HEAVY ION FUSION

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Introduction

Of all the proposed drivers for an ICF power plant the heavy ion accelerator is by far the most promising candidate[1]. Stimulated by some accelerator physicists about eight years ago[2], studies on various accelerator scenarios for heavy ion fusion have been started at several laboratories in various countries. Results of these studies were discussed at several workshops in Berkeley, Argonne and Brookhaven in 1976 through 1979[3] and finally one year ago in Darmstadt[4]. Some of the early concepts and ideas had to be abandoned, others became quite realistic and have been worked out in great detail. One can summarize the results of the world-wide effort of the last years by saying, that considerable progress has been made on many essential issues of heavy ion fusion and that reasonable concepts for a near-term program have been developed.

Two accelerator scenarios are considered as driver candidates for an ICF power plant: the RF-linac with storage rings and the induction linac (Fig. 1). As far as we can extrapolate from our present knowledge the necessary beam intensity and beam quality requirements are believed to be achievable on the long run: Repetition rate and accelerator efficiency are not critical issues. Present accelerator technology is at a high standard, particularly for conventional accelerator concepts. Conceptual design studies have increased our confidence that the technical problems of the ICF concept with a heavy ion driver including the reactor can be solved, and they have shown that the economical aspects are not prohibitive as compared to other ICF concepts. Nevertheless many open problems still exist and some new ones have been exhibited by systematic studies in the last few years. It has become evident that most of them cannot be investigated with existing facilities and at the present level of effort.

What are the long-term and near-term perspectives?

1. Our research is oriented at the final goal: the economic production of energy in the next century. This is a well defined mission, and we have theoretical predictions about the objectives which have to be attained. But we have to realize that this aim is in the distant future, that it is a long way to get there and that some of our present achievements are still orders of magnitude apart from these objectives. On the other hand, conceptual design studies have considerably improved our assessment of the physical and technical feasibility of the HIF concept. In the first section, I would therefore like to present results of these studies.

2. Our present programs, which I will briefly summarize in the second section, are basic research programs, and it would be, in my opinion, unwise to confine them too narrowly to problems only defined by this final-goal perspective. The scope of our present activities has to be extended and basic research should be intensified mainly in two areas:

- accelerator physics and
- beam-target interaction and target physics.

A program like that calls for a dedicated facility. In my last section I will report on plans and ideas that have been developed for such an intermediate facility.

1. Conceptual Design Studies

The early studies on HIF concepts were focused on the accelerator scenarios only. Ignoring the reactor seemed justified to some extent because of the loose coupling between driver and reactor, which obviously is one of the great advantages of inertial confinement by heavy ion beams (as compared to magnetic confinement). There are, however, important reasons for a joint consideration of both components:

- the compatibility between two extremely different environments must be demonstrated
- the technical concept of the accelerator/reactor interface has to be defined
- final focusing, one of the key issues of the accelerator, depends on the reactor environment
- many issues can be estimated and optimized only for the integral facility
- research problems requiring priority treatment must be identified

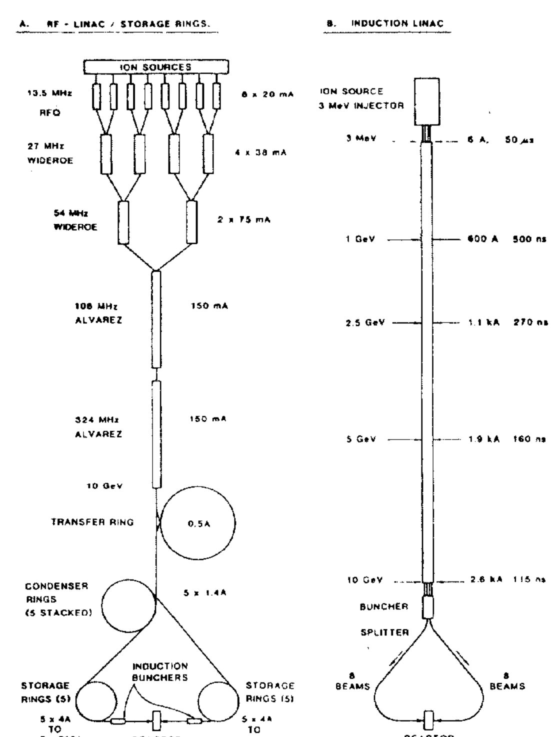

Fig.1 Scheme of two proposed accelerator driver systems: A) the proposed driver for HIBALL (5 MJ/pulse) and B) a single-pass four-beam induction linac (3 MJ/pulse).

