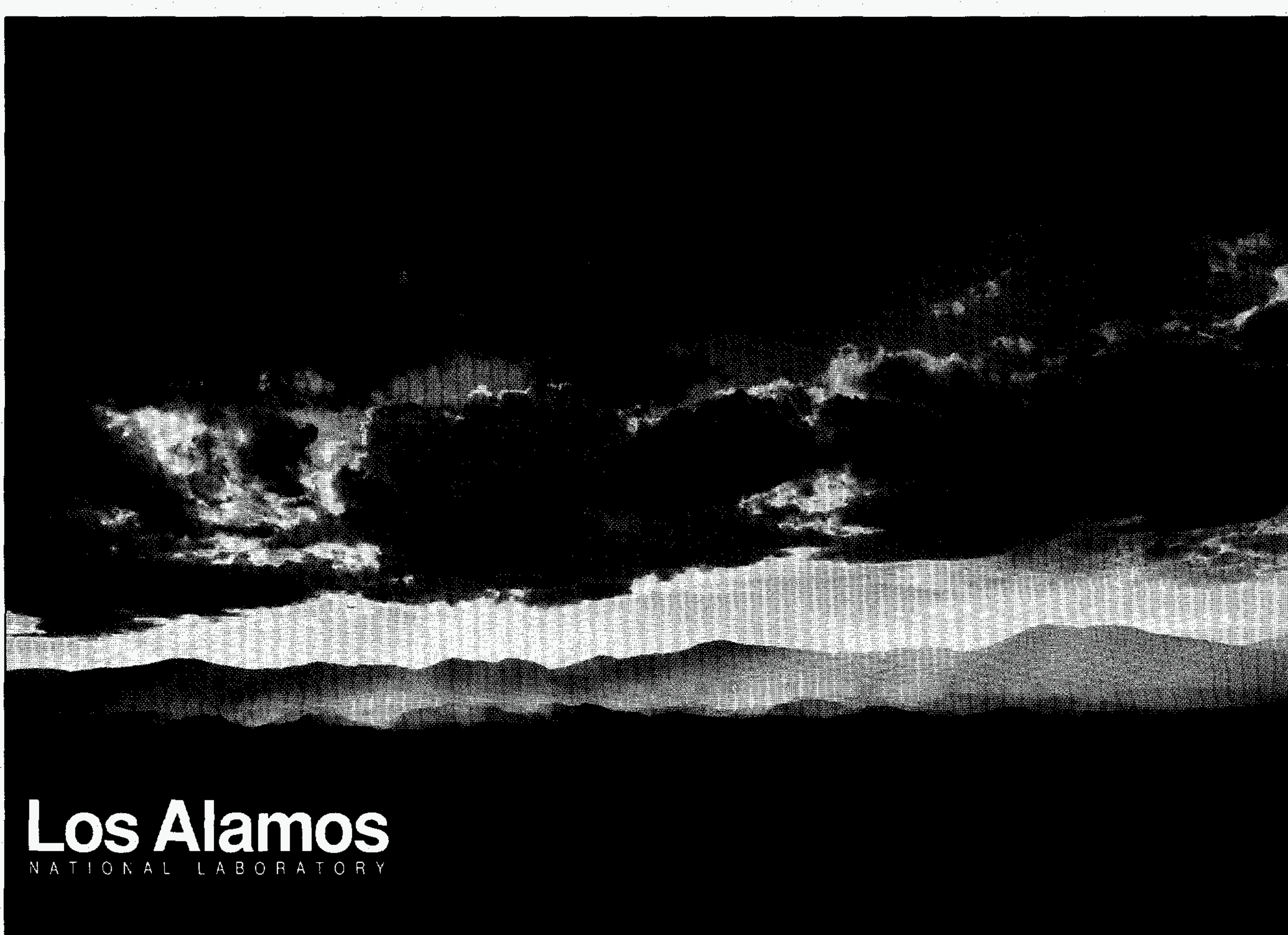
Preprint LA-UR-97-1659

CONF-970503--217

Title: SYNCHROTRONS AND BEAMLINES FOR PROTON RADIOGRAPHY

Author(s): Filippo Neri — LANSCE-1
H.A. Thiessen — P-25
Peter Walstrom — LANSCE-1

