STORAGE RING GROUP SUMMARY

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1. INTRODUCTION

The Storage Ring Group set out to identify and pursue salient problems in accelerator physics for heavy ion fusion, divorced from any particular reference design concept. However, it became apparent that some basic parameter framework was required to correlate the different study topics.

Accordingly, three sets of skeleton system data were developed, starting from target estimates provided by R. Bangerter[1], repeated here as Table I along with some immediate implications on accelerated beam requirements.

Further definition of storage ring parameters involved feedback from the work in progress in the RF Linac Group[2] and the Final Beam Transport Group.[3]

As the Workshop progressed, ring parameters were modified and updated: Consequently, the accompanying papers on individual topics will be found to refer to slightly varied parameters, according to the stage at which the different problems were tackled.

1.1 Effects of Latest Target Data

In contrast to earlier HIF Workshops, the latest target data referred to lower kinetic energies exemplified by 5 GeV U^+ ions for 1 MJ

TABLE I
SAMPLE TARGET DATA SETS[1], U^{+1} IONS,
AND IMPLICATIONS ON ACCELERATED BEAM PARAMETERS

CASE		A	B	C
Beam Stored Energy	E(MJ)	1	3	10
Beam Kinetic Energy	T(GeV)	5	10	10
Total No. of Ions	$N(\times 10^{15})$	1.25	1.875	6.25
Pulse Time	t(ns)	20	40	70
Pulse Time at Peak Power	t_p(ns)	6	16	20
Pulse Length at Target	ℓ_b(m)	1.25	3.49	6.10
Power in Pulse Peak	P_p(TW)	100	150	300
Beam Stored Energy in Peak	E_p(MJ)	0.6	2.4	6.0
No. of Ions in Peak	$N_p(\times 10^{15})$	0.75	1.5	3.75
Peak Current	I_p(kA)	20	15	30
Average Current in Pulse	I_{av}(kA)	10	7.5	14.3
Beam Momentum	P(GeV/c)	47.349	67.334	67.334
γ		1.0226	1.0451	1.0451
β		0.2089	0.2906	0.2906
$\beta\gamma$		0.2136	0.3037	0.3037
Beam Radius at Target	γ(mm)	2.0	2.5	4.0
Approx. Target Gain	g	8	30	120

stored energy in the beams (Case A), and 10 GeV U^+ ions for either 3 MJ (Case B) or 10 MJ (Case C) stored energy. For the great majority of storage ring problems, Case A was identified to be extremely difficult, due to space charge effects at the low kinetic energy. Most of the later detailed work was carried out for Case B, where the problems already looked tractable.

Another striking aspect of the target data was the much more conservative estimate of target gain than heretofore: the basis for a heavy ion fusion demonstration plant now seemed to be above 1 MJ, and the 3 MJ case looked much more appropriate in that context.

On the other hand, encouraging features of the new target data concerned the larger pellet radii and longer pulse times than had been quoted previously, leading to considerable easing of the space-charge-dominated accelerator problems.

1.2 Ion Charge State

From the outset, the decision was made to consider singly-charged ions exemplified throughout the study by U^{+1}. Although higher charge states were not analyzed in detail, the space-charge problems encountered were sufficiently formidable that, as a general concensus of opinion, anything other than a very low charge state was regarded with some scepticism.

1.3 Basic Framework

The basic framework envisaged for a storage ring system involved the following features:

(i) Injection from a 'funnelled' RF linac system, starting from 16 ion sources, each providing about 20 mA. Allowing for losses in the linac system, a total linac current at injection, I_{lin} = 300 mA was taken[(2)].

(ii) Stacking a total of S turns into each of N_{SR} storage rings, accomplished via $\sqrt{S}$ turns into each transverse plane.[(4),(5),(6)] In parctice, this probably requires one or more large accummulation rings feeding into the smaller storage rings in turn.

