

# ANALYSIS OF NORMAL- AND SUPER-CONDUCTING OPTIONS FOR ESS LOW ENERGY PART OF PROTON LINEAR ACCELERATOR

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## Abstract

At present ESS project is reconsidered to give the new impulse to the development of the neutron source project in Europe. A super-conducting option of the high-energy part from 200 MeV to 1330 MeV for the ESS linear accelerator is presently under discussion. Simultaneously, the new additional option of the proton beam long pulse is going to be implemented, what increases RF duty factor after funnelling up to 15% (see fig.1). Therefore the accelerator structure of the low energy part (from 20 MeV to 200 MeV) has to have the required high shunt impedance at frequency 704 MHz.

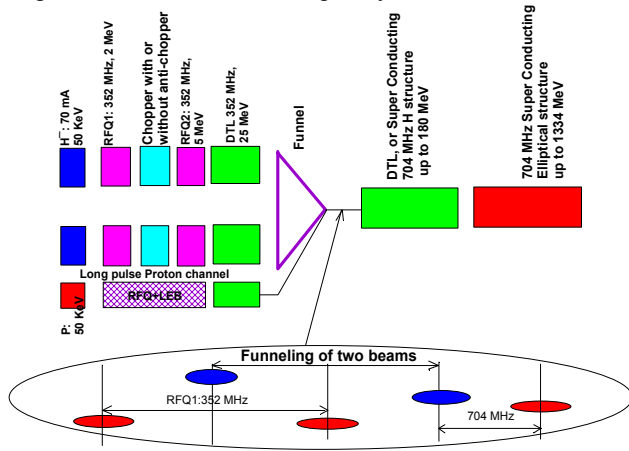


Figure 1: Super-conducting option of ESS linac

In this paper we consider the E and H types of DTL normal conducting structure and H type super-conducting structures for the low  $\beta$ . We compare the normal-conducting and super-conducting options on the basis of the electro-dynamical parameters of structures and the beam dynamics analysis. The lowest value of  $\beta$ , the number cells in one cavity and the focusing structure are entirely determined by the beam dynamics. As a result we submit the optimised super-conducting conception of the low energy part of high duty cycle ESS linear accelerator.

## 1 NORMAL CONDUCTING OPTION

In the accelerator with the high duty cycle the shunt impedance plays even the bigger role, since the structure is restricted by the maximum possible power dissipated by the cooling system, what brings up a question “yes” or “no”. The maximum power losses is determined by the construction of the structure itself and it can be varied from 10kW/m and up to 50 kW/m versus of the frequency region. To increase the shunt impedance the outer sizes of

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drift tube have to be minimized as much as possible. For that there are two possibilities: one of them is the permanent quadrupole magnet installation inside of the drift tubes and another is the taking out the quadrupoles from the cavity, what means the accelerating and focusing functions are separated. We have done MAFIA calculations for all these options at 350 MHz frequency (see fig.2).

### 1.1 SDTL and BDTL structures

The separated DTL Alvarez structure is the DTL structure with the external quadrupoles located between the cavities. Due to the external placement the drift tube is easier optimised. Therefore the losses of power can be minimized so significantly. However, the length of such cavity is determined by the required transverse acceptance and it is reasonable from this point of view to take it  $L = 5 \div 6 \beta\lambda$ . Thus, the structure has to be divided into many resonators and each one has to be fed by own generator.

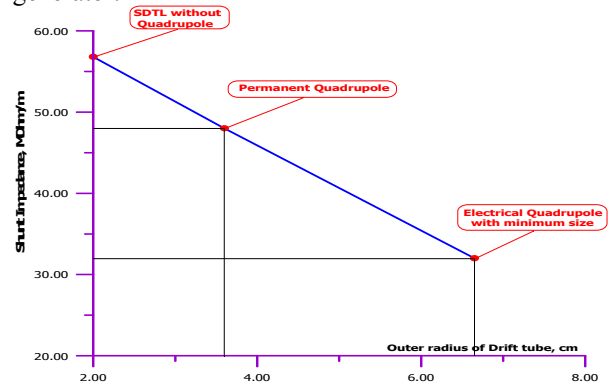


Figure 2: Shunt impedance of DTL structure with 350 MHz vs outer drift tube radius method.

It leads to very expensive RF system, since each of them requires own RF control system. Additionally the effective longitudinal emittance grows with the number of resonators  $n$  as  $\sqrt{n[\langle\delta\phi\rangle^2 + \langle\delta A\rangle^2]}$  due to RF amplitude  $\delta A$  and phase  $\delta\phi$  instabilities.

