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pp INTERACTION REGIONS

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Summary

This group served as the interface between experimenters and accelerator physicists. A start was made on a portfolio of IR's, building on previous studies including the Reference Designs Study (RDS). The group also looked at limits on time structure and luminosity, the clustering of IR's, external beams of secondary particles from the IR's, and various operational issues connected with the IR's.

Designs were developed for interaction regions for RDS-B (individual cryostats for two 5-T rings, separated by 60 cm vertically). For a fixed geometry, the quadrupoles have been tuned over a range to give a factor of 100 variation in β^* (1 to 100 m) and thus in luminosity; an even larger variation may well be possible. Variation of the minimum β^* with free space between the quadrupole triplets, for a quad strength of 280 T/m and under the constraint of fixed chromaticity, showed a factor of five decrease in maximum luminosity in going from a high luminosity region with ±20 m free space to a small-angle region with ±100 m. Similar variants of the RDS-A IR were also found.

The crossing angle of the standard IR can be easily varied to avoid adverse long-range beam-beam effects over a wide range of β^* (1 to 1000 m). A short luminous region ("diamond") of ±1 cm, as requested for silicon vertex detectors, was shown to be straightforward using special dipoles to give a "large" (1 mrad) crossing angle at the collision point.

There was considerable interaction with experimenters interested in measurements of small-angle elastic scattering and diffraction dissociation. Many of their requirements can be met with simple modifications to one of the RDS-A utility straight sections. A special region with β = 4 km for the study of Coulomb interference was designed.

There appear to be no fundamental limits in eventually achieving a luminosity of 10^{34} cm^{-2} sec^{-1}. This will require an increase in the total stored beam energy and a careful design of the scraper/collimator system to ensure protection of the superconducting magnets from beam losses. A bunch spacing of less than 10 nsec also appears possible, although this is again at the cost of more protons.

The best duty cycle for the detectors would be achieved with continuous beams; rf questions (relating to the abort gap and restoration of energy lost by synchrotron radiation) were investigated.

The clustering of IR's looks attractive for several reasons. Backgrounds of particles from one IR hitting the next appear manageable for IR separations of 1 to 2 km, with some bending in between to offset neighboring detectors from forward muons. There are no apparent problems with the first-order optics for clustering, but the effect on dynamic aperture is yet to be explored.

Clustering allows for test beams made of particles produced from one IR to be conducted to the "garage area" of the next IR for calibration purposes. The transport of such beams is greatly facilitated if the garages are on the outside of the ring. Although over-focussed by the low-β quads, fluxes of a few × 10^5 particles/TeV/sec (at 10^{33} cm^{-2} sec^{-1}) are expected at 5 - 10 TeV into a beam transport solid angle, perhaps enough for certain fixed target experiments. Test beams of 1 to 15 TeV (including electron beams from a lead finger to convert γ-rays from forward π^0's) should be readily available. The construction of such beams would be greatly facilitated by minor changes in the IR design.

A feedback system to keep the beams centered on one another appears straightforward, as does the measurement of luminosity.

Detector Requirements

An important aspect of this Snowmass study was the possibility of discussion between detector and accelerator designers. To help focus this discussion, a series of questions was developed and is reproduced below:

For each detector, it would be useful to know the following:

1. What is the maximum luminosity desired for the detector under the following assumptions on bunch spacing:
   a. 100 nsec
   b. 33 nsec (Reference Design)
   c. 10 nsec
   d. continuous (DC) beams
2. Over what range of luminosity will the detector need to run, as different physics and systematics are studied?
3. What is the relative amount of time the detector will run at different energies, or should it only be run at the maximum?
4. What is the optimal rms length of the luminous region ("diamond")? What limits are still useable?
5. How much free space along the beam does the

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detector need between the low-β quadrupoles? Will additional space be needed along the beam for detectors beyond the low-β quads?

6. How close to the beam do the detector components need to be (both at the IR itself and elsewhere)?

7. Are there any special requirements on the rms beam size or divergence at the IR? Are small-angle detectors needed at some special point back in the lattice?

8. To what accuracy must the luminosity be known? Will this measurement be generated internally to the experiment, or are the machine people to provide it?

9. What backgrounds can the detector tolerate? This is, of course, a very tough, multifaceted question. It is especially important, however, to determine how much collimation and bend is needed between IR's to reduce the spray of hadrons and muons from one IR to the next.

10. What magnetic fields (if any) will the detector exert on the beam?

11. How big a collision hall is needed for the detector, including space for any disassembly needed for repairs in place? How large a "garage" area is needed at beam level? How big must the openings be between the garage and collision hall (horizontal throat) and between the garage and ground-level assembly hall (vertical throat)? What other special requirements (power, water, assembly hall space, office space, ...) are there in the experimental area?

12. Can the IR be shared with other detectors? What kind?

Many of these questions were considered in a series of iterative discussions with each side going away and pondering the problems in the light of the desires and/or constraints of the other side. The answers to some of these questions can be found scattered throughout the reports of the various detector groups. Other questions remain largely unanswered, in some cases being highly dependent on the detailed capabilities of the detectors and/or nature of the backgrounds.

A final, more global question is the number of IR's needed for the SSC.

Example IR Optics

The Reference Designs Study (RDS)[1] shows an IR insertion with a small-angle (30 - 100 μrad) crossing of bunched beams. This scheme grew out of discussions at earlier studies[2] and is shown in Fig. 1. The beams are strongly focussed, to $\beta^* = 1$ m, by common quadrupole triplets on either side of the interaction point (IP), followed by beam splitter magnets to separate the two proton beams horizontally by 14 cm, to match the RDS-A two-in-one magnets. Some of the RDS-A beam parameters are shown in Table I. Because of the common magnets in the IR's, it would be very difficult (if not impossible) to run with beams of asymmetric energy.

Garren examined the flexibility of this design by adjusting the gradients of the six low-β quadrupoles in order to vary beta at the IP.[3] Tunes were found over the range $\beta^* = 0.5$ to 20 m, for fixed quadrupole locations and for maximum gradients of 280 T/m. Due to the interleaving of beam splitting dipoles and low-beta quads, he also found a small variation of horizontal dispersion at the IP, over the range 0 to 30 mm. Plots of these functions vs. β^* are shown in Fig. 2; it is expected that the dispersion could be

Table I. Comparison of RDS (6.5 T) parameters with a possible mode for eventual operation at high luminosity.

