

## THE FERMILAB BOOSTER AS A KAON FACTORY

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## ABSTRACT

We review the performance of the Fermilab rapid-cycling Booster emphasizing those aspects which allow acceleration of up to  $4.5 \times 10^{13}$  protons per second to energies of 8 to 10 GeV. Characteristics of a kaon factory based on this machine will be discussed.

## INTRODUCTION

With the success of the high intensity medium energy accelerators (the "meson factories", TRIUMF, SIN, LAMPF) attention has shifted to the design of accelerators of sufficient energy and currents (tens of  $\mu\text{A}$ ) to provide large Kaon fluxes for research. Designs for new accelerators are the reason for this workshop. It is our purpose to evaluate the possibilities of the Fermilab Booster as a Kaon factory. To this aim we will ignore the increasing commitment of the Booster to the future High Energy Physics  $\bar{p}p$  collider program at Fermilab.<sup>1</sup>

The potential of existing synchrotrons as Kaon factories was already discussed by L. Teng.<sup>2</sup> The advantage of the proton flux obtainable from a rapid-cycling accelerator like the Fermilab Booster was clear from that comparison. On the other hand, methods of increasing the naturally low duty factor are mandatory.

In the first section we describe the Fermilab Booster accelerator, its present performance and possible maximum intensity achievable. In the second section the characteristics of a Kaon factory based on the Booster will be discussed.

## THE FERMILAB BOOSTER

The Fermilab Booster accelerator<sup>3</sup> has an injection energy of 200 MeV and a nominal top energy of 8 GeV. At present it is operated at 9 GeV as part of an upgrading program towards future operation at 10 GeV.

The guiding field is provided by combined function magnets excited with a resonant power supply at 15 Hz. The vacuum vessel is provided by the laminated pole pieces, and no vacuum chambers are utilized in the regions of magnetic field.<sup>4</sup> The average radius is 75.47 meters.

The Booster lattice consists of 24 identical periods, with no super-period structure. Each period consists of 4 combined function magnets, two focussing and two horizontally defocussing magnets. Each period has two straight sections; a 6 meters long (LS) and another 1.2 meters long (SS). The considerable length of the long straight sections, 30% of the machine circumference, gives the machine great flexibility. Of the 24 LS one is used for injection and one for extraction; 9 of them are utilized for rf stations; 2 of them are committed for antiproton injection/extraction, 1 for reversed injection into the Main Ring and a total of 6

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are presently utilized for correction elements.

The nominal operating point is for betatron frequencies of  $\nu_H=6.7$  horizontal and  $\nu_V=6.8$  (at injection 6.9) vertical. Transition energy occurs at  $\gamma=5.446$ . The  $\beta$ -functions vary between 6.1m and 33.7m (at SS) horizontal and between 20.0m (at LS) to 5.3m in the vertical plane.

The rf system consists of 18 cavities, each one with two accelerating gaps. The harmonic number is 84 resulting in frequencies which change from 30.3 MHz at injection to 52.8 MHz at extraction. The maximum energy gain per turn is a function of frequency and varies between 300 keV at the low end to 750 keV at the high end. The total bucket area is of the order of 2 eV/sec for  $\Delta p/p$  of  $\sim 1.1 \times 10^{-3}$ . Present modifications<sup>5</sup> to the power amplifiers are expected to better handle the ferrite tuners losses and raise the available bucket area.

The originally designed apertures of  $90\pi \times 10^{-6}$ m horizontal and  $40\pi \times 10^{-6}$ m vertical have not yet been achieved. Understanding the Booster aperture is the subject of present interest.<sup>6</sup> Hardware modifications are underway to improve the vertical aperture. The quoted numbers for the present Booster apertures are  $25\pi \times 10^{-6}$ m horizontal and  $16\pi \times 10^{-6}$ m vertical.

Since March 1978 the Booster has operated with  $H^-$  multiturn charge exchange injection.<sup>7</sup> A linac provides an  $H^-$  beam pulse with 200 MeV emittances of  $8\pi \times 10^{-6}$ m both vertical and horizontal, up to 43 mA and 60 $\mu$ s long. This injection method allows injecting a maximum of protons far larger than the maximum accelerated so far of  $3.02 \times 10^{12}$  per booster cycle. Figure 1 shows the present Booster transmission for  $H^-$  operation vs. the injected beam intensity. For comparison, the best recorded transmission with single turn  $H^+$  injection is also shown (the number of protons in this figure is expressed per 13 Booster cycles as normally operated for injection into the Main Ring).

