

TITLE: SYNCHROTRON ISSUES/OPTIMIZATION FOR PROTON RADIOGRAPHY

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SYNCHROTRON ISSUES/OPTIMIZATION FOR PROTON RADIOGRAPHY

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ABSTRACT

The radiographic requirements loosely define the synchrotron required for AHF. A part of the task of the AHF design team is to translate the radiographic requirements into facility requirements that are sufficiently defined so engineering decisions can be made.

I INTRODUCTION

In Table 1, we list the synchrotron specifications that have direct consequences for radiography. The main point to notice is that there are a few details of the synchrotron that are clearly defined by the requirements. Among these are:

- The spatial resolution, which defines the minimum beam energy if a particular confinement system design is assumed;
- the density resolution, which determines the number of protons needed per frame per axis (the total count of protons in the ring must be sufficient to service the entire facility with sufficient statistical accuracy in each frame);
- the number of frames and pulse pattern available - (so far, only a minimum number of consecutive frames (≥ 10) has been clearly defined), with an unclear need for some "early" pulses (up to 75 microseconds earlier);
- the minimum pulse spacing - the 200

ns assumed here is only roughly defined in the radiographic requirements documentation; and

- the repetition time - which must not be so long that radiographic experiments and calibrations are hindered.

These requirements are insufficient to fully define a synchrotron.

Table 1. Synchrotron Specifications of Importance to Radiography

	1999 and earlier	Change in 2000
Resolution	0.5-1 mm	No change
Protons/frame/axis at diffuser	5×10^{10} to 1×10^{11}	
Number of consecutive frames	≥ 10	No Change
Minimum pulse spacing	200 ns	200 ns
Time Range (maximum)	75 μ sec	75 μ sec
Number of Axes	8	12
Minimum Pulse Spacing	200 ns	No Change
Repetition time	10 sec	Up to 100 sec

The synchrotron design team in cooperation with the LANL's P-Division radiographic team

has made a number of additional design assumptions in order to provide a fully defined facility design that is consistent with the radiographic requirements, minimize the estimated facility construction cost, and, at the same time, provide a set of specifications that is stable against parameter changes that are within the range of the precision of definition of the requirements.

There are four major additional assumptions that are needed to proceed with the design. These assumptions are basic to the design of the facility as proposed and should be changed only if clear need for such a change is demonstrated in the radiographic requirements.

First among these design assumptions is the beam energy of 50 GeV. This energy is sufficient to achieve the desired resolution in through 1-in.-thick steel confinement vessel without windows, with better resolution available if a composite system is developed. Slightly worse resolution will be obtained should an armored liner or external safety vessel be required in addition to a 1-in. thick steel confinement vessel.

The second assumption is that an 797-MeV H⁻ beam is available for injection of the synchrotron. This allows a single stage synchrotron with iron-dominated magnets to deliver the required maximum energy beam. For example, should a final beam energy of 100 GeV be desired, or if a lower energy injection beam be provided, then a very different synchrotron architecture would be called for.

(We note that in the design assumption of 797-MeV H⁻ beam for injection, we have tied the design to LANSCE. However, we have provided an option for a 3-GeV booster synchrotron that can inject the same 50-GeV synchrotron. One of the purposes of this booster is to provide the injection beam at such other sites. For these other sites, an "inexpensive" lower energy linac would be needed. It is clear that such a design will provide the necessary injection beam. Because of funding limitations of studies to date, the "inexpensive" linac

option has not been fully developed, while a more explicit version of the booster is available).

The next major assumption is that a maximum synchrotron fill of 3.3×10^{13} protons per pulse is sufficient to meet the radiographic requirements. A further implicit assumption is that the project will be staged in a way that a smaller fill will be sufficient during early operation, and that an operational period of several years will elapse before the synchrotron is required to routinely meet the maximum fill needs. For example, with a harmonic number of 1276 LANSCE bunches, 12 axes worth of beam (1×10^{11} protons per frame per axis delivered to the diffusers, with 26 frames and 12 axes, or 3.16×10^{13} total protons) can be provided including a small allowances for beam losses in extraction, beam splitters, etc. The maximum fill of 3.3×10^{13} protons per synchrotron cycle is simultaneously

- a judgment on the state of the art in high energy proton synchrotrons,
- a match to the capability of the LANSCE H⁻ linac (after an in progress upgrade, PSR will operate at 4.1×10^{13} protons per cycle with injection from a single LANSCE macropulse including chopping losses for bunch-to-bucket transfer), and
- a cost issue (more protons will increase costs).

Our model for the synchrotron is the Fermi National Accelerator Laboratory (FNAL) Main Injector, which is designed for 3×10^{13} protons per synchrotron cycle at 120 GeV. The Main Injector is expected to achieve this intensity without large phase space "dilution" after a few years of initial operation. "Proton Drivers" for neutrino production and/or sources for muon colliders at intensities on the order of 10^{14} or more protons per cycle are under consideration at other laboratories, but these require development beyond the present state-of-the-art. Incorporating such developments are

beyond the scope of the studies so far undertaken. The reason for the assumption of slow development toward the maximum intensity is that no large margins in apertures and other hardware performance need be provided in order to assure that the synchrotron meets beam intensity requirements for initial operation.

The final assumption is that the six-dimensional phase space naturally available from a typical proton synchrotron is consistent with the radiographic requirements. There is no issue of a requirement on phase space to achieve the desired resolution. This occurs because the beam interaction with the diffuser and the object under test (multiple Coulomb scattering and straggling) results in an effective phase space at the center of the object that is many times larger than the emittance of a typical synchrotron.

