HEAVY ION ACCELERATOR STUDY SESSION

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Objective

To study the physics of high-intensity heavy-ion accelerators to assess their promise as ignitor systems for inertially confined fusion.

Participation

Approximately one hundred accelerator scientists participated in the study session held at the Claremont Hotel, Oakland, California for two weeks during the period October 29 to November 9, 1979.

Organization

The study session was jointly sponsored by the Office of Inertial Fusion, (OIF) U.S. Department of Energy and the Lawrence Berkeley Laboratory, (LBL). The chairman of the conference was Professor Burton Richter, Stanford Linear Accelerator Center (SLAC). The organizing committee was chaired by W.B. Herrmannsfeldt, SLAC, and T. Godlove, OIF. Other members of the organizing committee were: A. Maschke and E. Courant, BNL, R. Martin and T. Khoe, ANL, and D. Keefe and L. Smith, LBL.

The study was divided into five working groups with attendees participating in one or more of these according to their specific interests and areas of specialization. Chairmen for these groups were chosen from among the attendees who were not part of one of the funded OIF heavy-ion fusion (HIF) programs. (More than half of the attendees were from programs other than HIF, including universities, foreign countries, high-energy physics, etc.) The working groups and their cochairmen were:

Low-beta Accelerators: R. Jameson, LASL and P. Lapostolle, France.

(Beta refers to the velocity in units of the velocity of light, v/c.)

Linear Accelerators: S. Penner and M. Wilson, both NBS.

Storage Rings: L. Teng, FNAL, E. Courant, BNL, and N. M. King, Great Britain.

Final Transport in Vacuum: A. Garren, LBL and I. Hofmann, West Germany.

Final Transport in Gas: C. Olson, SLA.

Background

This was the fourth in the series of annual workshops held to study the subject of heavy ion accelerator drivers for inertial fusion. Since the status of the field has changed rapidly during this period, the purpose and style of each of these sessions has also changed.

The first Claremont meeting, held in the same hotel in 1976, actually preceded formal funding for accelerator laboratories for HIF. This study was held to test the validity of early claims by proponents that HIF was in fact feasible, and to identify the most promising techniques and most critical questions.

The second workshop, held at BNL in 1977, saw a multitude of proposed systems and subsystems being sorted out to enable the community to better concentrate on comparable approaches. Some of the theoretical studies, such as the space charge limits for beam transport, began to show some progress.

The third workshop, held at ANL in 1978, resulted in over 400 pages of technical proceedings complete with a comparative evaluation of the complete driver systems proposed by each of the three major centers; ANL, BNL and LBL. During this workshop, one of the systems, that using synchrotrons as the principal element for increasing the total energy in the beam, was more or less dropped leaving two main line approaches: 1) a conventional rf accelerator with a system of storage rings for current multiplication, and 2) a single-pass linear induction accelerator propelling a single high intensity bunch of ions using waveform shaping to compress the bunch and increase the current. Both approaches require the use of a system of pulsed induction modules followed by a system of tranport magnets extending over a distance sufficient to allow the beam to ballistically compress longitudinally to achieve the peak pulse power needed to ignite a fusion pellet.

It should be noted that the synchrotron approach, which was dropped at least partially because of the limited funding and manpower available to study it, has continued to be studied by two Japanese laboratories which were represented by three attendees at this year's workshop.

Finally, the 1979 study was convened with the express purpose of looking carefully at the physics questions (as opposed to questions of systems, pellets, economics, etc.) posed by the two main-line approaches. These questions were to be formulated and examined particularly in the light of recent experiences with other new accelerator systems such as storage rings for high-energy physics and induction accelerators for weapons-related activities. The majority of attendees, and all of the chairmen of the working groups, were from such outside groups, and many had not attended any of the previous workshops. A brief discussion of target parameters and the results of recent theoretical work in pellet design was presented by way of an introduction for new workers. A significant change in beam requirements was identified by R. Bangerter, LLL, who presented the following table of target beam parameters:

Case	A	B	C
Beam energy	1 MJ	3 MJ	10 MJ
Peak power	100 TW	150 TW	300 TW
Kinetic energy	5 GeV	10 GeV	10 GeV
Spot radius	1 mm	2.5 mm	3 mm
Pulse length (total)	20 ns	40 ns	70 ns
Pulse length (peak)	6 ns	16 ns	20 ns