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For both accelerator concepts, RF-linac and induction linac, conceptual design consideration have been carried out during the past few years. The most complete study of this kind carried out for an RF-linac driver is HIBALL[5] (an acronym for Heavy Ion Beams and Lithium Lead) which we started in 1980 as part of the W. German program on the "feasibility of heavy ion beams for inertial confinement fusion" in a collaboration with the Nuclear Engineering Department of the University of Wisconsin. The goal for this study was to demonstrate the compatibility of physics and engineering design in areas of driver, target and reactor chamber through a self-consistent conceptual design.

I will first report on this study and subsequently make some remarks on the induction linac driver. For HIBALL the following basic assumptions were made:

- the driver is an RF-linac with storage rings
- the reactor has a novel first-wall protection using a lithium lead eutectic as coolant and breeder material
- the pellet has a moderate gain of about 80 and needs heavy ion pulses of 5 MJ and 240 TW for ignition.

A parameter list for pellet and accelerator is given in Table 1. For the following one should keep in mind that the present HIBALL report is a very first approximation and has to be upgraded continuously along with the progress of driver and reactor concepts.

Table 1. Beam and pellet parameters

Ion species	^{209}Bi
Ion energy	10 GeV
Pulse energy on target	5 MJ
Pulse duration	20 ns
Pulse current per beam-line	2.5 kA
Number of beam-lines	20
Fuel mass per pellet	4 mg
Pellet diameter	8 mm

1.1 RF-Linac with Storage Rings

First I should point out that there are two different HIBALL concepts. The first one, developed 1980-81 and described in the HIBALL-Report, was submitted to a critical examination at the workshop in Darmstadt one year ago. Some assumptions turned out to be not realistic, some of the specifications of the driver concept, therefore, had to be changed. The revised and improved concept which I present here (Fig. 2) has not yet been worked out completely and still may have some inconsistencies[6].

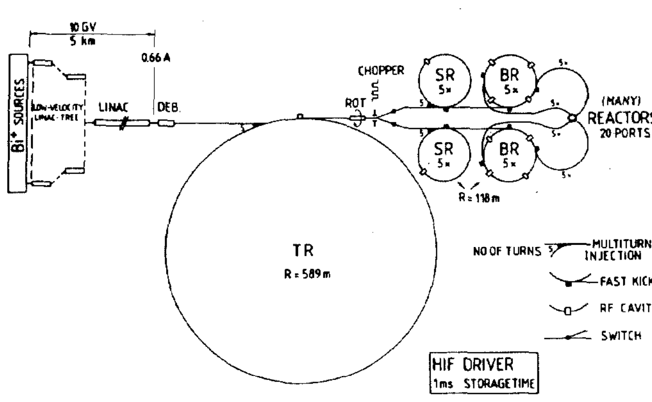

Fig.2 Conceptual HIBALL design study: Revised driver concept.

a) The Driver concept. A Bi^+ beam was chosen with a current of 660 mA at the end of the linac. In order to avoid space-charge limitations, the accelerator consists at its front end of about 32 parallel channels which are fed together by funneling. The accelerator consists of RFQ, Wideröe and Alvarez structures with a total length of about 5 km. The maximum energy is 50 MeV/nucleon, the necessary momentum spread $\Delta p/p \approx 5 \times 10^{-4}$ at the end of the accelerator and 5×10^{-5} after debunching. A first current multiplication is achieved by horizontal stacking of 5 turns in a "transfer" ring. After rotating the beam by 90°, 10 parallel storage rings are filled successively with 5 turns each. Another set of 10 superconducting storage rings is provided for the final bunching. 20 beam pipes of less than 1 km each are feeding the reactor. The pulse current is 250 A at the exit of the storage rings and attains 2500 A in each beam line at the target. After 1 ms the cycle of filling and extracting is finished. Since the maximum repetition rate of the reactor is limited to 5 Hz, the accelerator can serve many more reactor chambers with only little additional load, thus reducing the investment costs for the power plant.