The main emittance issue is then to assure that the beam from the synchrotron fits in the aperture of the beam transport system at any stage in the development of the synchrotron. In particular, we need to be sure that the transport system is designed for the largest phase space beam, which will be the beam at maximum intensity, including an allowance for phase space dilution. Finally, since the transport system has only a limited dp/p acceptance, it will be necessary to fix dp/p and show that the time spread of the pulse meets the radiographic requirements and does not degrade the performance of the extraction and pulse routing systems.

In the absence of compelling reasons driven by the physics requirements for changes in these "project design specifications" (50-GeV energy, either 797-MeV H- injection or a 3-GeV booster for injection, 3.3×10^{13} protons per cycle, and that typical synchrotron emittance meets the requirements), the synchrotron design team has kept these constant for several years in order to allow steady progress towards a system design for AHF.

II. PRE-CDR DESIGN

In the 1999 pre-CDR report (LA-CP-98-316), a 50-GeV synchrotron design was provided. This design met all requirements. The particular features of this design included :

- Use of existing Fermilab (FNAL) B1 dipoles,
- Injection energy 797 MeV, extraction energy 50 GeV
- FODO lattice with a single length of dipole, transition gamma of 15.71,
- 5-MHz rf, harmonic number 24,
- Flexible extraction pattern, 200-ns minimum spacing, designed for synchronous transport layout,
- "Full Aperture" abort system, 800-ns gap,
- Space -charge intensity limit for 797

MeV injection 0.5×10^{13} protons per cycle, 3-GeV booster required to reach 3.3×10^{13} protons per cycle

The only unique item requiring development beyond the state-of-the-art in this system is the extraction kicker modulator. (Extraction with single pulse "cable modulator" requiring no new development meets most requirements). A study of instabilities expected was included in the 1999 study. No problems were found. However, insufficient attention was paid to the issue of longitudinal phase space blowup during crossing transition. Also, the issue of high peak power required to operate the magnet system was noted in 1999, but no effort was made to rectify this situation.

The conclusion of the 1999 study was that a synchrotron of this type is feasible. No show stoppers were found. However, a number of issues were raised that required further study.

1.3. Issues Addressed in FY-2000 Synchrotron Trade Study

The major thrust of the FY-2000 synchrotron trade study was to consider options that might result in substantial project cost savings. At the start of the trade study, it was recognized that a

change of the beam distribution system design from synchronous to asynchronous might have large cost impact. This change impacts the synchrotron through the extraction system, which must be able to provide beam pulses in a pattern that depends both on the layout of the beam distribution system and the pulse pattern on target required by the experiment. A further impact is the rf frequency of the synchrotron, which needs to be either 5 \pm MHz or 10 MHz depending on the pulse pattern scenario adopted, and also on the booster, which needs to deliver a beam appropriately formatted for a 5-MHz or 10-MHz synchrotron.

The second issue addressed was a study of the how to reduce power requirements (peak and average) while minimizing construction cost for the very low repetition rate needed for AHF. This study involves a tradeoff among power supply costs, magnet current ramp, magnet design (magnet coil cross section), power distribution costs, and power conditioning cost. The third major issue addressed was a study of transition crossing in the synchrotron. Experience at other laboratories (European Center for Nuclear Research (CERN), FNAL, and Brookhaven National Laboratory (BNL)) shows that above some intensity, longitudinal beam motion becomes unstable for a short time during transition crossing. In this time, the longitudinal phase space may blow up by a substantial factor. This blowup may be avoided by crossing transition quickly enough (by addition of a "gamma-t jump" scheme), or by other techniques. For example, by careful control of longitudinal parameters at transition crossing, there may be no blowup at all during transition crossing (the FNAL Main Injector has successfully crossed transition at 90% of its design current without significant phase space blowup). In the FY-2000 trade study, we have studied the threshold for phase-space blowup in transition crossing, considered what it takes to provide for future addition of a "gamma-t jump" scheme, and have considered the design of a "transitionless" lattice that avoids the

problem altogether.

The final major issue studied concerns the options for achieving the design goal of 3.3×10^{13} protons per accelerator cycle. In the pre-CDR design, the transverse acceptance of the synchrotron was not large enough to accept this many protons during the injection process at 797 MeV. Thus the need for the inclusion of a 3-GeV booster in the project design. In the FY-2000 trade study, we chose to consider what it would take to avoid a booster. Three approaches were considered, namely:

- 1) a lattice design with increased transverse acceptance in the same size dipole magnet;
- 2) increasing the aperture of the dipoles and quadrupoles in the synchrotron; and
- 3) raising the injection energy from the linac to 1.2 or 1.5 GeV, values being considered for some future LANSCE upgrades.

One less fundamental issue considered in the FY-2000 trade study was the role of the existing FNAL B1 dipoles in AHF. In particular, we chose to evaluate the cost and technical impact of replacing these dipoles with dipoles of a different design.

III. LATTICE STUDY

We chose to study five lattice types in the FY-2000 synchrotron trade study. These were:

1. Pre-CDR type simple FODO lattice,
2. Superconducting magnet synchrotron,
3. Modified FODO lattice with provision for Gamma-t jump,
4. Transitionless lattice, and
5. Triplet lattice

We summarize the results of these lattice studies here.

