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SUSPENDED GROUND MICROSTRIP COUPLED SLOTLINE ELECTRODE FOR STOCHASTIC COOLING

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Abstract

An alternative design of a slotline electrode has been developed and simulated. In contrast to the planar slotline pick-up designed for FAIR CR and the slot-ring electrode built by FZJ for FAIR HESR, the presented design uses suspended microstrip lines for the coupling to a planar slotline. This has some advantages and disadvantages for kicker and pick-up applications in respect of losses, power handling, and mechanical aspects.

INTRODUCTION

At the moment there are two different electrode designs foreseen for the FAIR Collector Ring (CR), one planar slotline electrode as plunging pickup [1] (also called PU17) and the well-known Forschungszentrum Jülich (FZJ) slot-ring electrode design [2] as kicker (see Fig. 1).

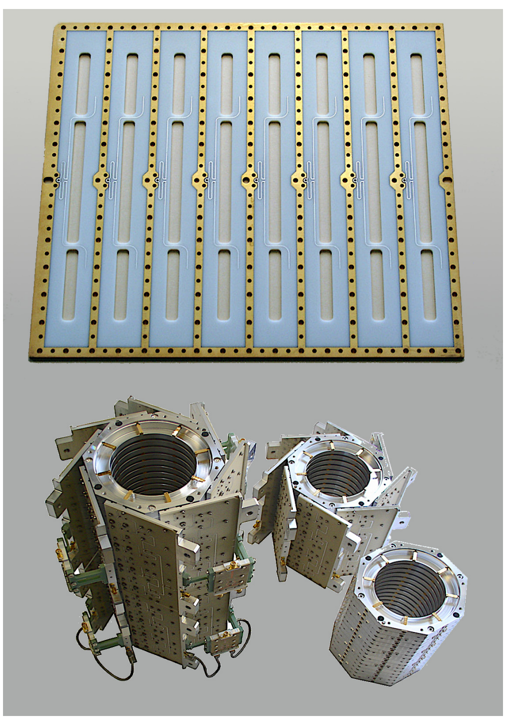

Figure 1: Top: Planar slotline electrode PU17 combiner (non beam) side. Bottom: FZJ slot-ring kickers (for FAIR HESR [2]).

All electrodes are optimized for antiprotons (pbars) at a velocity factor of $\beta = 0.97$ (3 GeV), but should also be functional for rare isotope beams (RIBs) at $\beta = 0.83$ (740 MeV/u) within the CR stochastic cooling band $f = 1$ to 2 GHz and $f = 2$ to 4 GHz for the HESR, respectively.

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Design Comparison

Both designs exhibit high impedances, flat frequency response and large beam apertures. Whereas the FZJ design is especially suited as a kicker due to its robust design and large structures, PU17 is less suited as kicker because of the fine microstrip structures on the non beam side (see Fig. 1), which can only handle a limited amount of power. An additional disadvantage of PU17 is the thick 1.905 mm Al_2O_3 ceramic, which is expensive and difficult to manufacture.

The FZJ slot-ring kicker is—due to its mechanical design—not able to be used as plunging pick-up. Whereas PU17 is especially designed for plunging operation, with beneficial factors like planar structures and low mass.

Since every slot of PU17 is housed in its own compartment, and thereby isolated from its neighboring slots, it is possible to inject a test signal into each slot—via an additional coupling loop—for testing without beam. This feature is not foreseen for the FZJ kicker.

Conclusion

While PU17 has some advantages, there is also the inherent disadvantage of not being able to be used as kicker and the fact that it uses thick Al_2O_3 ceramic, which not only increases cost but also lowers manufacturing quality. Thereby increasing risk of failure and lowering performance characteristics, i. e. non constant characteristic impedance and high resistive losses along its microstrip structures.

Therefore, it was decided to start a new development of a slotline electrode with suspended ground technology.

NEW DEVELOPMENT

The original slotline electrode design PU17 was used as a starting point to create a new suspended ground design PU18. Suspended ground microstrip lines experience a significantly lower effective dielectric constant ε_{eff}, thus the mechanical dimensions of the structures have to become larger to exhibit the same characteristic impedance Z_0. This results not only in reduced ohmic losses but also in reduced thermal resistance along the microstrip lines. Furthermore, suspended ground structures tend to have lower dielectric losses and less dispersion effects.

Design

A 6 mm wide slot line milled thru aluminum sheet, perpendicular to the beam, is used as a coupling element between beam (compartment) and an internal suspended coupling bridge. The coupling bridge itself is placed in a distance of ~ $\lambda/4$ to the end of the slotline, it is designed as a spring element which holds two suspended ground printed circuit boards (PCBs) with 635 µm Al_2O_3 substrate in their

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place. At the same time, it electrically connects both PCBs. One PCB contains a Wilkinson power combiner, which merges the two coupling elements (bridges) of one slot into one signal. The output of the Wilkinson is connected to a coaxial 50 Ω feed port. The other PCB contains a ~ $\lambda/4$ open end microstrip line for matching.

