FROM EUROTRANS TO MAX: NEW STRATEGIES AND APPROACHES FOR THE INJECTOR DEVELOPMENT*

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Abstract

As the successor of the EUROTRANS project, the MAX project is aiming to continue the R&D effects for a European Accelerator-Driven System and to bring the conceptual design to reality. The layout of the driver linac for MAX will follow the reference design made for the XT-ADS phase of the EUROTRANS project. For the injector part, new design strategies and approaches, e.g. half resonant frequency, half transition-energy between the RFQ and the CH-DTL, and using the 4-rod RFQ structure instead of the originally proposed 4-vane RFQ, have been conceived and studied to reach a more reliable CW operation at reduced costs. In this paper, the design and simulation results of the MAX injector are presented.

INTRODUCTION

Launched by the European Commission in 2005 and ended in 2010, EUROTRANS [1] is a EUROpean research programme for the TRANSmutation of high level nuclear waste in an accelerator driven system. As a successor, MAX [2], the so-called MYRRHA Accelerator eXperiment research and development programme, has been just started in February, 2011. Different than EUROTRANS which was a pure research project, MAX is pursuing to not only continue the R&D studies but also deliver an updated consolidated design for the real construction and demonstration in Mol, Belgium. Fig. 1 shows the schematic plots of the driver linacs for EUROTRANS and MAX. It can be seen that the required MAX accelerator is very similar to that for the XT-ADS phase of EUROTRANS, except the linac front end.

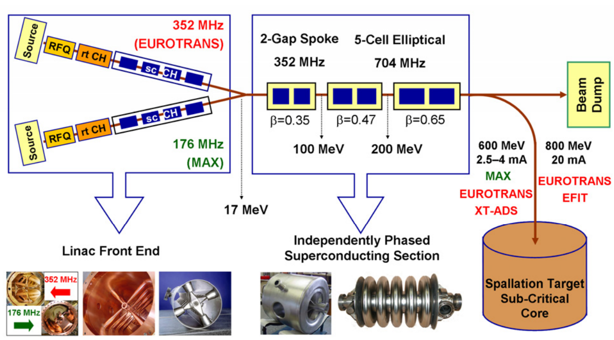

Figure 1: The driver linacs for EUROTRANS and MAX.

During the EUROTRANS project, a 352MHz, 17MeV, and upgradeable 5-30mA injector, which mainly consists of one RFQ accelerator, two RT (room-temperature) CH (Cross-bar H-mode)-DTL (Drift-Tube Linac) cavities and four SC (superconducting) CH-DTL cavities, was designed by IAP, Frankfurt University and successfully accepted as the reference design by the project [3]. Fig. 2 compares the EUROTRANS injector with the MAX one newly proposed also by IAP. It's clear that MAX has inherited the basic layout design of the injector from EUROTRANS. Meanwhile, some significant changes based on new strategies and approaches have been made. The main differences are: 1) the resonant frequency was lowered by a factor of 2 i.e. from 352MHz to 176MHz; 2) the higher design beam intensity, 30mA, is not necessary any more; 3) the 4-vane RFQ structure is now replaced by the 4-rod one; 4) the input and output energies of the RFQ were reduced from 0.05MeV and 3MeV to 0.03MeV and 1.5MeV, respectively; 5) one rebuncher cavity and two solenoids have been removed.

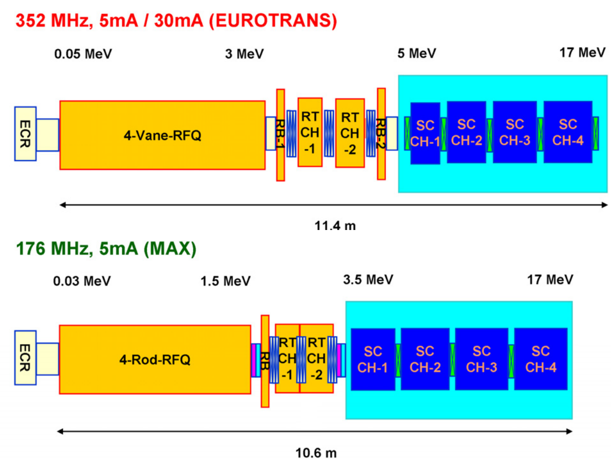

Figure 2: The 17MeV injectors proposed by Frankfurt University for EUROTRANS and MAX, respectively.

