COUPLER DESIGN FOR RISP SPOKE CAVITY*

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Abstract

The RISP project includes a heavy ion linac to accelerate ions up to 238U to 200 MeV/u with 400 kW of beam power. The same accelerator will also be capable of accelerating light ions with proton currents and final energy of 0.66 mA and 600 MeV. TRIUMF designed the superconducting single spoke resonator for the linac SSR1 at 325 MHz for beta=0.3. According to specifications the cavity will require the RF coupler to be capable for operation in CW regime close to full reflection with a forward power of 5 kW. This paper reports about the RF coupler specifications, simulations and design.

INTRODUCTION

The RISP multi-purpose accelerator facility has been proposed at the Institute for Basic Science (IBS), Korea, for research in atomic and nuclear physics, material science, bio and medical science, etc. It can provide various energy beams from protons to exotic rare isotopes up to uranium [1]. A prototype cavity of the β=0.3 single spoke resonator SSR1 has been designed and fabricated at TRIUMF under collaboration with IBS [2]. A coupler for the SSR1 spoke cavity operating at 2K was designed at TRIUMF.

COUPLER SPECIFICATIONS

The coupler specification is based on cavity and beam parameters, coupling and assembling considerations and cryogenic load for the cryomodule.

Cavity and Beam Parameters

The SSR1 main cavity parameters and nominal beam parameters are presented in Table 1. For nominal operation the coupler should transmit in the cavity an RF power of 1.64 kW for the beam and 5.4 W for the structure walls.

Table 1: Cavity and Beam Parameters

Parameter	Unit	Value
Frequency, f	MHz	352
Geometry beta, β_o		0.30
Shunt impedance, R/Q	Ohm	233
Quality factor, Q_o		5×10^9
Effective voltage, V_{eff}	MV	2.50
Cavity power, P_{cav}	W	5.4
Beam current, I_{beam}	μA	656
Beam power, P_{beam}	kW	1.64

Cavity Detuning and Forward Power

The forward power requirement is given by equation [3]

$$P_{for} = \frac{P_{cav}}{4\beta}\left[(1+\beta+b_o cos\varphi)^2 + \left(-2Q_o\frac{\Delta f_{tot}}{f_o} - bsin\varphi\right)^2\right] \quad (1)$$

where $b_o = \frac{P_{beam}}{P_{cav}}$, $\beta = \frac{Q_o}{Q_{ext}}$, $\Delta f_{tot} = \Delta f_s \pm \Delta f_d$ total detuning consists of static (controllable) detuning Δf_s=0 (we assume that it's compensated) and random dynamic (uncontrollable) detuning Δf_d. For estimation of power requirement we set the accelerating phase angle $\varphi = 0$ (for maximum beam power). Finally the equation (1) is reduced to

$$P_{for} = \frac{P_{cav}}{4\beta}\left[(1+\beta+b_o)^2 + \left(-2Q_o\frac{\Delta f_d}{f_o}\right)^2\right] \quad (2)$$

The cavity will operate at 2K in superfluid helium at a pressure of 31±0.3 mbar. The expected sensitivity to helium pressure fluctuations should be ≤ 10 Hz/mbar and results in detuning of ≤ ±3 Hz. These tend to be slow variations and easily compensated by the tuner.

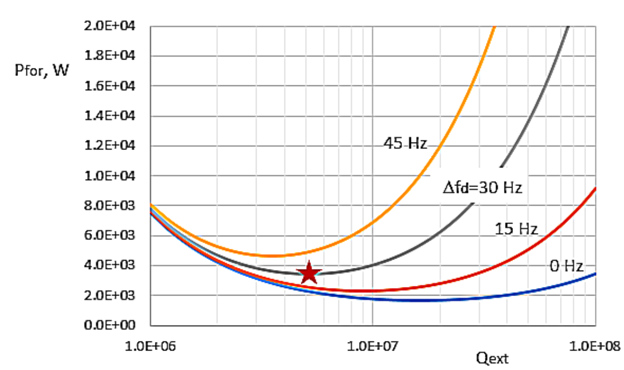

Figure 1: P_{for} vs. Q_{ext} for nominal accelerating regime at various Δf_d; optimum point P_{for}=3.4 kW at $Q_{ext}=5.2\cdot10^6$ for Δf_d=30 Hz is marked with red star.

The cavities will operate in CW regime so we do not consider Lorentz force detuning (LFD). This will only be an issue at turn on if the cavity is locked at low gradient and ramped up to higher gradient.

Microphonics is the main source of fast oscillation typically driven by the lowest mechanical mode. Previous measurements from other similar cavities (either SSR or

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HWR cavities) indicate frequency errors distributed in a Gaussian with σ<2 Hz. In order to be stable the half of the bandwidth should be at least 10σ to avoid low probability events unlocking the cavities or 20 Hz [4].

