THE CHALLENGE OF INERTIAL FUSION DRIVEN BY HEAVY ION ACCELERATORS

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Abstract

Accelerators have a chance to participate in the enormously growing energy market of the 21st century if inertial confinement fusion can be shown to be competitive with fossil and fission alternatives. While it is expected that ignition and gain of fusion pellets will be demonstrated by the National Ignition Facility after 2005, the development of a suitable driver with high efficiency and rep-rate capability remains the next challenging issue. We review the status of the European HIDIF study group which has set itself the goal of demonstrating the feasibility of the RF linac based heavy ion driver. Related experimental investigations (beam halo) are briefly discussed.

1 INTRODUCTION

Thermonuclear fusion promises a long-term supply of energy under all presently discussed scenarios of population development and environmental constraints (CO_2). It can be assumed that the expected expansion of the energy market in non-OECD countries within the next fifty years will dramatically increase the need for new, affordable energy sources other than fossil. It is estimated that the non-OECD energy market doubles every 25 years; on the other hand stabilization of the CO_2-level at 550 ppm (parts per million, with presently 350 ppm and a pre-industrial value of 270 ppm) would require 15 TW of additional carbon-free primary energy by the year 2050 [1]. Note that the present total energy consumption is 13 TW. This perspective describes the tremendous potential of fusion energy.

Although enormous progress has been achieved in both approaches to fusion energy, magnetic confinement (MFE) and inertial fusion energy (IFE), the gap between scientific understanding and attractive commercial realization is still big. One of the crucial questions is the complexity of a thermonuclear energy plant, which seems to exceed significantly that of fission reactors. The presently most advanced study exists for the tokamak based ITER (International Thermonuclear Experimental Reactor), which is designed for 1 GW fusion power and has a volume exceeding that of the Westinghouse AP-600 light water reactor by two orders of magnitude. We expect that inertial fusion reactors are significantly more compact and offer a number of conceptual advantages, for the following reasons :

- decoupling of driver and reactor chamber, which reduces the complexity of the overall system and allows to use several chambers for one driver; this could also shorten substantially the development path of a commercial system.
- liquid blanket protection, which offers the potential for lifetime reactor chambers, instead of solid walls (as in MFE) that would be exposed to serious radiation damage requiring frequent replacement [2].
- while the standard fuel is an equimolar D-T mix, it is not excluded for IFE to consider (at a more advanced stage) fuels with significantly less or no T inventory, for instance D-^{3}He; in MFE the only option is D-T due to excessive bremsstrahlung losses at the higher temperatures required for all other reactions.

The next milestone in inertial fusion is the expected low-gain target ignition with the laser driven "National Ignition Facility" at Livermore (NIF) and "Megajoule" in Bordeaux, France. These facilities are designed to demonstrate (beyond the year 2006) for the first time propagating fusion burn in D-T fuel on a single-shot basis, which would clearly set inertial fusion to the forefront of fusion development.

In parallel to this the development of a suitable driver with a rep-rate capability of the order of 10 Hz is the next most important requirement for advancing inertial fusion energy. For heavy ion accelerators the necessary rep-rates are common standard, but the required intensities and phase space densities have yet to be demonstrated. Heavy ion accelerators can satisfy the efficiency requirement of 20-30% which follows from the relationship $\eta G \geq 7-10$ needed for a reasonably small re-circulating energy. Here G is the target gain and η the driver efficiency. An η of 20% is consistent with a low-risk gain $G \approx 40$ and achievable with the RF driver. This perspective of heavy ion drivers applies equally to the RF linac/storage ring concept as to the induction linear accelerator, a concept pursued by the US community [3].

Other presently discussed options are high rep-rate diode pumped glass lasers developed at Livermore and expected to get from the presently 1 J per unit to the 100 J level

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at 10 Hz in 2-3 years [4]. Electron beam pumped KrF laser concepts have been proposed at NRL/USA [5] and in Japan [6], which are expected to deliver up to 200 J at a few Hz. For the long–term future of GSI a 100 T-m synchrotron is presently explored, which would deliver up to 10^{13} U^{4+} ions and 40-50 kJ total energy in a single bunch. The SIS heavy ion synchrotron at GSI can in principle operate at 1 Hz, but public grid load restrictions limit the present rep-rate to 0.5 Hz. Using an Ar^{10+} beam at 300 MeV/u and the highest presently achieved intensities (5×10^{10} particles) it is able to produce bunches with 100 J energy at this rate. The next step will be in 1999 the possibility of accelerating highest currents of U^{28+} after completion of the new IH-structure high-current injector for UNILAC. With the expected 10^{11} U ions in the SIS the bunch energy can be raised to close to 1 kJ.

