A COAXIAL SUBHARMONIC CAVITY DESIGN FOR DIRECT INJECTION AT THE ADVANCED PHOTON SOURCE*

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Abstract

Coaxial subharmonic cavity designs are being investigated at the Advanced Photon Source to improve injector reliability by injecting beam directly from the linac to the booster in storage ring top-up mode. The subharmonic system must operate jointly with the present 352-MHz booster to accelerate the beam to 7 GeV with minimal beam degradation. Design considerations must be made to ensure that bunch purity is maintained and that a large percentage of the linac macropulse is captured. An analysis of rf cavity designs using electromagnetic simulation software has been conducted at 29 MHz and 117 MHz. Higher-order modes are evaluated as well as the total power loss and peak surface fields produced at the required gap voltage.

INTRODUCTION

At the APS, a 325-MeV electron beam is injected from the linac into the particle accumulator ring (PAR). The electrons are collected and then compressed in the PAR using a 9.8- and a 117.6-MHz rf cavity and then injected into the booster where the bunch is accelerated to 7 GeV. Top-up mode has been successfully implemented at the APS and is used to maintain constant beam current levels in the storage ring by periodically reinjecting into the storage ring.

Since the PAR is a 30-m ring consisting of magnets, rf and vacuum systems, and beam diagnostics, a simpler subharmonic system in the booster was proposed as a replacement for the PAR. Although, the PAR has been extremely reliable, a subharmonic cavity would permit direct injection into the booster and substantially reduce the complexity of the system, in addition to making it possible to explore other accelerator applications for the PAR. It will also support future upgrades to the booster including stacking at low energy for uniform top-up and lifetime adjustment of the stored beam.

CAVITY DESIGN OBJECTIVE

In order to create a tenable design, the subharmonic cavity must capture a large percentage of the linac macropulse, maintain bunch purity, and allow minimal particle loss from injection at 325 MeV to extraction at 7 GeV for up to 10 nC of charge. Based on simulations, it was found that these objectives could be achieved with the appropriate subharmonic rf system [1].

The operating frequency and gap voltage were chosen as a compromise between cavity size and power requirements while achieving the required bunching. The rf frequency was determined such that the rf period was no smaller than the 10-ns macropulse length of the linac rf thermionic electron gun at the APS. The magnitude of the gap voltage is a function of the cavity frequency and must be sufficient to bunch the beam.

Based on these considerations, a two-cavity system consisting of a 12th subharmonic cavity at 29 MHz and a 3rd subharmonic cavity at 117 MHz was proposed [1]. In the design simulations, the 12th subharmonic cavity would operate CW with a 200-kV gap voltage, and the 3rd subharmonic cavity would be linearly ramped to 250 kV. With this rf system the beam was captured and compressed to < 2.5 ns with about 0.5% particle loss at injection. The current booster ramp profile was maintained so that the present magnet ramping profile would remain unchanged.

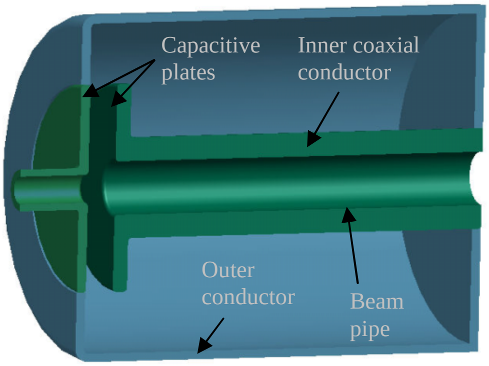

Figure 1: Internal geometry profile for a 29-MHz capacitively loaded coaxial subharmonic cavity.

CAVITY PARAMETERS

Geometry

Since the design of the 29-MHz and 117-MHz cavities are similar, this paper will focus primarily on the details pertaining to the 29-MHz cavity. A number of options have been explored for possible cavity designs [2,3]. Due to the low operating frequency and after an investigation of the various cavity parameters, a capacitively loaded, normal conducting cavity was chosen (see Fig. 1).

Two capacitive plates span a 10.1-cm accelerating gap corresponding to a 3.5° rf phase shift for an electron accelerator. Frequency tuning of the cavity can be performed by adjusting the capacitive plate on the high voltage side of the cavity to permit up to 500 kHz of range, or ferrite tuners may be installed. Cavity

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dimensions are listed in Table 1 and cavity parameters are summarized in Table 2.

