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ON THE SELECTION OF INJECTOR SYSTEMS

J. M. Peterson

September 12, 1967

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ON THE SELECTION OF INJECTOR SYSTEMS

J. M. Peterson

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On the Selection of Injector Systems

I. Introduction: A Problem with Many Solutions

It has already been demonstrated at this conference that the selection of injector systems for large proton accelerators is at best an inexact science. It is not difficult to find several solutions, all of them apparently valid, for the problem of finding a satisfactory type of injector for a given accelerator. What is difficult is to convince someone that you have found the best type of solution to the injector problem.

I should like to illustrate this situation by reviewing the considerations that led to the choice of a particular fast booster synchrotron as the injector system for the 200 Bev accelerator in the LRL Design Study.

II. Injectors Considered for the 200 Bev Accelerator

We considered a large variety of possible injector systems for the 200 Bev machine. To illustrate this spectrum I have chosen five as typical examples of basic injector types to which we gave serious attention. For each of these five I shall list its major advantages and disadvantages. Some systematic conclusions should emerge from these comparisons.

IIa. 2Bev Linac Injector

The first example is the 2-Bev proton Linac, which is included here mainly for its historical interest. It is illustrated in Figure 1. The energy of 2 Bev was chosen as being as large as one could realistically consider building. The good features of this linac system are its perfect beam extraction, its nice beam optics, and its general simplicity (i.e., the absence of magnetic cycling and other synchrotron complications and zero filling time of the main ring). The principal disadvantages of this Linac injector system are its low output energy and its high cost. It turned out that an 8-Bev booster synchrotron was considerably cheaper and quicker to build and, furthermore, could produce considerably more beam in the 200-Bev main ring.

Thus the linac was cut back to 200 Mev and relegated to the role of a pre-injector into the booster.

IIb. Fast Booster

The fast booster, or fast-cycling synchrotron injector, illustrated in Figure 2, was suggested by Matt Sands in 1959 as a suitable injection system for a 300 Bev machine, and Sands in turn credits Robert Wilson with the basic concept (around 1956). The practicality of the fast booster depends, of course, upon having efficient beam

extraction, and this was finally realized by the successful development of fast-extraction techniques at CERN and at Brookhaven.

It is readily apparent from the figure that a booster whose radius is N times smaller than that of the main ring must cycle N times to fill the circumference of the main ring (if we assume one-turn extraction). This geometrical requirement of splitting the main ring charge into N parts is also a principal virtue of the fast booster, in that the booster space charge limit need be only 1/N times that of the main ring. This lower space charge limit in the lower energy machine is very important because of the fast energy dependence of the space charge detuning effect. For this reason and because of the desire of reducing the number of synchrotron oscillations per revolution, one tends to reduce the booster radius as far as possible. One is limited in this direction, of course, by the lengths of magnets, RF cavities, and other hardware necessary in the ring or by cycling-rate problems.

The principal virtues then of the fast booster injector are its reduced beam requirements, a clean, efficient extraction system, a generally proven fast-cycling technology, and an acceptable cost. Its main disadvantages (relative to a"slow" system) are the finite filling time in the main ring cycle, a "large" RF voltage requirement, a

somewhat more difficult technology (finer magnet laminations, a more expensive vacuum chamber, ...), the requirement of synchronizing the beam in the booster with the RF in the main ring, and a problem in cycle-to-cycle momentum jitter.

IIc. Slow Booster

Just as the successful development of fast extraction techniques led to the acceptance of the fast booster, so did the development of slow, multi-turn extraction techniques lead to the acceptance of the "slow booster." By "slow booster" I mean a small synchrotron which cycles only once per main ring cycle and whose beam is extracted in, say, 10, 20, or 30 turns. It is shown schematically in Figure 3.

The slow booster is attractive to consider because it avoids all of the disadvantages of the fast booster which were just mentioned. Furthermore, the slow booster injector is cheaper than the comparable fast booster. However, the overall cost, including main ring costs, is about the same.

The main disadvantages of the slow booster have to do with the large charge per pulse and the multi-turn extraction problem. The slow booster must accelerate all of the main ring charge each cycle, plus a bit more to compensate the beam loss at extraction. This large charge requires

typically 50 to 100 turns of input beam from the linac, which is too many to accommodate without simultaneous vertical and radial multi-turn injection techniques. An efficient and convenient input system of this type has not been worked out. Another consequence of the large charge per pulse in the slow booster is the large dilution in emittance necessary to obtain an adequate space charge limit. This dilution enlarges not only the slow booster magnet aperture but also that of the main ring. It is the additional cost in the main ring that compensates for the smaller cost of the slow booster. The decrease in main ring beam brightness is another disadvantage of this system.

