PRELIMINARY STUDIES FOR A 1000 GeV SUPERCONDUCTING EXTENSION OF THE EUROPEAN ACCELERATOR

by the GESSS Machine Design Working Group*

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(presented by N.M. King)

Abstract

Design problems for a 1000 GeV superconducting (S/C) synchrotron at CERN are outlined.

1. Introduction

The GESSS Machine Design Working Group was created early this year, with the aim of identifying salient parameters for a high energy S/C synchrotron, and hence guiding the practical development programme at the three GESSS Laboratories. As a minimum objective, we consider parameters appropriate to a 1000 GeV machine on the CERN site, corresponding to dipole fields of 4.5T. Our studies are still at an early, comparative, stage.

We discuss two major alternative approaches:-

I Conventional 300 GeV magnets replaced by S/C magnets: injection from CPS at 28 GeV/c.

II New S/C ring installed above conventional one, in same tunnel: typical transfer 200 GeV/c.

In both cases a missing-magnet philosophy[1] may be applied to give, say, an intermediate 500 GeV stage. Here, for Type I cases, we do not consider a *mixed machine* with conventional and S/C dipoles energised in the same ring.

The two solutions also have the common feature that the choice of conventional lattice also determines the S/C lattice. Sagitta considerations dictate that these may differ only in minor ways, in the proposed tunnel.

Thus, current decisions on the conventional machine have significant bearing on a future S/C extension. We hope that the present review will clarify the issues involved, and will prove helpful to the CERN team in arriving at their design with a possible 1000 GeV end-point in mind.

2. Magnet Design Implications

The criterion of minimising dipole aperture looms over all the problems of S/C synchrotron design:[15] increased aperture implies more stored energy and S/C material, with consequent effects on AC losses and power, - hence on capital and running costs[12]. Fig. 1 shows typical stored energies for 1000 GeV at 4.5T, with and without iron shielding[13,20]. Similar behaviour is shown by curves of S/C amperemetres. We use the data which includes iron.

Elliptical apertures lead to little saving in stored energy or materials, whereas the mechanical design problems become formidable.[3,4] Hence in contrast to conventional machines, there is no *a priori* advantage in designing for non-circular aperture occupation.

The iron location affects machine design in several ways. An unsaturated shield protects the aperture from external magnetic influences without introducing

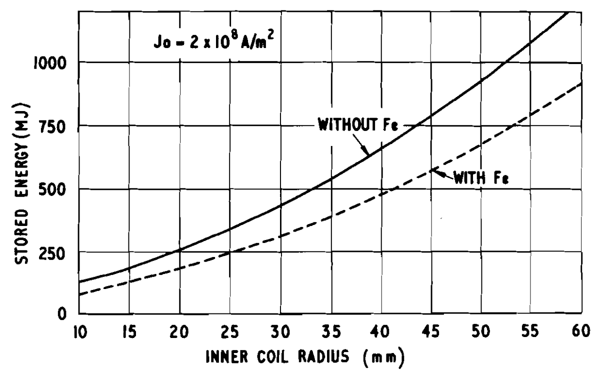


Fig.1. DIPOLE STORED ENERGY FOR 1000 GeV AT 4·5T

serious harmonics or non-linear field-rise. Saturated iron, closer to the conductor, *does* induce such effects, but may give greater savings in stored energy and materials. It may also give reduced outer dimensions, important at Ejection and Transfer: cf. §4 and §7. Within some reasonable outer radius, say 300 mm, it is evidently more attractive, for machine physics, to have unsaturated iron. In dipoles the amount of iron can be reduced vertically: for quads. the dimensions are equal in both planes.

The question of cold vs. warm iron only affects our arguments insofar as the different heat losses modify the cost estimates: we assume cold iron. We also assume that the magnets are cold-bore, so that no extra aperture is required for a cryostat.

3. Injection

For the 300 GeV conventional machine, CPS injection is envisaged at 10 GeV/c, and involves crossing γ_t in the main ring, so that apertures are determined by conditions at transition [1]. These apertures would be undesirable for the S/C machine[13].