Ions at or above A = 200 atomic mass are assumed. Comparison with data given to previous workshops shows that, while the multimegajoule cases continue to be favored as higher confidence for achieving useful gain, the kinetic energy allowed for the ion beams has decreased. This requires a corresponding increase in beam intensity, although some growth (about a factor of two) has occured in spot radius and peak pulse length. Qualitatively, of course, increased intensity adds to the difficulty of achieving the necessary beam parameters while increasing the spot size and the peak pulse length increases the permitted six-dimensional beam emittance, thus easing the requirements. Paradoxically, increases in beam energy and kinetic energy tend to make the accelerator parameters somewhat less stringent. This is because it is easier to contain and transport a higher energy beam in which overcoming collective (space charge) forces requires a relatively smaller fraction of the total force needed for confinement.

Technical questions

A representative list of specific technical questions was defined by the organizing committee:

(1) For low-beta and rf linacs:
  a) Preservation of emittance during combining of beamlets.
  b) Coherent instabilities in the main accelerator.

(2) For induction linacs:
  a) High current injector systems.
  b) Coherent instabilities, both transverse and longitudinal.
  c) Waveform tolerances and jitter.

(3) For storage rings:
  a) Injection requiring debunching and stacking.
  b) Rebunching in the ring.
  c) Coherent effects, both transverse and longitudinal.

d) Vacuum requirements.
e) Charge exchange.
f) Extraction.
g) Cooling techniques, if useful.

(4) Final Transport, vacuum:
a) Longitudinal pulse compression.
b) Geometric aberrations.
c) Chromatic aberrations.
d) Beam splitting.
e) Coherent effects.

(5) Final transport, gas (may be required in a power reactor):
a) Charge and current neutralization.
b) Two-stream instability.
c) Availability of "windows" for beam transport, i.e., ranges of pressure in which beam transport and reactor first-wall protection are compatible.

Test Beds

The two largest DOE laboratory programs in HIF, ANL and LBL, have each developed proposals to design and construct accelerator systems, called Test Beds, to demonstrate the principal parameters and components needed to construct a full-scale prototype driver. The test beds would be far too small and too low in energy to be useful as pellet drivers, but should serve to provide for the testing of components and verification of theoretical stability calculations. The study session did not have time to assess adquately the degreee to which the proposed test beds would fulfill these requirements, but did establish some specific questions which the test beds should be designed to answer.

Working Group Summaries

At the end of the study session the meeting site was shifted to the LBL auditorium to allow unlimited attendance by interested scientists who had not been able to participate in the workshop. The reports began with a summary of the target parameters described above. Then the working groups reported their findings starting with the final transport groups and working backwards.

(1) Final transport in gas: The group considered possible reactor scenarios to test the compatibility of the reactor environment (diameter and kind and pressure of gas) with the problem of transporting the beam to the target. The presently favored design concept, using either a lithium fall or a lithium wetted wall operating at about 375°C, would have a pressure in the range 10^{-4} to 10^{-3} Torr. (This temperature is about the same as the operating temperature for light water reactors.) The group found that transport at pressures up to about 10^{-3} Torr for a reactor radius of five meters would be suffciently unaffected by the two-stream instability to be effectively stable. The 0.1 to 1.0 Torr "window" that had been defined earlier (assuming a noble gas to provide reactor front wall protection) appears to be closing off with the lower kinetic energies called for (5-10 GeV). A practical problem with this scenario is the difficulty of pumping a noble gas well enough to avoid beam loss due to stripping in the last focusing magnet. The pinch mode, similar to that required for light ion beam fusion, still appears to be a possible transport mode. The most promising conclusion, however, is that the newly found window, coinciding with the parameters of the liquid lithium reactor scenario, provides a final beam transport scenario consistent with the favored reactor system.

(2) Final transport in vacuum: The transport line from the accelerator and/or storage ring to the reactor is evacuated. The problem of stable transport in this system is complicated by the fact that the beam is rapidly compressing longitudinally, thus causing the current to be continuously increasing. The approach used by the working group was to design the best possible system without space charge and then to modify the solution assuming uniform

charge density in both the transverse and longitudinal directions. The designs resulting from this approach would then be tested using the numercial simulation methods developed for the space charge limited transport studies by Haber, Penner, Laslett, etc. These simulations, which were beyond the capabilities of the workshop during the limited time available, would account for the nonuniform space charge distribution. An example beam line was designed by K. Brown and J. Peterson during the study. It consists of three one-half wave modules and includes sextupole magnets for chromatic correction. Second order calculations yielded 85% transmission onto a 4 mm diameter target with 3% momentum spread. The relatively large momentum spread permits higher currents to be transported below instability thresholds, and is a significant parameter for all the preceding parts of an accelerator system. The principal effect of including space charge was to increase the maximum beam radius from 25 to 36 cm. In spite of the promising result given above, there was concern expressed in the summary that chromatic correction schemes may in practice do more harm than good, and that momentum spreads should be limited to ± 1%. The final transport group also issued a call for an intensified program of numerical calculation for the full simulation of these transport system.

