High Brilliance uranium beams for FAIR

Winfried Barth, GSI&HIM

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2. High intensity proton beam measurements at GSI-UNILAC
3. Pushing the limits for uranium beam operation
4. Heavy ion stripping
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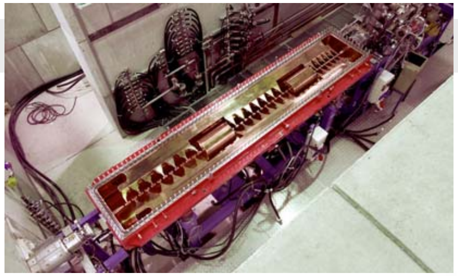
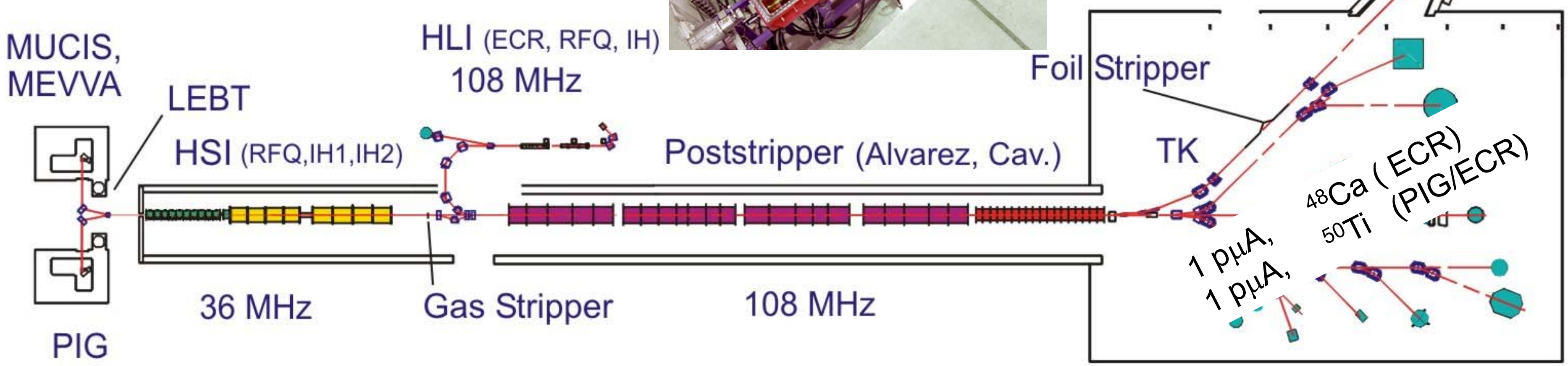
The GSI UNIversal Linear ACcelerator

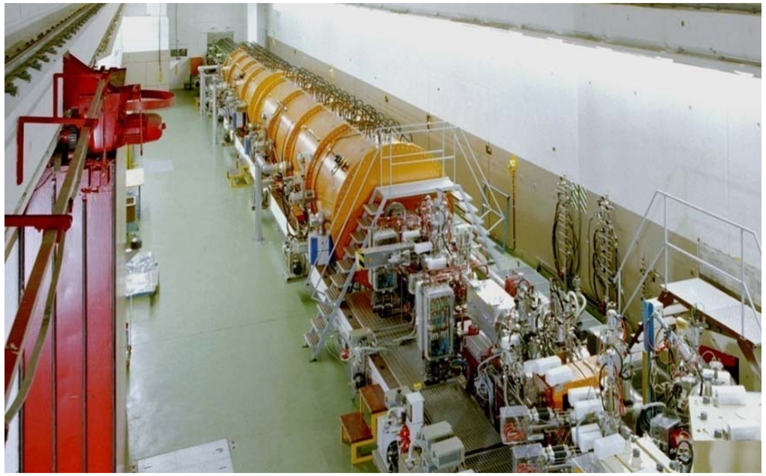
High Charge State Injector (1991)



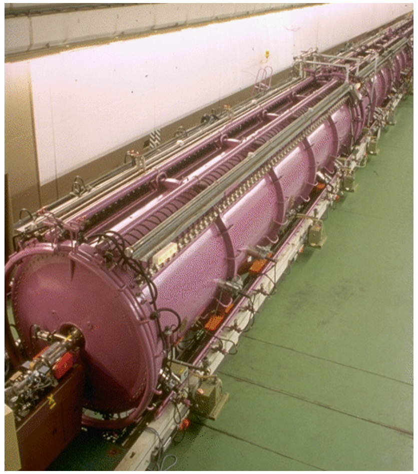
0.1 emA, p+ (MUCIS)
4.5 emA, 238U28+ (MeVVa)
to SIS 18



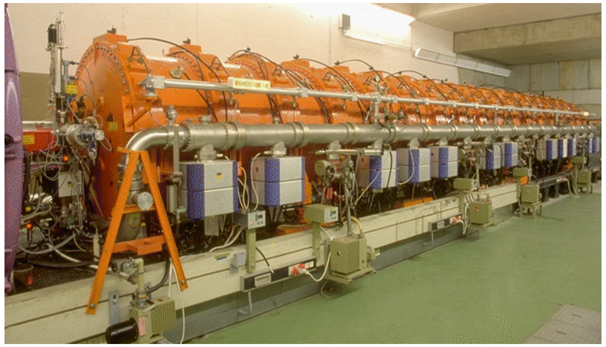
High Current Injector (1999)



Alvarez (1975)

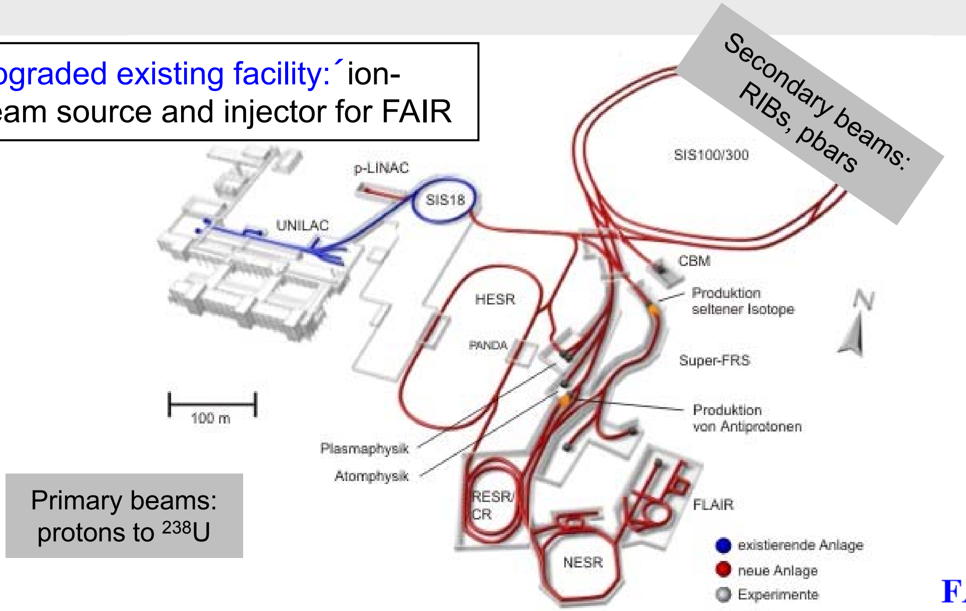


Single Gap Resonators (1975)



Facility for Antiproton and Ion Research

Upgraded existing facility:´ion-beam source and injector for FAIR



New future facility: ion and anti-matter beams of highest intensities and high energies

