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Review of accelerator driven heavy ion nuclear fusion

Abstract

Using high energy accelerators for energy production by nuclear fission goes back to the 1950's with plans for "breeder accelerators" as well as with early ideas on subcritical reactors, which are currently pursued in China and other countries. Also, fusion came in, when the idea emerged in the mid 1970's to use accelerators and their highly time and space compressed beams in order to generate the extremely high density and temperatures required for inertial fusion energy production. Due to the higher repetition rates and efficiencies of accelerators, this was seen as a promising alternative to using high power lasers. After an introduction to nuclear fission applications of accelerators, this review summarizes some of the scientific developments directed towards this challenging application − with focus on the European HIDIF-study- and outlines parameters of future high energy density experiments after construction of the FAIR/Germany and HIAF/China heavy ion accelerator projects.

1. Introduction and overview

From its beginning, the development of particle accelerators for scientific purposes was accompanied by a steadily growing interest in applications, primarily in medical diagnostics and therapy, also in food treatment and others. They all had in common the need of relatively low currents of low energy protons or ions. Applications of higher levels of particle energy (GeV or a few GeV) and high beam power only emerged with the increasing interest in nuclear energy applications in the 1950's.

The focus has been both nuclear fission and fusion. In the former, accelerators are assumed to serve as drivers for neutron generation; in the latter, "heavy ion fusion" (HIF) by inertial confinement is for target heating and compression to extreme values favorable to nuclear fusion on a sub-ns time scale. While reviewing work on HIF is the main focus of this paper, it is also of interest to briefly compare the accelerator needs of different approaches.

1.1. Nuclear breeder accelerators

First discussions go back to the early 1950's when needs for fissile material were rising and the idea of using accelerators to breed such material gained ground. However, with the discovery of larger amounts of uranium ore, followed by the growing interest in several countries in Liquid Metal Fast Breeder Reactors (LMFBR), the interest in accelerator breeders vanished again in the 1960's.

In the 1970's, when the LMFBR came under criticism in the United States and elsewhere (e.g. in Germany), interest in proton accelerator technology to both breed fissile fuel and also "burn" nuclear waste revived. Studies were carried out based on the idea that a combination of an accelerator "breeder" and a Light Water Reactor (LWR) could be competitive with a LMFBR (for a review see Grand and Takahashi [1]).

The working principle of accelerator breeders was seen in two steps:

- A linear proton or deuteron accelerator delivered continuously high currents of typically 1 GeV/u particles, which were directed on a thick target of heavy nuclei generated fast neutrons by fission and spallation with an effective neutron multiplication and a spectrum faster than in a light water reactor;
- In the end, the optimized processes led to an effective generation of fissile target nuclei − uranium or thorium, which was accompanied by a significant energy generation from the fission processes. The fuel would then be used in a LWR.

Although projected needs of nuclear energy were found not to be in favor of further developing such a new approach to the

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energy problem, these early breeder accelerator studies to some extent prepared the ground for two subsequent developments, HIF and accelerator driven subcritical reactors (Accelerator Driven Systems, ADS).

1.2. Heavy ion inertial fusion (HIF)

Nuclear fusion energy—first by magnetic confinement — entered the energy discussion already after peaceful work on controlled fusion as the energy source was made possible at the 2nd "Geneva Conference on Atoms for Peace" in 1958.

Fusion in a steady state magnetic confinement was soon seen as a promising candidate for unlimited energy production. In the 1960's, high power lasers entered the stage with the option of using their extremely short pulsed energy to enable fusion of tiny quantities of deuterium and tritium by using the ns-scale inertial confinement of the hot, compressed fusion fuel. This concept was treated as an attractive alternative to the more advanced stellarator and tokamak devices.

From the beginning, the idea of economical energy production by inertial fusion suffered from the lack of a suitable laser as the driver, which would allow high repetition rates of many shots per second — typically 10 Hz or more — and at the same time good efficiency.

In the early years, no solution was in sight until the mid 1970's, Maschke from Brookhaven National Laboratory realized that high intense proton beams from high energy accelerators might also be transported and focused on a pellet under inertial confinement conditions [2]. Originally, Maschke thought of high energy proton synchrotrons, which had already played the leading role in nuclear and high energy physics since the early 1960's. But it was soon understood that the range of the high energy protons from synchrotrons would be too long for small-scale pellets, and the early studies switched to medium energy heavy ions of less than 100 MeV/u accessible through linear accelerators, which would have the advantage of much shorter range at comparable total kinetic energy.

Investigations on what was from then called HIF emerged since 1976, when this concept was presented by Maschke and Martin at the first ERDA Workshop on Heavy Ion Fusion in Oakland, California [3]. The perspective was to use the already impressive success story of particle accelerators to solve humanity's energy problem (see also Ref. [4]) — without the risks inherent to nuclear fission. A typical HIF scenario was seen to have two major steps:

- An accelerator driver for heavy ions to accelerate high intensity beams to the required kinetic energy as needed for a single target ignition; accompanied by a bunch compression scheme to compress the beam energy to the typical time scale of 10 ns;
- An inertial fusion target, which absorbed the pulsed energy and thus enabled fast heating and shock-induced compression of the target (pellet) such that fusion conditions on high temperature and density were met in the stagnation phase.

On the other hand, it was soon realized that due to the extremely short pulse structure, the challenges of HIF on accelerator design would significantly exceed those of nuclear fission applications. In all cases — whether fission or fusion — driver accelerators for a typical 10^9 W power station would have to deliver of the order of 10^8 W average beam power. Inertial fusion, however, required in addition a factor of 10^6 total pulse energy compression of initial linac pulses, and repeated several times per second.

1.3. Accelerator Driven Systems (ADS)

As for breeders, the idea of accelerator driven subcritical systems also goes back to the 1950's, but no real need was seen [5].

It was mainly in the 1990's with the decreasing public acceptance of nuclear energy in general, and of higher awareness of safety risks as well as unresolved issues with waste disposal that interest revived in a number of countries.

