A NOVEL EXTRACTION SCHEME FROM A SYNCHROTRON USING A MAGNETIC SHIELD

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Abstract

A new beam extraction scheme from a synchrotron is put forward. The main difference from other schemes of extraction is the use of magnetic shields instead of a septum. Magnetic shields are located in the central dipole magnets of a pulsed chicane. The magnetic shield is a multi-layer copper-iron tube. Numerical simulations and experimental results for the magnetic shield are presented. A good accordance between them was shown. The advantages of the new scheme are easy technical implementation and compactness. The area of application is extraction from a synchrotron. The proposed scheme will be used in a new synchrotron radiation source in Novosibirsk.

THEORY

A method of beam extraction from a synchrotron with a magnetic shield is considered in the article. A pulsed chicane and a kicker are installed on a synchrotron orbit. Magnetic shields are located in two central dipole magnets of the chicane. Before the extraction, the magnetic field in the chicane dipoles increases and brings the orbit closer to the magnetic shields. Then the kicker shifts the beam trajectory and it goes through the shields. As a result, beam goes to the outlet beamline (fig. 1). One of the main problems of all extraction schemes is a field perturbation on the shifted orbit. In our case the source of field perturbation is the magnetic shields.

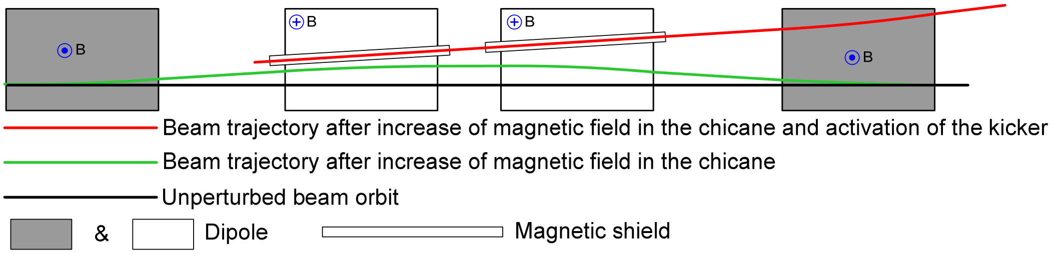

Figure 1: A method of beam extraction using a magnetic shield.

The field perturbation due to the magnetic shield obviously depends on the material used in the shield (fig. 2). If a magnetic shield consists of iron, constant and low-frequency magnetic field concentrates in its walls and field perturbation is high. In the case of a copper shield, pulsed magnetic field goes outside the shield and field perturbation is also high but with the opposite sign. Thus in the case of a multi-layer copper-iron shield we can expect that field perturbation can be significantly reduced.

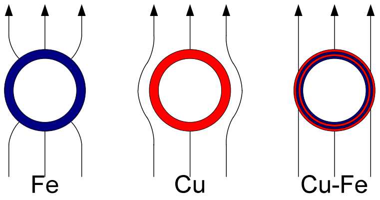

Figure 2: Perturbation of external magnetic field by shields from different materials.

Therefore consider the field perturbation caused by a multi-layer copper-iron shield in detail. In the case of slowly rising external magnetic field, the eddy current inside the shield walls are small. Thus the field distribution is similar to the case of iron shield. In the case of fast rise of external magnetic field, the eddy currents are prevented the magnetic flux penetration in shield walls. Magnetic field goes outside the shield and the field distribution is similar to the case of a copper shield. Thus field perturbations by multilayer copper-iron shield in the cases of slow and fast increasing of external magnetic field are high but have different signs. Thus one can expect near zero field perturbation at some intermediate external field increasing rate.

In the optimal case, magnetic field outside the shield is homogenous. Because of this:

$$\varphi_0 \approx B_0 \cdot a_y \,, \tag{1}$$

where φ_0 is flux flowing through the shield wall per unit of length, B_0 is external magnetic field, and a_y is transverse shield semiaxis. Equation 1 is a necessary condition of small field perturbation caused by a shield. If the penetration depth of magnetic field is small enough, we can consider a shield wall as planar (fig. 3).

