STATUS OF THE HIDIF STUDY

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Abstract

The HIDIF study dating from 1994 explores the use of accelerated heavy ion beams as a driving mechanism for inertial confinement fusion. Representatives of several European laboratories, headed by the centre for heavy ion research, GSI, at Darmstadt, Germany, have collaborated to develop a self-consistent scheme based mainly on existing levels of technological expertise. The aim is to demonstrate the feasibility of an RF linac-compressor ring system for igniting an indirectly-driven deuterium-tritium target at a high repetition rate. The design is modular, which enables different aspects of the scheme to be investigated independently and provides the flexibility needed to respond to new ideas and future developments. Crucial issues include beam loss, the control of emittance and beam behaviour under current multiplication and space charge effects, while the need for further target development is becoming increasingly important. An overview of the study is presented and the status of research in the main aspects of the system discussed. Alternative ideas under consideration by the HIDIF group are also mentioned.

1 INTRODUCTION

With the declassification by the U.S.A. in 1994 of important material on target design, an opportunity was provided for re-consideration of heavy ion accelerators as drivers for inertial confinement fusion. Newly available data on indirectly driven targets prompted re-evaluation of earlier studies such as HIBALL [1], and a new design was prepared incorporating advances in accelerator technology and improvements in computational techniques. Up to 14 laboratories have been associated with the study, which at the end of 1997 culminated in a complete layout described in an interim report [2]. The ethos is for a power plant, utilising the special advantages provided by accelerator drivers in terms of efficiency, reliability and repetition rate, with the study aimed purely at demonstrating feasibility with no consideration of cost. Based on medium gain and short pulse duration, the design is modular in the sense that units may be multiplied as development advances into areas of higher driver energy and increased target gain.

2 THE HIDIF REFERENCE SCENARIO

Fig. 1 depicts the layout of the HIDIF reference design. The choice of driver energy of 3 MJ and target spot size of 1.7 mm derives from target gain curves published for the NIF project [3]. These figures determine to a large extent the layout of the driver, which adopts an RF linac-compressor ring approach, and set of parameters consistent with the requirements of the target-driver interface is given in Table 1.

Table 1: Main parameters of HIDIF reference design

Ion kinetic energy (GeV)	10
Total beam energy per pulse (MJ)	3
Linac peak current (mA)	400
No. of storage rings	12
No. of stored bunches	144
Stored bunch length (ns)	250
No. of ion species (telescoping)	3
Final pulse length (ns)	6
Peak power (TW)	750
Total peak current (kA)	75
Focal spot size (mm)	1.7
Number of final beam lines	48
Number of target convertors	2

The short pulse length and small focal spot size are the main problems to be faced in the design, together with requirements of low beam loss and minimum dilution of (6D) phase space in the rings. A technique known as "telescoping" is used, which avoids constraints of Liouville's theorem and involves three different ion species with masses differing by about 10%. These are accelerated to the same momentum within the same linac, but accumulated in different storage rings and taken on separate beam lines into different induction bunchers. During the final transport they are deflected into common beamlines and the differences in velocities (also $\pm 10\%$) are used to bring all three ion species to the target at the same time. The central ion is taken to be singly charged bismuth (Bi^{+1}_{209}), and rhenium (Re^{+1}_{186}) and thorium (Th^{+1}_{232}) are the other likely candidates.

2.1 Ion Sources

16 ion sources are used for each ion type and are designed for 35 mA of current with small beam emittances. Experiments at the University of Frankfurt with Bi^{+1} have been carried out with plasma generators driven by arc discharge and a multi-aperture extraction system [2]. These have demonstrated feasibility and show good power efficiency, favourable for the cathode lifetime.

2.2 Linac Design

Initial acceleration through RF quadrupole linacs is followed by a four-stage funnelling system which combines the pulses sequentially into the main linac. Parallel linac

