

CONCEPTUAL DESIGN OF A MICROWAVE CONFOCAL RESONATOR PICK-UP

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Abstract

A confocal resonator may be used as a pick-up for frequencies in the multi-GHz region. In this report we present the design, by analytical and numerical methods, of such a device. Furthermore, we discuss engineering issues, such as the damping of unwanted modes, shielding of image fields and manufacturing tolerances. Such a device can be used both as a pick-up and a kicker where the actual structure is several wavelengths away from the beam in the transverse direction. It is intended for highly relativistic beams and does not require changing the particle trajectory, as opposed to a diagnostic wiggler.

INTRODUCTION

Diagnostic devices aimed at measuring beam position, current or time profiles in high intensity accelerators are often perturbed by microwave fields, which are generated upstream by the beam itself and which may then propagate behind the beam, provided that their frequency is above the vacuum pipe cut-off frequency. These parasitic fields can be described as a superposition of waveguide modes. They can significantly reduce the signal-to-noise ratio and thus the sensitivity of the beam monitor. This warrants the investigation of diagnostic devices that are only sensitive to the direct TEM-like fields of the beam and that largely ignore parasitic waveguide modes which were generated upstream in the vacuum pipe.

Here, we discuss a non-intercepting detector based on a confocal resonator configuration situated transversely to the direction of propagation of the beam, which picks up electromagnetic fields in the multi-GHz region [1]. Since such a device does not change the particle trajectory, the critical distance from the beam axis is of the order of $\gamma \times \lambda/2$ [2]. Since a confocal resonator can have a high quality factor (Q-value), reciprocity suggests that it couples weakly to parasitic waveguide modes while anyway keeping a significant coupling to the direct TEM-like fields of the beam. In this paper, we present analytical design formulas that we then compare to numerical simulations.

ANALYTICAL DESIGN

The modes in a confocal resonator are identical to those found in lasers and they can thus be described by Gauss-Laguerre functions [3, 4]. In reference [1] a set of simple design equations is given for the geometry of the confocal resonator as a function of the wavelength λ and the number of nodes l . In particular, the mirror distance D is related

to the wavelength by $D = (l + 3/4)\lambda$. For our design we choose $l = 3$ and $\lambda = 2$ cm. The corresponding geometry is shown in Figure 1.

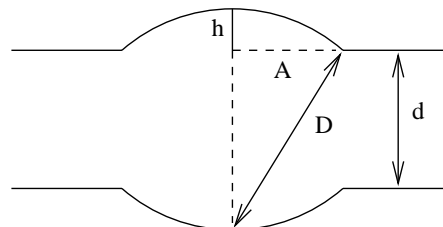


Figure 1: Sketch of the confocal resonator geometry: in our design, $A = 38.73$ mm, $D = 75.00$ mm, $d = 53.45$ mm and $h = 10.77$ mm.

The mirrors have a finite extension and this leads to diffraction losses. Also, the finite conductivity gives rise to resistive losses. A hole in one of the mirrors is needed to extract power for detection and will also contribute to the losses that determine the total quality factor. The diameter of the extraction hole can be chosen optimally by matching the combined impedance of the hole and the resonator to the impedance of the extraction waveguide [5]. Doing so, we have deduced a diameter of 3 mm. In our design, the various loss factors are $Q_{diff} = 43\,000$, $Q_{cond} = 57\,000$, and $Q_{hole} = 110\,000$. The combined effect of all losses is parametrized by the overall Q-value, which is 20 000.

The coupling impedance from the beam to a detection device in the extraction waveguide can be estimated using reciprocity [2], i.e. by calculating the effect of an excitation device inserted in the waveguide onto the electric field on the beam axis in the resonator, through the coupling hole. For this analysis, we have used the power emitted from an antenna in a waveguide, as taken from [5]. If it is matched properly, then the coupling hole transmits all the radiated power into the resonator, which reaches equilibrium at a power level that in turn defines the electric field on axis. Here, a complication arises from the transit time factor, because the non-zero field region – the mode waist – is large and the oscillating electric field changes sign several times during the passage of the beam. As a result, the effective coupling of the beam to the mode is reduced to a few per-mille. Taking all these effects into account, we obtain a transfer impedance of $50\ \Omega$, from the excitation device to the beam. Reciprocity suggests that this is equal to the transfer impedance from the beam to the detection device in the extraction waveguide.

NUMERICAL STUDY

In the analytical study, we only focused on a single mode and its coupling to the beam. However, the real resonator, once coupled to the beam pipe, will allow a larger number of resonating modes, which may perturb measurements, as well as the beam itself. These unwanted modes need to be damped by suitable absorbing materials but, at the same time, one wants to avoid excessive heating induced by the beam image currents that pass through this material. The engineering performance of the pick-up must be considered as well, in order to enable installation of the device into a beam line. As a result, we came up with the configuration shown in Figure 2.

