# High Current Uranium Beam Measurements at GSI-UNILAC for FAIR

*Winfried Barth, GSI&HIM*

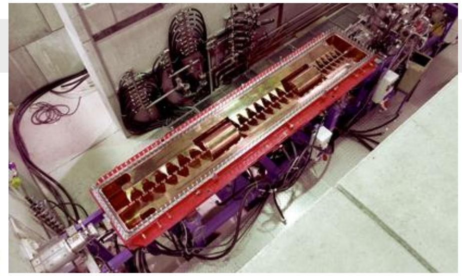
A. Adonin[2], Ch. E. Düllmann[1,2,3], M. Heilmann[2], R. Hollinger[2], E. Jäger[2], O. Kester[2], J. Khuyagbaatar[1,2], J. Krier[2], E. Plechov[2], P. Scharrer[1,2,3], W. Vinzenz[2], H. Vormann[2], A. Yakushev[1,2], S. Yaramyshev[2]

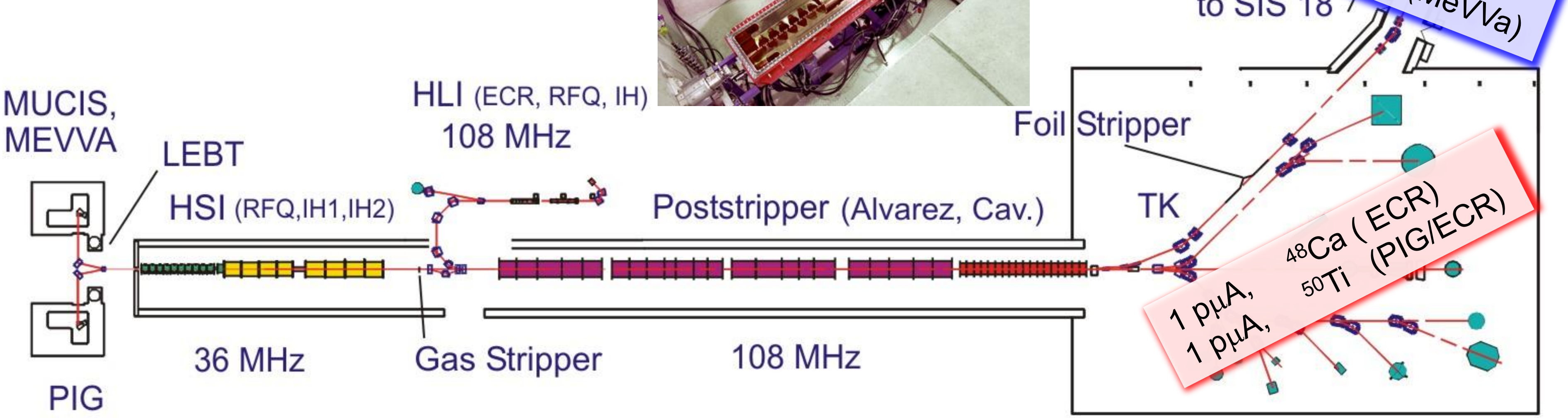
[1] Helmholtz Institute Mainz, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[3] Johannes Gutenberg-Universität Mainz, Germany

1. Introduction
2. High intensity proton beam measurements at GSI-UNILAC
3. Pushing the limits for uranium beam operation
4. Heavy ion stripping
5. beam brilliance analysis
6. $U^{28+}$-beam brilliance at SIS18 injection
7. Summary&Outlook

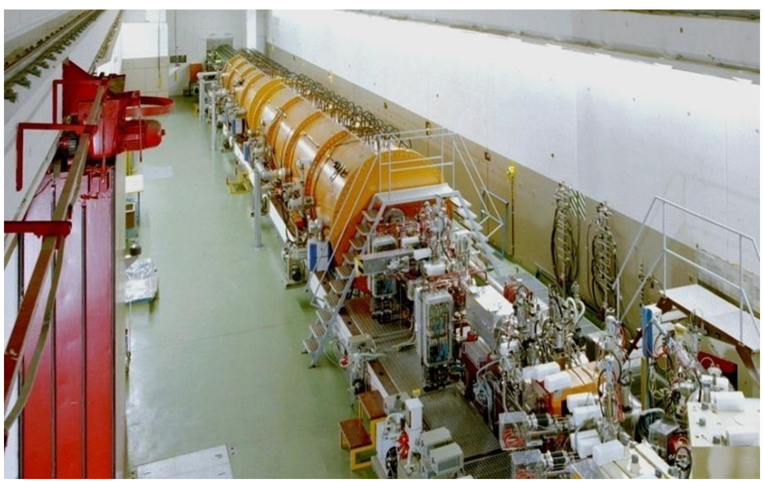
# 1. Introduction
# The GSI UNIversal Linear ACcelerator

High Charge State Injector (1991)

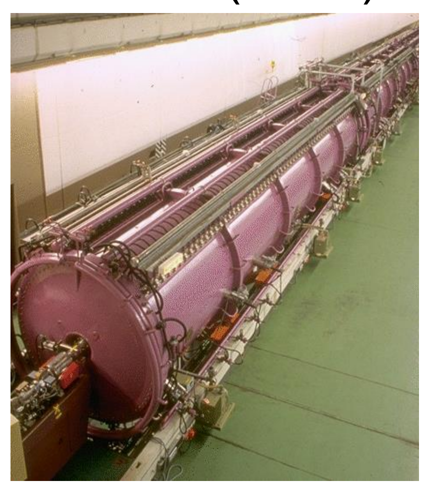





High Current Injector (1999)



Alvarez (1975)



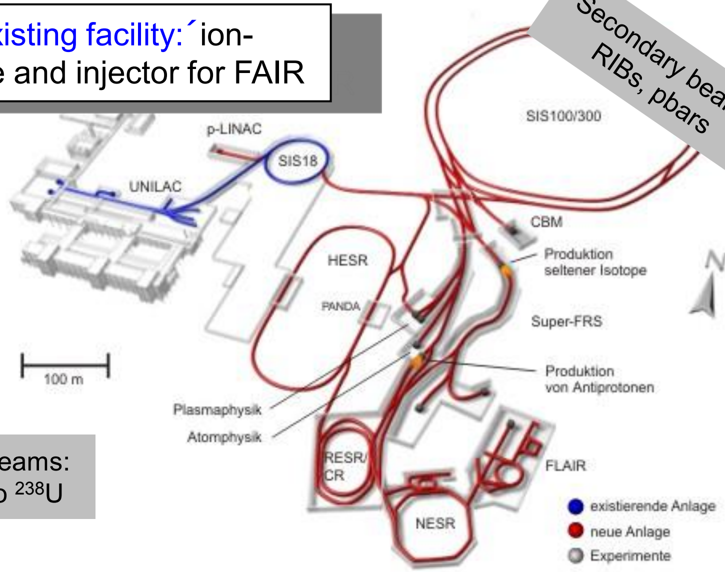
Single Gap Resonators (1975)

