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EXAMPLES OF HEAVY-ION DRIVER SCHEMES FOR INDIRECT DRIVE

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Schemes for heavy-ion inertial fusion drivers are presented which use (a) Indirect pellet drive, and (b) Non-Liouvillean processes for accumulation of the beams in the phase-space of the buncher rings. Examples for reactor drivers as well as for ignition test facilities are given.

1 INTRODUCTION

Indirect drive fusion targets, containing one or more converter masses inside a hohlraum, require a deposition power density in the converters an order of magnitude higher than the deposition in direct drive targets[1]; but indirect drive is required to achieve the necessary symmetry for implosion. Overlapping beams from several directions in the same converter helps to increase the deposition power, but the beams still need to be concentrated in phase space more than for direct drive. The required additional factor of three or four can be provided by beam manipulations using non-Liouvillean processes, e.g. using laser-induced q/A changes during final bunch stacking[2]. In this way the limitations of longitudinal instabilities can be circumvented, although the space-charge limits in rings and beamlines remain.

We have established a list of candidates for q/A changing processes; they are presented in Table 1. Not included in this list is electron cooling; while it is a non-Liouvillean phase-space enhancing process, and it works, we believe it will be too slow to be useful in reactor-driver technology. We concentrate here on laser-initiated processes which can be utilized in final bunch formation.

In this study we have chosen the last process, resonant multiple photon ionization from a negative ion up to the first positive charge state, because relevant photoionization cross-section data are known, Au^- ion sources of several mA output are known[8], orbit separation is good, and the required laser parameters are not far from currently available technology. Thus, Au^- appears the best choice based on current knowledge.

TABLE 1
Candidate Reactions for Non-Liouvillean Beam Manipulation

"In-Beam Chemistry"	Examples	Problems/Remarks/Status
Molecule Dissociation	$HI^+ + h\nu \rightarrow H^0 + I^+$ $I_2^+ + h\nu \rightarrow 2I^+ + e^-$	Low dispersion Unknown branching (I^0?)
Photo Ionization	$Bi^+ + \Sigma h\nu \rightarrow Bi^{++} + e^-$	Space-charge problem with Bi^{++}
Stimulated Recombination	$Bi^{++} + e^- + h\nu \rightarrow Bi^+ + 2h\nu$	To be studied; ideal candidate *if it works*
Multiple-Photon Ionization of Negative Ions	$Au^- + \Sigma h\nu \rightarrow Au^+ + 2e^-$	Ideally good dispersion; best available data; best known overall case

We would like to point out, however, that the third process—stimulated recombination in an electron beam with external pulsed laser photons—would be attractive if proved feasible. The basic rates will be studied in the ESR at GSI. This process might also be applied at the end of a linac, to reduce the length by using higher charge states in the beginning.

The first process mentioned in Table 1, photodissociation of HI^+, was proposed by the group at Argonne[4] in the beginning of HIF studies to enhance the phase space density at injection into a storage ring. The second process mentioned, photoionization of Bi^+, was suggested by Rubbia[5] again to enhance phase-space density during injection into a ring. These prior suggestions did not apply to final bunch formation using short laser pulses, which we discuss here, although the physical processes are the same.

2 BEAM MANIPULATIONS WITH Au

The species Au^- is copiously produced in some existing ion sources. Up to 7 mA has been reported[6]. The photodetachment of the outer electron requires 2.3-eV laser light, with a cross section of order 10^{-17} cm^2 [7]. Using a conventional laser, then, it is possible to obtain complete detachment in less than 1 meter.

To photoionize the neutral Au we can utilize resonant multiphoton ionization, which has already been extensively studied for the purposes of Au isotope separation[6]. The limiting cross-section here is the last step leading to an autoionizing state. Three separate laser frequencies are required, i.e., using tunable lasers with an intensity of order 10 MW/cm^2, in the visible (370, 563, and 737 nm).

The repetition rate required is determined by the circulation time of the ion beam in the bunching and/or storage rings, but is of order 300–800 kHz for the cases we have studied. This rate is somewhat higher than is available with present-day lasers, but we believe it is not a critical problem. Use of optical delay lines to increase the number of passes for one laser pulse could be one solution[9].

Negative ions as well as other loosely bound ions are subject to dissociation in the strong electric fields seen by the ions during passage through dipole magnets. We have calculated a critical magnetic field level of 2.2 tesla for Au^- ions with velocity 0.3 c, assuming that the exponent in the tunnelling rate formula for H^-[10] is proportional to the square root of the binding energy.

