Upgrade of the UNILAC for FAIR

L. Groening[1], S. Mickat[1], A. Adonin[1], W. Barth[1,3], X. Du[1], Ch.E. Düllmann[1,3,4], H. Hähnel[2], R. Hollinger[1], E. Jäger[1], M.S. Kaiser[1], U. Ratzinger[2], A. Rubin[1], P. Scharrer[1,3,4], B. Schlitt[1], G. Schreiber[1], A. Seibel[1,2], R. Tiede[2], H. Vormann[1], C. Xiao[1], C. Zhang[1]

[1]GSI, D-64291 Darmstadt, Germany
[2]Goethe University of Frankfurt, D-60438 Frankfurt, Germany
[3]Helmholtz Institute Mainz, Mainz, Germany
[4]Johannes Gutenberg-University, Mainz, Germany

- FAIR Project
- UNIversal Linear ACcelerator UNILAC
- Upgrade Activities

FAIR Facility for Antiproton and Ion Research

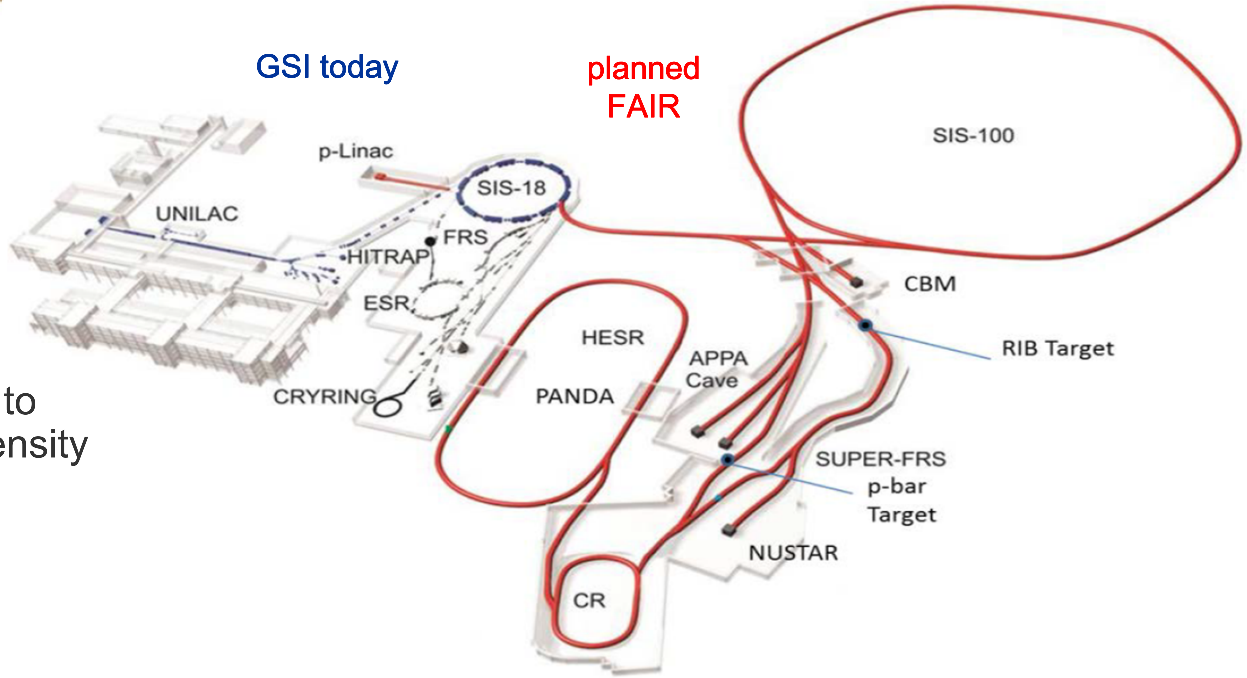
Primary Beams SIS 100
- 5 × 10^{11} U^{28+} ions/s; 1.5 GeV/u
- 10^{10} / s $^{238}U^{92+}$ up to 11 GeV/u
- 2 × 10^{12} protons/s; 29 GeV

Secondary Beams
- range of radioactive ion beams up to 1.5 - 2 GeV/u; up to a factor of 10'000 higher in intensity than presently
- antiprotons 1.5 - 14.1 GeV

Storage and Cooler Rings
- radioactive ion beams
- antiproton beams:

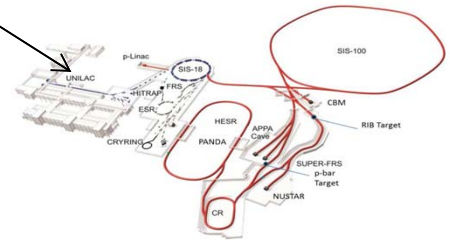
  CR: 10^8 antiprotons; 3 GeV

  HESR: 10^{10} antiprotons; 1.5 - 14.1 GeV



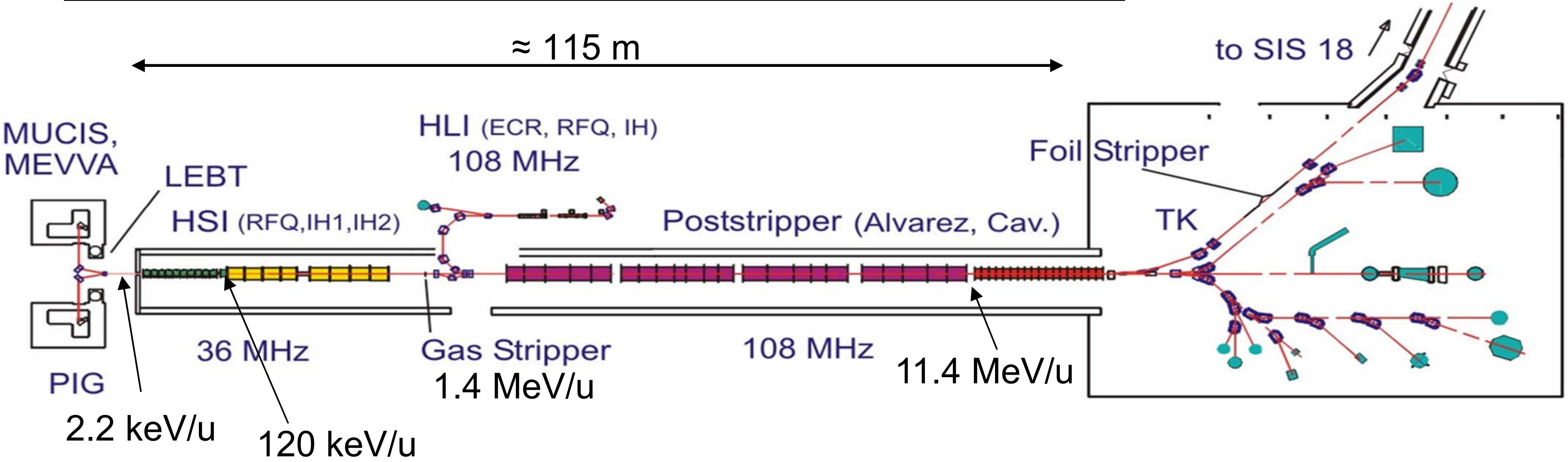
Technical Challenges
- Rapid cycling superconducting magnets
- rf-systems and control
- Beam lifetime (dynamic vacuum)
- Cooled beams

UNIversal Linear ACcelerator UNILAC



design parameters

ion A/q	≤ 8.5, i.e. $^{238}U^{28+}$	
beam current (pulse) * A/q	1.76 (0.5% duty cycle)	mA
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	≈ 115	m