# Facility for Antiproton and Ion Research

GSI
HIM Helmholtz-Institut Mainz

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

Secondary beams: RIBs, pbars




Primary beams: protons to $^{238}U$

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

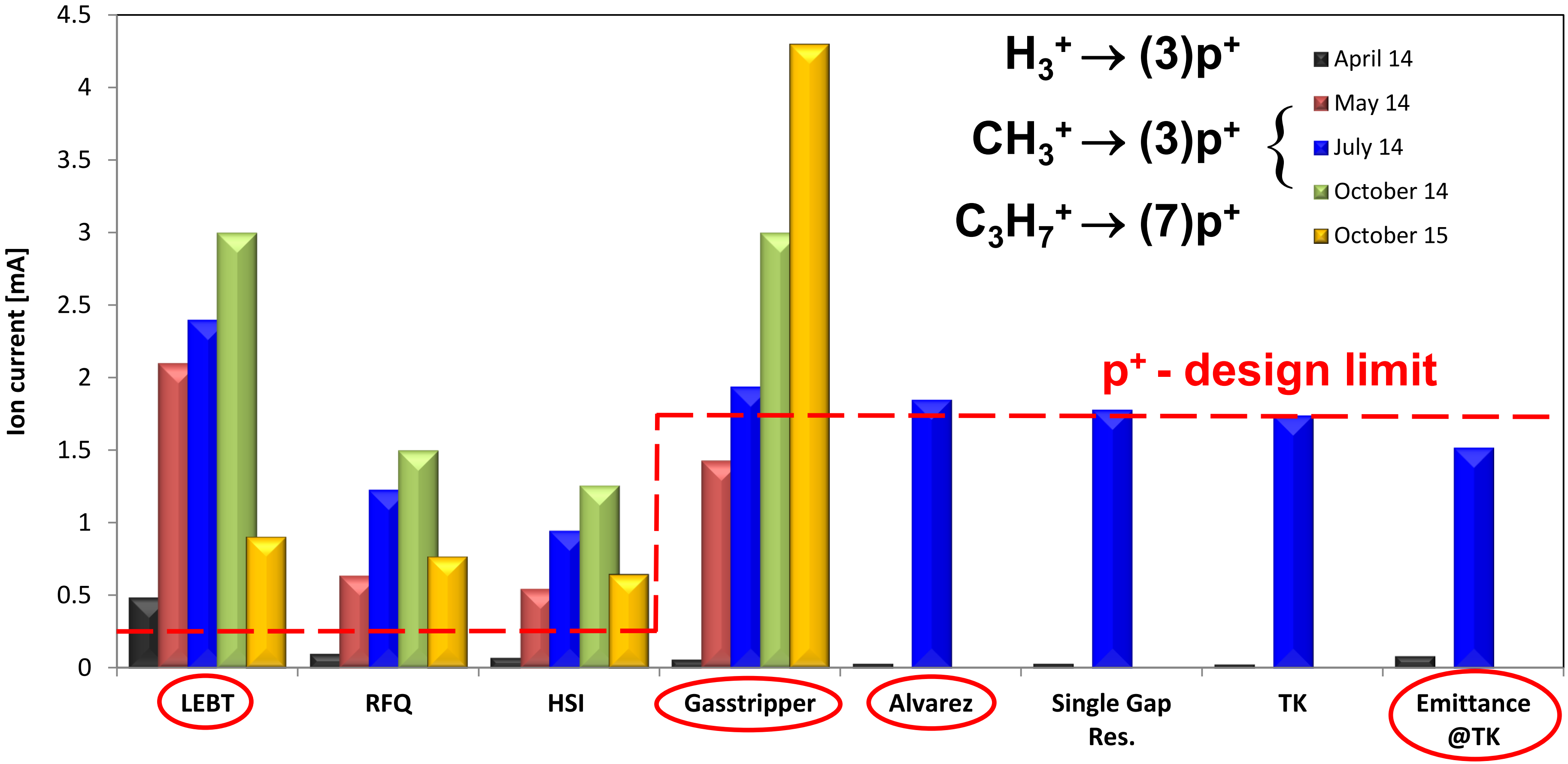
## Accelerator Components & Key Characteristics

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

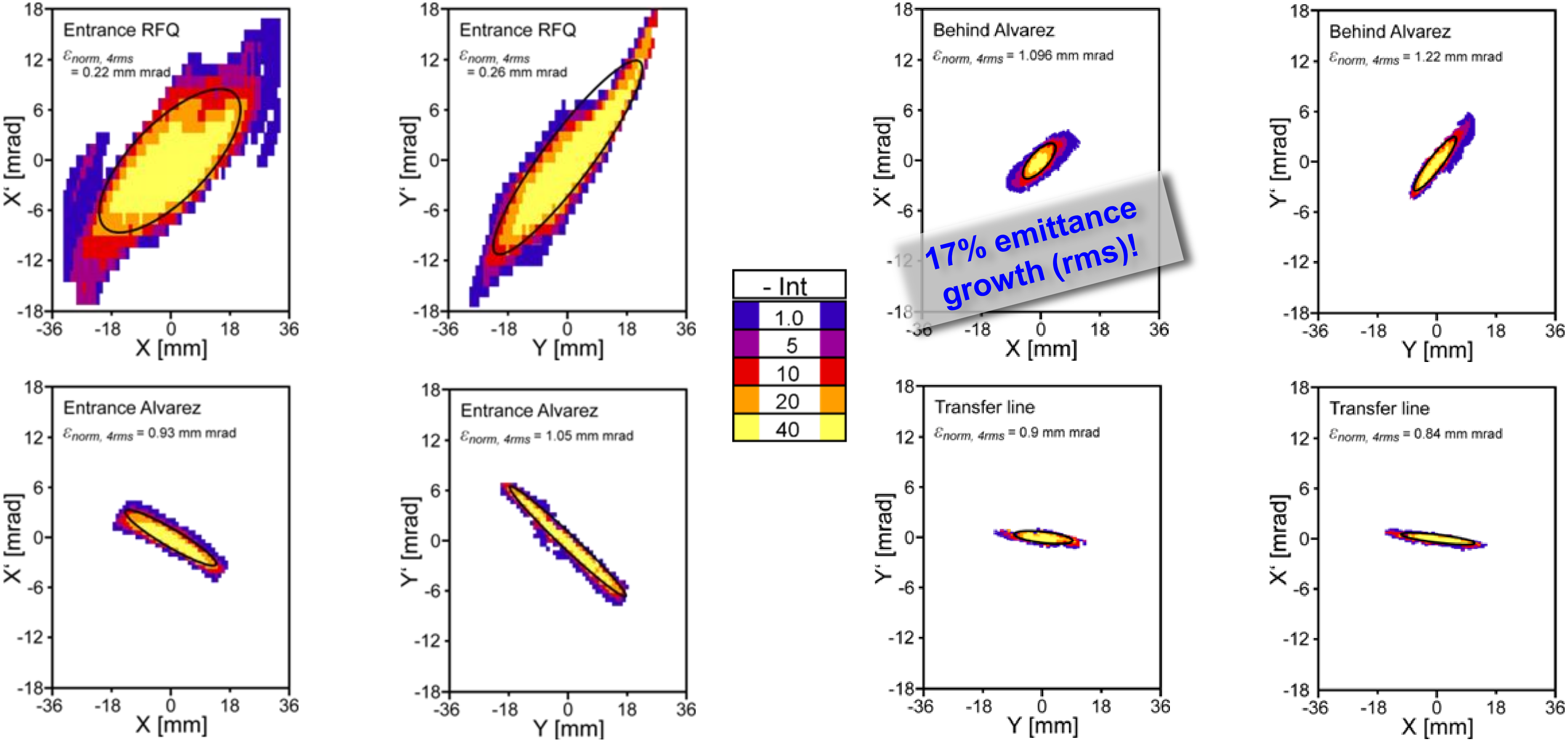
## FAIR-design uranium beam parameters at the UNILAC

| | 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 | $3.9 \cdot 10^{12}$ | $2.8 \cdot 10^{12}$ | $3.3 \cdot 10^{11}$ | $3.3 \cdot 10^{11}$ |
| Energy [MeV/u] | 0.0022 | 1.4 | 1.4 | 11.4 |
| $\Delta W/W$ | - | $4 \cdot 10^{-3}$ | $\pm 1 \cdot 10^{-2}$ | $\pm 2 \cdot 10^{-3}$ |
| $\varepsilon_{norm,x}$ [mm mrad] | 0.3 | 0.5 | 0.75 | 1.0 |
| $\varepsilon_{norm,y}$ [mm mrad] | 0.3 | 0.5 | 0.75 | 2.5 |

