A HIGHER HARMONIC CAVITY AT 800 MHz FOR HL-LHC

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Abstract

A superconducting 800 MHz second harmonic system is proposed for HL-LHC. It serves as a cure for beam instabilities with high beam currents by improving Landau damping and will allow for bunch profile manipulation. This can potentially help to reduce intra-beam-scattering, beam induced heating and e-cloud effects, pile-up density in the detectors and beam losses. An overview of the 800 MHz cavity design and RF power requirements is given. In particular the design parameters of the cavity shape and HOM couplers are described. Some other aspects such as RF power requirements and cryomodule layout are also addressed.

INTRODUCTION

For HL-LHC a mechanism to provide Landau damping is useful to increase the instability threshold of the future high intensity beams [1]. A superconducting (SC) 800 MHz second harmonic RF system, operating in conjunction with the existing 400 MHz accelerating LHC cavities (ACS) suits these requirements. In addition longitudinal bunch profiles can be flattened [2] or shortened [3, 4], and beam induced heating, e-cloud effects [5], Intra-Beam-Scattering (IBS), beam losses on the flat bottom [6] and pile-up density in the detectors can all be reduced. Each 800 MHz cavity is equipped with a proper Fundamental Power Coupler (FPC) and proper Higher Order Mode (HOM) couplers. An initial design study of the higher harmonic system was carried out in [7]. This paper summates on the 800 MHz cavity design and RF power requirements, notably the cavity shape design parameters and HOM coupler characteristics. RF power requirements and cryomodule layout are also addressed.

GENERAL CONSIDERATIONS

The SC 400 MHz ACS cavity cell and FPC were developed to handle 300 kW CW at 400.8 MHz. Two types of dedicated HOM couplers damp excited HOMs in the system: A narrow-band hook-type coupler and a broad-band probe-type coupler [8, 9]. The 400 MHz ACS system has proven its functionality and reliability during LHC run I, operating from 2008 onward with 1/2 the nominal LHC beam current. It therefore serves as an 800 MHz design reference by scaling the geometry with a factor 1/2. Subsequently the model is iteratively refined and verified to comply with the specifications. Substantial beam loading due to beam intensities of $2.2e^{11}$ p^+ and operation of the 400 MHz ACS system in full detuning mode will require a large amounts of 800 MHz RF power. 300 kW CW has to be considered as an upper boundary. It is therefore mandatory to keep the Fundamental Mode (FM) R/Q low and the voltage levels at a rather moderate 2 MV/cavity, in contrast with today's trend to reliably increase SC cavity voltage levels to 10 MV/m.

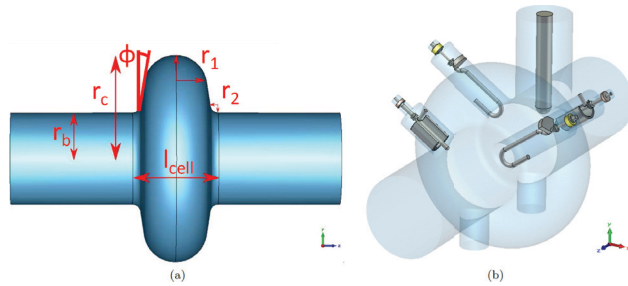

Figure 1: HL-LHC 800 MHz cavity: (a) Design parameters: cell length l_{cell}, beam pipe radius r_b, cavity height r_c, cavity cell radius r_1, iris radius r_2 and cavity wall angle ϕ. (b) RF cavity with installed HOM couplers and FPC.

Table 1: HL-LHC 800 MHz Cavity Design Parameters and Characteristics [7]

Parameter	Value [mm]	Spec	Value [unit]
l_{cell}	140	f	801.4 [MHz]
r_b	75	R/Q[2]	45 [Ω]
r_c	169.3	E_p/V_{acc}	14.6 [m^{-1}]
r_1	52	H_p/V_{acc}	28.2 [mT/MV]
r_2	12.5	K	14.3 [kN/mm]
Φ	10°		

