Investigating Eddy Current Effects within the RCS Vacuum Chamber

Erik Kvikne

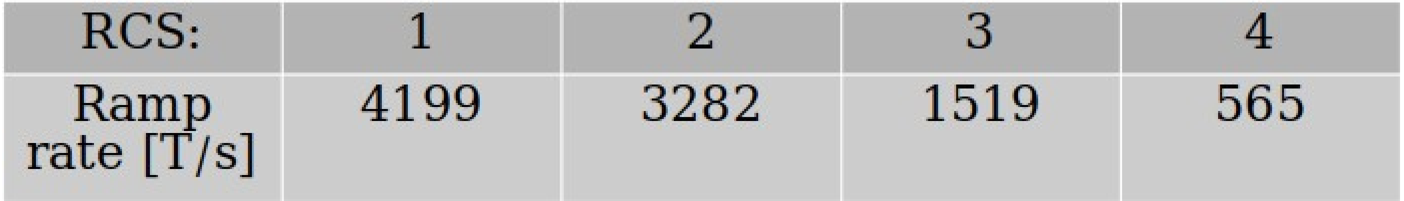
David Amorim, Fabian Batsch, Fulvio Boattini, Heiko Damerau, Marco Gast,
Elias Metral, Leonard Sebastian Thiele

IMCC and MuCol Annual Meeting 2024
14-03-2024

Eddy Currents & Motivation

- **Rapid changes** in the magnetic field strength of the RCS NC magnet will induce significant **Eddy currents** within a metallic vacuum chamber.
- The dissipated power due to these currents scales with the **ramp rate squared**.
- The objective of this work is to get a **first order estimation** of the loss using analytical formulas.
- The losses puts **restrictions on chamber material and geometry** which is important for the beam coupling impedance study.

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



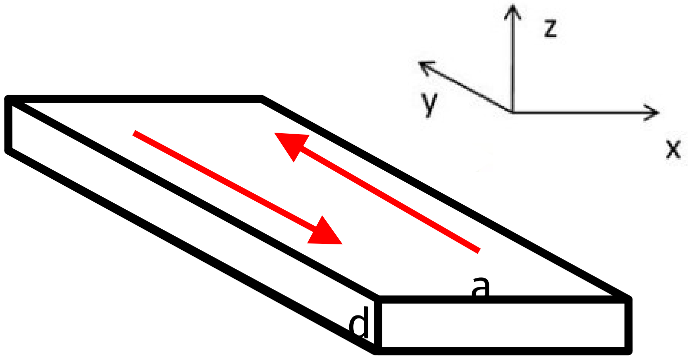
RCS:	1	2	3	4
Ramp rate [T/s]	4199	3282	1519	565

(Tentative Parameter list for the IMCC)

The simplest case: Thin plate

The formula for the **ohmic loss per unit length** in a rectangular **thin plate** due to Eddy currents can be derived analytically:

$$\frac{P}{L} = \frac{da^3\sigma}{12}\dot{B}^2$$



P/L: Ohmic loss per unit length
d: Plate thickness
a: Plate width
σ: Electrical conductivity
B: Magnetic field

The following conditions must be fulfilled:

- B field vertical to the plate, with constant ramp rate.
- Plate magnetically thin: a << penetration depth δ.
- Plate geometrically thin: d << a
- Plate long enough to neglect the ends: a,d << L
- Steady-state conditions.

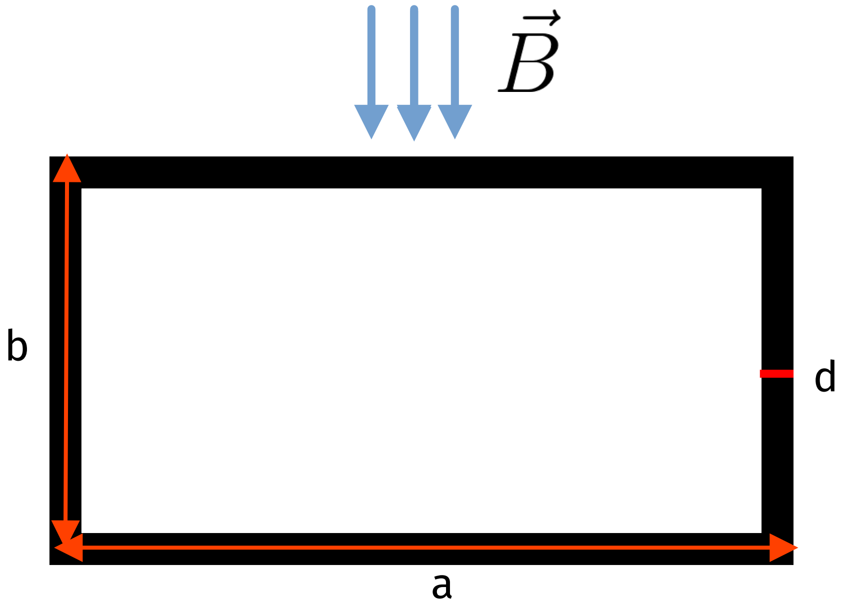
(G. Moritz)

Rectangular Vacuum Chamber

The **ohmic loss per unit length** due to Eddy currents in a **rectangular vacuum chamber** is:

$$P/L = \frac{\dot{B}^2 a^2 d\sigma}{2}(\frac{a}{3} + b)$$

(A. Lachaize)

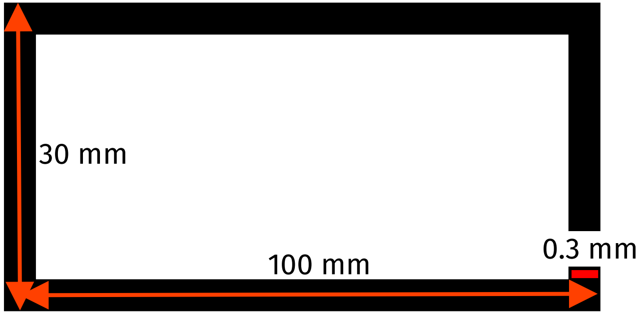


P/L: Ohmic loss per unit length
d: Wall thickness
a: Chamber width
b: Chamber height
σ: Electrical conductivity
B: Magnetic field

