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"SEPARATED FUNCTION" STORAGE RINGS

(Combination of a Medium Current Accelerator-Storage Ring With a High Current Dc Storage Ring)

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ABSTRACT

The conceptual design of a medium current accelerator-storage ring combined with a high current dc storage ring is given. It provides for a direct accelerator with maximum radius within the FNAL boundary, with a peak proton beam energy for fixed target physics of $(0.54\ \hat{B})$ TeV ($\hat{B} \equiv$ maximum dipole field value in Tesla). This accelerator is combined with a dc storage ring incorporating two 1 km long straight sections for single or multiple beam-beam interaction regions, with a maximum c-of-m pp energy of $\sim (0.54\ \hat{B})$ TeV.

Introduction

It is anticipated, within the (foreseeable) future, that, in addition to a 0.5 to 1.0 TeV c-of-m energy pp storage ring, a multi TeV fixed (external) target proton accelerator will be constructed.[1] Since the cost of each of these facilities is such that construction of one may likely delay the other by one or two decades, it is relevant to explore combining the facilities into one. In the following a conceptual design is presented of such a facility.

General Considerations

Since the goal is to take advantage of one of the magnet rings of the storage ring facility as an accelerator for secondary beam production, its terminal energy capability should be high compared with the present FNAL maximum proton energy. This then requires a maximum radius of curvature ring

*POPAE fall study, 1974.

1. For example: L.M. Lederman, "The Next Step: Accelerators vs Storage Rings", Proc. IX Int. Conf. on H.E. Accel., Stanford, USA, May 1974.

system. Therefore the largest ring fitting on the FNAL site has been adopted here.* In order to maintain the highest accelerator proton energy, the desired 1 km long straight sections for p-p collisions are obtained by combining a basic 6-fold structure with insertion section lengths of ≃ 270 m each with 2 "inner" bypass segments. This is done by using higher field magnet segments "$\pi/6$" in length, joining at four of the six straight sections. Consequently, whereas the peak energy of the direct accelerator proton beam would be (0.54 $\hat{B}$) TeV ($\hat{B}$ in Tesla), the maximum single beam energy in the storage ring configuration would be ~ (0.28 $\hat{B}$) TeV. The general layout is illustrated in Fig. 1. Site constraints mandates an "inner" external beam switchyard, as shown. Since it makes use of a higher field "trunk" line the maximum external proton beam energy would be ~ (0.28 $\hat{B}$) TeV. Sequential site expansion and use of an "external" external beam switchyard (see dashed lines, Fig. 1) would permit an external beam proton energy of (0.54 $\hat{B}$) TeV. It is clear that a staged construction approach is available and in fact appropriate in the light of superconducting magnet developments (Nb_3Sn vs NbTi). For example: a) Construct "racetrack" configuration only (2/3 circ. $B = \hat{B}/2$; < 1/3 circ. $B = \hat{B}$**; two straight sections, 1 km each) for a 1 TeV-1 TeV p-p storage ring system only ($\hat{B} \simeq 3.5$ T), b) add "$2\pi/6$" segments to complete a (6-fold symmetry) ring without higher than average field sections plus an external beam switchyard system for use as a fixed external target facility of maximum proton energy of ~ (0.54 $\hat{B}$) TeV ($\hat{B} \simeq 6$ T ?). The interaction region long straight section arrangement is shown schematically in Fig. 2. Some operational options are indicated.

Here, no attempt will be made to detail the 6-fold symmetric maximum proton energy accelerator ring (designated as RI). The structure is quite analogous to the FNAL main ring structure and actually its asymmetric long straight section insertion scaled up to ~ 270 m insertion length is adequate for injection, ring to ring transfer, etc. Only the 2-fold symmetry "low field-high field" ring structure (designated here as rings RrI and RrII, where RrI makes use of 2/3 of the circumference of RI) will be further detailed here because of its unconventional design.

*The circumference adopted here is only a factor of (14.66/9.54) ≃ 1.5 larger than the preliminary racetrack configuration considered so far for the 1 TeV-1 TeV p-p system.[2]

**21% of the lattice dipoles, $B = \hat{B}$.

2. A.G. Ruggierro, FNAL Rep., TM-529, August 1974.

Beam injection in the location shown in Fig. 1 in both of the rings RrI and RrII, is possible allowing for a reversal of the direction of proton beam circulation in the main ring injector synchrotron. Although it also requires an additional Booster-Main Ring transfer channel (tunnel) and 8 GeV beam injection into a short main ring straight section, the required changes are thought to be straightforward.[3] The actual beam stacking in either ring can be done by means of the momentum stacking mode as is used for the ISR. Instead, a storage ring charging mode quite different from this will considered here. Rather than filling both rings at 400* GeV, accelerating each high current stack to high energy and then going into the beam-beam collision mode, here only one ring (RrI) will be cycled between injection energy and beam collision energy. At high energy this "medium" intensity beam from RrI (bunched with azimuthal "hole") will be transferred and momentum stacked in the second ring RrII ("dc"). After repeating this cycle nominally 50 times a current of approximately 20 A would be accumulated in this ring. Subsequently, and with reversal of beam direction in the injector synchrotron, a beam current of approximately 1 A would be stacked by three-turn horizontal transverse phase space stacking in RrI. After acceleration, p-p collisions would be achieved in the 1000 m long straight sections by colliding the 1 A (I_w) and 20 A (I_s) colliding beams.