For those knowing the original HIBALL parameters here a list of the most significant changes:

- The charge state of Bi ions was reduced from 2+ to 1
- The number of parallel channels at the front end had to be increased by a factor of 4, in order to obtain the necessary current
- The holding time in storage rings was reduced (because of microwave instabilities) from 7.5 to 1.0 ms
- Linear induction modules were replaced by a set of buncher rings

b) The Reactor Concept. The reactor chamber is a cylindric vessel with 20 ports for the beam entrance (Fig. 3). A unique feature is its first-wall protection concept. Using a eutectic of Pb(83 %), Li(17 %) as coolant and breeder material, the vapor pressure at the time of beam and pellet injection can be kept as low as 10^{-5} Torr. Through a system of porous SiC tubes the coolant is streaming down

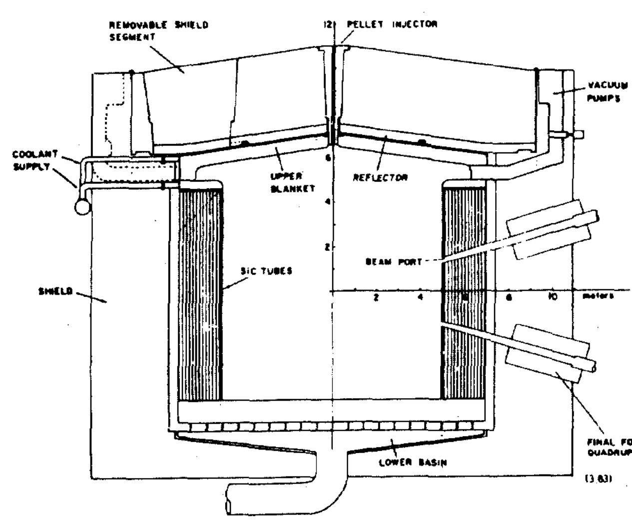

Fig.3 Conceptual HIBALL design study: Reactor chamber

along the wall and can be fed around the beam ports. The repetition rate is 5 Hz for each chamber, the total plant consists of 4 chambers. The characteristic parameters are listed in Table 2.

Table 2. HIBALL reactor parameters

Target gain	80
Target yield	400 MJ
Number of reactor chambers	4
Number of beam-lines per chamber	20
Repetition rate per chamber	5 Hz
Net electric power (total)	3.8 GW_e

The following reactor and interface issues have been studied in detail:

- the final focusing lens concept
- the neutron shielding of the beam tubes and final focusing lenses
- the pellet injection system
- the liquid wall concept, consisting of "Inhibited Flow Porous Tubes" (INPORT) fabricated of SiC tissue
- the tritium breeding and handling
- neutronics and activation problems
- cost and efficiency estimates.

Recent progress was made with an improved final focusing design, in which the lens and beam diameter could be reduced considerably.

c) Economic aspects. Preliminary HIBALL cost estimates for the first driver concept are about 1800 $/kWe for the capital investment. Fig. 4 shows the breakdown of plant costs and electricity price. With the new driver version the capital costs of the power plant are increased by 25 %. It is still competitive with other ICF reactor concepts.

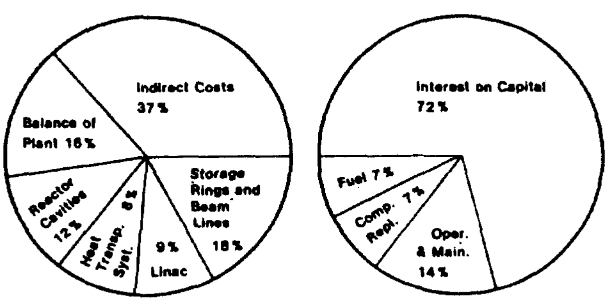

Fig.4 Preliminary HIBALL cost estimates. Breakdown of plant cost (left) and electricity price (right).

d) Results and critical issues. As a result of this design study, it could be shown in a first approach that a power plant based on an RF-linac driver seems to be a viable concept. HIBALL as a consistent design for accelerator and reactor can be used as a reference design for forthcoming studies. For the accelerator the following key issues deserve more detailed (experimental) investigations

- Generation of high-brilliance heavy ion beams
- Funnelling
- Phase space dilution in multi-turn stacking
- Losses at injection and extraction
- Instabilities at space-charge limits, in particular microwave instabilities
- Bunching with space-charge compensation
- Final focusing.