RF CAVITY

To ensure sufficient separation between the FM and first two HOM frequencies TE_{111} and TM_{110} (important for FM rejection in the HOM couplers) but simultaneously guarantee sufficient margin for mechanical tuning, the 800 MHz cavity wall inclination was reduced to 10° by shortening the cavity length l_{cell} from 160 mm to 140 mm. The fully parametrised model in CST Studio Suite (Fig. 1a) preserves the 400 MHz cavity wall thickness of 2.9 mm to withstand similar liquid helium pressure, including pressure fluctuations. The choice of l_{cell} originates from the sensitivity studies performed in [7], ensuring separation of the HOM frequencies and a more pronounced R/Q increase with respect to B_p/V_{acc}. Finally r_c was adjusted to have the FM resonating exactly at 801.4 MHz (Table 1). The R/Q analysis is performed along the central beam line within a 4 cm^2 area and shows increased $R/Q_\perp$ for the TE_{111} mode (2.34 Ω) and TM_{110} mode (13.6 Ω), two polarisations each. Their frequencies (1047 MHz and 1087 MHz respectively) are sufficiently separated from the FM to allow appropriate damping using dedicated narrowband hook-type couplers. In the beam pipe

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[2] Circuit definition

both modes transform to a non-propagating TE_{11} mode. The beam pipe radius choice (r_b = 75 mm) is based on a trade-off between mode propagation, frequency separation and FM R/Q. The next HOM is a quadrupole (TM_{210}) at 1488 MHz, having low R/Q. The first significant modes are the TM_{020} (1615 MHz, $R/Q_{\parallel}$ = 3.07 Ω) and the TM_{011} (1629 MHz, $R/Q_{\parallel}$ = 24.0 Ω). A high-pass probe-type coupler will damp the frequency spectrum above 1450 MHz.

HOM COUPLERS

Hook-type HOM Coupler

The requirements for the hook-type coupler (Fig. 2a) consist of a FM rejection and high transmission for the TE_{111} and TM_{110} modes. The transmission of both modes is weighted according to their R/Q ratio, which corresponds to a difference of 7 dB. The hook-type coupler design is initiated from an equivalent circuit approach, with each element representing a component of the coupler [9, 10]. Figure 2b shows the circuit for magnetic coupling, Figure 2c the circuit for electric coupling. The circuits are tuned to the required transmission curve using an iterative MATLAB optimisation code based on the methods described in [9, 10]. Subsequently the elements are translated into a 3D electromagnetic model and simulated in CST Studio Suite. To account for assumptions made in the equivalent circuit model, a few simulation iterations are needed to obtain the final transmission curve (Fig. 2d). A loaded Q, Q_L of 25.9 and 32.9 was obtained for the TE_{111} and TM_{110} modes respectively.

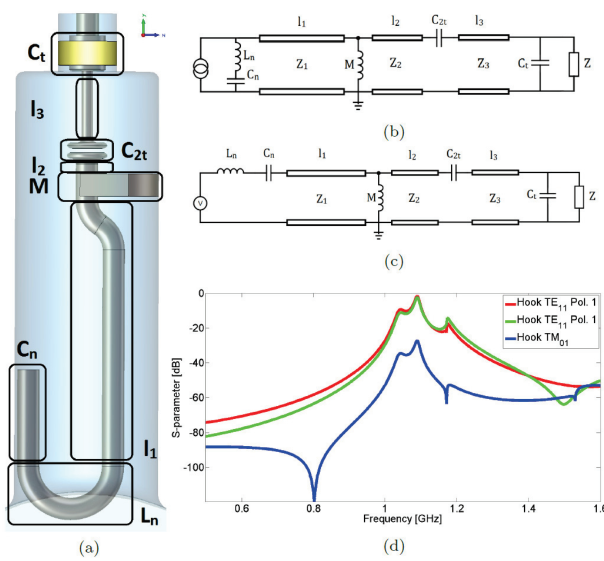

Figure 2: Narrow-band hook-type coupler: (a) 3D model, (b) TM_{01} equivalent circuit, (c) TE_{11} equivalent circuit, (d) Transmission curves.

Probe-type HOM Coupler

The probe coupler (Fig. 3a) acts as a high pass filter with rejection at 801.4 MHz and a pass band at 1450 MHz (Q_L = 20.6), 1950 MHz (Q_L = 13.6) and 2600 MHz (Q_L = 7.1). An equivalent circuit (Fig. 3b) is tuned with an iterative MATLAB optimisation code analogue to the hook-type coupler and according to the methods for a probe coupler described in [9, 10]. Afterwards a 3D electromagnetic model is simulated in CST Studio Suite, accounting for the assumptions made in the equivalent circuit model and yielding the final transmission curve (Fig. 3c). It is noted that the non-physical notch appearing around 1944 MHz is introduced by the presence of a beam pipe cutoff frequency in that region.