In a first approximation the maximum achievable luminosity is linearly proportional with the magnitude of I_w. (Actually $\propto I_w I_s^{\frac{1}{2}}$.) Consequently a lower luminosity value results. Notwithstanding this, this mode of storage ring operation has certain features making it of interest for further study, i.e.:

a) The design luminosity will be limited by the maximum value of the beam-beam linear tune shift, here taken as $\Delta\nu = 0.005$. With this choice the "usable" beam lifetime is expected to be $\gtrsim$ 16 hours. Here a shorter beam lifetime for I_w is acceptable because of the very short recharge time for I_w

*Since it is assumed that because of the long cycling time of the "Doubler" synchrotron,[4] and consequent long charging time of the high current storage rings, it is unsuitable as an injector synchrotron, here, only the use of the 400 GeV main ring accelerator has been contemplated.

3. Private communication, L.C. Teng.
4. "The Energy Doubler Design Study", D. Edwards, ed., FN-263, FNAL Rep., 1974.

($\sim$ 1 min.). Consequently, since only the weak beam is at the beam-beam limit, the design luminosity would be higher (by using a larger design limit on $\Delta\nu_{b-b}$) than the direct proportionality with I_w indicates. The relative higher "background" in the beam crossing domain, associated with the shorter lifetime of I_w, would have to be countered with more frequent periodic beam clean-up by means of beam scrapers.

By adopting a design current value of 1 A for RrI (but not necessarily ruling out the possibility of higher beam currents) a number of accelerator-storage ring parameters are affected, making a more economical construction of Ring RI possible.

b) Vacuum requirements. It is possible that an increase in spacing of the vacuum pumps by a factor of 5 would be acceptable in most of the ring RrI circumference. This follows from the fact that the value of $(\eta I)_{cr}$ could be $\sim$ 5 rather than $\sim$ 30 in ring RrI (taking η, the net desorption coefficient $\sim$ 3 for a warm bore system). This means a significantly decreased cost for the vacuum system.

The background associated with beam growth due to multiple coulomb scattering with the (now higher pressure) rest gas will not be a problem since the mean square betatron amplitude growth, $\Delta \langle x^2 \rangle$, is proportional to n_g/p^2, where n_g is the rest gas density and p the particle momentum. Thus, the increased momentum will tend to cancel the increase in rest gas pressure.

c) Magnet aperture. Where the magnet aperture is not dictated by vacuum requirements, a smaller aperture is possible since it need accommodate only the betatron amplitude associated with 3-turn transverse stacking rather than the additional 1%-3% momentum bite associated with momentum stacking.

d) Relaxation of wall impedance requirements. The various transverse and longitudinal stability criteria are summarized in Ref. 5, where it is indicated that, for a given momentum spread (and tune spread), the limiting current $I \propto \sqrt{\sigma}$, where σ is the vacuum chamber material conductivity. A lower design value for the maximum beam current permits use of the more economical stainless steel vacuum chamber envelope.

e) By making use of the ring RrI as a low current booster ring, in order to fill ring RrII, no rebunching or acceleration of a high current stack is required.

The various features mentioned above are summarized in Table I.

TABLE I

"Separated Function" Storage Rings

	Ring I	Ring II
Beam Current	Medium, ~ 1 A	High, ~ 20 A
Magnet System	Cycling and dc	Dc only
Stacking	Transverse phase space stacking at 400 GeV (momentum stacking optional)	Momentum stacking a la ISR at collision energy only
Charging Time	~ 1 min.	~ 2 hr.
Lifetime	Modest lifetime acceptable	Long lifetime essential
Vacuum	Design value $(\eta I)_{cr} \simeq 5$	$(\eta I)_{cr} \simeq 30$
Acceleration	Medium current only	No acceleration, except for stack formation
Luminosity	Only weak beam at beam-beam limit. Because of fast recharge $\Delta\nu$ could possibly be higher	$\Delta\nu_{b-b} = 0.005$

Weak Beam-Strong Beam Luminosity

For storage rings with unequal colliding beam currents the equations detailing the optimization of the luminosity have to be rewritten in order to arrive at the relevant design parameters. With reference to previous work[5], but adding here weak beam, strong beam designations, the luminosity and limiting tune shifts are given by**:

$$L = \frac{c\, I_w I_s}{\sqrt{\pi}\, \sigma_w^* \alpha_o} \qquad (\Delta\nu_y)_w = \frac{\sqrt{2}\, I_s r_p \beta^*}{\sqrt{\pi}\, \gamma\, \sigma_s^* \alpha_o}$$

**The assumption is made that $\sigma_w^* = \sigma_s^*$, consequently that $(\varepsilon_{2,t})_w = (\varepsilon_{2,t})_s$. This is not necessarily the case. A more detailed design would take this into account.