# 2. High intensity proton beam measurements at GSI-UNILAC



# Front to end emittance measurements with a high current proton beam

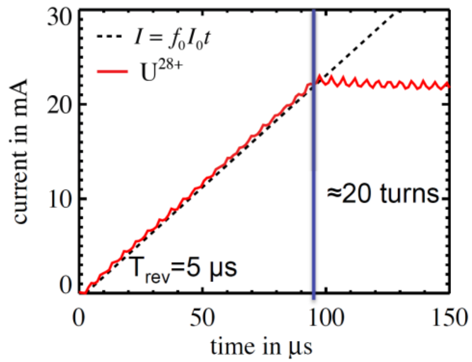


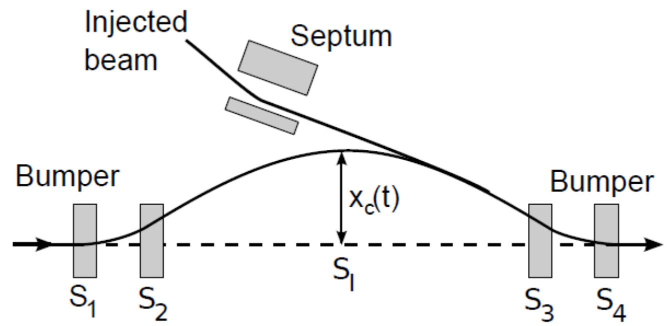

W. Barth, et al., Phys. Rev. ST Accel. & Beams 18, 050102 (2015)

# High Current Proton Beam Analysis

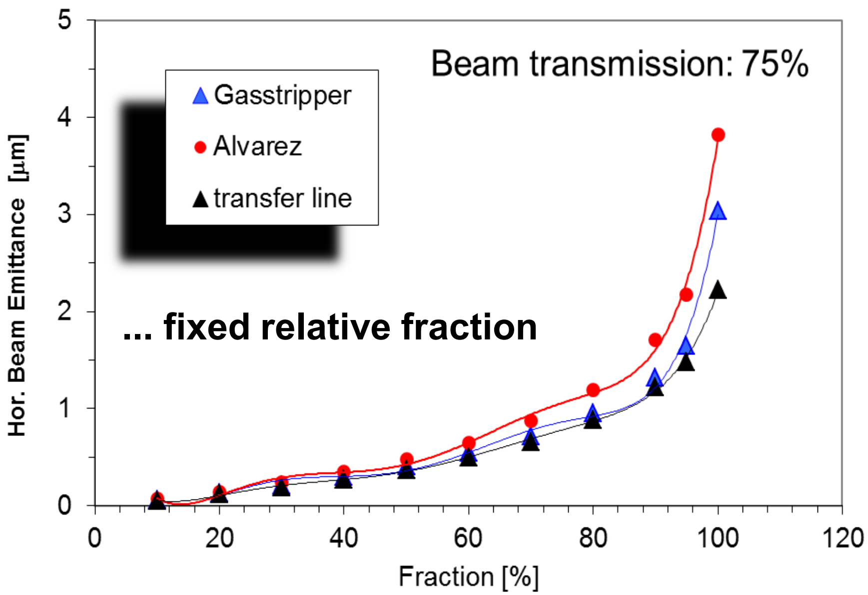
## Horizontal multi-turn injection into SIS18

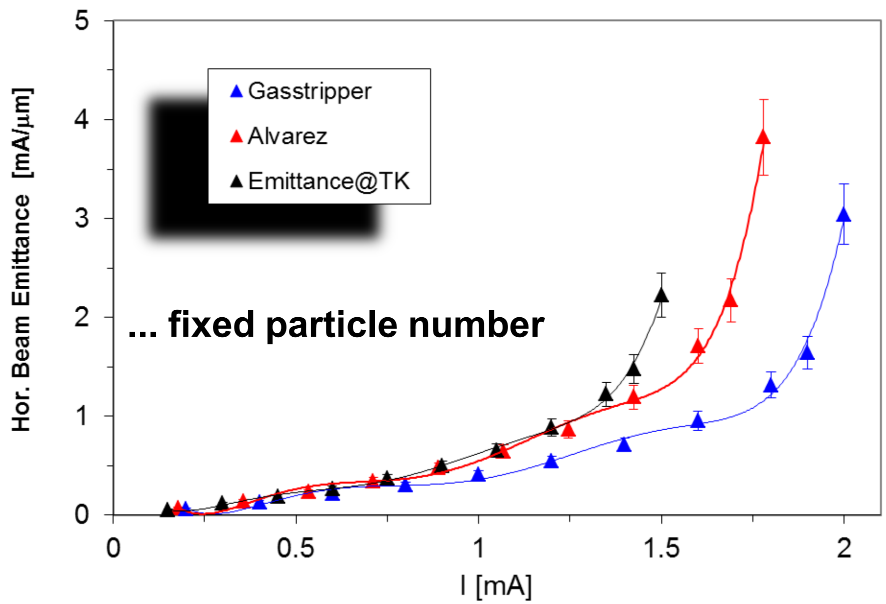
- Beams are stacked until machine acceptance is reached
- Loss should be as low as possible due to activation, damage, vacuum




## Analysis of (horizontal) beam emittance

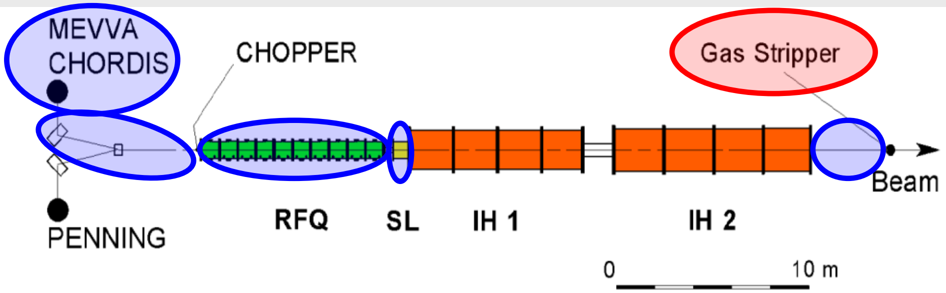


# 3. Pushing the limits for uranium beam operation

HIM Helmholtz-Institut Mainz

**High Current Injector**




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

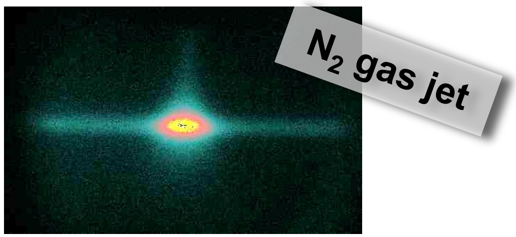
- **Low Energy Beam Transport:** Improved LEBT-performance and RFQ-Matching using high brilliance uranium beam from the VARIS → 70% RFQ-Transmission ($I_{out}$ = 9.7 emA)

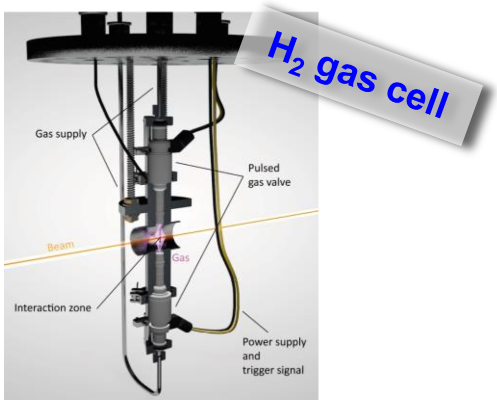
- **RFQ:** RF optimization by adjusting plunger positions at the HSI RFQ tank and extensive rf-conditioning → Reduction of forwarded rf-power, yielding for reliable high-current uranium beam operation.

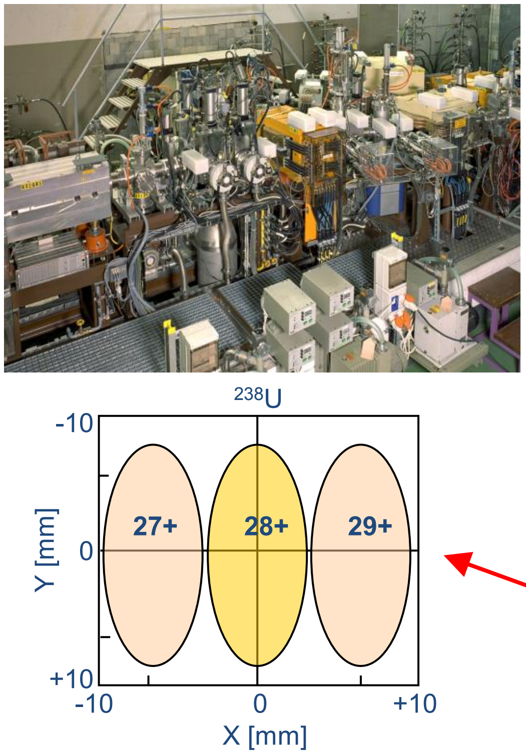
- **MEBT:** Optimizing the between RFQ and IH DTL by increasing the transverse and longitudinal focusing strength (3%) → Reduction of beam loss, stable high current operation

