BEAM-DISTRIBUTION SYSTEM FOR MULTI-AXIS IMAGING AT THE ADVANCED HYDROTEST FACILITY*

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Abstract

The Advanced Hydrotest Facility is to provide a time sequence of multiple radiographic images using a proton beam produced by a 50-GeV synchrotron. We give an overview of the approaches devised to produce up to twelve simultaneous radiographic images of an object by a sequence of beam-transport lines. The required distribution system has undergone a parametric study that optimized its configuration within operational constraints. These constraints and our approach to configuration optimization for both superconducting and normal-conducting transport lines are described. Additionally, we describe the optics stratagems that were devised to meet system requirements.

1 INTRODUCTION

The AHF is planned as an important part of the U.S. Stockpile Stewardship Program to perform proton radiography[1], i.e., the observation of fast events by illumination with protons that are subsequently focused to provide an image of the events. In addition to a spatial image, the lens system provides an angular image, which allows determination of the materials involved in the event[2].

1.1 Radiography Requirements on the Transport System

In order to obtain a tomographic reconstruction of events, views from several directions are needed. The number of views desired is determined by the required resolution, assumptions about symmetry, and *a priori* knowledge of the events under observation. At present, up to 12 views has been specified, requiring 12 beamlines converging on an interaction region, close to the maximum number practical.

Obtaining information on the time evolution of events requires several frames separated by from about 200 ns to several μs. A mixture of such framing sequences may be desirable for certain applications. Although pulse patterns do not originate with the transport lines, such timing considerations affect the beamline configuration and switching devices. A cycle rate of above 25 s mainly affects the magnet cooling systems as well as the average power.

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The transport configuration is also strongly influenced by the required beam energy, which has been specified at 50 GeV. This choice of energy is a compromise between increased imaging resolution with energy and cost of implementation. Since bending radii and quadrupole strengths are proportional to particle momentum, transport-system size and cost become awkward at energies much above 50 GeV.

An additional requirement of 3×10^{13} particles/cycle at an estimated 10^5 cycles/year affects beam transport in that the fractional beam loss should not result in substantial activation of the transport-line components. Beamline-aperture and alignment choices adjust such loss as does choice of diagnostic complement. The peak current in the transport lines corresponding to the 3×10^{13} particles, divided among several pulses, does not result in significant space-charge effects.

Other requirements place complementary or additional constraints on other of the AHF systems; we mention only those that bear on the transport system.

1.2 Selected Transport Configuration

An extensive study has been made to arrive at a transport configuration that minimizes cost, effort, schedule and power while fulfilling radiographic requirements. The transport configuration selected is shown in Fig. 1 along with a conceptual sketch of a linac, booster synchrotron, and 50-GeV synchrotron.

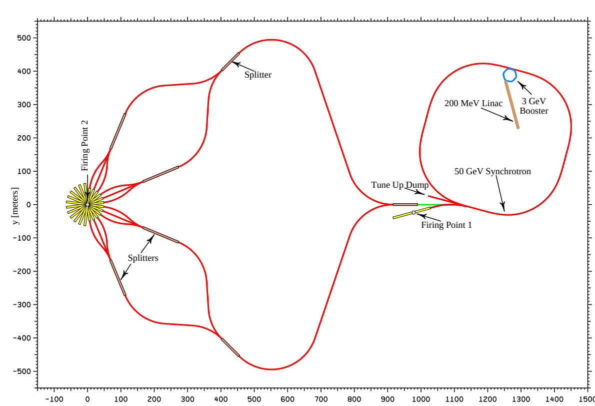
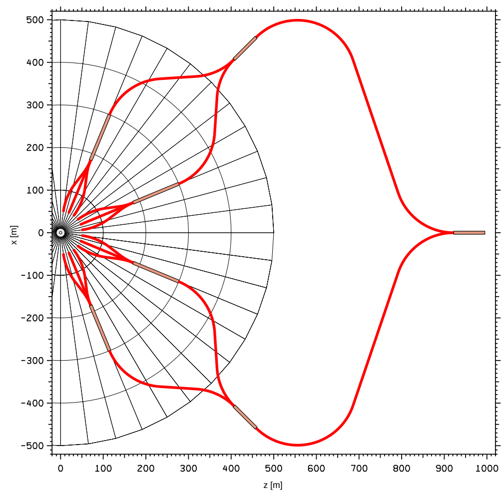


Figure 1: Selected beam-transport configuration showing relation to a linac and booster/synchrotron system.

