ION BEAM COCKTAIL DEVELOPMENT AND ECR ION SOURCE PLASMA PHYSICS EXPERIMENTS AT JYFL*

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Abstract

The accelerator based experiments at JYFL (University of Jyväskylä, Department of Physics) range from basic research in nuclear physics to industrial applications. A substantial share of the beam time hours is allocated for heavy ion beam cocktails, used for irradiation tests of electronics. Producing the required ion beam cocktails has required active development of the JYFL ECR ion sources. This work is briefly discussed together with the implications of the beam cocktail campaign to the beam time allocation procedure. The JYFL ion source group has conducted experiments on plasma physics of ECR ion sources including plasma potential and time-resolved bremsstrahlung measurements, for example. The plasma physics experiments are discussed from the point of view of beam cocktail development.

INTRODUCTION

The JYFL accelerator laboratory has been operational since 1992 in its present location. The heart of the facility is the K-130 isochronous cyclotron [1] with annual operation time exceeding 6000 hours already more than ten years. The ion beams for the cyclotron are produced with two electron cyclotron resonance ion sources (ECRIS) [2,3] for heavy, highly charged ions and with a negative filament-driven multicusp ion source for H^- and D^- [4]. Due to the intense use of the cyclotron, the development work of the accelerator systems has concentrated on the ECR ion sources and the available selection of ion beams.

A substantial share of the beam time hours at JYFL is allocated for heavy ion beam cocktails, used for irradiation tests of electronics at RADEF-facility [5]. The users of the facility range from privately owned companies to large scale institutions e.g. the European Space Agency. The irradiation tests of electronic components are nearly indispensable for the JYFL accelerator laboratory from the economic point of view. This is reflected to the annual distribution of accelerated ions. The share of heavy ion cocktails has grown gradually from < 5 % in 2002 to > 25 % in 2009 (January - June).

HEAVY ION BEAM COCKTAILS AT JYFL

For efficient irradiation tests of single event effects (SEE's) in semiconductors with the cyclotron three requirements have to be met by the ion beam cocktails. First of all, the linear energy transfer (LET) value of the ions has to be varied in order to study the sensitivity of the component. This is done by varying the mass of the ions. Secondly, the penetration depth of the projectile has to be sufficient to reach the sensitive area of the component from the reverse side (due to assembly technique). The penetration depth, and more importantly the location of the Bragg peak, is determined by the beam energy. Finally, the mass to charge ratio (m/q) of the ion beams has to be virtually constant to allow fast transitions between different ion species. However, the variation of the m/q value, $\Delta(m/q)$, has to be greater than 0.03 % to resolve different species with the JYFL K-130 cyclotron. Properties of the high penetration cocktail used by the RADEF-facility are listed in Table 1.

Table 1: Properties of the 9.28 MeV/u Ion Beam Cocktail

Ion	Energy [MeV]	Penetration depth [μm]	LET [MeV/(mg/cm^2)]	$\Delta(m/q)$ [%]
$^{15}N^{4+}$	139	202	1.7	0.0
$^{30}Si^{8+}$	278	130	6.0	-0.09
$^{56}Fe^{15+}$	523	97	18	-0.56
$^{82}Kr^{22+}$	768	94	30	-0.71
$^{131}Xe^{35+}$	1217	89	53	-0.26

Reaching adequate beam currents of $^{131}Xe^{35+}$ with the JYFL 14 GHz ECRIS has required extensive development work. The most significant improvement during the recent years has been the implementation of multiple frequency plasma heating [6], which typically more than doubles the extracted beam currents of the highest charge states.

It would be desirable to increase the energy of the heaviest component of the beam cocktail even further to ensure that the Bragg peak of the energy transfer curve is well within the sensitive area of the component. In practice the performance of the ion source has to be increased to reach even higher charge states of xenon. The properties of a proposed (upgraded) beam cocktail are listed in Table 2. In order to reach Xe^{38+} with the JYFL 14 GHz ECRIS a new hexapole (plasma chamber) has been designed and is foreseen to be installed by the end of 2009. With the new hexapole the simulated radial field on the magnetic pole at the plasma chamber wall reaches 1.07 T in comparison to the presently used hexapole with field strength of 0.93 T. The improvement of the magnetic field strength on the poles has been obtained by changing the magnetization angle of the permanent magnet blocks and moving them radially. The

*This work has been supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2006-2011 (Nuclear and Accelerator Based Physics Programme at JYFL).

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new design follows the proven upgrade of the 14 GHz ECRIS at Argonne National Laboratory [7].