Thus, in Type I solutions, we consider CPS operation at 28 GeV/c, above main ring transition.[14] This demands pre-bunching in the CPS, and 11-turn ***continuous ejection***[1]: it has not yet been verified that the consequent RF problems in the CPS can be solved satisfactorily. In the main ring, the beam-loading problem requires a 90° bunch-rotation scheme, leading to slight phase space dilution[16].

Residual S/C fields may present a serious objection to low injection energy. Adopting $\Delta B/B \simeq 1.5 \times 10^{-3}$ as our criterion of corrigible sextupole error at injection, predictions based on present-day 5μm S/C performance[2] indicate that it would be unwise to contemplate injecting below about 0.22T, (50 GeV/c).

Type II solutions circumvent these problems of low-field injection. In their place, they introduce the special difficulties of high-momentum transfer in the confined tunnel space, discussed in §7.

In assessing injected beam emittance, we take account of unexplained blow-up[6] in the CPS: Type I emittances at 28 GeV/c in the main ring become[1],

E_H/π = 2.3 µm x rad; E_V/π = 3.4 µm x rad.

The 90° bunch rotation determines momentum spread in the main ring[16]: for Q ≈ 21.75, we obtain $\Delta p/p \approx 1.6 \times 10^{-3}$. For Type II at 200 GeV/c:

E_H/π = 1.0 µm x rad: E_V/π = 0.5 µm x rad,

including a further factor 1.5 for mismatch and errors at transfer. Here, $\Delta p/p \approx 0.5 \times 10^{-3}$.

4. Ejection

4.1 Aperture for Resonant Ejection

So far, we have concentrated on third-integral, rather than integral, resonant slow ejection - on the grounds that closed orbit deviations may not be so serious near resonance for off-momentum protons.

The basic phase-space situation at S_1, the first (electrostatic) septum, is indicated in Fig. 2. Symon's theory[7] may be used to minimise the outer radius x_3, and to determine the corresponding capture efficiency. Fig. 2(a) typifies results[23] giving about 98% efficiency for the lattices studied so far: Fig. 2(b) shows the effect of varying the S_1 radius. A similar approach to integral resonance[8] is also indicated in Fig. 2(b).

Typically, for a 4mm beam radius, 98% efficiency is achieved when S_1 is located at about 15mm radius with 15mm aperture: the range of jumps is then 5-15mm.

During its last two turns the *maximum jump* proton of Fig. 2 must be held in good-field: hence the 30mm S_1 outer aperture is translated typically into 37.5mm elsewhere around the lattice. This demand is reduced if we relax the efficiency criterion. We are also looking into the possible advantages of a high-β lattice insertion at the S_1 position.

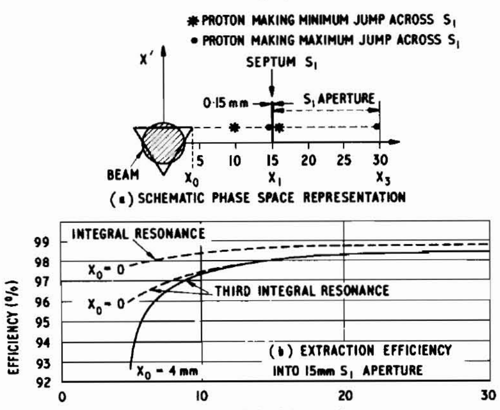


Fig.2. RESONANT EJECTION

For Type II machines, ejection is the aperture-determining factor, but for Type I the issue is not so clear-cut. With H-ejection, the S_1 radius may be inside the maximum injected profile by the amount

$$[(\alpha_p)_{max} - (\alpha_p)_{S_1}] \times (\Delta p/p)_{inj} + \delta_{co}$$

For each lattice, this radius is compared with x_1 of Fig. 2, and the greater value selected.

As will be seen in §6, final apertures for Types I and II solutions are not dramatically different, as a direct result of resonant slow ejection.

Finally, we remark that target-scattering ejection might be an attractive alternative for Type II solutions: since no resonant build-up is required, S_1 may be located closer to the beam. We have not yet assessed this technique for 1000 GeV.

