DESIGN OF THE PALMER PICKUP FOR STOCHASTIC PRE-COOLING OF HEAVY IONS IN THE CR

D.J. Barker, C. Dimopoulou and C. Peschke, GSI, Darmstadt, Germany
L. Thorndahl, CERN, Geneva, Switzerland

Abstract

We report on the design of a Faltin type pickup for the stochastic cooling of rare isotope beams (RIBs), using a bandwidth of 1–2 GHz, for the Collector Ring (CR) at GSI. Through HFSS simulations using an eigenmode solver, the impedance and signal output phases are calculated and presented.

INTRODUCTION

The CR is designed for the efficient collection and fast 3D stochastic cooling of antiprotons at 3 GeV or rare isotopes (RIBs) at 740 MeV/u [1]. The CR stochastic cooling system will operate in the frequency band 1–2 GHz.

For the noise-limited antiproton cooling, slotline pickups are foreseen [2]. In the CR, the notch filter method [3] is indispensable for longitudinal cooling.

Heavy ion cooling in the CR is limited by the undesired mixing, and for the hot RIBs, the Schottky bands overlap, so that only the Palmer method [4] can be applied initially. After the momentum spread is decreased so as to fit into the acceptance of the notch filter, cooling will proceed with the slotline pickups down to the final beam quality.

At present, slotline kickers, reciprocal to the slotline pickups are planned, but their current design may change if they cannot withstand the high microwave power (250 W/ 8 slots).

The RIBs have to be cooled from ε_{xy}= 45 mm·mrad and $\delta p/p = 0.2\%$ to ε_{xy}=0.125 mm·mrad and $\delta p/p = 0.025\%$ (all values are 1 σ values) within 1.5 s.

The Palmer pickup tank will be equipped with Faltin type pickups which are favorable due to their robustness, ease of manufacture and the fact that combiner boards are not needed in principle. A good signal to noise ratio is envisioned due to the high charge of the RIBs, therefore cryogenics or plunging is not foreseen.

3D Cooling at the Palmer Pickup

The Faltin pickups are placed at a point of high dispersion in the ring so as to fulfill momentum cooling as envisioned by R. Palmer in 1975, private communication. The signals at the pickup are combined to extract a vertical error signal and a combined horizontal and longitudinal error signal as shown in Fig. 1.

Faltin Electrode

The Faltin electrode [5] is a rectangular coaxial waveguide with slots which couple to the beam as shown in Fig. 2. Figure 2 shows a diagram of four Faltin rails installed in a beam chamber in the configuration envisioned for Palmer cooling in the CR.

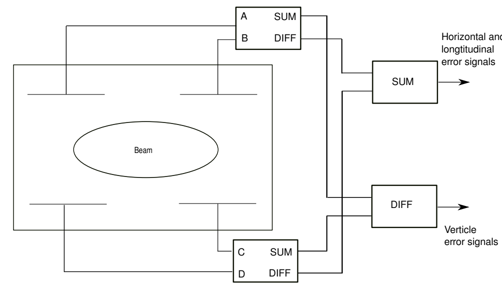

Figure 1: Diagram of the Palmer cooling method showing the combination of signals in sum and difference modes.

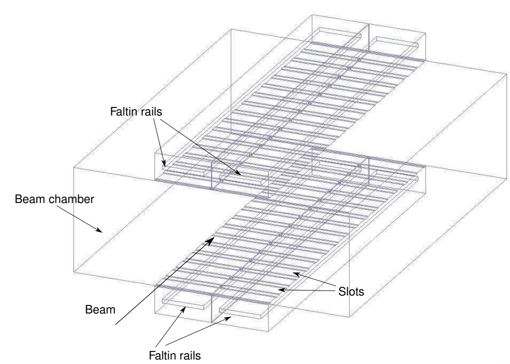

Figure 2: Diagram of a section of the beam chamber at the Palmer pickup with the Faltin rails.

The wave in the pickup induced by the beam travels parallel to the beam direction such that every time a particle passes a slot it induces an additional wave which adds to the existing wave. Therefore, in a Faltin type pickup, it is crucial that the waveguide be designed such that the phase velocity approximately equals the particle velocity so that all waves induced by a particle passing a slot interfere constructively to produce a good output signal.

Previous work on these type of pickups has included analytical approaches to calculating the coupling and the characteristics of induced waves [6, 7]. Experimental results were later published for a slot to TEM type pickup [8].

The primary mode in the waveguide is TEM due to its coaxial structure. However, in addition to slowing down the wave, the slots in the top of the waveguide have the effect of creating a quasi TEM mode which is subject to some dispersion.

Both the dispersion and the mismatch between particle velocity and phase velocity in the waveguide will result in

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a broadening of the signal in the time domain at the output. Both these effects are proportional to the waveguide length and hence the number of slots which are used.

For these reasons it was decided to split each Faltin rail into two halves, one part optimized for 1–1.5 GHz and the other optimized for 1.5–2 GHz. Therefore the Faltin rails shown in Fig. 2 would each be split into two parts and the output signals combined at the outputs. In this way, an improved output signal can be achieved due to optimization over a shorter band, and a lessening of the effect of dispersion.

