ENERGY PRODUCTION WITH ACCELERATORS

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Dedicated to Christoph Schmelzer on Occasion of his 80th Birthday

Abstract

The prospects of Heavy Ion Inertial Fusion for energy production are discussed and the current programs are reviewed.

Introduction

After 15 years of research on inertial confinement fusion (ICF) it is evident that this concept provides a realistic chance for future energy generation. Powerful laser facilities, in particular in the U.S. and in Japan, have provided the necessary data base for the most crucial issue, the pellet implosion. Underground experiments carried out two years ago (which have been kept classified and came to our knowledge only recently[1]) seem to show that the principle of inertial confinement works also for such micro-implosions. Among the various drivers suggested for an ICF power plant, heavy ion accelerators clearly have been identified as the most promising device for an economic production of electrical energy. This recognition is based on the extremely high energy density which can be obtained by stopping energetic heavy ions in matter as well as on the enormous progress in accelerator technology and operational reliability during the last decade. Of course, the heavy ion driver for a fusion power plant requires beam specifications exceeding those of existing accelerators considerably. However, there is a great deal of knowledge and experience in construction and operation of large systems of accelerators in many laboratories which could provide a solid basis for such a project. In my opinion, it is now mandatory to consider accelerators strongly for such an application.

After 12 years of research in this field with very limited funds the following question will be discussed here: Is a heavy ion accelerator a suitable driver for ICF? A status report will be given on research which started 10 years ago with theoretical work on beam dynamics and systems studies and with first experimental investigations on crucial elements which finally lead to the construction of first dedicated facilities which are now starting operation or will be available soon. These facilities will enable investigations on problems of accelerator physics as well as beam plasma interaction in a more systematic way.

After a short reminder about facts and numbers of ICF, I will mainly concentrate on two accelerator concepts of heavy ion inertial fusion, the induction-linac and the rf-linac/storage ring concept and finally review the near-term perspectives of future research.

Basic Facts and Numbers of Heavy Ion Inertial Fusion

A DT-mixture of a few milligrams is confined in a pellet of up to 10 mm diameter, which is heated and compressed by ablation up to ignition conditions. The energy supplied by heavy ion beams has to be as symmetrical as possible. The inertial forces of the implosion keep the pellet together for a few nanoseconds, long enough to burn a considerable fraction of the fuel. At an ignition temperature of about 5 keV a compression of about 10^3 (200 g/cm³) has to be reached in order to fulfill the Lawson Criterium $n_o \cdot \tau_c \geq 10^{15}$ s/cm³ (n_o being the number of D and T per cm³ and τ_c the confinement time) which characterizes the breakeven for the flow of energy.

A similar relation exists between the fuel density ρ and the fuel radius R at ignition

$$\rho \cdot R \geq 3 \text{ g/cm}^2$$

which relates the amount of fuel in a pellet necessary for substantial burn with the necessary fuel compression. It tells us that e.g. for an amount of fuel, which can be handled in a reactor chamber, up to a few milligrams, a compression of about 1000 times liquid density is needed. Due to calculations the energy to be supplied for the ignition of such a pellet is 5 about MJ at 250-500 TW.

An ICF power plant consists of three major facilities: (1) The driver, (2) the reactor cavity (including the technical installations) and (3) the pellet fabrication. One advantage as compared to magnetic confinement is the local separation of the driver and the reactor cavity which facilitates its construction and maintainance as well as the extraction of generated energy. Others are the simple geometry of the cavity and the absence of magnetic fields. Many concepts and their technical implications have been investigated but cannot be presented here. Economical aspects will be discussed later.

In trying to evaluate the situation of heavy ion inertial fusion, three basic questions have to be asked:

1) Does the pellet work as predicted by theory?
2) Can the necessary beam conditions be reached by a heavy ion accelerator?
3) Can the overall concept be realized (technologically, economically, environmentally)?

Question (3) was subject of a number of system studies made in Germany, in Japan and in the U.S.. They look promising, also from an economical point of view, but more detailed investigations are necessary. Question (2) will be the main subject of my talk. Question (1) is the most crucial and critical issue, because the functioning of the pellet is the prerequisite of the whole concept. Here, the results obtained with laser beams are giving the essential input into our present understanding of ICF, so some relevant data should be briefly summarized.