4.2 Sextupole Errors

In line with studies carried out for the Brookhaven CMS[10], we have investigated the effects of sextupole errors in dipoles during vertical ejection. Fig. 3 shows the ejection separatrix for the MR-47 lattice[1] assuming a dipole field error $\Delta B/B = a_2(x^2 - y^2)$, with $a_2 = 1.67 m^{-2}$, (eg. 1.5×10^{-3} at 30mm radius), with and without correction. We conclude that errors up to this level may be corrected using one 80 (T/m^2) x m sextupole per period.

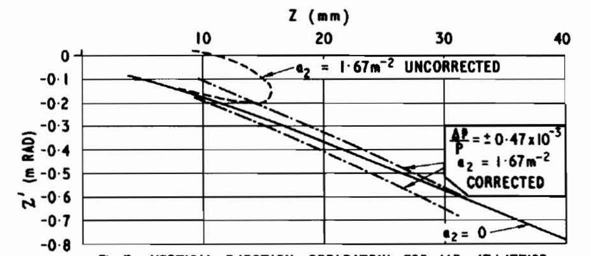


Fig.3. VERTICAL EJECTION SEPARATRIX FOR MR-47 LATTICE WITH AND WITHOUT CORRECTION OF SEXTUPOLE ERROR TERM $a_2 = 1{\cdot}67m^{-2}$

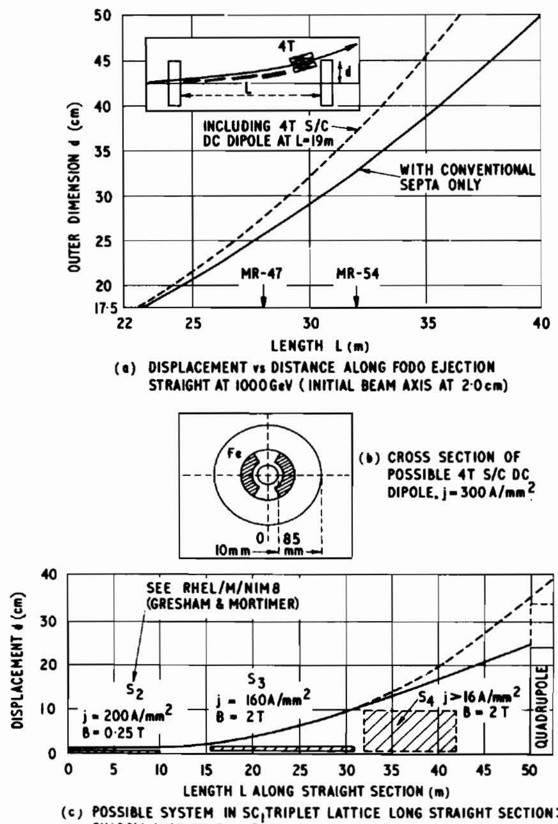


Fig. 4. EJECTION SYSTEM IN LONG STRAIGHT SECTION

4.3 Straight Sections and Outer Magnet Dimensions

Performance of conventional extraction elements at 1000 GeV places stringent limits on outer S/C magnet dimensions: for FODO lattices, Fig. 4(a) indicates that outer radii would have to be less than about 25cm in MR-47 and 33cm in MR-54[5].

The situation would be improved by using S/C elements, including a small 4 T DC dipole as the final element in the long straight[19]; cf. Figs. 4(a) and (b). As part of this study, calculations of septum magnet field shape have been carried out[18].

In the case of an SC_1 Triplet Lattice[22], Fig. 4(c) shows a possible scheme using conventional septa. The first two take the beam to 25cm, and a further typical septum gives a final displacement of 36cm.

5. C.O. Deviation, Sagitta, 'Bad Field'

In S/C as in conventional accelerators, the aperture allocated to remanent closed orbit deviation seems limited mainly by the monies devoted to the control sensors and correction system.