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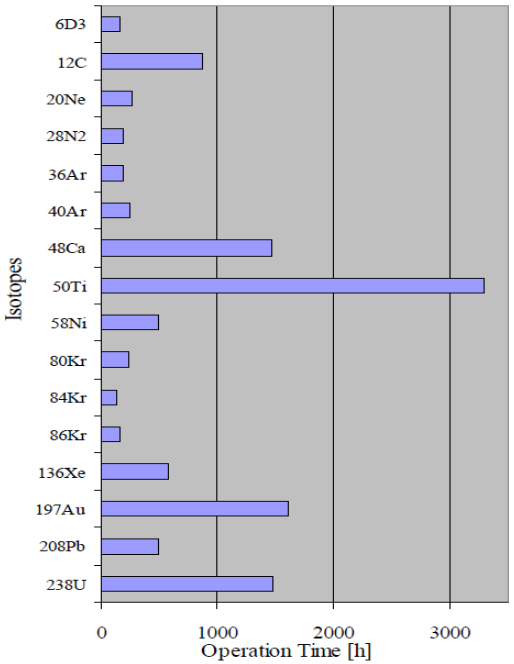
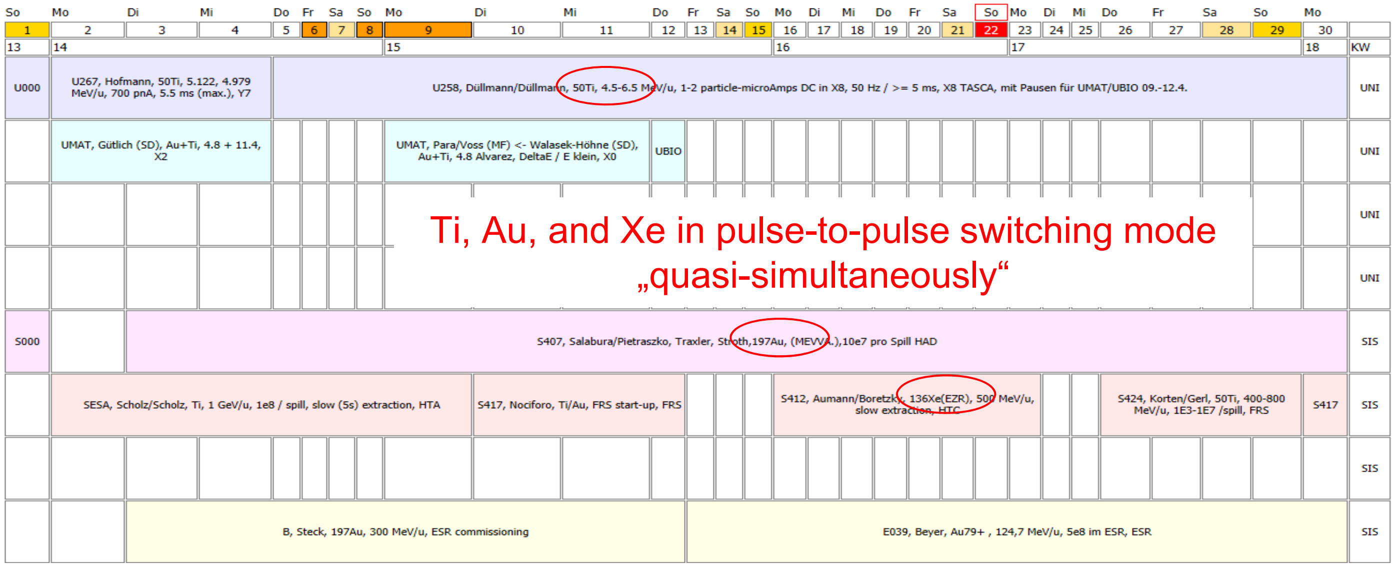
UNILAC: Available Beams

statistics 2012



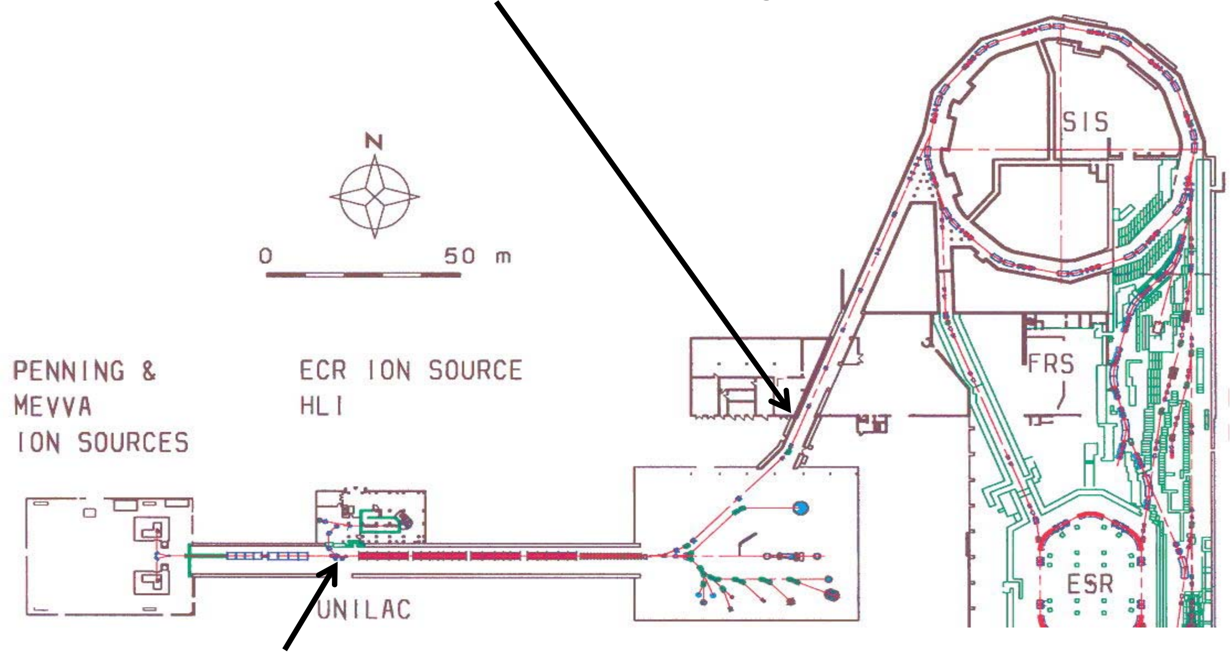
beam time schedule April 2012



2013-2015 saw considerable maintenance works

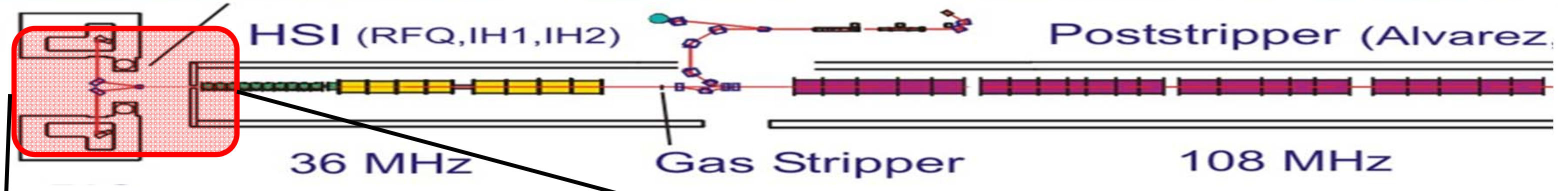
UNILAC: Achieved Uranium Current

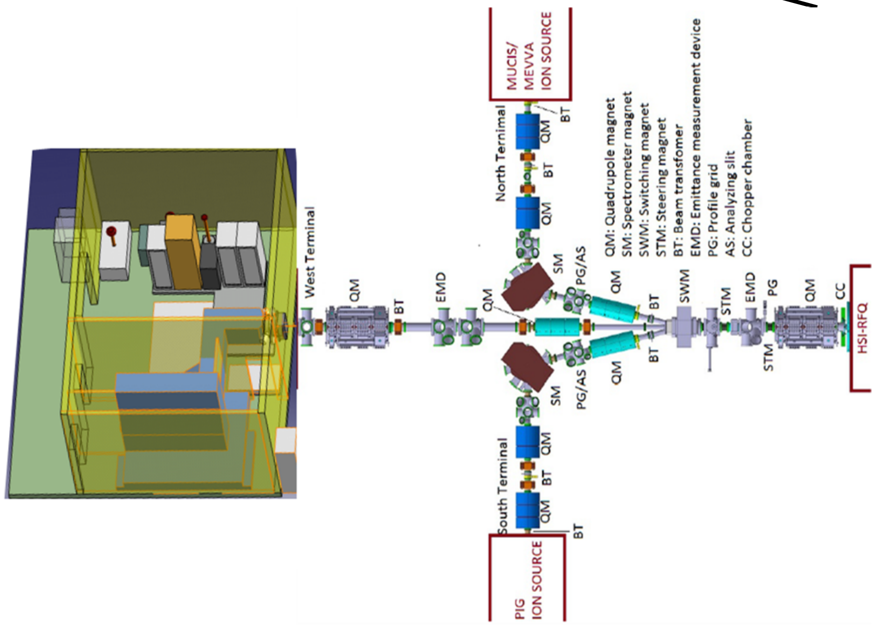
- June 2007: current of 6.0 mA $^{238}U^{27+}$ along the transfer to SIS18 was achieved



- Nov 2014: 7.8 mA w @ 18 mm mrad $^{238}U^{28+}$ at stripper section
- i.e. norm. hor. brilliance of 8 mA/µm (prstab **18** 040101 2015)
- although UNILAC did not achieve yet the target value of 15 mA, this machine keeps holding the uranium intensity world record and might do so for many years

UNILAC Upgrade: Dedicated Uranium Source & LEBT



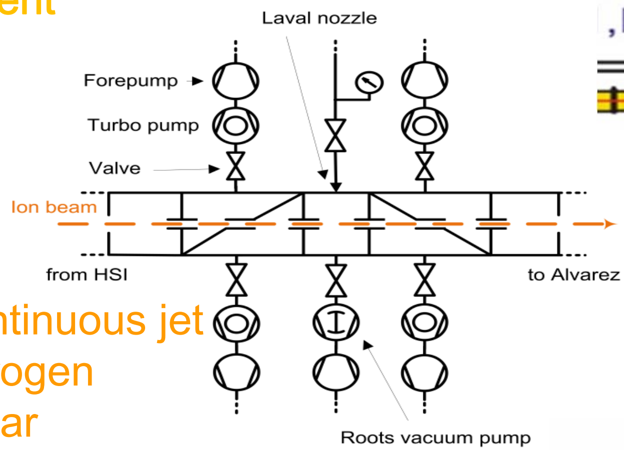


NIM A **788** 173 (2015)