Results with laser beams and driver evaluation. The trend during the last years was to shorter wave lengths, aiming at a better coupling of the laser beam to the pellet, and to indirect-driven (X-ray driven) pellets, in order to achieve more symmetrical illumination. In the US, after SHIVA (10 kJ) a new facility NOVA (100 kJ, 100 TW, 10 beams) has been built and is in operation since 1986. These facilities are based on Nd-Glass (1.08 μm) and can also be operated at 1/2 or 1/3 wave length with high efficiency. As to recent reports 1.7 keV and $n_o\tau_c = 2 \cdot 10^{14}$ s/cm³ has been reached. NOVA, when operated at its design parameters, is supposed to reach a compression of 10^3 and will come near to breakeven. In Japan a similar facility (GEKKO, 40 kJ, 12 beams) is in operation. Because there is no classification many important results on the physics of pellet dynamics have been reported during the past year. A new facility "Laboratory for Microfusion (LMF)" is considered as a next step in the U.S.. Design aims are 10 MJ at 1000 TW, which would deliver an energy output of 1 GJ per pellet implosion. If approved it could be completed until the end of the century at a cost level of about 850 M$.

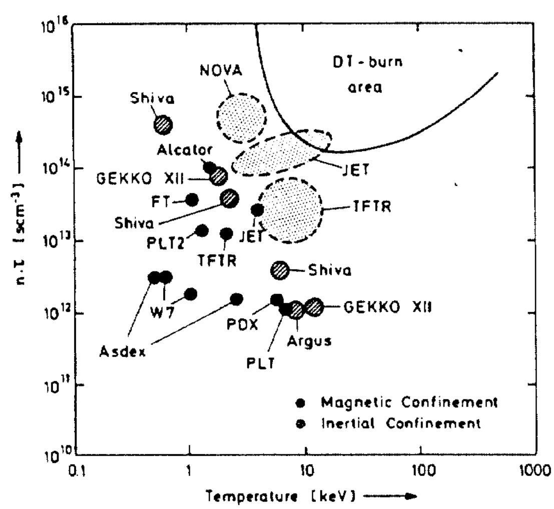

FIG. 1. Lawson diagram showing the product of density n and confinement time τ versus the temperature achieved in some magnetic and inertial fusion devices.

Inspite of all these exciting achievements and fascinating perspectives, laser facilities have some essential features, which make its application to power production extremely questionable. These are in particular

- the low repetition rate and
- the low efficiency

For a qualitativ comparison between various drivers Table 1 shows a list of the essential properties of a driver. This list and its evaluation made 1982 by Nuckolls[2] is still valid except the prospects of the repetition rate for laser and light ion facilities which are evaluated, in my opinion, too optimistic. But for power production this is the crucial issue. Because of its excellent prospects for the repetition rate, the beam-target coupling and the efficiency the heavy ion accelerator is the most preferable driver. Its efficiency should reach about 20 - 25 %

	KrF Laser	Heavy Ion	Light Ion
Efficiency (10–20%)	?	++	+
Focusing	+	+	?
Target Coupling (10%)	++	++	+
Rep. Rate (10–20 Hz)	+	++	+
Cost ($200/J at 2MJ)	+	+	++

Table 1: Inertial fusion driver evaluation (Nuckolls [2]).

Parameters for a heavy ion driver. As to our present understanding for the ignition of a pellet, a heavy ion pulse of 5 MJ has to be delivered within about 20 ns. Consequently the pulse power is 250 TW. This number is a product of the heavy ion kinetic energy and the beam current. Since the kinetic energy of the ions is limited to about 50 MeV/nucleon by their range in matter (10 GeV for the heaviest ions) the necessary pulse current must reach 25 kA. The corresponding figure for a proton beam, for example, would be 25 MA due to the stopping power which is lower by a factor of 1000 as compared to a Bismuth beam. Based on a 5 MJ pulse and a pellet gain of 100 (which is a realistic assumption) the output energy of a single pulse would be 500 MJ, and assuming a pulse rate of 20 pulses per second a thermal power of 10 GW would be obtained which is equivalent to an electrical power of about 3 GW, (Table 2). Some more problems, connected to the effective beam/pellet interaction, e.g. the pulse shaping, the range shortening in a plasma, all kind of pellet design questions, can not be discussed here.

