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THE NEW FAIR POST-STRIPPER DTL - ALVAREZ 2.0

Sascha Mickat, Norbert Bönsch, Xiaonan Du, Peter Gerhard, Jens Holluba, Lars Groening, Manuel Heilmann, Stefan Jagsch, Michael Kaiser, Eberhard Merz, Carsten Mühle, Markus Romig, Marcel Rosan, Anna Rubin, Vaishnavi Srinivasan, Wilfried Sturm, Stephan Teich

GSI Helmholtzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, GER

Abstract

The existing GSI accelerator facility, comprising both the UNILAC and the SIS18, is assigned to be the dedicated injector chain for FAIR. Two aspects require the substitution of the existing post-stripper section of the UNILAC, which is an Alvarez type drift tube linac (DTL).

- With respect to its beam dynamic design the existing Alvarez DTL does not cover high current applications for heavy ions as required for FAIR. This will limit the performance of FAIR from the middle 2020's on.
- The existing Alvarez DTL is in regular operation since 1978. An increase in failures due to material fatigue is observable and can be avoided in parts just by an out of scale maintenance effort. A new Alvarez DTL will minimize the operational risk for FAIR commissioning from the middle 2020's.

THE UNILAC POST-STRIPPER DTL

Since the commissioning of the original UNILAC in 1978 the facility was adapted to the demands of its users and to its present expansion (Fig. 1). A complex technical system has grown comprising technologies of different decades. Within this context next to the performance upgrades for reaching the FAIR design parameters, the upgrades aiming at operation reliability have to be considered also. Sections like the existing Alvarez (DTL), the section behind the gaseous stripper (post-stripper), are over 40 years in operation, which is far beyond of its expected lifetime of about 20 years.