A plot of the forward power P_{for} as a function of Q_{ext} and expected detuning Δf_d (to have sufficient bandwidth for stable operation) is shown on Fig. 1. A very conservative operating point would assume a bandwidth to compensate $\Delta f_d=\pm30$ Hz of total detuning corresponding to an optimum $Q_{ext}=5.2\cdot10^6$ with a required P_{for} at the detuning limit of 3.4 kW and 2.2 kW in the center of the tuning window.

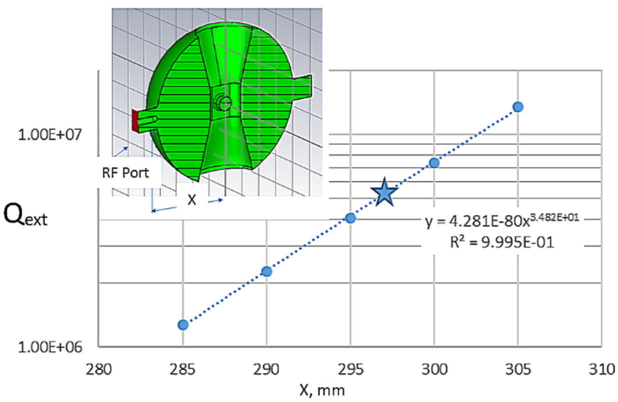

Figure 2: Coupler design for SSR1 RISP cavity.

Antenna and Transmission Line Considerations

The cavity has 3-1/8" RF port for electrical antenna. We choose 100 Ohm wave impedance for the antenna vacuum section of the coupler in consideration of increasing of multipacting level. Simulations in CST Microwave Studio for the cavity and antenna in 100 Ohm coaxial give us the distance of the antenna tip *x* from the cavity center for different Q_{ext} (Fig. 2). Analyzing Qext(x) and $P_{for}(Q_{ext})$ data for Δf_d=30 Hz and $Q_{ext}=5.2\cdot10^6$ we see that an error of ±2 mm in antenna position will lead to an increase of P_{for} for 2.5%, which is not very critical. In such a way we can choose a fixed coupler option for the design. Power loss on the copper antenna tip from the cavity field is estimated at ~0.15 W.

During operation while Δf_d is fluctuating from 0 to 30 Hz VSWR is changing from 3.1 to 6.1. Therefore the transmission line (TL) is operating close to the standing wave (SW) regime. The TL power rating has to be 4 times more than for TW regime. For external TL we choose 50 Ohm 3-1/8" coaxial transmission line; at 325 MHz it has 25 kW rating for TW and 6.25 kW for SW regimes. This rating is sufficient even for a regime with 25% more gradient when P_{for}=5 kW is required.

Cryogenic Load

The coupler cryogenic load should not add significantly to the cryogenic load expected from the cavities and other cryomodule elements. Thermal strapping should be provided to remove the heat at various thermal stages from 2K (superfluid He), 4.5K (liquid He), 40K (He gas) and 300K (room temperature). The guidelines for heat loads are: 0.5 W for 2K, 1 W for 4.5K and 15 W for 40K.

COUPLER DESIGN

The design of the coupler is shown on Fig. 3. It consists of 3 main sections: the antenna 'cold' vacuum section, a single RF vacuum window and a 'warm' 50 Ohm air TL section. The hermetic unit consists of the cavity, 'cold' section and RF window. It is intended that the cold section be assembled on the cavity in clean room conditions.

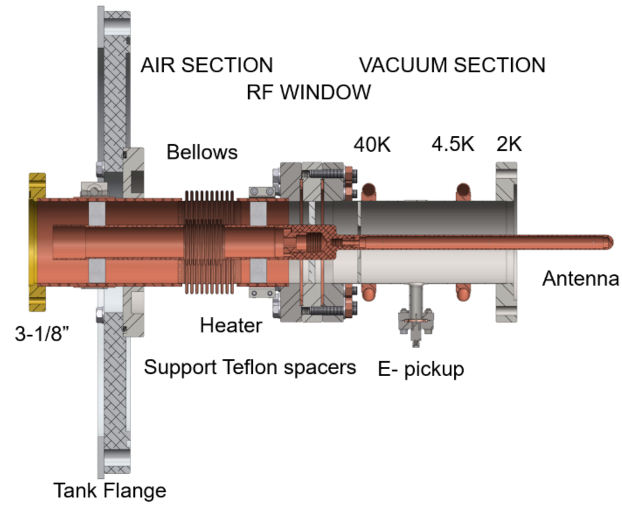

Figure 3: Coupler design for SSR1 RISP cavity.

Vacuum Section

The vacuum section provides coupling and is mounted to the cavity via a 3-1/8" RF port. A copper capacitive antenna is centered inside the 3-1/8" stainless steel (SS) tube forming a 100 Ohm coaxial TL. The SS tube has 4K and 40K cryogenics intercepts to reduce the heat load to the 2K (superfluid He) system with a wall thickness of 0.4 mm to further reduce the heat load for the 2K, 4K and 40K intercepts. Copper coating inside the SS tube is not required. The copper hollow antenna rod has pumping holes and thread connection to the RF window and penetrates to the cavity RF port.

