Nb_3-Sn Coil Configurations for Accelerators
Part I: Separated Function Elements

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It is of interest to examine the possibility of producing magnetic fields suitable for high-energy accelerators or storage rings, by using currently available Nb_3-Sn. This means that it is necessary to consider dipole, quadrupole, and di-quad elements since one or all of these might be used. The magnetic field structures may be either circular or elliptic in cross section depending on the needs of the system or the whim of the designer. However, the elliptic cross section requires less Nb_3-Sn ribbon than the circular cross section and thus is cheaper by about a factor of $(a + b)/2r$ where a and b are the semi-major and minor axes of the ellipse and r is the radius of the circle for the circular case.

Theoretically [1] the turn distribution for a dipole-ellipse is given by $N \propto (a + b) \{\Delta [\sin \theta_p]\}$ where θ_p is the parametric angle for an ellipse and is related to the central angle of an ellipse, by $\tan\theta = (b/a) \tan\theta_p$. N is the number of turns for a $\Delta\theta$ angle interval and θ is the central angle of the ellipse.

The resultant field along the major(minor) axis is calculated [2] in a way similar to that for the circular case.[3]

<u>Circular Structures:</u> The first of these concerns a full scale quadrupole lens [4] denoted by M4-24 which signifies that the lens has a 4-inch inside diameter and is 24 inches long. The turn distribution for this lens is given in Table I and a picture of this full scale lens is in Fig. 1.

Table I
Turn Distribution for M4-24 Quadrupole

$\Delta\theta$ (degrees)	Number of turns per $\Delta\theta$	θ_f mean angle for turns in $\Delta\theta$ group (degrees)
0° - 10° and 80° - 90°	56	5° and 85°
10° - 20° and 70° - 80°	49	15° and 75°
20° - 30° and 60° - 70°	36	25° and 65°
30° - 40° and 50° - 60°	19	35° and 55°
40° - 50°	0	---

The ribbon [5] used in this lens was 0.5 inches wide, 0.0052 inches thick and has a measured critical current of 1600 Amp. at 70 kG.

Calculations [6] indicate that at 1600 Amp. the field gradient, $dB/dr = 10.020$ (kG/cm) $\pm$ 0.0013% over an internal diameter of 3 inches. If larger field gradients (or fields) are desired they may be obtained by winding a second layer of superconducting one-half inch ribbon on top of the first layer.[3,8]

Experimental measurements of the field produced by this lens at 4.2°K gave an average $dB/dr = 6.33$ (kG/cm) $\pm$ 0.56% at 1000 Amperes. Correspondingly the gradient at 1600 Amperes would be 10.13 kG/cm. Also, measurements made with a long (33 inches) rotating coil so that the end effects of the field are taken into account indicate that at a radius of 1.375 inches all higher harmonics exist to less than about 0.5%. Thus, this structure and turn distribution provide a good quadrupole lens.

Calculations [6] also have been made for a Bucking Quadrupole (M9-24QB) for this lens so that the field at distances larger than 14" from the center of the lens and on a line perpendicular to the axis of the lens is cancelled to less than 1 gauss. This takes 136 more turns and reduces the field gradient inside the quadrupole by only 4.9% which is a small price to pay for a field-free region outside of the quadrupole.

The second circular structure considered here is a dipole 20 inches in diameter and 80 inches long, M20-80D.[4,9] It has an assumed current of 2000 Amp in the 1/2" ribbon.[10] This dipole has 3060 turns so that the estimated cost of the Nb_3-Sn ribbon at present prices is about $62,000, but it would provide a field of 35.78 kG which is constant to $\pm$ 0.16% over 18 inches of the 20-inch diameter of the structure. Since about 1 inch of insulation is needed on the inside of the dipole if it is to be used at room temperature the 18-inch aperture is all than can be used.

<u>Elliptic Structures</u>: One of these concerns a full-scale dipole with a major axis of the ellipse 7.5 inches, a minor axis of 4 inches and a length of 26 inches. This is designated M7.5-4-26 [2] and one similar to it may be constructed at Brookhaven National Laboratory. The turn distribution for this dipole is given in Table II where the $\Delta\theta$ angle interval refers to the central angle of the ellipse.