The acceleration of this large amount of charge in the low energy machine is another serious worry, because many unpleasant space charge effects other than the usual transverse incoherent detuning effect can come into play at high intensity. Among these is the blow-up in longitudinal phase space which can occur at transition energy. This particular problem can be avoided by putting transition above the output energy of the machine, but this solution is usually inconvenient or undesirable with respect to other beam properties.

The greatest worry in the slow booster is the decaturn extraction process. Decaturn extraction using half

integral resonance has been analyzed both by Helmut Reich (CERN/BNL) and by Jan Claus (LRL/BNL) with equivalent results. Slicing the beam into, say, 20 turns of equal intensity and equal emittance is not possible, even in principle, with a beam with a realistic density distribution, unless one somehow selectively dilutes the emittance of each turn to match that of the lowest density turn. Furthermore, the shape in phase space of the extracted beam varies continuously from turn to turn and thus requires time-dependent focussing in the transport system -- otherwise even more dilution occurs. Because of these problems it seems very difficult to avoid having the distribution of the beam around the main ring wobble either in intensity or in emittance. In either case a severe modulation can be produced in the slow extracted beam from the main ring, which, of course, would be objectionable to most counter experiments. This wobble in the main ring beam distribution also serves to reduce the effective aperture available for the beam and/or the effective space charge limit in the main ring. The minimum amount of dilution in emittance to be expected in a relatively efficient slow extraction system is about a factor of 2. It could be much higher if the change of betatron time with momentum is not well compensated or if there is an appreciable pulse-to-pulse variation in tune. Close control of the closed-orbit and of the

perturbation which excites the resonance also is necessary. Another complication in the optics of the transport system from the slow booster to the main ring is the need to interchange radial and vertical phase space so as to better match the beam produced by radial multi-turn extraction to the shape of the main ring aperture.

The efficiency of beam extraction in a slow extraction might be as high as 90%, although existing systems have produced at best only 70% and typically run closer to 50%. Although a 10% beam loss at extraction does not seriously affect the intensity of the main ring, it does represent a much greater induced radio-activity problem in the extraction system than is possible with the inherently more efficient one-turn extraction process used in the fast booster.

These several difficulties with decaturn extraction were the factors which weighed most heavily against the slow booster in our considerations. The lower beam brightness in the main ring, and the lack of any overall cost advantage also helped eliminate the slow booster from serious contention.

This picture of decaturn extraction may be overly pessimistic. K. Symon has pointed out that theoretically there are methods of breaking up the beam in a slow booster into several equal and spatially separated components

by means of non-linear perturbations. Each beam component could be individually extracted. Such a multi-turn extraction process could remove the objections of beam non-uniformity, dilution and beam loss inherent in the linear, half-integral method of decaturn extraction. Experiments anticipated at the AGS in Brookhaven in 1968 on decaturn extraction should clarify this problem.

Although decaturn beam extraction was found to be difficult and unpleasant, it was realized that two-turn extraction is a special case of "multi-turn" extraction in which the intensity, emittance area, and emittance shape are the same for each turn. Two-turn extraction systems are considered acceptable for this reason, although the method has not yet been tried experimentally.

IId. Slow Quart

An injector which has most of the good features of both the fast and the slow injector is the slow-cycling Quart, which is a descendant of the original multiple-ring machine described by Hardt at the Frascati conference. As illustrated in Figure 4, the Quart consists of a nest of four identical independent accelerator rings, each of which is 1/8 the size of the main ring, so that with two-turn extraction the four rings can fill the main ring in one cycle. Thus this system has no filling time

problem, it employs slow accelerator technology, its space charge limit need be only ¼ that of the main ring, and it has a reliable, straightforward extraction system. One-turn (fast) extraction would be even better except that then the radius of the Quart would be ¼ that of the main ring, which would be uncomfortably large and expensive in this case.

Whether a multiple-ring machine is the best type of injector for some system depends mostly upon three factors -- the intensity level and energy range involved and the maximum allowable filling time. Unless the intensity level is high ($>10^{12}$ particles per pulse), there is little reason to subdivide the required beam intensity among several rings. If the intensity is high and if the competing injector is a linac, the multiple ring is likely to win because, as is well known, the linac is much more costly per Mev than a circular machine.