Submitted To: 1997 Particle Accelerator Conference
Vancouver, BC, Canada
May 12-16, 1997



Photograph: by Chris J. Lindberg

SYNCHROTRONS AND BEAMLINES FOR PROTON RADIOGRAPHY*

F. Neri and H. A. Thiessen, Los Alamos National Laboratory, Los Alamos, NM 87545
and P. L. Walstrom, Northrop Grumman, Los Alamos National Laboratory, Los Alamos NM 87545

Abstract
A 50 GeV accelerator complex for dynamic proton radiography, including a linac, synchrotron, and multiple isochronous beamlines is described, and critical technology development is outlined.

1. INTRODUCTION

Transmission radiographic images with high spatial and temporal resolution can be made when proton pulses illuminate an imploding test object that is placed in the object plane of a point-to-point magnetic quadrupole imaging system. From 2 to 16 simultaneously-illuminated views and approximately 50 time-separated exposures per view are desired. The desired beam-pulse structure should be flexible, with 10^{10} to 10^{11} protons in a 10-20 nsec-long pulse per view, and a variable time separation between pulses in a view of that is a minimum 100 nsec and a maximum of many microseconds. These requirements lead to use of a low-duty-factor, slowly cycling proton synchrotron with a flexible multipulse beam-extraction system feeding into a multistage beam-splitting and transport-line system that transmits proton pulses to the test facility. The total number of protons in the ring is approximately 3×10^{12}. In the paper, a conceptual point design for a system that can meet the above requirements is presented. The nominal beam energy of 50 GeV is set by object thickness and also by the thickness of the windows that must contain the blast.

2. SYNCHROTRON

The present study is based on use of an 800-MeV linac injecting an H^- beam directly into a 50 GeV synchrotron. The synchrotron is fairly conventional, except for use of a lattice with an imaginary transition γ and certain features of the achromatic arcs.

2.1 Ring acceptance

With an injection energy of 800 MeV (the energy of the LAMPF linac at LANL), and 5×10^{12} protons in the ring, a minimum 95% emittance of 4.7 π-mm-mrad is required. For calculating magnet apertures, we use a total emittance of 10 π-mm-mrad. It should be kept in mind that, with the low duty cycle, fairly high losses are tolerable. Injecting directly from the linac simplifies operation, but the dipole magnets are required to have a good field quality at the injection field of 0.04 T. At an energy of 50 GeV, the dipole field is 1.4 T. If we assume using dipoles like the ones designed for the proposed LISS synchrotron at IUCF, a maximum field of 1.7 T is possible, increasing the energy to about 60 GeV. Beyond this, the synchrotron needs to be redesigned and a booster added. Table I is a summary of the parameters for the 50-GeV ring.

Table I. Ring Description

RING	
Max Momentum	51 GeV/c
Circumference	1710 m
Ring Size	649.34 m × 361.14 m
Tunes	$Q_x = 16.23$, $Q_y = 13.19$
Transition γ	38.839 i
Uncorrected chromaticity	$Q'_x = -19.68$, $Q'_y = -21.39$
ACHROMATIC ARCS	
Arc cell number	8 (× 2)
Arc length	566.8 m (× 2)
Arc tunes	$Q_x = 6$, $Q_y = 5$
Arc max beta functions	$\beta_x = 56.6$ m, $\beta_y = 57.7$ m
Arc max dispersion	4.21 m
STRAIGHTS	
Length	288.2 m (× 2)
Straight cell number	10 (× 2)
Straight cell phase advance	$\theta_x = 76.14°$, $\theta_y = 57.42°$
Max beta functions	$\beta_x = 44.8$ m, $\beta_y = 54.4$ m
MAGNETS	
Number of dipoles	128
Dipole length	6 m
Dipole max B	1.4 T
Number of quadrupoles	152

2.2 Lattice design

We are proposing a lattice for the synchrotron with a transition gamma of about $40i$. A lattice with an imaginary transition energy avoids transition and stays away from some instabilities. Figure 2 gives the lattice functions and dispersion for a quarter of the ring, including half of one of the achromatic arcs. Figure 3 shows the lattice functions and dispersion for one arc cell. A useful feature of this particular lattice is that the maximum of the horizontal beta is reached near a zero of the dispersion: this reduces the apertures required. With a full-aperture emittance of 10 π-mm-mrad, Figs. 2 and 3 show that magnets with full apertures of 8 cm should be sufficient.