In addition, research on accelerator technology and development of beam manipulation elements (kickers, septa, bunchers, etc.) must be considered equally.

Finally it should be mentioned that in Japan a similar conceptual design study, HIBLIC, consisting of 10 reactor chambers is under consideration[7]. The main parameters are: Pb^+, 15 GeV, 4 MJ, 160 TW, 6 beams, 10 Hz.

1.2 Induction Linac.

The induction linac has some intriguing features as a driver candidate. As a single-pass accelerator its pulse structure can be very well adapted to the repetition rate of the reactor and no beam storage is necessary. This structure is very well suited to the acceleration of very high beam currents, and the amplification of this current takes place continuously during acceleration (Fig. 1). As will be discussed in the next section considerable progress has been made in Berkeley during the last few years both in conceptual as well as technological respect[8]. In particular, the idea of beam splitting during acceleration into many separately-focused beamlets[9] (Fig 5) can be considered as a breakthrough. The use of beamlets leads to less longitudinal and transversal space-charge defocussing and facilitates the longitudinal stability requirement as well as the splitting after acceleration. Present systems considerations have shown that a large number of electrostatically-focused beamlets which would merge at a few 100 MeV to a smaller number of magnetically focussed sub-sets would be advantageous with respect to emittance growth and to cost.

A rough cost estimate[10] for such a driver led to a total projected cost of 2 G$ for a 3 MJ case based on present technology. It is intimated that with the progress of technology some reduction of cost could be achieved. This is a very attractive number compared to the RF-linac. However, it may be premature to make too detailed cost estimates at this stage. Any concept may benefit from future developments, but a more futuristic concept has more imponderabilities.

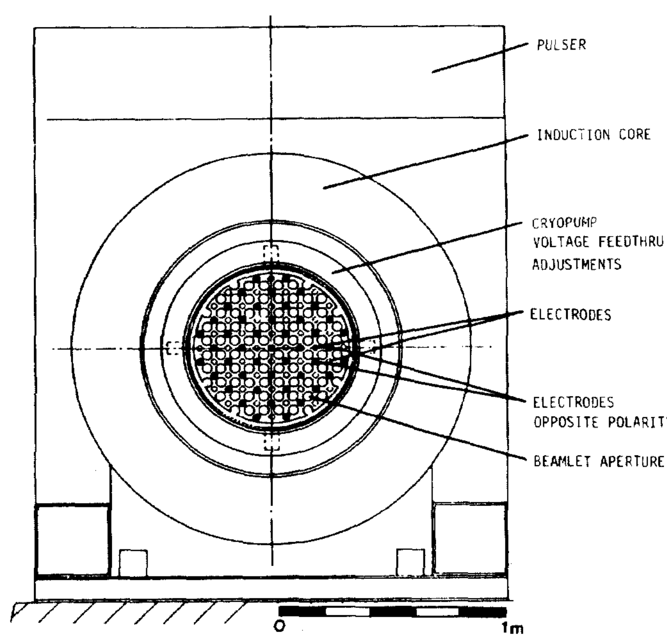

Fig.5 An example arrangement of the induction linac modules and electrostatic quadrupole system for a 64-beamlet array. (D. Keefe, Berkeley).

The following issues and areas, specifically for the induction linac, deserve intensified studies in the near future:

- Ion Source: Generation of beams with extremely high current density and high brilliance
- Front end of the accelerator
- Beamlet concept
- Beam instabilities
- Induction module

2. Present Activities in HIF

Major experimental and theoretical activities exist in the US, in England, Japan and West Germany, mainly in the field of accelerator physics, but also in other related areas such as atomic and target physics. In this section I would like to characterize the directions of present national programs and briefly summarize the essential results.