Table 2: Input Parameters for the Coupler Simulation

Parameter	Unit	Value
Effective voltage, V_{eff}	MV	3.12
Cavity power, P_{cav}	W	7.9
Beam current, I_{beam}	μA	656
Beam power, P_{beam}	kW	2.05
Quality factor, Q_o		$5.0\cdot10^9$
Coupler Q_{ext}		$5.2\cdot10^6$
Antenna $VSWR_a$		7.61
P_{for} in antenna	kW	5.04

The SS tube has an inner baffle disk protecting the RF window ceramic surface from energetic electrons which potentially could come from cavity multipacting and field

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emission processes. CST Particle Studio multipacting simulations show that the disk also mitigates multipacting in the vacuum section itself by confining the multipacting region; it stops secondary electrons propagating to the ceramic RF window. The antenna section is equipped with a pickup for secondary electrons – E-pickup – an electrical antenna based on a single ended ceramic RF feedthrough mounted on 1-1/3" flange on the SS pipe welded to the SS tube. The antenna section components should be polished inside to minimize radiative heat load for 2K. Since the coupler is operating in standing wave (SW) overcoupling regime, the length of the antenna is about λ/4 to provide a minimum of the E-field longitudinal distribution at the ceramic RF window; it significantly reduces RF loss and mitigates multipacting in the RF window.

RF Window Section

The coupler has a single RF window as a barrier between cavity vacuum and atmosphere. The RF window consists of a 3-1/8" Al_2O_3 6 mm thick ceramic disk brazed with flange and inner conductor, it provides interfaces for the vacuum and air 'warm' 50 Ohm TL sections. The step of impedances close to the RF window location improves matching in the 50 Ohm TL section; the decrease of VSWR is ~2 times. The vacuum or 'cold' side of the ceramics should be sputtered with TiN or TiO_x to provide a discharge path and mitigate multipacting on the ceramic surface.

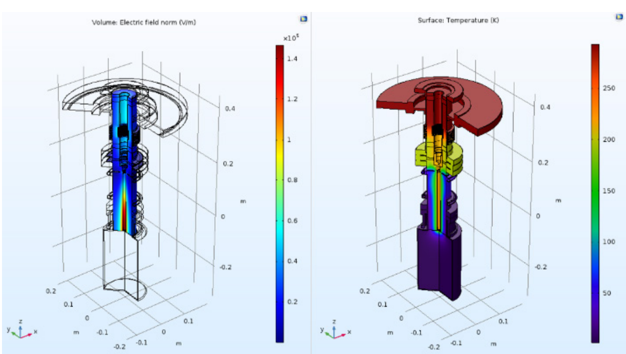

Figure 4: RF E-field and temperature distributions in the coupler from COMSOL simulations.

50 Ohm 'warm' Section

The 50 Ohm 'warm' TL section has a standard 3-1/8" interface for the 50 Ohm coaxial TL. Outer and inner conductors are equipped with BeCu bellows which provide matching of the mechanical assembly and protect RF window ceramics from mechanical overload. A 20W heater clamped to the outer conductor keeps the RF window at room temperature and to avoid a dew point condition on the atmospheric side of the RF window.

COUPLER DESIGN SIMULATION

The Coupler design has been optimized with 2D Comsol Multiphysics simulations verified in ANSYS. Final option was checked for a regime with maximum beam loading for an accelerating voltage of 1.25 of the nominal value – a conservative `worst case' condition. (Table 2). RF (at frequency 325 MHz) and Thermal simulations with radiation heat transfer with RF losses, boundary temperatures and material properties are included. The results of the simulations are presented on Fig. 4 and Table 3 and prove that this coupler design is capable to provide the cavity maximum operating regime with $Pfor_a$=5 kW CW in the antenna section while the input requires a forward power of 2.68 kW due to the matching impedance step. This sets the requirement for RF amplifier to ~3 kW. The RF loss in the coupler is ~9 W, in the RF window is very low, E-field on bellows is low, cryogenic heat loads are acceptable.

Table 3: Results of the Coupler Simulation

Parameter	Unit	Value
Input P_{for_in}	kW	2.68
Input $VSWR_{in}$		2.8
Coupler RF loss, P_{loss}	W	8.8
RF window loss, P_{window}	mW	40
E_{max} in air section	kV/cm	<1.4
Heater, P_{heat}	W	10
Window ΔT^o	K	20
Heat load for 2K	W	0.36
Heat load for 4.5K	W	0.97
Heat load for 40K	W	17.5

Multipacting simulations of the vacuum section in CST Particle Studio show that the baffle disk covering the RF window from multipacting decreases the intensity of multipacting ~4 times. DC bias is required to fully mitigate multipacting for reliable coupler operation.

CONCLUSION

The design of a single window fixed coupler for RISP SSR1 spoke cavity was proposed at TRIUMF. In according to COMSOL simulations it's capable for 5 kW CW of forward power in SW regime in the antenna section.

Next steps for future will be RF window development in cooperation with ceramic RF window provider and development of DC bias unit to mitigate multipacting for reliable coupler operation.

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