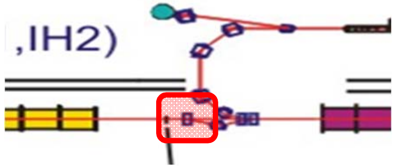
- new „Terminal West“ under design
- will provide exclusively ^{238}U
- improved (compact) extraction system
- LEBT is w/o bends (hex-pole fringes, dispersion)
- no dispersive separation of charge states (3^+,4^+)
- just chromatic separation (envelopes + irises)
- compromise between:
  - vast ion species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

High Pressure Pulsed Gaseous Stripper

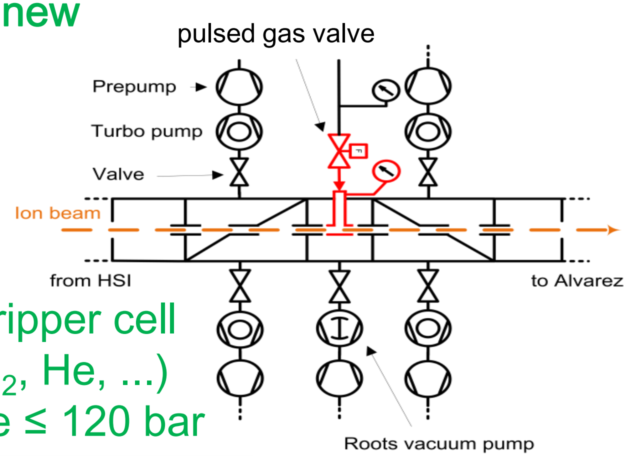
present



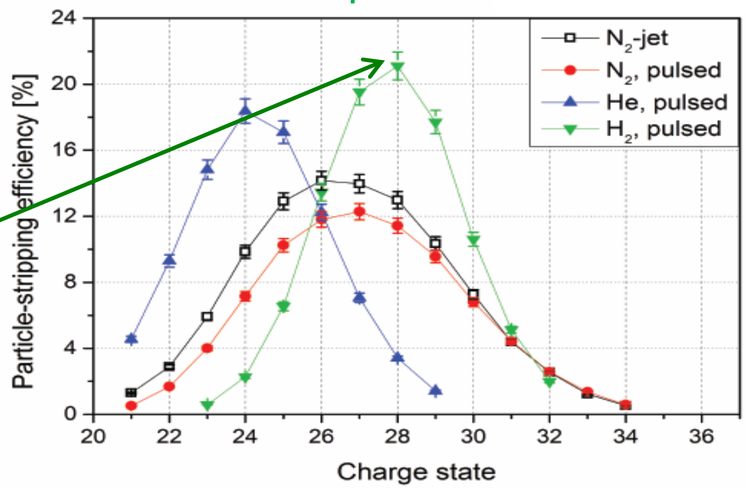
- continuous jet
- nitrogen
- 4 bar



new



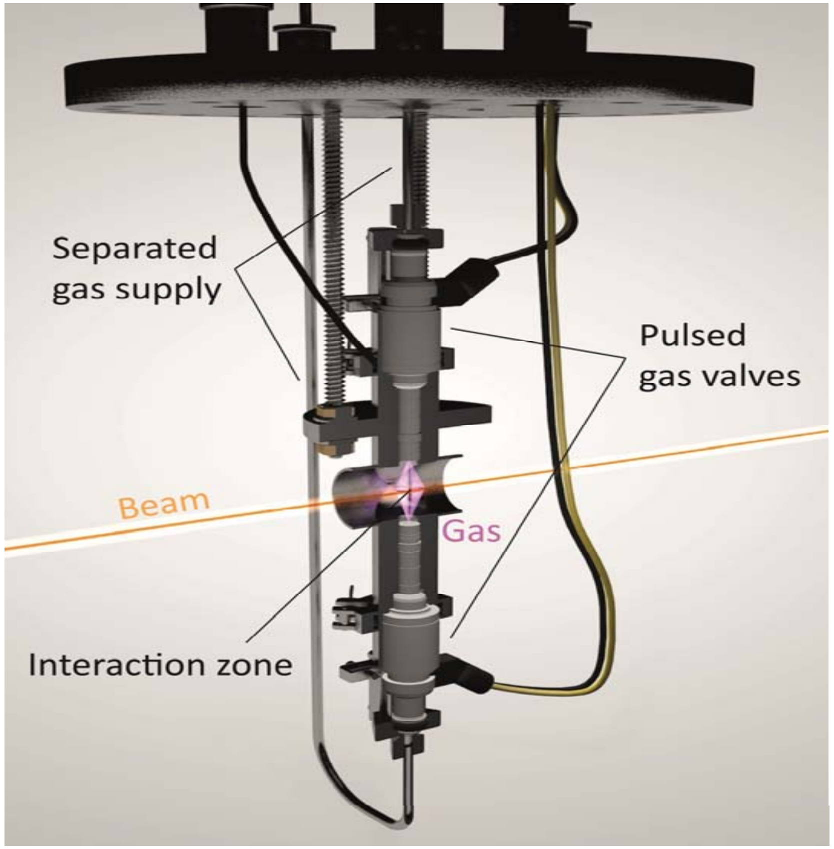
- pulsed gas stripper cell
- light gases (H_2, He, ...)
- back-pressure ≤ 120 bar

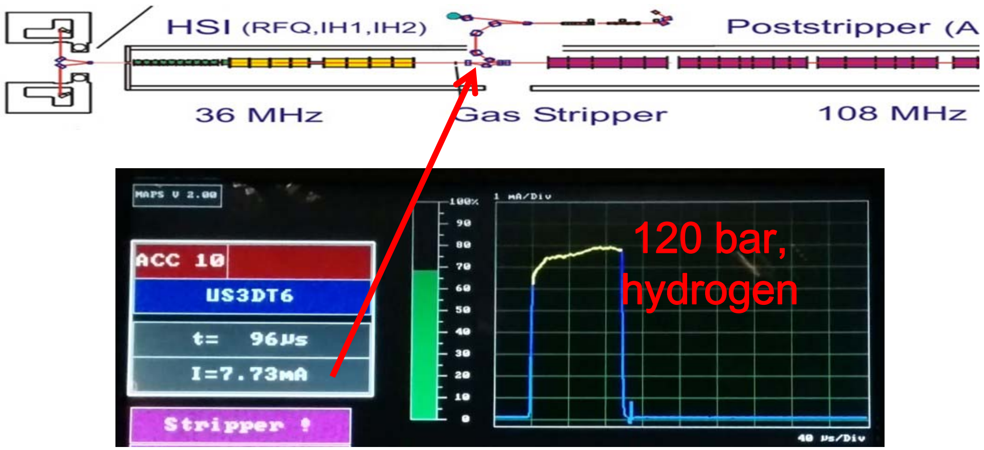


60% increase of stripping efficiency into U^{28+} achieved, by using pulsed H_2-injection

High Pressure Pulsed Gaseous Stripper

Pulsed gas cell setup (2015)