In the US, both accelerator lines have been pursued since 1976 with many studies on accelerator components and beam dynamics, ion sources and beam transport. The main emphasis is on the induction linac in Berkeley[8] with the near-term goal of a facility for a high-temperature experiment. The importance of these studies is enhanced by the fact that it is the only place, world-wide, with major activities and experience in induction linacs. In addition to the work already mentioned in the previous section, present experimental investigations are concerned mainly with the front end of the accelerator, the large-area high-brilliance cesium ion source and a 200 keV injector for a single beam transport experiment. Diagnostic tools have been developed, in particular a non-destructive electron beam technique has been developed for studying ion beams in varying stages of charge neutralization. Concerning the technology of induction modules prototypes have been built and tested, the development of high-current switches and pulse-forming network has proceeded successfully. New types of core and insulating material are under consideration which show favourable cost perspectives. A long-pulse induction module, to be used at the front end for slowly moving ions, is in its final stage of construction. Summing up one can say that a broad range of very important developments is underway. These efforts would have to be considerably increased, however, if the induction linac should be chosen for the high-temperature facility. In addition, outstanding theoretical work on beam dynamics has contributed considerably to the concepts developed.

Los Alamos, in a complementary program, is concentrating on topics of the RF-linac with respect to an alternative for the high-temperature experiment[11]. Areas of this program are

- the development of low-frequency RFQ resonator structures (Fig. 6), a field with an excellent record at this laboratory[12]
- beam dynamical studies on storage rings, funneling, multi-channel linacs and studies on octupole radial focussing
- considerations for a high-temperature experiment.

In addition, theoretical and simulation studies on target physics, pellet dynamics and beam-target interaction in collaboration with Livermore are in progress.

One more activity, Maschke's novel approach to thermonuclear ignition with momentum-rich beams needs not to be discussed here, because it is the subject of the next talk. At Maryland University a beam transport experiment is underway[14].

The situation in the UK[13] is quite different and more concentrated on some selected issues. On one hand, there is a notable community, mainly at universities experienced in problems of target physics and intra-beam ion-ion interaction. Measurements on charge-change cross section are outstanding and are accompanied by theoretical activities. On the other hand, a high-intensity synchrotron to be used as a spallation neutron source is under construction at Rutherford Laboratory and will be a unique machine for beam dynamic studies. Many groups from various countries have submitted proposals for such experiments and are still hoping to have a chance to use this machine after completion at the end of 1984. In addition, a beam transport experiment at Rutherford Laboratory should be mentioned[13].

In Japan, objectives of HIF are investigated at several laboratories. Some years ago, plans came up to build the Numatron heavy-ion accelerator (a proposed Bevalac-size machine for relativistic heavy ions) for use as an accelerator for HIF target experiments. These plans at INS Tokyo are further pursued, but plans for a realization in collaboration with and at the Plasma Physics Institute in Nagoya, seem to have failed, for the time being [7].

A conceptual design study on a full scale driver accelerator for HIF is in progress at INS, as already mentioned in the first section. It is carried out together with target physicists and reactor engineers and will be available soon. The storage ring TARN at INS is being used for beam storage experiments and an RFQ structure has been completed. At Kanazawa University work on development of a induction linac has been started some time ago. The first stage of a proton model has been finished with plans for a 1 MeV, 1 A upgrading during 1983. More details will be presented at this conference[7].

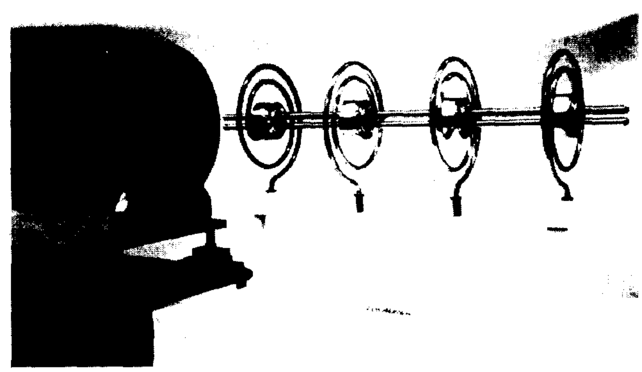

Fig.6 Los Alamos low-frequency RFQ spiral resonator[12])

The German program on heavy ion fusion is covering nearly equally the three main topics (1) accelerator research, (2) target and atomic physics and (3) the conceptual design study, with some preference for accelerator physics. It has been funded for a first period of 6 years until end of 1984. Several research laboratories and university institutes are participating. Here I will concentrate on the accelerator research. The main topics are

- Ion sources and beam injection (GSI and Frankfurt University)
- High current experiments at the existing Wideröe accelerator (GSI)
- RFQ structures (for protons and heavy ions) (GSI and Frankfurt University) (Fig. 7)
- RF-linac problems (e.g. funneling) (KfK)

- Beam transport experiment (GSI)
- Beam dynamics (IPP Garching)
- Consideration of target experiments (MPQ Garching and GSI)
- Charge exchange measurements (Gießen University)
- Final focussing (IPP Garching and Gießen Univ.)

