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# COST OPTIMIZATION OF THE AHF BOOSTER ENERGY

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## ABSTRACT

The effect of booster energy on the cost of the AHF has been investigated. Increasing its energy raises the cost of the booster but lowers that of the main ring, creating a minimum in total cost. It is shown that this minimum occurs where the apertures of the booster and the main ring magnets are simultaneously matched to the beam emittance. For high intensity (~100 μA) boosters, such as LAMPF II, the minimum is quite pronounced. For lower intensity (~25 μA) boosters, (such as the AHF) it is shallower and other considerations may outweigh those of cost in choosing the energy.

## INTRODUCTION

In studying the effect of the Booster energy on the overall cost of the TRIUMF KAON Factory it was found[1,2] that a minimum occurred near 3 GeV, where the rising cost of the Booster was just offset by the falling cost of the Driver. A similar situation is to be expected for the Los Alamos AHF, although at a slightly higher energy because of the higher injection and final energies. For TRIUMF the minimum appeared in the costs of the magnet, rf and other systems separately, but was most marked for the magnets. It was associated with the apertures of the Booster and the Driver magnets being simultaneously matched to the beam emittance. To see why this is so we note that the aperture is set by the larger of two emittances ($\varepsilon$) — that determined by the incoming or outgoing beam, and that required to limit the space charge tune shift $\Delta\nu$ at injection to say 0.2 to avoid low-order resonances:

$$\varepsilon_z^* = \frac{r_p}{\pi} \frac{F\,G\,H}{B_f \Delta\nu_z} \frac{N}{\beta\gamma^2} \quad . \tag{1}$$

Here $\varepsilon^* = \varepsilon\beta\gamma$ denotes the normalized emittance, $\beta$ and $\gamma$ the dimensionless speed and energy, N the number of protons per pulse, $r_p = e^2/4\pi\varepsilon_0 m_p c^2 = 1.5347 \times 10^{-18}$ m the classical radius of the proton, $B_f$ the bunching factor, and F, G and H factors describing the effects of image forces, the transverse density distribution and the aspect ratio of the beam respectively. Insofar as the linear particle density dN/ds and other parameters are constant from ring to ring we may write

$$\varepsilon_z^* = \text{constant} \times \frac{C}{\beta\gamma^2} \tag{2}$$

where C denotes the circumference. Since the largest tune shift occurs at injection Eq. 2 implies that, for the same emittance requirement in each ring, their circumferences should increase in proportion to the value of $\beta\gamma^2$ at injection. Since the circumference is set essentially by the maximum momentum we have a relation between the initial and final energies for each ring, from which the optimum Booster energy may be determined. To be more specific, and using subscripts I, B and D to denote the injector, booster and driver respectively, we may write

$$\varepsilon_B^* \approx \text{constant} \times \frac{C_B}{(\beta\gamma^2)_I} \propto (\beta\gamma)_B \qquad (3)$$

$$\varepsilon_D^* \approx \text{constant} \times \frac{C_D}{(\beta\gamma^2)_B} \propto \frac{1}{(\beta\gamma^2)_B} \qquad (4)$$

where the injector and driver energies are considered fixed. Figure 1 shows how $\varepsilon_B^*$ rises with booster energy as the circumference and number of particles injected increases. On the other hand the emittance needed in the driver falls as the space charge becomes less effective at higher injection energies. The minimum beam emittance, magnet aperture and cost for both rings occur where the two curves cross.

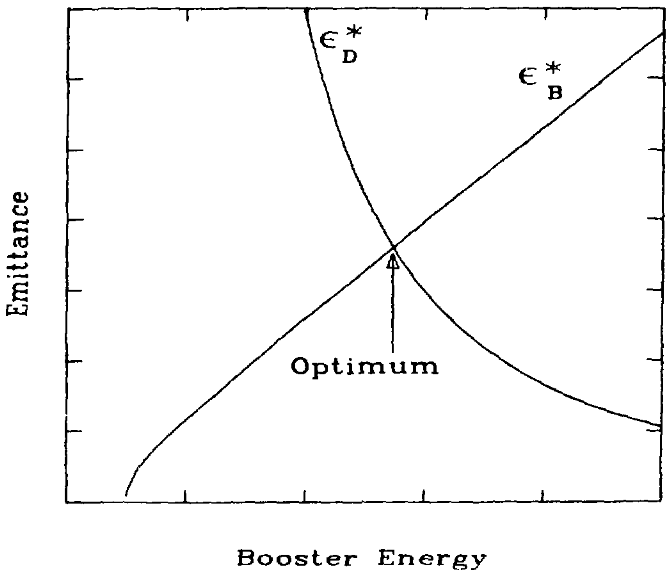


Fig. 1. Normalized emittances $\varepsilon_B^*$ and $\varepsilon_D^*$ plotted against booster energy $\gamma_B$.