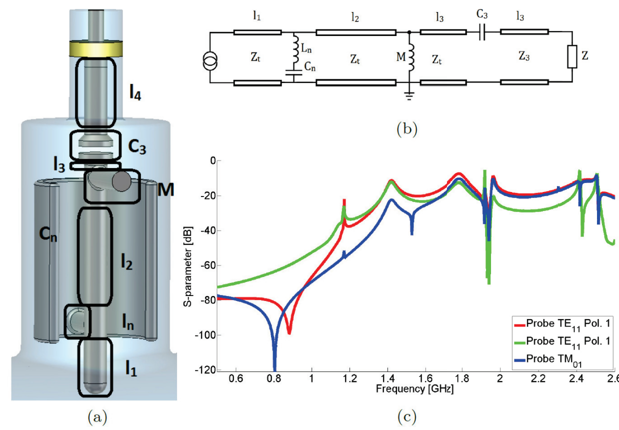

Figure 3: High-pass probe-type coupler: (a) 3D model, (b) Equivalent circuit, (c) Transmission curves.

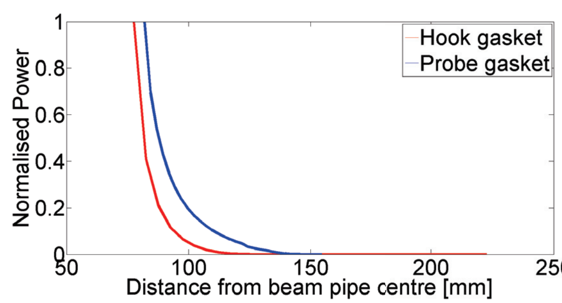

Figure 4: Normalised FM power dissipated in the vacuum gasket for different locations on the coupler tube. The gasket location is measured from the beam pipe centre.

Mounting Aspects

Each cavity is equipped with four HOM couplers, as in the 400 MHz system. An HOM coupler of each type is placed on either side of the cavity for symmetry reasons. Liquid helium cooling of the central conductor restricts the mounting to the upper half of the beam pipe. The mounting angle θ_M is expressed with respect to the FPC (θ = 0°). The asymmetry introduced by the FPC and HOM couplers fixes the TE_{11} mode polarisation in the beam pipe: One in parallel with the FPC, the other one perpendicular to it. This insinuates θ_M = ±45° to be an optimal choice. The HOMs that couple to the probe coupler change the situation, since θ_M = ±45° would be ineffective for some of these HOM polarisations. Mounting the probe couplers under a

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different angle would destroy the symmetry and affect the TE_{111} and TM_{110} polarisation layout. HOMs coupling to a (uniform) TM_{01} beam pipe mode are insensitive to the coupler mounting angle, and can therefore be ignored. From different approaches to define an optimum mounting angle, a conservative angle of 55° was decided for.

The location of the HOM coupler mounting flange must allow to dismount the coupler including the hook/probe. Typically the vacuum seals are installed outside the wall area that heats up due to current flows induced by the (shorted) FM (Fig. 4). The hook-type coupler mounting flange location is set at 120 mm from the beam pipe centre. The probe-type coupler flange is preferably installed at 127 mm from the beam pipe centre, just below the mutual inductance, to still allow dismounting the probe.

RF CAVITY - HOM COUPLERS - FPC

In this section the RF cavity with installed HOM couplers and FPC is simulated. An analysis of the structure's resonant modes and the transmission characteristics of the complete system were performed to ensure compatibility of all individual components (Table 2). In the presence of HOM couplers and FPC the mode frequencies, polarisations and R/Qs are shifted. In particular one polarisation frequency typically decreases, while the other polarisation frequency increases. In practise a low Q HOM coupler will cover the frequency spectrum. The FM characteristics remain unchanged.

