BEAM COUPLING IMPEDANCE STUDIES OF THE CSNS RING

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Abstract

The China Spallation Neutron Source (CSNS) is a high intensity proton accelerator with an injection energy of 80 MeV. The knowledge of the impedance in the vacuum chamber is necessary for optimizing the beam performance. In this paper, the longitudinal and transverse coupling impedances of the CSNS Rapid Cycling Synchrotron (RCS) are estimated.

INTRODUCTION

The CSNS is comprised of an 80 MeV Linac and a 1.6 GeV RCS ring [1]. Two bunches of 1.88×10^{13} protons are accelerated in the ring with a repetition frequency of 25 Hz. Many elements installed in the ring will cause beam instability via coupling impedance. Impedance from sources, such as space charge, vacuum wall and vacuum components, is calculated with analytical formulae. Impedance of other devices such as kicker magnets and RF cavities are difficult to calculate and should be measured. The results have been derived according to their preliminary design, rather than the impedance threshold given by the beam instability criterion. For further study, we will calculate the beam current threshold based on the impedance budget obtained, and then re-evaluate the impedance according to the stability criterion. This iteration will compromise the requirements of mechanical design for each vacuum component under an acceptable beam instability effect.

The main parameters of the CSNS/RCS are shown in Table 1.

Table 1: CSNS/RCS ring parameters

Circumference	m	230.8
Inj./Ext. energy	GeV	0.08/1.6
Repetition rate	Hz	25
Beam power	kW	120
Average Current	mA	63
RF harmonics		2
Trans. acceptance	πμm·rad	540

COUPLING IMPEDANCE

Transverse and longitudinal coupling impedance are calculated analytically for both injection and extraction energies.

Space Charge

The transverse space charge impedance for a round beam of radius a in a round pipe of radius b is given by

$$Z_{\perp} = -j\frac{Z_0 R}{\beta^2\gamma^2}\left(\frac{1}{a^2}-\frac{1}{b^2}\right), \quad (1)$$

where Z_0 = 377 Ω, $\beta = v/c$, γ is the Lorentz factor, and $2\pi R$ is the accelerator circumference. The longitudinal space charge impedance under the same condition is

$$\frac{Z_{//}}{n} = -j\frac{Z_0}{2\beta\gamma^2}\left[1+2\ln\frac{b}{a}\right], \quad (2)$$

where $n = \omega/\omega_0$ and ω_0 is the revolution frequency.

Chambers in the dipole magnets will be designed to have racetrack cross-sections. They are taken as rectangular chambers in calculation for simplicity. The space charge impedance for a rectangular beam pipe is given as [2]

$$Z_{H,V}(\omega) = -j\frac{Z_0 R}{\beta^2\gamma^2}\left[\frac{1}{a^2}-\frac{8}{h^2}\left(\xi_1^{H,V}-\varepsilon_1^{H,V}\right)\right],$$
$$\frac{Z_{//}(\omega)}{n} = -j\frac{Z_0}{2\beta\gamma^2}\left[1+2\ln\left(\frac{2h}{\pi a}\tanh\left(\frac{\pi w}{2h}\right)\right)\right], \quad (3)$$

where w and h stand for width and height of the chamber, and $\xi_1^{H,V}$ and $\varepsilon_1^{H,V}$ are electric image coefficients. For the CSNS/RCS ring, the space charge impedance are $Z_{//}/n = -j$ 792 Ω, $Z_{\perp x} = -j$ 17.5 MΩ/m and $Z_{\perp y} = -j$ 9.5 MΩ/m at 80 MeV, and $Z_{//}/n = -j$ 102.8 Ω, $Z_{\perp x} = -j$ 4.7 MΩ/m and $Z_{\perp y} = -j$ 4.5 MΩ/m at 1.6 GeV. It plays a dominant role in the whole impedance.

Resistive Wall

The RF shielded ceramic chambers will be chosen in the dipoles and quadrupoles due to the rapid field variation, and stainless steel (or titanium) chambers could be at the field free regions.