The incoherent space charge tune shift limit has been studied as a guide to what maximum intensity could be obtained. This limit depends strongly on the assumptions about available aperture, beam blow up and the details of the charge distribution. Figure 2 shows the result of two calculations for a uniform charge distribution, and  $\Delta v = 0.38$ , calculated using the incoherent space charge tune shift formula,<sup>8</sup> and plotted versus time into the Booster cycle. The lower curve is for no beam dilution with emittances at 200 MeV of  $8\pi \times 10^{-6}$ m. The upper curve assumes beam dilution as to always fill the available aperture of  $25\pi$  by  $16\pi$ . The decrease of the maximum number of protons in the early part of the cycle is due to the increasing charge density because of rf bunching. This effect predominates until  $\sim 3$ ms, where the kinematical effects start to dominate. The charge injected and accelerated to 8 GeV for the Booster intensity record are also shown. The largest fraction of the loss of intensity during operation takes place in a time period of 2 to 3 ms more or less as it would be predicted from Figure 2. (The minimum of the RF bucket area also occurs at the same time). From measurements of beam sizes at extraction there is evidence for intensity dependent beam blow up, but not as large as to fill the available aperture. As expected, Figure 2 is optimistic and the curves for real charge distributions should be depressed by a factor of approximately 2. We conclude that the present record of  $3.02 \times 10^{12}$  p's/booster cycle could probably be improved to maybe  $5 \times 10^{12}$  p's/booster cycle if beam blow up is tolerated, some

gains in aperture and longitudinal bucket area are realized, and no limits other than space charge tune shift exist. The present H<sup>-</sup> multi-turn charge exchange injection system is capable of delivering to the Booster up to  $1.6 \times 10^{13}$  protons in 22 injected turns.

The initial complement of correction elements consisted of a package containing skew-quadrupole, quadrupole, vertical and horizontal dipole elements each operated from individual dc supplies, at each LS and SS. These elements obtain appropriate injection apertures and tunes. Initial operation of the Booster resulted in intensities near  $1 \times 10^{11}$  per cycle. The elements which contributed most importantly to the increased intensity to the present record include injection improvements, aperture improvements, increases in rf power and control of instabilities.

An important low intensity instability is the head-tail effect which occurs in the Booster<sup>9</sup> at intensities above  $1.5 \times 10^{11}$ . Chromaticity control through use of sextupoles effected a cure over a large range of intensities. One circuit of sextupoles in three symmetric long straight sections and a circuit of 24 sextupoles in the short straight sections are now operated from programmed supplies to provide flexibility in operation. Note however that compensation of the width of some resonance lines in the working area is available but has not been fully implemented.<sup>10</sup> Programmed control has been added to the quadrupole correction elements in circuits for short and long straight sections. Further control of transverse instabilities has been provided through active, bunch-by-bunch dampers for vertical and horizontal control.<sup>11</sup> Coupled bunch longitudinal instabilities have been controlled through "harmonic damping". One rf station is operated one harmonic number lower than the beam and another station is operated one harmonic number above the beam during the last 5 ms of the Booster cycle. This provides a bunch to bunch modulation on the rf voltage with harmonic number 1 and no phase error, thereby decoupling the bunches.<sup>12</sup>

Current operation for injection in the main synchrotron requires intensities from  $1.5-2.2 \times 10^{12}$  protons per cycle. Since the installation on the negative ion injection system, three periods of operation have been devoted to high intensity Booster operation. Intensities greater than  $2.5 \times 10^{12}$  p per cycle have been achieved in all cases with a record intensity of  $3.02 \times 10^{12}$  achieved in September 1978.

#### BOOSTER AS A KAON FACTORY

The most relevant parameter to evaluate the Fermilab Booster is the flux of kaons obtainable. To this effect on Table I we have scaled the conclusions of reference 2 to the present Booster performance and to the future maximum intensity and energy. For comparison the fluxes for a kaon factory such as the ring cyclotron proposal are included.<sup>13</sup>

TABLE I. Yield of 2 GeV/c  $K^+$  and  $K^-$  for the Fermilab Booster

	Energy (GeV)	p/pulse ( $10^{12}$ )	p/sec ( $10^{13}$ )	I ( $\mu$ A)	$K^+$ /sec* ( $10^8$ )	$K^-$ /sec* ( $10^8$ )
Present	8.0	3.0	4.5	7.2	7.2	1.7
Future	10.0	5.0	7.5	12.0	16.0	3.7
Ref. 13	8.5	-	-	100.0	110.0	26.0

(\*) Acceptance: cone  $\theta_0 = 3.5^\circ$ , momentum =  $2 \times 10^{-2}$  GeV/c. All protons interact

For single turn extraction onto the production target the duty factor is  $2.4 \times 10^{-5}$ . This is unreasonably low and would render the kaons useless for conventional nuclear or particle physics experiments. Two schemes could be utilized to improve the duty factor: slow extraction from the Booster and the utilization of a "stretcher" ring.

