Inertial confinement fusion with heavy-ion beams

A challenge for accelerator physics

Accelerators have the potential to contribute to in the enormously growing energy market of the 21st century, if inertial confinement fusion can be shown to be competitive with fossil and other nuclear alternatives. It is expected that ignition of fusion targets and energy gain will be demonstrated within the next decade by the powerful laser facilities now under construction at Livermore and Bordeaux. The development of a suitable driver with high efficiency and high repetition rate capability, however, remains a challenging issue. At present, heavy-ion accelerators are considered to be the most promising option for such an inertial fusion driver.

In this context, GSI initiated a Study Group to investigate, on an advanced level, the feasibility for a Heavy Ion Driver for Inertial Fusion (HIDIF) in 1995. This collaboration of research groups in France, Germany, Italy, Russia, Spain, the UK, the United States, and at CERN published a comprehensive report at the end of 1998.

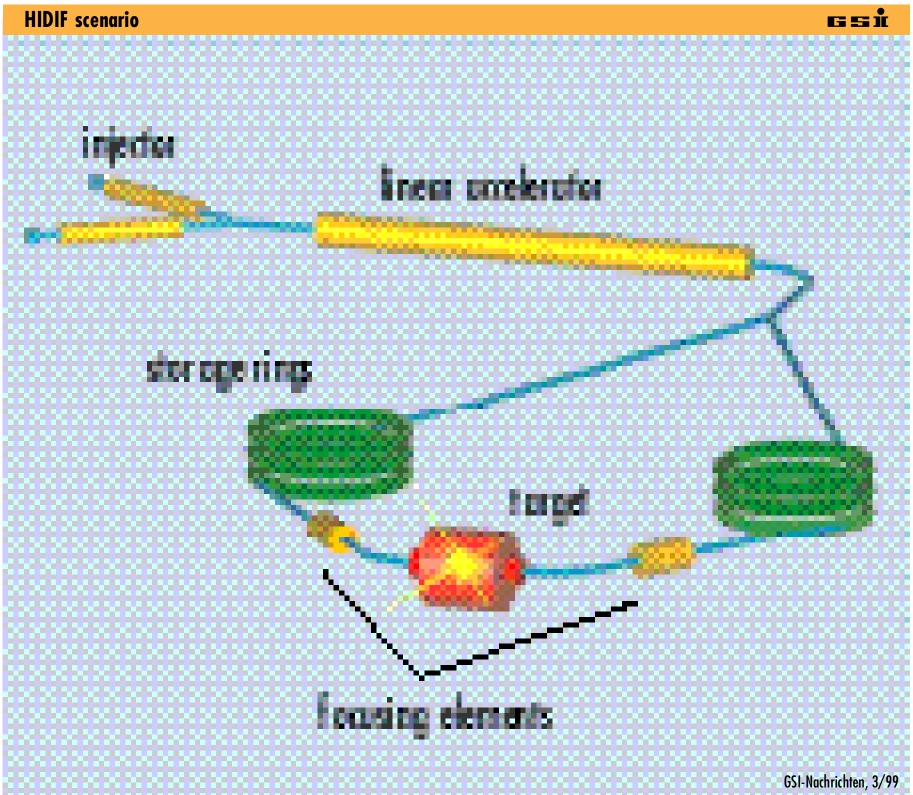

Fig. 1: HIDIF scenario for an ignition facility, consisting of a rf linac, two stacks of 3 (or 6) storage rings, and induction bunch compressors for final focusing onto the target. The linac delivers bismuth ions with an energy of 10 GeV that fill the storage rings to accumulate the total beam energy of 3 MJ. After extraction, the ion bunches are synchronised, compressed and then focused onto the target.

The HIDIF driver accelerator

Based on previous studies in the fields of accelerator and target physics, the HIDIF driver accelerator has been conceived following the rf linac and storage ring principle. The kinetic energy of 10 GeV (as a good compromise between enhanced space charge problems for lower energies and excessive range at significantly higher energy) is provided by a linear rf accelerator which fills a set of storage rings to accumulate the total beam energy of 3 MJ (typically 10^{15} bismuth ions). The reference scenario for the HIDIF driver includes a total number of 6 to 12 storage rings arranged in two stacks delivering 144 beamlets, which are compressed in induction bunchers and guided to the target chamber. The rf linac is fed by 16 ion sources and RFQ's which are funneled into the main drift tube. One of the innovative ideas used in the HIDIF scheme is the so-called 'telescoping' of three ion species differing by about ten percent in mass, but accelerated to the identical momentum (same magnetic rigidity). This allows to merge them in the final beam lines and helps to reduce the number of lines required from 144 to 48.