A. Pre-CDR type simple FODO lattice

The pre-CDR lattice was chosen to be as simple and straightforward as possible (see Reference 1.) It was based on a FODO type lattice with four long, dispersionless straight insertions. Magnets were assumed to be the existing FNAL

B1 (main ring) dipoles, available in one length only. Dispersion matching was provided with 16 cells that have one (of two) dipoles missing. This was a simple lattice that could be constructed on a short construction schedule. However the limitations of this lattice and the existing dipoles showed up in several ways. The limited aperture of the existing dipoles limits the number of protons available with 797 MeV injection to about 5×10^{12} protons per cycle, thus requiring the addition of a 3-GeV booster to reach full design intensity. The dynamic aperture in this design is marginal, a result of the poor field quality and sagitta of these (nearly straight) magnets. It is necessary to cross transition with this type of lattice, but a gamma-t jump scheme cannot be implemented with the type of dispersion suppression scheme adopted. This dispersion suppression scheme was made necessary by the use of a single length of dipole as all the existing magnets are the same length. Finally, there are some reliability problems expected due to the 30-year age of the magnets and the design of the insulation in the existing coils.

Although none of the problems with this design is a show stopper, the combination of issues raised is very serious. For this reason, we recommend no further study of the use of the existing Fermilab B1 dipoles.

B. Superconducting magnet lattice

We studied the possible application of superconducting magnets to a 50-GeV synchrotron for AHF. After a look at the technology, we dropped this idea for two reasons. First, there is a "persistent current" problem with ramped superconducting magnets. This limits the useful energy gain in one stage to a factor of 7 to 10. Thus a 5- to 7-GeV booster would be required, even for initial operation. Second, there is a problem with beam losses that might "quench" the magnets. This would require very careful operation of the booster and synchrotron, which would be difficult to achieve in early operation of AHF. We decided to shelve this idea, but save it for

possible consideration should an increase in beam energy to ~ 100 GeV be considered.

C. Modified FODO lattice with provision for Gamma-t jump

We considered minimal modifications to the pre-CDR lattice that would enable the future addition of a gamma-t jump system, allow use of new lower power consumption magnets of the type used in the FNAL Main injector (MI) but properly bent to match the radius of 50-GeV protons, and some changes in the straight sections that better match them to the needs of the AHF injection, extraction, and abort systems.

We found that with the proposed newly designed magnets, the dynamic aperture is much increased. We also found that a reasonable gamma-t jump system can be incorporated if and only if dispersion suppression is accomplished with 16 cells containing two half-length magnets each. In addition, peak power consumption is much reduced, and injection, extraction, and a full aperture abort can be accommodated within a circumference that is the same as the pre-CDR design. The space charge limit for 797-MeV injection is $\sim 1.5 \times 10^{13}$ protons per cycle with a 2-in. (5-cm) gap magnet (as in the MI magnets). A second version, with 3-in. (7.5-cm) gap, was considered. In the 3-in. gap version, we can get to 3.3×10^{13} protons per cycle without need for a booster. Injection, extraction, and full aperture abort can be accommodated in the 3-in. gap version, but only if we increase the circumference from $h=24$ (wrt 200-ns bunch spacing) to $\sim h=26$. Power consumption is larger, but still reasonable, in the 3-in. gap version if magnets with larger coil cross section are adopted. The two versions of this lattice, 2-in. gap with booster and 3-in. gap without booster, were chosen for costing in the FY-2000 synchrotron trade study.

D. Transitionless lattice

It is possible to design a lattice that avoids transition altogether. We studied such a lattice

in the FY-2000 trade study and found that it incorporates all of the beam dynamics properties required for AHF. The straight sections are essentially the same as in the lattice above, but were not studied in great detail. This lattice is a bit more complicated, requiring several lengths of quadrupole and six families of quadrupole power supplies. The circumference needs to be somewhat longer, but this was not studied in detail. Only a 2-in. gap version was studied, but we see no reason why a 3-in. gap version could not be developed. We have shelved this version because it appears to be more complicated and more expensive than the gamma-t jump lattice. It can quickly be adopted if problems with the gamma-t jump lattice are discovered.

E. Triplet lattice

We studied a lattice in which the focussing is accomplished with quadrupole triplets rather than the doublets that make up FODO lattices. In this way, larger phase space can be accommodated with 2-in. gap dipoles, enough

to avoid a booster for operation at 3.3×10^{13} protons per cycle with an 797-MeV injection. The penalty for this type of lattice is that the quadrupoles must be $\sim 2x$ stronger than in a FODO, leading to a synchrotron that is somewhat longer. Extraction is a bit more difficult, but was not studied in detail. The biggest problem with this type of lattice is that a gamma-t jump scheme will not be possible, leading to a possible bottleneck in intensity at some time in the future. We have shelved this version in favor of the gamma-t jump lattice.

F. Lattice Study Conclusions

We have studied several lattices and have narrowed the selection down to one type with two magnet sizes, namely, a gamma-t jump conventional FODO lattice with either 2-in. or 3-in. dipole gap. A detailed comparison of the lattices is given in Synchrotron Appendix section 1.3.

The parameters of the lattices adopted are given in Table 2.

Table 2. Lattice Parameters for Reference Lattices

	2-in. gap	3-in. gap
Synch Circumference (meters) (LANSCE Bunches)	1443.6 meters 1152 bunches	1563.9 meters 1248 bunches
Betatron Tune	17.36 H / 17.44 V	17.36 H / 17.44 V
Number of Cells	68	68
Cell Length	21.23 m	23.00 m
Transition Gamma	14.18	14.16
Number of Dipoles	80/32	80/32
Dipole Length	6.783 m/3.3915 m	7.00 m/3.50 m
Dipole Field at 50 GeV	1.635 T	1.588 T
Number of Quadrupoles	136	136
Quadrupole length/ bore radius	1.295 m / 5.0 cm	1.75 m / 7.5 cm
Quad Gradient at 50 GeV	18.53 T/m	12.84 T/m
Protons/Cycle,no Booster	1.5×10^{13}	3.3×10^{13}

The beam distribution system needs to be designed for the largest emittance expected from the synchrotron. Our six-dimensional particle tracking study is incomplete. We have

therefore assumed a factor of 2 phase-space dilution in each of the two transverse planes and in the longitudinal plane. These are given in Table 3, below. Note that the phase space

quoted in Table 2 is nominally "hard-edged", and must be fully transported in order to avoid beam losses. Also, the beam size due to transverse and longitudinal dimensions must be added "linearly," not "in quadrature."

