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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Target raster system at CEBAF

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Abstract

A fast raster (FR) system consisting of two Litz cable air-core magnets (x, y) has been installed and tested in the Hall C beam line tunnel, 21 m from the cryogenic target. The system provides a maximum deflection of 0.06 mrad at a frequency range of 15–45 kHz for a 6 GeV electron beam. The FR magnets are driven by a MOSFET bipolar switching power source with a triangle current waveform, the peak-to-peak current is 40 A.

A 200 W cryogenic target (liquid hydrogen and liquid deuterium) will be installed at the CEBAF end station Hall C for planned studies of few-body system physics. In the case of a Hall C 10 cm liquid hydrogen target operating at 15 K, the maximum power dissipation due to the energy loss in the target cell by a 200 μA beam is about 1 kW. The liquid hydrogen is overheated by the deposited beam energy and bubbles are formed, therefore, a density variation is eventually generated. In order to minimize this bubble formation effect and reduce the forced flow velocity to a reasonable level (1 to 10 m/s), the best solution is beam rastering. The global and local beam heating analysis by Ref. [1] shows that a 18 kHz rastering with 2 mm rastering amplitude is preferable.

To obtain a sharp turning point at the boundary of the rastering pattern, a triangle current waveform is selected to drive the raster magnet [2]. Based on the Fourier theorem, the Fourier expansion of the triangle waveform is:

$$y = \frac{4T}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{(2n-1)^2} \sin \frac{(2n-1)\pi x}{T}$$
$$= \frac{4T}{\pi^2} \left[\sin\left(\frac{\pi x}{T}\right) - \frac{1}{9} \sin\left(\frac{3\pi x}{T}\right) + \frac{1}{25} \sin\left(\frac{5\pi x}{T}\right) - \cdots \right],$$

therefore, the ratios of the amplitudes and the intensities of the first, the third, and the fifth harmonic components are $1 : \frac{1}{9} : \frac{1}{25}$ and $1 : \frac{1}{81} : \frac{1}{225}$ respectively. We truncate the harmonic frequency of FR triangle waveform at the 5th order component (100 kHz).

Losses in the alternative-mode power magnet occur in both magnet core material and the electrical conductors which make the magnet windings. The common used ferrite magnetic core materials have intrinsic losses; eddy current, residual and hysteresis losses which eventually generate thermal energy. As the FR magnet must be operated at 100 kHz, an air-core coil is adequate because of its fast frequency response and better electric performance than ferrite material. Eddy currents circulating within the conductor may be represented as an increase in conductor resistance. The magnitude of the eddy current becomes larger as frequency and wire diameter increase. The skin effect is caused by eddy current generated in the conductor by alternating current in the conductor and the proximity effect is generated by stray alternating magnetic fields in a conductor as a result of winding geometry.

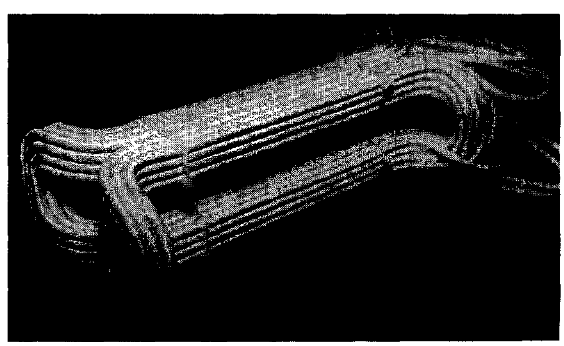

Fig. 1. The prototype FR bedstead air-core magnet is winded by a Litz cable 1650/38 (Nylon wrapped). The magnet is shaped by gluing individual cables together and no potting material is applied.

