High Current Uranium Beam Measurements at GSI high intensity RFQ operation experience - from beam point of view

Winfried Barth, GSI&HIM

1. Introduction

2. Operation experience

   - HSI-commissioning (1999)
   - First acceleration of U^{4+} beam at HSI (2000)
   - HSI-RFQ-Upgrade I (2004)
   - HSI-RFQ-Upgrade II (2010)

2. Further RFQ-Optimization (2014-2016)

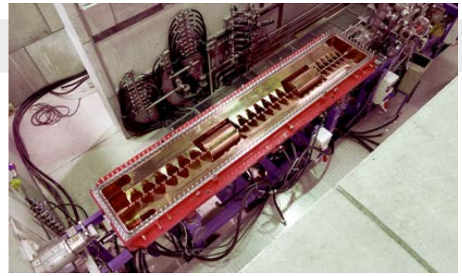
3. Pushing the limits for uranium beam (and p^+) operation

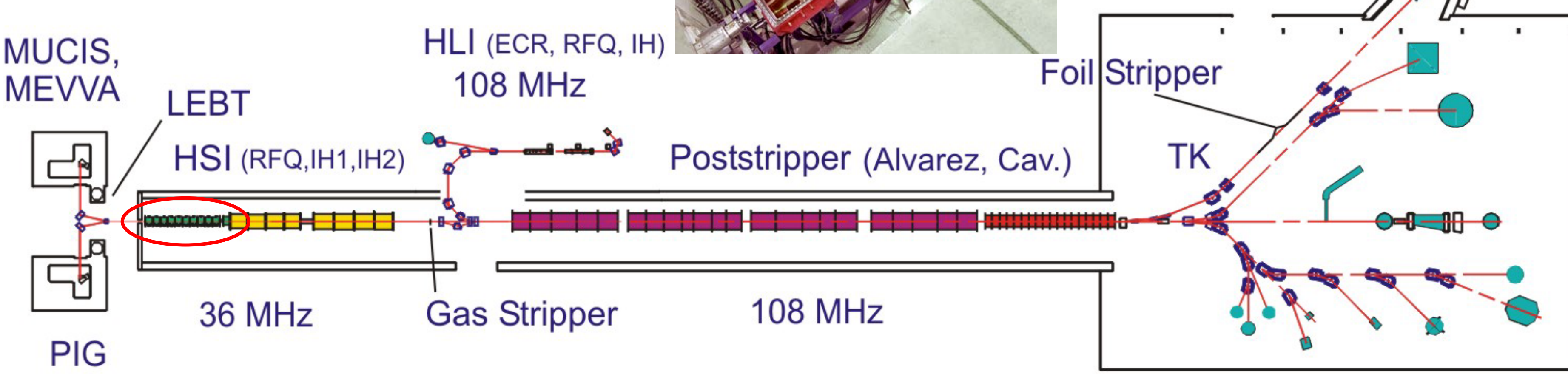
4. Beam brilliance analysis

5. Summary

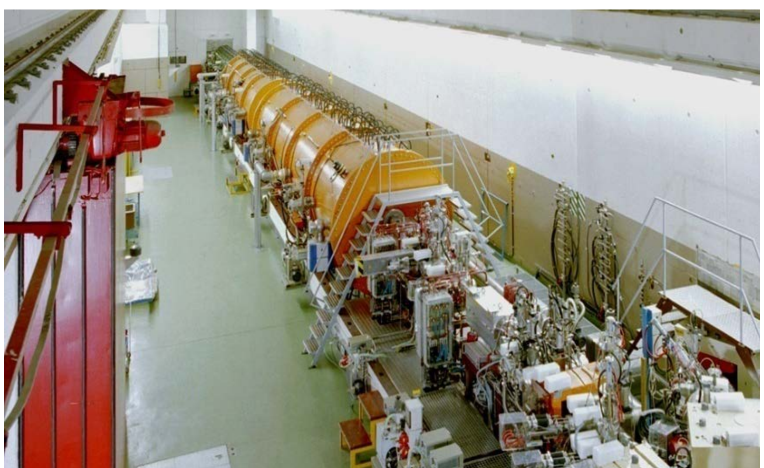
1. Introduction
The GSI UNIversal Linear ACcelerator