In this concept, a high power proton beam couples with a spallation target, which was directly embedded in the core of a nuclear reactor. This accelerator driven spallation source contributed a small fraction of the total neutrons, which allowed subcritical operation of the reactor (see Bowman [6] and Rubbia [7] for their "energy amplifier" concept).

Advantages are: (1) An increased safety due to subcritical operation, where turning off the accelerator beam avoids super-criticality; (2) The option of transmuting long-term (minor actinides) waste into short-term by using the fast neutron spectrum; and (3) The breeding of fissile fuel with the perspective of using the abundant thorium as fuel (no need for adding fissile uranium or plutonium). Especially the latter has become a driving force to develop large-scale experiments in China (C-ADS [8]) and also in India, while projects in Europe (The European MYRRHA Project [9] — originally planned for 2025) are facing funding difficulties.

An ADS system—if compared with a pure breeder-has an increased complexity due to the interplay of a subcritical reactor core with an accelerator. On the accelerator side, besides the general challenges in designing and operating accelerators at tens of MW power, reliability and availability are primary issues. Beam-trip rates must be significantly lower than in research accelerators to minimize thermal stress and fatigue in the reactor core system and window to the spallation target. Optimizing such systems to allow few trips per month without exceeding few seconds each is challenging [10].

2. Historical evolution of HIF

The early momentum of Heavy Ion Fusion was amazing. The starting workshop of 1976 was continued at Brookhaven in 1977 [11] and at Argonne in 1978 [12], with significant international participation and a clearer understanding of the problems involved in the required accelerator facility, the target as well as reactor chamber. In 1979, the fourth workshop [13] of the series was held at the Claremont Hotel in Oakland. The goal was to obtain sufficient government funding to develop “test-beds” for heavy ion fusion in the two leading laboratories in the field, Berkeley and Argonne − with the help of the 1976 Nobel Prize winner and SLAC (Standard Linear Accelerator Center) director Burton Richter. In his letter to the Department of Energy, Richter wrote about the outcome of the workshop: “*It is gratifying to note that these experts found no fatal flaws in the heavy ion drivers but, as you might expect, they did find some matters which needed further theoretical as well as experimental work*.” (see Ref. [13]). In the following years, heavy ion fusion turned into a research field yet without big funding in the United States, and similar in Europe and Japan. For a number of years, the subject continued to fascinate researchers on dedicated issues of accelerators for high intensity as well as on target and reactor concepts.

- In the United States, the LBNL (Lawrence Berkeley National Laboratory, USA) in Berkeley continued the work on a constant level and remained the leading lab on the induction linear accelerator concept for more than three further decades, with a number of accompanying activities in other laboratories and universities.
- In Germany, Heavy Ion Fusion studies for energy production were initiated in 1979, by the initiative of Rudolf Bock from GSI (Gesellschaft fuer Schwerionenforschung, Darmstadt, Germany), within a government-funded research program and a focus on the linear accelerator-storage ring concept. The first workshop on HIF outside the United States was held at GSI Darmstadt, Germany, in 1982 [14].

The early work on heavy ion fusion triggered pioneering studies in theoretical [15,16] and experimental [17] high current beam transport; also in target physics [18] (where up to this point little published work could be found in the open literature); in atomic physics problems, in plasmas which is important for beam stopping [19]; furthermore on storage rings limitations [20], intense beam simulation [21] or heavy ion fusion in general [22]. For a more recent review of these activities at GSI, including plasma physics developments applied to HIF as well as the induction linac approach at LBNL see Bock et al. [23].

HIF also found a broad echo in a variety of other countries, where different studies have been carried out and still continue up to now:

- In Japan, with the HIBLIC ((Heavy Ion Beam and Lithium Curtain) − study in 1985 [24] and a variety of HIF-related target physics studies (for a review see Kawata et al. [25])
- At ITEP (Institute for Theoretical and Experimental Physics, Moscow, Russia) since the late 1980's until today (reviewed by Sharkov et al. [26])
- More recently by a research activity at the IMP (Institute of Modern Physics) in Lanzhou, China, with experiments at their nuclear physics heavy ion facility (reviewed by Zhao [27]). A heavy ion fusion workshop − the 20th of its series-was also held in Lanzhou in 2014 [28].

Two conceptual design studies for the linear accelerator-storage ring concept are in the focus of this review: the HIBALL Study [29] (Heavy Ion Beams and Lead Lithium, 1981−1985) in collaboration between German research groups and the University of Wisconsin; and, in particular, the later HIDIF Study [30] (Heavy Ion Driven Ignition Facility, 1995−1998) elaborated by a European Study Group under the leadership of CERN and GSI. Results of the Berkeley induction linac based studies − the complementary viable approach to heavy ion fusion-are not discussed here; they were reported in a review paper elsewhere [31].

3. Issues and parameters for HIF

The challenging issues of a heavy ion fusion driver accelerator have their origin in the simultaneous requirement of high energy per pulse and extremely short time duration, which is determined by the hydrodynamic expansion during beam absorption.

3.1. Some basic numbers

The concept of inertial confinement is based on uniform heating of a spherical pellet on its surface − by photons or particles of short range − such that plasma is ablating from it and strong shock waves are generated. In ideal spherical geometry, they collapse in the center and heat the enclosed small amounts of DT fuel to the required ignition temperatures of the order of 10^4 eV. The compressed and heated fuel is confined by its inertia before it expands, which is assumed to be long enough to allow propagation of a burn wave in the fuel as shown schematically in Fig. 1.

Compared with other fusion reactions not involving tritium, the reaction $D + T \rightarrow n + {}^4He + 17.6$ MeV is the “easiest” one in terms of cross section and high energy release leading to the specific energy release of 3.37×10^{11} J/g.

As in magnetic confinement, the confinement parameter $n\tau$ has to satisfy the Lawson criterion $n\tau > 10^{15}$ s/cm^3, where n is the plasma density and τ the confinement time. The short confinement time τ of about 10^{-10} s results in a typically 100-fold compressed fuel density, which must be achieved by typically 100 TW of beam power − whether lasers or heavy ions.