2.3 *Extraction Kicker*

With staged beam splitting in the transport lines, only one extraction kicker is required. A straight section almost 15-m long between an F and a D quadrupole is available for the kicker. The kicked beam will pass through the following D and F quadrupoles and into a septum magnet just downstream of the following F quadrupole. The injected-beam full aperture is about 4-cm diameter at the

* Supported by the US Department of Energy

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

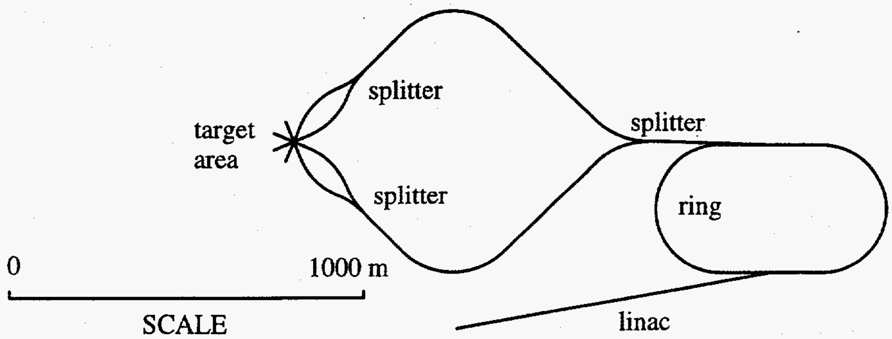


Fig: 1 Layout of the entire facility, showing the linac, synchrotron ring and beamlines.

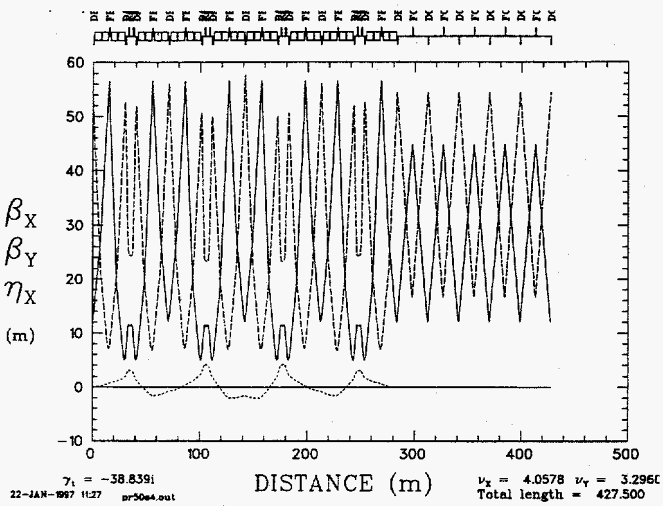


Fig: 2 Lattice functions and dispersion for a ring quadrant

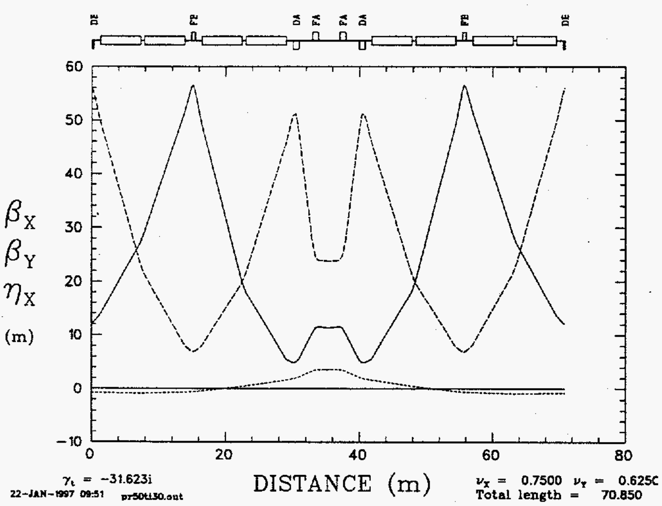


Fig: 3 Lattice functions and dispersion for an arc cell.