(iii) Bunching and Bunch Compression in the storage rings to give a number of bunches 'N_{bunch}' and a compression factor 'C_{SR}' in each ring.[(13),(14)]

(iv) Ejection of each bunch into a separate beam line to give a total number of beams $N_b = N_{bunch} \times N_{SR}$ directed towards the target.

(v) Further Bunch Compression in the beam lines by a factor 'C_b'.

The final current reaching the target is therefore given by:

$$I = I_{lin} \cdot S \cdot C_{SR} \cdot C_b \cdot N_b . \qquad (1)$$

As storage ring bunch compression studies progressed,[(13)] it became clear that a factor C_{SR} greater than about 7 would be difficult to achieve, whereas the total compression factor $C_{SR} \times C_b$ needed to be about 50. Accordingly, the factor C_b = 50/7 was assumed to be accomplished in the final beam line, notionally using induction linac modules. The consequences of this latter requirement (e.g., on beam transport length and power required) were not analyzed in detail by the Storage Ring Group.

Inserting the above values for I_{lin}, C_{SR}, and C_b, the final current at the target is given by:

$$I_{kV}(kA) = 0.0147 \times S \times N_b \qquad (2)$$

A glance at Table I shows that the product $S \times N_b$ has to be in the range 500-1000 for all three cases: immediate problems were therefore to examine how space charge limits in the beam lines and storage rings would determine the product $N_b = N_{bunch} \times N_{SR}$, and how emittance dilution during stacking would limit the number of possible injected turns S.

1.4 Problems Identified and Studied

The following broad pattern of problems emerged during the course of the Study. All References given are to other papers in these Proceedings.

(i) Injection
Emittance and Momentum Spread from Linac[2]
*Multi-turn stacking in 2 Transverse Planes: Emittance Dilution[4],[5]
R.F. Stacking[6],[7]
*Beam loss on Septa[8]

(ii) Accumulation and Storage
Laslett Tune Shift
*Longitudinal and transverse microwave instabilities: thresholds and growth rates[9],[10],[6]
Beam loss and lifetime due to Ion-Ion charge exchange and ionization scattering[11],[6]
Storage Ring Parameters

(iii) Bunch Compression[13],[14]
*Compression factor attainable: RF system requirements
momentum spread
Integer and Half-Integer Resonance Crossing: Non-Linear Effects and Emittance Growth.

(iv) Extraction
Mechanism: Kickers
Possible Beam Loss

(v) Final Beam Line and Focussing onto Target
Space charge limit in beam lines
*Effective Emittance Growth due to Aberrations: Uncorrected Momentum Spread.
Power Density to First Wall
Neutron Loss Through Beam Ports.

Some of these problems were seen to be serious, particularly those marked with an asterisk, but none was identified as being insuperable for beam energies of 3 MJ or above.

2. EMITTANCE MOMENTUM SPREAD BUNCH LENGTHS

2.1. Emittance at Injection

From the work of the RF Linac Group,[2] a value of emittance at the end of the injector was given:

$$\varepsilon_{lin} = 1.5 \times 10^{-6}/\beta\gamma(\mathrm{m}). \tag{3}$$

(All emittances here are quoted in their un-normalized form, and without the factor π).

After stacking $\sqrt{s}$ turns in each plane, the storage ring emittance may therefore be written as:

$$\varepsilon_{SR} = 1.5 \times 10^{-6} \cdot D_\varepsilon(s) \cdot \sqrt{s}\ /\beta\gamma \quad (\mathrm{m}), \tag{4}$$

where D_ε is a dilution factor depending on the number of stacked turns. At the workshop, it was judged that the minimum value for D_ε should be 1.4, and the criterion was adopted that for $\varepsilon_{SR} = 60 \times 10^{-6}$m,

$$D_\varepsilon = 40\beta\gamma/\sqrt{s} > 1.4 \tag{5}$$

Further discussions of this topic will be found in References (4) and (5), and the final allowances arrived at during the Workshop are listed in Table VII.

