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A NEW DESIGN OF A DRESSED BALLOON CAVITY WITH SUPERIOR MECHANICAL PROPERTIES*

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Abstract

Superconducting spoke cavities are prone to multipactor – resonant rise of number of electrons due to secondary emission. Recently proposed and tested by TRIUMF balloon type spoke cavity showed an outstanding multipactor (MP) suppression property but unfortunately serious Q degradation at high fields [1]. A new fully developed design of a dressed balloon cavity which can be used for any proton linac SSR2 section is developed. The design incorporates additional EP ports for high Q-factor demonstration. Superior properties are demonstrated, such as effective multipactor suppression, 40% lower Lorentz force coefficient, zero sensitivity to external pressure. This paper presents the results of coupled structural Multiphysics analysis, and engineering design of the dressed balloon cavity with EP ports. Thorough RF properties optimization and multipactor performance analysis will be presented somewhere else.

INTRODUCTION

A new balloon-shaped spoke cavity is proposed, with a refined mechanical design that will demonstrate a high unloaded Q. Balloon cavities are known for their extremely effective multipactor suppression, and for moving the multipactor barriers far away from the operational gradients. Unfortunately, the first prototype of this type of cavity suffered from significant residual resistance. One potential reason for this is the geometry, specifically the connection of the spoke to the cavity body. The best multipactor performance requires no rounding in this area (a sharp corner) [2], but this causes additional problems for surface processing, i.e., insufficient surface etching, poor surface quality in this region, and, consequently, a cavity quench at low gradients. The proposed balloon-spoke cavity will have no sharp corner between the spoke and the cavity body and will have additional ports for electro-polishing. Together with proper surface processing, the proposed balloon cavity will be able to demonstrate outstanding performance with high Q, no multipactor, and no field emission. This will significantly reduce the cost of conditioning and operation. The balloon cavity is developed to meet the SSR2 Technical Requirements Specifications (TRS) of the PIP-II linac which is under construction at Fermilab. This is the only section which is still being developed [3] and any insights obtained during execution of the current project will potentially benefit PIP-II. The developed balloon cavity was compared to PIP-II SSR2 cavity [4], which was also simulated for the sake of the obtained results validation.

GEOMETRY, RF AND MP PROPERTIES

Geometry

A standard single spoke resonator usually formed by a cylindrical body, poked by a spoke and two side caps (flat or curved). A balloon cavity does not have any cylindrical body, but only spherical side caps and a spoke and can be found on Fig. 1 below.

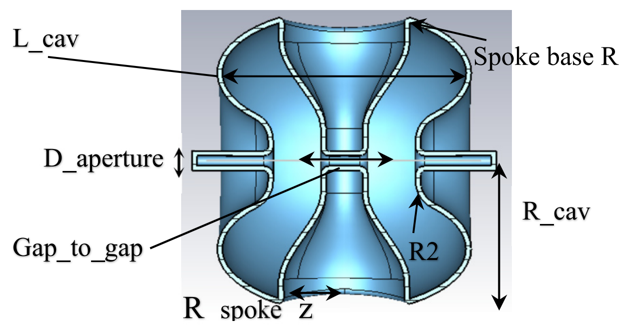

Figure 1: 325 MHz β = 0.475 balloon cavity cross-section.

The balloon cavity presented on Fig. 1 has 10 mm spoke base rounding and does not have ports for electropolishing added yet. Any cavity geometry change results in resonant frequency change which was tuned back by a beam pipe rounding R2. The main cavity parameters are presented in Table 1 below. As one can see from this table the spoke top has an elliptical cross section for field enhancements reduction. The balloon cavity has a little bit bigger radius than SSR2 V3.1 (current PIP-II base line design), but other parameters are about the same. The cavity geometry was optimized to the required particle velocity, see the next section for details. The spoke base rounding of 10 mm was chosen based on the multipactor simulation results.