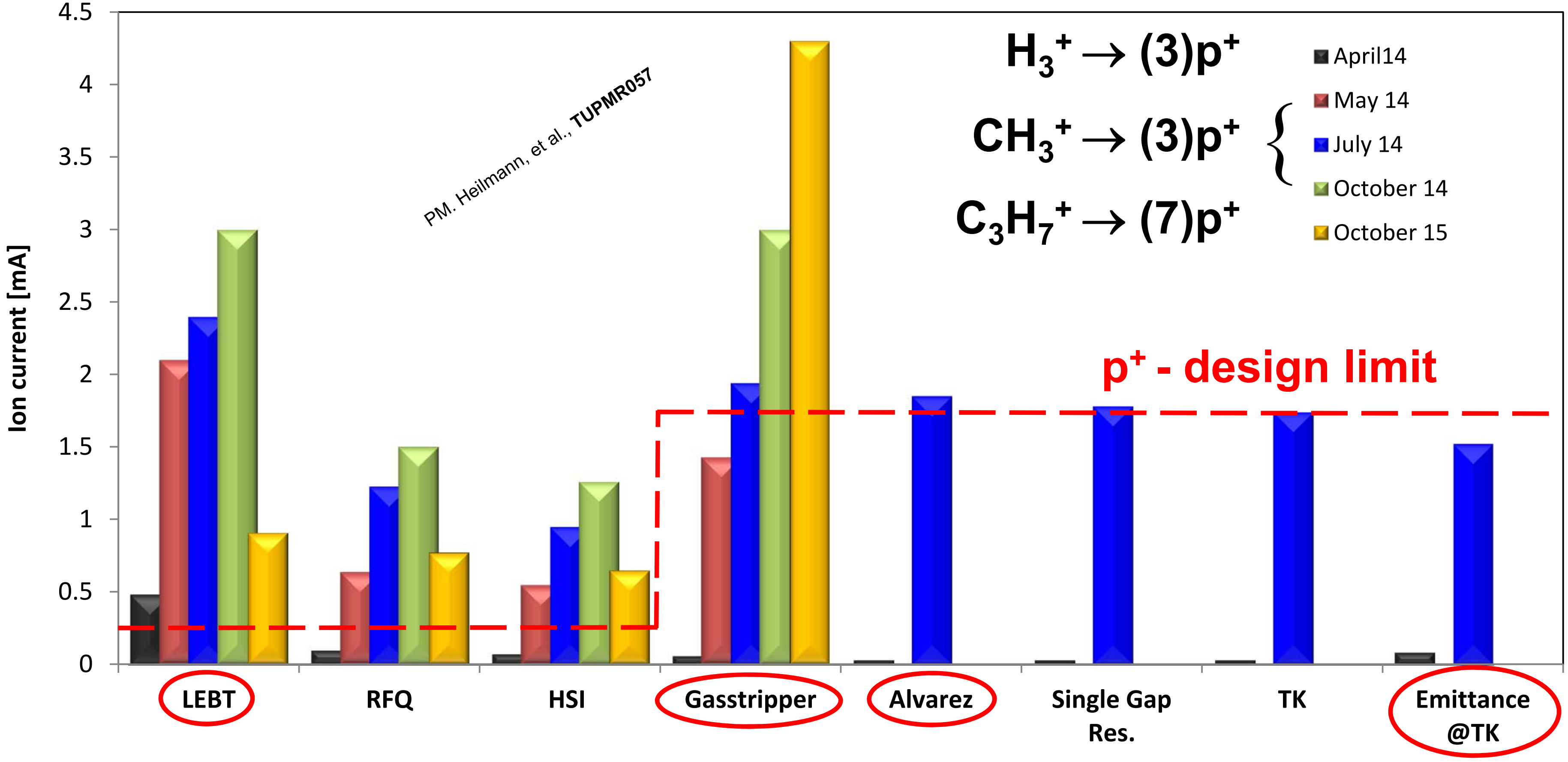
Accelerator Components & Key Characteristics

Ring/Device	Beam	Energy	Intensity
SIS 100 (100Tm)	protons	30 GeV	4×10^{13}
	^{238}U	1 GeV/u	5×10^{11}
	(intensity factor 100 over present)		
SIS 300 (300Tm)	^{40}Ar	45 GeV/u	2×10^{9}
	^{238}U	34 GeV/u	2×10^{10}
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim10^{11}$
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

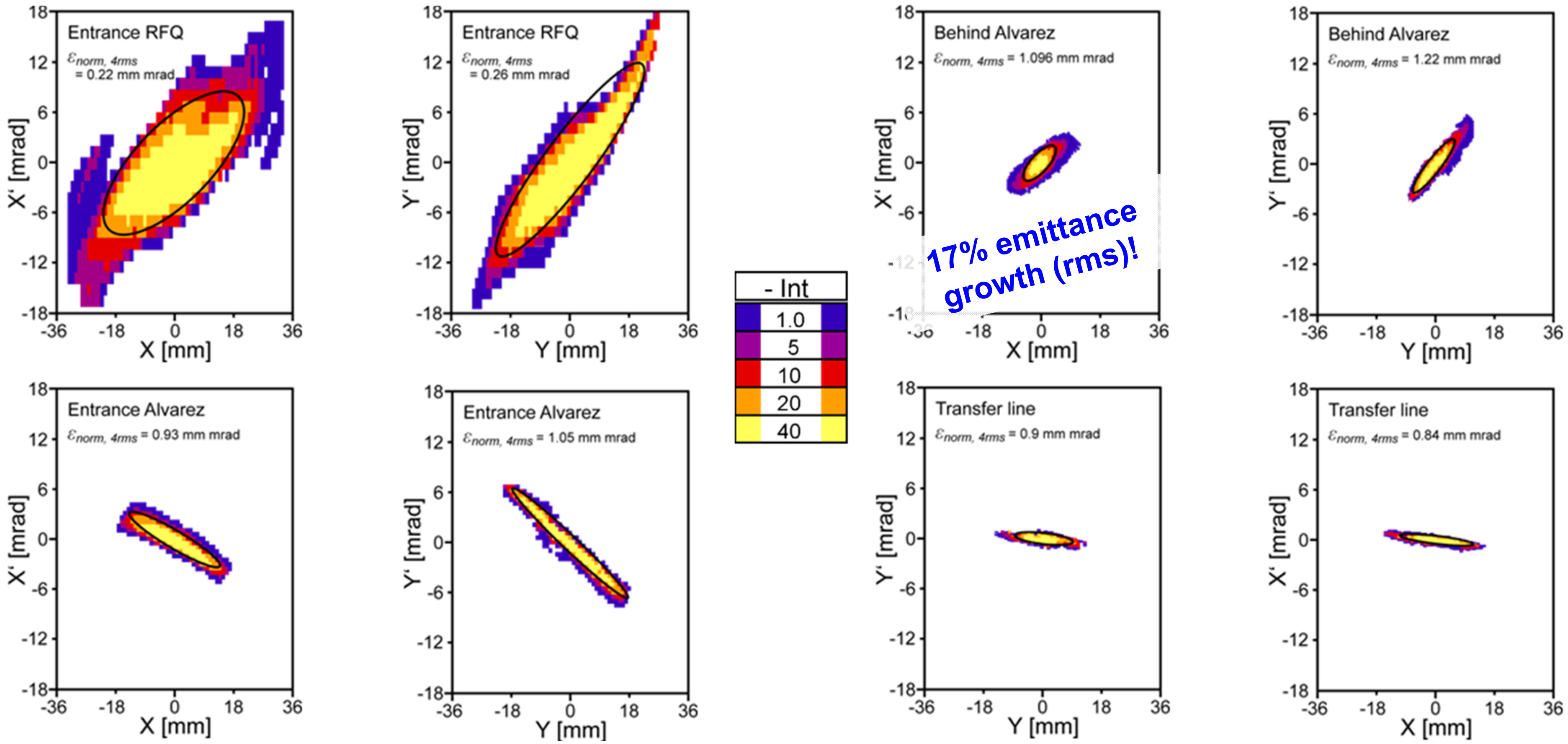
FAIR-design uranium beam parameters at the UNILAC

