**Summer Student Project**

**Accelerator Systems Department**

**Group SY-RF-BR. Summer 2023**

---

# SPS RF Power Predictor for the Main 200 MHz Cavities

---

**Author**
**Tanvir Sayed**

**Supervisors**
**Ivan Karpov**
**Giulia Papotti**

**CDS upload**
September 15, 2023

# Abstract

The performance of the Super Proton Synchrotron (SPS) RF system has to be pushed to the limits to achieve the LHC injector upgrade (LIU) goals of higher beam intensities desired in the high luminosity large hadron collider (HL-LHC). To assess the performance, a RF power predictor tool has been developed for the main 200 MHz traveling wave structures for calculations of the required RF power for accelerating different beams in the SPS. Calibration measurements have been carried to fit center frequencies of the cavities as well as obtain a scale factor to match the power predictions to the measurements. Comparisons of the calibrated power predictor with forward power measurements for different beams have been carried out. Further measurements and investigation for obtaining better calibration parameters are still required for better success in comparisons & more confident predictions.

# Acknowledgments

I am very thankful to my supervisors, Ivan Karpov & Giulia Papotti, for giving me the opportunity to tackle this very exciting, challenging & undoubtedly important project allowing me to get into the CERN world and get a true taste of how cool it is to be an accelerator physicist. I am grateful for all the guidance and aid along the course of the project. I would also want to give big thanks to Bartosz Przemyslaw Bielawski for aiding me in the software side with setting up the virtual environment, making scripts more readable, as well as guidance on the data retrieval from LSA & the pyQT setup. Shout out to Oleksandr Naumenko for all the help when getting started with my project. Finally, thanks to everyone in the RF-BR group for all the good times & fond memories.

# Contents

# 1 Introduction

To achieve the higher luminosity of future high intensity beams desired in the High Luminosity Large Hadron Collider (HL-LHC), the LHC injector upgrade (LIU) project involved upgrading the configuration of the Super Proton Synchrotron (SPS) main accelerating 200 MHz traveling wave structures (TWS), and replacing the analog cavity controllers that drive amplifiers to a fully digital system. The new SPS 200 MHz TWS consists of four 3-section structures driven by existing Philips and Siemens tube amplifiers, as well as two 4-section structures driven by new solid state amplifiers with much higher power. This new configuration should provide higher total voltages for the same power while having a lower total impedance and reduced beam loading, thus allowing to have higher available voltages with increasing intensity (i.e. higher number of particles per bunch, ppb). To reach LIU goals, the performance of the SPS RF system needs to be pushed to the limit. To that end, a tool for the calculation of the RF power required for acceleration of different beams in the SPS, before extraction into the LHC, was developed. Once comparisons of the calculated data with measurements are found to be successful, the tool will be used in machine operation and machine development studies to better understand RF system capabilities, as well as optimize equipment protection and beam operation.

The first part of the report overviews the SPS 200 MHz accelerating structure. This is followed up by the relation describing the required RF power in a cavity for a selected voltage – the transfer function. In addition, the process of power balancing is brought up. The next part discusses the RF power predictor tool, portraying its functionality as well as presenting example outputs. Afterwards, calibration measurements are outlined that were done to determine fit parameters which should allow the power predictor to produce more accurate calculations. Finally, comparisons between power measurements and calculations are shown, and the report is rounded off with some concluding remarks & future outlook.

# 2 SPS Traveling Wave Structure Configuration

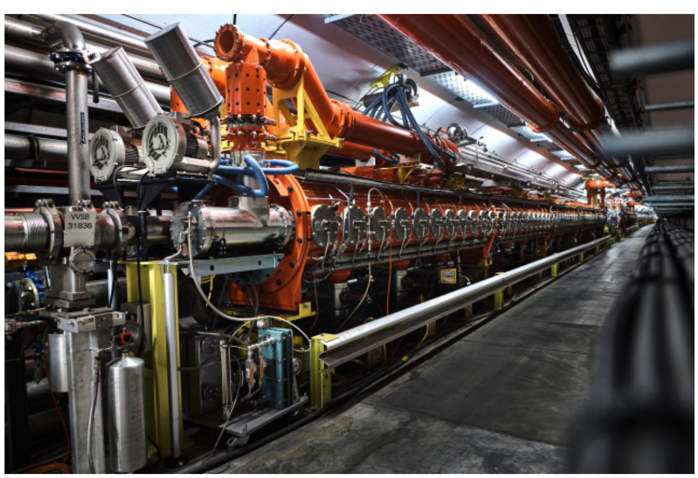

**Figure 1:** The SPS 200 MHz accelerating structure. [1]

The Super Proton Synchrotron (SPS), Fig. 1, accelerates charged particles using a traveling wave system. This system consists of traveling wave structures (TWS) – which are periodically loaded waveguides – operated at a fundamental frequency of about 200 MHz - hence also referred to as the 200 MHz TWS or 200 MHz cavities [1]. Each structure consists of a certain number of sections, while each section is formed of unit cells. Each unit cell, as shown in Fig. 2, has a length $L_0$ of 0.374 m and is a circular wave-guide loaded by a drift-tube and has stems suspended on pedestals giving the SPS a parallel stem drift tube structure. 11 of these unit cells are placed periodically along a section (see Fig. 3) [2].

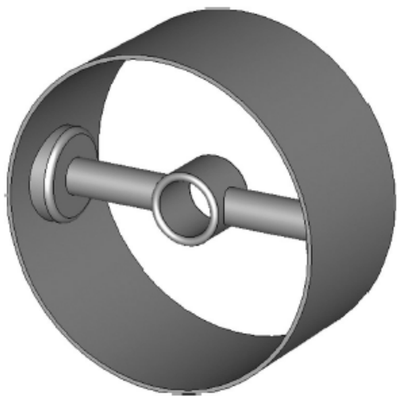

**Figure 2:** The SPS parallel stem unit cell. [2]

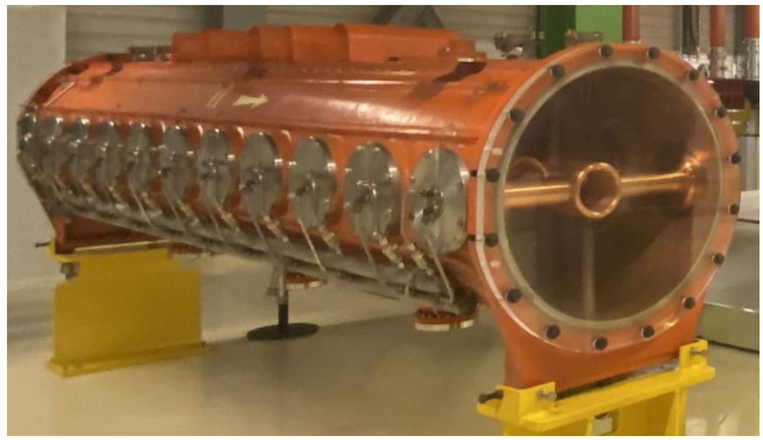

**Figure 3:** An example of a 11-cell section of the TWS present in SPS. [2]

Following the LHC injector upgrade (LIU) for the SPS during long shutdown 2 (LS2), the SPS 200 MHz cavities were reconfigured to four 3-sections and two 4-sections. The 3-section cavities are powered by existing Philips & Siemens tube amplifiers with peak power of $\approx$ 1.0 MW. The 4-section cavities are powered by the newly installed solid-state amplifiers Thales capable of delivering much higher power of $\approx$ 1.6 MW. Compared to the pre-LS2 SPS configuration of two 4-section and two 5-section cavities powered by only Philips & Siemens, the total RF power deliverable has been considerably increased. In addition, the new configuration has a lower total impedance (by $\approx$ 18 %) and the shorter sections mean reduced beam loading. As a result, the total available voltage achievable in the cavities will also be higher enabling to reach higher beam intensities. The analog cavity controllers that drive these amplifiers have also been replaced to a fully digital system [3].