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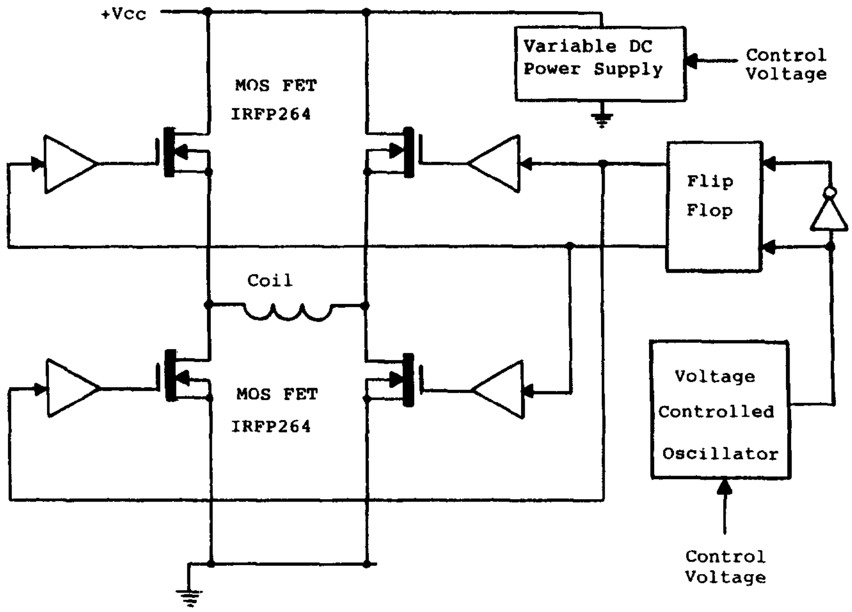

Fig. 2. Block diagram of the MOSFET bipolar switching mode power source. The FR magnet is settled at the middle of the bridge.

In order to minimize the skin effect and proximity effect produced by eddy current, and also to avoid core-material losses, a bedstead air-core coil with Litz wire windings was designed [3]. Two bedstead air-core coils are combined as the raster magnets. The prototype FR raster magnet is shown in Fig. 1. The bedstead shape coil will generate a larger uniform field region and smaller high order field components, mainly the sextupole component, than the flat coil. Litz cable (Kerrigan-Lewis wire products, equivalent to Awg 6 cable, 1650 strand of Awg. 38 wire) was used to wind the coils. Based on TOSCA calculation and the experimental measurement of the prototype coils, the specifications of the raster magnets are listed in Table 1.

Table 1
Specification of the FR magnet

Parameter	Designed	Measured
Peak central field [G]	80.1	77.4
Bending angle at 6 GeV [mrad]	0.0588	0.056
$\int B\,dl$ [kG cm]	1.2	1.16
Field uniformity	10^{-2}	10^{-2}
Effective length [cm]	15.0	15.3
Physical dimension [cm]	25	25.5
Inner radius [cm]	1.27	1.27
Number of turns	20	20
Ampere-turns [A t]	240	240
Current density [A/cm^2]	100	100
Inductance [μH]	84	89
DC resistance [Ω]	0.003	0.044
Type of conductors	–	Litz 1650/38
Rastering frequency [kHz]	20	10 –45

The prototype current power source for the FR magnet was specially designed by Industrial Test Equipment Company. The power source is capable of providing a triangle current of 40 A peak to peak into the FR magnet, having a high quality factor (larger than 50). The inductance of the coils may vary over a range of a few tens of μH to several 100 μH. The principle of the FR power source is to apply a bipolar switching voltage to the FR magnet, which is almost a pure inductive load with very low losses, the current waveform in the ends of the load will follow an exponential decay curve. With certain compensation, a triangle waveform can be obtained. As shown in Fig. 2 the basic circuit of the power source is a bipolar MOSFET

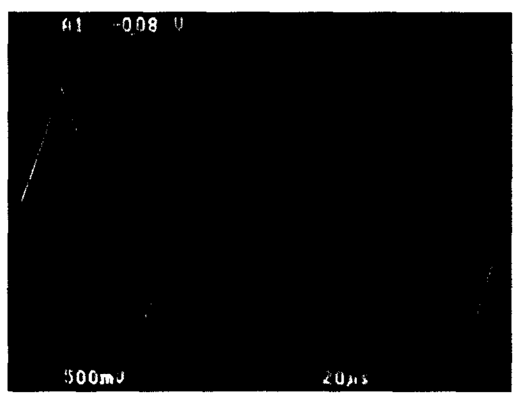

Fig. 3. The output signal from the LEM current probe, which is connected with the FR raster magnet in series. The terminate resistor of LEM module is 100 Ω, and the calibration factor is 10 A/V. It represents a 20 kHz and I_{p-p} = 40 A driving current.

