PROPOSAL OF THE ACCELERATING STRUCTURE FOR THE FIRST CAVITY OF THE MAIN PART OF INR LINAC

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Abstract

For the improvement of beam power and operational stability of INR linac, replacement of the first four section cavity of the main linac part is required. The new cavity should not lose to the present one in beam dynamics and RF parameters with minimal modifications in the other linac systems. The results of more detailed study of possible accelerating structure are presented in this paper.

INTRODUCTION

The first cavity of the main part of INR linac works for proton acceleration in the range β=0.4313 – 0.4489 with acceleration gradient $E_0T\cos\varphi_s$ = 2.5 MV/m and the synchronous phase φ_s=-33°. The cavity has the aperture radius r_a= 17 mm, operating frequency f_a=991.0 MHz and the required operating regime is with RF pulse length τ=200 µs and Repetition Rate (RR) up to 100 Hz, Fig. 1.

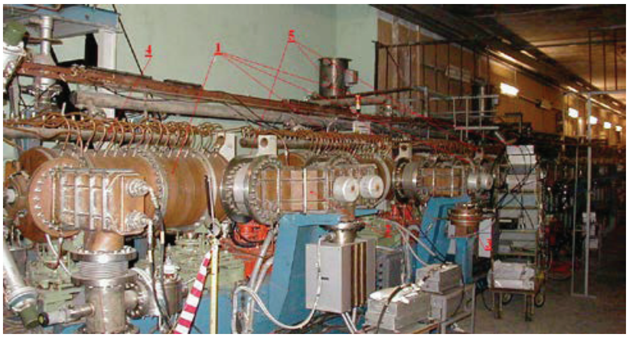

Figure 1: The existing INR DAW cavity. 1 – accelerating sections, 2 – bridge coupling cavities, 3 – RF input, 4- focusing elements.

The main part of the INR linac is based on the Disks and Washers (DAW) structure [1], Fig. 1c. After a long time after linac construction, the direct repetition of the single DAW cavity in the industry is expensive and another options should be considered. Both proven in high intensity hadron linacs and promising new developments were considered preliminary for this purpose, [2], considering parameters of the existing DAW cavity as the reference points. From the total set of required parameters the INR development – Cut Disk Structure (CDS) - was pointed out as the most effective choice. This structure already is used for electron acceleration, β=1.0, with the accelerating gradient up to E_0T= 12 MV/m as the PITZ CDS booster cavity, [3], and operates in the regime with RF pulse length up to τ=800 µs, RR =10 Hz, hence, with the heavy heat load up to 25 kW/m. Application for low β~0.4313 case is not favorable for CDS parameters. We not can scale simply solutions for β=1.0 case, and additional development is required. Results of the more detailed CDS development for applications in the intense hadron linac with a moderate velocity of accelerating particles β=0.4313 – 0.4489 are presented below.

PARAMETERS OF THE STRUCTURES

Compared structures, DAW, CDS, Side Coupled Structure (SCS) [4] and Annular Coupled Structure (ACS) [5], are shown in Fig. 2 in a common scale for the same operating frequency.

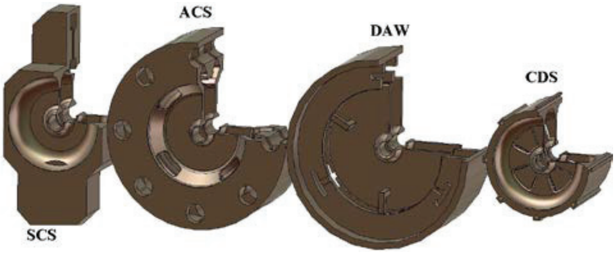

Figure 2: Considered accelerating structures: a) SCS, b) ACS, c) DAW, d) CDS.