The new digital LLRF system allows to have amplitude modulation (AM) for all beam cycles, i.e. the RF voltage can be modulated in amplitude along the turn (23 µ) such that the RF voltage is provided only during the beam passage through the cavities. Currently, the voltage is modulated to be active for about half a turn (11 µ) for all cycles where AM is logical. During the voltage inactive period, very low power of just 10 kW is necessary for keeping the loops closed. AM is relevant and necessary for LHC & AWAKE type beams to reach higher particles per bunch (ppb), while not applicable for proton fixed target (pFT) beams where the beam fills almost the entire ring [3].

# 3 RF Power Function & Power balancing

The power $P_n$ necessary to sustain a voltage $V_n$ in a TWS is given by the relation [4]

$$P_n = \frac{1}{\mathrm{Re}(\alpha_n)}\left[\frac{V_n^2}{RL_n^2} + \frac{RL_n^2 I_{\mathrm{RF}}^2 \left|\alpha_n\right|^2}{64} + \frac{V_n I_{\mathrm{RF}} \left|\alpha_n\right| \sin\left(\phi_s - \arg\alpha_n\right)}{4}\right], \tag{1}$$

where $L_n = L_0(11n-1)$ is the length of a $n$-section structure, $\alpha_n$ is a parameter related to the phase slip $\tau_n$ and relativistic $\beta$. The expressions for $\alpha_n$ & $\tau_n$ are as follows:

$$\alpha_n = \left[\frac{\sin\left(\tau_n/2\right)}{\tau_n/2}\right]^2 - j\frac{2\left(\tau_n - \sin\tau_n\right)}{\tau_n^2}, \tag{2}$$

$$\tau_n = \frac{2\pi L_n}{|v_g|}\left(f_{\mathrm{RF}} - f_{0,n}\right)\left(1 - \frac{v_g}{\beta c}\right). \tag{3}$$

In the expression for $\tau_n$, $v_g = -0.0946c$ is the group velocity of the RF wave, $f_{RF}$ is the RF frequency, while $f_{0,n}$ is the $n$-section cavity's center frequency. The design values of the cavity center frequencies are 200.222 MHz, but the presence of installed higher order mode (HOM) couplers detune the center frequencies to lower values. A 'conservative' scenario that is often assumed in calculations uses $f_{0,3} = f_{0,4} = 200.1$ MHz. From the power function equations, one sees that the required power depends on the RF component of the beam current in addition to $I_{RF}$ in addition to the desired voltage and impedance of the structure. As a result, the power is also somewhat modulated by the presence of beam in the cavity even without AM, drawing slightly less power when there is no beam.

The different power plants are capable of reaching different maximum power, while longer cavities produce more voltage proportional to their length. To best exploit the maximum potential of the power plants, i.e. amounts of power proportional to the respective maximum, a system of simultaneous equations should be solved for the $i$ number of cavities:

$$\frac{P_{n,i}}{P_{n,i,\max}} = \frac{P_{n,j}}{P_{n,j,\max}}; i \neq j, \tag{4}$$

$$\sum V_{n,i} = V_{tot}, \tag{5}$$

where $P_{n,i,\max}$ is the maximum possible power from the power plant for cavity $i$ and $V_{tot}$ is the total RF voltage, i.e. sum of voltages in the six cavities.

# 4 The RF Power Predictor

A RF Power Predictor has been developed following the power function & power balancing equations presented in section 3. The predictor tool is available in both raw python script form as well as in a graphical user interface GUI form; the GUI with its different possible inputs is illustrated in Fig. 4. The GUI version has basically all the functionality possible using the scripts. On the bright side, it is more user friendly allowing for faster & easier input, and technically anyone should be able to use and run calculations without knowing details of the script such as where to adjust parameters. However, the user has less control over the intrinsics of the calculation in cases where the user would want to run something more 'special'.

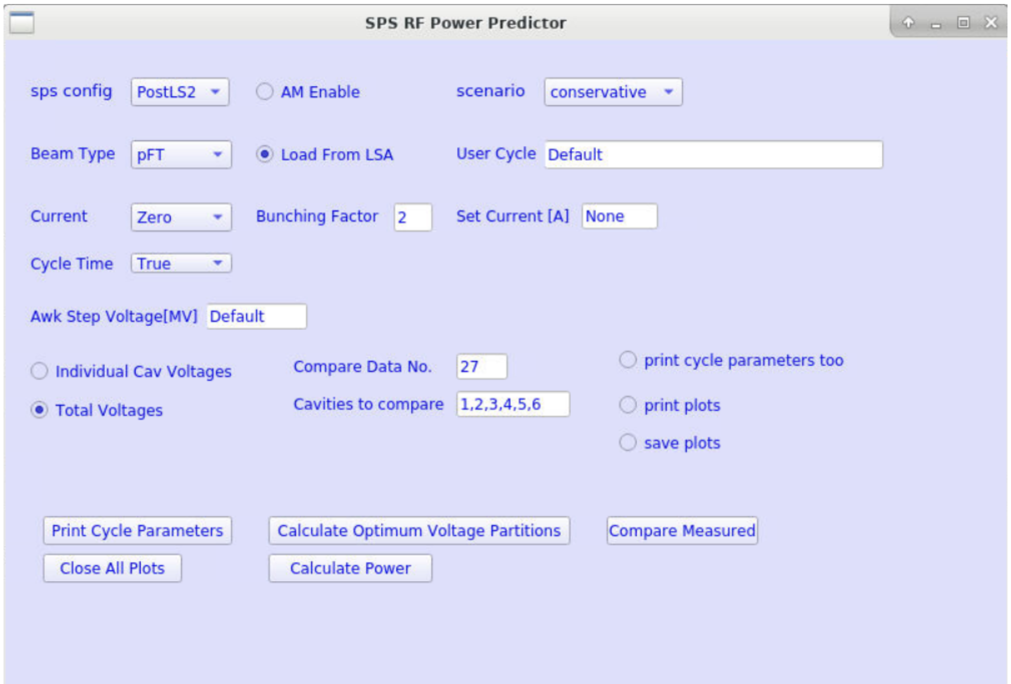


**Figure 4:** The RF Predictor GUI with parameters set to calculate for pFT cycles using BCT beam intensities.

The power predictor has two different options for calculations: using total RF voltage or using individual cavity voltage. For both options, key parameters are input directly from LSA – LHC software architecture, responsible for operating all the CERN accelerators [5]– or from saved csv files, and then peak and average powers for specified cycles are computed. Current cycles for which calculations are dedicated include SFTPRO (pFT beam), AWAKE (high intensity proton single bunch), and LHC1 (proton multibunch beam). At present, calculations for the pFT and Awake cycles have been verified and comparisons with actual forward power measurements carried out. The current used in the calculations can be selected as zero, some specified value, current calculated from typical desired beam intensities for the cycle, or the current calculated from beam intensities measured in the machine (BCT total intensity).

