UPGRADE OF THE UNILAC FOR FAIR

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Abstract

The UNIversal Linear Accelerator (UNILAC) at GSI serves as injector for all ion species from protons to uranium since four decades. Its 108 MHz Alvarez type DTL providing acceleration from 1.4 MeV/u to 11.4 MeV/u has suffered from material fatigue. The DTL will be replaced by a completely new section with almost same design parameters, i.e. pulsed current of up to 15 mA of $^{238}U^{28+}$ at 11.4 MeV/u. A dedicated source terminal & LEBT for operation with $^{238}U^{4+}$ is currently constructed. The uranium source needs to be upgraded in order to provide increased beam brilliances and for operation at 2.7 Hz.

INTRODUCTION

GSI is currently constructing the Facility for Ion and Antiproton Research (FAIR) [1]. It aims at provision of 3×10^{11}/s uranium ions at 1.5 GeV/u. Due to its high rigidity uranium imposes the highest challenges to the accelerator chain wrt fields and machine protection. Additionally, a total of 4×10^{12}/s cooled anti-protons are to be delivered. The complete accelerator chain is depicted in Fig. 1. The existing UNIversal Linear ACcelerator UNILAC will provide all primary ions but protons. A dedicated proton linac is currently under design and construction [2]. In order to deal with the FAIR requirements in the upcoming decades the UNILAC needs a considerable upgrade.

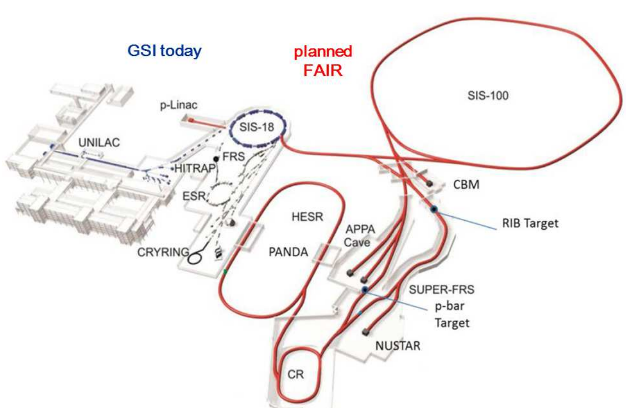

Figure 1: Facility for Anti proton and Ion Research (FAIR) under construction at GSI.

The existing UNILAC (Fig. 2) together with the subsequent synchrotron SIS18 serves as injector for FAIR. The

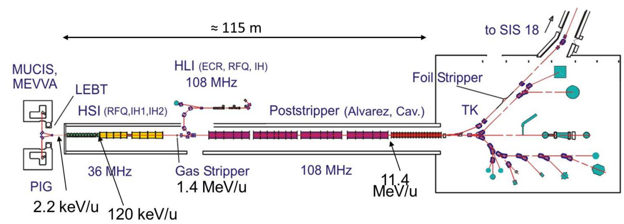

Figure 2: The UNIversal Linear ACcelerator (UNILAC) at GSI.

UNILAC has three ion source terminals that can be operated in pulse-to-pulse switching mode at 50 Hz. One terminal is equipped with an ECR source providing highly charged ions. Another terminal houses a Penning source providing low intensity beams at intermediate charge states. The third terminal is dedicated to provision of intense beams of low-charged ions. It can be equipped with various source types as MUCIS and CHORDIS for light to intermediate-mass ions for instance. Intense heavy ion beams are produced in a MEVVA or VARIS source at 2.2 keV/u. Beams are bunched and pre-accelerated to 120 keV/u along a 9 m long RFQ operated at 36 MHz. Afterwards two IH-cavities provide for acceleration to 1.4 MeV/u. For uranium the highest particle numbers are obtained by using the charge state $^{238}U^{4+}$. After the IH-DTL the acceleration efficiency is increased by passing the beam through a gaseous stripper which delivers a mean charge state of $^{238}U^{28+}$ at its exit. This increase of charge state is at the expense of intrinsic particle loss as prior to 2014 about 87% of the uranium ions are stripped to a charge state different from 28+. After dispersive selection of the desired charge state the beam is matched to the subsequent post stripper Alvarez DTL. The latter is operated at 108 MHz and comprises five tanks. Its exit beam energy is 11.4 MeV/u being the injection energy for the synchrotron SIS18. The UNILAC design parameters are listed in Table 1. The age of the UNILAC together with the requirement to provide reliable and intense beams for the upcoming FAIR era calls for a revision of the UNILAC. In the following the planned upgrade activities are described.