5. E. Keil, Proc. IX Int. Conf. on H.E. Accel., Stanford, Ca., May 1974.

At the beam-beam limit, it follows then

$$L = \frac{c\ \gamma\ I_w (\Delta\hat{\nu}_y)_w}{\sqrt{2}\ r_p\ \beta^*} .$$

Taking the long range beam-beam interaction into account, an optimum value of β^* may be deduced, given by

$$\beta^* = \left(\frac{(\Delta\hat{\nu}_y)_w\ \varepsilon_{2,t}\ \ell}{8\ \pi\ I_s\ r_p}\right)^{\frac{1}{2}} .$$

Consequently; the maximum achievable luminosity is

$$L_{max} = \left(\frac{4}{3}\right)\ c\ \gamma\ I_w I_s^{\frac{1}{2}} \left(\frac{\pi\ (\Delta\hat{\nu}_y)_w}{\varepsilon_{2,t}\ \ell\ r_p}\right)^{\frac{1}{2}} .$$

To compare the present approach with the conventional mode of storage ring operation, one writes:

$$\frac{L_{max}(s\text{-}w)}{L_{max}} \propto \frac{I_w I_s^{\frac{1}{2}}}{I^{3/2}}\ \frac{(\Delta\nu)_w^{\frac{1}{2}}}{(\Delta\nu)^{\frac{1}{2}}} .$$

Taking the second part of the right hand side arbitrarily equal to ~ 2, then, with $(I_s/I) = 2$ and $(I_w/I) = 0.1$ it follows that $[L_{max}(s\text{-}w)/L_{max}] \cong 0.3$.

Main Parameters of the Accelerator-Storage Rings

Direct Accelerator

Final energy	$(0.54\ \hat{B})$ TeV ($\hat{B}$ in Tesla)
Circumference (RI)	14.659 km
Maximum dipole field (all cells)	$\hat{B}$ ($R_{av} = 2.33$ km)
Cycling time (for $\hat{B} \sim 4$T)	136 sec (rise time 40 sec)
Protons per pulse	$3.7\ 10^{14}$ ppp ($2.7\ 10^{12}$ p/sec)

Storage Rings

Final energy	1 TeV-1 TeV
Circumference	14.580 km
Maximum dipole field	1.86 T ($R_{av} = 2.33$ km) (79% of all cells
21% of all dipole cells	3.51 T ($r_{av} = 1.25$ km)
Protons/ring	RrI, $3\ 10^{14}$ p/r; RrII, $6\ 10^{15}$ p/r
Beam currents	RrI, 1 A ; RrII, 20 A

Basic mode for charging the storage rings is to single turn transverse inject in Ring RrI nominally 1.2 10^{14} ppp (~ 0.4 A), to accelerate this to the desired interaction region energy, and then to transfer into Ring RrII. This would be repeated nominally 70 times (~ 2.18 hrs.) until, by repetitive momentum stacking in RrII, 6.0 10^{15} protons (≃ 20 A) are accumulated. Subsequently, the field polarity and injection direction for RrI would be reversed, and by 3-turn transverse stacking nominally 1 A (design parameter) would be accumulated, to be followed again by acceleration to the desired p-p interaction energy. (The option to "momentum stack" in RrI for potential higher current remains open.)

Injector Synchrotron	Existing accelerator
Beam energy	400 GeV
Protons per pulse	5.3 10^{13} ppp (0.4 A)
Repetition rate	6 sec
Protons per bunch	4.76 10^{10} p/b
Transverse emittance	0.13 π 10^{-6} rad.m (H,V)
Longitudinal emittance	0.1 eV.sec/bunch
($\Delta p/p$)	± 0.84 10^{-4}
Bunching factor	10
Bunch train structure	Separation 5.65527 m 18.818 10^{-9} sec
h_o	1113
τ_{orb}	20.94 10^{-6} sec
ν_{rf}	53.105 MHz

Injector Synchrotron Ejection Options	
Charging mode for RrII via RrI	Fast single turn ejection Bunch train 1105 bunches 1 ejection kicker (τ_k ≃ 150 nsec) Approx. 70 cycles per RrII charge
Charging mode for RrI only	Fast one third turn ejection Bunch train 363 bunches 3 ejection kickers, delayed 48.8 μsec 6 cycles per RrI charge

Beam Transfer		[B]	[RI	RrI]	[RrII]
Circumference	(km)	6.283	14.659	14.580	14.580
h (harmonic number)		$h_o = 1113$	$h_1 = 2597$	$h_2 = 2583$	$h_2 = 2583$
Δh			$\Delta h=14$		
Δ path length	(m)		$\Delta s=79$		
τ_{orb}	(μsec)	20.94	48.87	48.61	48.61

(Note: $(C_{RI}/C_B) = 7/3$

Injection Into RrI, Mode For Charging RrII	1 turn transverse stacking
Charging time	3 booster (75%) charges = 12 sec
Cycling time	~ 100 sec
Protons per pulse	$1.2\ 10^{14}$ ppp (0.4 A)
Injected beam emittance, at 400 GeV	$0.13\ \pi \times 0.13\ \pi$ (μrad-m)^2
Number of buckets filled	2567*

Injection Into RrI, Mode For Beam Storage RrI	3 turn transverse stacking
Charging time	6 booster charges $\simeq$ 30 sec
Protons stacked	$3.1\ 10^{14}$ (1.0 A)
Beam stored at 1 TeV	50 MJ
Injected beam emittance, at 400 GeV†	$0.13\ \pi \times 0.78\ \pi$ (μrad-m)^2 (V-H)
(Number of buckets filled prior to debunching	2424)‡

*(Injection kicker** rise time ~ 300 nsec, also azimuthal "hole" required for high energy transfer RrI → RrII.)

