OPERATION OF THE NAL MAIN RING EXTRACTION SYSTEM

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Summary

The NAL Main Ring extraction system has delivered both slow and fast extracted beam at 100, 200 and 300 GeV. Construction progress, operating conditions, instrumentation and beam characteristics are discussed.

Introduction

Previous papers at the 1969 and 1971 Accelerator Conferences have discussed the design of the Main Ring extraction channel and the beam lines to the Neutrino, Meson and Proton Laboratories[1,2]. In this report, we will discuss the construction progress to date; operating conditions; instrumentation and beam characteristics.

Beam Line Equipment

Figure 1a shows the extraction channel elements, consisting of: (1) the extraction electrostatic septa, which deflect the extracted portion of the beam radially outward 0.2 milliradians (mr); (2) Lambertson magnetic septa, which give the extracted portion of the beam a 3 mr downbend; (3) a pair of C magnets and a pair of H magnets, which bend the beam radially outward 10 mr; (4) a vertical H magnet (VH), which bends the beam to within 0.25 mr of horizontal; and finally (5) four additional H magnets, which bend the beam radially outward 12 mr. The C magnets have a magnetic aperture of 1.5"H x 0.650"V, and the H magnets have an aperture of 1.5"H x 0.625"V. The Lambertsons' aperture is 0.585"H x 0.8"V. With the vacuum pipe inserted in the C and H magnets, there is an effective aperture of 0.5" x 0.5", since the VH magnet is a rotated H magnet. The Lambertsons, C's and H's are powered in series with a single 1700A, 1/2 MW peak programmable power supply. The Lambertsons and VH magnet have additional shunt supplies, providing up to 10% correction for positioning the vertical height and exit angle of the beam in the channel. Instrumentation in the extraction channel consists of Segmented Wire Ionization Chambers (SWIC's) with 1/2 mm wire spacing for measuring beam profiles[3] and ionization chambers for detecting radiation losses.

Downstream of the extraction channel, there is instrumentation consisting of (1) a toroid, (2) an ionization chamber, (3) a split-plate, non-intersection beam position detector and (4) a Secondary Emission Monitor (SEM).

Figure 1b shows the most recent configuration of the Neutrino, Meson and Proton beam lines. There are two splitting stations[4] presently installed to divide the beam among the three experimental laboratories. An upstream station, located 200 ft. from the extraction point, produces the split between the Neutrino and Proton Laboratory beam lines. A second station, at 700 ft., splits that portion of the beam directed to the Neutrino Laboratory, sending a quantity to the Meson Laboratory. The Meson Laboratory beam is bent achromatically left 165 mr by four Lambertsons, forty 10 ft. dipoles (3.927 mr each) and seven 10 ft. quadrupoles. For the Proton Laboratory, a right bend of 97.4 mr is accomplished with five Lambertsons, 34 dipoles (2.66 mr each) and five quadrupoles. All the bending magnets in the Meson or Proton Laboratories are powered in series with programmable supplies which provide up to 1500 amperes. Another splitting station has been designed to provide a triple split for three separate beam lines within the Proton Laboratory itself.

The Meson and Neutrino Laboratory beam lines are described in more detail in Reference 1; however, the Neutrino Laboratory beam line has been altered slightly to allow the installation of splitting station equipment. The Neutrino Target Hall is in a direct horizontal line from the exit of the extraction channel and has five quadrupole doublets and one singlet quadrupole for beam focussing. To establish the beam near ground elevation in the target halls of all three laboratories, an upstream 10 mr upbend followed by a 10 mr downbend is used. Additional quadrupoles exist in each laboratory to target the proton beam. At strategic locations along all three beam lines, there are low power trim dipoles for slight steering adjustments. The Meson Laboratory beam can be tuned from 50 to 300 GeV, while the Neutrino and Proton Laboratory beam lines may be tuned to 500 GeV.

Instrumentation

Early stages of tuning were done using phosphorescent flags made from a Radelin surface on aluminum backing; some of these flags are still in use. The flags are retractable from the beam and may be viewed remotely with the aid of TV cameras. Čerenkov radiation loss monitors made from paint cans containing 1P21 phototubes immersed in oil were used to detect beam losses originally, but their usefulness is limited by their saturation at relatively low levels of radiation.

