PROTOTYPE PICK-UP MODULE FOR CR STOCHASTIC COOLING AT FAIR*

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Abstract

The performance of the collector ring (CR) of the FAIR project will strongly depend on a stochastic cooling system which is designed for fast pre-cooling of rare isotope and antiproton beams injected at different velocities. A prototype of the cryogenic movable pick-up module has been built. It consists of four circuit boards on an aluminum body and includes two times eight slotline electrodes, combiners and test electronics. It has been optimized for high sensitivity and flat frequency response. Measurements of the electric near-field over frequency and position will be presented.

INTRODUCTION

The collector ring (CR) will be a storage ring in the FAIR project at GSI which has three different operating modes.

The first mode is stochastic cooling of rare isotope beams. The rare isotope beams have a velocity of 0.83*c*. After bunch rotation and adiabatic debunching, they will be cooled down from ε_{xy} = 200 mm·mrad and $\delta p/p$ = 0.4% (2σ) to ε_{xy} = 0.5 mm·mrad and $\delta p/p$ = 0.05% within 2 s.

The second mode is stochastic cooling of antiproton beams with a velocity of 0.97*c*. After bunch rotation and adiabatic debunching, they will be cooled down from 240 mm·mrad and 0.7% to 5 mm·mrad and 0.1% within 10 s. Due to the low charge, this is the most demanding mode for the stochastic cooling system.

The last mode uses an isochronous optical setting for nuclear mass measurements of very short-lived nuclei. In this mode, no stochastic cooling will be used.

In the CR, four pick-up and three kicker tanks are foreseen. Three pick-up tanks will be placed in straight sections without dispersion for horizontal, vertical, and longitudinal cooling. Each of this pick-up tanks will be equipped with eight movable, cryogenic pick-up modules described in this paper. A fourth pick-up tank is foreseen for Palmer cooling of rare isotope beams. This one will be located in an arc with high dispersion. It will use the same slotline electrodes in a different arrangement. The three kicker tanks, foreseen in straight sections without dispersion will use the same slotline electrode board and a similar module body, but a different power splitter board.

SLOTLINE PICK-UP MODULE

To meet the requirements for large bandwidth, high signal to noise ratio and large aperture, a planar slotline electrode has been developed [1]. The stochastic cooling system for the CR is designed for a band from 1 GHz to 2 GHz. A pick-up module consists of a milled aluminum (Al) body, two alumina (Al_2O_3) pick-up boards, two combiner boards, and a lot of small electrical and mechanical parts. Figure 1 shows the aluminum body with one pick-up and one combiner board. Each module will be mounted with a steel tube to a linear motor drive outside the vacuum. It will be individually movable to any distance between 10 mm and 70 mm from beam axis. Two times four of such modules will be mounted in one cryogenic tank. This will allow us to have a large, non-uniform aperture along the tank for the incoming hot beams and a small aperture with high sensitivity for the cooled beam [2].

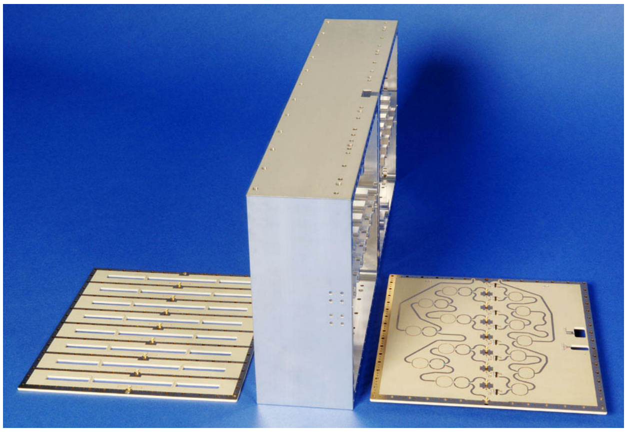

Figure 1: Main components of the pick-up module.