		RDS-A	High Lumin.
Beam Energy	E (GeV)	20	20
Luminosity	$\mathscr{L}$ (cm^{-2} sec^{-1})	10^{33}	10^{34}
Bunch spacing	D_B (m)	10	5
Inel. events/crossing	< n >	3.3	17
Machine param. at IP	β^* (m)	1	0.5
Inv. emittance (rms)	ϵ_n (10^{-6} m)	1	1
Beam-beam tune shift	$\Delta\nu$ (10^{-3}/IR)	1.7	3.0
Protons/bunch	N (10^{10}/bunch)	1.4	2.2
Protons/90-km ring	N_{ring} (10^{14})	1.3	4.0
Stored beam energy	U (MJ/ring)	400	1300
Syn. rad. power	P_{sr} (kW/ring)	8	25
Length. of lum. region	$\sigma_{diamond}$ (cm)	5	5

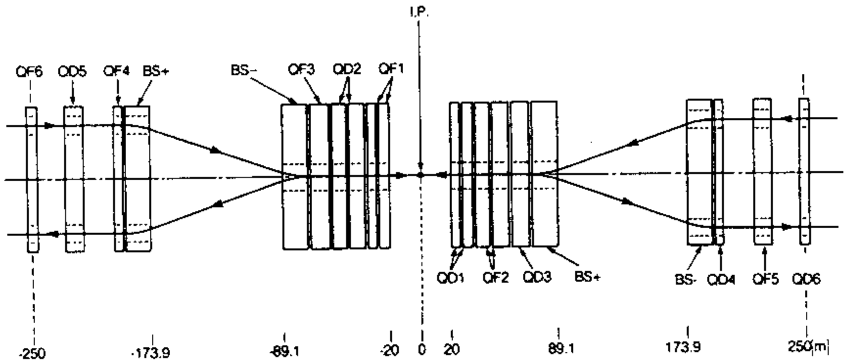

Fig. 1. Schematic of the RDS-A (Ref. 1) interaction region indicating the bending magnets that split the beams (BS+, BS-) and the focussing and defocussing quadrupoles (QF1-QF6, QD1-QD6), which focus the beams to high density at the interaction point (I.P).

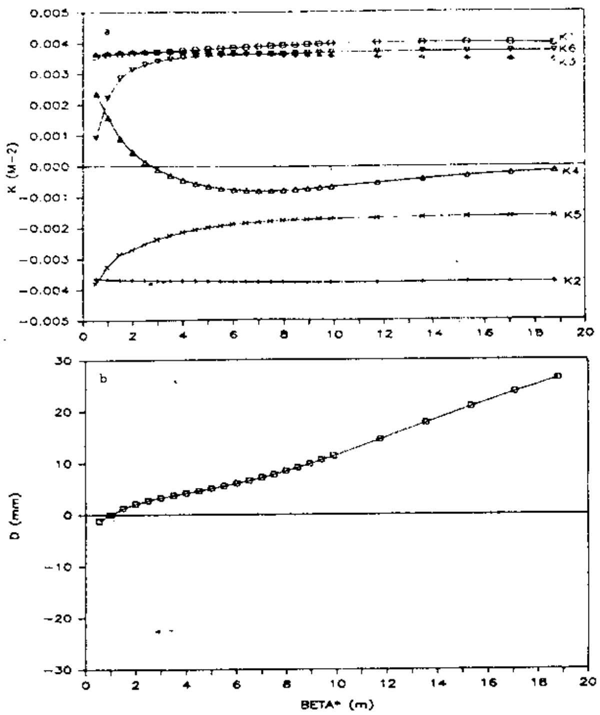

Fig. 2. RDS-A insertions as a function of β^* (Ref. 3). (a) Variation of quadrupole gradients, $K = B'/B\rho$; (b) horizontal dispersion at the interaction points, $D = \Delta x/\Delta p/p$.

tuned to zero by adjustments of the quadrupoles in the dispersion-killer regions.

At this study IR insertions for RDS-B were also discussed. A low-beta design was presented[4] which consists of a tunable, dispersionless, low-beta section followed by an achromatic vertical splitting section which achieves a 60-cm beam separation, matching the RDS-B design of separate magnets and cryostats. One half of this IR is shown in Fig. 3. There are three two-in-one magnets on either side of the IP. Since the low-beta quadrupoles are not in the splitting section, this design allows a large variation of β^* which does not disturb either the horizontal or vertical dispersion functions. Tunes, not yet optimized, were found for $\beta^* = 1$ to 100 m by adjusting the gradients of the five innermost pairs of quads. These tunes are shown in Table II.

The flexibility to vary β^* over a wide range is very important as it will allow experimenters to run at a β^* giving the optimal luminosity ($\mathscr{L} \propto 1/\beta^*$) for their particular detector and physics, largely

Table II. Quadrupole gradients (Tesla/meter) for several RDS-B low-beta values.

β^*(m)	1	10	50	100
Q1	269	139	197	201
Q2	-249	-194	-205	-209
Q3	250	269	243	232
Q4	-100	-221	-238	-251
Q5	212	145	134	138