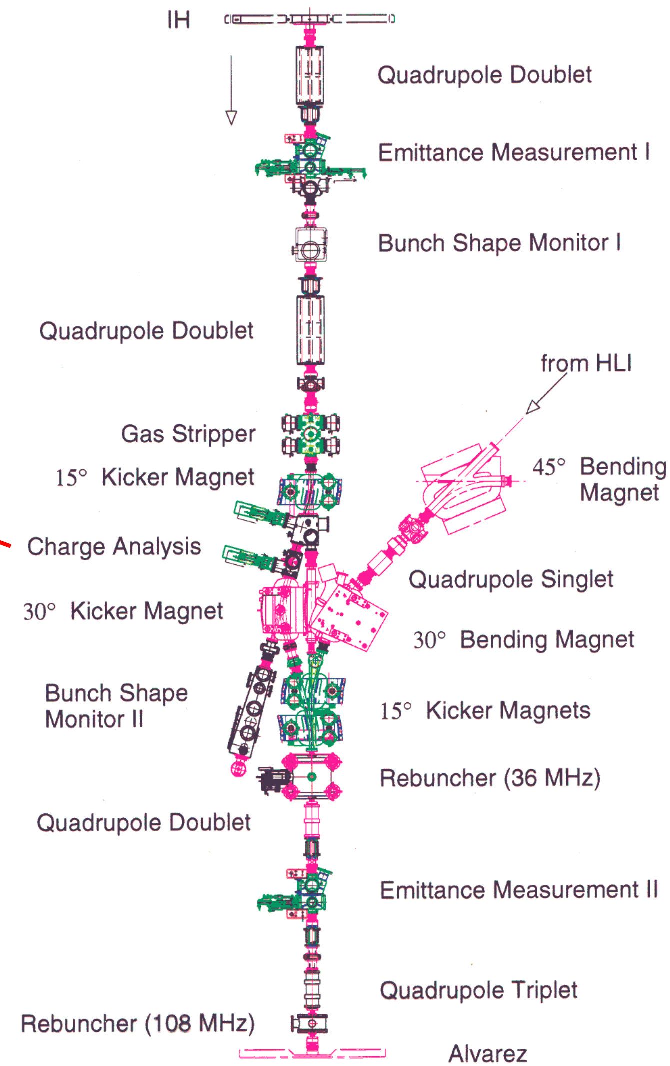
- **1.4 MeV/u-Transport Line:** Adapting the quadrupole channel (matching the gas stripper) → 90% beam transmission, $U^{4+}$ beam current of 6.6 emA available for heavy ion stripping.

# 4. Heavy Ion Stripping




- 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 (~ $Z^5$) and e-loss (~ $Z^4$)
- (Pulsed) H2 gas stripping cell with target thickness > 10 µg/cm²

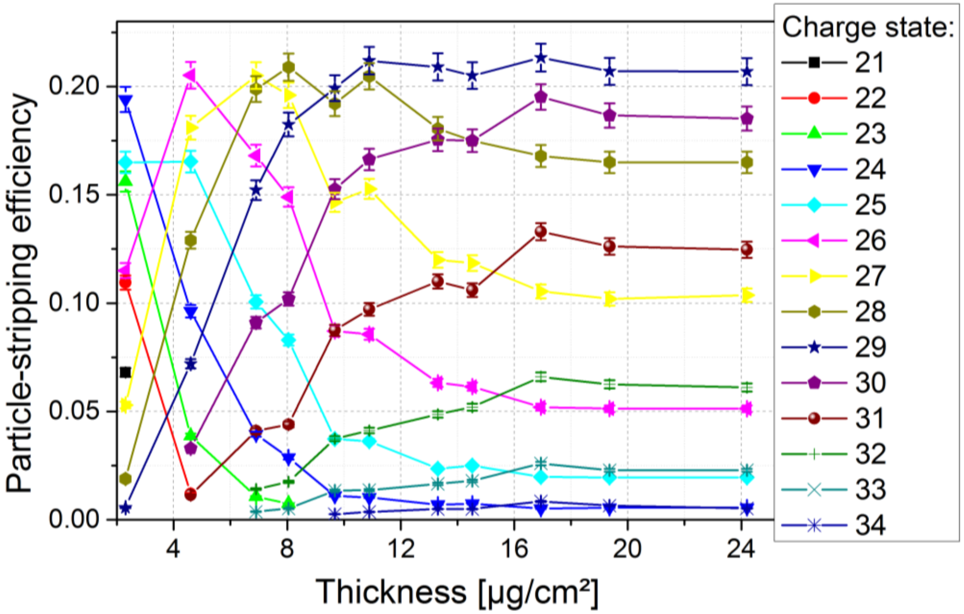
# Particle Stripping Efficiency

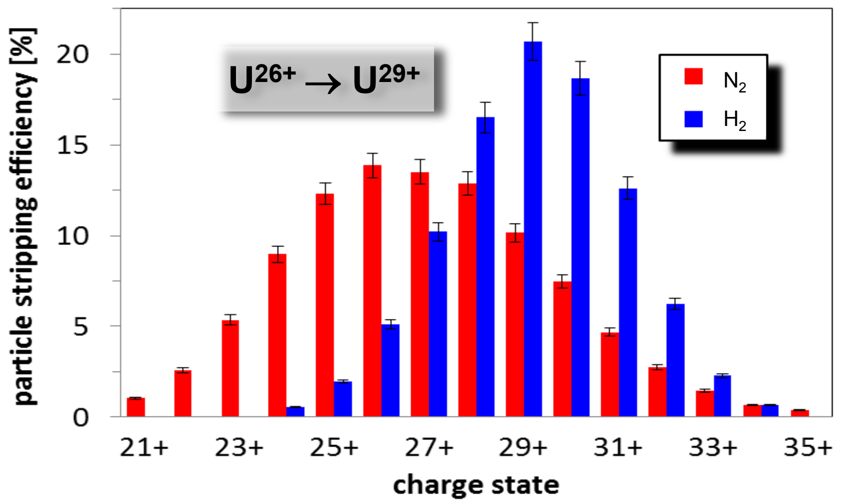
## Beam Parameters:

| | $N_2$-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 |
| $\varepsilon_x$ (90%, tot.) norm. | 0.76 µm | 0.66 µm |
| $\varepsilon_y$ (90%, tot.) norm. | 0.84 µm | 1.15 µm |
| Hor. brilliance (90%) | 5.32 mA/µm | 13.60 mA/µm |

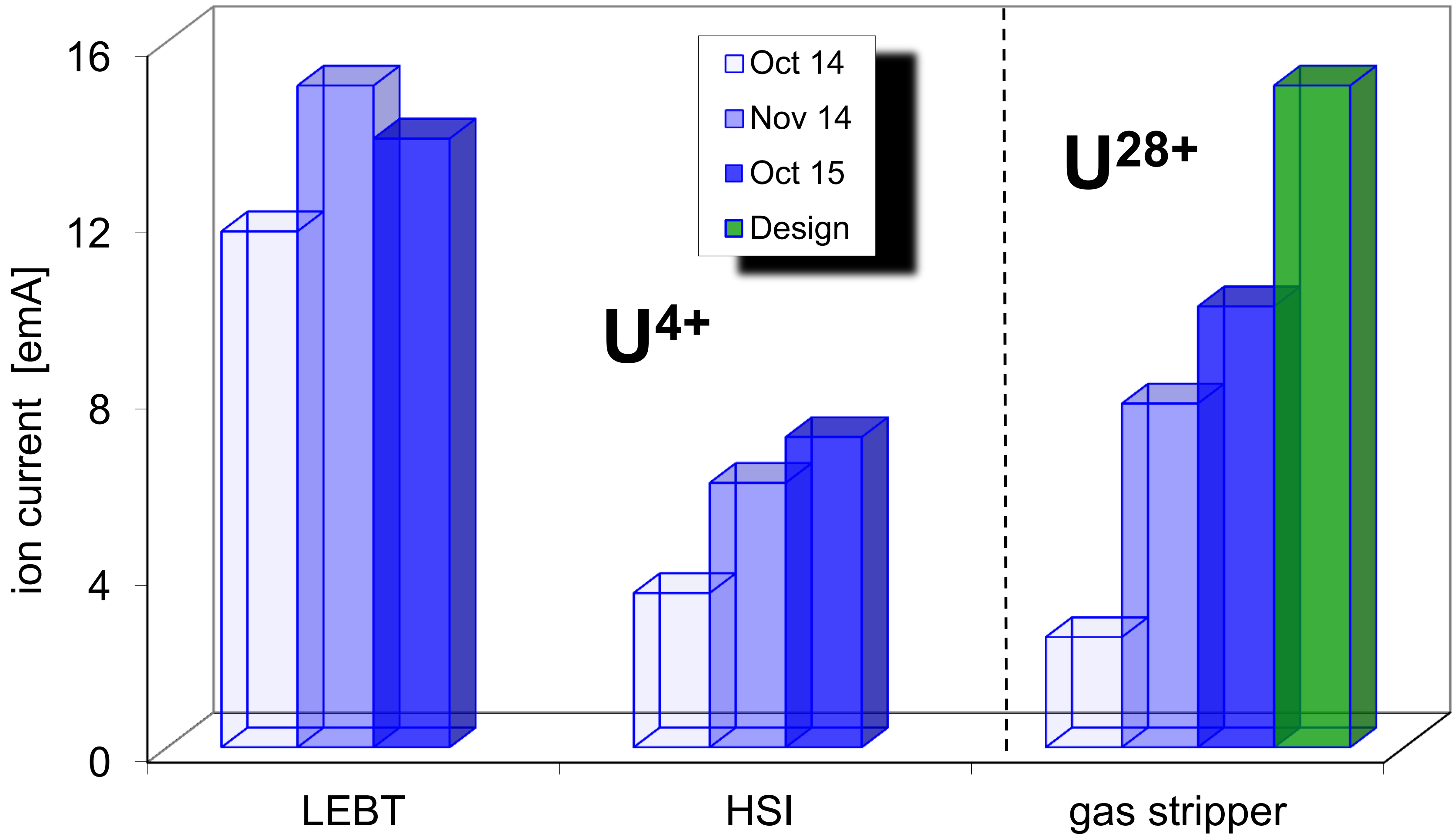
## Beam Energy Loss:

| | | |
|---|---|---|
| $U^{28+}$ | $N_2$-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** |