For the total RF voltage option, the total RF voltages for the cycle are used to determine the optimum voltage partitions to ensure power balancing and in turn the computed cavity voltages are used to compute power. In this case, manual counter-phasing is carried out such that for all total voltages below 3 MV, the individual cavity voltages are set to 500 kV. For the end part of the cycle, where the voltage programs don't show that they actually go down, the sections of counter-phasing and zero voltages when RF is off have been hard-coded for the respective cycles. For Awake cycles, the voltage step for bunch rotation and extraction of the shortest possible bunch is also included at the cycle point around extraction time.

For the individual cavity voltage option, as the name implies, the RF voltage for each cavity is retrieved directly from LSA along with the voltage phases, and the peak and average powers are then computed directly without having to carry out the optimum voltage partition calculations. Since the cavity voltage and voltage phases are used, counter-phasing is automatically taken into account for the beginning of the cycle. For the end parts, counter-phasing and RF off points are set manually. The voltage steps for Awake cycle are chosen as fixed partitions of the total voltage proportional to the cavity length.

The following subsection presents typical calculations output from the power predictor tool for pFT & Awake cycles.

## 4.1 Power Predictor Calculations

The main parameters that the RF power predictor takes in for power calculations are the voltage, momentum (to get relativistic $\beta$ and revolution frequency that is equal to $f_{RF}$), the stable phase, and the current. Plots of the voltage, momentum, stable phase programs for the pFT cycle is shown in Figs. 5 to 7. The current from total intensity measured by BCT when the cycle is running is also shown in Fig. 8. When using the total voltage, calculation of the optimum voltage partition is performed; this is shown in Fig. 9. From the calculated voltage partitions, the required power is calculated. The corresponding pFT cycle power calculation output is illustrated in Fig 10

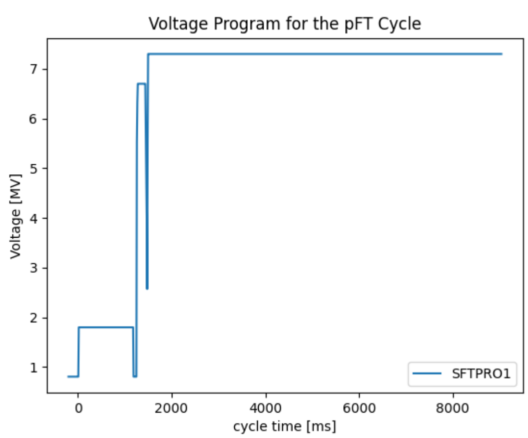


**Figure 5:** The voltage program for a pFT cycle (SFTPRO1).

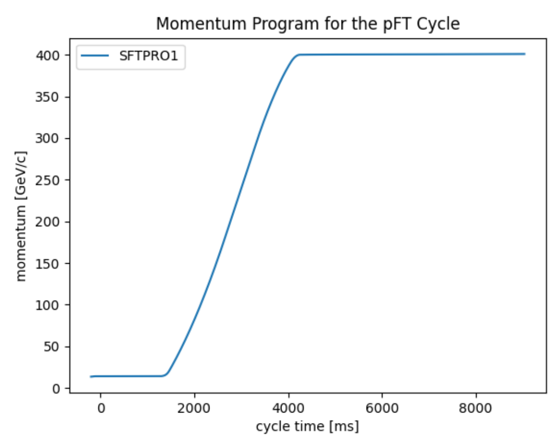


**Figure 6:** The momentum program for pFT cycle.

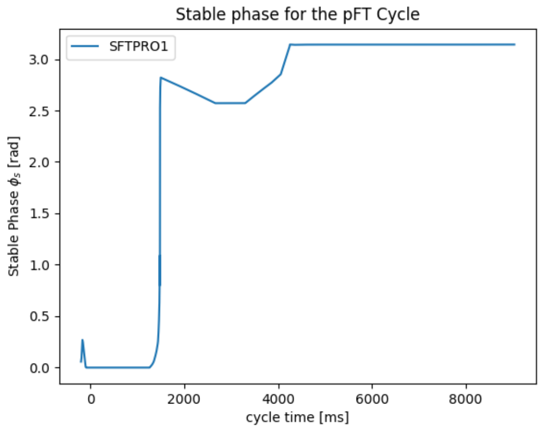


Figure 7: The stable phase program for pFT cycle.

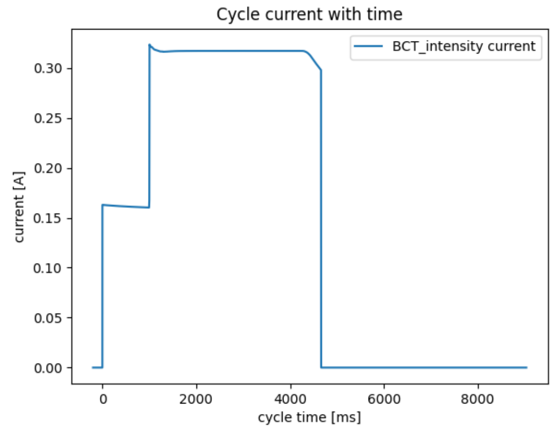


Figure 8: Current from intensity recorded by BCT during a SFTPRO1 cycle.

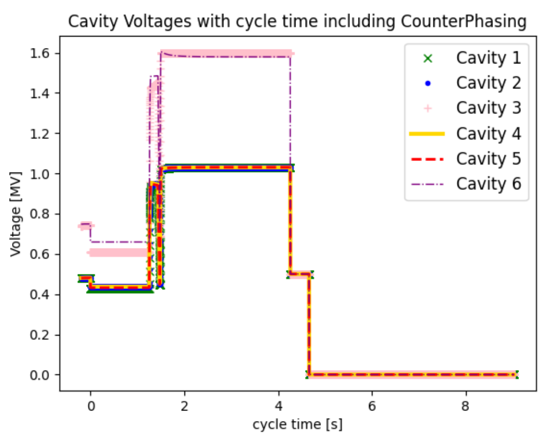


Figure 9: Optimum voltage partitions computed for SFTPRO1.

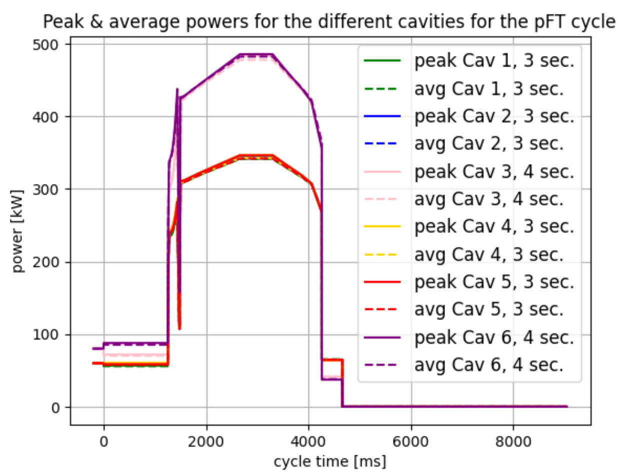


Figure 10: The RF power computed from using the optimum voltage partitions for pFT cycle.

