Upgrade of the UNILAC for FAIR

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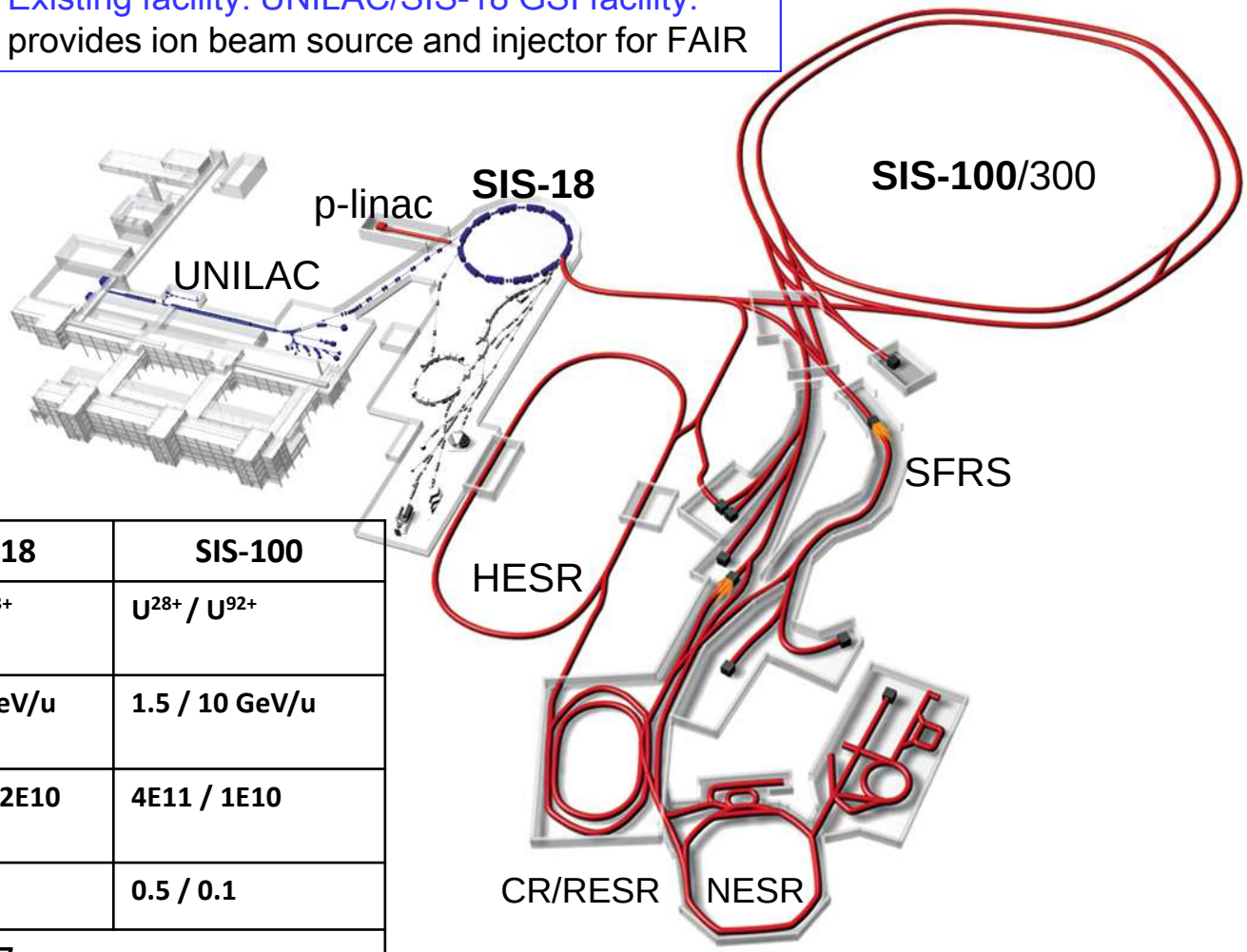
- Overview of FAIR and Injector Requirements
- UNILAC and its Status
- Upgrade Measures:
  - Source & LEBT
  - RFQ
  - MEBT & IH DTL
  - Stripper Section
  - Alvarez DTL

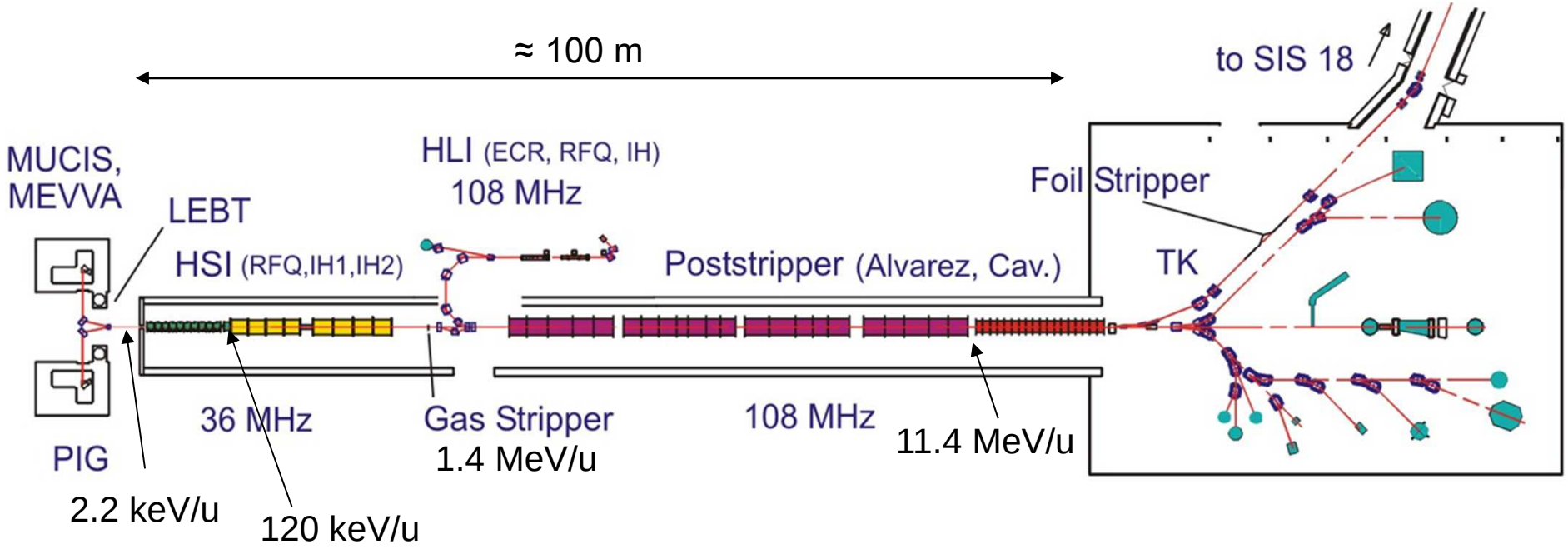
FAIR Primary Beam Chain

Existing facility: UNILAC/SIS-18 GSI facility:
provides ion beam source and injector for FAIR