Slow resonant extraction from the Booster could be implemented over a momentum range where the Kaon production cross section does not vary significantly. As deceleration can take place in the Booster<sup>14</sup> extraction could be extended to the downward part of the guiding field ramp. The significant requirement is that the proton targeting transport line would need to follow the momentum excursion of the proton beam. This may be possible if targeting could be performed close to the Booster ring. As an example from the production curves of reference 2 we select 7 GeV as the minimum momentum. Extraction could then take place between 19.2 ms and 47.5 ms into the Booster cycle, for a resulting duty factor of 42%. However, resonant extraction may be an unpleasant complication.

The use of "stretcher" rings (SR) to provide suitable duty factors has been previously discussed.<sup>15</sup> A SR for the Fermilab Booster does not exist but it could provide more flexibility to a kaon factory than the resonant extraction discussed above.<sup>16</sup> A suitable DC ring of small aperture could be constructed, variable transition energy could provide a variable debunching time. Complete debunching within a few hundred microseconds could provide a spill with no time structure, by using a transition energy below that of the proton beam. By raising the transition energy, the Booster bunch structure could be preserved for experiments than require accurate time measurements. Such an SR could utilize the same single turn extraction area and part of the transport line now under construction for reversed injection into the Main Ring. A ring of the Booster circumference but with a race track design to allow for a long straight section to locate an intricate resonant extraction, could be placed near to the Stochastic Cooling Ring under design.<sup>1</sup> This location provides enough ground space for a targeting system, particle separation and an experimental hall. The use of the Stochastic Cooling Ring as a SR would be less desirable due to the large aperture required for its application.

FINAL REMARKS

The Booster accelerator at Fermilab with improvements in average power capability of its rf and pulsed-magnet systems can provide intensities greater than  $4.5 \times 10^{13}$  protons per second at 10 GeV. Although such intensities are a factor of fourteen below the kaon factory designs being considered, they can still provide interesting fluxes of kaons at a modest investment. No plan exists at Fermilab for implementing such a facility although a site location could certainly be found. Operation would be compatibly interspersed with 400 or 1000 GeV fixed-target operation at Fermilab but incompatible with pp collider operation.

FOOTNOTES AND REFERENCES

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#### FIGURES

Figure 1. Fermilab Booster transmission versus injected number of protons per Main Ring cycle (13 Booster cycles), from reference 7.

Figure 2. Number of protons versus time in the Booster cycle resulting in a tune shift of  $\Delta\nu = 0.38$ , assuming a uniform charge distribution. The lower curve assumes no dilution. The upper curve assumes beam blow-up to always fill the presently available aperture.