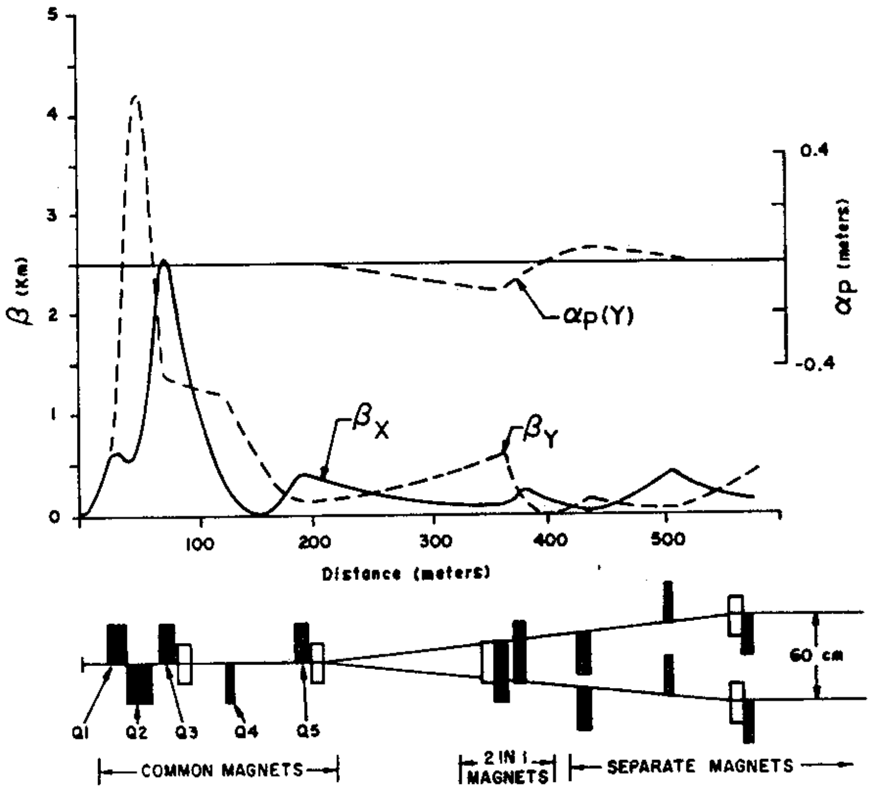

Fig. 3. Lattice functions (β), dispersion (α_p), and layout for one-half of the RDS-B interaction region design (Ref. 4) for $\beta^* = 1$ m and a free space $L = \pm 20$ m. The design is antisymmetric and consists of two parts - a low-beta section which is tuned by adjusting quadrupole gradients Q1-Q5, and an achromatic vertical splitting section.

independent of the needs of other detectors. It may also prove advantageous to detune the IR's to modest values of β^* in order to inject the 1-TeV beam into a "relaxed" machine. After injection and acceleration to 20 TeV, β^* in the IR's can be squeezed down to the final values. Changing β^* will take careful computer coordination in order to maintain the correct machine tune, chromaticity, etc., but this process is already being done at both Fermilab and the CERN SPS and should not present a problem.

Although the 4π-detector designs developed at this study[5] were able to fit within a space of $L = \pm 20$ m to the first beam magnets, some of the specialized detectors will need more space.[6] To accommodate these detectors, a study was made of the dependence of luminosity versus free space for the RDS-B interaction region. It was found that different IR's could be designed, using the magnet lengths and spacings of RDS-B, in which the free space ranged from $L = \pm 20$ m to ± 100 m. In each case β^* was adjusted so as to keep constant the IR's contribution to the machine chromaticity. For the parameters chosen, β^* varies from 1 m at $L = \pm 20$ m up to 5 m for $L = \pm 100$ m (see Fig. 4). It was generally agreed at this study that chromatic effects from the IR's were most likely to limit the ultimate low-beta. An examination of the nonlinear dynamic aperture of the machine as a function of β^* and L should be done, but was beyond the scope of the present study.

Crossing Angle

The value of the crossing angle, α, is a compromise between several factors:

Factors pointing toward small α:

1. Highest luminosity for a given number of protons and other fixed parameters:

$$\mathscr{L} = \mathscr{L}_o / [1 + (\alpha/\alpha_o)]^{1/2} \quad ,$$

$$\alpha_o = 2\sigma^* / \sigma_z \quad ,$$

where $\mathscr{L}_o$ is the corresponding head-on luminosity. For the RDS parameters, the transverse rms size of the beam is ± 7 μm and the rms bunch length 7 cm, giving $\alpha_o = 200$ μrad.

2. Minimum synchro-betatron resonance excitation;[7] this also suggests that $\alpha/\alpha_o \ll 1$.

3. Small beam excursion in the low-β^* quadrupoles. For RDS-A, $\alpha = 250$ μrad probes out to a radius of about 8 mm.

Factors pointing toward large α:

4. Reduction of satellite interactions coming from the first close encounter points (located at half the bunch spacing from the nominal IP):

$$\mathscr{L}_{ce} / \mathscr{L}_o = e^{-\delta^2/4\sigma^2}$$
$$= 1.8 \times 10^{-2} \quad \text{for} \quad \eta = \delta/\sigma = 4$$
$$= 1.2 \times 10^{-4} \quad = 6$$
$$= 1.1 \times 10^{-7} \quad = 8$$

where $\delta = \alpha D_B/2$ is the separation of the two beams as the bunches pass one another and η is the separation in units of the rms width of the beam. For $\beta^* \ll D_B/2$, $\delta/\sigma = \beta^* \alpha/\sigma^*$.

5. Long range beam-beam tune shift:

$$\delta\nu = 2\Delta\nu_o \sum_i \left(\frac{\sigma_i}{\delta_i}\right)^2 \quad ,$$

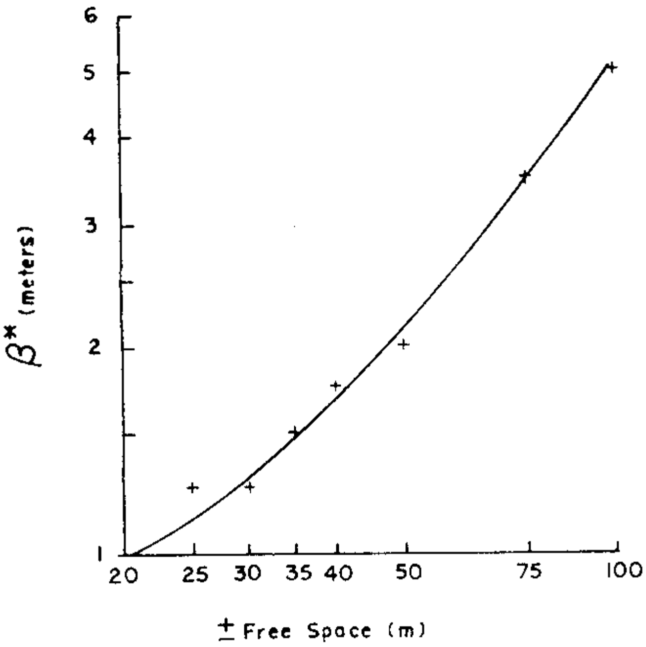

Fig. 4. Minimum β^* as a function of free space from the IP to the nearest magnet for RDS-B (Ref. 4). For a given geometry, the free space and β^* were adjusted such that the maximum quadrupole strength did not exceed 280 T/m, and such that the contribution of the IR to machine chromaticity, $\Delta\psi/\Delta p/p$, remained approximately constant. The curve is a guide to the eye.

where $\Delta\nu_o$ is the usual nonlinear beam-beam tune shift calculated for the IP itself and the sum is over the close encounters, out to the point at which the two beams are well separated by the splitter magnets.[8] For RDS-A, the number of close encounters per IR is $N_{ce} = 29$ and $\delta\nu = \Delta\nu/2$ for $\alpha = 75$ μrad ($\delta_i/\sigma_i \approx 11$ for all i). For the longer IR insertion of RDS-B, there will be more close encounters and the angle would have to be larger for the same tune shift.

