# A kicker impedance reduction scheme with diode stack and resistor at the RCS in J-PARC

*(Selected as Editors' Suggestions by PRAB)*

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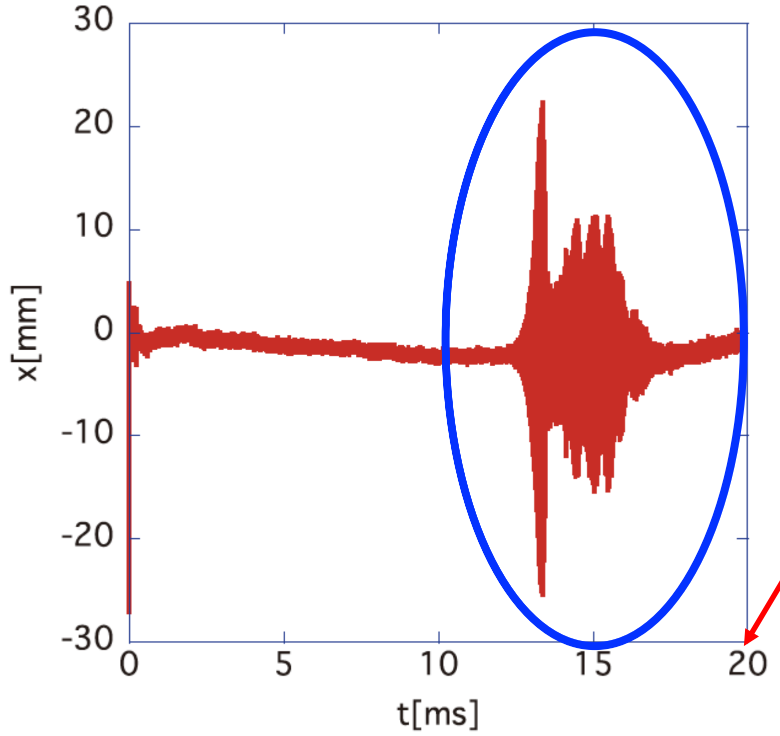
- ***Introduction***
- ***Characteristics of RCS*** (a kicker impedance, space charge-dominate)
- ***Motivation for reducing the kicker impedance***
  - Characteristics of the RCS kicker
  - A basic idea reducing the kicker impedance using **diode units (diodes+matched resistors)**
- ***The impact of the diode units on the extraction beam by measurements.***
- ***How to enhance the durability of the diode unit***
  - Estimation of the heating rate of the diode unit.
  - Analytical and simulation estimates of the diode unit's temperature.
  - Confirmation through measurements and a durability test.
- ***Suppression of the kicker impedance and beam instabilities*** (measurements)
- ***Summary***

## ➢ *Introduction*

- The RCS at J-PARC accelerates **two bunched** proton beams for **20ms**.
- One megawatt beam is equivalent to the case where **4.15** x **$10^{13}$** protons per bunch are accelerated with a repetition rate of **25 Hz.**
- Coupled bunch instability is observed during the latter half of the acceleration period **at high energies.**

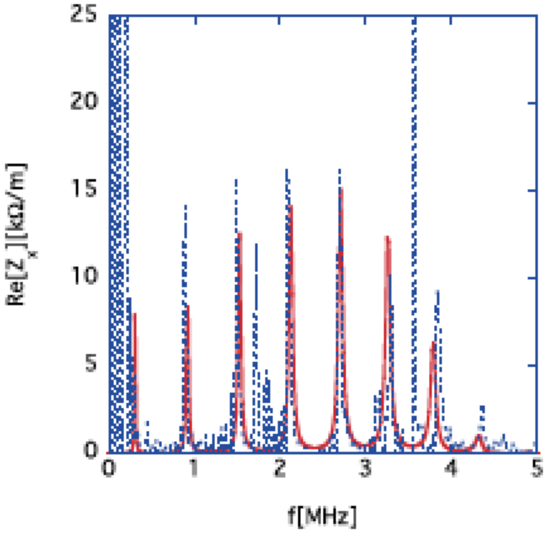
***Measurements for 4.15 x $10^{13}$ ppb***

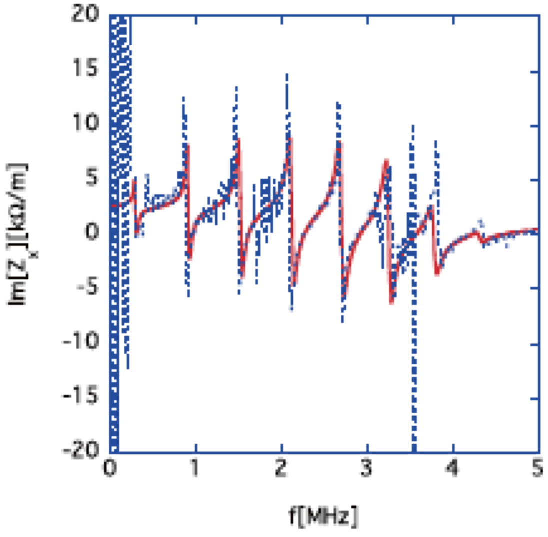


# ➢ *Characteristics of RCS.*

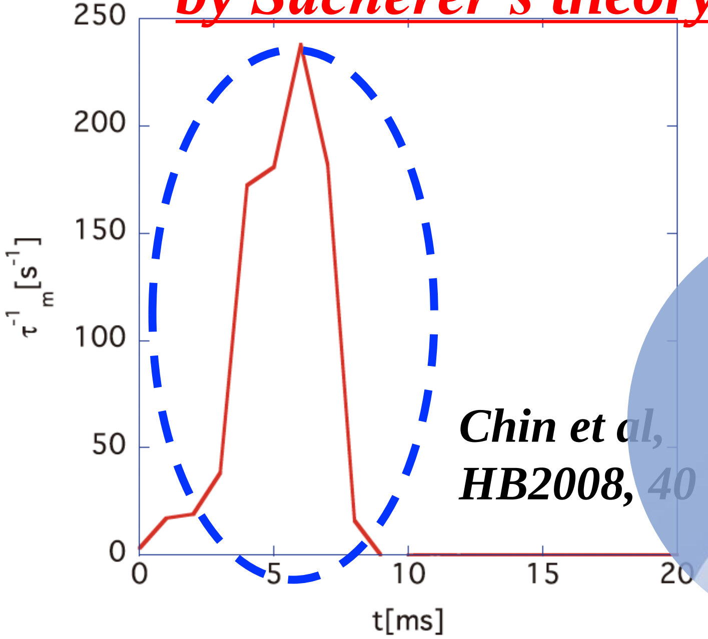
- The **8 kickers** are installed at the RCS for beam extraction.
- The kicker impedance was measured using **the standard wire method, and beam-induced voltage** (*Shobuda et al, NIMA713, 52, (2013)*).
- It was **10 times larger** than that of SNS (in **ORNL**)
- *Sacherer's theory, which* ***neglects the space charge effect****, predicted the kicker impedance excites* ***beam instabilities at low energy, making it impossible to achieve high-intensity beams*** *at the RCS.*

***Measured horizontal impedance (for one kicker)***



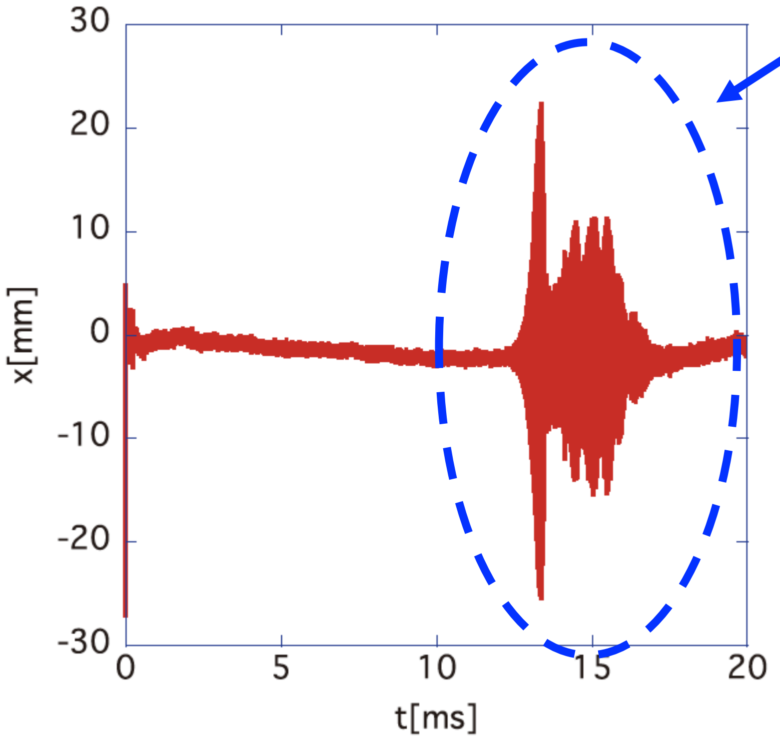




***Beam growth rate during ramping time by Sacherer's theory***

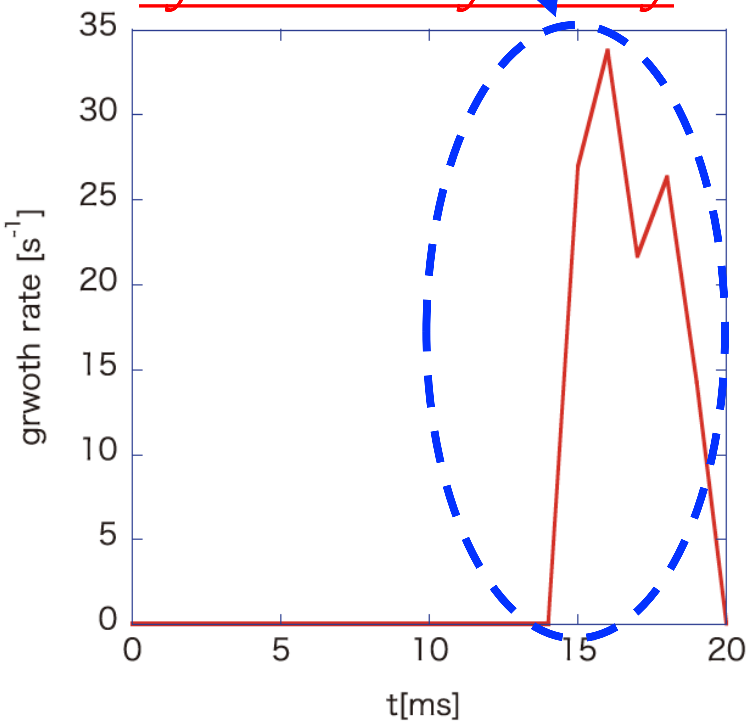


- However, ***indirect*** **space charge effects are effective in** ***suppressing beam instability*** **at low energy** *(Shobuda et al, Progress of Theoretical and Experimental Physics, 013G01, 2017)*
- We can theoretically comprehend ***the beam instability at high energy.***
- These results are validated by simulations *(Saha et al, PRAB, 024203, 2018).*

