LOW-POWER RF TUNING OF THE SPALLATION NEUTRON SOURCE WARM LINAC STRUCTURES

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Abstract

The Spallation Neutron Source (SNS) is an accelerator-based neutron source being built at Oak Ridge National Laboratory. A conventional 402.5-MHz drift-tube linac (DTL) accelerates the H^- beam from 2.5 to 86 MeV, followed by a 805-MHz coupled-cavity linac (CCL) to 186 MeV. Tuning the six DTL tanks involves adjusting post-coupler lengths and slug tuners to achieve the design resonant frequency and stabilized field distribution. A 2.5-MW klystron feeds RF power into a DTL through a ridge-loaded waveguide. The CCL consists of 4 RF modules operating in the $\pi/2$ mode. Each module contains 96 accelerating cavities in 12 segments of 8 cavities each, 11 active bridge coupler cavities, and 106 nominally unexcited coupling cavities. For each RF module, power from a 5-MW klystron splits and drives bridge couplers 3 and 9. We will discuss the procedures and special tools developed for the structure tuning.

INTRODUCTION

We describe the low-power RF tuning of the SNS warm linac designed by LANL. For each of 10 RF structures (6 DTL tanks and 4 CCL modules), the tuning goals are:

- Resonant frequency within ±20 kHz of design under normal operating conditions.
- Field distribution within ±2% of design.
- Fields stable against frequency perturbations.
- Cavity-to-waveguide coupling matched for full beam current.

We convert all frequency measurements made under ambient conditions to 20 C structure temperature under vacuum. Flowing dry nitrogen through the cavities avoids any uncertainty from inaccurate or varying humidity measurements.

DRIFT-TUBE LINAC

The six 402.5-MHz DTL cavities have between 22 and 60 1-$\beta\lambda$-long cells with half drift tubes on the end walls. A tank contains three (two for tank 1) ~2-m-long, copper-plated steel sections bolted together. Tank 1 with 60 cells and tank 2 with 48 cells have a ramped field distribution. Tanks 3-6 with 34, 28, 24, and 22 cells all have a flat field distribution. Slug tuners evenly spaced along the tank bottom (4 per section) provide each tank with 2.1 MHz of static tuning to correct for expected manufacturing dimensional tolerances. In operation, water coolant temperature controls the frequency. Water-cooled copper drift tubes (DTs) mounted on copper-plated steel stems contain focusing, steering, or diagnostic elements. The FFODDO focusing lattice uses permanent-magnet quadrupole lenses in 2/3 of the DTs. In each tank, 4 downstream DTs contain dipole steering magnets and 2 upstream DTs contain beam-position monitors. Some DTs are empty.

Post couplers (PCs) are quarter-wave resonators that provide field stabilization. Rotating the bent the PC adjusts the longitudinal field distribution. A DT-to-tank-wall spacing of ~0.95λ/4 ensures adequate coupling between the PC tip and DT. Tank 1 has 19 PCs, one at every third DT and alternating side to side. Tanks 2 and 3 have 23 and 17 PCs (one at every other DT), and tanks 4,5,and 6 have a PC at every DT location.

RF power enters the cavity through a tapered ridge-loaded waveguide that terminates in a barbell shaped iris (see Fig. 1). Because the iris is small (~2 mm wide), it has a negligible effect on the cavity frequency and field distribution.

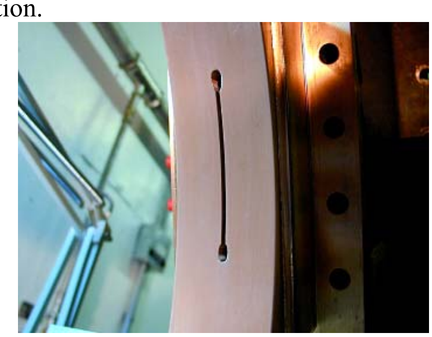

Figure 1: Iris viewed from the DTL side.

DTL Tuning

For low-power DTL tuning we adjust temporary aluminum slug tuners (STs) and PCs (see Figs. 2 and 3). Upon completed, fixed copper parts are finish machined to the measured final dimensions. For low PC excitation during operation, we adjust the STs to achieve the design field distribution before installing PCs. The PCs raise tank frequency 100 to 200 kHz when installed. From this point forward, we move all STs together to maintain the tank target frequency.

Figure 2: An adjustable aluminum slug tuner.

Figure 3: An adjustable aluminum post coupler.

