BNL-105670-2014-TECH

BNL/SNS Technical Note No. 102;BNL-105670-2014-IR

Measurement and Analysis of the Transverse Coupling Impedance of the SNS Extraction Kickers

D. Davino

October 2001

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

Measurement and analysis of the transverse coupling impedance of the SNS extraction kickers

BNL/SNS TECHNICAL NOTE

NO. 102

D. Davino and H. Hahn

October 22, 2001

COLLIDER-ACCELERATOR DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

Measurements and analysis of the transverse coupling impedance of the SNS extraction kickers

D. Davino and H. Hahn

Brookhaven National Laboratory, Upton, NY 11973 USA

Abstract

Measurements of the transverse coupling impedance of one full size model representative of the 14 extraction kickers for the SNS accumulator ring are discussed in this technical note. The measurements were made by means of the standard two-wire method. The dependence on various terminations of the bus bar is discussed, as well as the behavior of a new ferrite winding, intended to reduce impedances. Finally, data to enter into the SNS ring impedance budget are quoted and an analytical expression that fits the impedance measurements is indicated.

I. Introduction

The transverse coupling impedance of the extraction kickers is believed to be the largest contribution to the impedance budget of the SNS accumulator ring. Previous measurements on the AGS booster dump kicker had shown values to be of concern for the transverse stability of the SNS high intensity beam [1,2]. Therefore, a study has been carried out to develop methods and technical solutions to reduce the transverse impedance.

One of the first solutions proposed was to use a 25 Ω resistive termination in parallel with the pulse form network (PFN) circuit that feeds the kicker. This solution helps to damp the natural resonance of the bus bar which represents a resonator with small losses introduced by the CMD5005 ferrite bricks.

Furthermore, Lee has proposed a new type of ferrite winding which was expected to reduce the transverse impedance without appreciable degradation of the other extraction kicker performances, namely the kicker magnetic field strength and its rise time [3]. In the following, we refer to that winding as the ferrite loop. The measurements on a small kicker model were presented in a previous technical note and the results for the ferrite loop were encouraging [4]. The advantage of using a resistive termination was already shown in that report and complemented with a comparison of the loop versus a resistive termination of the PFN.

However, the impedance values scaled from this model were still unacceptably large predicting beam instability at SNS design intensity. This justified a series of impedance measurements and tests on the accessible RHIC kickers [5] and finally the full-size SNS prototype, for which the results are presented in this report.

The full size SNS extraction kicker in its vacuum vessel is shown in Figure 1. In particular, it is possible to see the vessel in which the kicker is placed, the feed through to which the PFN circuit is connected, the eddy current strips and the ceramic assembly to keep the kicker assembled. The aperture dimensions are about h =25 cm in the vertical plane and w =14.6 cm in the horizontal one, the bus bar is 40 cm long, and the vacuum vessel has a 62 cm inner diameter and it is 88 cm long. The bus bar current plates are perpendicular to the vertical plane.

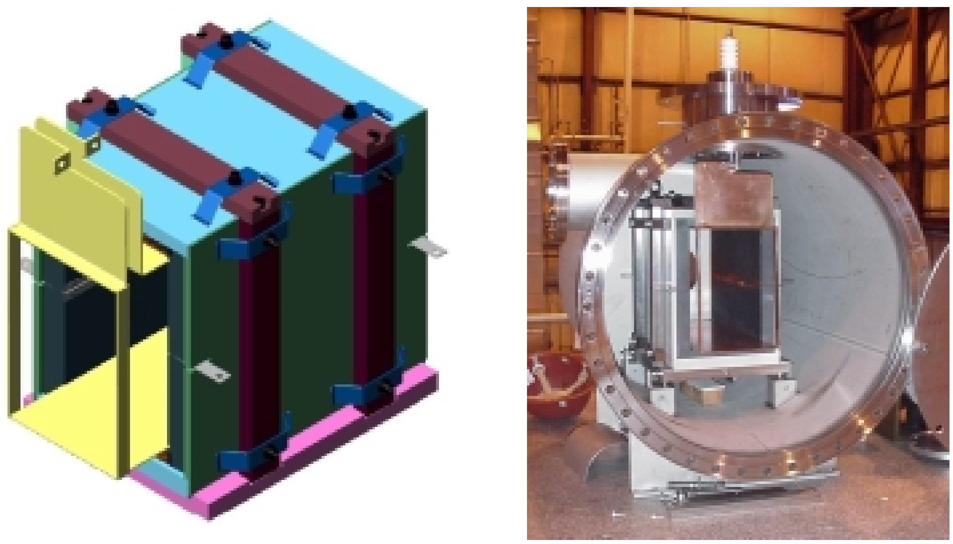

Fig. 1. The SNS extraction kicker: schematic view (left), the kicker in the vessel used for the measurement (right).