In inertial fusion, it is common to replace the above Lawson criterion by an analogous criterion for the product ρR, where ρ is the mass density and R the radius [32]. Fuel burn-up is achieved by a propagating alpha particle burn wave, and the range of fusion alpha particles is given by a value for ρR of about 3 g/cm^2. Assuming a total of 1 mg DT fuel per pellet, this leads to a fuel density of 300 g/cm^3 and a corresponding thermonuclear energy release of about 100 MJ. Since the reactor cavity has to stand the micro-explosion0, the amount of DT per pellet is limited to about 10 mg, and a correspondingly high repetition rate of the order of 10 Hz is needed for commercial energy production. This limitation explains the extremely high fuel compression requirement − and an associated beam pulse duration of the order of 10 ns-which is an essential condition to make inertial fusion work.

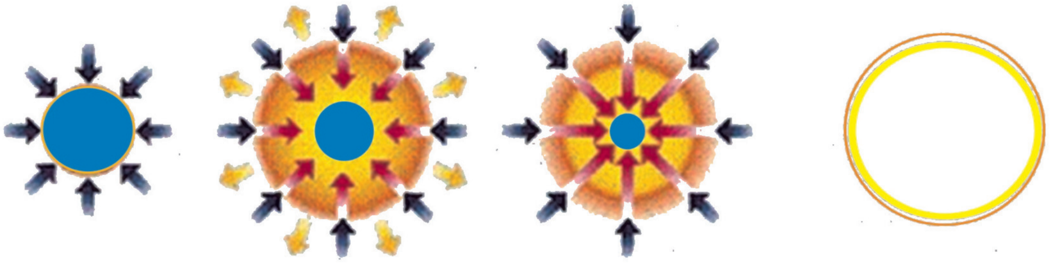

Fig. 1. Scheme of inertial fusion phases: heating, plasma ablation, shock compression of fuel sphere and thermonuclear burn.

3.2. Working principle of inertial fusion targets

The DT fuel is frozen on the inner surface of a hollow sphere, the "pellet" (see Fig. 2). It is injected into the reactor chamber and guided to its center, ignited by a relatively large number of time-synchronized heavy ion beam pulses. In "directly driven targets"—as opposed to the "indirectly driven targets" discussed in the next Section – the outer shell, glass or metal, is heated by the incident heavy ions and ablated. The radial pressure from the ablation compresses the fuel and heats it up to ignition temperature and ignited by a converging sequence of shock waves.

The total energy for ignition and high gain is found to be in the range of 5–10 MJ. Isentropic compression is achieved by adequate pulse shaping of the heavy ion beams. Simulation codes suggest that an energy gain between 50 and 100 should be theoretically possible [33].

3.3. Directly vs indirectly driven targets

A necessary condition to achieve ignition and high gain is the spherical symmetry of energy deposition on the fusion pellet. Irradiation asymmetries may be generated at the initial phase of ablation and compression due to insufficient smoothness of the target surface, but most of all a limited number of beams. For heavy ions, the number of beam lines is limited by geometrical constraints due to their large bending radius, thus the symmetry requirement is most difficult to achieve in a directly driven target scheme.

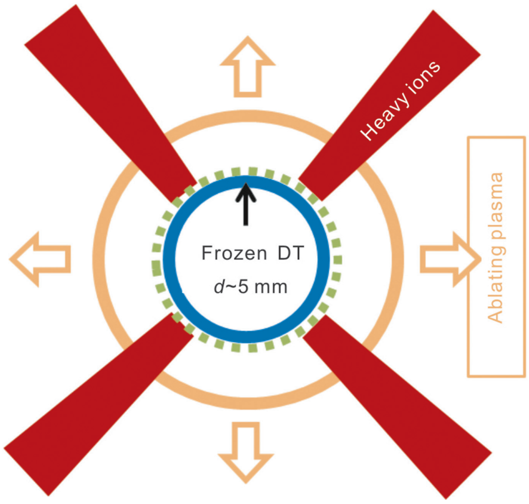

Fig. 2. Schematic principle of a directly driven spherical shell ("pellet") with cryogenic DT fuel, which is compressed by ablation.

From the point of view of irradiation symmetry, the indirectly driven scheme is advantageous. It was first published at Livermore in 1993 for laser driven targets in the process of gradual de-classification of inertial fusion target physics [34]. Here the spherical fusion capsule is enclosed by a cylindrical casing of high-Z material. The kinetic energy of the heavy ion beam is absorbed by two converters on opposite sides and transformed-according to the Stefan–Boltzmann law – into soft X-ray radiation inside the casing, which gets filled by symmetric hohlraum radiation after repeated reflections (see Fig. 3). The spherical fusion capsule is radiatively imploded at high symmetry. Many different arrangements of converters and shields of indirectly driven targets have been investigated by simulations. It was shown that by introducing additional shine shields inside the casing, the radiation symmetry could be considerably improved and—as shown by simulation and demanding optimization-kept down theoretically to the required level of about 1% [35].

Target production and the development of target preparation techniques are challenging issues. The DT fuel is filled into micro-shells by diffusion. Filling and layering techniques have been developed to prepare cryogenic fuel layers in the shells with the necessary smoothness and high precision. These issues are demanding and a major cost factor, with high impact on the cost of electricity [36].

3.4. Efficiency considerations

With the numbers estimated in the previous sections, the energy balance is typically as follows: For a single heavy ion beam pulse of 10 MJ and a gain of 75, the output energy per

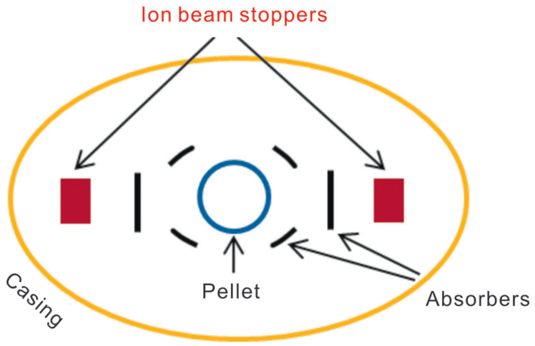

Fig. 3. Indirectly driven target scheme with ion beam stoppers, shine shields and central fusion pellet.

pulse is 750 MJ, which is deposited in the fluid wall of the reactor. With this amount of energy and a repetition rate of 10 Hz, the thermal power of the plant is 7.5 GW. A crucial factor is f, the recirculation fraction of the electrical power, which should be a small fraction of the total output. Assuming that the electrical power is produced with an efficiency η_{th} from thermal to electrical and a driver efficiency η_{d}, f is given by

$$f\,\eta_{\mathrm{th}}\,\eta_{\mathrm{d}}G = 1, \tag{1}$$

with, for example, $\eta_{\mathrm{th}} = 0.3$ and $\eta_{\mathrm{d}} = 0.25$, the recirculation fraction becomes $f = 0.18$, and the electrical power output is 1.85 GW. The overall efficiency scheme of the plant is shown in Fig. 4.

