HEAVY ION STRIPPERS *

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Abstract

Stripping of high current heavy ion beams is a key technology for future accelerators as FAIR (Germany) [1] and FRIB (USA) [2] and current ones as RIBF (RIKEN, Japan) [3]. A small change in the peak charge state produced at the stripper could require a significant expense in additional accelerating stages to obtain the required final energy.

The main challenges are the thermal effects due to the high power deposition (~ 50 kW/mm^3) and the radiation damage due to the high energy deposition. The effects of heavy ion beams are quite different from proton beams because of the much shorter range in matter.

We present an overview considering charge stripping devices like carbon foils and gas cells used worldwide as well as the current research efforts on plasma stripping, liquid metal strippers, etc. The advantages and disadvantages of the different options will be presented.

INTRODUCTION

The use of strippers in heavy ion accelerators provides a way of increasing the final energy without increasing the total accelerating voltage. But there are drawbacks. Usually the stripper efficiency is low, especially when only one charge state can be accelerated like it occurs in cyclotrons, and only a fraction of the incoming particles are in the correct charge state. In the new high beam power regimes proposed for linear accelerators under construction an additional problem occurs because of the high power deposition in the stripping media.

STRIPPER CHALLENGES

Power Deposition and Radiation Damage

The major issue associated with beam strippers for high intensity heavy ion accelerators compared with H- accelerators is the much larger energy deposition per unit length of the heavy ions compared with the protons. Using the code SRIM [4] we can calculate the energy loss. As an example, a U ion at 16.5 MeV/u (FRIB stripper case) deposits 25.7 MeV/µm and has a range of 0.14 mm in a C foil (2.25 g/cm^3), while a 1 GeV proton (i.e. SNS stripper) deposits about 0.44 keV/µm and has a range of 1.62 m; a ratio of close to 60000 in linear energy deposition.

This much higher linear energy deposition produces significantly larger radiation damage effects in solids.

Thermal Effects

Although the beam powers are quite different (40 kW at the FRIB stripper and 1.4 MW at the SNS stripper) the much higher linear energy deposition more than compensates it and the thermal effects are also more severe. These become important when gas or liquid strippers are proposed to avoid the radiation damage to the solid lattice. They could produce density variations that result in large energy spreads of the stripped beam.

EXAMPLES OF STRIPPERS IN USE

Brookhaven National Laboratory

The Relativistic Heavy Ion Collider (RHIC) is the major heavy ion accelerator at Brookhaven National Laboratory (BNL) (see Figure 1). The Au beam was until recently accelerated in a tandem (now an EBIT is being used) with the first stripper in the tandem terminal (S1), a second stripper after the tandem (S2), a third between the Booster and the AGS (S3) and a fourth one between the AGS and the Collider (S4) [5].

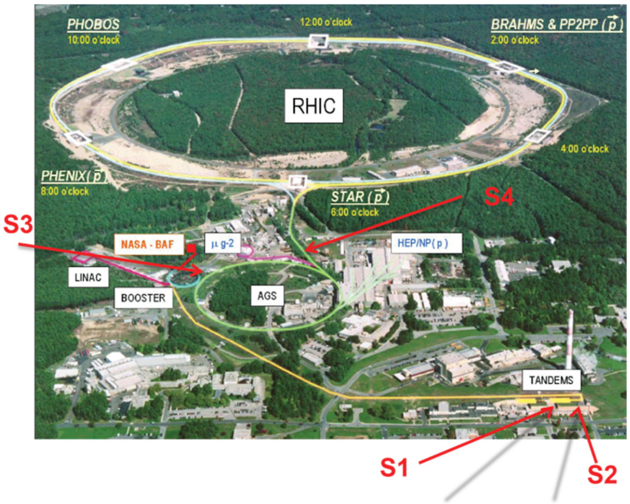

Figure 1: Layout of the RHIC accelerator at BNL showing the location of the four strippers, S1 at the tandem terminal, S2 after the tandem, S3 between the Booster and the AGS and S4 after the AGS.

The two more challenging strippers are S1 and S3. The first stripper (S1) is very thin, just 2 micro grams/cm^2. The Au ions are stripped from Au^{-1} to Au^{+12}. The lifetime of this stripper when using evaporated carbon foils was short. The introduction of foil produced by laser ablation of carbon extended the average lifetime by a factor of three. A ladder with several hundred foils is located at the terminal and oscillates to spread the beam damage over a larger surface.