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$
Elect. Current [mA]	25	18	15	15.0
Part./100μs pulse	$3.9\cdot10^{12}$	$2.8\cdot10^{12}$	$3.3\cdot10^{11}$	$3.3\cdot10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4
ΔW/W	-	$4\cdot10^{-3}$	$\pm1\cdot10^{-2}$	$\pm2\cdot10^{-3}$
$\varepsilon_{norm,x}$ [mm mrad]	0.3	0.5	0.75	1.0
$\varepsilon_{norm,y}$ [mm mrad]	0.3	0.5	0.75	2.5

High intensity proton beam measurements at GSI-UNILAC



Front to end emittance measurements with a high current proton beam

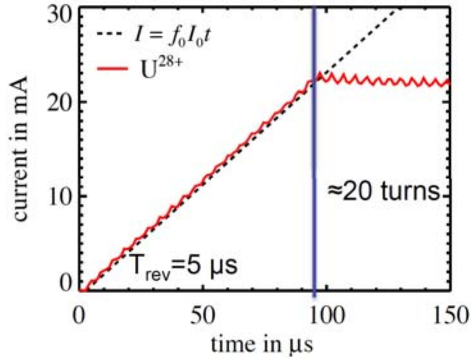


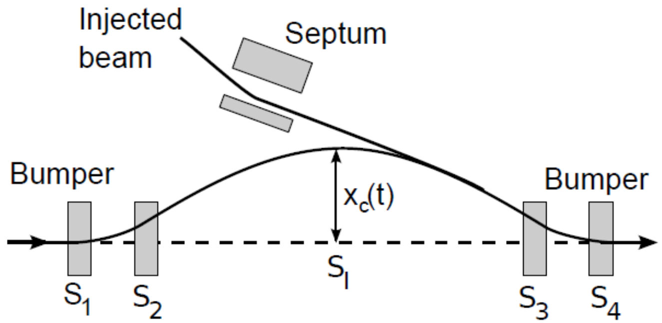
W. Barth, et al., Phys. Rev. ST Accel. & Beams 18, 050102 (2015)

High Current Proton Beam Analysis

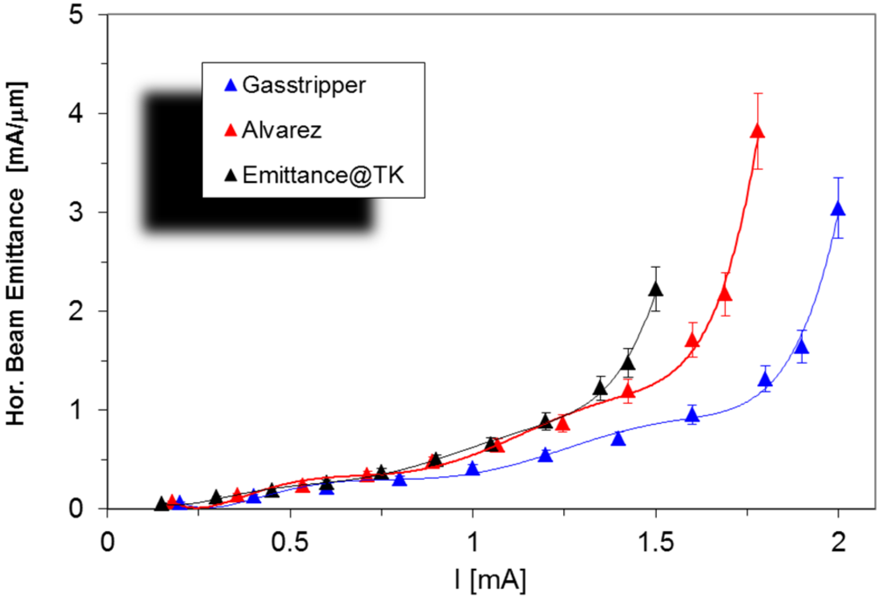
Horizontal multi-turn injection into SIS18

- **Beams are stacked until machine acceptance is reached**
- **Loss should be as low as possible due to activation, damage, vacuum**

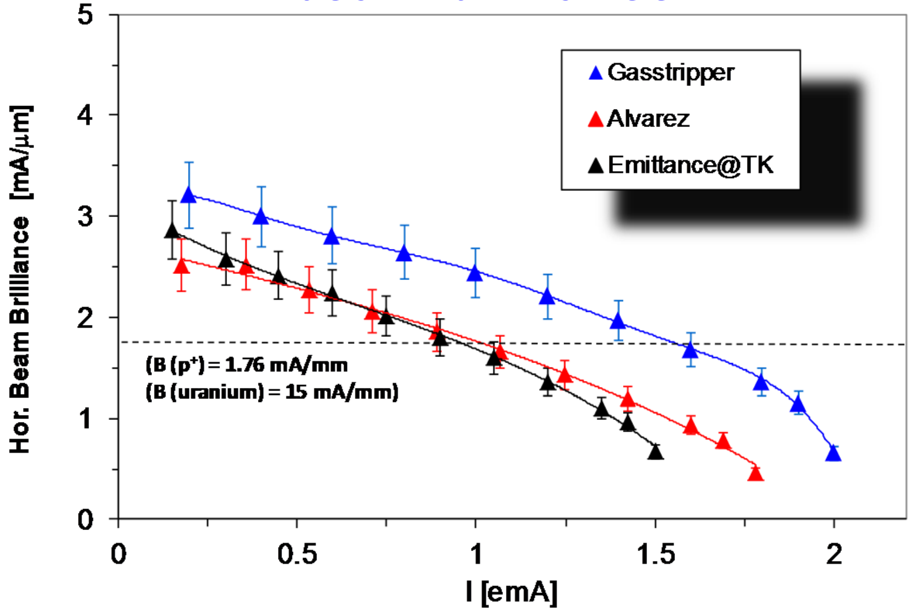




beam emittance



beam brilliance



Pushing the limits for uranium beam operation

- **Ion Source:** Applying a multi-aperture extraction system at the VARIS ion source → Increased U^{4+}-intensity and improved primary beam brilliance

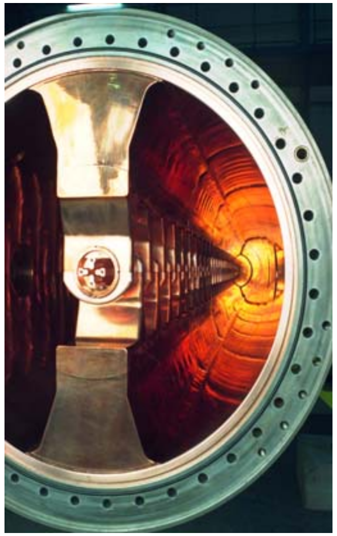
- **Low Energy Beam Transport:** Improved LEBT-performance and RFQ-Matching using high brilliance uranium beam from the VARIS → 70% RFQ-Transmission (I_{out} = 9.7 emA)

- **RFQ:** RF optimization by adjusting plunger positions at the HSI RFQ tank and extensive rf-conditioning → Reduction of forwarded rf-power, yielding for reliable high-current uranium beam operation.