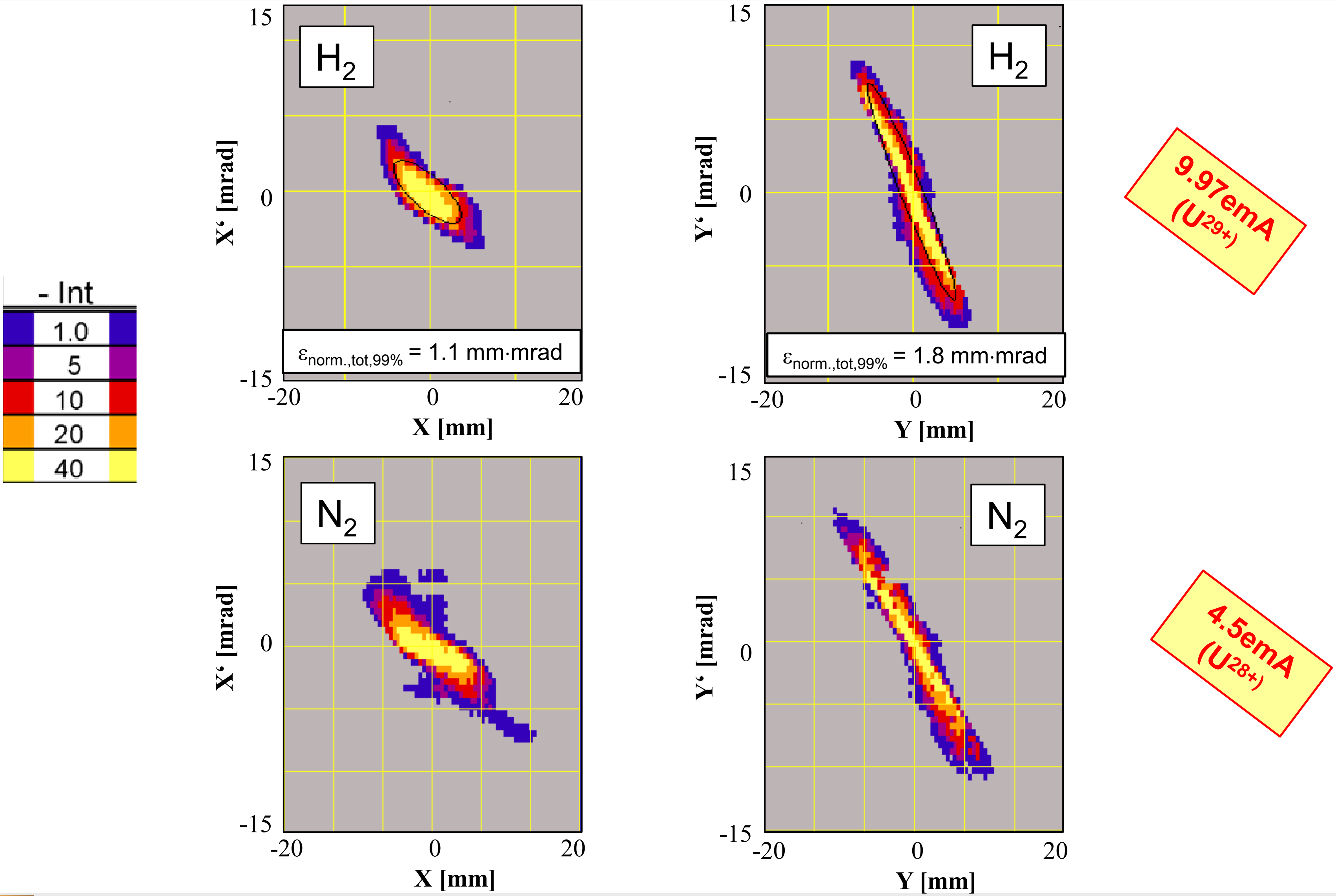



# High Current Uranium Beam Transmission

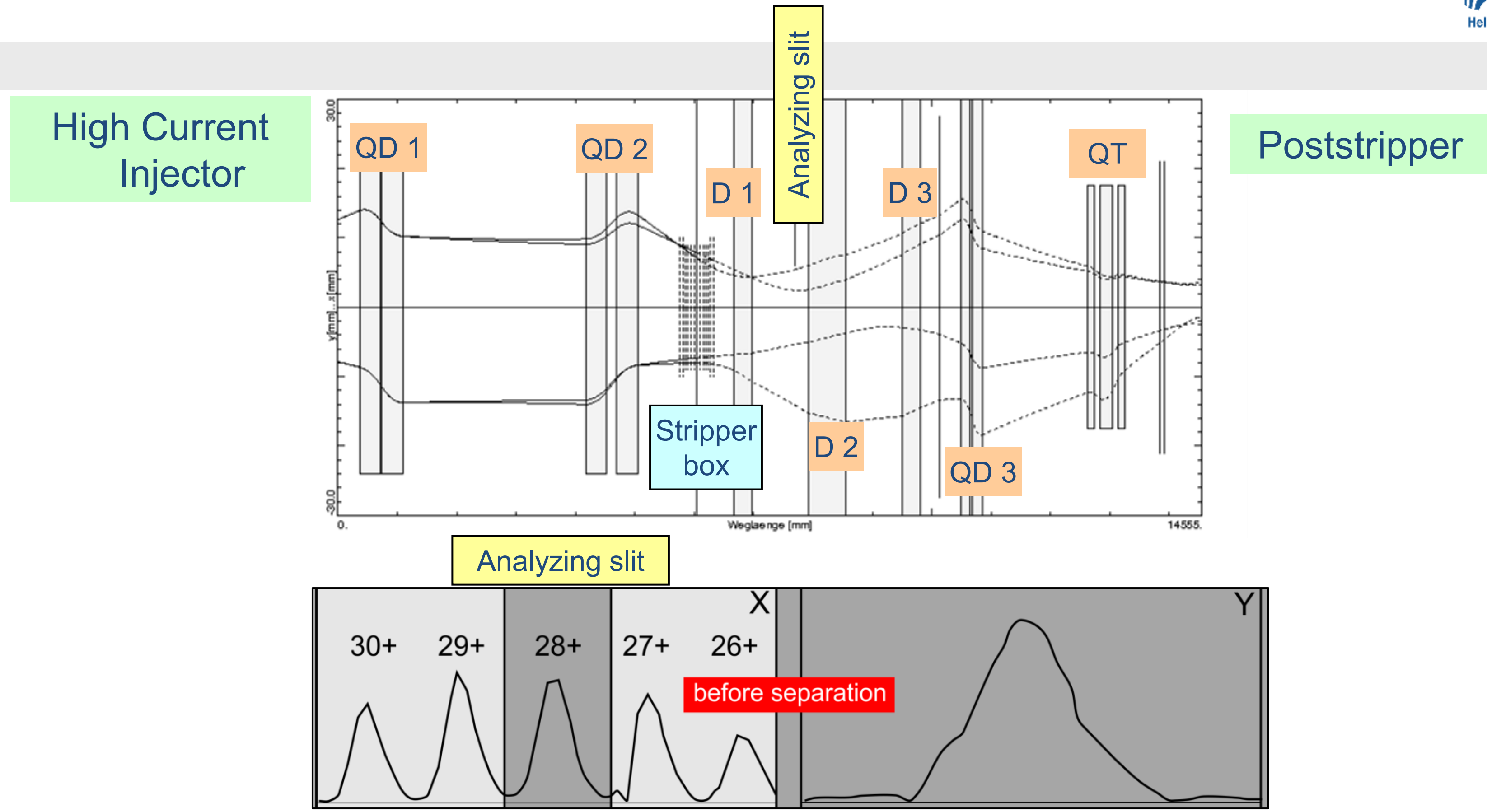


# High Current Uranium Beam Measurements at 1.4 MeV/u

horizontal vertical



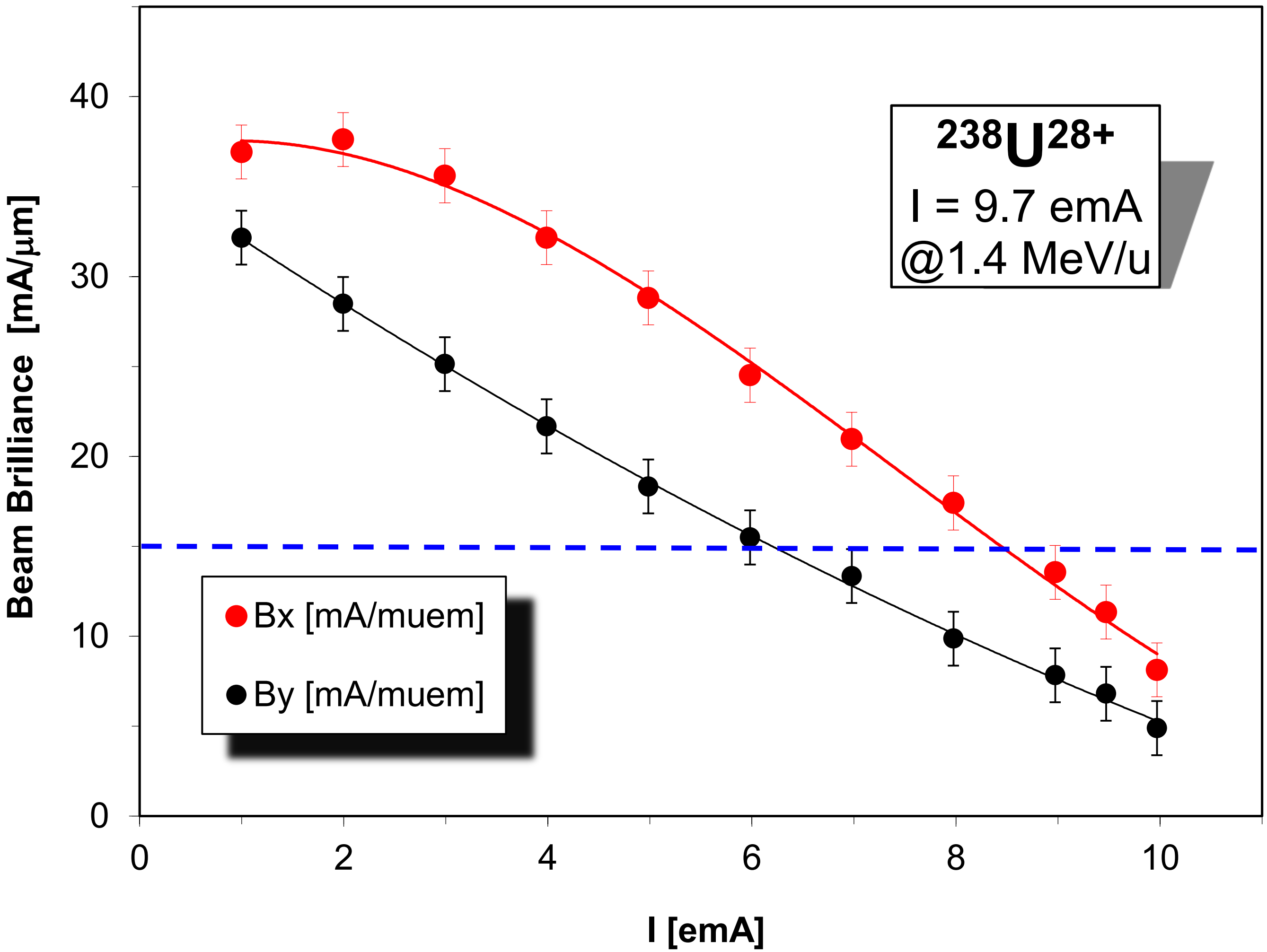
# Beam Profile Measurements at 1.4 MeV/u




**Beam spot (charge separation):**

- Pure separation from neighbouring charge states