Every slot is housed in a separated hollow aluminum body, which provides some isolation between the single slots. The distance between slot center to slot center is $\Delta z = 25$ mm. Beam compartment (aperture) size is $A = 230\,\text{mm} \cdot 140\,\text{mm}$ (WxH). Ferroxcube 4S60 ferrites are placed along the outer wall for providing unwanted mode damping and isolation between beam compartment and outer vacuum chamber. Figure 2 shows a sketch of the new PU18 design.

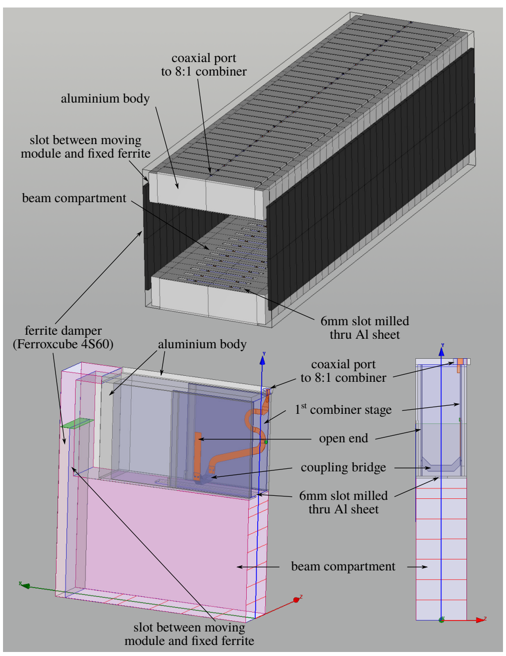

Figure 2: Top: 33 cell structure in vertical orientation (CST). Bottom: One quarter of one cell (HFSS).

Properties

Advantages compared to old PU17:

- The reduction of the Al_2O_3 ceramic thickness from 1905 µm to 635 µm does reduce production cost drastically and reduces production risks.
- The width of the microstrip structures increase from 0.19 mm to 3.9 mm. Thereby reducing resistive losses and thermal resistance along the microstrip line.

Advantages compared to FZJ slot-ring design:

- The new structure allows plunging operation.
- The injection of test signals—via additional coupling loops—for testing without beam is possible.

Disadvantages and potential risks of new PU18 :

- The coupling bridge, only pressed against its contact points by its own spring force, is a potential point of failure, which has to be thoroughly tested under different conditions like cryogenic temperatures and plunging operation.
- This holds also true for the PCBs which are only hold in place by the spring force of the coupling bridge.
- One intrinsic drawback of using Al_2O_3 ceramics is the unevenness of the substrate, negatively influencing mechanical and RF parameters.
- Since the PCB substrates no longer lie flat on the aluminum body—because of the suspended ground—there is an increased thermal resistance between the microstrip structures and the aluminum body. Therefore, it is not yet sure if the new electrode design is able to be used as kicker.
- It is not yet tested how much the ferrites along the outer wall are heated by the radiated field.

Simulation Parameter

In order to get a high confidence level of the results it was decided to use two different simulation programs with different solvers for the simulation:

- HFSS with a frequency domain solver, single cell with periodic boundaries and tetrahedral mesh.
- CST with a time domain solver, 57 cell structure and hexahedral mesh. Where only the mid port No. 29 was used as stimulus, all other ports as passive loads.

SIMULATION RESULTS

Theory

All simulation results are using the kicker circuit convention derived in [3] for the longitudinal shunt impedance:

$$R_{\|} = \frac{|V|^2}{2 \cdot \overline{P}_{in}} \tag{1}$$

where $\overline{P}_{in}$ is the root mean square (RMS) input power and V is the complex beam voltage defined by:

$$V = \int E_z(z) \cdot e^{j\omega \frac{z}{\beta c_0}} dz \tag{2}$$

with E_z the complex z-component of the electric field along the mid-line of the structure—the line through the center of the beam compartment at: $y = 0$ and $x = 0$. c_0 is the speed of light in vacuum and $\int dz$ the line integral along the z-axis.

The phase of the beam voltage is defined by:

$$\varphi(f) = Arg(V) = Arg(K_{\|}) \text{ with } K_{\|} = \frac{V}{V_k} \tag{3}$$

where V_k is the real valued terminal voltage at the input port and $K_{\|}$ the kicker constant.

