Eddy Current Reduction in Fast Ramped Bending Magnets

Marco Negrazus, David George, Vjeran Vrankovic, and Manfred Werner

***Abstract*—At the Paul Scherrer Institute (PSI/Switzerland) a new proton gantry for cancer treatment is planned. A fast 3 dimensional scanning technique of the tumour volume is one of the medical highlights of this new gantry. The gantry will be driven by the new COMET proton cyclotron, which will deliver a cw proton beam. The energy of this beam will be adjusted by a fast degrader device. All beam line magnets should follow the energy changes of the degrader as fast as possible. Therefore the eddy current effects in the laminated bending magnets of the beam line and the gantry must be reduced by an appropriate magnet design. The paper shows measurements and numerical simulation of the dynamic behaviour of the fast switched bending magnets and design schemes for eddy current reduction in the bending magnets.**

***Index Terms*—eddy currents, magnetic variables measurement, magnets.**

I. Introduction

At the Paul Scherrer Institute PSI in Switzerland the new proton cyclotron COMET [1] is now in its commissioning phase. The cyclotron provides a 250 MeV proton beam which is adjusted for tumour treatment within an energy range of 70 – 230 MeV by a fast degrader. A new gantry with sophisticated spot scanning capabilities [2] is planned.

The spot scanning technique requires a relatively fast change of the beam energy for tumour treatment in various depths of tissue. Energy steps of 1 – 2% of the maximum energy within 50 ms are foreseen and all beam line and gantry magnets have to switch to the new energy on time. This energy switching generates eddy currents. To avoid eddy currents all magnets are build in laminated technique. However, laminated magnets are not completely free of eddy current effects and they can still have distorting influence on the beam. This limits the quickest possible energy switching and causes longer medical treatment time.

II. Eddy Current Effects

In an ideal laminated iron magnet, the return magnetic flux stays inside one lamination and never moves to the neighbouring lamination. There are no magnetic field components perpendicular to the lamination and therefore no eddy currents occur in the lamination plane. In a real magnet this is not always true. At the magnet beam entrance and exit, magnetic flux with a component perpendicular to the lamination is unavoidable, especially at the poles of the magnet. Moreover, due to saturation in the laminated iron yoke the magnetic flux can move between laminations or even leave the yoke to the surrounding air, which also produces perpendicular flux components and eddy currents. The decay of the eddy currents can have time constants up to several seconds.

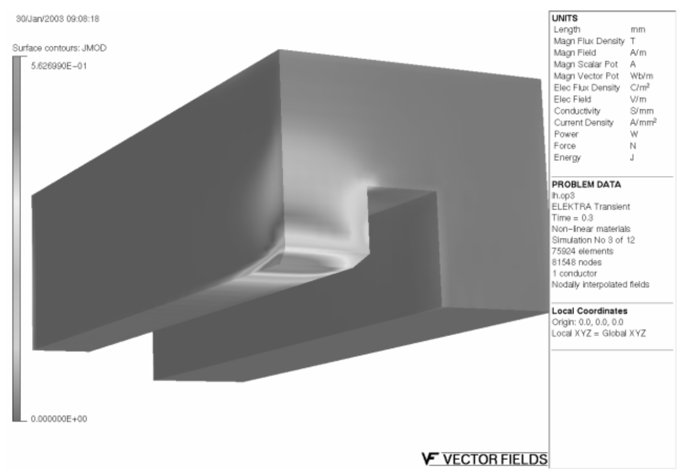

Fig 1. One eighth of a simulated H-type bending magnet without coils. The current density is shown during ramping.

A. *Numerical Simulation of Eddy Current Effects*

To study the eddy current effects in bending magnets with laminated iron yokes numerical simulations with the ELEKTRA code (version 10.0) from the company Vector Fields [3] were made. The program code allows time domain simulations with nonlinear anisotropic iron. To simulate the properties of laminated material, the electrical conductivity was set to zero and the permeability reduced perpendicular to the lamination. Using these approximations a complete linear ramp of the driving current in the coils is simulated. The program requires a roughly five times more RAM and much more calculation time than static calculations. It is therefore unavoidable to simplify the model of the magnet and the grid in comparison with static calculations with the program code TOSCA [3]. The simulation of a complete current ramp can take 6 – 12 hours of calculation time for a problem with

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200000 grid nodes on a 2.8 GHz PC.

Fig. 1 shows a 3D plot of the current density in the bending magnet yoke. The eddy currents are concentrated in the front part of the pole where most of the perpendicular flux components occur.

B. Measurement of Eddy Current Effects

To approve the results of simulations we made time domain measurements with a laminated beam line bending magnet of the COMET cyclotron. Fig. 2 shows the magnet on the measuring machine.

