CHARGE STRIPPING AT HIGH ENERGY HEAVY ION LINACS

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Abstract

For each heavy-ion accelerator facility charge stripping is a key technology – the stripping charge state, its efficiency to produce ions in the selected charge state, and the beam quality after stripping substantially determine the entire accelerator performance. Modern heavy ion accelerator facilities such as the future Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt, Germany provide for high-intensity heavy-ion beams beyond 200 MeV/u. Heavy ions generated in an ion source at comparatively low charge states are pre-accelerated in a Linac to a few MeV/u, after charge stripping the average charge state is increased and one (or several) ion charge states are selected for further acceleration. This enables more efficient acceleration up to the final beam energy, compared to acceleration of ions with a low charge state. C-foil stripping allows for highest mean charge state and best stripping efficiency into the desired charge state. Therefore minimum acceleration voltage could be expected utilizing C-foil stripping. Due to the high power deposited by the ions in the stripping media and radiation damages if solids are used, self-recovering stripper media must be used in any case. First layout scenarios for a 200 MeV/u heavy ion Linac considering efficient heavy ion stripping will be presented.

INTRODUCTION

Suitable charge stripper technologies are crucial to meet the challenging demands of modern state of the art heavy ion accelerator facilities, as the Radioisotope Beam Factory (RIBF) at RIKEN, Wako, Japan [1], the future Facility for Rare Isotope Beams (FRIB) at MSU, East Lansing, MI, USA [2], the High Intensity heavy ion Accelerator Facility (HIAF) at HIRFL, Lanzhou, China [3], and the future Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt, Germany [4] to provide high intensity heavy ion beams beyond 200 MeV/u. Heavy ions generated in an ion source at comparatively low charge states are pre-accelerated to a few MeV/u, after charge stripping the average charge state is increased and one (or several) ion charge states are selected for further acceleration. This enables more efficient acceleration up to the final beam energy, compared to acceleration of ions with a low charge state [5].

After passing heavier gas targets the shape of the charge state distribution becomes broader and asymmetric. This behaviour is caused by an increased contribution of so-called "multi-electron processes" in the charge-changing collisions. In these processes, more than one electron is lost or captured by the ion. The cross sections for multi-electron loss are increasing for higher-Z targets. By using low-Z gases, like H_2 and He for stripping of ^{238}U-beams, the cross sections for multi-electron processes are decreased resulting in narrower charge state distributions. The use of H_2 and He gas enables for increased stripping efficiencies and, thus, higher beam intensities behind the gas stripper for the targeted charge states.

For the application in accelerators it is important to note that an increased thickness of the stripping target affects the ion beam energy, as well as the beam emittance. The ion beam energy is an important parameter for the injection of the beam into the subsequent accelerator structures. Therefore, the energy loss in the stripper has to be taken into account when increasing the applied target thickness. The beam emittance is a crucial parameter for the accelerator performance. It is influenced by the angular straggling of the ions in the gas target as well as by increased space charge forces due to higher charge states of the stripped ions. However, multi-electron processes as well as the evolution of the beam emittance, passing the gas stripper, are not discussed here, but have to be considered later on during detailed accelerator investigations.

CHARGE STRIPPING

A major issue associated with beam strippers for high intensity heavy ion accelerators is the large energy deposition per unit length. Using the code SRIM [6] the energy loss could be calculated. As an example, an Uranium ion at 16.5 MeV/u (FRIB stripper case) deposits 25.7 MeV/μm and has a range of 0.14 mm in a Carbon foil (2.25 g/cm³), while a 1 GeV proton (i.e. SNS stripper) deposits about 0.44 keV/μm and has a range of 1.62 m. It means a ratio of close to 60000 in linear energy deposition. This much higher linear energy deposition produces significantly larger radiation damage effects in solids although the beam powers are quite lower (40 kW at the FRIB stripper and 1.4 MW at the SNS stripper). The thermal effects are also more severe. This becomes important when gas or liquid strippers are used avoiding the radiation damage to the solid lattice. Both stripper media could produce density

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variations, resulting in additional momentum spread of the stripped beam. The main challenges in the stripper design are the high power deposited by the ions in the stripping media (~ 30 MW/cm³) and radiation damage, if solids are used. For that reason self-recovering stripper media should be used [7].