Rather than computing the voltage partitions from the total voltage, the individual cavity voltages desired can also be retrieved directly from LSA; see Fig. 11 for pFT cycle. Along with the voltage, the respective voltage phases are also retrieved which allows to take into account counter-phasing directly. The corresponding voltage phases for the pFT cycle cavity voltages is displayed in Fig. 12. The power calculations from using these individual cavity voltages and voltage phases is presented in Fig. 13. This gives a more accurate representation of RF power supplied.

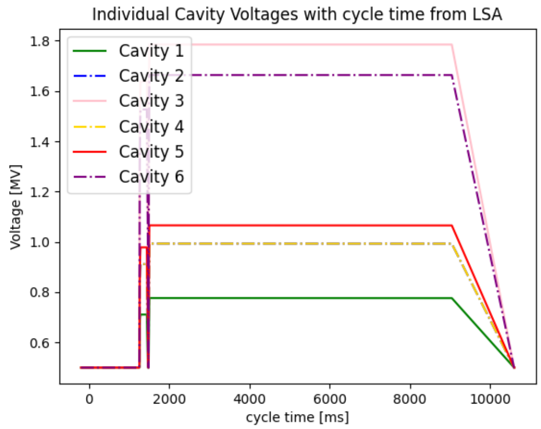


**Figure 11:** The individual cavity voltages as read from LSA for SFTPRO1.

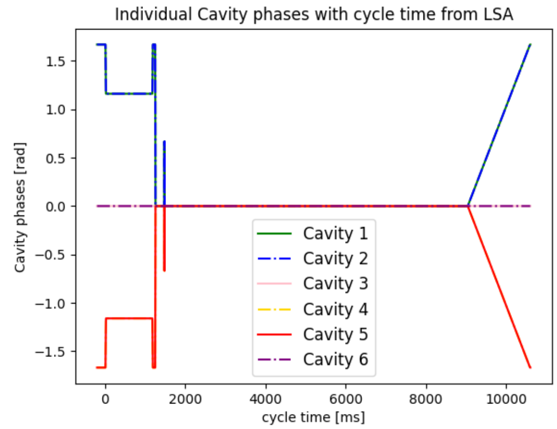


**Figure 12:** The individual cavity voltage phases as read from LSA for SFTPRO1.

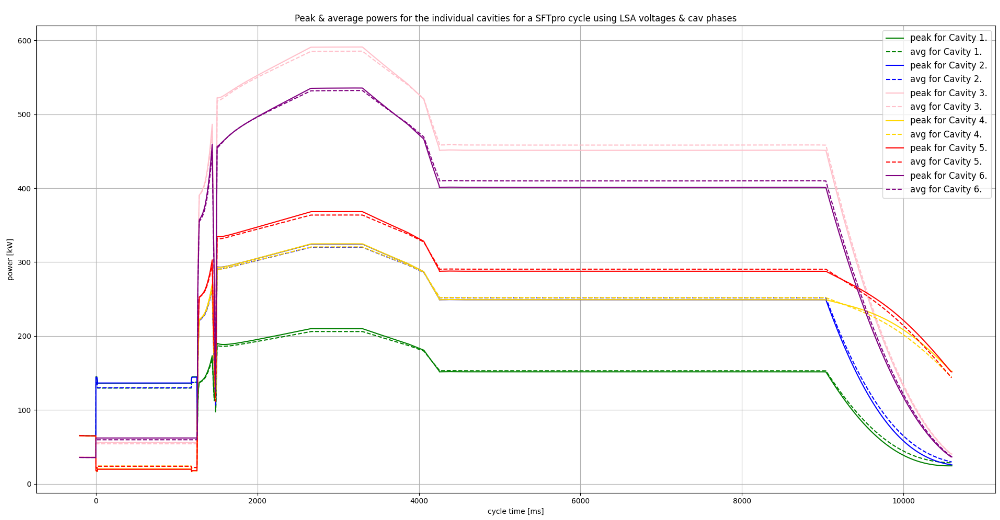


**Figure 13:** The computed RF power using the direct individual cavity voltages and phases from LSA for SFTPRO1.

The power plot for the Awake cycle using individual cavity voltage option is displayed in Fig. 14. All the other respective plots for the Awake cycle ,like the pFT cycle shown, are presented in the Appendix.

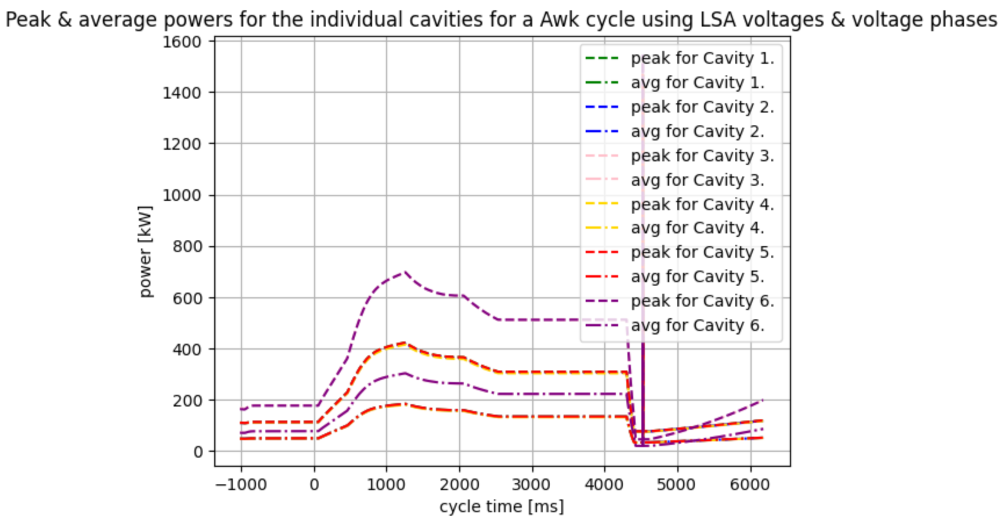


**Figure 14:** The computed RF power using the direct individual cavity voltages and phases from LSA for AWAKE1.

# 5 Calibration

In order to ensure that RF power predictor tool is able to produce more accurate results that match real data when performing calculations, some calibration was necessary. This involved determining the actual center frequencies of the different cavities at present day. Secondly, a scale factor for the power was determined as un-scaled calculations underestimate the required power, mainly close to the maximum voltages in the cycle, when compared to the forward power measurements.