Stainless Steel Rectangular Vacuum Chamber

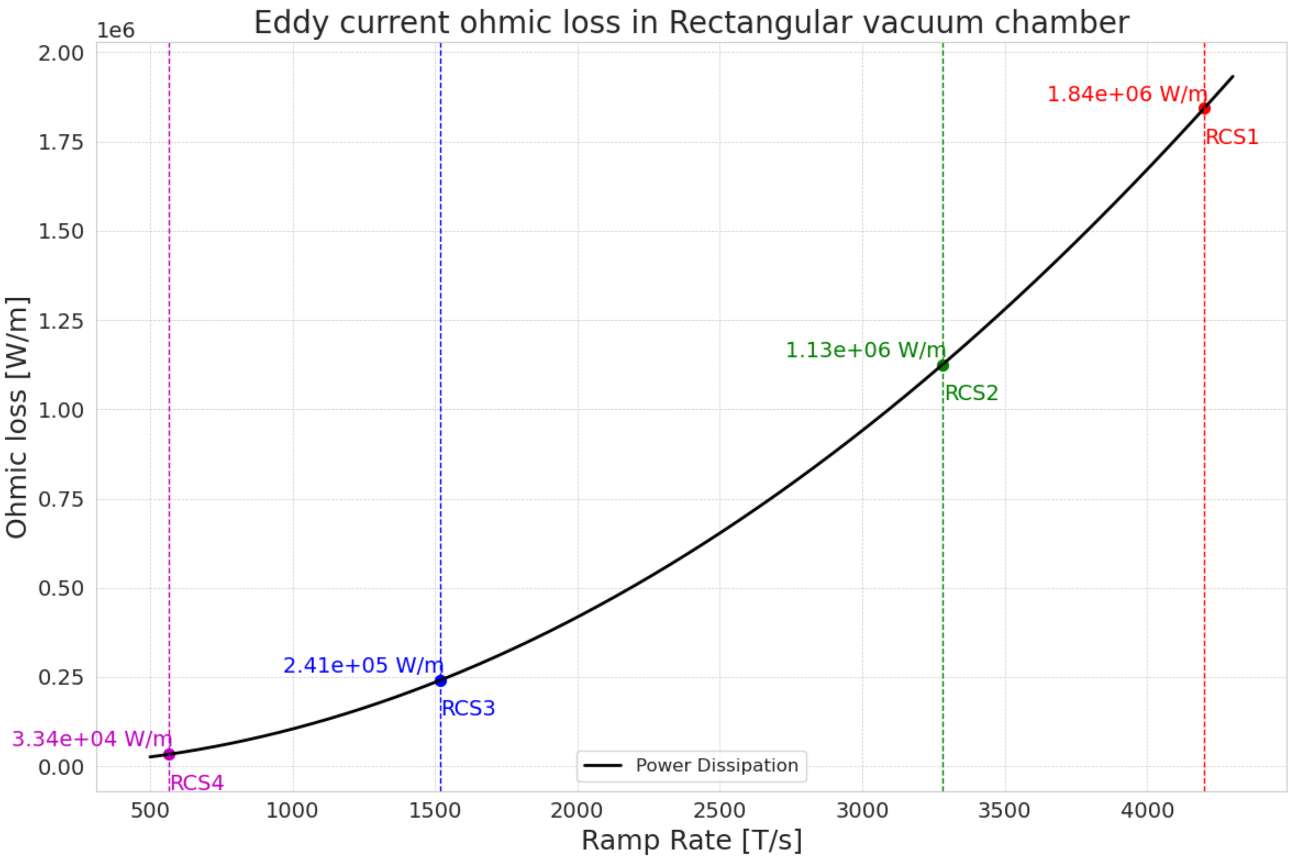
Stainless steel vacuum chamber:

- Conductivity: 1.1 × 10^6 S/m
- Height and width: 30X100mm*
- Thickness: 0.3mm



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

*(Tentative Parameter list for the IMCC)

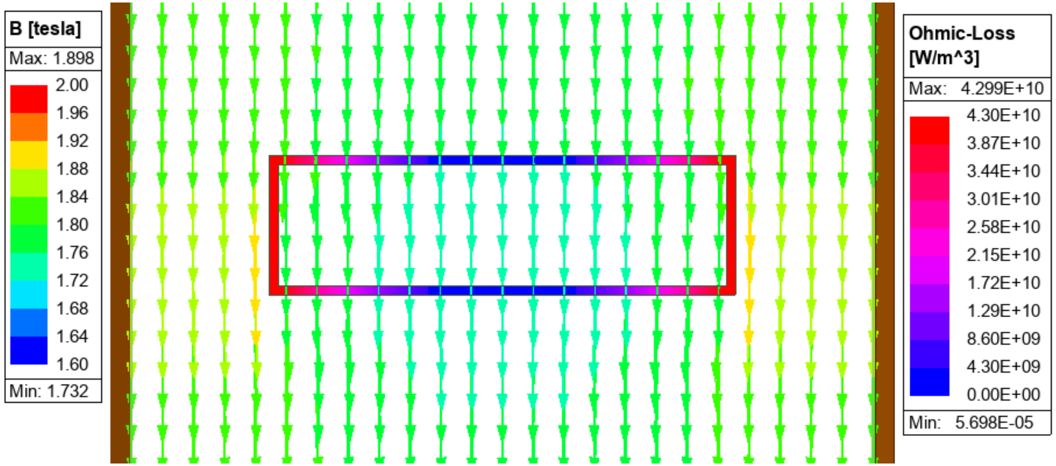


Electromagnetic Simulation

International
MUON Collider
Collaboration

MAXWELL

- Uncertainties arise regarding the analytical formula's applicability due to the rapid ramp rates of the RCS.
- **Ansys Maxwell2D** was used to validate the analytical formula by comparing with **electromagnetic simulations** for conditions similar to the ones of the RCS.
- In these simulations a **uniform magnetic field** is created between two large conducting plates, excited by an alternating current with **frequency *f***. The field strength at any point is approximately given by:



$$B(t) = B_0 cos(2\pi f \cdot t)$$

Electromagnetic Simulation

The Ansys Eddy current solver computes the **time averaged ohmic loss**. In order to compare simulated results with our analytical formula we need to calculate the time average.

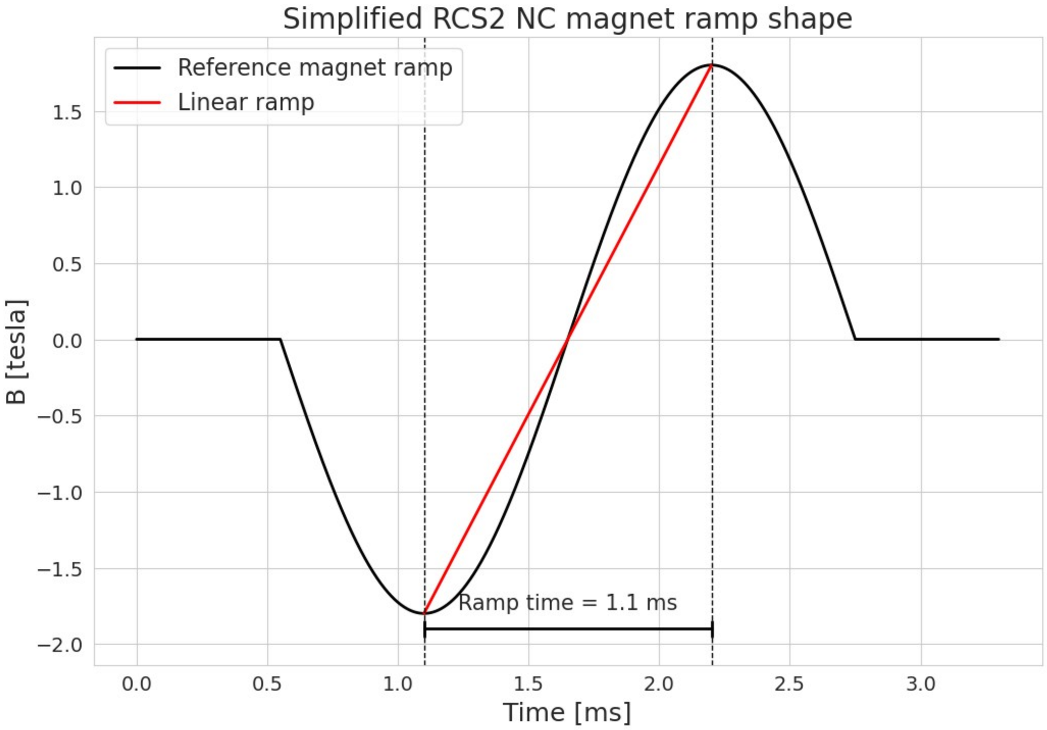
$$\langle P \rangle = \frac{1}{T}\int_0^T P(t)dt$$