Table 3. Beam Emittance of Synchrotron including Allowance for Phase-Space Dilution

	Transverse (normalized)	Longitudinal (5MHz)	Longitudinal (10MHz)
2-in. Gap	56 pi mm-mrad	20 ns max x 100 MeV max 1.5 eV-sec	10 ns max x 100 MeV max 0.75 eV-sec
3-in. Gap	80 pi mm-mrad	20 ns max x 100 MeV max 1.5 eV-sec	10 ns max x 100 MeV max 0.75 eV-sec

We have chosen the 3-in. gap gamma-t jump lattice without booster as the reference design, with an option of using the 2-in. gap lattice with booster. It should be noted that even if the booster is not needed for 797 MeV, continued study of the booster is needed for application to sites at which 797-MeV injection is not available.

We note also that the synchrotron circumference needs to be increased in the 2-in gap version if an asynchronous beam distribution system is adopted, and a further increase is needed if the 3-in. dipole gap option

is adopted. This increase in circumference was not anticipated early enough in the year, so that it is inconsistent with the circumference used in the balance-of-plant study. This inconsistency needs to be resolved in a future study.

IV. SYNCHROTRON MAGNET STUDY

One of the issues undertaken in the FY-2000 synchrotron trade study was the relationship between the coil cross sectional area of the magnet coil and the lifetime cost of the magnet and its power system, including its power consumption. For our low-repetition-rate regime, we concluded that the dominant power system costs are related to the peak power demand of the magnet. By increasing the magnet coil cross-sectional area, which raises the magnet cost but lowers the power system cost, we reduce the peak power demand. A practical limit occurs when the dipole coil cross sectional area (for 2-in. gap version) is about 2x the area of the coil in the FNAL MI magnet. This large-coil was adopted for the 2-in. gap dipole, and a scaled-up version of the same magnet cross section was adopted for the 3-in. gap dipoles. A similar analysis was used to choose a quadrupole coil cross sectional area. The results of the dipole magnet study are presented in Table 4 below.

Table 4. Peak power requirements for synchrotron dipoles considered in magnet cross section study.

Magnet Type	Length	Max DC Power per Magnet (MW)	L/R (sec.)	Ramp Time (sec.)	Number Required	Peak Power Demand Total (MVA)
FNAL B1 (1.5" gap)	All	0.135	1.08	3.0	104	15.4
MI-Like (2" gap)	Long	0.0656	2.57	5.0	80	7.4
	Short	0.0352	2.4		32	
Extra Copper (2" gap)	Long	0.0520	3.25	6.4	80	5.8
	Short	0.0279	3.03		32	
Extra Copper (3" gap)	Long	0.0727	5.01	9.8	80	8.2
	Short	0.040	4.55		32	

With injection at 797 MeV into a 50 GeV synchrotron with 16 kGauss peak field, the magnetic field at injection time is approximately 450 Gauss. There will be a number of problems associated with the low injection-time magnetic field. These issues were beyond the limited scope of the FY-2000 trade study and need to be resolved in future work.

V. MAGNET REQUIREMENTS FOR SLOW RAMP WAVEFORM

We considered the issues that determine the desired magnet ramp waveform in the low-repetition-rate regime. When we optimize for the case of a magnet power system directly connected to the power grid ("direct drive"), we conclude that an exponentially rising pulse (constant applied voltage) is acceptable for the synchrotron beam dynamics. Costs of the power system decrease as the voltage applied to the magnets decreases, but average power consumption goes up. When we choose to have the magnet current reach the design current after a time on the order of $2xL/R$ (applied voltage $= 1.1566x$ dc value), the total costs of the magnet, plus the power system, plus 10 years' worth of power consumption is minimized.

The current waveform during the "down ramp" of the magnet system was briefly considered. Of course, since there is no beam in the synchrotron during the down ramp, there are no beam dynamics issues involved in this choice. The relevant issues are returning energy to the power grid, grid power transients, and repetition rate. If the magnet voltage is reversed during the down ramp, the magnet current will return to zero after a time on the order of $0.5xL/R$. If the voltage is set to zero, then the current will return close enough to zero after a time on the order of $4xL/R$. Reversing the magnet voltage during the down ramp maximizes grid impedance transients but reduces average

power consumption by on the order of 20%. Total pulse time (ignoring injection, flattop, and parabolas) is reduced from $6xL/R$ to $2.5xL/R$. If we were to choose the longer down ramp for the 3-in. gap dipoles, then the resulting total cycle time would be ~ 36 s. This could be reduced to 15 s if magnet voltage were reversed. Because neither power grid transients nor system tune-up was considered during the FY-2000 synchrotron trade study, the issue of the magnet down ramp was left for resolution in a future year.