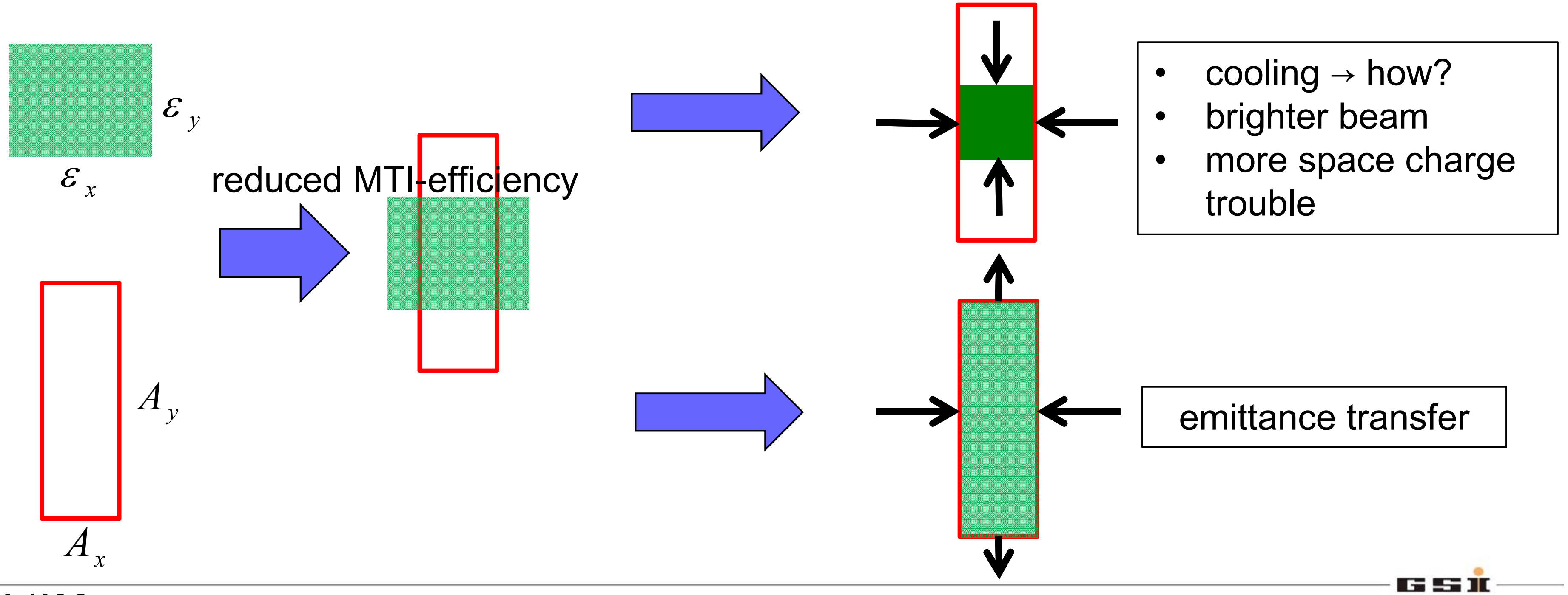


Uranium pulsed beam world record thanks to new set-up

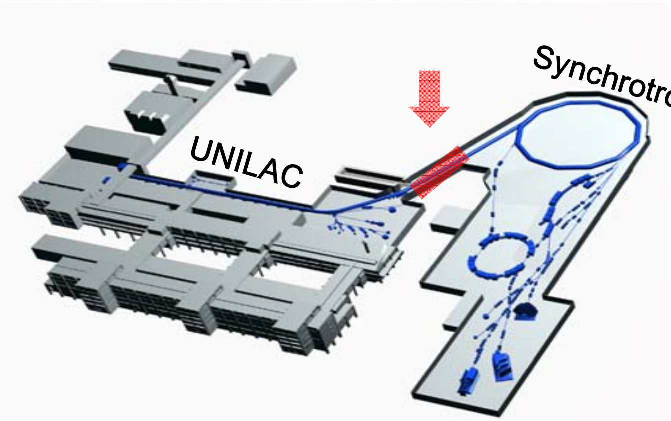
see dedicated talk on set-up by P. Scharrer (TUA1C01)

Linac Emittances vs effective Ring Acceptances

- “round” beam is provided by injector linac $\varepsilon_x \approx \varepsilon_y$
- flat beams might be required by rings (MTI) $A_x < A_y$

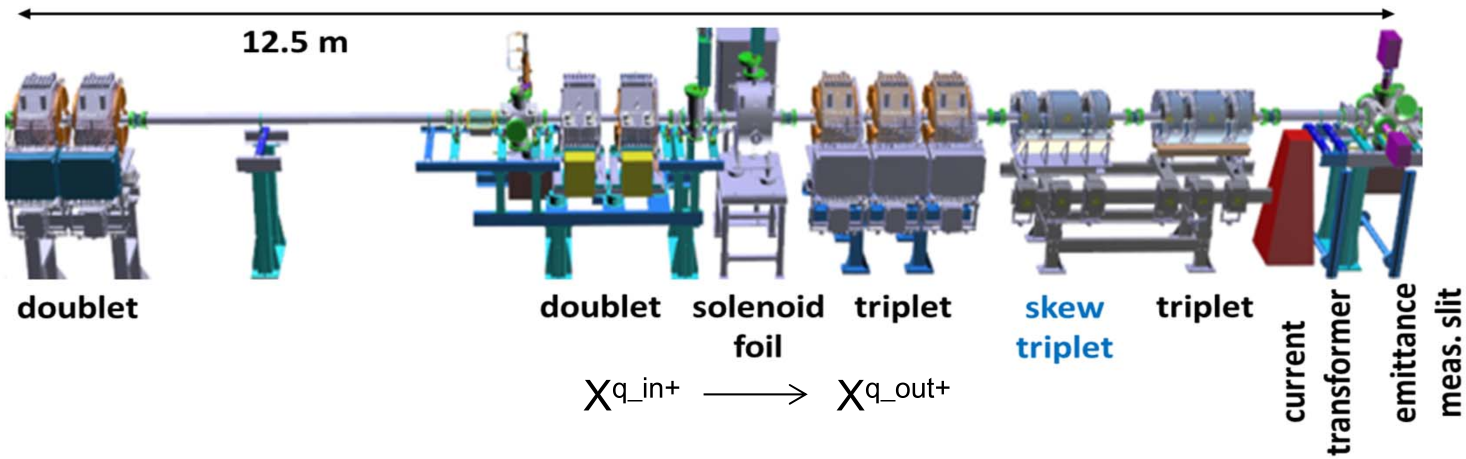


Beam Line for Testing Emittance Transfer (EmTEx)

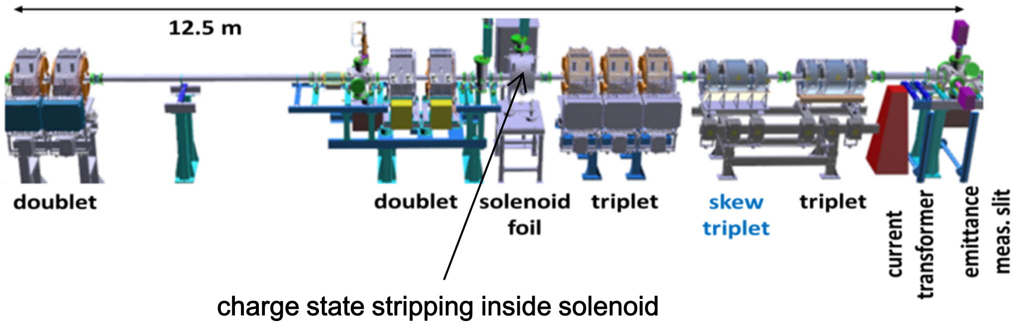


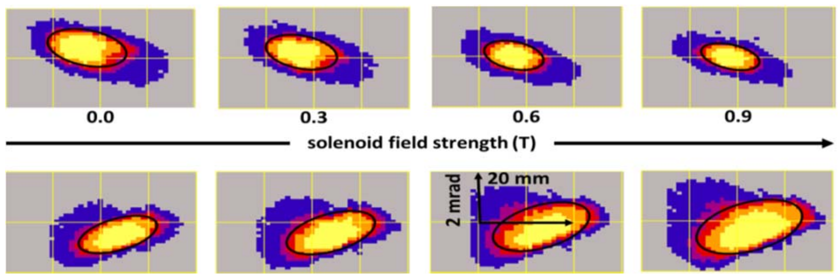
key components:

- charge stripper placed at center of a solenoid
- skew triplet to remove inter-plane correlations

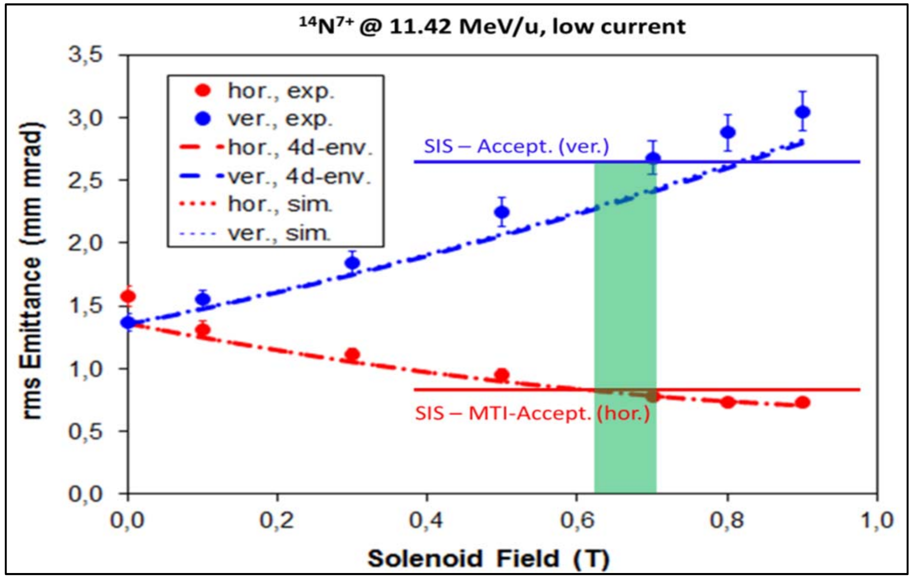


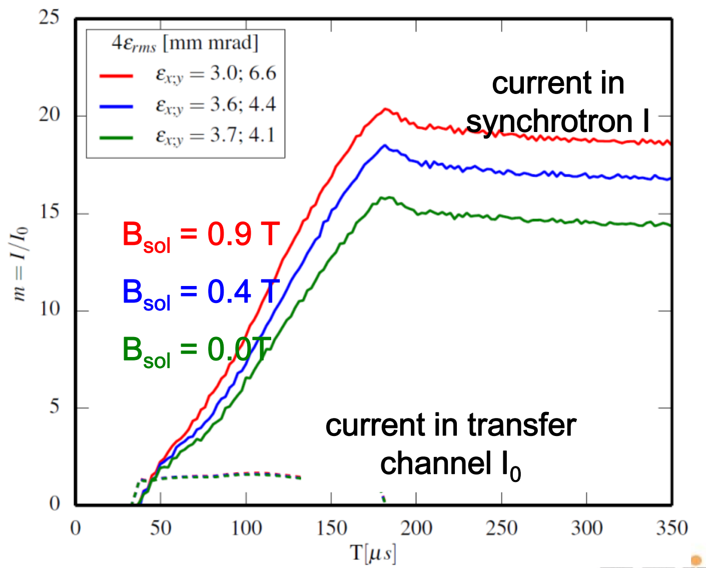
Proof of Principle EmTEx





Phys. Rev. Lett. **113** 264802 (2014)