Thin plate:

$$\frac{\langle P \rangle}{L} = \frac{da^3\sigma\pi^2}{6}(B_0 f)^2$$

Rectangular beam pipe:

$$\frac{\langle P \rangle}{L} = 8a^2 d\sigma(\frac{a}{3}+b)(B_0 f)^2$$

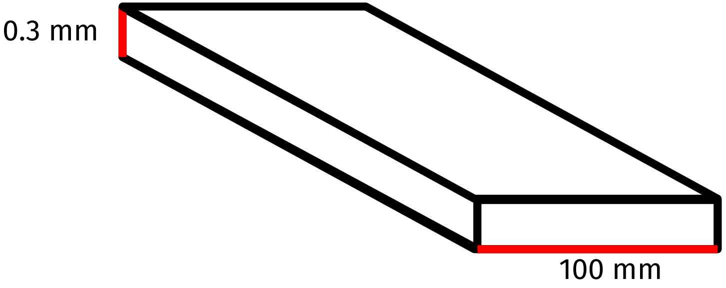


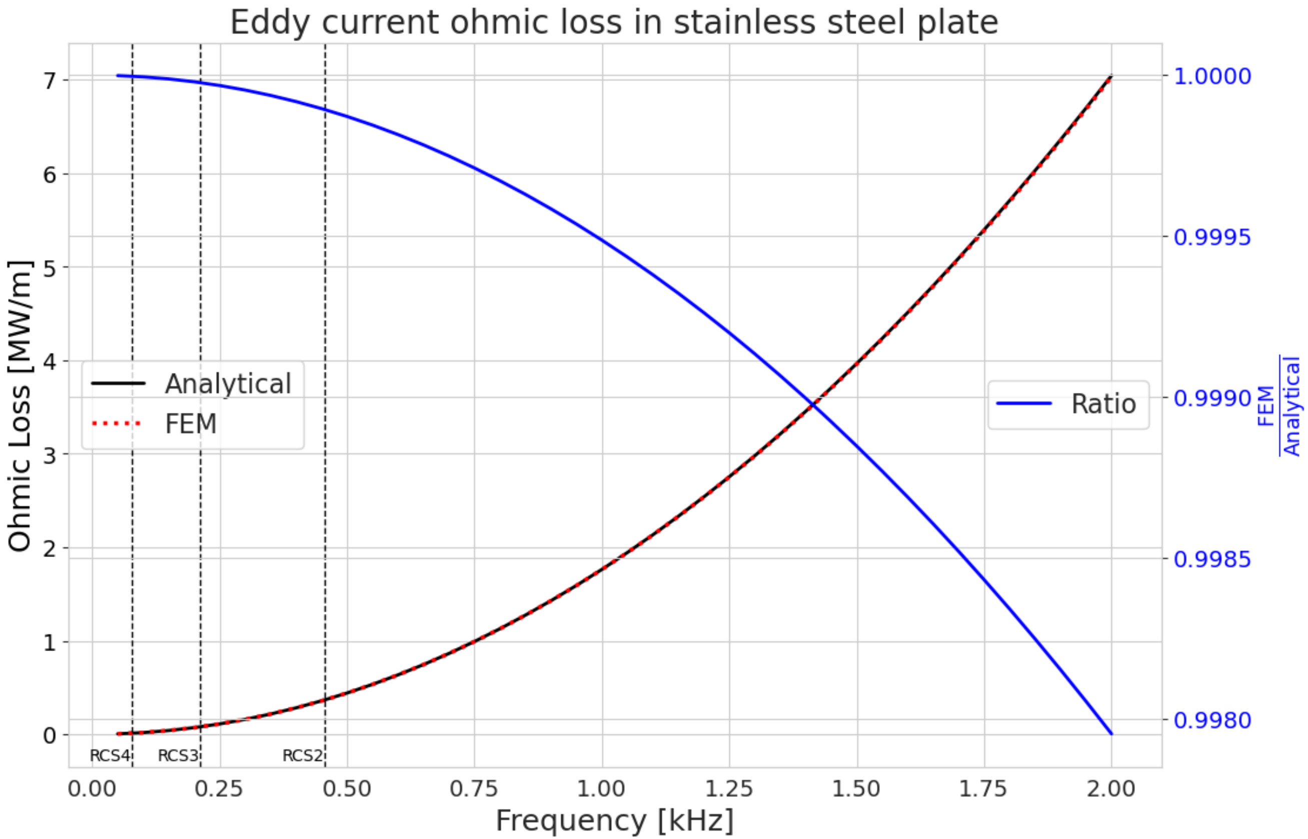
d: Thickness
a: Width
b: Height (Rectangular beam pipe only)
σ: Electrical conductivity
B_0: Magnetic field amplitude
f: B field’s frequency of oscillation

Stainless Steel thin plate

Stainless steel plate:

- Conductivity: 1.1 × 10^6 S/m
- Width: 100mm
- Thickness: 0.3mm

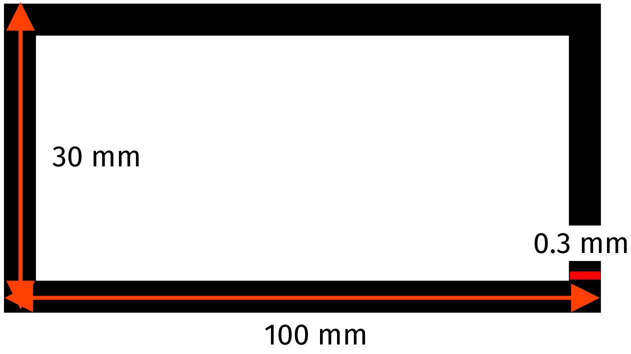


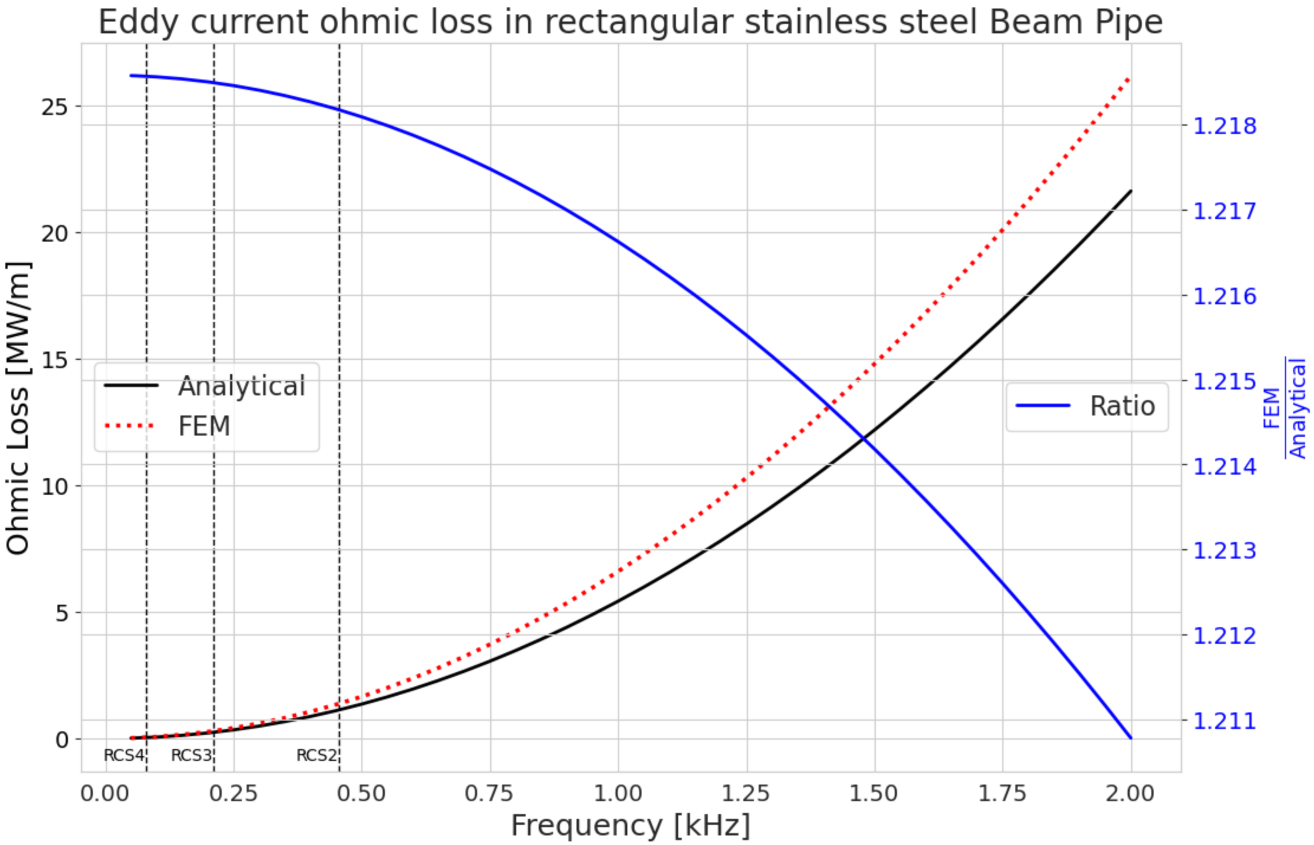


Stainless Steel Rectangular Vacuum Chamber

Stainless steel:

- Conductivity: 1.1 × 10^6 S/m
- Height and width: 30X100mm*
- Thickness: 0.3mm





*(Tentative Parameter list for the IMCC)

Energy loss

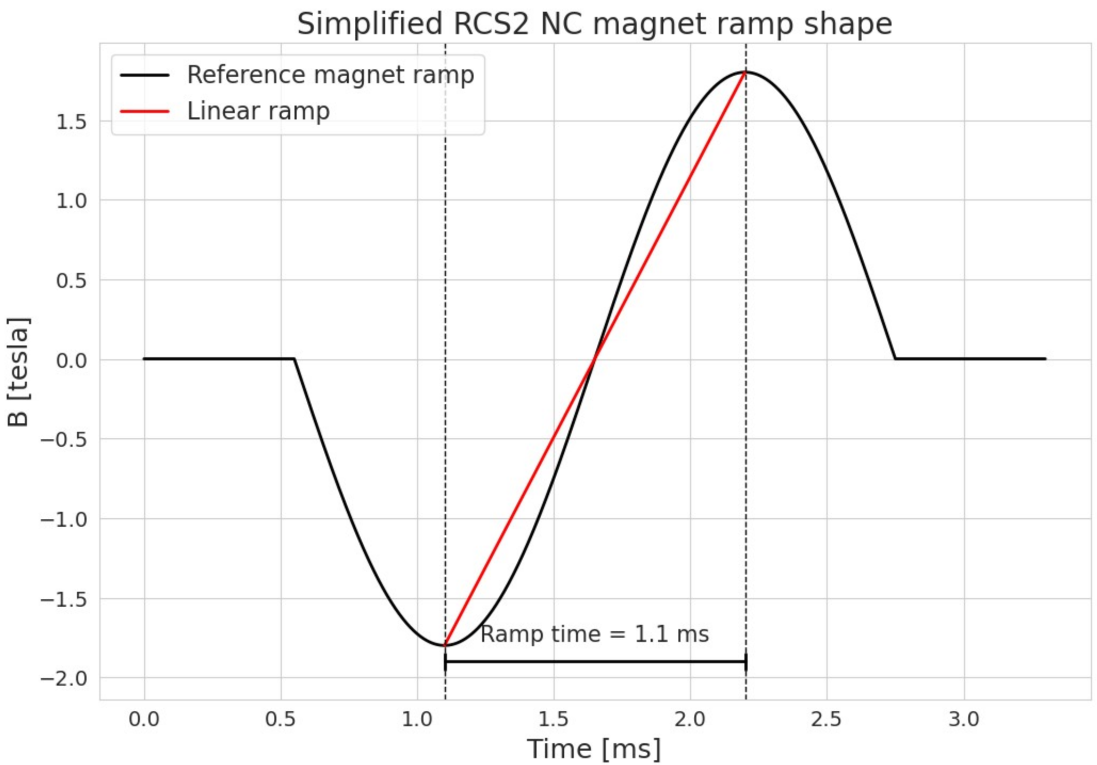
The **energy loss** per cycle can be estimated by using the ramp time (T_{ramp}) from the tentative parameters list.

RCS:	2	3	4
T_{ramp} [ms]	1.1	2.37	6.37

And by assuming the magnetic field of one cycle can be modeled as a **sine wave** with a period of $2T_{ramp}$.

$$Q \approx \frac{\langle P \rangle}{L} \cdot 2T_{ramp}$$

Where Q is the energy loss per cycle in the rectangular vacuum chamber due to Eddy currents.



Energy loss per cycle rectangular beam pipe:

RCS:	2	3	4
Energy loss [J/cycle/m]	2462	1143	425

Energy loss

The **energy loss** per cycle can be estimated by using the ramp time (T_{ramp}) from the tentative parameters list.

