AN IMPROVED FORWARD TRAVELLING WAVE STRUCTURE DESIGN FOR STOCHASTIC COOLING AT EXPERIMENTAL COOLER STORAGE RING (CSRE), AT THE INSTITUTE OF MODERN PHYSICS (IMP) IN CHINA*

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Abstract

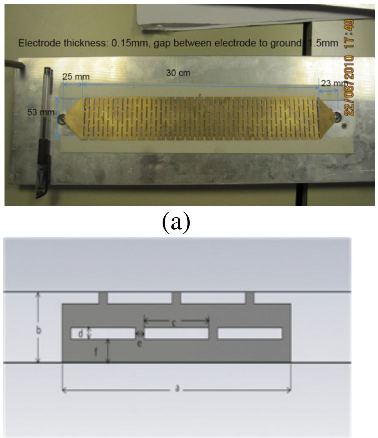
An improved forward travelling wave (TW) structure as the pick-up/kicker is designed for the stochastic cooling to match the field wave’s (phase) velocity to that of the beam. The theoretical analysis is performed together with the simulations of the propagation characteristics. Using CST Microwave Studio (CST MWS), the simulated results, including phase velocity, characteristics impedance, and distributions of the longitudinal fields, are implemented and compared with the experimented results. The improved forward TW structure can be satisfied the requirements of stochastic cooling project at CSRe, which the phase velocity is closed to 0.70 (matching the desired beam energy of 400 MeV/u) and the characteristics impedance is 17 ohm.

INTRODUCTION

At the experimental cooler storage Ring, CSRe at the Institute of Modern Physics (IMP) in China, the electron cooler is already equipped and is successfully operated [1]. For the Radio Isotope beam experiment planned at the CSRe, the injected beam emittance will be 20–50 π mm. mrad and the momentum spread △p/p will be +/- 0.5 ~ 1.0 %. The pre-cooling of stochastic cooling is quite effective for these RI beam to reduce the emittance to less than 5π mm. mrad and △p/p of 0.05 % within 2 – 20 sec. which is dependent upon the injected RI particle numbers. The energy range of RI beam is expected from 300 MeV/u to 500 MeV/u. The frequency range of the stochastic cooling system is determined as roughly from 0.2 to 0.7 GHz. The structure of pick-up /kicker should have a matched phase velocity, the high coupling impedance and a simple structure to be constructed and installed in the storage ring. In the present CSRe case, the pick-up/kicker should be installed in the bending magnet chamber. The size and the number of pick-up/kicker are severely limited. In this paper, an improved forward travelling wave (TW) structure, based on the electrode designed by Fritz Caspers, as the pick-up/kicker will be shown.

MODEL OF A FORWARD TRAVELLING WAVE ELECTRODE

A photo and an equivalent representation of the forward TW structure is shown in Fig. 1. This multi-slot strip-line structure was designed by Fritz Caspers and produced at CERN in 1998 for tests of the concept [2]. In contrast to the conventional travelling wave structures as pick-up/kicker, such as Flatin type slotted transmission line [3] and McGinnis type slotted wave guide structure [4] , this structure is very broadband, operating from low frequencies upwards as a forward coupler. We need a structure for the installations in the bending magnet, which has a large bandwidth, which works for the required beta and does not need many feedthroughs and has no significant aperture reduction. Thus this multi-slot strip-line electrode is full of interest to us. As shown in Fig. 1(b), the reduction in phase velocity is a function of slot length *c*, slot width *d*, electrode thickness, and the spacing between the electrode to ground. From the measurement and simulated results it is evident that up to 1.5 GHz this structure has a very low phase dispersion.



(a)

(b)

Figure 1: (a) The multi-slot strip-line electrode. The total number of cells in this example is 25. (b) An equivalent representation of this structure (*a*=53mm, *b*=12mm, *c*=15mm, *d*=2mm, *e*=2mm, *f*=4mm).