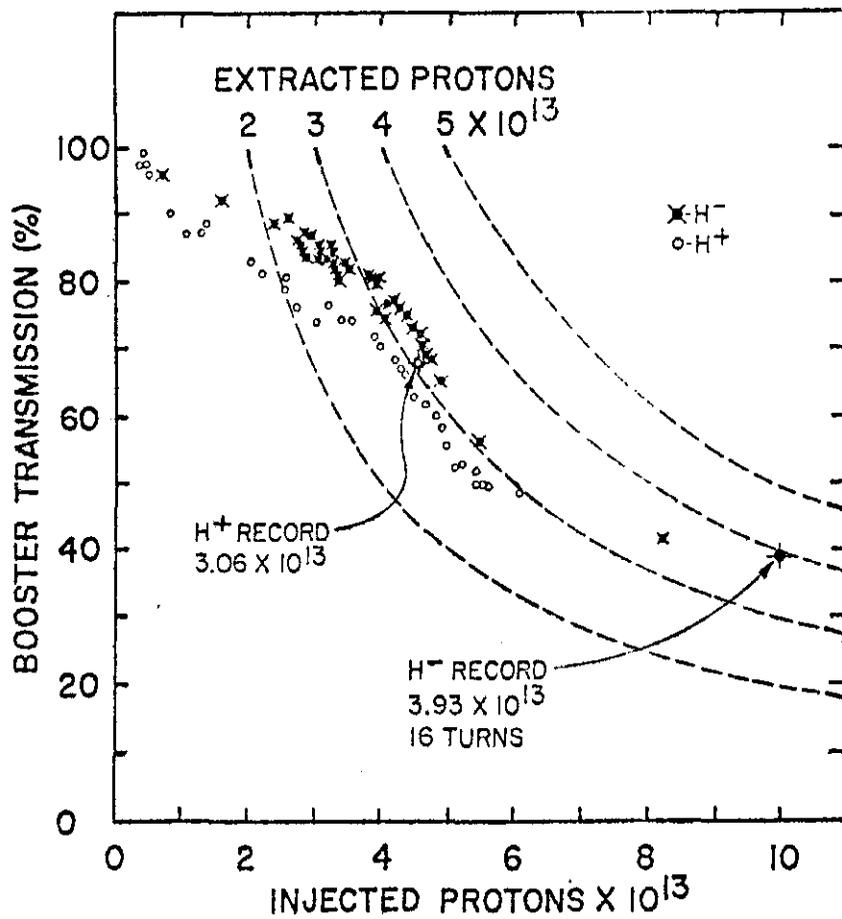


Figure 1

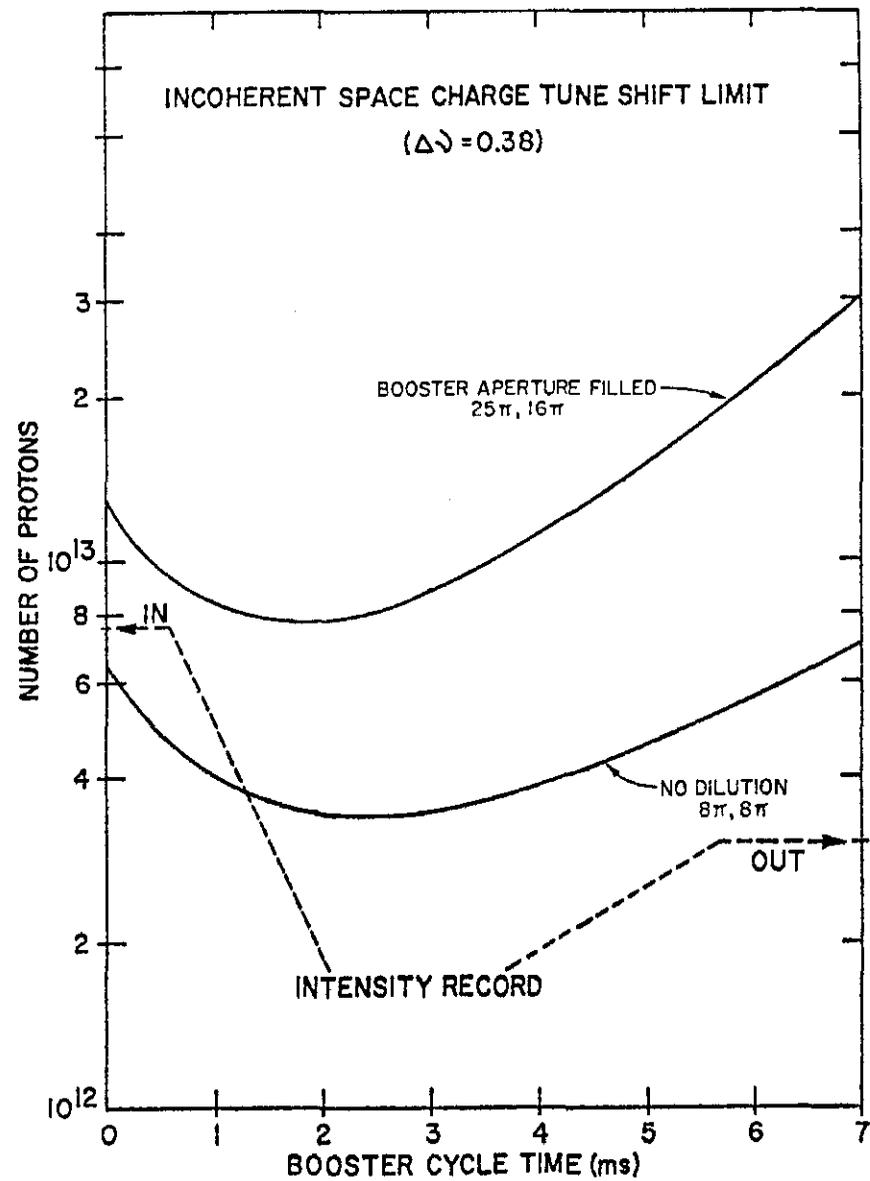


Figure 2