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VACUUM REQUIREMENTS FOR HEAVY ION SYNCHROTRONS

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ABSTRACT

Experimental charge-changing cross sections for uranium ions incident on H_2 and N_2 at 1.4 MeV/u are presented and extrapolation to higher energies is discussed briefly. The beam losses caused by charge-changing collisions between heaviest ions and residual gas molecules in a synchrotron have been calculated for different injection energies and ionic charge states. For example, if a beam of U^{+10}-ions is accelerated from 1.4 MeV/u to 100 MeV/u by an average electric field $\dot{B}R$=112 V/m an average working pressure of about $1x10^{-11}$ mbar is necessary to limit beam losses to several percent.

INTRODUCTION

If synchrotron designs include the acceleration of heaviest particles like uranium, the layout of the vacuum system should be suitable for residual gas pressures in the UHV-range, in order to avoid too high beam losses due to charge-changing of ions. There are several reasons for the very high probability of charge-changing processes between heavy ions and residual gas molecules in the synchrotron compared to protons:

(i) At a given specific ion energy the cross section for capture of electrons, σ_C, by ions in charge states q from stationary atoms increases with q^2 or even stronger.

(ii) Heavy ions normally are not totally stripped when injected into the synchrotron. Therefore, cross sections for loss of electrons (stripping), σ_L, are added to the σ_C. As the σ_L drop much weaker with increasing energy than the σ_C, stripping becomes the predominant process causing heavy ion losses in the synchrotron above 20 MeV/u.

(iii) If the average accelerating field $\dot{B}R$ is constant, the number of revolutions needed per unit gain of specific energy is proportional to the mass-to-charge ratio A/q, which is 1 for protons, 2 for Ne^{+10}, but 24 for U^{+10}.

(iv) Most of the present designs for heavy ion synchrotrons are based on relatively low injection energies, where the charge-changing cross sections, σ_T, are rather large. For Pb- and U-ions at 10 MeV/u σ_T is expected to be in the order of 10^{-16} cm^2, whereas that for protons at typical injection energy of 50 MeV is in the order of nuclear cross sections.

The acceleration of ions with maximum atomic number (Z = 92) in low charge state (q = +10) starting from low energy (1.4 MeV/u) may be defined as worst case of synchrotron operation with respect to vacuum requirements. Although this definition seems to be somewhat strange, if higher injection energies are available, this condition, nevertheless, has turned out to be necessary if the machine is designed for extraction energies as low as possible.

Consequently, measurements of charge-changing cross sections have been concentrated on uranium ions at 1.4 MeV/u, where low charge states between +10 and +30 are available. At higher energies up to 10 MeV/u, only few experimental points for higher charge states up to +63 have been gathered. Mainly H_2 and N_2 were used as targets, because they should be representative for the most important constituents of the residual gas in the UHV-range.

CHARGE-CHANGING CROSS SECTIONS

a) Experimental data

Results of the cross section measurements are presented in part in Fig. 1 and Table I. The dependence of single and multiple electron capture and loss on the charge states q of 1.4 MeV/u-uranium incident on H_2 and N_2 may be deduced from Fig. 1. As expected, the absolute values of cross sections as well as the multiple-to-single loss ratio are significantly larger in the N_2-target. In addition, the dependence on q is evidently different for both targets. Therefore, simple scaling rules for both the target and the q-influence seem to be problematic or even impossible.

For the determination of vacuum requirements the knowledge about total charge changing cross sections, σ_T, would be sufficient. However, electron capture and loss are essentially different processes, which require quite different theoretical or empirical treatment. Therefore, we may define σ_C and σ_L by summing up the cross sections for single and multiple capture or loss, respectively.