kicker, and shrinks during acceleration to about 1 cm diameter. If a TEM-mode (i.e., transmission-line) kicker is used, the kicker can have an aperture that is large enough for 50-GeV beam, but not large enough for the injected beam. The kicker is vertically offset from the machine midplane and steering magnets are used to move the beam up into the kicker after full energy is reached. Steering magnets are also used to bring the beam next to the septum magnet in order to minimize the required kick. Assuming that both kinds of steering are used, a kick of about 0.6 mR is needed. This can be obtained with an 8-m TEM-type kicker. A TEM-type kicker scaled from the kickers in the LANL Proton Storage Ring requires 600A at ±30 kV in a push-pull configuration. A flattop of about 64 nsec is needed for an 8-m TEM kicker (beam time-of flight+TEM pulse transit time+10 nsec beam pulse width). In order to get the total time for the kicker pulse to rise and fall, the modulator switching time for up plus down must be added to the flattop width. Using an estimated 140 nsec for this time, a total 205-nsec pulse width results. This will fit between ring pulses with 220 nsec spacing. Ringing of more than a few percent after fall time cannot be tolerated. If needed, end-of-pulse effects can be canceled by placing a properly-timed identical second kicker at a point 180 degrees in betatron phase downstream of the first kicker. A conventional pulse-forming cable (PFCs) with a thyratron switch could be used to drive the kicker if all of the particles in the entire ring were to be extracted at once (fall time is then of course not an issue). On-demand pulse extraction, in which selected pulses are to be extracted, while others are allowed to remain in the ring for later extraction, will require a modulator with a faster cycling time. A brute-force, but expensive option would be to employ multiple PFC/thyratron modulators isolated with high-voltage diodes. A more attractive possibility is to use high-power vacuum tubes. Another possibility is to use multiple lumped-inductor-type full-aperture (4 cm) kickers without bumping. These kickers would be driven with directly-coupled tubes or solid-state switches right next to the kickers.

3. BEAMLINES AND SPLITTERS

Both beam transport and beam splitting are performed in the beam transport system (see Fig. 1). The beamlines are achromatic and isochronous; the latter feature is enforced by symmetry. In the present study, there are 4 beamlines all in a plane illuminating the target at equally-spaced angles from 22.5° to 157.5°. At the end of each beamline, there is a 45-m target-illuminating section that includes a diffuser and magnetic quadrupoles that prepare the beam size and convergence angles for target illumination. On the opposite side of the target chamber from each target-illuminating section, there are a magnetic imaging system and detector arrays. The target-illuminating section and imaging systems are described elsewhere in these proceedings. [1]

3.1 Beamlines

The basic building block for achromatic bends is 4 cells with a 90-degree betatron phase advance per cell, and with two conventional iron-pole-piece dipoles per cell. A maximum of 5.75 degrees bend per cell is assumed. This corresponds to about 1.2-T bending field in the dipoles, which occupy 14 m of each cell's length. Straight sections and bends use the same 20-m (F to F) FODO cell. Most four-cell bends are 22.5 deg., which means the field in the dipoles is a little less than the maximum. Some bend angles are slightly less than 22.5 deg. in order to direct thre beams appropriately. Straight dipoles, all of a single design, are used to minimize cost. The sagitta for the maximum bend angle is about 4 cm. With the 22.5° bend, the maximum of the dispersion function in the middle of the bend is about 6 m. With $\delta p/p$ of 0.1 %, this gives a 6 mm spread. The maximum β function in the bends and straight sections is 36 m; the unnormalized full-aperture emittance is 0.5 π-mm-mR. A 2-in. beam pipe, curved inside the dipoles, will therefore accommodate the beam in both the bends and straights with some margin.

