Eddy current effects in the RCS vacuum chamber

Erik Kvikne

David Amorim

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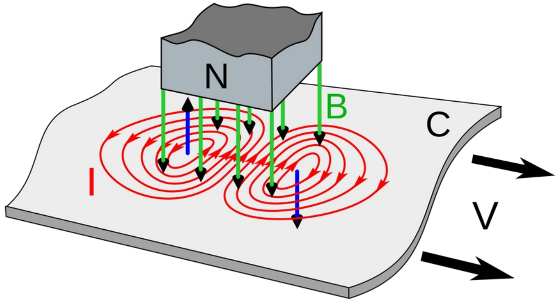
Eddy Currents



- Rapid **changes** in the **magnetic field** of the RCS will generate **eddy currents** in the metallic vacuum chamber.
- The **power dissipation** in a thin sheet or wire scales as the **ramp rate squared**.

$$P \propto \dot{B}^2$$

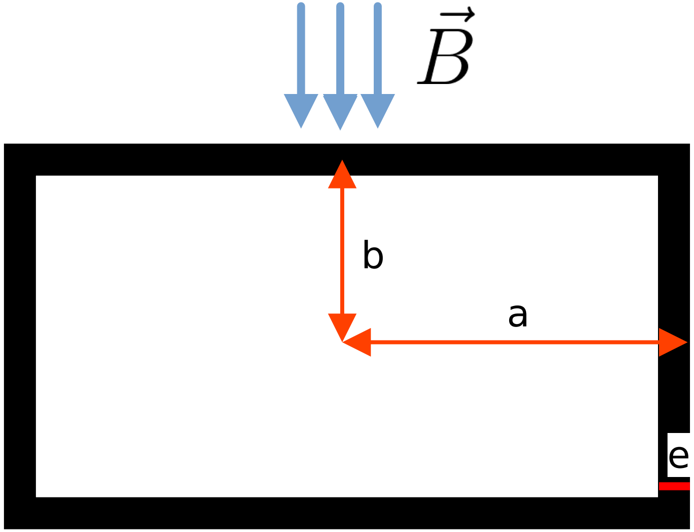
- First order **estimation** of the dissipated power using **analytical formulas**.
- Choice of materials for vacuum chamber is important for the **impedance study**.

RCS:	1	2	3	4
Ramp rate [T/s]	4199	3282	1519	565

(Tentative Parameter list for the IMCC)

Rectangular Vacuum Chamber

- **P_{eddy}/L** is the Eddy current **power loss** per unit length.
- **B** is assumed to be **uniform**.



$$P_{eddy}/L = 4\dot{B}^2 a^2 e\sigma(\frac{a}{3} + b)$$

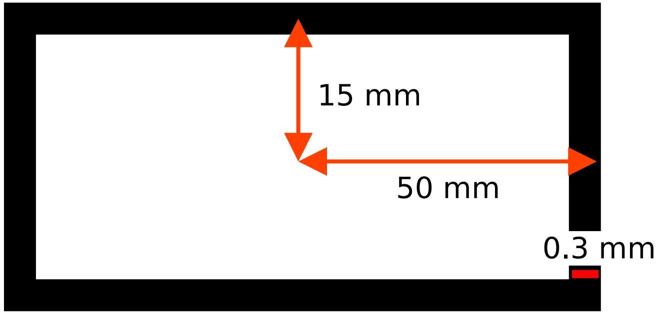
(Lachaize, 2007)

- **B** is the magnetic field
- **a** is the chamber half-width
- **b** is the chamber half-height
- **σ** is the chamber's electrical conductivity
- **e** is the chamber thickness

Stainless Steel Rectangular Vacuum Chamber

Stainless steel 316LN:

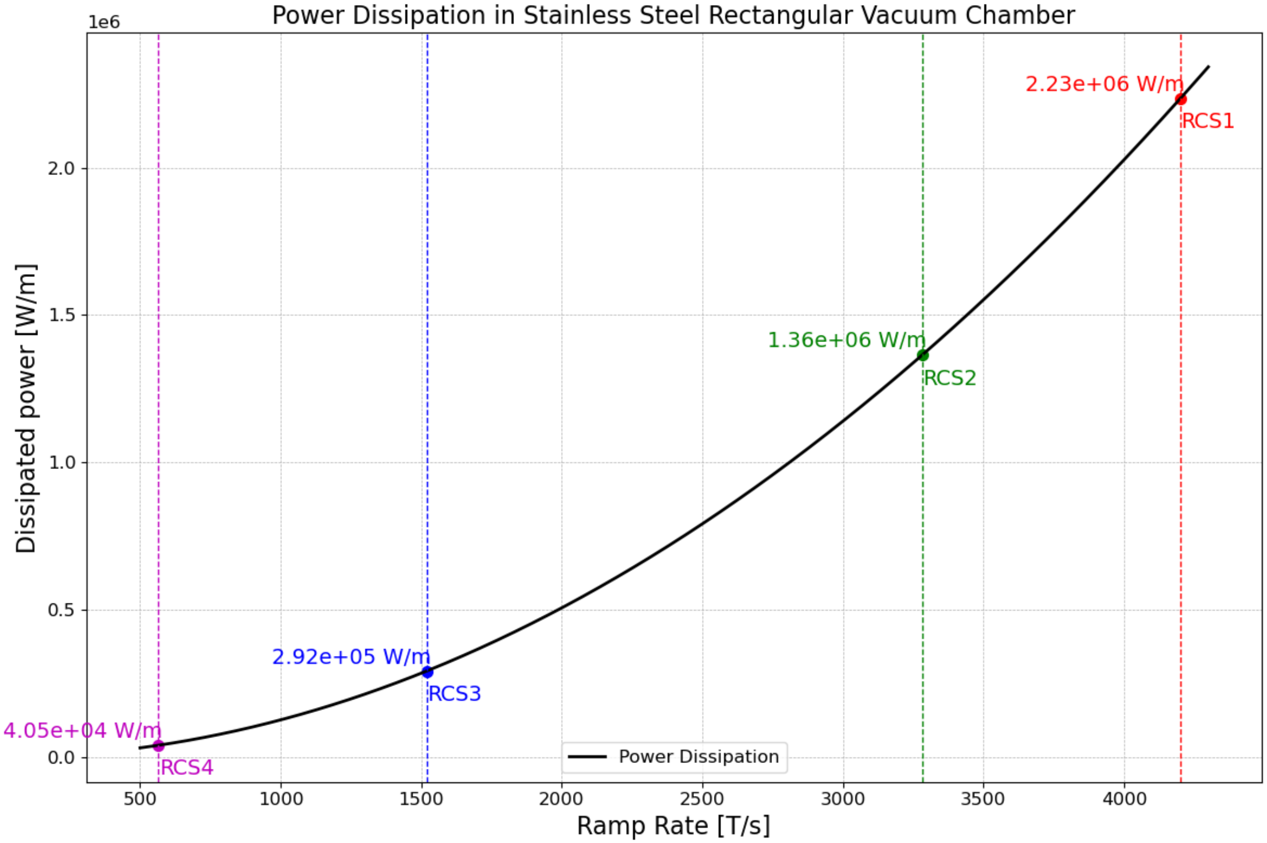
- Resistivity: 7.5×10^{-7} Ωm
- Height and width: 30X100mm*
- Thickness: 0.3mm**



Power loss in the **MW/m** range

*(Tentative Parameter list for the IMCC)

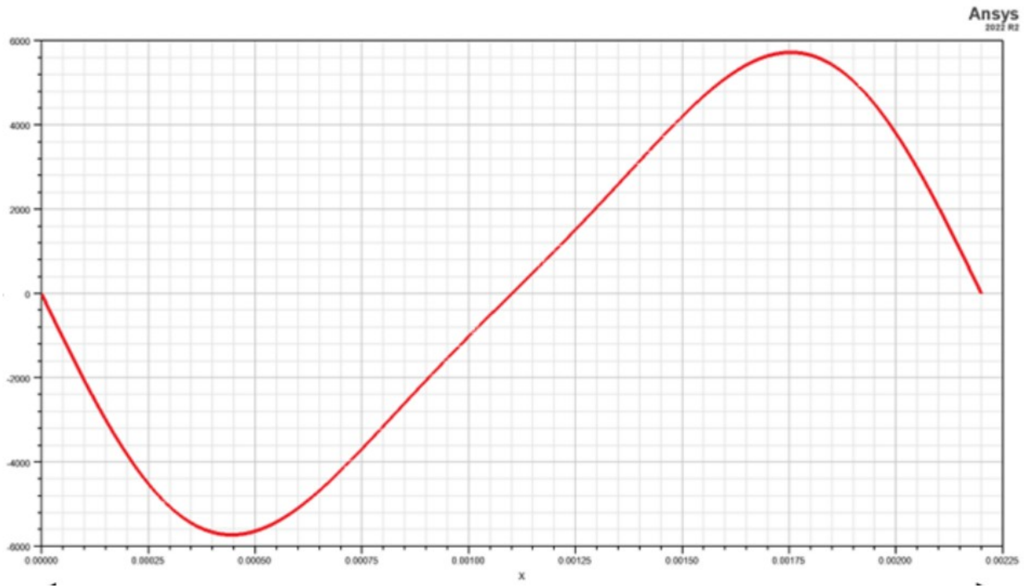
**(Lachaize, 2007)



