CHOICE OF THE INJECTOR SYSTEM FOR THE 200-BeV ACCELERATOR*

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Summary

Many different types of injection systems are possible for the 200-BeV accelerator. A single-stage, single ring, 8-BeV "fast booster" is the best choice.

I. Introduction

An acceptable injection system for a synchrotron must satisfy many simultaneous requirements. It must provide the desired number of particles within acceptable ranges in transverse and longitudinal phase space. Its energy must be large enough that magnet field distortions are unimportant and that the space-charge limit in the large machine is adequate for the desired beam intensity. The injector must be of high confidence and reliability, as it directly affects the performance of the large machine. A short time for filling the large machine and uniform beam qualities also are desirable features for an injection system. Cost considerations invariably enter the arguments also--not only the costs of the injector system itself, but also those of the large machine which are affected by the characteristics of the injector.

Fortunately, or unfortunately, a large number of different types of injector systems can satisfy the basic requirements for an injector into the 200-BeV accelerator. It has been necessary to examine many of these in some detail in order to compare their technical features, costs, and other characteristics.

In this paper I shall sketch the arguments and procedures used in this study, and present the conclusions. This work was a cooperative effort involving Frank B. Selph, Alper A. Garren, Edward L. Hubbard, Johannes Claus, H. Paul Hernandez, Peter T. Clee, myself, and several other members of the LRL Accelerator Study Group.

II. Types of Injector Systems

In the first phase of the injector study just three types of injector systems were considered, as was reported in the 1965 Design Study.[1] These three systems were a 2-BeV linear accelerator, an 8-BeV FFAG synchroton, and an 8-BeV, rapid cycling, single-ring, alternating-gradient synchrotron ("fast booster") fed by a 200-MeV linear accelerator. The fast booster emerged as the clear winner; it seemed adequate in every respect, and much of its technology was already proven. The FFAG system was significantly more expensive, required further development work, and, since little experience existed with FFAG machines, its confidence level was not high. The 2-BeV linac system suffered in that it too was appreciably more expensive than the 8-BeV fast booster, the space-charge limit at injection into the 200-BeV ring was an order of magnitude lower, it required a larger magnet aperture and a much greater RF tuning range in the main ring, and it needed more development work. The energy of the fast booster was set at 8 BeV, which an optimization study[2] showed to be slightly above the point of minimum overall cost. The study showed also that a booster radius of 1/7 the main ring radius was approximately optimum, which determined that in each cycle the booster must accelerate 1/7 of the main ring charge of protons. Similarly the optimum energy of the linac feeding the booster was found to be 200 MeV.

Since that study in 1965, several more types of injector systems have arisen to demand attention. The success of multi-turn extraction systems at the CERN proton synchrotron and at the large electron synchrotrons at CEA and DESY prompted the suggestion that a slowly cycling (one cycle per main-ring cycle) injector synchrotron with decaturn extraction ("slow booster") might be a reasonable alternative, partly because the filling time would then be eliminated from the main-ring acceleration cycle.

Another suggestion was to consider more than one stage of circular injectors. Since linacs have been found to be considerably more expensive per MeV than round machines, it seemed reasonable to consider stopping the linac at 25 or 50 MeV and inserting a circular machine of 500 to 1000 MeV between it and the 8-BeV booster. This idea was reinforced by the conclusion at CERN that a circular machine of 600 to 1000 MeV fed by a 50-MeV linac was preferable to a 200-MeV linac in the CPS improvement program. (At Brookhaven a similar study for the AGS conversion program produced the opposite result, but the circular machines considered and other constraints in the two studies were different.)

A further complication is the possibility of using a multiple-ring structure[3] in one or more of the stages of the injector system. This class of machines was invented by Hardt of CERN, and it was further developed by Garren of LRL. A

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multiple-ring machine has M independent orbits operating simultaneously. The M orbits can be interlaced or geometrically parallel. In most cases the total length of the M orbits equals the circumference of the next accelerator stage, so that the ratio of radii also is M. The multiplicity M in principle is unlimited, but practical constraints have limited M to 3 or 4 in most considerations.