MAX RFQ DESIGN

The most important purpose for lowering the resonant frequency from 352MHz to 176MHz is to use the 4-rod RFQ instead of the originally proposed 4-vane RFQ. Fig. 3 compares these two kinds of mainstream RFQ resonant structures. The 4-vane structure works in the TE-mode and its RF properties are determined by not only the vanes but also the cavity wall, while the 4-rod one is actually a chain of $\lambda/4$ resonators so that the inner structure is almost independent to the cavity wall. The pros and cons of the 4-vane RFQ are that it has relatively even RF power density and could be easily cooled, but it will have a large radial size at frequencies ≤200MHz and the construction and tuning are relatively complicated and expensive due to fairly tight tolerances. In case of the 4-rod RFQ, it could always have a compact radial size and an easy construction, tuning, and even repair, but its local RF power density is typically ~2 times higher, so to work

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at ≥200MHz for a CW operation will be usually challenging. For reducing the difficulties and costs in realizing the MAX RFQ as well as ensuring a safe CW operation, to use a half frequency is proposed. Besides, as R', the shunt impedance of an RFQ, is roughly proportional to $f^{-1.5}$ [4], another major advantage is that the RF power consumption could be considably reduced.

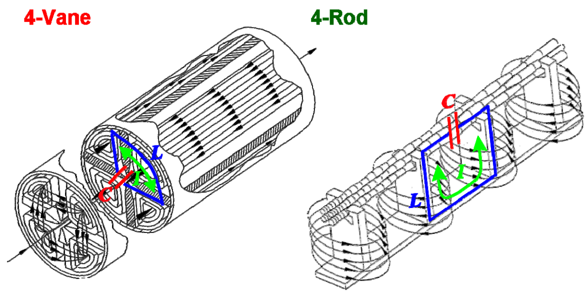

Figure 3: Mainstream RFQ resonant structures.

As the MAX user in Mol just needs a beam intensity up to 4 mA, only 5mA will be taken as the design intensity. Consequently, the inter-vane voltage could have a drop from 65kV to 40kV in order to further reduce the RF power density. To compensate the structure length growth caused by the frequency and inter-vane voltage reduction, the input and output energies were cut by 40% and 50%, respectively, for the MAX RFQ. This resulted in a 4m long machine, so similar to the SARAF RFQ [5], another 176MHz CW 4-rod RFQ, only one tank will be needed.

Table 1: RFQ parameters for EUROTRANS & MAX

Parameter	EUROTRANS@5mA	MAX
f [MHz]	352	176
W_{in} / W_{out} [MeV]	0.05 / 3	0.03 / 1.5
U [kV]	65	40
$E_{s,\,max}$ / E_k	1.7	1
g_{min} [mm]	2.6	3.6
$\varepsilon_{in}^{t.,\,n.,\,rms}$ [π mm-mrad]	0.2	0.2
$\varepsilon_{out}^{t.,\,n.,\,rms}$ [π mm-mrad]	0.21 / 0.20	0.22 / 0.22
$\varepsilon_{out}^{l.,\,rms}$ [π keV-deg]	109	64.6
L [m]	4.3	4.0
T [%]	~100	~100

The design and simulation results of the MAX RFQ designed also using the NFSP method [6] are presented in Table 1 and Fig. 4, respectively. For comparison, the corresponding parameters from the 5mA design of the EUROTRANS RFQ are also listed in Table 1. Obviously, the transmission and transverse output emittances are still very similar to the old values, while the longitudinal output emittance is decreased greatly. In addition, the Kilpatric factor is now only 1, well below 1.8, a safe value proven by the LEDA RFQ for CW operation. And the minimum gap between electrodes is enlarged by 1mm, which is favorable to lead to a more reliable CW operation.