Energy loss

We can estimate the **energy loss** during the **ramp up** of the magnet, assuming **constant ramp rate**.

$$Q = \frac{P_{eddy}}{L} \cdot t_{ramp}$$



(F. Boattini, M. Gast)

- **Q** is the energy loss of the chamber
- $\mathbf{P_{eddy}/L}$ is the power loss per unit length from last slide
- $\mathbf{t_{ramp}}$ is the ramp time

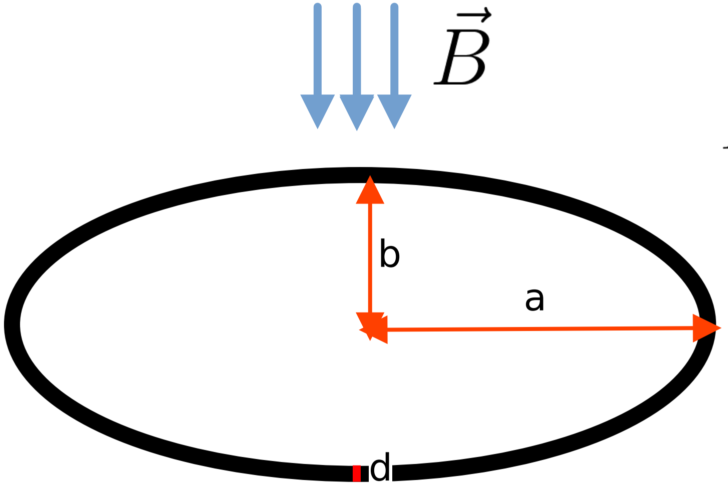
RCS:	1	2	3	4
Ramp time[ms]	0.343	1.097	2.37	6.37

(Tentative Parameter list for the IMCC)

