NORMAL AND SUPERCONDUCTING PARTS OF LINEAR ACCELERATOR FOR NEUTRON SPALLATION SOURCES: MAIN PROBLEMS AND POSSIBLE SOLUTIONS

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Abstract

At present neutron source projects are developed in Europe, USA, Japan and Russia based on a linear accelerator with energy of 1.0-1.3 GeV followed by a compressor ring or a rapid cycling synchrotron with a maximum beam power of 5 MW /1/. The dominating design principle for the accelerators is the minimisation of beam losses to be kept below 1 nA/m.

In case ESS the linear accelerator is divided into two main parts: the low energy part up to 100 MeV and the high energy part from 100 MeV to 1333 MeV.

In this report we consider the conception, where the high-energy part of the linear accelerator is based on super-conducting cavities /2/. The basic parameters of the beam are taken from the normal conducting option /3/ with exception of the higher RF frequency 700 MHz for the low energy part /4/. Actually, only one change of frequency just after the funnelling allows to fill each separatrix in the accelerator, which results in the smaller number of particles in each bunch and makes easier to fulfil the particles losses requirements.

Thus, the ESS super-conducting option requires at least the solution of three fundamental problems: the super-conducting cavity development at 700 MHz with high accelerating rate in the region of $\beta \approx 0.4 \div 0.9$; the normal-conducting accelerating structure with shunt impedance in the region $\beta \approx 0.1 \div 0.4$ at 700 MHz as well; the RFQ design for 350 MHz frequency and high value of current $\approx 70mA$; the funneling system for 350 MHz at energy 5 MeV.

1 LOW ENERGY NORMAL CONDUCTING PART

The low energy part consists of two RFQs and DTL with external quadrupoles. RFQ operates at 350 MHz and accelerates the beam from 50 KeV up to 5 MeV. Two beams are joined together in the funneling system at the energy 5 MeV. The DTL operates at 700 MHz and accelerates the beam from 5 MeV up to 100 MeV.

1.1 RFQ as an accelerator and a chopper.

The RFQ forms very compact bunches after acceleration and has almost 100% efficiency. To make a shorter RFQ we refused from the conception of the quasi-constant density in the bunch and followed the principle of maximum rate of acceleration and minimum losses of particles. We have done the design of RFQ/4/, which has the length 3.2 m together with the chopping section. The potential between the electrodes U=163 kV and the average radius between electrodes R=6.71 mm. The total number of the accelerating periods is 210. The maximum value of the efficiency and the minimum synchronous phase are restricted by the matching condition with DTL. The emittance in RFQ grows by 25% and the normalized value equals to 0.25 mm mrad. The momentum spread and length of the bunch equal 0.6% and $\pm 12^0$ correspondingly. Due to low initial efficiency the momentum spread of the separatrix is relatively small. If to modulate the particle energy inside the source or just after the source the particle with the lower energy will not be accepted in the longitudinal separatrix. To minimize the required modulation of particle energy we use four from each five periods without modulation. The length of this section should be equal to one longitudinal oscillation.

1.2 Funneling system

To reach the required beam intensity for ESS of 107 mA in peak per micro pulse, two identically bunched beams have to be merged into a single beam with double intensity. The first RF facility for funnelling based on the coaxial $\lambda/2$ cavity has been designed in Los Alamos /5/. A.Schemp proposed to use two RFQs as transport channels to deliver the beams to the RF

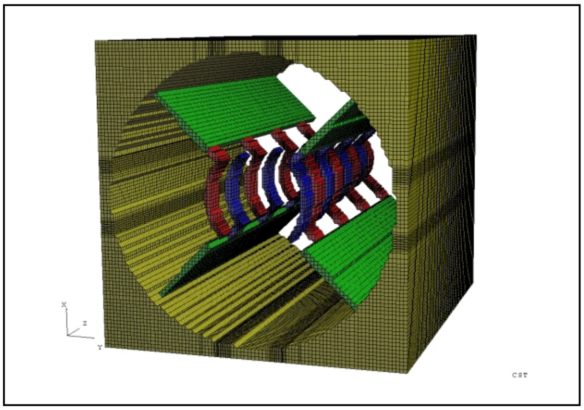

Figure 1: The funnelling multi-gaps resonant structure

deflector /6/. In these versions the funnelling system has one gap design.