The booster for the improvement program at the CERN proton synchrotron is a good example of this situation. Here an injector consisting of four parallel 600 (or 800) Mev rings was found to be preferable to a 200 Mev linac system. A counter example might be considered the Brookhaven conclusion that the 200 Mev linac was to be chosen over a 1 Bev slow booster. However, in the Brookhaven case, budgetary considerations in favor of the linac were

a big factor in the decision. Also in this conference we have heard of three synchrotrons in the 40 Gev, 10^{12} protons per pulse category, two of which have purely linac injectors, whereas the third prefers a multiple-ring injector. These examples support my remark that injectors represent an inexact science.

~~In~~ This slow-cycling Quart for the LRL 200 Bev design study had an energy in the 8 Bev range and so was competing, not with a very expensive linac, but only with a moderately expensive fast booster. Thus, the slow-cycling Quart turned out to be appreciably more expensive than the fast booster. Since it also required a greater charge per pulse and thus a higher energy linac, this Quart system lost out to the fast booster system.

IIe. Fast Quart, Fast Booster System

This last example of injector systems has two stages of circular injectors -- a low-energy, fast Quart followed by an 8 Bev fast booster. It is illustrated in Figure 5. Here the Quart, since it feeds the fast booster, has to cycle at the same rate. The linac energy was chosen by Garren to be about 30 Mev so as to provide single-turn injection into each of the Quart's rings, which is a great deal simpler than multi-turn injection into an interlaced multi-ring system. In this system the Quart can be

considered to be in competition with the 200 Mev linac.

The main advantages of this two-stage synchrotron injector are: a smaller charge per pulse (and thus a lower linac energy and a better space charge safety factor), better beam brightness in the main ring, single-turn injection, and a smaller aperture and smaller tuning range in the fast booster. The principal disadvantages of this two-stage system are: the complexity and operational cost of an additional stage of acceleration, possible beam dilution in the many complicated beam transfers, and a slightly greater cost. In this example the Quart did not look as good as the 200 Mev linac system mostly because the fast booster is not in bad trouble with respect to its space charge limit, so that there is no real need to subdivide its charge in the Quart pre-injector. If the required beam level of the machine were to rise by a factor of 3 or 10, the Quart pre-injector would probably become necessary.

IIf. Systematic Conclusions

These five samples of different types of injectors allow some systematic conclusions to be drawn, which are not invalidated, I believe, by the neglect, in this short survey, of the several other interesting types of injector systems which have been proposed (e.g., storage ring systems). The conclusions are:

(1) for the domain of low charge per pulse in the main ring (on the order of 10^{12} or less per pulse), the standard 50 or 100 Mev linac is adequate, simplest, and probably cheapest as well.

(2) for the domain of high charge per pulse (10^{13} or more), subdivision of the charge by some factor N is indicated by subdividing either in time (fast booster) or in space (multiple ring). Fast booster is the first preference because a greater subdivision factor N is available generally -- if the allowable filling time permits. If only a very short filling time is available for the next ring, a multiple-ring system becomes preferable.

(3) Slow boosters with decaturn extraction appear at this time to be quite difficult and to have poor beam properties.

III. The Berkeley Booster

It was reasoning such as this that led to the adoption in Berkeley of the fast-booster type of system for injection into the 200 Bev accelerator. It was a long and laborious process and took the efforts of many people

besides myself: Frank B. Selph, Alper A. Garren, Edward L. Hubbard, Johannes Claus, H. Paul Hernandez, Peter T. Clee, Robert Avery, and others in the LRL Accelerator Study Group.

Choosing the optimum parameters of a given type of injector system is another laborious job and a further example of an inexact science. After going through an optimization one is generally convinced that the overall optima, with respect either to cost or to technical value, are quite broad with respect to most of the main parameters, as long as each solution is done in a self-consistent manner. In this talk I shall content myself with putting down the main parameters of the final version of the Berkeley booster:

Table I.

PARAMETERS OF THE LRL FAST BOOSTER

Input energy	200 Mev (Linac)
Output energy	8 Bev
Beam level	3.75×10^{12} ppp
Radius	86.4 m. (1/8 R_{MR})
Cycling rate	20 Hz
Fill time	0.35 sec.
Peak magnetic field	8 kG
Magnet lattice	FOOFDOD (combined function)
ν_r, ν_z	7¼, 6¼

The Weston 200 Bev accelerator represents an appreciable change from the LRL version, and this of course causes some changes in the injector system as well. There have been discussions all this summer at Oakbrook regarding the choice of the injector system and its parameters, and our arguments are still in progress. However, some points have finally been settled, and as of last week the following things about the injector were known:

Table II.