The non-linear phase variation of the beam voltage V is defined by the following expression:

$$\begin{aligned}\Delta\varphi = \varphi(f) - \varphi_{aff}(f) &= \varphi(f) - \varphi_{lin}(f) - \varphi_c \\ &= \varphi(f) - 360° \cdot \tau_\varphi \cdot f - \varphi_c\end{aligned} \tag{4}$$

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with $\varphi_{aff}(f)$ being the affine linear least square fit of the unwrapped beam voltage phase, consisting of a linear part $\varphi_{lin}(f)$ and a constant part φ_c, where the linear part can also be expressed by the constant phase delay τ_φ.

Longitudinal Shunt Impedance and Non-linear Phase Response

Figure 3 shows the results of the CST and HFSS simulation for antiprotons. We see a good agreement between both solver methods. The minimum shunt impedance is ~610 Ω/m at 2 GHz and a maximum value of ~1580 Ω/m at 1 GHz. Non-linear phase variation is within an upper limit of +6.3° and a lower limit of −10.1°.

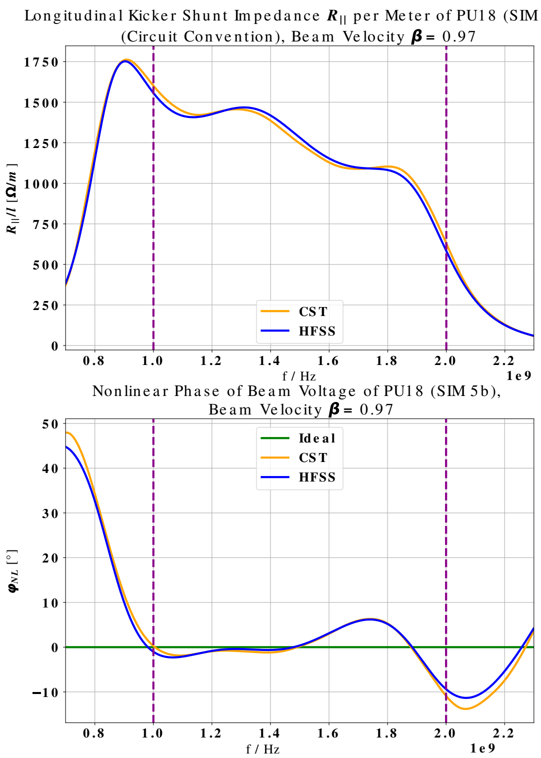

Figure 3: Comparison between CST and HFSS.

Figure 4 shows the results of the CST simulation for antiprotons and rare isotopes. Since the structure is optimized for antiprotons, some degradation in the performance of RIBs is expected. At 1 GHz we see a reduction from 1601 Ω/m to 914 Ω/m (−42.94 %). At 2 GHz we see a reduction from 634 Ω/m to 219 Ω/m (−65.53 %). The non-linear phase variation stays virtually the same, which was expected.

CONCLUSION

A new type of slotline electrode with suspended ground coupling elements for stochastic cooling purposes was developed and simulated. Simulation results show high sensitivity and flat frequency response in the targeted bandwidth, especially for antiprotons at high velocity.

While the new electrode shows promising simulation results, there are still open questions regarding mechanical reliability of the structure and suitability as kicker electrode in terms of power handling capabilities. Therefore, it is planned to perform additional simulations and to construct a prototype module. With the available (non cryogenic) vacuum test chamber for plunging electrodes it is possible to test the prototype under realistic operation conditions. A computer controlled three-dimensional near-field measurements probe can be used to verify the simulation results.

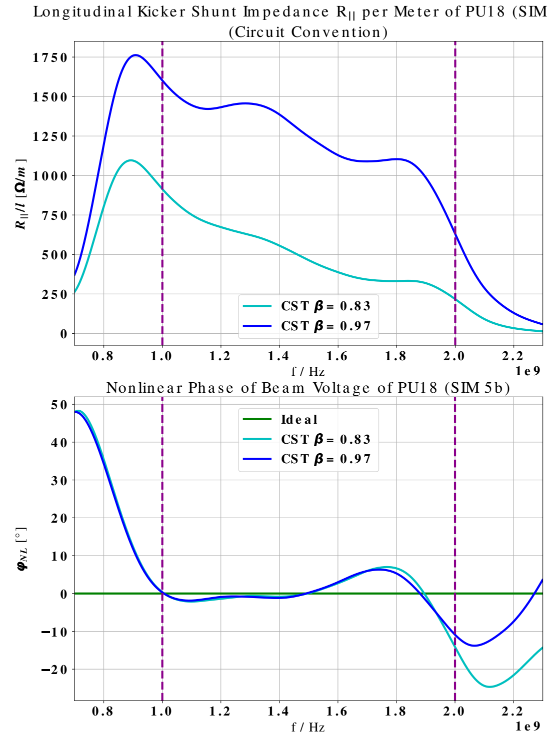

Figure 4: Comparison between RIBs and pbars in CST.

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