SOURCE, LEBT, MEBT, AND RFQ

In order to provide the mean uranium intensity required for FAIR the source has to be operated with a repetition rate of 2.7 Hz. Although this target has been reached for lead

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Table 1: Beam Design Parameters for the Upgraded UNILAC

Ion A/q	≤ 8.5	
Beam Current	1.76·A/q	mA
Input Beam Energy	1.4	MeV/u
Beam Energy	11.4	MeV/u
Emit. (norm., tot.) hor/ver	0.8/2.5	µm
Beam Pulse Length	200	µs
Beam Repetition Rate	10	Hz
Rf Frequency	108.408	MHz

ions, reliable operation with uranium is currently limited to about 1.5 Hz. New uranium alloys shall be investigated as well as the reduction of the source beam pulse length in order to reduce the gas load in the plasma chamber. The latter mitigates the production of $^{238}U^{4+}$ ions by recombination. The existing LEBT includes two bends which impose dispersion and hexapolar fringe fields. Additionally, operation and handling of uranium comes along with restrictions from safety requirements. For these reasons a new and dedicated uranium branch is under design as shown in Fig. 3. It is a

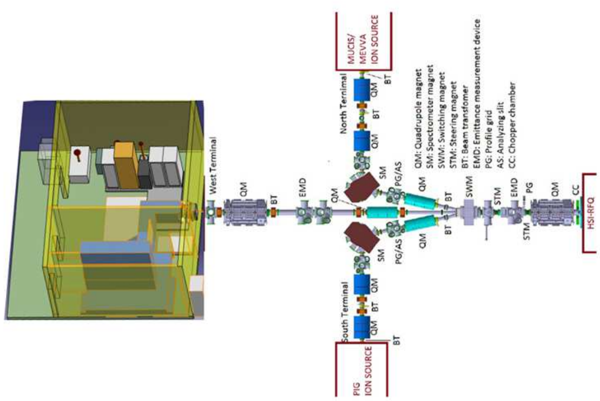

Figure 3: The existing north and south ion source terminals and LEBT branches together with the new uranium terminal (west).

straight LEBT comprising two quadruplets and one triplet. The source will deliver several charge states of uranium but only $^{238}U^{4+}$ is accepted by the RFQ. The fractions of other charge states (mainly 3+) are reduced by chromaticity together with an circular iris located at a beam waist of the charge state 4+. Reference [3] is on the detailed design of the new LEBT.

The RFQ suffered from sparking during operation with varying rf-duty cycles and rf-amplitudes. The attainable rf-voltages are about 10% below the required values for uranium. This leads to serious degradation of longitudinal beam quality from insufficient bunching. Additionally, the beam divergence at the RFQ exit is too large, triggering losses inside the subsequent super lens, which in consequence also has to be operated at lower voltages causing further degradation of beam quality. The design of the RFQ will be revised such that lower surface fields are applied at the expense of reduced acceptance.

The super lens is a non-accelerating RFQ, i.e. being used for focusing in all three planes. Accordingly, transverse and longitudinal focusing strengths are coupled. In total the present MEBT offers just four knobs to tune its matching performance to the IH-DTL: two quadrupole gradients, one rf-amplitude, and one rf-phase. This limitation together with too low rf-amplitudes (from sparking) causes poor longitudinal matching to the subsequent IH-DTL. A new MEBT design foresees two symmetric triplets and one buncher, i.e. four additional tuning knobs [4].

HIGH PRESSURE H_2-STRIPPER

For time being as stripping medium a continuous jet of nitrogen has been used at a back pressure of 4 bar. The achieved stripping efficiency from $^{238}U^{4+}$ to $^{238}U^{28+}$ was 13%. Last year a pulsed gas stripper cell has been tested. It injects short gas pulses (0.5 ms) at back-pressures of up to 120 bar into the stripping chamber. Measured charge state distributions behind the stripper for some stripper configurations are compared in Fig. 4. A relative increase of $^{238}U^{28+}$ intensity of 60% has been measured [5] using H_2. Future tests aim at increasing the back pressure to about 300 bar and at routine operation of this new stripping setup. References [5–7] are on the successful campaign of increasing the stripping efficiency.