Type of injector	fast booster (possibly with provisions for running as a slow booster)
Input energy	200 Mev
Output energy	10 Bev
Beam level	3.85×10^{12} ppp
Radius	75 m. $\left(R_{MR}/13^{1}/_{3}\right)$
Cycling rate	15 Hz
Fill time	0.8 sec
Lattice and other parameters	undetermined

Since the parameters of the LRL booster were set, a new worry has arisen, namely the coupling of synchrotron and betatron oscillations through the space charge forces, which is now referred to as the Möhl effect. One of the ways to avoid being hurt by the Möhl effect is to reduce

the radius of the booster, and this is one of the reasons for looking for a smaller radius. Another reason is the larger charge per pulse in the main ring, which is necessary in order to maintain the same average beam with a longer main ring cycle (5×10^{13} ppp, 4 sec cycle).

The radius of 75 meters is a non-integral sub-multiple (13 1/3) of the main ring radius (1000 meters). Although this choice of radius does not provide a precise fill of the main ring after 13 pulses, the gap left over is at most only 2.5%, which could be useful in preventing space charge neutralization of the main ring beam. This non-integral radius ratio also provides for flexibility in efficient high beam loading of the main ring by the booster. The ratio 13 1/3 allows, e.g., the convenient parking of all the beam in the booster in 1/40th of the main ring circumference and with relatively high beam brightness.

Figure Captions

Figure 1: schematic layout and time sequence of operation for a 2 Bev linac injection system.

Figure 2: schematic layout and time sequence of operation for a fast booster type of injector.

Figure 3: schematic layout and time sequence of operation for a slow booster type of injector.

Figure 4: schematic layout and time sequence of operation for a slow Quart type of injector.

Figure 5: schematic layout and time sequence of operation for a two stage, fast cycling injector system.

