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THE ITALIAN STUDY PROJECT FOR ICF DRIVEN BY HEAVY IONS

RENATO ANGELO RICCI

Italian Physical Society and Laboratori Nazionali di Legnaro, Italy.

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1 INTRODUCTION

Beginning in 1989 a study project concerning the possibility of a national research program on ICF driven by heavy ions started in Italy, following an agreement between ENEA (Ente Nazionale Energie Nucleare e Alternative) and SIF (Societa Italiana di Fisica).

The main motivations were the following:

- the renewed interest of the international scientific community in the physics of thermonuclear processes based on inertial confinement driven either by lasers or by charged-particle beams;
- the increased confidence in the feasibility of commercial energy generation based on the research progress made in the field of acceleration technology and of heavy-ion physics. It has been realized that heavy-ion beams might be an excellent tool for achieving the necessary confinement conditions;
- the possibility of a common effort of the Italian and German research groups in establishing a joint program in this field, taking into account that the European effort had been nearly exclusively devoted to magnetic confinement. This might have been justified in the early stage of the European Community programs, but now it seems that new common initiatives concerning inertial confinement should be considered.

The basic terms of reference for a research program are:

- the early system study for a heavy-ion beam driven power plant performed by German groups, called the HIBALL project, which provides the basic parameters for a reactor driver[1];
- the renewed driver concept, using "non-Liouvillian" stacking as an essential tool for providing heavy ion beams (e.g., Bi) with the proper intensity and energy, as suggested, for instance, by C. Rubbia[2]. The limitations to particle densities can be overcome in this case, and a practical scheme is proposed where a selective ionization mechanism (i.e. $Bi^{+} \rightarrow Bi^{++}$) is chosen using, for instance, the photoionization induced by the photons of an appropriate Free Electron Laser (FEL)[3];

- the study of a driving chain (injection, acceleration, storage, bunching) to achieve the beam parameters required for ignition (energy, specific power deposition, pulse time...). These parameters have to be considered as derived from the non-Liouvillian stacking and from the reactor requirements both in the direct or indirect drive;
- beam-target interaction and target-geometry investigations of both direct and indirect drive and related issues with possible computational and/or experimental studies.

Such a working scheme is also considered for a specific Italian-German collaboration.

2 THE BASIC ISSUES OF THE STUDY PROJECT

The terms of reference are reported in Tables 1 and 2, starting from the HIBALL basic parameters for the main non-Liouvillian scenario.

TABLE 1
Driver Reference Parameters for an ICF (HI) Scheme

	Hiball (Bi^+; single-shell pellet)	Revised (Non-Liouvillian; many beams)
Kinetic Energy E_k (GeV)	10	10
Input Energy E_{in} (MJ)	4.7	5–10
Beam Power W_{in} (TW)	240	500
D-T fuel at ignition	4.0	
Energy gain (1-d pellet)	83	≥ 100

TABLE 2
Pellet Reference Parameters for ICF (HI) Scheme

	Direct drive	Indirect drive
Absorber Mass M_{abs} (mg)	400	45
Diameter R_{spot} (mm)	8	2.7
Specific Power W_{spot} (W/g)	6×10^{14}	2×10^{16}
Pulse-time Δt_{puls} (ns) (non-Liouvillean)	20	10

3 STUDIES AT WORKSHOPS AND SUMMARY OF RESEARCH EFFORTS

These parameters are related to the different approaches studied and reported to a number of workshops held in Varenna and in collaboration with German groups, namely at GSI (Darmstadt), and at CERN.

The following Italian groups and laboratories are researching the different items:

Sincrotrone Trieste	Driving chain design
Laboratori Nazional di Legnaro (INFN) (in collaboration with INFN-Cagliari)	Ion source and acceleration techniques; Beam-target interaction
INFN and University of Padova and Genova	HI acceleration problems
INFN and University of Milano	Plasma Diagnostics and FEL for UV photoionization
ENEA-Frascati Laboratory	Beam-target interaction; target design; FEL Studies

The main conclusions of the workshop and proposals are the following:

3.1 Non-Liouvillian Stacking

There is a consensus that the non-Liouvillian stacking is an advanced efficient tool for accumulating high-current ($\sim 10^{15}$ ions/pulse) heavy-ion beams without the usually unavoidable increase of phase-space volume. A possible problem could be optimization of the requirement of not exceeding space-charge effect with a high-power (~ 500 TW) deposition into a reduced-size pellet (~ 3 mm). This is related to the choice of the accelerating phase where the photoionization process will be performed.