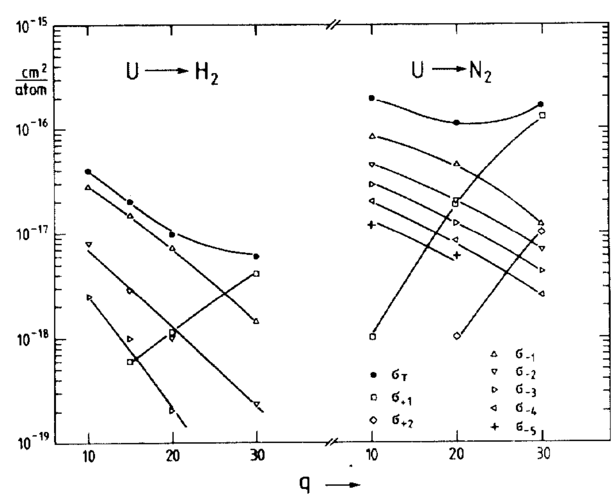

Fig. 1: Cross sections for capture and loss of electrons by 1.4 MeV/u-uranium incident on H_2 and N_2 versus charge state q. σ_T designates the total charge-changing cross section, σ_{+n} and σ_{-n} the cross sections for capture and loss of n electrons, respectively. Errors of $\sigma_{\pm n}$ are between ±10% and ±30%.

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Table I: Cross sections for electron capture σ_C and loss σ_L (in units of $1 \times 10^{-16} cm^2$/molecule) for some charge states q and specific energies T of U- and Pb-ions incident on H_2 or N_2. Errors range from ±10% up to ±30%.

Ion/Target	T(MeV/u)	σ_C	σ_L
Pb^{+40}/N_2	5.9	0.13	0.16
Pb^{+55}/N_2	5.9	0.22	0.086
U^{+40}/H_2	7.80	0.012	0.001
U^{+63}/H_2	10.00	0.0036	0.0016
U^{+63}/N_2	10.00	0.16	0.080

The influence of charge state q on σ_C and σ_L has been investigated also with Kr-, Xe- and Pb-ions at 1.4 MeV/u incident on He, N_2, and Ar.

Less data were available for the investigation of the dependence on projectile velocity, because energy variation for constant q normally is possible only in very limited intervals. Therefore, experiments at higher energies had to be carried out with different q (see Table I) and may be used as spot checks for theoretical results or empirical extrapolations.

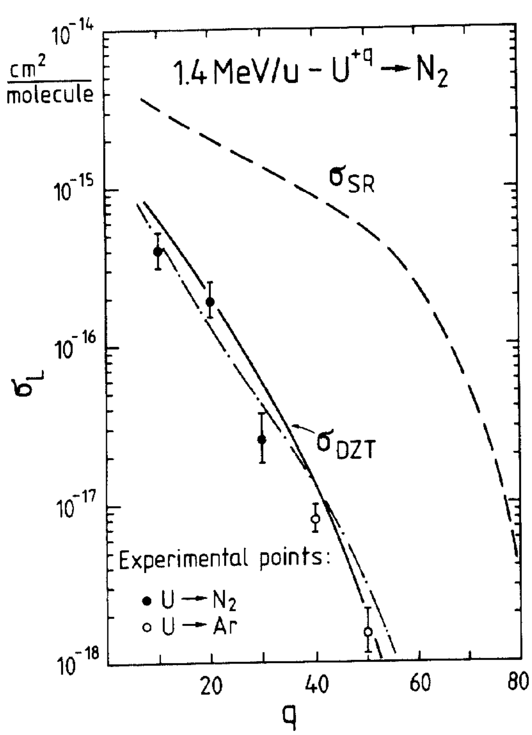

Fig. 2: Comparison of theoretical and empirical extrapolations with experimental loss cross sections for 1.4 MeV/u-uranium in N_2 versus charge state q. Dashed curve from Gillespie et al.[2], solid from Dmitriev et al.[3], and point-dash from empirical relation eq. (2).