Simulating errors by a random, 0.5mm standard deviation, gaussian of quad. displacements, a rapid analytic method[9] of calculating c.o. correction has been applied. Allotting gaussians to the sensor misalignment, sensor resolution and corrector movement precision, - with 0.5mm, 0.5mm, and 0.1mm standard deviations respectively, δ_{co} may be reduced to about 5mm in both planes, with 98% probability, for lattices considered so far.

Sagitta allowances in S/C machines are worth examining more critically than in conventional ones, since H- and V- apertures are equally important. For the moment, we continue to consider dipoles about 6m or 7m long: cf. sagittae in Table I.

The §4 ejection arguments point to a *good field* of $\Delta B/B \leqslant 2 \times 10^{-3}$, consistent with the §3 residual field criterion: it seems that inner coil radii should be at least 10mm more than good field radii to achieve this tolerance. Hence, up to 40mm good field radius we allot 10mm ***bad field***: for larger dipoles we assume that 20% of aperture is bad field. These allowances may be a lower limit, particularly when the effects of higher multipoles are assessed.

6. Lattice Comparison

Table I lists some possible 1000 GeV lattices: the resulting apertures and stored energies are summarized in Table II. The Type II apertures are all determined by ejection, as are some Type I cases[24].

The implications of the Table II stored energies should be regarded in the following light:

i) If the constraints imposed by resonant slow ejection may be overcome, then the Type II apertures, uninhibited by injected beam size, hold out more hope of improvement.
ii) Residual field arguments also favour Type II.
iii) Since we have V-transfer in Type II schemes, then H-ejection is preferable, evading conflict between ejected beam and injection septum.
iv) Non-aperture criteria tend to favour Triplet Lattices: eg. straight section length (§4); ease of transfer (§7); fewer magnet types.

TABLE I - SOME 1000 GeV LATTICES

No.	DESCRIPTION	CELL No	γ_t	DIPOLE L (m)	SAGITTA (± mm)	Nos OF DIPOLES B_1	B_2	B_3	LS (m)
TYPE I - 28 GeV/c INJECTION Q = 21.75 :-									
1	MR-47 FODO[1]	108	20.3	6.02	3.1	186	192	396	28.8
2	MR-54 FODO[5]	96	19.5	7.13	4.3	144	168	336	33.3
3	SC_1 TRIPLET[22]	90	21.0	5.75	2.8	648	162	-	51.4
TYPE II - 200 GeV/c INJECTION Q = 27.75 :-									
4	MR-47	108	24.8	AS FOR LATTICE No 1					
5	MR-54	96	24.0	AS FOR LATTICE No 2					
6	SC_1	90	27.1	AS FOR LATTICE No 3					

TABLE II. FINAL APERTURE RADII,(mm) AND STORED ENERGY (MJ).

RADII INCLUDE 5mm CLOSED ORBIT DEVIATION, AND 10mm OR MORE 'BAD FIELD' ALLOWANCE (10mm UP TO 40mm BEAM OCCUPATION 'b' AND 0.25b WHERE b > 40mm)

LATTICE NO	EJECTION PLANE	B_1	B_2	B_3	F	D	STORED ENERGY (MJ)* DIPOLES	QUADS	TOTAL
1	H	56.4	42.0	50.5	53.9	34.8	680	10	690
	V	43.7	49.3	45.0	41.5	50.1	605	17	622
2	H	55.9	40.5	49.6	51.6	35.2	655	10	665
	V	44.7	50.3	45.2	41.2	51.3	620	14	634
3	H	49.0	47.8	-	46.4	40.8	669	32	701
	V	42.0	54.3	-	44.1	60.3	567	54	621
4	H	54.1	37.9	47.8	51.9	30.2	618	14	632
	V	32.6	46.2	41.4	28.4	47.2	498	20	518
5	H	57.1	37.7	49.4	53.3	28.3	648	14	662
	V	32.1	46.2	40.8	28.2	47.1	498	20	518
6	H	49.0	47.8	-	46.6	39.5	669	66	735
	V	41.0	57.9	-	43.9	65.8	569	125	694

*DIPOLE STORED ENERGY DETERMINED FROM FIG. 1 BROKEN CURVE. (INCLUDING -IRON) QUAD. STORED ENERGY FROM REF.(13) FIG.3, WITH NO ALLOWANCE FOR IRON.