Longitude electric field distribution

A quarter cell (of 12mm length in vertical beam direction) model used by CST MWS is shown in Fig. 2(a). The xz axis and the y = 35 mm planes are magnetic symmetry planes. The beam moves vertically in the z-direction at x=0 and y = 34 mm. There are strong E_x fields in the cell mid-plane off the cell centre shown in Fig. 2. There is good agreement with HFSS cell simulations done at CERN as show in Fig. 2 (b).

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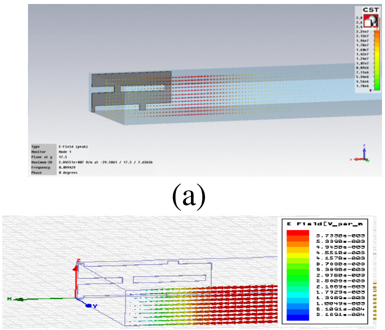

(a)

(b)

Figure 2: Electric fields distribution along x-axis in the cell mid-plane of the model. (a) CST MWS simulated results was done at CSRe (b) HFSS simulated results was done at CERN.

Phase dispersion and phase velocity data

A comparison of measurement and simulation results is shown in Fig. 3. We notice that the phase dispersion is rather small and the deviation from linear phase (displayed in Fig. 3) amounts only 11 degrees at a frequency of 1.5 GHz for a 30 cm long structure (length of the elementary cell b = 12 mm). Fig. 4 shows the simulated results for the phase dispersion when the electrode has 25 cells (L = 30 cm long electrode), 40 cells (L = 0.48 m long electrode) and 80 cells (L = 0.96 m long electrode). The phase deviation is 24 degrees at 1.5 GHz for 80 cells and thus is still not very large. Thus in a frequency range from a few MHz to 1.5 GHz this structure has a phase dispersion acceptable for many applications.

For this type of electrode, the phase velocity is determined by the slot size, thickness of the electrode and the distance from the electrode to ground. When increasing the thickness of the metal strip and its distance to the ground plane the phase velocity rises as well. In the measurement the phase velocity can be deduced from the phase Φ of the complex transmission coefficient S_{21} or alternatively in the time domain from the travel time τ (Fig. 4) by the relation given in Equ. (1).

$$\beta = \frac{2L}{c\tau} \qquad (1)$$

where L stands for the electrode length, τ is the round-trip travel time. The agreement between both results is good. Minor deviations partly related to the interpretation of measurement data, both in the time and frequency domain.

Characteristic impedance from time domain measurements and simulation by CST MWS

Figure 5 shows the step response in real time obtained with a Lecroy sampling scope where the characteristic impedance returns as about 17 Ohm, which is nearly equal to the simulated result obtained from CST MWS (Figure 6). The variation of the characteristic impedance versus spacing s between electrode and ground is also depicted in Fig. 7.

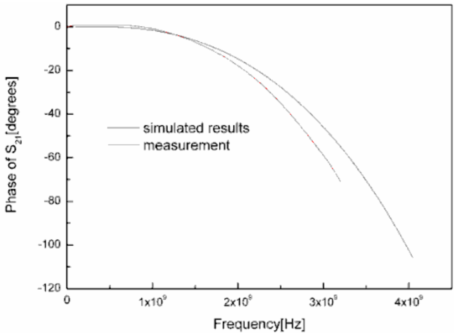

Figure 3: Phase of S_{21} for 25 cells. The black line shows the simulated and the red line the measured results.

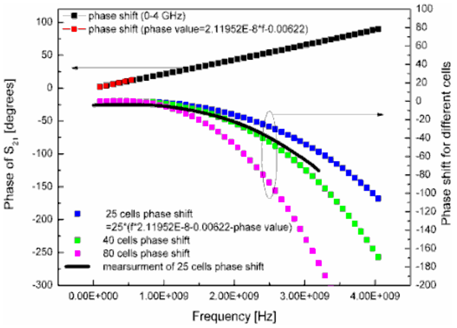

Figure 4: Phase dispersion for 25 cells (blue dots), 40 cells (green dots) and 80 cells (pink dots). Black and red dots mean the phase shift versus frequency when sweeping frequency from 0 to 4 GHz.

