FINAL DESIGN AND INITIAL PERFORMANCE OF THE NEVIS SECONDARY BEAM CHANNELS *

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ABSTRACT

The Synchrocyclotron conversion program nearing completion at Nevis includes the design and construction of an external primary proton and three secondary charged particle transport systems. The optical and mechanical designs of the secondary beam lines, as well as certain novel features, are described. Calculated values of beam fluxes are presented and beam line tuning employing an α-particle system to simulate 101.1 MeV/c singly charged particle beams is discussed.

I. INTRODUCTION

The details of the conversion program are presented in a companion paper.[1] The major features are 1) conversion of the existing cyclotron magnet to a three-fold symmetric, sector focusing, spiral ridge geometry; 2) installation of new RF and high efficiency extraction systems; and 3) considerable expansion of the experimental beams and facilities. The basic machine parameters are an internal proton beam energy and intensity of 560 MeV and 30 μA, respectively, and a slow (> 50% duty cycle), high efficiency (> 70%) extraction.

Figure 1 depicts a plan view of the southeastern portion of the cyclotron building. As the proton beam exits the accelerator, it passes through horizontal and vertical bending magnets which steer the beam onto the production targets, 1.75 m above the building floor. A quadrupole triplet produces a 2.5 cm diameter spot size at the first production target. Downstream from the second production target, a quadrupole singlet and a wedge bending magnet, focusing in the bending plane (b.p.), refocus the beam onto a stop located some 6 m outside the building and 8 m below ground.

The three charged particle secondary channels indicated in the figure are nearing completion. Also indicated are