Because of lack of time and because several contributions of this work will be presented at this conference I will concentrate on only a few results. (1) Measurements and design considerations for RFQ structures have been continued. The construction of the first tank of a heavy ion RFQ structure has been finished (Fig. 7). Five tanks of this kind will be built in the near future as a high brilliance injector for UNILAC. (2) A beam transport experiment has been assembled and has produced first results, as reported at this conference[14]. (3) A new set up is now available for measuring ion-ion charge exchange cross sections. (4) In studies on beam dynamics in rings it was found that microwave instabilities can be suppressed by proper choice of the particle distribution[15].

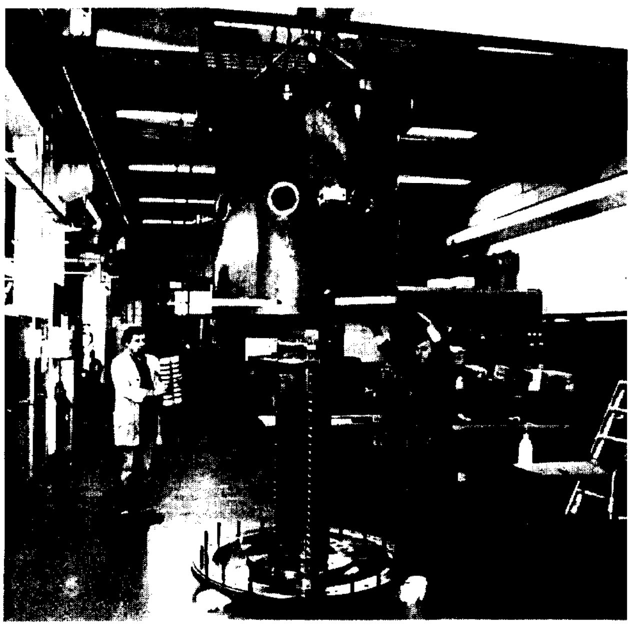

Fig.7 RFQ module (GSI-Frankfurt design).

3. Facility for target experiments

Evidence has been given in the previous sections that many essential problems of HIF can not be investigated, both in the areas of accelerator physics as well as in target physics, because appropriate accelerator facilities are not available.

The JASON Committee, in a recent assessment on HIF and in particular on the US National Plan for a High-Temperatur Experiment (HTE), came to the following conclusions what the scientific goals of such a facility would be:

- check acceleration and transport of beams near space charge limit
- develop technology of drivers
- allow a more reliable estimate of the cost
- permit experiments on beam propagation in a reactor environment
- check effects in coupling physics

The scientific goal of a high-temperature experiment is the investigation of beam target interaction with high-intensity beams and of the physics of solid-density plasmas. The areas of physics which can be investigated depend on the maximum temperature obtainable. Several regimes can be distinguished. The minimum temperature which should be obtained is about 20 eV. In a range up to about 50 eV ion energy deposition, beam propagation and the equation-of-state would be an interesting subject to investigate. Other issues are the creation of shock waves, energy transport mechanisms by electronic conduction and radiative transfer. Above 50 eV a fraction of the beam energy will be transformed into electromagnetic radiation, so the radiation physics with its implications on the mechanisms in the pellet is an interesting subject for research. Hydrodynamic flow and hydrodynamic instabilities are very crucial issues. Only at energies higher than 100 eV one would expect that implosion studies could be done.

Two different approaches to such a target facility are under consideration:

(a) In the US a dedicated facility is proposed aiming at the investigation of accelerator issues and target issues with equal weight, the new program being called "Accelerator Inertial Fusion Program" (AIF)[11]. The objective is a temperature range of 50 to 100 eV. The time schedule considers first a 3 year period for accelerator research, after which the decision for the technical concept (whether induction or RF-linac) shall be made and another 3 year period for construction. In Japan similar plans exist, but without a definite time schedule.