Temperature increase for single ramp up

RCS:	1	2	3	4
Energy loss [J/ramp/m]	766	1497	693	257

Elliptical Vacuum Chamber



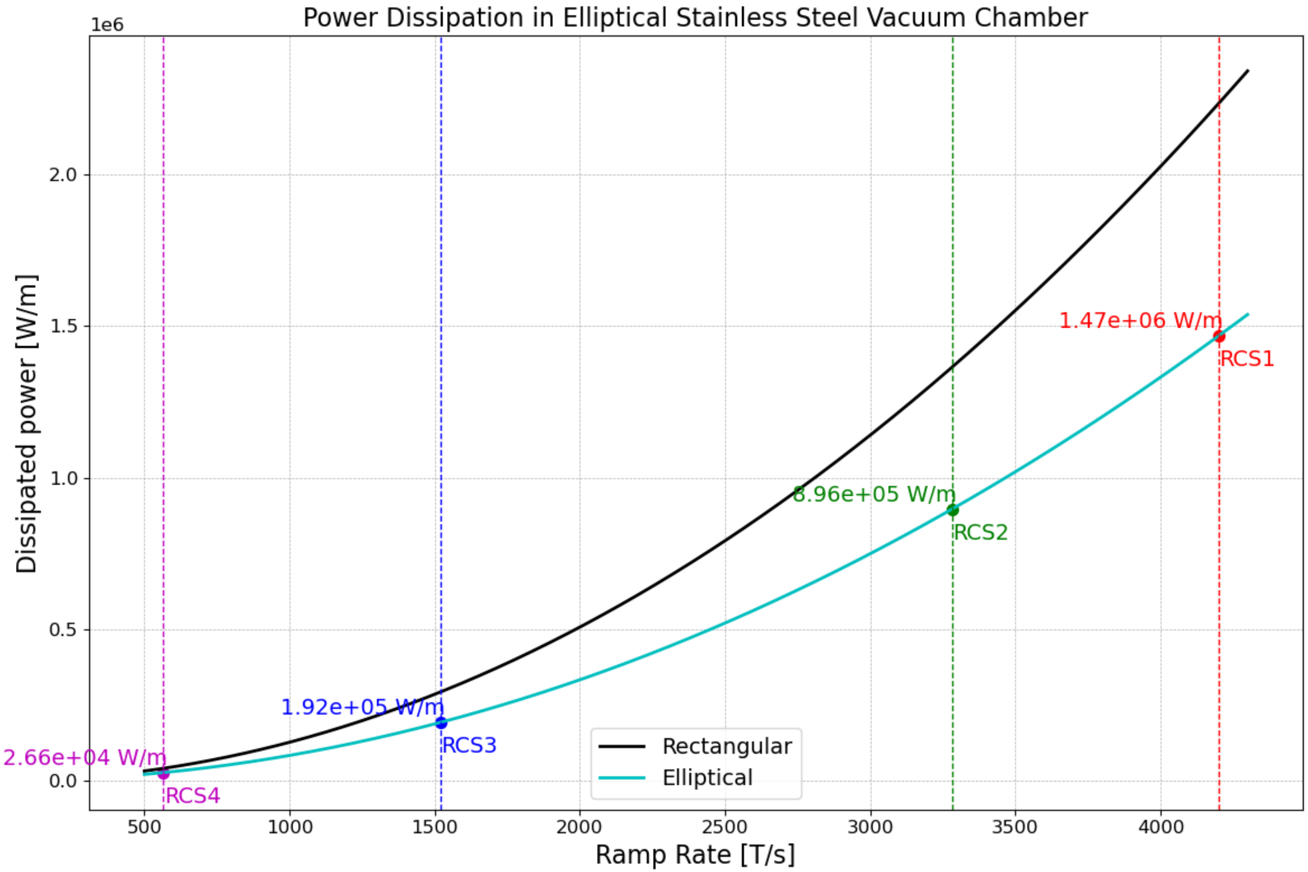
$$P_{eddy}/L = 4\dot{B}^2\sigma d a^3 \int_0^{\frac{\pi}{2}} \sin^2(\theta)\sqrt{1-(1-\frac{b^2}{a^2})\sin^2(\theta)}d\theta$$

(Xu & Wang, 2012)

- **B** is the magnetic field
- **a** is the chamber half-width
- **b** is the chamber half-height
- **σ** is the chamber's electrical conductivity
- **d** is the chamber thickness

Stainless Steel Vacuum Chamber

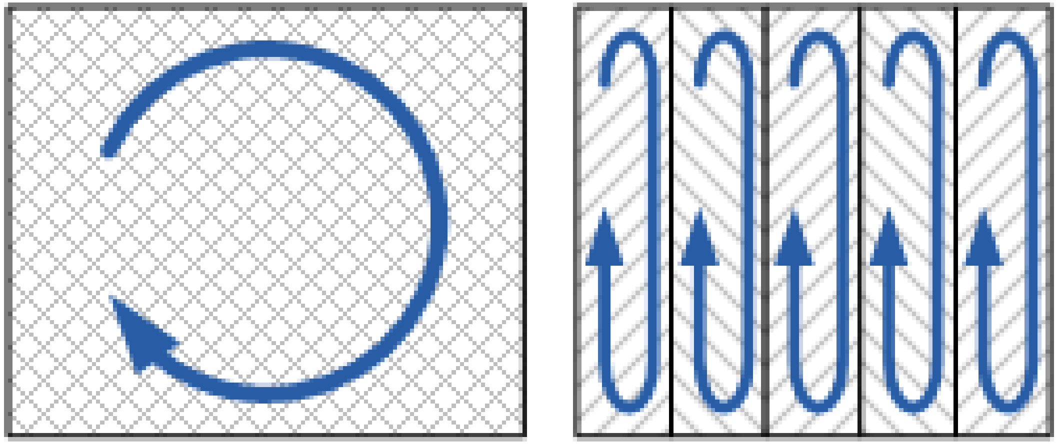
An elliptical cross-section reduces power loss by **34%** compared to rectangular with the same chamber height, width and thickness.