**The use of a full aperture kicker is contemplated. As has been shown before[6] this does not rule out stacking in momentum space.

†Due to horizontal betatron stacking, $\epsilon_H > \epsilon_V$. This may also result from vertical beam shaving to increase the luminosity. Since in the storage ring the "working" line will be close to the coupling line proper corrections are required in order to avoid "diluting" the vertical phase space. That this is possible has been shown at the ISR.

‡The option is open to avoid cycling the high field segments of Ring RrI, by accelerating the beam in Ring RI and switching the beam into RrI at collision energy. The indicated number of filled buckets leaves an azimuthal "hole" of 6.7 μsec for the switching transients.

6. A. van Steenbergen, "Injection Criteria Storage Ring", FNAL Rep. FN-171, 1968.

Injection Into RrII, Mode For Beam Storage RrII

Injection	1 turn transverse, synchronous
Mode of Stacking	Momentum stacking
Number of RrI → RrII transfers	70
Charging time	2.18 hrs.
Protons stacked	$6\ 10^{15}$ (20 A)
Beam stored energy, at 1 TeV	960 MJ

p-p Collision Mode, Luminosity

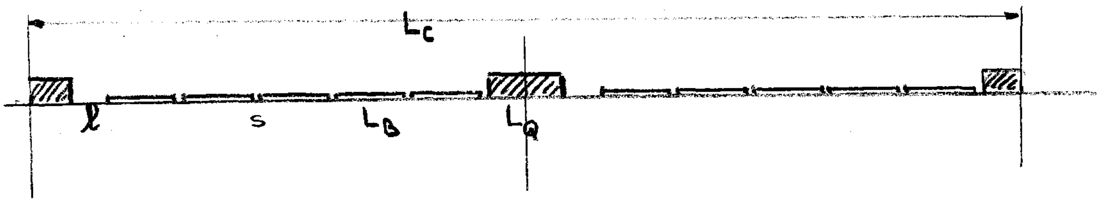
Total charging time	2.19 hrs.
Normalized emittances ($\varepsilon = \beta\gamma A$)	$55.5\ \pi\ \mu$rad.m (ε_V)
	$333\ \pi\ \mu$rad.m (ε_H)
Intersection parameters	$\beta_x^* = 20.0$ m
	$1.0 \le \beta_y^* \le 3.5$ m
	$\hat{y}_p = 0$ (vertical crossing)
Crossing angle, for L_{max}	$\alpha_{\frac{1}{2}} = 0.85$ mrad
Luminosity	$1.5\ 10^{33}$ cm^{-2} sec^{-1} at 1 TeV-1 TeV, unbunched

Storage Ring Structure , 2 fold symmetry

One superperiod (schematically shown next page) as follows:

1.5(CLS)32(NBL)3(CLS)8.5(NBH)(LIN)/(LIN)$^{-1}$8.5(NBH)3(CLS)32(NBL)1.5(CLS).

NBL or NBH



L_c = 69.80 m. L_B = 5.8 m. s = 0.4 m. L_Q = 3.4 m. ℓ = 1.5 m.

Low field cells (NBL), BL = 1.78 T.

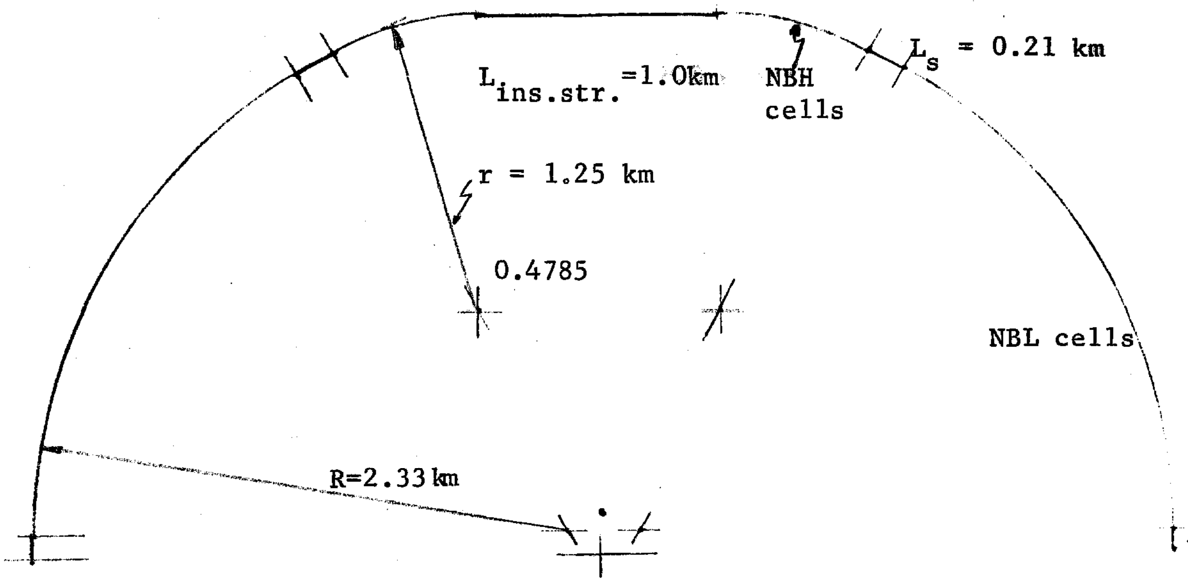
High field cells(NBH), BH = 3.34 T.

