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DIGITAL SUBTRACTION ANGIOGRAPHY SOURCE**

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September, 1993

NATIONAL SYNCHROTRON LIGHT SOURCE

**BROOKHAVEN NATIONAL LABORATORY
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Under Contract No. DE-AC02-76CH00916 with the

UNITED STATES DEPARTMENT OF ENERGY

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Conceptual Design of an 8 Tesla Superconducting Wiggler for a Dedicated Digital Subtraction Angiography Source

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One of the most important techniques used to diagnose heart disease is coronary angiography. It is performed using x-rays from a conventional source to follow the flow of a contrast agent containing iodine through the coronary arteries. The contrast agent is introduced by direct injection from a catheter in the coronary arteries that was threaded through the femoral artery all the way from the groin to the heart. Coronary angiography is only used when it is absolutely essential because of the risk of fatalities and other serious complications arising from the insertion of the catheter. The technique also exposes the patients to large amounts of x-rays.

Research, begun at SSRL¹ and continued on the X17 beam line at NSLS², demonstrated the feasibility of imaging human coronary arteries following venous injection of the contrast agent. The technique, called digital subtraction angiography (DSA), uses two monochromatic beams of x-rays, one slightly above and one slightly below the iodine K absorption edge (33.169 KeV) to collect simultaneous images. When the two images are subtracted, the contrast agent, contained primarily in the blood vessels, is revealed and the background that is common to both images is suppressed. The images must be collected during a single heartbeat to avoid blurring from motion of the blood vessels. Conventional x-ray sources are too weak to provide the intense flux that is required in the narrow energy bandwidth of the beams. Only the most powerful synchrotron radiation beams from wiggler magnet sources can provide the intensity required in the short exposure time.

Although DSA experiments have shown promise, they have been conducted at large, research synchrotron radiation facilities. A small, dedicated source will be needed before DSA can be used as a standard medical procedure. Such exotic x-ray sources as laser back-scattering, Cherenkov radiation, parametric x-radiation, and channeling radiation, and others have been suggested for hospital based DSA sources but none of them appear to produce enough flux to be useful.³ Barring the discovery of a new source of intense x-rays, only synchrotron radiation seems to meet the requirements for DSA. What is needed then, is a small storage ring with a wiggler magnet beamline that can be dedicated to DSA.

This report will briefly describe the preliminary design of a high field, superconducting wiggler magnet that can be used as a DSA source. The design began with the assumption that a peak field of 8 T can be reached in a wiggler with iron poles and NiTi RHIC cable at 4.35 K. The assumption was justified as the designs for the poles and coils were developed.

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1. E. Rubenstein, et. al., Nucl. Inst. and Meth. A291 (1990) p. 80.
 2. W. Thomlinson, et. al., Rev. Sci. Instrum. 63 (1992) p. 625.
 3. R. Carr, to be published in the proceedings of the 1993 Synchrotron Radiation Instrumentation Conference, Gaithersburg, MD.

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Given that an 8T wiggler can be built, what sort of storage ring will be needed to produce enough flux for DSA? One way to answer this question is to say that a dedicated source must produce as much flux at the iodine edge as the 4.7 T wiggler on X17 with 200 mA of electrons in the 2.5 GeV NSLS x-ray storage ring. Based on the experience with the NSLS UV storage ring it was assumed that a 1 Amp beam can be stored in a small storage ring. Fig. 1 shows that a 1 A, 1.32 GeV beam from a 7 pole, 8 T wiggler can produce just as much flux at the iodine edge as a 200 mA, 2.5 GeV beam from a 5 pole, 4.7 T wiggler. The smaller critical energy from the dedicated source will also produce less flux at high energies, thereby reducing the undesired production of radiation at monochromator harmonics.