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The third stripper (S3) originally made of carbon has been replaced by a composite stripper of a first layer of aluminum (6.4 mg/cm^2) followed by a glassy carbon layer (9.2 mg/cm^2) [5]. The difference between the two materials is that the ions reach a high charge state faster (thinner stripper thickness) in aluminium than in carbon, but the final charge state is not as high. With the new double layer stripper the total stripper thickness mass is reduced and lower energy loss (important for the matching between the Booster and AGS). In addition a lower energy spread has been obtained than previously because of the non-uniformities in the previous thicker carbon stripper.

GSI Helmholtz Centre for Heavy Ion Research

The GSI accelerator complex includes a low energy section that accelerates the U beam up to energy of 11.4 MeV/u (see Figure 2).

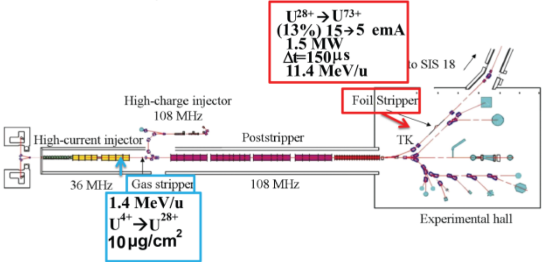

Figure 2: Layout of the low energy section of the GSI accelerator.

In this section two strippers are normally used to bring the U beam to a charge state acceptable for injection into the SIS 18 synchrotron. The first is a gas stripper at energy of 1.4 MeV/u consisting of a N_2 jet with a total thickness of approximately 10 μg/cm^2. The U ions are stripped from a charge of 4+ to a charge of 28+. The second stripper is a carbon foil that takes the 28+ to a 73+ at an a energy of 11.4 MeV/u. The drawback of this scheme for the new facility is the low efficiency associated with the losses inherent in selecting only one charge state from the distribution produced by each stripper. Studies have been performed to replace both strippers with a single foil (20 μg/cm^2) at 1.4 MeV/u. The experiments have shown that U^{39+} can be obtained with a total efficiency of 20 % to be injected in the SIS 18. Intensity significantly higher than what is obtained using the present pair of strippers [6].

A very comprehensive study of the material modifications of these foils is being pursued at GSI by M. Tomut and colleagues [7-8]. It appears that there is a beam-induced graphitization of the amorphous foil that leads to stresses due to the higher density of the crystalline phase. The lifetime of the foils seems to average 0.8 10^{16} ions/cm^2.

The interesting point is that the GSI experiments do not seem to indicate a thinning of the foils, contrary to the experience at RIKEN [9] and at MSU [10]. This last experimental work seems to point toward the "ion hammering" effect described by Klaumunzer and collaborators [11] as the cause of the foil thinning.

RIKEN Nishina Center

The RIKEN accelerator complex is shown in Figure 3. The U beam is first accelerated by a linac and later by four cyclotrons in series, achieving a final energy of 350 MeV/u. The intensity goal is 1 pμA. Two strippers are being used, between the first and second cyclotron and between the second and third. Due to the limitation of selecting a single charge state after each stripping the efficiency is intrinsically low and a high intensity at the first stripper is necessary.

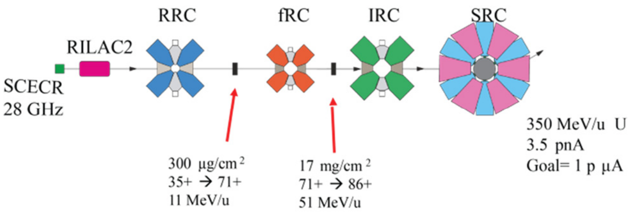

Figure 3: Layout of the RIKEN accelerator showing the linac followed by the four cyclotrons

Extensive development of carbon foils has been performed by H. Hasebe and collaborators for RIKEN [12-13]. The carbon foils, either static or in rotating cylinders do not seem to be able to withstand the higher current needed to achieve the RIKEN RIBF design goals. The present operating point is about 100 times below design.

With the expectation of achieving higher beam intensities the RIKEN team has been pursuing several variations of gas strippers. The first attempt with a nitrogen stripper produced charge states too low to be accepted by the second cyclotron. An important measurement performed at RIKEN by Okuno and collaborators [14] determined the equilibrium charge state for U in a helium gas at three energies between 11 and 15 MeV/u (see Figure 4).