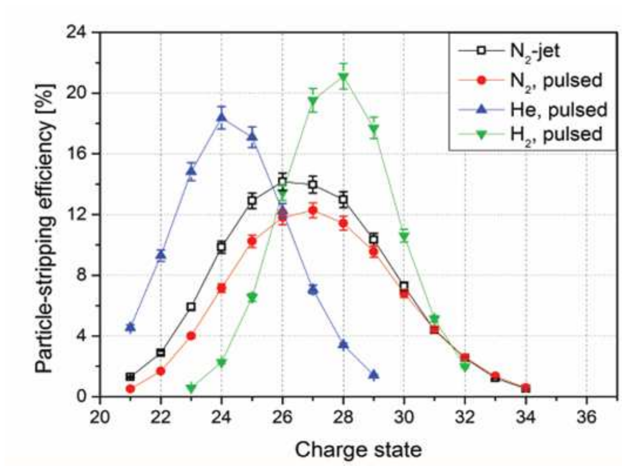

Figure 4: Uranium charge state distributions for an incoming beam of $^{238}U^{4+}$ at 1.4 MeV/u for different gas stripper configurations [7].

ROUND TO FLAT BEAM TRANSFORMATION

As seen from Table 1 the final transverse design emittances of the UNILAC differ by a factor of three. This requirement is imposed by the horizontal multi-turn injection (MTI) scheme to fill the synchrotron SIS18 [8]. Beams provided by linacs are generally round, i.e. the horizontal

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and the vertical emittance are equal. Although the product of the two linac emittances is smaller than the product of the two corresponding effective synchrotron acceptances, the horizontal linac emittance exceeds the effective horizontal acceptance. Thus a scheme for convenient emittance re-partitioning has been proposed and experimentally demonstrated at GSI with a nitrogen beam [9–11]. The round-to-flat adopter is shown in Fig. 5 together with measured final phase space distributions at its exit. Charge state stripping inside a solenoid is required together with a skew triplet to arbitrarily partition the transverse emittances by varying the solenoid field strength only. A corresponding increase in MTI efficiency was measured [12].

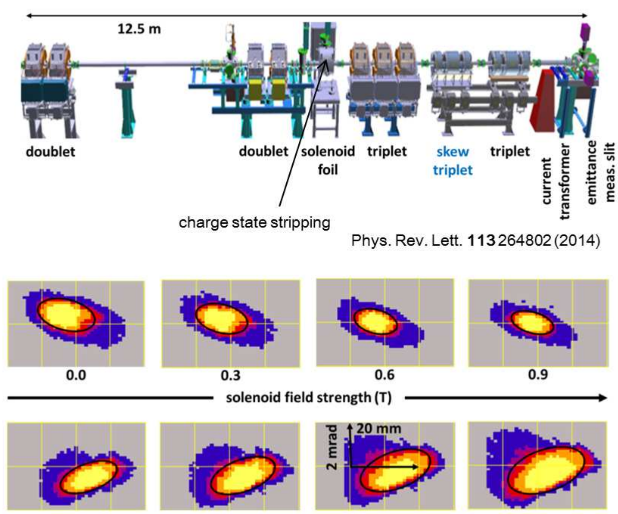

Figure 5: The EmTEx beam line providing round-to-flat transformation.

GSI currently designs a set-up to flatten beams of uranium along the gaseous stripper section. To this end 4d transverse beam diagnostics is required, i.e. the four 2^{nd} order inter-plane correlations <xy>, <xy'>, <x'y>, and <x'y'>, must be measurable. To our knowledge such measurements never were conducted successfully before at ion energies beyond about 150 keV/u. Using the EmTEx set-up these correlations were measured for $^{238}U^{28+}$ ions at 11.4 MeV/u with a beam current of 1.7 mA. Regular slit/grid measurements were done in combination with skewed quadrupoles. Figure 6 compares horizontal and vertical emittance measurements behind the skew triplet together with calculations ignoring/including inter-plane correlations. As the measurements could be reproduced, the inter-plane correlations were determined to sufficient accuracy. A round-to-flat transformer will be installed along the gaseous stripper section if it is foreseeable that the other upgrade measures will not be sufficient to reach the UNILAC design beam parameters with uranium.