(3) Storage Rings: The working group on the storage rings developed parameter sets for each of the three target cases. The special situations considered include:

a) Stacking at injection, with resulting emittance dilution,
b) Bunch compression in the ring prior to extraction,
c) Losses due to charge exchange collisions,
d) Current limitations imposed by coherent longitudinal effects.

Among the more significant conclusions was the finding that injection and ejection elements must be carefully protected against significant beam loss. The workshop resulted in a more intensified look at problems of coherent longitudinal instabilities. The thresholds for such instabilities were used to define the maximum currents to be stored. The limitations are acceptable if the coupling impedance can be limited to ~ 25 ohms per mode. Even if this should be difficult, the growth times for the instabilities may be longer than the necessary storage time. The spokesman for the working group called for intensified efforts to determine charge exchange cross sections of ions suitable for the HIF application. One rather high cross section for cesium was reported from the University of Belfast by the delegates from Great Britain. There was also a call for intensified studies of the coherent longitudinal effects and the structure impedances that can drive longitudinal instabilities. The summary concluded that there are important and fascinating problems but "no insuperable obstacles" were found.

(4) Linacs: The linac working group considered both rf linacs and induction linacs.

RF linacs: The problem of merging beams by frequency multiplying, and the resultant emittance dilution, attracted the most attention. Numerical methods exist to treat these problems and need to be applied. Impedance effects and possible resulting instabilities need further study. The working group reported their concensus that transverse blowup is not to be expected and longitudinal blowup is unlikely but need to be calculated.

The induction linac presents a very different, and in some ways, a simpler case than the rf linac. However, because there is so little relevant experience, there are more questions remaining than for the rf case. Most of these questions deal with longitudinal stability; the use of feedback control, waveform tolerances, behavior of the bunch ends, etc. Transverse dynamics, at least in the absence of transverse-longitudinal coupling, appears to be in good theoretical shape.

The recommendations of the linac working group include development of numerical methods of treating the problems described above and careful diagnostics to ensure useful measurements when beams are available from the proposed test bed systems. The conclusions were that "no fatal flaws were found and the concensus is that there probably aren't any."

(5) Low-beta accelerators: There are now several candidate systems for the low-beta accelerator for injection into the rf linac. These include, a) conventional high voltage injection into a low frequency Wideroe linac. b) the rf quadrupole accelerators first developed in Russia and now being tested at LASL, and c) the arrays of small electrostatic quadrupoles, called MEQALAC by A. Maschke of BNL. The low-beta working group considered many of the same problems faced by the linac group, and emerged with essentially the same conclusions described above. They ran some comparisons of the three systems defined above to check the scaling laws reported. They concluded that adequate safety margins exist for all parameters, although the necessary intensity could require some beam scraping. Scraping at low energy is quite tolerable and, in the worst case, simply requires more branches to the linac trees at slight overall increased cost.

European and Japanese Programs

The foreign delegates were asked to describe their HIF programs during the summary session. S. Kawasaki of Kanasawa University gave a brief discussion of the synchrotron program in Japan and discussed energy balance accounting in fusion. Since a fusion power plant of the same size is expected to be somewhat more expensive than a similar fission plant, it was not surprising that the energy balance payoff period is similarly longer. D. Bohne of GSI described the German effort. It is presently split between GSI, Frankfurt and Garching and is only just beginning to be funded. N.M. King described the program in Great Britain. Some funds that are available are earmarked for university programs. This permits starting such work as the charge exchange cross section work described earlier, but makes it difficult to begin serious work in a laboratory such as Rutherford which could act as a focus of the university efforts. John Lawson discussed broader international collaborations, either among the European states or with independent alliances with the U.S. DOE programs. Since the classification problems do not directly affect the accelerator systems, the heavy ion drivers would be the ideal vehicle for such collaborations.