Each pick-up board (Fig. 2, top, left) consists of eight slotline electrodes. Each electrode consist of a slotline perpendicular to the beam and a microstrip circuit on the rear side of the Al_2O_3 board. The mirror currents of the charged particles induce traveling waves in both directions of the slotline. At approximately $\lambda/4$ from the end of the slotline, the signal is coupled out to the microstrip line. The $\lambda/4$-section at the beginning of the microstrip is a virtual short to one of the two conductors of the slotline. The exact length of these sections has been optimized to get large signals and a flat frequency response in magnitude and phase [3]. The two signals are coupled out to microstrip lines and are combined in the first stage 100 Ω to 50 Ω Wilkinson combiner. For the wanted signal, this combiner could also be replaced by a simple parallel connection, but it helps to damp unwanted modes in the pick-up system.

Behind the first combiner, the signal goes through a coaxial line in the module body (Fig. 2, bottom) to the combiner board or an optional low noise amplifier. The slotline electrode with the first combiner stage have a high reflection factor. An amplifier at this position would see its own

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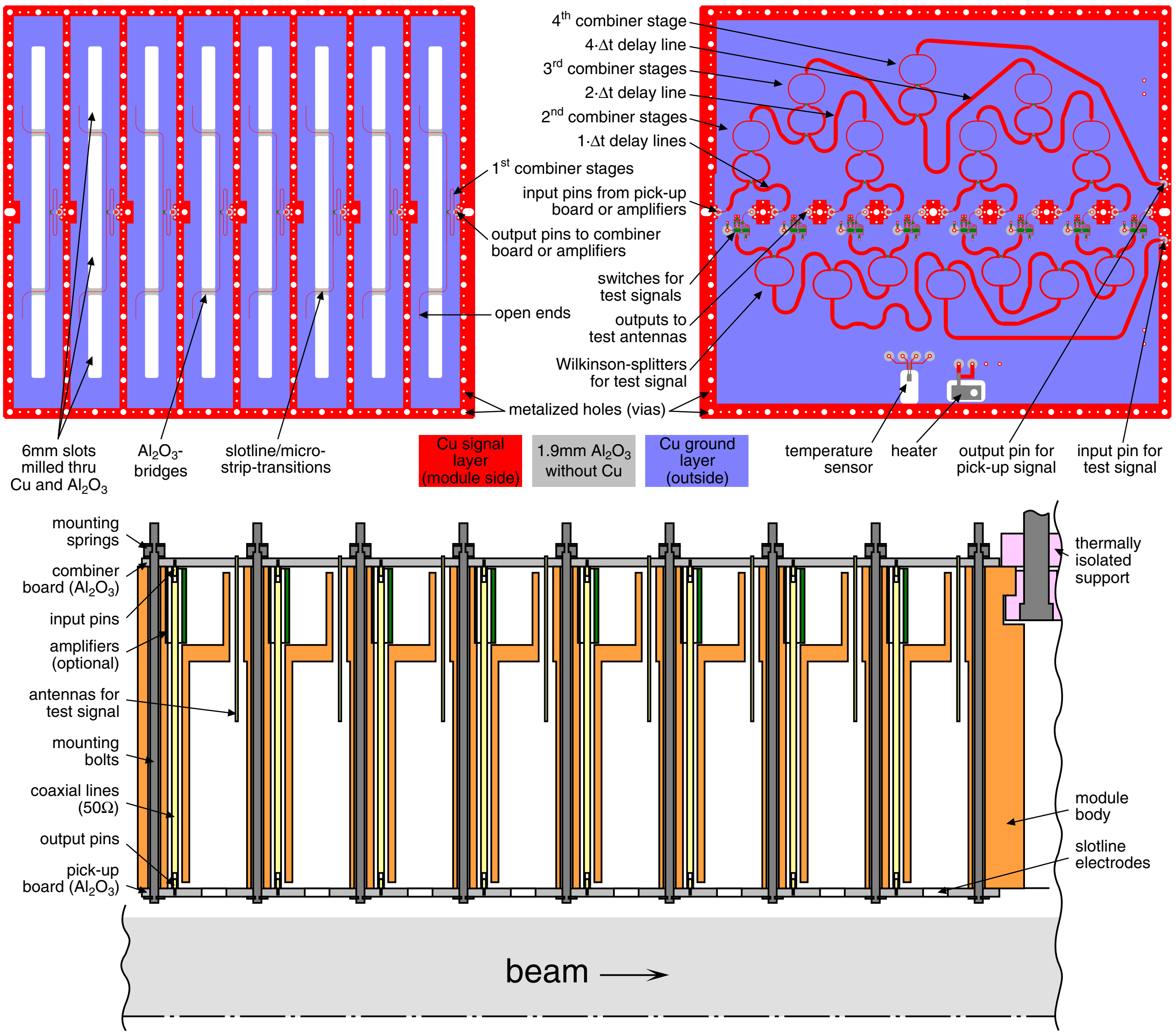