	SIS-18	SIS-100
reference primary ion	U^{28+} / U^{73+}	U^{28+} / U^{92+}
reference energy	0.2 / 1 GeV/u	1.5 / 10 GeV/u
ions per cycle	1.2E11 / 2E10	4E11 / 1E10
cycle rate (Hz)	2.7	0.5 / 0.1
FAIR parameter booklet, April 2007, (Ed.) O. Boine-F., P. Spiller, M. Steck + corrections for MSV -> update under way		

UNIversal Linear ACcelerator UNILAC



ion A/q	≤ 8.5, i.e. $^{238}U^{28+}$	
beam current (pulse) * q/A	1.76 (0.5% duty cycle)	emA
input beam energy	1.4	MeV/u
output beam energy	11.4	MeV/u
normalized total output emittance, horizontal/vertical	0.8 / 2.5	mm mrad
beam pulse duration	≤ 5000	µs
beam repetition rate	≤ 50	Hz
operating frequency	108.408	MHz
length	≈ 100	m

UNILAC Status

Figures of merit for an injector :

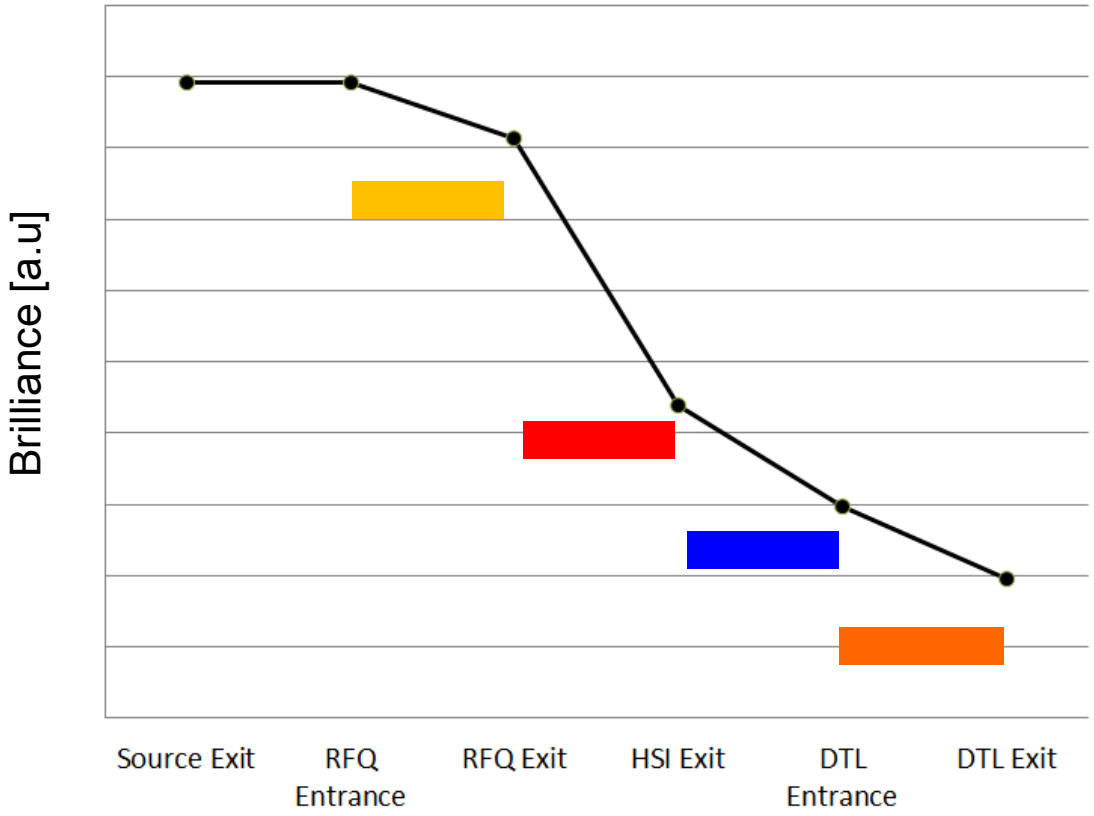
- small emittance
- high current

→ high ratio current / emittance = brilliance

- define the normalized (energy), scaled (q/A) brilliance $\tilde{B}_n := \frac{q}{A_{mass}} \frac{I}{\epsilon_n}$
- requirement for FAIR ($^{238}U^{28+}$, 11.4 MeV/u): 1.9 mA / mm mrad
- achieved with $^{40}Ar^{10+}$, 3.6 MeV/u: 1.2 mA / mm mrad
- achieved with $^{238}U^{28+}$, 11.4 MeV/u: 0.5 mA / mm mrad

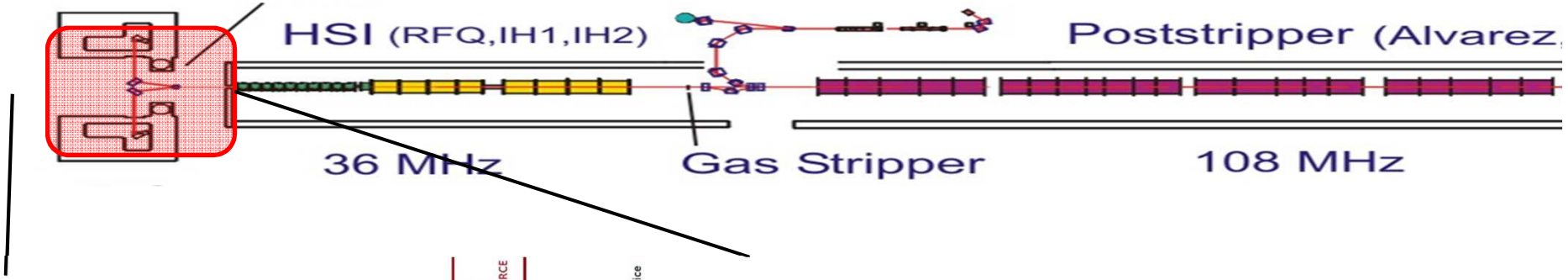
- UNILAC may deal with the space charge
- limitations from high e.m. fields demanded by uranium