2.2 Emittance in Final Beam

Turning to the far end of the system, emittance at the target is determined mainly by the target radius 'r', the reaction vessel radius 'R_v' and the beam port radius 'a'. That is, the final beam line emittance is given approximately by $\varepsilon_b \approx ar/R_v$.

However, it was felt that some allowance should be made for aberrations in the beam line. For example, if there were an effective uncorrected momentum spread $(\Delta p/p)_u$ in the beam, then since all of the beam should hit the target,

$$\epsilon_b \approx a[r - a(\Delta p/p)_u]/R_v = a\, r_{eff}/R_v \qquad (6)$$

That is, the on-momentum component of the beam should be focussed on to a smaller target and radius, r_{eff}, leaving $a(\Delta p/p)_u$ for the chromatic effect. The criterion adopted was that $(\Delta p/p)_u = 2 \times 10^{-3}$ was a reasonable assessment for a beam whose total $(\Delta p/p)$ was $\pm 10^{-2}$, so that with $a = 0.15$ m, $r_{eff} = r - 0.3$ mm.

On subsequent reflection, this may only be one of several allowance that should be made, and more work is required on the final focussing problem.

At one point in the study, limitations on the choice of 'R_v' and 'a' imposed by power density deposition at the first wall, and by constraints on the neutron flux through the beam ports, were considered. However, it was felt that insufficient information was available about future improvements in reaction vessel design, and that uncertainties about the degree of conservatism in the gain estimates made it difficult to form any worthwhile criteria on these topics. The final parameters adopted are summarized in Table II.

2.3 Emittance in Storage Rings

As will be seen from the last line of Table II, a factor 1.2 effective dilution was allowed between storage ring and beam line, to take account of mismatch due to non-linear effects after bunch compression.(13) This factor was chosen rather arbitrarily and more work is required to confirm or modify it. The resulting value of $\epsilon_{SR} = 60 \times 10^{-6}$m, consistent with current ring design experience, was selected for all three cases.

2.4 Momentum Spread

The value of $(\Delta p/p)$ at injection, provided by the RF Linac Group,(2), was taken to be $\pm 2 \times 10^{-4}$. Similarly the Final Beam Transport Group(3) provided the value $(\Delta p/p)_b = \pm 10^{-2}$ as the likely spread that could be handled in the final beam line.

Starting from the above $(\Delta p/p)_{inj}$ value, the bunch compression studies(13) for a compression factor 7, led to the value $\pm 4 \times 10^{-3}$ at injection from the storage rings. This is not simply $7 \times (\Delta p/p)_{inj}$, due to the mechanism of phase space rotation during compression(13). Summarizing:

TABLE II

FINAL BEAM EMITTANCE

CASE		A	B	C
Target Radius	r(mm)	2.0	2.5	4.0
Effective "	r_{eff}(mm)	1.7	2.2	3.7
Reaction Vessel Radius	R_v(m)	3.54	4.58	7.71
Beam Port Radius	a(m)	0.15	0.15	0.15
Beam Line Emittance	$\epsilon_b(\times 10^{-6}$m)	72	72	72
Storage Ring "	$\epsilon_{SR}(\times 10^{-6}$m)	60	60	60

It will be seen that the beam port radius was kept at what seemed to be a reasonable maximum value of 15 cm, consistent with attainable gradients in the final focussing quadrupoles, and that the beam emittance was kept at 72×10^{-6} m for all three cases.

$$(\Delta p/p)_{inj} = \pm 2 \times 10^{-4}$$
$$(\Delta p/p)_{ej} = \pm 4 \times 10^{-3}$$
$$\text{Max.}(\Delta p/p)_b = \pm 10^{-2}$$

As remarked in Section 2.2, an assumed effective uncorrected spread at the target was taken to be:

$$(\Delta p/p)_u = \pm 2 \times 10^{-3}$$

2.5 Bunch Lengths

Finally to set the scene for storage ring parameters, the bunch lengths at target (cf. Table I), combined with the selected compression factors in beam lines and storage rings, lead to the following values as shown in Table III.