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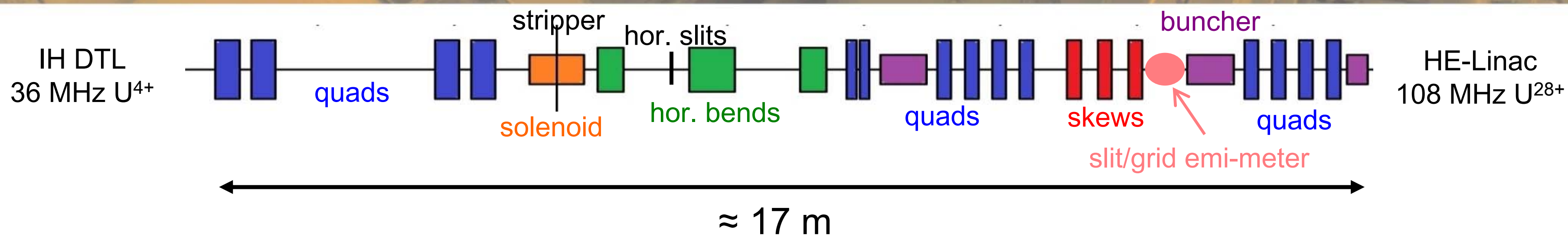
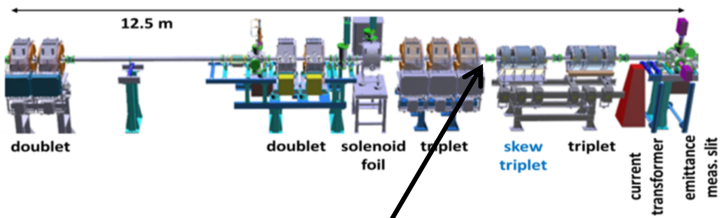
Stripper Section $U^{4+} \rightarrow U^{28+}$ (optional emittance transfer)



- design of an emittance transfer section in front of post-stripper DTL is ongoing
- if it will be built depends on the success of other upgrade activities:
  - source extraction system
  - LEBT
  - RFQ
  - MEBT
  - gaseous stripper
- if these measures will not be sufficient, the emittance transfer will be included

4d Beam Diagnostics for $^{238}U^{28+}$ at 11.4 MeV/u

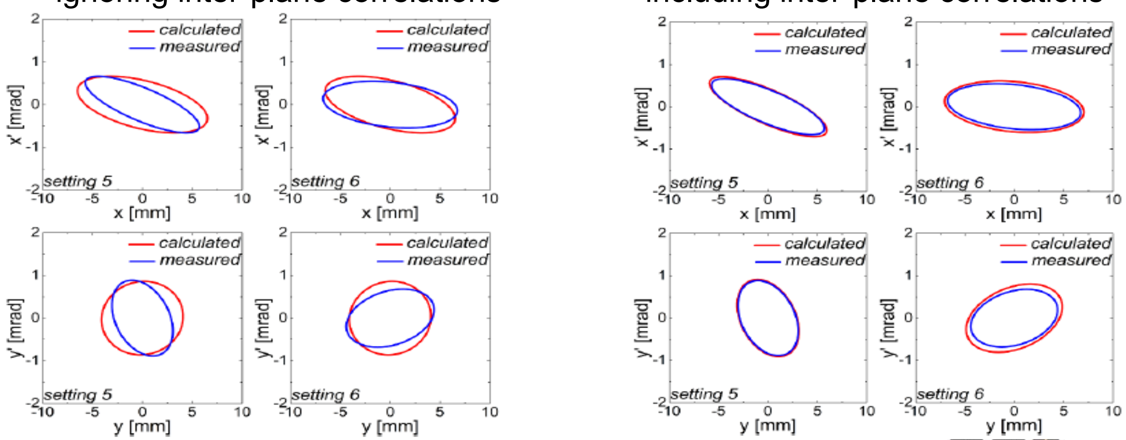
- slit/grid emittance meters just measure the (x,x‘) & (y,y‘) planes separately
- correlations are not measured $\begin{bmatrix} \langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle x'x\rangle & \langle x'x'\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle yx\rangle & \langle yx'\rangle & \langle yy\rangle & \langle yy'\rangle \\ \langle y'x\rangle & \langle y'x'\rangle & \langle y'y\rangle & \langle y'y'\rangle \end{bmatrix} = \begin{bmatrix} 12.79 & 1.89 & ? & \\ 1.89 & 0.62 & & \\ & & 32.18 & 3.49 \\ ? & & 3.49 & 0.46 \end{bmatrix}$
- pepper pots have not been applied successfuly for ions > 150 keV/u
- complete 4d 2^{nd} moments matrix has been measured at GSI UNILAC
- Using EmTEx: scans with skew quadrupoles were perfomed



$$\begin{bmatrix} \langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle x'x\rangle & \langle x'x'\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle yx\rangle & \langle yx'\rangle & \langle yy\rangle & \langle yy'\rangle \\ \langle y'x\rangle & \langle y'x'\rangle & \langle y'y\rangle & \langle y'y'\rangle \end{bmatrix} = \begin{bmatrix} 12.79 & 1.89 & 0.18 & 0.37 \\ 1.89 & 0.62 & 1.69 & 0.29 \\ 0.18 & 1.69 & 32.18 & 3.49 \\ 0.37 & 0.29 & 3.49 & 0.46 \end{bmatrix}$$

removing correlations would lower horizontal emittance by 42% !

calculation and measurements



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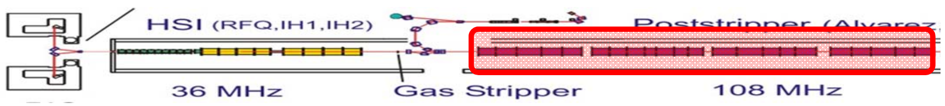
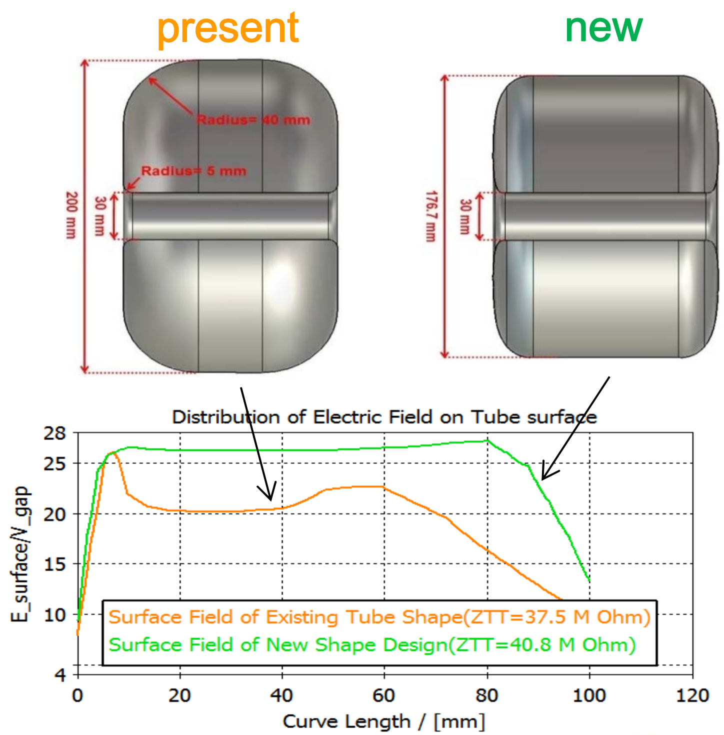
New Alvarez Cavities



- improved shapes of drift tube end plates
- optimizition of shunt impedance per surface field
- „freehand-shape“



