# OVERVIEW OF INTERNATIONAL HEAVY ION FUSION EXPERIMENTS

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*Abstract*

The initiation of inertial confinement fusion with intense heavy-ion beams is pursued with experiments and theories in the U.S., Europe, Russia and Japan. The beam dynamics of these studies are characterized by very intense, space charge-dominated beams. From the extraction of high current, high brightness beams, to long-distance beam transport and acceleration, and the final focusing schemes, new frontiers are explored. In this talk, we summarize the key experiments conducted worldwide. Particular emphasis will be placed upon the U.S. program where the Virtual National Laboratory for Heavy Ion Fusion is engaged in experiments in 3 areas. First, there is a multiple-prong approach in intense heavy ion source development. Secondly, the propagation of space charge-dominated beams over multiple lattice periods is being addressed in the High current Transport Experiment (HCX). Finally, the final focus beam dynamics of high perveance beams, and the reduction of space charge effects with plasma neutralization are studied in the Neutralized Transport Experiment (NTX).

## 1 OVERVIEW

The ultimate objective of Heavy Ion fusion is to deliver several megajoules of heavy ions in a few nanoseconds onto a millimeter spot to initiate ignition of a fusion target. In the US, the quest for this ultimate goal is pursued under three somewhat separate and yet closely coupled research areas: target physics, fusion chamber technology, and driver development. The fusion driver of choice in the US is the induction linac. Multiple beams of intense heavy ions are produced, accelerated, compressed, and finally focused onto the target. The primary difference between the US and the rest of the worldwide HIF communities lies in the driver technology. In Europe, Russia and Japan the technology of choice consists of multiple rf linacs, synchrotrons and accumulator rings. The latest HIDIF study in Europe (1997) is an example of a fusion driver based on rf technology.

Three major facilities are now under development in Russia, Germany and Japan. These heavy ion machines are all multi-purpose facilities. When complete they will contribute significantly to the eventual goals of heavy ion fusion. Besides demonstrating the necessary beam manipulations with intense heavy ions, all three machines deliver sufficiently intense beams to do significant beam-target interaction experiments.

In Russia, the Institute for Theoretical and Experimental Physics (ITEP) has made some rapid progress in the past few years in refurbishing existing synchrotrons into the Terawatt Accumulator Ring (TWAC). During the recent HIF symposium in Moscow, they report first beams into the accumulator ring. In full operation, they will be capable of heating targets to tens of electron volts. A new consortium of fusion laboratories in Russia is now working on all aspects of heavy ion fusion under the leadership of ITEP.

In Germany, a detailed plan has been developed for a major expansion of the GSI facility. The new proposed SIS100/200 will be capable of delivering 40kJ of heavy ions for some extremely interesting experiments on targets under high temperature conditions. A plasma physics target cave is an integral part of this new proposal. This plan has received very favorable reviews from the German Science Council. The longstanding experience at GSI with plasma lens focusing is likely to play a role in many of the test facilities, and possibly in the final fusion driver as well.

In Japan, Riken has begun a $600M project on a rare-isotope beam factory. A significant component of this project is the Multi-Use Experimental Storage Rings (MUSES). Proposed experiments include a very interesting Heavy Ion Fusion component to extract an intense 40 ns beam from MUSES, and, by a combination of an induction buncher and beam drift-section, to compress the beam by a factor of 2. This is followed by a plasma lens to focus the beam onto a small spot for beam-target interaction studies. The drift compression and final focusing studies will be relevant for all driver approaches.

In the US, while there is a well-coordinated roadmap to reach inertial fusion in about 25 years, the immediate experimental plans are more modest. Three experiments are in progress under the auspices of the Virtual National Laboratory (a partnership of Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory). The objective of the ongoing experimental activities, together with theories and simulations in parallel, is to move towards the next step: an integrated beam experiment (IBX). The 3 experiments address respectively source development (STS500), high current transport (HCX), and final focus (NTX). The IBX is proposed to be a $50M class machine that will address all beam dynamics issues from source-to-target in an integrated manner.

In order to produce sufficient charge for heavy ion fusion (~millicoulombs), the source must be able to produce multiple beams at the ~1A level for tens of microseconds. The emittance of these beams must be sufficiently low. To develop these sources, the STS 500, a flexible test stand with 20μs capability, began operation at LLNL in December 2001. The most recent source studies focus on a merging beamlets concept, which has the advantage of being quite compact. Simulations to date suggest that the emittance of the merged beam will be acceptable.

The high current experiment (HCX) also began operation at the beginning of this year. It is located at LBNL, and will study long-distance transport of space-charge dominated beams. Effects of various nonlinearities, electrons and gas effects, mismatches and misalignments, will be studied on this machine. A key to these experiments is detailed and quantitative comparisons with 3-D PIC simulations to gain confidence in driver-related code predictions.

