

# CHARGE EXCHANGE INJECTION BY MEANS OF CRYSTALS

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## Abstract

We discuss the use of diamonds as a replacement for amorphous carbon or aluminum oxide foils in charge exchange injection schemes. Diamond yields a number of advantages: 1) Reduced multiple Coulomb scattering, 2) reduced (restricted) energy loss and thus reduced heating, 3) drastically higher thermal conductivity, 4) smaller energy loss straggling with a potential gain in longitudinal emittance and 5) at least as large a stripping efficiency.

The behaviour of the reduction of the overall emittance growth by means of diamond compared to amorphous carbon is investigated.

## 1 INTRODUCTION

In order to increase the intensity in proton machines, the charge exchange injection scheme has been widely used since the 70's. The advantage of injecting particles in another charge state than the stored one is that it enables a 'circumvention' of the Liouville Theorem which prevents accumulation of like particles in an already occupied volume of phase-space.

However, the charge exchange injection necessarily takes place by some means of stripping which may increase the emittance of the beam.

Although other schemes have been proposed, e.g. field detachment of the  $H^+$  ion to  $H^0$  followed by laser excitation and subsequent Lorentz stripping of the resulting  $3P$  state of  $H^0$  [1], the injection schemes in most planned and operating machines are based on electron detachment in an amorphous foil.

## 2 THIN DIAMONDS

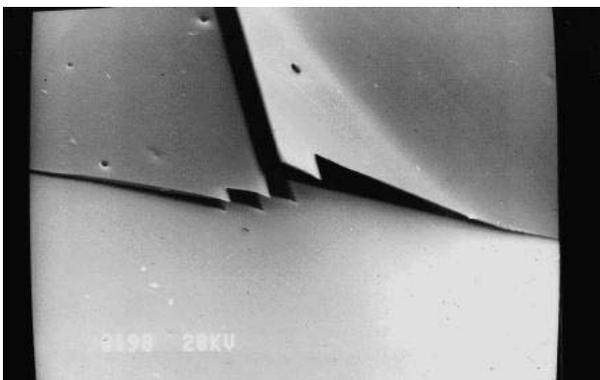


Figure 1: An electron microscope picture of a 4  $\mu\text{m}$  thick diamond wafer

Recent developments in the production of ultra-thin single crystal diamond wafers, have now raised the

prospect of making large diamonds (about a cm on each side) of thicknesses as low as a  $\mu\text{m}$ , corresponding to about  $350 \mu\text{g}/\text{cm}^2$ .

We propose to use such crystals for the charge exchange injection schemes based on stripping foils since diamond offers many advantages compared to amorphous carbon and the only apparent drawback is the slightly more complicated mounting and control of the stripping foil.

## 3 CHANNELING

The large fields present near the nuclei in solid materials may in the case of single crystals add coherently such that a penetrating particle experiences a continuous field along its direction of motion. If further the particle is incident with a sufficiently small angle to a particular crystallographic direction, inside the so-called Lindhard angle,  $\psi_1$ , the negatively/positively charged particle is constrained to move near/far from the nuclei and the electron clouds surrounding these. This is the channeling phenomenon [2] which has found widespread applications in physics.

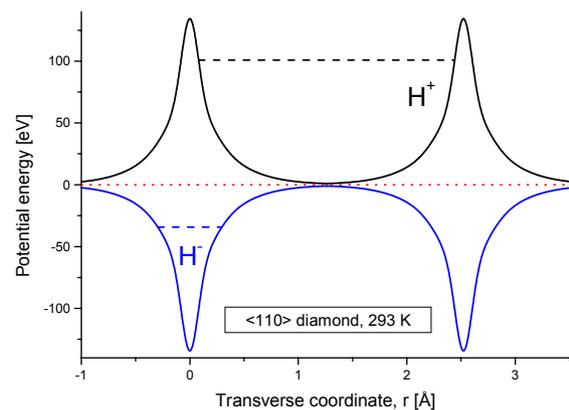


Figure 2: The transverse potential curves calculated for an axially channeled proton and  $H^-$  in diamond at room temperature.

