCL is divided into three sections with different geometric β valueβ_0 (SCL1, SCL2, SCL3). 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 the parameters of all the components and their relative positions in the period are the same.

For saving the cost of construction and operation, we hope to use as few cavities and low power as possible. For an accelerating cavity with N identical cells, the proton energy gain is

$$\Delta W = qNLE_a T_{cav} \cos\phi,$$

where q is the proton charge, L is the cell length, E_a is the accelerating gradient, T_{cav} is the relative transit time factor of the cavity, ϕ is the synchronous phase [3,5]. Figure 2 shows the variations of T_{cav} with β and N. A larger N reduces the velocity acceptance and a smaller N reduces the energy gain per cavity. We adopt the 5-cell superconducting cavities.

The RF power required per cavity, which is approximately equal to the product of the proton current and the proton energy gain, cannot exceed RF coupler capability 350 kW. 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.

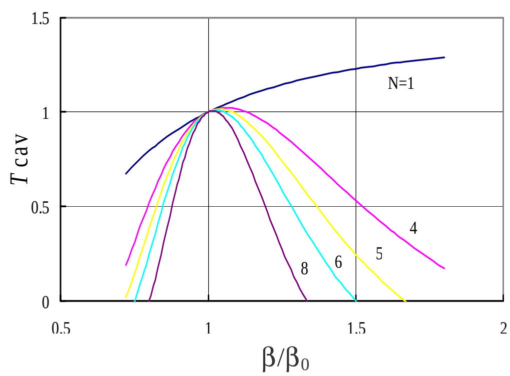

Figure2: The variations of T_{cav} with β and N.

We adopt the constant gain mode. To maintain constant energy gain per cavity ΔW 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 proton velocity. As an exception, the first four cavities of SCL1 operate in the constant gradient mode, where E_a=8.8 MV/m.

The cell geometric parameters determine its electromagnetic performances. The cell radius is used for the RF frequency tuning. The beam bore radius should be larger than 30 times of beam radius. It determines the cavity coupling factor. The shapes of ellipses determine the peak surface electric field and peak surface magnetic field on the cavity walls. For determination of the cell geometry that has the necessary electromagnetic performances we do the RF electromagnetic field computation by means of the software SUPERFISH. For determination of a cavity geometry a separate iterative procedure is need for the end cells because their geometry is different from that of the inner cells. Then we do the particle trace computation by particle dynamics software PARMILA. The results are satisfied. The main parameters of SCL are listed in Table 3.

4 FURTHER WORK

(1) We will build a 3.5 or 5 MeV RFQ with average current of 2-3 mA and duty factor of 5%.

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

Moreover, a proposal for constructing a spallation neutron source in China is presented [6]. The constuction of its injector (a 150 MeV H^- ion linac) will provide helpful experience for us.

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Table 3: The main parameters of SCL

Section	1	2	3
Design β	0.50	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)	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
Number of Cryomodules	20	13	21
Cavities per Cryomodule	2	3	4
Cavities per Klystron	2	3	2
Beam Power (MW)	3.51	5.85	17.64

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