High Charge State Injector (1991)

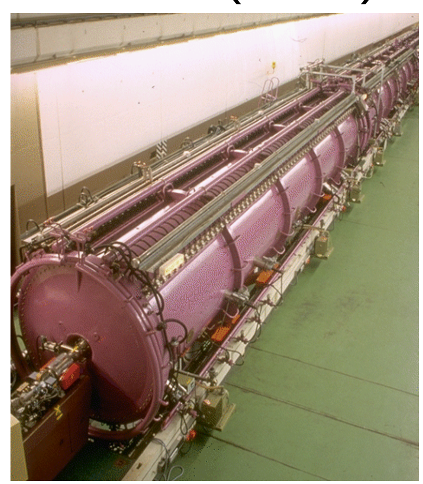




High Current Injector (1999)



Alvarez (1975)



Single Gap Resonators (1975)

UNILAC-Design Beam Parameters

Commissioning of the 1.4 MeV/u High Current Heavy Ion Linac at GSI, Winfried Barth

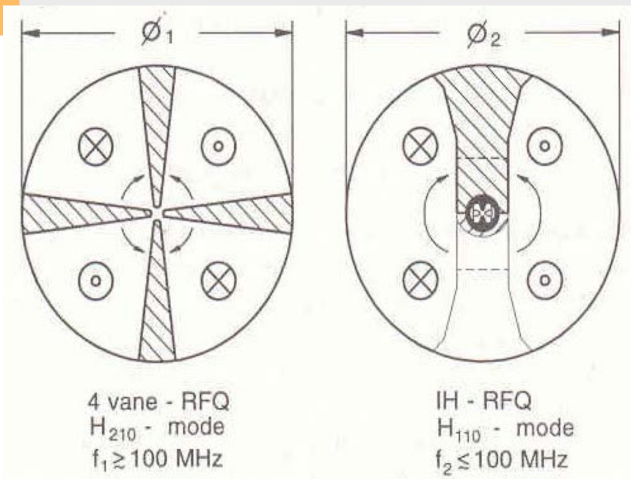
DESIGN BEAM PARAMETERS AT UNILAC AND SIS INJECTION

Requirements to obtain the SIS space charge limit
(a twentyfold multiturn injection is supposed)

	HSI entrance	HSI exit	Alvarez entrance	SIS injection	FAIR SIS injection
ION SPECIES	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{73+}$	$^{238}U^{28+}$
El. Current [mA]	16.5	15	12.5	4.6	15
Part. per 100µs pulse	$2.6 \cdot 10^{12}$	$2.3 \cdot 10^{12}$	$2.8 \cdot 10^{11}$	$4.2 \cdot 10^{10}$	$3.5 \cdot 10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4	11.4
$\Delta W/W$	-	$\pm 4 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8	0.8-1.1
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5	"

LINAC 2000

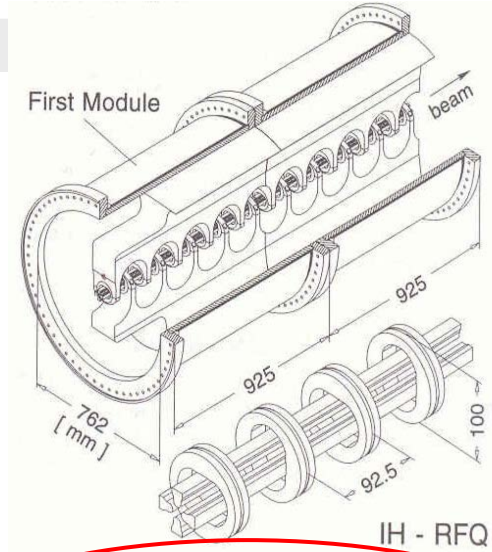
HSI-Radio Frequency Quadrupole (1999)