DERICA PROJECT

The upcoming DERICA-project [8] is recently initiated at JINR (Dubna, Russia). Providing for 100 MeV/u Uranium beam from the DERICA driver Linac a two-step stripper approach is proposed. The baseline is one stripper (Str-1) applying a gas target at lower beam energy (≤ 10 MeV/u). As a further upgrade option, boosting the DERICA-Linac beam energy to its maximum, a high energy stripper (Str_2) in the form of a gas stripper device too, could provide for high intensity high charge state beam. In any case the Linac layout should provide for sufficient free space to install Str_2 and an adjacent charge analyzing system. A nitrogen, hydrogen or helium gas target [9-11] could be considered for gas stripping. In case the upcoming FRIB-project operates a high-velocity thin film of liquid lithium successfully, this option could be considered too [7].

STRIPPER CHARGE STATES

In Fig. 1 the expected mean charge state after stripping of Uranium ions in two different stripper media (C-foil and N_2-gas target) at certain beam energies (up to 50 MeV/u) is depicted applying a simplified simulation code UNI-ABC [12]. Besides the simulations results, measured data, taken at GSI [4] and RIKEN [8] are shown, as well as the expected charge state range applying the liquid Lithium stripper/He-gas stripper [2, 11] at the FRIB heavy ion Linac. While the measured mean charge state data after solid state stripping could be confirmed in a wide range of beam energies, mean charge states generated by gas strippers are not as easy to predict. As already stated, the mean charge state strongly depends on the target media, while complex atomic physics processes have to be taken into account [13].

The following results from UNI-ABC simulations for Uranium projectiles on a N_2 gas target have been used to estimate the expected mean charge state as function of the beam energy. As shown in Fig. 1, N_2-gas stripping results in relatively low mean charge states, but provides for stable and reliable target operation.

A higher stripping energy $W_{stripper}$ provides for higher charge states Z_{out} and also higher acceleration at a certain voltage U_1; in other words, a lower voltage U_2 is necessary for acceleration to the desired (final) beam energy W_{final}. As a consequence, one should spent more power (voltage) to accelerate lower charge state beams to the high energy (where stripping is more efficient). Obviously there is a minimum total acceleration voltage U_{tot}, which could be estimated with a simplified calculation:

$$U_{tot} = U_1 + U_2 = W_{stripper}/Z_{in} + (W_{final} - W_{stripper})/Z_{out},$$

where Z_{out} is non-linearly dependent on $W_{stripper}$.
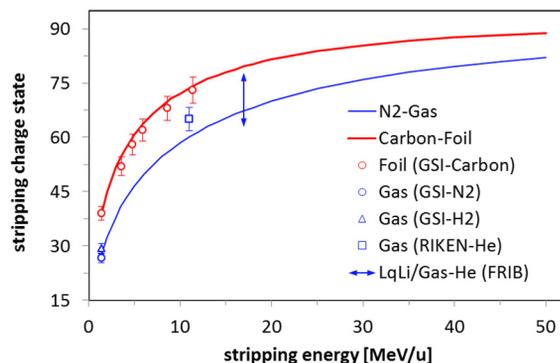
Figure 1: Stripping of Uranium ions applying C-foil or gaseous targets.

