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Transient Simulation of the ISIS Synchrotron Singlet Quadrupoles Using OPERA 3D

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Abstract

*Type QX106 singlet magnets are AC defocusing quadrupoles used in the **ISIS main synchrotron** ring. They have an aperture of 202 mm and a yoke length of 303 mm, so the end effects are significant. The iron poles and the yoke are **asymmetric** and the coils are driven by a 50Hz, 400 A AC current, biased with a DC current of 665 A. Therefore the yoke has to be **laminated**, and the laminations are **slitted** up to a depth of 90 mm on each end to further reduce the eddy current losses. Two 3D models (**DC and transient**) have been developed using **OPERA 3D** for different purposes. Both models require the use of an **anisotropic BH curve** for the yoke, and the transient model also requires an **anisotropic conductivity** and a prismatic/hexahedral mesh to overcome the limitations of the linear tetrahedral edge elements in OPERA's **vector potential** formulation. The quadrupole field quality was originally **measured in 1982** with a DC excitation at the biased peak current (1065 A) and those measurements are now compared to both models. The **iron losses** due to the eddy currents are also presented and compared to the original specifications defined in **1980**, as well as an estimation of the **eddy currents in the coils**.*

Specifications

The requirement to build a batch of **new spare coils** for the QX106 magnets has triggered the need to **better understand**/cross check the specifications from **1980's documents**.

Table 1. Main QX106 Specifications

Parameter	Value	Units
Peak gradient	3.545	T/m
Aperture	212	mm
Effective length	402	mm
Inductance	3	mH
Yoke length	303	mm
Peak current	1062	A
RMS current	720	A
Power loss in coils (40 °C)	**4.7**	**kW**
Power loss in iron	**~0.5**	**kW**

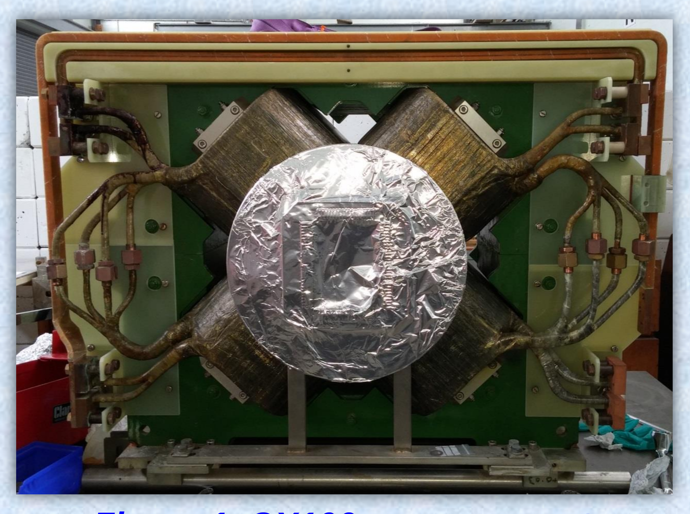

Figure 1. QX106 spare magnet

Magnetic simulations

Common requirements

The software used for the magnetic modelling of the QX106 singlet was **OPERA v18R2**. The **QX106 yoke** geometry is presented in **Figure 2** with the maximum allowable symmetry.

The pole ends have **0.9 mm wide slits** up to a depth of about 90 mm on each end of the poles to reduce the **eddy currents** due to the alternating axial B field. The small slits have to be modelled both in the magnetostatic and the transient models.

The **laminated yoke** is made of **0.35 mm** thickness, **non-oriented grain** electrical steel, with a **packing factor** (PF) of **0.92**. The anisotropic properties of the laminated yoke have been modelled using a **homogenisation approach** (anisotropic permeability).

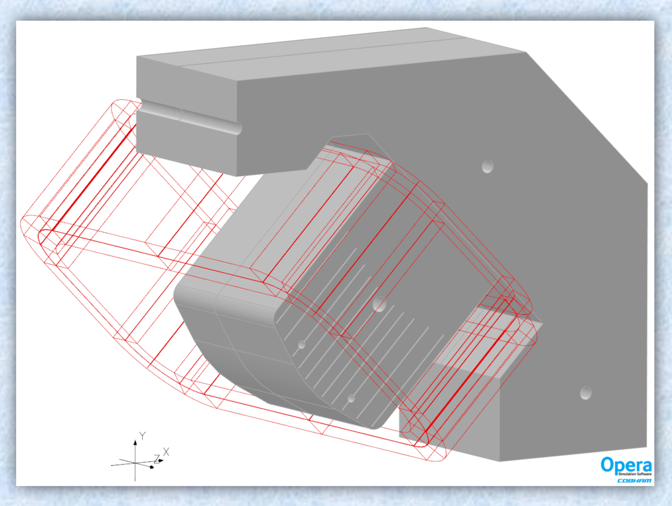

Figure 2. Geometry of 1/8th of the yoke

The **coils** have been modelled as **Biot-Savart** conductors.