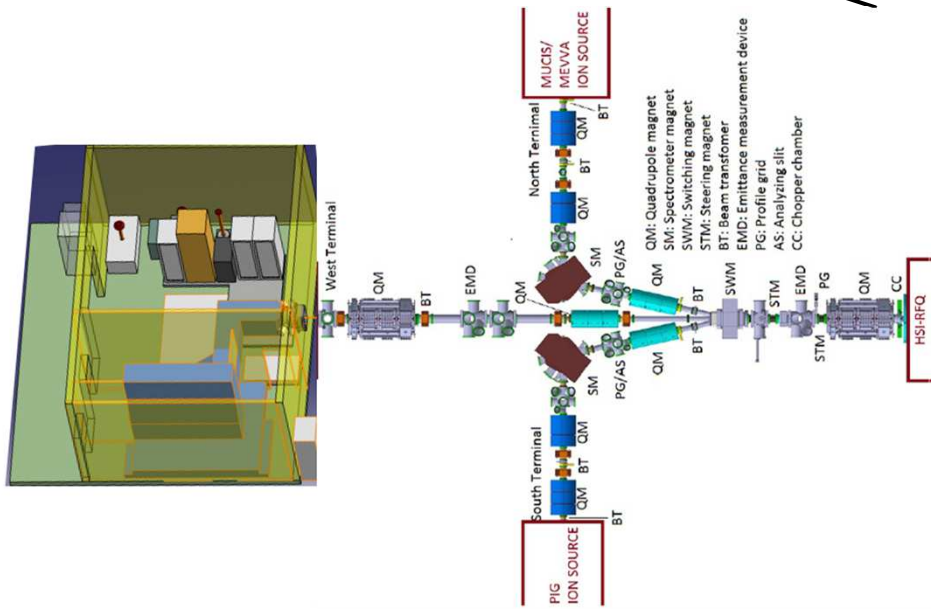
development of uranium brilliance along present machine from f2e simulations
(assuming optimized settings)



- source emit. / RFQ acceptance
- mis-matched injection into IH-DTL
- emit. growth from sc, stripping
- inter-tank mis-match, too low $\sigma_\perp$

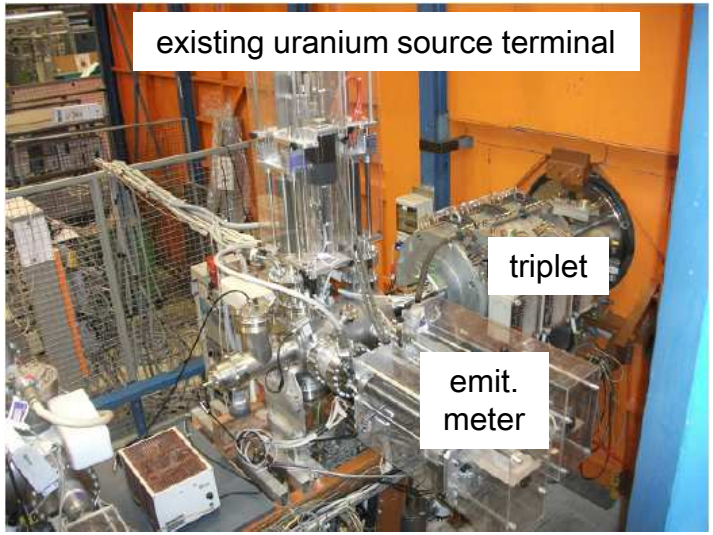
New and Dedicated Uranium Source & LEBT Branch



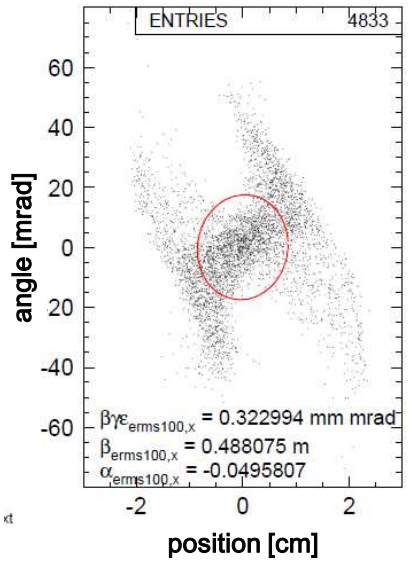


- new „Terminal West“ under design
- will provide exclusively ^{238}U
- improved (compact) extraction system
- LEBT is w/o bends (hex-pole fringes, dispersion)
- no dispersive separation of charge states (3^+,4^+)
- just chromatic separation (envelopes + irises)
- compromise between:
  - vast ion species portfolio
  - saftety issues wrt uranium operation/handling

Layout of LEBT Based on Measured Source Distributions

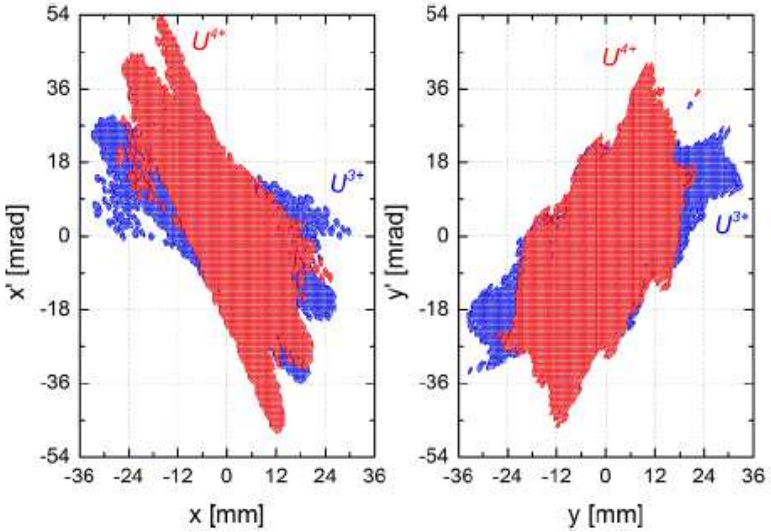


- triplet between source & emit. meter to distinguish charge states
- focusing inside source & extraction is electrostatic:
  → all charge states have same distribution at exit
- triplet focusing is magnetic
  → charge states at emit. meter have different distributions
- charge state spectrum and source exit distribution can be reconstructed → see IPAC2014, THPME007 (S. Yaramyshev)



