COUPLING IMPEDANCE MEASUREMENTS OF THE SNS RF CAVITY AND EXTRACTION KICKER MAGNET*

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Abstract

The Spallation Neutron Source (SNS) is a high intensity machine with peak currents in the accumulator ring reaching ~50 A at the 1.4 MW design level. This unprecedented beam intensity necessitates a careful investigation of coupling impedances posing as potential performance limitations. Impedance estimates of accelerator components pointed to the RF cavities and extraction kickers as the major contributors to the impedance budget and extensive measurements were performed on their prototypes. Impedance measurements were performed using the standard wire method.

INTRODUCTION

The Spallation Neutron Source consists of a linear accelerator, accumulator ring, and a mercury target [1]. A 1 GeV H^- beam is charge-exchange injected into the ring, where it is maintained as one bunch by the rf system, and extracted by a fast kicker magnet. The SNS RF system is based on three cavities operating at the fundamental frequency, ~1 MHz and one cavity at the second harmonic. The single turn beam extraction is achieved by means of fourteen kicker magnets.

At extraction time, there are 1.5×10^{14} protons corresponding to a ~50 A peak current. Maintaining stability of the high intensity beam until extraction is essential to minimize beam losses. Impedance driven instabilities are a potential source of beam loss and preventing them by establishing and enforcing the impedance budget represents a crucial design challenge. Impedance estimates from some sources such as space charge, beam position monitors, resistivity of the beam pipe, ceramic pipe coatings, bellows, steps, ports and vacuum valves can be calculated from handbook formulas with sufficient confidence. Other components, in particular the RF cavities and the extraction kicker magnets requires verification by measurement [2]. The estimates indicated that the performance of the SNS will largely depend on reducing the longitudinal impedance of the rf cavities and the transverse impedance of the extraction kickers [3,4]. Instability thresholds for longitudinal and transverse instabilities are established by the total impedance but the growth rate is determined by the resistive part and needs special care. In view of their importance, cavities and kickers were extensively measured. In this paper, the impedance measurement techniques using the single wire for the longitudinal impedance and the twin-wire for the transverse impedance are discussed and the experimental results are presented. The results from the RF cavity and extraction kicker prototypes generate the confidence that the design performance is achievable.

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RF CAVITIES

The SNS RF system consists of four cavities, three of them are operating on the fundamental and one on the second harmonic, with the rotation frequency being 1.058 MHz [5]. The reentrant cavity has two RF gaps and is driven by the power amplifier in parallel by means of side bus-bars. The inductance is provided by coaxial stacks of Philips 4M2 ferrite rings. The total length of the unit is about 2.7 m and the gaps are spaced ~1.3 m apart. The cavity is placed into a covering box, from which it is DC isolated by ceramic rings at each end. The preliminary coupling impedance measurements of the cavity showed a series of strong longitudinal resonances which were caused by the ceramic rings [6]. Shorting the ceramic rings, to simulate the operational capacitors, suppressed most of the resonances with the remaining analyzed in this paper.

The construction of the cavities is identical, and the operating frequency is adjusted by adding four gap capacitors of 750 pF for the fundamental or by adding only one 750 pF capacitor for the first harmonic. A view of the cavity end showing the placement of the capacitors is given in Fig.1. It was found that the radially concentrated capacitor arrangement resulted in a dipole mode responsible for a sharp horizontal transverse impedance resonance. Placing four 40 Ω carborundum rods (glow-bars) on top and bottom of each gap damped the resonances by a factor of two. The resonance appears only in the cavity with the fundamental capacitors. It is worth noting that the impedance contribution is only horizontal and not additive to the extraction kicker vertical impedance.

Longitudinal Impedance Measurement

The longitudinal coupling impedance of a component is conveniently measured on the bench by inserting a wire in the center of the beam pipe to form a coaxial transmission line. The forward scattering coefficient S_{21} is measured both for the device under test and a reference tube of the same length. The coupling impedance is then obtained from the ratio $S_{21}^{DUT}/S_{21}^{REF} = S_N e^{j\Phi}$ [7].

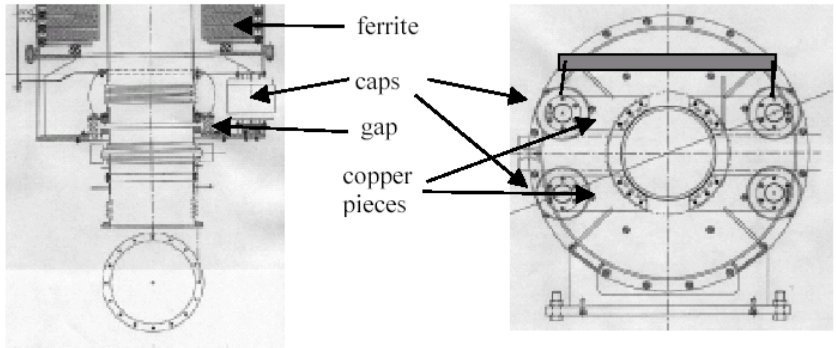

Fig. 1. Cavity end seen from the top (left) and from the end (right). Also shown is the carborundum rod.

