High Phase Space Density Beams for Heavy Ion Fusion Research

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Abstract

The GSI research program "High Energy Density in Matter" has the long-term goal of Inertial Fusion by Heavy Ion Beams. With the SIS/ESR synchrotron and storage ring facility it is possible to achieve the required highest phase space densities of heavy ions by means of stacking and electron cooling in the ESR. We describe the status of high phase space density studies with cooled heavy ion beams as well as theoretical projections to higher intensities necessary to carry out the planned experimental program.

1 GOALS OF EXPERIMENTS

1.1 Requirements for Targets

The first plasmas generated by heavy ion beams have been produced at GSI in 1988 with the RFQ injector MAXILAC at an energy of 45 keV/u and with a relatively low target density of 10^{-3}g/cm^3 (gas target). The temperature achieved is given by the beam power deposited per mass unit ("specific power"):

$$P \equiv \frac{E \cdot I}{R \cdot F} \quad (1)$$

with E the total kinetic energy, I the particle current, R the range (g/cm^2) and F the focal spot area (cm^2).

For SIS/ESR it is expected that the specific power can be increased by 3-4 orders of magnitude beyond the RFQ experiments (10^{-2} TW/g) and plasmas of solid matter densities will be produced for the first time by means of heavy ion beams [1]. A unique feature of heavy ion beam produced plasmas is the fact that the beam energy is deposited in depth of the material in contrast with laser produced plasmas, which ablate from the target surface.

The specific power P is directly related to the plasma temperature. Results of calculations for solid gold (within an uncertainty band, see Ref.[2]) can be related to the performance expected for SIS/ESR experiments as well as for larger steps leading to ignition (1eV=10^4 K) (see Fig.1). Note that $R \propto E^{3/2}$ over a large range of energies, which reduces somewhat the advantage of large kinetic energies.

Under optimistic asumptions the SIS/ESR could lead to 10 TW/g, which allows to study the hydrodynamic regime and equations of state. Target physics dominated by radiation requires a specific power between 10^3 and 10^4 TW/g, which could be achieved only by a significantly larger dedicated facility. It is assumed that reactor targets will work

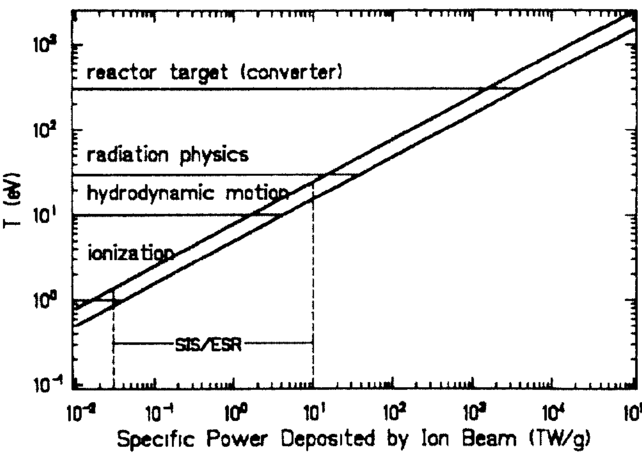

Figure 1: Temperature Regions of Interest for Fusion

according to the principle of "indirect drive": the beam energy is converted into radiation, which allows a pellet implosion of much higher spherical symmetry as in "directly driven" targets. The specific power necessary herefore is 10^4 TW/g or above (see Ref.[3]).

1.2 Beam Manipulations in SIS/ESR

The optimum strategy for achieving high phase space density as well as high intensity is the following:

- Acceleration in SIS
- Cooling stacking (rf stacking + electron cooling) in ESR (see Ref.[4]) until maximum intensity is achieved
- Cooling of coasting beam
- Adiabatic bunching on 1st harmonic and small rf amplitude (long bunch)
- Re-injection into SIS: bunch-into-bucket at full rf amplitude
- Fast bunch rotation (1/4 synchrotron revolution)
- Fast extraction to target area with fine focusing

Electron cooling is an efficient way to obtain beams with highest phase space densities in the ESR and also to accumulate intensity by cooling stacking [4]. We therefore prefer fully stripped heavy ions, which have a sufficiently long lifetime with respect to capture of electrons from the cooling electron beam. It should be noted here that electron cooling cannot be considered in a reactor driver accelerator, since single charged heavy ions have too long cooling times (scaling with A/Z^2). All other manipulations mentioned above are, however, typical for a reactor driver. Thus the experiments with SIS/ESR are also a test for the feasibility of a full reactor driver [5].

2 STATUS OF HIGH PHASE SPACE DENSITIES

2.1 Keil-Schnell Factor

The quality of longitudinal phase space density can be expressed in terms of the factor, by which the actual current exceeds the Keil-Schnell circle threshold (applicable to a parabolic distribution):

$$\frac{I}{I_{KS}} = \frac{4eZIZ_{\parallel}\ln 2}{\pi|\eta|^2\beta^2\gamma Amc^2(\frac{\Delta p}{p})^2_{fwhm}} \quad (2)$$

with $Z_{\parallel}$ the coupling impedance, $\eta = 1/\gamma^2 - 1/\gamma_t^2$ and $(\frac{\Delta p}{p})^2_{fwhm}$ the fwhm momentum spread. This dimensionless factor can be regarded as "figure of merit" of longitudinal cooling [6]. It can be considerably larger than unity, since the actual distribution resembles more a Gaussian rather than a parabolic shape and the resistive part of the coupling impedance is small compared with the reactive part (mainly space charge impedance $\approx 1-2$ kOhms). Best values achieved so far in the ESR for coasting beams have been $I/I_{KS} = 5.5$ (Ref.[7]).