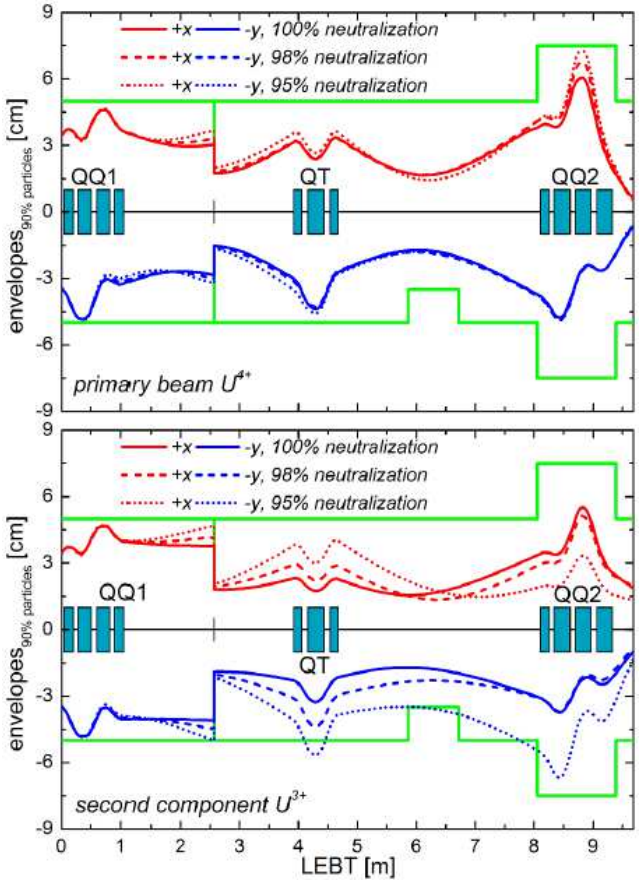
source exit:
U^{3+} ~ 20 mA
U^{4+} ~ 36 mA, 15 mA inside RFQ acceptance

triplet exit:

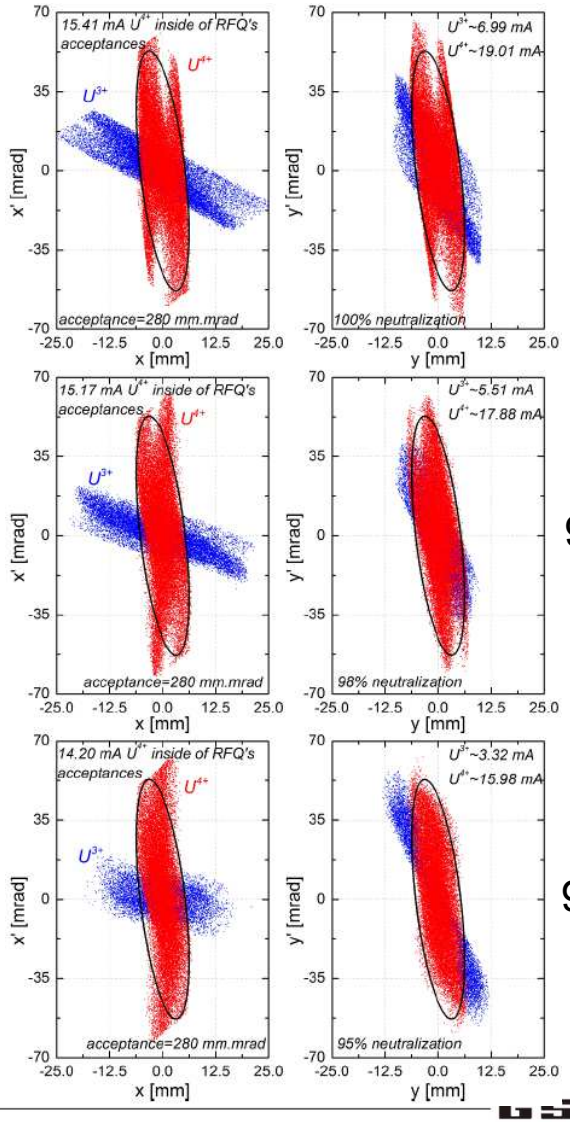


Simulations along new LEBT *(assuming different sc compensations)*

Envelopes

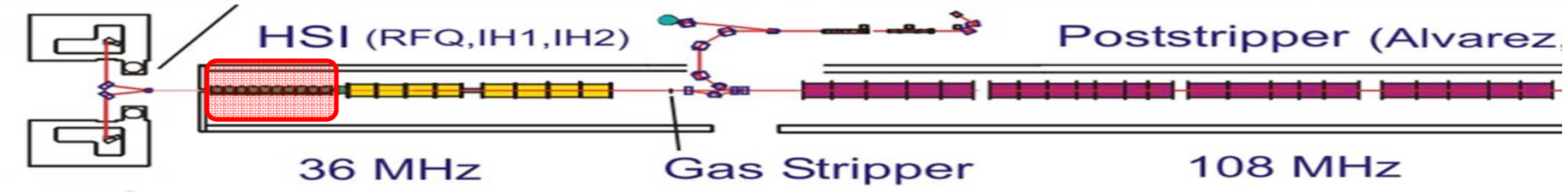


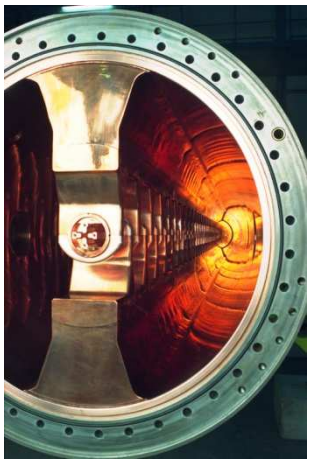
RFQ Entrance



- increase of current/emittance by factor 2 wrt value optained in 2007
- 30% still missing (→ new extraction system to be tested)

RFQ





- acceleration from 2.2 to 120 keV/u
- 418 cells, i.e. 9.27 m in length
- 31 MV/m = 2.8 E_K

