national accelerator laboratory

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SINGLE-PASS COLLIDING BEAMS FOR NAL

Lee C. Teng

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It was pointed out by Sam Ting of MIT that because of the rather large pp total cross-section (∿40 mb) for such an experiment single-pass colliding beams are adequate. To produce this at NAL the simplest way is to collide an extracted beam from the main ring, say, at 400 GeV with an extracted beam from the booster, say, at 10 GeV. This will give a center-of-mass energy of $s \sim 16000 \left(\frac{\text{GeV}}{c}\right)^2$. For collision of the 84 rf beam bunches from the booster containing say, 10^{12} protons with 84 bunches from the main ring (The remaining bunches in the main ring can be used for regular experiments.) also containing 10^{12} protons we get an event rate at 40 mb of

$$\frac{10^{12} \times 10^{12}}{84 \times 0.01 \text{ cm}^2} \times \left(40 \times 10^{-27} \text{cm}^2\right) = 4.8 \times 10^{-2} \text{ per pulse}$$

or ∿700 per 24-hour day, where we have assumed that the cross-sectional area of the beams is focused down to 1 mm^2 and the accelerator rep-rate is 1 pulse per 6 sec. The interaction region has a length equal to the beam-bunch length which is ∿2 ft. We shall examine various aspects of this arrangement more in detail.

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A. <u>Overall Geometry</u>

The best geometry is to extract the 400-GeV beam in the main ring from long straight-section F and the 10-GeV beam in the booster from long straight-section 23. The 10-GeV beam is then bent ∿90° by an achromatic and isochronous