Estimating the loss rate from intrabeam charge-changing collisions is more difficult. Crossed-beam experiments to determine the cross-sections are possible; H^- experiments have already been done[11]. We have estimated for our driver examples that a cross section of 10^{-10} cm^2 would allow a beam lifetime of order one second. We are proceeding on the assumption that data will be available well before any engineering effort for a driver is begun.

3 DRIVER ARCHITECTURE

We have considered two types of driver. One is a full-scale reactor driver using a linac tree with high efficiency and repetition rate delivering 5 MJ in 10 ns in 20 beamlines to a reactor-size indirect-drive target with two converter elements[12]. The other is a test facility for ignition experiments which delivers 0.5 MJ in 5 ns to a smaller indirect-drive target with one converter element[15], using 2 beamlines.

The test facility would use a rapid-cycling synchrotron (10 Hz) instead of a long linac, to reduce costs. Both would use Au^- ions accelerated to 50 MeV/u, accumulated in storage rings, ionized up to Au^+ by laser systems with 4 frequencies, while rapidly stacking pulses 100–400 ns long in a non-Liouvillean stacking ring. The final compression would use strong RF bunching down to 5–10 ns on the target converter. Figure 1 shows the reactor ground plan; Figure 2 the test facility.

The beam manipulations in the reactor driver are as follows. A continuous beam from the linac is routed through the transfer ring (TR) to the storage rings (SR), filling them one by one using transverse stacking. The first stacking is 5 turns into the transfer ring; then 5 of these stacks are transferred to each SR, for a total of 25 × transverse stacking at that point. After all the storage rings are loaded their tune shift is about 0.5. A carefully timed series of high-power laser pulses is then introduced into the overlap sections between the storage rings and the large buncher ring. Each pulse is 100 ns long, and of sufficient intensity to completely change the charge stage (here Au^- into Au^+) of all ions passing through the overlap section during the laser pulse duration. Thus, pulses of positive ions 100 ns long are created, circulating in the buncher ring. RF in the BR holds these in buckets. As a bunch in the BR passes the next SR, another laser pulse is entering that overlap region. Another 100 ns bunch of positive ions is added thereby to the bunch circulating in the BR. Since this is a non-Liouvillean process there is no dilution in phase space. During about 4 revolutions in the BR a current increase of 38 × is accomplished in 20 circulating bunches. The tune is depressed to a value very low compared to the initial tune but only during these few revolutions. When the non-Liouvillean bunch stacking is complete, bunching cavities are switched on rapidly; they induce bunch compression ballistically (bunch rotation). Only a few turns are allowed for bunching before it is necessary