We propose the resonant method of the beams funnelling based on the multi-gaps merging /7/. The figure 1 shows MAFIA picture of this structure. We have analysed, designed and compared four types of different H-cavities, which would provide the effective resonant merging of beams. Additionally, instead of the pulse dividing method into two rings (or more for multi-purposes facilities) it can be taken into account to use such a device to split the beam after acceleration into two or three beams and to deliver them to different facilities simultaneously.

1.3 DTL accelerator with bridges.

At the DTL operating frequency of 700 MHz the accelerating period $\beta\lambda$ is quite short and is changed from 4.4 cm up to 18.3 cm for energy 5-100 MeV range. Therefore the quadrupoles can be taken out of the cavity /8/. The relatively short cavities can be joined by the bridges in one module /4/. We consider the variant with 5 accelerating periods in each cavity. Totally DTL consists of 76 cavities. Each four cavities are combined in one module. The total number of modules is 19. One generator feeds one module.

Table 1: Parameters of DTL with Bridge

Input and Final Energy, MeV	5-100
Total length, m	58
Frequency, MHz	700
Operating mode	TM_{010}
Internal radius of drift tube, mm	7
Shunt impedance, $M\Omega/m$	110-60
Unloaded Q factor	60000-40000
Number of gaps per cavity	5
Number of cavities per module	4
Total number of modules	19
Length of cavity, m	0.22-0.92
Bridge length, m	0.11-0.46
Losses power per module, MW	0.04-0.32
Beam power per module, MW	0.14-0.58
Accelerating gradient, MeV/m	2.5

The acceleration rate is chosen 2.5 MeV/m in order not to exceed 1 MW power together with the reserve of 10-20% required for the system control. Due to the external placement of the quadrupoles and the higher RF frequency the shunt impedance is very high. MAFIA calculation shows the shunt impedance to be 110-60 MΩ/m and the unloaded quality factor 60000-40000 for the first and the last module correspondingly. A total power 9.7 MW for all DTL is required. The operating mode is TM_{010} and the radius of the cavity equals to 16-13 cm. The nearest mode TM_{011} for the cavity with the highest $\beta = 0.4284$ is located on 72.5 MHz from TM_{010}. Therefore we do not need a stabilizing post coupler, which allows increasing additionally the quality factor of the cavity in comparison with the conventional DTL. The bridge is the segment of the bend waveguide with the rectangular cross section, where the mode TE_{01n} is excited. Both the cavity and the bridge can be considered as coupled cells. In the case of $\pi/2$ mode the bridge plays the role of the coupling cell, where the field almost equals to zero. The nearest "bridge" mode is located 17.5 MHz from the fundamental $\frac{\pi}{2}$ mode. Such a system is a self-stabilized system, that makes it easier to tune the whole module. The rectangular shape of the bridge is more preferable in comparison with the cylindrical cross section, since it gives the higher coupling with the cavity and the stronger separation of the neighbor modes. The electrical length of the bridge has to give a place to the focusing quadrupole between cavities. We took $5\beta\lambda/2$, since the shorter distance makes the problem for the quadrupole placement. The most appropriate focusing system is FODO lattice, since the doublet requires the longer bridge. The rms beam radius remains almost constant along DTL and equals 1.2 mm at the normalized emittance 0.2 mm mrad. The aperture radius of the drift tube is chosen 7 mm.

2 HIGH ENERGY SUPER CONDUCTING PART

The high-energy part is based on the superconducting cavities /2/: the elliptical or the spoke resonator /9/. At present we test the elliptical type, although all results can be applied to another type of structure, taking in to account the electrodynamics difference between them. The working mode in the elliptical cavity is π mode of the E_{010} band. The shape of the cavity is optimised to get the maximum ratio between the accelerating and surface field (see figure 2)