ONE STRIPPER APPROACH

Table 1: Baseline Approach with One Stripper; Final Uranium Beam Energy $W_{final} = 100$ MeV/u

	W [MeV/u]	1.4	3.0	6.0	9.0	15.0	20.0	25.0	30.0	35.0
N2-Gas	q (mean)	27	38	50	57	65	70	74	76	78
	A/q	8.7	6.2	4.8	4.2	3.6	3.4	3.2	3.1	3.1
	U_acc [MV]	869	625	492	446	415	412	418	429	443
C-Foil	A/q	39	52	64	71	76	82	84	85	87
	q (mean)	6.1	4.6	3.7	3.4	3.1	2.9	2.8	2.8	2.7
	U_acc [MV]	612	465	393	369	370	373	388	405	423

As shown in Table 1 and Fig. 2, the minimum acceleration voltage needed to gain for 100 MeV/u of Uranium beam is achieved for a C-foil stripper device at 10 MeV/u or at 20 MeV/u for a N_2-gas target. The stripping energy is chosen according to the expected initial charge state delivered by the ion source and in particular according to the stripper target media (low-Z gaseous target, liquid or solid). Only about 10% of accelerating voltage (20% of RF-power) could be saved by choosing the most efficient C-foil stripping target instead of a N_2 gas target.
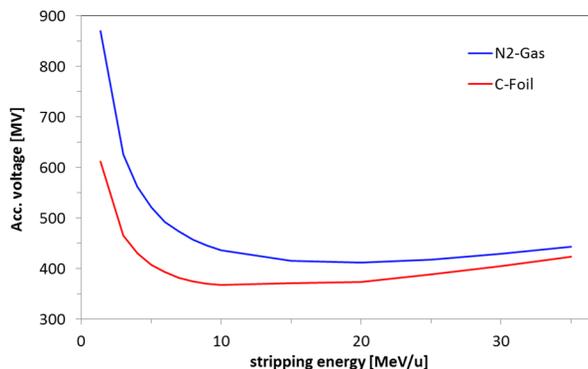
Figure 2: One stage stripping approach; Uranium charge state from ion source is 34+.

TWO STRIPPER APPROACH

A second stripper to be inserted at higher beam energy is beneficial to reduce the accelerating voltage for a given Linac energy of 100 MeV/u by 10%, if two N_2-gas stripper devices are taken into account (Tab. 2 and Fig. 3). Applying C-foil stripping (Table 3, Fig. 4) potentially 11% of accelerating voltage could be saved. In both cases it is mandatory to set both strippers (Str_1 and Str_2) according to

the charge state delivered by ion source and according the expected charge state after stripping in Str_1 resp. Str_2.

Table 2: N2-Gas stripping of Uranium ions, final Uranium beam energy W_{final} = 100 MeV/u

Accelerating Voltage [MV]			Stripper 1							
Stripper 2			W [MeV/u]	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
			A/q	6.2	5.6	5.1	4.8	4.6	4.4	4.2	4.1
W [MeV/u]	A/q	q (mean)	q (mean)	38	43	47	50	52	55	57	59
10.0	4.1	59		431	428	427	427	429	431	433	436
15.0	3.6	65		406	399	396	395	395	396	398	400
20.0	3.4	70		399	389	384	381	380	380	381	383
25.0	3.2	74		401	388	380	376	374	373	373	374
30.0	3.1	76		408	392	382	376	373	371	371	371
35.0	3.1	78		419	399	387	379	375	372	371	370
40.0	3.0	80		431	408	394	384	379	375	373	371
45.0	2.9	81		444	418	401	390	384	379	376	374
50.0	2.9	82		459	429	410	398	390	384	380	378
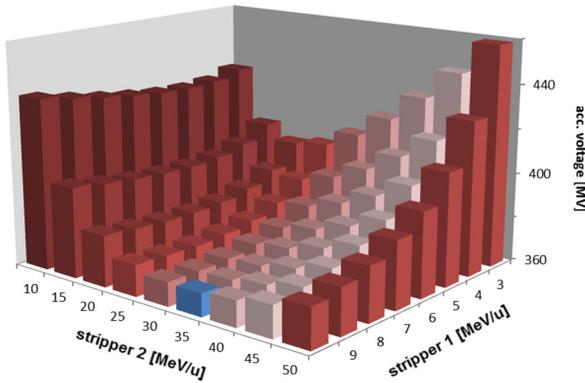
Figure 3: Two stage Gas-stripping approach; Uranium charge state from ion source is 34+.