Pulse Energy (needed for pellet ignition)	5 MJ
Pulse Duration (implosion time)	20 ns
Pulse Power	250 TW
Projectile Energy (for Bi or Pb) 50 MeV/nucleon	10 GeV
Pulse Current	25 kA
Pulse Current per beam (for 20 beams)	1.25 kA
Repetition Rate (for thermal power 10 GW) (assumed gain 100; energy/pellet 500 MJ)	20 Hz

Table 2: Beam and plant requirements for a heavy ion driver.

Concepts for Driver Accelerators[3]

After the design parameters have been fixed (Table 2), the question is whether an accelerator can meet these requirements. Among the various accelerator combinations investigated, two concepts have survived the early discussions and are both considered as suitable drivers:

(1) the induction linac and
(2) the RF-linac with storage rings

Inspite of some common features, the transport and manipulation of space-charge dominated beams, the technical problems of both concepts are quite different. In particular, they are very different with respect to the pulse structure.

(1) The pulse sequence of the induction linac can be directly accommodated to the needs of the reactor right from the beginning, no transformation of the pulse structure is needed. Consequently, extremely high intensity from a pulsed ion source is necessary and a pulse compression during acceleration by many orders of magnitude.

(2) A high-current RF-linac may deliver a heavy ion beam continuously up to several 100 mA. In order to create the pulse structure and the pulse currents needed by the reactor, accumulator and buncher rings are needed for current amplification and storage rings to hold the pulses for several milliseconds before feeding the reactor.

Induction Linac Scenario

Research on heavy ion induction linacs has been carried out by Keefe and his group[4] at LBL in Berkeley. The basic idea is to inject a long beam bunch and to achieve current amplification by ramping the inductive accleleration fields as the bunch passes. By this procedure the pulses are compressed from initially 20 μs at injection down to 10 ns at the target, the current being increased from amperes to kiloamperes. One of the important conceptual improvements was the splitting of a single high-intensity beam into a large number of parallel beamlets, each of them being separately focussed inside the same accelerating structure (Maschke's Meqalac concept). This concept has improved focussing because of smaller emittance and has shown to be cost effective if the number of beams is in the range of 8 to 16. The present concept for a driver starts with 64 beamlets at injection which later, when space-charge forces decrease, are combined, each 4 beams into 1. For a 3^+ charge state of bismuth, the whole length of the accelerator is about 5 km (Fig. 2).

Another important result was observed in a beam transport experiment which showed that the maximum transportable current without significant emittance growth can be much higher than the limits given by Maschke's formula.

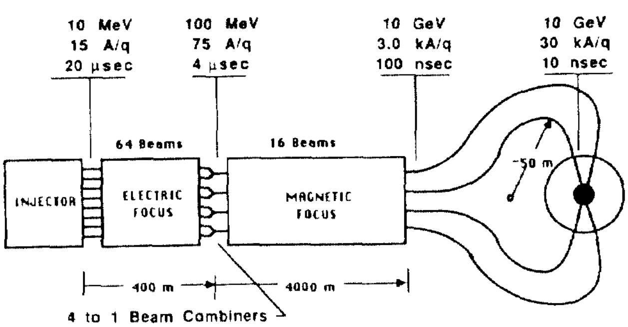

Figure 2: **INDUCTION LINAC DRIVER (A=200, q=3)**

Present work concentrates on a prototype experiment for the multi-beam concept. It is named MBE-4 and consists of 4 beamlets. In spite of its limitation to the front-end only it allows many critical issues to be investigated because the front-end with the initial pulse formation is the most critical part. These issues are in particular:

- the creation of long high-intensity pulses
- the principle of current amplification
- handling of multiple beams
- longitudinal and vertical beam dynamics

These experiments are far from being finished but already now important experiences for the design of future facilities have been made. A. Warwick[6] has presented first data at this conference.