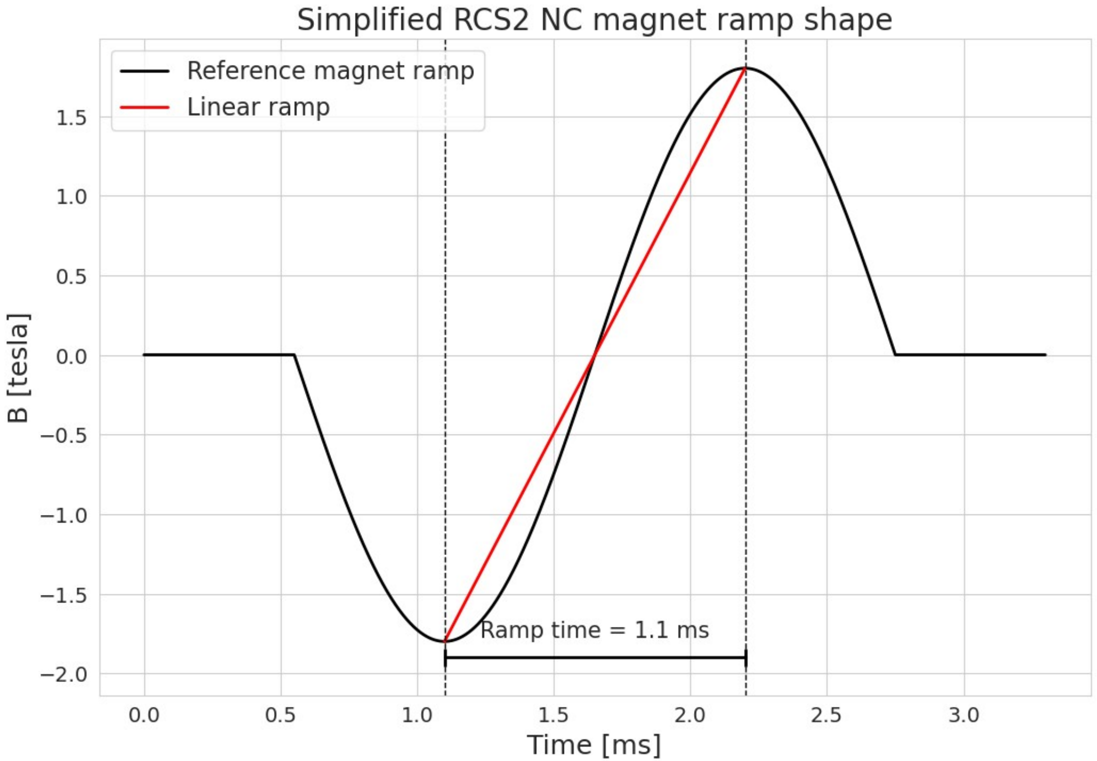
RCS:	2	3	4
T_{ramp} [ms]	1.1	2.37	6.37

And by assuming the magnetic field of one cycle can be modeled as a **sine wave** with a period of $2T_{ramp}$.

$$Q \approx \frac{\langle P \rangle}{L} \cdot 2T_{ramp}$$

Larger than total energy loss of magnet! (F. Boattini, M. Gast)

<u>A continuous conducting beam pipe will cause too large losses.</u>



Energy loss per cycle rectangular beam pipe:

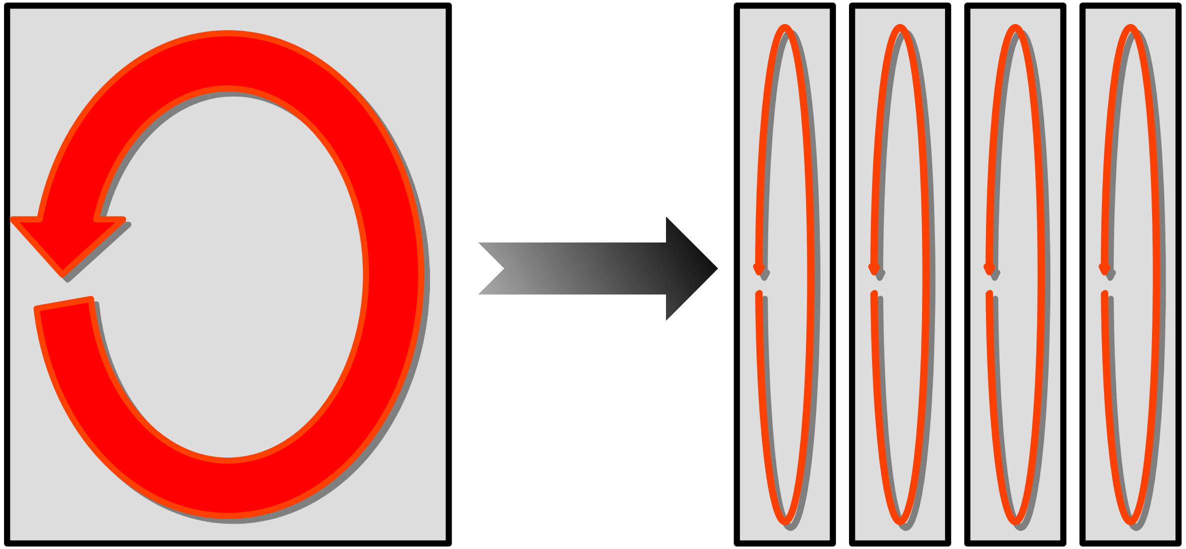
RCS:	2	3	4
Energy loss [J/cycle/m]	<u>2462</u>	1143	425

Reducing Eddy Current Losses

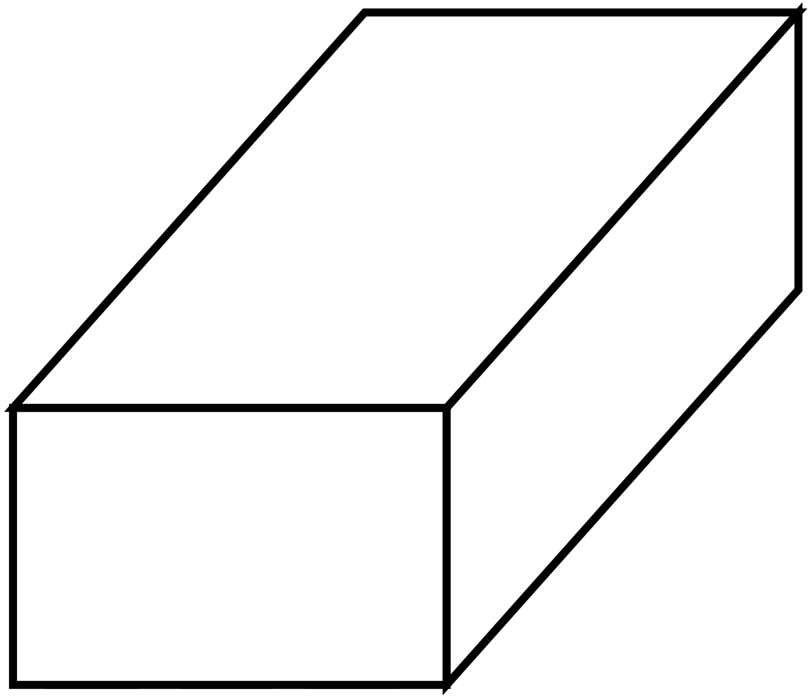
A vacuum chamber made of a material with low conductivity, like **ceramic** ($\sigma \sim 10^{-12}$ S/m), would eliminate the problem of Eddy currents.

But RF shield is necessary to keep the **chamber impedance** low.

Since the losses within a plate is proportional to the **cube of its width**, we can significantly reduce the losses by segmenting the beam pipe into **thin parallel strips**.