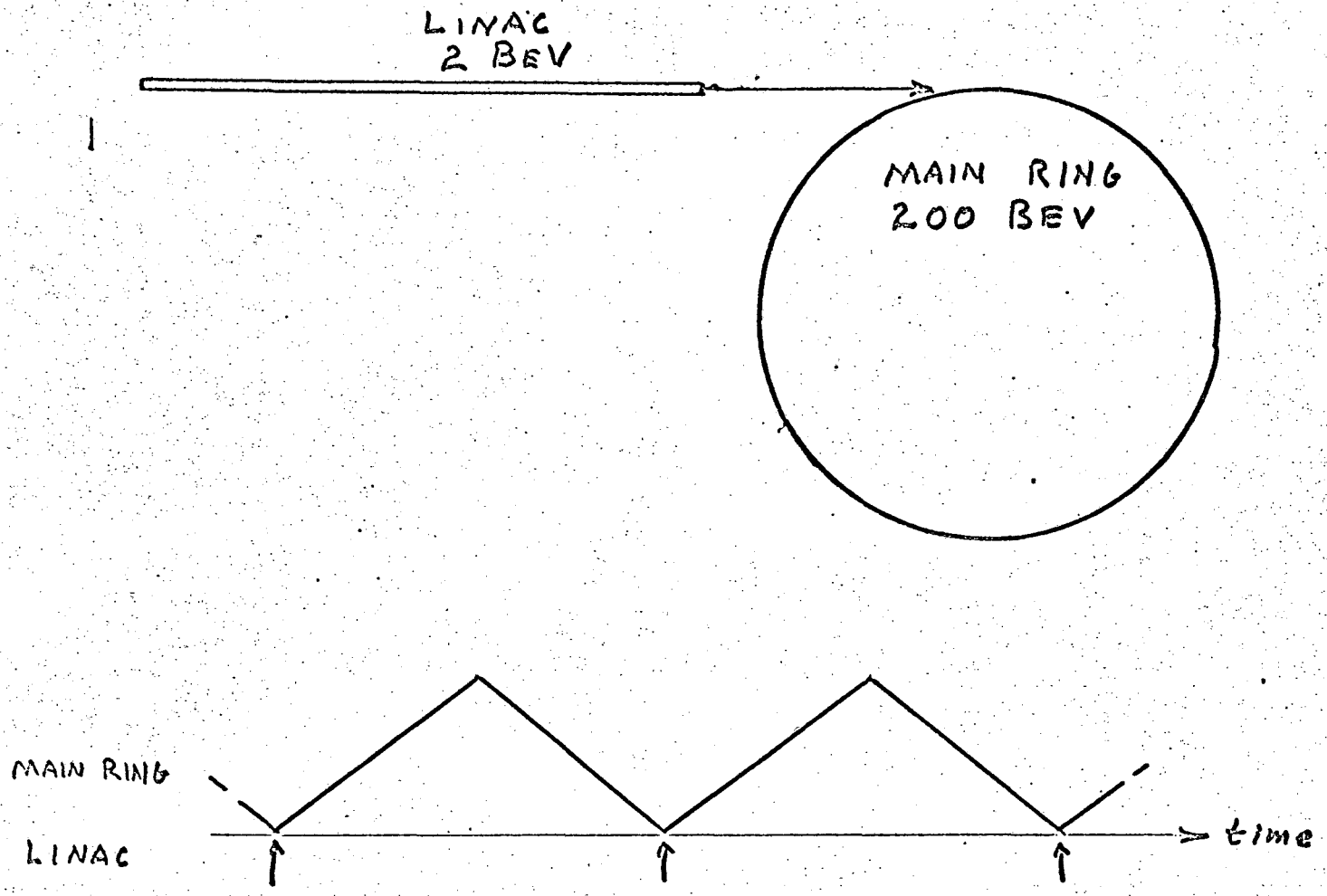
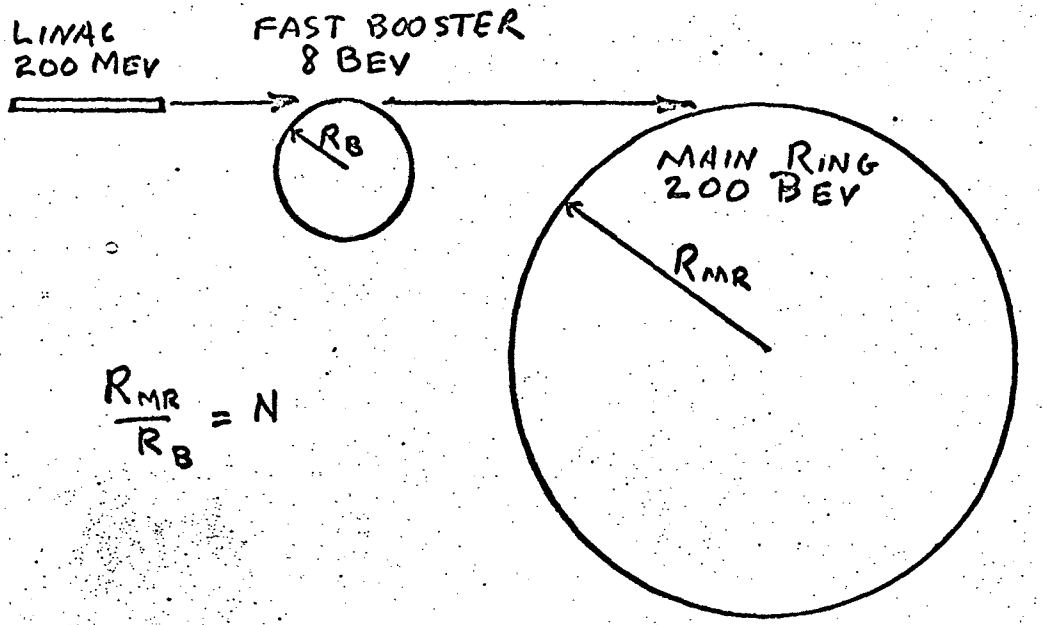