We choose ~ 0.5 mm in thickness and 5 mm in width copper stripes as the RF shield. The selection of the thickness of the copper stripes compromises the shielding efficiency and the ohmic loss due to eddy current.

A quick disconnect Ti flange will be welded to a sleeve attached to the ceramic segment by metal and brazing. Beam chambers in the straight sections, the vacuum chambers for steering magnets, DC bumpers, and extraction septum, are stainless steel pipes. They present an important portion for the resistive wall impedance due to its low conductivity [3].

For a round beam pipe, whose skin depth is small compared to the thickness of the vacuum chamber, the resistive wall impedance is [4]

$$Z_{//}(\omega) = (1+j\,\mathrm{sgn}(\omega))\frac{l}{2\pi b\sigma\delta},$$
$$Z_{\perp}(\omega) \approx 2cZ_{//}(\omega)/(\omega b^2), \quad (4)$$

where we have introduced the skin depth at ω

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$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}} \ , \quad (5)$$

and σ is the conductivity. The resistive wall impedance is usually the dominant contribution of the transverse impedance at low frequencies.

The resistive wall impedance of the rectangular chamber with a width w and a height h can be represented by [2]

$$Z_{//}(\omega) = (1+j)\left(\frac{l}{\pi h \sigma \delta}\right) F\left(0, \frac{w}{h}\right), \text{ and}$$

$$Z_{V,H}(\omega) = (1+j)\frac{cl}{\pi \sigma \omega \delta}\left(\frac{2}{h}\right)^3 F_{V,H}\left(0, \frac{w}{h}\right), \quad (6)$$

where the first parts are the resistive wall impedance of a circular beam pipe of a radius $h/2$ with the beam at the centre. F (0, w/h) and $F_{V,H}$ (0, w/h) are form factors determined by the width to height ratio w/h. For the CSNS case $w/h \sim 1.57$, then we have $F \sim 0.35$, $F_H \sim 0.4$, and $F_V \sim 0.825$.

The resistive wall impedance of the CSNS/RCS is $Z_{//}/n = 1.2(1+j)/n^{1/2}$ Ω, $Z_{\perp x} = 25.6(1+j)/n^{1/2}$ kΩ/m and $Z_{\perp y} = 26.5(1+j)/n^{1/2}$ kΩ/m at 80 MeV, while $Z_{//}/n = 1.8(1+j)/n^{1/2}$ Ω, $Z_{\perp x} = 16.6(1+j)/n^{1/2}$ kΩ/m and $Z_{\perp y} = 17.2(1+j)/n^{1/2}$ kΩ/m at 1.6 GeV.

The inner surface of the ceramic chamber will be coated with a 10 nm ~ 15 nm in thickness TiN to suppress secondary electron emission. This part of impedance is calculated by [5]

$$\mathrm{Im}\left(\frac{Z_{//}}{n}\right)_{Ceramic-TiN} = -Z_0 \frac{\varepsilon_r \beta^2 - 1}{\varepsilon_r \beta} \ln\frac{d}{b}\frac{l}{C},$$

$$\mathrm{Re}\left(\frac{Z_{//}}{n}\right)_{Ceramic-TiN} = 2Z_0 \left(\frac{\varepsilon_r \beta^2 - 1}{\varepsilon_r \beta} \ln\frac{d}{b}\right)^2 \frac{bt}{\delta_0^2} n \frac{l}{C},$$

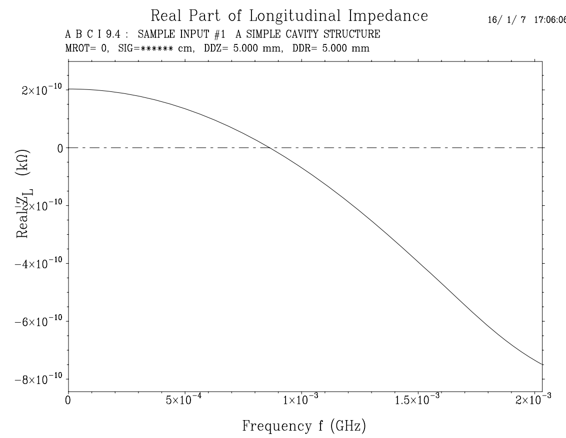
$$\text{and } \left(Z_\perp\right)_{Ceramic-TiN} = \frac{2R}{b^2 \beta}\left(\frac{Z_{//}}{n}\right)_{Ceramic-TiN}, \quad (7)$$