The only solution is to join some number of cavities in one module by bridges, what is called BDTL structure. It is very compact cavity and the ratio between cavity and drift tube radius is quite reasonable to get the high shunt impedance. However, the cavities joined by the bridges create the new resonant system with the own eigen

modes. Both the cavity and the bridge can be considered as the coupled cells. These modes have to be separated to have the uniform distribution of the field along the whole module (cavities with bridges). In case of  $\pi/2$  mode of such resonant system the bridge plays the role of the coupling cell, where the field almost equals to zero and the cavity is the accelerating cell. We have analysed the system of four cavities joined by three bridges by MAFIA (see fig.3).

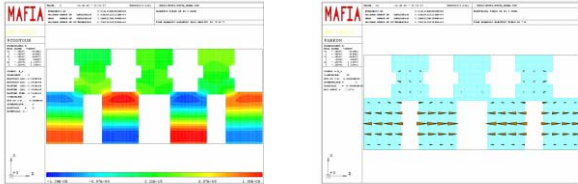


Figure 3: Magnetic and electric field distribution of  $\pi/2$  mode in BDTL system

The results are appeared to be not so inspirational for the longer cavity (higher energy). It is because the frequency difference between  $\pi/2$  and 0 modes is determined by the coupler window size  $a$ , the field in the region of window  $H$  and the stored energy in cavity  $W$  :

$$f_{\pi/2}^2 - f_0^2 \propto a^3 H^2 / W \quad (1)$$

But the stored energy is increased with growth of the cavity length (it is proportional to  $\beta$ ) and therefore the coupling goes down. After 20 MeV it is very significant effect. Additionally there is another possibility to get the high-coupled structure for the higher energy. It is CCDTL structure, when the number of drift tubes minimized up to one-two. However, such a structure is the tri-periodical structure requiring the special procedure of tuning, and the frequent separation of cavity by the transverse walls gives the significant contribution in the decreasing of the shunt impedance as well.

### 1.2 CBDTL structure with bridges structures

The next step has been done in direction of H cavities joined through the bridges in one module. Due to the lower quality factor of H cavities we hoped to get the structure with the higher coupling of the system “cavity-bridge-cavity”. The cavity itself was based on the cross-bar drift tube linac structure (CBDTL), developed by Ratzinger [1]. We added the bridges to join cavities (see fig. 4). The focusing elements are placed just between cavities. The number of drift tubes is determined as before by the required value of the transverse acceptance, and it is about 10. The bridges play the role of the coupling cells and the fundamental mode of the system “cavity-bridge-cavity” is  $\pi/2$ . It means the magnetic and electric fields are shifted by  $\pi/2$  from the cavity to the bridge and from the bridge to the next cavity. Therefore the bridges practically does not affect to the total shunt impedance of whole system.

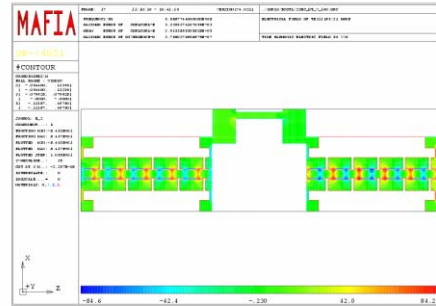


Figure 4: Electrical field in CBDTL structure with bridge.

However, in this structure we could not get the coupling coefficient higher of 1%. Due to this reason the maximum number of cavities joint by bridge is two only. Another disadvantage of this type structure is the high sensitivity of the shunt impedance value to the drift tube radius. For instance, the structure with 5 mm radius of the drift tube has 50-60 MOhm/m. But for our case, when we need 10 mm, the shunt impedance falls down to 25 MOhm/m. It is not enough for the structure with 15% duty cycle.

### 1.3 DTL with permanent magnet

From figure 1 we can see that DTL structure with the permanent magnet gives the shunt impedance around 45-50 MOhm/m, what meets to the satisfactory condition for the cooling system. However, from the beam dynamics point of view the permanent magnet is uncontrollable, and therefore we need simultaneously the steering system, for instance the trim-quadrupoles. But any additional element gives the increasing of the focusing period and therefore the beam radius increases as well. Simultaneously, we have found out the FFtrDDtr lattice is more sensitive to the space charge due to the longer focusing period. Thus, the permanent magnet requires the larger aperture, what neutralizes all advantages of this option in comparison with the conventional DTL with the electrical quadrupoles.

## 2 SUPER-CONDUCTING STRUCTURE

We considered the normal conducting structures at 350 MHz frequency. But after the funnelling the frequency is changed to 700 MHz. Thus, it is doubt to get the appropriate normal conducting structure with high duty cycle for the energy region 20-200 MeV. Therefore it is reasonable to consider the super-conducting structure.