Thus a negative particle is attracted to regions of high nuclear and electron density while a positive particle is kept away from these regions resulting in an energy loss higher than that for amorphous foils for e.g. electrons and smaller for protons. Furthermore, the phenomenon of surface transmission – the fraction of initially channeled particles from an incident beam – behaves very differently for negative and positive particles. Due to the translational symmetry of the environment of a channeled

particle, a separation of transverse and longitudinal motions arise, leading to a so-called transverse energy,  $U(r) + \frac{1}{2}pv\psi^2$ , which is conserved. Here  $p$  is the momentum,  $v$  the velocity,  $\psi$  the angle of incidence to the crystallographic direction and  $U(r)$  is the potential energy as a function of transverse distance,  $r$ , to the plane or string. In figure 2 is shown calculated curves for the transverse potentials of protons and  $H^-$  in diamond. The horizontal lines indicate the total energy of a particle and thus only the region between the two endpoints of this line is accessible to the particle. As figure 2 represents a one-dimensional projection of the two-dimensional string potential for an axially channeled particle, the restrictions on the regions of accessibility apply in both transverse directions. This means that negative particles are much more difficult to channel than positive ones, i.e. the surface transmission is low for  $H^-$  and high for  $p^+$ .

#### 4 SIMULATIONS

In order to evaluate the advantages of diamonds compared

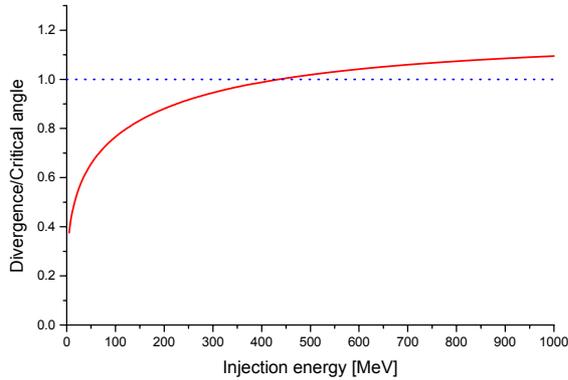


Figure 3: The divergence normalized to the critical angle for channeling as a function of injection energy.

to amorphous carbon more quantitatively, a simulation of the charge exchange injection process and following survival fraction has been performed. The outline of the

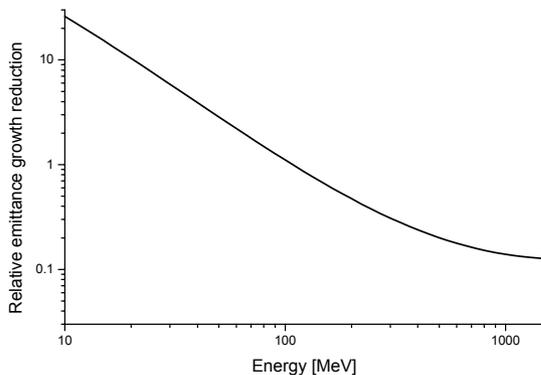


Figure 4: The relative emittance growth at turn 250 during the injection phase as a function of injection energy.

simulation is as given in [3] except for the following phenomena which are influenced by the channeling:

- Multiple Coulomb scattering (eq. (8) in [3])
- Ionization energy loss (eq. (3) in [3])

The higher thermal conductivity (by a factor of more than 400) possibly allows a thicker foil without the risk of evaporation or melting. A full description of the implementation and physical arguments for the channeling processes can be found in [4].

Table 1: Parameter specifications for the simulation

Parameter	Symbol	Value
Twiss	$\beta_T$	5 m
Twiss	$\alpha_T$	0
Emittance	$\varepsilon\beta\gamma$	$1 \pi \text{ mm}\cdot\text{mrad}$
Dispersion	$D$	1 m
Stripping foil edge	$x_F$	-0.01 m
Stripping foil thickness	$t/\gamma$	$240 \mu\text{g}/\text{cm}^2$
Aperture	$r_x$	-0.02 m

However, instead of simulating the KEK Booster Synchrotron as in [3], we choose the accelerator parameters given in table 1 and an energy adjustable in the range 10-1500 MeV and we consider only the horizontal motion, assuming that the vertical behaves analogously, typically with zero dispersion which anyway contributes only marginally.

In figure 3 is shown the normalized divergence,  $(\varepsilon\gamma_T)^{1/2}/\psi_1$ , as a function of injection energy and it is seen that as the energy approaches several hundreds of MeV, the divergence becomes larger than the critical angle, thus diminishing the advantages of using diamond. However, over the whole range, a substantial fraction of the incident particles are channeled.

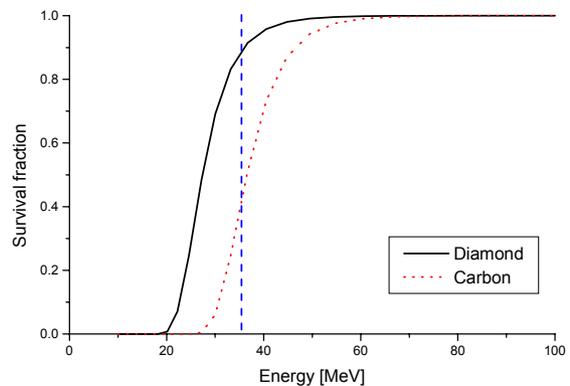


Figure 5: The survival fraction at turn 250 during the injection phase as a function of injection energy. The full-drawn line is for diamond and the dotted line for carbon.