This demonstrates the importance of high efficiency and high repetition rate of the driver accelerator in order to keep the circulating energy as low as possible. A reasonable ratio between circulating energy and thermal energy output from the reactor can be reached only by sufficiently high driver efficiency. This makes accelerators, which have demonstrated high efficiency, attractive as drivers. For a given target gain, reducing the driver efficiency from 25% to 10%, for example, would increase the re-circulating power from 18% to the unacceptably large value of 44%. An efficiency of 20%−25% can in principle be reached with conventional accelerator technology of the kind used in high energy physics for protons or heavy ions.

One of the benefits of inertial confinement as compared to magnetic confinement is obviously the separation of driver and reactor vessel, which allows optimization of the main components of both parts rather independently. Compared with laser fusion, the deposition of beam energy to the pellet is classical and well understood. Based on experience, the repetition rate of the driver accelerator is not a critical issue, and the needed efficiency should be achievable by suitable accelerator design. However, high beam intensity simultaneously with high beam quality at the space charge limit has been found to be challenging. The degree of challenge is correlated with target physics: relaxing on target physics makes the task of the accelerator design more difficult, and vice versa. In any future development this would have to be a major object of optimization and research.

4. The inertial fusion reactor

An inertial fusion power plant consists of two main components, the driver and the reactor vessel, where both are clearly separated units connected only by beam ports.

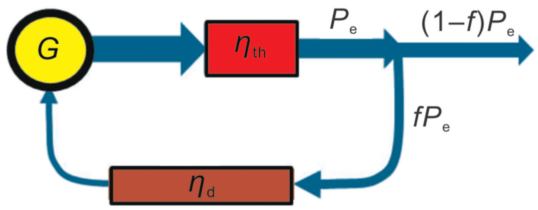

Fig. 4. Efficiency considerations for an IFE plant with G target gain, η_{th} conversion efficiency into electrical power, fP_{e} recirculating power, η_{d} driver efficiency and $(1-f)P_{\mathrm{e}}$ electrical output power.

As compared with magnetic fusion, an advantage of the inertial fusion reactor design is that chamber walls can be protected from radiation by a thick fluid wall in which the energy of the fusion neutrons is deposited and the breeding of tritium fuel from lithium is achieved. The breeding follows the exothermic reaction $\mathrm{n} + {}^{6}\mathrm{Li} \Rightarrow \mathrm{T} + {}^{4}\mathrm{He} + 4.8\ \mathrm{MeV}$, which contributes to the energy production. In addition to wall protection and breeding, the fluid is used to transport the produced energy out of the chamber to the conventional electricity generating systems.

Among various materials proposed for this purpose, lithium-lead ($\mathrm{Li_{17}Pb_{83}}$) was chosen for HIBALL, while the molten salts Flibe ($\mathrm{Li_2BeF_4}$) and Flinabe ($\mathrm{LiNaBeF_4}$) have been considered in other designs. These chemical compounds are not combustible, and have a very low solubility for tritium, a low activation rate and, in particular, an extremely low vapor pressure at the operational reactor temperatures. Several reactor designs have been developed by various groups. With the HIBALL study, a direct drive concept-the economic feasibility of a complete heavy ion beam driver concept was studied for the first time. It was followed by the Japanese design HIBLIC. Other reactor concepts were developed in the United States for laser as well as for heavy ion beams: HILYFE II and OSIRIS [37]. For HILIFE II, detailed investigations on neutron flow, tritium breeding ratios, activation and radiation damage have been carried out, showing that the tritium breeding ratio can be 1.17 and radiation damage rates in terms of displacements per atom are sufficiently low. A cross section of the cylindrical reactor vessel of Osiris is shown in Fig. 5.

A two-sided illumination is chosen, with 60 beams from each side. Flinabe is used as molten salt blanket for protecting the first structural wall from neutron and blast damage as well as shielding the beam ports and super-conducting finalfocus magnets from radiation. Many flow dynamical investigations and experimental studies have been performed for various geometrical arrangements of jets in the new designs, also taking into account the neutron-induced heating of the blanket. Several conditions must be considered to allow operation at high repetition rate. Following the explosion of the target, the resulting Flinabe splash from the previous pulse must be cleared away to allow target injection and beam propagation through the chamber for the next shot. From the study of Flinabe performance, sufficient condensation should be achievable for a 6 Hz operation.

5. Heavy ion driver accelerators

Existing accelerator technology for high energy physics and for megawatt power spallation neutron sources is of a certain relevance here, but a heavy ion fusion driver goes significantly beyond such experience due to the unusually high demands by compression in time.