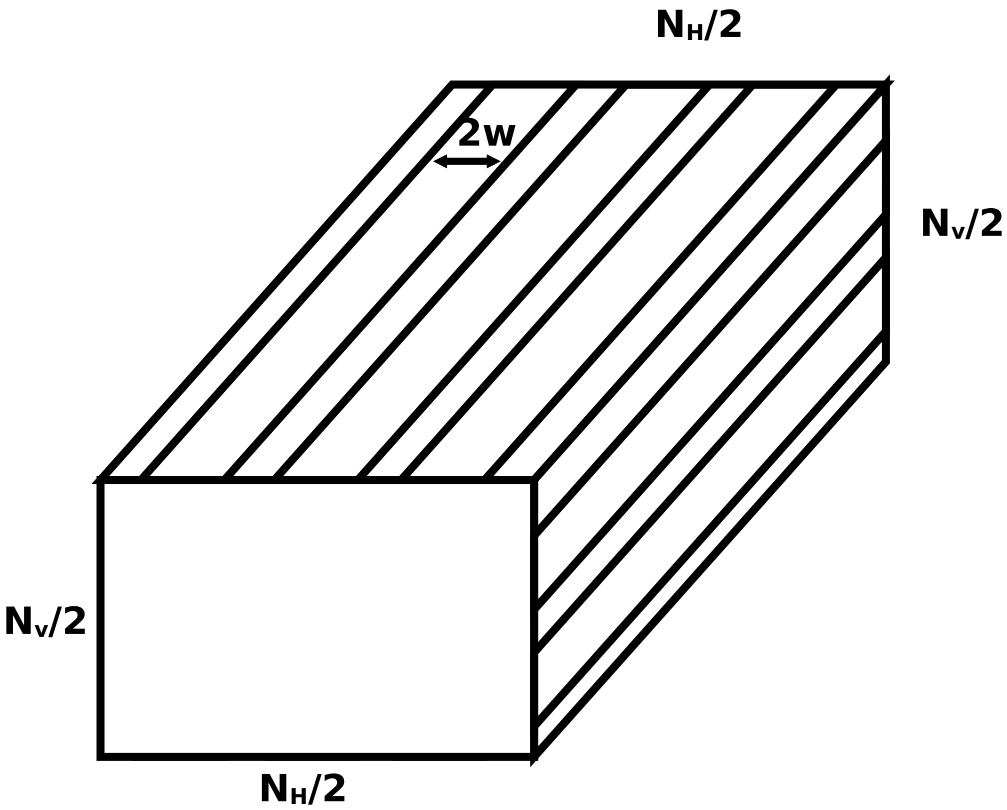
Reduction of Eddy current loss

- Eddy currents can be **reduced** by dividing the vacuum chamber into **thin parallel stripes**.

- Electrons cannot cross between stripes, which will force the currents to circulate in **smaller arcs**, reducing the eddy current loss.