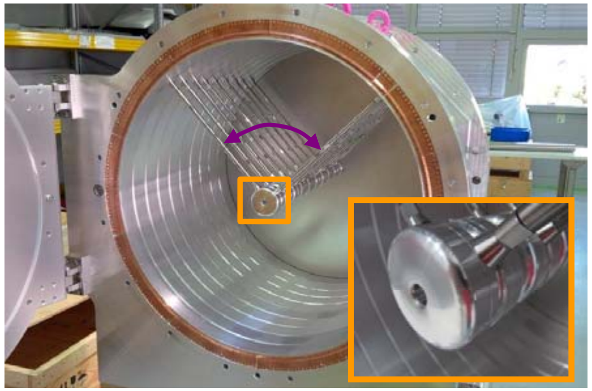
	tank I	tank II	...	*tank V*
energy range [MeV/u]	**1.39 – 3.30**	**3.30 – 5.39**		- 11.4
# cells	**55**	**45**		
L_{gap} / L_{cell}	**0.26**	**0.23 – 0.25**		
rf-length [m]	**10.7**	**12.2**		
$E_{surf,max}$ [E_K]	**1.03**	**0.97**		1.03
$P_{loss,MWS}$ [MW]	**0.878**	**0.862**		
P_{beam} [MW]	**0.243**	**0.266**		
<Z_{eff}> [MΩ/m]	**14.0**	**15.0**		

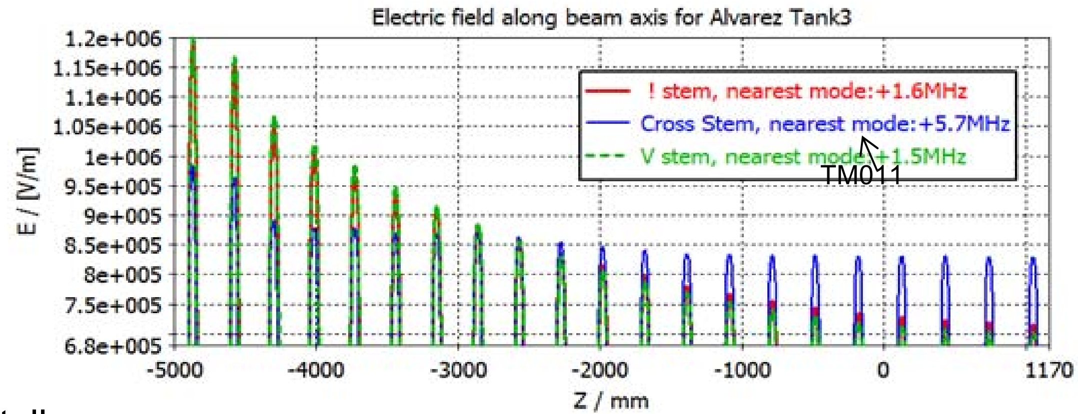
DTL Cavity Stem Orientations

drift tubes kept by two stems (as today):

- provision of quad current and water cooling of tubes & quads
- well-considered orientations of stems mitigate parasitic TM rf-modes

robustness of field flatness
wrt perturbations



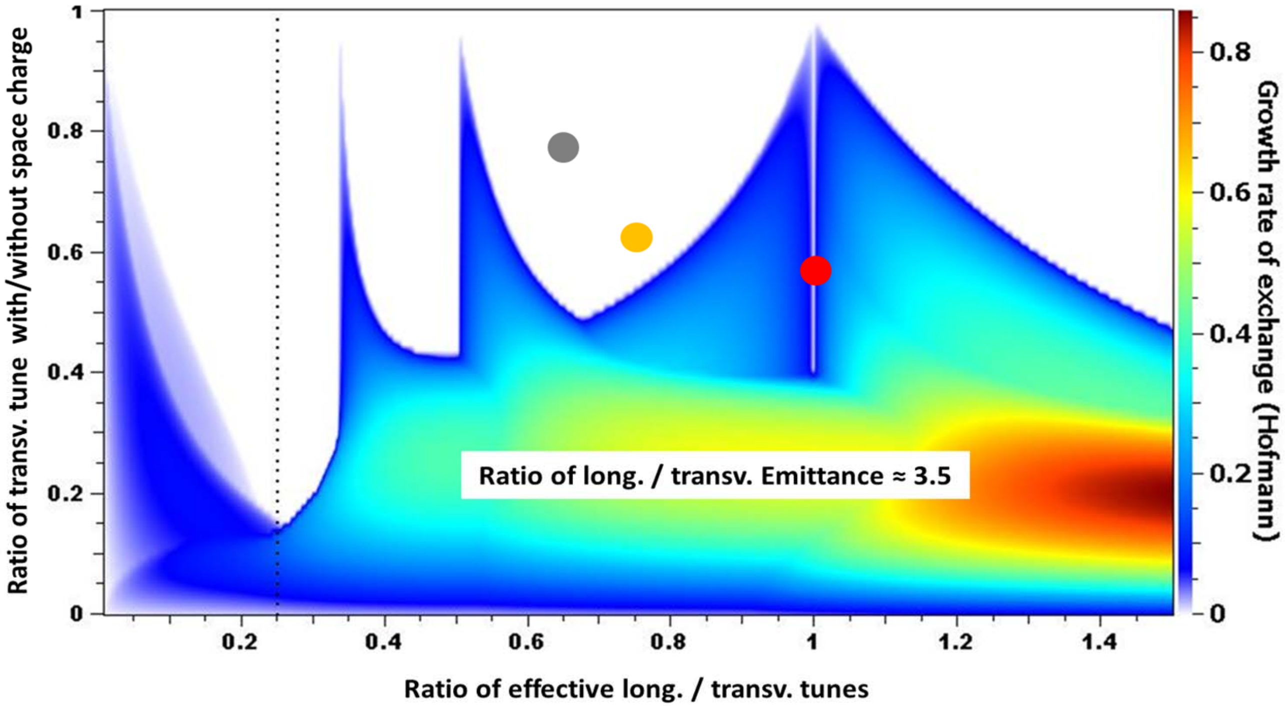


1:3 scaled cold model to probe experimentally:

- adjustable stem orientation
- exchangeable drift tube surfaces

Stronger Transverse Focusing

- today transv phase advance is limited to σ_0 = 53° (zero current) with $^{238}U^{28+}$
- bad working point in Hofmann‘s stability chart



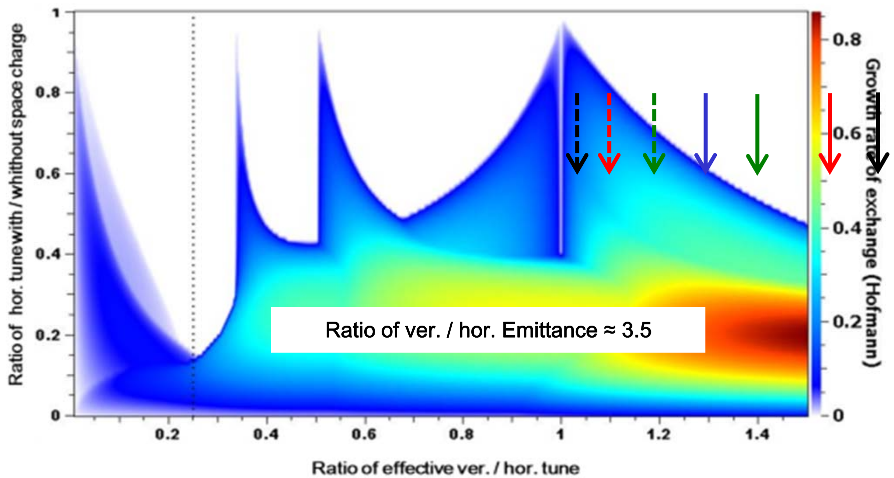
today‘s DTL design with low phase advance, $\varepsilon_y = \varepsilon_x$

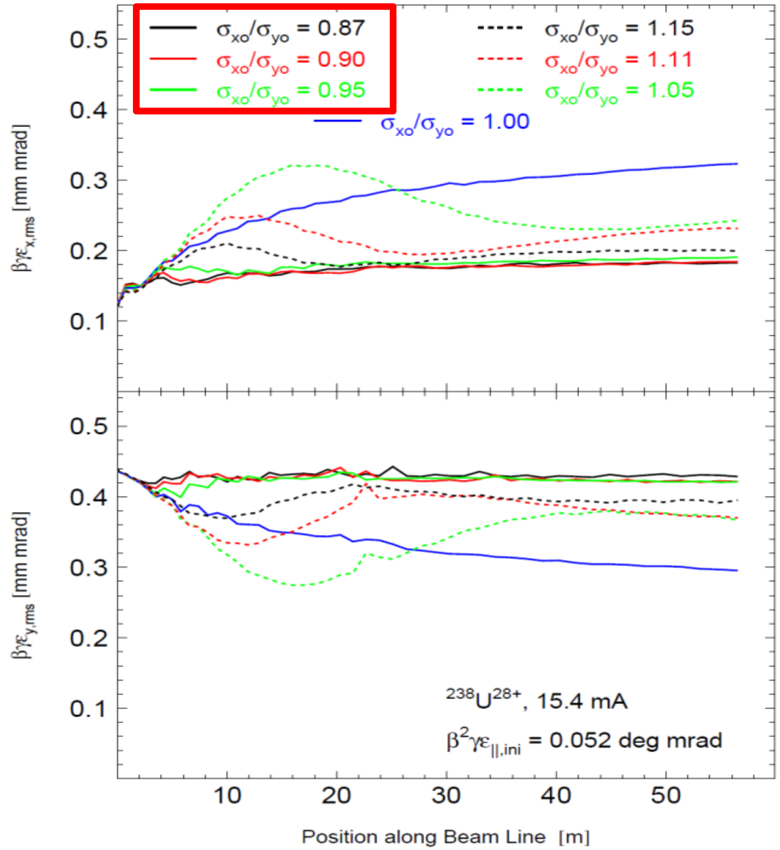
new design with increased focusing, $\varepsilon_y = \varepsilon_x$

design with flat beam operation, i.e. $\varepsilon_y = 3\varepsilon_x$

Asymmetric Transverse Focusing (optional)