Quadrupole gradients, regular structure, GQF ≅ GQD ≅ 80.2 T/m.

$\hat{\beta}_x$ (regular structure) = $\hat{\beta}_y$ = 121 m.

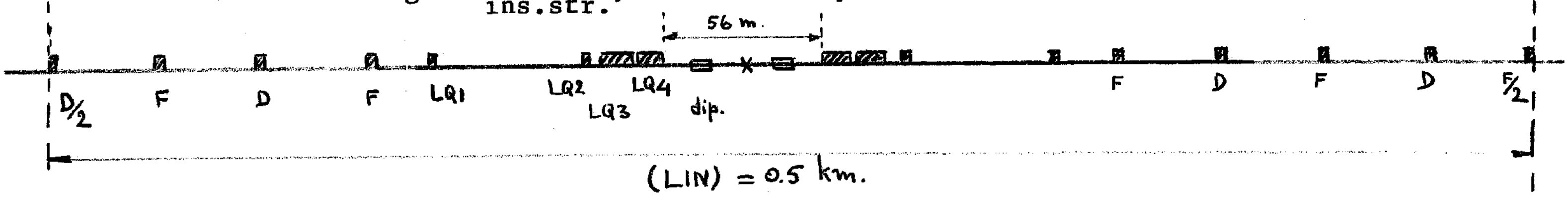
Maximum dispersion, X_p = 5.2 m.*

*See footnote, next page.



<u>Experimental Insertion</u> (First pass calculated example)*

One half length $L_{ins.str.}$, schematically as shown here.



Quadrupoles F, D. Regular structure quads.

LQ1	+	119.9 kg/m	3.3 m	Interspaces --	F-LQ1	19.0 m
LQ2	-	868.7 kg/m	3.3 m		LQ1-LQ2	51.3 m
LQ3	+	955.1 kg/m	6.7 m		LQ2-LQ3	8.2 m
LQ4	-	782.1 kg/m	6.7 m		LQ3-LQ4	1.3 m
Dipole		($\Delta\theta_{\frac{1}{2}}$ = 5 mrad)			LQ4-*	28 m

Crossing angle $\alpha_{\frac{1}{2}} = 0.85$ mrad.

$\beta_x^* = 20$ m. $1.0 \leq \beta_y^* \leq 3.5$ m. $\hat{\beta}_y = 790$ m for $\beta_y^* = 1.0$ m.

$\hat{\beta}_y = 211$ m for $\beta_y^* = 3.5$ m.

*There has been no attempt in this first pass example to match the dispersion function of the experimental insertion to that of the regular structure. As a result the X_p values fluctuate to a peak value of 5.2 m. The effect is mainly due to the interface between the experimental insertion and the regular structure and not to the transition between high and low field regular lattice cells, as was ascertained from additional "synch" runs.