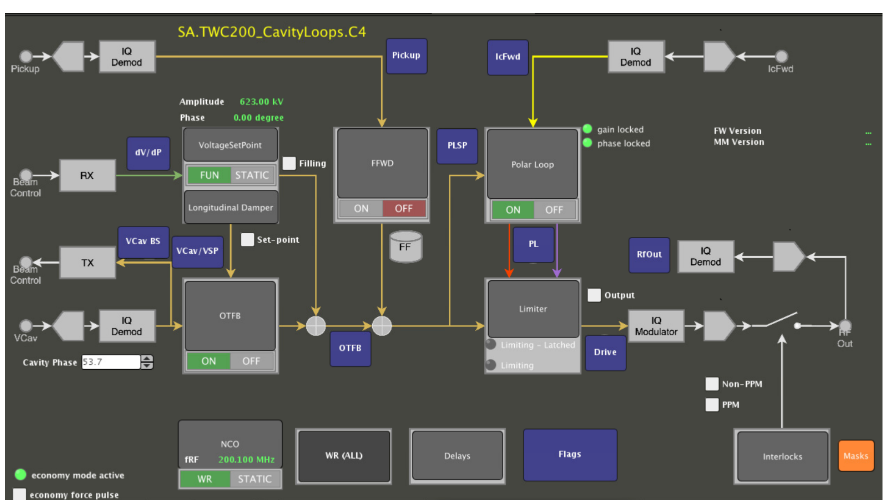


**Figure 15:** The cavity loop controller widget in inspector.

The calibration measurement procedure was as follows. First, all cavity loops, except for the polar loops, for each cavity was closed using the cavity loop control inspector (see Fig. 15). The cavity filling option was turned on and the voltage changed to static. A RF frequency scan was then carried from 199.70 MHz to 200.40 MHz, in steps of 0.01 MHz. The mean forward power and the mean voltage was measured for each RF frequency applied to the cavities in the presence of no beam, i.e. zero current. The forward power is kept almost constant in the process. Plots of the mean measured voltage as a function of the set RF frequency for three different data sets is shown in Figs. 16 & 17. The first data set was taken with MD (machine development) cycle where other cycles not part of the measurement were present in the supercycle. The pulse-to-pulse modulation of the beams in those cycles likely affected the measured voltage making the trends somewhat jittery. The next two data sets were taken when only the MD cycles were present in the supercycle, and the trend are smoother and almost identical.

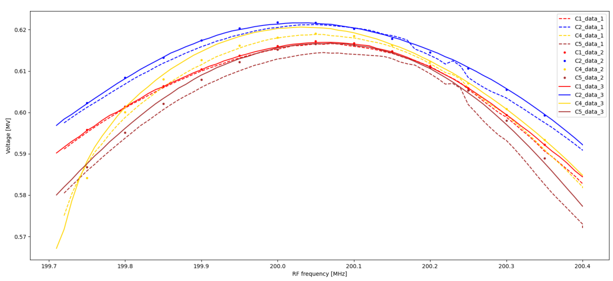


**Figure 16:** The measured voltages as function of set RF frequencies for the 3-section cavities.

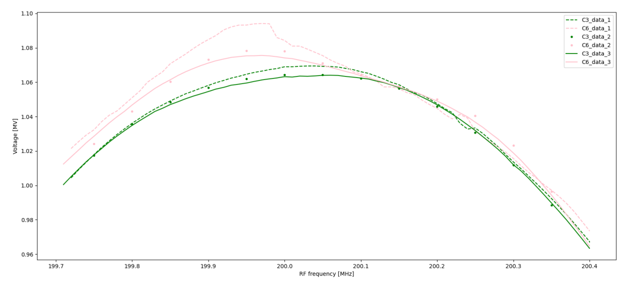


**Figure 17:** The measured voltages as function of set RF frequencies for the 4-section cavities.

To get the parameters for calibration, one uses the power function relation (Eq. 1) at zero current. The equations of interest for forming the fits become:

$$P_n = \frac{1}{\mathrm{Re}(\alpha_n)} \left[ \frac{V_n^2}{RL_n^2} \right], \tag{6}$$

$$\mathrm{Re}\,(\alpha_n) = \left[ \frac{\sin\left(\tau_n/2\right)}{\tau_n/2} \right]^2, \text{with} \tag{7}$$

$$\tau_n = \frac{2\pi L_n}{|v_g|} \left(f_{\mathrm{RF}} - f_{0,n}\right) \left(1 - \frac{v_g}{\beta c}\right). \tag{8}$$

The scale factor $sf$ for power is obtained from using the maximum voltage measured to get a calculated power $P_{calc}$. The ratio between the mean measured forward power $P_{meas}$ and the calculated power $P_{calc}$, then gives the scale factor:

$$sf = \frac{P_{meas}}{P_{calc}}. \tag{9}$$

Next, the cavity center frequencies $f_{0,n}$ is fitted into the sinc function for $\mathrm{Re}\,(\alpha_n)$ with the normalised measured mean voltage squared used as values of $\mathrm{Re}\,(\alpha_n)$ for fitting. Here, all the other variables are known except for the fit parameter $f_{0,n}$.

**Table 1:** The fit parameters for calibration.

| Cavity | $f_{0,n}$ [MHz] | sf |
|---|---|---|
| 1 | 200.04 | 1.09 |
| 2 | 200.04 | 1.08 |
| 3 | 200.02 | 1.06 |
| 4 | 200.06 | 1.08 |
| 5 | 200.04 | 1.09 |
| 6 | 200.00 | 1.04 |

The $sf$ and $f_{0,n}$ obtained are presented in Table 1. Fits performed using the calibration measurements for the six cavities are displayed in Figs. 18 to 23.