Table 2: Suggested 10.77 MeV/u Ion Beam Cocktail

Ion	**Energy [MeV]**	**Penetration depth [μm]**	**LET [MeV/ (mg/cm²)]**	***Δ(m/q)* [%]**
$^{14}N^{4+}$	151	242	1.6	0.0
$^{35}Cl^{10+}$	377	138	8.3	-0.11
$^{56}Fe^{16+}$	603	117	17	-0.14
$^{80}Kr^{23+}$	862	108	29	-0.74
$^{132}Xe^{38+}$	1422	106	52	-0.85

Introducing the new plasma chamber has profound implications on the beam time allocation procedure at JYFL. It has been decided that the experiments with ion beam cocktails at RADEF-facility, requiring highest possible performance of the ion source, will be carried out in campaigns lasting 3-6 months. The new hexapole will be used during these runs while the old plasma chamber will be installed for nuclear physics experiments requiring metallic ion beams. In particular, employment of the MIVOC-method [8] with the new chamber is to be strictly avoided as the inevitable carbon contamination degrades the performance of the ion source by reducing secondary electron emission from the plasma chamber walls (see section 3). Following this procedure minimizes the maintenance time of the ion sources.

ECRIS PLASMA PHYSICS EXPERIMENTS AT JYFL

In order to gain understanding on the ECR ion source parameters and different techniques, e.g. biased disc and multiple frequency heating, affecting the production of highly charged ions, a series of plasma physics experiments has been carried out at JYFL in recent years. These experiments include plasma potential measurements [9-11] and time-resolved measurements of bremsstrahlung emission, ion currents [12,13] and bias disc current [14]. One objective of the experiments is to study the feasibility of pulsed operation mode for the production of highly charged ions for the beam cocktails for which the time structure of the beam is almost irrelevant. In this section we review some of the results obtained in these experiments.

Plasma Potential Measurements

The plasma potential measurements with the JYFL ECR ion sources have been performed with a retarding field analyzer [9]. Figure 1 shows the results obtained with the JYFL 6.4 GHz ECRIS with different ion species namely hydrogen, deuterium, helium, nitrogen, oxygen, neon, argon and krypton. The vertical range represent the effect of the ion source tuning parameters i.e. neutral gas pressure, microwave power and magnetic field configuration within their typical limits. The plasma potential clearly depends on the ion mass. The difference between electron and ion mobilities increases with increasing ion mass. Higher plasma potential is consequently required to balance the loss rates of positive and negative charges. The plasma potential of the JYFL 14 GHz ECRIS, exhibiting a similar mass dependence, is typically about 50 % lower than the plasma potential of the 6.4 GHz ion source.

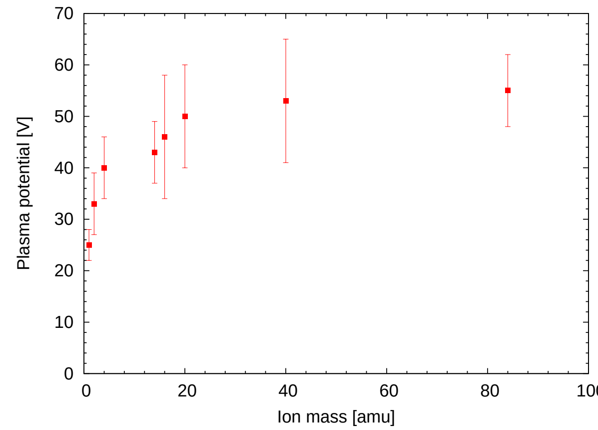

Figure 1: Plasma potential of the JYFL 6.4 GHz ECRIS as a function of ion mass. Vertical range corresponds to the variation of ion source parameters within typical limits.

One of the most important findings with the retarding field analyzer has been the effect of carbon contamination on the plasma potential and energy spread. Figure 2 shows data curves measured with O^{7+} under different contamination levels i.e. before and after a 2 week MIVOC-run (Ti). The plasma potential values associated with each case are given in the figure label. The corresponding beam currents (optimized tune) were 160 μA and 48 μA before and after the MIVOC-run, respectively.

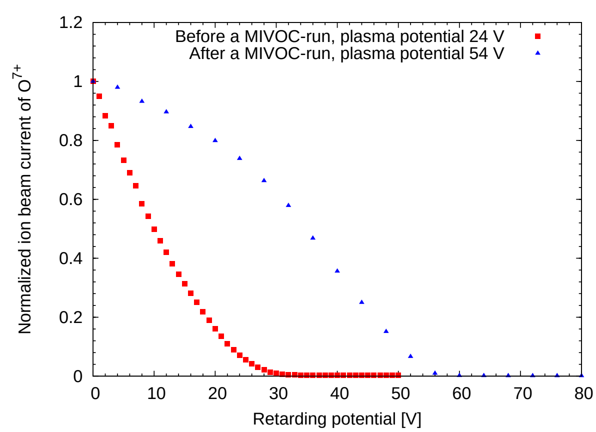

Figure 2: Normalized “plasma potential curves” with a clean aluminium plasma chamber and under heavy carbon contamination due to a MIVOC-run.