3. CHOICE OF N_b, N_{SR}, S, AND STORAGE RING PARAMETERS

Following the argument of Section 1.3, embodied in eqn. (2), the first obvious constraints on the numbers N_b and N_{SR} to be considered involved the Courant-Maschke formula for space-charge-limited power in the beam lines, and the Laslett tune shift formula for space charge during accumulation in the rings.

3.1 Space Charge Limit in Beam Lines

The Courant-Maschke formula for a periodic focussing channel was used in the form:

$$P_b(\text{TW}) \leqslant 1687 \times (\beta\gamma)^{7/3} \cdot (\gamma - 1) \cdot (A/q)^{4/3} \cdot \epsilon_b^{2/3} \cdot B_Q^{2/3} \,, \qquad (7)$$

with A = 238, q = 1 for U^{+1} ions, and using B_Q = 4T for the field on the superconducting quadrupole poletips. The minimum tolerable number of beam lines $(N_b)_{min}$ is then given by

$$N_b > P_p/P_b \,, \qquad (7a)$$

where P_p is the peak power in the total beam pulse, quoted in Table I. Results for the 3 sample cases are quoted in Table IV.

TABLE III
BUNCH LENGTHS

CASE		A	B	C
Bunch length at target	ℓ_b(m)	1.25	3.485	6.10
Bunch length at S.R. Exit	50 ℓ_b/7(m)	8.93	24.89	43.57
Bunch length in S.R.	50 ℓ_b(m)	62.5	174.25	305

TABLE IV
SPACE-CHARGE-LIMITED POWER IN BEAM LINES

CASE	A	B	C
P_b(TW)	5.9	26.9	26.9
P_p(TW)	100	150	300
$(N_b)_{min}$	17	6	12

Each of the N_b beam lines is derived from a compressed bunch in a storage ring.

3.2 Laslett Tune Shift During Accumulation

The usually-accepted limit $\Delta\nu \lesssim 0.25$ due to space charge during accumulation and storage in the rings was expressed in the simplified form:

$$\Delta\nu = \frac{q^2}{A} \cdot \frac{1.5347 \times 10^{-18}}{2\pi} \cdot \frac{n_{SR}}{\epsilon_{SR}} \cdot \frac{\beta}{(\beta\gamma)^3} \lesssim 0.25 \quad (8)$$

for the same ϵ_{SR} in both planes, and where n_{SR} is the number of ions in each storage ring. For A = 238 and q = 1, as before,

$$n_{SR} \lesssim 2.436 \times 10^{20} \cdot \epsilon_{SR} \cdot (\beta\gamma)^3/\beta, \quad (8a)$$

so that the minimum acceptable number of rings $(N_{SR})_{min}$ is given by N/n_{SR}, with N given in Table I. The resulting calculations give:

TABLE V

LASLETT TUNE SHIFT LIMIT IN RINGS

CASE	A	B	C
$(n_{SR})_{min} \times 10^{14}$	6.82	14.1	14.1
$(N_{SR})_{min}$	2	2	5

It should be remarked that a more accurate analysis shows a rather stricter constraint during the stacking process, when only one of the phase planes has been filled.

3.3 Longitudinal Microwave Instability

One of the most serious problems studied during the Workshop concerned the longitudinal microwave instability, which occurs due to coupling of the beam with its containing environment and manifests itself by a momentum spread blow-up. The problem is discussed in detail in References (9), (10), and (6).