- First of all due to the higher acceleration rate the number of super-conducting cavities is smaller, and therefore we have the smaller number of the generators, which one is very important advantage in comparison with SDTL.
- Secondly, we have no problems with the shunt impedance.
- Finally, we can pass to the frequency 700 MHz just after the funnelling, what makes sense from the point of view of

the peak current decreasing in each bunch. Analysing the possible candidates of the super-conducting cavity for the low energy part of ESS we have taken the H cavity with the cross-bar electrodes system. For RF structure the electrode shape plays the significant role, since for higher frequency the aperture should be the same and it affects to the maximum possible accelerating rate through the ratio of  $B_{peak} / E_{ac}$  and  $E_{peak} / E_{ac}$ . We consider the toro-shape electrode [2], which one has more freedom in choice of shape (see fig.5).

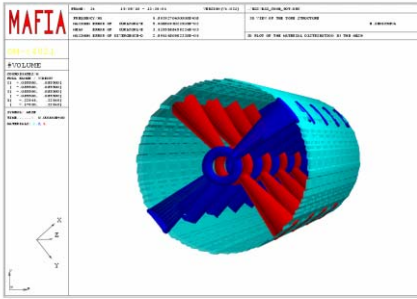


Figure 5: SCH cavity

The super-conducting H structure is one-resonator cavity, where the  $\pi$  shifted electrical field gap to gap is created by the alternating rotation of the electrodes in the transverse plane, but not as in the multi-cell elliptical E structure.

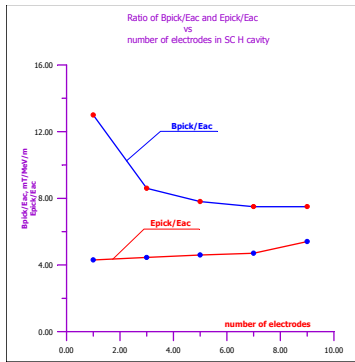


Figure 6:  $E_{peak} / E_{ac}$  and  $B_{peak} / E_{ac}$  vs electrodes number.

The H cavity can be based on the dipole mode TE111 or the quadrupole mode TE211. Obviously, in case of the dipole mode the electrodes have to be rotated by  $180^0$  and for the quadrupole mode by  $90^0$ . Due to the one-resonator cavity features the coupling coefficient does not play any role. The critical wavelength  $\lambda_{cr}$ , the

resonant wavelength  $\lambda$  and the cavity length  $L \approx N_{gap} \beta \lambda / 2$  determines the separation of the neighbouring modes:

$$\frac{\Delta f}{f} = \left( \frac{\lambda_{cr}}{\lambda} \right)^3 \frac{3}{\beta^2 N_{gap}^2}, \quad (2)$$

where  $N_{gap}$  is the number of accelerating gaps (what in principle is the same as  $N_{cell}$  in the elliptical cavity),  $\beta$  is the relative phase velocity. Thus, in the H cavity we have the strong factor  $1/\beta^2$ . The optimised ratio  $E_{peak} / E_{ac}$  and  $B_{peak} / E_{ac}$  depends on the number of electrodes inside cavity (fig.6). Taking into account the maximum magnetic field  $B_{peak} = 60mT$ , we can use the accelerating field  $E_{ac} = 5 \div 8 MeV / m$ . The number cells in one cavity is determined by the beam dynamics.

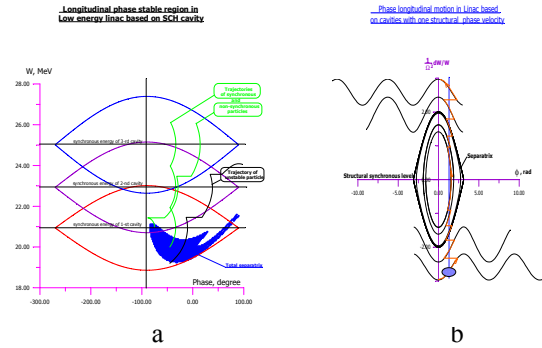


Figure 7: Synchronous motion in longitudinal phase space in two options.

The maximum accelerating field is limited by the magnetic field and for reliability it is taken 5 MeV/m. The total number of SCH cavity for beam acceleration from 20 MeV to 200 MeV depends on how the longitudinal phase motion is organized. We analysed two options. In the first each cavity has own structure phase velocity (a) and in this case the total number of 10-cells cavities is 21. In the second all cavities have three meaning of phase velocity (b) and the total number of 5-cells cavities is 41. The doublet focusing system is quite appropriated to this lattice.

### 3 REFERENCES

[1] U.Ratzinger, The new high current accelerator at GSI and perspectives for linac design based on H-mode cavities, EPAC 2000, Vienna.  
 [2] Yu.Senichev, ESS preprint ISSN 1433-559X ESS 01-120-L October 2001