- emittance growth (momentum straggling) ~ spot size

# 5. Beam Brilliance Analysis

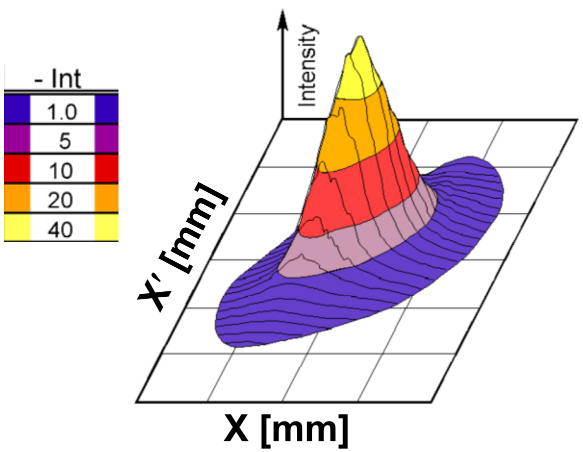


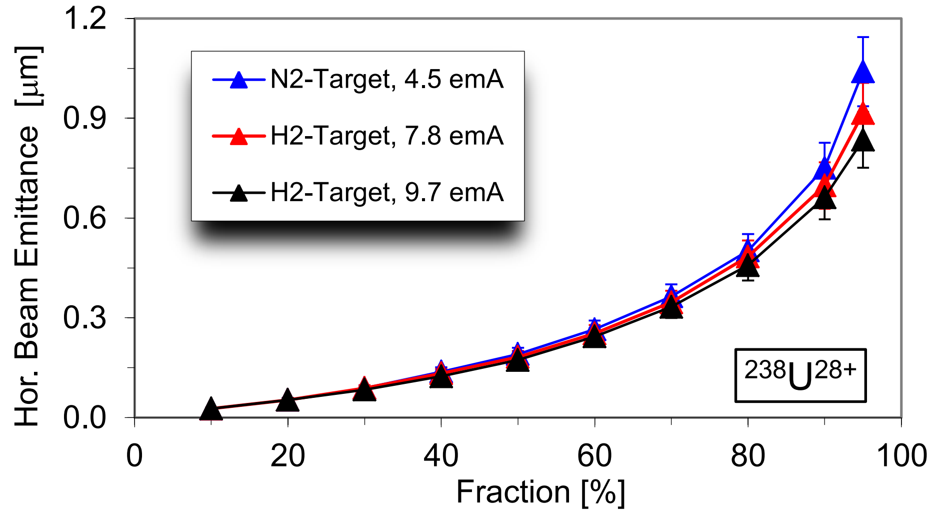

**FAIR-Requirement at SIS18 injection:**

$e_x(tot.,norm) = 1\ mm{\cdot}mrad$
$I = 15\ emA$
$B_x(tot.,norm) = \mathbf{15\ mm{\cdot}mrad}$

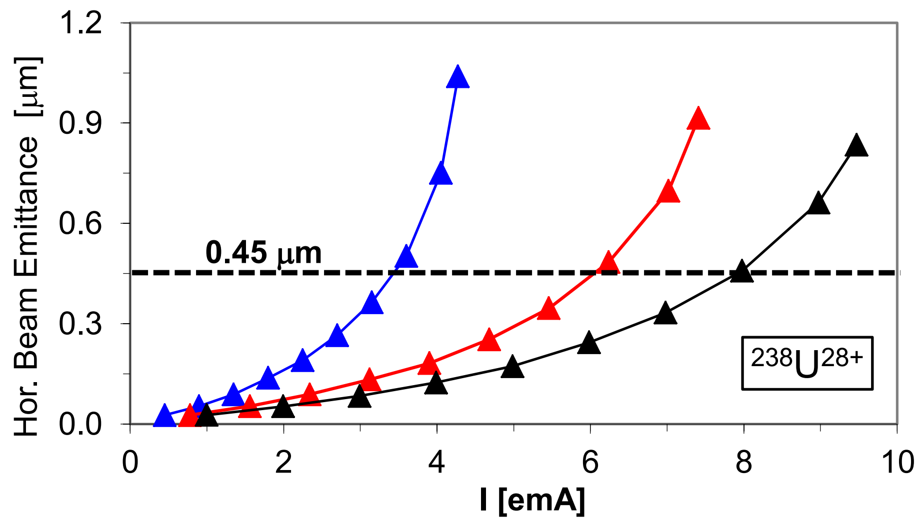
# High brilliance uranium beam measure-ments at 1.4 MeV/u