Table II
Turn Distribution for the Elliptic Dipole
M7.5-4-26
Nb_3-Sn Ribbon 1/2 inch wide

$\Delta\theta$ angle interval (degrees)	Number of turns per $\Delta\theta$	θ_f mean angle for turns in $\Delta\theta$ group (degrees)
0°- 5° and 175°-180°	51	2.5 and 177.5
5°-10° and 170°-175°	47	7.5 and 172.5
10°-15° and 165°-170°	43	12.5 and 167.5
15°-20° and 160°-165°	36	17.5 and 162.5
20°-30° and 150°-160°	55	25. and 155.
30°-40° and 140°-150°	36	35. and 145.
40°-50° and 130°-140°	23	45. and 135.
50°-60° and 120°-130°	14	55. and 125.
60°-70° and 110°-120°	9	65. and 115.
70°-80° and 100°-110°	5	75. and 105.
80°-87° and 93°-100°	2	83. and 96.
87°-93°	1	93

Calculations indicate that over 5 inches along the major axis the field to be expected is 24.64 kG $^{+0.04\%}_{-0.1\%}$ for a 1000 Amp. current in the 1/2" ribbon. However, for 2350 Amp. one would get about 58 kG which for the RCA ribbon number R-60322 does not violate the critical current-field data.

For 1284 turns total, the length of the necessary Nb_3-Sn is about 1000 meters and the estimated cost at present prices is $15,000.

Fig. 2 shows a sketch of an elliptic frame on which this dipole might be wound.

It is to be anticipated that these estimated costs will be reduced in the future when larger production of the Nb_3-Sn ribbon is achieved.

In any case, it is clear that such quadrupole, dipole, and di-quad (See Part II) structures are feasible now and may be used in beam-handling systems as well as in accelerators and storage rings.

1. R. A. Beth, "Elliptical and Circular Current Sheets to Produce a Prescribed Internal Field," Proceedings of the National Particle-Accelerator Conference, Washington, D. C., March 1-3, 1967.
2. P. Gerald Kruger and J. N Snyder. Internal Report, "The Brookhaven Dipole-Ellipse M7.5-4-26" April - May 1967.
3. P. Gerald Kruger, J. N. Snyder, and W. B. Sampson. BNL Accelerator Department Internal Report AADD-113R, revised Sept. 16, 1966.
4. P. Gerald Kruger, W. B. Sampson, R. B. Britton, and J. N. Snyder. National Superconductivity Information Meeting: BNL Nov. 9-11, 1966: p. 38 BNL 50038 (C-49).
5. The Nb_3-Sn ribbon was supplied by RCA. About 825 meters were used to wind the 1280 turns on the lens. This corresponds approximately to RCA number R-60305 which is quoted by RCA as of June 1, 1967 to cost $12.50 per meter. Thus, the Nb_3-Sn ribbon for such a lens at this price would cost about $10,300.00.
6. P. Gerald Kruger and J. N Snyder. Internal Report, "Final Calculations for the Quadrupole M4-24." June 1967.
7. All experimental work has been done at BNL in cooperation with W. B. Sampson and his colleagues.
8. P. Gerald Kruger, J. N. Snyder, and W. B. Sampson. "Digital Calculations of Magnetic Fields Owing to Currents in Nb_3-Sn Ribbon in a Superconducting Lens." Internal Report June 1966.
9. P. Gerald Kruger and J. N. Snyder. "Internal Report: Calculated Dipole and FFAG Fields from Superconducting Structures," Sept. 1966.
10. This corresponds to RCA Number R-60322 and has a quoted price of $15.00 per meter.

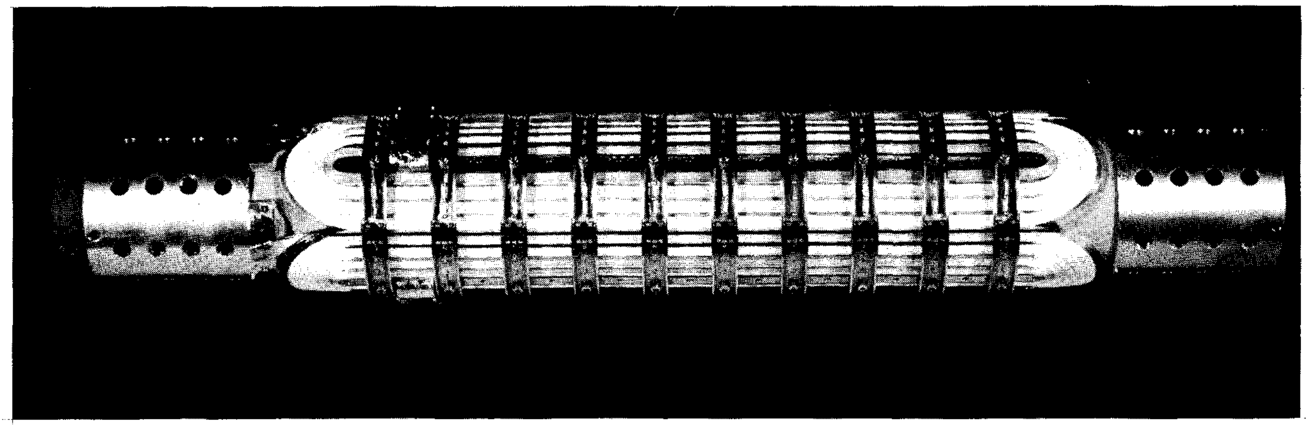

Fig. 1. Photograph of the M4-24 Quadrupole: It is four inches inside diameter and twenty four inches long. Also shown are two extensions on the ends of the lens of about four and one-half inches each. These were supports for the long rotating coil used in making measurements of the harmonic content of the field of the lens.