- **MEBT:** Optimizing transport between RFQ and IH DTL by increasing the transverse and longitudinal focusing strength (3%) → Reduction of beam loss, stable high current operation

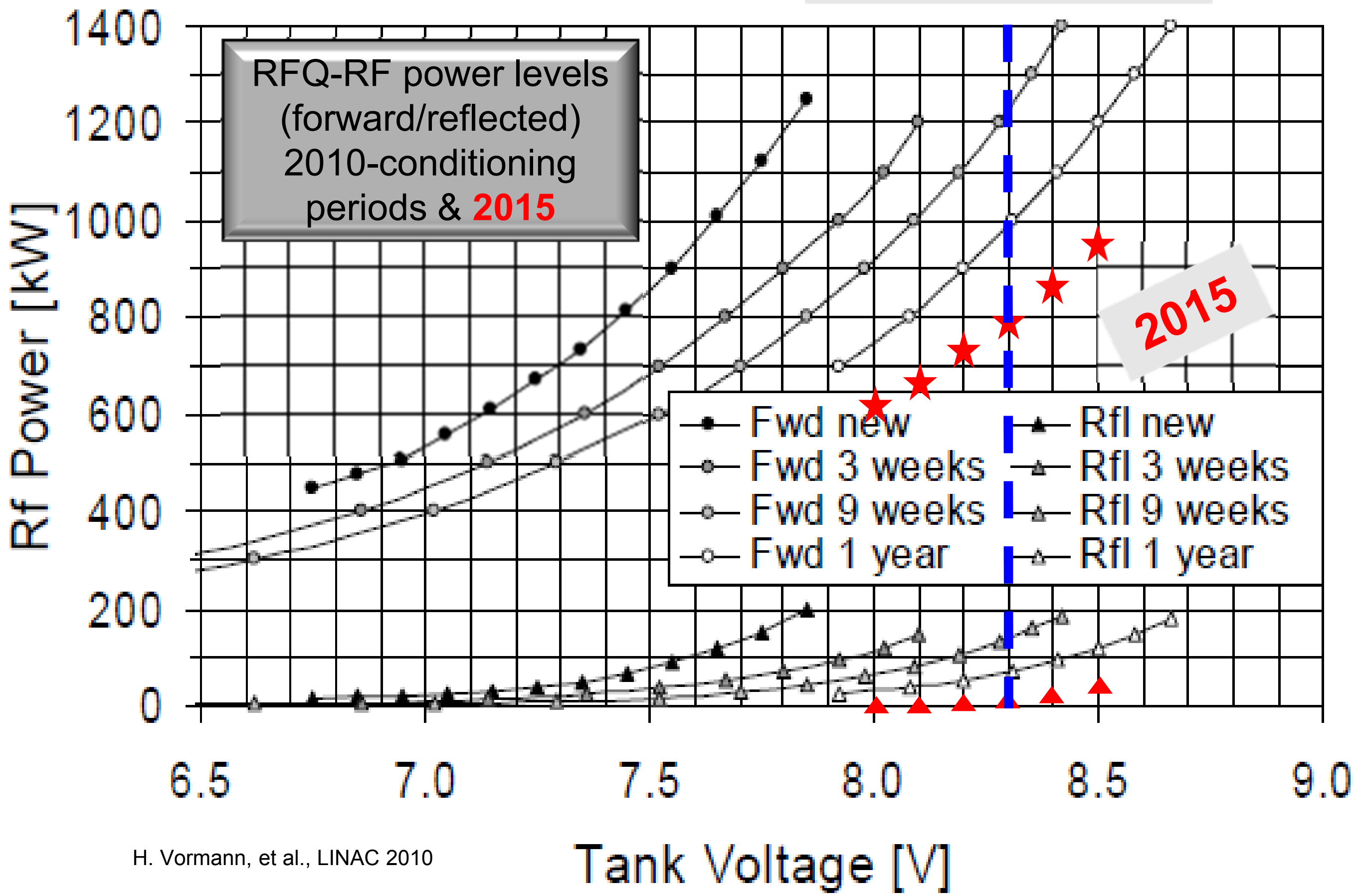
- **1.4 MeV/u-Transport Line:** Adapting the quadrupole channel (matching the gas stripper) → 90% beam transmission, U^{4+} beam current of 6.6 emA available for heavy ion stripping.

HSI-Radio Frequency Quadrupole RF-Optimization



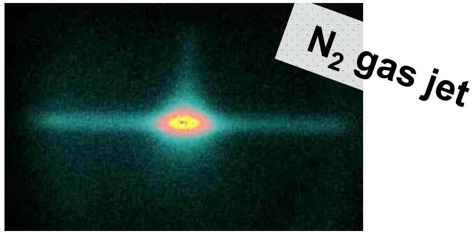
Electrode voltage / kV	155
Av. aperture radius / cm	0.6
Electrode width / cm	0.846
Maximum field / kV/cm	312.0
Modulation	1.012 – 1.93
Min. transv. phase advance / rad	0.555
Synch. Phase, degrees	-90^0 - -28^0
Min. aperture radius, cm	0.410
Norm. transv. acceptance / µm	0.856
Number of cells with modulation	394
Length of electrodes, cm	921.74

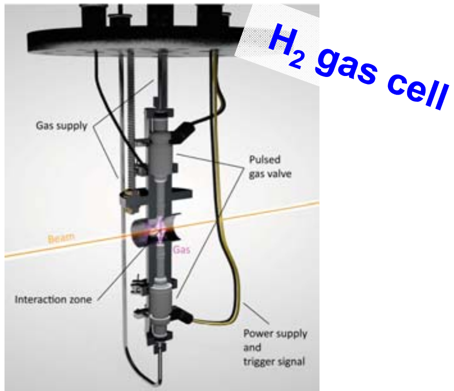
rf-voltage
(acceleration of U^{4+})