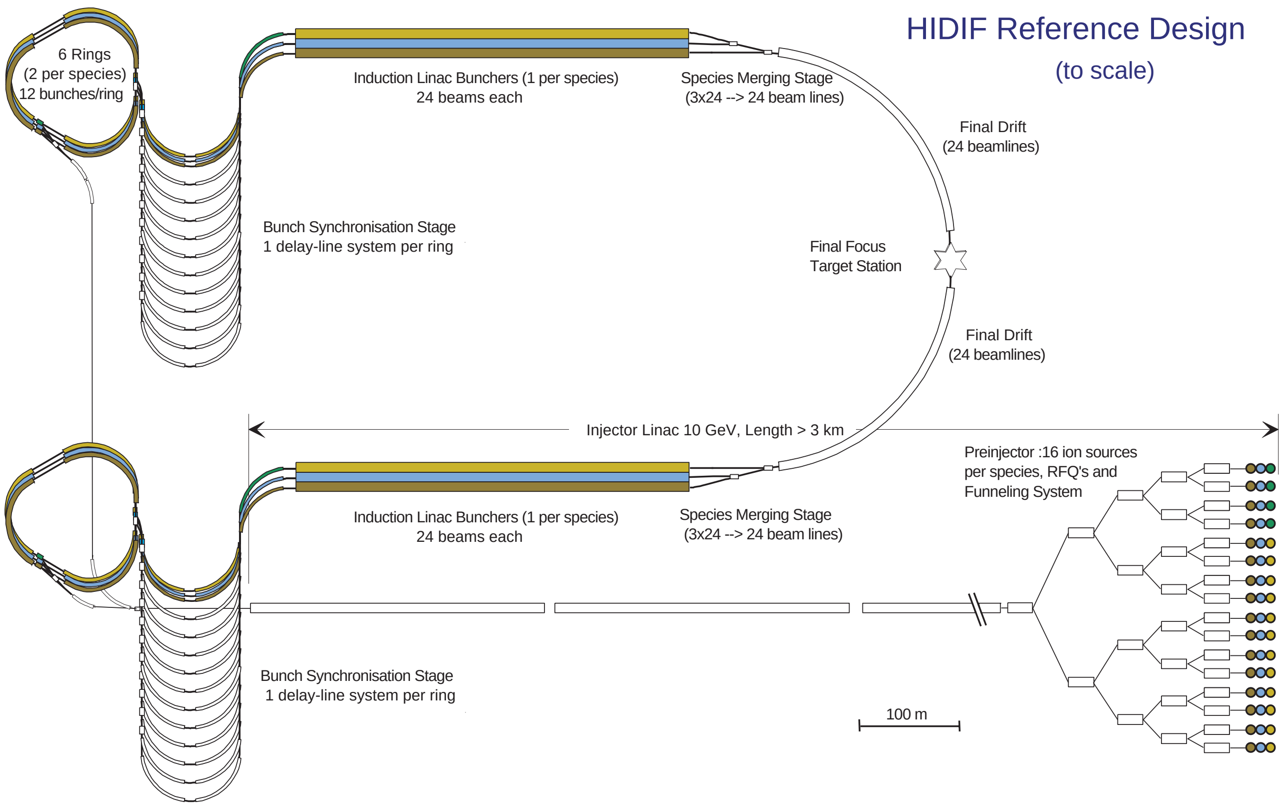

Figure 1: Layout of the HIDIF reference design

studies have been undertaken, the first for a conventional 200 MHz drift tube linac of the Alvarez type with a 5F5D focusing period [4]. This is designed to accelerate the ions to 10 GeV and a current of 400 mA, and meet ring injection requirements of (unnormalized, full) emittances of 4 (π) mm.mrad and a momentum spread, after bunch rotation, of $\pm 2.3 \times 10^{-4}$. The beam is also chopped into 250 ns macro-pulses for longitudinal injection into the ring. The second linac study is based on the use of H-mode cavities, which can handle high accelerating gradients. The use of multi-beam cavities in the low energy linac sections has also been suggested.

2.3 Compressor Rings; injection and extraction

The required total number of particles ($\sim 2 \times 10^{15}$) are accumulated in two stacks of six storage rings by multi-turn injection and the current is multiplied by RF compression. Injection into the rings is via a tilted electrostatic septum, allowing simultaneous filling of both transverse phase planes. The choice of tunes is critical and, taking into account space charge, values of $Q_h = 8.57$, $Q_v = 8.69$ are found to be optimum when combined with programmed horizontal and vertical orbit bumps. Computer modelling suggests that 20 turns may be injected with beam losses of about 2% and final (99%) transverse emittances approximately equal to the 50 (π) mm.mrad of the reference design [5]. Analogous results have been found in a second study using a corner septum and slightly different combinations of tunes. Space charge tune shifts are only of the order of -0.04 and a conclusion from the analysis is that injection limitations stem more from losses through the mechanics of the process than from space charge effects. Longitudinally the linac macro-pulses are captured in RF barrier-like potential wells and compressed to about 120 ns. Simulations with the potential modelled by 5-7 Fourier harmonics based on $h = 12$ as fundamental show nearly loss-free trapping and good longitudinal matching.

The storage ring itself has three superperiods, a mean radius of 70.474 m and uses long superconducting dipoles (6 T) in the arcs. Long dispersion-free straight sections provide flexibilty for injection and extraction and space for the RF barrier bucket systems. Extraction is by fast kicker magnets with the extraction magnet superconducting. The choice of 12 bunches per storage ring is a consequence of estimates of the extraction kicker rise times.