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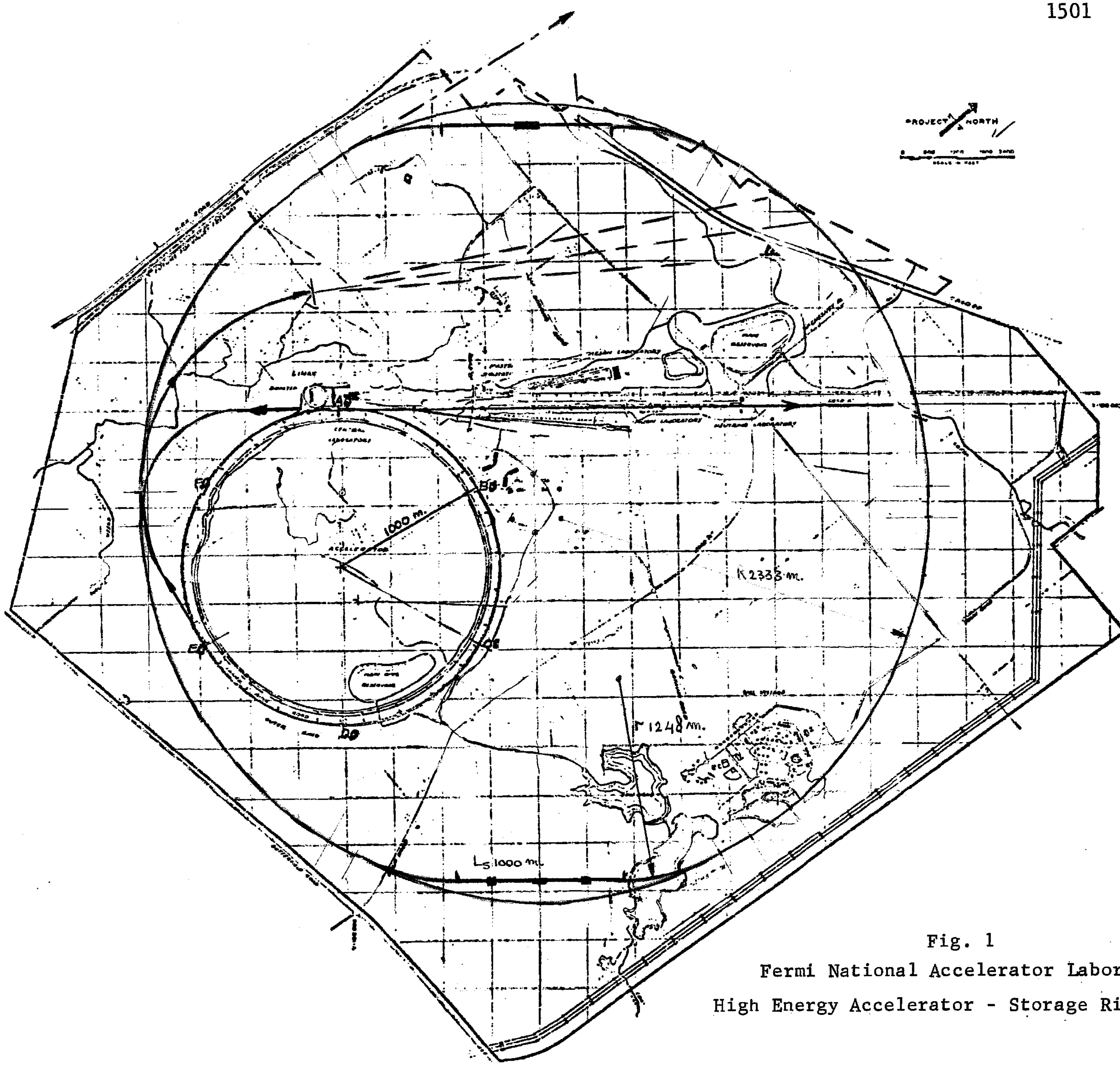
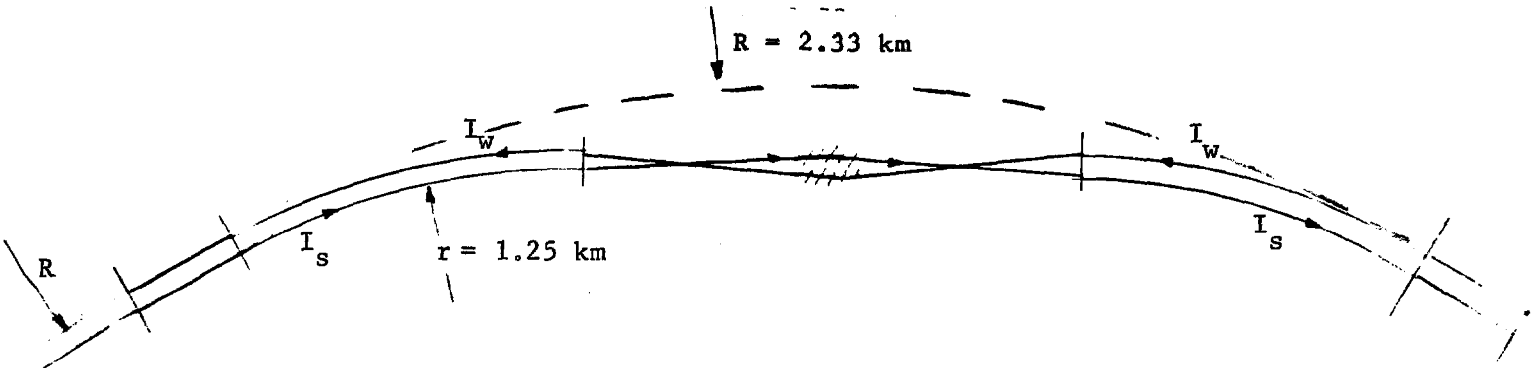


Fig. 1
Fermi National Accelerator Laboratory
High Energy Accelerator - Storage Ring Complex