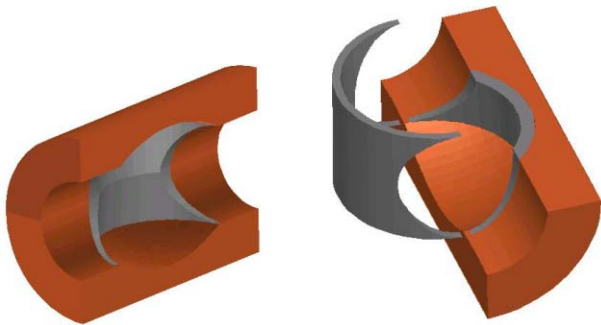


Figure 2: Artistic view of the confocal resonator pick-up with some high-order mode dampers integrated into the beam pipe. The absorbing material used here is SiC.

The optimization of the damper geometry was done with HFSS [6], by bringing the loaded Q-factors of the lowest-order longitudinal and transverse trapped modes below 10, while keeping the Q-factors of the desired modes as high as possible. Doing so, the following results were obtained for the operating mode at 15 GHz: $Q_{diff} = 41\,000$, $Q_{cond} = 65\,000$, and $Q_{SiC} = 14\,000$ (no coupling hole was considered for these simulations). The overall Q-factor is thus about 9 000.

Also, HFSS simulations lead to $R/Q = 1.67 \times 10^{-3}$ and in turn to a cavity impedance of 15Ω . Without damping, the overall Q-factor and the cavity impedance at 15 GHz become respectively 25 000 and 42Ω (if the damping does not change the mode pattern, then R/Q does not depend on the losses).

The intensity distribution obtained with HFSS for the operating mode at 15 GHz in the confocal resonator is shown in Figure 3. The pattern agrees very well with our theoretical predictions for the fundamental mode of the cavity with $l = 3$.

Note that the HFSS simulations were mostly aimed at giving us an idea on the mechanical design and the RF performance of a possible pick-up rather than at establishing a final design. That is why a reduction of the operating mode overall Q-factor at 15 GHz, as compared to our theoretical value, was accepted at this stage.

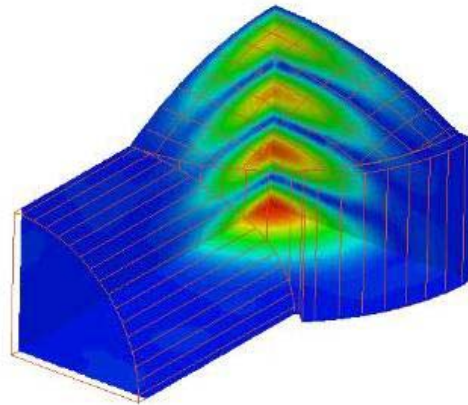


Figure 3: Intensity distribution in the confocal resonator for the operating mode at 15 GHz.

Next, the RF properties of the pick-up were studied with the time-domain code GDFIDL [7]. The envelopes of the longitudinal wake are shown in Figure 4, for both the damped and undamped versions of the confocal resonator. These plots were obtained by integrating the electric field that a spectator particle experiences when passing through the structure, following the particle that generated the wake at a given distance (or time) behind it. With the proposed configuration, heavy damping of the low frequency trapped mode is possible ($Q \simeq 6$).

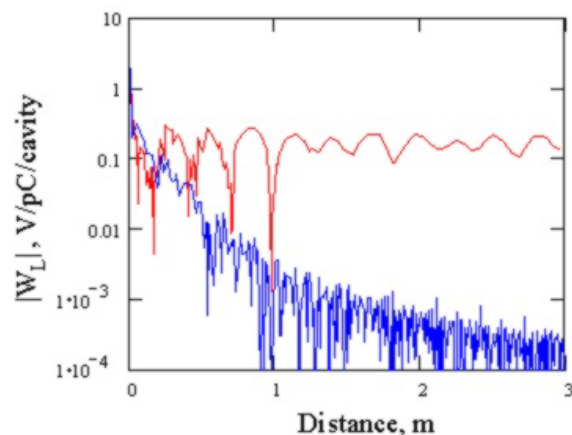


Figure 4: The longitudinal wake envelopes for the damped and undamped versions of the confocal resonator pick-up, as obtained with GDFIDL.

In order to estimate the signal spectrum which may be detected from a diagnostic waveguide coupled to the confocal resonator, we performed a Fourier transform of the longitudinal wake envelope after damping. By starting the integration from 1.7 m (i.e. approximately 6 ns), we could filter the low frequency part of the spectrum which, by that distance (time), will already have decayed significantly. In

Figure 5, the upper and lower curves respectively show the spectrum obtained by starting the Fourier transform from 0.1 m and 1.7 m: the various modes developed by the pick-up when a beam passes through are clearly visible.