Table 1: Balloon Main Geometric Parameters

Parameter	Balloon	SSR2 V3.1
L_cav, mm	500	500
R_cav, mm	300	273.2
R_spoke (ellipse x/z), mm	118.5/124	114
D_aperture, mm	40	40
Gap_to_gap, mm	186	185.9

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RF Properties

The balloon cavity RF properties were optimized to meet PIP-II Technical Requirements Specifications (TRS) and are presented in Table 2. PIP-II SSR2 current (V3.1) and previous (V2.6) baseline designs are presented as well. SSR2 V3.1 RF parameters were simulated and are in good agreement with previously presented results [4]. As one can see from this table, the balloon cavity has similar RF properties to V3.1 but can provide higher R/Q and lower surface magnetic field. It is worth to mention that the balloon cavity has additional four ports for electropolishing which were successfully optimized to reduce surface magnetic field.

Table 2: RF Parameters of the Balloon Compared to PIP-II SSR2 Current (V3.1) and Previous (V2.6) Design

Parameter	Balloon	V3.1	V2.6
Frequency, MHz	325	325	325
Optimal beta β_{opt}	0.475	0.472	0.475
Effective length $\lambda \cdot \beta_{opt}$, m	0.438	0.436	0.438
E_{pk}/E_{acc}	3.55	3.41	3.38
B_{pk}/E_{acc}, mT/(MV/m)	5.95	6.78	5.93
G, Ω	115.70	115.18	115.00
R/Q, Ω	320	306	297
B_{pk} at 5MeV, mT	68.0	77.6	67.7

Multipactor Properties

Multipactor studies were done for SSR2 V3.1 first with the help of CST software. After a good agreement with previously reported results was achieved [4] the balloon cavity was investigated with the same parameters. The influence of the spoke base rounding of the balloon cavity was investigated and presented on Fig. 2.

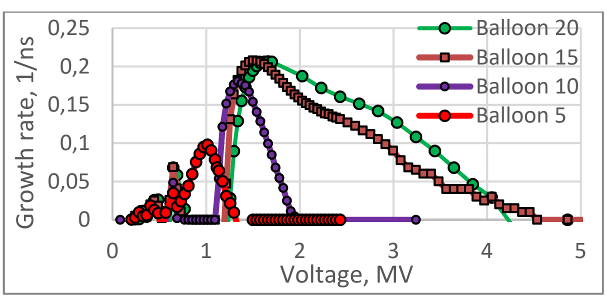

Figure 2: Balloon cavity multipactor (MP) performance for different spoke rounding.

Two main barriers are observed which are split with a no MP gap around 1 MV (not for 5 mm). The multipactor suppression efficiency drops with the bigger rounding and saturates after 15 mm providing the same performance as SSR2 V3.1 – no multipactor after 4 MV [4] which is lower than the operating voltage of 5 MV. The rounding of the spoke of 10 mm provides much better MP suppression and at the same time decent rounding for surface treatment and was chosen for the baseline design of the balloon cavity.

MECHANICAL STUDIES

A bare balloon cavity with a wall thickness of 4 mm was analysed first and achieved almost all the TRS values of the SSR2 section of the PIP-II project. The two remaining items are: Maximum Allowable Working Pressure (MAWP) and sensitivity to external pressure fluctuations or dF/dP. These two characteristics are mainly applicable to a dressed cavity. The MAWP is determined by the mechanical stress level introduced by differential pressure in different load cases. Sensitivity to external pressure variation (dF/dP) should be lower than 25 Hz/mbar according to TRS, but it is known that it can be reduced to zero which will be the target of our studies.

The first version of the vessel design is presented in Fig. 3 and is called V1. It is a simpler version and was inspired by the TRIUMF design [1]. The primary goal was to achieve dF/dP = 0. The vessel is made of 4 mm thick Titanium sheet and consists of a cylindrical body and flat side caps . The side caps are connected to the beampipes, in addition one side is connected to the side of the cavity through a stiffening ring, and the other side is not connected with the ring. A quarter of the geometry was used for vessel simulations as the symmetry along the cavity axis is no longer valid. One side is connected to a tuner with 30 kN/mm stiffness, which is substituted by a corresponding spring coefficient, the other side is free. The tuner stiffness plays a significant role in dF/dP and LFD results. The chosen stiffness is pretty conservative and relaxes requirements to the tuner design. The fixed support is applied to a Fundamental Power Coupler (FPC) port. These boundary conditions (BC) describe a cavity in a cryomodule the most precise. dF/dP studies were investigated for the version 1 of the dressed cavity. The results are presented on Fig. 4.