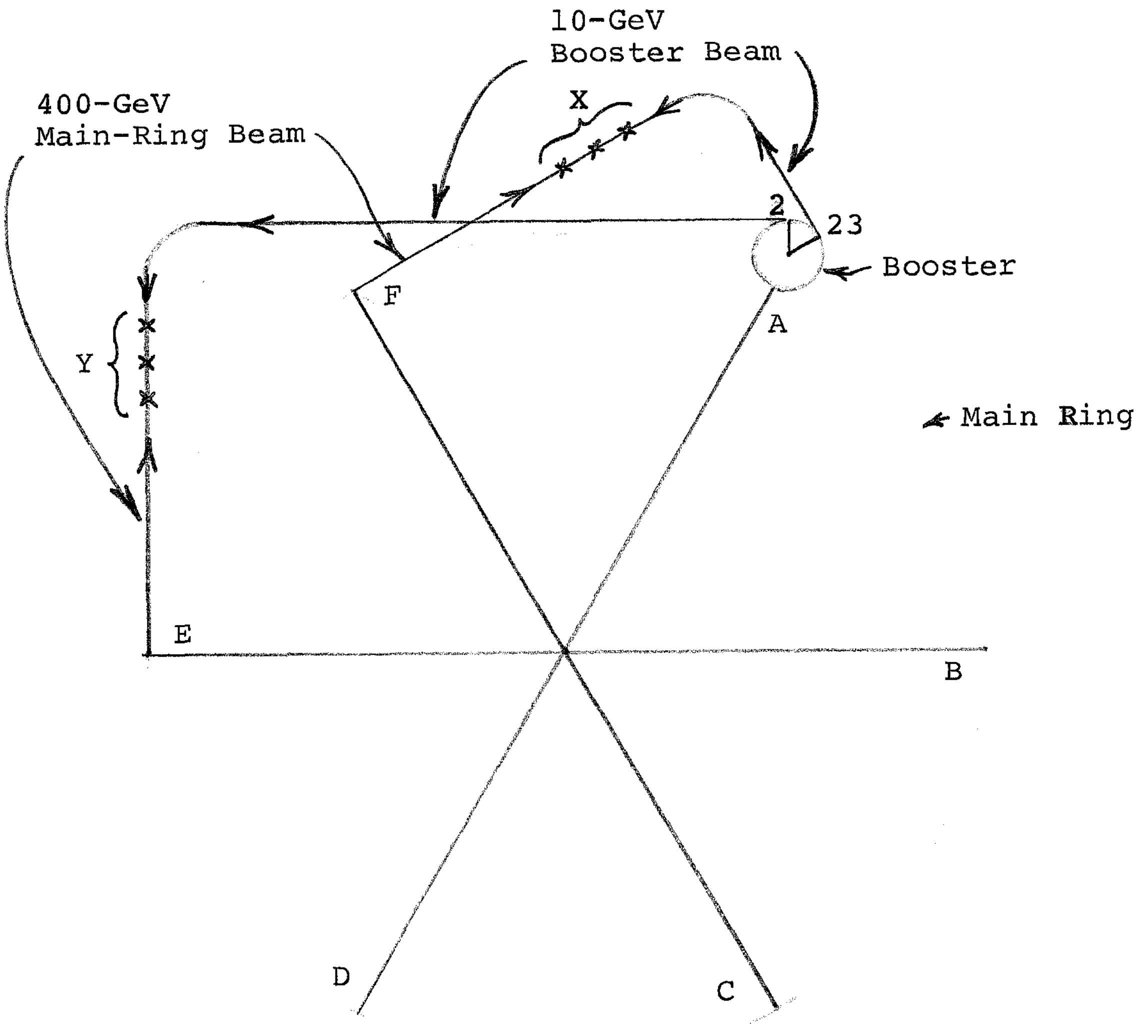

Figure 1

bend to collide with the 400-GeV beam at intersection points X as shown in Figure 1. The total beam and tunnel length is roughly 1500 m. The trouble with this geometry is that both the long-straight F in the main ring and the long-straight 23 in the booster are occupied by rf cavities. Unless one is willing to move these cavities one is forced to the following next-best geometry.

The 400-GeV beam is extracted from long-straight E of the main ring and goes straight without bending. The 10-GeV beam is extracted from long-straight 3 of the booster, goes straight for ∿1500 m, then turns ∿90° in an achromatic and isochronous bend to collide with the 400-GeV beam at intersection points Y. The total beam and tunnel length is roughly 2500 m. Compared to the best geometry this adds ∿1000 m of tunnel and beam. The additional ∿1000 m of straight 10-GeV beam costs very little; the main additional cost comes from the ∿1000 m of tunnel.

B. <u>Transverse Focusing</u>

The measured emittances are

	Booster (8 GeV)	Main Ring (300 GeV)
Half width x	5 mm	1.5 mm
β	33 m	96 m
emittance $\varepsilon = \pi\frac{x^2}{\beta}$	0.76π mm-mrad	0.023π mm-mrad.

So conservatively we shall take the emittances of the 10-GeV booster beam (ε_{10}) and the 400-GeV main-ring beam (ε_{400}) as

$$\varepsilon_{10} = \pi \text{ mm-mrad}, \qquad \varepsilon_{400} = 0.025\pi \text{ mm-mrad.}$$

At the collision point to get a half width of $x^{min} = 0.5$ mm we need minimum β-values for the 10-GeV and the 400-GeV beams respectively

$$\beta_{10}^{min} = 0.25 \text{ m} \qquad \beta_{400}^{min} = 10 \text{ m.}$$

Since the beam-bunch length is ∿2 ft = 0.6 m long, at either end of the interaction region, the β-values and the beam half widths are

	10-GeV beam	400-GeV beam
$\beta^{end} = \beta^{min} + \dfrac{(0.3\text{ m})^2}{\beta^{min}}$	0.61 m	10.01 m
$x^{end} = x^{min}\sqrt{\dfrac{\beta^{end}}{\beta^{min}}}$	0.78 mm	0.50 mm.

Although the 10-GeV beam is 1.56 mm wide at the ends of the bunch instead of the desired 1 mm, the larger width is still tolerable.