Magnetic induction B inside the wall is equal to the saturation value B_s. Transition region from saturation field to zero is small and moves with velocity w. As a result, electrical field E_0 is generated and it leads to Foucault currents inside the wall.

$$E_0 = wB_s \,, \tag{2}$$

$$j_0 = \langle\sigma\rangle E_0 = \langle\sigma\rangle wB_s \,, \tag{3}$$

where $\langle\sigma\rangle$ is the averaged conductivity of the shield and j_0 is current density.

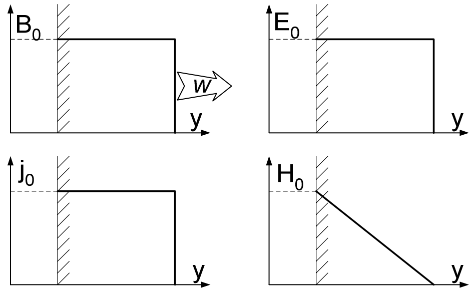

Figure 3: Magnetic field penetration into a planar wall in the case of linear rise of external field.

On the one hand, the derivative of magnetic field *H* is equal to the current density. On the other hand, magnetic field on surface is equal to the external field H_0. Thus in the case of linear rise of external magnetic field *H* is linearly decreases inside the wall and equals 0 at a front. The velocity of the front is constant and the magnetic flux flowing through the wall rises linearly.

$$H_0 = \frac{\alpha t}{\mu_0} = j_0 w t = \langle\sigma\rangle B_s w^2 t\,, \tag{4}$$

where α is the rise rate of external magnetic induction.

$$w = \sqrt{\frac{\alpha}{\langle\sigma\rangle \mu_0 B_s}} \tag{5}$$

$$\phi_0(t) \approx ctB_s \tag{6}$$

So if external magnetic field rises linearly on time, the flux flowing through shield walls also rises linearly. And the necessary condition of minimal field perturbation caused by a shield can be satisfied.

$$B_0(t) \approx \frac{B_s}{\mu_0\langle\sigma\rangle a_y^{\,2}}\cdot t \tag{7}$$

These results were proved by numerical simulations. The simulations of magnetic field penetration into an elliptical multilayer copper-iron shield (semiaxes are 11 mm and 17 mm) were performed in the case when external magnetic field increases linearly from 0 to 0.5 T (fig. 4).

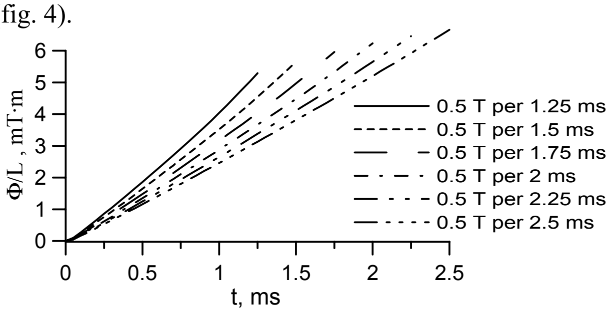

Figure 4: Flux flowing through the shield wall versus time for different rise rates of external magnetic field.

EXPERIMENT

In order to verify physical models and numerical methods a multi-layer copper-iron shield was made. The shield consists of 12 iron and 12 copper layers. The thickness of an iron layer is 0.08 mm; the thickness of copper one is 0.1 mm. The shield was installed in a dipole magnet, and measurement of field perturbation using search coil was performed (fig. 5).

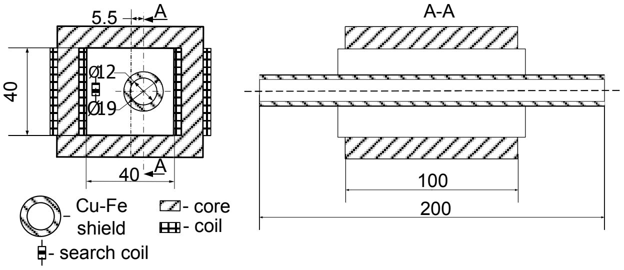

Figure 5: A dipole magnet with an installed Cu-Fe shield.