The motivation for considering a multiple-ring structure is primarily achievement of an adequate safety factor with respect to the space-charge limit, which in most cases is given by the transverse, incoherent, space-charge detuning effect near the time of injection. By dividing the total charge to be delivered to the next stage into M separate synchrotrons, the total space-charge safety factor can be increased considerably, and the beam brightness can generally be improved as well. This feature of multiple-ring injector stages can be used also to lower the injection energy into that stage, which serves not only to lower costs in the usual case but also to reduce the intensity or the number of turns of the input beam because of its lower velocity, thus further improving beam brightness. This advantage with respect to space-charge limit is analogous to that of a rapid-(multi-) cycling booster that delivers, say, M separate charges to the main ring. The multiple-ring machine has the advantage relative to the rapid-cycling machine in that its required cycling rate is inherently lower. If the multi-ring machine can deliver all of the main-ring charge in one cycle, it requires no filling time in the main-ring cycle and can use the easier technology of slow machines. It is obvious, of course, that the desirability of a multi-ring stage depends very much on the amount of charge to be delivered to the main ring. If a single-ring stage were not in difficulty with respect to its space-charge limit, and if there were no technical or financial pressures to reduce its injection energy, there would be little reason (other than filling-time arguments) to consider a multi-ring alternative.

These general considerations led us to consider a wide choice of injection systems for the 200-BeV accelerator, including slow and fast sytems, one and two circular stages, and single- and multiple-ring structures. In addition, synchrocyclotrons and separated-orbit cyclotrons (SOC) were briefly considered as intermediate stages of injection systems. Synchrocyclotrons of 500 to 1000 MeV are attractive in that they seem relatively inexpensive. However, at present their beam levels and extraction efficiencies are too low. Possibly the beam levels could be raised and extraction characteristics improved to a satisfactory degree, but this route was deemed too uncertain to risk. Separated-orbit cyclotrons are attractive because of their promise of automatic and perfect extraction. These cyclotrons were not examined in any detail by our group, but we were convinced by the work at other laboratories (Rutherford, Oak Ridge, Chalk River, and MURA) that a SOC injector stage would be too expensive and would require an extensive development program.

III. Analysis of Different Injection Systems

Numerous injection systems are possible if we consider the number of stages, ring multiplicity, and cycling rates as free variables. More than a dozen were analyzed for a quantitative comparison of beam characteristics, space-charge limit, and acceleration requirements. Four of these were selected for engineering analysis to determine technical feasibility and costs of the major components. The problems of injection, extraction, and beam transfer are particularly troublesome in interlaced, multiple-ring machines, so that particular attention was paid to these matters.

In the following sections each of the final types of injector systems is described and discussed, and its principal parameters are given in Table I. The cost figures are rough but internally consistent, so that differential costs in the intercomparison of any two systems should be accurate to within a few million dollars.

Because of the great and confusing variety of possible injector systems, a convenient notation was adopted for referring to each type. A symbol of the type M_P^E refers to a stage of M rings from which the beam is extracted in E turns and which pulses P times per cycle of the next stage. Thus, the symbol 4_1^2 represents a 4-ring machine (QUART) from which the beam is extracted in 2 turns from each ring and which pulses once per cycle of the next stage.

A. 1_1^N-Slow Booster

The slow booster is a single-stage, single-ring injection system which cycles just once per cycle of the main ring. In order to fill the entire circumference of the main ring, its beam must be extracted in at least N turns, where N equals the ratio of the main-ring radius to that of the injector and typically is of the order of 15 to 25. The slow booster is attractive to consider because it employs slow technology (coarse iron laminations, less RF voltage, metal vacuum chamber, and cheaper type of magnet power supply), and it avoids the filling time, synchronization, and cycle-to-cycle momentum jitter problems of the fast booster.

However, the slow booster has its own peculiar technical problems that are even more formidable than those of the fast booster. It must accelerate more than the full main-ring charge (3×10^{13} protons) per pulse because of the loss in the multiturn extraction system, which is at least 10% (30% is the lowest value achieved thus far).

Injection of this much charge into the slow booster also presents a formidable problem in beam dynamics because of the large number of turns. With a 50-mA linac beam at 200 MeV, 50 to 100 or more turns are required, depending on the radius of the booster and the injection efficiency. With this large number of turns both vertical and radial multiturn injection is required, which produces considerable dilution in the beam emittance. However, even more dilution, at least in the vertical emittance, is required in order to achieve a satisfactory space-charge limit. As a result a considerably larger magnet aperture is required, both in the booster and in the main ring, than is needed in the fast-booster system.