Magnetostatic model

The magnetostatic model was meshed with **3.3M elements**, using **2nd order tetrahedrons** (10 node). The OPERA's magnetostatic solver **TOSCA** (magnetic scalar potential) was used.

The model was solved at 2 currents (**1065 A** and **265 A**), to estimate the **eddy current loss** both in the **yoke** (parallel B fields) and in the **coils** by using the DC model.

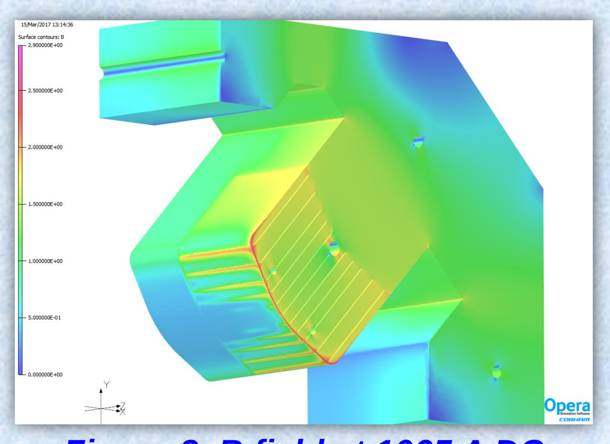

Figure 3. B field at 1065 A DC

Table 2: QX106 measurements and model results

Parameter	1982 measurement	Magnetostatic model
Integrated field (r=95.4 mm)	0.13465 T.m	0.13364 T.m
b1	-7.8x10^{-4}	0
a1	23.7x10^{-4}	0
b3	2.1x10^{-4}	0
a3	-1.8x10^{-4}	0
b4	-16.6x10^{-4}	-12.9x10^{-4}
b6	**-25.7x10^{-4}**	**-21.9x10^{-4}**
b10	12.1x10^{-4}	13.5x10^{-4}
b14	-18.8x10^{-4}	-19.9x10^{-4}

Transient model

Changes from the magnetostatic model to the transient model:

- The **conductivity** tensor has to be **anisotropic** (σ_{zz}=0) for the homogenisation approach to work. A **nonzero** equivalent conductivity in the Z direction has been chosen to both achieve **numerical convergence** and also to obtain a realistic value of the eddy current **losses** due to the B field **parallel to the laminations**.

$$\sigma_{zz} = \frac{1}{PF}\left({}^{d}/_{a}\right)^{2}\sigma \quad \textbf{(1)}$$

- The mesh was built using **prismatic/hexahedral** elements (Fig. 4) to avoid big errors due to the compulsory linear elements in **ELEKTRA**, the OPERA's transient solver (magnetic vector potential). The element count was **reduced to 1.5 M** and the solver was tuned for speed.
- The **iron holes** were **removed** to allow a full prismatic mesh in the iron (ACIS core problem).

