PIP-II RF Power Specifications for Dressed Cavity and Cryomodule Testing

Document number: EN04282

Document Approval

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Revision History

|  |  |  |
| --- | --- | --- |
| Revision | Date of Release | Description of Change |
| - | July 27, 2020 | Initial Version |
|  |  |  |

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# Purpose

The purpose of this document is to specify RF power amplifier requirements for performing cold cavity tests on PIP-II specified dressed cavities and cryomodules.

# Acronyms

|  |  |
| --- | --- |
| HB | High Beta |
| HWR | Half Wave Resonator |
| LB | Low Beta |
| PIP-II | Proton Improvement Plan II Project |
| RF | Radio Frequency |
| SSR | Single Spoke Resonator |
| SRF | Superconducting Radio Frequency |
| TTF | Transit Time Factor |

# Reference Documents

|  |  |  |
| --- | --- | --- |
| **#** | **Reference** | **Document #** |
| 1 | Summary of Formulas Used for the Table of PIP-II Cavity and RF Amplifier Parameters | ED0012235-- |
| 2 | PIP-II RF Parameter Table | ED0012235-- |
| 3 | SRF Cavity Parameters PRD | ED0010221-A |
| 4 | Cavity Test Power Calc | EN04282-- |

# Introduction

The PIP-II linac will utilize five different types of SRF cavities to accelerate H- ions to 800MeV or higher. The lattice design determines the accelerating gradient and synchronous phase required for each cavity. References 1 and 2 determine the RF power required to maintain the cavity field based on the lattice and cavity parameters (reference 3). These calculations also factor in margin required to maintain the cavity gradient during expected deviations in cavity resonant frequency.

Part of the process for commissioning the cryomodules involves testing the cavities within the cryomodule prior to operation. In some cases, these tests will be performed at a dedicated testing area for cryomodules or cavities that is not part of the PIP-II linac. The required RF power for performing the cavity tests is significantly lower than the required power needed to accelerate beam through the cavities. This can save cost and schedule when setting up the test amplifiers. This document describes the calculation of the power required to test the PIP-II SRF cavities with input couplers set for beam acceleration.

# Power Calculation

The power at the cavity input coupler required to maintain the cavity gradient to accelerate beam is given by the equation:

$P\_{f}=\frac{V\_{a}^{2}(1+β)^{2}}{4βQ\_{0}\left(\frac{r}{Q}\right)}\left[\left(1+\frac{I\_{Re}T\left(\frac{r}{Q}\right)Q\_{0}}{V\_{a}\left(1+β\right)}\right)^{2}+\left(\frac{Q\_{0}}{1+β}\frac{2δf}{f}+\left|\frac{Q\_{0}}{1+β}\frac{2∆f}{f}+\frac{I\_{Im}T\left(\frac{r}{Q}\right)Q\_{0}}{V\_{a}\left(1+β\right)}\right|\right)^{2}\right]$ 1)

where $I\_{Im}=I∙sin(φ)$, $I\_{Re}=I∙cos\left(φ\right)$, $φ$ is the cavity phase, $T$ is the transit time factor (TTF), $r/Q$ is the cavity impedance at the optimal velocity, $f$ is the cavity frequency, $Q\_{0}$ is the cavity unloaded quality factor, $δf$ is the microphonics detuning amplitude, $Δf$ is the static detuning. The cavity accelerating voltage, $V\_{a}$, is the energy gain at the optimal velocity for the zero synchronous phase.

For testing cold dressed cavities and cryomodules, we assume that the RF system tracks the resonant frequency of the cavity, and there is no beam loading current. This reduces the formula to:

$P\_{f}=\frac{V\_{a}^{2}(1+β)^{2}}{4βQ\_{0}\left(\frac{r}{Q}\right)}$ (2)

The accelerating cavity voltage (Va) is determined from beam simulations and captured in Ref 2. The maximum voltage for each cavity type is captured in Table 4-1 with a 10% increase to allow for higher gradient operation in the PIP-II linac and a 5% increase to allow for conditioning of the cavity beyond its expected operating gradient. The coupling coefficient (β) design value is captured in Ref. 3, and the maximum potential error in setting the coupling is 20% of the coupling value. This creates a minimum and maximum value for coupling that is captured in Ref 3. The maximum power required at the cavity input coupler for cavity tests is determined from the maximum possible coupling value within the error for the particular cavity type.

To determine the final value of the required linear range of the amplifier (1dB compression point), transmission line losses and some margin for dynamics was added. The final row in table 4-1 represents the minimum power specification for any RF amplifier used to test a PIP-II SRF cavity.

Table 4‑. Cavity Input Power Parameters for Cavity Testing

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **HWR** | **SSR1** | **SSR2** | **LB650** | **HB650** |
| Frequency (MHz) | 162.5 | 325 | 325 | 650 | 650 |
| Max Cavity Voltage for Conditioning and Testing (MV) | 2.31 | 2.37 | 5.78 | 13.62 | 22.88 |
| Q0 | 8.5e9 | 8.2e9 | 8.2e9 | 24e9 | 33e9 |
| Max Coupling (β) | 4434 | 3279 | 2028 | 2768 | 3999 |
| R/Q (Ω) | 272 | 242 | 305 | 340 | 610 |
| Peak RF Power at Coupler including coupling errors (kW) | 2.56 | 2.32 | 6.76 | 15.74 | 26.01 |
| Transmission Line Efficiency | 90% | 90% | 90% | 90% | 90% |
| Dynamics Overhead | 5% | 5% | 5% | 5% | 5% |
| Peak Amplifier Power Required with Errors and Margin (kW) | 2.84 | 2.57 | 7.52 | 17.49 | 28.9 |