The greatest difficulty of a slow booster is the problem of efficient and uniform decaturn extraction. Linear resonant systems for achieving 15- or 25-turn extraction have been analyzed theoretically by Claus[4] and by Reich[5] with equivalent results. A beam can be extracted in, say, 20 turns, but in order to obtain uniform intensity and an acceptable dilution in emittance, the process requires accurate modulation of the closed orbit (or of the strength of the perturbation) and a precise cancellation of the change in betatron frequency with momentum at a time when the guide magnets are beginning to saturate. The minimum dilution to be expected is about 1.6 if further beam loss (beyond the loss on the septum) is to be avoided. Actually, further emittance dilution is to be expected because the shape in phase space varies continually throughout the extraction process. Another requirement is that the transport system must interchange vertical and radial phase space in order to avoid an excessively expensive main-ring vacuum aperture.

If the transverse phase space of the beam in the slow booster is not uniformly populated, it is impossible to achieve both uniform intensity and uniform emittance area in the extracted beam. Therefore, less extracted beam can be accepted by the main ring, its effective space-charge limit is reduced, and time structure is produced in the slow-spill output beam from the main ring.

Cost studies[2] of the slow booster show that although it is less expensive than the fast booster, as expected, the cost of the total accelerator system is about the same or slightly greater for the case of the slow booster. The increased main-ring cost due to the large overall beam dilution required by the slow-booster system more than compensates for the lower injector costs.

The difficulties and lack of confidence in achieving a satisfactory decaturn extraction system are the most severe disadvantages of the slow booster. In addition, the poor beam brightness in the main ring, the modulation in time of its slow-extracted beam, the difficulties of simultaneous vertical and radial multiturn input into the slow booster, and the anticipated difficulties of accelerating a large charge, especially through transition, in the booster, plus the slight cost disadvantage all contributed to the decision against the slow booster. These reasons were sufficient to eliminate from further consideration all two-stage systems employing decaturn extraction from either stage.

Although decaturn extraction was found to be difficult and unpleasant because of its time variations, it was realized that two-turn extraction is a special case in which the intensity, emittance area, and emittance shape are all uniform and constant. Therefore, two-turn extraction systems were considered acceptable.

B. $3^1_1 - 1^1_8$, Two-Stage System, TART Plus Fast Booster

This two-stage injection system consists of an interlaced, three-ring TART machine with fast extraction, cycling once per cycle of the 8-BeV fast booster 1^1_8. (The difference between this fast booster 1^1_8 and the "standard" 1^1_7 is unimportant here.) The TART is fed by one-turn injection from a 28-MeV, 80-mA linac, and its output energy is 600 MeV. The linac energy of 28 MeV was chosen to allow one-turn injection into each of the three rings, because multiturn injection into an interlaced multiple ring is relatively difficult.

The TART magnet structure is a weak-focusing system[6] of 24 magnets. A "weak-focusing" system is preferable to a "strong-focusing" system in a multiple-ring machine of this energy range in that it produces a smaller beam cross section and a more open and uncluttered structure. Each magnet is a crossing point for two beams, so that each magnet does double duty, at the cost of some additional width due to crossing geometry. The average radius is 1/3 that of the 8-BeV ring.

There is a question as to whether each of the three independent orbits needs its own RF system so that each beam can be independently controlled. In this system we chose to consider the cheaper, single RF system which is common to all three orbits. Each accelerating cavity straddles all three beams.

The injection and ejection systems of the TART are somewhat complicated. The system considered has only one injection and one extraction point, and the beam is distributed among (and from) the three rings by means of internal transfer systems actuated by fast-kicker magnets. Each of these kicker magnets is turned on and off only once per injection (or extraction) period.

The principal advantages of this two-stage injection system relative to the standard single-stage, single-ring, fast booster are:

a. a better safety factor on the controlling space-charge limit by a factor of about 1.2

b. a smaller radial emittance (normalized) by a factor of 6 and hence a greater beam brightness in the main ring

c. single-turn injection

d. lower linac energy

e. smaller charge per pulse

f. smaller aperture and smaller tuning range in the 8-BeV ring.