2.2 RF Potential Well Flattening

For a bunched beam we take as "figure of merit" for high phase space density the ratio of applied rf voltage, V_{rf}, to the effective rf voltage, V_{eff}. The latter is the applied voltage reduced by the space charge induced voltage. For cooled beams this ratio can exceed unity considerably (strong potential well flattening). There is an important connection between this effect and the Keil-Schnell factor calculated for the local conditions at the bunch center:

$$\frac{I}{I_{KS}} = F \cdot \left(\frac{V_{rf}}{V_{eff}} - 1\right) \quad (3)$$

where we define $V_{eff} \equiv V_{rf} - V_{spacecharge}$ and a geometry factor $F \approx 2.5$ (weakly depending on the distribution function). For cooled bunched beams we have so far observed $V_{rf}/V_{eff} \approx 1.6$ (see Ref.[8]. We assume that this factor could be as large as 3, which would be equivalent to the phase space density of a coasting beam with $I/I_{KS} \approx 5$ as already observed.

2.3 Equilibrium with Intrabeam Scattering

Values for I/I_{KS} could, in principle, be as large as 10 according to the measured stability diagrams, but they are limited by intrabeam scattering from the horizontal direction into the longitudinal direction [9].

A common feature of the intrabeam scattering dominated behaviour is a scaling law

$$\Delta p/p \propto N^{1/3} \quad (4)$$

Measurements for different ions in the ESR [10] and in other cooler rings well agree with such a law. We use it to extrapolate cooled beam equilibria from measured data

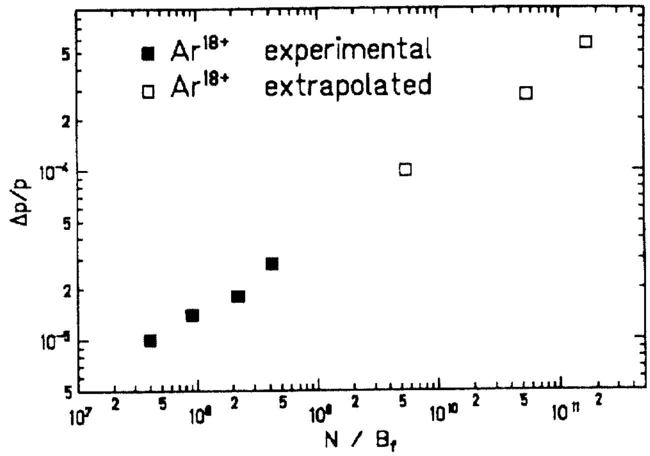

Figure 2: Experimental data for cooling equilibria and extrapolation to high intensity.

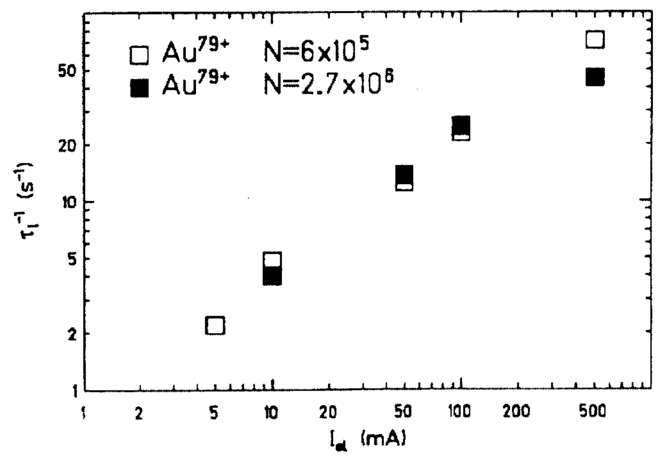

Figure 3: Calculated longitudinal intrabeam scattering for experimental values of N, ϵ, $\Delta p/p$ as function of cooler current.

for Ar^{18+} to the higher intensities required for the experiments discussed here. This is shown in Fig.2, where we plot N/B_f as total intensity divided by the bunching factor as a measure for the peak intensity in the bunch. A comparison of measured equilibria with intrabeam scattering calculations allows calculation of cooling rates (indirect method). As an example, we find a cooling rate between 50-80 sec^{-1} for the Au^{79+} ions in the experiment, with some dependence on the ion intensity, for an electron current of 500 mA (see Fig.3). We have used this value to scale cooling rates to other ions and energies.

3 PROJECTED PERFORMANCE FOR SIS/ESR

3.1 Variation with Intensity

Based on experimental data for intensities slightly below 10^9 Ar^{18+} ions we have extrapolated to higher intensities using intrabeam scattering calculations, which we assume are the dominant limitation for fully stripped heavy ions.