In the typical situation, the characteristic impedance, R_C, of the line is different from the standard impedance of the network analyzer, R_0. Consequently a matching network, such as an impedance transformer, must be inserted. Often, for simplicity's sake, a resistive matching is applied. On the input side, forward and backward matching is achieved with a series and parallel resistor,

$$R_P = G_P^{-1} = R_C \frac{\eta}{\sqrt{1-\eta}}, R_{IN} = R_C \left(\frac{\eta}{1-\sqrt{1-\eta}} - 1 \right) \quad (1)$$

with $\eta = R_0 / R_C$. Furthermore, on the output side, forward matching is achieved with a series resistor $R_{OUT} = R_C \left(1-\eta\right)$. As example for the present measurement, the characteristic impedance of the 1.25 mm ∅ wire in the ~15 cm beam tube is

$$R_C = \frac{Z_0}{2\pi} \ln \frac{r_o}{r_i} \approx 288\ \Omega \quad (2)$$

(vs. 265 Ω measured) requiring the matching resistors, $R_P \approx 55\ \Omega$, $R_{IN} \approx 262\ \Omega$, and $R_{OUT} \approx 238\ \Omega$.

Depending on the configuration of the DUT, the scattering coefficient is interpreted according to the log or HP formula. The log formula is only applicable to distributed impedances, small compared to R_C, thus precluding strong resonances. Here, the impedance is seen by the beam at the two cavity gaps. At sufficiently low frequencies, the two cavity gaps act as lumped impedances and the scattering coefficient is interpreted via the modified HP formula,

$$Z_{\parallel} = 2R_C \left\{ \left(\frac{\cos\Phi}{S_N} - 1 \right) - j\frac{\sin\Phi}{S_N} \right\} \quad (3)$$

The measurements were performed with the network analyzer, Agilent 8753ES. The ratio can be stored in the instrument as data/memory, and by using the conversion from scattering to impedance format, the real and imaginary part of the coupling impedance is directly obtained. The longitudinal coupling impedance of the RF cavity is shown in Fig. 2. with the ceramic rings shorted [8]. The remaining small resonances can be parameterized by fitting the measured results to

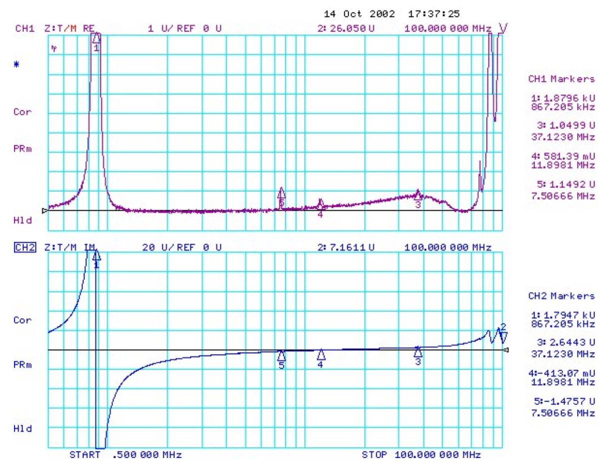

Fig. 2. Longitudinal impedance of RF cavity

$$Z_{\parallel} = \sum_i \frac{R_i}{1 + jQ\left(f/f_0 - f_0/f\right)} \quad (4)$$

with the parameters given in Table I.

Table I. Spurious Cavity Resonances

f (MHz)	*R* (Ω)	*Q*	*Z/n*
7.49	4.5	88	0.6
11.4	2.17	59	0.2
35	3.8	1	0.1
87	74	20	0.9
100	98	19	1

Transverse RF Cavity Impedance

The transverse coupling impedance of the RF cavity is measured by means of a homemade twin-wire (TW) line, driven by commercial wide-band transformers (North Hills NH15880) with a center-tapped secondary serving as 180° hybrid. The TW line has a spacing of $\Delta = 41$ mm and a characteristic impedance of $R_C = 215$ Ω as measured with the communication signal analyzer, Tektronix CSA 803.