Longitudinal striped design

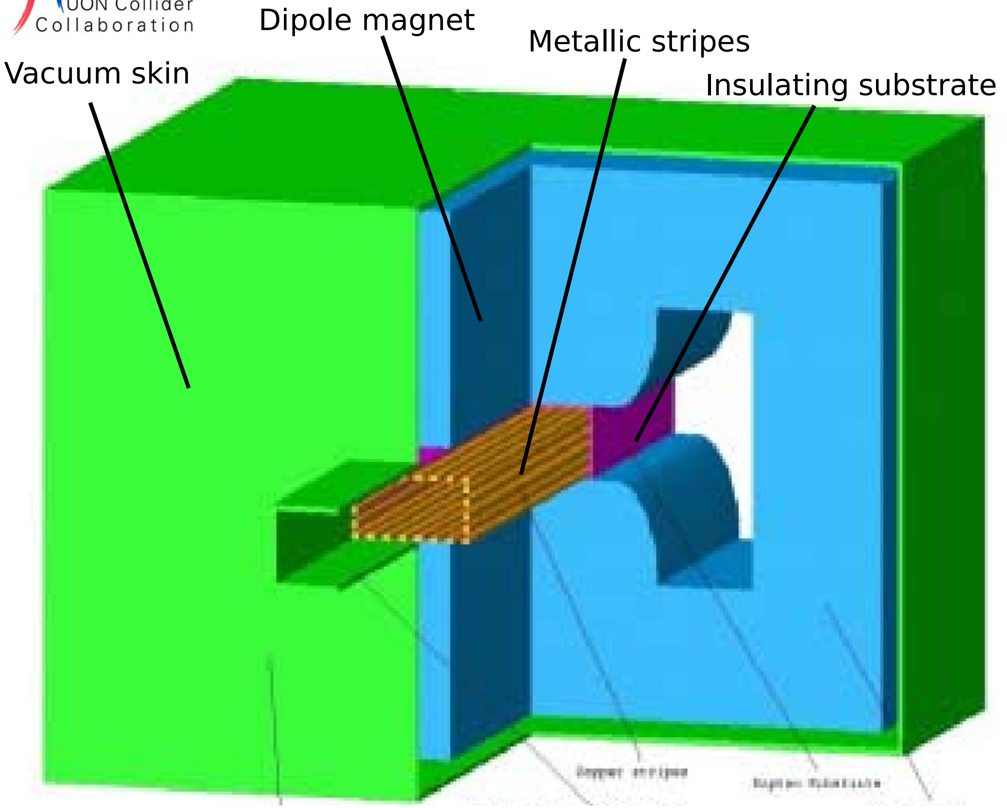


$$P_{eddy}/L = \frac{2}{3}\dot{B}^2 w d\sigma (N_H w^2 + N_V d^2)$$

(The proton driver design study, 2000)

- **B** is the magnetic field
- **w** is the stripe half-width
- **d** is the stripe thickness
- **N_H** is the number of horizontal stipes (top + bottom)
- **N_V** is the number of vertical stipes (left + right)
- **σ** is the chamber's electrical conductivity