A mode (915 MHz) trapped between the C_{2t} capacitor plates can exist in the hook-type coupler. It has no field component in the beam pipe or cavity and is therefore considered harmless. The assumed beam pipe modes in the bare cavity-model do not appear in the combined model or they appear with a frequency shift, identifying them as supposed unphysical modes. Additional modes appear in the full model, at frequencies close to already known HOMs, and with electromagnetic fields strongly resembling them. These modes are in some cases physical, and in other cases unphysical beam pipe modes. Wakefield simulations of the full model using a 1 ns bunch of 2.2e^{11} p^+ confirm transverse wakefield excitation around 1018 MHz, 1029 MHz, 1061 MHz, 1070 MHz, 1095 MHz and 1150 MHz. Two additional transverse wakefields are slightly excited as a trapped resonance in the probe-type coupler (264 MHz) and in the hook-type coupler (320 MHz). The wakefield simulation shows impedances for these modes that are lower than the already damped HOM impedances. The field components enter the beam pipe region only weakly and will most likely not perturb the beam dynamics. Equivalent trapped modes can be found in the 400 MHz HOM couplers as well, where until now no harmful effects were observed in LHC run I. From a thermal point of view some additional helium consumption can be expected due to the presence of these modes and a multipacting study is ongoing.

Table 2: Mode Characteristics Below 1.6 GHz for the RF Cavity - HOM Couplers - FPC Structure

Mode	f [MHz]	R/Q [Ω]	Q_{ext}
Trapped probe	264.0	0.28	3400
Trapped hook	320.0	0.58	40000
TM_{010}	801.3	45.4	12e4
TE_{111}	1017.6	6.01	7800
	1026.1	0.379	7800
	1027.2	0.686	121
	1030.0	1.32	121
TM_{110}	1060.7	5.72	373
	1075.1	9.70	373
	1098.6	2.13	205
	1101.5	3.74	241
TM_{210}	1485.5	0.126	3040
	1486.9	0.0930	2030
TE_{211}	1521.5	0.496	1420
	1541.2	0.210	1420
TM_{020}	1592.9	18.6	32
	1616.1	13.4	32
	1668.6	3.19	7

RF POWER REQUIREMENTS

FM Power

HL-LHC will operate with beam currents up to 1.1 A DC configured in a series of bunch trains (72 bunches, 2.2e^{11} p^+ per bunch) and small gaps, ending with an abort gap $T_{\text{gap}} = 3.2$ μs (additional HL-LHC beam characteristics in [11]). This implies strong beam loading in the 400 MHz cavities, to be compensated with RF power. Operation in half detuning mode [12] requires 550 kW per 400 MHz cavity and implies non-trivial FPC and klystron upgrades. The proposed full detuning scheme [12, 13] resolves the power issue since the RF system does not correct for the RF phase shift introduced by transient beam loading. As such the klystron current can be kept constant. The existing LHC tuning system ensures centring of the cavity voltage phase modulation around zero, reducing power consumption to an acceptable 187 kW (cavity voltage $V_0 = 2$ MV and $Q_L = 60000$). As a secondary effect bunches will be spaced unequally along the ring (±72 ps, ±2.2 cm), which will impede the harmonic system operation, that must be able to follow the phase of the ACS system. The phase offset with the 400 MHz system defines the operation mode: Bunch Shortening (BS, voltage phase offset ϕ_1 locked to $-\pi/2$) and Bunch Lengthening (BL, voltage phase offset ϕ_1 locked to $\pi/2$). Figure 5 shows the phasing of both 400 MHz and 800 MHz cavity systems as well as the total voltage seen by the beam in BS and BL mode.

The required power to operate the 800 MHz cavity is described below as calculated in [14]. $P_{g1}(t) = 1/2(R/Q)_1 Q_{L1}|I_{g1}(t)|^2$, with index 1 referring to the parameters of the harmonic system and I_{g1} the generator current expressed in Eq. 1. Part (1) represents the current to sustain the field in the cavity in the absence of beam. Parts (2) and (3)

$$I_{g1}(t)e^{-j[n\phi(t)+\phi_1]} = \underbrace{\frac{V_1}{2(R/Q)_1 Q_{L1}}}_{1} + j\frac{\overline{I_{b1,RF}}}{2}\left[\underbrace{\frac{\Delta\omega_1 - n\Delta\omega_0}{\Delta\omega_{01}}}_{2} + \underbrace{\frac{n\omega_0\tan(\phi(t))}{2Q_L\Delta\omega_{01}}}_{3} + \underbrace{\left(\frac{n\Delta\omega_0}{\Delta\omega_{01}} \mp 1\right)\frac{i_{b1}(t)}{\overline{I_{b1,RF}}}}_{4}\right] \quad (1)$$

