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DESIGN, CONSTRUCTION AND CHARACTERIZATION OF A BUNCH ARRIVAL MONITOR CAVITY FOR SPARC

D. Alesini, M. Bellaveglia, A. Gallo *(INFN/LNF)*

Abstract

Precise measurements of the arrival time of the laser UV pulse on the photocathode and of the electron bunches at some reference points along the linac are extremely important at SPARC in order to optimize and stabilize the FEL radiation production process and to perform experiments of FEL seeding and, on a longer time scale, experiments involving the SPARC electrons and the FLAME laser photons.

An arrival monitor of the photocathode laser based on the resonant pulse stretching method has been already commissioned and is currently used as a diagnostic tool at SPARC.

This method is based on the transformation of a short electric pulse (generated by a HV photodiode in the case of an UV laser pulse) in a long-lasting, exponentially decaying sine wave by using a finely tuned resonant cavity. The time-of-arrival is encoded in the sine-wave phase, which can be accurately measured thanks to the large number of oscillations (of the order of $10^3 \div 10^4$) by means of standard µ-wave techniques.

This method can be easy implemented to measure the electron bunch time-of-arrival. What is needed in this case is an RF cavity designed to have a selected longitudinal (accelerating) mode resonating at a convenient frequency for phase demodulation. The bunch passage excites free oscillations of the resonant mode coupled outside by dedicated antennas connected with vacuum feedthroughs.

The design, construction and bench characterization of the first unit of a pair of BAM cavities to be installed on the SPARC linac are reported in this note.

1. THE BAM CAVITY

The principal design characteristics of the BAM cavity for SPARC are reported in Table I. A sketch of the 3D cavity model is shown in Fig. 1.

Table I: BAM cavity parameters

Opearting mode	*TM010*
Frequency	f_0 = 2142MHz
Unloaded Q factor	Q_0 = 17000 (simulations) Q_0 = 13000 (measurements)
R/Q factor	$R/Q = 40$
Antenna ext. Q fact.	$Q_{ext} \approx 34000$
Loaded Q factor	$Q_L = 7400$
Decay time	$\tau_d \approx 1\ \mu s$
Output peak voltage	$V_{pk} \approx 2V$ (@ $q_b = 1\ nC$)
Tuning accuracy	$\lvert \Delta f \rvert \leq 10\ kHz$

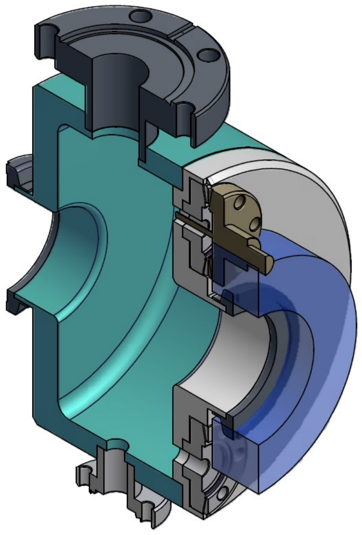


Fig. 1: BAM 3D model

The cavity has a standard pill-box shape, operating in the fundamental TM010 mode resonating at 2142 MHz, which is 3/4 of the 2856 MHz linac frequency. We chose two different working frequencies to reject interferences from the klystron high power pulse that could affect the measurements. However, being 2142 MHz a simple rationale of the 2856 MHz linac frequency, the reference sine-wave to demodulate the BAM signal is easily generated in the SPARC synchronization central unit.

The BAM cavity is equipped with two tuning ports. A large (∅ = 20 mm) fixed tuning plunger is used to correct the cavity resonant frequency after assembly and brazing, while a second one, smaller (∅ = 8 mm) and remotely controlled, is used for the fine tuning during the operation.

