Design Concept of Ceramic Chambers at the J-PARC RCS: An Analytical Perspective

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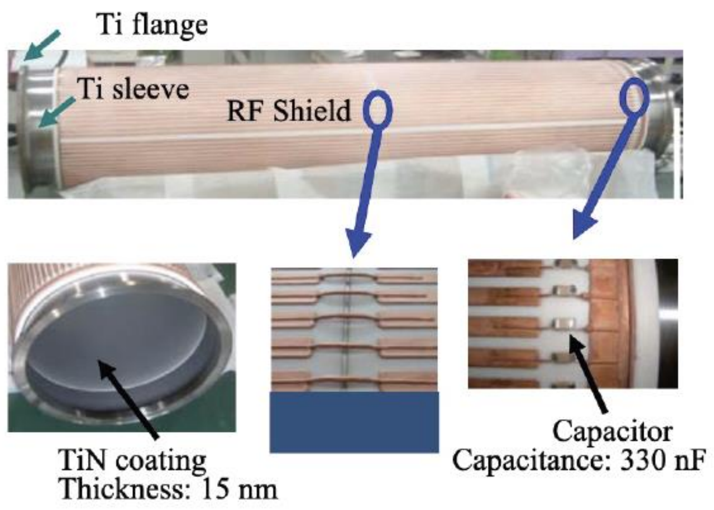
➢ *Abstract:*

Ceramic chambers are essential for rapidly accelerating high-intensity beams at the J-PARC RCS, as they mitigate the effects of eddy currents on the chambers. An analytical perspective could provide valuable insight into the design of ceramic chambers, though computer simulations and demanding measurements need to certify the estimates. The identity of bending magnets, including chambers, is a key to reducing beam losses at the injection area of the RCS.



(Kinsho *et al*, Vacuum. **73**, 187, 2004).

➢ Introduction

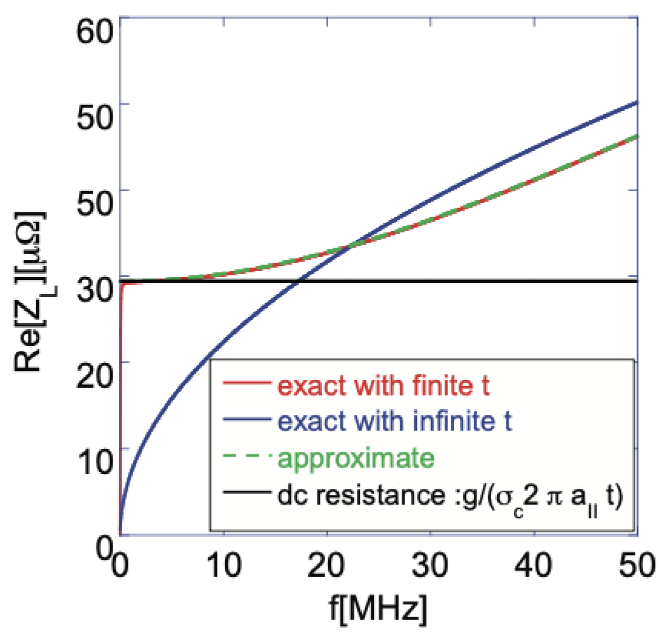
- ◆The 3-GeV RCS (rapid cycling synchrotron) at J-PARC is a proton accelerator to achieve a 1-MW beam by accelerating two bunches containing N_b=4.15 × 10^{13} particles per bunch (ppb) from 400 MeV to 3 GeV in 20 ms with a repetition rate of 25 Hz, without any transverse feedback system (Shobuda *et al*, PTEP **2017**, 013G01, (2017)).
- ◆The figure shows a developed ceramic chamber, placed in magnets at the RCS.
- ◆The outer surface of the ceramic, with radius a_{II}, is covered with N rectangular copper stripes (RF shields) of horizontal width h_x and radial thickness t, each terminated at one end by capacitors. The inner surface, with radius a_I, is coated with a titanium nitride (TiN) layer of thickness Δ.
- ◆The ceramic chambers with TiN coating are essential for rapidly accelerating high-intensity beams within 20 ms, as they mitigate the effects of eddy currents in the chamber and suppress secondary electron emission when the halo part of the proton beam collides with the chamber surface, avoiding the electron cloud instability (Ohmi *et al*, PRAB **5**, 114402, (2003)).
- ◆ An analytical analysis could provide valuable insights in designing the ceramic chambers, which may assist the development of ceramic chambers in the next generation, supported by the success of the J-PARC RCS.