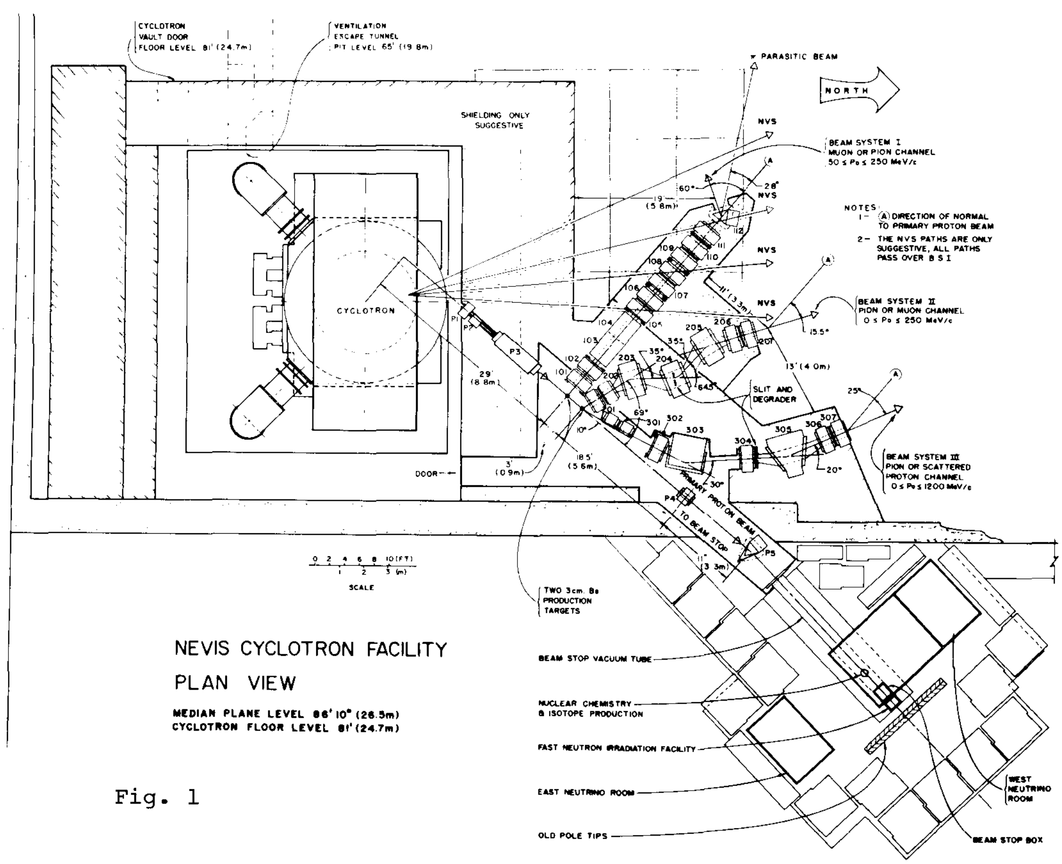

Fig. 1

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 299-305

the Neutron Velocity Spectrometer (NVS) flight paths which view a common internal target located near the north radius of the machine about 1.5 m from the center. When not in use, the beam pipes will be filled with shielding segments. Beam Line I and Beam Lines II and III view two separate production targets. Target wheels will make a variety of target sizes and materials available.

II. DESIGN GOALS AND TECHNIQUES

The details of the design objectives and methods have been previously reported.[2] For the convenience of the reader, the basic requirements for every beam line will be restated. Each channel is required to produce either positively or negatively charged beams parallel to the experimental floor at an accessible height and contain a sufficient number of bends for adequate neutral beam attenuation and momentum resolution. An effort must be made to maximize particle flux and beam optics versatility and to minimize particle contamination, cost, and interference between beam lines, including the NVS flight paths.

Specific criteria applied to each individual channel are as follows:

a.) Beam System I: This channel is intended to be used primarily as a stopped muon beam, but must also produce low momentum pion beams. All beams must be continuously variable in momentum. The muon line must operate in both the forward and backward decay modes and produce muon beams with high polarization. The production angle should be large to suppress contamination, since the production cross section is a slowly varying function of angle at low momenta.

b.) Beam System II: This channel is intended primarily for stopped pion experiments, but a mode of operation must be available to produce high intensity, pure muon beams. All beams should be achromatic and must be continuously variable in momentum and resolution between 0-250 MeV/c and $\pm$ 1-10%, respectively. Spot sizes between 2.5 cm x 2.5 cm and 10 cm x 10 cm and a parallel beam in the horizontal plane should be obtainable. A large production angle should be employed for reasons previously stated.

c.) Beam System III: This channel must produce either pions with continuously variable central momentum P_o and spread $\Delta P/P$ between 0-400 MeV/c and $\pm$ 0.5-3%, respectively, or polarized protons of $\sim$ 1150 MeV/c. The optics requirements are similar to those of Beam System II. A small production angle must be used to maximize flux.

III. DESIGN DETAILS

A. Optics

1. Beam System I. The three bend system indicated in Fig. 2 employs at 90^o production angle. A leading quadrupole doublet and two bend portion can be considered as a pion collection region. The seven quadrupole straight section is designated the pion decay and muon capture region. The total length is 10 m and the typical acceptance solid angle is 0.05 **srad.**

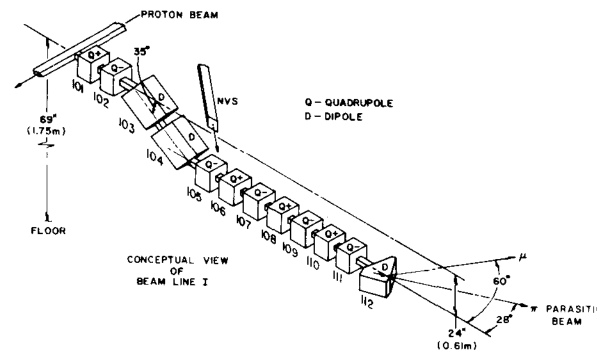

Fig. 2

Magnets 105-111 will be electrically connected in series and excited by a maximum 900 kW, 1700 A power supply obtained from the University of Chicago. Current regulation is better than 0.25% but I_{min} = 100 A. Magnet 111 will be operated in parallel with a water cooled shunt to permit individual control.