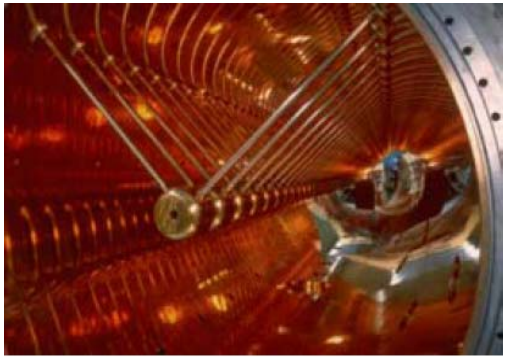
- focusing shall preserve beam emittance ratio (flatness)
- space charge drives re-equilibration of emittances
- can be mitigated by stronger focusing in ver plane
- ver focusing quads with stronger gradients wrt hor ones
- few % of increase of ver quad gradients is sufficient





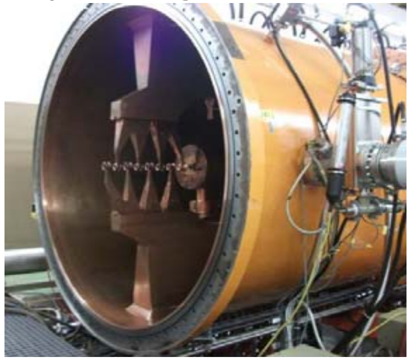
DTL: Alvarez vs IH-Mode

Alvarez



- state-of-the-art at high current proton/ion – linacs
- in operation at GSI
- mechanical dimensions
- needs more quads and power converters
- analytical beam dynamics model available
- higher beam quality

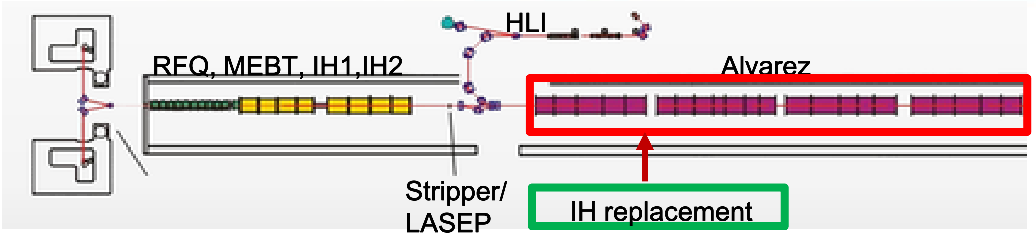
IH (Interdigital H-Mode)

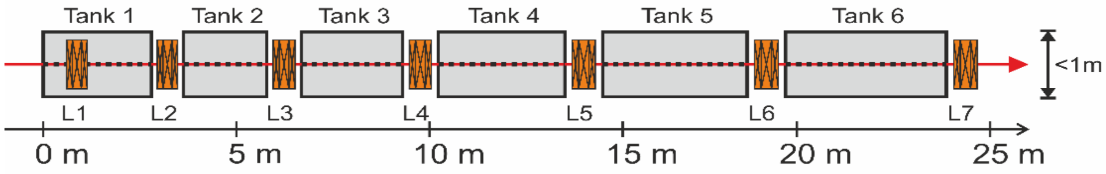


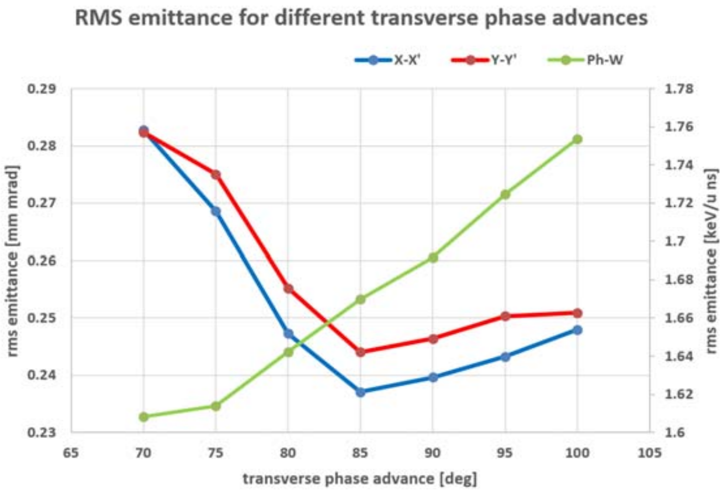
- in operation at GSI since 20 years
- mechanical dimensions
- high efficiency wrt operating cost / acceleration
- needs less quads and power converters
- no analytical beam dynamics model available
- lower beam quality

IH-DTL Design

- Six IH-DTL cavities @ 25 m total length
- Efficient KONUS beam dynamics concept
- Optimized transverse focusing for lowest emittance growth







energy range [MeV/u]	1.4 – 11.4
gap voltages [MV]	0.4 – 1
on axis field [MV/m]	< 11
mag. lens gradients [T/m]	45 – 50
# gaps per 0°-section	7 – 17
# gaps per reb.-section	4 – 6
phase advance per period	< 90°

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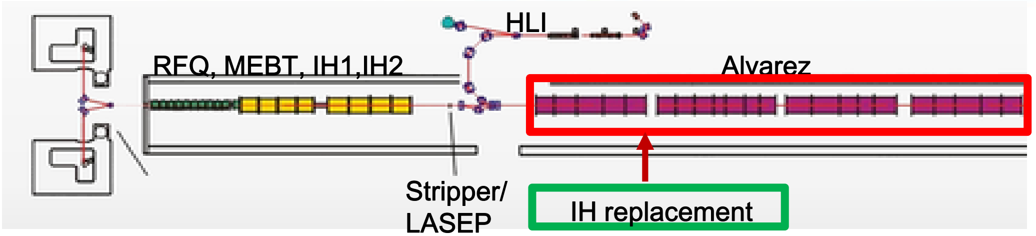
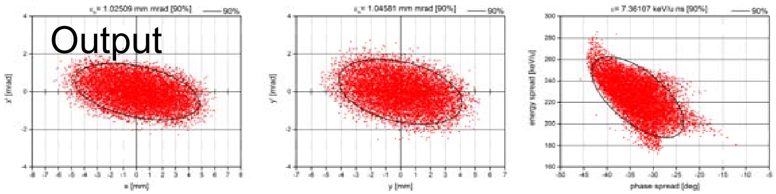
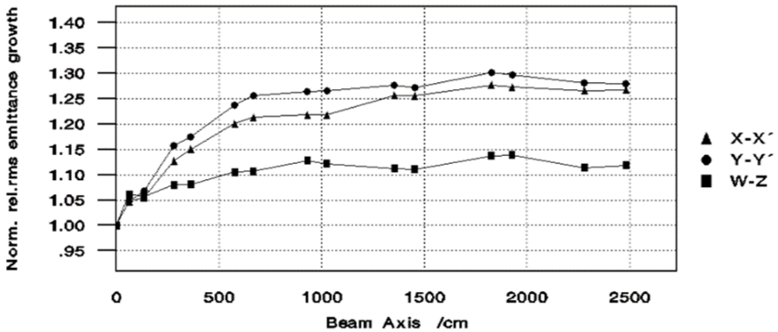
IH-DTL Beam Dynamics

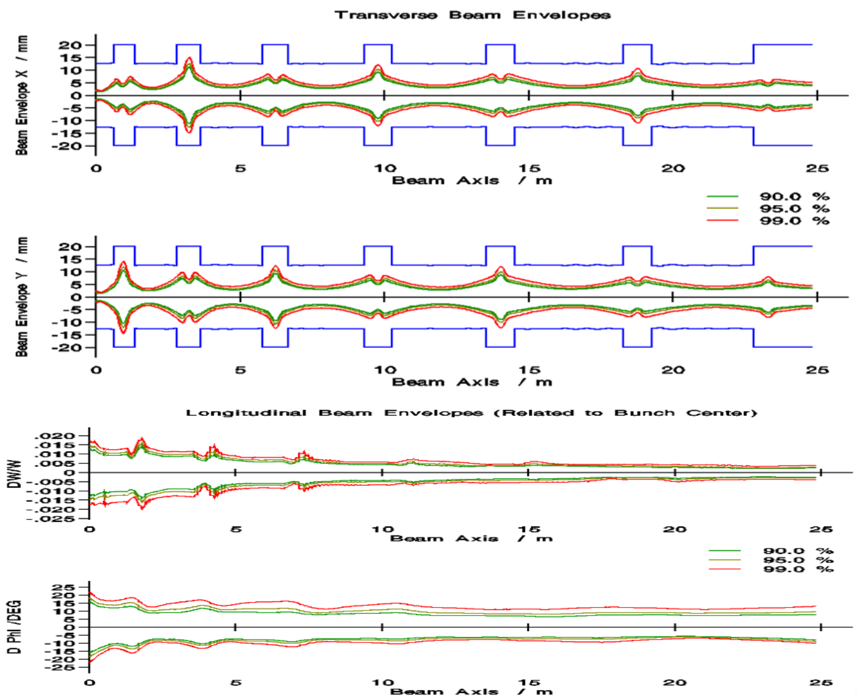
- simulated 16.7 mA U^{28+} with 15 mA within 1 mm mrad at the exit (almost FAIR requirement)

- emittance growth :
    - 30% transv.
    - 12 % long.