b) Extrapolation to high energies

We have tried to fit our experimental data to the theoretical estimations of N. Bohr and J. Lindhard[1] by introducing empirical parameters[4]. Relative good accordance with respect to the dependence on q was achieved mainly with the data measured at 1.4 MeV/u for ions with atomic numbers Z from 36 to 92 incident on He, N_2 and Ar. As stated above, much less experimental cross sections at other energies have been measured and, therefore, the influence of ion velocity may be less well described by our formulae. It is contained therein explicitly by the factor γ^2-1 (γ is the relativistic mass factor) and implicitly by the equilibrium charge states of ions, $\bar{q}$, and target, $\bar{q}_T$, which would be measured at given velocity in the same target:

$$\sigma_C = 2.0 \times 10^{-24} Z^{0.5} \bar{q}^2 \bar{q}_T (\gamma^2-1)^{-2} (q/\bar{q})^a \quad (1)$$

$$\sigma_L = 3.5 \times 10^{-18+X} \bar{q}^{-2} \bar{q}_T (\gamma^2-1)^{-0.5} (q/\bar{q})^b \quad (2)$$

$$Z \geq 36 \;;\; \gamma = (1+T/931.5) \leq 1.1 \;;\; \text{units: } cm^2/\text{atom}$$

Special features of the electronic structure of ions has been introduced into eq. (2) by the parameter $X = (0.71 \log Z)^{1.5}$, which has been deduced from calculated binding energies for the outermost electrons. a = 2 and b = -4 for high charge states $q \geq \bar{q}$ and a = 4 and b = -2.3 for $q \leq \bar{q}$.

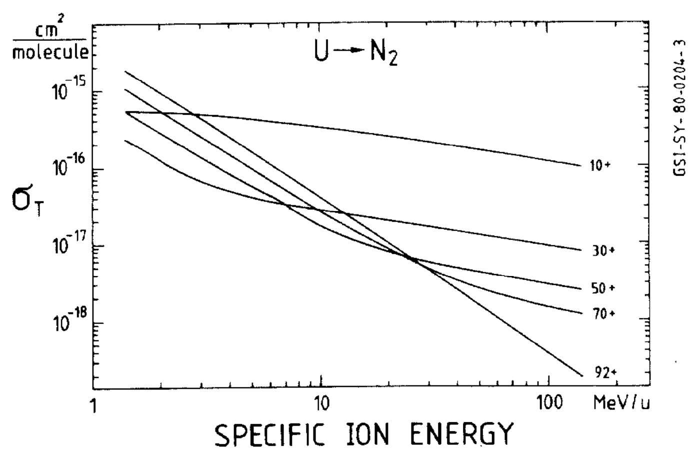

Fig. 3: Total charge-changing cross sections σ_T for several charge states of uranium ions in N_2 calculated by empirical formulae (eqs. (1) and (2)) versus specific projectile energy T.

In Fig. 2 experimental σ_L for 1.4 MeV/u-uranium incident on N_2 and Ar are compared with results from eq. (2), sum-rule calculations (SR) of Gillespie et al.[2], and semi-empirical estimations (DZT) of Dmitriev et al.[3]. The σ_{DZT}-curve is in surprisingly good accordance with the measured points with maximum deviations by a factor of about 2. On the contrary, the σ_{SR}-values, which include also the cross sections for ion excitation, are more than one order of magnitude above the experimental σ_L and depend much more weakly on incident charge state.

Total cross sections σ_T for several charge states of uranium incident on N_2 are plotted in Fig. 3 against the specific energy of ions. This diagram illustrates that especially for the lower charge states in the range above 10 MeV/u the σ_T are dominated by the weakly dropping loss cross sections. It should be noted that the DZT-cross sections decrease much more strongly with increasing energy and will, therefore, lead to more optimistic predictions with respect to beam losses in the high energy range.

CALCULATION OF BEAM LOSSES

Our calculations of beam losses in a heavy ion synchrotron were based on the designs of GSI-Darmstadt. A large machine with maximum magnetic rigidity of BR = 100 Tm was studied, which might be suitable for a wide range of extraction energy from 20 MeV/u (continuing the UNILAC-range) up to 15 GeV/u. For the lowest extraction energies we assumed that the injection should have to take place with low charge states at 1.4 MeV/u, if both high average projectile currents and simultaneously large duty factors are desired.