For the proven structures DAW, SCS and ACS the key points of cavities design and parameters are known from references. Structures have a similar value of the effective shunt impedance Z_e, but strongly differ in value of coupling coefficient K_c. At the background of the known experience for DAW, there is no sense to consider structures SCS and ACS for the single cavity. But with two times smaller CDS transverse dimensions we can reduce costs of construction by less amount of raw OFE material and applying more usual Numerically Controlled (NC) equipment. Operating regime of the first cavity results in the heat load more than 7 kW/m. For such regime all considered structures require an internal cooling – cooling channels should be placed inside the structure closer to drift tube region to prevent a significant shift of operating frequency Δf_a and the temperature increase ΔT at the drift tube tip during cavity operation. In the proven structures it is realized by internal cooling channels inside web between accelerating cells and with necessity in the design there are brazed joints water-vacuum. In CDS for low β~0.44 the cooling problem is more severe.

CDS OPTIMIZATION

The schematic sketch of the CDS period is shown in Fig. 3. Internal channels should be placed in the web between coupling and accelerating cells only, see Fig. 3. It limits the web thickness to $t_w \geq 10$ mm and the total distance $d_w \sim 25$ mm becomes comparable with the period length $d=\beta\lambda/2 \sim 65$ mm. In such conditions for all structures Z_e value decreases and we can not get directly required RF efficiency.

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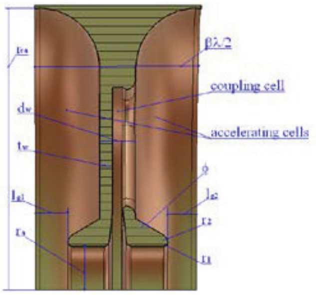

Figure 3: Schematic sketch of the CDS period.

The reference DAW design has a reserve – a single radius of the drift tube tip and the maximal electric field at the drift tubes is $E_{s.max}$=0.5 E_k where E_k =28.5 MV/m is the Kilpatrick threshold at operating frequency. It is too conservative value for present hadron linacs and there is a reserve for Z_e improvement.

CDS RF Parameters

The drift tube region for CDS structure was optimized following to the procedure, described in [6]. To improve further Z_e value the double radii tip shape is introduced for drift tube, see Fig. 3. For the accelerating cell in 2D approximation the data library was stored for different combinations of the drift tube dimensions. To have the same conditions for beam dynamics, aperture radius r_a is conserved as in reference design. In the further treatment the values of drift tube rounding r_1 and r_2 were connected to have the same $E_{s.max}$ value at both arcs and the optimal gap length was defined to have the maximal Z_e value. In each section of the cavity the cells have the same β value, which increases from first to forth sections. Taking into account the numbers of cells in each section, which is defined by lattice of particles focusing, [1], we define the total effective shunt impedance of the cavity Z_{et} and can analyze $Z_{et}(E_{s.max})$ dependencies, see Fig. 4.

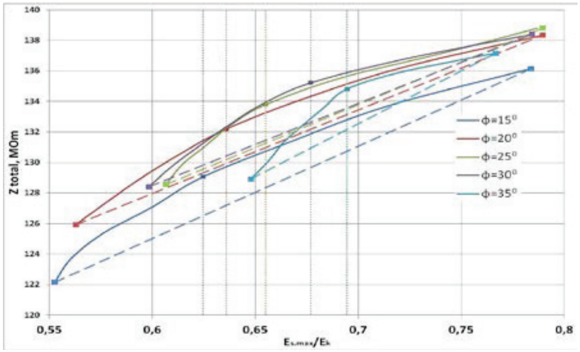

Figure 4: Plots of Z_{et} ($E_{s.max}$) for the total cavity different angles of drift tube, φ.

To reduce the cost of mechanical treatment, the main part of cells dimensions, which define CDS geometry, are the same for all four cavity sections. The fixed dimensions were defined to have the minimal Z_{et} reduction for the total cavity as compared to variable dimensions in four sections. Finally, at the expense of increasing to $E_{s.max}$=0.8 E_k, we obtain Z_{et} value for the CDS cavity at a small amount of 0.12% higher than Z_{et} for the reference DAW cavity. It is also rather conservative $E_{s.max}$ value. Further increasing is not reasonable. As can be seen from Fig. 4, Z_{et} ($E_{s.max}$) dependencies are not linear and with further $E_{s.max}$ rise, increasing a risk of electrical breakdowns, we do not have a sufficient compensation in cavity RF efficiency.