For the present, we note the apertures required for MR-47 with transfer at 200 GeV/c, and H-ejection:- there are three dipole types, with inner coil radii of about 38mm, 48mm and 54mm. It is vital to examine every possible means of reducing these values: such techniques as target-scattering ejection and high-β lattice insertions are being assessed, as will be the effects of reducing ejection efficiency.

7. Special Problems of 200 GeV/c Transfer

For Type II solutions, Fig. 5 indicates the problem of siting an S/C ring in the proposed tunnel[1]. To leave adequate room for transfer, it would be advisable to locate the conventional machine as close to the floor as practicable.

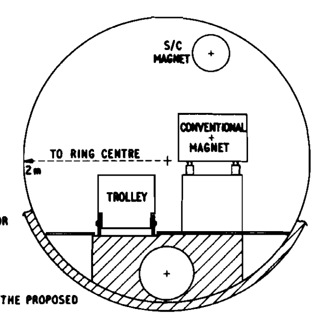


Fig.5. POSSIBLE LOCATION FOR S/C RING IN TYPE II SOLUTIONS

A NOTIONAL S/C MAGNET IS ILLUSTRATED IN RELATION TO THE PROPOSED MC/60 LAYOUT

For transfer between two MR-47 lattices, a possible scheme is illustrated in Fig. 6(a). Transverse phase-plane matching is achieved using two doublets. In the short distance available, a simultaneous momentum match is not possible, resulting in growth of effective emittances. If the transfer line simply contained one quad. near the normal lattice position, the emittance growth would be about 7% in the V-plane and 27% in the H-plane. The 200 GeV kicker and septum magnet parameters are reasonable in both machines.

A similar arrangement for SC_1[22] is shown in Fig. 6(b): the main difference is the absence of lattice quads to be avoided by the transfer line.

8. Machine Cycle, Power Requirements, Costs

8.1 Machine Cycle Considerations

We assume a minimum rise (and fall) time of 3 sec, since faster rise leads to unacceptable losses and rapidly increasing power. Then, for 10^{13} protons per pulse, the cycle time is given approximately by $t_{cyc} = (2t_R + t_{FT})$, and the mean intensity by $r = 10^{13}/t_{cyc}$ protons/s.

The other main parameter affecting the user is duty cycle. Here we include an empirical 75% efficiency factor: $d = 0.75\ t_{FT}/t_{cyc}$. Adopting some such criteria as $d \geqslant 20\%$ and $r \geqslant 10^{12}$/s., we get a possible range of cycle times between 8.2 sec and 10 sec: for example,

$$t_{cyc} = 10\ \text{s},\quad t_{FT} = 4\ \text{s},\quad r = 10^{12}/\text{s},\quad d = 30\%$$

The constraints of this situation would be relieved if multi-turn injection were possible - accelerating, say, 10^{14}p.p.p., and spilling over longer flat-top.

Without going into the resulting arguments on radiation damage and magnet ripple, we remark that normal multi-turn injection, with stacking in transverse phase space, may lead to large factors of emittance increase, and has not yet been studied in detail. It may be possible to stack in longitudinal phase space, but the consequent RF problems have yet to be examined.

8.2 Power Supplies

Stored energies in the region of 600 MJ with 3 sec rise time may eventually best be reached with S/C energy storage systems[11]. However, they also seem to be within the capabilities of conventional rotating plant. The former have not yet been developed to a stage where we may confidently predict their performance, limitations, and costs. Accordingly, we work on the assumption that the S/C ring would be powered by a number of MG sets[12]. Taking a current of 2kA in the superconductor, we assume a maximum voltage limitation of ±2.5 kV to ground.