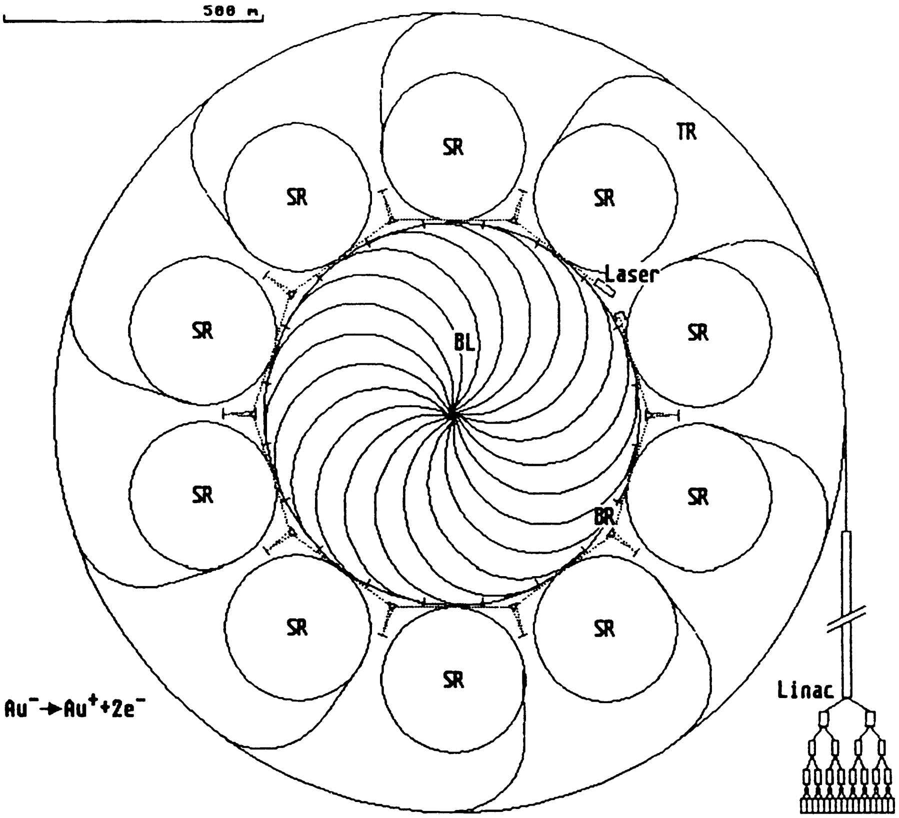

FIGURE 1 Reactor driver ground plan (schematic).

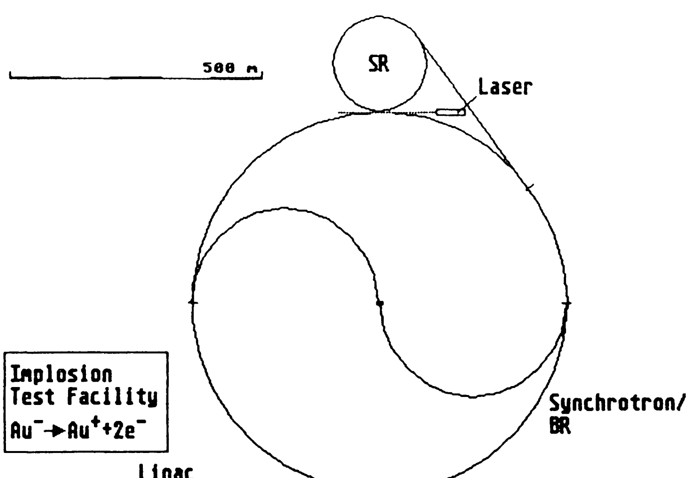

FIGURE 2 Ignition test facility (schematic).

to extract all bunches into their beam lines (BL) where they complete the compression down to a 10-ns pulse length as they strike the target.

The storage rings can be operated in a parameter region free of longitudinal microwave instability (below threshold) by proper choice of momentum spread. This is one of the main advantages of the non-Liouvillean bunch stacking; the momentum spread does not increase during formation of the 100-ns bunches, allowing a spread up to 1×10^{-3} to be used in the SR. In the BR, the bunch stacking is carried out so rapidly that the growth of longitudinal instability is not important. The residence time of bunches in the BR is only about 100 microseconds.

The main physics uncertainty in this scheme is the lifetime of the negative ions in the storage rings. Should the ion-ion charge-changing cross sections at the appropriate intrabeam collision energies be much greater than 10^{-16} cm^2, another choice of non-Liouvillean process might be necessary. The main technology problem is the low-frequency high-amplitude bunching cavities; otherwise the driver principles are not radically different from previous concepts.

The beam manipulations in a test facility (Figure 2) are basically a simplified version of those described above. A transfer ring is not necessary here; injection is direct from the linac into a rapid cycling synchrotron ring. After accelerating Au^-, this beam is transversely stacked into the SR. After accumulation, intense laser pulses chop the SR beam into short pulses of Au^+, which are stacked back into the synchrotron ring which now serves as a BR. Two circulating bunches are established. Final compression is again ballistic down to 5 ns and the residence time in the BR is again short enough to prevent damage to the beam from longitudinal instabilities or the large tune depression.

Table 2 gives a summary of important parameters for the reactor driver. We can see that the final-bunching RF system is one of the most difficult technological issues in any driver scheme of this kind. A large number of low-frequency (0.8-MHz) cavities is required, whose amplitude must be raised to the megavolt level within one or two ring revolution times. Both the cavities and the amplifiers will be expensive. This situation would be even worse if we would not expand the bunches (up to 400 ns in our example) before the onset of final bunching. The applied frequency would then be higher, but the voltage level per turn would have to be excessive; $U_{\mathrm{ring}} \propto h^2$, where h is the harmonic number.

These parameters have been calculated assuming an ideally smooth beam tube whose impedance is merely capacitative. Making a beam tube broad-band inductive (of order 2 microhenries per meter) would very much reduce the rf amplitude (integral around the ring) by allowing longer accumulation time for the momentum-spread tilt, and allow higher rf frequencies to be used. However, we do not have a solution at present, e.g., using ferrites to make the beam tube inductive.