Several modes of operation are anticipated: 1) Forward Decay - quadrupoles 101 and 102 in conjunction with magnets 105-110 will be tuned to provide a focus of less than unit magnification in the non-bending plane of magnets 103 and 104 at a point between magnets 110 and 111 where a pion stop will be located. Magnets 101 and 102 will be defocusing and focusing in the bending plane of magnet 103, respectively. The stop will cover the entire aperture in the bending plane and 2.5 cm in the non-bending plane. All pions at the central momentum are stopped, but chromatic dispersion effects cause half of the pions at 90 and 110 MeV/c to miss. However, less than 25% of the muons between 100-115 MeV/c are lost on the stop. Quadrupole #111 and dipole #112 provide average focusing of the beam in both the x and y planes. Additional purification of the beam will occur from the momentum dispersion caused by the dipole.

2) Backward Decay - this mode utilizes momentum separation to eliminate contaminants. Magnets 101 and 102 produce a slightly converging beam into the decay portion. Again, 101 and 102 are defocusing

and focusing in the bending plane of magnet 103, respectively. The decay region is tuned to maximize the acceptance of 130 MeV/c pions and 60 MeV/c muons (this combination of momenta is arbitrary). An attempt is made to achieve an average focusing of the muons in this region onto a target after the last dipole. Dipole 112 disperses the pions onto the walls of a collimator located after the magnet. The calculated beam characteristics for these modes of operation are listed in Table I.

This beam channel can also be used as a pion channel by eliminating the barrier and emphasizing the transmission of pions. This will be accomplished by removing dipole 112 and quadrupoles 107 through 111, leaving a two bend, mirror asymmetric system. Magnets 107-111 are aligned and rigidly connected as a unit resting on tracks permitting easy installation and removal. Two modes of operation will be employed. In each case, the first two quadrupoles are defocusing and focusing in the bending plane of magnet 103, respectively, and magnets 105 and 106 are focusing and defocusing respectively. In the case I(a) of Table II, i.e., achromatic, small spot size tuning, the beam is essentially parallel in both dimensions in the region between dipoles. In the second case, the beam is nearly parallel in the non-bending plane at the symmetry plane between dipoles and focused to a point in the bending plane.

As an additional explanatory note, the use of neutron spectroscopy time of flight paths would be excluded if all elements of this channel remained at original beam height. After bending magnet 104 the magnet tops (yokes) are below the neutron flight paths, which originate at median plane height inside the cyclotron chamber. Since a fan of flight path directions is desired, the final bending is in a horizontal rather than a vertical plane.

2. Beam System II. The system depicted in Fig. 1 fulfills all of the previously stated design goals. The channel is a mirror symmetric system composed of three bends with a quadrupole doublet placed before and after. A production angle of 69° with respect to the proton beam is employed. The total length is 9.3 m and the typical acceptance solid angle is 0.06 sr.

The basic mode of operation is the following: Pions are defocused and focused in the horizontal plane by quadrupoles 201 and 202, respectively, producing a net focus at the slit located at the midpoint of dipole 204. The magnification and dispersion terms of -1.1 and 128 cm (P/ΔP), respectively, produce a 1.3% resolution (half width at half maximum), assuming a 3 cm long production target. In the non-bending plane, the beam tends to cross over between magnets 203 and 204. At the intermediate focus within 204, a remotely and continuously variable width slit will provide a momentum band width selection between 1 and 10%, H.W.H.M., from a 3 cm long production target. A 0.5 cm wide Cu target is available for ~ 0.2% resolution, H.W.H.M., at ~ 40% of the intensity of the Be. Also, three remotely insertable sheets of beryllium (0.41, 0.81, and 1.63 mm thick),

Table I

Muon Channel [1]