***Measurements of beam positions during ramping time in the case of 4.15 x $10^{13}$ ppb***



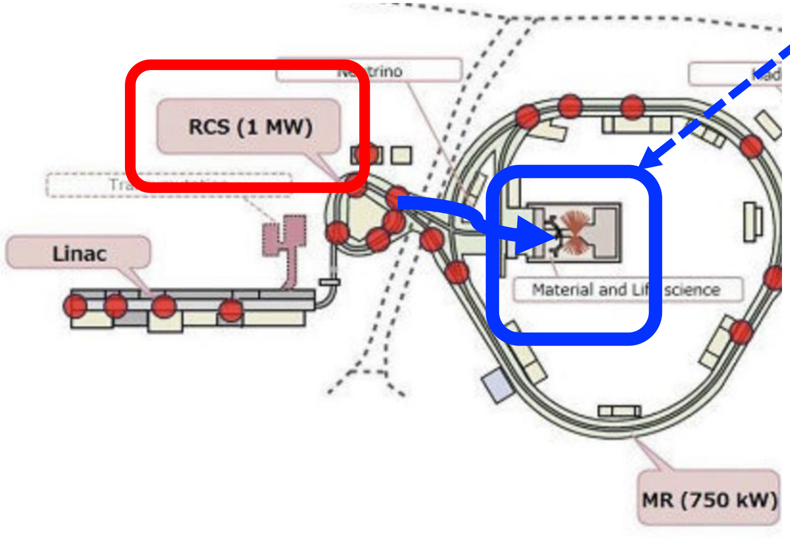

***Beam growth rate during ramping time by our theory theory***

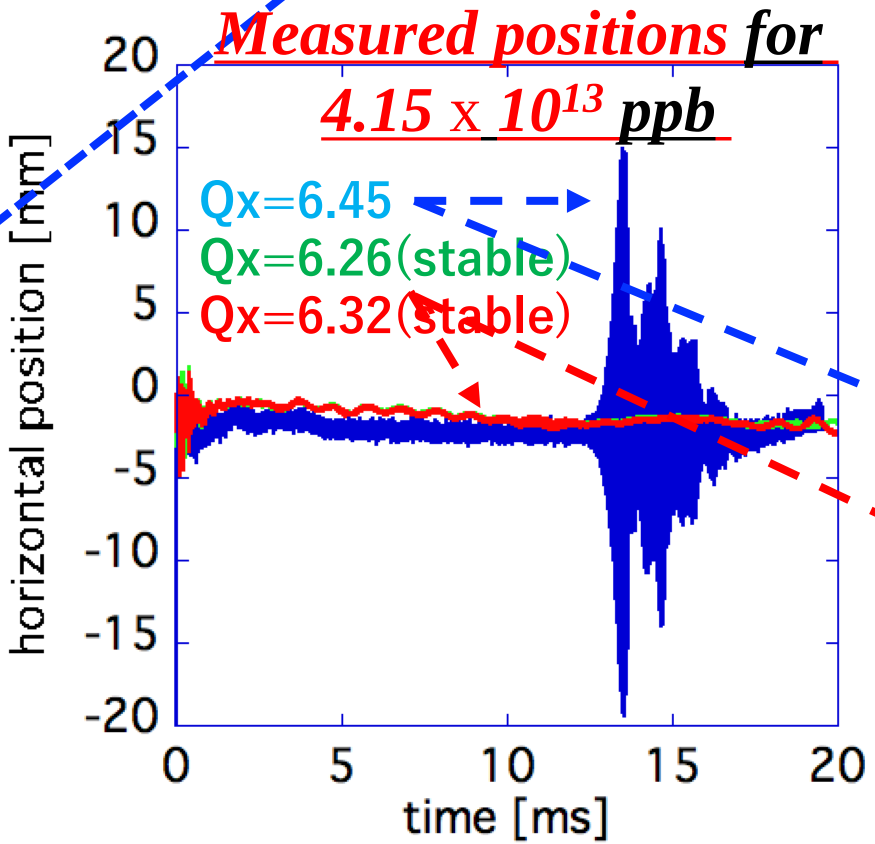


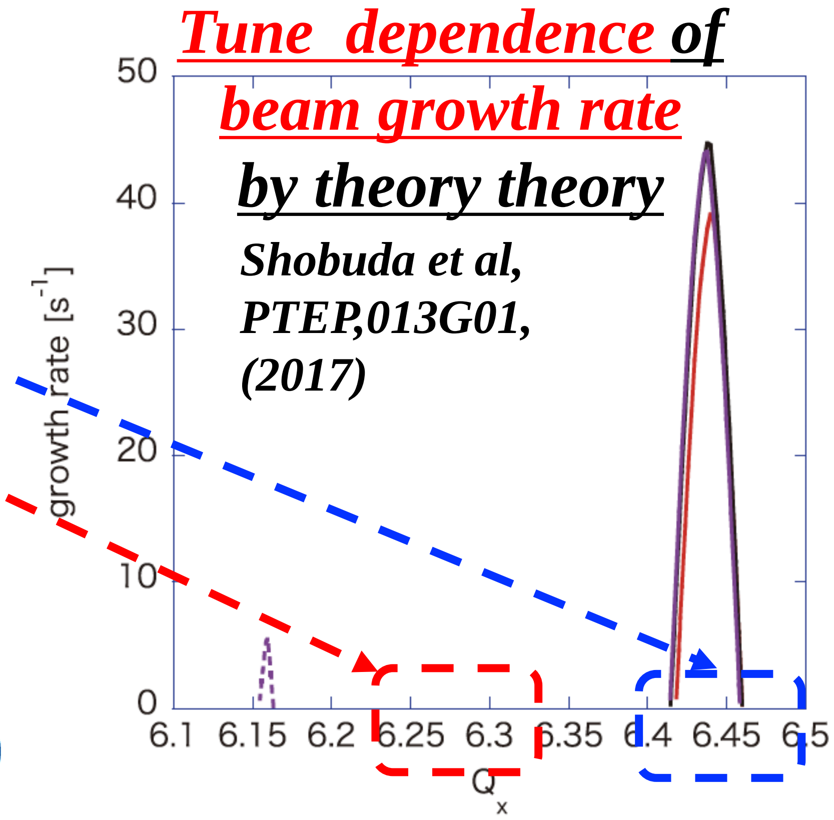

***Shobuda et al, PTEP,013G01, (2017)***

- Moreover, we have ***demonstrated*** **a 1-MW-equivalent beam with a *large transverse beam emittance*, delivered to the Material and Life Science Facility**, ***without the need for any transverse feedback system***
  - ☐ by deactivating the sextupole magnet,
  - ☐ optimizing the tune-tracking pattern during the acceleration period,
  - ☐ *because the beam growth rate exhibits **tune dependence** **specified by** **the kicker impedance**.*

***J-PARC Layout***



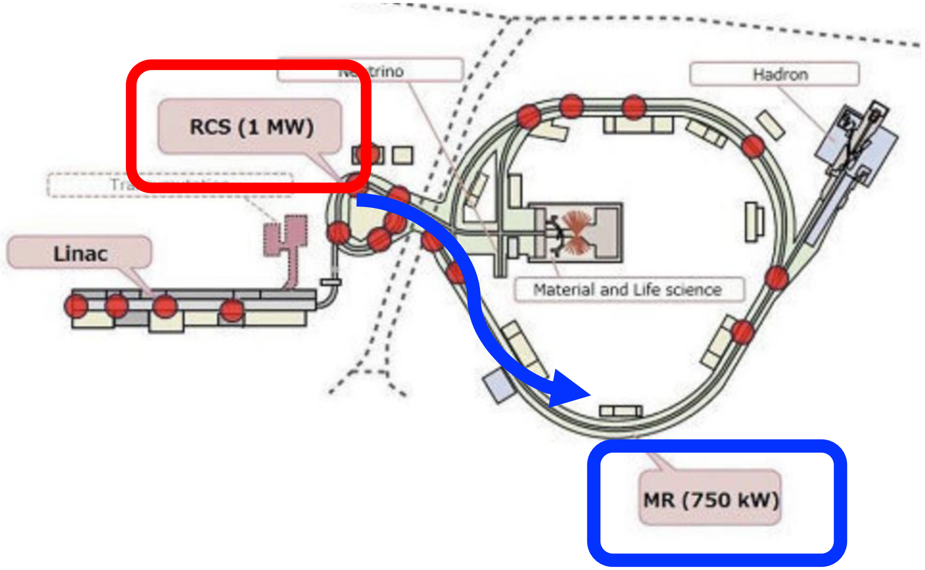



# ➢ *Motivation for reducing the kicker impedance*

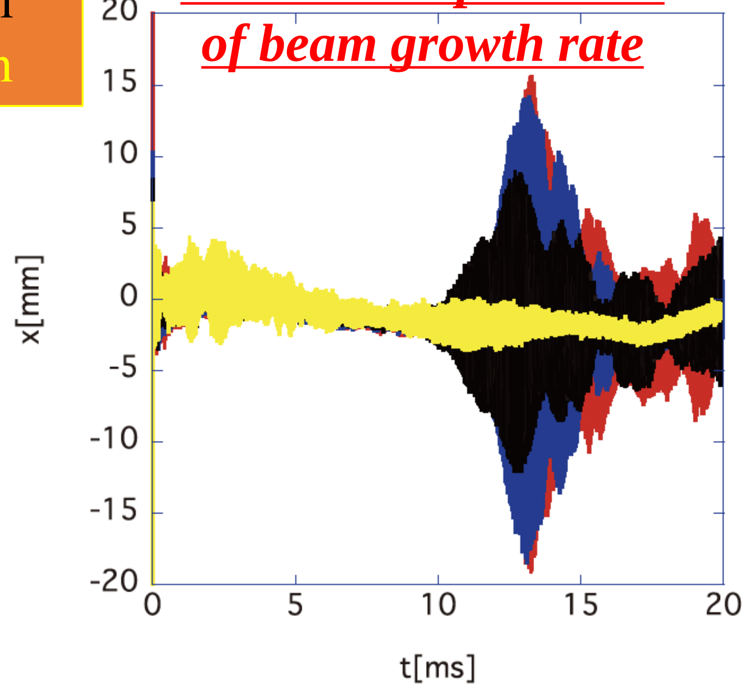
- It is desirable to reduce the kicker impedance for routine operations of the MR, especially for high-intensity beams with **smaller transverse emittance**.