2 THE HIDIF-STUDY

The scope of the HIDIF study has been to demonstrate the feasibility of an RF linac and storage ring based scheme for high repetition rate ignition consistent with an indirectly driven low-gain target. It has been carried out within the framework of a European Study Group in the years 1994-98. Collaborators in the field of the accelerator have been individuals from GSI, CERN, Rutherford, Frankfurt University (IAP) and FZ Juelich. The most challenging issue is the requirement of small beam loss and minimum dilution in all of the six-dimensional phase space in order to match the requirements of short pulse lengths (6 ns) and small focal spots (1.7 mm radius) at the target. The study succeeded to show that the designed driver satisfies the requirements of producing the necessary beam power. The concept of indirectly driven targets has been chosen since it appears difficult with heavy ion beams to achieve a 1% symmetry of implosion as required by direct drive (see Fig. 1 and Ref. [7]).

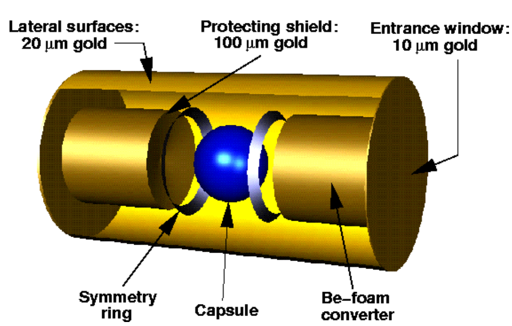

Figure 1: Indirectly driven reference target proposed for HIDIF. The heavy ion beams are converted into x-rays by two Be converters. The fusion capsule implosion is driven by the symmetrized radiation (courtesy of R. Ramis).

The HIDIF driver has a number of characteristic features, which are summarized in the following:

- charge state 1+ to reduce space charge effects,
- 3 ion species (for telescoping, see below) accelerated in the same linac but stored in different rings,
- 16 ion sources of each species,
- four funneling stages for RFQ's and DTL's and one main high-current DTL linac up to 10 GeV and a total pulse current of 400 mA,
- simultaneous two-plane multi-turn injection into storage rings to minimize injection losses,
- multi-turn injection into RF barrier buckets and, after filling of all rings, adiabatic prebunching,
- final bunch compression (fast) in induction bunchers with multiple beam lines to obtain the required 6 ns pulse length,
- conventional focusing using super-conducting quadrupoles in matrix array.

The funneled linac tree is shown schematically in Fig. 2 (see also Ref. [8]) assuming ion sources for Bi^{1+} with a current of 25 mA (for a prototype ion soutce see section 3).

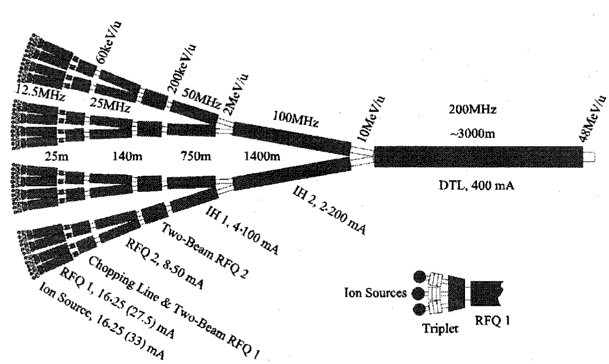

Figure 2: Scheme of a linac funnel tree for HIDIF (courtesy of A. Schempp).

The envisaged linac peak current of 400 mA and the gaps between different barrier buckets as well as the switching of the linac beam to different storage rings and to different ion species lead to a total pulse duration of 1.5 ms, which is also the duration of the RF power cycle (see Fig. 3).