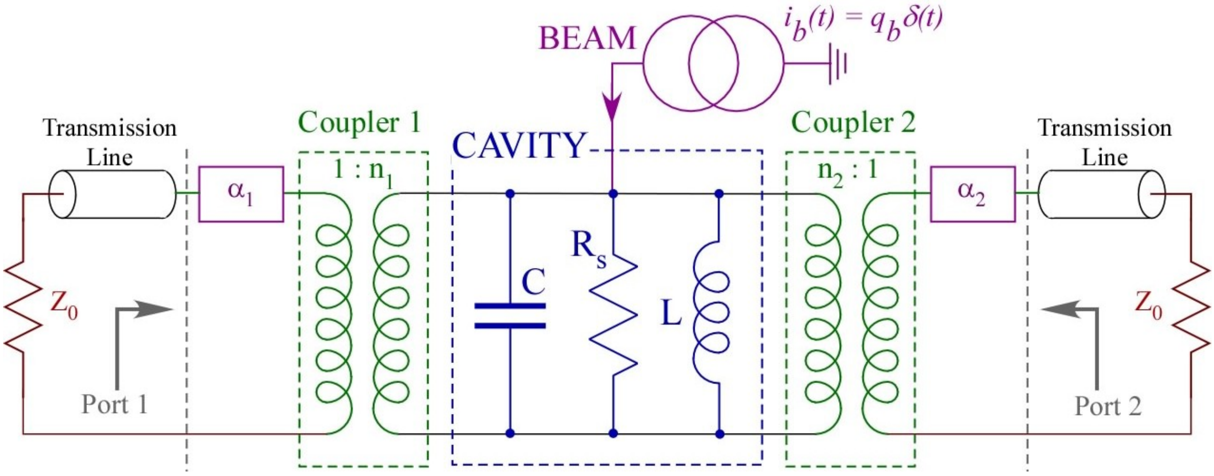


Fig. 2: BAM circuital model

The cavity detuning results in a phase slippage between the reference sine-wave and the BAM free oscillations, producing a slope in the detected phase. In order to limit the phase slippage to few degrees in the measurement time duration ($\approx 1\mu s$), the BAM resonant frequency has to be controlled with an accuracy of $\approx 10^{-5}$ ($|\Delta f| \leq 10\, kHz$) in operation.
The BAM cavity is equipped with 2 antennas coupling out a sample of the TM010 mode excited by the bunch passage.

According to the simple model reported in Fig. 2, the gap and the antenna voltages V_{gap} and V_{ext} are given by:

$$V_{gap} = q_b C = q_b \omega (R/Q);$$
$$V_{ext} = q_b \omega (R/Q) \alpha / n = \alpha\, q_b \omega (R/Q) \sqrt{\beta Z_0 / R_s} = \alpha\, q_b \omega \sqrt{(R/Q)\; Z_0 / Q_{ext}}$$

where α is a small attenuation factor ($\approx 0.15 dB$) associated to the ceramic vacuum-tight feedthrough coupling out the BAM free oscillation voltage.
The values of the lumped elements of the Fig. 2 model are related to the cavity resonator parameters by the following usual expressions:

$$R_S = V_{gap}^2 \big/ 2P_{cav}\, ;\; C = 1 \big/ \omega_0 (R/Q);\; L = (R/Q) \big/ \omega_0\, ;\; n_i^2 = R_S \big/ \beta_i Z_0 = (R/Q) Q_{ext_i} \big/ Z_0$$

2 CAVITY CONSTRUCTION AND BENCH CHARACTERIZATION

As a part of the FAST (Femtosecond Active Synchronization and Timing) experiment supported by the INFN V National Committee, two BAM cavities equipped with movable fine tuners have been built. Mechanical parts have been manufactured by an external company and brazed in the LNF oven.