3.2 Driving Chain

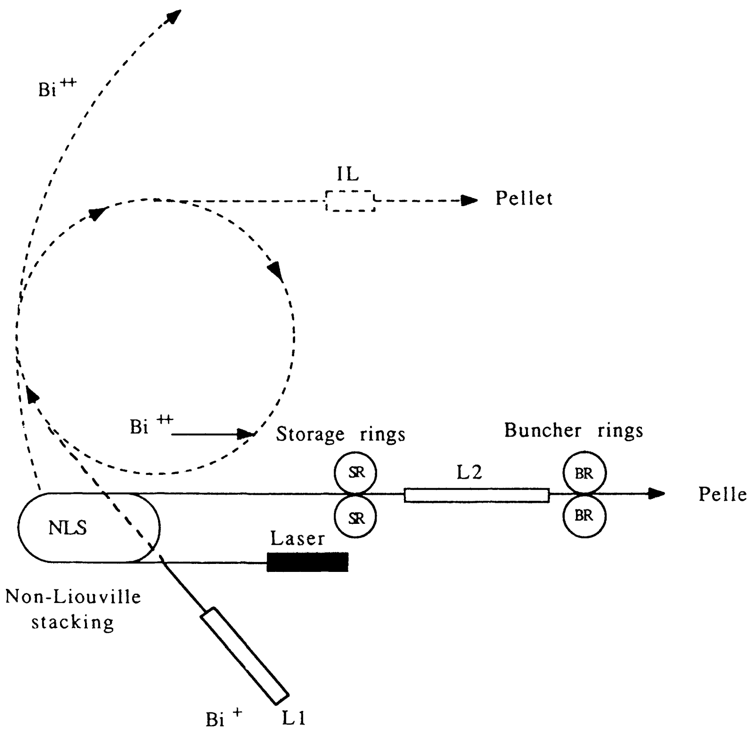
The driving chain could be designed following different schemes. The mainstream design would be as follows[4] and is shown in Figure 1.

- Bi^+ + RFQ (I = 5 mA, Δt = 13 ms)
- Acceleration 20 keV → 1 to 2 MeV → 1 GeV

Including the Non-Liouvillian Stacking Ring (NLS) and connected with the FEL inducing the photoionization ($Bi^+ \rightarrow Bi^{++}$) (photoionization in the storage phase) and eventually a transit-time linac if further acceleration from 1 MeV to 1 GeV is made after the NLS.

- Further storage (SR), acceleration (transit-time linac: 1 GeV → 10 GeV) and compression. (Bunching ring or BR: $\Delta t \rightarrow 10$ ns).

A second version, which seems to be more acceptable now, would perform the full acceleration (1 → 10 GeV) before the NLS, with the $Bi^+ \rightarrow Bi^{++}$ photoionization process at the compression (BR) phase.



	E_k [GeV]
L1	0.5->10
NLS	0.5->10
SR	0.5->10
L2	10
BR	10

FIGURE 1 Main design of a possible Heavy-Ion Driving Chain for Inertial Fusion. The different options concerning the acceleration before or after the non-liouvillian stacking are shown. The insert reports the corresponding energy-gains.

The final beam parameters would be

$$E_k \cong 10\ \text{GeV};$$

$$E_{in} \cong 5\ \text{MJ};$$

$$N = 3.125 \times 10^{15}\ \text{ions},$$

$$\Delta t = 10\ \text{ns};$$

$$P \cong 500\ \text{TW};$$

and taking into account the efficiency of the NLS and losses, one has $N = 4\ 10^{15}$ ions.

However, new designs requiring more comfortable intensities (10^{12}–10^{13}) are in progress, as studied by the Rubbia group.

3.3 FEL Photoionization

Photoionization by FEL appears possible in the UV (ultraviolet) region. It is necessary to work in the Self Amplified Spontaneous Emission (SASE) regime.

There are few options for obtaining an 84-nm wavelength as required for the $Bi^+ \rightarrow Bi^{++}$ photoionization, starting from the initial 240 nm of a standard (e.g., KrF) laser. This can be achieved by using a "frequency tripling" device. The possibility has been explored of obtaining (using an electron beam from a conventional linac of 200–400 MeV energy and 40 to $120 \cdot 10^4$ GW power) a set of UV output parameters as follows: $\lambda = 80$ nm (input value 240 nm); P (power) = 3 MW ($P_{input} = 100$ W); and ε(emittance) = 40 mmrad. The third harmonic of the light of a conventional input at a first undulator section is amplified at a resonance phase in a second undulator[3]. The study of such a possibility in a 3-d simulation is in progress and is already giving reliable results.

3.4 Beam-target Interaction and Target Design

The beam-target interaction and the pellet design seems to be one of the major issues to be investigated not only by computational and/or model calculations but also by real experiments.

The deposition into the target of a specific power of 10^{15}–10^{16} $W \cdot cm^{-2}$ poses serious problems in the achievement of the ignition conditions. These are of course affected by fluid instabilities as well as by the imperfections of the target design and illumination symmetry. The consensus seems to support the choice of indirect drive because of better uniformity, provided the X-ray conversion efficiency remains sufficient, which seems to be the case.

Target design and the corresponding physical issues are under study in Frascati[5] taking into account the expertise acquired in the context of a laser fusion program. The investigations have been and are actually focused on implosion symmetry and stability for direct and indirect drive.

Two-dimensional computer codes have been used to study implosion symmetry of simple capsules and X-ray conversion efficiency of cylindrical converters.

Preliminary analyses of thermal X rays suitable for indirect drive have been performed on heavy-ion-beam-driven generators, and analytical models for the evaluation of the efficiency of radiators suitable for use in ICF hohlraums have been developed[5].

4 PERSPECTIVES

The main guidelines for the future research program are:

- *Energy Transfer Modeling*, i.e., further studies (both theoretical and experimental) on the ignition feasibility and on the energy amount to be transferred to achieve net energy gain. Moreover, the effects in beam-target interaction studied either by laser (photon transfer onto the target) and/or accelerator experiments (uniformity, efficiency in the ion-X ray conversion) are an essential part of the investigations.

- *Development of high-performance accelerators*, where the design of non-Liouvillean stacking schemes including the photoionization mechanism, i.e., the type of accelerating sequence, is the main goal of the study project. This will be considered as an important part of the Italian-German collaboration.

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