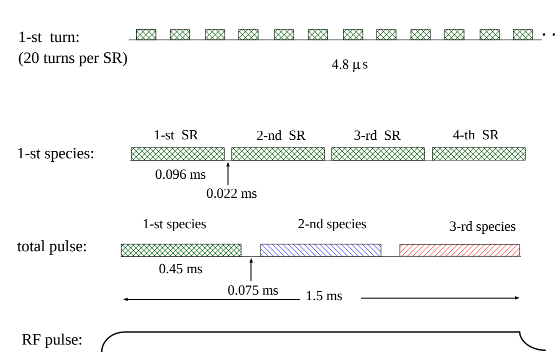

Figure 3: Linac pulse structure.

As a result the average linac current in this period is 192 mA. The scenario assumes 12 bunches per storage ring, which is equivalent to a stored energy of 250 kJ per ring.

The full scenario is shown in Fig. 4 for the reference case with 3 MJ requiring a total of 12 storage rings. Single-charged ions of three atomic species are accelerated in the same linear accelerator to identical momenta and stored and bunched in a set of 4 storage rings per species. The bunches are synchronized by delaying them in sets of delay lines (one set per storage ring) so that they coincide per species in time at the entry into the induction bunchers. Each bunch will at this stage travel on a separate trajectory, each induction buncher carrying 36 beam lines in parallel. In the final transport towards the target, bunches of each of the three species are merged together in a common beam line. This ”telescoping” goes back to an idea originally discussed by Burke [11]. Bunches of different ion species (here masses varied by 10%) but identical momenta can be superimposed in the longitudinal phase space in the final beam lines, which saves beam lines and final optics by the number of species (here three). The number of beam lines converging on the reaction vessel is now 48, which is reduced by a factor of three with respect to a single ion species (non-telescoping) scenario.

It is generally desirable to have the average linac current as high as possible as this determines the driver efficiency and helps to minimize beam loss in the storage rings due to ion-ion charge exchange. The linac efficiency is estimated to 30%, the total driver efficiency to close to 20% for the maximum rep-rate of 50 Hz.

2.1 Computer Modeling

The issue of space charge makes it necessary to model key issues by means of computer simulation. The following sub-sections of the driver have been studied with 2d or 3d codes:

– drift tube linac above 10 MeV/u (3d),

– debunching and capture in barrier buckets of rings,

– two-plane multi-turn stacking (2d with preliminary 3d), showing that the beam losses can be kept at the level of 1-2% [12]

– prebunching and final bunch compression,

– final focusing system to target.

The drift tube linac simulation shows that the required output results for current, emittance and momentum spread (ϵ_N = 1.2mm mrad and $\Delta p/p \leq 0.1\%$) can be satisfied [13]. A full linac simulation starting from injection into the first RFQ throughout the main linac remains a goal for future work. This includes the issue of beam loss throughout the linac and storage rings and the resulting activation, which must be considered carefully.

Driver parameters (for Bi^{+} and similar mass ions) for this standard target are summarized in Table 1. The scheme is modular in the sense that doubling of the energy requires doubling of the number of storage rings and bunches. For future work it is planned to study in more detail the option of a DTL based on H-mode cavities, which promises significantly higher linac current than the above considered 400 mA [14]. Such structures have been successfully taken into operation for the CERN Pb-Linac and the GSI U^{4+} high-current injector [15], which operates at 36 MHz and assumes a space charge limited current of I(emA)= $0.25A/q$. It accelerates U^{4+} at 16 mA current from a MEVVA ion source which has recently shown to exceed the required current on the test bench [16]. The main advantage of this structure for fusion applications is the high acceleration efficiency at relatively low values of β. The possibility is discussed of using multiple beam cavities for an IH-RFQ as well as an IH-DTL at relatively low frequencies (10 rsp. 20 MHz). The design is eased by the fact that quadrupoles are not used internal to the RF tanks (see Fig. 5). This concept requires a special funneling technique, which is possibly easier than the funneling of separate accelerator lines as in the usual approach. The maximum gradient that can be expected is about 7 MV/m using cavities in an H_{211} mode, which is another attractive feature of this scheme.

ion energy (GeV)	10
total driver energy (MJ)	3
linac current (mA)	400
storage rings	12
number of stored bunches	144
stored bunch length (ns)	250
ion species (telescoping)	3
final pulse length (ns) (base line of main pulse)	6

Table 1: Parameters of HIDIF driver for two-converter reference target.