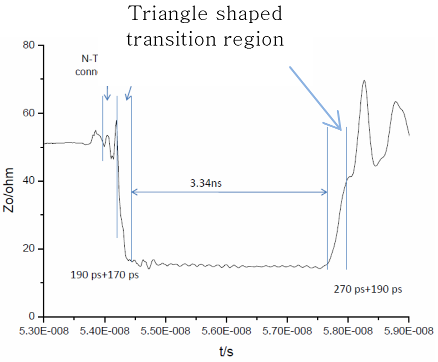

Figure 5: Impedance measurement results using the TDR (Time Domain Reflection) method on a 30 cm long model of 25 cells.

From the simulated and measured results, the phase velocity of this multi-slot strip-line structure doesn't match very well to the beam velocity, which corresponding the energy range of RI beam being expected from 300 MeV/u to 500 MeV/u. Thus we design an improved forward travelling wave (TW) structure as the pick-up/kicker for the stochastic cooling to match the field wave's (phase) velocity to that of the beam.

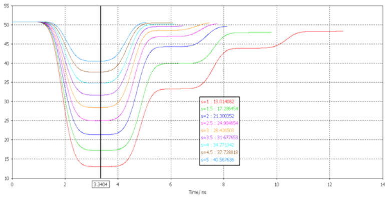

Figure 6: Simulated results of the characteristic impedance in vertical axis [Ω] for different *s* = distance electrode to the wall with CST MWS.

MODEL OF AN IMPROVED FORWARD TRAVELLING WAVE ELECTRODE

A prototype pickup electrode in the vacuum chamber

A photograph and a technical drawing of an improved forward travelling wave electrode is shown in Fig. 7. Five slots (*c* = 15mm by *d* = 2 mm) are positioned across the width of the pick-up/kicker metal strip. The unit cell length amounts to *b* = 12 mm and the thickness of the electrode is 0.4 mm. The electrode which follows the bending of the vacuum chamber inside the bending magnet is *a* = 87 mm wide and about *L* = 1 m long.

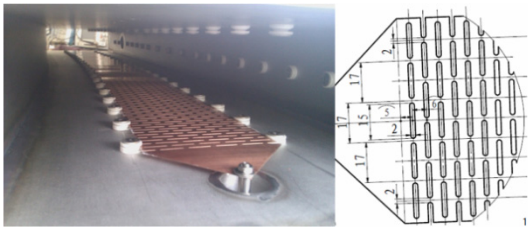

Figure 7: The slotted structure of travelling wave mode with number of cells = 80 and the length *L* ≈ 1 meter.

Simulation and measurement results in the frequency domain

To ensure the calculation accuracy, the refined mesh for the improved slotted electrode of one period is show in Fig. 8. The phase response of the measurement is shown in Fig. 9. The phase difference from the linear phase (with subtracted delay term) is not more than 45 degrees at 1.5 GHz for the nearly 1 m long electrode. The measured (network analyzer) and simulated results (CST MWS) are compared as well, as shown in Fig. 10. For frequencies below 1.5 GHz the agreement is reasonable.

The phase velocity is measured using the resonant method by replacing the connection of the electrode on both ends to the inner conductor of the measurement lines by (weak) capacitive coupling [5] i.e. positioning the pin of the feed-through very close to the electrode but leaving it unconnected. The measured results (S-parameter data) are depicted in Fig.11

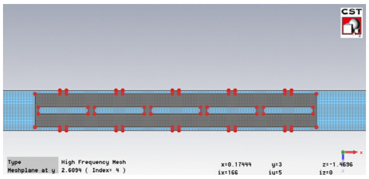

Figure 8: The refined mesh for the improved slotted electrode of one period.

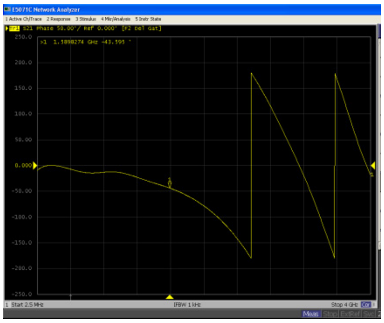

Figure 9: Phase of S_{21} for the improved slotted electrode of 80 cells.