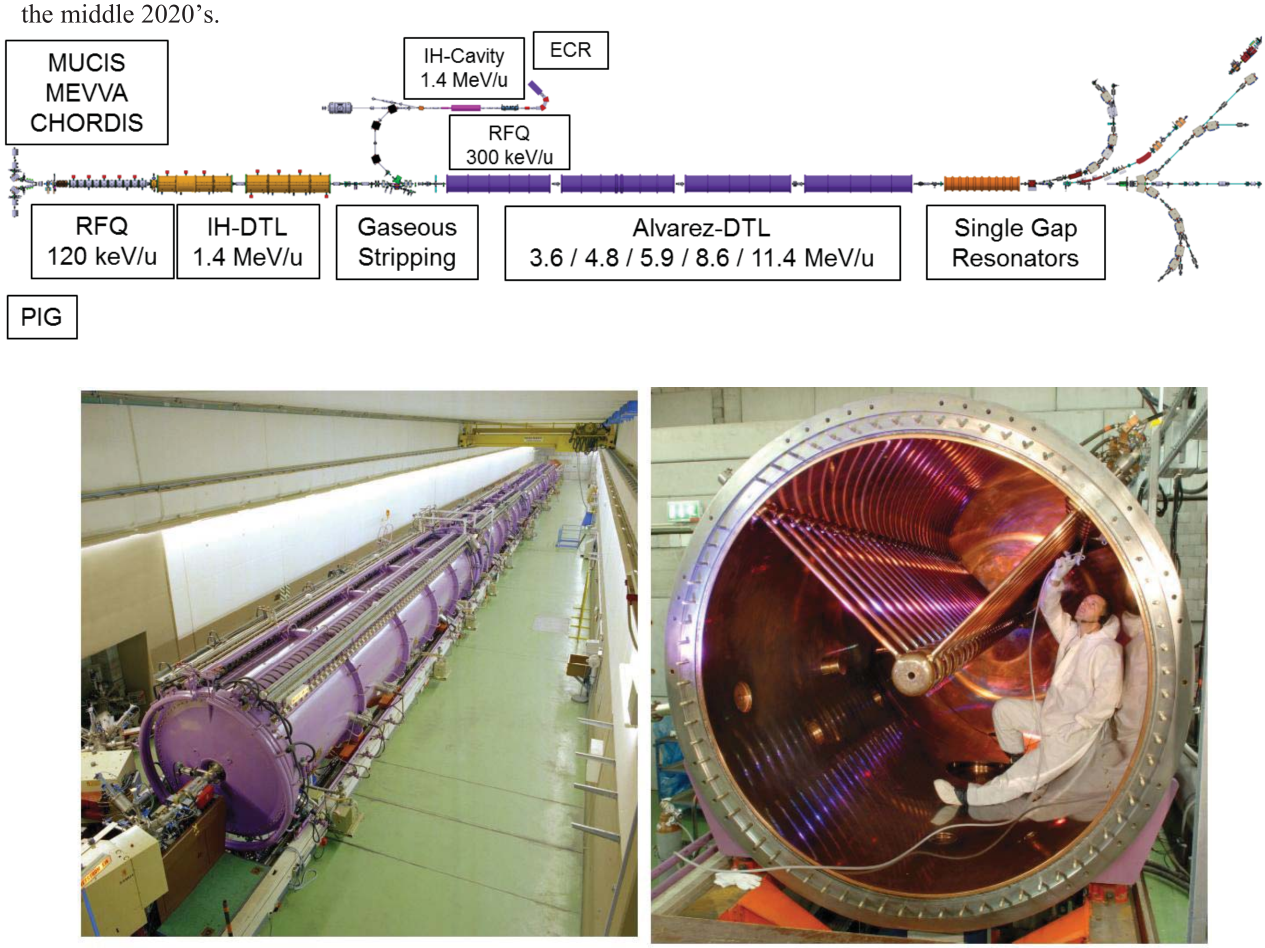

Figure 1: Top: Overview of the existing UNILAC. Left: View into the UNILAC tunnel along the 55 metres long post-stripper. Right: View into the Alvarez DTL cavity during maintenance.

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Operational Risk

As weak points of the existing Alvarez DTL the cooling concept of the drift tubes itself and its internal quadrupole magnets were recognised. Corrosion products clogged the filigree cooling channels in the past. The aged electric insulation of the internal quadrupoles' windings triggers short cuts increasingly. Next to the failures of the drift tubes a failure of the RF tanks themselves becomes probable. Taking the refurbishment of the existing Alvarez DTL into consideration the consequence is its substitution by its one-to-one copy. This makes no sense for economic reasons as well as for full-filling the FAIR beam intensity requirements.

FAIR Requirements

Regarding the UNILAC the space charge limit of the upgraded SIS18 defines its target parameters. The existing Alvarez DTL is not designed for high current heavy ion beam applications as required (16.5 emA, $^{238}U^{28+}$). Despite this it copes with intermediate mass ion beams of considerable space charge forces. For instance a $^{40}Ar^{10+}$ beam of 7.1 emA, which is equivalent to a $^{238}U^{28+}$ beam of 15 emA concerning its space charge characteristics, was provided successfully [1].

RF-LAYOUT

The RF layout of the new Alvarez follows the existing boundary conditions on the campus. The input energy is 1.4 MeV/u and the output energy is 11.4 MeV/u. The total installation length must fit into 55 meters. According to five cavities for the future RF supply five amplifiers each with 1.8 MW in total ($P_{cavity} + P_{beam} + P_{margin}$) are assumed.

Within the RF layout an algorithm was developed, which provides a homogeneous surface field distribution at the drift tube's front sides [2]. The peaks of the E-field at both radii of the existing Alvarez drift tubes, the radius at the beam pipe and the drift tube's outer radius, have been smoothened (Fig. 2).

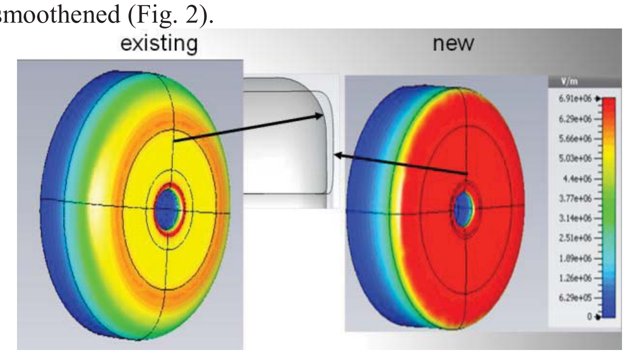

Figure 2: The new drift tube design realises a homogenous surface E-field on the drift tubes' front side.