Table 3: C-Foil Stripping of Heavy Ions, Final Uranium Beam Energy W_{final} = 100 MeV/u

Accelerating Voltage [MV]			Stripper 1							
Stripper 2			W [MeV/u]	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
			A/q	4.6	4.2	3.9	3.7	3.6	3.5	3.4	3.3
W [MeV/u]	A/q	q (mean)	q (mean)	52	57	61	64	67	69	71	72
10.0	3.30	72		350	350	352	354	357	360	363	367
15.0	3.05	78		335	333	334	335	337	340	343	346
20.0	2.92	82		332	328	327	328	329	331	333	336
25.0	2.84	84		335	329	326	326	326	328	330	333
30.0	2.79	85		340	332	328	327	326	327	329	331
35.0	2.74	87		346	336	331	328	327	328	329	331
40.0	2.71	88		353	342	335	332	330	330	330	332
45.0	2.70	88		361	348	340	336	333	332	332	334
50.0	2.68	89		370	355	345	340	337	336	335	336
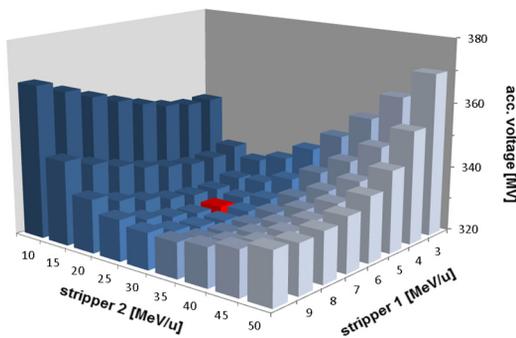
Figure 4: Two stage foil-stripping approach; Ion source charge state is 34+.

SUMMARY AND OUTLOOK

First considerations applying heavy ion stripping for the 100 MeV/u heavy ion driver Linac of the DERICA project have been carried out. A high Uranium charge state (34+) provided by an advanced heavy ion source (MS-ECRIS) is beneficial to reduce the accelerating voltage of the 100 MeV/u driver Linac and therefore the length of the accelerator and intrinsic Linac costs. In particular the stripper medium (gaseous, liquid or solid) is of highest importance for the entire Linac layout. C-foil stripping is the most promising stripping device to gain for highest mean charge state and best stripping efficiency into the desired charge state; therefore a minimum acceleration voltage could be expected utilizing C-foil stripping. Due to the high power deposited by the ions in the stripping media and radiation damages if solids are used, self-recovering stripper media must be used. Stripping in a N_2-gas target is successfully practiced at heavy ion accelerators since many decades. It is recommended to take N_2-gas stripping into account for the DERICA 100 MeV/u-Linac as a baseline, providing for most reliable heavy ion beam operation. Advanced stripper media, e.g. low-Z gas stripper targets (H_2-or He-gas targets) or liquid Lithium targets potentially provide for higher stripping charge states and higher stripping efficiency; also plasma stripping seems to be a very beneficial technology. Further R&D efforts are needed to investigate these ambitious stripping technologies. It is proposed to provide at first for a Linac design with one N_2-gas stripper (and an downstream charge separation system) at 10 Mev/u. This approach is close to best efficiency, if one stripper is applied. Space for high energy stripping at 35 MeV/u should be provided in the basic DERICA Linac-design. With a two stripper approach, applying gas stripper targets at 10 MeV/u (Str_1) and 35 MeV/u (Str-2), the Linac design could be optimized in terms of compactness, efficiency, reliability and last but not least in terms of costs. In addition a two stripper approach could boost for maximum Uranium beam energy at a given accelerating voltage during future DERICA-operation.