VI. PULSE-PATTERN ISSUES

A. 5MHz vs. 10 MHz RF

In the physics requirements, the only identified requirement on the pulse pattern is for a number of consecutive pulses at small spacing. This requirement has never been precisely defined, and is interpreted somewhat differently in the community. Los Alamos has interpreted this requirement to be 10 consecutive frames, simultaneous on all axes within 50 ns, with 200 ns frame spacing. The number 10 is chosen to include the minimum number of pulses actually needed plus an allowance for "jitter", etc. Although never formally set as a specific requirement, a sequence of "early" pulses will be necessary some experiments. All the time ranges specified in the requirements are longer than 1.8 μ s (10 short pulses spaced by 200ns), extending up to 75 \pm μ s. Some specific reasons have been mentioned for requiring additional "early pulses", without clear definition of the number of early pulses or the pattern required. Indeed, flexibility of the pulse pattern is of the essence, as future experiments are not likely to be precisely defined at this time. We have interpreted the requirement for additional pulses in the following way:

- a string of 10 consecutive pulses (extracted on the last turn of beam in the synchrotron) with 200-ns spacing is an absolute requirement of highest priority,
- the option to have one pulse per turn

(or skipped turns and/or a few pulses on selected turns) for up to 75 μ s is a desirable goal of lower priority.

One metric of the extraction system/beam transport design is the number of additional pulses that can be provided. A better metric awaits a clearer definition of the requirement.

A synchronous beam delivery system, with all beam transport branches the same length (within the 50-ns pulse width tolerance) meets all the requirements and, with 5-MHz rf (200-ns pulse spacing in the synchrotron), maximizes the number of early pulses available. Asynchronous systems with odd x 100-ns pathlength differences and a synchrotron with 10-MHz rf (100-ns pulse spacing in the synchrotron) give the same number of early pulses at lower cost. The drawback of this approach is that more demands are placed on the extraction kickers and modulators, and the design of the synchrotron and beam transport system become more tightly coupled.

The question studied in the synchrotron trade study was whether a choice of 100-ns pulse separation (10-MHz rf) is reasonable. The answer was that the beam dynamics, kickers, and abort system will be within the state-of-the-art. These will of higher cost when compared with the 200-ns (5-MHz rf) version, and a first estimate of the cost differential is included in the appendices. A kicker modulator of the "single pulse" type, ie., a modulator capable of extracting a single pulse from the synchrotron in any desired time sequence, is problematical if constructed using today's technology (if 100-ns pulse spacing is required). Such a modulator

can be built and would have reasonable cost if 200-ns pulse spacing were chosen.

The conclusion we came to was that we should start operation of AHF at ~200-ns pulse spacing, but not preclude a future upgrade to ~100-ns pulse spacing if we choose an asynchronous system. Note that this conclusion is strongly dependent on our interpretation of the requirement, which is presently not very clear.

It is possible to design an asynchronous system which is upgradeable from ~200ns spacing to ~100ns spacing if and only if we properly choose the harmonic numbers (in terms of linac bunches) of the synchrotron circumference, the bunch length, and the path length difference in the beam transport system. We repeat that the choice of a synchronous system avoids altogether the need for such complicated harmonic matches. Synchronous systems decouple the transport system from the synchrotron and allow the use of any synchrotron bunch length that is a sub-harmonic of the synchrotron circulation time, with bunch length changes possible at any time. Further, the additional cost and risk of 100ns kicker systems are eliminated by synchronous systems, which require only 200ns kickers. However, it appears that synchronous beam distribution systems are more costly than asynchronous systems and the total project cost is minimized by such a choice.

In Table 5 we present the harmonic numbers of our reference designs for the cases of interest in the FY-2000 trade studies.

Table 5: Reference Design for Synchrotron Harmonic Number*

	2-in. Gap Dipoles	3-in. Gap Dipoles
Superconducting Transport, Asynchronous	Synch h=1176=4916.4ns Trnspt Diff=168=702.3ns Bunch=42=175.6 ns initially Bunch=24=100.3 ns upgrade	Synch h=1248=5217.4ns Anharmonic Trnspt Diff=678.4ns hrf=23=226.8ns initially hrf=54=96.6ns upgrade
Room Temperature	Synch h=1176=4916.4ns	Synch h=1248=5217.4 ns

	2-in. Gap Dipoles	3-in. Gap Dipoles
Beam Transport, Asynchronous	Trnspt Diff=196=819.41ns Bunch=49=204.9 ns initially Bunch=28=117.1ns upgrade	Anharmonic Trnspt Diff=906.2ns Hrf=23=226.8ns initially hrf=54=96.6ns upgrade
Synchronous Transport	Synch h=1152=4815ns Trnspt Diff=0=0ns Bunch=48=201 ns initially No upgrade needed	Synch h=1248=5217ns Trnspt Diff=0=0ns Bunch=26=201 ns initially No upgrade needed

*Note that further study is required before adopting the recommendations of this table.

Note that for the 2-in. gap synchrotron with asynchronous beam distribution system, and for the 3-in. gap synchrotron for all options, the circumference of the synchrotron does not match the circumference of the reference design (1152 LANSCE bunches) used in the balance-of-plant studies. This inconsistency must be removed in a future study.

A second question studied is the effect of the

abort gap. We conclude that the abort gap makes only a small difference in the number of pulses available. If this is a problem, it can be corrected with a future upgrade. We choose initially an abort system with 400-ns rise time (400-ns abort gap). This is the version that is incorporated in our cost estimate.

The performance of our reference systems in terms of number of available pulses and pulse spacing is given in Table.6 below.

