IMPEDANCE GENERATED BY A CERAMIC CHAMBER WITH RF SHIELDS AND TIN COATING

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Abstract

We investigate possible impedance sources generated by a ceramic chamber with cupper RF shields and TiN coating used in the RCS ring of the J-PARC machine. Specially, the impedance due to thin (in the order of nm) TiN coating placed on the inner surface of the ceramic chamber cannot be estimated using the usual formula for the resistive-wall impedance and needs new treatment. The new formula is verified in good agreements with the measurement results. Finally, we summarize the longitudinal impedance budget of J-PARC RCS chambers.

CERAMIC CHAMBER WITH RF SHIELDS AT RCS

The J-PARC complex [1] is currently under construction in Tokai JAEA. This machine complex comprises a 181-MeV linac, 3-GeV rapid-cycling synchrotron (RCS) and 50-GeV synchrotron (MR). The RCS provided a beam power of 1 MW to the pulsed spallation neutron experimental area with a repletion rate of 25Hz. All chambers in electromagnets in the RCS ring are ceramic chambers to avoid the Eddy current. The photo of a sample chamber is shown in Fig. 1:

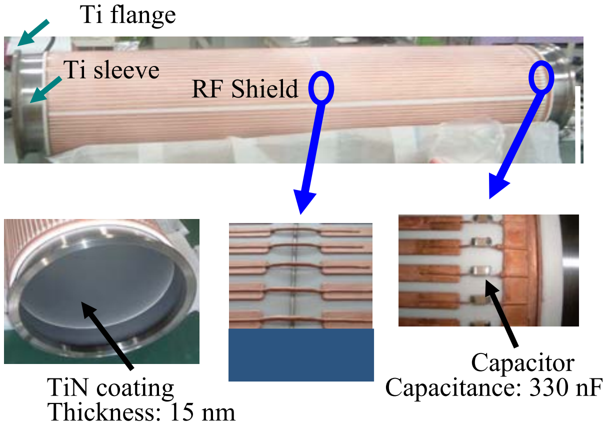

Figure 1: A ceramic chamber with RF shields.

The inner surface of the ceramic chamber is coated with TiN to preclude charge build-up. Cupper strips with capacitors (330nF each) surround the exterior of the ceramic chamber to provide a low-impedance path for the image current at high frequency but to preclude the passage of the image current at low frequency (25Hz). The cross-sectional view of the ceramic chamber is illustrated in Fig. 2.

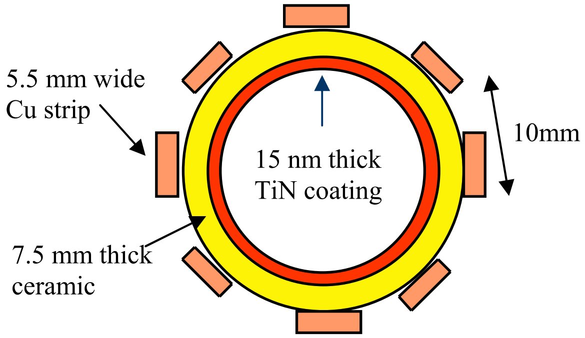

Figure 2: Illustration of the cross-sectional view of the ceramic chamber.

If the TiN coating is much thicker than the skin depth δ, the electro-magnetic fields created by a beam can be completely shielded by TiN coating and no fields will be leaked out to outside. The longitudinal impedance is then given by

$$\mathrm{Re}(Z_L) = \frac{\rho L}{2\pi a \cdot \delta} \quad , \qquad (1)$$
$$\propto \sqrt{\omega}$$

where ρ and L is the bulk resistively and length of the TiN coating, and a is the radius of the ceramic chamber. When the TiN coating is much thinner than the skin depth, however, nearly no electro-magnetic fields will be shielded by the TiN coating. In this case, a question arises on how much the impedance the TiN coating will create. If we simply replace the skin depth δ (typically in the order of micro-meter) by the thickness of the TiN coating, t (typically in the order of nano-meter) in formal (1), we will get enormous impedance, which contradicts with our instinct that the impedance should be reduced, rather than increased when the coating gets thinner. It is clear that we need a more sophisticated theory for this case.

IMPEDANCE OF TIN COATING + CERAMIC SYSTEM

Impedance formula

Not much theoretical work has been done on the impedance generated by this configuration. The oldest work may be one done by Zotter [2] in 1970. Recently, Tsutsui has developed a new theory using the filed matching method for relativistic particles. Later it was expanded by Lee for non-relativistic particles [3]. In all of them, the electro-magnetic fields are assumed to be completely shielded by either metal or cupper strips placed outside of the ceramic chamber. Both Zotter's and Tsutsui's theories agree for the case where the ceramic is replaced by air. The longitudinal impedance is given by the following formula:

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

$$\mathrm{Re}\left(\frac{Z_{//}}{n}\right)_{Ceramic-TiN} = 2Z_0 \left(\frac{\varepsilon_r \beta^2 - 1}{\varepsilon_r \beta} \ln\frac{d}{b}\right)^2 \frac{bt}{\delta_0^2} n \cdot \Delta_f \ , \tag{3}$$

where Z_0 is the impedance of the vacuum (=377Ω), ε_r is the relative dielectric constant (~10), β=is the velocity of particles divided by the speed of light, d is the outer radius of the ceramic chamber (=0.1275m), b is the inner radius of the TiN coating (=0.12m), a is the radius of the beam (=0.03m), t is the thickness of the TiN coating (=15nm), and Δ_f=is the occupancy ratio of the ceramic chamber over the ring (~0.5). Here,

$$\delta_0 = \sqrt{\frac{2}{\mu_0 \sigma_{TiN} \omega_0}} \tag{4}$$

is the skin depth of TiN coating at the revolution frequency, and σ_{TiN}=is the bulk resistivity of TiN (=5.88x 106/Ωm). The transverse impedance is given by

$$(Z_T)_{Ceramic-TiN} = \frac{2R}{b^2 \beta}\left(\frac{Z_{//}}{n}\right)_{Ceramic-TiN} \ . \tag{5}$$

The imaginary parts of $Z_{//}$ and Z_T are the correction terms for the space charge impedances due to the ceramic chamber. They are inductive because the electric fields are suppressed by a factor of ε_r inside the ceramic.

Heating on TiN Coating

The loss factor for a Gaussian bunch is given by

$$k_{//} = 2Z_0 \left(\frac{\varepsilon_r \beta^2 - 1}{\varepsilon_r \beta} \cdot \ln\frac{d}{b}\right)^2 \frac{tb}{\delta_0^2} \Delta_f \frac{c\beta R}{\sigma_z^2} \tag{6}$$

where σ_z is the rms bunch length (=$\tau_z/5^{1/2}$), and c is the speed of light. The power loss can be calculated using

$$P_{Loss} = 1.6\times 10^{-19} \cdot N_b \cdot I_c \cdot k_{//} \ , \tag{7}$$

where N_b is the number of protons per bunch and I_c is the average circulating current. The power loss is largest at the extraction energy of 3GeV, and numerically, it is about 0.45W/m only.

Comparison with Measurements

Toyama group has made measurements of the longitudinal impedance of the 1m-long ceramic chamber with Cu shields and TiN coating. They are shown in Fig. 3. At a typical frequency, say, 400MHz, they are

- Re $Z_{//}$~ 10 Ωat 400MHz,
- Im $Z_{//}$~ 24 Ωat 400MHz.

The theoretical impedances depend on the velocity of particles, β. For β (0.545, 0.713, and 0.971, respectively) at injection (181-MeV, 400-MeV) and extraction energy (3GeV), they become numerically

- Re $Z_{//}$~ 12 Ωat 400MHz for β=0.545,
- Re $Z_{//}$~ 20 Ωat 400MHz for β=0.713,
- Re $Z_{//}$~ 38Ω at 400MHz for β=0.971,
- Im $Z_{//}$~ 16Ω at 400MHz for β=0.545,
- Im $Z_{//}$~ 20Ω at 400MHz for β=0.713,
- Im $Z_{//}$~ 22 Ω at 400MHz for β=0.971.

Agreements are relatively good.

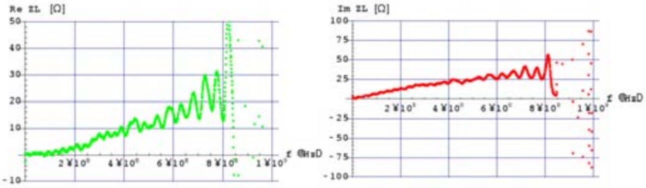

Figure 3: Measured longitudinal impedance of 1m-long ceramic chamber with Cu shields and TiN coating. Real part (left) and imaginary part (right).

OTHER IMPEDANCE SOURCES

Gaps between Cu Shields

Impedance will be also generated by gaps=slots between the Cu shields (see Fig. 4). Due to the existence of the ceramic in inside, the electric contribution would be suppressed by a factor of $\varepsilon_r^2/2$. Thus only the magnetic contribution is taken into account. The longitudinal and transverse impedance generated by gaps between the Cu shields are given by the following formulae:

$$\left(\frac{Z_{//}}{n}\right)_{Cu-Slot} = -iZ_0 \frac{\beta}{R} \frac{1}{4\pi^2 d^2} \cdot \frac{\pi}{16} w^2 L \cdot N_{slot} \cdot N_{ceramic} \ , \tag{8}$$

$$(Z_T)_{Cu-Slot} \cong -iZ_0 \frac{1}{\pi^2 d^4} \cdot \frac{\pi}{16} w^2 L \frac{N_{slot}}{2} \cdot N_{ceramic} \ , \tag{9}$$

where N_{slot} is the number of slots per chamber, $N_{ceramic}$ is the number of ceramic chambers in RCS, and d is the outer radius of the ceramic chamber. Numerically, they are at RCS:

- At dipole magnets, d=0.1075m, L=3.54m, w=0.0055m, N_{slot}=68, $N_{ceramic}$=24,
- At quadrupole magnets, d=0.1575m, L=1.25m, w=0.0055m, N_{slot}=99, $N_{ceramic}$=70.