The instability is characterized by a beam current threshold defined by the Keil-Schnell criterion:

$$I_{ks} \lesssim |n| \cdot \beta^2\gamma \cdot (\Delta p/p)^2 \cdot (AM_p/q) \cdot /(Z_n/n). \quad (9)$$

Taking $|n| \simeq 1$, $\Delta p/p = 2.8 \times 10^{-4}$ corresponding to full width at half maximum during bunch compression[13], A = 238, q = 1, and M_p = 938 MeV, the remaining difficulty is to estimate the effective coupling impedence (Z_n/N). Given this number, the average current per storage ring would be limited to

$$I_{av}/50\ N_{SR} \lesssim I_{ks} \quad (9a)$$

where I_{av} is taken from Table I; hence there is a lower limit on the number of rings N_{SR} if the instability threshold is not to be reached.

During the course of the study, the best estimate that could be made for (Z_n/n) was to say that it might not be too different from the PS and ISR value of 25Ω. Accordingly, this value was selected as a criterion, "faute de mieux", and led to the limits summarized in Table VI.

TABLE VI

KIEL-SCHNELL THRESHOLD FOR (Z_n/n) = 25Ω

CASE	A	B	C
I_{ks}(Amp)	31.8	63.16	63.16
$(N_{SR})_{min}$	7	3	5

Hence, compared with the Laslett tune-shift limit, this criterion determined a rather stricter limit on the minimum number of rings.

Lively discussion of this topic was pursued throughout the Workhsop, and by the end of the second week it was agreed that the coupling impedance for heavy ion rings could be 40-100 times greater than the above value: in other words, the instability could not be avoided. Attention then shifted to the growth time for the instability, and it was argued that the effect might not be serious under 10 ms or more, (less than the required storage time). These arguments are considered in detail in References (9), (10), and (6): however, by the end of the Workshop, the limitation propounded in Table VI was the best that could be put forward, and was incorporated into the parameter framework.

Further exploration of this problem is required to determine the growth time in a likely heavy ion system, and further theoretical or experimental contributions would be extremely valuable.

3.4 Storage Ring Lattice Considerations

To determine the minimum framework for a storage ring driver system, two further criteria are required, referring to the ring lattice:

(i) Dipole Field: $B \simeq 10P/3\rho \leq 5T$ (superconducting), leading to $\rho(m) \approx 2P/3$, (with P in GeV/c).

(ii) Circumference Ratio: $R/\rho \gtrsim 1.5$, leading to $C = 2\pi R \gtrsim 50 \cdot \ell_b N_{bunch}$

These assignments determine a minimum number of bunches, $N_{bunch} = N_b/N_{SR}$. Incorporating them into the range of constraints outlined above, the final assessment of minimum storage ring system was arrived at as follows:

TABLE VII

MINIMUM STORAGE RING SYSTEMS

CASE	A	B	C
$(N_{bunch})_{min}/SR$	5	3	2
$(N_{SR})_{min}$	7	3	6
$(N_b)_{min}$	35	9	12
$50\ell_b(m)$	62.5	174.25	305
C(m)	312.5	522.75	610
R(m)	49.74	83.20	97.08
ρ(m)	31.6	44.9	44.9
R/ρ(m)	1.57	1.85	2.16
B(T)	5	5	5
S	20	57	81
D_ε	1.91	1.61	1.35

It should be emphasized that these are 'minimum' systems, in the sense that the numbers of rings and beam lines are the minimum possible to avoid the various limitations. The space charge problems become less severe when larger values of N_{SR} and N_b are selected. This is already evident with Case C, where larger N_b is required in order to reduce S and raise D_ε above the minimum level 1.4 quoted at the Workshop. For example, the following choices for Cases B and C are possible, and would reduce the requirements on injected current, permit a larger dilution factor, and allow operation further from the space-charge limits in rings and beamlines.

CASE	N_{bunch}/SR	N_{SR}	N_b	S	D_ε	I_{lin}(mA)
B	3	6	18	36	2.02	231
C	3	10	30	36	2.02	265

4. FURTHER PROBLEMS

Most of the problems listed in Section 1.4 have already been discussed in the course of Sections 2 and 3, but four of them have not yet been referred to. They are as follows:

4.1 Beam Loss on Septa[8]

During the course of considering the injection process, the problem of beam loss on septa emerged as a severe constraint in high-intensity heavy ion machines. Due to their short range in material, even a small fraction of the heavy ions in the injected beam lost on a septum may vaporize the material, and the resulting 'black cloud' of vapor may destroy the following beam. The problem is described in detail in Reference (8), taking the 3MJ case B with $N_{SR} = 3$ as an example.