The principal disadvantages of this system are:

a. a large number of complicated beam transfers

b. beam dilution (possibly large) due to the several beam transfers. (This dilution is probably avoidable but a detailed solution has not been worked out.)

c. greater complexity and increased operating cost

d. greater cost by about 2 million dollars (including differential costs in the main ring)

e. less possibility for future beam increases because of the difficulty of multiturn injection in the TART

f. the worry of beam-beam interactions at the beam crossing points.

The linac, TART, and booster energies were not optimized in this example, but we feel that they are reasonable values and that the results for different energies would not be substantially different. A 400-MeV TART system was also considered, for example, and the overall cost was only 0.5 million dollars less.

The increase in the space-charge safety factor was an important reason for considering this system, but the 20% increase hardly seems to justify the trouble. This safety factor was increased to 2.0 dilution of the beam emittance, but the cost disadvantage then rose to 10 million dollars.

From this study we conclude that the relatively small advantages of this two-stage TART injection system are outweighed by its disadvantages relative to the single-stage, fast-booster system.

C. $4_1^1 - 1_8^1$ Two-Stage System, QUART Plus Fast Booster

This two-stage injection system is very similar to the $3_1^1 - 1_8^1$ system described in Section III. B, except that the first circular stage has four orbits, 32 magnets, and an average radius which is 1/4 of the 8-BeV ring.

The advantages and disadvantages of this QUART system also are quite similar to those of the TART two-stage injection system, with the following qualifications. The improvements of the QUART over the TART system are the lower charge per pulse and greater space-charge safety factor, which in this case is about 1.6 times better than that of the single-stage, fast-booster system. However, the four-ring geometry presents considerably greater mechanical restrictions and complications, so that its engineering feasibility has not been entirely established. The cost of this QUART type of two-stage system was found to be 3 million dollars greater than that of the single-stage, fast-booster system.

In addition to the QUART with an interlaced geometry, a parallel four-beam system was also considered in which the four beams are stacked vertically, a geometry that has been studied at CERN for the improvement program of their 30-BeV proton synchrotron. Although twice as many magnets are needed in this stacked system, it turns out that the magnet cost is about the same as that of the interlaced geometry because of the lack of width due to the crossing geometry of the beams in the interlaced system. However, more RF cavities are needed because the beam separations are so large that it seems unfeasible to have an RF cavity that can straddle all four beams. Also more extensive injection and extraction systems seem to be required. We conclude that a parallel-beam, four-ring machine is more expensive than an interlaced system, and that its overall advantages are not significant.

As with the TART two-stage system, the disadvantages of the QUART system were found to outweigh its advantages with respect to a single-stage, single-ring fast booster.

D. 4_1^2 Single-Stage QUART Injection System

This single-stage system uses an interlaced, four-beam geometry, with two-turn extraction for each beam, and cycles once per main-ring cycle. Its radius is 1/8 the main-ring radius. This system is attractive to consider, because it requires no filling time in the main-ring cycle and employs slow technology. Two-turn extraction is more difficult, has greater beam loss than single-turn extraction, produces some dilution in beam emittance, and is an untried system, but nevertheless it is considered to be a workable process.

The principal disadvantages of this QUART single-stage system relative to the fast booster are its greater charge per pulse, larger magnet system, more extensive beam handling, and general mechanical complexity. Because of the greater charge per pulse, this system requires a linac of at least 300-MeV in order to achieve a satisfactory space-charge limit without undesirable beam dilution. The magnet is considerably larger not only because of the greater total magnet length, but also because of the greater vacuum aperture, which is at least twice as big as that of the fast booster. The stored magnetic energy similarly is much larger. From these and similar considerations it quickly appears that in spite of the relatively cheaper type of technology employed in this slow, single-stage QUART system, the overall cost with this system would be considerably greater than with the fast-booster system.