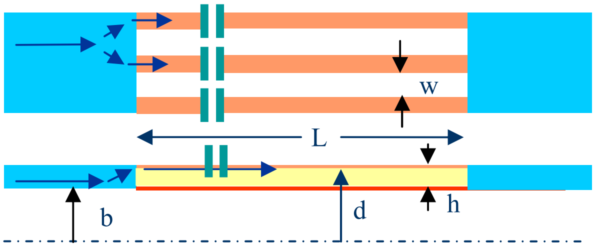

Figure 4: Gaps and steps in a ceramic chamber.

Steps between Ti Chamber and Cu Shields

Steps between Ti chamber and Cu shields will also generate impedance. For the same reason as before, only the magnetic contribution needs to be taken into account. The longitudinal and transverse impedance generated by steps between Ti chamber and Cu shields are given by the following formulae:

$$\left(\frac{Z_{//}}{n}\right)_{Ti-Cu} = -i\frac{Z_0}{R}\beta\frac{h}{2\pi}\cdot\Delta_f \ , \tag{10}$$

$$\left(Z_T\right)_{Ti-Cu} = -i\frac{Z_0}{\pi b^2}h\cdot\Delta_f \ , \tag{11}$$

where h is the thickness of the ceramic chamber.

Resistive-Wall Impedance

The cupper shields generate usual resistive-wall impedance given by the formulae for the longitudinal and transverse directions, respectively:

$$\left(\frac{Z_{//}}{n}\right)_{Cu-RW} = Z_0\beta\frac{1-i}{2}\frac{\delta}{d}\frac{\Delta_f}{\Delta_A} \ , \tag{12}$$

$$\left(Z_T\right)_{Cu-RW} = Z_0(\mathrm{sgn}(\omega)-i)\frac{\delta R}{d^3}\frac{\Delta_f}{\Delta_A} \ , \tag{13}$$

where Δ_A is the occupation ratio of the Cu shields over the exterior of the ceramic chamber, and is about 0.5. Here, δ is the skin depth of cupper and R is the average radius of the ring.

Space Charge

At last but not least, the ceramic chamber with RF shields creates the space-charge impedance. Since the space charge impedance due to ceramic is already included in the formulae (2) and (3), we only need to take into account the contribution from the space up to the interior of the ceramic chamber. Then, the formulae are given by

$$\left(\frac{Z_{//}}{n}\right)_{SC} = i\frac{Z_0}{2\beta\gamma^2}\left(1+2\ln\frac{b}{a}\right) \ , \tag{14}$$

$$\left(Z_T\right)_{SC} = i\frac{Z_0 R}{\beta^2\gamma^2}\left(\frac{1}{a^2}-\frac{1}{b^2}\right), \tag{15}$$

where γ is the Lorentz factor, b is the inner radius of the ceramic chamber and a is the radius of the beam.

RCS CHAMBER IMPEDANCE BUDGET

The longitudinal impedance budget of RCS chambers is summarized in Table 1. We can see that the ceramic chambers with Cu shields and TiN coating can produce some unusual impedances and phenomenon, but their effects are rather small.

REFERENCES

[1] Accelerator Technical Design Report for J-PARC, KEK-Report 2002-13, JAERI-Tech 2003-044, J-PARC -3-01, Accelerator Group JAERI/KEK Joint Project Group, 2003.

[2] B. Zotter, "Longitudinal Instabilities of Charged Particle Beams Inside Cylindrical Walls of Finite Thickness", Part. Accelerators, Vol.1, pp.311-326, 1970.

[3] H. Tsutsui and S. Lee, private communications, 2001-2003.

Table 1: The longitudinal impedance budget of RCS chambers

Longitudinal: $Z_{//}/n$ (Ω)

Kinetic energy (GeV)	0.181	0.4	3
Space charge	i916	i490	i42
Resistive-wall of Ti chamber	$0.23(1-i)/n^{1/2}$	$0.27(1-i)/n^{1/2}$	$0.31(1-i)/n^{1/2}$
Resistive-wall of Cu shields	$0.082(1-i)/n^{1/2}$	$0.094(1-i)/n^{1/2}$	$0.11(1-i)/n^{1/2}$
Capacitors	$i1.04/n^2$	$i0.8/n^2$	$i0.59/n^2$
Ceramic + TiN coating	-i4.2+0.0036n	-i6.6+0.012n	-i10+0.037n
Gaps between Cu shields	-i2.5	-i3.3	-i4.5
Steps between Ti and Cu shield	-i0.0022	-i0.0029	-i0.0039