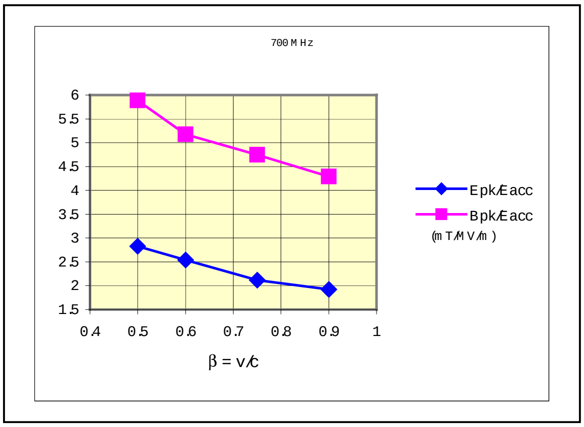

Figure 2: E_{pk}/E_{ac} vs β

together with the required coupling coefficient, which depends on the cavity aperture. Therefore at the maximum field on the surface of 40 MeV/m the accelerating rate in the first cavities does not exceed 13 MeV/m. For the high β cavities the acceleration rate is determined by the generator power. At present the industry has a 1 MW generator with the required pulse length, which really restricts the achieved acceleration rate. Each cavity consists of 5 accelerating cells. The number of cells is limited by both the RF power of the generator (1 MW) and the required coupling coefficient of structure for 1-2% to keep the slope less 1%: $\frac{\Delta E}{E_{ac}} \propto \frac{\pi}{K_f\left[1-\cos\frac{\pi}{N_{cell}}\right]\cdot Q_L E_{ac}}$. The length of the cavity equals to $2.5\beta\lambda$ and varies from 0.46 m to 0.975 m.

The accelerating field in the cavity and the ratio between the cavity length and the focusing period determines the average gain of acceleration. Since the distance between two cavities should be minimum 0.5 m and the distance between the quadrupole and the cavity not shorter than 0.7 m, the effective acceleration significantly decreases after β=0.5 down to 2 MeV/m. We analysed the cases when one, two and four cavities are placed between two neighbor focusing elements. We made choice for the option with two cavities. Each two cavities are joined in one cryogenic module and the doublet is installed between them. In the superconducting part the focusing system FDO is more appropriate due to the shorter focusing period. The phase advance for zero current is kept to be equal 90^0 along whole superconducting part of accelerator.

Due to economical reasons one type of cavity can be used with the fixed phase velocity. Such a structure is called stepped-phase-velocity structure. The number of cavities with the same phase velocity is determined by the efficiency of the non-resonant beam interaction with accelerating structure. The total gain per cavity is described by the expression: $\Delta W_{cavity} = eE_0 T_z n_c L_c \sin\varphi_0 \cdot T_\beta \cdot T_{cavity}$, where $T_{cavity} = \sin\left[\frac{\Omega(\varphi_0)}{\omega}\cdot\frac{\pi n_c}{2}\right]/\frac{\Omega(\varphi_0)}{\omega}\cdot\frac{\pi n_c}{2}$ is the time flight factor of cavity, $T_z = \int_0^{L_c} E_z(z)\cos\frac{2\pi}{L_c}z\cdot dz/\int_0^{L_c} E_z(z)\cdot dz$ is the transit factor of one cell and $T_\beta = \sin\left(\pi\cdot\frac{\delta\beta}{\beta_{ph}}\right)/\pi\cdot\frac{\delta\beta}{\beta_{ph}}$ is the non-synchronism factor, which arises from the difference $\delta\beta = \left|\beta_{particle} - \beta_{ph}\right|$ between the particle velocity and the phase velocity of accelerating structure. Actually, the effective separatrix of the stepped-phase-velocity structure is determined by the crossing of the stationary 2π phase length separatrixs of sections, where the phase velocity is constant /10/. There are two conceptions to design the stepped-phase-velocity structure. The first is when the bunch is stable and in the second it is unstable instantaneously in each stationary separatrix. Obviously, in both cases the bunch has to be stable in the effective separatrix. The first conception requires 13 groups of the constant β cavity, but it gives the higher acceleration efficiency and the higher quality beam. In the second conception $\delta\beta$ is bigger than the stationary separatrix momentum spread, and we need just only three groups of the cavities. To stabilize motion we have always to shift the RF phase on each cavity in order to compensate the bunch slipping, otherwise the total motion will be unstable as well. As a result we lose in the efficiency.

3 CONCLUSION

In the considered superconducting option we suggest to use RFQ as chopper and accelerator, the resonant multi-gap funnelling system, the very compact DTL and the super conducting structure operated both at 700 MHz. We have investigated the main aspects of the high intense linear accelerator: the halo phenomenon, the RF field distortion influence on the beam parameters and the possible regular cooling of the beam prevented the effective momentum spread growth /4/. We have studied the electrodynamics of the super conductive cavity consisting of few similar cells. We determine how the slope and the flatness of the field in the super conductive cavity are connected each with other through the group velocity.

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