It is possible to design a linear periodic lattice to produce these β^{min} - values at periodic intervals to provide several interaction points for several simultaneous experiments. The lattice spacings clearly must be simply related to the beam bunch spacing $\ell = \frac{2\pi R}{h} = \frac{2\pi \times 1000}{1113}$ m = 5.645 m. The simplest lattice conceptually is a superposition of the two lattices shown in Figure 2. The strength of the focusing

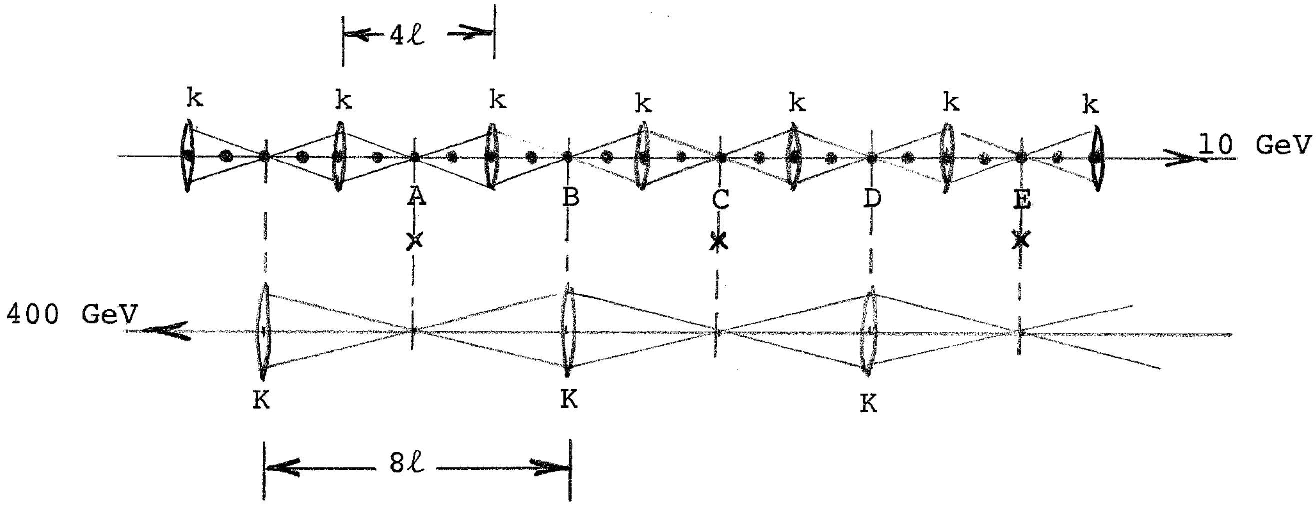

Figure 2

thin lenses in the upper lattice is so adjusted that $k \sim \frac{1}{\ell}$ at 10 GeV. A matched 10-GeV beam will form foci (very small waists or β^{min}) at midway points A, B, C, etc., in between the lenses. The lower lattice is so adjusted that $K \sim \frac{1}{2\ell}$ at 400 GeV. A matched 400-GeV beam will form small waists at A, C, etc., to produce colliding beams there. With both K and k at 10 GeV then $K/k \sim \frac{p_{400}}{p_{10}} \times \frac{1}{2} \cong 18$. When superimposed the k-lenses being so much weaker than the K-lenses, will not significantly modify the 400-GeV beam; whereas the K-lenses being placed at the foci of the 10-GeV beam, also will not significantly affect the 10-GeV beam. More exact calculation using thin-lens formulas give for ℓ = 5.645 m, β_{10}^{min} = 0.25 m, β_{400}^{min} = 10 m the lens strengths at 10 GeV.

$$k = 0.18288 \text{ m}^{-1} \qquad K = 2.6100 \text{ m}^{-1}.$$

Because β_{400}^{min} is not extremely small K is less than ~18 k indicated earlier. Nevertheless, K is rather large. We can reduce K by doubling the separation between the K-lenses to form a lattice shown in Figure 3. One then expects K to