The increase of the plasma potential is believed to be due to reduced secondary electron emission from the walls of the aluminum plasma chamber under heavy carbon contamination. Restoring the performance of the ion source to the original level after a serious carbon contamination by the means of plasma cleaning (with oxygen) takes typically more than 100 hours [15]. Therefore, the only viable option compatible with the beam time schedule at JYFL is mechanical cleaning of the plasma chamber. It has been observed that production of metal ion beams with evaporative oven or sputtering technique also affects the performance of the ion source. A layer of deposited metal lowers the secondary electron emission from the chamber walls resulting to a slight increase of the plasma potential. Another indication suggesting that the loss rate of electrons (net flux of electrons) defines the value of the plasma potential and affects the ion losses is the observation that the negative voltage applied to the biased disc reduces the plasma potential up to 20 % [9].

Time-resolved Plasma Diagnostics Experiments

The focus of the ECRIS plasma physics studies at JYFL has recently been time-resolved diagnostics of bremsstrahlung emission [12,13] and plasma breakdown [14]. For these experiments both JYFL ECR ion sources have been operated in pulsed mode. The goal of the studies is to gain understanding on the electron heating mechanism resulting into electron energies of hundreds of keV. The contribution of these so-called runaway electrons to the production of (highly charged) ions is minimal since the ionization cross section typically peaks at electron energies below a few keV. High energy electrons create problems as they produce bremsstrahlung, which gives rise to unnecessary heating of the cryostat of superconducting ECR ion sources [16] and poses a radiation hazard for the laboratory personnel.

In the measurements with several noble gases it has been observed that the ion currents of different charge states appear and saturate well before the bremsstrahlung emission reaches steady state. As an example Figures 3a and 3b present time-resolved ion currents of different charge states of neon, plotted together with the integrated (over the energy range > 30 keV) bremsstrahlung count rate. The rf pulse length was set to 1.76 seconds with off time of 5.9 seconds and the bremsstrahlung was recorded in radial direction from a magnetic pole as described in detail in Ref. 12. The rf power is applied at t=0.

Reaching steady state bremsstrahlung emission count rate takes 200-300 ms while the ion currents saturate in 50–150 ms depending on charge state. Figure 3b highlights the preglow effect [17] observed with low charge states. The preglow effect is much more pronounced than the afterglow observed only with highest charge states. Under the given ion source settings the plasma breakdown time is 8-10 ms. The step-wise nature of the ionization process is also clearly visible in Figure 3b i.e. ion currents of high charge states appear a few milliseconds after the breakdown. It can also be seen that the decay of the ion currents takes several hundreds of milliseconds.

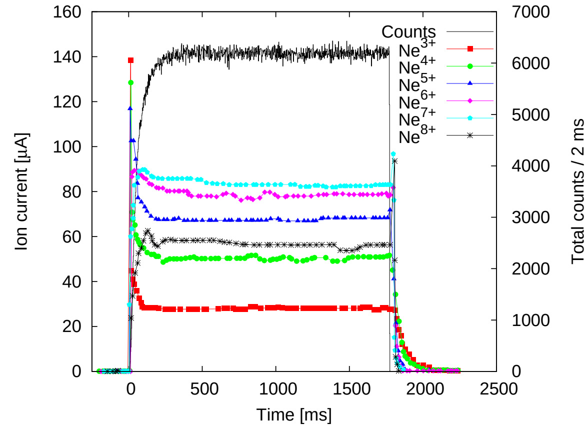

Figure 3a: Time-resolved ion currents of neon and corresponding bremsstrahlung count rate.

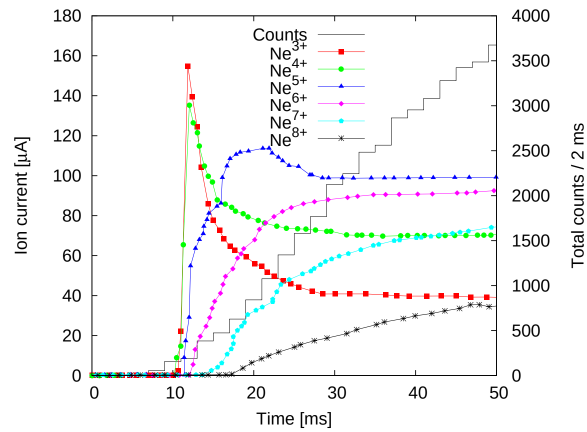

Figure 3b: Time-resolved ion currents of neon and corresponding bremsstrahlung count rate in the beginning of the rf pulse.