NEW POST STRIPPER ALVAREZ DTL

The existing post stripper DTL suffered considerably from material fatigue during that last four decades. Thus the amount of resources required for its maintenance increases

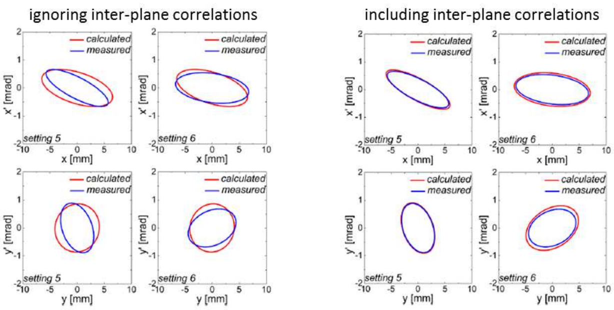

Figure 6: Projected rms ellipses from measurements (blue) and from calculations (red) ignoring inter-plane correlations (left) and including inter-plane correlations (right).

continuously. The section has to be replaced by a completely new DTL. The beam parameters of the new post stripper DTL are the same as for the existing one except the beam duty cycle. It will be limited to beam pulse lengths of 200 μs at a repetition rate of 10 Hz. The new UNILAC will serve just as an injector for the FAIR facility. Accordingly, the mixed operation between different rf-amplitudes and rf-pulse length, that caused damages at the cavity surface and limited the rf-amplitudes, will not be applied in the future. As beam quality is of utmost relevance for a low duty cycle injector, GSI aims at an Alvarez-type DTL. They proved to be reliable working horse accelerators. The related beam dynamics is fully understood even if considerable space charge is included. Periodic beam 3d-envelope solutions are properly defined as well as the procedure to match the incoming beam to these solutions. For IH-DTLs for time being we did not find a procedure to assure matched beam transport and acceleration that provides maximum mitigation of beam emittance growth from space charge [13].

Rf-Power Supply Chain

The existing rf-power systems are based on all-in-one technology of the 1970ies and are currently modernized to modular set-ups. Control and interlock units will be separated from the power units. A new 1.8 MW cavity amplifier prototype is under development. It is based on the widely-used THALES tetrode TH 558SC, thus promising availability for at least 25 years. The first new amplifier is tendered and will be installed and tested in the existing rf-gallery until 2017. New 150 kW solid state driver amplifiers will replace existing tube drivers. A digital LLRF system designed by industry was integrated into an existing amplifier driving a single gap resonator and was tested including ion beam tests. An overview of the RF system design and of the upgrades including results of digital LLRF tests is given in [14].

Drift Tube Geometry

The new DTL will comprise five tanks and the layout of the new cavities is progressing. It aims at optimization of the ratio of shunt-impedance to electric surface field [15]. The latter shall be limited to 1.0 Kilpatrick. For each tank a maximum rf-power of 1.8 MW is available of which about

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0.25 MW is beam load. Currently the beta-profiles for acceleration to 5.39 MeV/u are available. A new shape of drift tube plates (Fig. 7) has been found that allows saving 17% of rf-power with an increase of surface field strength by 8% wrt the existing design. The shape of the tube plate does