where ε_r is the relative dielectric constant ~ 10, δ_0 the skin depth of TiN at the revolutionary frequency. The results for the CSNS/RCS are $Z_{//}/n = j2.3+0.001n$ Ω and $Z_\perp = j44.9+0.2n$ kΩ/m at 80 MeV, $Z_{//}/n = j14.4+0.1n$ Ω and $Z_\perp = j\ 117.6+0.8\ n$ kΩ/m at 1.6 GeV, respectively.

RF gap

The CSNS RF system of the ring consists of eight stations and each station has two RF gaps. The impedance is divided into two parts: one from the inner copper duct which has the property of resistive wall, and the other from the cavity gap itself.

The cavity gap can be treated as a small cavity. It is only a few centimetres long so the transverse impedance could be negligible. The longitudinal impedance is calculated with the code ABCI [6]. The calculation results are shown in Fig.1. The real part is negligible compared to the imaginary part. The impedance is mostly inductive with a value of $Z_{//}/n = j\ 8.35\times10^{-3}$ Ω at 80 MeV and $Z_{//}/n = j\ 0.02$ Ω at 1.6 GeV.



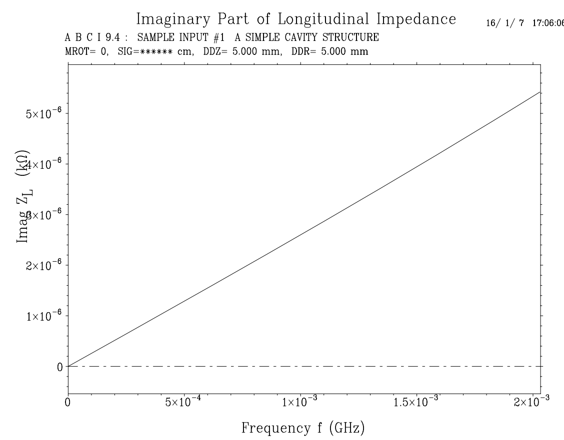


Figure1: Real and imaginary parts of the longitudinal impedance of the RF gap

Extraction Kicker Magnet

The CSNS adopts Lambertson magnets to extract the beam from the RCS ring. Five kicker magnets will be installed in the extraction straight section. The kickers will be designed as window frame magnets.

The transverse impedance of these kickers is modeled as a cylindrical ferrite shell inside a perfectly conducting pipe, yielding the transverse impedance as [7]

$$Z_\perp = \frac{c\omega\mu_0^2 l^2}{4a^2 Z_k}, \quad (8)$$

where l is the magnet length, $2a$ the inner height, and $Z_k = j\omega L + Z_g$ with L the magnet inductance, and Z_g the termination impedance.

The magnet inductance of window frame magnet unit is calculated with $L = \mu_0 bl/a$. And the winding termination of each unit is 25 Ω. The transverse impedance of the total five kickers is shown in Fig. 2. The real part of the impedance is peaked at a frequency of 24MHz with a peak value of $Z_\perp$ = 24 kΩ/m.

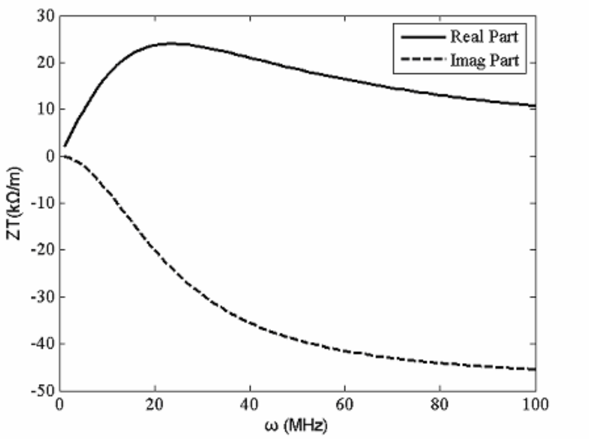


Figure 2: Transverse impedance of the extraction kickers.