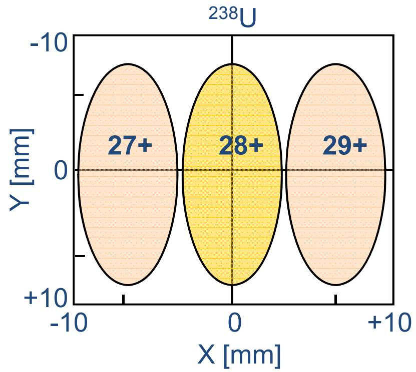


H. Vormann, et al., LINAC 2010

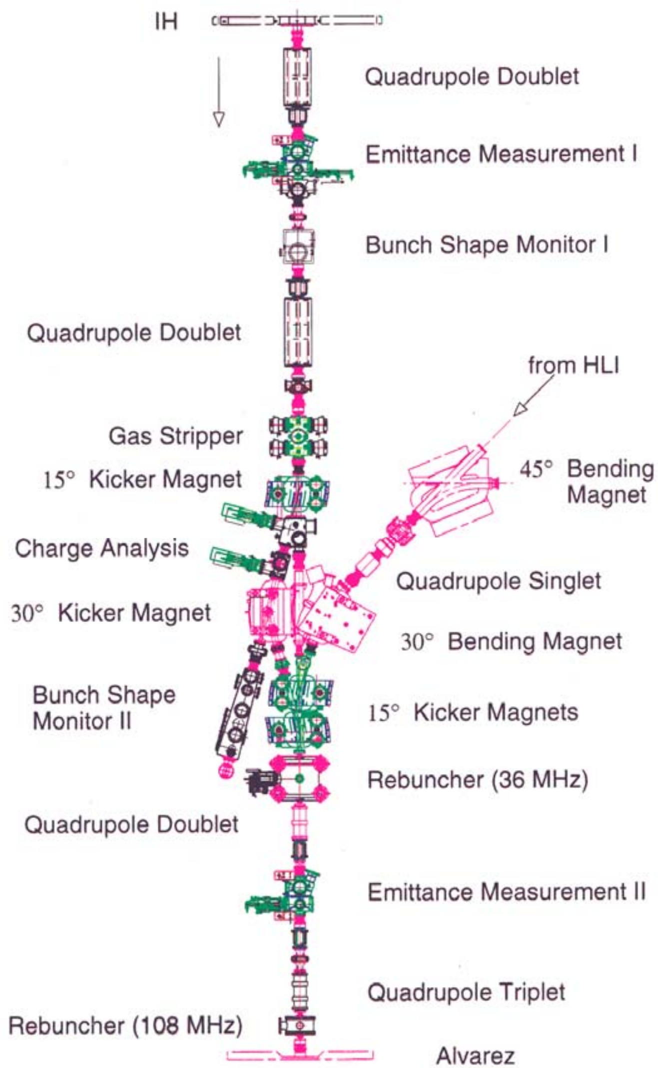
Heavy Ion Stripping







gas stripper section



- For high intensive heavy ion beams → Increase of the so called „ionic charge“ by collision with matter (= STRIPPING, Removal of electrons) → Reduction of the necessary effective potential for the acceleration of ions.
- Collision of heavy ions with matter → e⁻capture (~ $\mathbf{Z^5}$) and e⁻-loss (~ $\mathbf{Z^4}$)
- (Pulsed) H2 gas stripping cell with target thickness > 10 µg/cm²

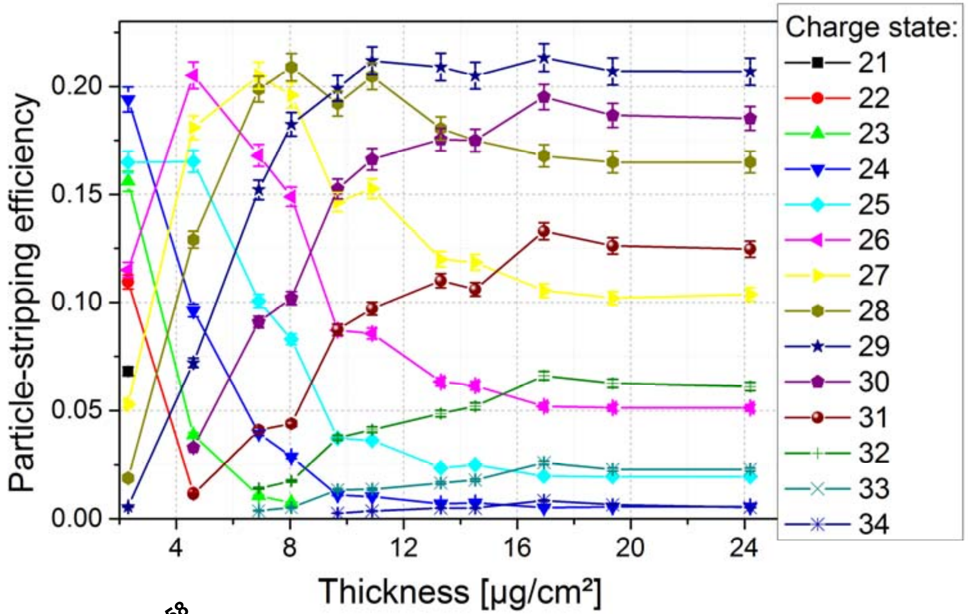
Particle Stripping Efficiency

Beam Parameters:

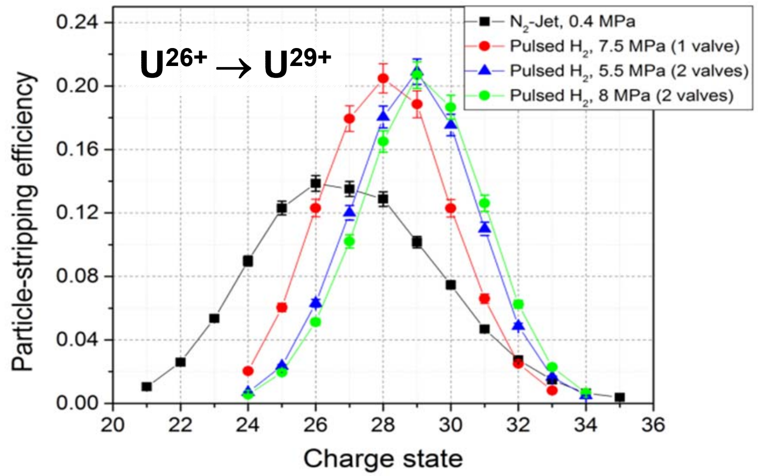
	N_2-gas jet [6]	H_2- gas cell
Stripper-back-pressure	0.4 MPa	5.5 MPa (pulsed)
U^{4+}-current (HSI)	6.0 emA	6.6 emA
Stripping charge state	28+	29+
Max.uranium-current	4.5 emA	9.97 emA
Stripping efficiency	12.7±0.5%	21.0±0.8%
Energy loss	14±5 keV/u	27±5 keV/u
ε_x (90%, tot.) norm.	0.76 μm	0.66 μm
ε_y (90%, tot.) norm.	0.84 μm	1.15 μm
Hor. brilliance (90%)	5.32 mA/μm	13.60 mA/μm

Beam Energy Loss:

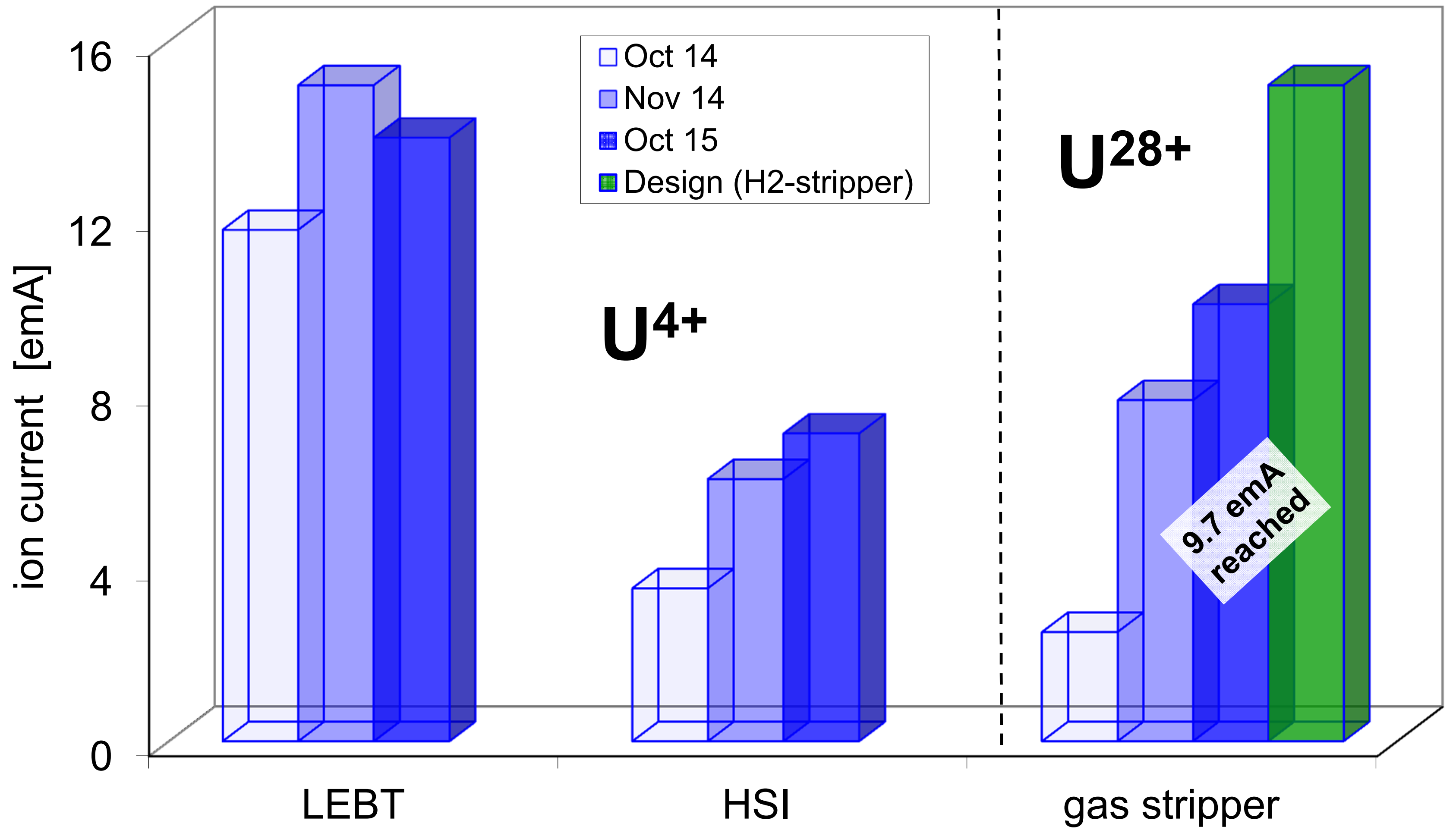
U^{28+}	N_2-jet (max.)	**14±5 keV/u**
U^{28+}	Pulsed H_2-stripper cell (1 valve, 7.5 MPa)	**17±5 keV/u**
U^{29+}	Pulsed H_2-stripper cell (2 valves, 5.5 MPa)	**27 ±5 keV/u**