Table 6

	2-in. Gap Dipoles	3-in. Gap Dipoles
Asynchronous, Superconducting		
Initial Operation ~5 MHz RF	4 early +10 consecutive (175.6 ns spacing)	3 early +10 consecutive (226.8 ns spacing)
After Upgrade ~10 MHz RF	16 early +10 consecutive (200.6 ns spacing)	13 early +10 consecutive (193.2 ns spacing)
Asynchronous, Room Temperature		
Initial Operation ~5 MHz RF	3 early +10 consecutive (204.9 ns spacing)	4 early +10 consecutive (226.8 ns spacing)
After Upgrade ~10 MHz RF	9 early +10 consecutive (234.2 ns spacing)	13 early +10 consecutive (193.2 ns spacing)
Synchronous		
Initial Operation ~5 MHz RF	4 early +20 consecutive (200.6 ns spacing)	4 early +22 consecutive (200.6 ns spacing)
After Upgrade ~5 MHz RF	13 early+10 consecutive (200.6 ns spacing)	15 early + 10 consecutive (200.6 ns spacing)

Table 6 gives the pulse patterns available for reference systems as number of early pulses plus a string of ten (or more) consecutive pulses. Limitations of initial operation include

choice of bunch spacing near 200ns and cable modulator with limit of four (max) early pulses and one long pulse, and 400 ns abort gap. After upgrade, we assume pulse spacing near 100 ns in synchrotron, flexible single-pulse modulator,

and 400 ns abort gap.

VII. BEAM DYNAMICS

A. Transverse Beam Dynamics.

First and foremost, we considered the issue of space-charge tune shift and the choice of injection energy. We considered the existing proton storage ring (PSR) at Los Alamos, which operates successfully with 797-MeV injection energy and an incoherent space charge tune shift of 0.4. This was adopted as the upper limit of the allowed space-charge tune shift for AHF. We considered four possible injection energies for AHF, namely: 797 MeV, 1200 MeV, 1500 MeV, and 3 GeV. The 797 MeV assumes LANSCE H⁻ injection. The 1200 MeV and 1500 MeV assume energy upgrades to LANSCE. Our conclusion is that for 2-in. gap dipoles, only the 3-GeV booster option lowers the tune shift sufficiently to get below the space charge limit with 3.3×10^{13} protons per cycle. For the 3-in. gap option, 797 MeV injection meets our requirement. Thus, as far as AHF is concerned, there is no requirement for 1200 MeV or 1500 MeV injection in any case of interest. The 3-GeV booster is required only for the 2-in. gap case with 797-MeV injection, or for application at a site where no linac presently exists.

Second, transverse tracking with error fields and misalignments has been performed for all lattices and the 2-in gap dipoles. In addition, we also tracked the gamma-t jump lattice with 3-in gap dipoles. In all cases tracked, the dynamic aperture is larger than the physical aperture.

B. Longitudinal Beam Dynamics

We also started a study of longitudinal tracking in the synchrotron. Some longitudinal information comes from the pre-CDR study. This work was done with a 3-s linear magnet current ramp, so more rf voltage is required in the FY-1999 study than is the case in the FY-

2000 study with exponential ramp, $2xL/R=11.8$ s. To date, the longitudinal tracking study (using ESME) has succeeded in transporting beam to 50 GeV with a linear magnet current ramp, crossing transition as required. Without a gamma-t jump, a factor of three dilution of longitudinal phase space is observed (exceeding the factor of two allowance we have built into the synchrotron design.) Possible remedies (in order of increasing cost) are:

1. modifications to the rf amplitude/phase program to increase bunch length at transition time.
2. compensation of the longitudinal impedance of the accelerator at transition time (using a variable inductor)
3. increasing the rate of transition crossing with a gamma-t jump scheme (already designed)

C. Transition-Gamma-Jump Scheme.

Figure 1 shows the transition crossing scheme using the gamma-jump quadrupoles. The fast part of the jump is specified to last about 2 msec. The magnitude of the jump is $\delta\gamma = 1.5$. The pulsed quadrupoles have a strength of ± 5.1 T/m and a length of 0.348 m. Three jump quadrupoles are placed in each dispersion-matching cell, for a total of 24.

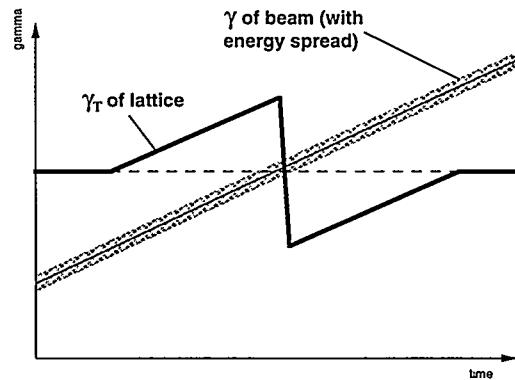


Figure 1. Transition-Crossing using pulsed quadrupoles.

Figures 2 to 4 show the effect of the pulsed quadrupoles on the lattice function and dispersion.