II. Scheme of measurement

Transverse impedance measurements of the SNS extraction kicker were made using the standard method [6] in which a double-wire "Lecher" line is inserted into the kicker, and the forward transmission coefficients S_{21} of the "Device Under Test" and of a reference line of equal length are interpreted according to

$$Z_{DUT} \approx -2Z_L \ln(S_{21DUT} / S_{21REF}), \tag{1}$$

from which one obtains the transverse impedance as

$$Z_{\perp} = \frac{cZ_{DUT}}{\omega\Delta^2} = -2\frac{cZ_L}{\omega\Delta^2}\ln\left(S_{21DUT} / S_{21REF}\right), \tag{2}$$

with Δ being the two wire spacing, and Z_L the characteristic impedance of the line. In order to obtain sufficiently strong signals and sufficient rigidity to assure alignment and repeatability, measurements were performed with a cable made at this laboratory, as shown in Figure 2. Matching of the 165 Ω characteristic impedance of that cable to the 50 Ω cables of the network analyzer was achieved by means of transformers with a center-tapped secondary winding, which serves as 180° hybrid. The transformers have a 50 Ω/150 Ω ratio and resistive matching by resistors was applied thereby covering frequencies up to 100 MHz. All measurements were made with the network analyzer, Agilent 8753ES, set for a logarithmic frequency scale from 30 kHz to 100 MHz, 1601 points, a 300 Hz bandwidth, and averaged over 5 sweeps.

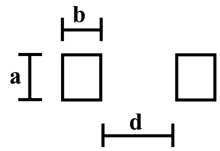

Fig. 2. The transverse section of the cable used for the measurements. The dimensions are a=b= 6.35 mm and d=10.8 mm (or d=35.6 mm).

Due to some electromagnetic background noise and due to the transformer properties, rated only for frequencies above 100 kHz, measurement results at lower frequencies become suspect and must be used with care. The typical ripple for the transmission coefficient, due to the instrument and connectors reproducibility, was $3\cdot10^{-4}$ for the amplitude and $20\cdot10^{-3}$ degree for the phase units. Those values are represented, through the formula (2), in the Figure 3. Those curves can be used as amplitude error bars for all the coupling impedance measurements presented in this report.

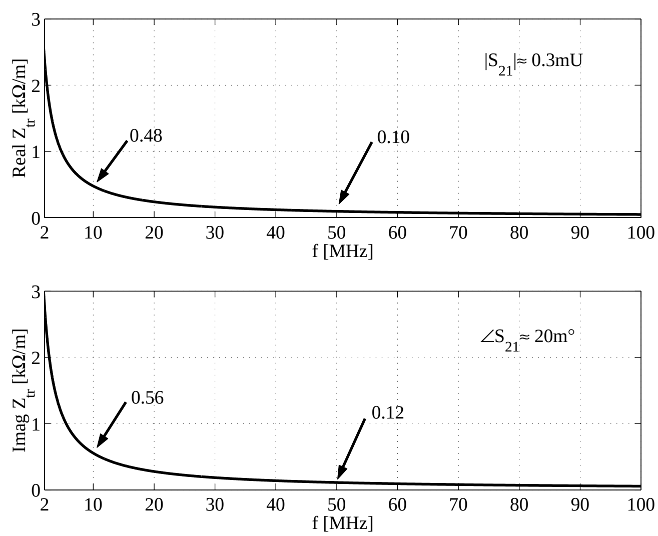

Fig. 3. The error bars amplitude of the measurement setup.