Description	P_o MeV/c π	P_o MeV/c μ	Particle Flux [2] x 10^5 Part./sec π^+	Particle Flux [2] x 10^5 Part./sec μ^+	μ^+/π^+	Particle Flux [2] x 10^5 Part./sec π^-	Particle Flux [2] x 10^5 Part./sec μ^-	μ^-/π^-	<Pol> %	$\Delta P/P_o$ %
Forward Decay Barrier After 6th Quad										
Location 1	100	115	380	73	0.2	95	19	0.2	-68	±10
Location 2	100	115	24	26	1.1	6	7	1.1	-68	±10
Backward Decay										
Location 1	130	50	400	21	0.05	100	6	0.06	+83	±10
Location 2	130	50	0	15	Pure	0	4	Pure	+83	±10

1 See text for discussion of each channel. Figures quoted assume a 6 cm beryllium target and 20 μA proton beam. Corrected differential cross sections at 580 MeV are used. Fluxes are integrated over the indicated momentum bite.

2 Fluxes are distributed over an 8-in. x 8-in. surface. Locations 1 and 2 are after quadrupole #110 and after the final dipole # 112, respectively.

Table II

Pion Channels *

Description	$\lvert P_o \rvert$ MeV/c	Acceptance x' mrad	Acceptance y' mrad	Emittance x' mrad	Emittance y' mrad	Spot Size x in./cm	Spot Size y in./cm	π Flux Part./sec $\times 10^7$	$\Delta P/P$ % HWHM†	Beam Impurity‡ e/π	Beam Impurity‡ μ/π	Channel Length in./m
I. Beam System I												
a. Non-dispersive small spot size	100	±60	±254	±62	±161	±0.50/1.30	±0.76/1.9	4.1 π^+	5	9%	17%	256/6.50
								1.1 π^-		30%		
	200	±60	±254	±62	±161	±0.50/1.30	±0.76/1.9	7.6	5	1%	10%	
								2.0		4%		
b. Momentum resolution=±1% dispersionless	100	±54	±268	±37	± 46	±4.25/10.8	±4.06/10.3	0.9	1	9%	23%	
								0.3		30%		
II. Beam System II												
a. Achromatic small spot 0.91 m beyond 207	150	±75	±315	±47	±110	±0.4/1.0	±1.0/2.5	6.0	5	5%	19%	368/9.30
								0.8		17%		
b. Achromatic parallel, 0.91 m beyond 207	150	±76	±322	± 8	±170	±3.0/7.6	±1.8/4.6	5.5	5	5%	25%	
								0.7		17%		
III. Beam System III												
a. Good Resolution Momentum Slit = 0.8 in.	400	±26	±120	±26	± 78	±1.3/3.3	±1.0/2.5	1.2	0.55	0.6%	<2.5%	528/13.4
								0.17		2.0%		
	364							1.1		0.6%		
								0.17		3.0%		
	310							0.8		1.3%		
								0.16		4.0%		
	254							0.4		2.5%		
								0.11		9.0%		
b. Poor Resolution Slit Open	400	±26	±123	±26	± 78	~±3/7.6	±1.0/2.5	12	5.0	0.6%	<2.5%	
								1.7		2.0%		
	364							11		0.6%		
								1.7		3.0%		
	310							8		1.3%		
								1.6		4.0%		
	254							4		2.5%		
								1.1		9.0%		

* The figures in the table assume: 1) a 3 cm^3 Be target, 2) a 20 μA incident proton beam, 3) differential production cross sections given by Refs. 3 and 4, and 4) electron contamination ratios given in Ref. 7. The fluxes are integrated over the indicated momentum band width. The phase space information includes 67% of the beam.

† Half Width at Half Maximum.

‡ Includes only electrons originating in the target. The total μ contamination over an approximately 20 x 20 cm^2 area is given. The contamination within the pion spot size is approximately the ratios of the areas.

inserted separately or in any combination, are available to differentially degrade protons by about 20% in momentum. The pions are typically degraded by 0.5% or less, and the 6 mrad multiple scattering contribution causes a beam loss of only a few percent. Provisions have been made to introduce radii of curvature to the three magnet edges upstream of the slit to effect second order corrections to selected terms.