There are two options to benefit from the new drift tube shape. Keeping the maximum surface field smaller than 1.0 Kilpatrick the shunt impedance as a measure of RF efficiency is increased by nearly 13% in comparison to the existing Alvarez DTL. This option is preferred. The other option is to lower the peak surface field by about 17% while keeping the shunt impedance of the existing design (Fig. 3). The need of reducing herewith the break down probability is not seen.

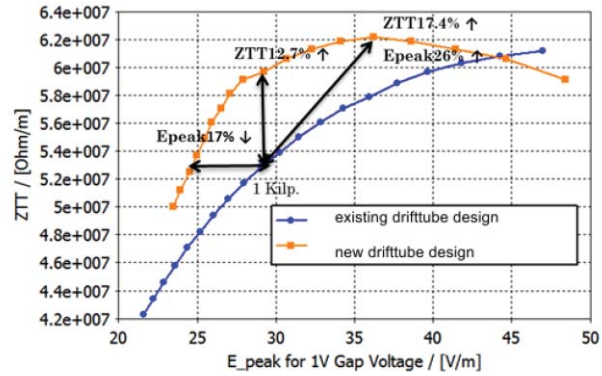

Figure 3: Shunt impedances for the original and the new drift tube design as functions of the peak field per gap voltage. The field is varied with the gap length while the voltage is normalised to 1 Volt. At surface fields about 1.0 Kilpatrick the RF-efficiency is increased by nearly 13%. The option to lower the peak surface field is marked as well.

BEAM DYNAMICS

To overcome the limitation of the existing Alvarez DTL in heavy ion beam intensity as well as quality the new Alvarez design follows the strategy of a strict focussing periodicity. The design of the existing inter-tank section breaks this strict periodicity, whereas the new design takes it into account (Fig. 4).

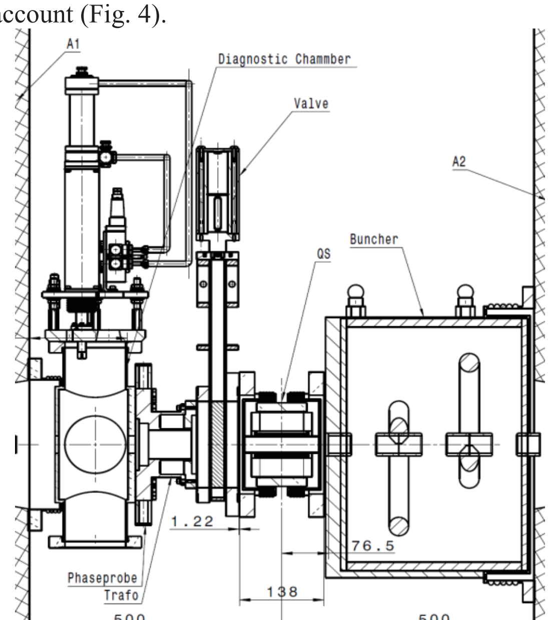

Figure 4: Cross section of the planned A1-A2 inter tank section. The quadrupole configuration (focusing periodicity) leaves tight installation length for beam diagnostics, a valve, and a re-buncher.

In addition, the new Alvarez DTL is designed to avoid the space charge driven emittance growth resonances (Fig. 5).