The HIM/GSI cw-Linac HELIAC (HElmholtz LInear ACcelerator) [14-21] design provides beam acceleration for a wide range of different ions (protons to uranium) above the design beam energy, featuring in the ambitious GSI-user program [22] applying heavy ion stripping as discussed in this paper, while the GSI-UNILAC is upgraded for short pulse high current FAIR-operation [23-31].

REFERENCES

[1] Y. Yano, "The RIKEN RI Beam Factory Project: A status report", *Nucl. Instrum. Methods Phys. Res., (Sect. B)* vol. 261, p. 1009, 2007.

[2] J. Wei *et al.,* "FRIB Accelerator Status and Challenges", in *Proc. 26th Linear Accelerator Conf. (LINAC'12)*, Tel Aviv, Israel, Sep. 2012, paper TU1A04, pp. 417-421.

[3] J. Yang, *et al.,* "High Intensity heavy ion Accelerator Facility (HIAF) in China", *Nucl. Instrum. Methods Phys. Res., (Sect. B)*, vol. 317, p. 263, 2013.

[4] W. Barth *et al.*, "U^{28+} intensity record applying a H2 gas stripper cell", *Phys. Rev. ST Accel. Beams* vol. 20, p. 050101, 2017,
    DOI: 10.1103/PhysRevAccelBeams.20.050101

[5] P. Scharrer *et al.*, "Measurements of charge state distributions of 0.74 and 1.4 MeV/u heavy ions passing through dilute gases*", *Phys. Rev. ST Accel. Beams*, vol. 20, p. 043503, 2017, DOI: 10.1103/PhysRevAccelBeams.20.043503

[6] J. Ziegler, http://www.srim.org

[7] L. V. Grigorenko *et al.*, "Scientific problems of perspective accelerator-accumulative complex DERICA for research of radioactive isotopes", Usp. Fiz. Nauk (2019, in press)

[8] H. Kuboki *et al.*, "Charge-state distribution measurements of 238U and 136 Xe at 11 MeV/nucleon using gas charge stripper", *Phys. Rev. ST Accel. Beams* 13 (2010) 093501

[9] H. Okuno *et al.*, "Low-Z gas stripper as an alternative to carbon foils for the acceleration of high-power uranium beams", *Phys. Rev. ST Accel. Beams,* vol. 14, p. 033503, 2011.

[10] H. Imao *et al.*, "R&D of Helium Gas Stripper for Intense Uranium Beams", in *Proc. 20th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'13)*, Vancouver, Canada, Sep. 2013, paper TU3PB03, pp. 265-268.

[11] F. Marti, "Heavy Ion Strippers", in *Proc. 26th Linear Accelerator Conf. (LINAC'12)*, Tel Aviv, Israel, Sep. 2012, paper FR1A01, pp. 1050-1054.

[12] J. Glatz, private communication

[13] V.P. Shevelko, P. Scharrer, C.E. Düllmann, W. Barth, J. Khuyagbaatar, I.Y. Tolstikhina, N. Winckler, A. Yakushev, „Charge-state dynamics of 1.4- and 11-MeV/u uranium ions penetrating H_2 and He gas targets", *Nucl. Instrum. Methods Phys. Res., (Sect. B)*, vol. 428, pp. 56-64, 2018, DOI: 10.1016/j.nimb.2018.04.048

[14] W. A. Barth *et al.*, "First heavy Ion Beam Test with a superconducting multi gap CH-cavity", *Phys. Rev. ST Accel. Beams* 21, 020102, (2018), DOI: 10.1103/PhysRevAccelBeams.21.020102

[15] M. Schwarz, S. Yaramyshev, "Reference Beam Dynamics Layout for the SC CW Heavy Ion HELIAC at GSI", Preprint submitted to *Nuclear Instruments & Methods A*, 2019, to be published.