This bunching problem is one of the important obstacles to adapting a (proposed) high-energy heavy-ion collider facility filled with low charge-state ions as an ignition test facility. The required rf and/or inductive beam tube would disturb the collider mode. We are currently studying this and other schemes, such as using relativistic beams with higher charge states.

A dedicated test facility for ignition of indirectly driven capsules could be designed

TABLE 2

Parameters of the Reactor Driver

General Data
Ion species in source, linac and SR: $^{197}Au^-$
in BR, BL and on target: $^{197}Au^+$
Kin. Energy/atomic number = 50 MeV/u; $\beta c = 0.945 * 10^8$ m/s;
momentum/charge = 203.16 Tm
Beam emittance = $1.6 * 10^{-5}$ m
Effective converter mass = 24 mg; physical converter mass ≈ 30 mg
Number of converters per hohlraum = 2
Number of beam lines per converter = 10, total = 20
Beam power per beam line = 24 TW = 9.85 GV * 2.44 kA
Specific converter power = 10000 TW/g
Effective pulse length on target = 10 ns
Beam energy per converter = 2.4 MJ, total = 4.8 MJ

20 Beam Lines (BL)
Average bending radius = 188 m; av. dipole field strength = 1.1 T
Max. period length/($\sigma_0 * \mu_{sc}$) near target = 1.43 m
$\Delta p/p$ (on target) ≈ $\pm 5 * 10^{-3}$

Buncher Ring (BR)
Average radius = 376 m; $2\pi R_{av}$ = 2.3625 km; rev. time = 25 μs
Av. dipole field strength = 0.54 T
Min. period number = 160; period length S = 14.76 m
RF: harmonic number = number of bunches = 20; f = 0.8 MHz
Amplitude * number of cavities = 5...360 MV, linearly rising from lower to upper level during 35 RF cycles
Number of circulating bunches = 20
Bunch length = 100 ns, expanded to 400 ns before fast compression;
$\Delta p/p$ before ≈ $\pm 1.25 * 10^{-4}$; after bunching ≈ $\pm 7 * 10^{-3}$

10 Storage Rings (SR)
Average Radius = 144.76 m; $2\pi R_{av}$ = 909.56 m; rev. time = 9.625 μs
Av. dipole field strength = 1.4 T; local field strength < 2.2 T
Tune sift by space charge (abs.) = −0.46
RF system: harmonic number = 77; frequency = 8 MHz
Peak beam current = 10 A
Injection from TR: 5 turns (horizontal stack)

Transfer from SR into BR
Length of light interaction zone = 9 m
Laser wavelengths = 370 nm, 562.5 nm and 737 nm (tunable)
Laser pulse power = 10 MW
Laser pulse repetition time = 1.25 μs (3.75 also possible)
Current multiplication = 38 (after transfer of 76 of 77 bunches)

Transfer Ring (TR)
Length = 4.91 km; R_{av} = 782 m; rev. time = 52 μs
Beam current = 1.05 A; Injection: 5 turns (vertical stack)

Linac
Total voltage = 9.85 GV; length ≈ 5 km
Beam current = 260 mA
Number of source branches = 16
Current per source = 16.5 mA
Macro pulse length = 210 μs = 5 * (38 μs (beam) + 4 μs (pause))
10 macro pulses needed for 1 shot

with much similarity to the reactor driver, except only one storage ring is used and the beam kinetic energy is produced by a synchrotron instead of a long and expensive linac. Energy efficiency does not play a major role in a test facility. The ring would be fitted using 10 pulses from a 10 GeV, 10-Hz synchrotron using conventional magnets (see Figure 2) with 200 T-m rigidity. A short 200 MV linac would be used as injector. Using Au^- in the storage ring, changed to Au^+ by lasers, the synchrotron ring can be re-used as a bunch stacking and compression ring.

A large emittance, e.g., 30 π mm-mrad, can be used if final-focus lenses with shorter focal length, e.g. plasma lenses[14] are used. The specific deposition power in our example, with a 1 mm-radius converter and a 500-kJ beam pulse in 5 ns, is 5.10^3 TW/g, giving a conversion efficiency about 0.2 at 200–300 eV.

Targets are being designed through a cooperative effort of several groups, using rough estimates for conversion efficiency[13], illumination symmetry, and wall losses, and capsule gain estimated using 3-T codes. For the ignition test facility a capsule gain of unity is expected with 100 kJ of confined X-ray energy in the hohlraum[15,16]; for the reactor target a capsule gain of more than 100 has been obtained in simulations[17].

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