At Snowmass, Diebold calculated the various limits on α as β^* is varied, with results shown in Fig. 5. To maintain at least 6σ separation at the first encounter 5 m from the IP

$$\alpha > 8.2 \sqrt{\beta^* + 25/\beta^*} \, ,$$

where β^* is in meters and α in μrad. The sum of close

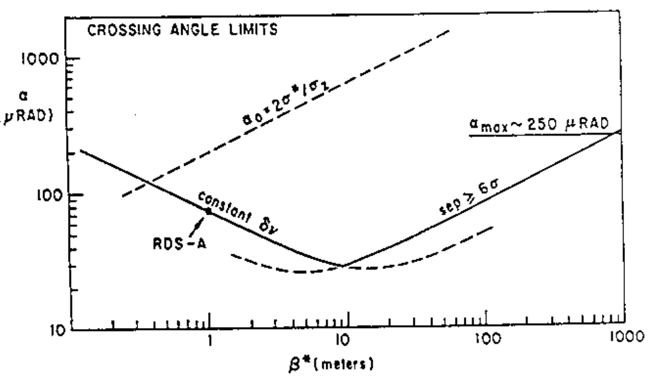

Fig. 5. Various limits on the crossing angle α as a function of β^*, starting from RDS-A.

encounters gives to a good approximation

$$\delta\nu = 2\Delta\nu_o \left[N_{ce} + 12 \left(\frac{\beta^*}{D_B}\right)^2\right]/\eta^2 \quad ,$$

where $\eta = \beta^*\alpha/\sigma^*$. The maximum allowable $\delta\nu$ will have to be determined empirically with the machine itself; in the meanwhile the limit is arbitrarily taken to be that given by the RDS-A parameters, in which case

$$\alpha > 75/\sqrt{\beta^*} \quad \text{for} \quad \beta^* << D_B$$

$$> 5\sqrt{\beta^*} \quad \text{for} \quad \beta^* >> D_B \quad .$$

For a 8-mm radius good-field region in the quadrupoles, $\alpha < 250$ µrad for RDS-A and this value (for a 6σ separation) requires that for $\beta^* \gtrsim 1000$ m a beam catcher magnet (see below) be used.

For $\sigma_z = 7$ cm and $\epsilon_N = 1$µm, as used in the RDS, $\alpha_o = 2\sigma^*/\sigma_z = 200$ µrad$/\sqrt{\beta^*}$. As β^* decreases, the lower limit on α from δν eventually conflicts with the need to keep $\alpha << \alpha_o$ to avoid synchro-betatron resonance excitation. Reducing β^* to less than 1 m in order to achieve higher luminosities may require shorter bunch lengths if these resonances are to be kept under control; an alternative would be to increase δν.

Short Diamond

The detector group asked for a short luminous region, or "diamond," of rms length $\sigma_\ell = \pm 1$ cm for those experiments requiring high precision silicon strip vertex detectors. For head-on collisions of beam bunches, having longitudinal rms lengths of σ_z, the length of the diamond is given by $\sigma_{\ell o} = \sigma_z/\sqrt{2}$ (±5 cm for the RDS).

The dependence on crossing angle is the same as for luminosity,

$$\sigma_\ell/\sigma_{\ell o} = \mathscr{L}/\mathscr{L}_o = 1/\sqrt{1 + (\alpha/\alpha_o)^2} \quad .$$

To reduce the length of the diamond by a factor of five, we need $\alpha \approx 5\alpha_o = 1$ mrad. The nominal luminosity at $\beta^* = 1$ m would then correspond to 2×10^{32} cm^{-2} sec^{-1}, which appears to be a good match to these detectors.

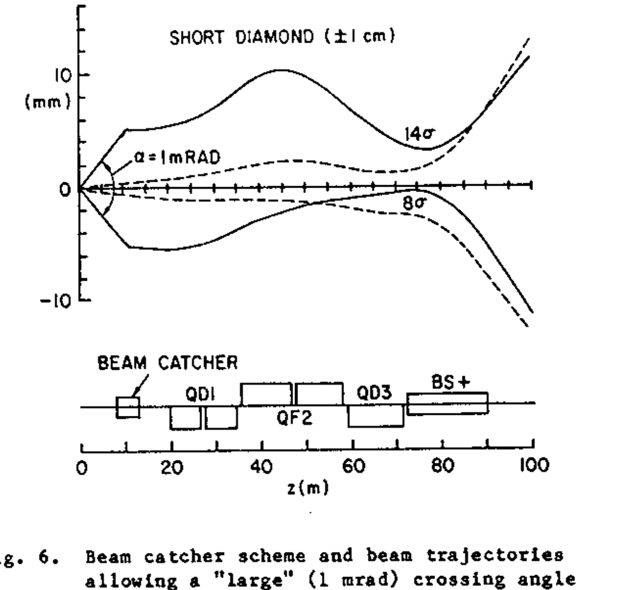

Fig. 6. Beam catcher scheme and beam trajectories allowing a "large" (1 mrad) crossing angle and short luminous region (±1 cm); the normal RDS-A trajectories are shown dotted for comparison.

Table III. Some examples of short diamond lengths that could be obtained starting from RDS-A.

σ_ℓ (cm)	α/α_o	Free Space (m)	Magnet Length (m)
1.7	3	± 17	3
1.0	5	± 8	5
0.6	8	± 2.5	8

Increasing α to 1 mrad would, however, require a 3-cm good-field radius in the low-β^* quad triplet if nothing were done. By placing a "beam catcher" 6.5-T dipole magnet 5 m long beginning at 8 m on either side of the IP, Diebold found that the beams can be made roughly parallel such that they will stay within a 1-cm good-field region and still maintain a separation of > 8 σ everywhere, as shown in Fig. 6.

This method only works over a range of 2 or 3, however; some typical values are given in Table III. The crossing angle must be much larger than α_o to avoid undue excitation of synchro-betatron resonances; on the other hand, it can't get too large or the free space in front of the beam catcher magnet becomes too short to accommodate the detector. If necessary, a wide range of diamond lengths might be achieved with different rf parameters, but this is not an easy change and would, of course, affect all experiments.