The longitudinal impedance can be expressed as

$$\frac{Z_{//}}{n} = j\omega_0 L \,, \tag{9}$$

where L is the inductance of the ferrite ring. We will put copper sheets of a thickness δ_{Copper}= 1 mm in the ferrite core to reduce the massive ferrite loss, so the corresponding leakage inductance is estimated as [8],

$$L = 2\frac{\mu_0 l}{2\pi}\ln\frac{\pi a}{2\delta_{Copper}} \cdot \tag{10}$$

The longitudinal impedance is $Z_{//}/n= j16.5$ Ω at the energy of 80MeV and $Z_{//}/n=j39$Ω at the energy of 1.6 GeV.

Pipe Transitions

The detailed structure of pipe transition between chambers has not been decided yet. Steps are used in this budget, which yield greater impedance than smooth transitions. The difference between a step-up and a step-down is negligible. The impedance of a step with transition height h is given as

$$\frac{Z_{//}}{n} = j\omega_0 \frac{Z_0 h^2}{4\pi^2 bc}\left(2\ln\frac{2\pi b}{h}+1\right),$$

$$Z_\perp = \frac{2R}{b^2\beta}\frac{Z_{//}}{n} \cdot \tag{11}$$

The total longitudinal impedance is $Z_{//}/n = j$ 0.27 Ω at 80 MeV and $Z_{//}/n=j0.64$Ω at 1.6 GeV, while the transverse impedance is $Z_\perp = j$ 55 kΩ/m.

Collimators

There will be one primary and three secondary transverse collimators, and two longitudinal collimators in the RCS ring. A simplified model of collimator is considered, which consists of a resistive wall with a smaller radius and the steps as well.

The impedance of the collimator steps is $Z_{//}/n = j$ 0.1 Ω and $Z_\perp = j$ 16 kΩ/m at 80 MeV, $Z_{//}/n = j$ 0.47 Ω and $Z_\perp = j$ 16 kΩ/m at 1.6 GeV, respectively.

The impedances for injection and extraction energies at frequency below 10MHz are summarized in Table 2 and 3.

Table 2: Coupling Impedance at 80 GeV

	$Z_{//}/n$ (Ω)	$Z_\perp$(kΩ/m)
Space charge	$-j$ 792	$-j$ 17500 (H)
		$-j$ 9539 (V)
Resistive wall	$1.2(1+j)/n^{1/2}$	$25.6(1+j)/n^{1/2}$ (H)
		$26.5(1+j)/n^{1/2}$ (V)
ceramic+TiN	$j2.3+0.001n$	$j44.9+0.2n$
RF gaps	j 0.13	
Ext. kickers	j 16.5	$j7.3+17.2$
Pipe transitions	j 0.27	j 55
Collimators	j 0.1	j 16

Table 3: Coupling Impedance at 1.6 GeV

	$Z_{//}/n$ (Ω)	$Z_\perp$(kΩ/m)
Space charge	$-j$ 102.8	$-j$ 4713 (H)
		$-j$ 4489 (V)
Resistive wall	$1.8(1+j)/n^{1/2}$	$16.6(1+j)/n^{1/2}$ (H)
		$17.2(1+j)/n^{1/2}$ (V)
ceramic+TiN	$j14.4+0.1n$	$j117.6+0.8n$
RF gaps	j 0.32	
Ext. kickers	j 39	$j7.3+17.2$
Pipe transitions	j 0.64	j 55
Collimators	j 0.47	j 16

SUMMARY

The coupling impedances of the components of the RCS ring are obtained according to their preliminary design. Structures of some elements such as bellows, ports, BPMs, valves, etc. are not yet decided, and further evaluation is needed.

The impedance measurement is needed to confirm calculation and stability needs further consideration.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. Y. H. Chin from KEK and J. Wei, J. Y. Tang, S. Wang, D. M. Zhou, W. Kang from IHEP for their valuable discussion and support.

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