- *This is **challenging** because **high-intensity beams with smaller emittances tend to become unstable** due to the mitigation of the indirect space-charge damping effect.*

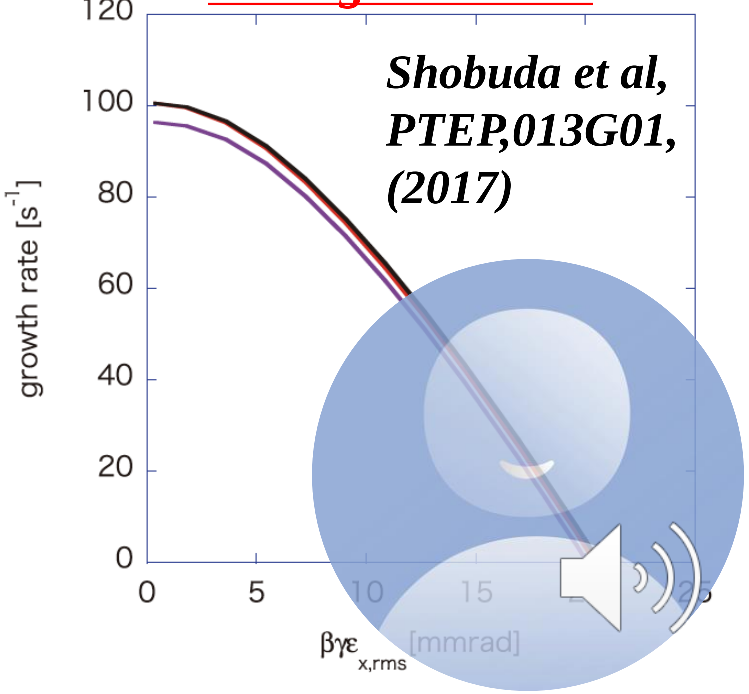
**Center injection**
**100 π injection**
150 π injection
200 π injection




***Measured beam positions showing the emittance dependence of beam growth rate***

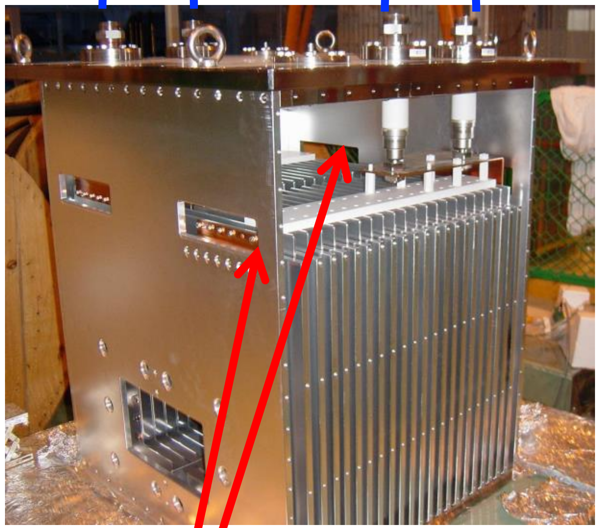



***Theoretical results showing the emittance dependence of beam growth rate***



# ❑ *Characteristics of the RCS kicker*

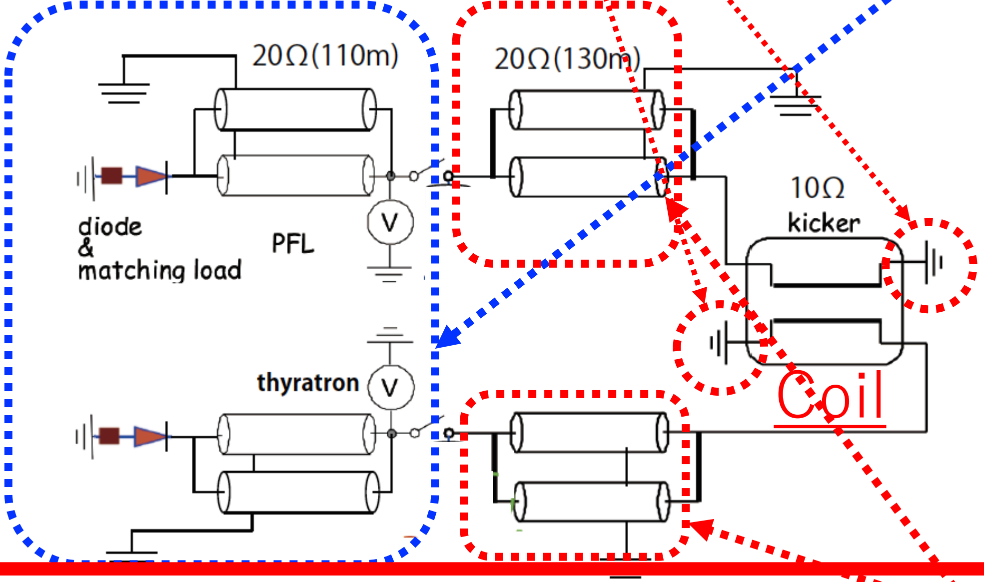
**Input of coaxial cable**



**Kicker magnet**

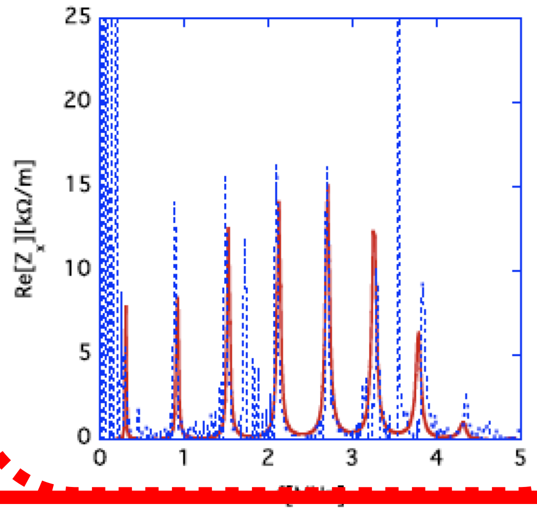
***short plates***

- The kicker magnet at the RCS has four terminals.
- Two are connected to Pulse Forming Line (PFL), while the others are terminated by the ***short plates.***
- These ***short plates*** generate **a power saving benefit** by **doubling** the excitation current through the superposing of the forward and backward currents, when a beam is extracted from the RCS.




Coil

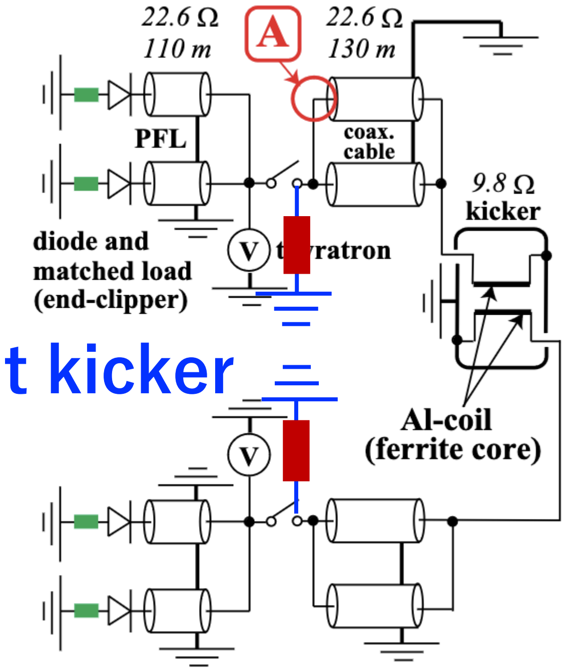
***Horizontal impedance***




- *However, it is the* ***short plates*** *in combination* ***with the 130 m coaxial cables*** *that create* ***the resonance structure*** *in the kicker impedance.*

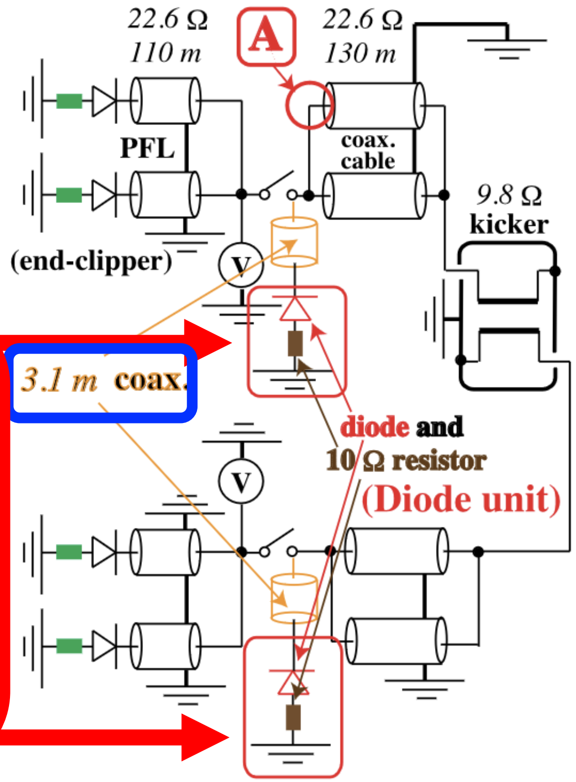
## ❑ *Basic idea of reducing the kicker impedance using diode units*

- ◆ To reduce the impedance, a **matched resistor** **(10 Ω)** should be inserted between the coaxial cable and PFL
- ◆ However, the resistor needs to be **isolated from the PFL** to retain the benefit of the short plates, while still being visible to the beam.
  - ●To achieve this isolation from the PFL, **we need a mechanism**.
  - ●From a mechanical perspective, the simplest approach is ***to insert a diode*** in front of the resistor.



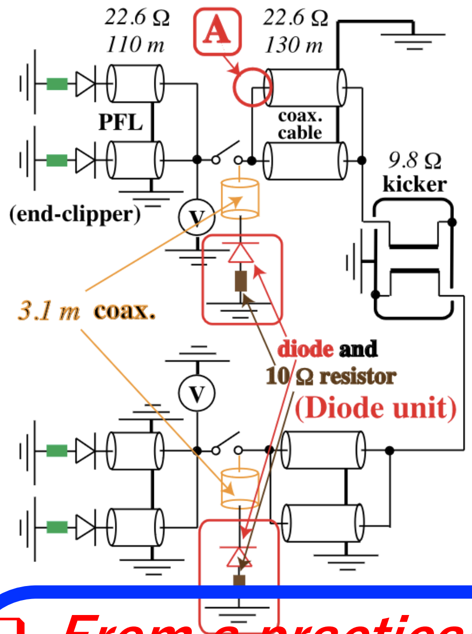

Present kicker

***Modified by diode unit (diode +10 Ω)***

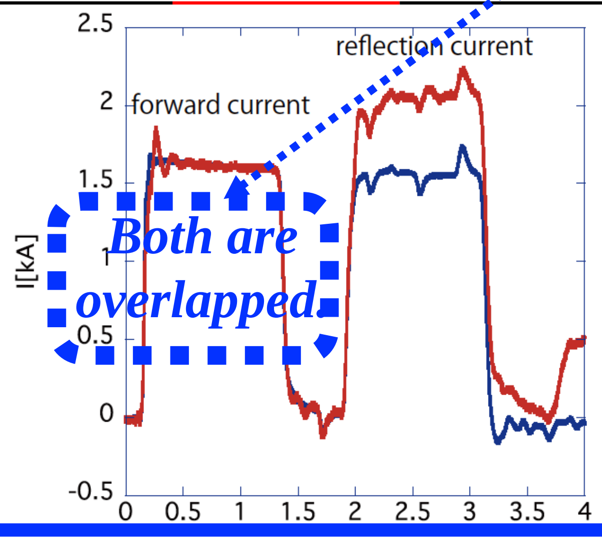



## ❖ *A prototype diode unit (diode+10Ω) was developed.*

- The **measurement demonstrated**
  - ❑ ***withstand voltage*** of the diode was ***sufficient*** for beam extraction from the RCS.
  - ❑ The measured ***kicker impedance*** was ***reduced***.