The calibration of the cable

The characteristic impedance, Z_L = 165 Ω, was measured by using an internal functionality of the communication signal analyzer, Tektronix CSA 803. The effective spacing, Δ, of the "home-made" cable was determined by means of a comparison with a known cable, the commercial line CQ 551 with a characteristic impedance Z_L = 450 Ω and a spacing Δ=13/16" (Δ=2.0637 cm). The calibration procedure consists in measuring the transmission coefficient in the vertical plane between the PFN port and the two cables, used without transformers and terminated, on one side, into a short-circuit. In the low frequency range, 30 kHz – 1 MHz, a simple transformer model can represent that configuration, and the following expansion applies

$$S_{21} = \frac{2j\omega M}{Z_C} + \frac{2\omega^2 \left(L_1 + L_2\right) M}{Z_C^2} + \dots$$

where M is the mutual inductance, L_1 and L_2 are respectively the inductances of the kicker, measured at the bus-bar port, and of the cable. Z_C is the characteristic impedance of the instrument. The mutual inductance depends linearly on the effective cable spacing and is given by,

$$M = \mu_0 \Delta \frac{l}{w}$$

where l is the magnet length and w is the horizontal width of the magnet. Comparing the forward transmission coefficients allows directly to determine the spacing of the cable used for the measurements. The cable in Figure 2 has an effective spacing of $\Delta \approx 1.43$ cm, roughly corresponding to the gap plus rod thickness.

In order to increase the signal and reduce the error bars, measurements were also made with the same cable but with a bigger gap, d=35.6 mm, and Z_L =275 Ω. The effective spacing was here 40.6 mm. It is to be noted that these measurements gave cleaner signals, but did not result in noteworthy changes.

III. Experimental results

Dependence on the bus-bar termination

The transverse coupling impedance of the SNS extraction kicker, without the ferrite loop, was measured in the vertical plane with terminations directly connected at the bus-bar port. Figure 4 shows the comparison of impedances for different terminations, namely open, 200 Ω, 50 Ω, 25 Ω, and short-circuit.

The transverse coupling impedance is significantly lower than the one measured with the AGS booster dump kicker, the difference being a factor 3 between the two kickers. This is not surprising and it is mainly due to the different apertures of the two kickers, since a larger aperture lowers the impedance. The AGS booster dump kicker has a 15.8 cm × 11 cm aperture whereas the measured SNS kicker has a 25 cm × 14.6 cm aperture.

From Figure 4, it is apparent that both finite terminations, 25 and 50 Ω, are able to damp the resonance at 35 MHz of the open-circuit termination, whereas the 200 Ω still presents a peak. On the other hand, the open and the short terminations case present a lower impedance for f < 15 MHz. However, one sees that both 50 Ω and 25 Ω terminations represent a good choice to reduce the real part of the coupling impedance, and that for practical terminations the real part is on the order of a few kΩ/m.

The conclusions of this comparison are that the open termination cannot be used because of the resonance at 35 MHz and that the 50 Ω and 25 Ω terminations are almost equivalent and both of them can be used. The short termination is shown only for comparison, since it is unfeasible and the kicker cannot be fed in that case.

Finally, it is possible to summarize the transverse impedance of the kicker without the use of the ferrite loop as follows,

$$Z_y^{25\Omega} = (2 + j6.5) \quad \text{k}\Omega\text{/m for } f \sim 10 \text{ MHz}$$
$$Z_y^{25\Omega} = (1.4 + j5.1) \quad \text{k}\Omega\text{/m for } f \sim 50 \text{ MHz}$$
$$Z_y^{op} = (0.6 + j7.4) \quad \text{k}\Omega\text{/m for } f \sim 10 \text{ MHz}$$
$$Z_y^{op} = (2.1 + j0.7) \quad \text{k}\Omega\text{/m for } f \sim 50 \text{ MHz}$$

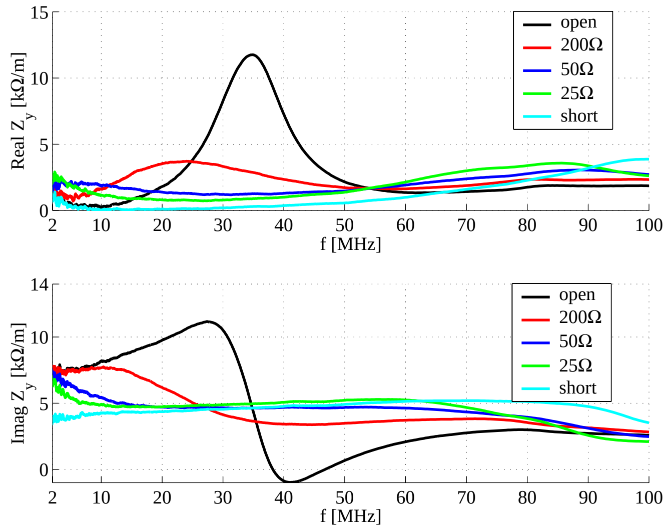

Fig. 4. The vertical transverse impedance: dependence on the termination at the bus-bar port.