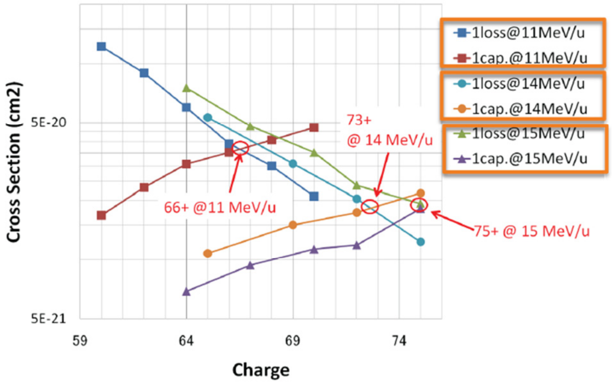

Figure 4: Cross sections for electron loss and electron capture for U in helium at three different energies 11, 14 and 15 MeV/u.

These measurements confirmed that the charge state emerging from a helium stripper is higher than from a nitrogen gas stripper. As described in [14] "The e-capture phenomenon is particularly highly suppressed because of

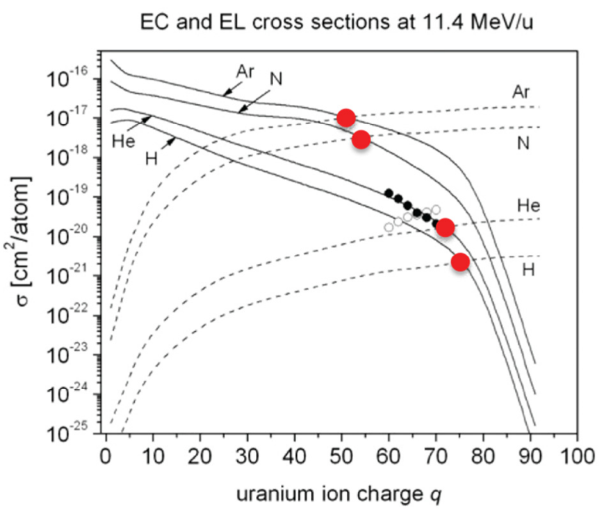

Figure 5: Calculated [15] cross sections of electron capture (EC, dashed curves) and electron loss (EL, solid curves) for Ar, N, He and H for U at 11.4 MeV/u. The red dots indicate the points where both cross sections are equal and determine the equilibrium charge state. The small open and closed circles are the RIKEN measurements at 10.8 MeV/u.

poor kinematical matching when the ion velocity significantly exceeds the velocity of 1s electrons, V_{1s}, which are the fastest target electrons". This mismatch is much higher for helium than for nitrogen, lowering the electron capture cross section and moving the equilibrium charge state to higher charges.

The relative effect can be seen in Figure 5 where the calculated cross sections and the expected equilibrium charges (red dots) are shown for four different gases [15]. Due to the hazards of handling hydrogen, helium is the preferred gas. On the other hand the drawback of helium is the difficulty in pumping it, due to the low efficiency of traditional vacuum pumps.

An extensive development program converged on the construction of a powerful helium gas stripper by Imao and collaborators [16] that has been tested with beam. The new system consists of five stages of differential pumping [9] and 21 pumps. The gas cell has a length of 50 cm at a pressure of 7 kPa to provide a 0.7 mg/cm^2 stripper. On each side of the gas cell four apertures of 10 mm separate the different stages. This system has produced the necessary charge state to inject into the second cyclotron after modifications to its magnetic field. Future work will include the improvement of the gas recycling system due to the large volume of gas circulating. It is also important to study the effect of impurities (oil, water, N2, etc) that could increase the capture cross sections. This is a well-known issue that has affected the gas stopping cell at MSU [17].

The development of this system is a major step in stripper R&D, especially when the beam current is increased and the gas will develop regions of high temperature and low density, increasing the energy spread introduced by the system. With the present beam intensities the RIKEN measurements indicated a lower energy spread than with the carbon foil it replaces due to the thickness non-uniformity of the foils, but an increase in intensity of a factor of 100 will be different territory.