More recently, tuning the extraction channel and associated beam lines has been facilitated by the SWIC's and ionization chamber beam loss monitors. The SWIC's are constructed in a manner similar to that described by Hornstra and Simanton[3]. Aluminum wire 0.004" in diameter is wound and glued with epoxy onto G-10 fiberglass printed circuit backing with a wire spacing of 1/2 or 1 mm. Each SWIC consists of a vertical and horizontal plane of wires separated by 1 cm with a positive high voltage plane midway between the two signal planes. The central 50 wires on each plane are individually connected to strip wires which, along with the HV lead and gas inlet and outlet tubes, exit from an antivacuum box to the outside world. The SWIC and its surrounding antivacuum box is mounted in a standard vacuum box. There is a 0.002 in. titanium window on the beam entrance and exit faces of each antivacuum box. The antivacuum box is made to rotate in the vacuum box so as to be removable from the beam. The chambers operate well with a high voltage of 1.5 kV for 10^{10} protons per pulse. A mixture of 90% argon and 10% methane gas flows through the chambers at about 1 cc/min. The current on each wire is integrated during the beam spill and then the 50 channels are displayed on a storage oscilloscope in a time span of 5 to 100 msec[5]. Presently, up to six chambers are connected in parallel to one set of electronics. High voltage is switched off on all those in parallel except for the SWIC to be used. Each SWIC can be operated remotely from the Main Control Room via the computer. Hardware exists for reading the SWIC data into the main ring computer and software is being developed to store and display beam profiles. Relative intensity can be obtained from the SWIC output by integrating the area under the profile.

The loss monitors are ionization chambers made from lengths of 2 in. diameter high frequency spiral insulated coaxial cable (RG-319, Andrew Corporation). The inner conductor acts as the signal electrode, while the outer conductor is operated at 1.5 kV. Argon-methane gas is circulated between the conductors.

The loss monitors vary in length. The longest one extends the length of the Transfer Hall (400 ft.) and is mounted near the ceiling. Two 50 ft. lengths exist six feet below and parallel to the splitting station Lambertson magnets. Two-foot lengths are located at critical elements and where small apertures exist. The integrated analog signals from these monitors are displayed on a common oscilloscope trace to provide a visual histogram for tuning purposes. For quantitive analysis, digital readout is also selectably available in the Main Control Room.

The intensity of the extracted beam is measured with a Secondary Emission Monitor (SEM), built at Cambridge Electron Accelerator (CEA), which has been loaned to us by Cornell University[6]. This SEM has been calibrated at NAL with 200 GeV protons by using a toroid in conjunction with the fast extracted beam and by foil activation analyses. A SEM constructed by members of the NAL Accelerator Section has been tested and shown to have a linear response with respect to the CEA SEM for intensities which vary from 10^{10} to 10^{12} protons per pulse. Additional SEM's, built outside the Laboratory, are now ready for testing. A SEM in the Neutrino Target Hall permits measurement of the beam transport efficiency.

Operation and Tuning

The various methods of extracting beam from the Main Ring (MR) have been: fast, slow, scraped and resonant pinged processes. Beam has been extracted at energies of 80, 100, 200 and 300 GeV.

At first, fast extraction of a single booster bunch was achieved with a fast kicker magnet (the pinger) located approximately 3/4 λ upstream of the wire septa. The pinger is made of two hair-pin-shaped coils above and below the beam, and is energized by discharging a capacitor bank with a resultant peak current of 6700 amperes. The half-wave shape of the current pulse is approximately 40 μsec in length and the strength of the resultant field is sufficient to extract cleanly three booster bunches (thirteen bunches are needed to fill the ring entirely). The pinger gives the beam a kick of approximately 0.1 mr at 200 GeV/c. For fast extraction at 300 GeV/c, two pingers have been used. In practice, the radial and vertical position of the beam and its horizontal angle at the septum are adjusted using programmable vertical (MR-V at F47-A18) and horizontal bumps (POS at F46-A17 and ANG at F44-A15) so that before the beam is pinged it is positioned a few millimeters from the wire septa.