High β^* Regions

For the standard RDS parameters ($\epsilon_N = 1$ µm rms, $\beta^* = 1$ m, etc.), the rms spread in transverse angle is $\sigma_{x'} = \pm 7$ µrad, or ±140 MeV/c in transverse momentum. This can be compared to the transverse momentum of 20 MeV/c for which the Coulomb and nuclear amplitudes are equal; clearly the beam must be made more parallel for Coulomb interference measurements. For this reason, R. Siemann[9] designed a high-β^* IR with

$$\sigma_{x'} = 7\ \mu\text{rad}/\sqrt{\beta^*} = 7\ \mu\text{rad}/\sqrt{4000\ \text{m}} = 0.1\ \mu\ \text{rad},$$

giving ±2 MeV/c.

To detect the scattered protons, the detectors are also placed at a large β location, roughly 90° in phase advance away from the IP:

$$\Delta x = L_{eff}\theta \quad ,$$

$$L_{eff} = \sqrt{\beta^*\beta_{det}}\ \sin\Delta\psi \quad .$$

For $\beta^* = \beta_{det} = 4000$ m, the rms beam size is 0.43 mm and $L_{eff} = 4000$ m. Assuming that the detector can be placed as close as 10σ (4.3 mm) to the beam center, a scattering angle as small as 1 µradian could be detected (20 MeV/c).

Siemann started with the machine parameters of the RDS utility straight section, in the region following the quadrupole at the end of the dispersion suppressor section. Three regions of β = 4 km were included in the design, separated by 90° phase advance in the scattering plane. Two example solutions were found, one with overall length of 3.6 km and the second with 4.2 km (to be compared to the RDS length of 2 km).

To avoid interactions at the close-encounter points (α = 500 μrad for 6σ separation), one would use beam catcher magnets close to the IR, as for the short diamond case which also needed large α. Alternatives would be to run at a smaller separation and use timing to reject events coming from the close encounter points, or to run with greater bunch spacing.

The RDS utility straight section already has a rather large β (~ 2 km) over a considerable distance (~ 1.2 km), and Garren devised a scheme whereby one of the utility straight sections would have two beam-crossing points, separated by considerable bending power.[3] One half of the straight section is shown in Fig. 7. For elastic scattering experiments detecting both protons, L_{eff} ~ 250 m can be achieved; 10 σ from the beam then corresponds to $t = 0.06\ \mathrm{GeV}^2$.

For diffractive dissociation, good momentum resolution is required. The dispersion 200 m downstream of the 6 mrad bend (B3) is 1.2 m. For detectors with $\sigma_x \lesssim 200$ μm, the measurement of momentum is dominated by the beam size of 300 μm: $\sigma_p/p = \pm 300\ \mu\mathrm{m}/1.2\ \mathrm{m} = 2.5 \times 10^{-4}$ (the nominal spread in beam momentum is five times smaller). Since $M_x^2 = (1 - x)s$, where $x = p/p_{beam}$, this gives $\sigma(M_x)/M_x = 20\%/M_x^2$ (for M_x in TeV). Detectors in the other direction could observe the decay products of the diffractively produced object, down to $M_x \approx 100$ GeV (at this mass, a calorimeter with a minimum useful radius of 10 cm at 100 m would observe 96% of the relativistic isotropic decay products).

Limits on Luminosity

For symmetric head-on collisions, the luminosity can be expressed in "engineering" units as

$$\mathscr{L} = 0.253 \times 10^{33} \frac{(N/10^{10})^2 E}{\beta^* D_B \epsilon_N} \quad , \text{ or}$$

$$\mathscr{L} = 0.208 \times 10^{33} \frac{(N/10^{10})\ (\Delta\nu/10^{-3})\ E}{\beta^* D_B} \quad ,$$

where luminosity is in $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, N is the number of protons/bunch, E the beam energy in TeV, β^* and D_B in meters, and ϵ_N the rms beam emittance in 10^{-6} m ($\sigma^2 = \epsilon_N \beta^*/\gamma$ where $\gamma = E/M$). For the RDS parameters, ϵ_N (rather than the beam-beam tune shift, $\Delta\nu$) appears to be the limiting factor and the first equation is the most useful; at higher luminosity $\Delta\nu$ may be limiting and the second equation can be used. Additional scaling formulae are displayed in the PSSC IR report.[2]

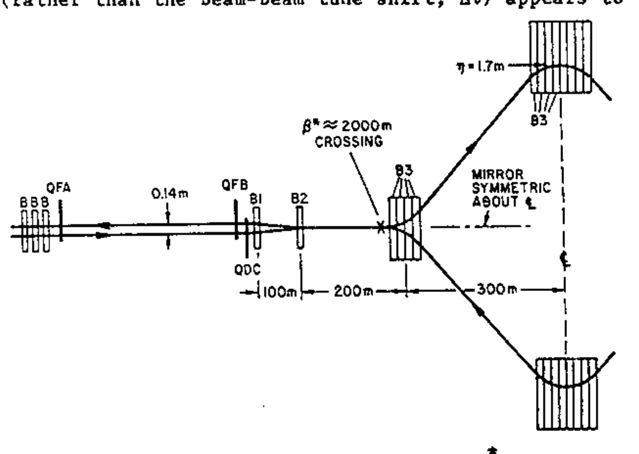

Fig. 7. Layout for beam crossings with $\beta^* \approx 2$ km in a RDS-A utility straight section (Ref. 3).

The RDS value $N = 1.4 \times 10^{10}$ is a factor of two below that obtained for years at Fermilab, and well below the 1.4×10^{11}/bunch used in the SPS collider[10] (though for very widely spaced bunches).

The 1-μm emittance assumed for the RDS will require very careful handling of the beam in the injector chain, especially during transfer from one ring to the next. Although synchrotron radiation damps ϵ_N at a rate of 7%/hour (at 6.5 Tesla), it is probably best not to count on a large improvement in emittance beyond the RDS value.

The lower limit on β^* is not well understood at present. It is presumably given by the increased nonlinear sextupole fields needed to correct the chromaticity coming from the large β values in the quad triplet. Tracking studies of the dynamic aperture are needed to understand this limit, but one might hope that with experience in running the machine, one might be able to push below the RDS value of $\beta^* = 1$ m.