FRIB/MSU- ANL: Liquid Lithium Stripper

The layout of the accelerator proposed for the Facility for Rare Isotope Beams (FRIB) is shown in Figure 6. It consists of a folded linac with the stripper at the end of the first segment [2]. The baseline design has selected a liquid lithium stripper with an alternate design of a helium gas stripper with plasma windows to contain the gas in the cell.

The liquid lithium stripper was proposed by J. Nolen from Argonne National Laboratory (ANL) [18]. It consists of a high pressure liquid lithium jet that impinges on a deflecting plate and produces a thin film (~ 10 µm) of lithium that is traversed by the heavy ion beam (see Figure 7). Lithium becomes liquid at approximately 180 C. An experimental test of a single pass liquid lithium loop has been developed by the ANL team collaborating with FRIB. This single pass loop consists of a reservoir pressurized with argon gas that in the production system will be replaced with an electromagnetic pump. In the test chamber the liquid is pumped back to its original vessel after it has completed one cycle and the process is repeated. The results achieved so far indicate that we can obtain the correct thickness of the liquid film and that it is stable in time. The next steps will be to test if the film is disturbed by depositing power with a proton beam on a beam spot of approximately 3 mm diameter. We expect the FRIB beam to deposit approximately 700 W on the liquid. The high velocity of the film (about 50 m/s) is expected to remove the hot liquid before bubbles can form. Another development will be the endurance tests. Lithium is a very corrosive substance and attacks many common materials like copper. Soft iron on the other hand is compatible with lithium.

The hazards associated with lithium make it necessary to take especial precautions to avoid contact with many substances, concrete, water, nitrogen, etc. For our prototype design (see Figure 8) we are planning to enclose the stripper system in a secondary containment vessel made of iron that will be filled with argon gas to prevent the possibility of starting a fire.

FRIB/MSU- BNL: Helium Gas Stripper

As an alternate solution to the liquid lithium we are developing a helium gas stripper with the ags cell enclosed by plasma windows, in collaboration with BNL. The excellent results obtained by RIKEN encouraged us to consider this alternate solution. The plasma windows sketched in Figure 9 were developed by A. Hershcovitch [19]. The plasma works as a buffer between the high pressure helium (1/3 atmosphere) and the low pressure in the beam line.

The high temperature of the plasma allows a lower

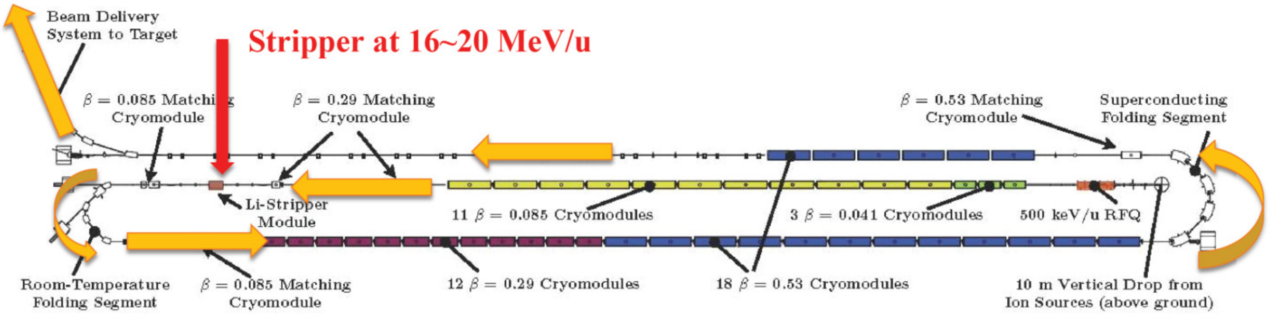

Figure 6: Layout of the Facility for Rare isotopes (FRIB) being designed at Michigan State University for US-DOE. It consists of a SRF linac folded in three sections. After the first section and before the first bend a stripper section is included. Typical stripping energies are between 16 and 20 MeV/u.

density gas to equal the pressure of a denser low temperature gas. Tests at BNL [20] have shown that we can obtain a conductance reduction factor (pressure on the low pressure side with plasma window off divided by pressure with the plasma window on) of 20 and larger in runs lasting many hours.