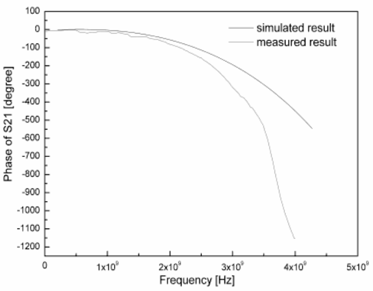

Figure 10: Comparison of S_{21} for the improved slotted electrode of 80 cells between the measured and the simulated result.

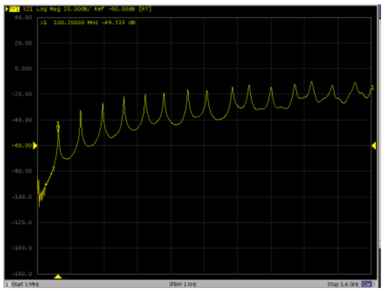

Figure 11: Resonant measurement result of the electrode.

From the resonant frequency and Q value, the phase velocity and the attenuation of the electrode can be calculated using Equ.2 and Equ.3,

$$\beta = \lambda \frac{f}{c} = \frac{2L}{n}\frac{f}{c} \tag{2}$$

$$\alpha = \frac{n}{2L}\frac{\pi}{Q}\left[\frac{Np}{m}\right] = \frac{n}{2L}\frac{\pi}{Q} 8.686 \left[\frac{dB}{m}\right] \tag{3}$$

where n is the resonant harmonic and L is the electrode length which is 1.03 m. The results for the phase velocity and attenuation are shown in Table 1. The phase velocity is roughly about 0.7, which is not too far away from the simulated result obtained with CST MWS, as shown in Fig. 12. The variation of the characteristic impedance versus spacing s between electrode and ground is also depicted in Fig. 13.

Table 1: Beta and attenuation result

n	f (MHz)	Q	β	Attenuation (dB/m)
1	101.66	110	0.69806	0.12036
2	208.36	138	0.71537	0.19188
3	314.20	157	0.71917	0.25299
4	415.80	163	0.71379	0.32490
5	518.48	163	0.71205	0.40613
6	607.66	171	0.69543	0.46455
7	722.04	172	0.70829	0.53883
8	812.94	167	0.69777	0.63424
9	935.06	164	0.71342	0.72657
10	1016.00	145	0.69765	0.91309
11	1120.70	144	0.69959	1.01137
12	1234.00	140	0.70612	1.13484
13	1315.00	113	0.69459	1.52316

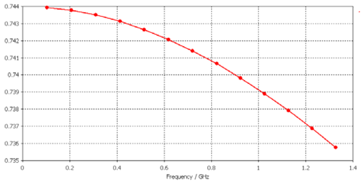

Figure 12: Simulated result for the phase velocity.

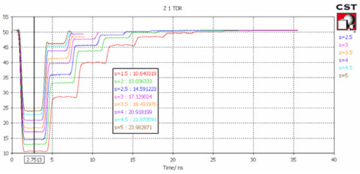

Figure 13: Simulated results of characteristic impedance in vertical axis [Ω] for different s = distance electrode to the wall.

CONCLUSION

Based on the analysis of a multi-slot strip-line of travelling mode proposed by Fritz Caspers, an improved structure as the pick-up/kicker is designed for CSRe stochastic cooling project. This kind of structure has the adequate phase velocity of 0.70 which is matched to the operation energy of the stochastic cooling 300 MeV/u - 500 MeV/u (beam velocity β = 0.654 – 0.759) and has the simple structure. Becaues the pick-up/kicker should be installed in the bending magnet chamber, the characteristic impedance is 17 ohm when keeping the space of 3 mm between ground and electrode. These characteristics can be satisfied the requirement of the CSRe stochastic cooling project.

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