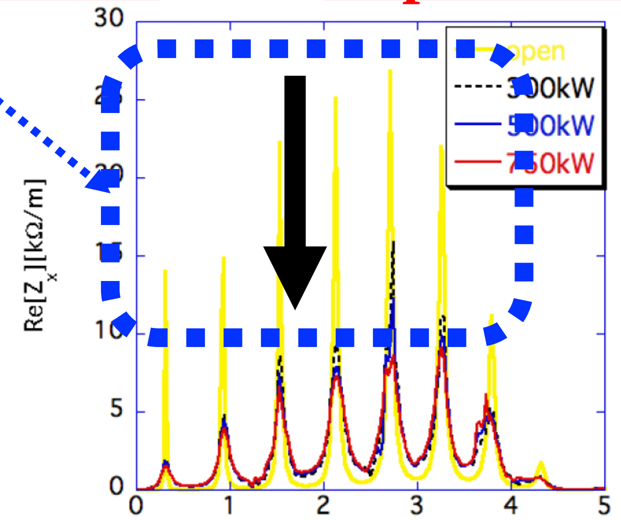




**Monitored current at location A.**




- **Diode PRESENT**
- **Diode ABSENT**

**Measured kicker impedance**




❑ ***From a practical perspective, significant concerns still exist*** (E. Koukovini-Platia et al, *PRAB* **22**, *124201, (2019)*)

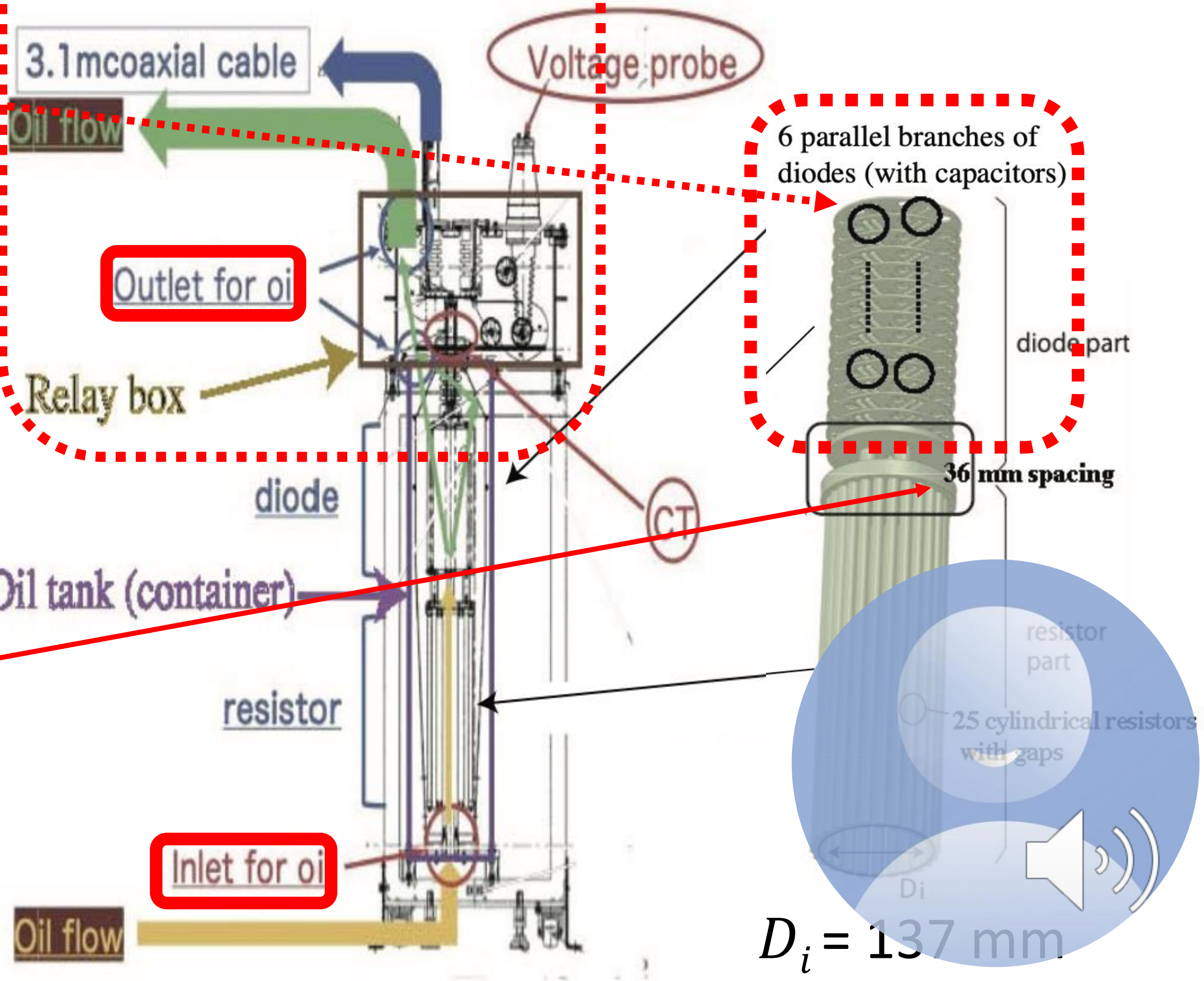
1. ***Heating*** *on the diodes and resistors can potentially* ***damage*** *these components under the 25 Hz operation.*
2. ***The fast-rising voltage*** *across the diode units during the turn-on of the thyratron switch may cause* ***degradation of the diode stack****.*
3. *The attached diode unit may have a significant effect on the extraction beams from the RCS.*

## ❖ *Strategy for the practical use of the diode module*

***Shobuda, et al PRAB 26, 053501, (2023) selected as ``Editors Suggestions"***

- Design the diode unit to be **cooled** by **circulating oil**.
- Construct the diode stack with **a ladder structure** to increase parallel branches and reduce inductance; this structure consists of small diodes.
- Each diode measures 7.6 mm ($l_d$) in length and 5.4 mm ($D_d$) in diameter, and is **in direct contact with** the circulating **oil** to enhance cooling efficiency.
- **Capacitors** are connected in parallel with the diodes to ensure their durability.
- **Spacing** is inserted between the diode and the resistor parts to suppress heat conduction.

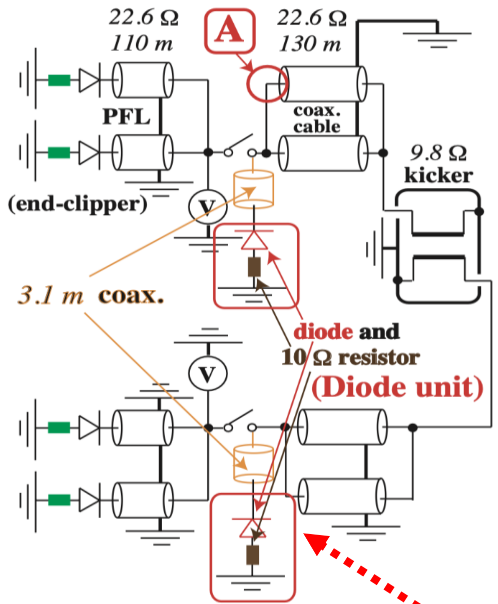
*A voltage probe and CT are installed to measure kicker impedance and heating rate.*

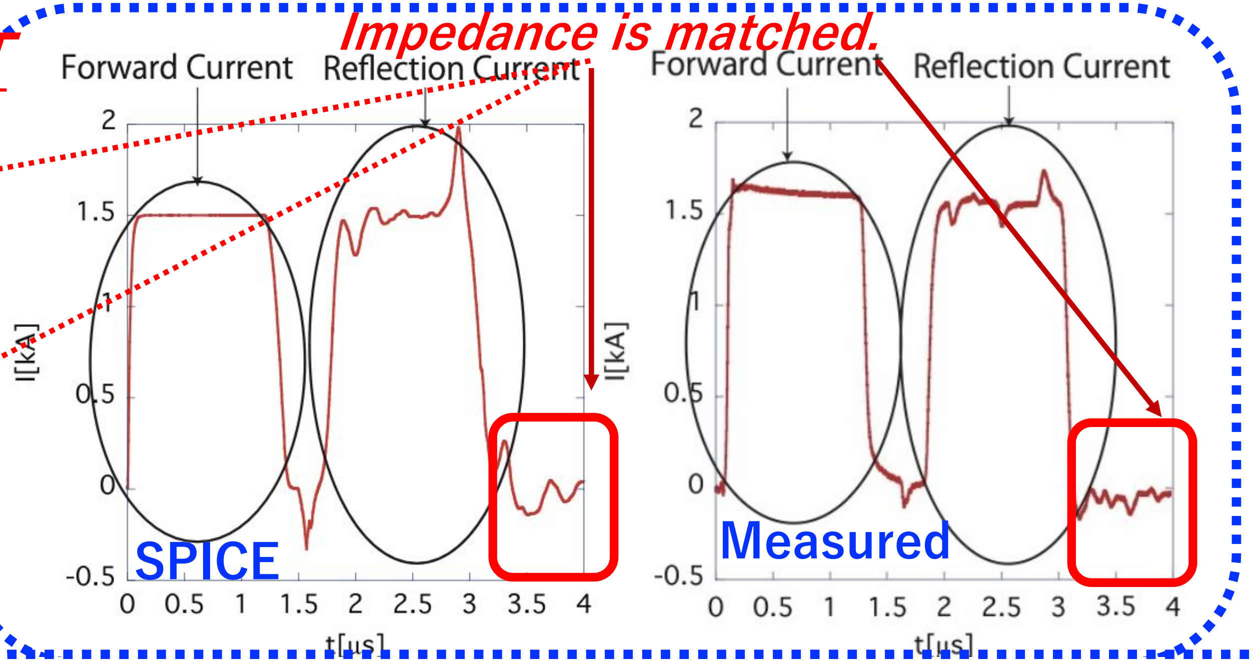



$D_i$ = 137 mm

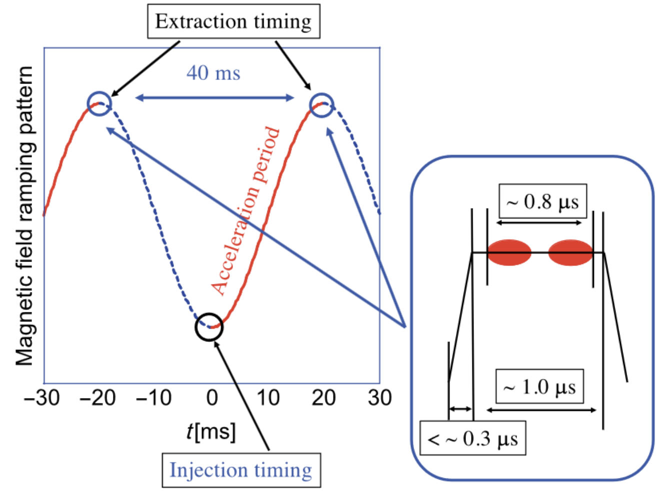
# ❖ Simulations and measurements of current waveform observed at location A