Slow extraction at NAL has been discussed in Reference 7. Briefly, the MR quadrupole current is increased to bring the tune near 20.4, and then two additional ramped iron core quadrupoles at F19 and A32 are energized to bring the tune to the half integral resonance at 20.5. The F19 quadrupole is software programmed to come on during flattop; the A32 quadrupole is servo-controlled by spill feedback. As in fast extraction, the MR beam position and angle are controlled by POS, MR-V and ANG to give reasonable extraction efficiency.

The extraction channel is tuned by centering the beam at the first two SWIC's in the channel while simultaneously adjusting the Lambertson trim supply and VH shunt to steer the beam through the center of the SWIC's and the first two quadrupole doublets, Q90-91 and Q100-101. Proper tuning through the channel is verified by observing low losses in the various ionization chamber loss monitors. Tuning the beam lines is normally a straightforward process.

300 GeV slow spill beam has been delivered to each of the laboratories, although the Neutrino Laboratory has used most of the time available for high energy physics. Typical operation of the Neutrino Line includes a fast resonant-pinged spike on the end of the slow spill for the 30" bubble chamber. The timing of this spike is coordinated with the pulsing of by-pass magnets in the Neutrino Target Hall which allow simultaneous operation of the 30" bubble chamber and several slow spill counter experiments.

An exposure of nuclear emulsions to 200 GeV protons has been carried out at low intensities ($\sim 10^8$ protons per pulse) in the Meson Laboratory by shaving a small fraction of the circulating beam into the extraction channel with the POS bump and the electrostatic septum.

Beam has been time-shared among the experimental areas by sending several MR pulses to each laboratory in turn. This is accomplished by alternately turning on and off the supplies which power the right and left bends to the Proton and Meson beam lines, respectively. This type of operation has become obsolete with the installation of the splitting stations.

Since September 1, 1972, high energy physics experiments have logged 1300 hours with extracted beam. Approximately 300 hours have been devoted to extraction turn-on, beam tuning and extraction experiments.

Beam Characteristics

Extraction efficiency for fast extraction at 200 GeV is measured to be consistent with 100% while an efficiency of 85% has been obtained for slow spill 300 GeV beam. Transport efficiency to the Neutrino Target Hall has been measured to be 100% when the pulsed bypass is not running. The fast extracted beam emittance phase space area has been measured at 200 GeV using, in part, the quadrupole focussing technique described by Banford[8].

We find: $\pi\varepsilon_H = \pi(0.11 \pm 0.02)$ mm mr, and

$\pi\varepsilon_V = \pi(0.06 \pm 0.02)$ mm mr.

This measurement and observation of beam size at four locations downstream of the extraction points with quadrupoles off allows calculation of X_0, X_0', Y_0, Y_0' and the locations of the waists of the extracted beam. The measurements indicate that the horizontal emittance is about half the design value while the vertical emittance is slightly smaller than predicted. Attempts to measure the slow extraction phase space have been hampered by ripple and a voltage droop in the extraction electrostatic septum, which recently has been largely eliminated.

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References

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1. R.A. Andrews, A.W. Maschke, R.M. Mobley and C.H. Rode, Proc. of the 1969 Particle Accelerator Conference, IEEE Trans. on Nuclear Science NS-16,3, 262 (1969).
2. C.H. Rode, R.A. Andrews, A.W. Maschke and R.M. Mobley, Proc. of the 1971 Particle Accelerator Conference, IEEE Trans. on Nuclear Science NS-18,3, 984 (1971)
3. F. Hornstra and J.R. Simanton, Nucl. Instr. and Methods 11, 4062 (1969).
4. L.W. Oleksiuk, R.A. Andrews, E.J. Bleser and C.H. Rode, Proc. of the 1973 Particle Accelerator Conference.
5. F. Hornstra and J.R. Simanton, Nucl. Instr. and Methods 11, 303 (1969).
6. G.F. Dell and M. Fotino, "The CEA Secondary Emission Monitors", CEA Report CEAL-1045 (1968).
7. H.T. Edwards', W.W. Lee, J.D. McCarthy, S. Ohnuma and L.C. Teng, Proc. of the 1973 Particle Accelerator Conference.
8. A.P. Banford, The Transport of Charged Particle Beams, E.& F.N. Spon. Ltd. (1969).