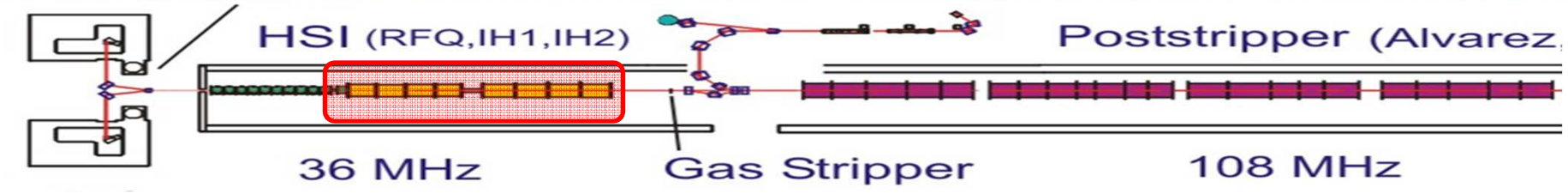
problems with existing RFQ (upgraded in 2009):

- output distribution too divergent to be captured by subsequent doublet → losses
- rods suffered from sparking (especially during mixed duty-cycle operation)
- just 90% of required vane voltage for $^{238}U^{4+}$ operation → insufficient bunching

plans for re-design :

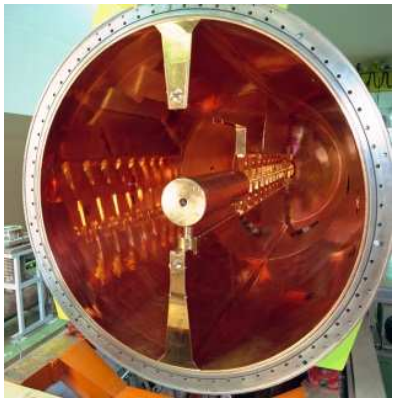
- reduce surface field at expense of acceptance
- keep overall length
- match output to subsequent MEBT & IH DTL requirements
- operation just at low duty cycles, no more mixed operation
- design works start in 2015

MEBT & IH DTL



- super lens: IH-type 11-cell RFQ, no acceleration, just matching to IH DTL

- IH-cavity I
  - KONUS-acceleration to 0.74 MeV/u
  - 53 gaps
  - 3 internal triplets
  - 1.6 MW rf-power

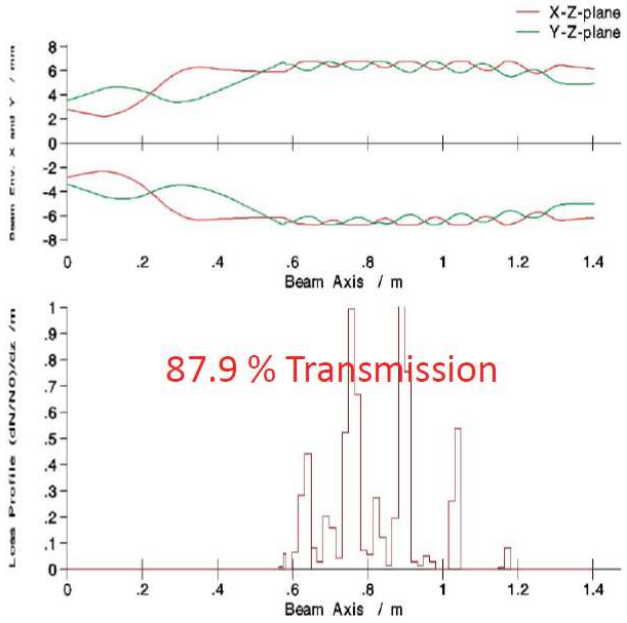


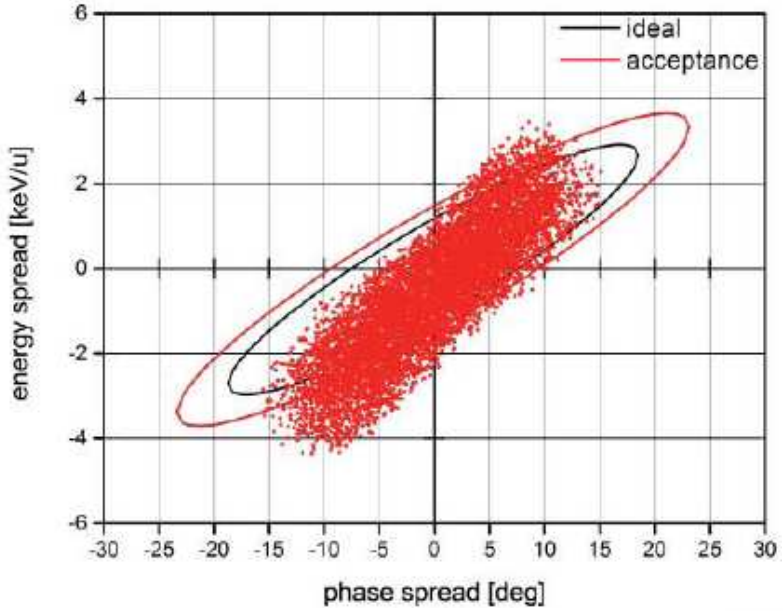
- IH-cavity II
  - KONUS-acceleration to 1.4 MeV/u
  - 46 gaps
  - 3 internal triplets
  - 1.6 MW rf-power

MEBT & IH DTL

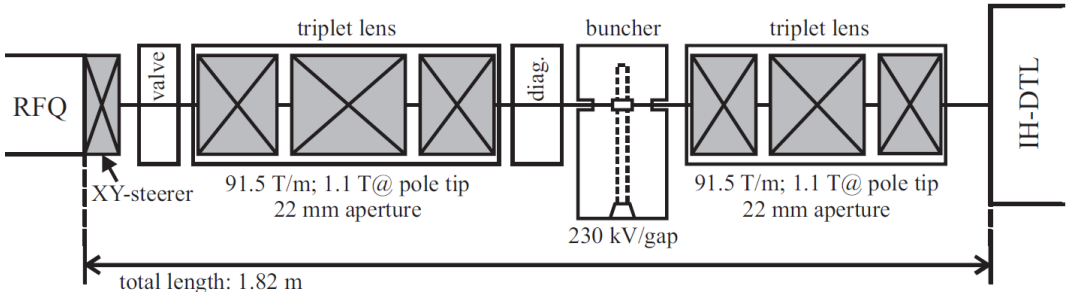
problems with existing MEBT:

- after RFQ upgrade: quad doublet in front of super lens cannot re-focus the beam sufficiently (too divergent)
- beam loss inside super lens → triggers sparking → enforces voltage reduction → poor optics
- super lens has just two knobs, i.e. long. & transv. matching capabilities are poor
- MEBT output is long. mis-matched wrt subsequent IH DTL entrance requirements
- overall MEBT & IH DTL performance (simulations):
  - transmission 86 %
  - emittance growths: 57/93/324 % hor/ver/long