➢ *Design concept in terms of beam impedances and chamber heating*

❖ *Determination of the thickness of RF shields*

- ❑Since the screening effect of the electromagnetic field is important for designing the RF shields, the thickness t of the RF shields is determined by considering the leakage field from the chamber.
- ❑ Consider a g long cylindrical metal chamber with conductivity σ_c, where the inner radius and the thickness are a_{II} and t, respectively.
- ❑It is essential to accelerate `non-relativistic' beams at the RCS. As a result, the general form of resistive-wall impedance, except for the space charge impedance, is simplified as

$$Z_L \simeq \frac{\nu_2 g}{2a_{II}\pi\sigma_c \tanh(\nu_2 t)},$$



- ❑ It becomes a dc-resistance when the skin depth is larger than t.
- ❑ The wall currents can shield the electromagnetic field from the non-relativistic beam with Lorentz-β=0.97 (3-GeV).

❖ *Determination of the thickness Δ of TiN coating*

- ❑ The secondary electron emission yield coefficient δ of the material on the inner surface of the chamber must be below 1.
- ❑ A significant reduction was observed for a TiN coating of 1-2 nm (Michizono *et al*, J. Vac. Sci. Technol. A **10**, 1180, 1992).
- ❑ TiN suppresses both the diffusion of adsorbed gases from the ceramic into the chamber and the adsorption of moisture on the chamber surface (Kato *et al*, Vac. **38**, 380, 1995).
- ❑ The impedance budget needs to be considered to determine Δ (Chin *et al*, HB'06, 125; Chin *et al*, HB'08, 40).
- ❑ By generalizing the model (T. Wang *et al*, PRAB 4, 104201, 2001), we can calculate the impedances of the ceramic chamber with TiN coating, approximated as a chamber multi-layered with TiN, ceramic, and the conductive pipes (Shobuda *et al*, PAC'05, 1898).

$$Z_L \simeq \frac{gZ_0}{2\pi\beta a_I\left[Z_0\Delta\sigma_{TiN} - \frac{j\epsilon'}{(\epsilon'\beta^2-1)ka_I\log[\frac{a_{II}}{a_I}]}\right]},$$

- ❑ Δ=15 nm satisfies the impedance budget (Chin *et al*, HB'06, 125) and suppresses the secondary electron emission.
- ❑ Thinner TiN is better only from an impedance point of view, because the wall currents flow predominantly on the RF shields as Δ approaches zero.

❖ *Determination of the area ratio covered by the stripes*

- ❑ The area ratio θ=N $h_x/2\pi a_{II}$ covered by N stripes is determined by referring to the space-charge impedance of a chamber composed of the stripes (T. Wang *et al*, PRAB 4, 104201, 2001) :

$$Z_L = \frac{j\omega R Z_0}{2c\beta^2\gamma^2}\left[2\log[\frac{a_{II}}{r_b}] + (1-\frac{2}{N}\log[\theta])\right]$$

- ❑ When the condition

$$\frac{2}{N}\log(\theta) \ll 1,$$

is satisfied, Z_L reproduces the space-charge impedance of a cylindrical chamber with inner radius a_{II}.

- ❑ We can set θ = 0.5 and N~100 as parameters, once the horizontal width h_x is determined by the heating condition due to eddy currents in the stripes.

❖ *Determination of the horizontal width*

- ❑ Thanks to the capacitors, the heating contribution of the ceramic chamber from the RLC circuit is negligible.
- ❑ The contribution from the inner part of the stripe is dominant.

$$i_z(\xi,\eta) = \frac{16c}{Z_0h_x^2}\int_{-\infty}^{t} dt'\frac{dB(t')}{dt'}e^{\frac{16c}{Z_0h_x^2\sigma_c}(t'-t)}\xi.$$

- ❑ For a 1m long stripe with h_x=5 mm and t=0.5 mm, the power consumption is ~0.5 W/stripe under 25 Hz operation.