Structure Cooling

In the proven CDS booster cavity [3] the cooling circuit is realised both with internal channels, placed in webs between cells, and with outer channels along the section. For the INR cavity the operating regime results in a lower heat loading and structure cooling was reconsidered by using ANSYS software [7] and following to the procedure, described in [8]. Assuming the safe value for cooling water velocity of < 2 m/sec, the calculated distribution of the temperature at the cell surface are shown in Fig. 5 for the input water temperature of 27 C°.

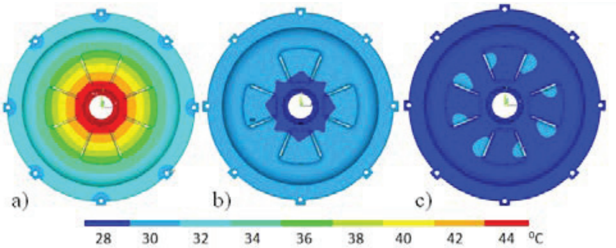

Figure 5: The temperature distributions at the CDS cell surface for cooling with external channels only, (a), internal only, (b), and for both external and internal channels, (c).

The non uniform heating due to RF power dissipation results in a non uniform temperature rise ΔT and induced thermal deformations of the cell surface, which results in frequency shifts both for accelerating Δf_a and coupling Δf_c modes. The calculated numerical results for different options of structure cooling are presented in Tab. 1. The thermal stress value is well inside elastic limit for the annealed OFE copper in all options of cells cooling.

Table 1. Calculated ΔT , Δf_a , Δf_c values for different options of the structure cooling.

Opt.\Par.	external	internal	Internal and external
ΔT, °C	15.24	3.30	2.10
Δf_a, kHz	-324.7	-49.3	-46.8
Δf_c, kHz	1131.2	171.7	165.1

Analyzing results in the Table 1 we see, that internal channels provide the major effect in the cell cooling. Addition of external channels results in very small effect on values of frequency shifts , Δf_a , Δf_c. To simplify the design of the total cavity and reduce cost of construction, in the cavity only internal cooling channels for cells cooling are foreseen. Basing on the small CDS transverse dimensions and the proven experience [3], internal cooling channels can be produced in cells without the brazed joints water-vacuum. It strongly improves reliability of the long term cavity operation.

Multipactor Discharge

For the PITZ booster [4] CDS was designed to avoid MultiPacting (MP) in operating cavity range. For INR cavity CDS should operate with much smaller accelerating gradient E_0T and with the period length $d=\beta\lambda/2 \sim 65$ mm we are limited in the selection of dimensions for coupling cell. Possibility of MP for INR cavity is studied in [10].

Accelerating CDS cells are free from discharge all time. But in compensated structures the total field contains addition of coupling mode, which should be excited to ensure RF power flow along the cavity to compensate losses for RF power dissipation in cavity walls and for beam acceleration, [10]. This addition linearly decreases from RF input point to the cavity ends. In the INR cavity RF input is into the central bridge cavity between the second and the third accelerating sections. Results of study show MP possibility for operating regime in the first and the fourth sections, e.g. for the low level of excitation for the coupling mode. For safety we introduce for these sections enforced excitation of coupling mode to the level above the upper range of MP zone by alternating detuning of adjacent accelerating cells at the frequency $df \sim 1.2$ MHz. Such detuning of adjacent cells results in a tolerable Z_e decreasing < 0.5%. Also detuning is regular along CDS section and does not results in a significant spread of the accelerating filed distribution.

According results of simulations, for the second and the third CDS sections this detuning of adjacent cells is not necessary. The natural excitation of the coupling mode is sufficient. Application of alternating cells detuning for these sections results in a more complicated procedure of RF tuning and will be defined in the consideration of the total CDS cavity parameters, taking into account bridge coupling cavities.