Fig. 1



$$\frac{R_{MR}}{R_B} = N$$

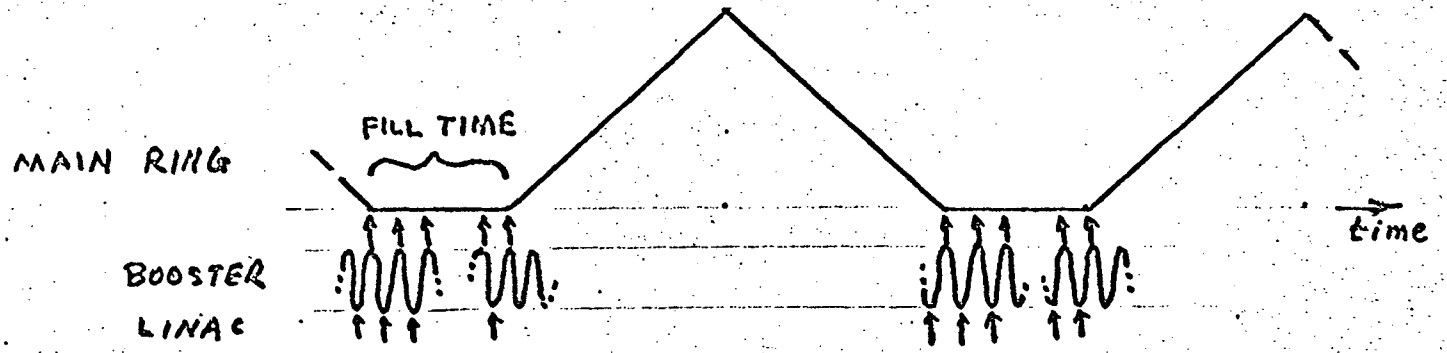


Fig. 2