The effect of vessel and of feed-through

It is interesting to compare the effect of vessel and of feed-through on the impedances of the kicker. Figure 5 left shows that the imaginary part of the transverse impedance with 50 Ω is generally higher for the kicker in the vessel, whereas the real part is unchanged. For this comparison the 50 Ω load was directly connected to the bus-bar port, without feed-through.

Figure 5 right shows the effect of the feed-through on the open termination case. The resonance at 35 MHz shifts to a lower frequency, 23 MHz, because of the feed-through. In fact, direct measurements of the feed-through have shown that it introduces a 20.5 pF capacitance in parallel and that, of course, reduces the resonant frequency of the kicker.

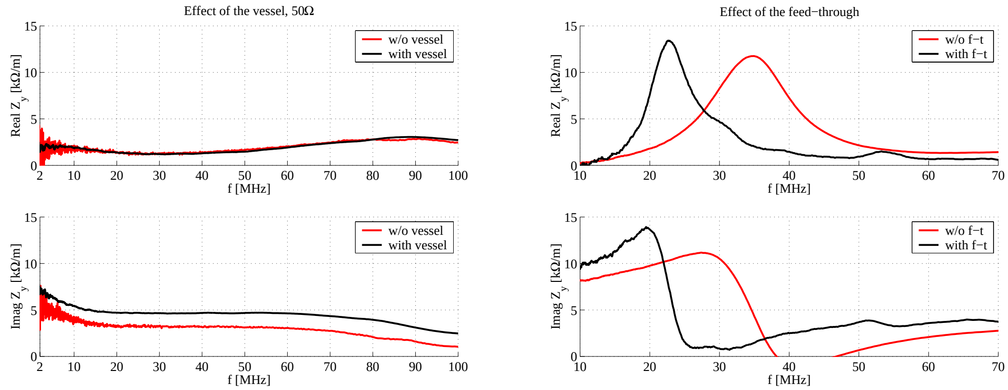

Fig. 5. The Effect of vessel and of feed-through on the vertical transverse impedance with 50 Ω (left) and open (right) termination.

The effect of a cable in the operational conditions

It is worth noting that all the previous measurements were made with the kicker mounted in a vessel, as shown in Figure 1, and the terminations connected directly to the bus-bar port. In contrast, the operational conditions foresee that the termination is connected over a coaxial cable with the characteristic impedance equal to the termination, namely $Z_0 = 25\ \Omega$ for a 25 Ω termination. Then, the coaxial cable, about 60 m long, is connected to the kicker through the feed-through. This last point does not imply changes to the coupling impedance as long as the cable is well matched. Measurements on the SNS kicker have been performed by using a 90 m long coaxial cable with $Z_L = 50\ \Omega$. Figure 6 left shows the comparison between the 50 Ω termination connected before and after the cable. The case with the termination after the cable has less wiggles at low frequencies, but this is true only as long as the cable is well matched.

It is clear that a strong mismatch of the cable introduces reflections which are seen by the kicker as a larger impedance termination. In this case, the coupling impedance has several narrow resonances that can sample the open-termination values, which in fact represent an upper limit [7]. Figure 6 right shows the extreme case when the end of the cable is terminated on a short-circuit. Of course, the effect of the termination is completely cancelled and the impedance shows all the resonances of the cable, whereas if the matching termination is connected near the kicker, the strong mismatch is largely damped. Therefore, with the termination after the cable, it is highly recommended that the rest of the parallel loads after the termination be sufficiently large not to perturb the matching of the cable.