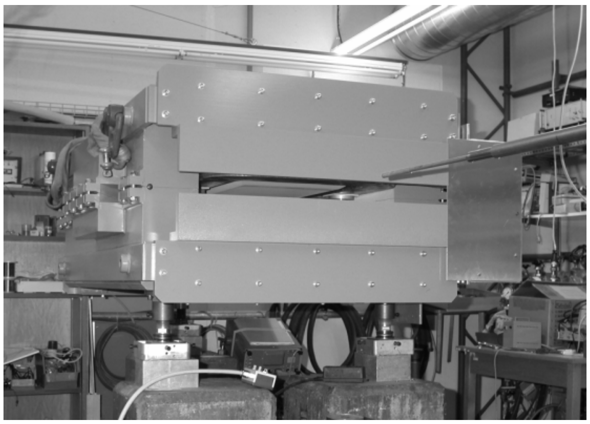

Fig. 2. *Beam line bending magnet at measurement.*

The magnet is straight with mirror plates and has a magnetic length of 1840 mm and a gap height of 62 mm. The maximum current is 220 Ampere, which can be reached with a 3 second long linear ramp. The magnet was simulated with the ELEKTRA code by using the same 3 second linear ramp and the vertical magnetic field on the longitudinal axis was compared with the calculated static field. The difference is shown in Fig. 3.

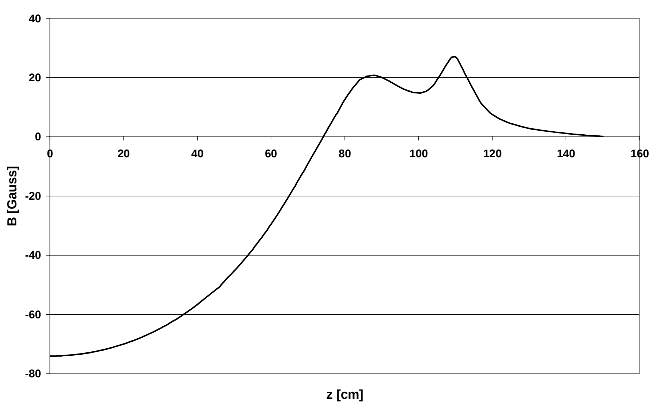

Fig. 3. *Simulated difference between the static field and the field at the end of the 3 second ramp. z = 0 cm is the centre of the magnet.*

The magnetic field in the centre of the magnet is more than 70 Gauss lower in comparison with the static field ($t \rightarrow \infty$). At the magnet entrance at z = 80 -120 cm the field is 20 Gauss higher.

The magnetic field measurements were made with a stationary Hall probe, taking readings every 2 ms. Fig. 4 shows the comparison of the simulated and the measured magnetic field in the centre (z = 0 cm) of the magnet during the first 6 seconds after the end of the ramp where the current stays constant at 220 Ampere. One can see that the measured field is less deviant than the simulated field. In particular, the time constant of the asymptotical decay of the distortion is significantly smaller in the measured field. Nevertheless the simulation results are very useful for design optimization.

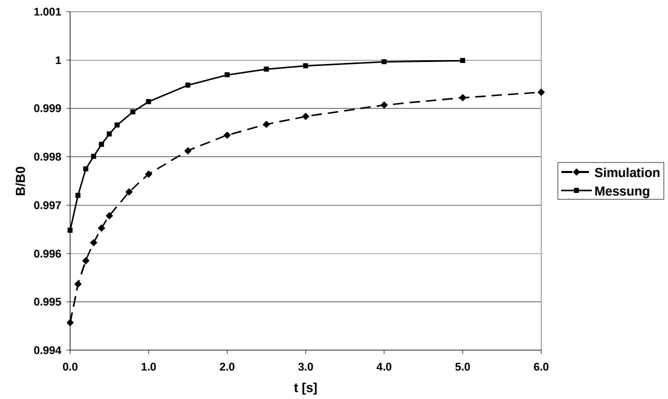

Fig. 4. *Comparison of measured and simulated magnetic field in the centre of the magnet after a linear 220 Ampere ramp.*

C. Design Schemes for Eddy Current Reduction

The eddy current effects due to saturation in the iron yoke were studied using an integral field measured long coil. For these studies, a special driving current ramp was programmed. The current was increased in 20 Ampere steps between 140 and 200 Ampere. After each step the current was constant for 0.7 s.