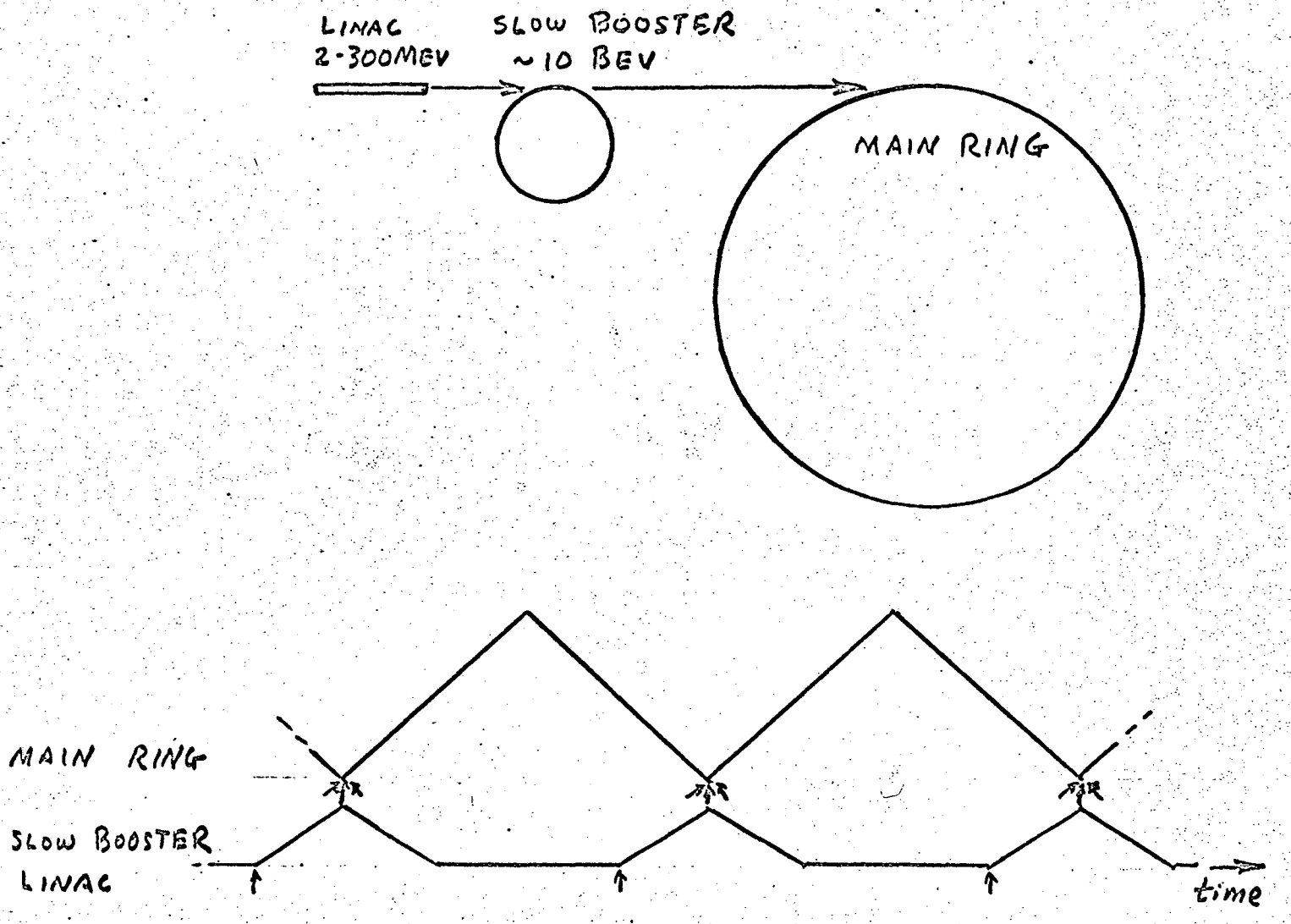
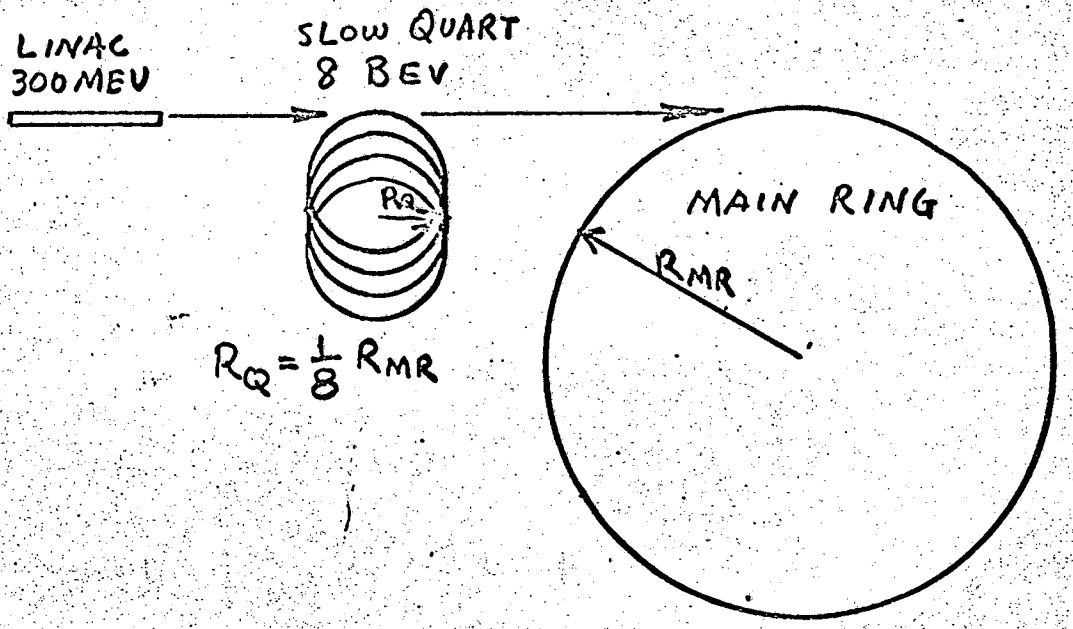