Transverse coupling impedance in the horizontal plane

The transverse coupling impedance in the horizontal plane is shown in Figure 7. For this measurement, an open termination was used, but it is worth noting that the horizontal plane impedance is independent of the bus-bar termination. As expected, this impedance is noticeably lower than the one in the vertical plane and can be summarized as:

$$Z_x = (0.5 + j5) \ \text{k}\Omega\text{/m for } 0 < f < 50 \text{ MHz}$$

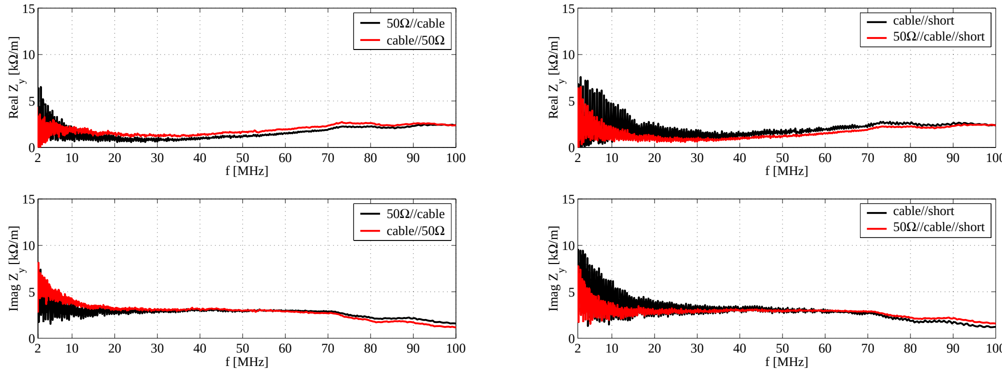

Fig. 6. The Effect of a 90 m coaxial cable with the resistive matching at the bus-bar port or at the end of the cable.

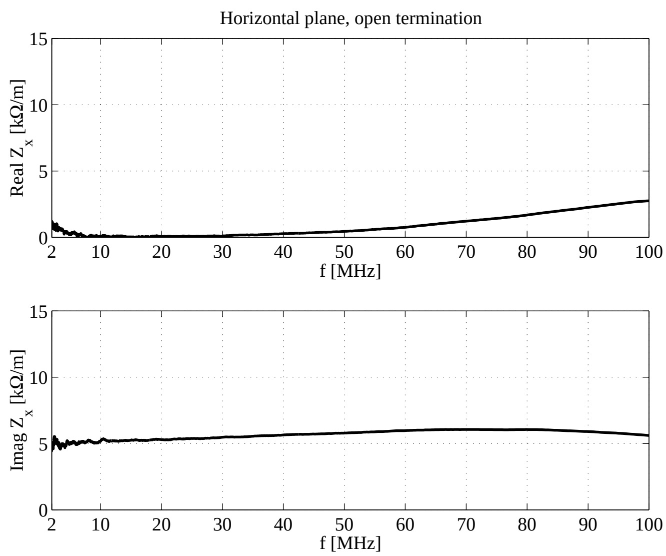

Fig. 7. The horizontal transverse impedance with open termination at the bus-bar port.

The input impedance at the bus-bar port

The aspect ratio of the SNS extraction kicker puts it into the category of short kicker which can be analyzed as transformer with lumped elements. Thus one can expect a direct relation between the input impedance, Z_{in}, measured at the bus bar port and the transverse coupling impedance, Z_y, seen by the beam (and measured by the two-wire method). In order to obtain an estimate of the transverse coupling impedance with open termination, one can consider the bus-bar as the cable in the wire measurement with its spacing given by the vertical dimension, *h*, of the kicker. In this approximation, the coupling impedance follows by scaling the input impedance according to

$$Z_y^{in} = \frac{c}{\omega h^2} Z_{in}$$

Figure 8 compares the transformed input impedance, Z_y^{in}, with the measured transverse impedance, Z_y, of the kicker in the vessel but without the feed-through connected. Z_y^{in} shows several resonances, the highest of which is found around 30 MHz, whereas the measured impedance has the main resonance around 35 MHz. However, it is apparent that the two impedances exhibit a similar character. This points to the possibility of getting a reasonable idea of the coupling impedance by measuring Z_{in}, even with the kicker mounted in the accelerator, provided that there is access to the bus-bar. It is worth noting that the effect of the external circuits, namely the feed-through, the PFN and the terminations, can be taken into account by considering them in parallel with those impedances of the bare kicker.