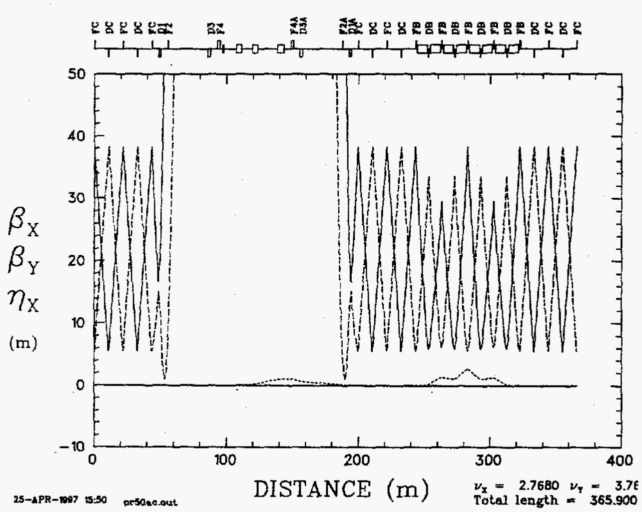


Fig: 4 The basic modules of the transport line system: the large beta insert, containing the beam splitting section on the left and the four-cell achromat on the right. The maximum β_x in the insert is off scale and is 6250 m; the maximum β_y is 1207m.

3.2 Beam-splitting insert

There are 2 stages of splitting in an 4-beam transport system. Each splitter section has a total length of 160 m and includes a 60-m expander section, a 50-m splitting section, and two parallel 60-m contractor sections. The expander section, which consists of 4 drifts and 4 quadrupoles, blows the x beam width up to 10 cm and the y beam width to 4 cm. The contractor sections are essentially the expander section in reverse order. The splitter section (see Fig. 5) contains a pulsed septum

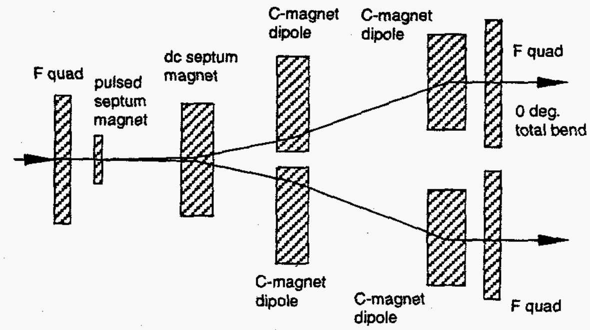


Fig: 5 Schematic of splitter section (vertical scale exaggerated by roughly a factor of 10). The first F quad in this figure is F4 in Fig. 4.

magnet, a dc septum magnet, C–dipoles, and drifts. The pulsed septum consists of a single sheet of copper 1 mm thick in a laminated iron yoke and intercepts about 3% of the beam. The septum is pulsed once for each ring cycle for a total of 2 msec. Fields are equal and opposite on each side of the septum. Each of the two legs forms an S bend. The insert is essentially achromatic because the beam has no net bend in the splitter section and the two half-beams leaving the splitter are not bent before they pass through contractor sections. Beam alignment, magnet field quality, and precision of net bend angle are critical in the insert.

3.3 Beamline component summary

The transport system parameters are listed in the table below. Beamline layouts with 2, 8 and 16 views with the same basic building blocks were also developed. It was found that the system length scaled very nearly linearly with the number of views.

Table II. Four-View Beamline Summary

Total splitter sections	3
Total straight cells	36
Total bend cells	96
Total target illumination sections	4
Total bend length	1920 m
Total straight length	720 m
Total length	3300 m

REFERENCES

[1] C. Thomas Mottershead, John D. Zumbro, Los Alamos National Laboratory, "Magnetic Optics for Proton Radiography", paper in 4V.16 of these proceedings.

DISCLAIMER