[16] W. A. Barth *et al.*, "Superconducting CH-Cavity Heavy Ion Beam Testing at GSI", *J. Phys.: Conf. Ser.* vol. 1067, p. 052007, 2018, doi: 10.1088/1742-6596/1067/5/052007

[17] S. Yaramyshev *et al.*, "Advanced Approach for Beam Matching along the Multi-Cavity SC CW Linac at GSI", *J. Phys.: Conf. Ser.* Vol. 1067, p. 052005, 2018, doi: 10.1088/17426596/1067/5/052005

[18] H. Podlech *et al.*, "Superconducting CH structure", *Phys. Rev. ST Accel. Beams*, vol. 10, p. 080101, 2007.

[19] M. Schwarz *et al.*, "Beam Dynamics Simulations for the New Superconducting CW Heavy Ion LINAC at GSI", *J. Phys.: Conf. Ser.* Vol. 1067, p. 052006, 2018, doi: 10.1088/1742-6596/1067/5/052006

[20] M. Gusarova *et al.*, "Design of the two-gap superconducting rebuncher", *J. Phys.: Conf. Ser.* vol. 1067, p. 082005, 2018, doi: 10.1088/1742-6596/1067/8/082005

[21] K. Taletskiy *et al.*, "Comparative study of low beta multi-gap superconducting bunchers", *J. Phys.: Conf. Ser.* vol. 1067, p. 082006, 2018, doi: 10.1088/1742-6596/1067/8/082006

[22] M. Block *et al.*, "Direct mass measurements above uranium bridge the gap to the island of stability", *Nature*, vol. 463, pp. 785–788, 2010, doi:10.1038/nature08774

[23] W. A. Barth *et al.*, "High brilliance uranium beams for the GSI FAIR", *Phys. Rev. ST Accel. Beams*, vol. 20, p. 050101, 2017, doi: 10.1103/Phys. Rev. Accel. Beams 20, 050101

[24] W. A. Barth *et al.*, "Heavy ion linac as a high current proton beam injector", *Phys. Rev. ST AB*, vol. 18, p. 050102, 2015, doi: 10.1103/PhysRevSTAB.18.050102

[25] A. Adonin *et al.*, "Beam brilliance investigation of high current ion beams at GSI heavy ion accelerator facility", *Rev. Sci. Instrum.*, vol. 85, p. 02A727, 2014, http://dx.doi.org/10.1063/1.4833931

[26] L. Groening *et al.*, "Benchmarking of measurement and simulation of transverse rms-emittance growth", *Phys. Rev. ST Accel. Beams,* vol. 11, p. 094201, 2008, doi: 10.1103/PhysRevSTAB.11.094201

[27] S. Yaramyshev *et al.*, "Virtual charge state separator as an advanced tool coupling measurements and simulations", *Phys. Rev. ST Accel. Beams,* vol. 18, p. 050103, 2015, doi: 10.1103/PhysRevSTAB.18.050103

[28] W. A. Barth *et al.*, "Upgrade program of the high current heavy ion UNILAC as injector for FAIR", *Nucl. Instrum. Methods Phys. Res., Sect. A,* vol. 577, p. 211, 2007, doi: 10.1016/j.nima.2007.02.054

[29] W. A. Barth *et al.*, "High brilliance uranium beams for the GSI FAIR", *Phys. Rev. ST Accel. Beams*, vol. 20, p. 050101, 2017, doi: 10.1103/PhysRevAccelBeams.20.050101

[30] U. Ratzinger *et al.*, "The 70 MeV p-injector design for FAIR", *AIP Conf. Proc.*, vol. 773, pp 249-253, 2005.

[31] C. M. Kleffner *et al.*, "Status of the FAIR pLinac", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 2208-2210. doi:10.18429/JACoW-IPAC2017-TUPVA058