As a ***next step*** an "Induction Linac System Experiment (ILSE)" has been proposed which is intended to address all key issues of a full scale driver, including

- transport of space-charge dominated beams
- combining and bending of beams
- compression and pulse-shaping
- final focussing

ILSE is a 30M$ project and is expected to be funded next year. Construction should be finished within 4-5 years and it is supposed to be the last step before a full-scale driver can be designed and constructed. Table 3 shows a comparison of the parameters for the three facilities, MBE-4, ILSE and the Induction Linac Driver.

Table 3 Beam parameters of MBE-4, ILSE and a driver.

Parameter	MBE-4	ILSE	Driver
Ion	Cs^+	C^+ (AL^{++})	200^{+++}
Final Volt. (MV)	1.0	10	3300
Final Current(A)	0.1	30	60000
Beam Energy (J)	0.1	125	3 MJ
Accel Grad. (MV/m)	0.07	0.22	0.5
# Beams	4	16-4	64-16
Pulse Width (µs)	2-1	1-0.5	24-.1
Charge (µCoul.)	0.1	15	900
Init. bunch length (m)	1.1	5.6	70

RF-Linac Scenario

The RF-linac/storage ring concept looks more conventional than the induction linac, because nearly all accelerator and beam handling elements are known from operating facilities. No experience however, exists about their operation in a regime of space-charge dominated non-relativistic beam dynamics, where various types of instabilities may occur and where the beam transport and any beam manipulations may be connected with severe emittance growth and intensity loss.

In order to identify all the critical issues we made a conceptual design study, HIBALL[6], in the first half of this decade, which was followed by studies in the U.S.[7], the USSR[8] and in Japan.[9] I will first briefly describe our own concept as far as the accelerator is concerned and focus on the problems identified and then present some results of the systems studies in general.

HIBALL II[10]: Concept and critical issues (Fig. 3). A 5km RF-linac provides acceleration at constant current using RFQ, Wideröe and Alvarez structures. The front end starts with 8 parallel channels because of space-charge limits at low velocity. By funneling connected with frequency doubling the parallel channels are combined stepwise over a length of about 500 m. To achieve the 165 mA design value of the linac current, sufficient Bi^{1+} intensity with a normalized emittance of $0.2 \cdot 10^{-6}$m•rad was already obtained by sources developed at GSI.

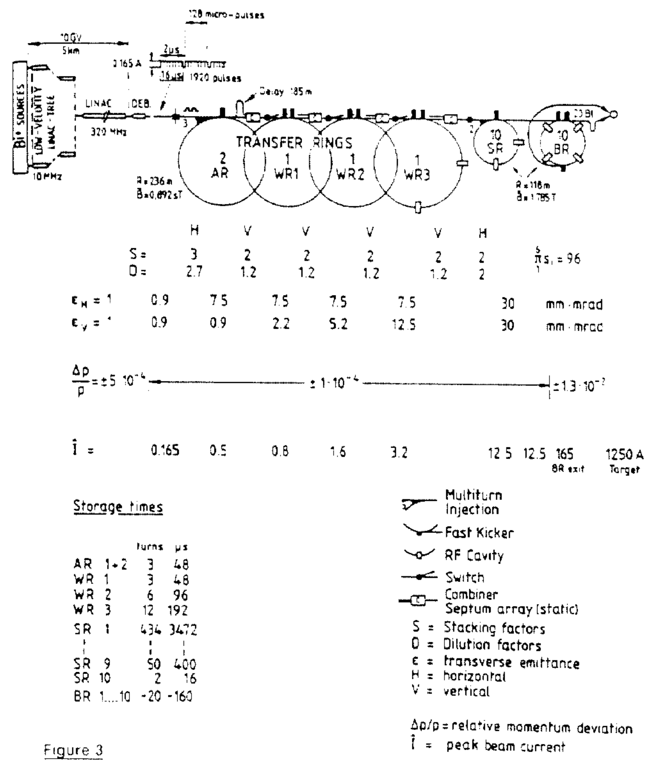

Figure 3

RF-linac/storage ring scenario for storage time 4 ms (HIBALL II[10]).