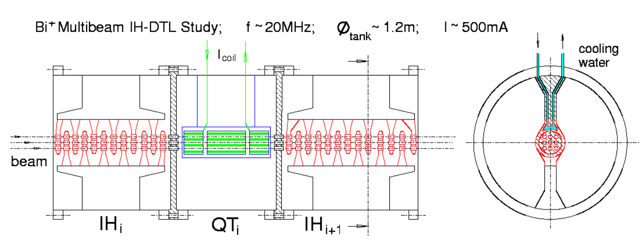

Figure 5: Schematic view of multiaperture IH mode DTL for heavy ion fusion (courtesy of U. Ratzinger).

3 EXPERIMENTS

A prototype Bi ion source at Frankfurt (IAP) has recently been shown to deliver 21 mA [9] (Fig. 6). The source has a seven hole extraction system with a maximum extraction voltage of 27 kV. The fraction of Bi^{1+} in the ex-

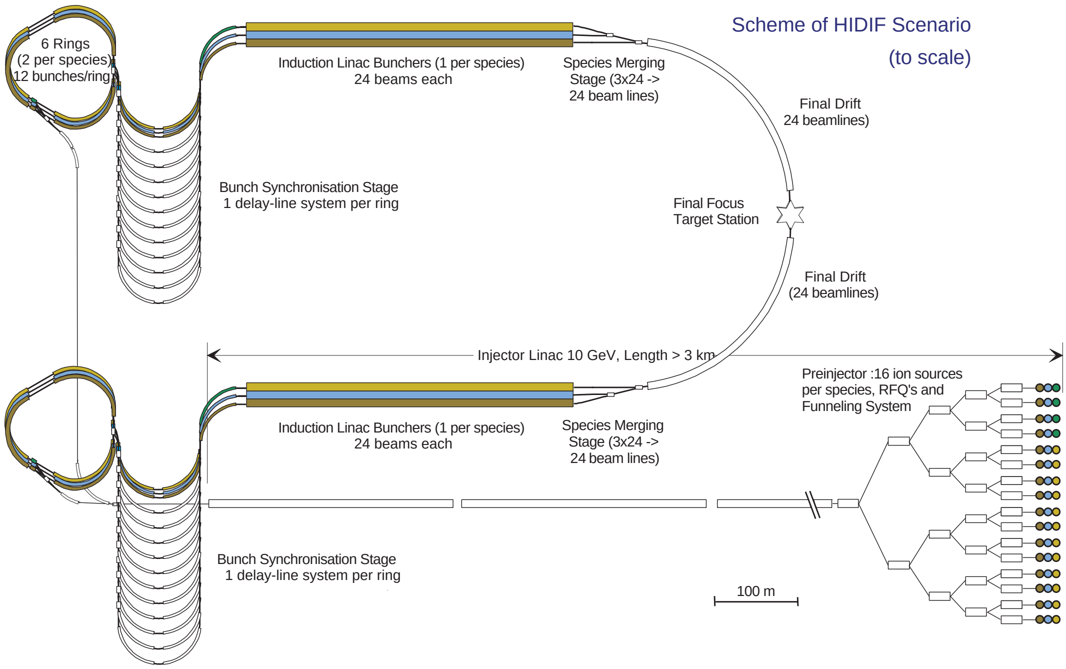

Figure 4: HIDIF layout for reference energy of 3 MJ.

tracted current was measured as 93%. The RFQ funneling concept is studied in another experiment at Frankfurt in a scaled version using two He^+ beams from 2 identical ion sources [10].