A power supply for the magnet produced only sinusoidal pulses. The measurement was made during 0.45 ms. It was 1/8 part of sinusoid period. Dependence field vs time during this interval was relatively linear.

Measurement of the optimal rise rate of external magnetic field was performed. The search coil was placed as close to magnetic shield as possible. The coil axis was parallel to external magnetic field. The distance between the coil axis and the surface of the magnetic shield was 2.5 mm. The dependence of the magnetic field on the time was measure with and without the shield. The position of the search coil was not changed. The difference between these two measurements is the field perturbation versus time. The measurement was made for different amplitudes of external magnetic field. Maxima of magnetic field perturbation versus external magnetic field at 0.45 ms from the start are shown in figure 6.

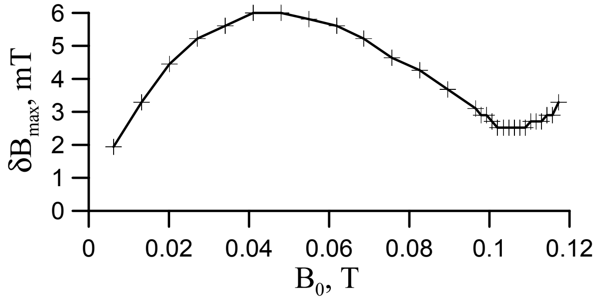

Figure 6: Maxima of magnetic field perturbation versus external magnetic field at 0.45 ms.

We can see that there is an optimal rise rate of external magnetic field. It is about 0.1 T per 0.45 ms. Perturbation field in the optimal case is about 2%.

To simulate the field perturbation, the magnetic permeability of iron foil in the shield was measured (fig. 7). The unmeasured region was interpolated linearly (dashed line).

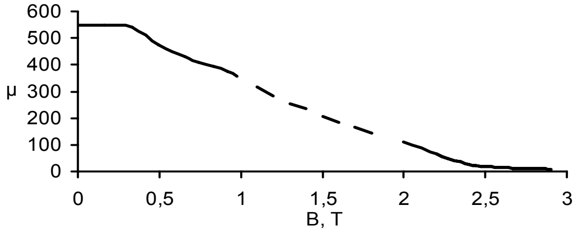

Figure 7: Relative permeability of iron foil versus magnetic induction.

The measured curve of magnetic permeability was used for simulation of field perturbation in a 2D model in the centre of the dipole (fig. 8). The field perturbation was measured by a search coil (fig. 9). Measurements and simulations near the edge of the dipole were done too. In each case the results of measurement coincide with ones of simulation.

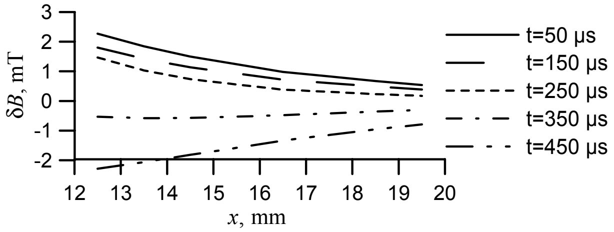

Figure 8: The distribution of the field perturbation near the magnetic shield (simulations). *x* is distance to shield axis.

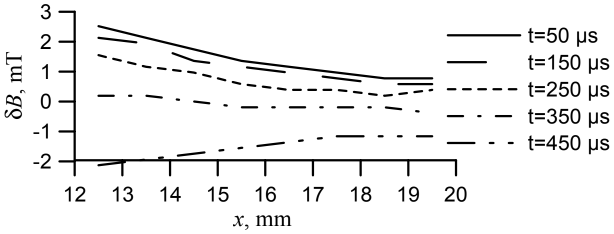

Figure 9: The distribution of the field perturbation near the magnetic shield (measurements). *x* is distance to shield axis.