The transverse cavity modes are excited at the gaps and represent lumped impedances. Since they are mall compared to R_C, the scattering coefficients can be interpreted with the log formula,

$$Z_{\perp} = \frac{cZ^{DUT}}{\omega\Delta^2} = -2\frac{cR_C}{\omega\Delta^2} \ln S_N \quad (5)$$

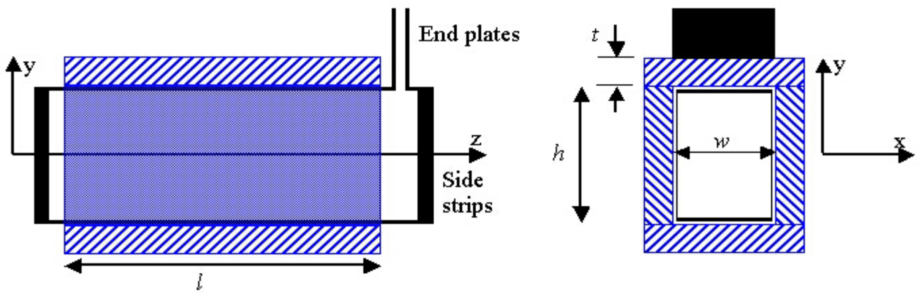

Fig.4. Schematic View of SNS Extraction Kicker Magnet, h = 248 mm, w = 159 mm, l = 360 mm.

No impedance is generated in vertical direction which thus allows an in-situ reference measurement [6]. The horizontal impedance with the gaps set for the first harmonic is shown in Fig. 3. The glow-bars (red curve) give a factor ~2 damping.

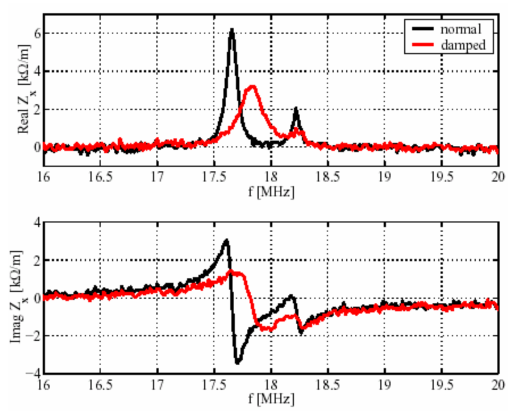

Fig. 3. Transverse impedance of the RF cavity

EXTRACTION KICKER MAGNET

A schematic view of the extraction kicker is shown in Fig.4. Since the 14 kickers make the biggest contribution to the transverse impedance budget, a prototype was constructed and extensively measured [9]. The longitudinal impedance is minimized by placing copper (so-called eddy current) stripes at the middle plane of the side ferrite bricks, thereby keeping the real $Z/n \leq 1\Omega$.

The transverse impedance is measured via the standard twin-wire method as described above. At low frequencies, from ~50 MHz down to below 1 MHz, the signals are small and the data is noisy, even after averaging and smoothing. Clean results were obtained by directly measuring the Z^{DUT} at the bus-bar gap and interpreting it by taking $\Delta = h$ in the conversion from longitudinal to transverse impedance [10].

The vertical transverse impedance is composed of a intrinsic value, obtained with the gap shorted, and the coupled value determined by the external termination. The kicker prototype was measured with feed-thru and the 25 Ω termination simulating the operational condition. The real part of the kicker impedance, obtained with the wire (W) and direct (D) method, is shown on top and with expanded frequency scale at the bottom of Fig. 5.

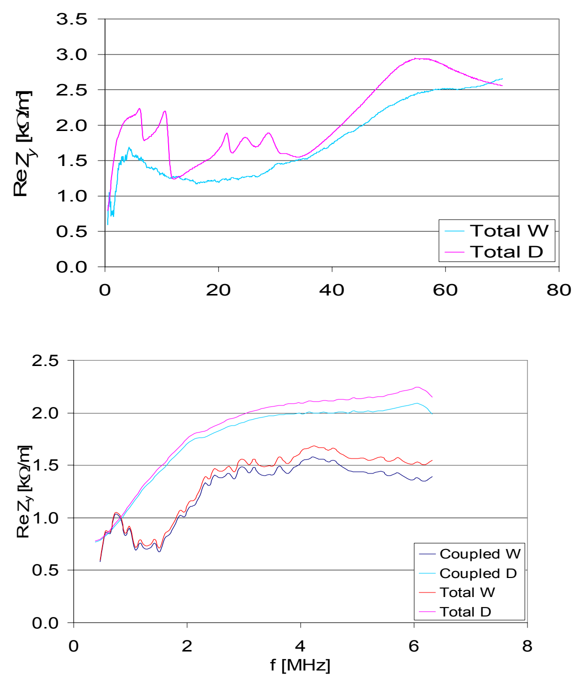

Fig. 5. Vertical impedance of kicker with 25 Ω

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