5.1. General properties and schemes

The primary development goals in heavy ion fusion design studies have raised confidence that the extremely high peak power needed for target compression and ignition can be

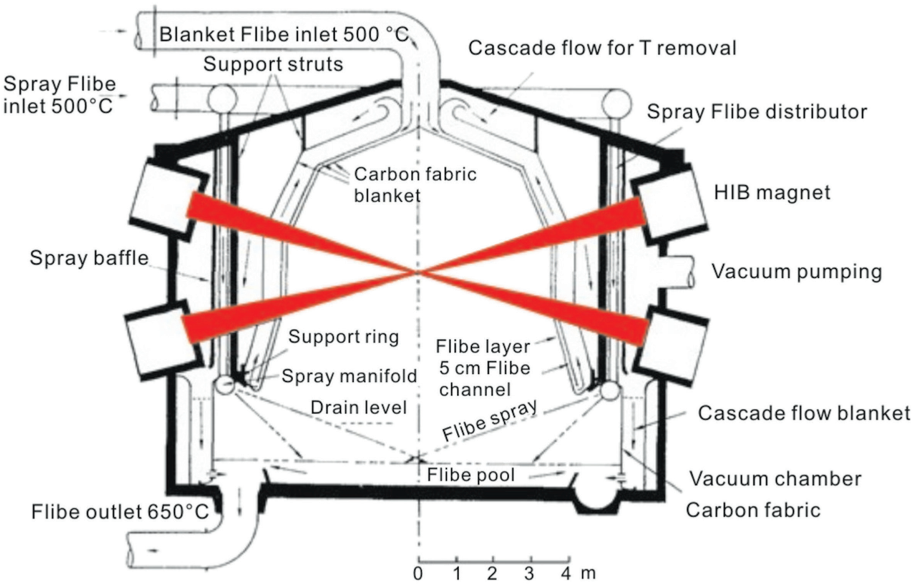

Fig. 5. "Osiris" — an example of heavy ion fusion reactor chamber design.

achieved by accelerators. Such high peak power is clearly the proven strength of laser drivers for ignition experiments, like the US National Ignition Facility (NIF) [38] or the French Megajoule Project [39]. While heavy ion accelerators can hardly be competitive with lasers developed for single shot ignition purposes, their potential has always been seen in terms of possible future application in commercial energy production, where efficiency, repetition rate and reliability are crucial issues.

A typical assumption in heavy ion systems studies is to use a target gain G of 80—100, which is confirmed by different gain models. Extensive code simulations have indicated that such a gain should be possible with an input energy of at least 5 MJ under "conservative" assumptions on entropy increase and hydrodynamic coupling efficiency during the implosion. For effective compression this energy has to be delivered during 10 ns or less, which sets the standard power requirement for the accelerator driver to a value of about 500 TW after final compression.

The specific power measures the power delivered per unit mass and determines the actual temperature and pressure rise in the target beam stopping material, whether ablation shell or discrete stoppers in indirect drive. It is given by

$$P = (E \cdot I)/(R \cdot F)[\mathrm{W/g}],$$

here, E is the total kinetic energy of the ions, I the particle current (A), R the range (g/cm^2) and F (cm^2) the focal spot area. In most studies ranges between 0.1 and 0.3 g/cm^2 have been adopted. The specific power required to achieve 300 eV plasma temperatures in the target is estimated as $P \geq 10^{16}$ W/g. Such high values can be reached only with small ranges of the ions, which leads to a typical kinetic energy of 10 GeV or 50 MeV/u for the heaviest ions.

The main task of the driver accelerator is to increase the kinetic energy and multiply the current extracted from the ion sources (typically tens of mA per source) to the order of 10^4 A at the target. In the very early discussions synchrotrons were considered, but soon discarded as they favor high energy, which could not be reconciled with the short range requirements set by the target.

Two complementary accelerator scenarios have remained as potential inertial fusion energy drivers: the RF linac & storage rings and the induction linear accelerator concept.

- The RF linac & storage rings concept shown schematically in Fig. 6 benefits from the large operating experience with RF linear accelerators, synchrotrons and storage rings. Acceleration in the RF-linac is followed by current multiplication via a sequence of beam manipulations in a stack of storage rings and the subsequent final target beam lines. This scheme has been in the focus of the two system studies coordinated by GSI Darmstadt, the HIBALL as well as the later HIDIF study.
- The ion induction linear accelerator concept was invented by Christophilos in the 1950's for high-current (kiloamperes) electron beams. Acceleration is achieved by the induction induced gap voltage using ferromagnetic cores, which allows acceleration of single micro-second long pulses. In 1976, Keefe at LBNL Berkeley [40] proposed it

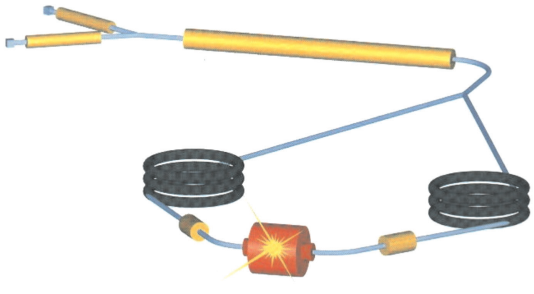

Fig. 6. Schematic layout of RF linac with two sets of storage rings and final bunchers to target chamber (source Ref. [30]).

for inertial fusion drivers with heavy ions as a novel technology. The idea was to have a device, where a single heavy ion bunch (or several parallel bunches) was at the same time accelerated and longitudinally compressed. Key experiments to this technology were carried out [41] until the program was terminated in the US in 2011/12.

5.2. The European HIDIF study

A significant weakness of the earlier HIBALL study — predominantly focusing on the reactor side-was that the accelerator limits were estimated on the basis of general thresholds only rather than detailed design or simulation. Moreover, the HIBALL target was a directly driven target not illuminated with the required high spherical symmetry, which was generally difficult to achieve with the rigid heavy ions.

In 1993, it was felt timely for a new effort, and a number of European laboratories agreed to set up a European Study Group following a suggestion by Nobel Prize winner Carlo Rubbia, then general director of CERN. He was challenging the scientific community with the idea that an accelerator had the potential of being competitive with the laser based NIF. The efforts of the study group merged into the European HIDIF-Study (Heavy Ion Driven Ignition Facility Study, coordinated by I. Hofmann (GSI) and G. Plass (CERN)) to demonstrate the accelerator needs for target ignition with significant energy gain.

The most challenging issue was the simultaneous requirement of small beam loss and of nearly no dilution in all of the six-dimensional phase space; the former is needed for hands-on-maintenance, the latter for matching with the small target size. Estimates of target parameters at the start of the study in 1994 were taken from published gain curves, based on DT-filled capsules that were developed for the NIF-project. According to these estimates, ignition with 10 GeV ions at the driver total energy of 3 MJ, pulse length 6 ns and a spot radius of about 1.7 mm seemed possible for a two-converter target as shown by Ramis (see Ref. [30] and Fig. 7).