In the RDS, the bunch spacing D_B is an integer multiple of 5 m, and 10 m was chosen as an example. For good duty cycle and from the luminosity equations above, one would like to reduce it. The limit on D_B is believed to be given by the increased damper system requirements as the bunches get closer. Experience with the Fermilab dampers (for D_B = 5.7 m) suggests a limit on D_B of (2 ± 1) m;[11] this might be helped with modern stochastic cooling technology. One reason the RDS took a larger value was to reduce the number of protons/ring (see below); for fixed ϵ_N, this number scales as $1/\sqrt{D_B}$, while it is constant for fixed $\Delta\nu$.

The beam-beam tune shift is given by

$$\Delta\nu = 1.22 \times 10^{-3}\ (N/10^{10})/\epsilon_N \quad .$$

Values up to (3 or 4) × 10^{-3} have been successfully run for head-on beams in the SPS collider[10] and can hopefully be achieved by the SSC for small values of α/α_o.

Perhaps the most uncertain limit in luminosity is the number of protons per ring that can ultimately be handled. There are several aspects of this limit, most of which are straight-forward (though not always cheap) to accommodate: synchrotron radiation (refrigeration and vacuum systems), the rf system, health-physics shielding, abort dumps, etc. The factor that remains highly uncertain relates to magnet quenches - as the beam intensity increases, a smaller and smaller fraction of the beam can cause a quench. Presumably, this intensity limit will improve with time as the machine becomes well understood, and will depend critically on the success of the scraper-collimator system. It is most important that a careful design of this system be made and implemented.

While most of the experimentalists at this workshop concentrated on the problems of general-purpose detectors operating at $10^{33}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, it appears that large solid angle calorimetric detectors, with little tracking, could profitably use $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ (or more).[12] This is also true of some of the smaller solid angle specialized detectors.[6] Although the experimenters will no doubt be happy initially with luminosities of well under $10^{33}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, the accelerator design should allow for improvements such that the full luminosity potential of the machine can

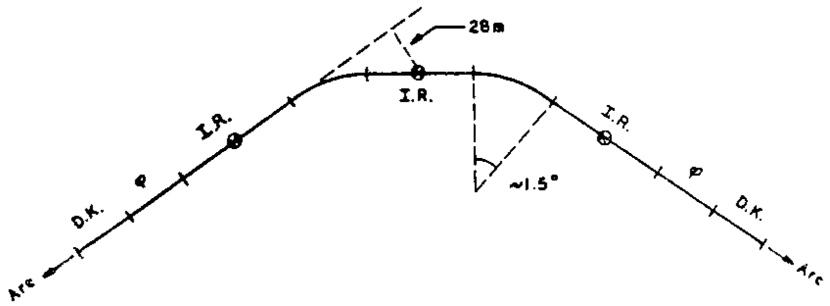

Fig. 8 Clustered straight section layout for RDS-B, consisting of horizontal dispersion killers (D.K.), phase adjusting sections (ϕ), and interaction regions (Ref. 4). The IR's are separated by 2.1 km. This separation includes four regular cells with half of the dipoles removed.

be reached.

Table I gives a possible set of parameters for 10^{34} cm^{-2} sec^{-1}; compared to the RDS, D_B and β^* have each been reduced by a factor of 2, while the total number of protons per ring has been increased by a factor of 3.2.

Unbunched Operation

Unbunched (continuous) beams would have several advantages:

1. close to 100% duty factor for detectors,
2. more stability expected against beam-beam instabilities,
3. the highest luminosity.

There are, however, several potential problems, perhaps the most important of which is the increased number of protons required over the bunched beam case:

$$\frac{\lambda_C}{\lambda_B} = \left[\frac{\eta}{7.09}\,\frac{D_B}{\beta^*}\,\frac{\epsilon_C}{\epsilon_B}\,\frac{\mathcal{L}_C}{\mathcal{L}_B}\right]^{1/2} \quad ,$$

where λ is the linear proton density ($\lambda_B = N/D_B$) and η is again the beam separation in rms units.[8] For fixed luminosity and emittance, and taking $\eta \approx 7$, a factor of $\sqrt{D_B/\beta^*}$ increase in the number of protons is required for continuous beams. If, as discussed above, the number of protons is indeed the limiting factor, the advantage of bunched beams is obvious.

Other aspects of continuous beams were also considered. Presumably there must be an abort gap of ~ 3 μsec (1 km) in each beam to allow for the rise time of the abort kickers. It appears that a rather modest rf system can easily generate this gap.[13]

A more difficult problem concerns the loss of energy due to synchrotron radiation. The simplest solution would be to simply allow the energy to slowly fade away (to 14 TeV after 10 hours), tracking the energy with the ring magnets. Experimenters may not like a continually varying beam energy, however.

Phase displacement acceleration, as was used at the ISR, appears not to be appropriate, due to the increasing energy spread introduced into the beam by the moving buckets.[14] Even increasing the rf-voltage by a factor of four, runs would be limited to 5 or 10 hours. Further, some protons would be lost during this acceleration process, and the ensuing backgrounds would likely require an alternation between acceleration and data taking. A problem not investigated is the lifetime due to quantum jumps (from synchrotron radiation) into the rf bucket.

A third possibility would be to periodically (perhaps once an hour) rebunch, accelerate back up to 20 TeV, and debunch again for data taking.

Any case, it appears that the continuous beam option does not affect the IR design; the small-angle crossing is equally applicable to bunched and unbunched beams. The luminous region would be longer, however, $\sigma_\ell = \sqrt{2}\,\beta^*/\eta \approx 20$ cm for continuous beams.

IR Clustering

The RDS assumed six IR insertions spaced symmetrically around the ring. The PSSC study group considered the possibility of clustering these insertions into two groups of three on opposite sides of the ring.[2] This would allow the experimental facilities, including shops, computers, etc. to be concentrated in two areas. As discussed below, it would also allow test beams of particles produced at one IR to be conducted to the assembly area of the next.

A possible problem in clustering the IR's concerns particles from one IR giving backgrounds in the detector in a neighboring region. The PSSC study concluded that a separation of IR's by about 1 mile and a 3^o bend should be adequate to reduce this background to a sufficiently low level. The bend would offset the detectors by about 120 feet from the flood of forward muons coming from interactions in a neighboring region. It would also produce a dispersion in the beam at an intermediate point where diffraction-dissociated protons with $p < 0.996\ p_o$ could be intercepted by a collimator-scrapper system (protons at higher momenta, including elastically diffracted protons, would remain within the beam pipe and harmlessly pass through the next IR).