The beam characteristics at the exit of the channel can be manipulated by adjusting the appropriate quadrupole strengths. Table II lists the description of two such tunes, each 0.91 m beyond magnet 207. The first is a point to point to point focus and the second, a point to point to parallel tune, both in the horizontal plane. The phase space information includes 67% of the beam at the central momentum. The fluxes are integrated over the indicated momentum bite and the electron contamination is only that which originates from the production target. The beam intensities assume: 1) a production angle of 69°, 2) an average proton current of 20 μA, 3) a 3 cm Be production target, and 4) the corrected differential production cross sections at 580 MeV.[3]

Beam System II can produce a rather pure muon beam by displacing the production target off of the optic axis and along the proton beam direction. Thus, by viewing the "muon cloud" surrounding the production target and imaging the target onto a collimator after magnet 207, a high purity muon beam of ~ 40% average polarization is obtained. For the 6 cm Be target planned, 10^6 μ^+/sec, integrated over ± 5%, are produced at 100 MeV/c in a 12.7 cm x 12.7 cm area.

3. Beam System III. The high momentum channel consists of a half-quadrupole and quadrupole doublet, a dipole C magnet, a quadrupole singlet, a wedge dipole magnet, and a final quadrupole doublet. The channel accepts particles emitted around a 10° production angle from the proton beam. The total length is 13.4 m and the typical acceptance solid angle is 0.007 srad.

The basic mode of operation is the following: 301 and 302 defocus and focus the beam, respectively, providing a net focus at the momentum defining slit after 304. In addition, 301 provides a net deflection of the beam of about 5^o. The beam is deflected 30^o horizontally and focused vertically by magnet 303. This magnet is C shaped with the open side toward the primary proton beam. This construction avoids having a large mass from which to produce secondary particle contamination and also permits the use of the small production angle from the target. Quadrupole 304 vertically focuses and, therefore, narrows the beam to pass through the relatively narrow gap dipole wedge magnet 305. At quadrupole 304, the horizontal beam dimension is small ($\sim$ 4 cm) and is thus only slightly affected. At the slit, the magnification and dispersion terms are -0.65 and 177 cm ($P/\Delta P$), respectively, producing a 0.55% resolution (H.W.H.M.) from a 3-cm wide target. In the vertical plane, the beam is 18 cm high, but converging. The remotely and continuously variable width slit will provide a momentum band width selection between 0.5 and 5%, H.W.H.M., from the 3 cm wide production target. A 0.5 cm wide Be target that presents 3 cm of thickness to the proton beam is available for 0.1% resolution, H.W.H.M., with no loss in intensity. However, this particular target presents a 25-cm wide target to Beam Line II. A continuously variable thickness Be degrader will be located at the slit to differentially degrade protons during π^+ operation of the channel.

Wedge magnet 305 is designed to enhance the vertical focusing of the beam as well as deflect the beam through 20^o. The final quadrupole pair (306-307) focus the beam horizontally and vertically, respectively, onto the experimenters target some 1.78 m beyond 307.

The beam characteristics at this point can be altered by the adjustment of appropriate quadrupole strengths. Table II details the characteristics of two such tunes. The comments from the last section about the table continue to apply. The pion fluxes assume: 1) a production angle of 10^o, 2) an average proton current of 20 μA, 3) a Be target, 3 cm thick in the proton beam direction, and 4) the corrected differential production cross sections at 600 MeV.[4)]

Also available on the target wheel is a 0.3 cm square tantalum wire for the production of 1150 MeV/c, elastically scattered, 50% polarized protons. The intensity and momentum resolution will be about 10^8 protons/sec and 0.05%, H.W.H.M., respectively.