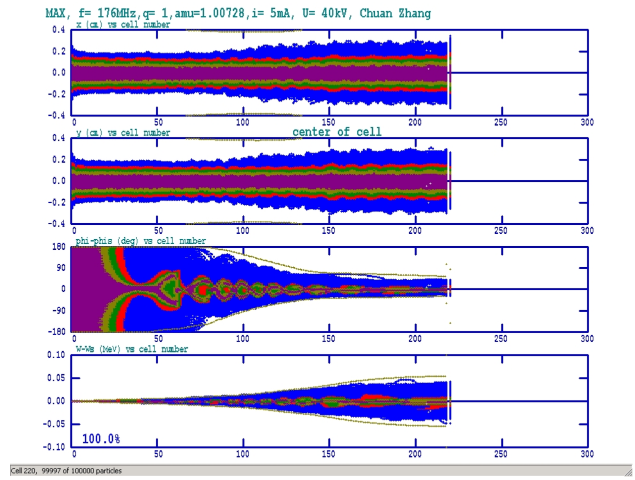

Figure 4: Beam transport plot of the MAX RFQ.

The error studies have been carried out for the MAX RFQ with respect to 7 input parameters: the intensity, emittance, inter-vane voltage, Twiss parameters, energy spread, and spatial displacement, respectively. Table 2 shows the lowest transmission is 97.5% in all tested cases.

Table 2: Error study results of the MAX RFQ

Parameter	Start value	End value	Design value	Step length	T_{min} [%]
I_{in} [mA]	0.5	9.5	5	1.5	99.9
$\varepsilon_{in}^{t.,\,un.}$ [π cm-rad]	0.006	0.024	0.015	0.003	99.6
U [%]	97	103	100	1	99.8
Twiss α	0.28	1.48	0.88	0.2	97.9
Twiss β [cm/rad]	2.48	5.48	3.98	0.5	97.5
ΔW [%]	2	12	0.0	2	~100
δx [mm]	0.1	0.6	0.0	0.1	99.5

MAX CH-DTL DESIGN

For the CH-DTL, the input energy is now lowered from 3MeV to 1.5MeV. Though it brings some difficulties to the beam dynamics design, it is favorable from the cavity design point of view: 1) the effective shunt impedance Z_{eff} ($\sim\beta^{-1}$) is increased by ~30%, which saves RF power as well as makes the cooling easier; 2) it could compensate the cell length growth caused by the lowered frequency. Actually, the new frequency is also helpful for the CH-cavity design. For example, the first cell of the first RT-CH was lengthened from 3.4cm to 4.8cm, which provides more space for the field flatness tuning.

Same as the EUROTRANS case, the two RT-CHs will cover also a energy gain of 2MeV, but both at 34% lower accelerating gradients E_a for further reducing RF power density. The three triplets are now inserted into the cavities, which will not only lead to a better field flatness but also save the drift space. In total, this part will be still maintained compact. The four SC-CHs have been decided to keep working at E_a≈4MV/m. They will take over some additional energy gain which was cut in the RFQ, so the total length of them will be somewhat longer, however, only a 5mA beam will be fed into the MAX injector, so some focusing elements in the previous design e.g. the 2nd rebuncher cavity and two solenoids could be removed. Totally, the whole CH-DTL part is even 0.5m shorter. Moreover, the new SC-CHs have much less gaps, so the construction work e.g. welding will be easier and cheaper.

A summary of the CH-DTL parameters for MAX (also compared with EUROTRANS) and the maximum transverse beam size along the accelerating channel are given in Table 3 and Fig. 5, respectively.