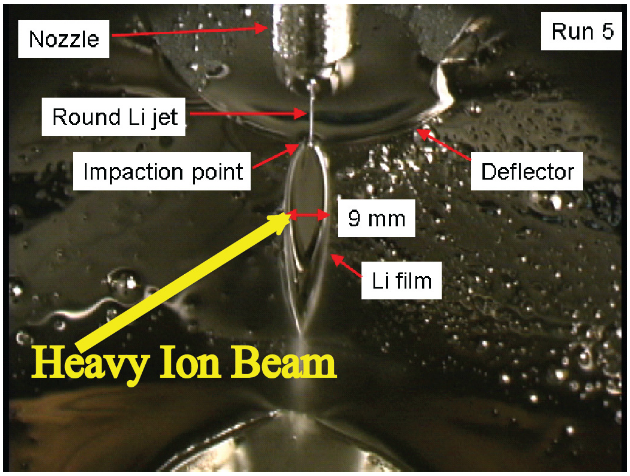

Figure 7: Liquid lithium film produced at ANL. The nozzle is shown at the center top of the photo with the lithium jet hitting the deflector plate. The yellow arrow indicates the direction of the heavy ions traversing the film.

A typical plasma window is shown in Figure 10. A reasonable question is why should we complicate the system with the plasma windows? As we saw from the RIKEN helium stripper it is a very complex system and it is important to be able to circulate the gas at high velocity to decrease the temperature increase. The reduction of the conductance and loss of the helium gas is a very desirable goal specially to reduce the possibility of introducing impurities. As in the case of the liquid lithium the study of the effect of power deposition is necessary to prevent the formation of a low density volume in the beam path.

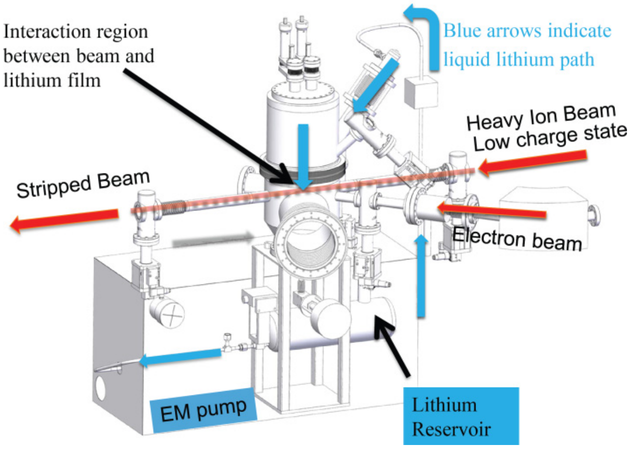

Figure 8: Prototype of the liquid lithium stripper for FRIB. The electron beam will be used to measure the film thickness.

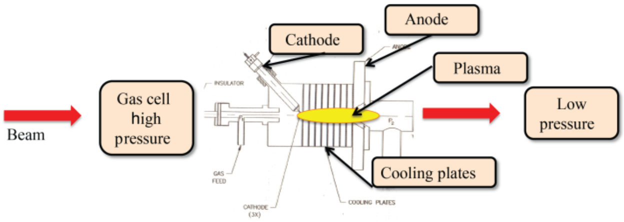

Figure 9: Configuration of a high pressure He gas cell enclosed in plasma windows.

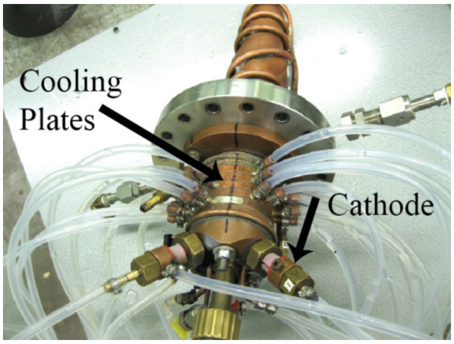

Figure 10: Plasma window developed by A. Hershcovitch [19]

Frankfurt/GSI – Plasma Strippers

The use of plasma strippers has not been implemented routinely yet but the Frankfurt group working at GSI is making important steps in that direction. The idea behind a plasma stripper is that direct capture of an electron by a moving ion violates the simultaneous conservation of energy and momentum [21-22]. The excess binding energy must be taken away by radiative recombination, 3-body recombination or dielectronic recombination, all low probability processes. This restriction lowers the electron capture cross section compared to the bound electron case increasing the charge of the ion compared with a cold target. This effect is more important at low energies. At higher energies the high relative velocity also depresses the capture process.