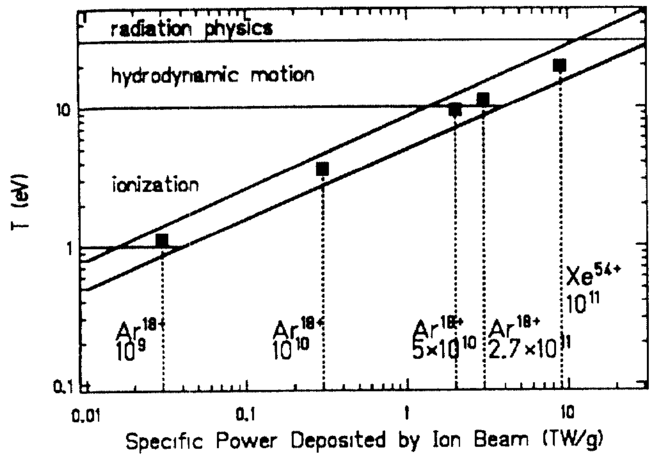

Figure 4: Target Experiments with optimum SIS/ESR performance

Results are summarized in Table 1 and Fig.4. We have chosen, as an example, Ar^{18+} which promises the highest currents from UNILAC. Case D assumes high intensity in the ESR for a heavy ion like Xe^{54+} or heavier. It should be noted that the highest intensities are only needed at time intervals of typically an hour or a fraction of it, hence activiation of the machine should not be a problem. If cooling stacking is insufficient for the highest intensities, this step can be achieved only with the high-current injector. Cases C and D require an additional rf cavity. With the presently available 32 kV the final bunch length would be twice as long, hence the specific power only half as big. The heaviest ions yield the best performance since the range R decreases with mass for constant β.

3.2 *Scaling with Ion Mass*

For energies typical for the ESR the dependence of the range on A and the kinetic energy per nucleon, E/A, can be put into an approximate scaling, which describes well the ranges used in Table 1:

$$R \propto A^{0.7} \cdot (E/A)^{1.5} \tag{5}$$

Table 1: Beam and machine parameters for increasing intensities assuming final $\Delta p/p \leq 5 \cdot 10^{-3}$ and $\epsilon \leq 5\pi$mm mrad and typical spot radius of $100\mu m$

	A	B	C	D
Ion	Ar^{18+}	Ar^{18+}	Ar^{18+}	Xe^{54+}
N	1×10^{9}	1×10^{10}	5×10^{10}	1×10^{11}
MeV/u	300	300	300	500
Joules	2	20	100	1000
during cooling of bunch:				
$\Delta p/p$	10^{-4}	3×10^{-4}	6×10^{-4}	1.5×10^{-3}
ϵ (πm-rad)	10^{-6}	5×10^{-6}	5×10^{-6}	3.5×10^{-6}
bunching voltage in SIS (kV)	-	32	130	130
bunch length at target (ns)	150	25	20	80
range (g/cm^2)	11	11	11	8
Terawatt/g	0.03	0.3	2	9
T (eV)	1	3	10	20

Table 2: Scaling to Different Ions

Ion	$^{20}Ne^{10+}$	$^{40}Ar^{18+}$	$^{132}Xe^{54+}$	$^{238}U^{92+}$
N	4.4×10^{11}	2.7×10^{11}	1×10^{11}	6.3×10^{10}
MeV/u	500	500	500	500
Joules	670	820	1000	1140
bunch length at target (ns)	80	80	80	80
range (g/cm^2)	34	20	8	5
Terawatt/g	1.4	3	9	15
T (eV)	1	12	20	27

The dependence of the machine performance with the ion mass can be seen most easily by the following scaling. We assume that a set of consistent parameters (N,$\Delta p/p$, ϵ, bunch length) is given for some ion either by the experiment or by theoretical calculations. It is then possible to directly scale to another ion by leaving β unchanged, since all of the intensity dependent thresholds are then only depending on powers of Z^2/A. In particular we have for the Keil-Schnell threshold and Laslett tune shift:

$$N \propto A/Z^2 \tag{6}$$

For the intrabeam scattering heating rates we have $\tau_i^{-1} \propto N \cdot Z^4/A^2$ and for the electron cooling rate $\tau_c^{-1} \propto Z^2/A$. Since the two rates should be equal in equilibrium we can conclude that the scaling of Eq. 6 leaves the intensity limits invariant as well as the equilibrium between heating and cooling forces. By adopting case D of Table 1 as reference case we can thus directly scale to a set of other ions and obtain the comparison shown in Table 2. It is noted that the best performance is obtainable with the heaviest ions.

4 CONCLUSION

For fully stripped ions the main limitation for the required phase space densities is intrabeam scattering, whereas the total intensity is limited by the injector current and the efficiency of cooling stacking in the ESR. Beam manipulations leading from cooled coasting beams to short bunched beams by fast bunch rotation need to be studied carefully at increasing intensities in order to avoid phase soace dilution, which would reduce the performence.

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