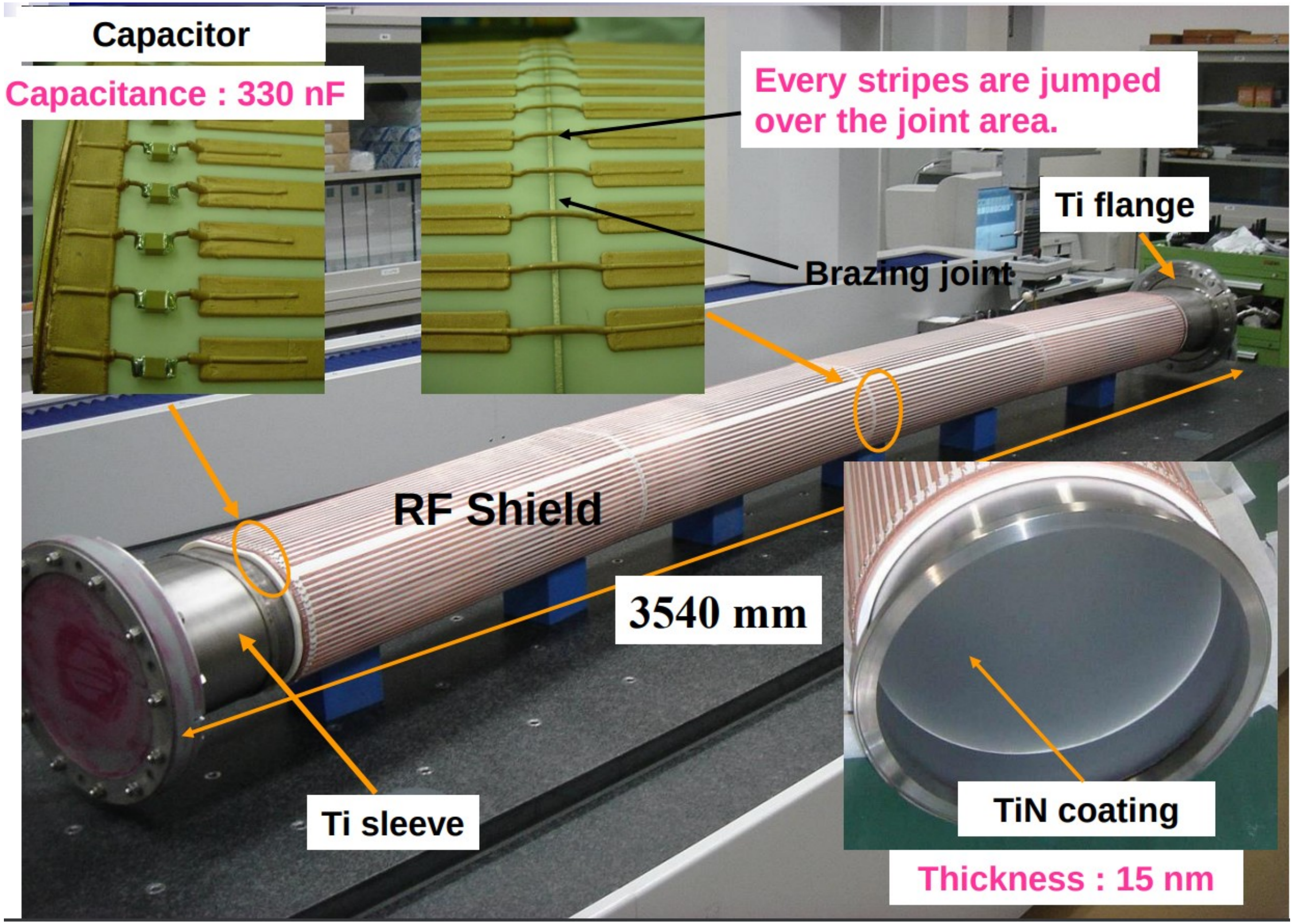
Vacuum problems



(The proton driver design study, 2000)

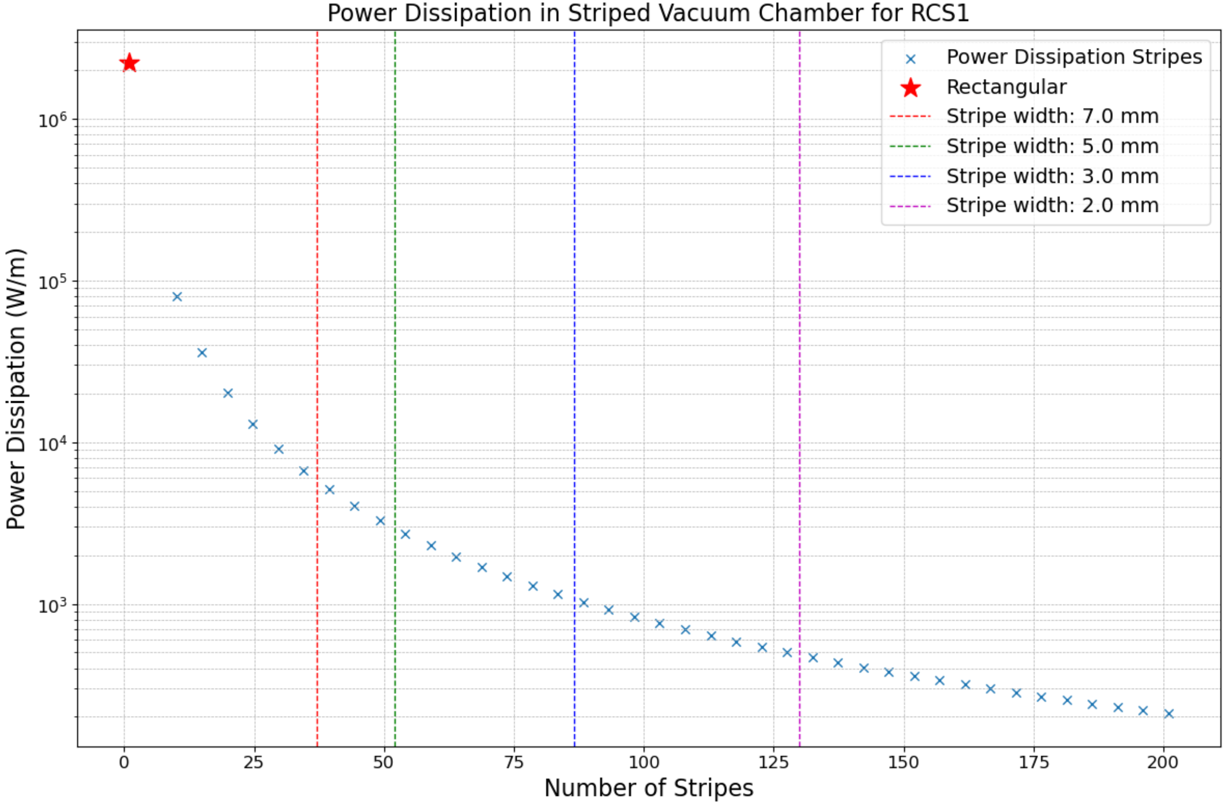
- Only the necessary amount of metal for **shielding** is placed inside the magnet.
- “Vacuum skin” (green) moved outside of magnet .
- Ceramic with longitudinal conducting stripes could be an alternative.