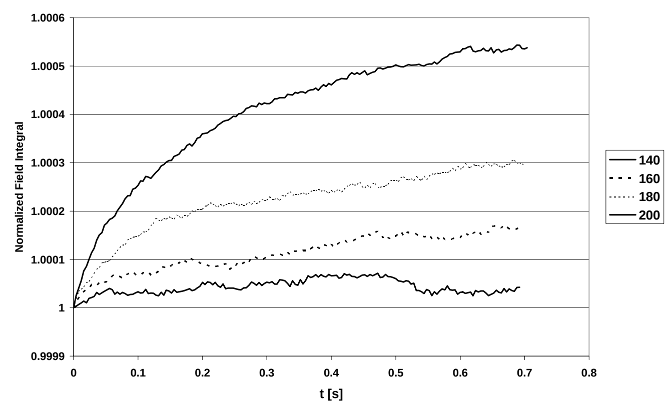

Fig. 5. *Measured normalized field integrals at successive 20 Ampere steps of the driving current.*

Fig. 5 shows the field integral normalized to the end of each 20 Ampere step. The step to 160 Ampere is the first one which shows a small distortion due to saturation induced eddy currents. The 180 and 200 Ampere steps show larger distortions. The value of 160 Ampere corresponds to a magnetic field of 1.3 Tesla in the iron yoke of the magnet. To keep the eddy current driven distortions as low as possible a magnet should be designed with a field lower than 1.3 Tesla in the iron yoke.

The eddy currents in the end laminations of the magnet are shown in Fig. 6. The eddy currents are concentrated in the first few centimetres in the pole above the magnetic gap. To suppress these eddy currents horizontal and vertical slits in the laminations of the magnet are simulated [4].

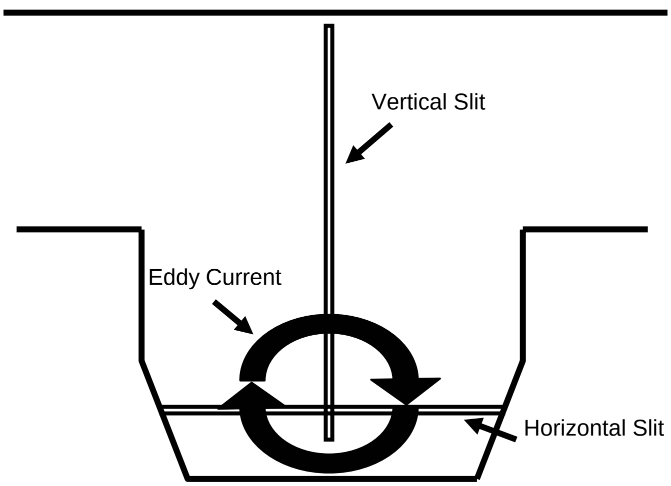

Fig. 6. *Eddy currents and possible horizontal and vertical slits in the front or end laminations of an H-type magnet.*

The vertical slit is 2 mm wide and placed in the centre of the lamination. It starts 5 cm above the pole face and ended 2 cm beneath the top of the lamination. The simulation does not show significant improvement due to the vertical slit, even if the slit is extended to the top of the lamination.

The horizontal slit is 0.5 mm wide and placed 4 cm above the pole face along the whole magnet. The simulation results show a significant reduction of the eddy current effects after the linear 220 Ampere ramp (Fig. 7). The improvement as shown in Fig. 7 seems to be relatively small because it is masked by the larger eddy current distortion due to the saturation in the yoke.

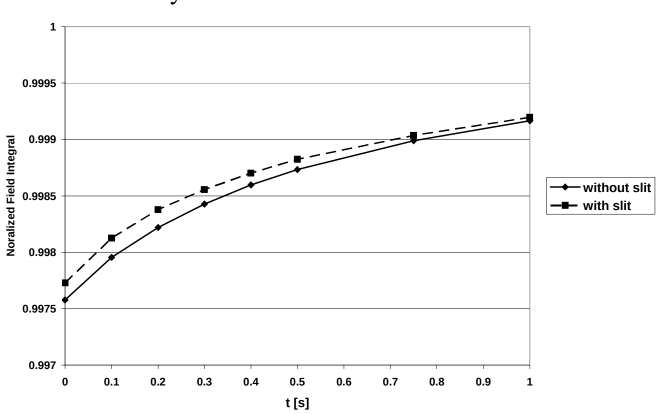

Fig. 7. *Simulated normalized field integrals of the magnet after a linear 220 Ampere ramp. The curves are with and without a horizontal slit.*

III. Conclusion

To study the eddy current effects in ramped laminated bending magnets, time domain simulations with the program code ELEKTRA by the company Vector Fields are compared with measurements of an existing bending magnet. The simulations give qualitatively correct results. A detailed comparison with measurements show that time constant of the asymptotic decay of the eddy current distortion is smaller than that shown by simulation. The simulations are especially useful to compare magnet design changes and its improvements to the eddy current reduction. The study of the saturation induced eddy current distortions show that a magnet should be designed with a field lower than 1.3 Tesla in the iron yoke to. The study of the eddy currents in end lamination of the magnet show that a horizontal slit in the pole a few centimetre above the pole face along the whole magnet significantly reduces the distortion.

References

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