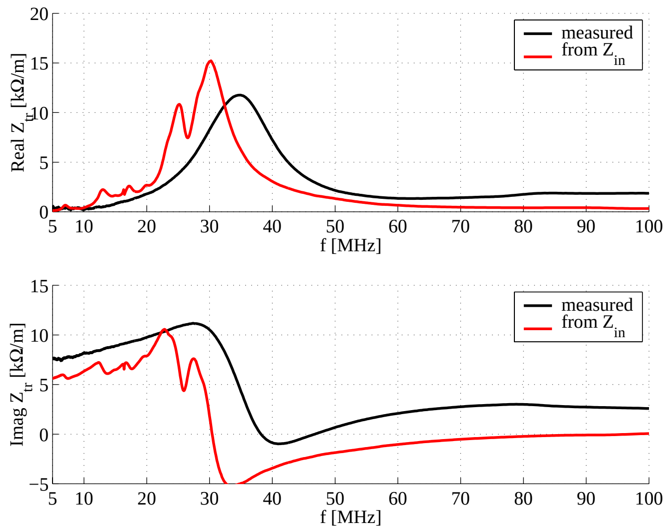

Fig. 8. The transverse impedance with open termination at the bus-bar port.

IV. Impact of the ferrite loop on the kicker

The transverse coupling impedances of the kicker with the ferrite loop is compared to the bare kicker in Figure 9, both for the case of 25 Ω and open termination. While the imaginary part for the 25 Ω case is always lower when the ferrite loop is placed in the kicker, the real part is clearly lower only above 32 MHz. The measurement of the kicker with ferrite loop with the open termination shows a sharp resonance at 12 MHz, while the resonance at 23 MHz is largely dropped down.

This comparison allows the conclusion that the effectiveness of using the ferrite loop is not obvious, at least not in the present realization, and that more engineering studies will be needed to realize the promises and potential advantages of this idea and to arrive at an optimized kicker design.

The effect of the ferrite loop on the kicker magnetic field

Consider the input impedance measured at the PFN port, shown in Figure 10. It is clear that the input impedance is the same with and without the ferrite loop up to about 5 MHz. Since the magnetic field of the kicker is required to have a rise time of 200 ns, corresponding to a highest frequency component of 5 MHz, the ferrite loop does not modify the magnetic flux or the rise time.

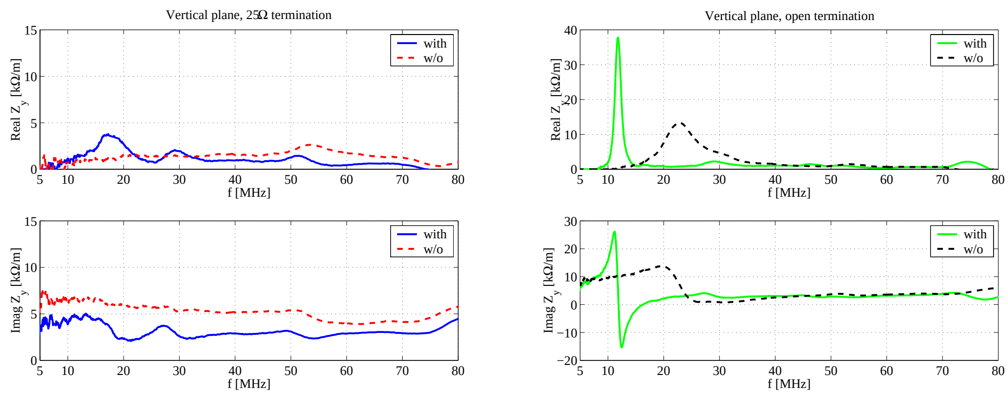

Fig. 9. Comparison of transverse impedance in the kicker with and without the ferrite loop, with 25 Ω (left) and open (right) terminations at the PFN port.

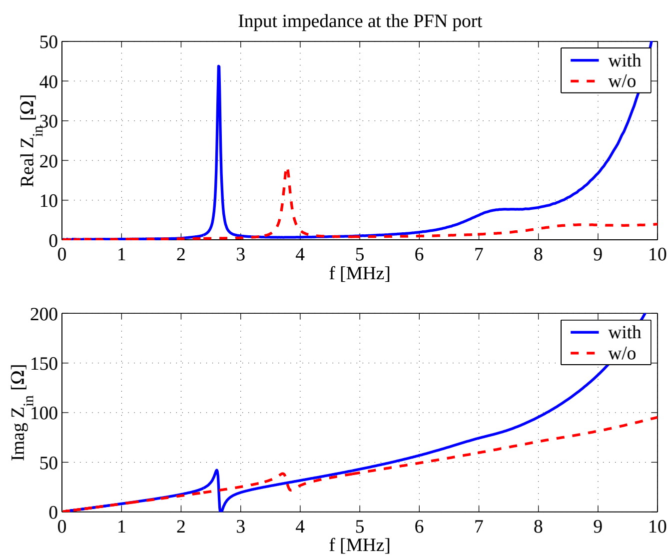

Fig. 10. The input impedance at the PFN port comparing the kicker with and without the ferrite loop.