B. <u>Mechanical Design Details</u>

The final designs of the beam channels reflect the desire to standardize the hardware wherever possible, for economy of effort and expense. The following standard transport elements have been designed, built, measured, and installed: 1) 30.48 cm bore, 45.72 cm long quadrupoles with hyperbolic shaped pole pieces and radiation hard coils, designated Hyperquads (magnets 101, 102, 201, 202, 206, 301, 302, and 304); 2) 68.58 cm wide, 76.2 cm long rectangular window frame bending magnets with a standard (but adjustable) 23.5 cm gap, designated Standard Dipoles (magnets 103, 104, 203, 204, and 205); 3) 30.48 cm bore, 45.72 cm long quadrupoles with terraced shaped pole tips, designated Danby Quads (magnets 105-111, 207, 306, and 307). The non-standard elements are 1) a 20.32 cm gap, equilateral wedge dipole #112, obtained from the University of Chicago, 2) a 63.5 cm wide, 1.37 m long C magnet #303 with a 17.0 cm gap, and 3) a 63.5 cm wide, 1.17 m long window frame wedge magnet #305 with a 15.24 cm gap. In general, each magnet is powered by a separate 50 kW, 1000 A supply that regulates to better than 0.1%, long term.

The first of two novel features in the design of the secondary beams is the use of hard anodized, aluminum coils[5)] in the Hyperquad magnets exposed to high radiation. The advantages over other commonly used fabrication techniques for radiation hardened coils are significant. At this point (August, 1975), we have had no experience with operating the magnets in high radiation environments. However, some of the magnets have been operated for hundreds of hours over the past two years with no mechanical, magnetic, or electrical problems.

The second unusual feature is the half quadrupole septum magnet #301. The small production angle of B.S. III and the need to deflect the beam away from the proton beam dictated a narrow, septum bending magnet. The desire to maximize the acceptance solid angle led to the choice of a half-quadrupole, which focuses in the vertical, while defocusing and deflecting the beam by $\sim 5^o$ in the horizontal. Magnet 301 is two halves of a Hyperquad in tandem and operated electrically in series and magnetically with the same polarity. The symmetry plane is maintained with a sheet of iron that increases linearly in thickness from 2.5 cm at the quadrupole center to 20 cm at the edge.

The magnets are prealigned on magnet stands that permit removal and reinsertion without realignment. All magnets within a given class are interchangeable.

Beams in channels I, II, and III are in vacuum from the production targets to

112, through 207, and through 304, respectively. A helium container will be used to complete B.S. III. Vacuum joints in high radiation areas are made with quick disconnect, metal gasket flanges. Provisions have been made to remotely disconnect water, power, and vacuum joints for fast removal of a defective magnet.

IV. Measurements and Analysis

A. Magnetic Fields

A comprehensive measurement and analysis program has been completed. A sufficient number of magnets within each class were measured to insure that their properties are identical. All of the unique, one-of-a-kind, magnets were also measured. In all cases, data were taken at the top, middle, and bottom of the excitation current range in order to permit interpolation for an arbitrary magnet current setting.

For quadrupoles, the data in planes perpendicular to the optic axis were fit to multipole expansion coefficients and the resulting data numerically integrated through the magnets. "Allowed" four-fold symmetric terms (2θ, 6θ, 10θ, and 14θ) and "unallowed" asymmetric terms (1θ, 3θ, 4θ, and 5θ) were included in the expansion. The numerical integration provided all transfer matrices through 3rd order. The effective strength and lengths of an equivalent hard edge magnet were found from the 1st order transfer matrix.

For dipoles, the data were numerically integrated along axes parallel to the symmetry axis that passes through the magnet. An effective length, and two effective fringing field (E.F.F.) correction parameters were calculated. The first, K1, is a vertical focusing correction factor and the second, a correction for the net displacement of the optic axis (compared to a sharp cutoff approach) in the bending plane.

The data were taken using a semi-automated, cartesian coordinate measuring machine. The sensing element was composed of three Hall devices, arranged mutually perpendicular to measure the three components of the field. The temperature regulation and constant current excitation source permitted measurements reproducible to better than 1.5 G. The positional accuracy was 0.13 mm. The data were recorded automatically on a magnetic computer tape and analyzed on an IBM 360/44. The data were corrected for 1) non-linearity of the probes, 2) the non-cosine behavior of Hall probes rotated in a uniform magnetic field,[6] and 3) the non-spatial coincidence of the three Hall elements.