Emphasis of detailed design and simulation studies was dedicated to storage rings and final compression and focussing. While the linear accelerator represents the essential part of the whole driver, the task of a consistent design based on detailed simulations from front to end has to be addressed in a forthcoming study.

The HIDIF target

The accelerator studies were conducted in close collaboration with the target experts. The target is indirectly driven by conversion of the heavy ion beam kinetic energy into soft x-rays. This requires two cylindrical converters made of beryllium foam and contained in a hohlraum with thin gold walls which confines the x-ray flux and provides spatial uniformity of the radiation (Fig.2). The fusion pellet—filled with the deuterium-tritium fuel—absorbs the x-rays which leads to surface heating and ablation. Spherical shock waves driven by the ablation pressure compress and heat the fusion pellet. The conditions for the thermonuclear burn (1000-fold compression and 5 – 10 keV temperature) are reached in the center provided that the implosion is spherically symmetric within typically 1% precision. It is estimated that 3 MJ beam energy with 6 ns pulse length and 1.7 mm spot radius are necessary to reach the ignition condition.

The study has shown that the overall budget on emittance and momentum spread available in the accelerator matches the requirements at the target. Hence the HIDIF Study can be considered as the first detailed feasibility study for this type of driver showing principal compatibility between driver and fusion target.

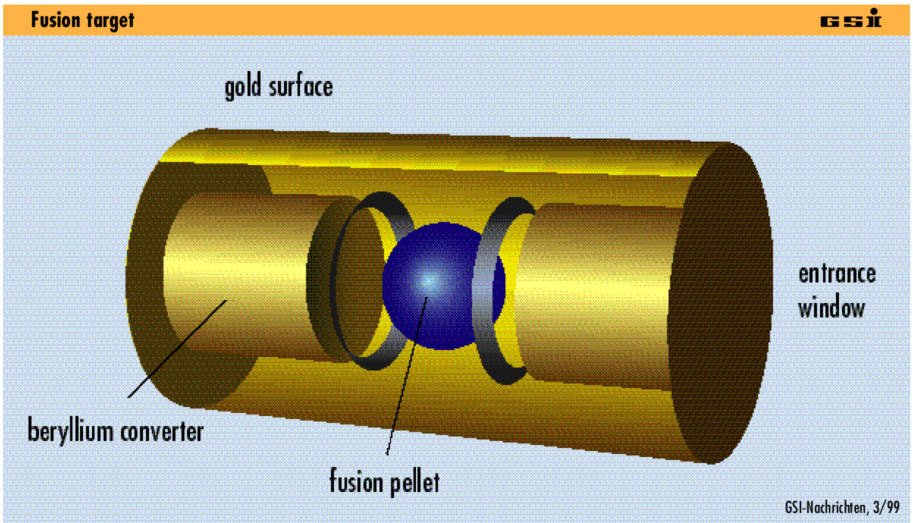

Fig. 2: The HIDIF fusion target. The compressed beamlets are directed from left and right onto the target. The kinetic energy of the ions is converted into soft X-rays by means of two cylindrical converters made of beryllium foam. The fusion pellet—filled with the D+T fuel—is located in the centre of the target.

Future perspectives

The results obtained form a reliable basis for future investigations into the detailed layout of a pilot ignition facility. At GSI the next steps will focus on accelerator experiments to gain a better understanding of space charge issues involved in a high-current linac, at injection into the rings and during bunch compression.

A bunch compression project with a new metallic alloy cavity for 240 kV voltage is presently under way at GSI which will allow compression of highest intensities to 50 ns pulse length and study of relevant space charge and dispersion issues (see page 17). Studies on a potential future accelerator facility including plasma physics as application have indicated the possible relevance of such a project for fusion drivers. One of the options for the future accelerator considers bunches with approximately the energy content of a single HIDIF bunch (20 kJ). Extension of the feasibility study towards the goal of energy production requires a high-gain (>40) target and a modification of the driver scheme towards more simplicity and reduced cost. To this end options for non-Liouvillean stripping techniques using lasers are presently examined.

In the present stage of fusion, where the mutual fertilisation of basic and applied physics still plays a significant role, the present HIDIF scenario —based on approved technical knowledge and experience—may still gain by new conceptual improvements and ideas. Exciting new prospects may come up, for example, in the context of the “fast ignitor” technique, where the requirements on the accelerators may be reduced to providing a pre-compression rather than ignition of the plasma, the final “ignition spark” being provided typically by a very short high-power laser pulse. ■

REFERENCES

[1] The HIDIF-Study, ed. by I. Hofmann and G. Plass, GSI Report-98-06 (1998)