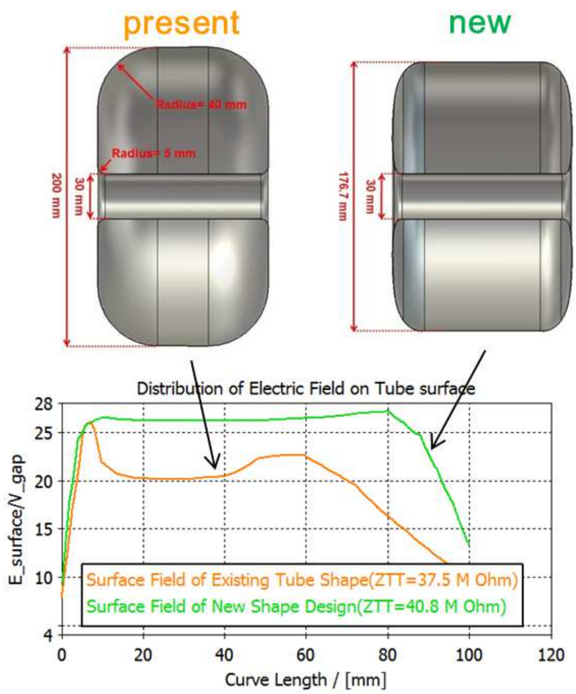

Figure 7: Comparison of the present and new drift tube design.

not include straight sections and is defined through about 200 fixed points. This approach provides a smooth surface field distribution and should lower the sparking rate. It does not cause significant additional cost for production nor it imposes restrictions wrt the achievable tolerances. Each drift tube along one tank will have the same end plate shape. The rf-frequency tuning of each cell is done through adoption of the drift tube length.

Stabilization of the accelerating field is done through well-considered orientations of the stems that keep the drift tubes [15]. As the drift tubes have to be provided with cooling water and electrical current for the quadrupoles, each tube is kept by two stems. It turned out that the orientation of the two stems plays a significant role in the suppression of parasitic modes as shown in Fig. 8. This innovative concept of field stabilization will be tested using a cold rf-model. Figure 9 illustrates how this model allows for variation of the stem orientation. Additionally, the end surfaces of each drift tube can be exchanged by simply unskrewing them from the main drift tube body.

Transverse Focusing

The transverse phase advance (zero current) has to be increased from 53° to 67° in order to avoid emittance growth

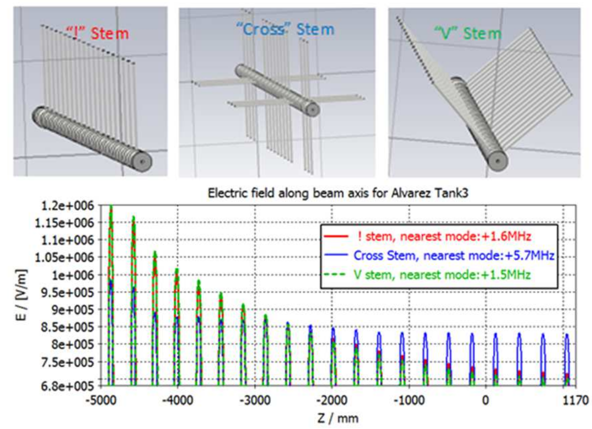

Figure 8: Several schemes of orientations of the DTL stems and their effect on the field stabilization.

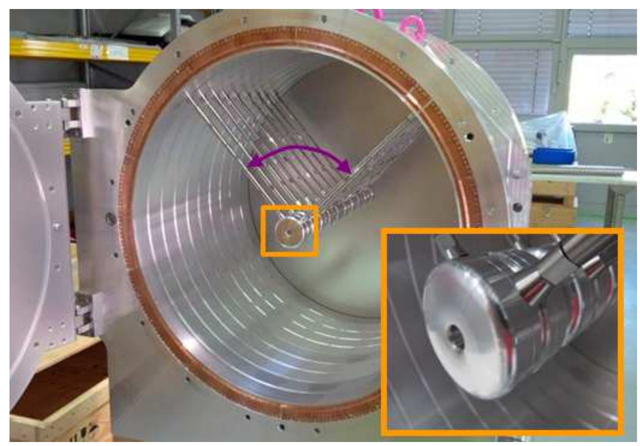

Figure 9: 1:3 scaled cold model of the first new Alvarez cavity.

from space charge driven resonances. Additionally, the emittance partition of flattened beams shall be preserved along the DTL by asymmetric focusing, i.e. the vertically focusing quadrupoles will be driven with stronger gradients wrt horizontally focusing quadrupoles [16]. Figure 10 shows how asymmetric transverse focusing avoids the corresponding transverse resonances driven by flat beams. Special care will be taken for proper beam envelope matching along inter-tank sections. These sections impose interruptions of the periodicity of the DTL lattice. If not being well-designed they will trigger emittance growth from mismatch in all three planes.