It has been observed at JYFL that the shape of the preglow signal (FWHM) depends on the ion beam optics, namely dipole magnet and solenoid settings. The effect of the dipole magnet could be explained by variation of the plasma potential during the transient. This will be investigated in near term future by measuring the time evolution of the plasma potential. The influence of the solenoids could be related to variations of focusing properties under evolving space charge compensation by electrons from ionized residual gas. This is also a subject of a further study.

The formation of the preglow has been thoroughly discussed in Ref. 17. During the initial stage of the plasma breakdown the plasma density is very low and the electron collision time is much longer than the interaction time between the electron and the rf in the resonance region. Essentially all free electrons are heated very efficiently since the total power absorbed by the plasma is less than the power provided by the rf amplifier. This is due to low electron density and stochastic heating limit resulting from the lack of phase randomization in consecutive resonance crossings [18]. Under these conditions the electron energy distribution function is superadiabatic [17] i.e. the average electron energy is very high but limited to a certain threshold value. As the electron density increases with the proceeding ionization cascade, the absorbed rf power becomes insufficient to maintain the superadiabatic EEDF. As a consequence the average electron energy collapses [17] and eventually becomes bi-Maxwellian described by cold and hot populations [19]. As this shift between the breakdown stages takes place, a sudden increase of ion currents (preglow) is observed due to exponentially increasing plasma density and surge of cold electrons escaping the confinement. The length of the preglow pulse is related to the depletion of neutrals and proceeding step-wise ionization towards the steady-state charge state distribution.

In order to test the validity of this qualitative description we measured the bremsstrahlung count rate with rf pulse length of 50 ms with a pulse separation of 500 ms. The pulse pattern was chosen in order to have enough electrons abrorbing the rf during the superadiabatic stage (seed electrons remaining from the previous pulse as discussed later). Sufficient electron density is required to obtain a detectable bremsstrahlung count rate during the initial stage of the breakdown. On the other hand the initial electron density has to be low enough to reach the superadiabatic EEDF. The recorded bremsstrahlung count rate and corresponding time-resolved biased disc current (for details of the measurement see Ref. 12-14) in the case of helium plasma are plotted in Figure 4.

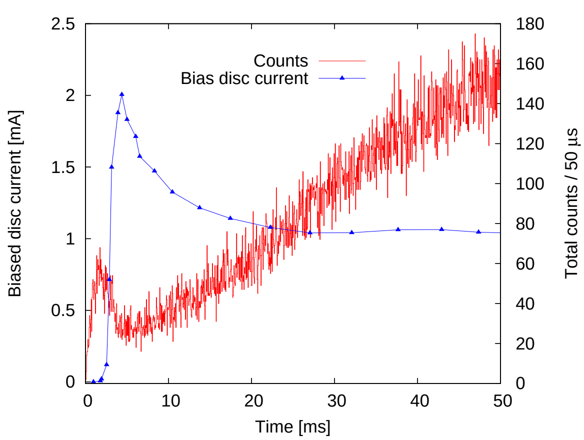

Figure 4: Comparison of time-resolved biased disc current and bremsstrahlung count rate. Rf pulse pattern: 50 ms on / 500 ms off.

The data presented in the figure shows that the bremsstrahlung count rate at energies above 30 keV decreases abruptly about 50 % when the plasma breakdown occurs. The observation supports the "superadiabatic model" claiming that initially a substantial portion of the electrons is heated to high energies followed by a sudden shift of the EEDF (collapse of average energy). The saturation time scale of the biased disc current is believed to be due to neutral depletion [14].

Figure 4 brings up another interesting issue, namely the density of "seed electrons", affecting the plasma breakdown time and the characteristics of the preglow transient. It has been observed that the rf pulse duration and pulse separation affect the time required for the plasma breakdown. This can be explained by the (hot) electrons from the preceding pulse remaining confined in the magnetic field structure of an ECRIS and thus acting as a source of "seed electrons". It has been observed that it can take up to 10 seconds to erase the influence of the previous rf pulse indicating that the (hot) electron confinement time can be on the order of seconds [14]. The effect of the seed electrons is seen by comparing the rise times of bremsstrahlung count rates presented in Figures 3 and 4 with long and relatively short rf pulse separations, correspondingly. In the case of Figure 4 the rf pulse pattern is adequate to maintain certain density of seed electrons resulting into immediate detection of bremsstrahlung and short plasma breakdown time.