Figures

1a. NAL Main Ring Extraction Channel.
1b. NAL Switchyard Beam Lines.

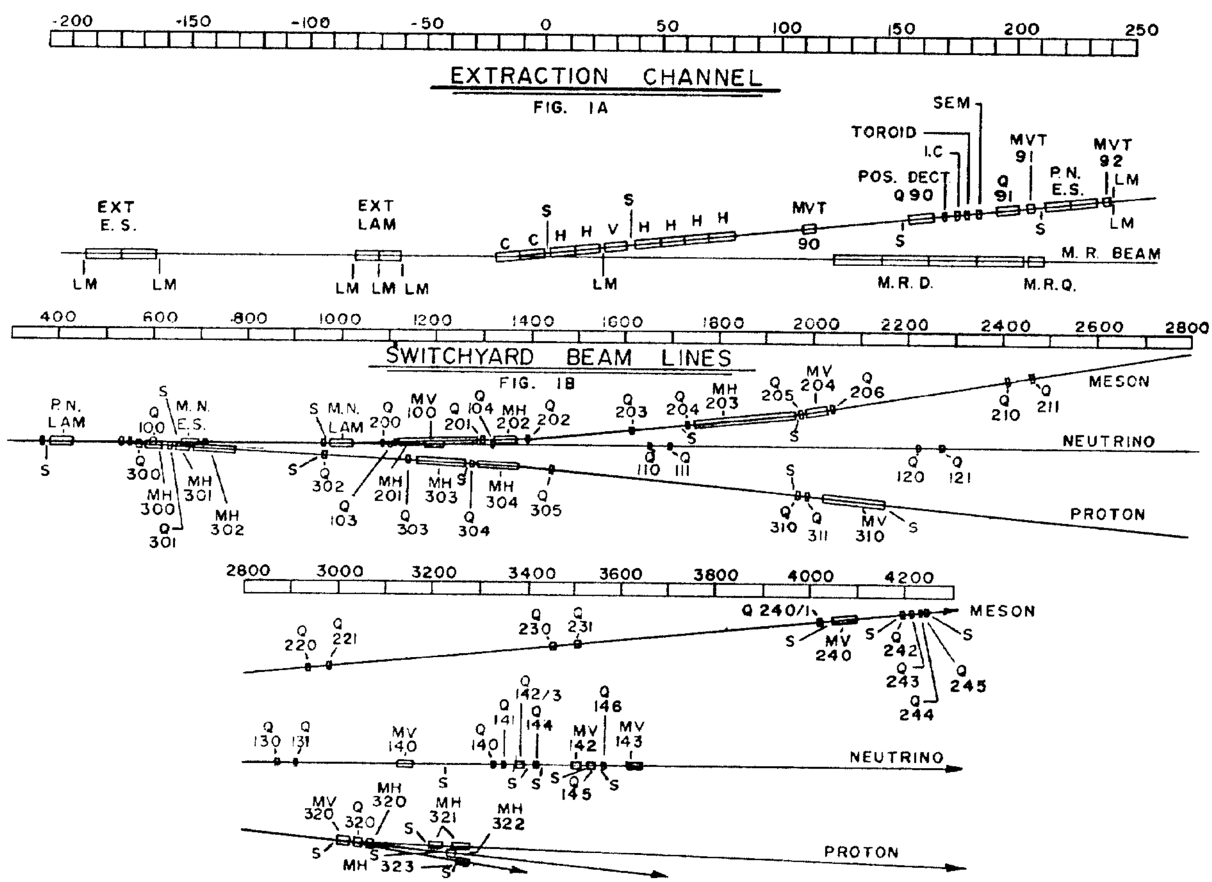

Figure 1.