Tolerances for Manufacturing and RF Tuning

For intense hadron linacs the input value for selection of tolerances for cells manufacturing is the standard deviation of the electric field distribution σ_e <1 %. This σ_e value is connected with K_c and tolerable values σ_{fa}, σ_{fc} for the spread in frequencies of accelerating and coupling modes, the stop band width $\delta f=f_c-f_a$ and the spread in coupling coefficient σ_{kc}, see [11] for details. CDS structure naturally realizes $K_c \sim 17$ % and, in comparison with SCS and ACS, $K_c \sim 5$ % already there is an one order σ_e decreasing for the same precision of cells production. Further K_c increasing, up to $K_c \sim 40$ % like in DAW, is possible for CDS at the expense of Z_e reduction, but is not so effective, because σ_{kc} contribution in σ_e dominates.

According the results of tolerances estimation, [11], for CDS cells we can apply a typical tolerance value up to +-50 μm and relax the tolerance for the stop band width in RF tuning of sections to $\delta f \sim (200 - 350)$ kHz. It overlaps the stop band opening due to structure heating in operating regime, see Table 1. The expected spread for accelerating cells is of $\sigma_{fa} \sim 3.8\ 10^{-4}$ and the calculated value $\sigma_e \sim 0.5$ % provides some reserve and freedom in RF tuning. Together with the moderate transverse dimensions, CDS cell outer diameter is of ~ 240 mm, the mechanical tolerances of ~ 50 μm are comfortable for cells production with an usual NC equipment.

The technique of the CDS sections tuning was developed during CDS booster cavity construction, [12]. Basing on the sufficient K_c value, we avoid the individual tuning of cells frequencies and tune the section as a whole. But the intermediate Quality Control (QC) for produced cells was introduced to prevent against accidental extra spikes in cell frequencies. With the regular detuning of accelerating cells for the first and the forth sections, taking into account the expected values $3\sigma_{fa} f_a \sim df$ =1.2 MHz, QC procedure, used in [12], should be extended to have the ensured difference between frequencies of adjacent accelerating cells.

SUMMARY

The results of the detailed study show, that, instead of initial CDS proposal and proven application for high energy particles, we can adapt structure for application in the high intensity hadron linac for moderate energy range. With the tolerable increasing $E_{s.max}$=0.8 E_k required RF efficiency is obtained. Structure cooling can be realised without not reliable joints water - vacuum. More complicated procedure of RF tuning to prevent multipackting is the acceptable price for the single cavity. CDS structure remains the mostly cost effective choice for application in replacement of the first cavity in the main part of INR linac.

REFERENCES

[1] B. Murin, "Biperiodic accelerating structures", in *Linear ion accelerators*, Atomizdat, Ed. Moscow, USSR: 1981

[2] I. Rybakov *et al.*, "Comparison of accelerating structures for the first cavity of the main part of the INR linac", *J. Phys.: Conf. Ser.*, vol. 747, p. 012073, 2016.

[3] V. Paramonov et al., in *Proc. LINAC'10, p.* 241

[4] S. Henderson et. al. , in *NIM A*, v. 763, pp. 610-673, 2014.

[5] "Accelerator Technical Design Report for J-PARC", KEK, Tsukuba, Ibaraki, Japan, 2003

[6] V. Paramonov, in *Proc. LINAC'96, p.* 493

[7] ANSYS, http://www.ansys.com

[8] A. Skassyrskaya et. al., in *Proc. LINAC'02*, p. 216

[9] I. Rybakov and I. Isaev, TUPSA035, this conference.

[10] V. Andreev and V. Paramonov, in *Proc. PAC'95*, p. 1702.

[11] I. Rybakov et. al., TUPSA036, this conference.

[12] A. Naboka et. al., "Results of CDS booster cavity RF tuning", *VANT, Series: Nuclear physics*, vol. 5, p. 35, 2008.