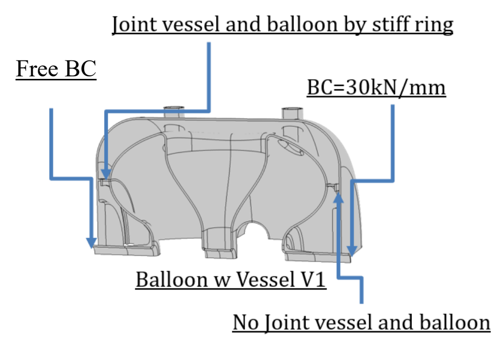

Figure 3: Dressed cavity model with helium vessel V1.

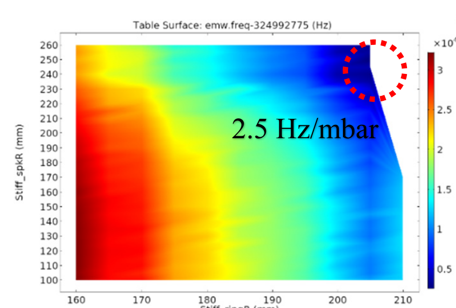

Figure 4: Frequency shift in the cavity with vessel V1 under 1 bar of external pressure.

The cavity was reinforced with a stiffening ring on a side and one stiffening rib inside the spoke. One bar of pressure

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was applied to the cavity and frequency shift is recorded. As one can see there is an optimum position of the stiffening ring at 205 mm. The first design of the vessel V1 can provide dF/dP as low as 2.5 Hz/mbar which is 10 times lower the TRS requirements however the point of no sensitivity, i.e. dF/dP = 0 Hz/mbar is not achievable without introduction of additional bellows. Since the SSR2 V3.1 cavity vessel has bellows introduced this vessel was fitted to the ballon cavity and investigated as a version 2 vessel (V2). The vessel was simplified as long as the balloon shape of the investigated cavity is naturally more rigid and does not require much reinforcements to reduce Lorentz force detuning (LFD), stresses etc. For example, the balloon cavity does not require any stiffening ring from the side of the tuner, otherwise it will be too rigid and will not meet the related TRS. There is no stiffening rings on the outside of the cavity (V3.1 has cylindrical body reinforced with two rings). The vessel V2 of the balloon cavity was optimized to provide as low as possible LFD and zero sensitivity to external pressure. The plots of dF/dP for different variants of the design of the vessel are presented on Fig. 5.

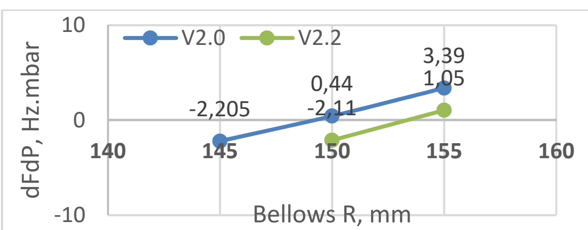

Figure 5: Balloon cavity with Vessel V2 dF/dP dependence on the bellows radius.

As one can see dF/dP = 0 Hz/mbar can be easily achieved for different variants and can be tuned by the bellows radii.

In order to satisfy Maximum Allowable Working Pressure (MAWP) TRS, welding seems need to be investigated according to ASME codes, which requires stress linearization into membrane and bending components. The most critical load case is 2.05 bar at room temperature because of low yield stress of Niobium. Stress distribution for this case is presented on Fig. 6. The highest stresses of 40 MPa are in the Titanium vessel and are much lower the yield (275 MPa). The highest stresses in the cavity are found in the spoke and are within the safety limits of pressurized vessels: membrane stress is 10 MPa (should be lower than 25 MPa), membrane+bending is 14 MPa (should be lower than 37.5 MPa).