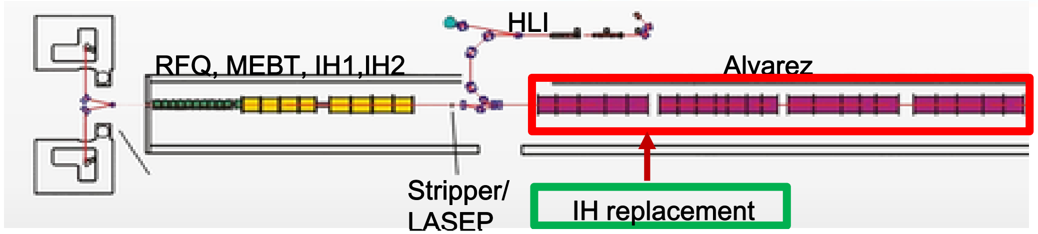


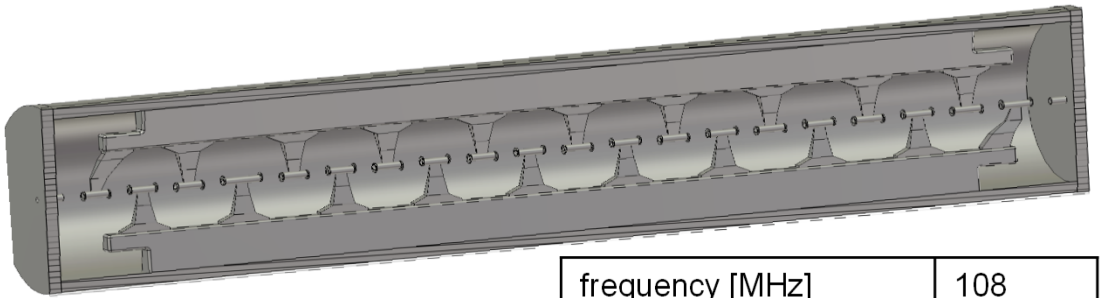


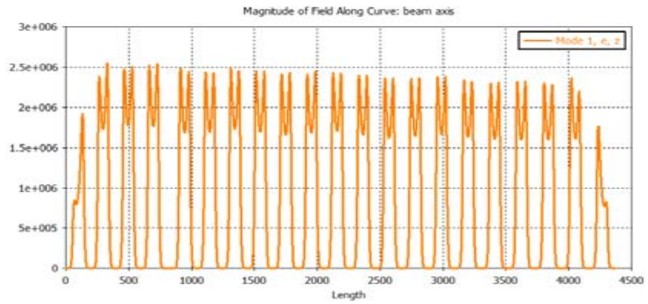


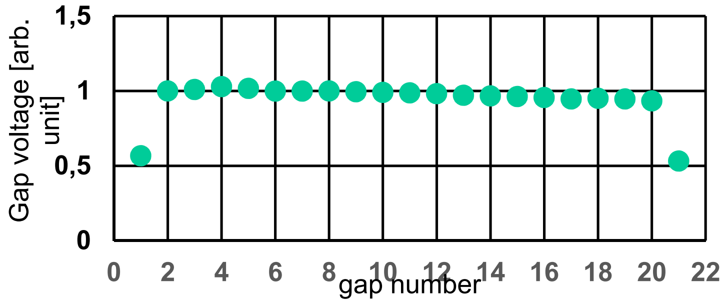
IH-DTL CST Simulation

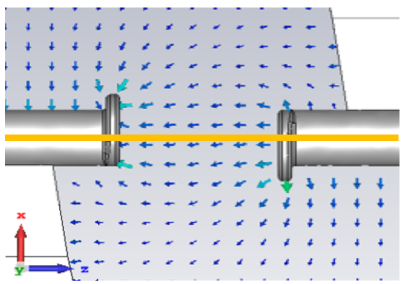
- 21 gaps (0°- and rebunching-section)
- optimization of field distribution by
  - girder undercuts
  - tilted outer stems
  - drift tube dipole correction
- power requirement calculated based on CST simulations (table)











frequency [MHz]	108
tank diameter [cm]	80
tank length [m]	4.4
P_{beam} [kW]	290
P_{loss} [kW]	760
P_{total} [MW]	**1.1**
Z_{eff} [MΩ/m]	**100**
Q-value	32000

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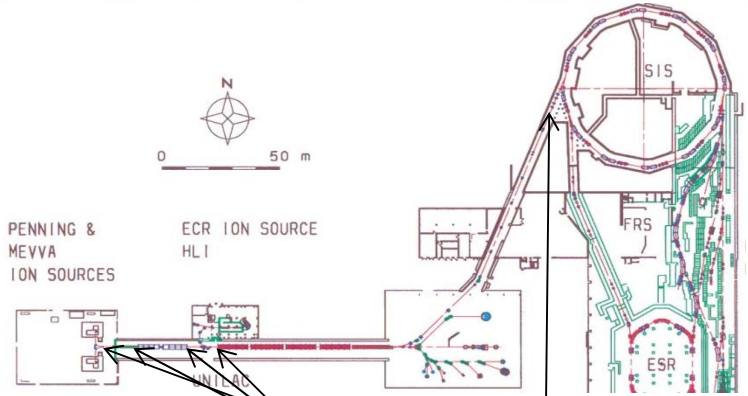
Estimate of attainable $^{238}U^{28+}$ Performance & Schedule



2014/15	concepts
2015	prototyping conceptual design
2016/17	final design
2017/18	tendering
2018/19	fabrication
2020	assembly
2021	commissioning

beamline section	current change factor	rel. emit. growth [%]	brilliance change factor	current [mA]	hor. emittance (norm., tot.90%)	upgrade activity
				18,0	0,38	source development
LEBT + RFQ	0,9	15	0,78			RFQ upgrade
				16,2	0,44	
MEBT + IH-DTL	0,9	70	0,53			new MEBT
				14,6	0,74	
gaseous stripper (to A1)	1,26	15	1,10			routine operation pulsed stripper
				18,4	0,85	
EmTEx	0,9	-60	2,25			installation
				16,5	0,34	
Alv-DTL, transf. to SIS18	0,85	50	0,57			new DTL
				14,1	**0,51**	
target value				**15,0**	**0,56**	

Summary

- dedicated uranium LEBT

- increase of stripping efficiency using pulsed H_2 jet ≥ 120 bar

- completely new post-stripper Alvarez DTL
  - provision of hor flat beams for MTI optimization (optional)
  - optimized DT shape wrt shunt impedance per surface field
  - varying stem orientations for parasitric mode damping
  - increase of transv focusing to avoid space charge driven resonances

- alternative DTL design based on IH-cavities followed by Univ. of Frankfurt
  - shorter DTL
  - allows for upgrade option to about 50 MeV/u

- upgrade finished in 2021

Thank you !

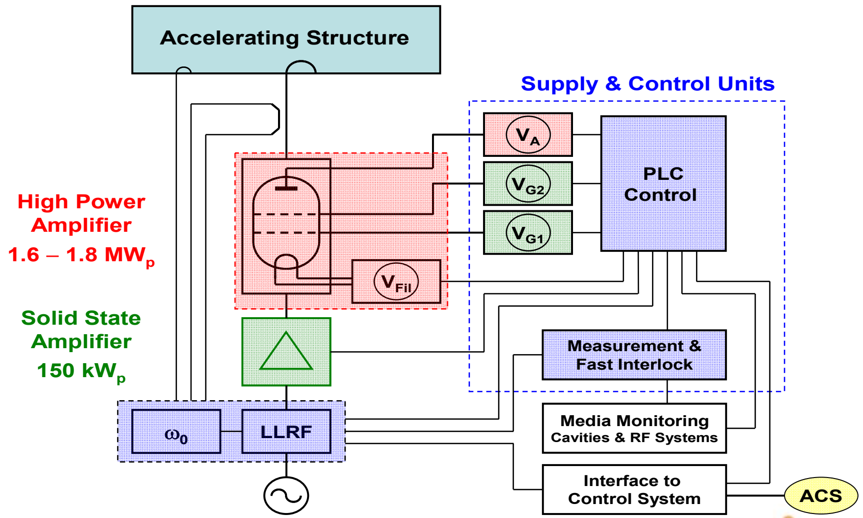
New DTL Parameters, Rf-Power

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 !

new rf-equipment for short pulses:



- 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