Title
SUMMARY OF THE WORKING GROUP ON HIGH CURRENT TRANSPORT AND FINAL FOCUS LENSES

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SUMMARY OF THE WORKING GROUP ON HIGH CURRENT TRANSPORT AND FINAL FOCUS LENSES*

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Introduction

The group reviewed recent work, and then addressed itself to relating the current understanding of relevant beam transport effects to the four reference concepts. In addition there was discussion on plans for future experimental and theoretical work.

Discussions covered the following topics:

Transverse instabilities on intense beams through periodic focusing systems,

Evaluation and correction of chromatic aberrations in the final beam transport lines,

Evaluation and correction of geometric aberrations due to quadrupole fringe fields,

Ion focusing by electrons.

To evaluate the current reference concepts, the group concentrated on three salient characteristics of the transport and focusing systems:

The zero-current transverse oscillation phase-advance per period and its space-charge induced depression,

The momentum spread in the beam,

The beam emittance in the final transport.

The group established approximate criteria for safe values of these three parameters assuming "no correction" or "correction" as currently envisaged. These criteria were compared with values quoted for the reference designs. While this exercise was rather imprecise, we believe it served to delineate roughly some of the most important requirements, and point to changes needed in the present designs.

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Transverse Instabilities

Instabilities of intense beams in periodic transport lines have been investigated through parallel analytic and computer-simulation approaches[1,2] with impressive agreement. The results can be described in terms of the betatron oscillation phase advance per period -- σ_0 in the zero intensity case, and σ in the presence of space charge. During the bunch compression process σ decreases monotonically with increasing current, and the practical importance of these studies is the charting of relatively safe values of this parameter.

The instabilities are characterized by the electrostatic potentials arising from density perturbations. Potentials of second order in the transverse coordinates are envelope perturbations. A result of the analytic work is that these instabilities may be avoided if the zero-intensity phase σ_0 is 90° or less.

For a Kapchinskij-Vladimirskij (K-V) distribution, work by Haber and Laslett has uncovered very troublesome third-order instabilities for σ-trajectories starting at $\sigma_0 = 90$ degrees, that center at a tune depression $\sigma \approx 46°$, and begin at 57.5°. Thus a $\sigma_0 = 90°$ transport system can probably only operate in the range $90° > \sigma > 60°$, which strongly limits the maximum transportable current. It appears likely at present that substantially more current can be transported by choosing a transport system that operates in the range from $\sigma_0 = 60°$ down to a final phase σ not less than 24°. In such a system the third-order instabilities do not occur at all, and higher-order ones appear only below 24°.

The promising $\sigma_0 = 60°$ system has not received as much attention as has the 90° system. Such work is very much needed and is now in progress.

Another important area for future work is the simulation of beams with non K-V distributions. The K-V distribution has been used because it leads to linear space charge forces which make the analysis far more tractable. Because of the good agreement between theory and simulation with the K-V distribution, one may have confidence in simulation studies done with other more realistic distributions.

The group concluded from the work done on this subject, that based on present knowledge, long transport lines for Heavy Ion Fusion should be designed to operate either in the range $90° > \sigma > 60°$ or $60° > \sigma > 24°$, with the latter promising higher current, but being less certain until further studies are completed.

Final Focusing

By this phrase we designated that part of the transport system that carries the beam from a storage ring or periodic transport line onto the target.

1. Linear beam matching - The system must accomplish first-order beam-matching between the periodic line and the target, so that all particles within the transverse emittance ellipses of the periodic system are

focussed to the target spot size, taking account of the expected momentum spread.

2. Chromatic effects - The system must be adequate to handle the expected momentum spread considering second-order chromatic effects. The group classified systems to have moderate or high confidence levels depending on whether sextupole corrections are required or not.

   The allowed momentum spread is determined by the estimated size of second-order chromatic transfer matrix elements between the entrance to the final lenses and the target. One finds

$$\frac{\Delta p}{p} \gtrsim \frac{0.2 r_T^{\,2}}{\varepsilon L}$$

   where r_T is the target radius, L is the distance from the target to the center of the lenses, and ε is the unnormalized emittance/π. Beam line examples worked out at ANL[7] and LBL are consistent with the above expression.

3. Geometric aberrations - in the final lenses limit transverse emittances. From work by Neuffer[5] one finds a limit that depends on various system parameters. One way of writing this is

$$\varepsilon \lesssim 0.15\ r_T^{5/4}\ \rho^{-1/4}$$

   where ρ is the radius of curvature in a field equal to that of the quadrupole pole tip.