PICKUP DESIGN

The pickup is designed as kicker which is possible due to reciprocity between kicker and pickup. The kicker and pickup impedances, Z_k and Z_{pu}, define the relationship between output signal and beam, and are given by

$$Z_k = \frac{V^2}{P_k} = \left(\frac{R}{Q}\right) m\omega T |F_{\phi slip}|^2 \quad (1)$$

and

$$Z_{pu} = \frac{P_{pu}}{I_b^2} = \frac{1}{4}\left(\frac{R}{Q}\right) m\omega T |F_{\phi slip}|^2 \quad (2)$$

where V is the rms accelerating/decelerating voltage acting on the beam, P_k is the power into the kicker, P_{pu} is the power from the pickup, I_b is the beam current, R is a resistance including conducting losses, Q is the quality factor, m is the number of cells, ω is the angular frequency, $T = ml_{cell}/v_{gr}$ is the structure fill time, where v_{gr} is the group velocity of the wave in the waveguide and l_{cell} is the cell length. $F_{\phi slip}$ is the phase slip which is the difference in phase between the wave in the pickup and a wave traveling at the velocity of the particle, summed over the number of cells. The phase slip is given by

$$F_{\phi slip} = \frac{1}{m}\sum_{k=1}^{m} exp\left[ik(\phi - \frac{\omega l_{cell}}{v_p})\right] exp\left[\frac{-kl_{cell}\omega}{2Qv_{gr}}\right] \quad (3)$$

where k is the cell index and v_p is the particle velocity.

Both the coupling of the waveguide to the beam (through the slots), and the phase velocity of a wave in the guide as a function of frequency determine the output signal amplitude. Z_{pu}, contains both these effects and is therefore the primary parameter to be optimized.

Pickup Simulation

High Frequency Structural Simulator, HFSS [9], was used, with an eigenmode solver, to find the frequency of a given cell by fixing the phase difference across the cell, hence simulating a traveling wave. The frequency, stored energy, power flow and loss per cell are extracted from HFSS. The longitudinal electric field along a certain particle path is integrated to give the accelerating/decelerating voltage. This is then used to calculate the impedance of the structure.

A Faltin rail, as shown in Fig. 2 is periodic along its length and is therefore divided into cells for simulation, each cell having one slot. The cell is then further divided according to electric and magnetic symmetry planes as shown in Fig. 3.

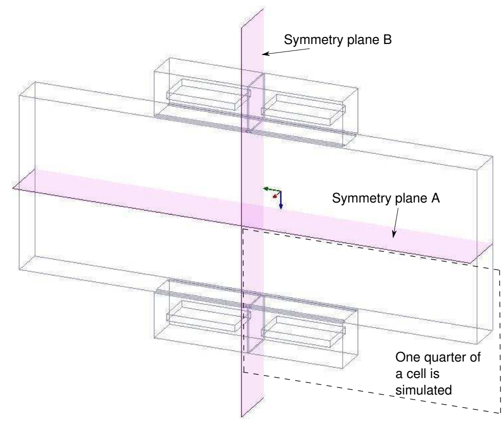

Figure 3: Diagram showing a single cell, symmetry planes A and B and one quarter of the cell which is simulated.

When the pickup is used in horizontal difference mode, a particle traveling in the longitudinal direction exactly on the symmetry plane B, will produce zero output signal. However, as the pickup is simulated as a kicker, the particle traveling on plane B should receive zero longitudinal kick, which is enforced in the simulation by application of an electric field symmetry plane. In sum mode the entire situation is reversed.

Two designs were considered, structures A and B, the dimensions shown in Table 1. They were simulated in difference mode.

Table 1: Faltin Rail Dimensions

Structure	A (1–1.5 GHz)	B(1.5–2 GHz)
Slot length	16 mm	20 mm
Slot width	68 mm	60 mm
Cell length	29 mm	29 mm
Inner Conductor width	36 mm	36 mm
Inner Conductor height	5 mm	5 mm
Outer Conductor width	68 mm	60 mm
Outer Conductor height	32 mm	34 mm

RESULTS

Figure 4 shows the pickup impedance, Z_{pu}, of the structures as a function of frequency for 10 and 15 cells.

Figure 4 shows that structure A has a peak response of $Z_{pu} = 15.16\,\Omega$ at f=1.60 GHz while structure B has a peak response of $Z_{pu} = 15.79\,\Omega$ at f=1.93 GHz for 15 cells. While the point of equal impedance for the two structures of 15 cells occurs at f=1.79 GHz and is $Z_{pu} = 10.89\,\Omega$. The overall lowest impedance exhibited by the pickup structure A is $Z_{pu} = 4.50\,\Omega$ at f=1 GHz.