ALTERNATIVE DTL DESIGN BASED ON IH-CAVITIES

Compared to Alvarez cavities H-mode resonators feature much higher shunt impedances. Additionally, they require much less transverse focusing quadrupoles. They have the potential to impose an alternative to Alvarez-type DTLs at reduced cost and even allow for an eventual future energy upgrade to about 50 MeV/u using the existing linac tunnel. The Goethe University at Frankfurt designs a post-stripper

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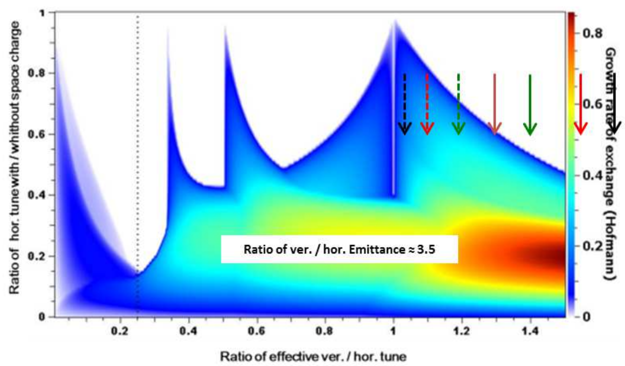

Figure 10: Stability chart and working points for the ver/hor emittance ratio of 3.5 at the entrance to the existing Alvarez type DTL of the GSI UNILAC assuming different focusing strengths in the transverse planes.

DTL for the UNILAC upgrade based on six IH-cavities as shown in Fig. 11. Currently extensive studies on the beam

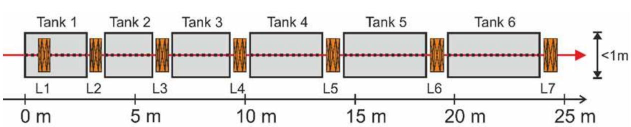

Figure 11: Conceptual layout of a DTL based on six IH cavities.

dynamics layout are performed. Figure 12 plots simulated emittance growth rates along the IH-DTL as functions of the depressed transverse phase advance. The study aims at providing straight forward procedures (comparable to Alvarez-DTLs) for setting phase advances, periodic envelopes, and properly matched settings.

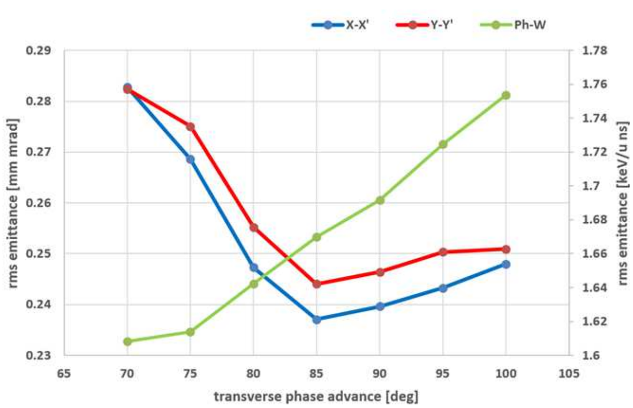

Figure 12: Simulated rms emittances at the exit of the IH-DTL as functions of the depressed transverse phase advance for a current of 17 mA of $^{238}U^{28+}$.

ESTIMATED PERFORMANCE AFTER UPGRADE

Table 2 summarizes the presented upgrade activities together with the corresponding estimated gains in beam current and emittance. The estimate assumes an Alvarez-type post-stripper DTL. Recent modifications of the source extraction system may indicate that currents in excess of 20 mA can be extracted under preservation of the emittances. But further investigations are required prior to commit to this value.

Table 2: Estimate of Expected $^{238}U^{28+}$ Performance After the Upgrade

section	I [mA]	ϵ_x [μm]	activity
	18.0	0.55	source development
LEBT + RFQ			new LEBT, RFQ upgrade
	16.2	0.63	
MEBT + IH-DTL			new MEBT
	14.6	1.1	
stripper			high press. H_2- jet
	18.4	1.2	
round-to-flat			installation
	16.5	0.49	
Alv. DTL			new DTL
	14.1	**0.73**	
target	*15.0*	*0.80*	

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