Table 3: CH-DTL parameters for EUROTRANS & MAX

	EUROTRANS				MAX			
	V_{eff} [MV]	L_{cell} [m]	β_{avg}	E_a [MV/m]	V_{eff} [MV]	L_{cell} [m]	β_{avg}	E_a [MV/m]
RB1	0.19	0.07	0.08	2.79	0.12	0.10	0.06	1.25
RT1	1.16	0.40	0.09	2.91	1.03	0.54	0.06	1.91
RT2	1.30	0.50	0.10	2.59	1.14	0.66	0.08	1.72
RB2	0.47	0.09	0.10	5.23	–	–	–	–
SC1	2.54	0.63	0.11	4.00	3.50	0.87	0.10	4.02
SC2	3.22	0.81	0.14	3.99	3.98	1.01	0.13	3.94
SC3	3.74	0.94	0.16	3.99	4.18	1.07	0.16	3.89
SC4	3.76	1.05	0.18	3.57	4.09	1.07	0.18	3.82

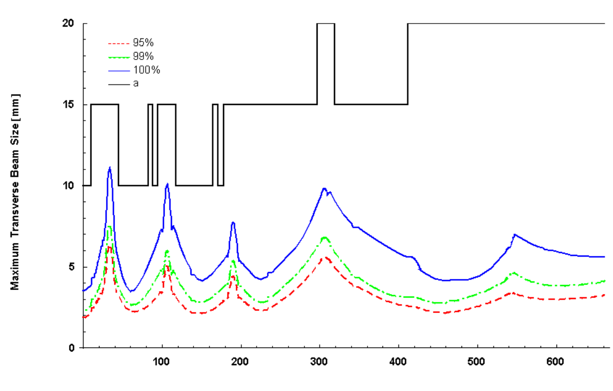

Figure 5: Max. trans. beam size along the MAX CH-DTL.

Table 4: Error settings for the MAX CH-DTL

Type	Setting1	Setting2
QMIS [mm]	$\Delta X, \Delta Y$=±0.1	$\Delta X, \Delta Y$=±0.2
QROT [mrad]	$\Delta\varphi_{x,y}$=±1.5, φ_z=±2.5	$\Delta\varphi_{x,y}$=±3, φ_z=±5
VERR [%]	ΔU_{gap}=±5, ΔU_{tank}=±1	ΔU_{gap}=±5, ΔU_{tank}=±1
PERR [°]	$\Delta\Phi_{tank}$=±1	$\Delta\Phi_{tank}$=±1

Also, studies using the same settings of lens and cavity errors applied to the EUROTRANS CH-DTL [3] have been performed. For both settings, no beam loss has been observed. With typical error values i.e. Setting 1, the maximum additional rms emittance growths for the x, y and z planes are 8%, 12% and 15%, respectively.

CONCLUSIONS

An overview of the RF power consumption of the main RT cavities for the EUROTRANS and MAX injectors is given in Fig. 6, where the value for the 4-vane RFQ was given by Microwave Studio (MWS) with a safety margin of 20%, that for the 4-rod RFQ was estimated using the measured shunt-impedance of the SARAF RFQ, 67kΩm [7], and those for the RT-CHs were obtained from MWS with a safety margin of 15%. Clearly, the total power consumption for the warm part is considerably reduced, and more important that all power densities for the MAX injector are well below 30kW/m, much lower than 50kW/m, a safe value proven by the SARAF RFQ [7].

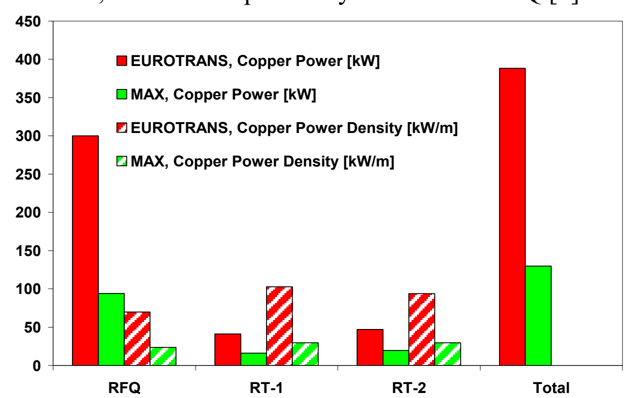

Figure 6: RF power consumption of the main RT cavities.

The MAX injector design studies show that the new design strategies and approaches, e.g. half resonant frequency, half RFQ-DTL transition energy, and the use of 4-rod RFQ, will lead to a not only cost-saving but also more reliable injector for CW operation while keeping the beam dynamics performance satisfying.

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