Figure 2: Layout of a two times eight slot pick-up module prototype

input, which could have an equivalent noise temperature below the physical temperature of the module and the amplifier. This in addition to the low losses from the slotline to the amplifier would result in a much lower noise temperature of the pick-up system. The disadvantage is, that defective amplifiers cannot be replaced without opening of the vacuum tank. Also, 128 amplifiers per tank instead of 16 are quiet expensive. The amplifiers would have separate power supply lines, so defective amplifiers can be switched off and do not prevent the operation of the remaining system. In the pick-up module analyzed in this paper, the foreseen amplifiers are replaced by aluminum dummies, which only exists as outer conductor of the coaxial lines. The dimensions of the coaxial lines and the connection pins are compatible to PC-3.5 connectors. This simplifies bench measurements and allows us, to use some standard parts.

On the combiner board (Fig. 2, top, right), three additional combiner stages form an eight to one power combiner. For a flat frequency response, the combiners are a two stage Wilkinson type. The resistors are standard SMD metal film parts (type 0603). The particles pass the slots one after another with a delay of $\Delta t = \Delta z / \beta c$ with the distance between the slots $\Delta z = 25$ mm (center to center). To get a phase-correct signal combination, the different delay lines before the combiners are necessary. The combiner board is designed for the velocity of the antiprotons with a β of 0.97. The rare isotopes with $\beta = 0.83$ deliver much stronger signals. Therefore, the slight amplitude degradation of 0.4 dB at 1.5 GHz is acceptable. The combination of the signals from two combiner boards would result in a unacceptable degradation of 1.8 dB at 1.5 GHz for rare isotopes. Therefore, the signals from the combiner boards go in separate coaxial lines to the vacuum feedthroughs at the other end of the support tube. The two times eight signals will be combined outside the vacuum using switchable delay lines.

There will also be two other coaxial lines for test signals from outside the tank. These test signals are split with single stage Wilkinson splitters on the combiner board into separate signals for each slotline. The signals are coupled with antennas into the pockets in the module body above the slotlines. This signals can be used to test whether each component and connection is working. This is also possible in shutdown periods without beam and even with poor vacuum. With installed low noise amplifiers inside the module, we could measure each slot separately by powering only a single amplifier. Without amplifiers, the semiconductor switches on the combiner board are necessary to address single slots.

The aluminum body of the module and the alumina printed circuit boards have a different thermal expansion coefficient. To prevent cracks in the alumina, there is only a single alignment dowel pin in the middle of each board. The outer edge of the board can move up to 500 µm during cool down. Two slot holes prevent rotation around the alignment pin. A good electrical contact between the module body and the circuit boards will be achieved by the tension of 133 mounting springs and bolts.

To lower the thermal noise, the module will be cooled down to approximately 20 K by the second stage of two Gifford-McMahon type two stage cold heads per tank. The support tube is thermally connected to the shield temperature of approximately 80 K from the first stage of the cold heads. A polymer isolator prevents a high thermal flux from the support tube to the module.

Two other parts on the combiner board are a temperature sensor diode and a resistive heater. The heater can help to drive out gas from the module, but the temperature is limited by the electronic components and the cold heads. It is not decided, whether it is needed for operation.