**General analysis of fraction emittance**




... fixed relative fraction



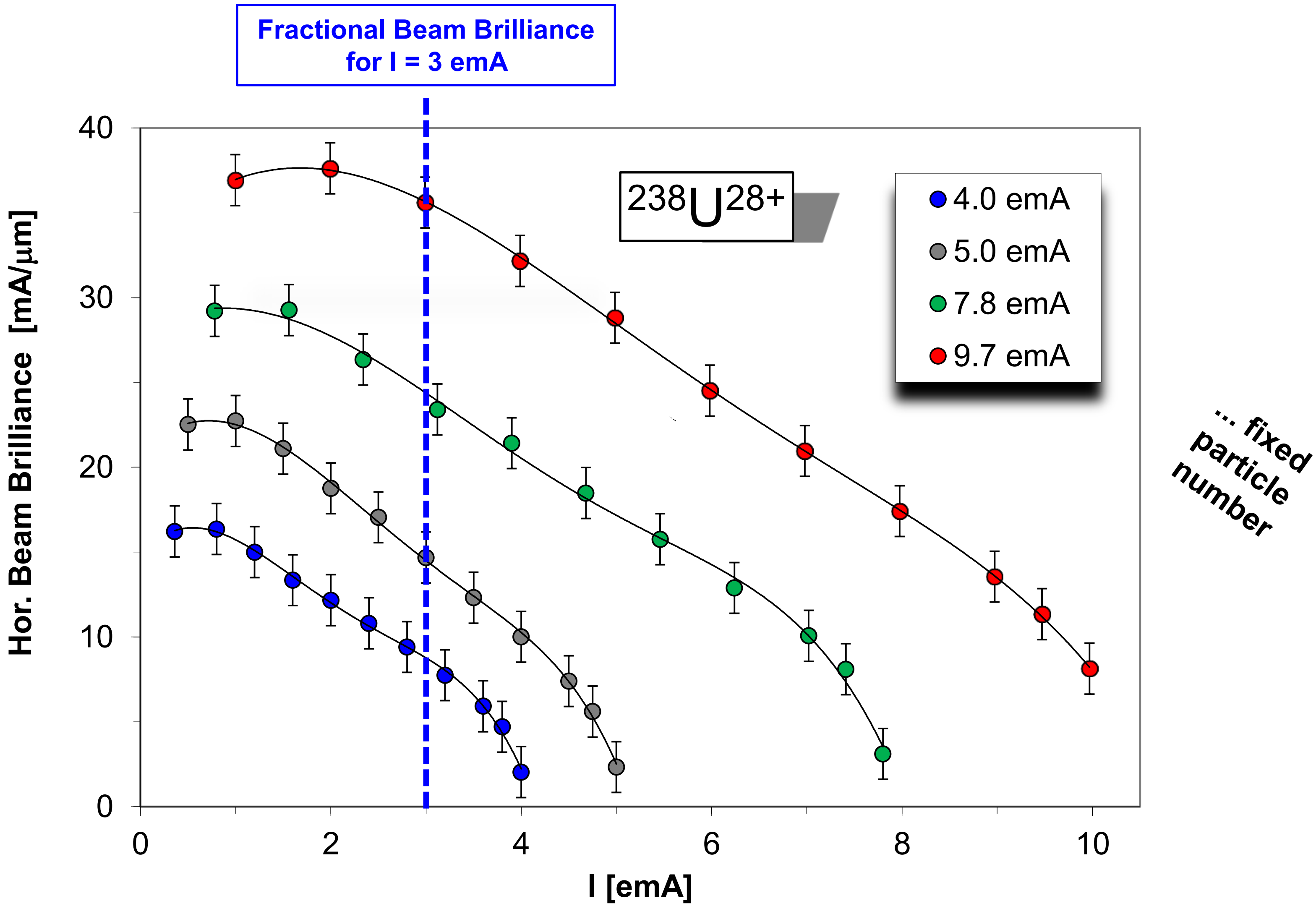

... fixed particle number

<u>Gain of intensity:</u>

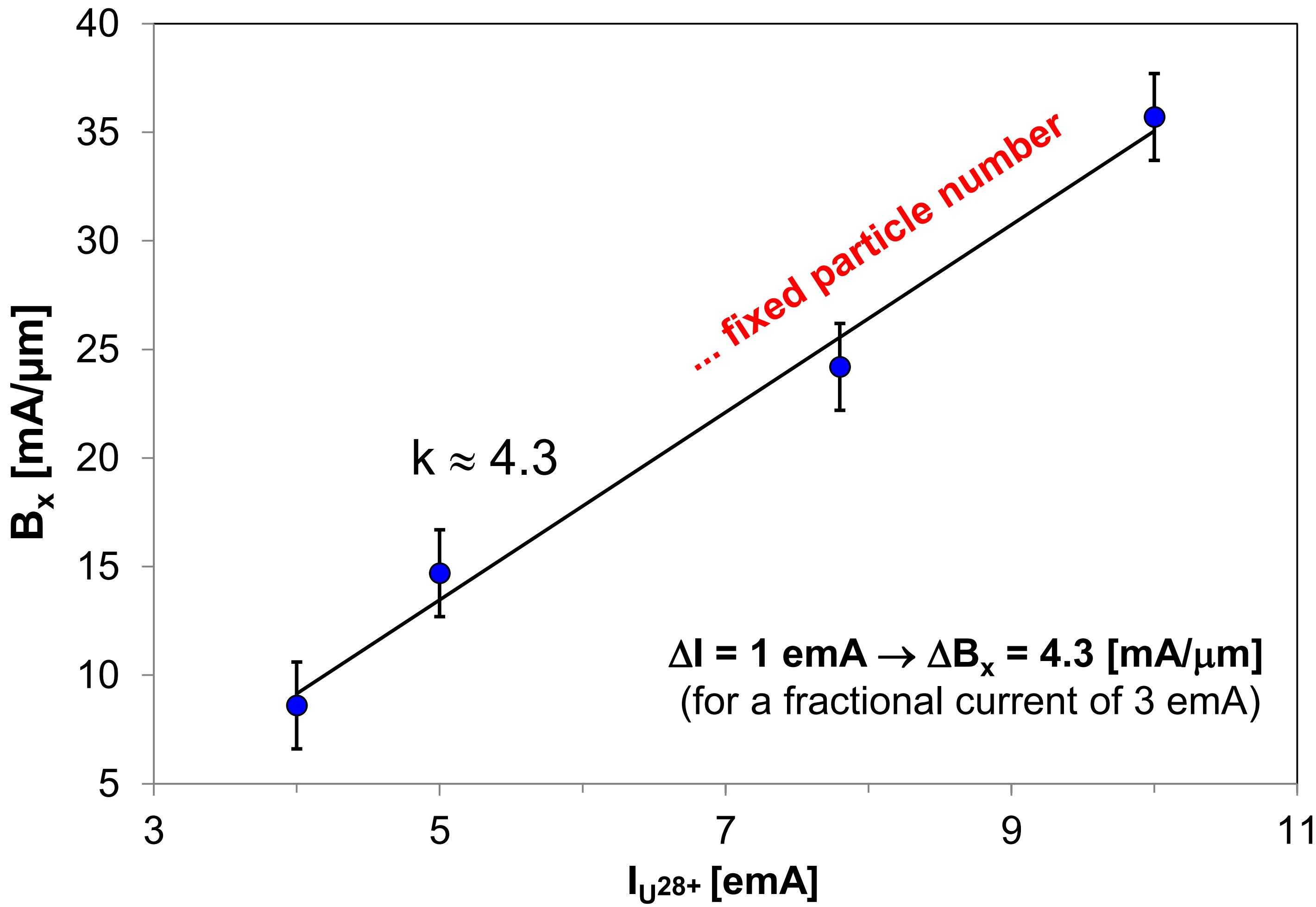
→ Increased particle number inside same hor. emittance