This is confirmed in Figure 11 by the measurements showing the transmission coefficient between the PFN port and a magnetic loop on the beam axis. Since the loop collects magnetic flux produced by the bus bar, this is sort of a low current measurement of the magnetic field along the beam axis, and it is apparent that the amplitude of S_{21} is the same within few percent for frequencies up to 8 MHz.

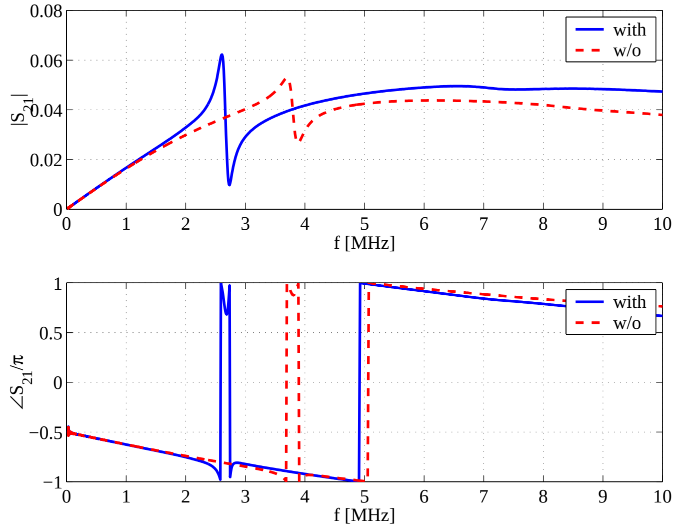

Fig. 11. The transmission coefficient between the PFN port and a magnetic loop on the beam axis. for the kicker with and without the ferrite loop.

V. Scaling law for the impedance budget and fitting curve

The SNS accumulator ring design has 14 kickers for the extraction of the beam [8]. The kickers have different beam apertures among them and therefore one should expect different coupling impedances. A scaling for the impedance is possible according to

$$\frac{Z_{y1}}{h_1^2} = \frac{Z_{y2}}{h_2^2}$$

where $h_{1/2}$ are the aperture dimensions in the vertical plane and $Z_{y1/2}$ are the transverse impedances. Therefore, Table 1 shows the impedances scaled according to the dimensions of the kickers. The total contribution to the impedance budget for the 14 kickers with a 25 Ω termination is 74+j209 kΩ/m for f < 10 MHz and 45+j164 kΩ/m for f ~50 MHz.

Table 1. Scaled impedances of the 14 kickers. The first column represents the number of identical kickers over the total.

#	h [cm]	$(h_1/h_2)^2$	Z_y [kΩ/m], f < 10 MHz	Z_y [kΩ/m], f ~ 50 MHz
7	25.0	1	2.3+j6.5	1.4+j5.1
3	13.65	0.298	7.7+j22	4.7+j17
2	12.64	0.256	9.0+j25	5.5+j20
2	13.05	0.272	8.4+j24	5.2+j19
		Total:	**74+j209**	**45+j164**

It is possible to deduce an analytical formula that can be used in numerical codes for beam-instability calculations. This is obtained by taking the open termination measurement and numerically scaling to the resistive terminations, in satisfactory agreement with the measured values. The model for one unit and 25 Ω termination, like the measured kicker, is based on a circuit with an inductor L_s in series with a RLC resonator, where Q=0.115 and f_0 = 35.27 MHz. Then, the transverse coupling impedance is given by

$$Z_y^{25\Omega} = \frac{c}{\omega h^2}\left\{\left[1/R + 1/(j\omega L) + j\omega C\right]^{-1} + j\omega L_s\right\} \tag{3}$$

where R =23.89 Ω , L =0.936 μH , C_{op} =0.217 pF and L_s =0.798 μH. Finally, Figure 12 shows, on the left side, the fitting curve for one unit compared with the measured impedance. It is worth noting that the capacitance of the feed-through, already discussed in the previous sections, has not a noticeable effect when the kicker is terminated with the 25 Ω termination.