Similar conclusions were arrived at independently in the context of RDS-B.[15] In this case, a separation of 2.1 km and 1.5^o were used to give a 28-m offset (see Fig. 8). Using muon production curves similar to those developed for the Cornell Accelerator Workshop,[16] fewer than 500 μ/sec might be expected over a 12 × 12 m^2 detector from a neighboring IR running at 10^8 interactions/sec. These rates were actually taken from Monte Carlo calculations for interactions in the walls of beam magnets; the increased space for meson decays in an IR may increase these estimates somewhat. Given the high-rate capabilities of the detectors, this background seems innocuous, but these muons will have a different direction and position than the expected particles and will have to be guarded against in the trigger logic.

Although the preliminary conclusion is that clustering looks quite safe from the background standpoint, this needs verification with detailed calculations. A careful design of the collimator-scrapper must be undertaken and the effects of edge leakage calculated. If the detector physicists could give specifications on the allowable backgrounds, a minimal separation of the IR's could be determined.

Whether clustering of IR's and the resulting loss of super-periodicity and concentration of chromaticity-producing elements cause a substantial decrease in the dynamic aperture of the machine must also be studied.

Test Beams from the IR's

Due to the short time constraints, the RDS was unable to address the question of test beams at the SSC and considerable thought was given to such beams at this Snowmass study. The test-beam group[17] concluded that in addition to lower energy beams which could be most economically supplied as part of the booster system, beams of several TeV would be highly desirable to calibrate and understand the systematics of calorimeters.

Several physicists considered test beams using forward-produced particles from the 10^8 interactions/sec in an IR. Dugan considered the overfocussing of particles with less than the beam momentum by the strong low-β^* quadrupoles, sweeping by the first beam splitter magnet, and the subsequent use of septum magnets in the drift space between the two beam splitter magnets to separate the secondaries from the primary proton beam (Fig. 9).[18]

As shown in Fig. 10, the fluxes are above 10^5 particles/TeV/sec (into a 5 cm × 5 cm beam-defining aperture) over a range of roughly 4 to 12 TeV/c, with a maximum of about 6×10^5/TeV/sec. Separation of the secondaries from the accelerator beam would be greatly facilitated (especially at high momenta) if there were more space between the beam splitter magnets (RDS-A was used in these calculations); this would also have the benefit of making the splitter magnets shorter and less expensive.

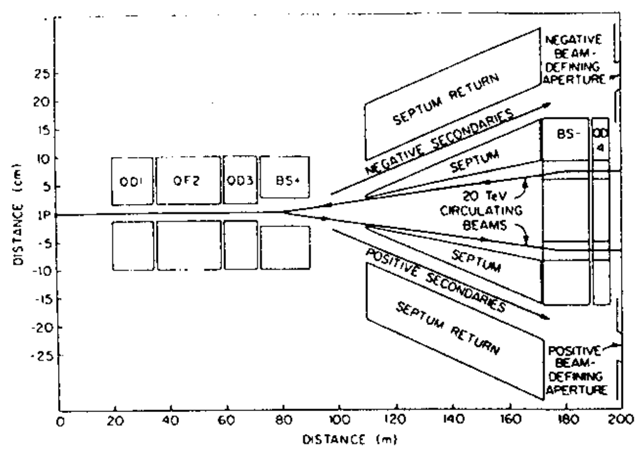

Fig. 9. Layout of the interaction region magnets with secondary beams (Ref. 18).

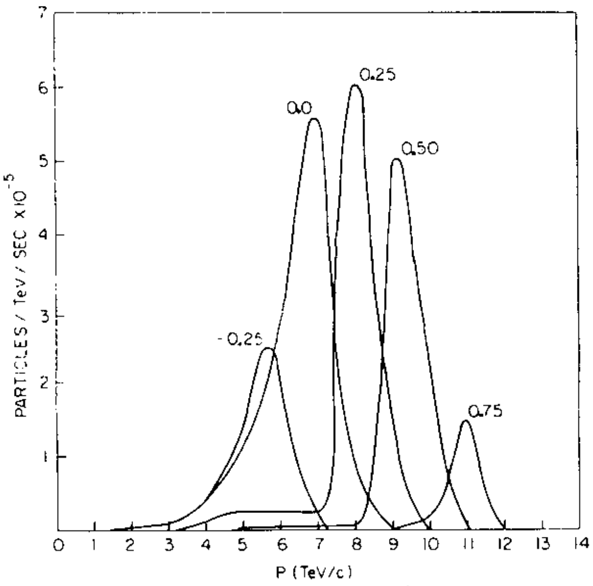

Fig. 10. π^-, K^- yields into the 5 cm by 5 cm beam-defining aperture. Curves are labelled by the septum magnet field (in Tesla).

To achieve the maximum flux, a relatively short beam ($\lesssim$ 200 m) would be called for. Such a test beam would likely be heavily used to calibrate components of the local detector resident at the IR. As pointed out by Lederman,[19] this beam could also serve for a limited fixed target program, including possibly the use of neutrinos and muons coming from the production and prompt decay of charmed particles. A dog leg in the beam (assuming $\bar{p}p$ operation) would be especially useful in accommodating a short neutrino beam capable of giving quite interesting interaction rates at a few TeV.

Murphy[20] considered the beam lines necessary to conduct particles from Dugan's output aperture to the next IR assembly-test area (assumed to be 40 m radially from the machine). Clustering was taken as suggested by the PSSC study: IR's separated by 1.5 km and 48 mrad. For assembly areas located inside the ring (to avoid possible muon spray from upstream beam losses), as in the RDS, 561 m of 4.5-T magnets are needed at 10 TeV. This is both very expensive and so selective in momentum (69 cm/% dispersion) that a simple beam would give only 3000 hadrons per second in a 10-cm wide swath at the detector being tested. If the assembly-test area were on the outside of the ring, a simple two-stage beam (40-m of bending magnets) would give up to 5×10^4 hadrons/sec.

Although it would thus be very attractive to put the assembly areas outside the ring (as is done for CDF at Fermilab), the health physics implications require study.

A method was devised by Diebold at the Snowmass study for directing high energy electron fluxes into the beam lines of Dugan and Murphy. A "presplitter" bending magnet would be placed just in front of the low-β^* triplet; such a magnet will likely be in place in any case in order to aid in adjusting the crossing angle and to reduce the long-range beam-beam tune shift. This dipole magnet would be adjusted to bend each beam by about 120 μrad such that the beams would be separated by $\gtrsim$ 1.5 cm in the first beam splitter magnet, as shown in Fig. 11. The rms width of the larger beam in this region is still quite small, ±0.4 mm at 20 TeV.