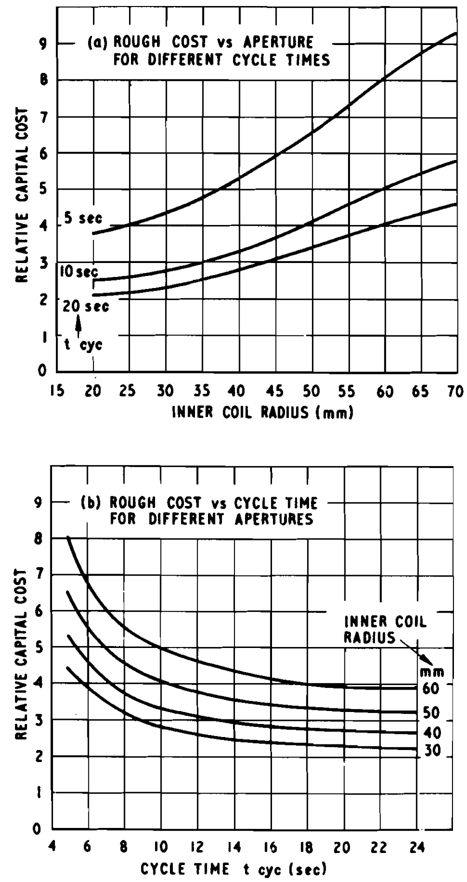
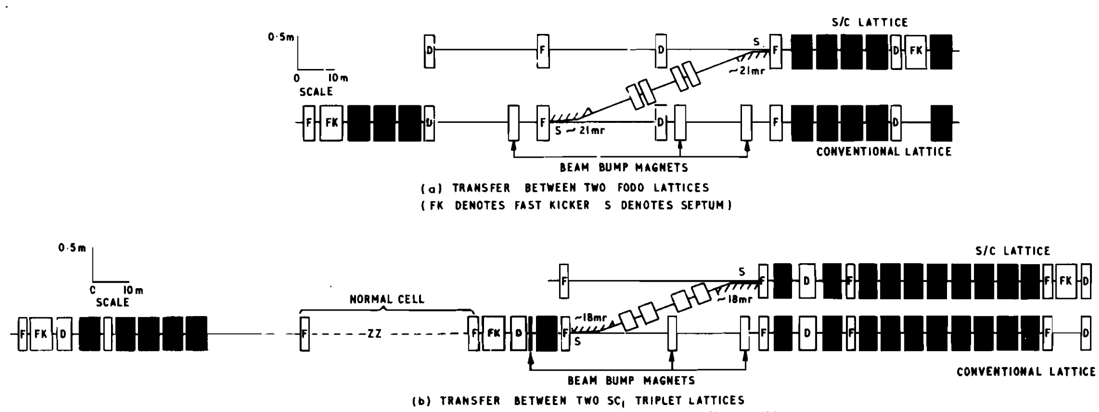


Fig.7. ESTIMATES OF RELATIVE CAPITAL COSTS



(a) TRANSFER BETWEEN TWO FODO LATTICES
(FK DENOTES FAST KICKER S DENOTES SEPTUM)

(b) TRANSFER BETWEEN TWO SC_1 TRIPLET LATTICES
(THERE ARE TWO FAST KICKERS IN THE CONVENTIONAL RING)

Fig. 6. SCHEMATICS OF BEAM TRANSFER

8.3 Costs

On this basis, comparative cost estimates have been carried out[12),20)] and Fig. 7 shows some results for 1000 GeV at 4.5T. To provide a rough gauge, one scale unit may be regarded as about 100 MSF, with a wide range of uncertainty at this stage; but the trends, as a function of aperture or cycle time, are significant. For example, with 10s cycle, there may be an 18% saving in going from 50mm to 40mm. Similarly, for 40mm dipoles, the saving in going from 10s to 14s cycle time would be about 13%.

These estimates emphasize the importance of reducing the dipole apertures by every possible means.

9. Further Options

We have noted the possibility of further variants, other than Types I and II: for example:-

- A new 60-100 GeV booster, interposed between CPS and main ring in the basic Type I scheme, would overcome the low injection field problem.

- As a variant on Type II, the S/C ring could be in a separate tunnel, (say under the original one), allowing independent lattice choice.

These options have not been investigated as they seem to be more expensive alternatives.