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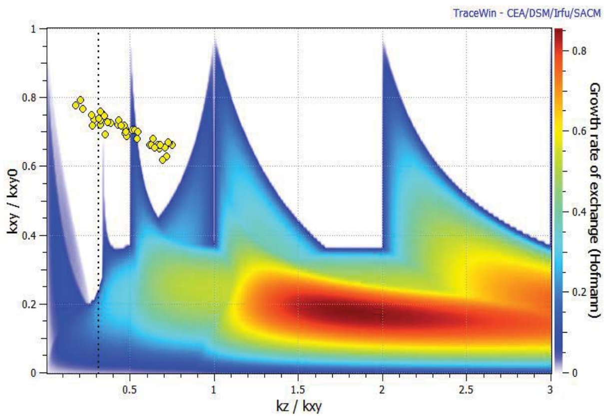

Figure 5: Hofmann's stability chart for the new DTL. The tune depression at the beginning of each tank is lower than 0.7, i.e. there is considerable space charge. The yellow dots mark the variation of the working point during acceleration along the Alvarez DTL.

The DTL's working point for the phase advances is shifted away from those resonances by setting the internal quadrupoles to higher gradients. The existing DC quadrupoles are limited to phase advances of up to 55°, while values between 65° and 70° are desirable. The synchronous rf-phases along the five cavities are -30°, -30°, -30°, -25°, and -25°.

The beam dynamic layout was done using the TraceWin code for $^{238}U^{28+}$ at currents of 16.5 emA, beam intensity requirement at the post-stripper DTL entrance. Input distributions are assumed as Gaussian truncated at 3σ. Input rms emittances were chosen as Ex=Ey=0.175 mm mrad (norm.) and Ez=70 deg keV/u. These parameters were deduced from various simulations and measurements [1, 3, 4, 5]. Corresponding transverse enevelopes assigned to the nominal FAIR case are shown in Fig. 6.

The beam dynamic design was benchmarked by means of six operational scenarios in total against three different DTL concepts successfully. Prioritised is the scenario as a FAIR high current injector. Further two scenarios taking into account that the UNILAC also serves established GSI experiments requiring lower currents and beam energies, i.e. it should provide energies in the range from 3.0 MeV/u up to 11.7 MeV/u. For low energy operation the RF-power of some tanks is switched off from the back end starting with A5, A4, A3, and A2 if requested. The gradients of the drift tubes quadrupoles are scaled down in such an operational mode with the corresponding beam rigidity. The benchmarking is completed by taking care about three further possible operational scenarios like twice larger or twice smaller input longitudinal emittances as well as a transverse flat input beam [6]. The results of beam dynamics simulations for the six different scenarios are presented in Tab. 1. For all scenarios 100% transmission and small emittance growth is reached.

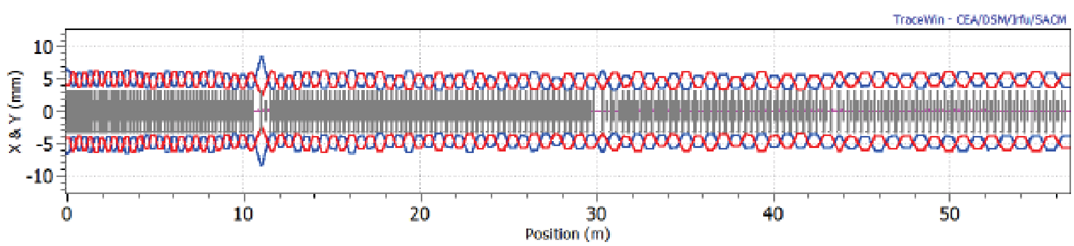

Figure 6: Transverse envelopes along the complete DTL for the nominal FAIR case (16.5 emA, $^{238}U^{28+}$) at an initial transverse zero current phase advance of 65°.

Table 1: Results of Beam Dynamic Simulations for the Six Operational Scenarios of the UNILAC

	FAIR	Zero current	Low energy	Larger long. emit.	Smaller long. emit.	Transvers. flat beam
Current, mA	16.5	**0**	**0**	16.5	16.5	16.5
Input ε_x (rms), mm mrad	0.175	0.175	0.175	0.175	0.175	**0.0875**
Input ε_y (rms), mm mrad	0.175	0.175	0.175	0.175	0.175	**0.35**
Input ε_z (rms), mm mrad	0.07	0.07	0.07	**0.14**	**0.035**	0.07
Output energy, MeV/u	11.4	11.4	**3.3**	11.4	11.4	11.4
Transmission, %	100	100	100	100	100	100
$\Delta\ \varepsilon_x$ (tot, 95%), %	7	0	0	7	8	16
$\Delta\ \varepsilon_y$ (tot, 95%), %	7	0	0	10	7	3
$\Delta\ \varepsilon_z$ (tot, 95%), %	10	0.7	1.7	5	11	4