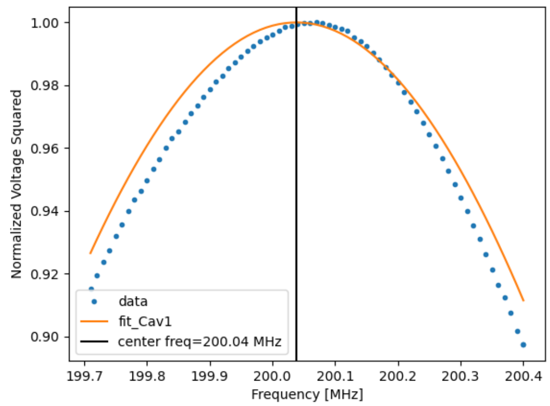


**Figure 18:** Fitted $\mathrm{Re}\,(\alpha_n)$ for cavity 1.

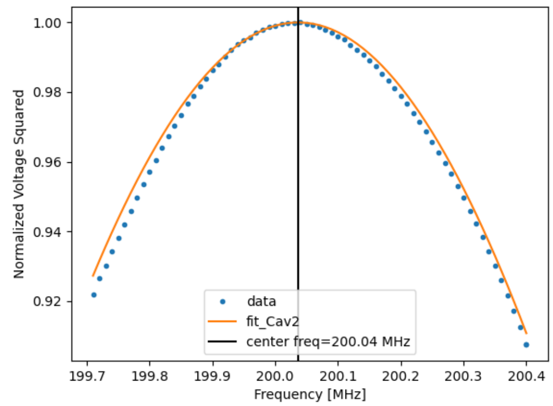


**Figure 19:** Fitted $\mathrm{Re}\,(\alpha_n)$ for cavity 2.

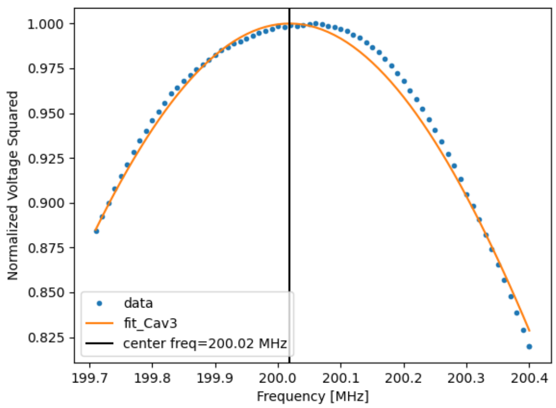


**Figure 20:** Fitted $\mathrm{Re}\,(\alpha_n)$ for cavity 3.

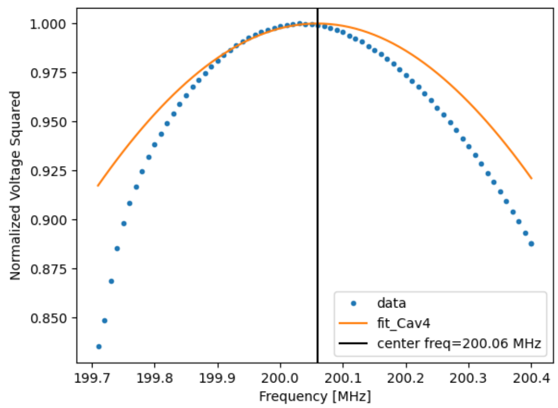


**Figure 21:** Fitted $\mathrm{Re}\,(\alpha_n)$ for cavity 4.

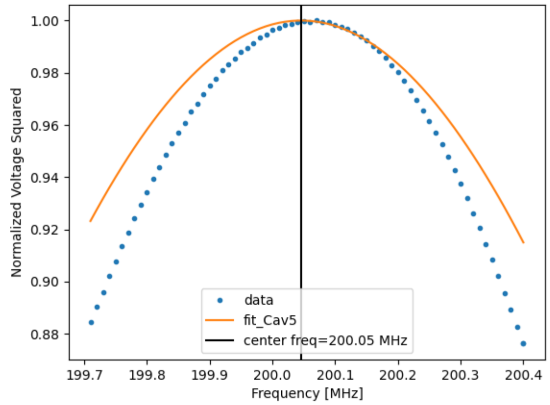


**Figure 22:** Fitted Re $(\alpha_n)$ for cavity 5.

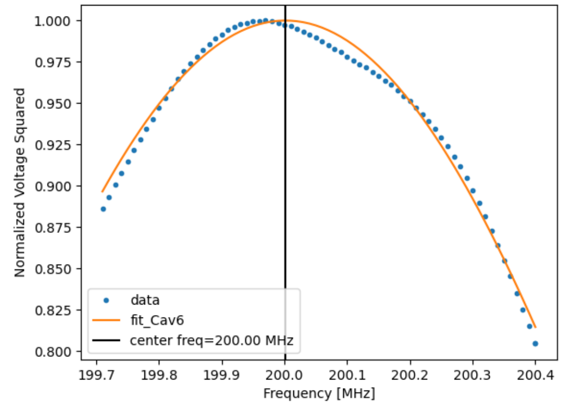


**Figure 23:** Fitted Re $(\alpha_n)$ for cavity 6.

It can be seen for most cavities, the fitting function could not be perfectly fitted with the width of the function being less wide than expected or presence of discrepancies in the cavity transfer function (shape somewhat distorted and peak shifted more towards lower frequencies).

The discrepancy in the transfer function could be a result of different reflected power present at different RF frequencies as shown in Fig. 24. The reflected power depends on the phase of the forward power and this varies with different RF frequencies input. The power seen by the cavity is then modified significantly leading to different voltage readings than expected by the power transfer function. Further investigations and follow up measurement is required to better explain the discrepancies and obtain better calibration parameters.

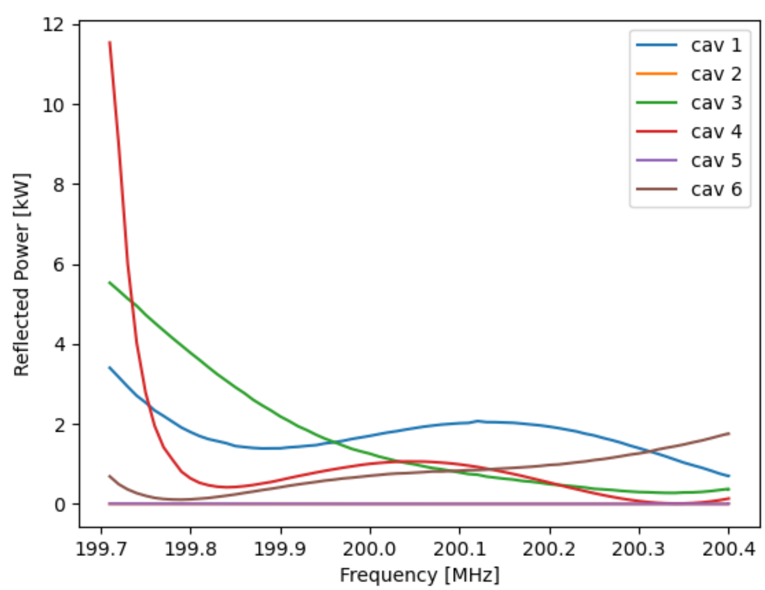


**Figure 24:** Reflected power acquired during the calibration measurements. Cavity 2 & 5 had some problems with the reflected power acquisition so shows zero readings.

# 6 Measurement Comparisons

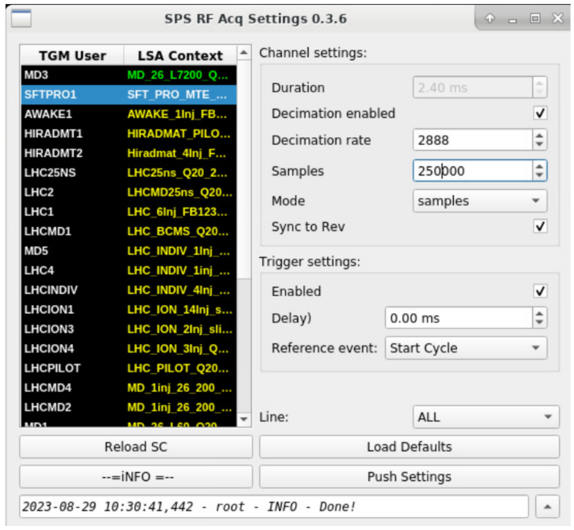


**Figure 25:** The SPS RF Acquisition system settings.

The final part in the assessment of the RF predictor tool involves comparing the calculated predictions with actual measured forward power for the cycles. To set up the power measurement acquisition, a buffer (as shown in Fig. 25) was set up such that a mean measurement point is acquired for every one turn in the beam cycle. This has been done for pFT and Awake cycles so far. Comparison of the measured forward power for the common pFT cycle 'SFTPRO1' is shown in Fig. 26. It can be seen that the measured forward powers, though similar, are slightly higher than the calculated power, mainly in the areas around the peak voltage. The comparisons match better with the the peak power than the average. This could hint that the pulse modulation occurs not precisely with $\frac{10}{11}^{th}$ of the cycle which should be the filled part, but is slightly higher.