The effect of the seed electrons on the plasma breakdown time and preglow has been studied further by sustaining low density plasma with a TWTA operated at very low power in cw mode and pulsing the klystron simultaneously. It was observed that the seed electrons cause the charge state distribution during the preglow transient to shift towards higher charge states. This is demonstrated in Figures 5a and 5b comparing the preglow in the case of helium with and without the seed electrons provided by the TWTA at 11.56 GHz. The 14 GHz rf power is applied at t=0. In this "forced preglow" mode the steady state charge state distribution is reached faster as the plasma breakdown shifts towards the leading edge of the rf pulse from the klystron. The maximum rf power from the TWTA was set to 10 W, matching the maximum power of cheap commercial units at 11-13 GHz. Thus, the "forced preglow" could offer an inexpensive technique to optimize the preglow characteristics (ionization time, pulse rate, charge state distribution). Similar behavior i.e. faster ionization and shift of the charge state distribution was also observed with neon.

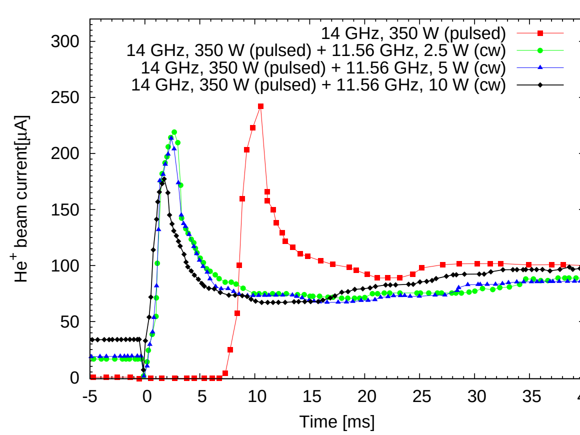

Figure 5a: Time-resolved ion beam currents of He^+ with and without seed electrons provided by TWTA.

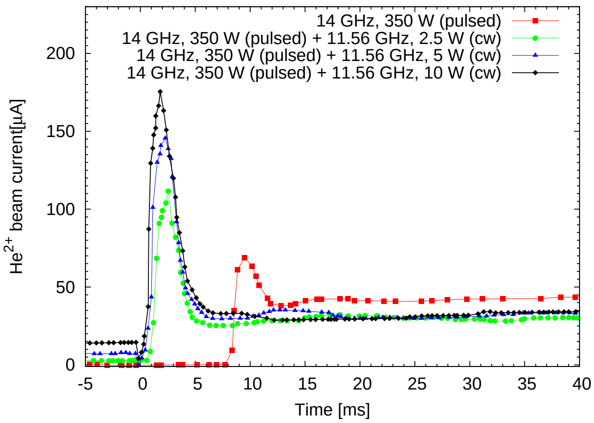

Figure 5b: Time-resolved ion beam currents of He^{2+} with and without seed electrons provided by TWTA.

DISCUSSION

The ECRIS plasma physics experiments have provided insight for the development of new beam cocktails with higher penetration depth i.e. higher energies. If the new plasma chamber with higher radial field proves not to be sufficient for producing enough Xe^{38+}, for example, operating the JYFL 14 GHz ECRIS in afterglow mode becomes a considerable option. Pulsed time structure of the beam is perfectly tolerable from the point of view of the irradiation tests as long as the time averaged flux of ions can be measured. However, it would be desirable to maximize the integrated number of ions by maximizing the repetition rate of the rf pulses (in the afterglow mode). In order to reach high charge states in shorter times, techniques to speed up the ionization process are being sought. It has been shown that seed electrons provided by a TWTA operated in cw mode at low rf power level result to faster ionization of high charge states. A future goal of this ongoing project is to study the feasibility of “forced preglow” to maximize the pulse repetition rate for the production of extremely high charge states in afterglow mode. Instead of operating the ion source in the classical afterglow mode, the recently discovered regime, so-called “micropulsed beam mode” [20] could be used. In this mode the rf pulse length is shortened to (sub)millisecond level, producing afterglow transients with highly charged ions current exceeding the classical afterglow currents by a large factor [20]. Explaining this observation is another goal of the plasma breakdown studies at JYFL.

The time-resolved plasma diagnostics provide valuable information for development of codes modeling e.g. electron heating [21]. The time-resolved bremsstrahlung experiments have clearly demonstrated that ions are produced faster than it takes to reach steady state electron energy distribution. Therefore, it might be possible to control the EEDF by pulsing the rf with (sub)microsecond pulses and optimize the production of highly charged ions.

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