

## 32. Neutrino Beam Lines at High-Energy Proton Synchrotrons

Revised August 2019 with numbers verified by representatives of the synchrotrons (contact C.-J. Lin, LBNL). For existing (future) neutrino beam lines the latest achieved (design) values are given.

The main source of neutrinos at proton synchrotrons is from the decay of pions and kaons produced by protons striking a nuclear target. There are different schemes to focus the secondary particles to enhance neutrino flux and/or tune the neutrino energy profile. In wide-band beams (WBB), the neutrino parent mesons are focused over a wide momentum range to obtain maximum neutrino intensity. In narrow-band beams (NBB), the secondary particles are first momentum-selected to produce a monochromatic parent beam. Another approach to generate a narrow-band neutrino spectrum is to select neutrinos that are emitted off-axis relative to the momentum of the parent mesons. For a comprehensive review of the topic, including other historical neutrino beam lines, see the article by S. E. Kopp, ‘‘Accelerator-based neutrino beams,’’ Phys. Rept. **439**, 101 (2007).

|                                 | PS<br>(CERN)    |                 |                    |             | SPS<br>(CERN)       |                        |               |               | PS<br>(KEK) | Main Ring<br>(JPARC) |
|---------------------------------|-----------------|-----------------|--------------------|-------------|---------------------|------------------------|---------------|---------------|-------------|----------------------|
|                                 | 1963            | 1969            | 1972               | 1983        | 1977                | 1977                   | 1995          | 2006          | 1999        | 2017                 |
| Date                            | 1963            | 1969            | 1972               | 1983        | 1977                | 1977                   | 1995          | 2006          | 1999        | 2017                 |
| Proton Kinetic Energy (GeV)     | 20.6            | 20.6            | 26                 | 19          | 350                 | 350                    | 450           | 400           | 12          | 30<br>(50)           |
| Protons per Cycle ( $10^{12}$ ) | 0.7             | 0.6             | 5                  | 5           | 10                  | 10                     | 36            | 48            | 6           | 240<br>(330)         |
| Cycle Time (s)                  | 3               | 2.3             | -                  | -           | -                   | -                      | 14.4          | 6             | 2.2         | 2.48<br>(3.5)        |
| Beam Power (kW)                 | 0.8             | 0.9             | -                  | -           | -                   | -                      | 180           | 510           | 5           | 500<br>(750)         |
| Target                          | -               | -               | -                  | -           | -                   | -                      | Be            | Graphite      | Al          | Graphite             |
| Target Length (cm)              | -               | -               | -                  | -           | -                   | -                      | 290           | 130           | 66          | 91                   |
| Secondary Focussing             | 1-horn WBB      | 3-horn WBB      | 2-horn WBB         | bare target | dichromatic NBB     | 2-horn WBB             | 2-horn WBB    | 2-horn WBB    | 2-horn WBB  | 3-horn off-axis      |
| Decay Pipe Length (m)           | -               | -               | -                  | -           | -                   | -                      | 110           | 1090          | 200         | 96                   |
| $\langle E_\nu \rangle$ (GeV)   | 1.5             | 1.5             | 1.5                | 1           | 50,150 <sup>†</sup> | 20                     | 24.3          | 17            | 1.3         | 0.6                  |
| Experiments                     | HLBC, Spark Ch. | HLBC, Spark Ch. | GGM, Aachen-Padova | CDHS, CHARM | CDHS, CHARM, BEBC   | GGM, CDHS, CHARM, BEBC | NOMAD, CHORUS | OPERA, ICARUS | K2K         | T2K                  |

|                                 | Main Ring<br>(Fermilab) |            |             |               |          | Booster<br>(Fermilab)                           | Main Injector<br>(Fermilab) |                       |                 |              |
|---------------------------------|-------------------------|------------|-------------|---------------|----------|-------------------------------------------------|-----------------------------|-----------------------|-----------------|--------------|
|                                 | 1974                    | 1979       | 1976        | 1991          | 1998     | 2002, (2020)                                    | 2005                        | 2017                  | (2020)          | (2026)       |
| Date                            | 1974                    | 1979       | 1976        | 1991          | 1998     | 2002, (2020)                                    | 2005                        | 2017                  | (2020)          | (2026)       |
| Proton Kinetic Energy (GeV)     | 300                     | 400        | 350         | 800           | 800      | 8                                               | 120                         | 120                   | 120             | (60 – 120)   |
| Protons per Cycle ( $10^{12}$ ) | 10                      | 10         | 13          | 10            | 12       | 4.5                                             | 37                          | 54                    | (65)            | (75)         |
| Cycle Time (s)                  | -                       | -          | -           | 60            | 60       | 0.2                                             | 2                           | 1.333                 | (1.2)           | (1.2)        |
| Beam Power (kW)                 | -                       | -          | -           | 20            | 25       | 29                                              | 350                         | 720                   | (1000)          | (1200)       |
| Target                          | -                       | -          | -           | -             | BeO      | Be                                              | Graphite                    | Graphite              | Graphite        | (Graphite)   |
| Target Length (cm)              | -                       | -          | -           | -             | 31       | 71                                              | 95                          | 120                   | 120             | (150-220)    |
| Secondary Focussing             | dichromatic NBB         | 2-horn WBB | 1-horn WBB  | quad trip.    | SSQT WBB | 1-horn WBB                                      | 2-horn WBB                  | 2-horn off-axis       | 2-horn off-axis | (3-horn WBB) |
| Decay Pipe Length (m)           | 400                     | 400        | 400         | 400           | 400      | 50                                              | 675                         | 675                   | 675             | (220)        |
| $\langle E_\nu \rangle$ (GeV)   | 50,180 <sup>†</sup>     | 25         | 100         | 90,260        | 70,180   | 1                                               | 3-20 <sup>‡</sup>           | 2                     | 2               | (2.5)        |
| Experiments                     | CITF, HPWF, 15' BC      | 15' BC     | HPWF 15' BC | 15' BC, CCFRR | NuTeV    | MiniBooNE, SciBooNE, MicroBooNE, (SBND, ICARUS) | MINOS, MINERνA              | NOνA, MINERνA, MINOS+ | NOνA            | LBNF/ DUNE   |

<sup>†</sup>Pion and kaon peaks in the momentum-selected channel.

<sup>‡</sup>Tunable WBB energy spectrum.