A PROCEDURE TO SET PHASE AND AMPLITUDE OF THE RF IN THE SNS LINAC'S SUPERCONDUCTING CAVITIES*

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Abstract

This paper describes a procedure to set the phase and amplitude of the RF fields in the Spallation Neutron Source (SNS) linac's superconducting cavities. The linac uses superconducting cavities to accelerate the H$^-$ ion beam from the normal conducting linac at 185 MeV to a final energy of ~1 GeV. There are two types of cavities in the linac, 33 cavities with a geometric beta of 0.61 and 48 cavities with a geometric beta of 0.81. The correct phase setting of any single superconducting cavity depends on the RF phase and amplitude of all the preceding superconducting cavities. For the beam to be properly accelerated it must arrive at each cavity with a relative phase (ϕ_s), called the synchronous phase, of about −20 degrees. That is, it must arrive early with respect to the phase at which it would gain the maximum energy by 20 degrees. This timing provides the longitudinal focusing. Beam particles arriving slightly later gain more energy and move faster relative to the synchronous beam particle. The problem is to set the phase and amplitude of each cavity in the linac so that the synchronous particle arrives at each cavity with the correct phase. The amplitude of each superconducting cavity will be adjusted as high as possible constrained only by the available RF power and the breakdown field of the cavity.

1 COMMISIONING THE SNS SUPERCONDUCTING H$^-$ PROTON LINAC

The superconducting linac [1] uses 6 cell cavities operating in the π mode to accelerate the H$^-$ beam. At 185 MeV, the energy at the beginning of the superconducting linac, the β (v/c) of the beam is 0.55. The first section of the linac uses 6-cell cavities with a geometric β of 0.61. Thus, the beam must arrive at the first cell early and leave the last cell late with respect to design synchronous phase. The 33 ($\beta = 0.61$) cavities accelerate the beam to ~387 MeV. At this energy the beam β is 0.706 and the beam must arrive late at the first cell and leave the last cell early. At 247 MeV the beam β matches the cavity β and the coupling of the beam to the accelerating field in the cavity is the strongest. To make the most efficient use of each superconducting cavity the field amplitude will be set as high a possible. This amplitude will not be known until the accelerator is ready for operation and the

accelerating field is calibrated. Using standard RF measurement techniques the field level can be calibrated to about ± 5%. This level of accuracy is not good enough to set the phase and amplitude of the RF fields in each of the superconducting cavities before the beam is turned on even if there was a method to determine the absolute phase of each cavity. Therefore, I propose to use the beam to calibrate the field amplitude and phase of each superconducting cavity.

1.1 Procedure to Commission SC Linac

- Calibrate RF pickup probes of first cavity.
  1. Tune the first cavity to 805 MHz by exciting cavity with klystron, switching off the RF drive, and watching the phase shift of the RF in the cavity with the RF reference. When the phase shift during ~ 100 μ seconds is less than ~ 2 degree the cavity is tuned to 805 MHz ± 56 Hz.
  2. Use beam to excite cavity. Compare excitation of cavity with calculations (RF off.) With the cavity tuned as in step (1) the phase of accelerating fields in the cavity will be excited with the phase that extracts the maximum energy from the beam. (Exactly 180° from the phase of maximum acceleration.)
  3. Use date from step 2 to calculate coefficients used by low level RF (LLRF) system to display the amplitude in MV/m. The cavity phase could be displayed relative to the beam phase.
  4. Amplitude and phase of cavity are set. Phase of cavity excited with beam is ± 180° + ϕ_s of required phase. (Add ± 180° + ϕ_s).
- Set amplitude and phase setpoints of first cavity and turn on RF.
- Calibrate RF pickup probes of next cavity.
- Set amplitude and phase setpoints of next cavity. Turn on RF.
- Repeat previous steps until all cavities are set.
- Periodically check beam energy with time-of-flight measurements.

2 PREREQUISITES FOR COMMISIONING THE LINAC

Before the first superconducting cavity can be commissioned with the above procedure, the beam from the room temperature linac must be transported all the way through all the superconducting cavities to the beam dump. This will require adjusting the quadrupole doublets

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and steering magnets between cyromodules to lower strength than the nominal operating values. The beam from the room-temperature linac at 185 MeV would be focused too strongly in the later parts of the linac by quads adjusted to focus the beam with energies up to 1000 MeV. The steering magnets will also need to be adjusted during the commissioning procedure when the energy is increased in the higher energy region of the linac. To first order, the quads and steering magnets could be programmed to increase in proportion to the beam energy as it is increased by the commissioning procedure each time a superconducting cavity is brought up to power. However, the superconducting cavities will not be placed exactly on the centerline of the linac. A misaligned superconducting cavity tends to steer the beam a small amount which must be corrected by adjusting the steering magnets downstream from the superconducting cavity being brought up to power. In order to streamline the RF commissioning of the superconducting cavities an automatic steering algorithm should be implemented in the computer control system. This algorithm would use beam position information from the beam position monitors (BPM's). The BPM's also provide phase information that can be used to calculate beam energy from time-of-flight between BPM's. This information could then be used by another algorithm in the computer control system to adjust the quadrupole focusing magnets.