## Diode unit ABSENT



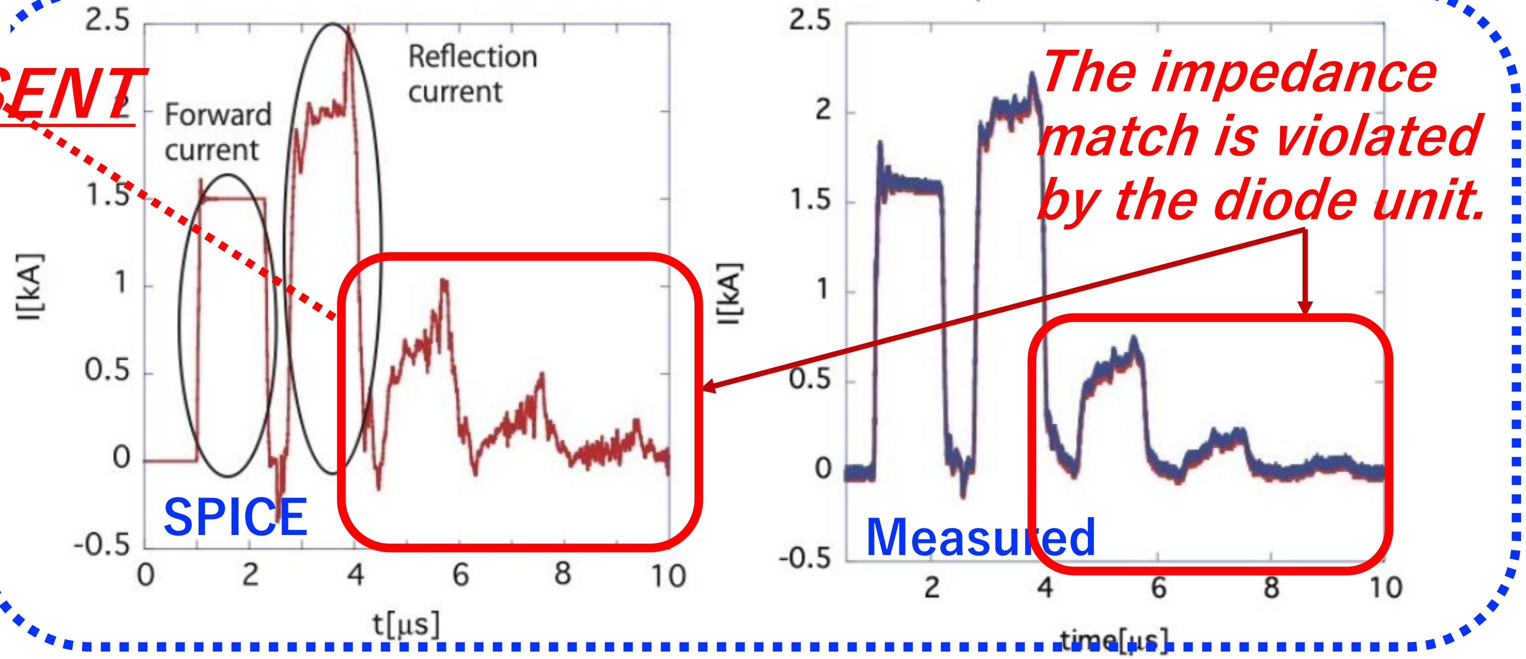




## Ramping pattern of RCS




## Diode unit PRESENT

Since the **SPICE** simulation matches the measurements, it is **valuable** for **unit design**.

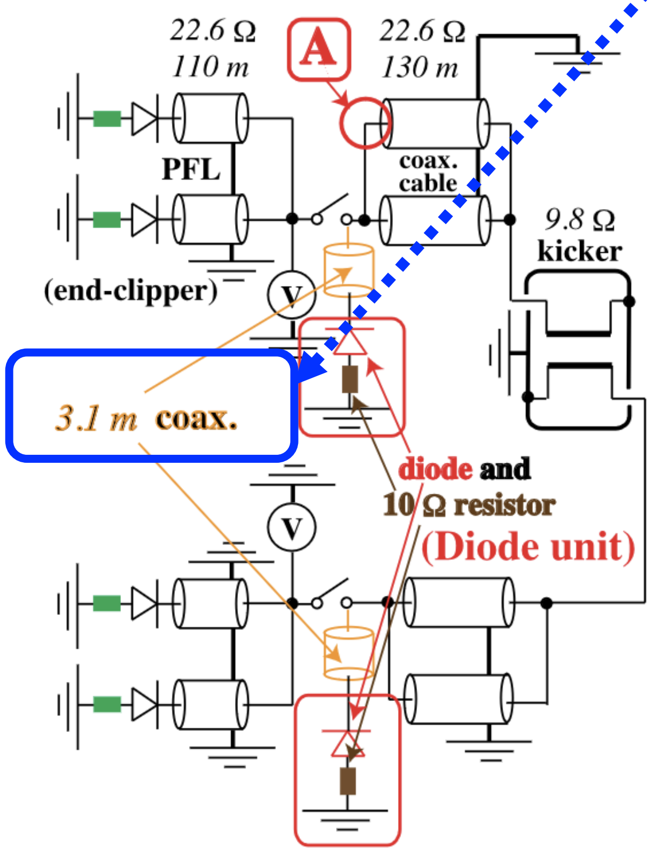


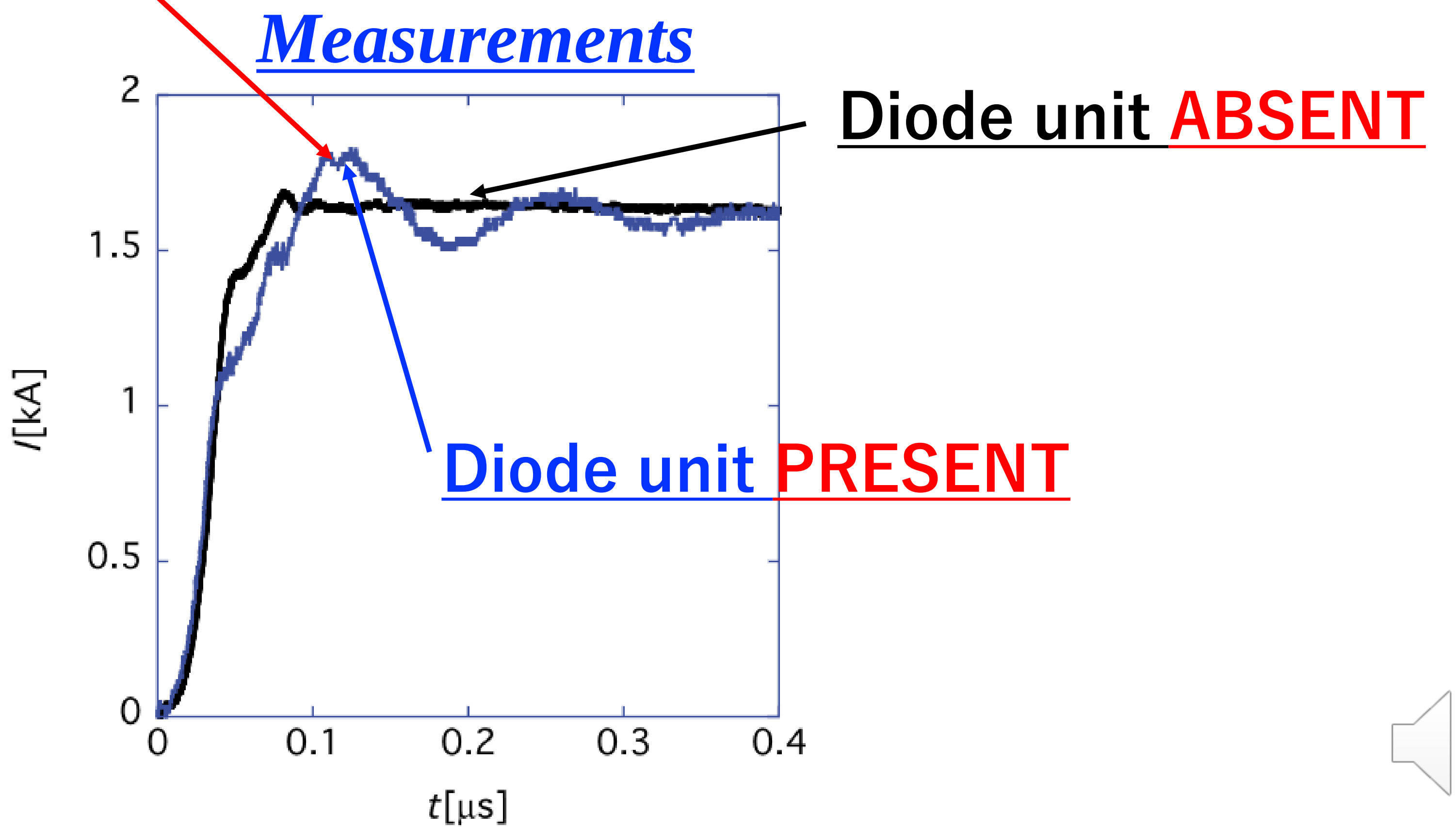

**No issues arise at the RCS, because the beam is injected 20 ms after extraction.**

## ❖ *Another issue concerning beam extraction.*

- The **oscillation appears** on the rising edge of forward currents, which is caused by a 3.1 m long coaxial cable connecting the diode unit and the thyratron end.