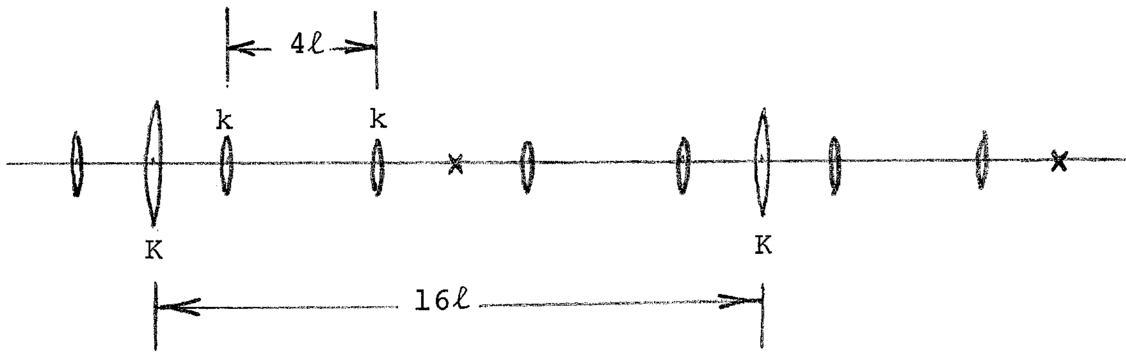

Figure 3

reduce roughly to half. The thin-lens calculation gives for the same values of ℓ, β_{10}^{min}, and β_{400}^{min} at 10 GeV.

$$k = 0.17722 \text{ m}^{-1} \qquad K = 1.3182 \text{ m}^{-1}.$$

Even this value of K is rather large especially since in order that these lens be focusing in both planes and for proton going in either directions they must all be triplets.

The required lens apertures are given by the β-values at the lenses which are approximately

$$\beta \text{ (10 GeV at k)} \cong 510.2 \text{ m}$$

$$\beta \text{ (400 GeV at K)} \cong 178.8 \text{ m}.$$

The half-apertures for k- and K-lenses are, therefore,

$$x \text{ (10-GeV beam at k)} \cong 22.6 \text{ mm}$$

$$x \text{ (400-GeV beam K)} \cong 2.11 \text{ mm.}$$

We see that the required aperture of the K-lenses is very small which at least makes it easier to obtain the high strength needed. There may be other clever lattice arrangements requiring less quadrupole strength, but it is idle to pursue this further at this time.

With the lattice shown in Figure 3 the beam intersecting points are $16\ell = 90.32$ m apart and if one intersecting point is adjusted to have each of the 84 bunches in one beam colliding with one of the 84 bunches in the other beam, at the immediate neighboring intersecting points there will only be 84-32=52 bunch-bunch collisions. Therefore it is not profitable to have more than 3 beam-beam interaction points with luminosities in the ratio 52:84:52. Together with the matching sections at either end the total length of this intersecting transport section is perhaps ∿500 m long as shown in Figure 1. Cryo-pumping is required to get a vacuum better than 10^{-11} Torr to reduce the background to a tolerable level.

C. Longitudinal Matching

The first thing to check is that the debunching of the 10-GeV beam over the ∿1500 m transport is negligible. The momentum spread in the beam is at most $\frac{\Delta p}{p} \sim 2 \times 10^{-3}$ which corresponds to a velocity spread of $\frac{\Delta v}{v} = \frac{1}{\gamma^2} \frac{\Delta p}{p} \cong 1.5 \times 10^{-5}$. Over $\sim$1500 m linear transport each rf bunch will lengthen by $(1.5 \times 10^{-5}) \times (1500 \text{ m}) = 23$ mm which is indeed negligible compared to the bunch length of 2 ft = 610 mm. The $\sim$90° bend can easily be made to be isochronous and achromatic so that it will not add to the debunching.

The principal problem is the difference (although small) between the bunch frequencies at 10 GeV (f_{10} = 52.90935 MHz) and at 400 GeV (f_{400} = 53.10493 MHz). This frequency difference of $\frac{\Delta f}{f} \cong 3.69 \times 10^{-3}$ will cause the position of the collision point to move $\frac{1}{2}(3.69 \times 10^{-3}) \times 84 \times 5.645 \text{ m} = 0.87$ m between collisions of the 1st and the 84th bunches in the two trains of 84 beam bunches. This motion of the collision point by 0.87 m is larger than the bunch length of $\sim$0.6 m and, therefore, must be rectified. Several possibilities are present.