PROJECT OF EXTRACTION SYSTEM

In order to discuss a possibility of this extraction method application, let's consider an extraction system from a booster synchrotron with a multilayer copper-iron shield. This booster is a part of a new synchrotron radiation source project in Novosibirsk. Its extraction electron energy is 2.2 GeV. An extraction kicker is a symmetric strip line. Its operating voltage is 50 kV, the distance between the plates is 27 mm and the angle of beam deflection is 1.7 mrad. Four meters of booster orbit is allocated for an extraction chicane. All dipoles in the chicane are of 0.48 m length, the distances between their centres are 0.85 m. Vertical and horizontal beam sizes in the chicane are 0.4 mm and 2.6 mm. The trajectory shift due to the kicker is 20 mm. The outer semiaxes of the magnetic shield are 17 mm and 11 mm, the inner semiaxes are 13 mm and 7 mm. The magnetic field in the dipoles of the chicane increases up to 0.45 T in 1.5 ms at the extraction moment. The distribution of magnetic field perturbation due to the shield was simulated (fig. 10).

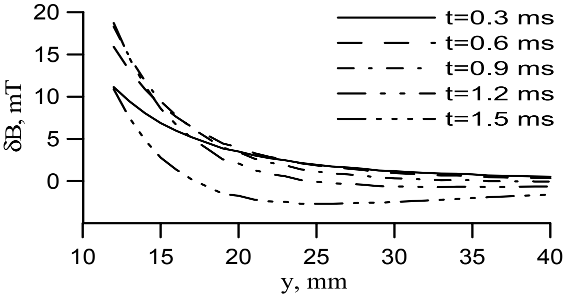

Figure 10: The distribution of magnetic field perturbation by the copper-iron shield.

An influence of field perturbation on a beam was calculated. The beam is deflected by 0.3 mrad. This angle leads to major orbit shift near the integer resonance. The resonant width was calculated from this effect. It is about $0.13 \cdot 2\pi$. Additional focusing in the extraction system is about 0.01 m^{-1}. It shifts betatron frequencies. Additional sextupole focusing is about 5 m^{-2}. First effect of this sextupole focusing is sextupole resonances. Second effect is additional chromatism. When the chicane is switched on, its dispersion is about 5 cm, and additional chromatism is about 0.4.

Numerical simulation of beam dynamics during extraction was performed (fig. 11). The booster optics was considered as linear. The field perturbation due to the copper-iron shields was considered as concentrated. As one can see, there are several areas without extraction loss.

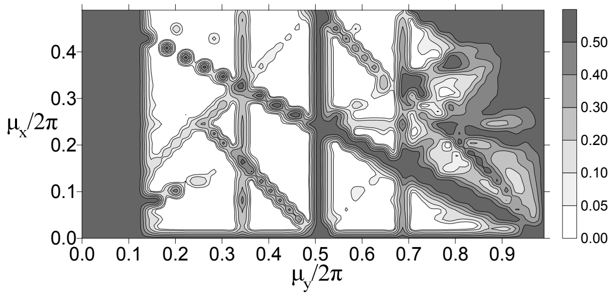

Figure 11: Relative extracted beam loss versus betatron phase incursion per one turn.

CONCLUSIONS

It was shown that the rate of magnetic flux penetration into a multilayer copper-iron shield wall is constant if the external magnetic field rises linearly. This effect can be used for minimization of magnetic field perturbation caused by a shield. The prototype of a multilayer copper-iron shield was made. Measurements and numerical simulation of its magnetic field perturbation were performed. The measurements confirm correctness of the method and the model which are used for simulation of field perturbation. Numerical simulation and analytical estimation of beam dynamics under the influence of field perturbation in this scheme prove a possibility of using the magnetic shield for extraction from a synchrotron.