5.3. HIDIF driver architecture

In a HIF driver, the basic parameters of driver emittance and momentum spread follow largely from the final focusing requirements once the general layout of the driver is determined [42]. The only 6 ns long final pulse length at the target is extremely challenging and requires several steps from the ion sources to the target.

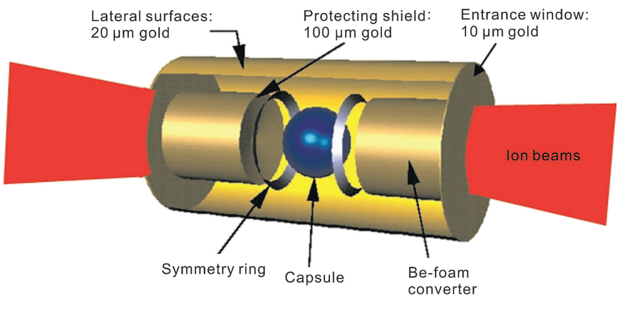

Fig. 7. Schematic design of HIDIF 3 MJ reference target (courtesy R. Ramis).

Table 1
General parameters of the HIDIF scenario.

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	44
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
No. of final beam lines	48
No. of target convertors	2

The general layout of the HIDIF driver has the following components, with some basic parameters summarized in Table 1:

- Linac: The funneled linac (from 16 ion sources) has the task of providing a pulse of 10 GeV Bi^+ ions sufficiently long to fill all storage rings with 2×10^{15} ions and thus accumulates the desired total energy. For a pulse current of 400 mA, this requires about 1.5 ms. A special feature is the idea of using three neighboring ion species ("telescoping") with identical momentum and differing velocities; they are filled into different storage rings, but catch up for synchronous arrival at the target. The total length of the RF linac is estimated to be 3.4 km.
- Storage rings: The linac beam is stacked in the transverse phase space to fill each of the two sets of six storage rings with ions corresponding to a stored energy of 250 kJ per ring. They have super-conducting dipoles, which are essential to realize the requirement of a mean radius as small as possible in favor of the short final pulse length (see Fig. 8). The "three-fold" symmetry is also in support

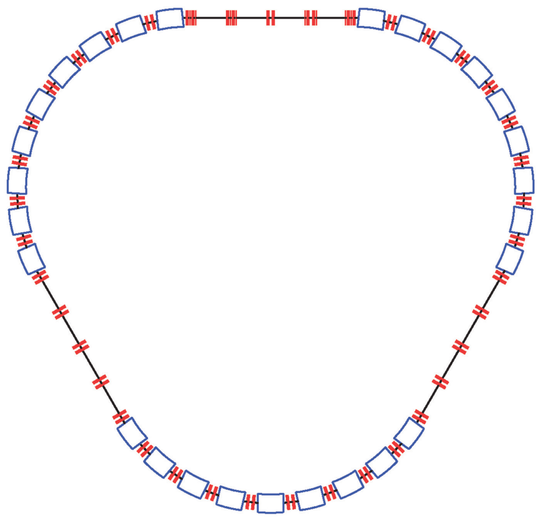

Fig. 8. HIDIF storage ring lattice (courtesy Ch. Prior).

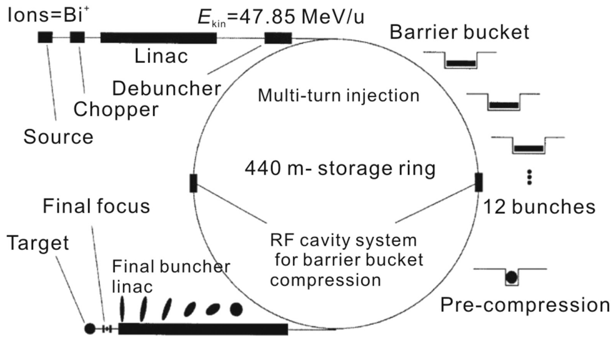

Fig. 9. Scheme of longitudinal bunch compression including barrier buckets in storage rings, adiabatic pre-compression and fast final compression by bunch rotation in phase space (source: Ref. [30]).

of this goal [43]. An important novel feature is the scheme of combined stacking in the vertical as well as horizontal phase planes using a tilted septum, with the set goal of keeping injection beam loss under 1% (for injection septum protection). The ions are distributed to the RF buckets such as to create 12 bunches, each 250 ns long. An adiabatic pre-compression in the barrier buckets is realized.

- Final longitudinal compression and focusing: An important task of the final transport is to remove the time difference of bunches stored in one ring by delay lines so as to synchronize their arrival at the target; also to provide the large voltage of the order of MV to achieve the final compression of the bunches to a duration of 6 ns as is required at the targets. This fast bunch rotation requires a set of MV induction buncher linacs, where each of them is connected with the reactor chamber.

The overall bunch compression scheme in various stages is shown in Fig. 9.

The complete layout of the reference HIDIF driver delivering 3 MJ of energy per single ignition shot is shown in Fig. 10.

5.4. Discussion of the HIDIF study

HIDIF was conceived as the heavy ion driven “ignition facility” − based on the expectation that the goal of an experimental “single-shot” facility (with a few shots per day) would relax the driver requirements if compared to a full reactor driver, where high-gain targets were used for continuous energy production. In the course of the study, it was, however, realized that no particular advantage could be drawn from the single-shot assumption, and that the inherent high rep-rate of the RF linac & storage ring based concept brought the size of this scheme closer to an energy production scenario.

The HIDIF study has shown that emittances and momentum spreads resulting from simulating the various driver key issues can be made approximately consistent with the target requirements as set in the study. However, a strong driving factor of the number of storage rings, and with it the final switchyard, was the requirement of less than 1% beam loss at injection. It also became clear that fusion targets designed with a somewhat larger focal spot and preferably longer pulse lengths − if feasible − would help to reduce the overall complexity and size of the HIDIF accelerator system.