- The effect on the extraction beams from the RCS **appears significant** when considering **only the observation of waveform currents.**



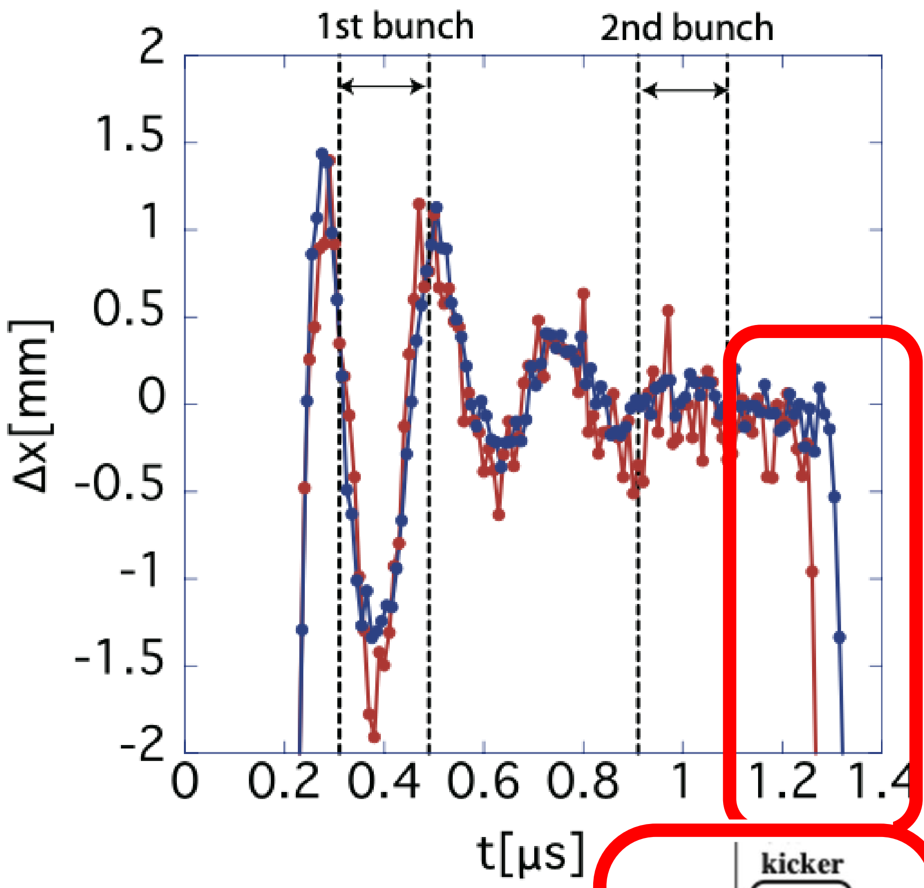
## ➢ *The impact of the diode unit on the extraction beam through beam measurements.*

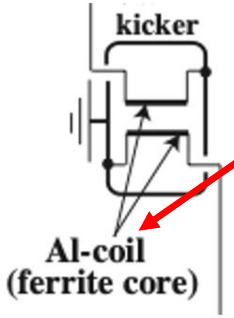
- There are **eight kicker magnets** along the extraction section.
- The **ringing** on the flat-top **fields** of the kicker magnets can **displace the extracted beam** from its ideal trajectory on the downstream beamline of the RCS.
- Two types of trigger systems are employed for the RCS kicker :
  - ❑ One timing module controls the overall trigger timing,
  - ❑ The other timing module manages individual trigger timing for the respective kicker magnets.

- Let us accelerate **tiny 30 ns beam pulses** under full chromaticity correction.
- **The field flatness** for the assigned kicker was determined by **observing the beam position shift** through incremental adjustments in the trigger timing for the kicker.

## ❑ Comparison of extracted beam positions (Δx) with (red) and without (blue) diode units

### Measurements




- The arrival timings and lengths of the first and second bunches during user operation are represented by **dashed lines.**
- **The impact of the diode unit is not significant** because coupling effects resulting from mutual inductances between two coils predominantly induce ringing in the magnetic field.

❖ An effectively flatter trapezoidal field has been achieved by adjusting the thyratron timings among the eight kickers to compensate for the ringing in the case without the unit.

❖ *The chip* appearing at the back of the trapezoidal field shortens the effective flat-top time, but there is still ample margin.

❖ ***With the diode unit, we have successfully delivered 830 kW beams for 45 days during user operation.***

## ➢ *How to enhance the durability of the diode unit*

### ❑ Estimate the electric power generated at the diode unit.

- ❖ Since the SPICE model for the kicker is already established, we can simulate the voltage and current of the diode unit, which can then be compared with measurements.

- ❖ The electric power generated at the diode part is indirectly determined by subtracting the contribution of resistors from the total diode unit.

- ❖ The electric power generated in the diode unit was calculated as 1.3 kW using SPICE, compared to a measured value of 1.25 kW.

- ❖ Simulations and measurements agree well with a margin of error within 4 %.

❖ ***SPICE simulation proves to be highly practical for diode unit design***

## ❑ *Analytical estimation of the temperature of resistors in the diode unit*

### ❖ Requirement: Resistors must remain below 150 °C.

- Analytical approach (resistor case)
  - **Newton's law of cooling** provides $T_R$ (resistor)

$$T_R = T_o + \frac{w_R}{h l_R \pi d_R \times 10^{-3}},$$

*$T_o$: Oil Temperature*
*$h$: Heat transfer coefficient*
*$l_R$: length of cylindrical resistor*
*$d_R$: diameter of cylindrical resistor*

  - ***Heat transfer coefficient h*** is calculated by oil property and velocity of oil (6.5L/min) *(thermal conductivity of oil $\lambda$, Prandtl number $Pr$, Nusselt number $Nu_D$, Reynolds number $Re_D$)*

$$\mathrm{Nu_D} = \frac{h d_R \times 10^{-3}}{\lambda}$$

$$= 0.3 + \frac{0.62 \mathrm{Re}_D^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}}}{[1+(0.4/\mathrm{Pr})^{\frac{2}{3}}]^{\frac{1}{4}}} \left[1 + \left(\frac{\mathrm{Re}_D}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \simeq 7,$$

- The heating rate due to one cylindrical resistor is

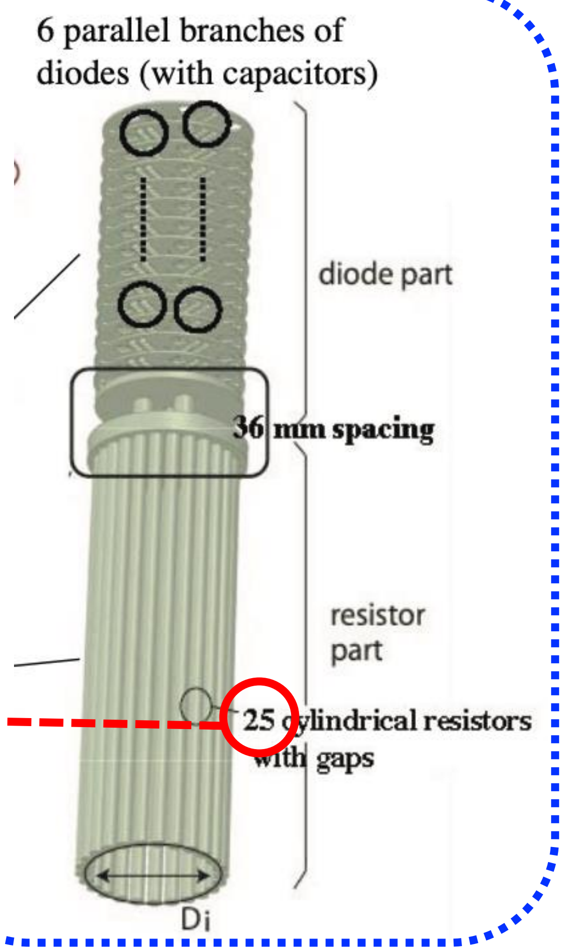
$$w_R = \frac{1160}{25} = 46.4[W],$$

- The temperature of a cylindrical resistor is

$$T_R = T_o + \frac{w_R}{h l_R \pi d_R \times 10^{-3}} = T_o + 31.$$

61 °C

❖ *Analytical estimates suggest resistors are durable.*



# ❑ *Analytical estimation of the temperature of diodes in the diode unit*

## ❖ Requirement: Diode must remain below 85 °C.

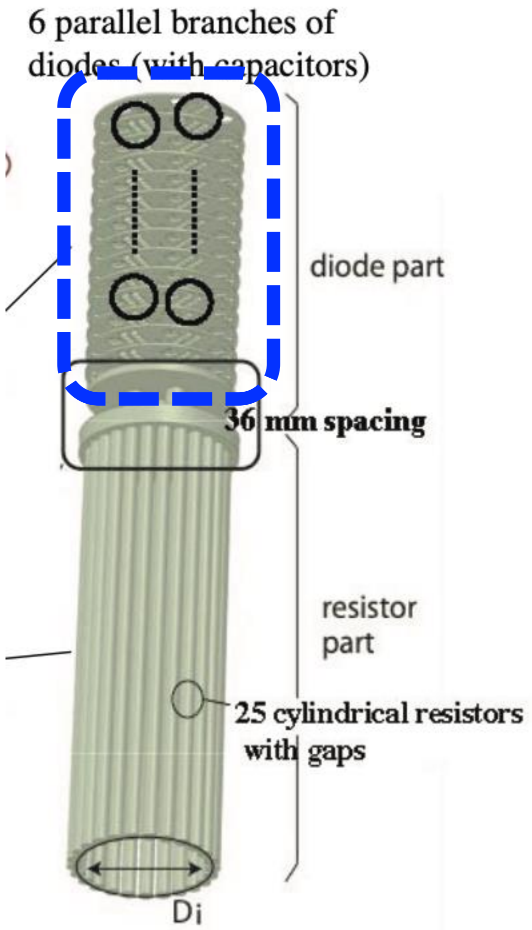
When the oil velocity is 6.5 L/min,

- the temperature of the diode is estimated to be

$$T_d = T_o + \frac{iv}{hl_d \times 10^{-3} \pi D_d \times 10^{-3}} = T_o + 7.75.$$

37 °C

***Analytically, the diodes are durable.***



## ❑ *Detailed analysis using ANSYS Fluent simulation.*

- Convection heat transfer (via oil)
- Heat conduction (through metal)
- Radiation

### ❖ Convection heat transfer

❑ **Heat flux on the surface of the diode and the cylindrical resistor** were used as **input parameters** of thermal conditions.

❑ **k-ϵ with RNG model was employed**, because the structure of the diode unit is similar to that of a pin pitch heat sink.

- o the flow becomes turbulent only near a structure and becomes relaminarized after passing through the structure.