An experiment is scheduled at GSI [23] to test a plasma stripper with a 4 MeV/u U beam. The ions will interact with a θ-pinch plasma (see Figure 11) produced by an induction coil. The process is geared toward low energy beams and in pulsed mode, not continuous beams.

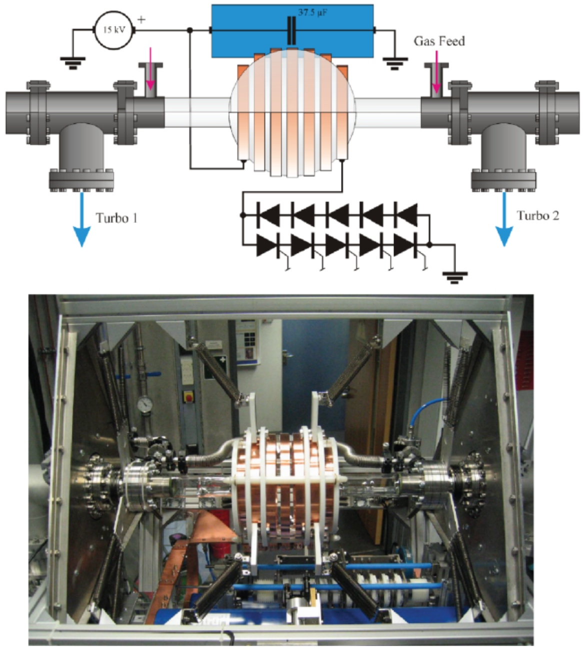

Figure 11: Plasma stripper setup, sketch (above) and equipment (below) showing the induction coil.

CONCLUSIONS

We have recently seen important developments in the field toward new gaseous and liquid metal strippers. The low power tests of helium strippers at RIKEN are very encouraging. The ANL work has shown the stability of the lithium film with the correct thickness. The next steps are to explore how they react to high power deposition by intense beams.

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REFERENCES

[1] FAIR Baseline Technical Report, Vol. 2 (2006). http://www.fair-center.eu/fair-users/publications/fair-publications.html
[2] J. Wei et al," Status and challenge of FRIB project", TU1A04, these proceedings.
[3] H. Imao et al., "Charge stripping of Uranium-238 ion beam with helium gas stripper", IPAC2012, New Orleans, THPPP084, p. 3930 (2012); http://www.JACoW.org
[4] J. Ziegler, http://www.srim.org
[5] P. Thieberger et al., PRST-AB **11** (2008) 011001.
[6] W. Barth et al., "Carbon stripper foils for high current heavy ion operation", INTDS 2012.
[7] M. Tomut et al., GSI SCIENTIFIC REPORT 2011, p. 412.
[8] M. Tomut, "Failure mode of carbon stripper foils exposed to intense heavy ion beams", INTDS 2012.
[9] H. Okuno, personal communication.
[10] F. Marti et al., "Stripper foil developments at NSCL/MSU", Cyclotrons 2010, Lanzhou, THM2CCO03, p. 373. http://www.JACoW.org
[11] A. Benyagoub and S. Klaumunzer, Radiation Effects and Defects in Solids, **126** (1993) p. 105.
[12] H. Hasebe et al., NIM A **613** (2010) 453.
[13] H. Hasebe et al., NIM A **655** (2011) 57.
[14] H. Okuno et al., PRST-AB **14** (2011) 033503.
[15] V. P. Shevelko et al., NIM B **278** (2012) 63.
[16] H. Imao et al., "Charge stripping of Uranium-238 ion beam with helium gas stripper", THPPP084, Proc. IPAC2012, p. 3930, http://www.JACoW.org
[17] D. J. Morrissey et al., NIM B **266** (2008) 4822.
[18] Y. Momozaki et al., JINST 4 (2009) P04005.
[19] A. Hershcovitch, Phys. of Plasmas **5** (1998) 2130.
[20] A. Hershcovitch, P. Thieberger, L. Snydstroup, personal communication.
[21] E. Nardi and Z. Zinamon, Phys. Rev. Lett., **49** (1982) 1251.
[22] J. Jacoby et al., Phys. Rev. Lett. **74** (1995) 1550.
[23] C. Teske, G. Xu, J. Jacoby, T. Rienecker –Frankfurt, Beam Time Proposal: U275.