6. Perspectives of future research

Research on heavy ion fusion as the energy source has always gone hand in hand with more advanced scientific programs to demonstrate the feasibility of inertial fusion by high power lasers; but also with ion beam driven high energy density in matter as a field of research of its own with possible applications to inertial fusion as well as planetary science and astrophysics.

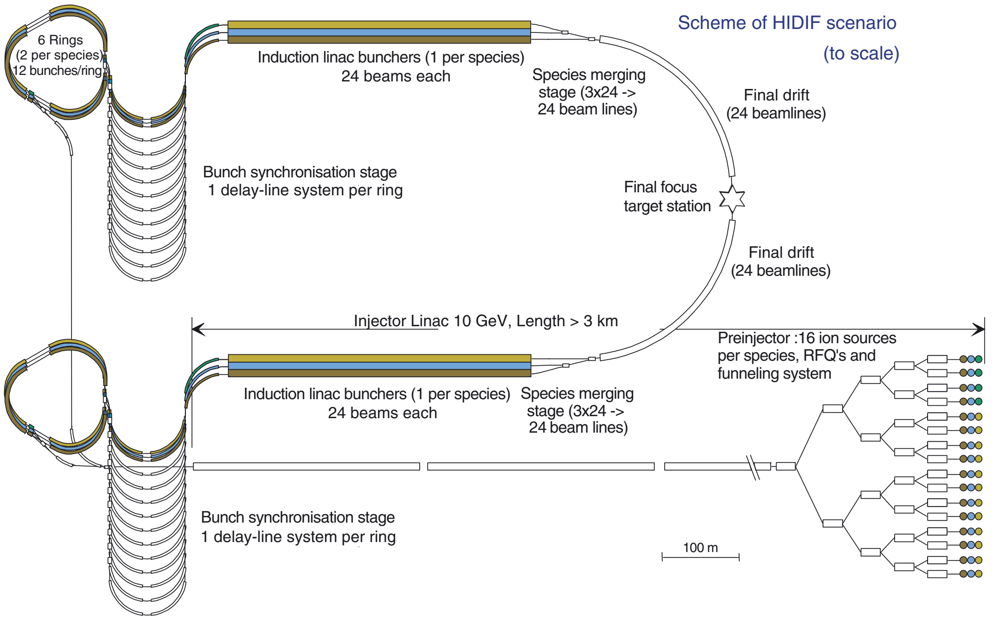

Fig. 10. HIDIF accelerator layout for 3 MJ of total energy per single ignition shot (source: Ref. [30]).

6.1. Heavy ion fusion beyond HIDIF and NIF?

No further feasibility studies have been carried out in heavy ion fusion beyond HIDIF, which has thus remained the most detailed reference to it.

The future of heavy ions as the inertial fusion energy driver depends on how the acceptance of energy by nuclear fusion is developing in general, but also on specific scientific findings. Some of them are summarized here:

i. What are the final conclusions from current laser ignition facilities like NIF or Megajoule Project? In spite of a first success by demonstrating “breakeven” (i.e. fusion energy output equal to energy input), the actual fusion gain lags significantly behind theoretical and simulation predictions − apparently due to lack of propagating burn [44]. In summary, are these laser ignition facilities likely to be able to demonstrate ignition and propagating burn in a pellet?

ii. If so, the next question relevant to heavy ion fusion is whether successful demonstration of ignition will lead to a target modelling and to predictions specifically optimized for heavy ions, their driver accelerators as well as for energy production. The main question then will be, whether a heavy ion specific target modelling − pursued with minimum effort only in the past, if compared to the tremendous effort that went into laser driven pellets − would be more in favor of the specific boundary conditions of a particle accelerator. For example, can one expect larger final beam spots or possibly longer pulse durations than those, which made life so difficult in HIDIF?

iii. Non-Liouvillean methods in order to “gain” higher phase space density might be promising. They have been discussed since the late 1980's; for instance by laser photoionization injection into storage rings [45]; or a photoionization scheme for final compression [46]; or telescoping of different ion species as was used quite beneficially in HIDIF. Apparently, intelligent ways of “phase space saving” beam manipulations, along with highly efficient minimization of dilution in all phases from the source to the target, would be beneficial for any future re-consideration of heavy ion fusion.

6.2. Heavy ion accelerator development

Independent from heavy ion fusion applications, significant progress is currently achieved in the field of high intensity heavy ion accelerators for nuclear structure and other areas of research, in particular towards preparing the large facilities FAIR at GSI Darmstadt, Germany and the HIAF facility project by IMP, Lanzhou, China.

Two subjects of crucial importance for any high intensity accelerator of ions, which remained unconsidered in HIDIF, are being addressed for these new projects:

- *Activation of the accelerator structure by uncontrolled heavy ion beam loss*: The main issue is to compare the activity induced by 1 W/m of proton beam loss − as a standard reference for hands-on maintenance − with that of heavy ions. Note that a full heavy ion fusion driver linac would have to generate typically up to 10 MJ of beam per ignition event at a rate of 10 Hz, which is equivalent to a 100 MW accelerator.

For quantifying the effect, a scaling factor was introduced by Strasik et al. [47] as the ratio of the normalized activity induced by a 1 GeV proton beam to the normalized activity induced by the beam of interest. Their FLUKA simulations of the beam pipe activation on stainless steel showed that the normalized activity induced by uranium ions at 200 MeV/u is about 75 times lower than that for 1 GeV protons. This is due to the short Coulomb stopping range of heavy ions in matter by which the projectile energy goes predominantly into electronic heating rather than nuclear reactions − a mechanism, which is needed for effective coupling of the heavy ion beam to the inertial fusion target converters. The completed results for different projectile masses and energies are shown in Fig. 11. Energies below 200 MeV/u have not been analyzed, but it is clear that the trend of lower activation effects continues.

- *“Loss-induced” degradation of the vacuum by gas desorption*: It was not realized by the community at the time of the HIDIF study, but observed shortly after at LEAR (CERN) [48], the AGS Booster [49], RHIC [50] and the SIS18 at GSI [51]. In this kind of instability, the large gas desorption coefficients for heavy ions from the beam pipes in the range 10^3−10^5 were made responsible for vacuum breakdown.