The transparency D of a beam transport system may be described by the differential expression for the natural logarithm of D

$$d\ln D = -\, n\cdot\sigma_T\, dz \qquad (3)$$

where $n = 2.69\times10^{16}$ p designates the number of residual gas molecules per cm^3 at the pressure p in units of mbar and dz the differential drift length of ions. The beam loss fraction is equal to 1 - D.

In synchrotrons the gain of specific energy T (in eV/u) per meter is given by the expression $dT/dz = q\,\dot{B}\,R/A$, which is a constant if the rise of magnetic field $\dot{B}$ is constant. Eq. (3) then may be written in the form

$$d\ln D = -\frac{n\cdot A}{q\cdot\dot{B}\cdot R}\,\sigma_T(T)\,dT \qquad (4)$$

Eq. (4) is easily integrated if $\sigma_T(T)$ is following any power of T. Unfortunately, as seen in Fig. 3, the dependence on T is rather complicated. The integration may therefore be performed in limited, consecutive intervals, in which $\sigma_T(T)$ can be approximated by power functions.

A plot of beam loss curves for U^{+10} and U^{+28} accelerated by the average electric field of $\dot{B}R$=112 V/m from 1.4 MeV/u to 100 MeV/u is given in Fig. 4. Cross sections have been taken from eqs. (1) and (2). Not included in the beam loss curves are losses during injection and extraction.

If the current of injected particles is independent of time, the transparency at the end of injection becomes $D_{inj} = (1-e^{-d})/d$, where $d = n\cdot\sigma_T\cdot v\cdot t_{inj}$, v the velocity of ions, and t_{inj} the injection time. For slow extraction with constant output current a similar relation is found: $D_{ext} = d/(e^{d}-1)$ with $d = n\cdot\sigma_T\cdot v\cdot t_{ext}$.

In cases of single turn or radial multi-turn injection beam losses will be neglegible because of the very short times in the order of 10^{-5} to 10^{-4} s. Slow rf-stacking procedures at low energy will certainly lead to essentially higher loss rates. Slow or even ultra-slow extraction, especially if performed in the low energy range, give rise to additional losses, which could be even higher than during acceleration.

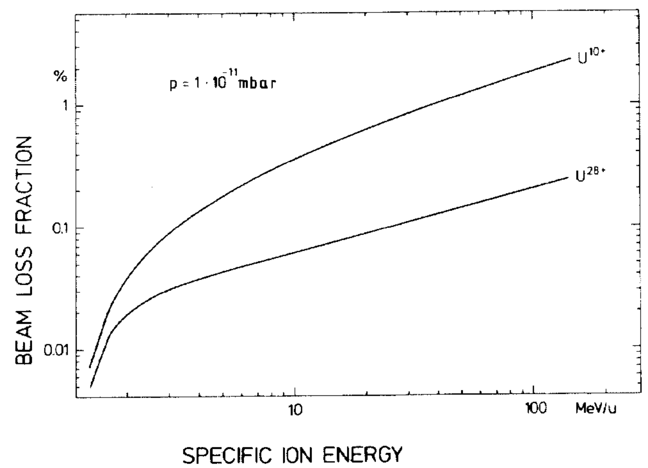

Fig. 4: Loss of uranium ions in charge states +10 and +28 during acceleration in a synchrotron by the average electric field $\dot{B}R$=112 V/m and at the average vacuum pressure of 1×10^{-11} mbar. The calculations are based on charge-changing cross sections σ_T estimated by eqs. (1) and (2) for a residual gas mixture of 90% H_2 and 10% N_2. Other typical components in the UHV-range as for instance H_2O, CO, and CO_2 should have σ_T comparable to N_2.

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