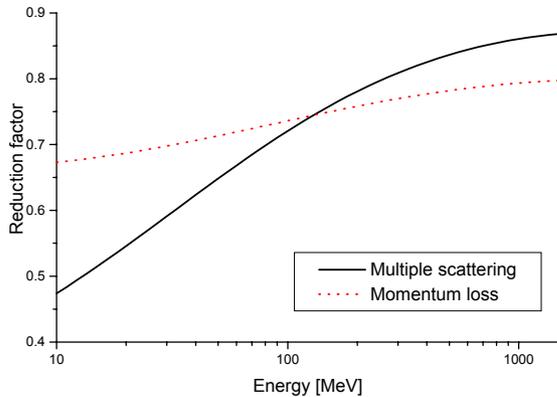


Figure 6: The reduction factors for multiple scattering and momentum loss for diamond compared to carbon as a function of injection energy.

Figure 4 shows the simulated reduction factor for the relative emittance growth,  $(\Delta\epsilon_{\text{carbon}} - \Delta\epsilon_{\text{diamond}})/\epsilon_{\text{in}}$ , after 250 turns in the machine at the location of the stripping foil. Here,  $\Delta\epsilon_{\text{carbon}}$  and  $\Delta\epsilon_{\text{diamond}}$  denote the respective emittance growths and  $\epsilon_{\text{in}}$  the initial emittance. The thickness has been set tentatively to  $t = \gamma \cdot 240 \mu\text{g}/\text{cm}^2$  which is about the optimum thickness, scaled with the injection energy [5]. Note the logarithmic scales. Clearly, as the energy increases beyond 100 MeV the advantage of using a diamond compared to a carbon foil diminishes, partly due to the decreased angular acceptance of the channeling phenomenon as observed in figure 3 and partly because of the stripping foil thickness and initial emittance.

In figure 5 is shown the corresponding survival fraction as a function of injection energy, again observed at turn 250. Evidently, the diamond presents a clear advantage over the carbon foil for an energy near 35 MeV. This optimum energy, in turn, depends on the number of revolutions in the machine at which the observation takes place.

Table 2: Relevant parameters for diamond and carbon. The values denoted with a \* are for an energy of 40 MeV and a thickness of  $240 \mu\text{g}/\text{cm}^2$ .

Parameter	Diamond	Carbon
Thermal conduct. [ $\text{Wg}^{-1}\text{K}^{-1}$ ]	600-1000	1.59
Specific heat [ $\text{cal}^{-1}\text{K}^{-1}$ ]	0.124	0.170
Emissivity	~0.4	0.96
Density [ $\text{g}/\text{cm}^3$ ]	3.53	2.2
Radiation length [cm]	12.2	18.8
Multiple scattering* [mrad]	0.149	0.227
Energy-loss* [keV]	2.4	3.3

Aluminum oxide is frequently used as stripper foils and in this case the advantage of diamond becomes even larger.

Figure 6 shows the simulated results for the reduction factors achieved by using diamond compared to carbon as a function of injection energy. Although the gain is reduced at high energies, we emphasize that the curves represent each only one dimension of the phase-space, i.e. even at 1000 MeV a considerable reduction of the total growth of phase-space can be expected from using diamond.

One important benefit of this reduction of the emittance growth is the resulting reduction in the nuclear activation of components in the part of the accelerator downstream the stripping foil. Close encounters with lattice nuclei leading to ions scattered to large angles are substantially suppressed for channeled protons [4].

There is only one apparent complication: The stripper foil must be mounted on a goniometer-stage with the possibility of aligning the crystal to the incident beam within the critical angle,  $\psi_1$ . However, experience shows that the alignment procedure, e.g. by means of observation of the large-angle scattered protons, takes only a few hours.

Finally, in table 2 we recapitulate the typical parameters relevant for stripper foils for charge exchange injection.

## 5 CONCLUSION

We have shown some of the advantages offered by single crystals instead of amorphous stripping foils by simulating values for a typical situation. The phenomenon is generally applicable although the advantages diminish with increasing injection energy.

Even though a complete simulation of the phenomenon seems possible by following each ion along the track, both in the machine and crystal, many parameters are not precisely known and thus it seems more fruitful to proceed to testing the benefits experimentally. Initial tests are foreseen to take place at the ASTRID facility in Denmark in the near future.

## 6 REFERENCES

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