The matter received much attention in the following years. At GSI, it got recognized as a key issue for realizing the intensity upgrade of the SIS18 as the injector for the FAIR SIS100 − for ions up to uranium. This development was summarized in a review by Spiller [52], where the relevance of SIS18 and FAIR development for heavy ion inertial fusion was also discussed along with the possible paths for cures. The

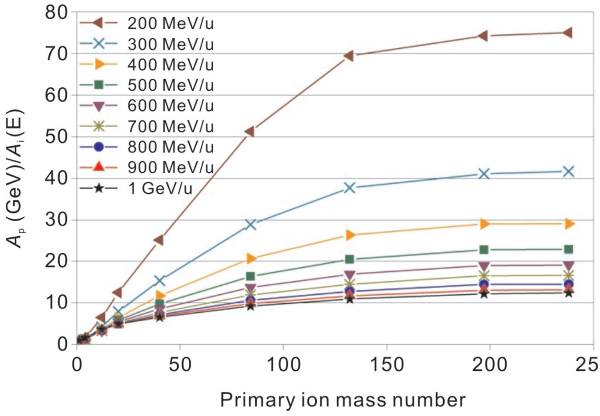

Fig. 11. FLUKA calculations of the scaling factor proton to heavy ion activation in stainless steel (courtesy I. Strasik).

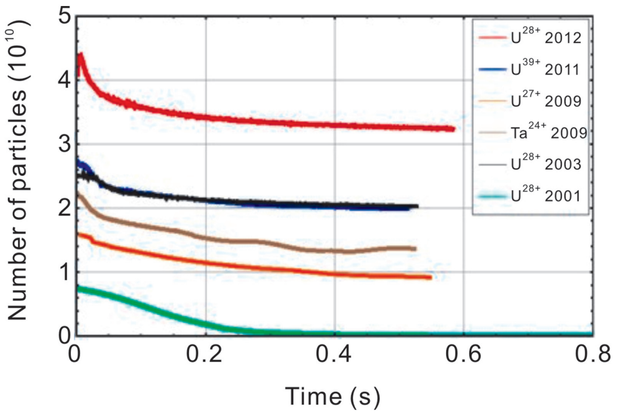

Fig. 12. SIS18 intensity upgrade by reducing beam loss induced desorption and ionization. Shown are loss curves after injection into the synchrotron SIS18 (courtesy P. Spiller).

main building blocks for this intensity upgrade have been: a new injection system for injection of U^{28+} beams at 11.4 MeV/u to reduce initial loss; NEG coated dipole and quadrupole vacuum chambers for distributed pumping; a novel ion catcher system for stripped ions to minimize the effective gas desorption yield. The significant progress in this area from 2001 to 2012 is outlined in Fig. 12. Ultimately, nearly two orders of magnitude intensity gain for U^{28+} have been achieved in this period.

Table 2
Parameter comparison expected for HEDP experiments in FAIR and HIAF (in phase 1) with E_{total} the total particle energy, S_f the beam spot radius, t pulse duration and E_ρ energy density (source: Ref. [27]).

	E_0 (GeV/u)	N	E_{total} (kJ)	S_f (mm)	t (ns)	E_ρ (J/m^3)
SIS-18	0.4	4×10^9	0.06	~1	130	2×10^{10}
FAIR	1	4×10^{11}	15	~1	50	2.4×10^{12}
HIAF	1.1	1×10^{12}	41	1−0.5	130−30	$(6−24) \times 10^{12}$

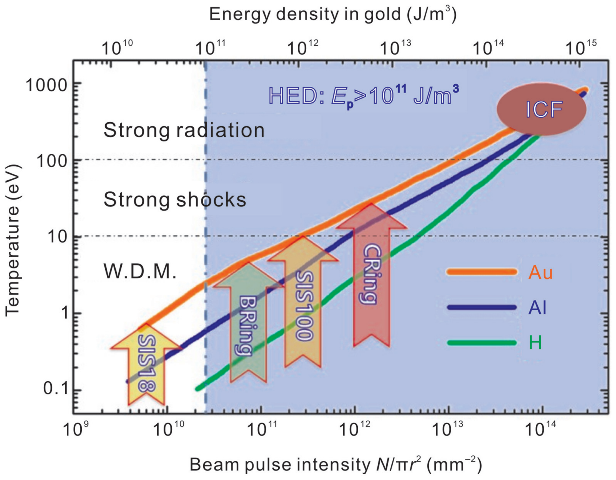

Fig. 13. Expected performance of energy densities and temperatures for FAIR and HIAF (courtesy Y. Zhao).

6.3. High energy density research with ions

Independent from heavy ion fusion applications, progress in the field of heavy ion driven dense matter has steadily progressed [53].

New intensity heavy ion accelerators under construction or planned for research in the field of nuclear structure and other areas of research, in particular the large facilities FAIR@GSI Darmstadt, Germany and the HIAF facility project by IMP, Lanzhou, China, offer research opportunities for high energy density physics (HEDP) as well.

Prospects to contribute to HEDP with heavy ions from particle accelerators are particularly high in the so-called “warm dense matter” regime, where the temperatures are of a few eV, but relatively high densities are of interest. This parameter regime lends itself in particular to accelerator beams, which allow volume heating in relatively large samples of matter as well as attractively high repetition rates for experiments.

The expected performance of the HIAF facility has been compared with FAIR, with a discussion of possible research applications (see Ref. [27]). For orientation, results of projected parameters are summarized in Table 2, with expected values for temperatures and energy densities in Au in Fig. 13.

7. Conclusion

Since the beginning of research on inertial fusion driven by high intensity heavy ion accelerators in the 1970's, progress in this field stimulated theoretical and experimental work in ion beam driven plasma physics and high energy density research. Developments since the 1990's have not been favorable to the realization of a sustainable program in HIF. Nonetheless, the existing and new − FAIR and HIAF − high intensity heavy ion accelerator facilities for nuclear physics provide promising opportunities for both research areas, HIF-relevant accelerator development, and in particular for high energy density physics.

Conflict of interest

The authors declare that there is no conflicts of interest.

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