1. The simplest remedy involving no additional hardware is to accelerate the special booster pulse used for colliding beams on the 85th harmonic up to an energy for which the bunch frequency equals f_{400} = 53.10493 MHz. This corresponds to an energy of

$$\left[\frac{1}{\sqrt{1-\left(\beta_{400} \times \frac{84}{85}\right)^2}} - 1\right] \times 0.938 \text{ GeV} = 5.2 \text{ GeV}$$

where β_{400} is the $\frac{v}{c}$ of a 400 GeV proton. So instead of colliding beams of 400 GeV on 10 GeV we must have those of 400 GeV on 5.2 GeV. This is, of course, a serious drawback of this simple remedy.

2. We could debunch the 400-GeV beam in the main ring on the flat-top and rebunch it at a harmonic number of 3339 (= 3 x 1113) using an added fixed-frequency cavity. The special booster pulse used for colliding beam should be accelerated on the 253th harmonic $\left[= (3 \times 84) + 1\right]$ by a different rf system to the proper bunch frequency. This is effectively equivalent to accelerating the booster pulse on a harmonic number of $84\frac{1}{3}$ relative to the old harmonic number of 1113 for the main ring. The energy corresponding to the proper frequency is, thus

$$\left(\frac{1}{\sqrt{1 - \left[\beta_{400} \times \frac{3 \times 84}{(3 \times 84) + 1}\right]^2}} - 1 \right) \times 0.938 \text{ GeV} = 9.6 \text{ GeV.}$$

In this manner we regain the 400 GeV on 9.6 GeV colliding beams. The remainder of the 400-GeV beam in the main ring which is to be used for regular experiments is, of course, also bunched at the 3339th harmonic, but this should not affect its utility for experiments.

The most serious drawback of this scheme is the additional rf systems required for both the booster and the main ring.

They are likely to be rather costly. The most attractive scheme to correct for the frequency difference is, perhaps, the following one.

3. The booster pulse used for colliding beams is accelerated in the normal manner on the 84th harmonic. Near the top of acceleration when the guide field is sensibly flat-topped the regular rf is rapidly turned off and a new rf is rapidly turned on at a fixed frequency $f_{new} = \frac{1}{2}\left(f_{10} + f_{400}\right) = 53.00714$ MHz halfway between f_{400} and f_{10}. The beam bunches will then undergo coherent phase-oscillations about the π phase ($\phi_s = \pi$) points of the new rf. Half phase-oscillation later the bunches will be spaced at the frequency f_{400} and back at the proper energy of 10 GeV. This process is shown exaggerated in Figure 4.