One of the remaining problems in this area is the question of emittance growth by funneling. The rest of the accelerator, transfer, storage and buncher rings is devoted to current multiplication and to provide the adequate pulse frequency and pulse shape for the reactor. The current multiplication factor is 8000 and the maximum emittance growth is allowed to be 30 at maximum. The maximum storage time of 4 ms is a compromise between the longitudinal microwave instability in the storage rings and the beam intensity provided by the linac. If the microwave instability would turn out to be not so serious the beam intensity of the linac could be further decreased. On the other hand, because of the short storage time the driver can provide a much higher pulse frequency (~ 100 Hz) than one reactor chamber could use (5Hz), the same accelerator therefore can serve a number of reactor chambers. The HIBALL study assumes 4 but even more would be possible, thus further reducing the cost of electricity.

For the ring system and the injection into the reactor the problems listed in Table 4 have been identified. In this area not much experience is available, so ideas and new techniques may improve the situation. Phase space stacking in the synchrotron, for example, might be greatly improved by changing the charge state of Bi^{1+} at injection by laser beams, as suggested by Rubbia[11]. A method for the suppression of microwave instabilities was proposed by Hofmann[12].

Cost of Electricity. The breakdown of costs for the HIBALL II power plant can be characterized by the following numbers:

Linac (including building + installation)	20%
Ring system and beam transport	39%
Reactor (4 cavities)	23%
Conventional facilities etc.	18%

The total costs of a 3.7 GW_e power plant was 6.2 G$ (cost level 1985). Under these assumptions the cost of electricity would be about 4.8 cents/kWh.

Table 4

Key issues to be investigated for the storage and buncher ring scenario and its effect on performance.

Issue	Consequence
- debunching of the linac beam	momentum spread
- beam combining by septa	emittance growth
- longitudinal instability	holding time in storage rings
- beam transport over long distances	emittance growth
- final bunch compression	pellet gain
- prepulse formation,pulse shaping	pellet gain
- final focussing	intensity loss
- phase space dilution in multiturn stacking	emittance growth
- ion-ion charge-exchange	intensity loss
- technological issues	

During the last 5 years systematic studies about cost estimates and cost optimization have been accomplished in the U.S..[7] In Table 5 comparisons are made between various concepts including Tokamak reactors. The comparison looks good for ICF. The variation of plant paramters (pulse rate, driver cost, size of the plant etc.) shows clear tendencies concerning the cost of electricity (COE). Strong dependence for the COE is observed from the net electric power of a plant and the number of reactor units per plant. For a reference design of a 1 GW_e power plant an increase by 50 % would reduce the COE by 25 %. A 25 % change in the driver cost results in a 13 % change in COE. Since the driver cost is relatively high, increasing the number of cavities per plant also reduces drastically the cost of electricity.

Table 5

Comparison of the cost of various reactor concepts and the effect on cost of electricity (COE) for two plant sizes, 1.2 and 3.8 GW_e (1985 Dollars). STARFIRE and MARS are magnetic fusion facilities, HIF/CAS are heavy ion driven plants with the reactor concept CASCADE of LLNL.

	Net Power = 1200 MW_e			Net Power = 3784 MW_e	
	STARFIRE	MARS	HIF/CAS	HIBALL-II	HIF/CAS
Direct cost (G$)	2.07	2.24	1.83	4.80	3.43
Total cost (G$)	3.78	4.10	3.34	8.78	6.30
COE (¢/kW_eh)	6.13	6.33	5.14	4.59	3.07

Future Research at GSI

The first funding period of the W. German Program 1980-86 was an ***exploratory phase***[13] devoted to the systems study, to the development of high brilliance ion sources, RFQ and other accelerator relevant components as well as to theoretical investigations on accelerator and target issues. A concept for a synchrotron/storage ring combination was designed for the study of beam dynamics in space-charge dominated regimes and for target experiments at high energy density in matter. This machine, SIS/ESR,[14] is now under construction at GSI in Darmstadt and will be finished 1989/90 (Fig. 4). The present funding period which started 1987 is devoted to the preparation and performance of experiments with this machine. These experiments will cover a number of driver relevant issues[15] as shown in Fig. 5. Moreover, the beam cooling in the ESR provides beams with high phase-space den-