- A further option would invoke two S/C rings in the Type II scheme. The first would have small aperture, with no allowance for slow ejection: from it, protons could be fast-ejected into a 1000 GeV DC ring, from which slow ejection could be programmed flexibly[3),21)].

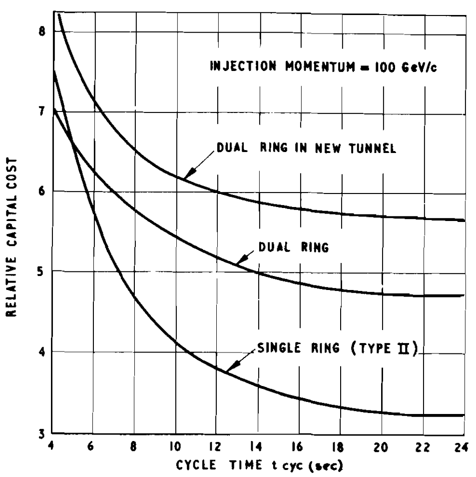


Fig.8. 'DUAL RING' COSTS
DIPOLE INNER COIL RADII :- SINGLE 50mm
DUAL { 25mm IN PULSED RING / 50mm IN D.C. RING

A brief costing study of this *dual ring* scheme has been carried out for particular parameters[21)]: results are summarized in Fig. 8. Compared with normal Type II, the dual ring scheme costs about 28% more for a 10s cycle, without considering the extra tunnel which would probably be required.

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DISCUSSION

P.F. SMITH: You have allowed a vertical distance of 1 m for transfer between the axes of the conventional and superconducting rings, thus requiring the latter to be situated very close to the tunnel roof. However, our first studies of the refrigeration distribution system indicate that a favourable scheme will involve a distribution pipe around the ring at a higher level than the magnet itself. Can one redesign the beam transfer scheme to reduce the 1 m figure, or do we need a tunnel of larger cross section?

N. MARSHALL KING: As mentioned in my talk, this diagram was not to be interpreted as a serious proposal, but was simply intended to indicate that a difficult problem is involved. A much more realistic engineering assessment is required. One possibility might be to site the conventional magnets closer to the floor, but I cannot comment on the practical difficulties involved. As John Adams remarked on Monday, a completely new tunnel for the superconducting ring would cost about 70 MSF, which may not be an extravagant fraction of the total cost. For example, we could consider a new tunnel underneath the original one, giving the advantage of independent lattice choice for the superconducting machine.

R. LEVY-MANDEL: We have to keep in mind that the first question to be answered is the possibility of putting superconducting magnets in the open gaps of the missing-magnet design, as has been pointed out by John Adams.

N. MARSHALL KING: Yes. The major difficulty here may prove to be the residual field problem: this may be enough to kill any Type I solution.

E.G. MICHAELIS: What assumptions have you made about flat-top operation, and have these been taken into account in your cost estimates?

N. MARSHALL KING: As a typical example, we consider a 10-sec cycle. With our assumption of 3-sec rise time, and 3-sec fall time, this leads to 4-sec flat top. We have not yet studied the flat top stability problems, beyond inserting an empirical 75% efficiency factor in quoting duty cycle.

With regard to the second part of your question, the flat top has indeed been taken into account in the cost estimating, for all the various cycle times.

G. BRIANTI: With FODO lattices, are the total apertures about the same for the cases of 28 GeV and 200 GeV injection?

N. MARSHALL KING: Yes, with present resonant slow ejection techniques. The largest ("B_1") dipole, the MR-47, typifies the situation: Type I and Type II apertures are not markedly different. However, the important point is the possibility of improving the ejection aperture requirement, for example, using high β insertions. Type II holds the opportunity of greater gains before the limit imposed by injected beam size is reached.

G. BRIANTI: Are your quoted ejection efficiencies theoretical ones given by (electrostatic septum thickness)/jump or are they more realistic?

N. MARSHALL KING: They are theoretical, but much more sophisticated than the simple first-order estimate you mention: they are based on Symon's theory. For instance, in the example illustrated, the range of jumps was from 5 mm to 15 mm across a 0.15 mm septum, giving about 98%. The simple formula would give a 7.5 mm jump for this case.