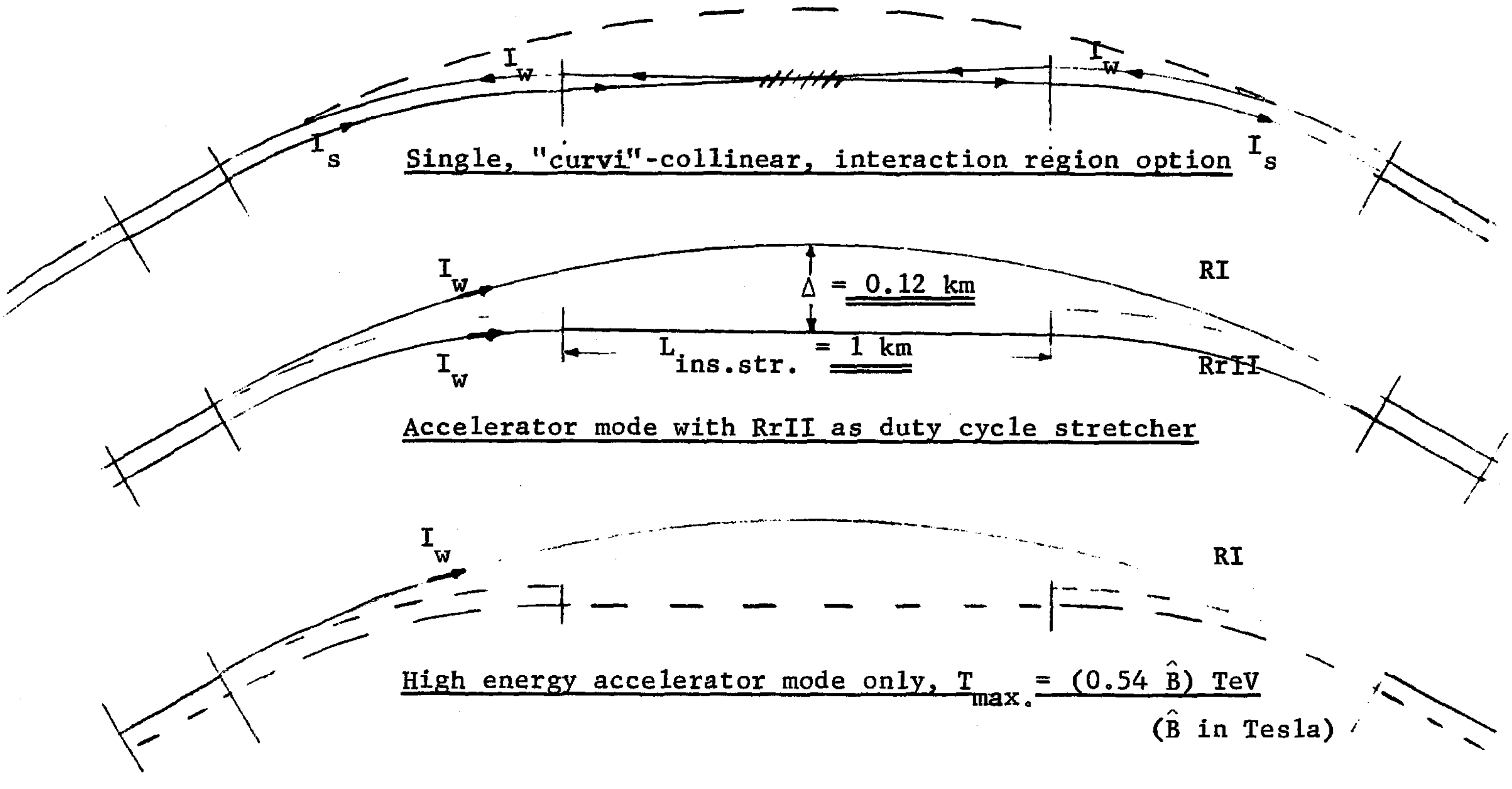
p-p colliding beam system, 1 TeV-1 TeV

Two interaction crossings in $L_{ins.str.}$

$L_{ins.str.}$ = 1.00 km; $\hat{B}_{low}$ = 18.6 kG, $\hat{B}_{high}$ = 35.1 kG, R=2.33 km, r=1.25 km

Luminosity: $\alpha_{\frac{1}{2}}$ = 0.85 mrad, β_y^* = 3.5 m, β_x^* = 20.0 m, $\Delta\upsilon = 5\ 10^{-3}$,

I_w = 1.0 A, I_s = 20.0 A, $L_{max} = 1.5\ 10^{33}\ cm^{-2} sec^{-1}$.

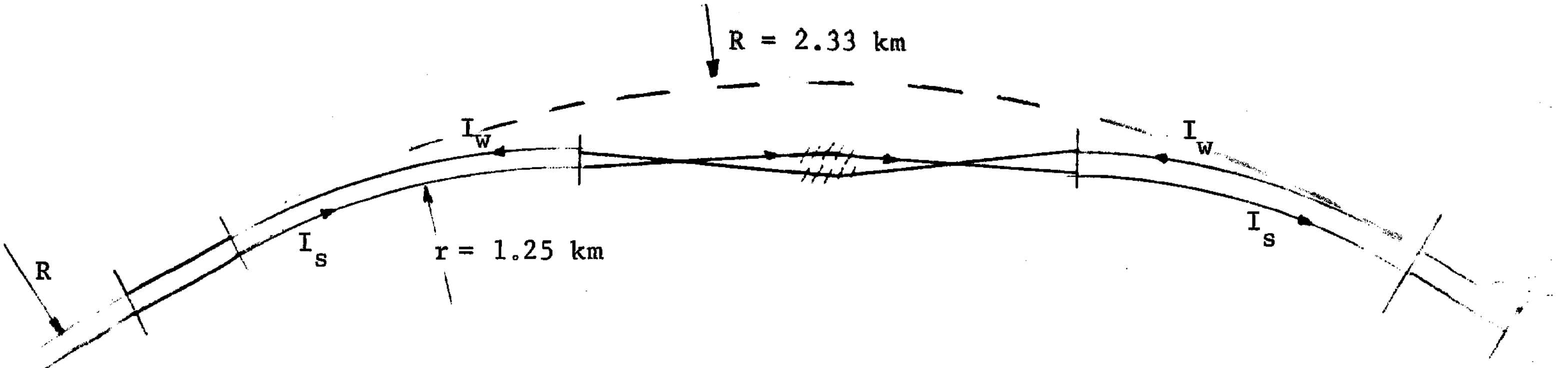


Single, "curvi"-collinear, interaction region option

Accelerator mode with RrII as duty cycle stretcher

High energy accelerator mode only, $T_{max.} = (0.54\ \hat{B})$ TeV
($\hat{B}$ in Tesla)