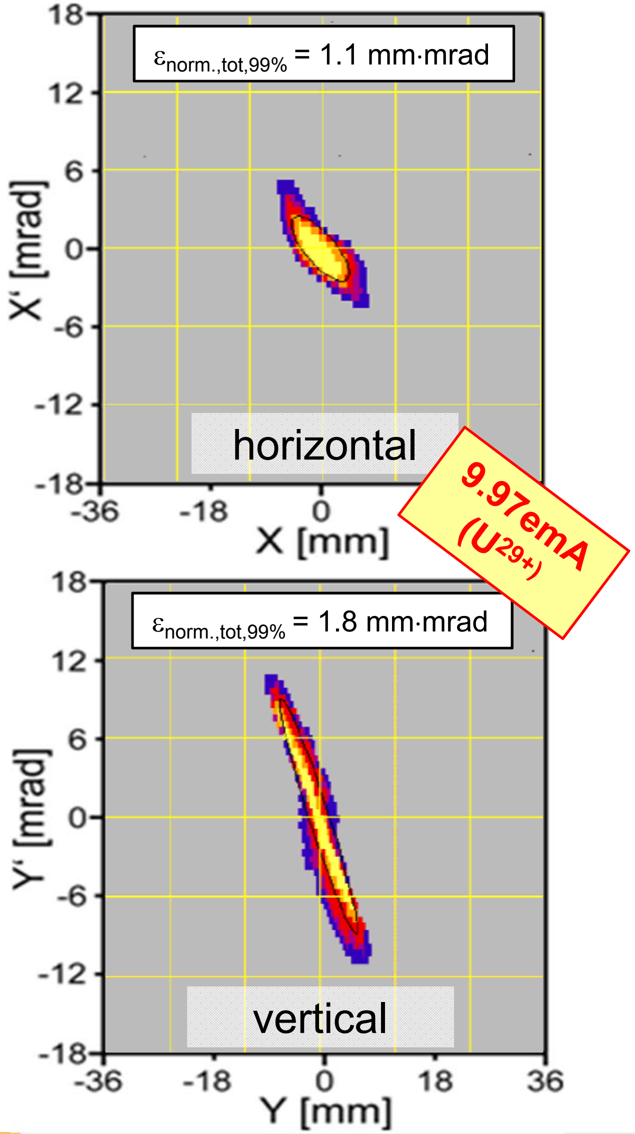
P. Scharrer, et al., TUPMR058

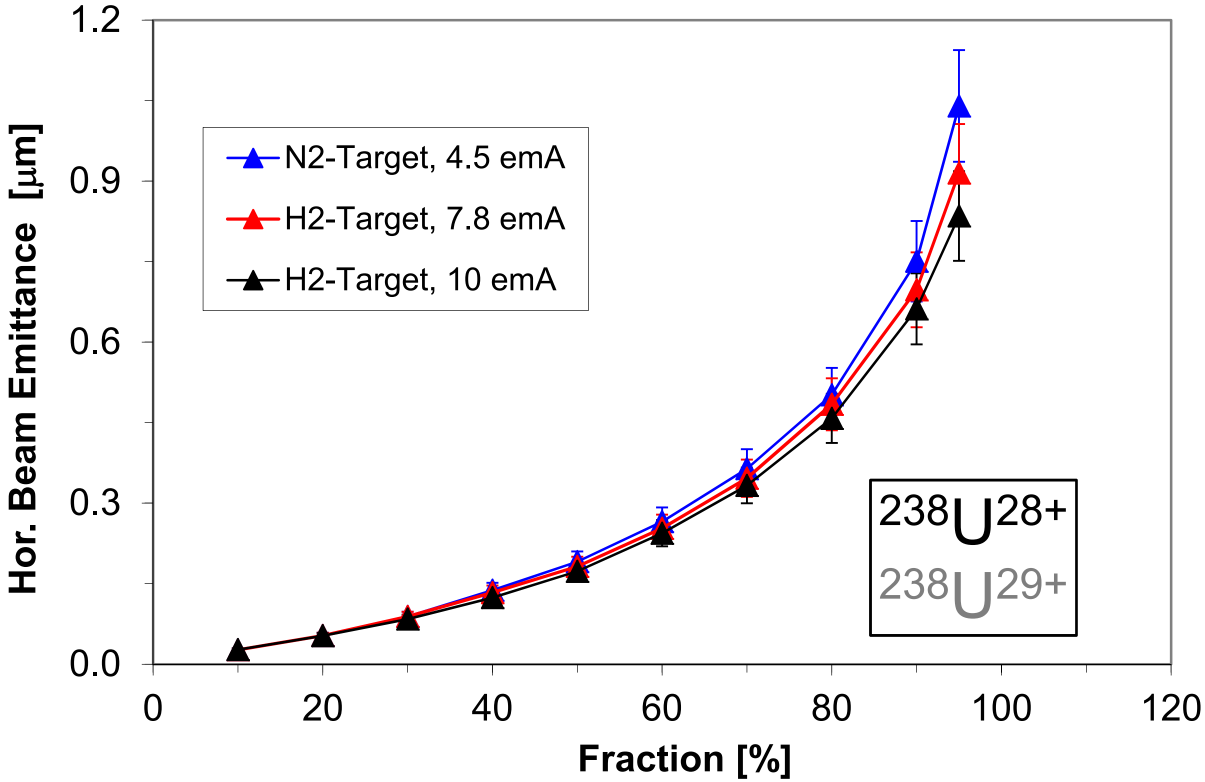


High Current Uranium Beam Transmission

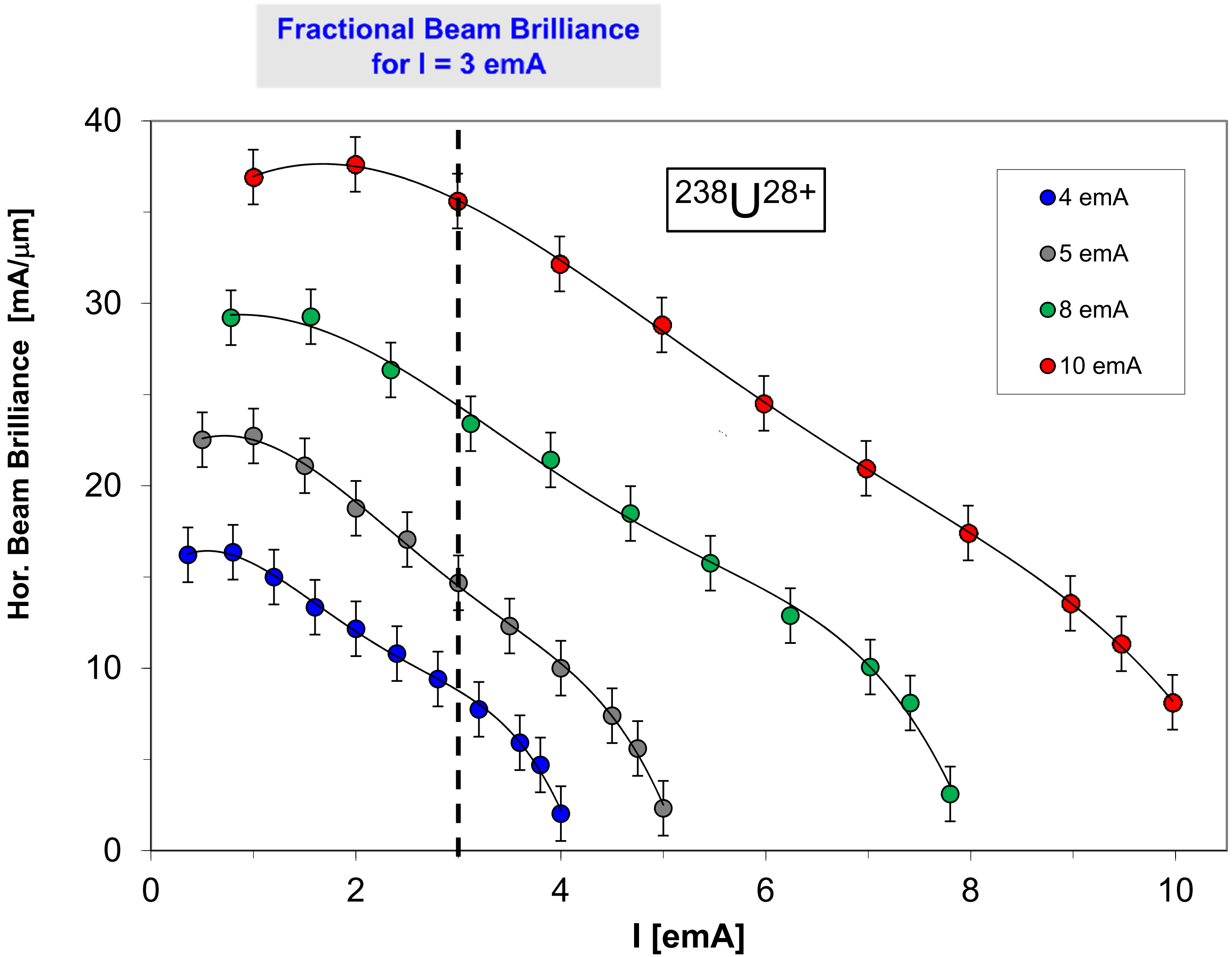


High current uranium beam emittance measurements at 1.4 MeV/u

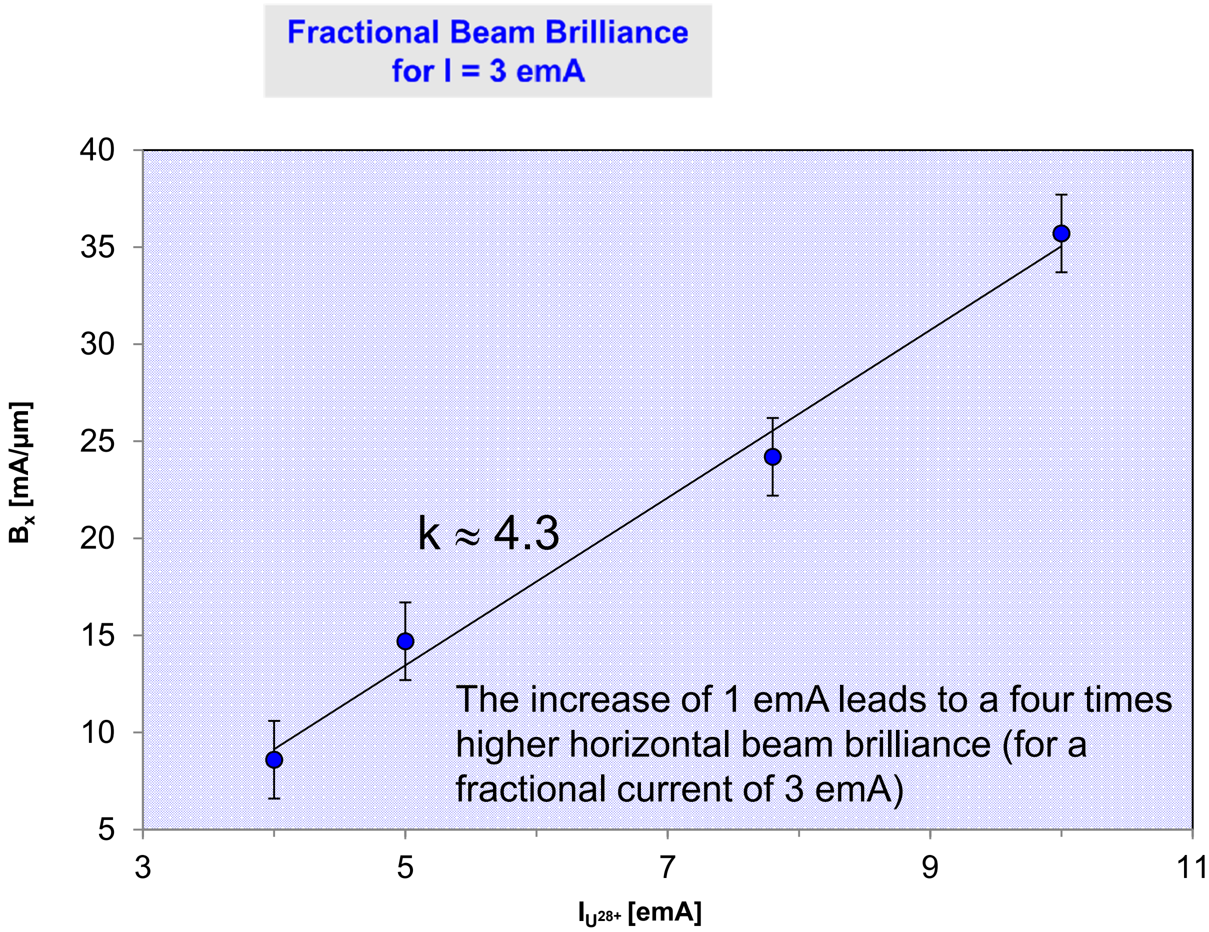




Horizontal Beam Brilliance Analysis



Horizontal Beam Brilliance Analysis



U^{28+}-beam brilliance at SIS18 injection

- Determination of U^{28+}-beam brilliance at SIS18 injection:
  - **High current U^{28+}-beam brilliance measurement at 1.4 MeV/u**
  - **Front-to-end high-current proton beam measurements (up to 11.4 MeV/u)**
- UNILAC parameters scale with the mass-to-charge ratio m/q:

$$\frac{m}{q}(scal) = \frac{m/q\,(U^{28+})}{m/q\,(p^{+})} = \frac{8.5}{1}$$

- Proton beam transmission TM_{fin} (stripper until) SIS18-injection:

$$TM_{fin}(p^{+}) = 75\%$$

- Proton rms emittance growth $EW_{fin}(p^{+})$; considering particle loss:

$$EW_{fin}(p^{+}) = -3\%$$

- Resulting proton beam brilliance loss $BL(p^{+})$:

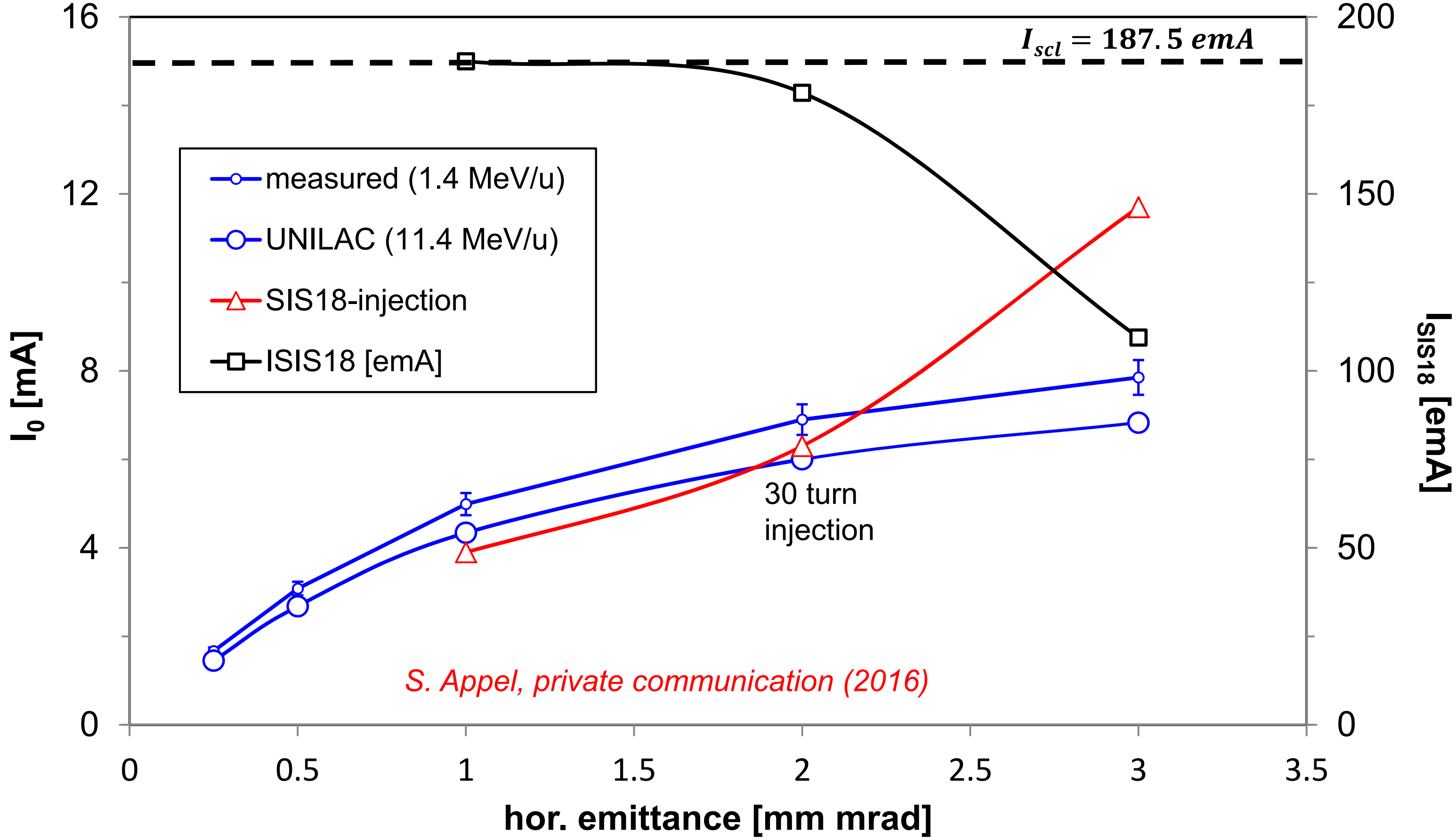
$$BL(p^{+}) = 100\% - \frac{TM_{fin}(p^{+})}{100\% + EW_{fin}(p^{+})} \cdot 100\% \approx 23\%$$

- Assuming brilliance loss scales with ion current density $\rightarrow$ brilliance loss $BL(U^{28+})$ for the measured maximum uranium beam current (for charge state 28+) of 9.70 emA:

$$BL(U^{28+}) = \frac{9.70emA}{2emA \cdot \frac{m}{q}(scal)} \cdot BL(p^{+}) = 0.6 \cdot 23\% \approx 15\%.$$