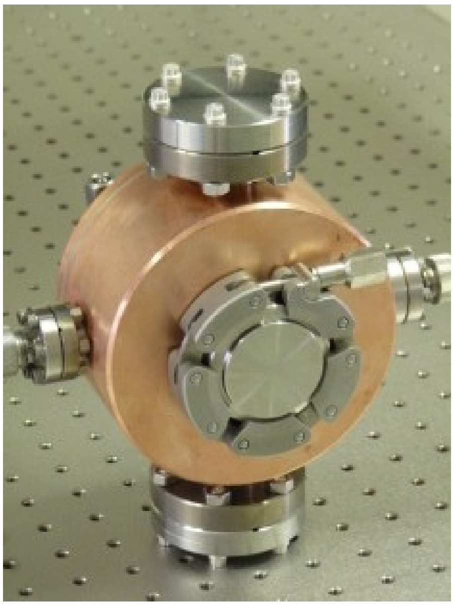
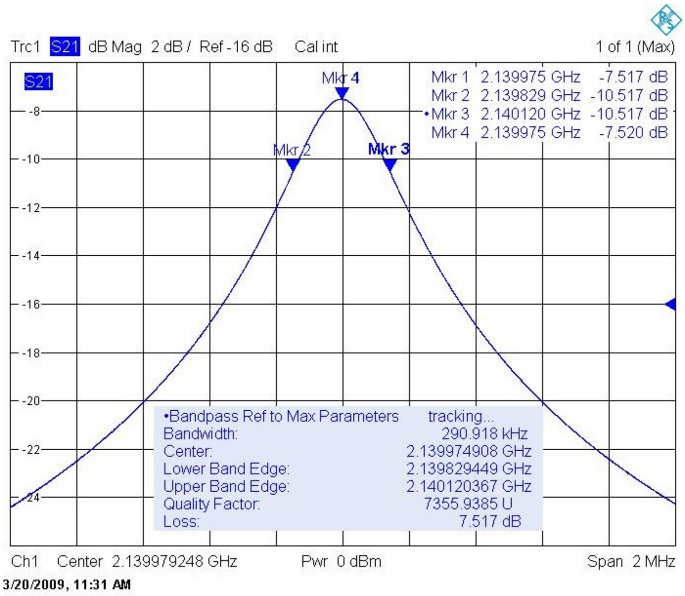


Fig. 3: BAM cavity on the bench



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 Mkr 1  2.139975 GHz   -7.517 dB
 Mkr 2  2.139829 GHz  -10.517 dB
•Mkr 3  2.140120 GHz  -10.517 dB
 Mkr 4  2.139975 GHz   -7.520 dB

•Bandpass Ref to Max Parameters     tracking...
Bandwidth:                           290.918 kHz
Center:                           2.139974908 GHz
Lower Band Edge:                  2.139829449 GHz
Upper Band Edge:                  2.140120367 GHz
Quality Factor:                     7355.9385 U
Loss:                                   7.517 dB
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Fig. 4: Plot of the s_{21} scattering parameter

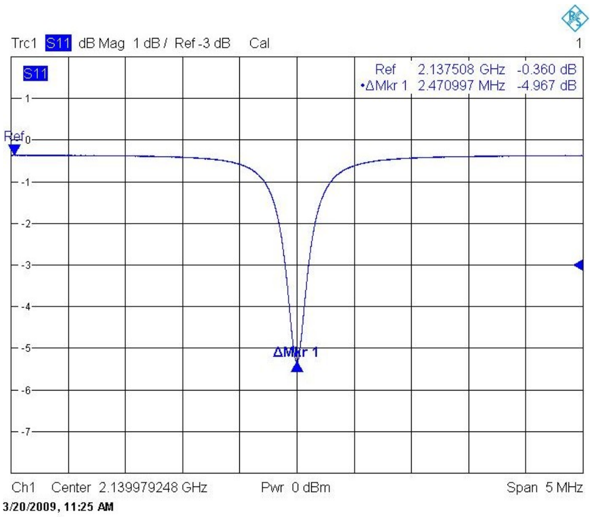

Fig. 5: Plot of the s$_{11}$ scattering parameter

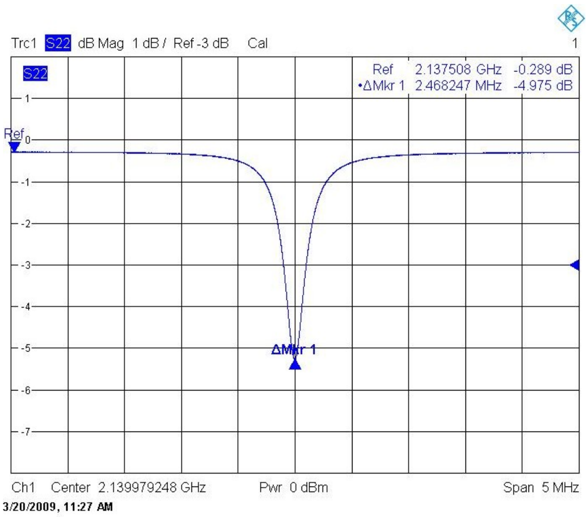

Fig. 6: Plot of the s$_{22}$ scattering parameter

A picture of one cavity is shown in Fig. 3, while measurements of the scattering parameters s$_{21}$, s$_{11}$ and s$_{22}$ performed with a *R&S ZVB 20* Network Analyzer connected to the BAM antennas are reported in Fig. 4, 5 and 6 respectively. The measured resonant frequency, in air and without the fine tuning plunger inserted, is $f_0 \approx 2140\,MHz$. If necessary, the position of the fixed coarse tuning plunger will be readjusted after the installation of the BAMs on the SPARC vacuum chamber.