→ **<u>higher beam brilliance</u>**

# Horizontal Beam Brilliance Analysis



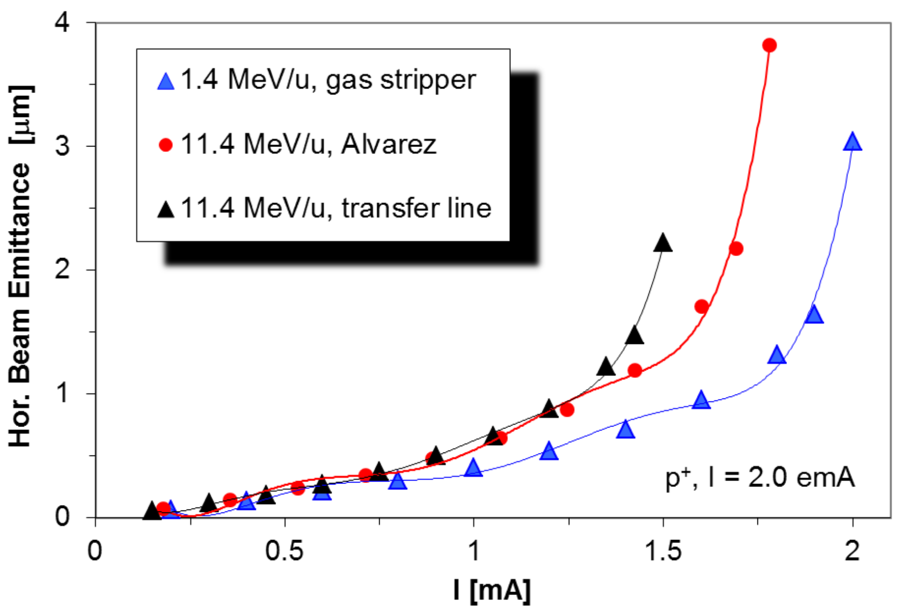
# Fractional Beam Brilliance for a fixed Particle Number I = 3 emA



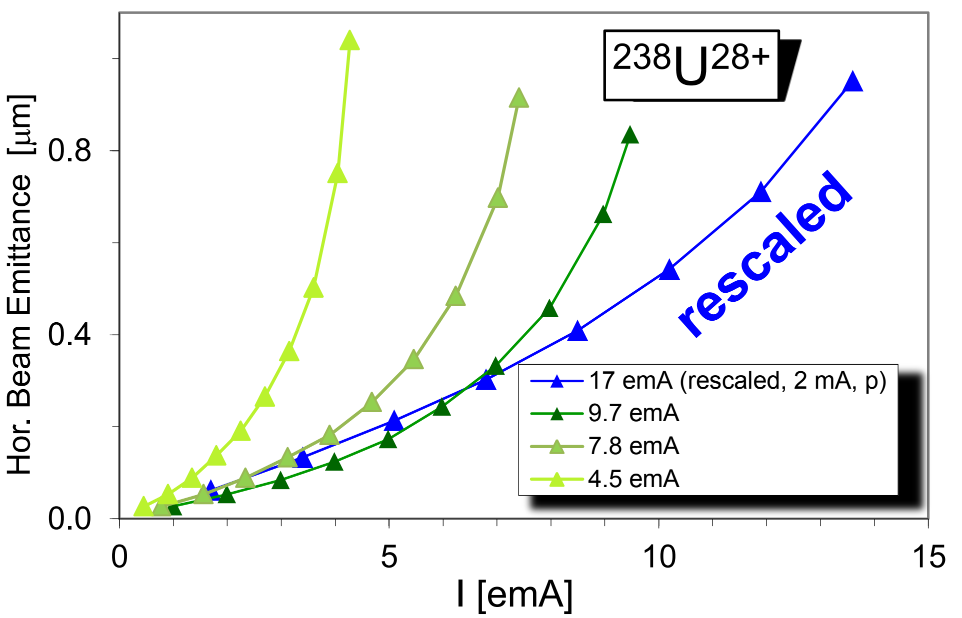
# Emittance Beam Analysis



## Proton beam emittance




## Uranium beam emittance



# 6. $U^{28+}$-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 $BL(p^{+})$:

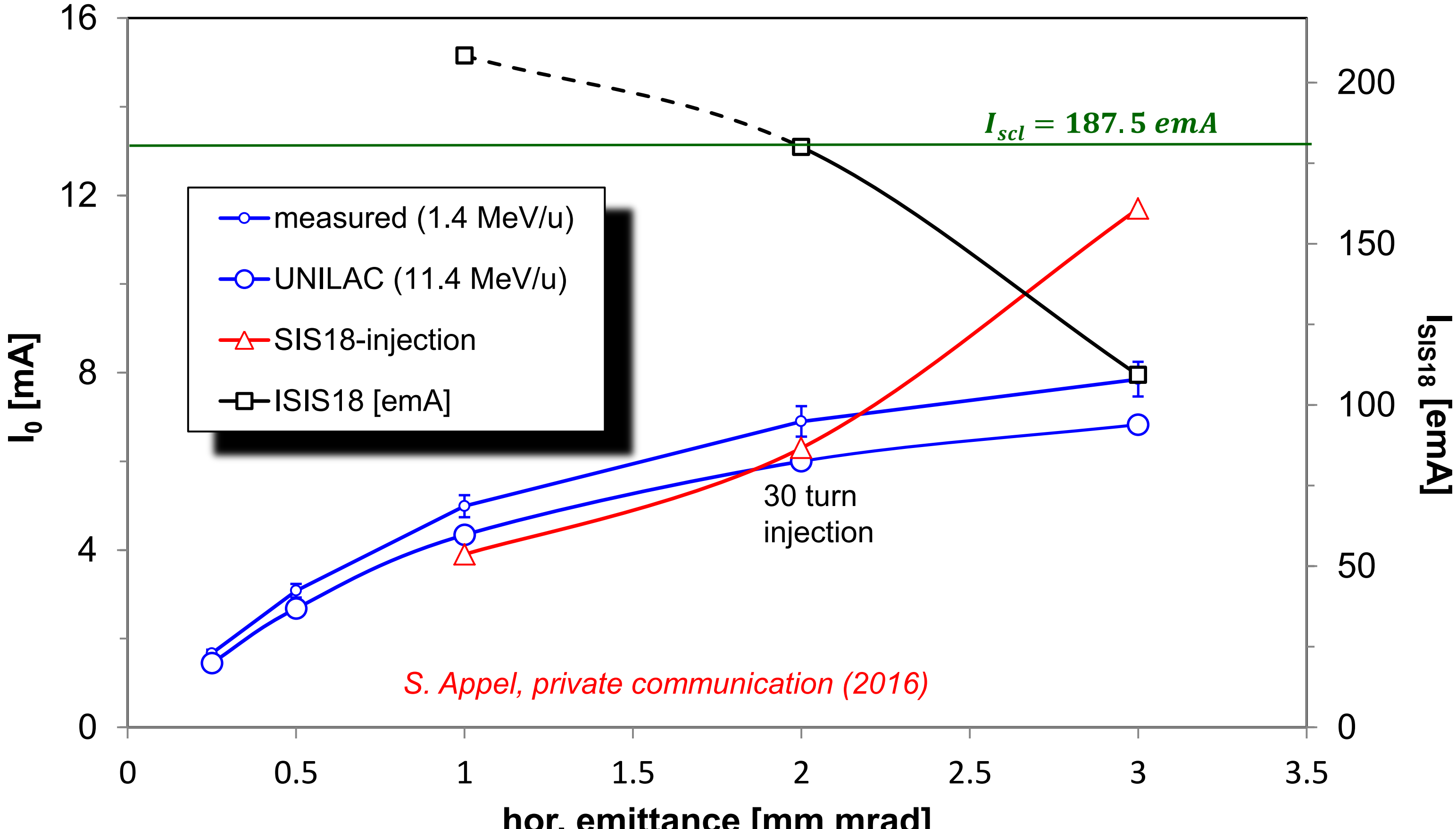
$$BL(p^{+}) = 100\% - \frac{TM_{fin}(p^{+})}{100\% + EW_{fin}(p^{+})} \cdot 100\% \approx 23\%$$

- Assuming brilliance loss scales with ion current density → 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 ($I_{scl} = 187.5\ emA$)



# 7. Summary and Outlook

- Loss-free injection into the SIS18 is a necessary condition, especially for operation with high intensity 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.
- The horizontal beam brilliance growths strongly with the beam intensity
- For higher currents the core of the uranium phase space distribution perhaps remains constant during acceleration and beam transport
- 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 ($2 \cdot 10^{11}$ part. per pulse).**

# *Thank You for Your Attention!*