The third ongoing experiment, located also at LBNL, studies the beam dynamics of final focusing. It consists of 4 pulsed magnets to study the physics of final magnetic transport, followed by a plasma neutralized drift section, to simulate the physics of driver beams, as they converge onto the target through a gas-filled (~millitorr) fusion chamber, aided by externally injected plasma. The magnetic transport experiment has just begun earlier this month, and the plasma drift section will be installed within the coming month.

There is a 3-year plan (FY02-04) to complete these 3 experiments and to position ourselves for IBX.

## 2 ELECTRON AND PLASMA EFFECTS IN INTENSE ION BEAMS

The ongoing experiments have intense beams with several kilovolt potential energy. It is not surprising then that they interact with electrons and plasma in significant ways. The key to good beam transport is to control the interaction of the beams with the electrons and plasmas. We give 3 examples from NTX and HCX.

In NTX, a requirement for the source is that it must produce beams with very low emittance and variable perveance (a parameter for the ratio between the potential energy and the kinetic energy of the beam). The technique that we employ is beam aperturing. It is straightforward to reduce the beam current , and therefore the perveance, by intercepting a portion of the beam with an aperture plate (with varying hole size) downstream of the diode. However, the intercepted ions will generate secondary electrons, which, if uncontrolled, will follow the ion beam, thereby partially neutralizing its space charge, leading subsequently to nonlinear space charge forces and emittance growth. The ‘trick’ to control these electrons is to apply a negative bias before and after the aperture plate, thereby confining the secondary electrons locally to the region around the aperture. In an experiment, we measure the beam profile with different bias voltages. We see that there is an enhancement of ion beams on axis as the bias is gradually turned off. Simulation shows qualitatively the same effect, as the electrons neutralize the central region of the beam, thereby enhancing current on axis. When the bias voltage of the electron trap is sufficiently large to overcome the space charge of the ion beam, a nice beam with almost uniform profile and very low emittance is measured.

While the NTX source production requires the suppression of secondary electron effects, the neutralized drift section at the downstream end of NTX requires effective neutralization of the beam space charge by the plasma for good focusing. The degree of neutralization depends on the spatial distribution of the plasmas as well as the density of the plasma. 3-D simulations with the LSP code has predicted varying degrees of neutralization and varying spot sizes as the plasma conditions are changed. We have two plasma sources which will be installed in the coming month and the measured spot size at focal point will be compared with theory.

The third example comes from the magnetic section of HCX, where the question of electron trapping by the magnetic field will be investigated. These electrons, if uncontrolled, can affect magnetic transport of the beam deleteriously. A special gas electron source diagnostic (GESD) has been constructed and will be deployed at HCX to measure the evolution of secondary electrons in the presence of magnetic quadrupole fields.

## 3 NONLINEAR FORCES AND EMITTANCE GROWTH IN SPACE-CHARGE DOMINATED BEAMS

Another prevailing theme in the study of intense beams is the presence of many nonlinearities that can lead to emittance growth. Effects of nonlinear fields is not new in accelerator physics. The complexity for heavy ion fusion is that these beams are completely space charge dominated. These collective effects add to the complexity of the problem, and learning to control them is essential.

A key mission of HCX is to study the origin and the evolution of these nonlinearities as the beam is going through multiple stages of evolution, first through the electrostatic quadrupole (ESQ) injector, then through a matching section of 6 quadrupoles of continuously decreasing sizes, in which the beam is reduced in transverse dimension for injection into the main electrostatic quadrupole transport section. This section consists presently 10 quadrupoles, and additional sections will be added in subsequent years. There are also 4 magnetic quadrupoles which will be installed later this year. How the emittance is generated and how it evolves will be a subject of detailed experimental study and accompanying 3-D simulations. A very important theoretical prediction, supported by simulations, is that the emittance of an initially non-uniform beam profile will, over long distances, settle down to an equilibrium value with no major deleterious effects to the beam. This is an important prediction that will be checked in HCX. Also, issues of halo generation due to mismatches, effects of misalignments etc, will also be studied in HCX.

In NTX, the beams go through only a few magnetic quadrupoles, but they generally go through large excursions as the beam is manipulated into the right entrance condition for final drift to the target. These beams may be of high perveance, and an important goal of NTX is to explore the perveance limit, which has important implications for driver design. These beams can suffer phase space distortions due to geometric aberrations (third order nonlinearities due to non-paraxial effects, pseudo-octupoles, and effects of Bz ). Again, the theoretical predictions will be quantitatively compared with experiments.

## 4 CONCLUSION

The next few years will see a lot of exciting experimental activities in Heavy Ion Fusion. The 3 major facilities in Russia, Germany and Japan will be producing important results on beam manipulations for rf machines as well as beam-target experiments, and the ongoing experiments in the US will be generating data and detailed comparisons with simulations. Hopefully, the integrated beam experiment IBX will also begin in the near future.