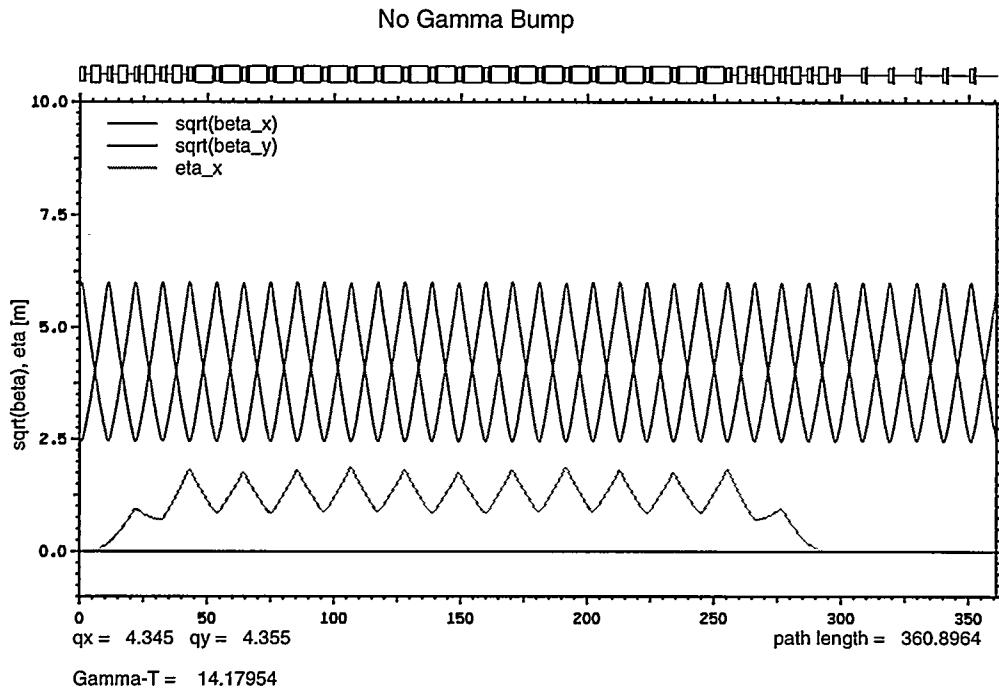


Figure 2. Dispersion and square roots of the beta functions plotted on the same scale. One quarter of the 3-in. ring shown for the nominal value of transition gamma, 14.18.

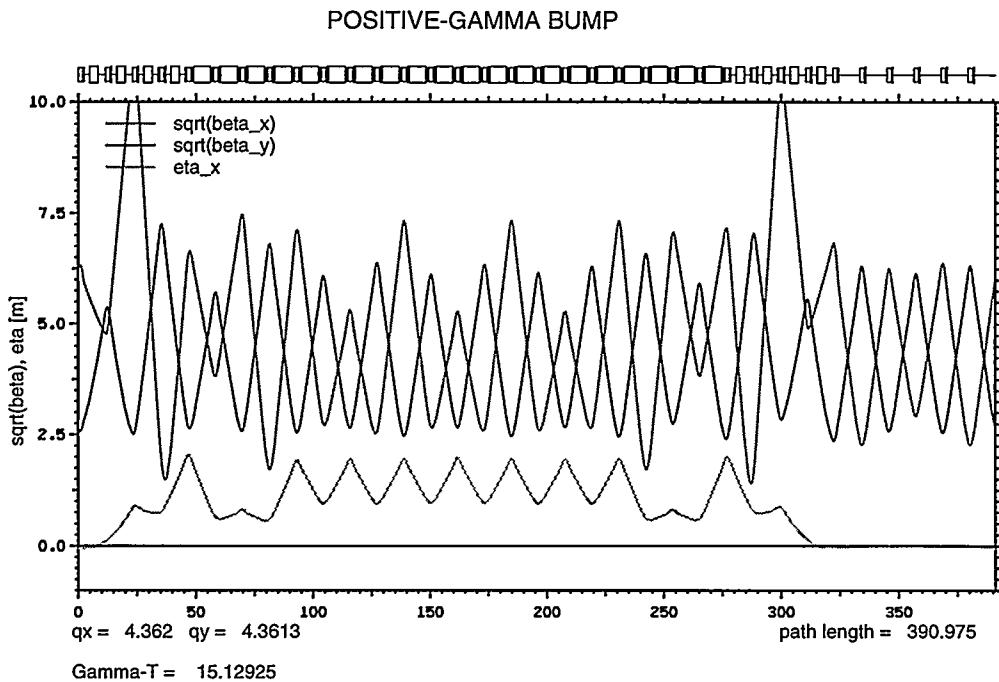


Figure 3. Dispersion and square roots of the beta functions plotted on the same scale. One quarter of the 3-in. ring shown for the maximum value of transition gamma, 15.13.

NEGATIVE-GAMMA BUMP

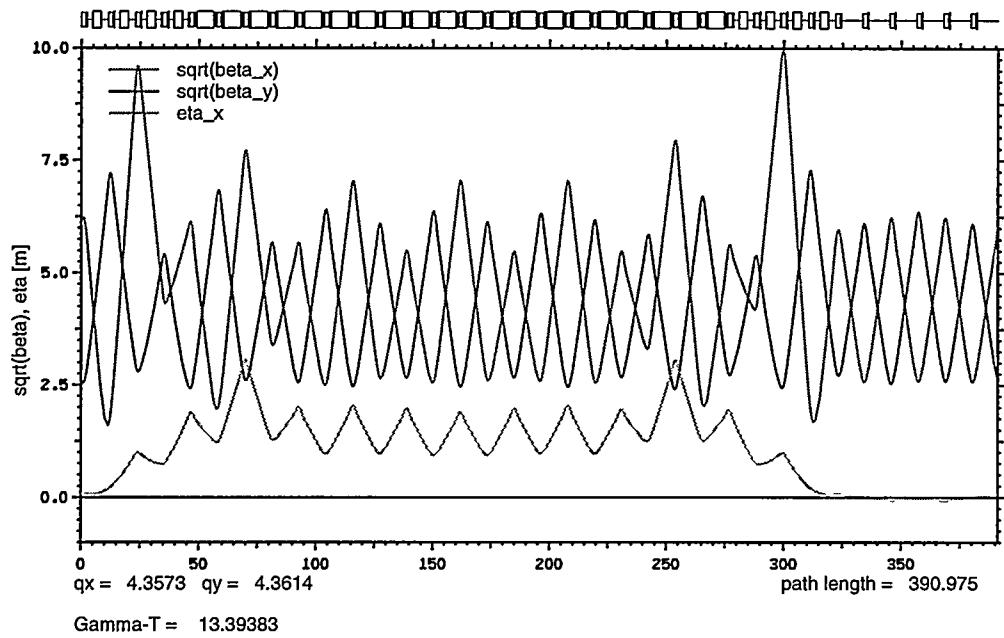


Figure 4. Dispersion and square roots of the beta functions plotted on the same scale. One quarter of the 3-in. ring shown for the minimum value of transition gamma, 13.39.