Fig. 2



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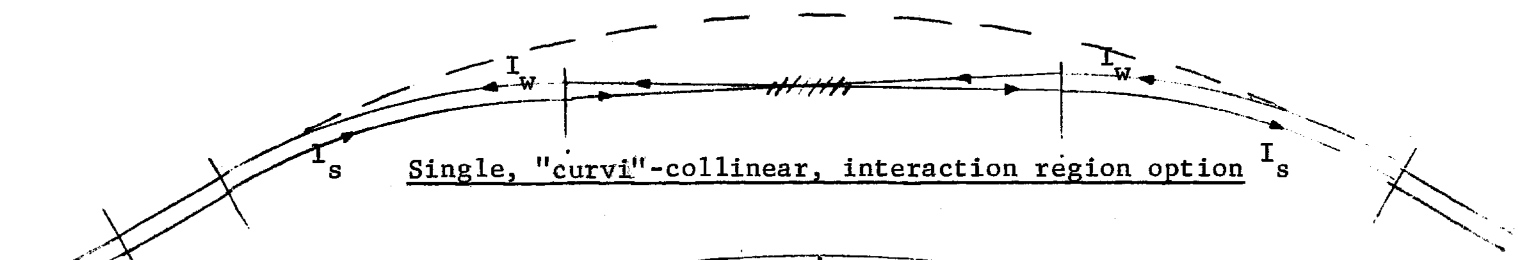
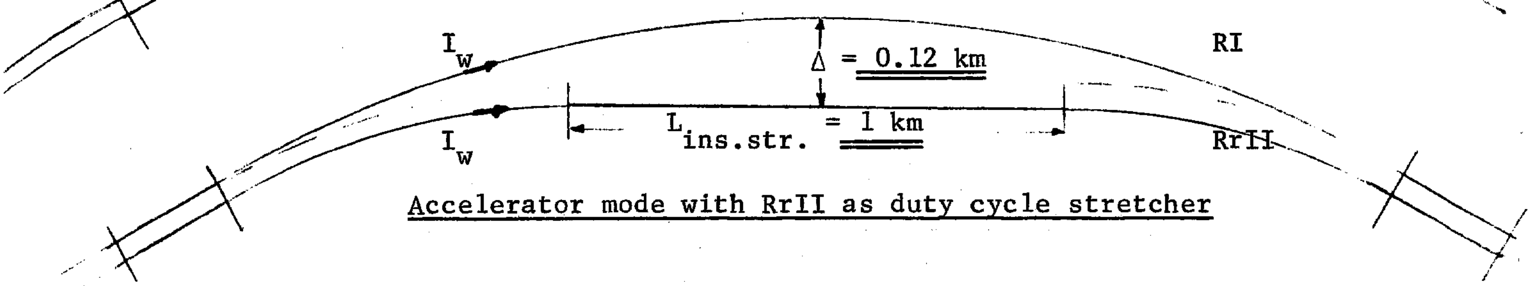


Single, "curvi"-collinear, interaction region option



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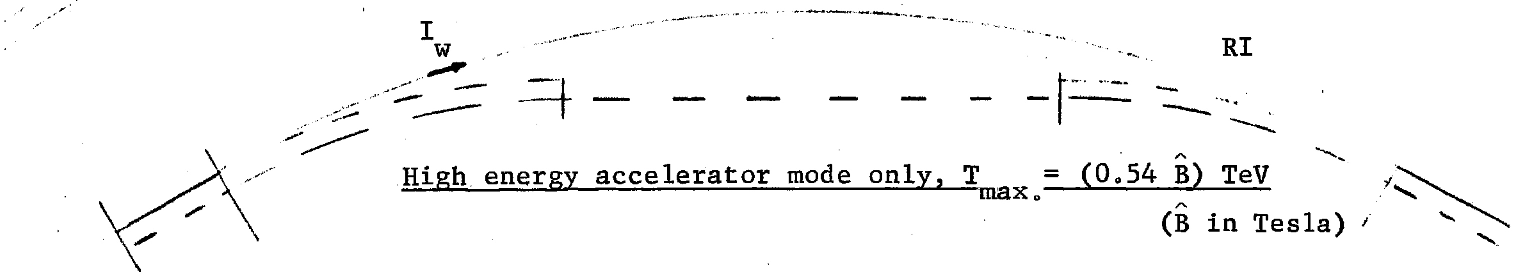

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($\hat{B}$ in Tesla)

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