2.4 Transfer Lines and Final Focusing at Target

After current multiplication in the compressor rings, the bunches are transported via delay lines, one set per ring, with lengths differing in accordance with the bunch spacing, so that ions of each species arrive simultaneously at a set of induction linac bunchers. 24 bunches travel in a matrix arrangement side by side through each of the bunchers, which are 440 m long and operate using a saw-toothed RF waveform to compress the bunches to 65 ns. Voltages of about 0.5 MV/m are required. A complicated scheme of quadrupoles and dipoles then merges one bunch of each ion species sequentially into a single line, timing the merging so that the different velocities of the species ultimately bring them into coincidence at the fusion target. During the final stages the bunches compress naturally to 6 ns.

Final focusing is based on conventional ballistic techniques using superconducting or pulsed quadrupoles. Separate beamlines are needed to reduce space charge effects, and in the HIDIF scenario twenty-four beams converge on the target from each side. These have first to be separated to create space for the quadrupoles. Each beamline carries a current of 1.2-1.5 kA, but studies show that, at this level, space charge is less of a problem than chromatic and other aberration effects in determining the fraction of the beam hitting the target converters.

An alternative approach under study is based on a plasma lens focusing the beam by the strong azimuthal magnetic field generated by a high current plasma discharge. The benefits are that the requirements of low emittance and energy spread may be relaxed and, since the beam would be largely space charge neutralised, the whole intensity could theoretically be transported in one focusing channel. The advantage for the reactor would be a lower number of beam ports, which would each have smaller area.

2.5 Target Design

Prompted by work on the NIF project, the target is assumed to be indirect-drive, using a hohlraum of a geometrical design to direct soft x-rays created by the impact of the heavy ions onto the target pellet. Earlier attempts at HIDIF designs were based around the "octopus" target of Basko [6] using eight convertors. However, a recent review suggested that x-ray conversion is only efficient (i.e. $> 50\%$) for very small spot sizes (< 1 mm), which, because of emittance and other considerations, are difficult for an accelerator driver. For the 1.7 mm reference spot, x-ray conversion is less than 35%. Accordingly, the preferred model for HIDIF is now the target due to Ramis [7] shown in Fig. 2, a simpler, compact x-radiator with two-sided irradiation, with generally better coupling efficiency and offering the possibility of lower driver energy.

3 FURTHER DEVELOPMENT

The HIDIF group recognises that, notwithstanding the publication of an interim report [2], there is still much work to be carried out in fully optimising the beam-target coupling aspects of the design. Research into innovative target geometries, particularly those taking into account the properties of heavy ion beams, is needed and could lead to improved efficiency in the x-ray conversion.

Studies are being undertaken into the possibility of storing two beams of the same ion type but with different momenta in the same ring. The difference in particle velocities would be about 2%. Simulations show that compression in

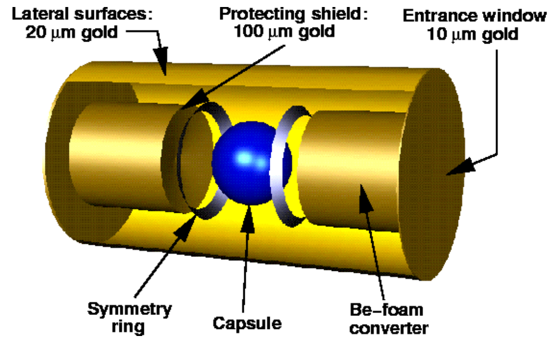

Figure 2: HIDIF Reference Target (Ramis 1997)

the barrier buckets is unchanged despite an overlap in the bunches of 0.5 μs.

Also under consideration is a model featuring ions with a higher charge state, since space charge appears to be less of a limiting factor in the rings than normal injection losses. Such a scheme would permit a shorter linac system and more efficient use of RF power. It may be that detailed evaluation of the consequences of beam losses during injection could lighten tolerances on some parameters and allow higher intensities in the rings. In addition, an alternative bunching scheme has recently been proposed [8] in which the present bunches are split into four sub-bunches with reduced momentum spread. The aim is to obviate the use of long induction linac bunchers, and investigation into the feasibility of the idea is currently in progress.

For any subsequent development to a full power driver, the HIDIF parameters would need to be scaled by a factor of at least three from their present basis of 3 MJ per pulse. This would place stringent demands on the linac high power RF generators, and require an extensive research and development programme from industry.

4 REFERENCES

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