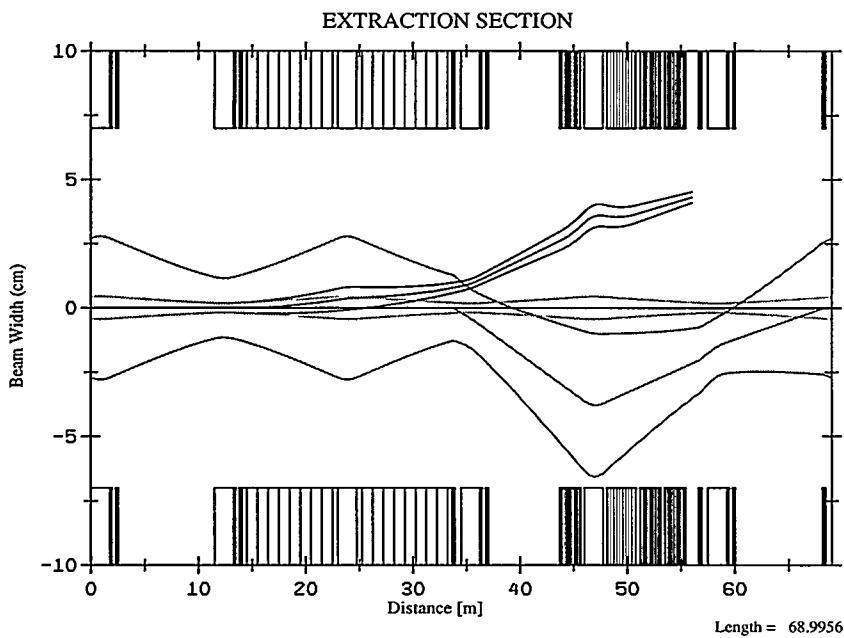


Figure 5. Extraction Section for the 3-in. reference ring. Horizontal view. Shown are the envelopes of the large beam at injection, the beam after acceleration, after being bumped closer to the septa, and the extracted beam.

VIII. EXTRACTION AND ABORT

A. Extraction-Section Layout

The layout of the extraction section is shown in Fig. 5. The figure represents the horizontal layout and beam envelopes for the 3-in. gap reference ring. This is the most challenging case. The extraction system uses two 9-m long, 50Ω TEM kickers of a type used in existing machines, like the Los Alamos Proton Storage Ring. The envelope shown in figure 5 assume a push-pull voltage of 50 kV. A schematic representation of the kicker is given in Fig. 6.

As shown in Fig. 5, the extraction system includes the two kickers, positioned symmetrically with respect to a focusing quadrupole, two Lambertson-type septa straddling a second focusing quad, followed by two C magnets. Except for the larger size, required for the 3-in. gap case, the septa and C magnets are similar to the magnets described in the FNAL MI report (Reference 2).

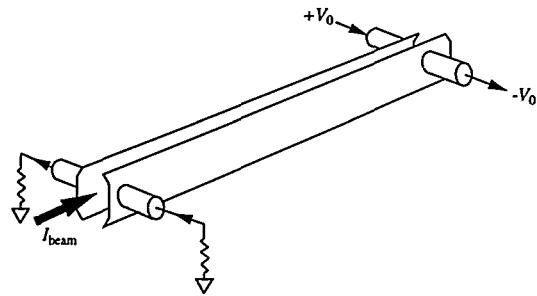


Fig. 6. TEM kicker schematic. Note that the power is fed in the direction opposite the beam.

B. Kicker Modulators.

We studied the necessary kicker modulators for the reference 3-in. gap and for the 2-in. gap gamma-t jump lattices. The kicker modulators were found to be reasonable, except for the "single pulse" 100-ns gap modulator. We have adopted cable modulators for initial operation and reserve the flexible single-pulse modulator

as an option for a future upgrade. Cable-type modulators for a single long pulse and four additional early pulses have been incorporated in our cost estimate. The flexible pulse-extraction upgrade would probably involve the use of stacked-FET modulator systems like the one shown in Figure 7.



Figure 7. Stacked-FET kicker modulator developed at LLNL.

X. REMARKS ON COST

We have collected here the presently available cost information for the synchrotron. We present these data in Table. These data should be viewed as a relative comparison only.

Table 7 Summary of accelerator hardware cost estimates for pre-CDR (with Booster), 3-in. gap (no Booster), and 2-in. gap (with Booster) options.

Synchrotron	pre-CDR	3" Gap	2" Gap
Quadrupoles	\$7200k	\$8925k	\$6175k
Dipoles	\$3848k	\$23322k	\$16899k
Skew Quads	\$160k	\$128k	\$128k
Sextupoles	\$2560k	\$3208k	\$2397k
Steering Mags	\$432k	\$1643k	\$1371k

Vacuum	\$1521k	\$1521k	\$1521k
Power Supplies	\$7992k	\$3113k	\$2368k
RF Systems	\$2204k	\$2204k	\$2204k
Inject/extract/a bort	\$4884k	\$6521k	\$6022k
Beam Diagnostics	\$3572k	\$3380k	\$3380k
Beam Dumps	\$600k	\$600k	\$600k
Special equipment	\$350k	\$650k	\$650k
50-GeV Synchrotron Subtotal	\$35323k	\$55214k	\$43714k
Booster	\$12000k	\$0k	\$12000k
Accelerators Subtotal	\$47323k	\$55214k	\$55714k
Installation Costs @ 20%	\$9465k	\$11043k	\$11143k
Accelerators Total	\$56788k	\$66256k	\$66856k

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2. The Fermilab Main Injector, Technical Design Handbook (November 1995)