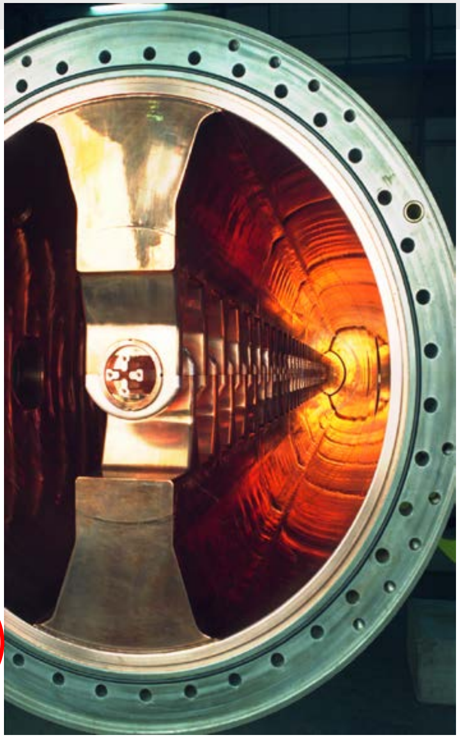
Für leeren Hohlraum mit R=1m, l=∞:

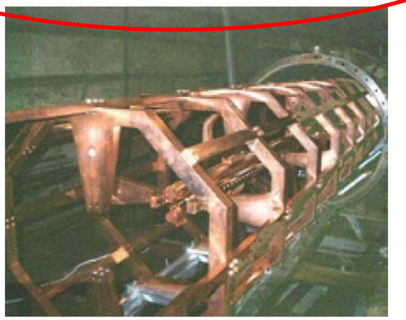
$f(H_{210})=146$ MHz $\quad$ $f(H_{110})=87.9$ MHz

electrode voltage / kV at A/q = 65	137
min. aperture diameter / mm	7.6
min. van-vane distance / mm	4.9
ρ/R_0	0.85
needed duty factors:	
for beams with A/q ≤ 65	1 %, 10 Hz
for beams with A/q ≤ 24	30 %, 50 Hz
distribution of heat losses / %:	
mini-vanes	4
stems with carrier rings	24
ridges	24
tank wall	48



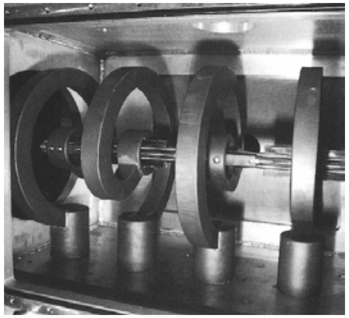
injection energy / keV/u	2.2
exit energy / keV/u	120
total length / m	9.2
resonance frequency / MHz	36.136
inner diameter / m	0.762
shunt impedance / kΩm	~ 600
Q-value	~10000





Ring-connected resonant structure

A.A.Kolomiets, V.A.Andreev, D.A.Kashinsky, S.A.Minaev, V.I.Pershin, R.M.Vengrov, V.L.Zviagintsev, S.G.Yaramishev



27 MHz Spiral-RFQ

A. Kipper, A. Schempp

HSI-commissioning

Commissioning of the 1.4 MeV/u High Current Heavy Ion Linac at GSI, Winfried Barth

HIGH CURRENT INJECTOR ASSEMBLY&COMMISSIONING MILESTONES

Dec. 98	Last operation-shift with Wideröe injector
Jan.-Feb. 99	Disassembly of Wideröe and rf, installation of LEBT section
March 99	Successful commissioning of LEBT
April-May 99	Mounting IH-RFQ and first acceleration up to 120 keV/u
June 99	Beam tests with Superlens, achieving 10 mA Ar^{1+} at RFQ exit
July 99	Assembly of IH1, verification of beam accelera-tion up to 743 keV/u
August 99	Completing HSI with IH2 and stripper Section
2.Sept. 99	Proof of acceleration up to 1.4 MeV/u, further on: 90% IH-transmission for highest argon intensities (8 mA)
October 99	Upgrade of transfer line to SIS and mounting of matching section to Alvarez
November 99	Establishing three beam operation, complete Alvarez transmission at highest current
Since Nov. 99	HSI in routine operation
February 2000	Achievement of the 90%-rf levels, first 1.4 MeV/u U^{4+} beam (3 mA)