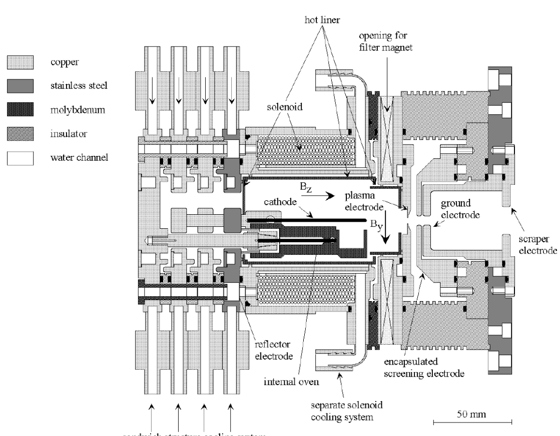

Figure 6: Schematic drawing of prototype of Bi^{1+} ion source and extraction (courtesy of M. Weber).

Beam loss plays an important role for high average beam power. The total activation of 10 GeV Bi ions is reduced by approximately two orders of magnitude compared with that of 1 GeV protons due to the substantially shorter Coulomb range of the heavy ion [17]. For a fusion driver at 10 Hz and 50 MW beam power the average linac current is ≈5 mA, and a loss of 10^{-3} seems acceptable. This is less stringent than the requirements of future high-current proton linacs discussed for various applications. A critical area appears to be the injection into the storage rings (operated at 2-5 MW beam power), where the presently studied two-plane injection with 1-2% loss would require a further reduction of the losses by an order of magnitude.

This leads to the conclusion that the study of halos in linacs and rings requires more attention than previously assumed. One of the first steps is experimental verification of the standard picture of halo formation driven by mismatch (envelope) modes [18, 19]. Such experiments are difficult to carry out in any existing linac. Since it is commonly accepted that the strength of space charge is less important, we are lead to the conclusion that such basic studies can be carried out in a synchrotron or storage ring as well. We have made some preliminary computer simulation studies of the effect of mismatch for a beam injected into the synchrotron SIS. Using a Ne^{10+} beam at the injection energy of 11 MeV/u and a current of 2.5 mA we have found that a mismatch of 1.5 leads to more than doubling of the rms emittance after 20 turns (corresponding to 200 cells). The phase advance per period is $\sigma_{0,h} = 130^o$ in horizontal and $\sigma_{0,v} = 99^o$ in vertical direction. The tune depression is only as small as 0.98. The initial distribution in the simulation is assumed as waterbag (see Fig. 7).

Comparing different values of mismatch and of current we have found that higher beam current primarily accelerates the emittance growth, whereas the mismatch is responsible for the size of the emittance growth as is shown in Fig. 8. It should be noted that the effect is unexpectedly large and presumably related to a resonance phenomenon with the FODO lattice, since a corresponding calculation for constant focusing gave only 1/4-th of the emittance growth.

As a next step we plan to realize this in an experiment at the SIS by extracting the beam after a variable number of turns and transport it to a plastic scintillator to observe its transverse density distribution with a gated CCD camera.

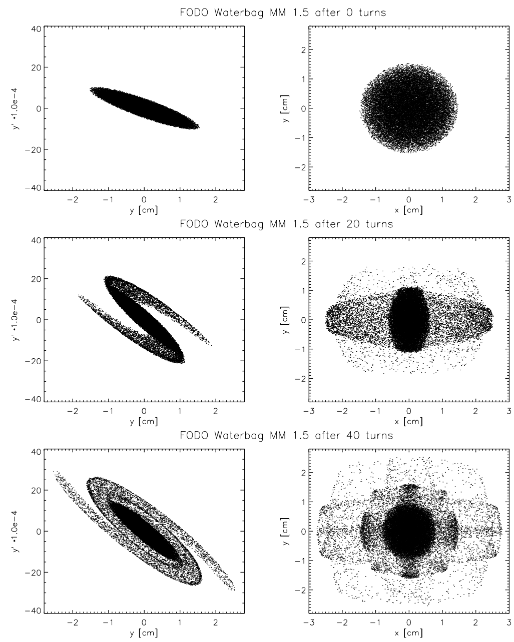

Figure 7: 2d-simulation (particle-in-cell) of halo development for a coasting beam in a FODO synchrotron lattice with weak space charge and 50% mismatch (shown are y-y' and x-y projections after 0,20,40 turns).