FIELD MEASUREMENTS

For three-dimensional field measurements, an electric near-field probe moved by a computer controlled mapper has been used. The near-field probe consists of a small electric dipole (8 mm) at the end of two thin semi-rigid cables. The two half dipoles are fed with opposite phases by an wide band 180° hybrid (Anzac H-183-4). The complex transmission S_{21} between the probe and the module output has been measured versus position and frequency using a vectorial network analyzer (R&S ZVA40). The transmission of the hybrid and all cables as well as the coupling of the dipole has been measured over the frequency. All following measurements have been corrected by this calibration values.

Figure 3 shows the voltage integrated along trajectories in different heights y above the center of the slotlines versus frequency f.

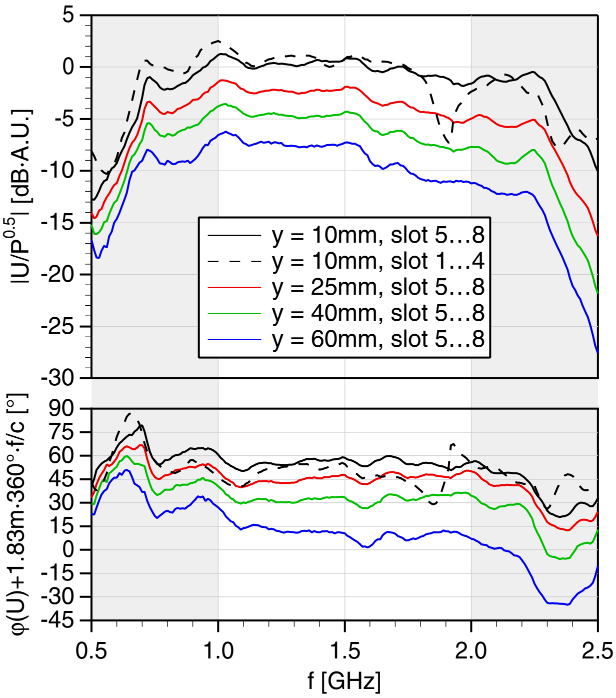

Figure 3: Normalized voltage and phase in different heights versus frequency.

The plotted value is the integral of the transmission from pick-up to near-field probe with a transit time factor for antiprotons ($\beta = 0.97$). This value is proportional to the voltage over the square root of power loss

$$\frac{U}{\sqrt{P_V}} \propto \int_{z_1}^{z_2} S_{21} \cdot e^{i\frac{\omega}{\beta \cdot c}}\, dz\,, \tag{1}$$

proportional to the sensitivity, and proportional to the square root of the shunt impedance. An electrical length of 1.83 m has been subtracted from the phase. So, the lower part of the diagram shows only the phase nonlinearity. The solid lines represent integrals from the center between slot 4 and 5 (z_1) to the end of the module, 12.5 mm behind slot 8 (z_2) in beam direction. The dashed line represent an integral from the front of the module, 12.5 mm in front of slot 1 to the center. The voltages from slot 5 to 8 looks promising. The voltage in a height of 10 mm above the pick-up is flat within ±1.5 dB and ±5° from 1 GHz to 2 GHz. The out-of-band response is also very good. There is no frequency point with high sensitivity and wrong phase nearby the operating band, which can heat up the beam. On the other hand, the voltage from slot 1 to 4 has more ripple and a nasty resonance at 1.9 GHz. This resonance is present at each of the slots 1 to 4 and none of slots 5 to 8. It can be explained as the result of a coupling between the output microstrip line and the two microstrip arcs nearby on the combiner board. The next combiner board will have an larger distance at these two critical points at the expense of a larger electrical length.

Figure 4 shows the voltage along trajectories from slot 1 to 8 versus the displacement in slotline direction in an height of $y = 10$ mm above the pick-up for different frequencies. At 1 GHz the response is very flat. The pick-up is usable for very wide beams of more than 100 mm. As expected, the effective width of the pick-up gets smaller for higher frequencies but is still wider then 50 mm for 2 GHz. The phase deviation is also very small between 1 and 1.5 GHz. Also at 2 GHz, the phase deviation is small enough to cool the beam.