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MATCHING FAIR REQUIREMENTS

The above introduced beam dynamic design was checked towards the beam requirements in front of the SIS18 by tracking the beam behind the DTL through the SIS18 transfer channel (TK) (Fig. 7). Pessimistic tolerances for alignment and machining of the accelerator components as well as for beam parameter fluctuations within the intervals were assumed (Table 2).

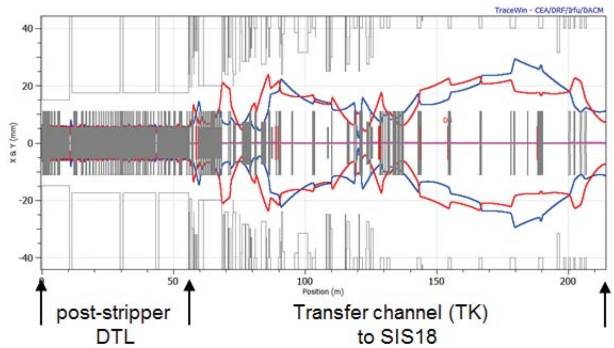

Figure 7: Transverse envelope along the post-stripper DTL and transfer channel to the SIS18 (TK).

Table 2: Tolerances for Error Studies

Quadrupole x,y displacement	± 0.15mm
Quadrupole x,y rotation	± 1°
Quadrupole z rotation	± 0.1°-0,4°
Gap voltage	± 1%
Gap phase	± 1°
Initial energy	± 0.5%
Input rms emittance (x,y,z)	± 15%
Input beam mismatches (x,y,z)	± 10%
Input Current	± 15%

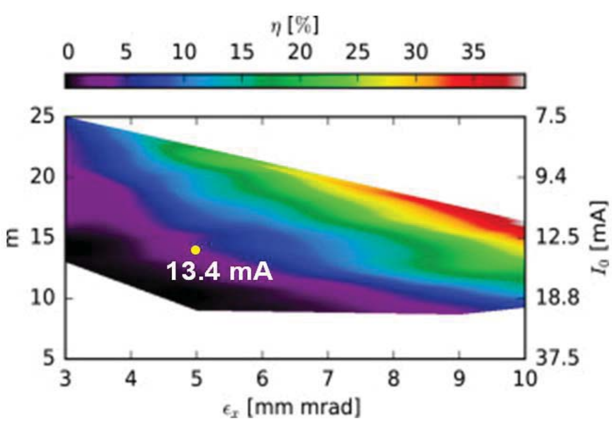

Figure 8: SIS18 multi-turn injection performance chart, where the dependency between multiplication factor, losses, and emittance as well as beam current is illustrated. Black and purple regions are preferable.

The results are classified with help of the SIS18 multi-turn performance chart, where the dependency between losses (η), multiplication factor (m), and emittance as well as beam current is illustrated [7]. Black and purple regions are preferable. Losses below 5% for the multi-turn injection into the SIS18 are accepted. The simulations result in beam currents of 13.4 mA within an emittance of 5 mm mrad in front of the SIS18, which is within the preferable region (Fig. 8).

FIRST OF SERIES (FOS)

The FoS (First of Series) is the realisation of the first cavity section of the Alvarez 2.0 DTL. Innovations in design and fabrication will be tested intensively with respect to their feasibility and reliability in future operation until 2021 (Table 3).

Table 3: FoS Milestones

Feb 2017	System decision: Alvarez type DTL
Jul/Aug 2017	FoS funded with 1.5 M€ until 2021
2018-2020	• R&D • Test stand assembly • Delivery • Process development (fabrication, handling, Cu-plating, etc.)
2021	Full performance tests

The FoS comprises the first tank section equipped with eleven drift tubes and two cooled endplates each with integrated half drift tubes (Fig. 9).