3 SIMULATING THE BEAM−CAVITY INTERACTION

The code TRAN simulates the transient response of the RF fields in a cavity from the beam current, the RF power from klystrons, RF losses in the cavity, and RF losses from the presence of the RF drive coupler. The code PARMELA [2] is contained within TRAN and is used to calculate the beam-field interaction in the cavity. The superconducting cavity has 6 cells electrically coupled through the bore. There are 6 modes in this cavity with the π mode used to accelerate the beam. In this mode the axial electric field alternates sign from one cavity to the next. However, all six modes are needed to accurately simulate the transient response of the fields. Let $\overline{a}(q,t)$ be a complex number that represents the amplitude and phase of the qth mode at time t. The phase is with respect to the to the RF reference at frequency *freq*. The angular frequency $\omega = 2 \cdot \pi \cdot freq$. Then, $e^{-\omega_q \cdot \Delta t / 2Q_q}$ represents losses in the cavity where ω_q is the angular frequency and Q_q is the quality factor of the qth mode, and Δt is a small increment of time. In this simulation with Q_q equal to about 1.0×10^{10} the losses in the cavity are negligible. However, Q_0 appears in the definition of β, the coupling to the RF drive coupler. Q_{loaded} is the Q loaded by the RF drive coupler. $\beta = (Q_0 / Q_{loaded}) - 1$, where Q_0 is the unloaded Q of the accelerating mode. Each mode rotates in the complex plane with respect to the drive frequency. This rotation is represented by: $e^{i(\omega_q - \omega)\Delta t}$. For a small time step Δt and small frequency difference, this term is ~1. Which means that the phase of the RF fields do not change very much. It is this fact that makes it possible to measure the phase of the beam accurately with short high-current beam pulses.

3.1 RF power induced voltage

The forward RF power vector, $\overline{pf}$ is a complex number that represents the amplitude and phase of the RF drive. The RF power vector $\overline{pt}$ (see Eq. 1) represents the amplitude and phase of the RF transmitted out of cavity through the coupling to the RF driveline. β is the coupling factor for the mode *n*.

$$\overline{pt} = \sum_{q=0}^{N} \overline{a}(q,t) \cdot X(q, N_d) \cdot \sqrt{\beta} \cdot \qquad (1)$$

Where N_d is the number of the cell that is coupled to the RF drive, and N is the total number of cells. Variable $X(q,m)$ is the normalized amplitude in cell *m* for the qth mode.

The values of $X(q,m)$ are calculated by the computer code LOOP [3,4], which is based on coupled electrical circuits composed of resistance, inductance and capacitance (RLC) loops. $X(q,m)$ represents the amplitude and sign of the RF field in each cavity for every mode in the coupled-cavity system. The net result (induced voltage vector) of the forward RF power and the reflected power on the qth mode is given by Eq. 2.

$$\overline{P}(q) = (2 \cdot \overline{pf} - \overline{pt}) \cdot \sqrt{\beta} \cdot X(q, Nd) / X(n, Nd) \quad (2)$$

3.2 Beam induced voltage

The beam-induced voltage in cell *m* is represented by $\overline{B}(m)$ (see Eq. 3). Program PARMELA computes $\overline{B}(m)$ by summing the effect of each particle passing through the electric fields $\vec{E}(z,m)$ of the cavity. $\vec{V}(z)$ is the velocity of the particle at position *z*. ϕ_0 is the phase of the RF fields.

$$\overline{B}(m) = \frac{charge \cdot \sum_{particles} \int_{z=0}^{z=L} \vec{V}(z) \bullet \vec{E}(z,m) \cdot e^{i(\omega \cdot z / \vec{V}(z) + \phi_0)} dz}{\int_0^L E_z(z,m) dz} \quad (3)$$

The code SUPERFISH [5] calculates the electric field distribution $\vec{E}(z,m)$.