Axial field measurements use the Slater bead-perturbation (BP) method [1]. A hollow aluminum sphere traverses the cavity at constant speed while a network analyzer under LabView control records the frequency at regular intervals. From frequency change data in each gap, and Superfish [2] field data for each cell, analysis code DTLplot computes each cell's average axial field E_0. Tilt Sensitivity (TS) measures field stability. TS is the cell-by-cell difference in E_0 between two BP measurements with different frequency perturbations of the end cells. We first insert a metal tube in the bore on one end to lower cavity frequency ~25 kHz. For the second measurement the tube is on the other end. DTLplot determines the end-cell frequency perturbations from stored energy ratios.

The procedure is to first stabilize the fields by tuning the PCs. We start with all PCs a bit too low in frequency (i.e., too long) and gradually pull out all PCs until the TS slope is near zero. Some individual PC adjustment results in a smooth TS curve. Once the PC lengths have been fixed, we adjust the PC orientation angle to achieve the design field distribution. Some iteration is usually needed. The left side of Fig. 4 (z = 0 to 36 m) shows E_0 and TS for the 6 DTL tanks. The TS measurements for tanks 4 and 6 show the both aluminum and copper PC data. The larger slope of the copper PC data mean that copper parts did not replicate the aluminum PC geometry as well as for other tanks. For the largest expected frequency errors of a few tens of kHz, the TS final data is still adequate.

Another measure of DTL stability is the stabilization factor $K_{st} = [\Delta S_1/\Delta f_1]/[\Delta S_2/\Delta f_2]$, where ΔS_1 and ΔS_2 are changes of the field slope in unstabilized and stabilized cavities for end-cavity frequency perturbations Δf_1 and Δf_2 [3,4]. The stabilization factor depends on the location and number of post couplers. Usually, DTLs have Kst in the range 10 to 100. The change in field slope measures the first harmonic compensation from the TM_{011} mode, which is closest in frequency to the TM_{010} mode and contributes most to the field distortion. We measured K_{st} = 15, 26, 75, 51, and 37 for tanks 1, 2, 4, 5, and 6, respectively.

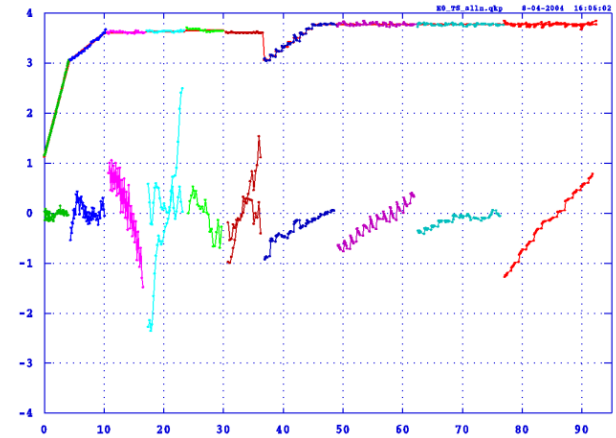

Figure 4: E $_0$ in MV/m (upper) and tilt sensitivity in %/MHz (lower) versus accelerating-gap longitudinal position z (m). Design E $_0$ is in red over the entire length. Measured E $_0$ for each structure (in various colors) covers up most plotted design values.

COUPLED-CAVITY LINAC

The CCL consists of 384 accelerating cavities (ACs) arranged in 48 segments of 8 identical ACs each. Segment length gradually increases to match the average particle velocity β. The length of an AC is βλ/2, and the distance between segments is 5βλ/2, where now β is the segment exit velocity. We further subdivide the 48 segments into 4 RF modules of 12 segments each. Within a module, 3-cell bridge couplers span the space between segments leaving room for quadrupole singlets and diagnostics. A module contains a total of 213 cavities: 96 ACs, 84 internal coupling cavities (CCs), 22 longer bridge CCs, and 11 powered bridge cavities (BCs).

An internal CC connects two ACs within a segment. These cavities attach above or below the ACs, alternating from top to bottom. All ACs have the same outer corner radius and septum thickness, and all the internal CCs are identical. The coupling slot between AC and CC starts as the intersection of their corner radii machined from both sides of a copper plate. We then mill the edge of the slot to specified dimensions, ensuring a consistent coupling factor within a segment. The nominal coupling factor k is 5%. Because of the increasing AC volume with β, k varies from 5.45% in segment 1 to 4.45% in segment 48.

CCL Tuning

CCL tuning is an integral part of the manufacturing process. Different AC tuning steps occur both before and after the segment braze. The first tuning of the internal CCs occurs after the segment braze. We tune the BC in a special 5-cell fixture before assembly in the module. Bridge CC tuning occurs only after module assembly.