❖ *Comparison to the measurements*

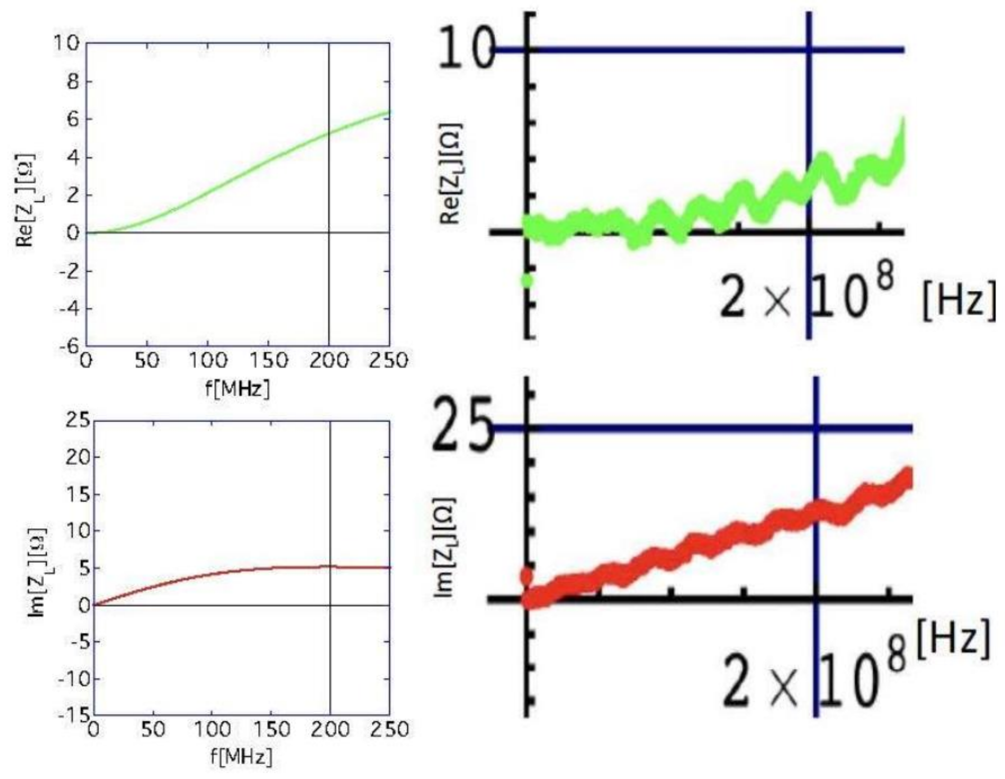


Figure 4: Longitudinal impedance (theory/measurement).

- ❑ The excellent agreement between the theoretical results and measurements up to at least 100 MHz, sufficient for the RCS.
- ❑ The heating due to the beam is ~0.5 W/chamber, acceptable.

❖ *Determination of the capacitance*

- ❑ Because the *capacitance is determined by the impedance becomes low for the circulating beam and high for the induced current with 25 Hz*, the capacitance is chosen as 330 nF.
- ❑ However, the RF shielded ceramic chamber functions as an LCR circuit in combination with both flanges at the ends (The strongest intrinsic frequency is around 250 kHz (Shobuda *et al*, PRAB **12**, 032401, 2009)).
- ❑ When the sinusoidal external magnetic field B_{ext} is applied, the field modulates as $\Delta B/B_{ext}$ < 2 × 10^{-7} , which is not so significant at the RCS.
- ❑ Measurements were performed with different tune-tracking patterns (red and blue) for a 1-MW beam (Black is the resonance line originating from 250 kHz).