3.3 Cavity fields

With the values of $\overline{a}(q,t)$ (see Eq. 4) determined, the rest of the calculations can be performed. The reflected

power can be calculated. Periodically, PARMELA simulations are performed to calculate the performance of the accelerator and update $\overline{B}(m)$. The field in cell m of the cavity is given by Eq. 5.

$$\overline{a}(q,t+\Delta t)=\overline{a}(q,t)\cdot e^{\left\{-\omega_q/2\cdot Q_q+i\cdot(\omega_q-\omega)\right\}\cdot\Delta t}$$
$$+\left\{\overline{P}(q)+\sum_{m=1}^{N}\overline{B}(m)\cdot X(q,m)/N\right\}\cdot\Delta t \qquad (4)$$

$$\overline{\vec{E}}(z,m,t)=\vec{E}(z,m)\cdot\sum_{q}\overline{a}(q,t)\cdot X(q,m) \qquad (5)$$

PARMELA is an integral part of TRANS. It transports the beam multiple times through the part of the accelerator simulated by TRANS. The evolution of the beam pulse is thereby simulated. TRANS provides PARMELA with the phase and amplitude of the field in the accelerating cells. PARMELA returns the beam drive to TRANS. TRANS also simulates the digital RF feedback system controlling the RF power feeding the superconducting cavities.

3.4 Example of using the code TRANS

Figure 1 shows the output screen of the code TRANS simulating the beam excitation of a superconducting cavity. The labels on this figure point out some of the information that is displayed by the code. This figure is a combination of 3 runs of the code with 3 different cavity tunes (+100, 0, and –100 Hz. The important information contained in this figure is the phase and amplitude response of the cavity to the beam. Note that the amplitude is not sensitive to tuning errors, it is only reduced from 2.97 to 2.96 MV/m (a 0.3% reduction) for a 100 Hz error. The 100 Hz tuning errors result in less than 2° phase error. If the cavity is tuned to an accuracy of 50 Hz this source can be ignored. The cavity can be tuned by
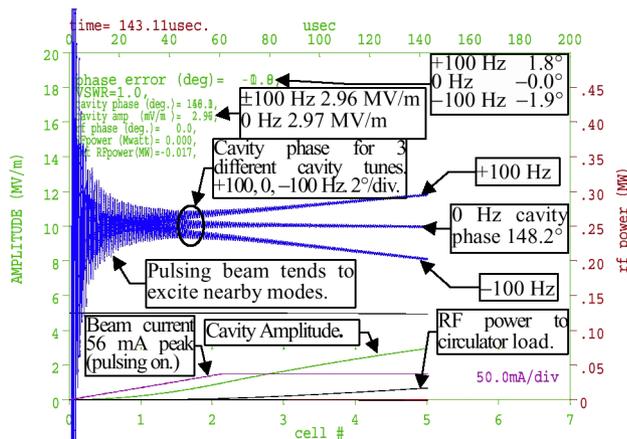
turning on the RF power for a short time (~50 μs) then following the phase of the cavity for ~100 μs. When the phase change is less than ~2° during this period the cavity is tuned to within 50 Hz of 805 MHz. When tuning the cavity with this method the cavity field remains low enough to ignore the Lorentz force detuning. The remaining source of tune error is caused by microphonics that is estimated to have σ of 9 Hz.

At least 60 μs is required to get an accurate value of the phase because the contribution to the measurement from the other 5 modes in the superconducting cavity needs to damp away. Without beam chopping the excitation of the nearby modes is greatly reduced. The linac injects 1000 turns into the accumulator ring. The beam chopping is required by the accumulator ring to limit beam loss when the beam is extracted in one turn. The chopping frequency is ~1000 kHz and the nearest mode in the cavity is ~800 kHz lower in frequency then π-mode. In Fig. 1, increasing the chopper-on window ramps up the beam current to its maximum value in 60 μs. If the full beam current appears all at once, transients in the phase and amplitude of the room-temperature linac could affect the phase of the beam arriving at the superconducting accelerator. Thus, chopping should be used to keep the transients in the beam phase small.

4 CONCLUSION

With the method presented in this paper the phase of the beam can be measured with the SC cavities. Using TRANS the excitation of the cavity can be predicted given the measured current and beam energy. Thus the LLRF system can be calibrated to give the accelerating field of the SC cavities in MV/m. The phase and amplitude setpoints of each SC cavity can be set one at a time. However, with ~ 90 cavities, the procedure would take quite a while if done manually one SC cavity at a time. This calls for an automatic procedure implemented in the control system to perform the setup of all the phase and amplitude setpoints for the SC linac.

5 REFERENCES

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[2] L. M. Young, "PARMELA," Los Alamos National Laboratory report LA-UR-96-1835 (Revised February 27, 2001).

[3] http://laacg1.lanl.gov/laacg/componl.html

[4] S. O. Schriber, "Pi-Mode Structures -- Results and Implications for Operation", This conference.

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Figure 1: Example of phase response of superconducting cavity to 36 mA beam pulse when cavity is tuned 100 Hz high, correctly, and low 100 Hz. The phase error at 143 μsecond into pulse is +1.8°, 0°, and –1.9°. Note that there is some ringing in the cavity that damps in about 60 μs, sufficient to see the effect of the cavity tune on the phase.