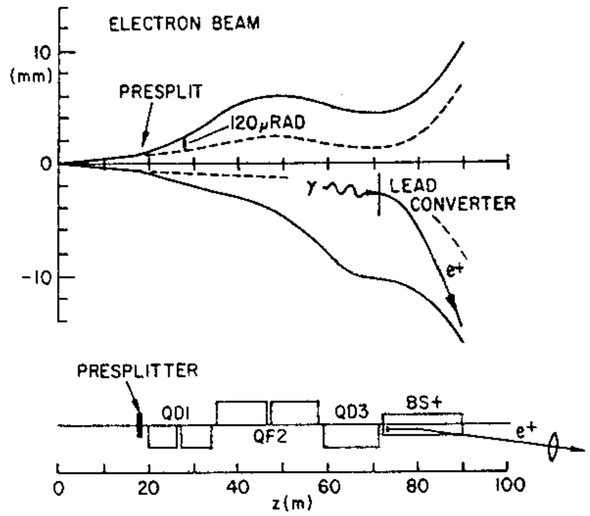

Fig. 11. Presplitter scheme showing beam trajectories spread to allow the placement of a lead converter for the generation of electron test beams.

A lead finger converter can then be used to convert forward-produced γ-rays from π^0 decays. By moving the converter along the beam, the beam-splitter magnet will steer different momenta electrons into the test beam. Since the electrons are generated after the low-β^* quadrupoles, low momenta are not overfocussed and a wide range of momentum should be available. Forward-going neutrons, interacting in a beryllium finger, might be used to give useful fluxes of low momenta (few TeV or less) hadrons. Flux calculations for both electrons and hadrons are needed to verify that adequate rates (and electron purity) can be obtained.

Operational Techniques

Given the small size (rms width of ±7 μm for the RDS parameters) of the beams at the IR's, a feedback system is needed to maintain centering of one beam on the other. This is required not only to achieve maximum luminosity, but also to maintain a long lifetime. The nonlinear beam-beam effects are particularly virulent when the beams are offset from one another by a distance of the order of the rms beam width.

A scheme has been devised by Jöstlein for this purpose.[21] One of the beams is continously moved in a small circular fashion to give a minute modulation of the luminosity when the beams are slightly off center from one another. For the case where the beam centers are offset by an amount of d,

$$\mathscr{L}/\mathscr{L}_0 = e^{-d^2/4\sigma^2}.$$

Steering one of the beams in a circular pattern of radius b will then give a modulation of

$$\mathscr{L}/\mathscr{L}_0 = 1 + A\cos(\theta + \omega t)$$

where $A \approx db/2\sigma^2$ for d and b both << σ. Fourier analyzing a set of data with a total of N events detected in some (relative) luminosity monitor gives an uncertainty on the offset,

$$\sigma_d = (2\sigma^2/b)\sqrt{2/N}.$$

For example, taking a radius $b = 0.05\ \sigma$, and $N = 10^7$ events ($10^{32}\ cm^{-2}\ sec^{-1}$ and 100 mb effective cross section for 1 sec) would give $\sigma_d = 0.02\sigma = 0.12$ μm. Additional Fourier transforms over longer periods of time would be used to pick out 60-cycle, etc., ripple.

The steering magnets needed for this are very weak. Each plane (x and y) will need a pair of magnets in each IR. For simplicity, we take these to be ±20 m from the interaction point. Each magnet acts as a tiny splitter magnet; for $b = 0.05\ \sigma$, a mere ±20 Gauss feet is needed. (As an aside, this simple calculation gives some indication of the ripple control needed for the low-β^* quadrupoles and beam splitter magnets.) Operationally, one would likely impose the small modulation directly onto the steering trim magnets used to center the beams on one another.

A second operational issue is the luminosity measurement itself. Each IR will rely on relative rates from counter arrays detecting some fraction of the pp interactions. Several methods have been successfully used in the past to determine the absolute calibration of these relative monitors: small angle Coulomb scattering (< 1 μrad for the SSC); optical theorem comparison of forward elastic scattering to the total cross section; Van der Meer method of steering the beams across one another to find their effective area; flying wires to measure the beam emittance. Presumably, all of these methods will eventually be used at the SSC and compared with one another to better understand the systematic errors. Which method will turn out to be the most accurate remains to be seen.

Future Work

1. Develop IR portfolio - for machines A/B/C
   - maintain $\eta^* = 0$ while varying β^*
   - phase advance control
   - minimum β^* - with adequate dynamic aperture
   - high β^*; long free space
   - IR clustering - chromatic corrections, dynamic aperture

   Are there significant advantages for H or V crossing? Small or large beam separations in arcs?

2. Careful design, experiments, etc. on scrapping/collimation system:
   Maximize N_{tot} and luminosity without quenching.
   Reduce backgrounds in detectors (especially clustered IR's).

3. Study rf needs of continuous beams:
   Abort gap; make up of synchrotron radiation energy loss.

4. Redesign IR's to facilitate external beams from IP's; e.g., in RDS-A leave more drift space between splitters.

5. Develop capability for bunch spacings < 5 m: dampers; booster rf.

6. Ensure flexibility for future increase in luminosity:
   - more protons - scraping, refrigeration, rf, etc.
   - decrease bunch spacing
   - reduce ε_N, β^*

Conclusions

1. In a standard IR, the β^* can be varied to vary the luminosity by a factor $\geq$ 40-100.

2. An IR with $\pm$100 m of free space can achieve luminosity ~ 20% of that from $\pm$20 m.

3. Short diamonds of $\pm$1 cm should be straightforward.

4. Special IR's for elastic scattering/diffraction dissociation can be built into a utility straight.

5. Bunch spacings down to ~ 1 m look feasible (though the number of protons required goes as $1/\sqrt{D_B}$) .

6. No fundamental limitations were found for luminosity up to 10^{34} cm^{-2} sec^{-1}, though this will take a careful understanding and tuning of the machine

7. Test beams of particles from the IR's of ~ 1 to 12 TeV look straightforward and may even be useful for fixed target physics.

8. Clustering of IR's looks attractive; there are no apparent problems with first-order optics and backgrounds.

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