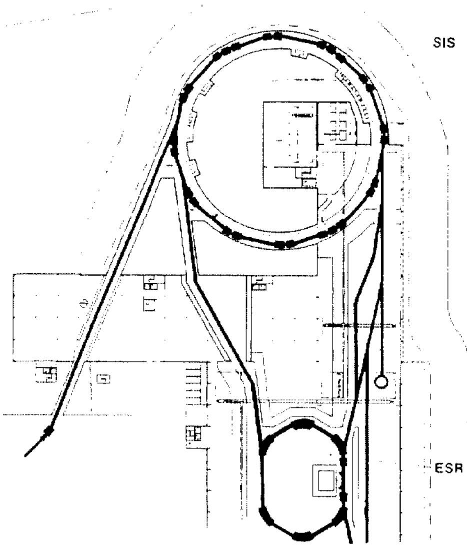

Figure 4
SIS/ESR, a 1.3 GeV/nucleon Heavy Ion Synchrotron/Storage Ring Facility, under construction at GSI (SIS diameter 65 m).

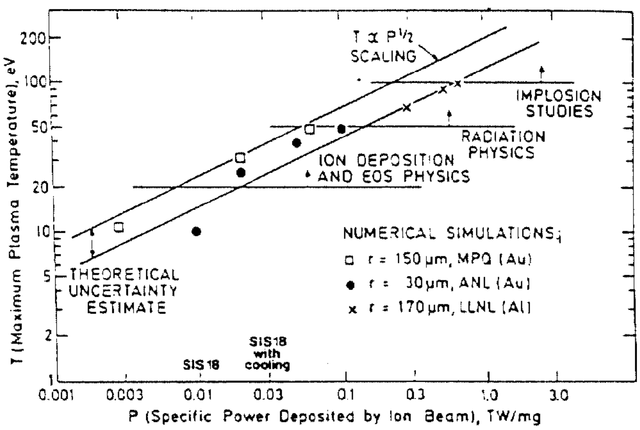

Figure 6
Temperaturs to be achieved by energy deposition of a heavy ion beam in solid material. (Arnold and Meyer-ter-Vehn[16])

sity which can be used for heating small samples of matter up to temperatures of 20 eV or more (Fig. 6). This powerful facility will open a new field of fusion relevant research, covering a broad spectrum of problems in target physics, beam plasma interaction, pumping of short wave length laser by intense heavy ion beams. Many key issues remain open, but the results with this facility should help to define the future direction more clearly.

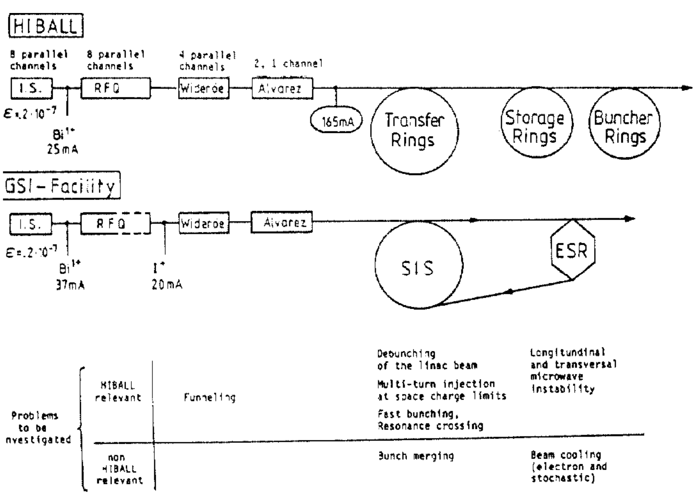

Figure 5
HIBALL relevant beam dynamics problems to be investigated at SIS/ESR. Figures for emittance and beam intensities are experimental results.

In conclusion the following statements can be made: 1) Heavy Ion Inertial Fusion is a promizing alternative to magnetic confinement. 2) Two accelerator concepts have been developed which may satisfy the driver requirements. 3) In an existing near-term research program most of the key issues will be addressed, some have been solved already. 4) A decision for a dedicated facility should be made on the basis of present investigations in the beginning of the next decade.

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