The remaining advantage of this slow injection system is its negligible filling time of the main ring. In the fast-booster system, the filling time is 1/3 s, which is just 13% of 2.6 s, the total length of the main-ring cycle at 200-BeV with flat top. To first order, then, the filling time loss is equivalent to a reduction in average beam intensity by about 13%. This percentage is, of course, greater for operation at lower energy and without flat top, but such operation is expected to be relatively infrequent. The typical low-energy experiment will usually be time-sharing the machine with high-energy experiments that will require the full cycle length. The conclusion of these arguments is that the slow, single-stage QUART system is inferior to the single-stage fast booster.

E. $1\frac{1}{8}$ Single-Stage, Single-Ring Fast Booster

This single-stage, single-ring injector uses single-turn extraction and cycles eight times in filling the main ring. The factor of eight in radius relative to the main ring is now preferred to the factor of seven formerly considered because an even factor has the potential that such a system can more conveniently be converted at some later time to a two-turn extraction system ($1\frac{2}{4}$). The advantage of this conversion could be either a halving of the filling time or a reduction in the injector cycling rate.

We feel that there are satisfactory answers to all objections that have been raised to the fast-booster system. The filling time argument has already been discussed. The resonant magnet power supply is more expensive per joule of stored energy, but its total cost is no larger than that of a competing slow system because of the smaller stored energy in the fast system. Some of the large resonant power supplies now in operation at DESY, CEA, and PPA have had choke failure and trouble with stray-capacity modes, but these failures are now understood and have known, straightforward solutions. With respect to the stray-capacity modes, the fast booster has about two orders of magnitude advantage because of a much higher injection field, a lower cycling rate, and the opportunity to design around them.

The ceramic chamber needed for a fast system is more expensive than that of a slow system, but not significantly so. Ceramic technology has advanced rapidly in recent years, and there now is widespread confidence in its use. A section of ceramic chamber has recently been successfully tested in the Cambridge Electron Accelerator. Fast-cycling magnets need end-shaping and finer laminations, but magnet end-shaping is now a known and successful technique and not terribly expensive. The booster iron laminations are 0.025 in. thick, which is not much thinner than the 0.030 in. laminations of the Brookhaven AGS.

Synchronization of the booster beam with the RF of the main ring is a new and important problem, but at least three or four different systems have been invented which seem practical. People who have examined this problem in detail are confident of its solution. Momentum jitter of the booster output beam from cycle to cycle is another new problem. Momentum jitter and synchronization errors both cause collective phase oscillations in the main ring, which requires additional main-ring aperture and cause some time-structure in the slow spill. The tolerable fractional momentum jitter is about 2 or 3×10^{-4}, which although tight is thought to be achievable without heroic efforts. The inherent pulse-to-pulse stability of the resonant power supply (with a Q of about 100) eases this problem considerably.

IV. Conclusion

The conclusion of our examination of these several types of injection systems is that the single-stage, single-ring fast-booster system is the best choice for the 200-BeV accelerator project. The fast booster has the simplest and cleanest injection and extraction systems, has an adequate space-charge safety factor, employs technology in which there is confidence, and has no feature about which there is a serious doubt. The fast booster promises to be an injector of high reliability. In addition, no other injection system produces a lower overall cost for the 200-BeV accelerator with a beam level of 3×10^{13} protons per pulse.

References

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Table I. Parameters of the injection systems considered.

		1_8^1	1_1^N	4_1^2	$3_1^1(-1_8^1)$	$4_1^1(-1_8^1)$
Energy in	(MeV)	200	200	~300	28	28
Energy out	(BeV)	8	~ 8	8	0.6	0.6
Inj. field	(kG)	0.6	~ 1	~ 1	1.9	1.9
Peak field	(kG)	7	12	10	10	10
Inj. beam	(mA)	50	50	>100	80	80
Inj. turns		4	~ 80	4	1	1
Ext. turns		1	~ 18	2	1	1
Av. radius	(m)	86	~ 40	86	29	22
Mag. radius	(m)	42	~ 25	30	4.1	4.1
No. magnets		66	--	--	24	32
β_{max}, rad.	(m)	17	--	--	14	13
β_{max}, vert.	(m)	23	--	--	22	17
ν rad.		7.25	~ 3.25	--	2.4	1.9
ν vert.		8.25	~ 3.25	--	1.3	1.4
Vac. aperture	(cm^2)	6 by 15	~15 by 20	9 by 28	13 by 24	11 by 28
Cycling rate	(Hz)	21	0.43	0.43	21	21