Example from J-PARC



(Michikazu Kinsho, 2005)

Longitudinal striped design



Same parameters as for the rectangular design:

Stainless steel 316LN:

- Resistivity: 7.5×10^{-7} Ωm
- Height and width: 30X100mm
- Thickness: 0.3mm

Reduction of **3 orders of magnitude**.

The rcsparameters package (link)


```python
    @property
    def power_dissipation(self):
        """
        Power dissipation in the beam pipe due to Eddy Currents caused by the fast ramping dipole magnets.
        We assume a uniform magnetic field in the vertical direction.

        Formulas are taken from 'Study of eddy current power loss in an RCS vacuum chamber': https://iopscience.iop.org/article/10.1088/1674-1137/36/2/011/pdf
        and 'The Proton Driver Design Study', FERMILAB-TM-2136, Table 8.4.

        :return: dissipated power per unit length [W/m]
        :rtype: float
        """
        if self.chamber_geometry == 'rectangular':
            return 4 * self.ramping_rate**2 * (self.chamber_width/2)**2 * self.chamber_thickness * self.electrical_conductivity * (self.chamber_width/6 + self.chamber_height/2)

        elif self.chamber_geometry == 'elliptical':
            def integrand(theta, a, b):
                return (np.sin(theta)**2) * np.sqrt(1 - (1 - (b**2 / a**2)) * np.sin(theta)**2)

            result, error = quad(integrand, 0, np.pi/2, args = (self.chamber_width/2, self.chamber_height/2))

            return 4 * self.electrical_conductivity * (self.chamber_width/2)**3 * self.chamber_thickness * self.ramping_rate**2 * result

        elif self.chamber_geometry == 'longitudinal_stripes':
            return 2 * self.ramping_rate**2 * (self.stripe_width / 2) * self.chamber_thickness * self.electrical_conductivity * (self.horizontal_stripes * (self.stripe_width / 2)**2 + self.vertical_stripes * self.chamber_thickness**2) / 3

        else:
            raise ValueError(f"Invalid geometry: '{self.chamber_geometry}'. Chamber needs to be either 'rectangular', 'elliptical', or 'longitudinal_stripes'")
```

```python
            self._chamber_width = eddy_current_input_parameters['Chamber width [m]']

        elif self._chamber_geometry == 'longitudinal_stripes':
            self._horizontal_stripes = eddy_current_input_parameters['Horizontal stripes']
            self._vertical_stripes = eddy_current_input_parameters['Vertical stripes']
            self._stripe_width = eddy_current_input_parameters['Stripe width [m]']

        else:
            raise ValueError(f"Invalid geometry: '{self._chamber_geometry}'. Chamber needs to be either 'rectangular', 'elliptical', or 'longitudinal_stripes'")
```

Conclusion

- A vacuum chamber with large metallic surfaces will result in too large Eddy current losses.

- By using a longitudinally striped design we can get a reduction in power loss of **3 orders of magnitude**.

- Future:
  - Make the RCS parameter class able to calculate power and energy loss from B profile.

Backup

International MUON Collider Collaboration

Overview of the magnet (dipole) model: Losses calculation

	Full resonance circuit		Switched resonance circuit	
	Energy lost [J/cycle/m]	Avg Magnetic Energy [J/m]	Energy lost [J/cycle/m]	Avg Magnetic Energy [J/m]
Iron Joke	58.2	90.2	26.4	12.3
Iron poles	33.2	122.5	16.5	23.0
Total Iron	91.4	212.7	42.9	35.3
Air Gap	0	2003.9	0	1645.3
Stray field	0	1148.8	42.9	964.6
Coil1	13.2	0	36.9	0
Coil 2	40.2	0	78.3	0
Coil 3	36.0	0	68.9	0
Coil 4	59.7	0	95.4	0
Total Cu	149.1	0	322.4	0
Total	240.5	3365.4	365.3	2645.2

(F. Boattini, M. Gast)