Below the optimum energy the magnet apertures of both rings will be determined by the driver emittance $\varepsilon_D^*$; the apertures will be roughly proportional to the betatron amplitude $A=\sqrt{\varepsilon\beta_z}$ so that

$$A_B^2 \propto \frac{1}{(\beta\gamma^2)_B} \qquad A_D^2 \propto \frac{1}{(\beta^2\gamma^3)_B} \quad . \qquad (5)$$

Above the optimum the apertures of both rings are determined by the booster emittance $\varepsilon_B^*$ and so

$$A_B^2 \propto (\beta\gamma)_B \qquad A_D = \text{constant} \ . \qquad (6)$$

Thus increasing the booster energy above the optimum produces no further reduction in driver magnet aperture; it has to be maintained constant to contain the larger emittance required for the extra particles in the booster. $A_B$ and $A_D$ are plotted against $\gamma_B$ in Fig. 2.

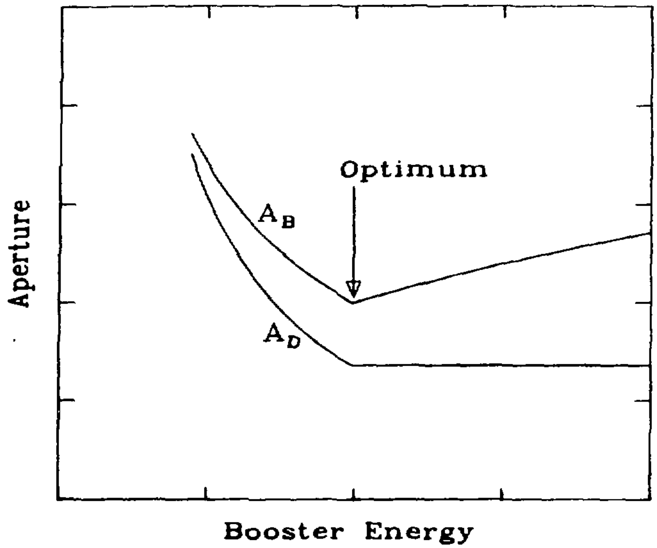


Fig. 2. Magnet apertures plotted against booster energy.

To determine the optimum energy of the booster Eqs. 3 and 4 tell us that

$$(\beta^2\gamma^3)_B \approx (\beta\gamma^2)_I \; (\beta\gamma)_D \; . \qquad (7)$$

In deriving this, gross assumptions have been made about the equality of various parameters in the booster and driver rings. In practice these approximations seem to balance out; thus the larger bunching factor $B_f$ in the booster is compensated by the lower average magnetic field achievable in a faster-cycling machine.

For TRIUMF the injection energy is 440 MeV and the Driver energy 30 GeV, indicating an optimum Booster energy of 2.2 GeV. For the AHF, with an injection energy of 1.6 GeV and final energy of 60 GeV, Eq. 7 suggests a booster energy of 6.2 GeV.

## COST VARIATION

To obtain more detailed information about how the costs vary with AHF booster energy the same code was used as for the TRIUMF KAON Factory[1]. Cost figures are based on the detailed estimates for the TRIUMF proposal together with appropriate scaling laws. For the present purpose the costs have been converted to US dollars ($1.00 CDN = $0.78 US). The figures include material and installation costs but not Engineering, Design and Inspection or Project Management/ Construction Management. Table I shows that there is reasonable agreement between the costs predicted by the code for the LAMPF II booster and main ring and those listed in the 1986 LAMPF II Proposal.

TABLE I Comparison of Cost Estimates (K$) for LAMPF II

| | Booster (6 GeV × 144 μA) | Main Ring (45 GeV × 32μA) |
|---|---|---|
| LAMPF II Proposal (1986) | 42,400 | 77,820 |
| TRIUMF Computer Code | 38,310 | 83,120 |

For the present AHF Proposal the cost estimates for different booster energies are displayed in Fig. 3. Costs for the booster, collector and main ring are displayed; the total does not include the