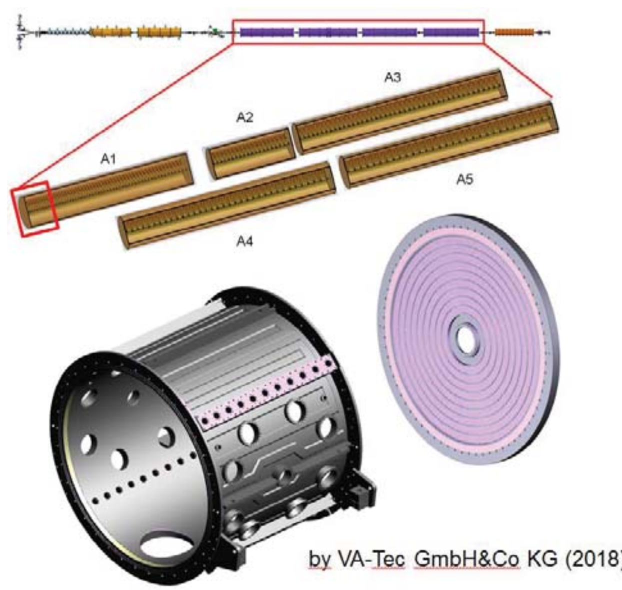

Figure 9: The FoS as the 1st section of cavity *A1*.

The aim of the FoS is testing at nominal operational parameters. The expected RF-properties of the new drift tube geometry shall be confirmed, the superposition of the accelerating fields with the pulsed quadrupole fields shall be investigated, and the performance of the cooling system at high power operation shall be checked for instance. Next to the technical innovations the FoS allows to optimise the processing of the next Alvarez DTL generation starting

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from ordering, fabrication, Cu-plating, and installation in the tunnel.

SCHEDULE

Table 4 gives the major milestones of the post-stripper DTL project under assumption of successful FoS tests in 2021. If pursued with priority and according scheduling of future beam times, the new DTL could be finished with commissioning at full performance at the end of 2025.

Table 4: Alvarez 2.0 Milestones

Q2/2021	Successful FoS project, TDR & funding available
Q2/2022	Delivery of components/cavities starts
Q2/2024	All components in-house
Q2/2024 + X	De-installation of existing post-stripper DTL
Q4/2024 + X	Cavity-wise installation and commissioning
Q4/2025 + X	DTL commissioning w/o and with beam

The focus on the substitution is to minimise the UNILAC downtime. The existing post-stripper shall not be de-installed as there are any uncertainties with the new DTL. Since from first principles there is no urgency to install the components as soon as they are ready for doing so, a planned delay X can be allowed for until de-/ installation starts. At that time an appropriate slot for the replacement shall be defined in view of the overall advance of the FAIR project.

STATUS

Dummy Cavity

A dummy cavity, which has been delivered in September 2018, serves two purposes (Fig.10). i) Finding the balance between effort for fabrication and acceptable tolerances. ii) Cu-plating w.r.t. handling, alternative Cu-plating process, sufficient surface quality ex factory.

Figure 10: Dummy cavity (L=2.5m, D_{out}=2.4m) at the factory acceptance test (FAT).

Drift Tube Prototyping and Quadrupole Design

The new rf-design leads to a new drift tube geometry, which leaves in comparison to the 1970's design less installation space for the internal quadrupole. Simultaneously, the conditions are tightened by the requirements of higher quadrupole gradients (Tab.5).

Table 5: Quadrupole Parameters

Gradient	51 T/m
Effective length	99.5 mm
Integral field	5.07 T
Current	1109.6 A
Yoke material	VACOFLUX50
Conductor	5.5mm x 1 mm
No. of windings	5

A 1st drift tube prototype with a dummy quadrupole has been fabricated for checking its feasibility w.r.t. single part production, welding, fitting the quadrupole into the drift tube, etc. (Fig.11).

Figure 11: Drift tube prototyping.

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