An AC half-cell includes a raised tuning ring that we machine to make the segment's π/2 mode frequency $f_{\pi/2}$ ~200 kHz low before brazing. After brazing we first tune all internal CCs to the module's target frequency f_T, which includes a small offset that anticipates the effects of thermal gradients under power. Squeezing the CC noses together lowers frequency and prying the noses apart raises frequency. Based upon measurements $f_{\pi/2}$ and individual AC frequencies (with nearby cavities shorted in a consistent manner), we tune the 6 internal ACs by "dimpling" the outer wall. Each AC has 12 dimpling ports where the wall is only a few mm thick. Together the 12 ports provide up to 400 kHz of tuning range. The dimpling takes place while observing the frequency f_{AC} of a single AC. This mode is typically 4.5 MHz higher in frequency than $f_{\pi/2}$ because of the ~1.1% direct coupling between ACs. Metal rods inserted from the segment ends short other cavities. Each rod contains an electric antenna. We short nearby CCs with copper wedges inserted through the pumping ports.

Pushing or pulling the segment end walls tunes the end ACs. For a single segment, an end AC is tuned correctly when the adjacent CC contains no stored energy in the π/2 mode. This frequency is approximately the average of $f_{\pi/2}$ and f_{AC}. In the module, we retune only the 22 end ACs next to bridge couplers to a common frequency to change the module frequency.

The BC bolts into the center of a 5-cell tuning fixture for measurements that determine the length if its fixed slug tuner. Tuning is complete when the end cavities have the same frequency (measured individually), the 5-cell π/2-mode frequency f_T, and the two bridge CCs contain no significant RF power in the π/2 mode. After meeting these conditions using an adjustable slug tuner, we machine the water-cooled copper slug to the required length.

An important BC feature is the TE-mode tuner, which is a solid copper rod welded to the top of the cavity. The large slots (see Fig. 5) in the BC split the degeneracy between two TE_{111} modes. One mode couples strongly to the adjacent bridge CC TM_{010} field in the slot and would interfere with the proper behavior of the coupled chain of resonators. The vertical TE-mode tuner lowers the frequency of this mode to <690 MHz, well below the TM_{010} pass band. Bending the rod affects the ratio of coupling to the bridge CCs and changes the segment-to-segment field distribution.

After assembly of an entire module, we tune the 22 bridge CCs to f_T and retune the 22 end ACs to make the module's π/2-mode frequency f_T. At this point, axial BP and TS measurements begin. Analysis code CCLplot computes segment averages of E_0, TS slopes for each segment, and the step in TS between segments. We tune the bridge CCs to adjust these TS steps. Raising the frequency of the bridge CCs makes the step more positive. A slightly positive overall slope of the TS curve helps prevent a possible thermal runaway situation because the field will tend to drop in a hotter (lower frequency) segment. If the TS slopes for individual segments need adjustment, we retune the internal CCs. However, the three CCs on the segment bottom are only accessible with the segment removed from the support stand.

Because of the large slot between the BC and the bridge CCs we cannot measure reliably an isolated bridge CC frequency. If, instead, we short ACs and CCs in adjacent segments, then the π/2-mode frequency of the 3-cell system of two bridge CCs and the BC is the average frequency of the bridge CCs. The drive and pickup probes are in the bore-tube shorting rods in the gap of the adjacent end ACs. Their frequency difference comes from single-cavity measurements with a plug (see Fig. 5) in the slot, which is inserted by reaching in through the BC slug-tuner port.

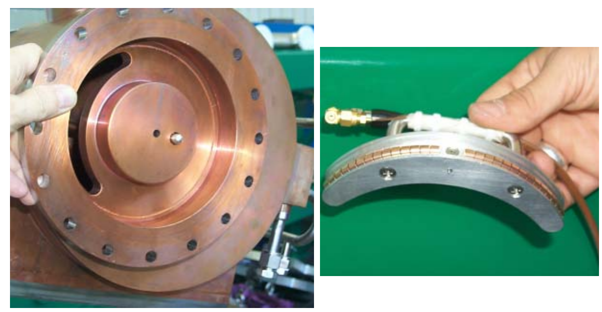

Figure 5: Left: bridge-coupler end view. Right: plug with pickup loop inserted from the BC side of the slot.

Tuning of a bridge CC occurs with the coupling-slot plug in place. A silver-plated stainless-steel screw, adjusted from the BC side, provides >5 MHz of tuning range. Power losses are negligible because the screw is in a primarily electric field region of a nominally unexcited cavity. Contacts are well inside the tapped hole. After final adjustment, another screw inserted behind the tuner locks it in place. Both screws include vacuum relief.

The right side of Fig. 4 (z = 36 to 92 m) shows E_0 and TS for the 4 CCL modules.

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