The structure shows the four sections ($\Delta\theta$ = 10°) of the coil for each quadrant of the lens.

The lens was built at Brookhaven National Laboratory by W. B. Sampson and colleagues and the photograph was supplied by the BNL Photographic Department.

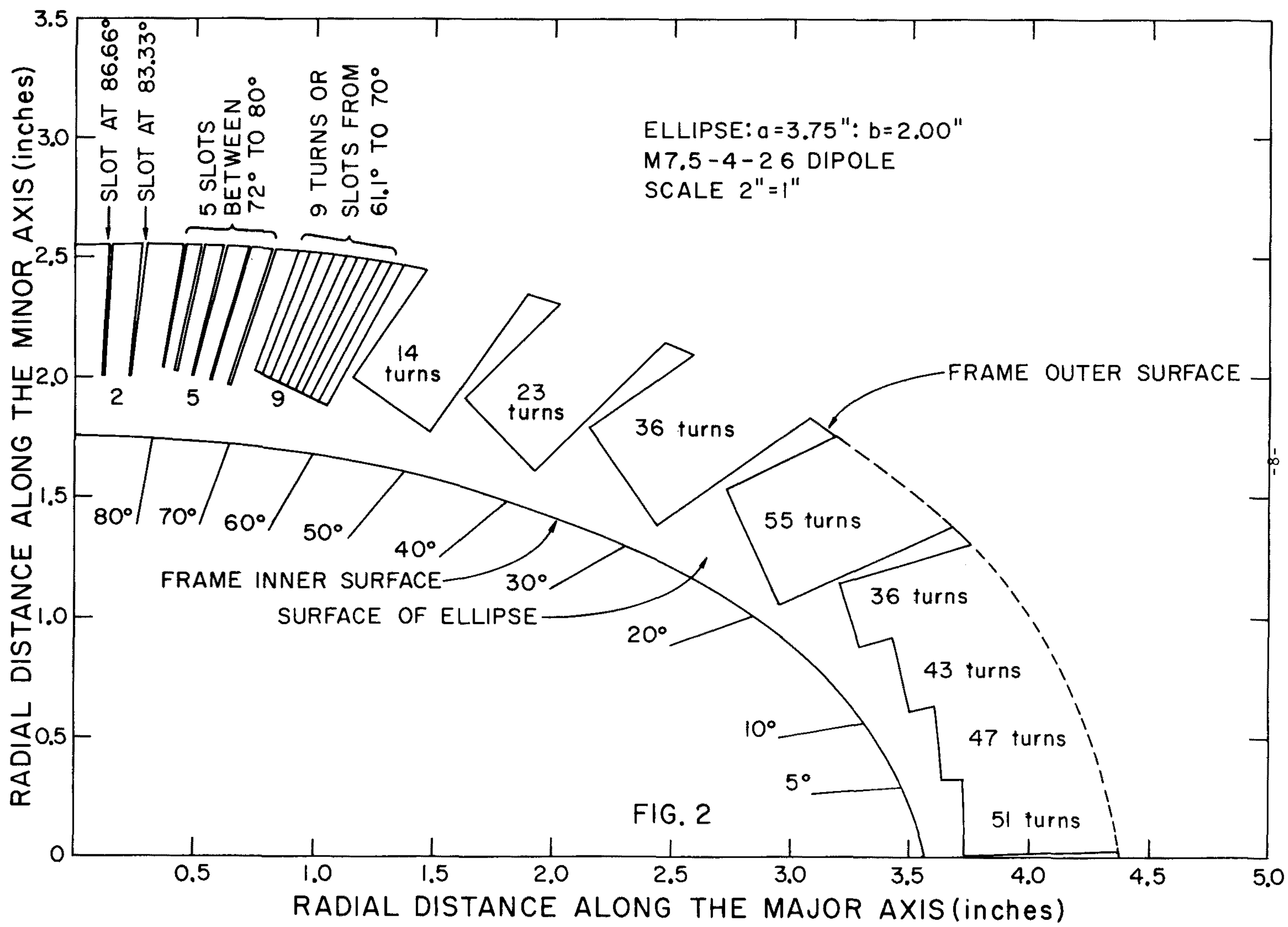

Fig. 2: A Cross Section of one quadruant of the M7.5-4-26 elliptic dipole frame on which the Nb_3-Sn ribbon might be wound. The number of turns of ribbon for each slot is specified in the sketch.