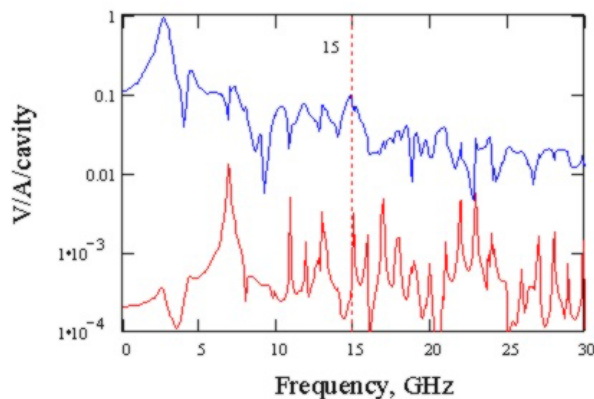


Figure 5: *Filtered impedance spectra derived from a Fourier transform of the wake envelopes given by GDFIDL (with damping). For the upper curve, the integration starts at 0.1 m, while it starts at 1.7 m for the lower curve.*

As for the waveguide modes propagating along the beam pipe, which can induce background in a diagnostic circuit, we expect that, with such a heavy damping, there will be no strong coupling of these parasitic modes to the confocal resonator and we thus neglect them. However, detailed simulations should be performed to numerically estimate the corresponding S-parameters.

PROTOTYPE CONSIDERATIONS

After performing more detailed simulations, in order to finalize the mechanical design of the confocal resonator and fully study its RF performances, we plan to build an open cavity completely immersed in air. This allows use of microwave horns to excite the structure and to verify that external microwaves are significantly attenuated. In addition, we plan to have extraction waveguides attached to both domes, in order to perform network analysis measurements with the structure.

The selection of the desired modes can be accomplished in the extraction waveguide. A circulator placed just upstream of the coupling hole will allow use of bandpass filters to select the desired frequencies, on condition that the frequency spacing between the various modes is large enough. The circulator indeed removes reflections from the filters, which would otherwise perturb the field in the resonator. Another way to suppress the unwanted modes is the shape of the extraction waveguide. Making it small will attenuate the 3 GHz modes because they are likely to be below cut-off. Making it rectangular will help select the mode with the desired polarization.

In later tests with beam, a vacuum feedthrough for the multi-GHz microwaves will be needed, which requires a

more careful study. Other issues to be considered as well are, for instance, the image currents that pass through the damping material or the fact that the SiC surface can get charged by the beam. Some cooling of the structure may be needed, possibly to cope with some heating in the absorber, but more likely to ensure that the distance between the mirror is kept constant. Indeed, a change in the mirror distance D directly affects the resonance frequency. Piezoelectric or mechanical three-legged support for the domes can also be envisaged to allow tuning in a realistic range.

CONCLUSION AND OUTLOOK

In this paper, we have discussed a confocal resonator pick-up, which shall be mostly sensitive to the direct TEM-like field of the beam and largely ignore the parasitic waveguide modes generated upstream and that propagate in the vacuum pipe behind the beam. An analytical study of the modes in the confocal resonator was presented and successfully compared with HFSS simulations. Using the time-domain GDFIDL code, we then showed that a beam may indeed excite various modes in the confocal resonator. Engineering issues related to the building of a prototype were also briefly discussed.

Using the confocal resonator pick-up as a position sensitive device can be accomplished by comparing the excitation of the $l = 3$ mode, which has a field-maximum on the beam axis, to that of the $l = 4$ mode, which has zero field on the beam axis. Careful numerical studies will be needed, though.

Knowing the transfer impedance as a function of the frequency, one may use the confocal resonator pick-up as a bunch length monitor. However, a major complication may arise from the fact that, for a multi-bunch operation, one needs to match the various modes of the pick-up to the beam spectrum. A careful study should also be performed in order to check how the modes excited by one bunch may perturb the trajectory of the following ones.

REFERENCES

- [1] T. Lofnes, A. Ferrari, and V. Ziemann, "Analytical Design of a Confocal Resonator", CTF3 Note 060 (Tech.), 2003.
- [2] F. Caspers and G. Dome, "Reciprocity between Pickup and Kicker Structures including the Far-Field Zone", Proceedings of the 4th Particle Accelerator Conference in London, UK, p. 1208, 1994.
- [3] A. Fox and T. Li, "Resonant Modes in a Maser Interferometer", Bell Syst. Tech. J.40, 453, 1961.
- [4] H. Kogelnik and T. Li, "Laser Beams and Resonators", Applied Optics, Vol. 5, 1550, 1966.
- [5] D. Pozar, "Microwave Engineering, 2nd ed.", J. Wiley and Sons, New York, 1998.
- [6] <http://www.ansoft.com>
- [7] W. Bruns, "GDFIDL: A finite difference program with reduced memory and CPU usage", Proceedings of PAC97, Vancouver, 1997.