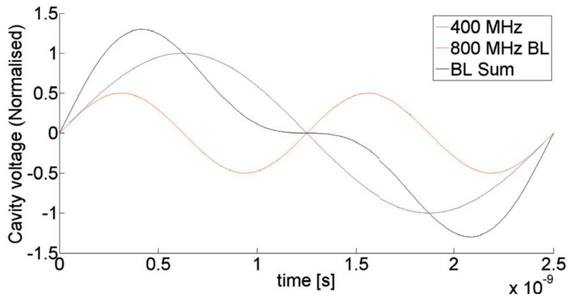

Figure 5: RF voltage in BL mode for the 400 MHz and 800 MHz cavity. The beam current peaks on the negative slope zero crossing of the fundamental cavity voltage. RF voltages are normalised to the 400 MHz RF voltage.

represent the additional current to compensate for the phase modulation introduced by the 400 MHz ACS and part (4) the current to compensate for the beam passage. Equation 1 with a "-" and a "+" sign in part (4) represents BS and BL respectively. $\overline{I_{b1,RF}}$ is the mean RF beam current over one turn, $\Delta\omega_1$ the actual cavity detuning and $\Delta\omega_{01}$ the optimum cavity detuning in the absence of the phase modulation introduced by the 400 MHz system (Eq. 2). n is the harmonic index and $i_{b1}(t)$ the beam current modulation at the harmonic frequency. Power reduction is achieved by reducing Q_{L1} or I_{g1}. In BS mode ("-") part (4) of Eq. 1 can be zeroed by choosing the appropriate detuning $\Delta\omega_1 = \Delta\omega_{01} = n\Delta\omega_0$ (i.e. changing V_1): The beam is invisible for the cavity and only part (3) of the imaginary current remains. This part makes an excursion between $\pm(n\omega_0\tan(\phi(t)))/(2Q_L\Delta\omega_{01})$ due to the phase modulation introduced by the 400 MHz ACS. Q_{L1} can then be optimised by matching both real and imaginary parts of $I_{g1}(t)$, to minimize the power.

$$\Delta\omega_{01} = -\frac{1}{2}\frac{\omega_1(R/Q)_1\overline{I_{b1,RF}}}{V_1} \quad (2)$$

In BL mode ("+") part (3) still oscillates between $\pm(n\omega_0\tan(\phi(t)))/(2Q_L\Delta\omega_{01})$. When a bunch passes ($i_{b1}(t) \neq 0$), part (4) will contribute significantly to the generator current. During gap instances this component is zero. In part (2) one can find an optimum detuning $\Delta\omega_1$ that reduces the overall contribution of part (4) in beam and no-beam situations by matching them. Q_{L1} can then be optimised, matching both real and imaginary parts of $I_{g1}(t)$, to minimize the power (Eq. 3).

$$Q_{L1,opt} = \frac{V_1}{2(R/Q)_1\left(\left|\frac{n\Delta\omega_0}{\Delta\omega_{01}} \mp 1\right|\frac{I_{b1,pk}}{4} + \left|\frac{n\omega_0\tan(\phi(t))}{2Q_L\Delta\omega_{01}}\right|\frac{\overline{I_{b1,RF}}}{2}\right)} \quad (3)$$

Optimisation of the 800 MHz system for BS mode reduces the power to 57 kW with cavity voltages of $V_1 = 1.4$ MV, but disables the BL mode due to the tremendous power requirements (2 MW). Optimisation for BL mode (Table 3) requires the cavity voltage to drop to $V_1 = 0.8$ MV to stay below 300 kW. This implies ten cavities to deliver the required total voltage of the harmonic system. BS mode power increases to 161 kW but is far below the critical 300 kW value. A variable FPC enables changing V_1 and Q_{L1} according to the desired mode, but complicates the FPC design significantly on a mechanical and thermal point of view. The choice of power source is limited to klystrons or IOTs, given the 300 kW CW power at 800 MHz. The FPC has a diameter of about 100 mm to safely transfer the power into the cavity and is preferably fixed and not moveable.