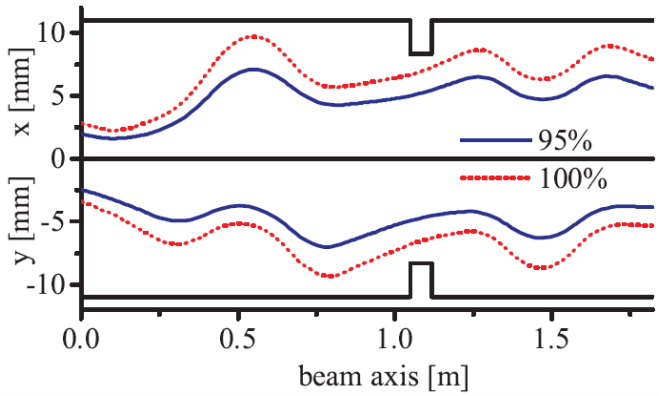


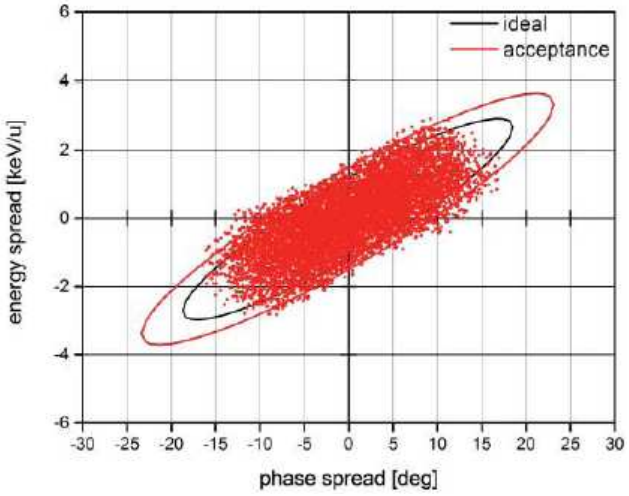
MEBT & IH DTL



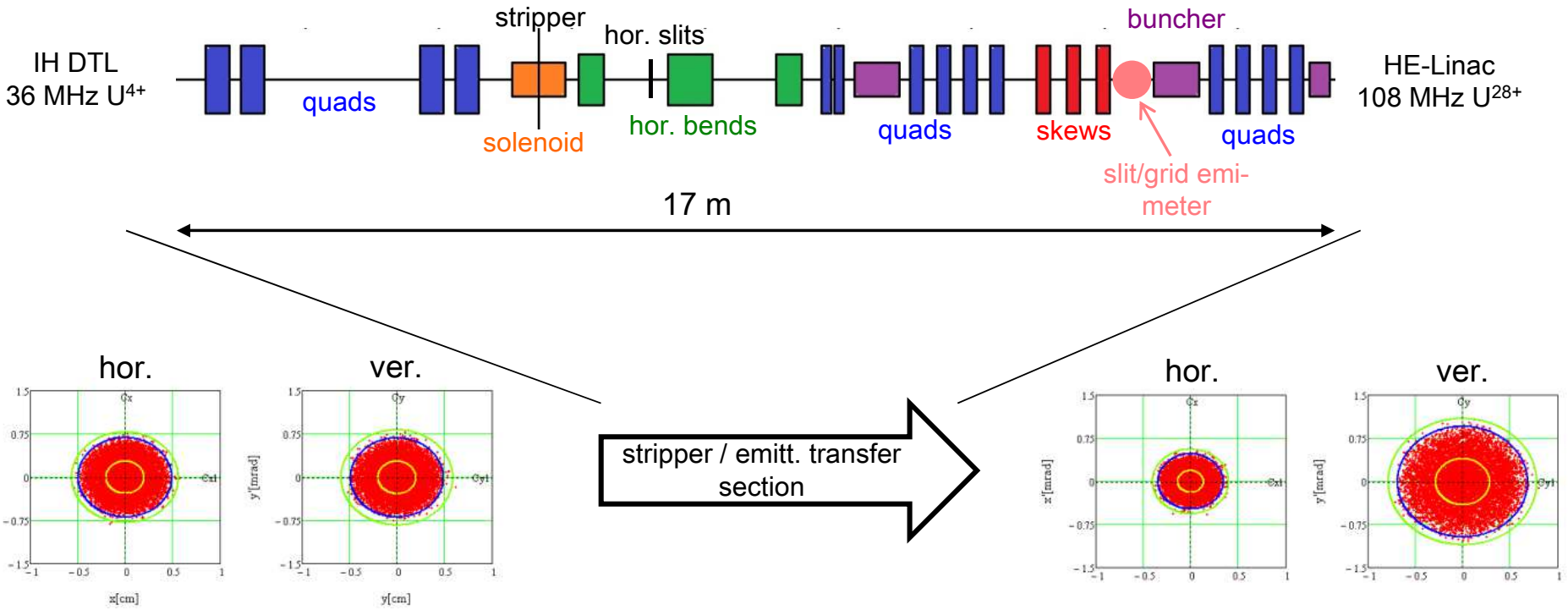
new MEBT design:

- is 1.4 m longer → requires moving two IH cavities of 10 m length each
- 6 knobs: 4 gradients (2 symmetric triplets), rf-amplitude & -phase
- long. & transv. well matched to subsequent IH DTL
- overall new MEBT & IH DTL performance (simulations):
  - transmission 100 %
  - emittance growths: 54/61/ 65 % hor/ver/long
    57/93/324 % (existing)





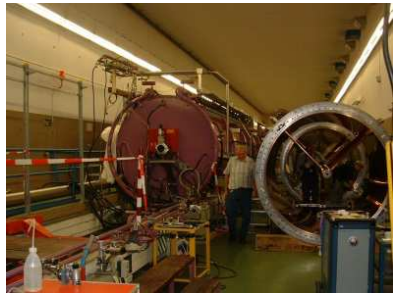
Stripper Section $U^{4+} \rightarrow U^{28+}$ (with optional emittance transfer)