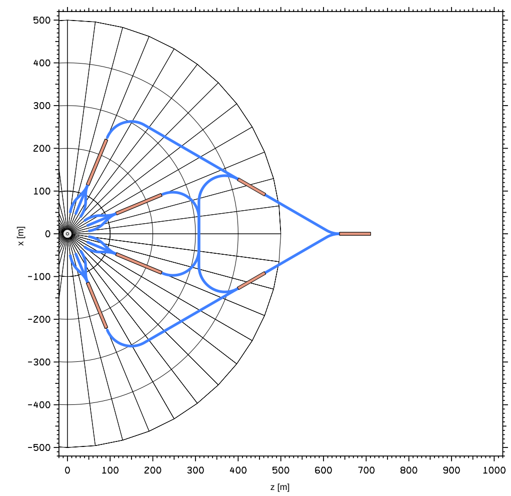
In the site-independent version shown in Fig. 1, a 200-MeV linac injects 1.5×10^{12} H^- ions into a 3-GeV booster. An alternative for Los Alamos siting uses the LANSCE linac to inject an 800-MeV chopped beam into a suitably configured booster. Each booster cycle injects a single bunch into a harmonic-24 synchrotron to produce 20 short (20-ns) bunches that are extracted at will into the transport system. As it progresses through the transport line, beam is cut into 12 equal parts by a series of splitters. Each part then converges on the object of interest, labeled Firing Point 2 in Fig. 1, with all parts arriving simultaneously (to within 15 ns). Alternatively, just after extraction the synchrotron beam pulse can be directed to Firing Point 1.

2 TRANSPORT LATTICE

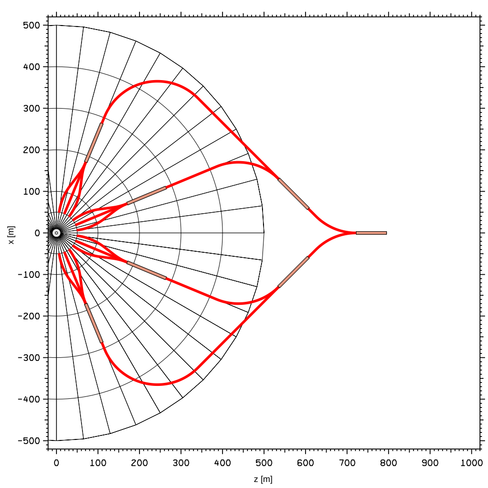
A recent study has gathered requirements and proposed a number of options that were then detailed and the option tradeoffs evaluated. In particular, emphasis has been on minimizing power consumption and cost. Power is a special issue in both capital and operating costs since the peak power of the earlier designs (up to 180 MW) would require extensive modifications to the power grid and/or large energy-storage means. Hence, superconducting magnets were considered and configurations with optimal routing for fewer magnets and shorter beamlines were studied. Figure 2 shows four strawman designs that were selected from a continuum of possible variations as the best of their type.



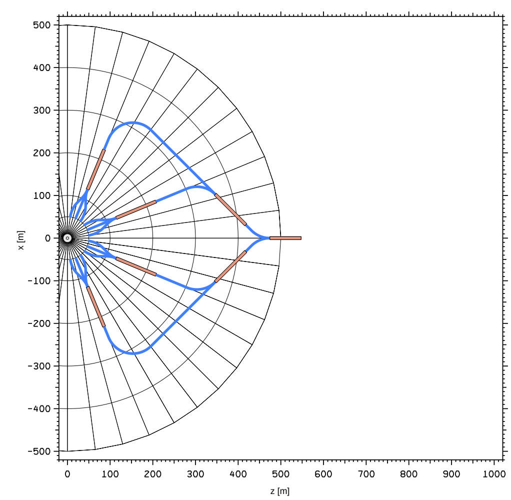
A. Normal-conducting synchronous.



B Superconducting synchronous.



C. Normal-conducting non-synchronous, with 900-ns time difference between outer and inner lines.



D. Superconducting non-synchronous with 700-ns time difference between outer and inner lines

Figure 2. The four baseline designs chosen for further analysis. All have been selected for minimum cost for their type within given constraints. The superconducting versions use superconducting magnets only in the periodic-lattice bends. The normal-conducting synchronous configuration was chosen as the project baseline as shown in Fig. 1.