The analysis of the data is incomplete, but preliminary results can be summarized as follows:

a) Hyperquads: These magnets were found to have an effective length that changed by 0.4% over the entire excitation range. The two dimensional harmonic content at $R = R_{Max}$ is in general, one to two tenths of one percent of the quadrupole term. The effective lengths between magnets agree within 1.3%.

b) DanbyQuads: The effective length changes by 0.6% over the excitation range. The two dimensional harmonic content at $R = R_{Max}$ is less than 1%, and in general, about twice the Hyperquads.

c) The dipoles, in general, follow the rule of thumb of ℓ_{eff} = physical length + gap. The K_1 and K_2 correction factors were similar to other values found in the literature.

B. Beam Tuning

A beam tuning and debugging program has been undertaken to compare the beam optics with calculated values and to verify the alignment and performance of the various beam line components. An α-particle system has been employed to simulate the flight of pions and muons. The system is composed of a 1 cm diameter ^{241}Am source (5.48 MeV (85%), 5.44 MeV (15%) and a low pressure (~ 0.1 atmosphere) multiwire proportional chamber (MWPC)). The 5.48 MeV α particles simulate 101.1 MeV/c positive, singly charged particles, and the 5.44 MeV α's provide a 0.4% $\Delta P/P$ beam for momentum dispersion and chromaticity measurements.

The MWPC, which must be interfaced with the vacuum chamber, has a 0.013 mm thick mylar window to contain the isobutane gas and 96 signal wires per plane, interfaced directly on-line to a computer. The wire spacing is 2 mm. The MWPC is typically operated at 1650 V. The measured and calculated spot sizes of a beam through the 101-102 doublet were 3.25 cm and 3.43 cm in x and 0.6 cm and 0.2 cm in y, respectively. The calculation used the average value of the g_{eff} found from the analysis for the focusing and defocusing planes. The source was collimated to $\pm$ 57 mrad in the x and y (horizontal and vertical) planes. Presently measurements are being taken between the production and 50 cm beyond magnet 104. More detailed measurements and their comparison with calculated values will be published in the near future.

Many people have contributed to the success of this program at Nevis, too many, in fact to acknowledge separately. However, the authors would like to express their appreciation to these people and especially to Dr. Klaus Steffen of DESY and Dr. Gordon Danby of BNL for their assistance in adapting quadrupole magnet designs to Nevis requirements.

References

1) Status of the Nevis Synchrocyclotron, R.C. Cohen et al, Nevis Labs., Columbia U., these proceedings.
2) Design of Secondary Beam Channels for the Nevis Synchrocyclotron Conversion Program, M.M. Holland et al, IEEE Trans. on Nucl. Sci., Vol. NS-18, #3 (June 1971).
3) Low Energy, Large Angle Pion Production by 580 MeV Proton Bombardment of Various Nuclei, P.W. James et al, TRIUMF Rpt. #VPN-75-1 (March 1975).
4) Etude Experimentale de la Production de Pions Charges dans les Collisions Proton-Noyan A 600 MeV, W. Hirt et al, CERN Rpt. #69-24 (September 1969).
5) Radiation Resistant Magnet Coils from Hard Anodized Aluminum Conductor, M.M. Holland, J. Shill, IEEE Trans. on Nucl. Sci. Vol. NS-20, #3 (June 1973).
6) Beam Transport Magnet Measurements at DESY, K. Holm, K.G. Steffen, Proceedings of the International Symposium on Magnet Technology (Ed., H. Brechna, H.S. Gordon) SLAC (September 1965), CONF 650922, U.C.-28, TID-4500, 44th Ed.
7) Production of Charged Pions by 730 MeV Protons from Hydrogen and Selected Nuclei, D.R.F. Cochran et al, Los Alamos Rpt. #LA-DC-72-133 (December 1971).

* Research supported by the National Science Foundation.