The feedthroughs attenuations are measured as half of the off-resonance return losses in the s$_{11}$ and s$_{22}$ plots ($\alpha_1 \approx 0.18\,dB, \alpha_2 \approx 0.144\,dB$), while coupling coefficients β_1, β_2 and external Q-factors Q_{ext_1}, Q_{ext_2} can be extrapolated from the Δs_{11} and Δs_{22} values (referred to the off-resonance residual reflection), and from the s_{21} 3-dB bandwidth measurement of the Q_L value, according to:

$$\begin{cases} \Delta s_{11} = \dfrac{1+\beta_1-\beta_2}{1+\beta_1+\beta_2} \\[2ex] \Delta s_{22} = \dfrac{1+\beta_2-\beta_1}{1+\beta_1+\beta_2} \end{cases} \Rightarrow \begin{cases} \beta_1 = \dfrac{1-\Delta s_{11}}{\Delta s_{11}+\Delta s_{22}} \\[2ex] \beta_2 = \dfrac{1-\Delta s_{22}}{\Delta s_{11}+\Delta s_{22}} \end{cases} \Rightarrow \begin{cases} Q_{ext_1} = \dfrac{(1+\beta_1+\beta_2)Q_L}{\beta_1} = \dfrac{2Q_L}{1-\Delta s_{11}} \\[2ex] Q_{ext_2} = \dfrac{(1+\beta_1+\beta_2)Q_L}{\beta_2} = \dfrac{2Q_L}{1-\Delta s_{22}} \end{cases}$$

$$Q_0 = (1+\beta_1+\beta_2)Q_L = \frac{2Q_L}{\Delta s_{11}+\Delta s_{22}}$$

The previous relations have been calculated considering the Fig. 2 circuital model. The elaboration of the data of the scattering matrix plots gives the results reported in Table II.

Table II: BAM cavity measured parameters

α_1	α_2	Δs_{11}	Δs_{22}	$s_{21}\big\|_{pk}$	Q_L	Q_0	$Q_{ext_1} \approx Q_{ext_2}$	$\beta_1 \approx \beta_2$
-0.18 dB ≡ 0.9795	-0.144 dB ≡ 0.9835	-4.967 dB ≡ 0.564	-4.975 dB ≡ 0.564	-7.52 dB	7356	13043	33743	0.3865

The Fig. 2 circuital model also predicts a peak s_{21} value given by:

$$s_{21}\Big|_{pk} = \frac{2\alpha_1 \alpha_2 \sqrt{\beta_1 \beta_2}}{1+\beta_1+\beta_2} = -7.53\,dB$$

which is in perfect agreement with the measured value of Fig. 4.
The actual Q_0 value is ≈ 24 % lower respect to simulations, probably because of a non optimal design of the RF contact between the two building blocks of the cavity (the cell body and the closing plate) brazed together. Being the cavity decay time still larger than *1 μs*, the *Q* reduction is not relevant for the BAM operation

CONCLUSIONS

A BAM cavity has been designed to measure the bunch time-of-arrival on the SPARC linac with a *sub 100 fs* resolution, and two units of such a device have been built. The first delivered unit has been characterized on bench, and the measured RF parameters are in good agreement with our expectations. The 2 BAM cavities will be installed on the SPARC vacuum chamber in the 3 weeks machine shutdown planned just after Easter 2009.

ACKNOWLEDGMENTS

Valerio Lollo has made the mechanical design and the manufacturing supervision of the BAM cavities, while Roberto Di Raddo has assembled and brazed the mechanical parts. We wish to thank them for their invaluable, high professional contribution.