(b) The approach we have in W. Germany is much more pragmatic[17]. We have at GSI a proposal for a synchrotron for nuclear physics research with relativistic heavy ions, which hopefully will be funded next year. We discussed last year whether a high energy heavy ion beam also could be used for target experiments, and whether conditions can be achieved attractive for target experiments. The construction time is considered to be about 4 years.

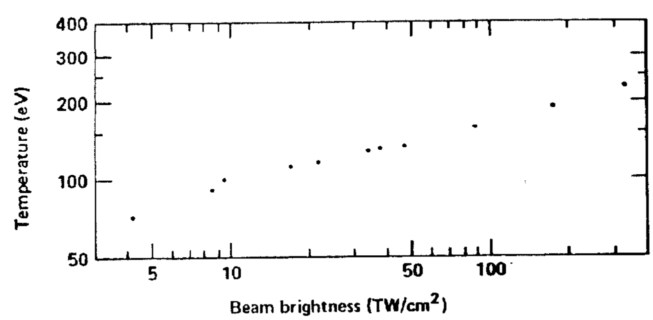

Fig.8 Calculated temperature of a disk heated by a heavy ion beam[11]).

3.1. The US High-Temperature Experiment

The experimental target scenario on which these considerations are based is the heating of a disk about 1 mm in diameter embedded in high-Z tamper material in order to reduce hydrodynamic losses. Because of the radiation losses (proportional σT^4) of a heated target sample the maximum temperature which can be reached is a function of beam brightness. Calculated temperatures of a disk heated target are shown in Fig. 8 as a function of beam brightness. Application of scaling laws for beam brightness as a function of q, A and ε_N lead to the following preferred parameters for an accelerator facility.

Ion	Sodium, Potassium
Beam pulse energy	1 to 5 kJ
Kinetic energy	50 to 200 MeV
Number of ions per pulse	1-3 x 10^{14}
Emittance/beamlet(normalized)	2-10 x 10^{-7} rad x m
Number of beamlets	50 or more

In contrast to the HIF driver accelerator there is an advantage in choosing a relatively light ion at low energy.

3.2 Target Experiments at the proposed GSI Heavy Ion Synchrotron

The target scenario is very different because of the high ion energy of about 0.3 GeV/nucleon. Instead of a disk shape it has the shape of a pencil with a diameter of 0.25 mm and a length of a few millimeters and is embedded in a cylindrical piece of material. Under the assumption that the accelerator (Synchrotron and UNILAC as an injector) would already exist, the additional expenditure for the facility would be very modest:

- a high-brilliance injector of RFQ-structures (beam specification see Fig. 9)
- additional RF for bunching (pulse width on target 16 ns)
- a fast extraction for the synchrotron

All the relevant accelerator parameters are given in Fig. 9.

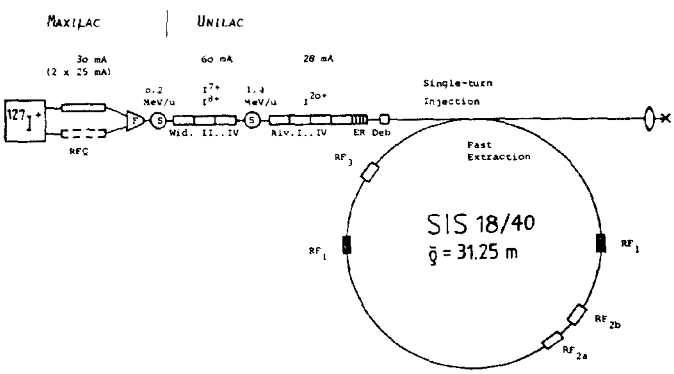

Fig.9 Proposed synchrotron facility to be used for target experiments.

With this facility and the suggested target geometry a power density of some 20 GW/mg can be obtained. (In this geometry the specific power is the relevant quantity.) The corresponding maximum temperature should be about 20 to 30 eV[18].

In conclusion one can say that with the realization of the proposed facilities Heavy Ion Fusion will enter a new era. For accelerator physics new directions would be opened and new technological developments would be stimulated. Apart from acquiring essential and necessary data on beam-target interaction, an exciting field of basic research could be explored.

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