Following the same arguments of the previous paragraphs, the fitting curve for the total of 14 kickers can be obtained by considering 32.2 times the one represented by the formula (3) and it is shown in Figure 12 on the right side.

It is worth noting that, in principle, the changes of the aperture dimensions should influence the resonator parameters too, presumably giving an increase of the resonant frequencies. However, the expression quoted before represents an upper bound of that result and should be considered safer for instability calculations.

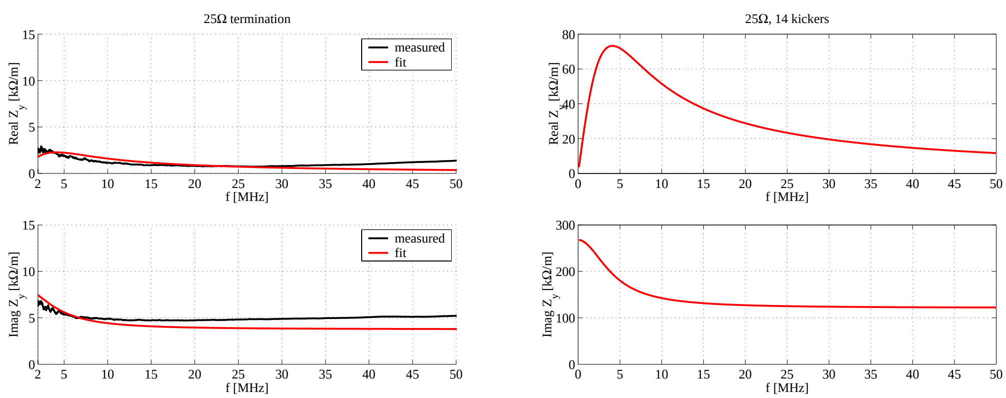

Fig. 12. The fitting curve compared with the measured vertical transverse impedance (left). The total impedance (factor 32.2) for 25 Ω termination (right).

VI. Summary

The transverse coupling impedance of the SNS extraction kicker has been measured. The effectiveness of the 50 Ω and 25 Ω terminations in damping resonances has been demonstrated. A scaling procedure to estimate the transverse coupling impedance of the 14 different kickers has been proposed, resulting in a total contribution to the impedance budget from all of them, given as 74+j209 kΩ/m for f<10 MHz and 45+j164 kΩ/m for f ~50 MHz. Finally, the results obtained so far indicate that, due to urgent production schedule and lack of engineering reliability testing, it is probably not advisable to use the ferrite loop as a method to reduce the impedance. Although, in the present realization, the ferrite loop has shown effectiveness above 32 MHz, it is of marginal advantage since this is not in the primary range of interests for the SNS beam stability.

Acknowledgements

The authors would like to thank Dr. J. Wei for comments on the manuscript, Drs. Y.Y. Lee and M. Blaskiewicz for stimulating discussions, and acknowledge C. Pai for the mechanical design of the kicker. The technical help provided by A. Esper, C. Trabocchi and J. Cupolo in setting-up the measurement is appreciated.

References

[1] S.Y. Zhang, SNS Storage Ring Impedances, BNL/SNS Technical Note n. 061, BNL, 1999.

[2] J.G. Wang and S.Y. Zhang, Measurements of Coupling Impedance for the SNS Accumulator Ring, BNL/SNS Technical Note No. 079, BNL, 2000.

[3] Y.Y. Lee in Accelerator Systems Advisory Committee Review, Agenda and Presentations, ORNL, September 11-13, 2000 .

[4] D. Davino and H. Hahn, Transverse impedance measurement of a simplified model of the SNS extraction kicker, BNL/SNS Technical Note No. 088, BNL, March 2001.

[5] H. Hahn and D. Davino, Measured transverse coupling impedance of RHIC injection and abort kicker, Proc. PAC2001, Chicago, IL, p. 1711.

[6] F. Caspers, in *Handbook of Accelerator Physics and Engineering*, ed. A.W. Chao and M. Tigner, (World Scientific, Singapore, 1998), p. 571.

[7] H. Hahn and D. Davino, Technical Report C-A/AP/ 45, BNL, March 2001.

[8] N. Tsoupas et al., Beam extraction from the SNS ring and design of the extraction kickers, Proc. EPAC 2000, Vienna, p. 2270 .