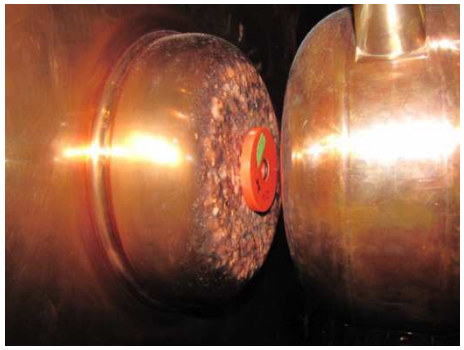


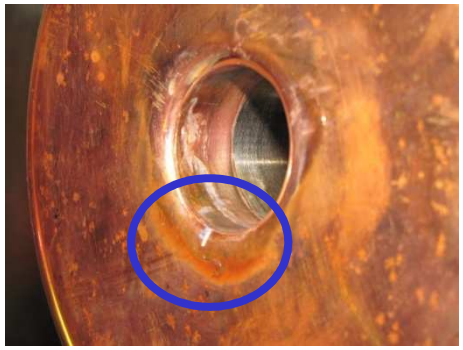
- testing of new stripping gases & pressures
- concept of adjustable hor → ver emittance transfer may be applied in stripper section
- design work will start soon
- *emittance transfer: talk on concept and its experimental demonstration: WEO3LR, Wed. 3^{05} pm*

Todays Alvarez DTL

- first three Alvarez tanks in operation since 40 years
- warranty expired 15 years ago
- drift tubes are obviously damaged
- copper plating has bubbles & bumps
- resources for maintanance increase rapidly







- tanks suffer especially from mixed operation mode, i.e. within one second (example):
  - 1 short rf-pulse (1 ms) with highest rf-power
  - 25 long rf-pulses (6 ms) with intermediate power_1
  - 24 long rf-pulses (6 ms) with intermediate power_2

- quadrupole cooling channel leakages

- Alvarez DTL needs to be replaced prior to routine operation of FAIR

New DTL Parameters, Rf-Power

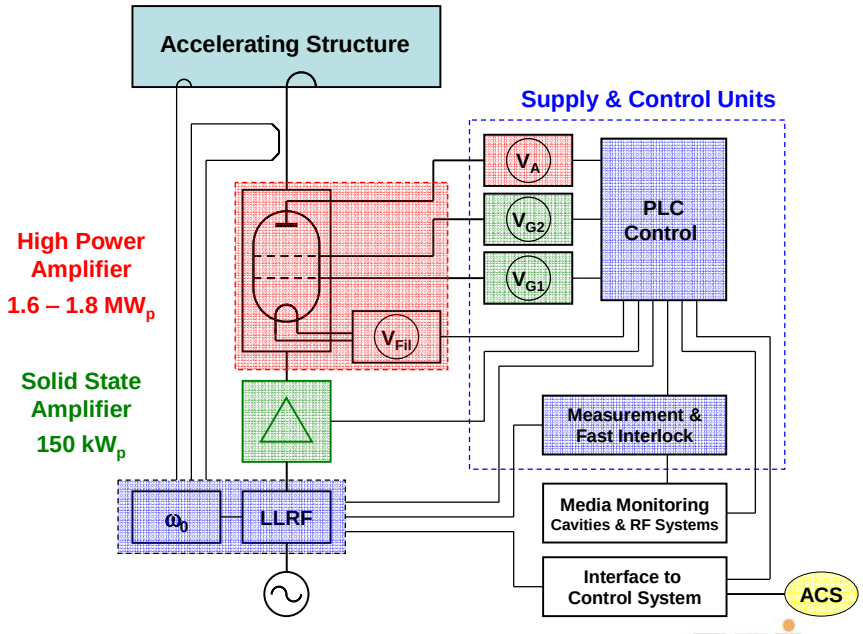
design parameters remain, except duty cycle

Ion A/q	≤ 8.5, i.e. $^{238}U^{28+}$	
Beam Current (Pulse)	15	emA
Input Beam Energy	1.4	MeV/u
Output Beam Energy	11.4	MeV/u
Normalized, total output Emittance, horizontal/vertical	0.8 / 2.5	mm mrad
Beam Pulse Length	≤ 100	µs
Beam Repetition Rate	≤ 2.7	Hz
Operating Frequency	108.408	MHz

no mixed-mode operation in future !

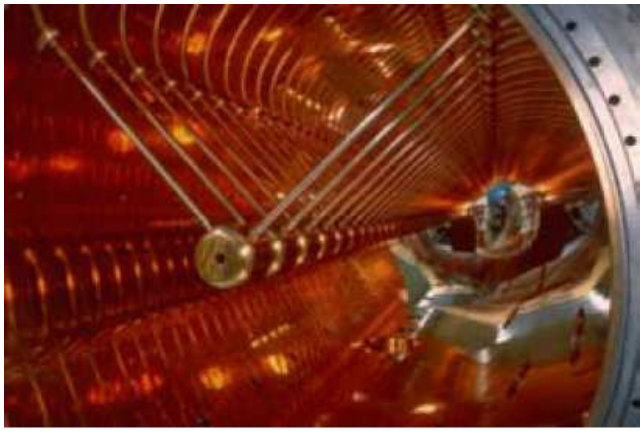
- existing power sources are 40 years old
- replace all-in-one high power amplifiers by modular system
- replace relais-based control system by PLC
- replace two-staged tube pre-amplifiers by one single solid state device
- cost per power source ≈ 2 M€

new rf-equpiment for short pulses:



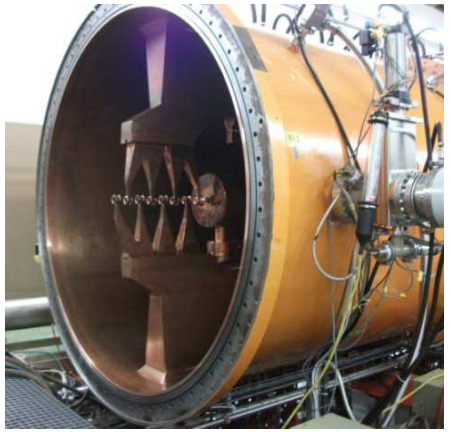
DTL: Alvarez vs IH-Mode

Alvarez



- state-of-the-art at high current proton/ion – linacs
- in operation at GSI
- mechanical length
- low efficiency wrt operating cost / acceleration
- needs more quads and power converters
- higher beam quality
- analytical beam dynamics model available