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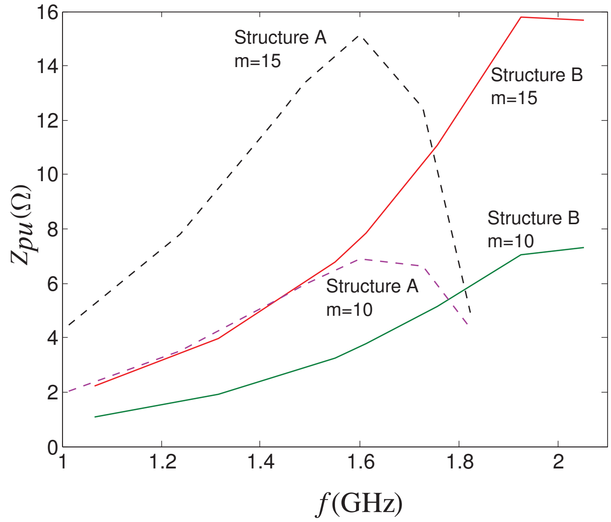

Figure 4: Pickup impedance for structures A and B, for 10 and 15 cells, vs frequency.

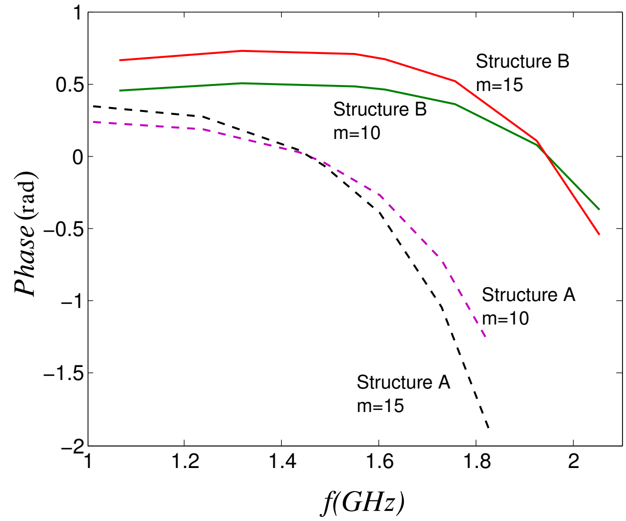

Figure 5: Phase of output signals for structures A and B, for 10 and 15 cells vs frequency.

The better response of structure A at low frequency, as can be seen from Fig. 4, is due to the increased slot width (which is perpendicular to the wave direction, see Table 1) allowing a greater coupling at lower frequencies to the waveguide.

To estimate the power in the pickup (assuming a flat spectral density) at the point of worst response one can use $Z_{pu} \cdot I_b^2/f_{rev} = Z_{pu}2e^2q^2f_{rev}N$ to give the output power per Hz, where $e = 1.6 \cdot 10^{-19}$ C is the charge of an electron, $q = 50$ is the number of charges in a particle, $f_{rev} = 1.12 \cdot 10^6$ Hz is the revolution frequency, and $N = 10^8$ is the number of particles in the beam. This gives $6.45 \cdot 10^{-20}$ WHz^{-1} which can be compared with the energy due to thermal noise at room temperature, $kT = 4.14 \cdot 10^{-21}$ J. This shows that at the point of worst response the power in the pickup is only one order of magnitude larger than the thermal noise floor. The size of this signal will be improved in further design work.

Figure 5 shows the phase of the output signals with respect to a wave traveling at the particle velocity for the two structures, A and B, for 10 and 15 cells, which is obtained from the real and imaginary parts of $F_{\phi slip}$. At low frequencies, the phase velocity is faster than the particle velocity and as frequency increases the phase velocity in the waveguide slows down. The point where the structures show zero phase shift is the frequency at which the phase velocity equals the particle velocity.

Figure 5 shows that for structure A, 15 cells, the difference in phase, $\Delta\phi$, between components at f=1.01 GHz and f=1.88 GHz is $\Delta\phi$ = 2.17 rad = 124.47°. Figure 5 also shows that for structure B, 15 cells, the difference in phase, $\Delta\phi$, between components at f=1.07 GHz and f=2.05 GHz is $\Delta\phi$ = 1.20 rad = 68.78°.

The phases of the signals shown in Fig. 5 must be corrected, however, the amount of electrical length between pickup and kicker is limited. The phase of the output signals will be improved upon in further design work.

One solution to correct the phase differences could be to further divide the length of the Faltin rails into 3 or 4 sections, using less cells, lessening the effects of error between signal and particle velocities. This would require additional combiner boards and delays lines after the pickups meaning more electrical length. Another option would be to cool the pickups down to improve signal to noise ratio and then use less cells to improve signal phase. Cooling to liquid helium temperatures, < 4 K, may prove too expensive and complicated, however, liquid nitrogen temperatures, < 77 K could be easier to implement and result in the required gain in signal to noise ratio.

In conclusion, the designs presented show mostly acceptable signal strengths but suffer from phase errors at their outputs. Whether the phase errors at the output are acceptable or not depends on the available electrical length between pickup and kicker and is still being calculated. However, in general, they will be improved in further work.

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