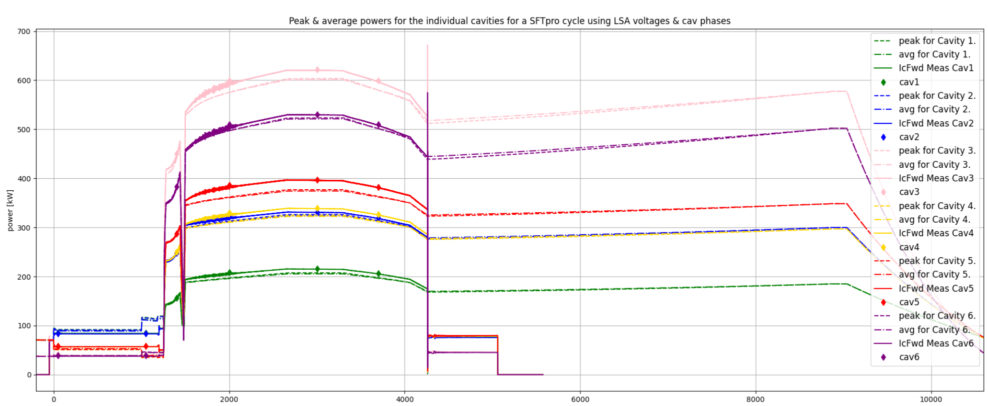


**Figure 26:** Comparison between the measured & predicted RF power in the different cavities for a SFTPRO1 cycle.

For the Awake cycle, comparisons of the average power were very precise for cavities 3 & 2, while similar for the rest.

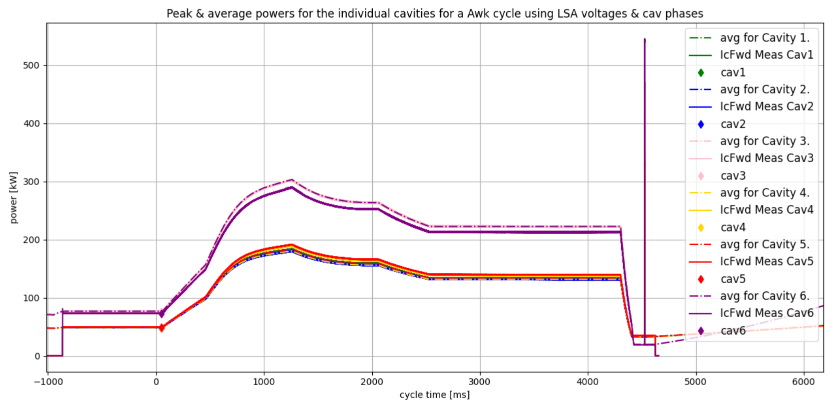


**Figure 27:** Comparison between the measured & predicted RF power in the different cavities for a AWAKE1 cycle..

While the comparisons show similar RF power for the calculations and measurements, it's still too early to call them successful and there have already been strange behaviour seen in the transfer function plots for most of the cavities. Further investigation to explain the cause of the is desired to carry out new calibration measurements that would results in better fits of the calibration parameters and boost the RF power predictor to make more confident predictions.

# 7 Conclusion & Outlook

A RF power predictor tool has been developed which has been tested and verified to correctly calculate the required RF power for different beam cycles in the SPS, in particular for pFT and Awake cycles. During the calibration measurement to get the cavities' center frequency and a power scale factor that would make the power predictions more solid, some discrepancies were found in the transfer function. This behaviour is one of the things that needs to be studied and carry out new calibration measurements to achieve more accurate fit functions. Other upgrades to the tool involve adding the settings for the 800 MHz cavities, RF power calculations for not only cycles but also the whole supercycle or for coast mode (maintain a set voltage for a long time period), and add the possibility to compute for more SPS cycles such as those that use ions. Finally, a more ambitious and challenging improvement that could be done is that the RF power predictor is able to do continuous automatic power calculations as the SPS voltage and other parameters are changed in really time when trying to push beam intensities and give warnings when it estimates that the power would cross some interlock or breakdown limit.

# References

1. The Super Proton Synchrotron. https://cds.cern.ch/record/1997188 (2012).
2. Kramer, P. & Vollinger, C. Measurement of rf voltage in long traveling wave accelerating structures with application to the CERN Super Proton Synchrotron. *Physical Review Accelerators and Beams* **22.** https://doi.org/10.1103/physrevaccelbeams.22.101002 (Oct. 2019).
3. Baudrenghien, P. *et al.* Operation and protection of the SPS RF power system for the various beams after the LIU upgrades (2020).
4. Dôme, G. The SPS acceleration system travelling wave drift-tube structure for the CERN SPS. https://cds.cern.ch/record/319440 (1976).
5. Roderick, C. & Billen, R. *The LSA Database to Drive the Accelerator Settings* tech. rep. (CERN, Geneva, 2009). https://cds.cern.ch/record/1215575.

# A Appendix

## A.1 Calibration measurement with all cavity loops off including polar loops

A set of calibration measurements were taken where the mean voltage for each cavity at set frequencies were measured with all cavity loops including the polar loops off. This results in the measured voltage showing a lot more discrepancies from how the transfer function describes. This made fitting a center frequency very unreasonable and hence the measurements were redone with polar loops on. The plots of these measured voltage against set frequencies for cavities 4 & 5 are shown in Figs. 28 & 29.

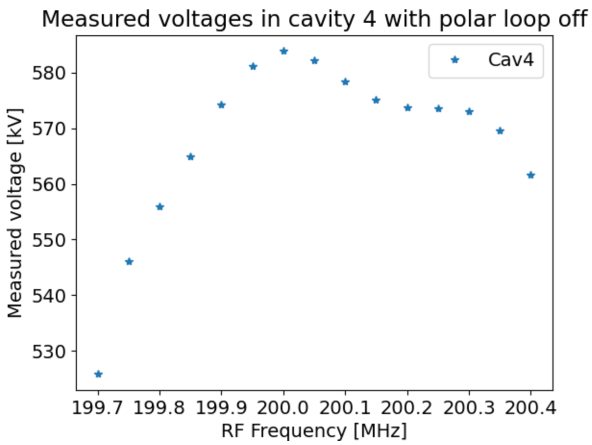


**Figure 28:** Measured voltage for cavity 4 with all cavity loops off.

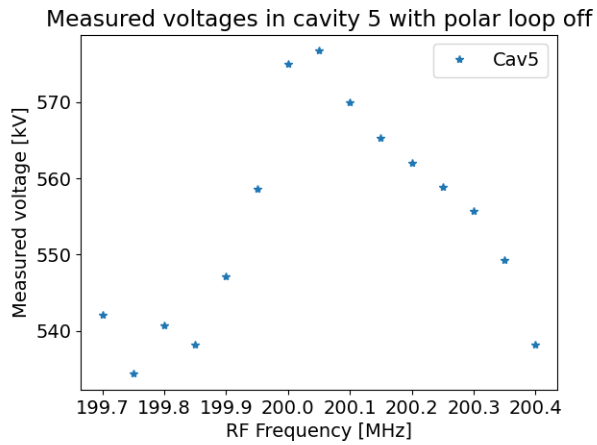


**Figure 29:** Measured voltage for cavity 5 with all cavity loops off.

## A.2 Power Predictor Calculations for Awake

This sections presents the different key parameters and power plots that were shown for the pFT cycle in the earlier section. The total voltage, momentum, stable phase programs as well as the Awake BCT intensity current is displayed in Figs. 30 to 33. The corresponding optimum voltage partition & RF power calculations are shown in Figs. 34 & 35. Lastly, the individual cavity voltages as read from LSA along with the voltage phases used to compute the RF power with present settings are displayed in Figs. 36 & 37.