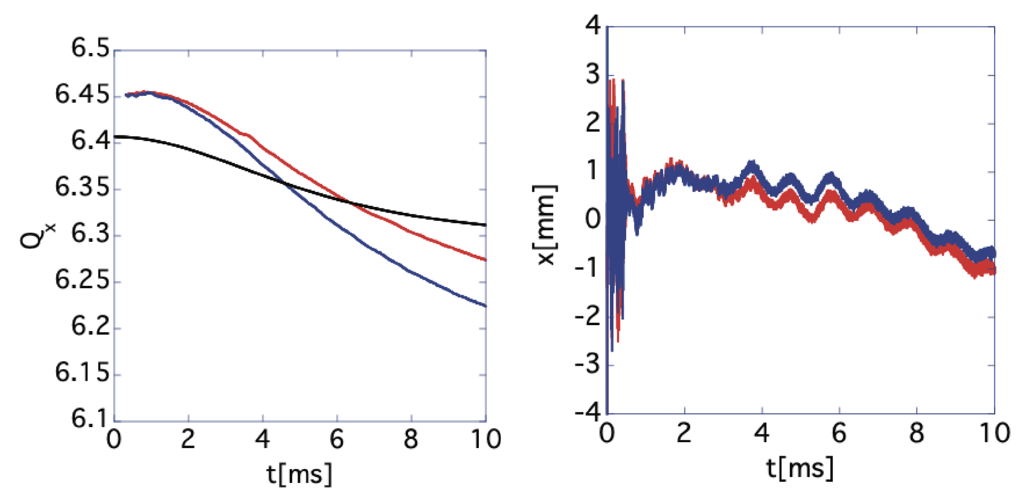
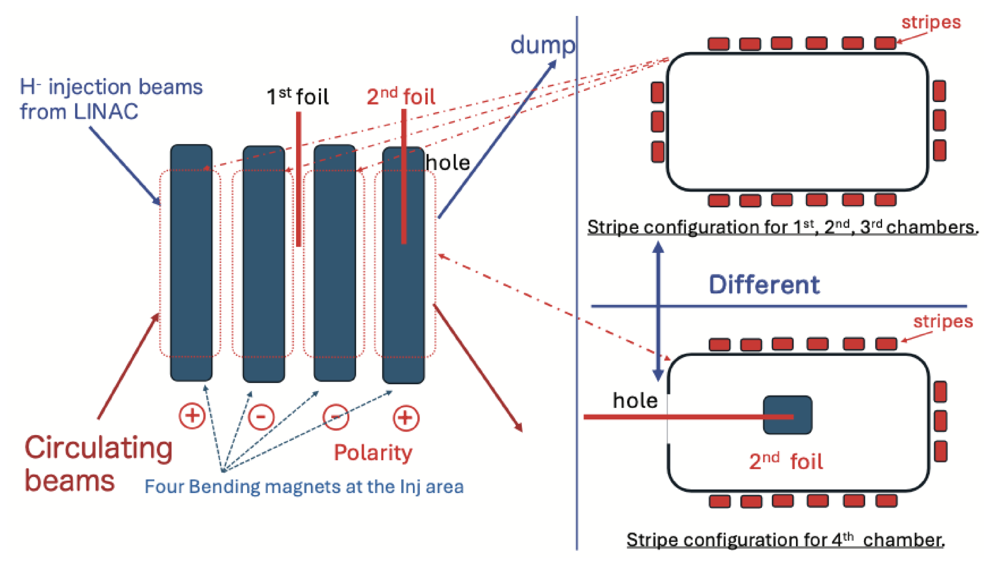


Figure 3: Tune tracking pattern and beam positions [4].

- ❑ Though the red and blue lines cross the resonance line at approximately 6 ms and 4.5 ms, respectively, no beam instability or beam loss is observed.

➢ *Mitigation of Resonance Losses Associated with the Injection Scheme*



- ❑ Four bending magnets, including the chambers, must be perfectly identical because a trapezoidal magnetic field is excited at the injection period, causing $\Delta B/B_{ext}$ > 0.018 for each chamber (Shobuda *et al*, PRAB **12**, 032401, 2009)).
- ❑ The identity was significantly violated at 181 MeV injection, causing huge beam losses at ν_x=ν_y=6.2, analytically explained (Shobuda *et al*, JPS Conf. Proc. **8**, 012003, 2015).
- ❑ After 400 MeV upgrade, beam losses at ν_x=6.14 are still observed, explained analytically (Shobuda *et al*, JPS Conf. Proc. **8**, 012003, 2015) because of partial recovery of the identity.

➢ *Summary*

- ❑ An analytical analysis could be a good guideline in designing ceramic chambers to capture some physical perspective, although simulations and measurements need to certify the estimate in the end.