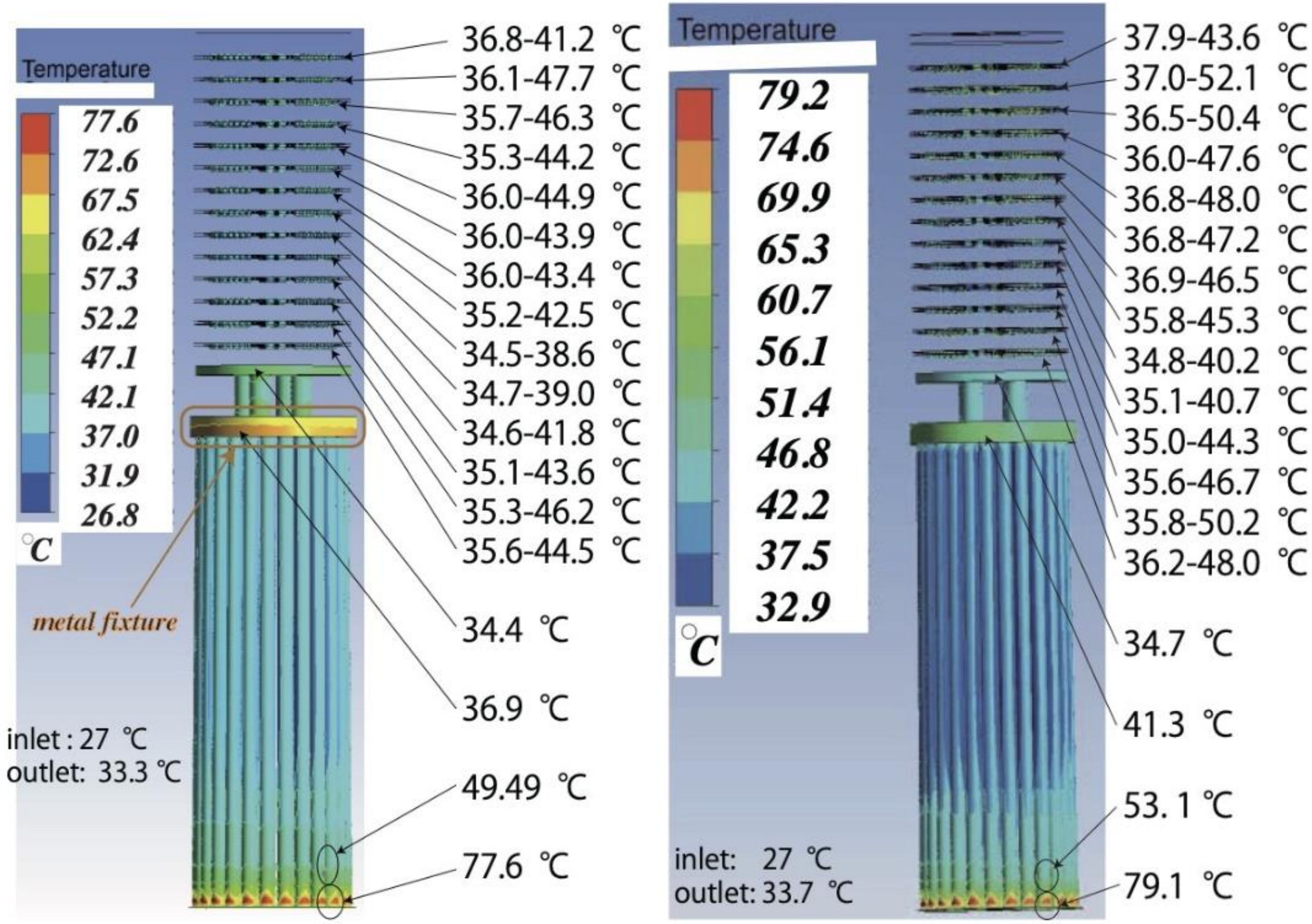
### ❖ Heat conduction

❑ **'coupled' boundary conditions were adopted** on the diode and resistor surfaces, to account for heat transfer to the supporting metals.

❖ **Radiation effects** were included by **assuming black body radiation**.

## ❖ *Simulation results*

**No beam** — **1MW beam is assumed**



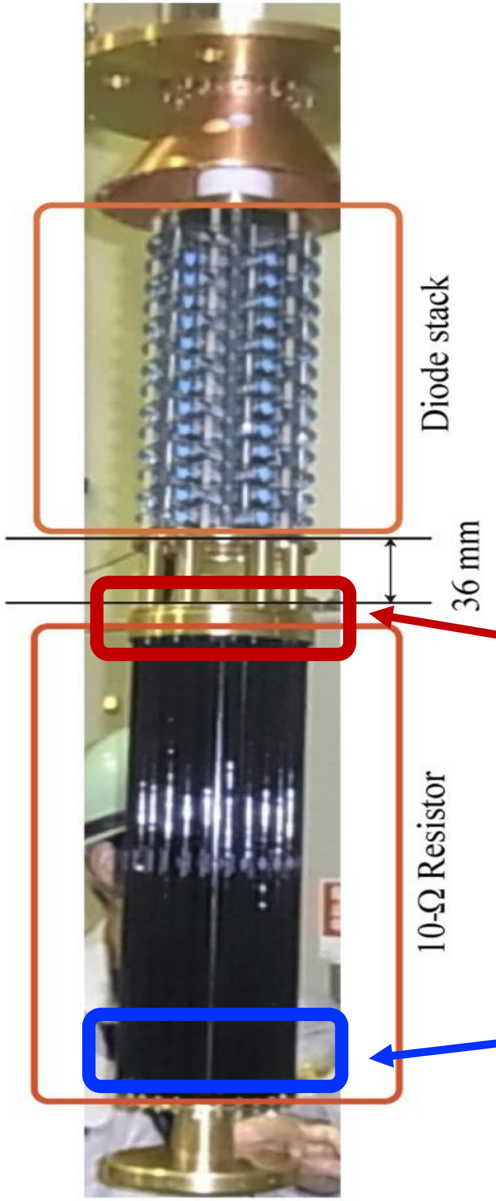

- The diode temperatures range from 34.5 to 52.1°C,
- The resistor temperatures range from 36.9 to 79.1°C,
- ***meeting the specified requirements (diodes < 85 ℃, resistors <150 ℃).***

Roughly, the analytical estimates align well with the simulations.

- the average diode temperature is ~41°C (analytically 37 °C),
- the average resistor temperature is ~57°C (analytically 61 °C).

- ***These analytical estimates serve as valuable guidelines during the initial design stage.***

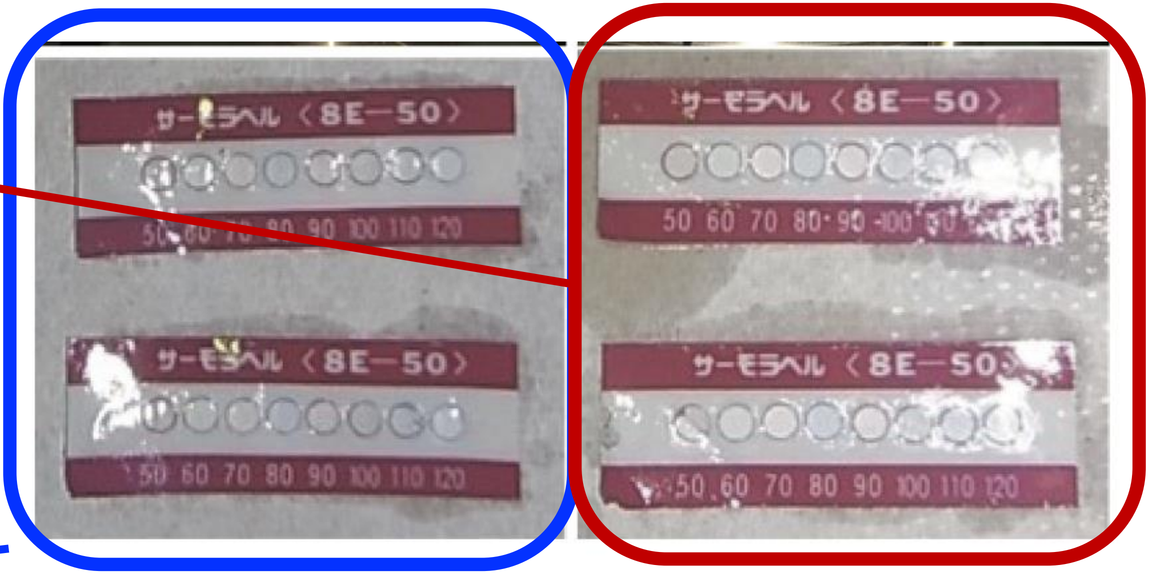
## ❑ *Measurements of the temperature and a durability test.*




- ❑ Thermo-label, capable of detecting temperatures from 50 to 120 ° C, was attached to the diode unit to measure temperatures.

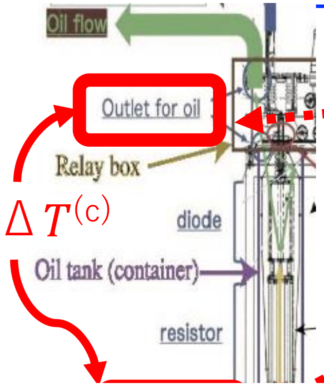

- If the color of the numbered part on the label changes, it has reached the designated temperature.

❖ ***After a 24-hour continuous operation,***



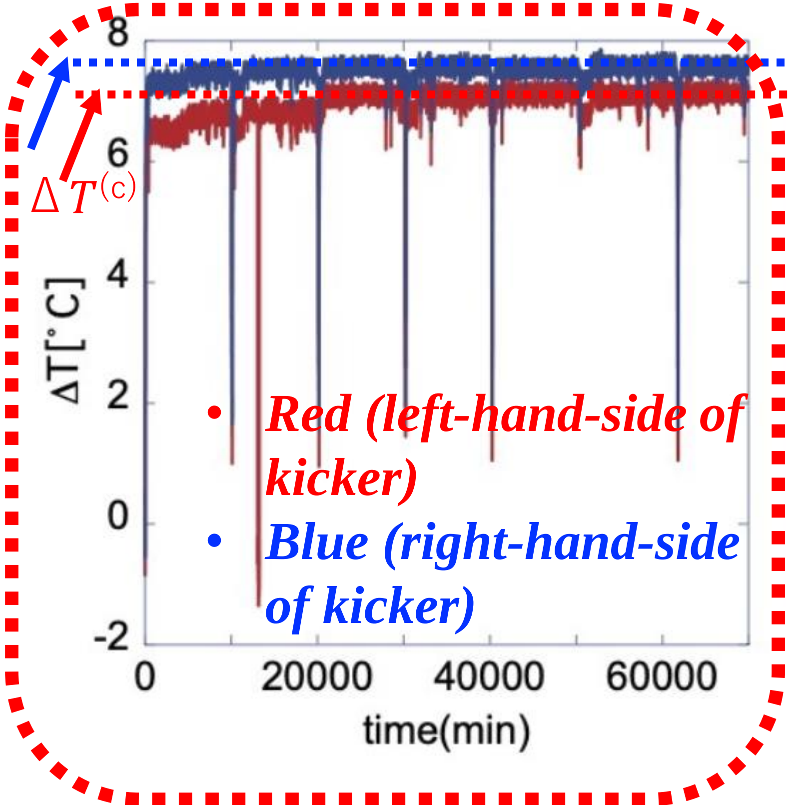

❖ No attached parts were heated beyond 50° C, which aligns with simulations.

❖ The relationship between ***the oil flow*** $\mathbb{V}$ and the ***saturated oil temperature difference*** $\Delta T^{(c)}$ between the inlet and outlet, which is derived **analytically** as




$$\Delta T^{(c)} = \frac{1000W[kW]}{r[\frac{g}{cm^3}]\frac{1}{60}\mathbb{V}[\frac{L}{min}]4.184\bar{c}_p[\frac{cal}{gK}]},$$

- **W: Heating rate of the diode unit**
- **r=0.941: oil specific gravity**
- **$\mathbb{V}$=6.5 L/min: oil flow velocity**
- **$c_p$ =382.4 cal/gK: specific heat of the oil**



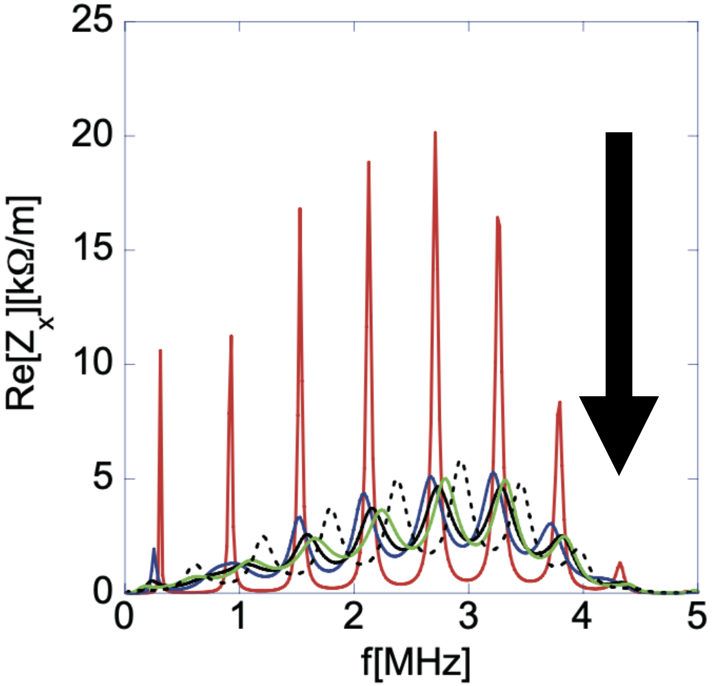

❑ **Measurements of $\Delta T$(t)** using thermocouples during a 45-day durability test, including 830 kW beam contributions.