Longitudinal striped design



Instantaneous:

$$\frac{P}{L} = \frac{\dot{B}^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

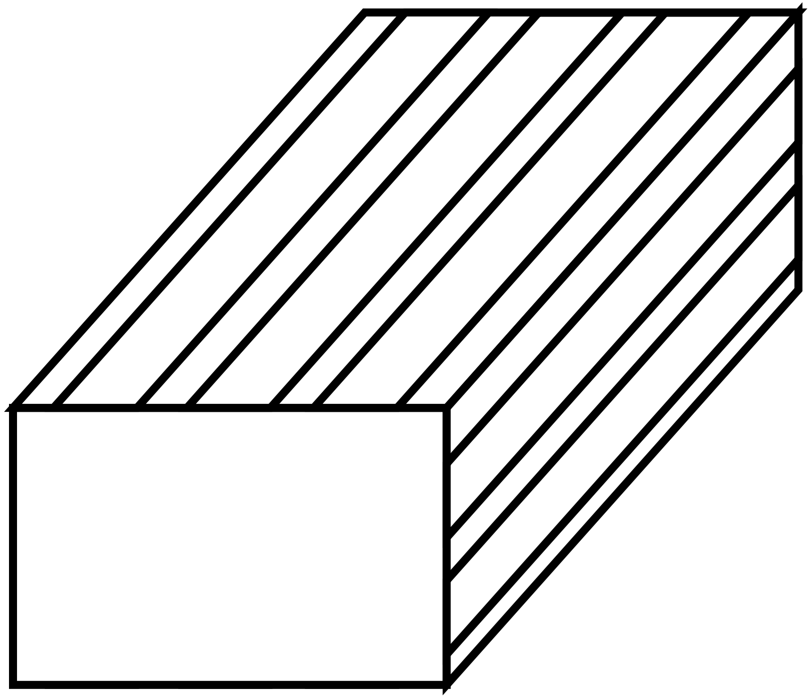
(The proton driver design study, 2000)

Time averaged:

$$\frac{\langle P\rangle}{L} = \frac{2\pi^2(B_0 f)^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

w: Stripe width
d: stripe thickness
N_H: Number of horizontal stripes (top + bottom)
N_V: Number of vertical stripes (left + right)
σ: Electrical conductivity
Instantaneous:
B: Magnetic field strength
Time averaged:
B_0: Magnetic field amplitude
f: B field's frequency of oscillation

Longitudinal striped design



Instantaneous:

$$\frac{P}{L} = \frac{\dot{B}^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

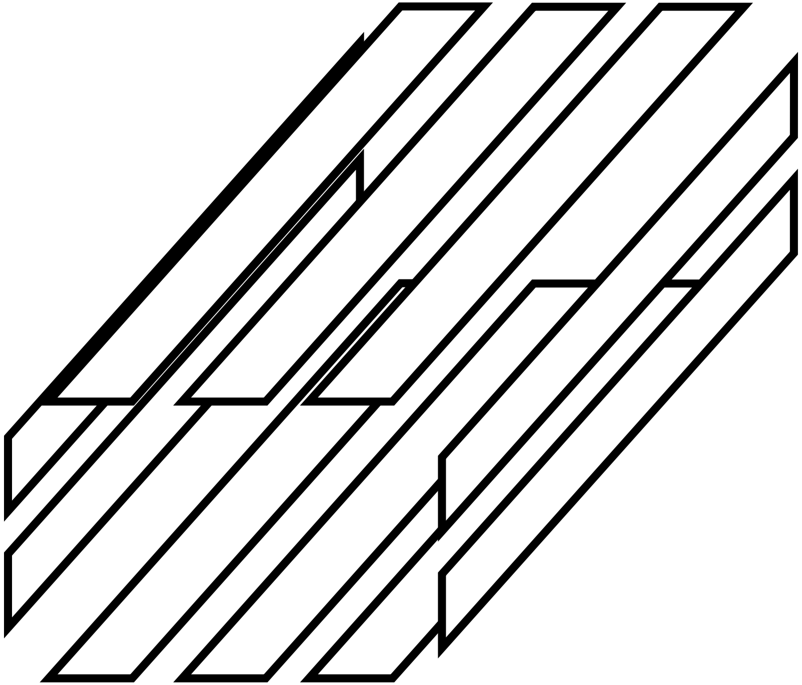
(The proton driver design study, 2000)

Time averaged:

$$\frac{\langle P\rangle}{L} = \frac{2\pi^2 (B_0 f)^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

w: Stripe width
d: stripe thickness
N_H: Number of horizontal stripes (top + bottom)
N_V: Number of vertical stripes (left + right)
σ: Electrical conductivity
Instantaneous:
B: Magnetic field strength
Time averaged:
B_0: Magnetic field amplitude
f: B field's frequency of oscillation

Longitudinal striped design



Instantaneous:

$$\frac{P}{L} = \frac{\dot{B}^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

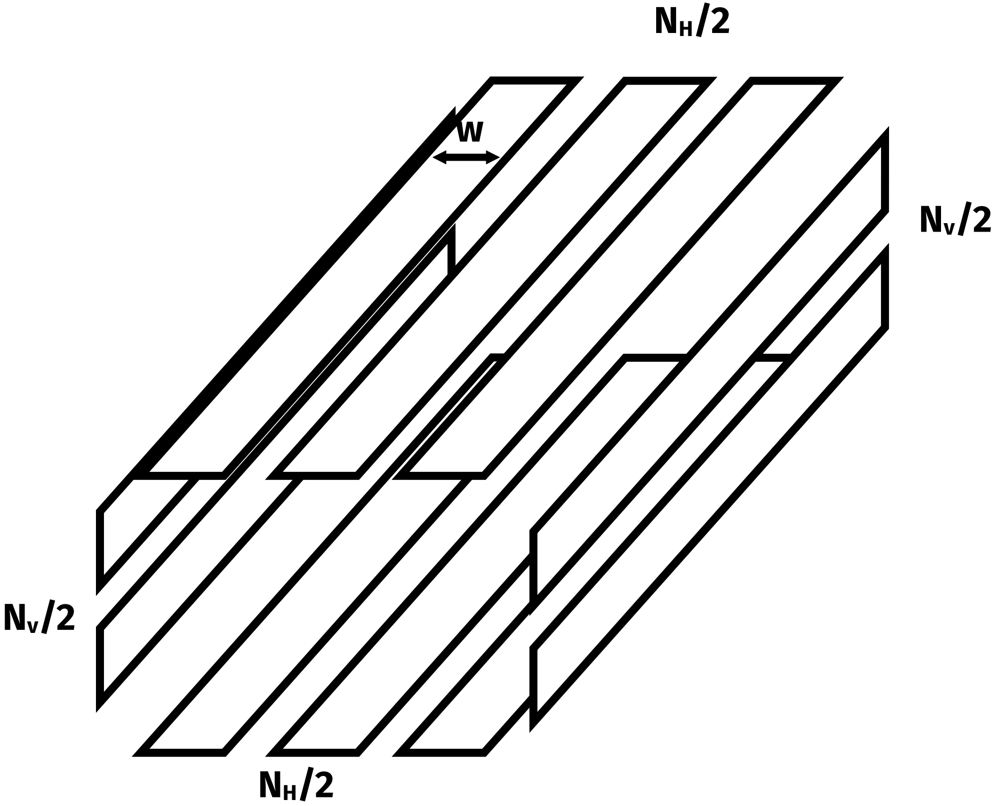
(The proton driver design study, 2000)

Time averaged:

$$\frac{\langle P \rangle}{L} = \frac{2\pi^2 (B_0 f)^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

w: Stripe width
d: stripe thickness
N_H: Number of horizontal stripes (top + bottom)
N_V: Number of vertical stripes (left + right)
σ: Electrical conductivity
Instantaneous:
B: Magnetic field strength
Time averaged:
B_0: Magnetic field amplitude
f: B field's frequency of oscillation