In order to determine the operating limits of the cavity designs and to ensure reliable operation, issues regarding electrical breakdown and resistive surface losses were addressed. To reduce rf stresses on the cavity, the edges of the cavity and the capacitive plates were rounded. Since the cavity frequency is a strong function of the capacitance between the plates, cavity length and radius were enlarged when necessary to reduce stresses.

Table 1: Dimensions for a 29-MHz Coaxial Cavity

Outer length	1.442 m
Outer radius	0.654 m
Inner length	1.311 m
Inner radius	0.101 m
Cap plate thickness	0.039 m
Cap plate radius	0.392 m
Cap plate gap	0.098 m
Beam pipe radius	0.101 m

Table 2: Parameters for 29- and 117-MHz Cavities

	29 MHz	117 MHz	117 MHz (Modified)
Gap voltage (kV)	200	250	250
Gap rf phase	3.5°	3.5°	5.3°
Q_0	27,100	13,300	14,400
R_S (MΩ)	1.67	0.83	0.92
E_{peak} (MV/m)	3.4	19.6	13.5
Kilpatrick limit (MV/m)	7.4	12.0	12.0
P_{loss} (kW)	12.0	38.2	33.8

Electrical Breakdown

Electrical breakdown or sparking on the surface of the capacitive plates limits the maximum gap voltage that can be applied. A convenient measure of the maximum safe electric field on a metal surface was defined by Kilpatrick [4]. From Table 2, the 29-MHz cavity is shown to be well within safety limits, but the peak surface electric field for the 117-MHz cavity exceeds the Kilpatrick limit, as seen in Fig. 2. The Kilpatrick criterion is a conservative estimate. As a result, designers have exceeded the value by a factor known as the 'bravery factor,' which can be as high as twice the Kilpatrick limit.

Although the 117-MHz cavity will operate in ramped mode, it was redesigned to ensure reliable cavity performance. The accelerating gap was increased by 50% to reduce the field gradient, and the cavity radius and cavity capacitance were modified to achieve the proper frequency. These modifications reduced the peak surface field to a value closer to the Kilpatrick limit.

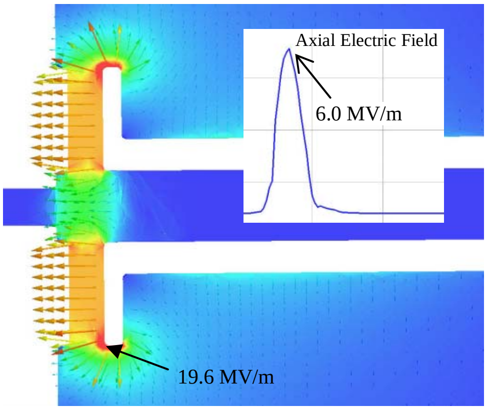

Figure 2: Electric field vector and magnitude plot for the fundamental mode at 117 MHz. Peak surface fields at the rounded edges of the capacitive plate exceed the conservative Kilpatrick criterion.

Power Dissipation

For water-cooled cavities, it is generally considered safe to have a power density no greater than 20 W/cm^2 along any metal surface [5]. An analysis of the rf losses was peformed in lieu of a full thermal analysis to determine if this limit had been exceeded and to what extent cooling was needed.

With a gap voltage of 200 kV, a total of 12.0 kW of power was dissipated in resistive wall losses at 29 MHz. The cooling requirements for the cavity designs were not excessive. As shown in Fig. 3, the power losses were largest along the coaxial surface of the inner conductor. The rear face of the capacitive plate had a much higher power density compared to the front of the capacitive plate where the peak surface fields were large.

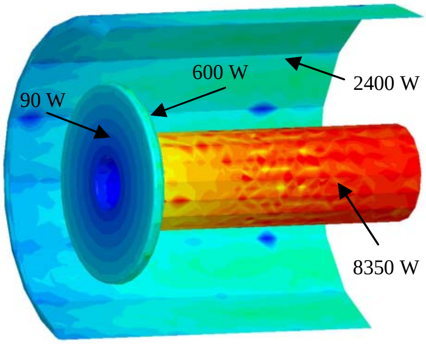

Figure 3: Surface current along inner and outer conductors and their associated resistive losses with a 200-kV gap voltage at 29 MHz.