- In the case of W=PFL(1.25 kW)+ 830kW beam (0.053 kW), dT$^{(c)}$=8 °C (**analytical**), which is **consistent** with **measurements** within 1.5 °C.
- For the 1MW beam case,
  - ❑ dT$^{(c)}$~8.0 °C (**analytical**), dT$^{(c)}$~6.7 °C (**simulations**)
  - ❑ Both results are **consistent** within 1.5 °C.

❑ ***Monitoring the temperature at the inlet and outlet, as well as the oil flow, is an effective method for detecting malfunctions in the diode unit.***

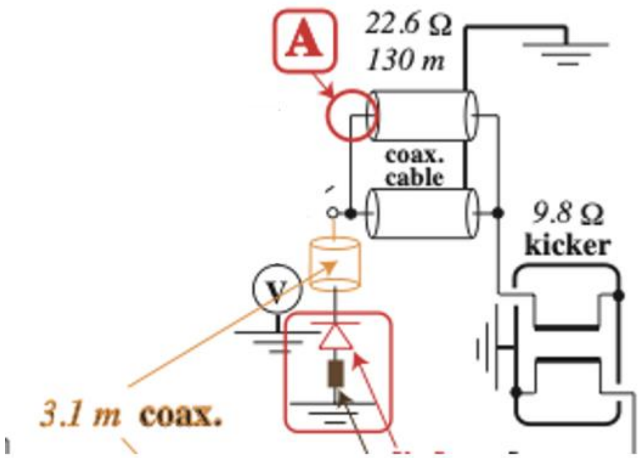
# ➢ Suppression of the kicker impedance and beam-instabilities

- Red: diode unit absent.
- Blue(240 kW beam)
- Black(480 kW beam)
- Green (960 kW beams)
- Black dotted line (only a 10Ω resistor[hypothetical result])




## ❖ Measurements of the kicker impedance

❑ The kicker impedance was measured by monitoring the beam-induced voltage and currents.




❑ In the black dot line, the resistor is attached **after 3.1 m cox. cable**; causing differences in resonance frequencies compared to the setup without the diode unit.

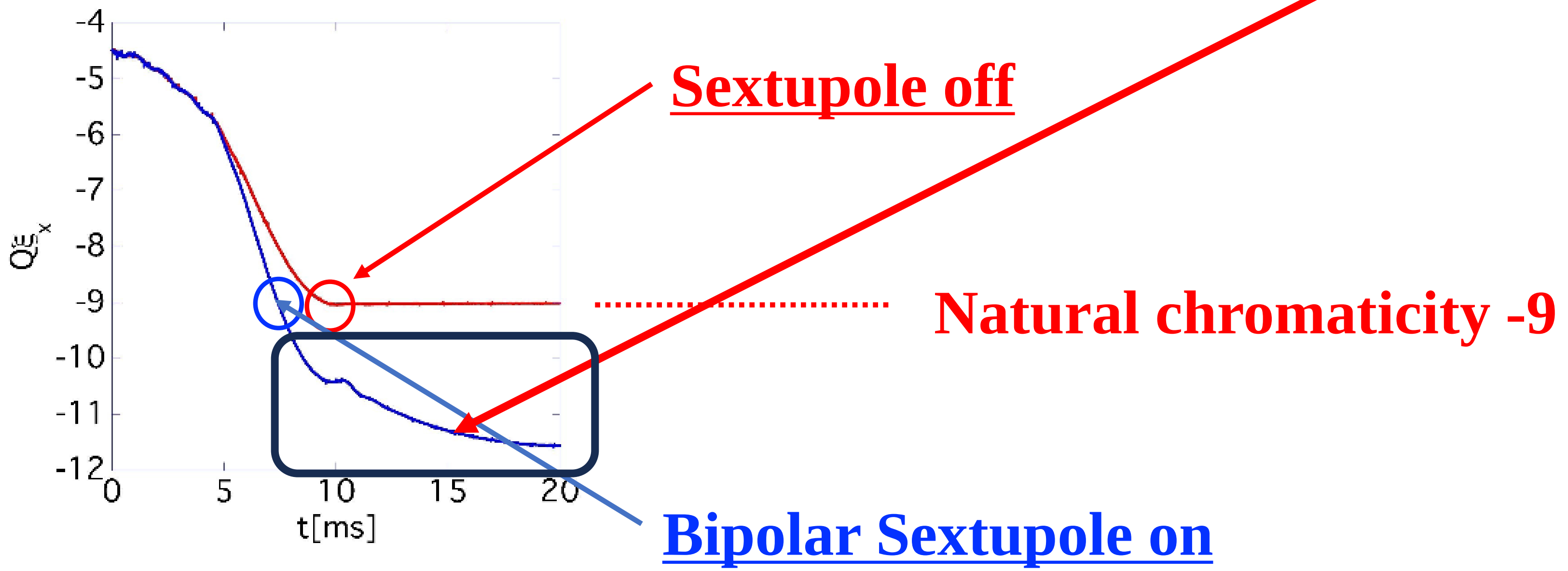
❑ ***The kicker impedance is drastically reduced, when compared to that of the kicker without the diode unit.***

❑ The **parallelized branching** of the diode stack is **effective** in **reducing** the kicker impedance because intensity dependence is nearly negligible.

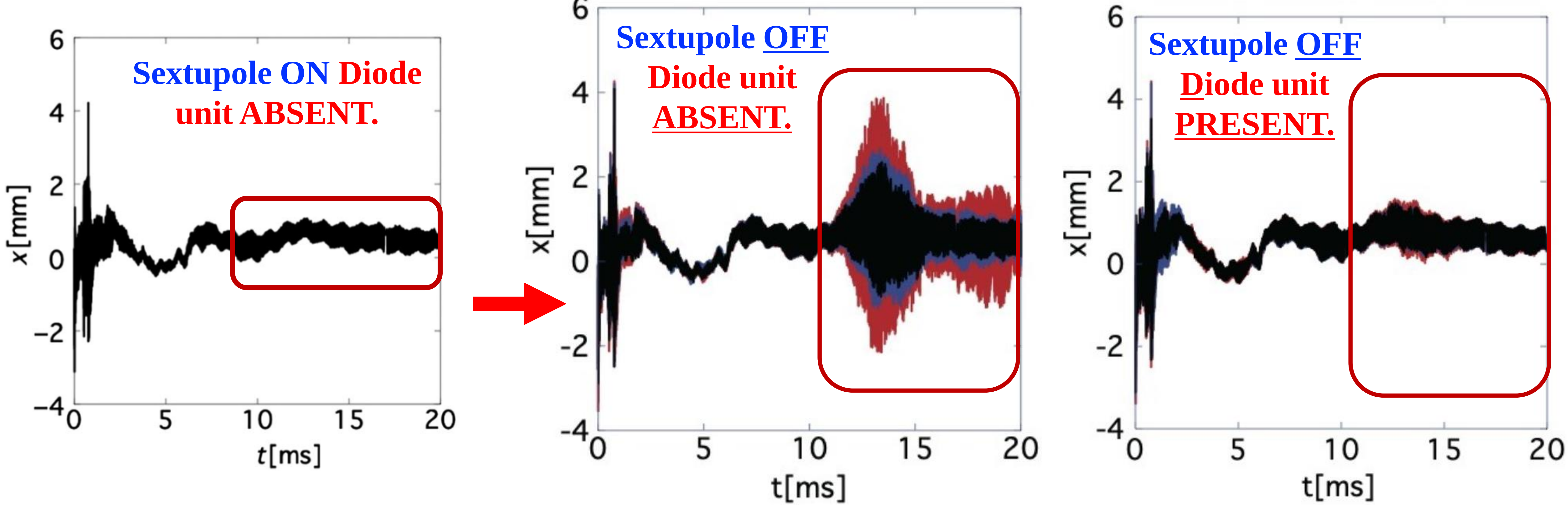
## ❖ *Suppression effect on beam instability*

- The diode unit is attached to "**only one**" of eight RCS kickers.
- **50 π mm-mmrad correlated painting scheme** is employed.
- **4.15 x $10^{13}$ ppb** (2 bunches, 1MW-eq) are accelerated.
- When the **sextupole turns off**, the chromaticity becomes **-9**, as the **natural chromaticity is -9**. Since 2016, chromaticity has **increased in the negative direction** at high energy regions by activating a **Bipolar power supply** to **suppress beam instability** for **small emittance** beams.

**Chromaticity behavior along the ramping time**



## ❑ *Measured beam positions during ramping time*




- When the bipolar **sextupole magnet is ON** **without a diode unit,** **the beam is stabilized.**
- When the bipolar **sextupole magnet is OFF** **without a diode unit,** **beam instability occurs.**
- *After installing one diode unit,* ***the beam instability is significantly suppressed.***
  - The measured unnormalized r.m.s. horizontal and vertical emittances at 3 GeV were 6.42 π mm-mrad and 5.52 π mm-mrad, respectively.
  - The simulated emittances were 4.4 π mm-mrad and 5.4 π mm-mrad, (*Hotchi PRAB* ***23****, 050401, (2020)*)
  - agreeing with a factor of 1.5.

## ➢ Summary

- The **diode unit**, which has already been put into **practical use**, was **developed** to **suppress beam instability** in **high-intensity** and **smaller emittance** beams.
- The unit effectively **reduces** the **kicker impedance** while **retaining the advantages** of the doubled excitation current of the **shorted kicker**.
- **Increasing** the number of **parallel branches** of the diodes **enhances** the **durability** of the diode unit, which also **contributes to the reduc**tion of kicker impedance.
- We investigated the **diode unit's impact** on the extraction beam by monitoring it and found that it was **negligible**.
- Both **SPICE and ANSYS Fluent** simulations are **valuable** tools for designing the diode unit.
- Additionally, **analytical estimates** of temperature increase remain **beneficial** for **unit design** and **malfunction detection**.
- This **accomplishment** holds **significant** importance as it **extends** the **parameter windows** in the tune diagram of the **RCS**, enabling future higher-power operations of the MR.