LINAC
2-300MEV
SLOW BOOSTER
~10 BEV
MAIN RING
MAIN RING
SLOW BOOSTER
LINAC
time

Fig. 3


LINAC
300 MEV
SLOW QUART
8 BEV
R_Q
MAIN RING
R_{MR}
$R_Q = \frac{1}{8} R_{MR}$

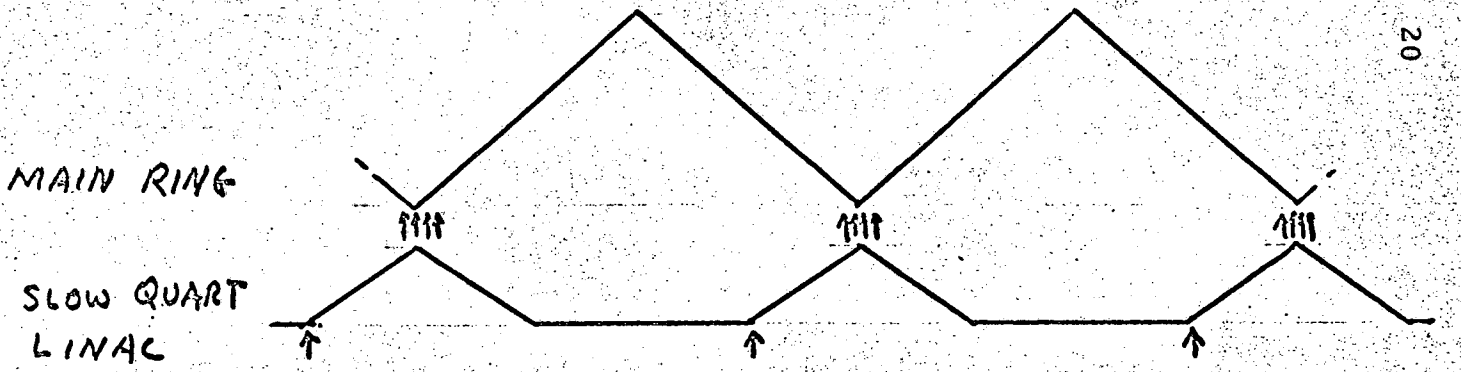
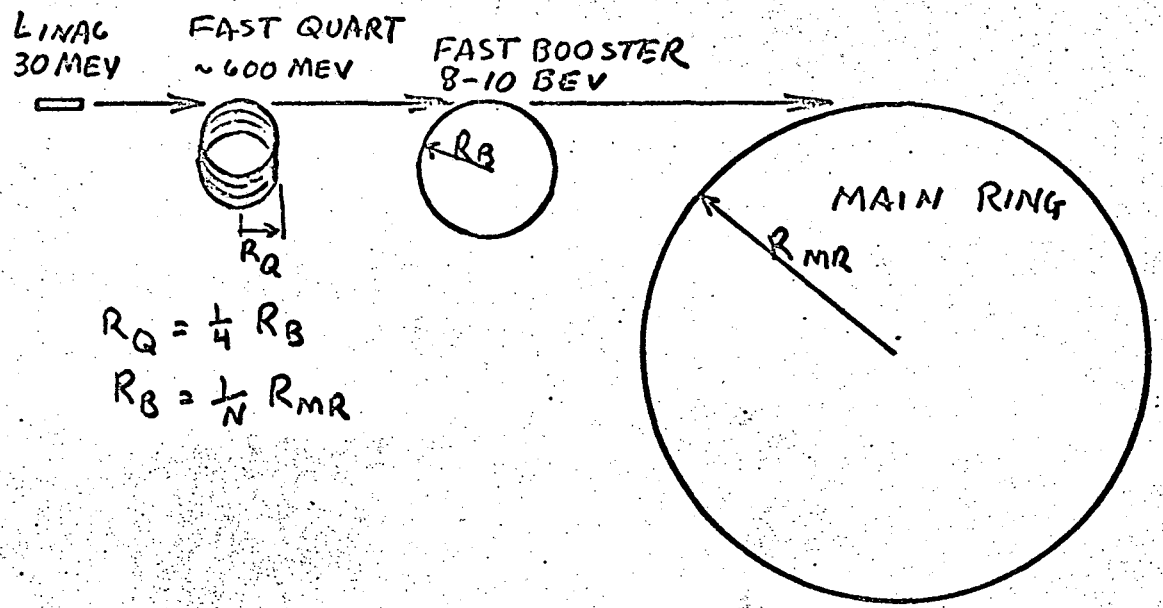

MAIN RING
SLOW QUART
LINAC

Fig. 4


LINAC
30 MEV
FAST QUART
~ 600 MEV
FAST BOOSTER
8-10 BEV
R_B
R_Q
MAIN RING
R_{MR}
$R_Q = \frac{1}{4} R_B$
$R_B = \frac{1}{N} R_{MR}$

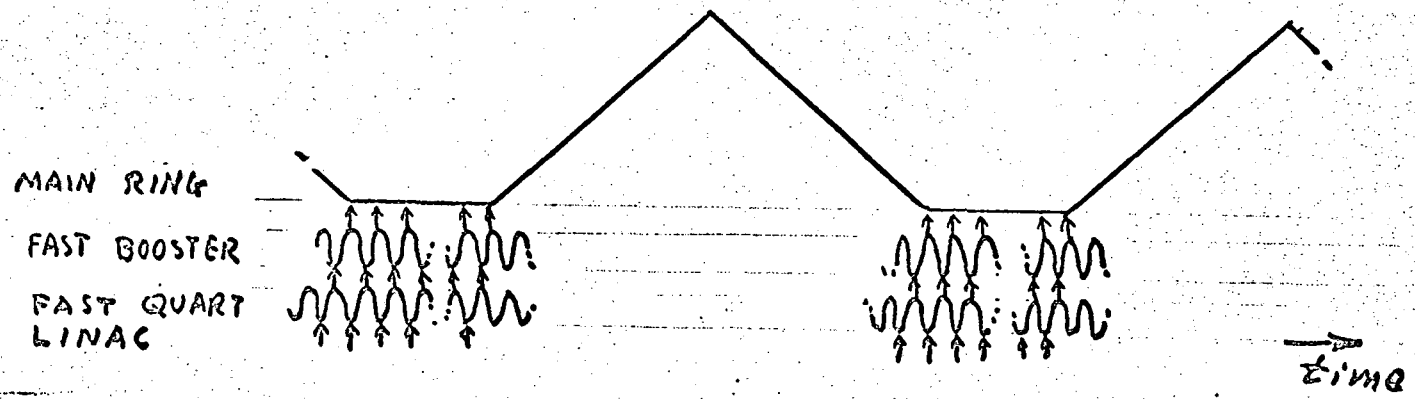

MAIN RING
FAST BOOSTER
FAST QUART
LINAC
TIME

Fig. 5

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