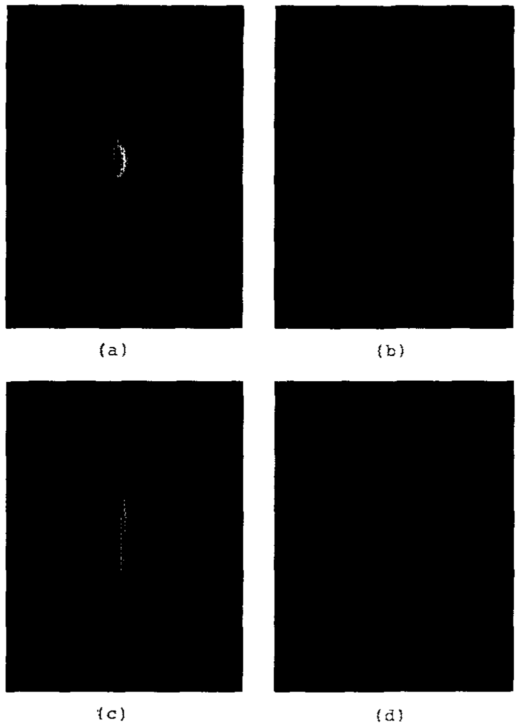

Fig. 4. Fluorescent images of beam spots on the BeO target. (a) Stationary beam spot without rastering. (b) One dimensional rastering pattern with horizontal rastering only. (c) One dimensional rastering pattern with vertical rastering only. (d) Two dimensional rastering pattern.

switching bridge controlled by a pulse generator which determines the fundamental raster frequency. A LEM current sensor (LEM USA, Inc.) is connected with the FR magnet in series to convert the load current by 1:1000 ratio to a voltage signal with a 0–200 kHz frequency band. The LEM current signal is shown in Fig. 3. The terminate resistor of LEM is 100 Ω, therefore, the calibration factor is 10 A/V.

The prototype of the CEBAF FR raster system was tested during beam line commissioning period in late 1994. The 750 MeV 25 μA 60 Hz pulsed electron beam was guided by the Hall C beam transport line and focused on a 150 mg/cm^2 BeO target which is tilted to the normal beam direction at 30°. A TV camera located in the upper window of the target chamber was used to observe the fluorescent image of beam spot on the BeO target. Several pictures taken from the TV monitor screen display in Fig. 4 describe the operational function of the FR raster system. Fig. 4a shows the stationary beam spot without rastering; Fig. 4b – one dimensional rastering pattern with horizontal rastering only; Fig. 4c – one dimensional rastering pattern with vertical rastering only; and Fig. 4d – the two dimensional beam rastering pattern. The FR raster system was also tested on a 5 μA CW (continuous wave) beam. A very sharp and bright square shape rastering pattern (the rastering area ~ 1 cm^2) was observed as the interference between beam pulse frequency and TV frame frequency disappeared in CW mode.

The frequency ratio between horizontal and vertical rastering is selected in such a way that the beam density distribution over the entire scanning area becomes uniform just after a few cycles as a fast rolling pattern can be generated. Therefore, a ratio $f_x/f_y = 0.58$ is preferable.

A ceramic duct should be used as the vacuum pipe of FR magnet to avoid the heating-up effect and the field attenuation due to eddy currents induced by alternating magnetic field. A very thin titanium layer (R_{dc} rate ~ 10 MΩ/cm) was coated on the inner wall of the duct for releasing the accumulate charge.

Acknowledgements

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