Loss free (high current) U^{28+}-beam injection into the GSI-synchrotron SIS18

- UNILAC beam measurement at 1.4 MeV/u
- Reduced UNILAC beam brilliance at SIS18 injection
- SIS18-beam intensity to achieve space charge limit ($2 \cdot 10^{11}$ part. per pulse)
- SIS18-beam intensity after multi turn injection ($I_{scl} = 187.5\ emA$)



Summary and Outlook

- Loss-free injection into the SIS18 is a necessary condition, especially for operation with high intensity (medium charge) heavy ion beams.
- By horizontal collimation of the UNILAC beam emittance in the transfer line, the SIS18 space charge limit could be reached at significantly lower peak currents, but accordingly longer injection times (55 µs → 138 µs)
- The conducted high current proton beam emittance measurement throughout the UNILAC shows a loss of horizontal beam brilliance of 23% → the high current uranium beam brilliance (measured at 1.4 MeV/u) grows until SIS18 injection accordingly.
- 30 turns have to be injected in the SIS 18 to fill up to the SCL (Design: 12 turns; I_{unilac} = 15 emA)
- For further confirmation, it is evident to perform uranium measurements at full UNILAC energy.
- **Through horizontal collimation (≤ 2 mm·mrad), the number of measured uranium particles in this phase space area could be sufficient to fill the SIS18 up to the space charge limit (2•10^{11} part. per pulse).**

Thank You for Your Attention!