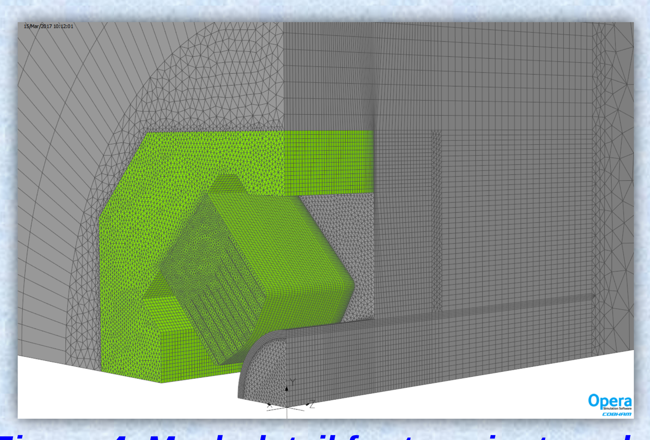

Figure 4. Mesh detail for transient model

SOLVING TIME: ~19.5 days

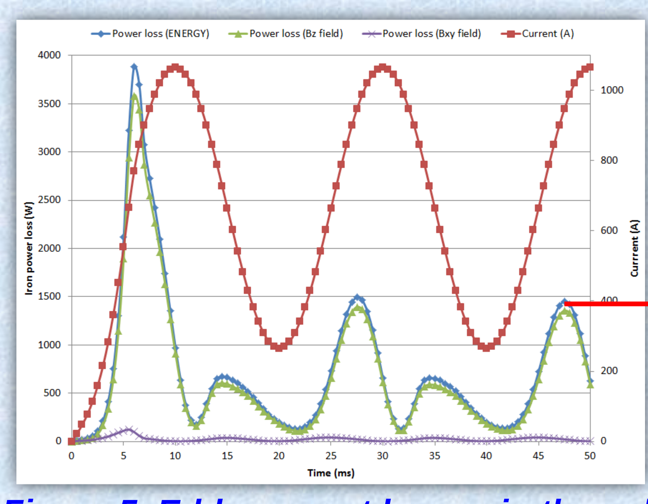

Figure 5. Eddy current losses in the yoke

The calculated **eddy power loss** averaged in one cycle (30 to 50 ms) is **537W**, being 518 W due to B_z field and only 19 W due to B_{xy} fields (**Fig. 5**).

The power due to the **hysteresis and anomalous losses** is calculated from the steel manufacturer's data at different fields and frequencies, and it results in **41.7 W** and **24.5 W** respectively (B_{xy} fields).

The **total power loss** in the iron is around **603 W**, roughly similar to the estimation in Table 1.

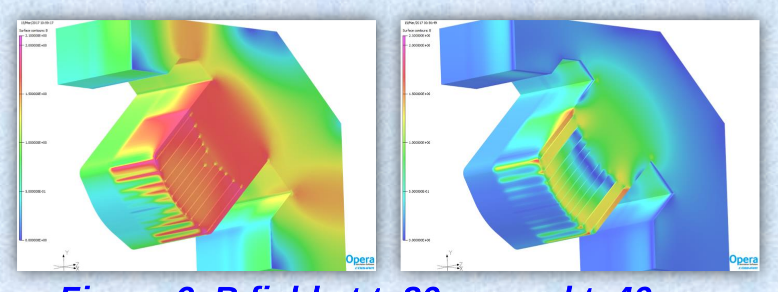

Figure 6. B field at t=30 ms and t=40 ms

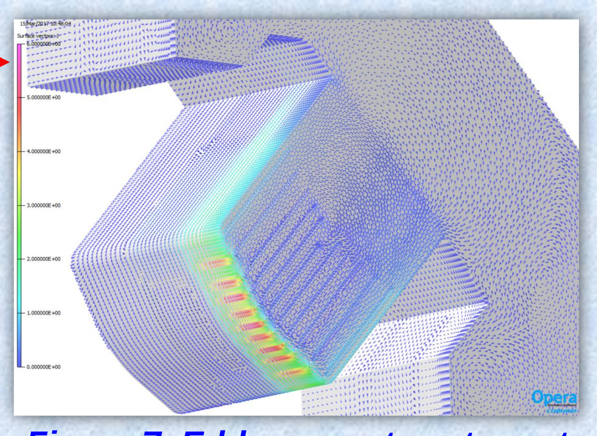

Figure 7. Eddy current vectors at peak loss (t=47.5 ms)

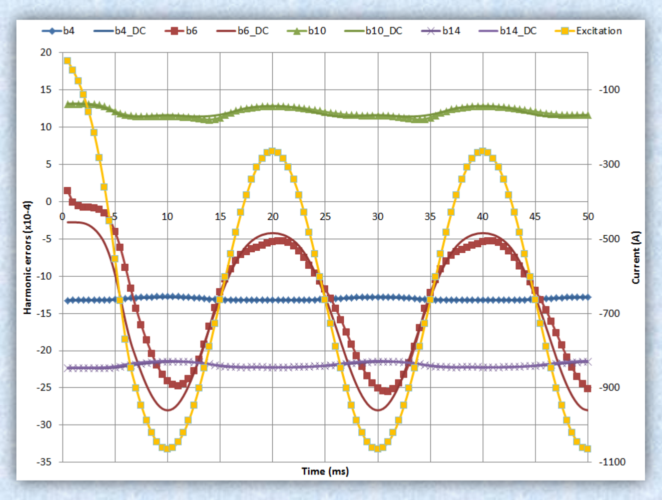

Figure 8. Dynamic field quality

The **transient field quality** shown in **Fig. 8** includes the **DC harmonics** calculated in an additional transient model with a stationary excitation.