The beam-transport systems are composed of three basic modules: bend arcs, splitters, and bridges between the arcs and splitters. For the normal-conducting lattice, the bend arcs are periodic structures with an 18.82-m unit cell containing two 3.75° dipoles. The splitters are 41-m-long assemblies that use an electrostatic septum and several septum and dipole magnets to separate the split beams. Bridging through the long straight sections containing splitters is done by expanding the beam and drifting through a nominal 80 meters between focusing stations.

The four systems shown have estimated cost ratios A/B/C/D of 1.0/0.84/0.83/0.74 (with system A costing about 255 M$) including tunnel, power supplies and cryosystems but excluding other balance-of-plant facilities such as water supply and primary power. Extensive efforts in magnet design have minimized the power of the bend-cell magnets so that the peak powers of the normal-conducting configurations (~20 MW) are less than a factor of two greater than for the superconducting designs. Because of the need for cryogenic systems, the average power is less for the normal-conducting systems.

The non-synchronous configurations require complex pulse-transfer timing so that all beams arrive at the object simultaneously. Since the time difference between the outer and inner lines is fixed by construction, the pulse pattern cannot be easily varied for a given ring conformation. Hence, versatility to varying experimental requirements is preempted for non-synchronous systems. Therefore synchronous systems are chosen for the project baseline.

The normal-conducting systems occupy a factor of two larger footprint than the superconducting systems and are judged more expensive. However, the normal-conducting systems are technologically simpler and do not require magnet development. Additionally, superconducting magnets are susceptible to quenching by the ~1% of the beam scattered by the splitters and require greater alignment accuracy. Since there is perceived technical risk and no advantage in attaining high radiographic performance with superconducting transport systems, a downselect to the normal-conducting synchronous transport has been made.

3 LENS SYSTEMS

The lens systems impinge the 12 beams from the transport lines on the object and focus the scattered beam to provide images and material-identification information. There are two types of lens systems distributed among the 12 lines. Four of the lines transmit a large field-of-view (30 cm) image and the remaining eight view a smaller area (12 cm). A diagram of the large system is shown in Fig. 3. The beam matched to the lens system encounters an "illuminator" section that expands the beam to an appropriate size, first via interaction with a material diffuser that removes nonlinearities induced by the transport splitters and then by a lens configuration that provides a phase-space correlation which minimizes system chromatic aberrations. The remainder of the lens consists of three identical quadruplet modules that each provide a unity transformation with sign change, called a –I lens. The first such unit serves as a monitor of the nominally 2-rms beam that will be transmitted to the object. The beam scattered by the object is then imaged at two points by each of the –I lenses and recorded by fast detectors, e.g., a scintillator/camera arrangement. The resolution achieved can be as low as a fraction of a millimeter, limited by chromatic aberrations and effects of containment windows. A second-order-achromat configuration with third-order correction is under study as is a corrected magnifier system.

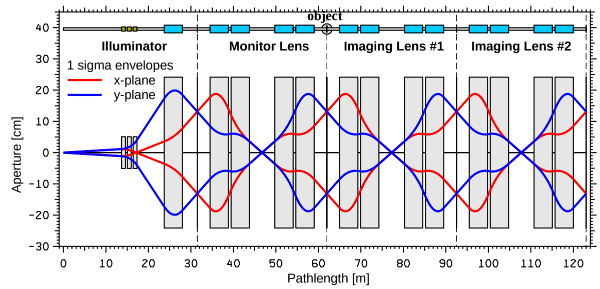


Figure 3: Schematic of the large-bore lens system.

The –I lens, consisting of identical quadrupole lenses with alternating signs, has the useful property of having an "angular focus" at its midpoint. That is, the unscattered beam is there focused to a small size determined by the beam emittance and aberrations. In the presence of object scattering, the position of a ray at this point is proportional to the scattering angle. Insertion of a positive or negative collimator changes the image contrast, accentuating the image of low- or high-angle scatterers, respectively. Mathematical analysis of the images thereby allows separate determination of the atomic number and thickness, allowing for material identification.

Superconducting magnets are under development with bore diameters of 9" and 19" and with gradients of 18.4 and 10.4 T/m for the small- and large-bore lenses, respectively. Normal-conducting lens systems are possible, but with decreased chromatic performance, longer line lengths, high peak power (~80 MW), and decreased versatility. Hence the lens systems will be superconducting.

4 REFERENCES

[1] G. E. Hogan, et al. "Proton Radiography", Proceedings of the 1999 Particle Accelerator Conference, 579 (1999).

[2] C. Thomas Mottershead and John D. Zumbro, "Magnetic Optics for Proton Radiography", Proceedings of the 1997 Particle Accelerator Conference, Vancouver, 1397 (1997).