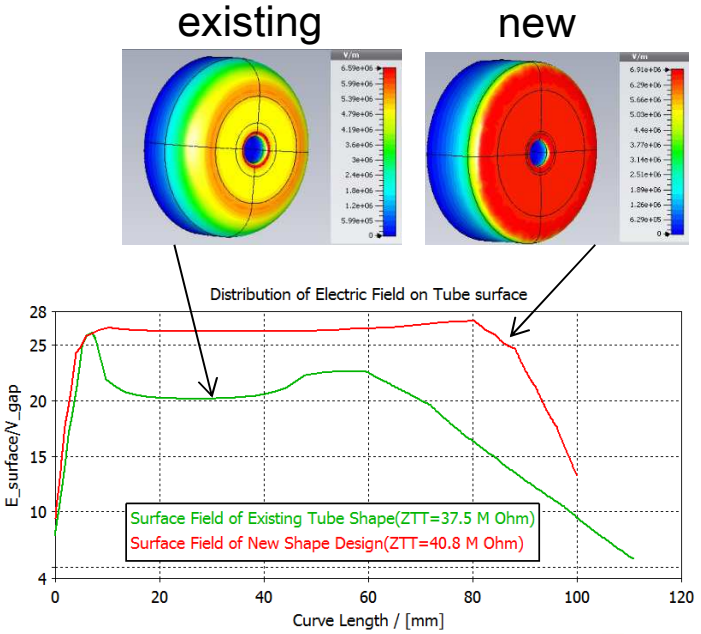
IH (Interdigital H-Mode)



- in operation at GSI
- mechanical length
- high efficiency wrt operating cost / acceleration
- needs less quads and power converters
- existing tunnel allows for 50 MeV/u DTL (bypassing SIS18 and direct injection into SIS100)
- lower beam quality
- no analytical beam dynamics model available

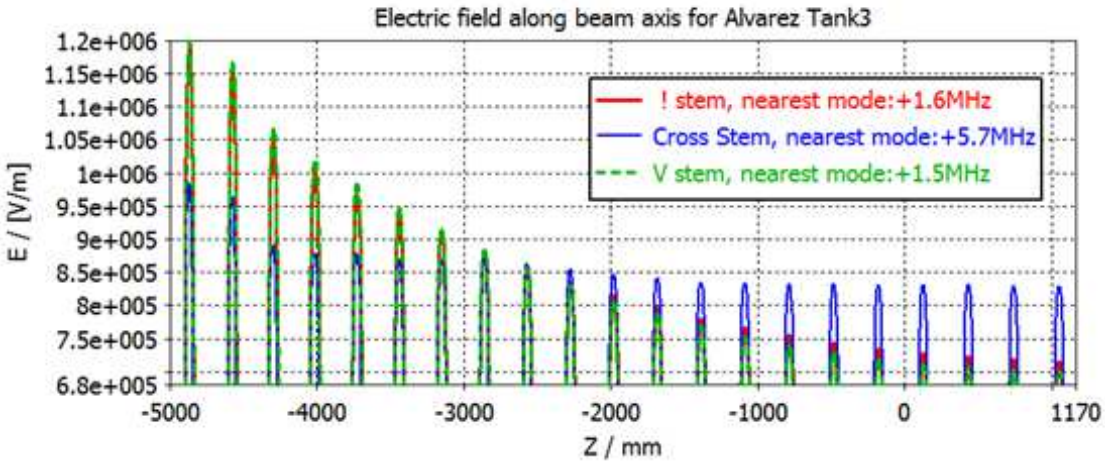
Alvarez DTL

- for time being GSI foresees replacing existing Alvarez DTL by another Alvarez DTL
- IH/CH DTL + KONUS is more rf-efficient, but GSI shall give priority to beam quality, i.e.
  - proper definition of periodic lattice
  - proper definition of periodic solution
  - procedure for envelope matching with space charge is available & tested
- if H-mode cavities do deliver same or better beam quality → design review indicated
- DTL design works are at beginning
- improved drift tube end plate shape wrt to existing design
- optimizition of ratio shunt_impedance / surface_field
- shape is „freehand-shape“ defined by 200 fix-points
- manufacturers:
  - „freehand-shape is no considerable cost driver“
  - feasible with same tolerances as const-R-shapes
  - cavity model will be ordered soon



Alvarez DTL

- end plate shape of drift tube is constant for all tubes of same tank
- five tanks total, 1.8 MW of rf-power available per tank
- each drift tube is kept by two stems (as today):
  - facilitates provision of quad current, water cooling of tubes & quads
  - well-considered orientation of stems mitigates parasitic TM rf-modes



Alvarez DTL

- constant tank radius, cell tuning by changing gap/cell ratio with beta

- first „favoured“ version of beta-profile of first tank available:
  - acceleration from 1.4 to 3.6 MeV/u
  - 66 cells
  - total length: 13.0 m
  - rf-power: (0.95+0.28) MW (heat+beam)
  - max. electric surface field : 0.99 E_k (today: 0.95 E_k)
  - transv. beam dynamics layout to started ...

# cell	length	E(surf)/Ek		U(gap)	b_in	E_in	gap/cell
0	1,52E+02	0,997237072	0,108413	2,88E+05	0,0546	1,391578	0,239574
1	1,53E+02	0,996324675	0,108415	2,91E+05	0,055085	1,416442	0,239376
2	1,54E+02	0,993390732	0,108412	2,93E+05	0,05557	1,441573	0,239174
3	1,56E+02	0,992124759	0,108411	2,96E+05	0,056055	1,466937	0,238997
4	1,57E+02	0,988525382	0,108412	2,98E+05	0,056542	1,492571	0,238808
5	1,58E+02	0,983101175	0,108412	3,01E+05	0,057029	1,518462	0,238642
6	1,60E+02	0,983902734	0,108411	3,03E+05	0,057517	1,544614	0,238503
7	1,61E+02	0,982321995	0,108413	3,06E+05	0,058005	1,571027	0,238367
8	1,62E+02	0,979789461	0,108414	3,09E+05	0,058495	1,597727	0,238236
9	1,64E+02	0,976062701	0,108413	3,11E+05	0,058985	1,624698	0,238091

Summary

- existing UNILAC cannot reach FAIR requirements

- sections which cause drop of beam quality have been identified

- upgrade plans:
  - source: improved extraction system
  - LEBT: no bends, uranium only
  - RFQ: lower surface fields & acceptance
  - MEBT: replace RFQ-super lens with: 2 triplets, 1 buncher, i.e. more knobs
  - stripper section:
    - new stripping gases & pressures
    - include option for hor → ver emittance transfer
  - post-stripping DTL:
    - no mixed rf-pulse length operation, new tube shape
    - currently Alvarez type preferred