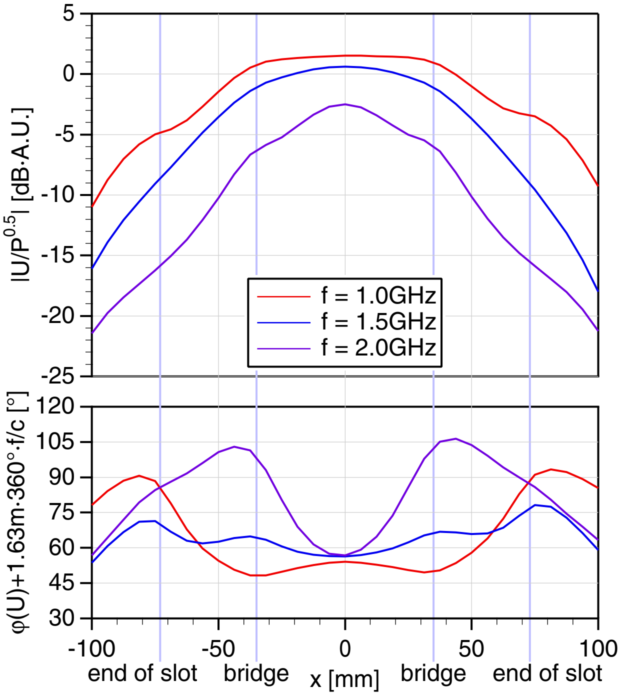

Figure 4: Normalized voltage and phase at different frequencies versus x-displacement.

The last diagram (Fig. 5) shows the dependence on the height y of the trajectory above the pick-up at different frequencies for slot 1 to 8. As expected for the open pick-up, the voltage drops exponentially with the distance. The phase deviation is relatively flat for all frequencies. Please note, that this behavior will change slightly if there is a second pick-up module at the opposite side of the beam, because the fields of the two modules will add up. This diagram demonstrates the necessity of movable pick-ups for fast cooling. The sensitivity at 1.5 GHz drops by 8.1 dB between 5 mm and 65 mm distance.

SUMMARY AND OUTLOOK

A complete pick-up module for the stochastic cooling in the CR with all electrical and mechanical aspects has been designed and a first prototype has been built up. The field measurements show a good behavior of sensitivity and phase linearity versus frequency and displacement for the slots five to eight. In the next step, we will slightly modify the wiring of the output line to fight against the resonance of the combiner for slot 1 to 4. If the behavior is the same as for slot 5 to 8 after the modification, the module fulfills all electrical requirements.

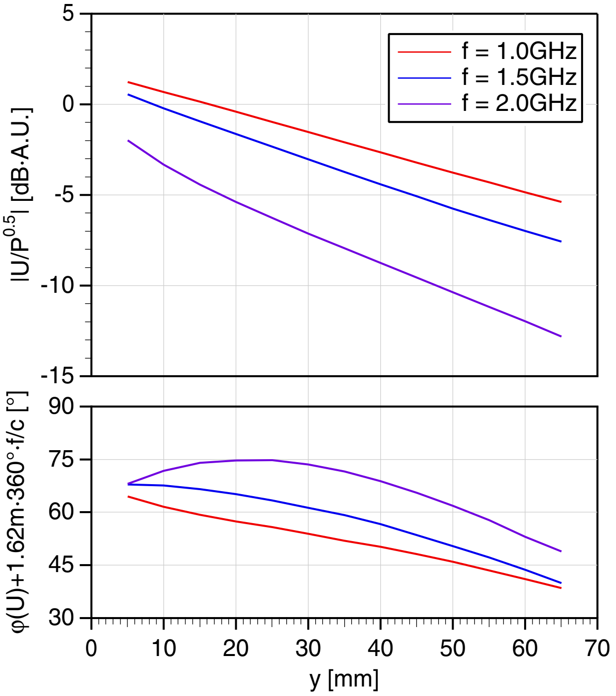

Figure 5: Normalized voltage and phase at different frequencies versus height y.

After the modification, two of these modules will be mounted in the new prototype tank for tests with movable electrodes, vacuum and in the next step with cryogenic temperatures.

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