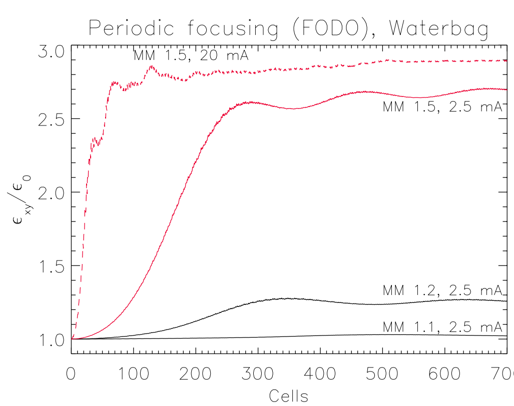

Figure 8: RMS emittance growth of simulated mismatched coasting beam in a FODO synchrotron lattice.

An important ingredient to the halo formation is the frequency of the mismatch oscillations, which is shifted by space charge. In this context it is also worth mentioning that we have recently measured in the SIS the frequency shift of these mismatch oscillations, both the "breathing" and the "quadrupolar" mode. The beam was excited by a quadrupolar exciter in the frequency band considered and the response signal on a quadrupolar pickup was evaluated [20].

4 CONCLUSIONS

The HIDIF accelerator study has for the first time considered detailed computer simulation studies of key areas in the RF linac/storage ring approach to inertial fusion. Future work will have to concentrate on the low-energy part of the linac (in particular funneling) and include new developments like the H-mode structure. Developments on the side of the target play an important role, in particular if novel concepts like the "fast igniter" [21] are better understood and their relevance for energy producing targets is consolidated. The expected reduction in Megajoules could result in significant reduction of the complexity of the driver. Accelerator experiments on key issues, including beam halo, are needed to verify the increasingly demanding computer simulation.

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5 REFERENCES

[1] L.J. Perkins, Proc. Int. Symposium on Heavy Ion Inertial Fusion, Heidelberg, Sept. 22-27, 1997, to be published in Nucl. Instr. Meth. **A**

[2] R.W. Moir et al., *Fusion Technology* **25**, 5 (1994)

[3] R.O. Bangerter, Fus. Eng. Des. **32-33**, p. 27 (1996)

[4] S.A. Payne, Proc. of the IAEA Technical Committee Meeting on Drivers and Ignition Facilities for Inertial Fusion, Osaka University, Japan, March 10-14, 1997

[5] J.D. Sethian et al., ibid.

[6] I. Okuda et al., ibid.

[7] R. Ramis, Proc. Int. Symposium on Heavy Ion Inertial Fusion, Heidelberg, Sept. 22-27, 1997, to be published in Nucl. Instr. Meth. **A**

[8] A. Schempp, Proc. Int. Symposium on Heavy Ion Inertial Fusion, ibid.

[9] M. Weber et al., Proc. Int. Symposium on Heavy Ion Inertial Fusion, Heidelberg, ibid.

[10] A. Firjahn-Andersch et al., these Proceedings

[11] R. Burke, Argonne National Laboratory unpublished note (1978)

[12] C.R. Prior and G.H. Rees, Proc. Int. Symposium on Heavy Ion Inertial Fusion, Heidelberg, Sept. 22-27, 1997, to be published in Nucl. Instr. Meth. **A**

[13] G. Parisi et al., these Proceedings

[14] U. Ratzinger and R. Tiede, Proc. Int. Symposium on Heavy Ion Inertial Fusion, Heidelberg, Sept. 22-27, 1997, to be published in Nucl. Instr. Meth. **A**

[15] W. Barth et al. these Proceedings

[16] P. Spädtke et al., these Proceedings

[17] K.-H. Schmidt, private communication (1998)

[18] J.S. O'Connell, T.P. Wangler, R.S. Mills and K.R. Crandall, Proc. 1993 Part. Accel.Conf., Washington DC, 3651 (1993)

[19] R.L. Gluckstern, *Phys. Rev. Lett.*, **73**, 1247 (1994)

[20] R. Bär et al., Proc. Int. Symposium on Heavy Ion Inertial Fusion, Heidelberg, Sept. 22-27, 1997, to be published in Nucl. Instr. Meth. **A**

[21] M. Tabak et al., Phys. Plasmas **1**, 1626 (1994)