HIGHER-ORDER MODES

A higher-order mode (HOM) analysis was performed to quantify the important longitudinal and transverse modes in the subharmonic cavities. Tables 3-6 list the modes in the 29-MHz and 117-MHz modified cavities. The longitudinal shunt impedance is defined using the typical circuit definition. The transverse shunt impedance, on the other hand, is calculated using Panofsky-Wenzel's theorem [6], which relates the off-axis longitudinal electric field to the fields on axis that interact with the beam:

$$\frac{R_T}{Q} = \frac{\left|\int E_Z(r_0)\, e^{jkz}\, dz\right|^2}{(kr_0)^2\, \omega U}, \tag{1}$$

where k is the rf wave number, U is the cavity energy, and $r = r_o$ is the location of the line integral.

Table 3: Transverse Modes for the 29-MHz Cavity

Freq (MHz)	Q_0	R_T / Q	R_T (MΩ/m)
146.7	38,400	19.9	0.767
188.4	39,400	31.5	1.242
263.2	61,800	10.9	0.673
319.6	61,200	3.5	0.214
320.1	68,200	2.9	0.197
346.1	67,500	0.72	0.048
370.3	72,600	0.37	0.027
400.0	69,700	0.67	0.047
445.1	71,600	1.35	0.097
492.4	84,100	0.08	0.007

Table 4: Longitudinal Modes for the 29-MHz Cavity

Freq (MHz)	Q_0	R_S (MΩ)
29	27,100	1.670
122.7	44,300	0.198
223.4	54,900	0.214
283.9	48,000	0.185
323.6	58,500	0.020
350.5	61,800	0.032
377.9	59,700	0.124
411.0	74,600	0.010
450.2	87,800	0.014
451.2	51,500	0.456

CONCLUSION

A subharmonic cavity system has been proposed as a possible future replacement for the PAR at the APS. A capacitively loaded coaxial cavity was designed at 29 and 117 MHz with sufficient gap voltage to produce the proper bunching and compression of the electron bunch based on a previous beam simulation. An analysis was performed on the higher-order mode spectrum as well as on rf breakdown and power loss due to resistive heating in the cavity to help ensure reliable operation.

Table 5: Transverse Modes for the 117-MHz Cavity

Freq (MHz)	Q_0	R_T / Q	R_T (MΩ/m)
521.7	19,500	39.1	0.765
703.2	27,700	14.1	0.391
1026.0	32,000	13.8	0.442
1129.1	35,000	2.1	0.074
1199.7	32,800	2.1	0.070
1267.9	38,000	0.6	0.021
1360.6	44,400	0.08	0.004
1368.2	42,600	2.4	0.102
1377.9	41,000	1.0	0.039
1679.2	47,100	1.5	0.069

Table 6: Longitudinal Modes for the 117-MHz Cavity

Freq (MHz)	Q_0	R_S (MΩ)
117	14,400	0.923
501.6	23,800	0.117
854.9	25,600	0.243
1033.4	29,400	0.020
1105.0	33,800	0.034
1270.2	31,000	0.163
1460.6	27,700	0.289
1491.3	33,100	0.275

REFERENCES

[1] N. Sereno, "Booster Subharmonic RF Capture Design," APS Light Source Note LS-297, Argonne National Laboratory, July 2002.

[2] R. Kustom, "38.9 MHz Capacitively-Loaded Coaxial Cavity Design for the Booster" APS Light Source Note LS-26, Argonne National Laboratory, June 1985.

[3] R. Kustom, "Folded Coaxial Line Design for the 38.9 MHz Booster Cavity" APS Light Source Note LS-28, Argonne National Laboratory, July 1985.

[4] T. Wangler, *RF Linear Accelerators*, (John Wiley & Sons, Inc., New York), pp. 88, 1998.

[5] Sushil Sharma, private communication.

[6] W. Panofsky, W. Wenzel, "Transverse Deflection of Charged Particles in Radiofrequency Fields," Rev. Sci. Instrum. 27 (1956) 967.