A cross sectional view of the superconducting wiggler is shown in Fig. 2. The wiggler has seven full strength poles that produce a peak field of 8.0 T in the midplane with a magnet gap of 4.0 cm. Half-strength poles are provided at each end of the magnet as required to cancel the angle and position errors given to the beam by the wiggler field. Iron field clamps are used to reduce the stray field that escapes from the end. The 2 cm gaps between the coils are to allow space for gussets to strengthen the inner wall of the cryostat. Coil design is described in Table 1.

Table 1
Coil Design

Conductor:

RHIC Cable (No Keystone)

conductor width (cm)	0.117
conductor height (cm)	0.973

Insulation:

2 layers

1 mil kapton

0.25 mil polyimide adhesive

	Coil 1	Coil 2	Coil 3	Coil 4
number of coils	14	14	4	4
allowed height (cm)	33.21	33.21	33.21	33.21
allowed width (cm)	5.00	2.00	5.00	2.00
horizontal layers	33	12	33	12
vertical layers	33	33	33	33
number of turns	1089	396	1089	396
current (kA)	1.96	0.50	1.13	-0.64

(Note: The currents in coils 3 and 4 have opposite polarities.)

The 2D magnetostatic program POISSON was used to calculate the magnetic field in the wiggler. Fig. 3 shows the field lines in the quarter period model used for the calculations. The standard B(H) curve provided in the program was used to account for saturation in the iron.

The pole and coil configuration were chosen to ensure that the critical current and field are not exceeded. Two coils were used to excite each pole. A low current coil is used for the 2 cm closest to the pole where the magnetic field is highest. Higher current is used in the remaining space. Fig. 4 shows the operating point for the current in each coil vs. the

peak magnetic field on the coil calculated by POISSON. This data is compared with the maximum I vs. H curve for the RHIC conductor at 4.35K.⁴ The operating point for each coil is less than 95% of the critical field.

Fig. 5 contains a plot of the field on-axis as a function of longitudinal position. The field is well described by the formula

$$B(z) = 7.534 \cos(2\pi z/\lambda) + 0.490 \cos(6\pi z/\lambda)$$

where B is the magnetic field in Tesla, λ is the period of the wiggler (40 cm), and z is the distance along the wiggler. The significant third harmonic component appears because of the contributions to the field from the saturated pole and the two coils. For proper cancelation of the position and orbit errors, the field under the half strength poles should be described by a similar formula with half strength coefficients. Although the effects of the fringe field at the end of the magnet will add additional harmonics, POISSON calculations show that reasonable cancelation can be achieved by adjusting the relative currents in the pair of coils around the half strength poles. The final values for the currents will have to be found by measurement.

A plot of the peak on-axis field vs. coil excitation (assuming a constant current ratio between the high and low current coils) is shown in fig. 6. The graph is linear above approximately 1.2 T. This will simplify correction magnet adjustment when the wiggler field is changed.

The author thanks Roy Blumberg, Mike Iarocci, and Bill Thomlinson for their assistance.

4. I vs. H data supplied by William Sampson, RHIC project.

Fig. 1. Comparison of the flux produced by the X17 wiggler and an 8 T wiggler in a dedicated source. Both graphs show the number of photons that reach a 0.5 mm horizontal pixel of a detector during a typical 4 msec angiography exposure. The calculation for X17 assumes a wiggler that is 30 m from the detector with 5 poles producing a peak field of 4.7 T, 2 half-strength poles, and 200 mA of 2.5 GeV beam. The 8 T wiggler has 7 full strength poles, 2 half strength poles, 1 A of 1.32 GeV beam, and is 20 m from the detector.

Fig. 3. Magnetic field lines calculated by POISSON in $1/4$ period of the wiggler.

Fig. 4. Operating points for the coils around the full strength poles compared to the critical current for the superconducting cable.

Fig. 5. Vertical, on-axis field vs. longitudinal distance through 1/4 period of the wiggler. The plotted points were calculated by POISSON and the solid line is the curve described in the text.

Fig. 6. Peak on-axis magnetic field vs. current calculated by POISSON. A relative current of 1 corresponds to the values in Table 1. All currents scale in ratio.

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