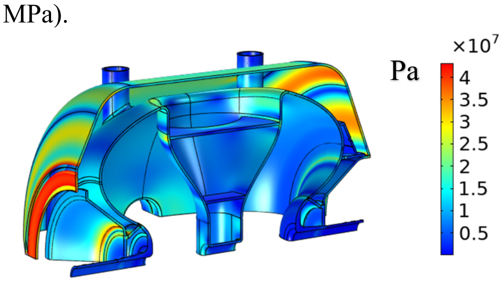

Figure 6: Stresses (Pa) in the dressed balloon cavity under 2.05 bar of He pressure.

The summarized mechanical properties of the balloon cavity with the V2 vessel and SSR2 V3.1 are presented in Table 3. Although the dressed balloon cavity satisfies all the PIP-II Technical Requirements Specifications for the SSR2 section it provides zero sensitivity to external pressure fluctuations and exceptionally low Lorentz Force detuning which is 40% lower than in SSR2 V3.1.

Table 3: Main Mechanical Properties of the Balloon and PIP-II SSR2 Cavities with a Tuner Stiffness k=30 kN/mm

Mechanical property	**TRS**	**Dressed Balloon**	**SSR2 V3.1**
Stiffness, kN/mm	<16	16.5	15
Sensitivity, kHz/mm	>250	292	308
MAWP at RT/2K, bar	2/4	OK	OK
Inelastic tuning, kHz	>500	534	NA
LFD, $Hz/(MV/m)^2$	min	3.0	4.7
dF/dP, Hz/mbar	<25	0	0

ENGINEERING DESIGN

An engineering design of the dressed Balloon cavity with optimized electrodynamics, multipactor and mechanical properties was created using SolidWorks software and is presented in Fig. 7. The engineering design shares similar components with PIP-II SSR2 V3.1, including flanges, helium vessel, tuner plates etc, so these components can be directly used for the test of the Balloon cavity in the future with no redesign needed.

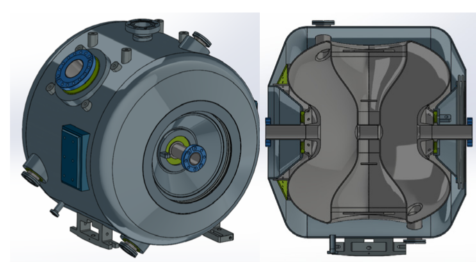

Figure 7: 3D model (on the left) and section view (on the right) of 325 MHz SSR2 dressed balloon cavity with EP ports.

CONCLUSION

In the period of 9 months, a new Balloon cavity with a helium vessel was designed from scratch to a final engineering design which is ready for production and compatible with existing components. Table 2 and 3 present the parameters of the developed cavity. The dressed balloon cavity with ports for electropolishing meets all the design values of the PIP-II SSR2 section and provides outstanding properties such as exceptional multipactor suppression and 40% lower Lorentz Force Detuning compared to conventional single spoke resonators.

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REFERENCES

[1] Z. Y. Yao *et al.*, "Fabrication and Test of β=0.3 325 MHz Balloon Single Spoke Resonator", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, BC, Canada, Apr.-May 2018, pp. 3934-3936. doi:10.18429/JACoW-IPAC2018-THPAL123

[2] Z. Y. Yao, R. E. Laxdal, V. Zvyagintsev, X. Y. Lu, and K. Zhao, "Multipacting Suppression in a Single Spoke Cavity", in *Proc. 16th Int. Conf. RF Superconductivity (SRF'13)*, Paris, France, Sep. 2013, paper THP034, pp. 975-977.

[3] C. Mossey, "Building for Discovery: PIP-II, LBNF, and DUNE", presented at High Energy Physics Advisory Panel (HEPAP) Meeting, Dec. 2020, unpublished.

[4] P. Berrutti *et al.*, "New Design of SSR2 Spoke Cavity for PIP II SRF Linac", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, pp. 600-604. doi:10.18429/JACoW-SRF2019-TUP066