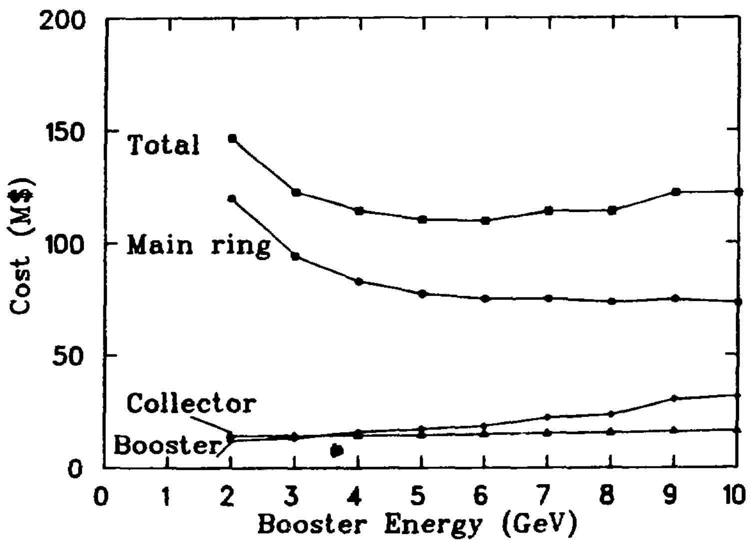


Fig. 3. Cost variation of AHF rings with Booster energy.

cost of the 1.6 GeV injection linac. The main ring magnet cycle is assumed to have no flat top or flat bottom. The collector is assumed to be located in the main tunnel. The irregularity in the points is associated with the discrete choices of booster circumference available for a given booster energy. The code selects the booster circumference giving the minimum cost.

The total cost shows a minimum at 5–6 GeV as suggested by Eq. 7. The minimum is, however, not very pronounced, compared to that observed for say the TRIUMF KAON Factory.[1,2] Dropping the booster energy from 10 GeV to 6 GeV lowers the cost by only $13M. Indeed when it is noted that the 9 or 10 GeV boosters are one half the circumference of the main ring, allowing a half-sized collector to be used located in the booster tunnel, it appears that in this case there is little cost advantage to reducing the booster energy below 9 GeV. The major parameters for the 6 GeV and 10 GeV boosters are listed in Table II.

Table II Design parameters for AHF boosters

| Booster Energy | 6 GeV | 10 GeV |
|---|---|---|
| Beam Current | 25 μA | 25 μA |
| Rep Rate | 48 Hz | 24 Hz |
| Charge per pulse | 0.5 μC | 1 μC |
| Circumference $C_B$ | 317.5 m | 635 m |
| $C_D/C_B$ | 4 | 2 |
| Harmonic number | 98 | 49 |

The shallowness of the minimum stems from the relatively low cost of the booster and therefore its small rate of rise with energy — direct consequences of the relatively low current being accelerated (25 μA).

As a comparison we present the corresponding cost variation data for the LAMPF II proposal where the booster current was to be 144 μA at an injection energy of 0.8 GeV, and the main-ring current was to be 32 μA (Fig. 4). As expected the booster cost is higher and the

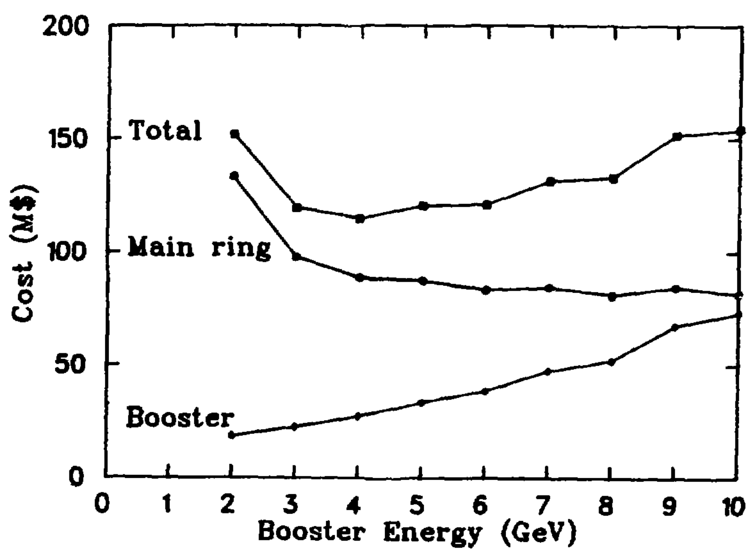


Fig. 4. Cost variation of LAMPF II rings with Booster energy.

minimum in total cost much more pronounced. The cost minimum occurs at about 4 GeV booster energy. The cost advantage of a 4 GeV booster over a 10 GeV one is $37M, while the cost advantage of the chosen 6 GeV booster is $33M.

## REFERENCES

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[3]"The Physics and a Plan For a 45 GeV Facility that Extends the High-Intensity Capability in Nuclear and Particle Physics." Los Alamos Report LA-10720-MS. (1986).