Table 3: 800 MHz RF Power Requirements: System Parameters for BL-mode Optimisation

Parameter	Value	Parameter	Value
$(R/Q)_1$	45 Ω	$I_{b1,pk}$	1.833 [A]
Q_{L1}	12000	$\Delta\omega_0$	-56662 [rad/s]
V_1	0.8 MV	n	2
$\overline{I_{b1,RF}}$	1.444 A	ω_0	2.518e^9 [rad/s]

HOM Power

The estimated HOM power deposited by the beam was based on different methods [8, 15–17], benchmarked for the 400 MHz LHC cavity and beam described in [8]. All methods show excellent agreement. The applied filling scheme characteristics can be found in [11]. The deposited HOM power is based on a worst case scenario, assuming that every HOM resonance falls exactly on a beam frequency line. Table 4 shows the total power induced by the beam for each beam type, based on the two methods that predict the highest power depositions ([15] and [16]). The two hook-type couplers per cavity must handle at least 525 W each, which is about half of the 1 kW upper boundary set by hardware limitations (cables and connectors) [8]. Q_L for each coupler is hence still a factor 2 smaller than required. The two probe-type couplers per cavity must handle at least 61 W each, permitting less stringent conditions for Q_L. Two probe-type couplers are still mandatory to cover all HOM polarisations.

CRYOMODULE LAYOUT

BL mode limitations require 10 cavities to be fitted within about 10 m, for each beam line. Cryomodules with two,

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Table 4: Total HOM Power Extracted by the 800 MHz Cavity Couplers for On-resonance Excitation by Different Beams.

Beam (Current)]	Method [15] P_{Hook} [W]	P_{Probe}[W]	P_{Tot}[W]
HL-LHC 25 ns std (1.09 A)	890.0	98.18	988.18
HL-LHC 25 ns BCMS (1.03 A)	799.2	88.16	887.36
HL-LHC 50 ns (0.89 A)	981.6	120.50	1092.10
Nom. LHC (0.58 A)	253.9	28.10	275.00
Beam	**Method [16] P_{Hook}[W]**	**P_{Probe}[W]**	**P_{Tot}[W]**
HL-LHC 25 ns std (1.09 A)	932.0	67.29	999.29
HL-LHC 25 ns BCMS (1.03 A)	836.8	60.42	897.22
HL-LHC 50 ns (0.89 A)	1043	84.78	1127.80
Nom. LHC (0.58 A)	265.9	19.20	285.10

four or five cavities are considered. Cross-talk is reduced to -90 dB with 2λ spacing and proper tapers of 150 mm (300 mm) long ensure low-reflection transition for a diameter reduction of 150 mm to 100 mm (-20 dB above 1.95 GHz (1.89 GHz) for TE_{11} and 2.64 GHz (2.59 GHz) for TM_{01}). A TE_{111} beam pipe mode exists between the two cavities (1200 MHz, $R/Q_{\perp}$ = 0.32 Ω), which has to be extracted by the probe-type coupler. A niobium coated copper two-cavity cryomodule prototype program will be initiated.

CONCLUSIONS

The RF design of the proposed SC 800 MHz higher harmonic system ensures low R/Q, mostly propagating HOMs, allows mechanical tuning and a moderate FM R/Q to administer beam loading. Two hook-type couplers damp the non-propagating TE_{111} and TM_{110} HOMs, handling 525 W each. Higher (propagating) HOMs above 1450 MHz are damped with two probe-type couplers, handling 61 W each. Both designs reject coupling to the FM and are mounted at 55° with respect to the vertical axis. Simulations of the RF cavity with installed HOM couplers and FPC reflect the aspired behaviour. Wakefield simulations indicated presence of a trapped mode (probe: 264 MHz, hook: 320 MHz), that is considered harmless, based on their impedance and non-interfering presence in the 400 MHz design. BL mode can have a maximum cavity voltage of 0.8 MV to stay below 300 kW. A fixed FPC is preferred from engineering point of view for its comprehensible design, given that a variable coupler only improves BS power consumption and allows a higher cavity voltage in this mode. As a power source klystrons or multi-IOTs are adequate. A prototype program for a niobium coated copper two-cavity cryomodule is foreseen.

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