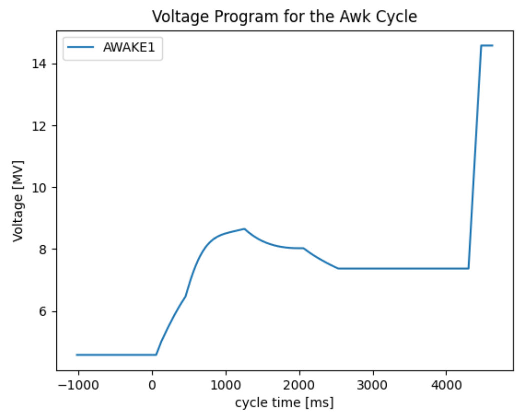


**Figure 30:** Voltage program for Awake cycle.

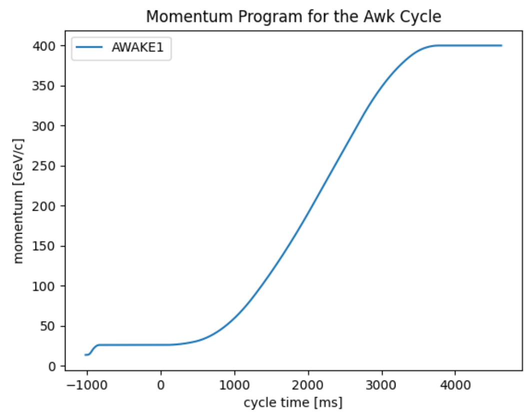


**Figure 31:** Momentum program for Awake cycle

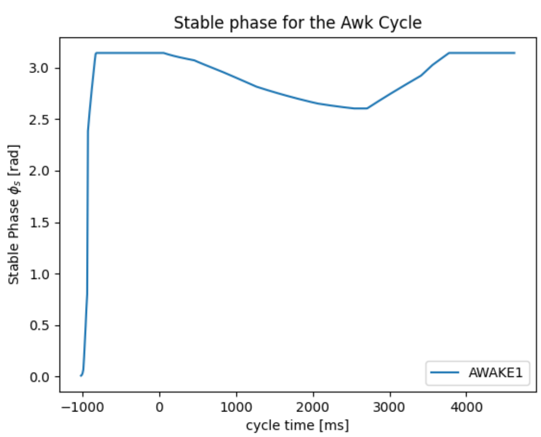


**Figure 32:** The stable phase program for Awake cycle.

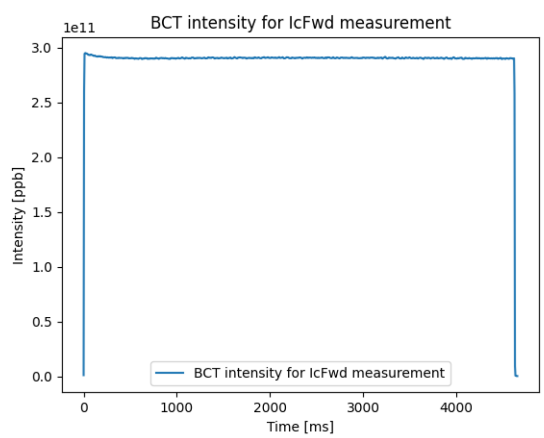


**Figure 33:** Current according to BCT intensity measured during a AWAKE1 cycle.

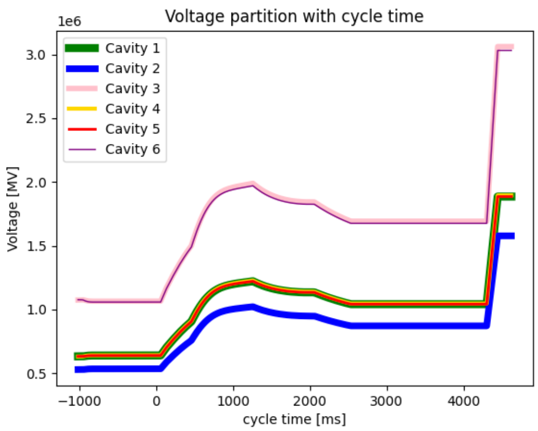


**Figure 34:** Optimum voltage partitions computed for AWAKE1.

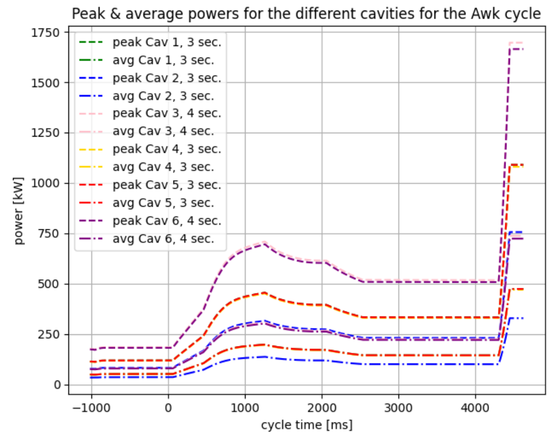


**Figure 35:** RF power calculated using the AWAKE1 optimum voltages.

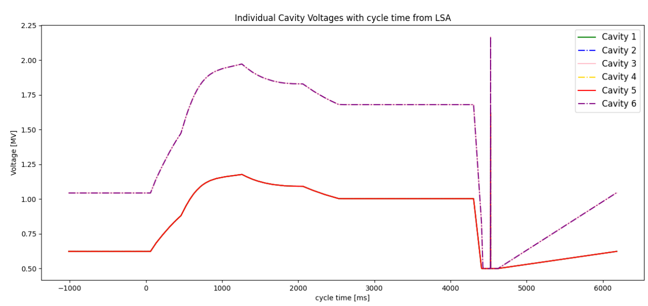


**Figure 36:** The individual cavity voltages read from LSA for AWAKE1.

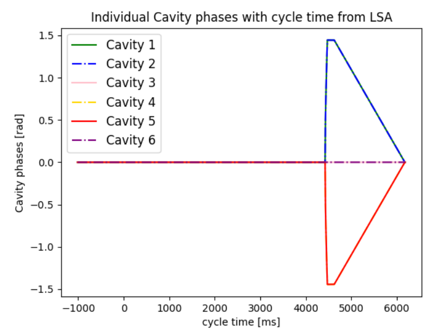


**Figure 37:** The individual cavity voltage phases read from LSA for AWAKE1.