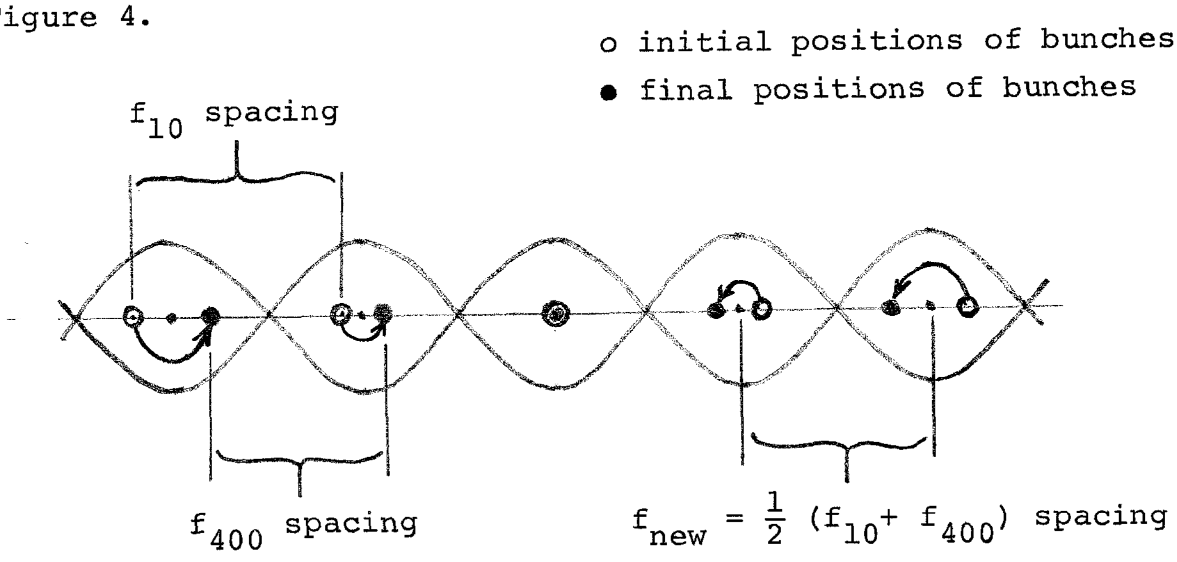

Figure 4

The crucial feature of this scheme is the phase jump required every revolution. At 10 GeV there are $84 \frac{f_{new}}{f_{10}} = 84.155$ rf oscillations per revolution period at the new frequency f_{new}. Therefore, $\frac{1}{2}$ (revolution period) after the time when f_{new} and f_{10} (if existent) are in phase the new rf should jump backward in phase by $0.155 \times 360° = 55.9°$ so that in another $\frac{1}{2}$ (revolution period) f_{new} and f_{10} are again in phase. The largest coherent phase oscillation is at the phase jump where the phase-amplitude is $\frac{55.9°}{2} = 27.9°$. This is a rather small oscillation and can be expected to be quite linear. For an rf voltage of, say, 300 kV/turn the small phase-oscillation period is ∿0.51 msec (∿320 turns). During the $\frac{1}{2}$ phase-oscillation of 0.25 msec over the top of the sinusoidal guide field the maximum field variation is $\frac{\Delta B}{B} = 3.38 \times 10^{-5}$ which is so small that the guide field can indeed be considered flat-topped during this frequency matching operation.

The phase jump should be made as fast as possible; the few beam bunches passing the cavities while the phase is being shifted will not be synchronized, hence not effective in the colliding beams. This rapid phase-jump (in a few oscillations) requires low-Q cavities and makes the new rf system rather difficult.

It is easier to perform the bunch-frequency matching in the main ring. To do this, on the 400-GeV flat-top of the main ring the regular rf system is turned off. A new rf system at fixed frequency $f_{new} = \frac{1}{2} (f_{10} + f_{400})$ is turned on and off during every revolution to affect only a train of 84 beam bunches corresponding to one booster pulse. The phasing is such that in the middle of the bunch-train (say, the 42nd bunch) the beam bunch should pass through the cavities at the falling zero of the rf ($\phi_s = \pi$). The rf voltage should be $\gtrsim$ 1 MV/turn. At 400 GeV, 1 MV/turn gives a phase-oscillation period of 19.6 msec (~934 turns). The rf should be kept operating for $\frac{1}{2}$ phase-oscillation or ~9.8 msec. At the end of the $\frac{1}{2}$ phase-oscillation the bunch spacing frequency of the 84-bunch train is reduced from f_{400} to f_{10} to match that of the booster beam. This train of 84 beam bunches is then fast-extracted to collide with the 10-GeV booster beam bunches.

The turn-on and turn-off of the rf can extend over a significant fraction of a main-ring revolution period, (say, a few μsec) as long as the rf is full-on at the proper phase when the specific train of 84 beam bunches comes around. The part of the main-ring beam during the turn-on and the turn-off of the rf will be affected by the rf, but this does not harm the usefullness of these parts of the beam for regular experiments. Even for these relatively slow turn-on and turn-off the rf cavities must have a relatively low Q.

Or perhaps a travelling-wave cavity similar to that designed for the CERN SPS can be more appropriately applied.

In conclusion, such a simple-minded single-pass 400-GeV on 10-GeV colliding-beam facility for NAL does look feasible.