A **good agreement** between DC and transient results can be observed, which confirms that the eddy currents are **not playing a major role** in the magnetic behaviour of the quadrupole.

A **small field delay** of about 1 ms can be clearly noticed in the **b6 response**, but that field delay is almost **invisible in b2**, the main quadrupolar field (not in the figure).

Coil loss calculations

Three **different methods** used:

1. Integrate **Eq. 2** in the coil **volume** using the magnetostatic solution at 2 excitations.

$$P_{xy}[W/m^3] = \frac{\omega^2 d^2}{24\rho}\left(\frac{B_p - B_v}{2}\right)^2 \quad \textbf{(2)}$$

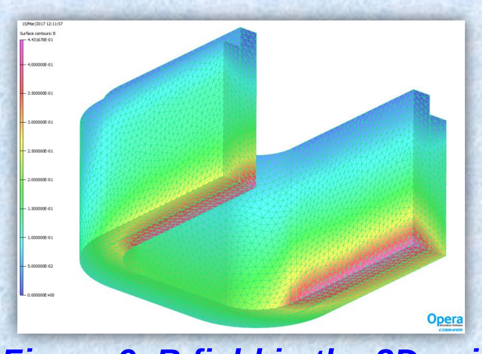

Figure 9. B field in the 3D coil

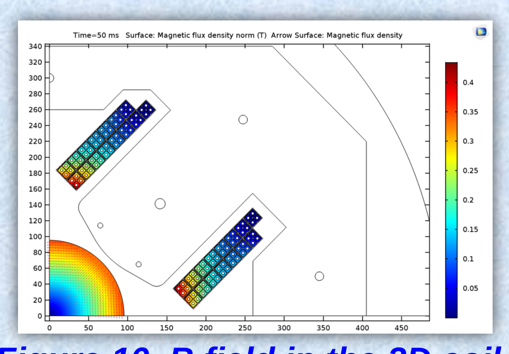

Figure 10. B field in the 2D coil

2. Calculate the magnetic field distribution in a **2D magnetostatic** model and then estimate the power loss on **every turn/conductor** using Eq. 2. This is **pessimistic**.
3. Build a **2D frequency-domain / time-domain** electromagnetic model, which includes the **skin and proximity effects** in the conductors. **COMSOL** Multiphysics was used in this method. The **AC resistance** was thus calculated and compared to **measurements** with a precision LCR meter, showing a **good agreement**.

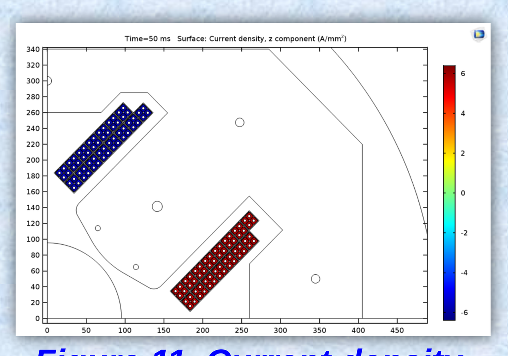

Figure 11. Current density distribution in coil

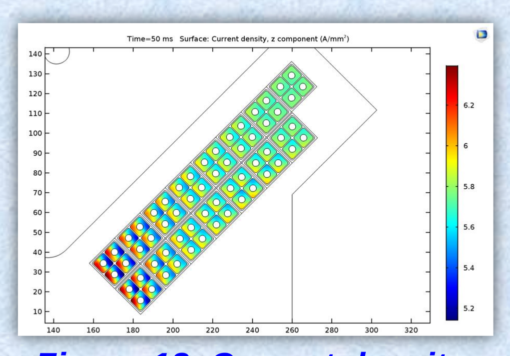

Figure 12. Current density distribution in conductors

Table 3: Coil loss calculations summary

Method 1	Method 2	Method 3
779 W	840 W	746 W

+ resistive losses (DC bias & AC) = **4.77 kW**

Conclusion

The **results** from modern advanced simulations have shown a **good agreement** with the original specifications, which are believed to have come from **physical measurements** of a prototype. A correctly designed AC magnet has been shown to **behave quite similarly** in both DC and transient excitations from the **field quality** point of view. Therefore, a DC model is a much quicker way of calculating or optimizing the magnetic behaviour of a magnet, leaving the transient model as a **final check** to ensure the eddy currents are well controlled. With regard to the **coil loss** calculations, they can be accurately estimated by using a **2D** frequency domain model or a **DC 3D** model.

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