Longitudinal striped design



Instantaneous:

$$\frac{P}{L} = \frac{\dot{B}^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

(The proton driver design study, 2000)

Time averaged:

$$\frac{\langle P\rangle}{L} = \frac{2\pi^2 (B_0 f)^2 w d\sigma}{3}\left(\frac{N_H w^2}{4} + N_V d^2\right)$$

w: Stripe width
d: stripe thickness
N_H: Number of horizontal stripes (top + bottom)
N_V: Number of vertical stripes (left + right)
σ: Electrical conductivity

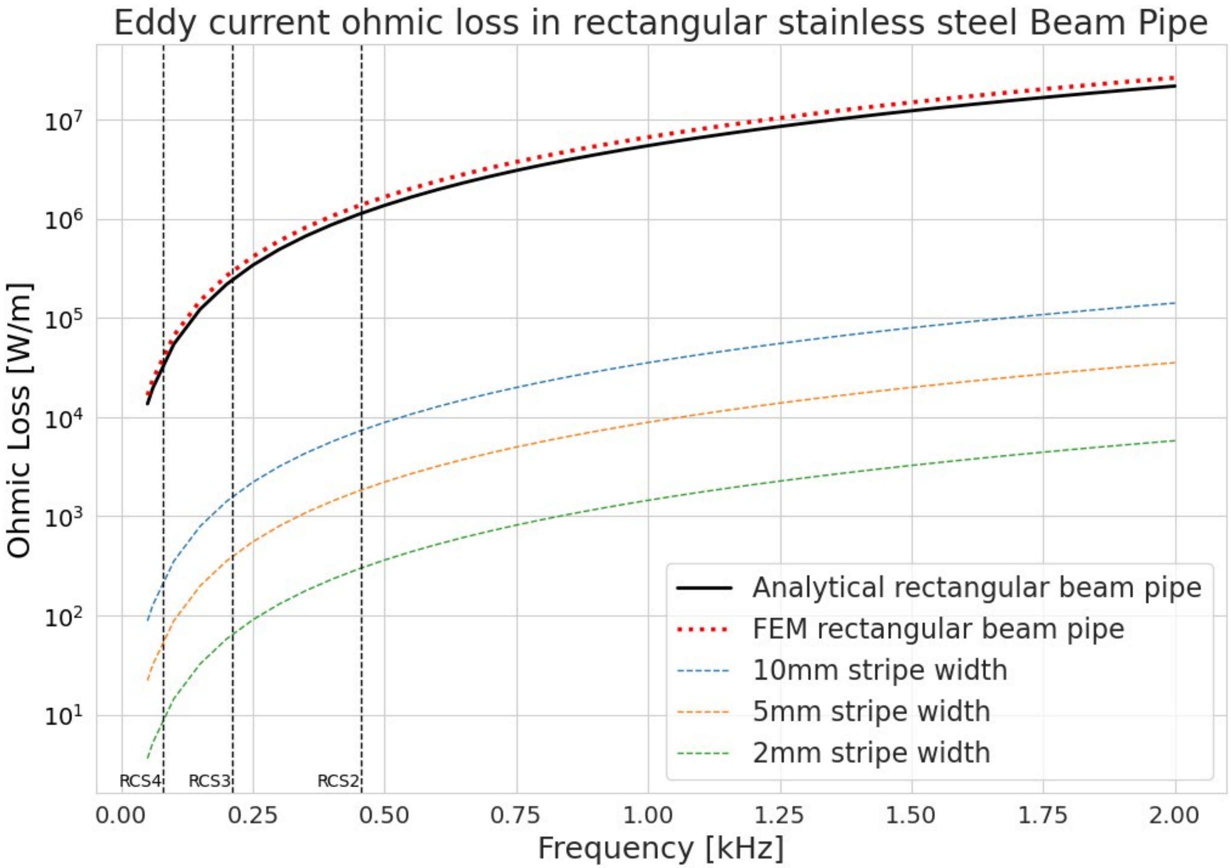
Instantaneous:

B: Magnetic field strength

Time averaged:

B_0: Magnetic field amplitude
f: B field's frequency of oscillation

Longitudinal striped design



By changing to a striped design, while keeping the thickness unchanged, we see a reduction of ohmic loss of **2-3 orders of magnitude** depending on the width of the stripes.

This assumes the parallel stripes to be touching. In reality we would have some spacing between them. This will in turn reduce the number of stripes and thus the ohmic loss further.

Energy loss

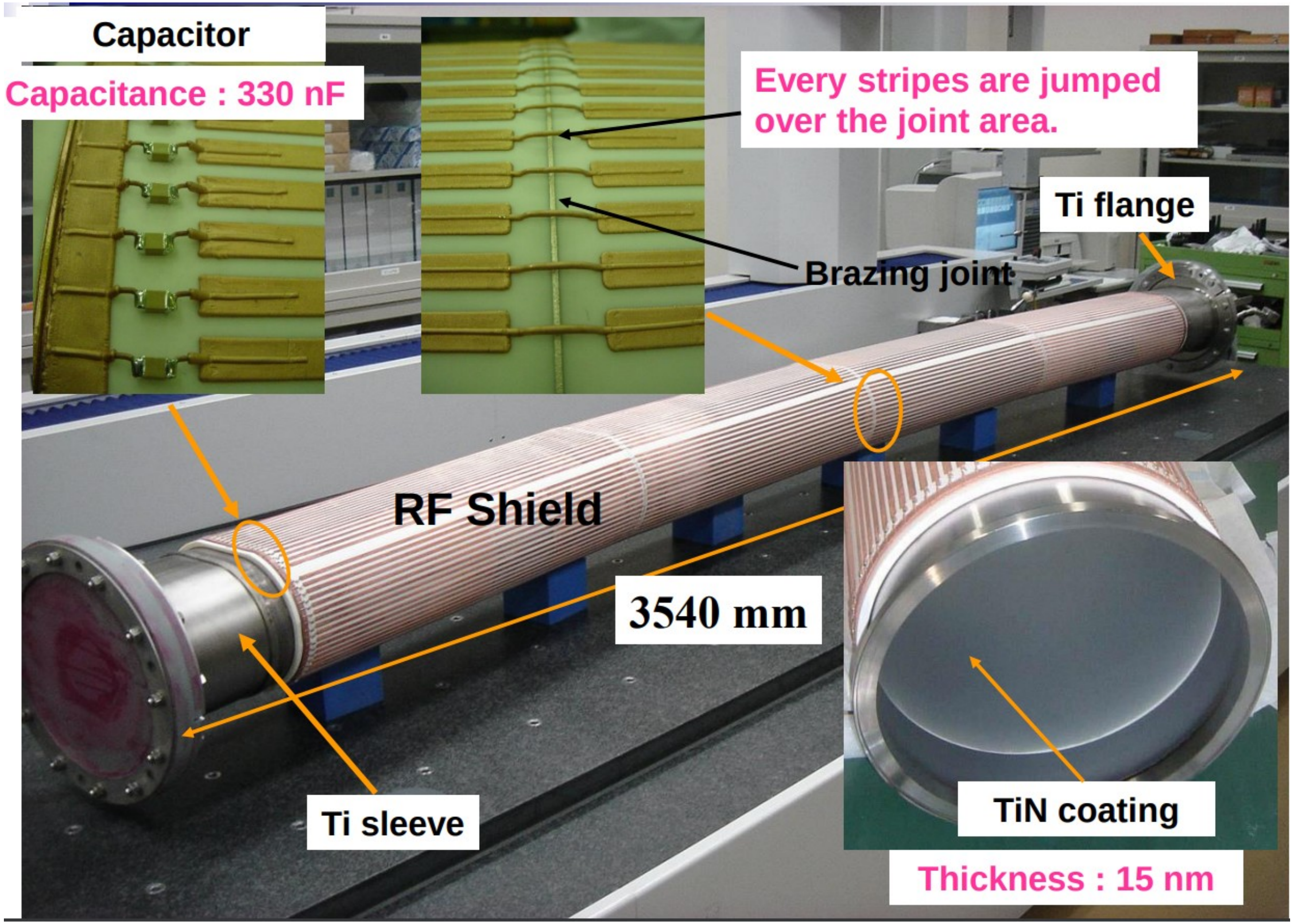
Energy loss per cycle for rectangular beam pipe:

RCS:	2	3	4
Energy loss [J/cycle/m]	2462	1143	425

Energy loss per cycle for the longitudinally striped design:

	RCS:	2	3	4
10 mm stripe width	Energy loss [J/cycle/m]	16.01	7.43	2.76
5 mm stripe width	Energy loss [J/cycle/m]	4.01	1.86	0.69
2 mm stripe width	Energy loss [J/cycle/m]	0.65	0.30	0.11

Example from J-PARC



(Michikazu Kinsho, 2005)

Conclusion and next step

- Large metallic surfaces in the RCS vacuum chamber leads to unacceptable Eddy current losses.

- By using a ceramic vacuum chamber with a RF shield consisting of thin longitudinal stripes on the outside we can reduce the Eddy current losses significantly.

- Next steps:
  - Confirm the analytical formula for the longitudinally striped design with electromagnetic simulations.
  - Further investigate the beam coupling impedance of a ceramic beam pipe with longitudinal conducting stripes on the outer surface.

International
MUON Collider
Collaboration

MuCol

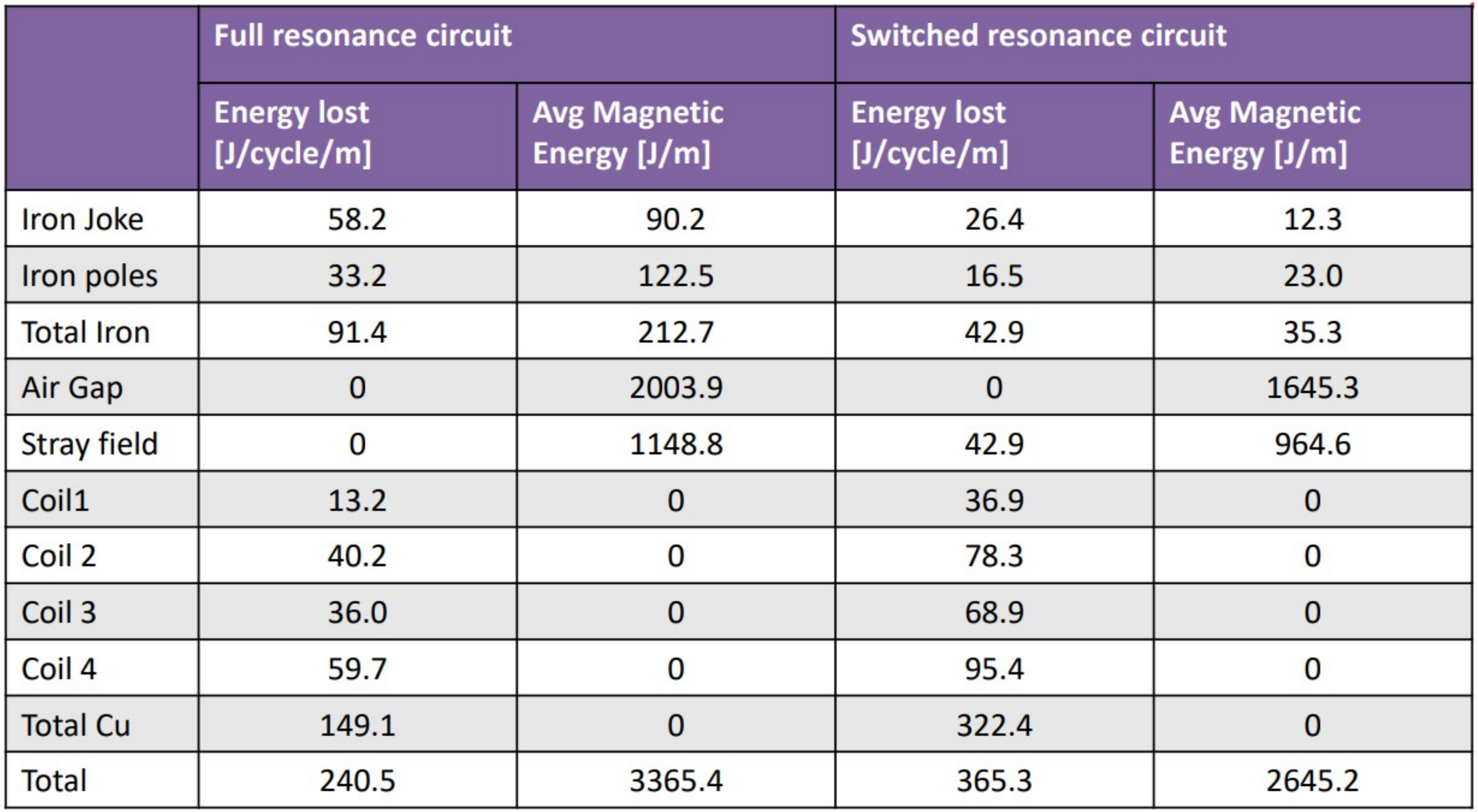
NTNU
Norwegian University of
Science and Technology

CERN

Thank you for your attention!

Backup

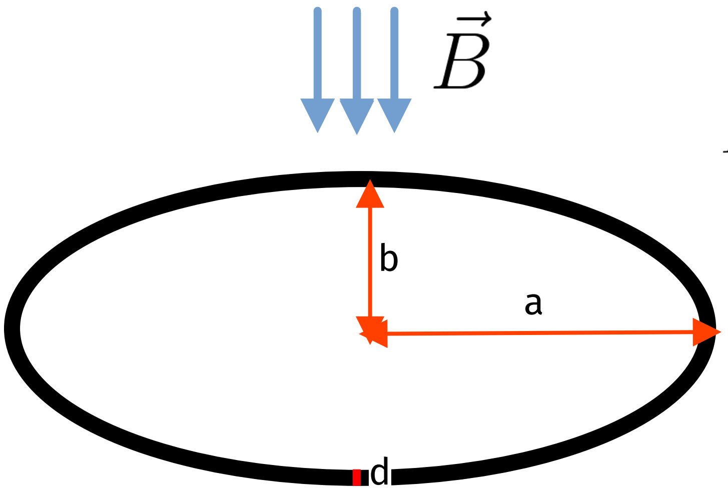
Overview of the magnet (dipole) model: Losses calculation



	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)

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