Expressed at its worst, the effect is that the tolerable fractional beam loss is of order 10^{-5}. Less dramatically, it may be said that the beam halo at the septum should be less dense than the central beam by a factor 1330; and this factor is reduced if the number of storage rings is increased.

This constraint was recognized as a particularly severe feature of heavy ion storage rings, and detailed numerical studies are needed to examine whether it may not be the determining factor in the choice of N_{SR}.

4.2 Beam Loss from Charge Exchange Scattering

Newly available data on the cross-section for charge-exchange scattering was used to assess the importance of this effect on determining the tolerable lifetime in heavy ion storage rings. The detailed analysis is described in References (11) and (6).

Taking a conservatively-large estimate of the cross-section for U^+ ions, beam loss for the cases listed in Table VII would be a few percent during the filling time. Although it is not clear what loss is tolerable around the ring, this effect also suggests that a larger value of N_{SR} is preferable. Again, more detailed numerical studies and more experimental evidence on cross-sections is desirable.

4.3 RF Stacking

As an alternative (or an addition) to multiturn stacking in transverse phase space, RF stacking was considered, and interesting schemes were described by the Japanese members of the Group[6], [7]. Although such schemes have considerable attraction, it was generally felt that the long filling times make them unsuitable for the HIF systems considered at the Workshop.

4.4 Ejection Studies

The ejection problem for heavy ion storage rings was examined in terms of normal fast ejection techniques. Apart from the stipulation that large full-aperture kickers would be required, no serious problems were identified: the septum-loss problem described in Section 4.1 is avoided.

5. CONCLUSIONS

The Workshop served to clarify the major constraints involved in designing a storage ring system for heavy ion fusion, and to identify several serious and fascinating problems.

It was generally agreed that longer-term studies of these interesting topics was very desirable, if resources could be made available at the different accelerator laboratories: theoretical, numerical, and experimental studies where appropriate could be identified over a wide range of topics.

Many of the problems are common to all modern high-intensity accelerator and storage ring designs, but a few are peculiar to or particularly serious in, heavy ion machines: for example, beam loss on septa, charge exchange scattering loss, high bunch compression. Although seen to be severe, none of these problems was identified to be insuperable.

REFERENCES

All of the following papers appear in these Proceedings.

(1) R.O. Bangerter. Sample Target Data

(2) RF Linac Group. Summary Report

(3) Final Beam Transport Group. Summary Report

(4) R.J. Burke. Storage Ring Injection

(5) N. Takeda and S. Fenster. Study of Inter-Beam interaction in Injection Processes at the Space Charge Limit.

(6) T. Katayama, A. Noda, N. Tokuda, Y. Hirao. Beam Injection and Accumulation Method for Heavy Ion Fusion Storage Rings.

(7) Same authors. Design Study of an Accelerator for Heavy Ion Fusion.

(8) L.W. Jones. Beam Scraping Problems in Storage Rings: The Black Cloud.

(9) D. Möhl. Longitudinal Beam Stability in Heavy Ion Storage Rings.

(10) S. Fenster. Longitudinal Microwave Instability.

(11) J.R. Le Duff and J.R. Maidment. Beam Loss in the Storage Ring Complex Due to Charge Exchange Scattering.

(12) T. Katayama, A. Noda and Y. Hirao. Numatron and TARN.

(13) M. Cornacchia and G.H. Rees. Bunch Compression in Heavy Ion Fusion Storage Rings.

(14) J.R. Le Duff. Integer Resonance Crossing in H.I. Accumulator Ring.