4. Corrections - A beginning has been made on methods to reduce chromatic and geometric aberrations in beam line examples. So far this work has ignored space charge effects, and the complications that these will introduce account for the group's caution in predicting dramatic improvements.

   a) Chromatic Corrections - In one example at ANL of chromatic correction,[7] two sextupole pairs are used. Runs were made using the program DECAY TURTLE,[8] which gave 40% transmission of a ± 1% momentum spread beam onto a 1 mm target, representing a factor of two improvement due to the sextupoles. Similar work is in progress at LBL, using four sextupole pairs.

      Another approach was reported by J. Steinhoff,[10] who developed a search computer program to adjust the parameters of a large number of quadrupoles so as to maximize the transmission of a large sample of particles onto a target spot.

      In the light of such work in progress, and aware of space-charge complications, the group felt that at this time one might predict a factor of three improvement with corrections.

b) Correction of geometric aberrations - Analysis of geometric aberrations from quadrupoles and their correction with octupoles have been made by S. Fenster[8]. He shows that for point-to-point focusing there are four third-order aberrations to be corrected, of which three are independent. An example has been worked out in which six octupoles are placed among the final lenses. He succeeded in cancelling the relevant coefficients, but the system has not yet been tested with ray tracing. Ray tracing is essential here for two reasons: first, in systems with large aperture quadrupoles, higher order aberrations can produce effects as large as third-order (octupole) effects; and second, the non-linear part of space charge effects may be important. Nevertheless, it is the general belief of the group that suitable compensation of geometrical aberrations can be designed into the system, and therefore, as with chromatic corrections, the group predicted that corrections may allow a factor of three increase in emittance, or $\epsilon \lesssim 0.5\, r_0^{5/4}\, \rho^{-1/4}$.

Implications for the Reference Designs

An attempt was made to compare the values of tune depression, momentum spread, and emittance suggested above with those of the reference designs, so far as these were known. The time available for this exercise was very limited, so the results should not be taken literally, but rather as indicating areas requiring future attention. The results are summarized in Table I. The numbers on the first line are those currently predicted by the designers, those bracketed below recommended values (without/with) corrections.

We see that Hearthfire II has a very good (small) momentum spread but somewhat large emittance, as does Hearthfire II; the latter also has too much space-charge tune depression. The numbers given for both linac systems satisfy the criteria, though chromatic correction is needed for the rf linac.

Table I - Parameters of Reference Designs Relevant to Transport and Final Focusing*

	Hearthfire II	Hearthfire III	RF Linac	Induction Linac
Phase advance per period at zero current σ_0 (deg)	-	60	60	60
		(60)	(60)	(60)
at maximum current σ (deg)	-	11	24	24
		(24)	(24)	(24)
Momentum spread at final lenses $\Delta p/p$ (%)	0.035	0.25	0.5	0.1
	(.12/.36¢)	(.11/.33)	(.14/.42)	(.3/.9)
Emittance/π per beam (unnormalized) ε(cm-mrad)	4.4	4.75	6.0	0.75
	(1.1/3.3)	(1.1/3.3)	(10/30)	(1.1/3.3)
Emittance/π (normalized) ε_N (cm-mrad)	2.1	2.85	3.0	1.5

*The numbers in brackets are values suggested by criteria in the text, (without/with corrections).

Other Topics

1. Electron Focusing - Possible use of electrons to focus the ion beams was discussed. An account of the theory of the Gabor Lens, in which the electrons are confined by a solenoid, was given by A. A. Irani,[11] and R. Mobley discussed experience with these lenses at BNL. Gabor lenses give quite linear focusing. The scaling is such that they will be most useful at low ion energies.

   Another electron focusing scheme was presented in a formal talk by S. Humphries,[12] who gave further details to the group.

2. Transport Experiments - M. Reiser gave a talk on plans at the University of Maryland to set up an experimental 40 period electron transport line to observe emittance growth at high current. Similar experiments with heavy ions are being prepared at ANL and LBL. These experiments will then be compared with numerical simulation predictions.

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This summary is a very imperfect attempt to summarize the hard work of the participants of the High Current Transport and Final Focus Lenses group listed below:

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S. Fenster	(ANL)	D. Neuffer	(LBL)
A. Garren	(LBL)	S. Penner	(NBS)
I. Haber	(NRL)	M. Reimer	(Univ. of Maryland)
S. Humphries	(SLA)	L. Smith	(LBL)
A. A. Irani	(BNL)	J. Steinhoff	(Grumman Aerospace)

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