LINAC 2000

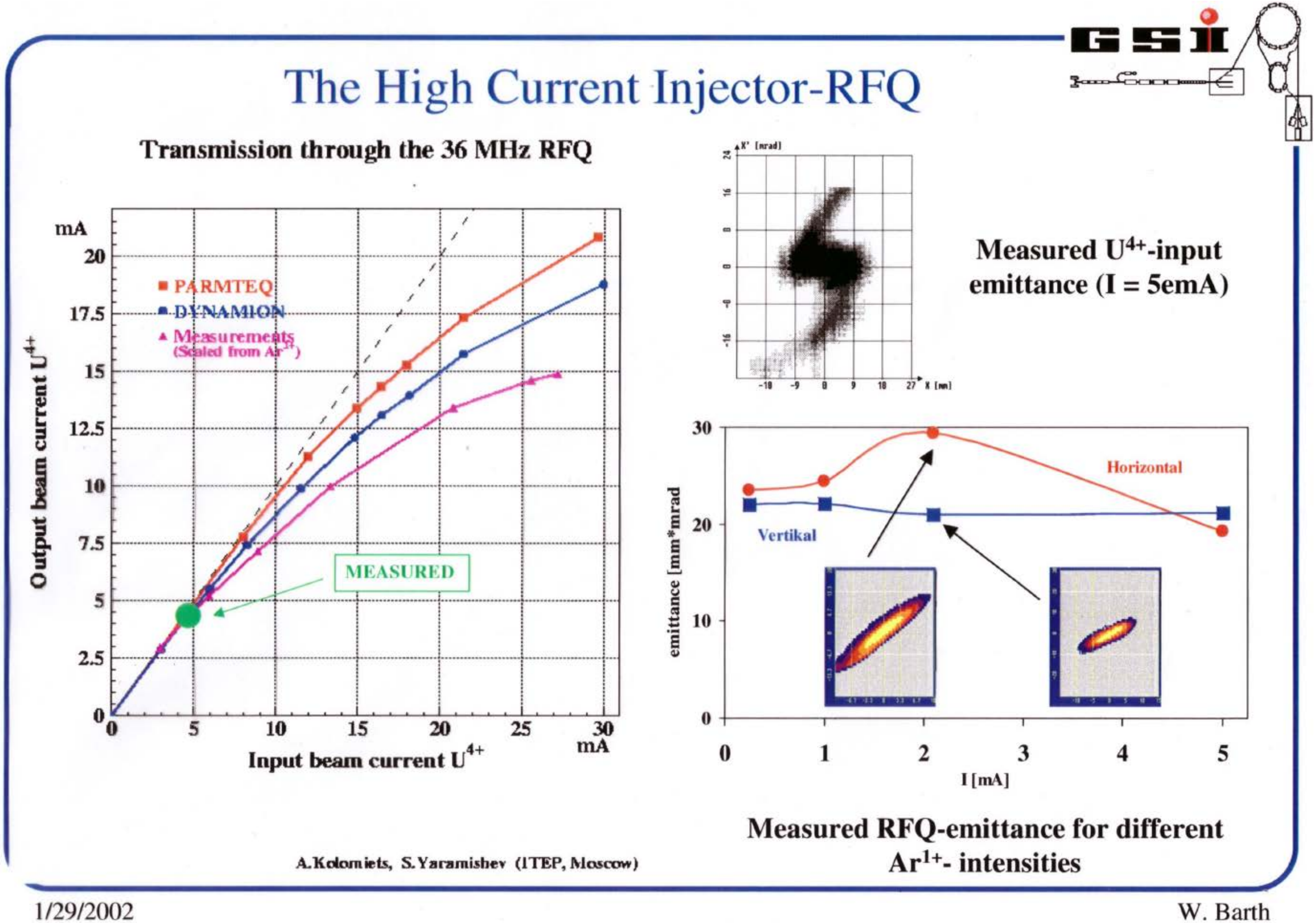
Commissioning of the 1.4 MeV/u High Current Heavy Ion Linac at GSI, Winfried Barth

CONCLUSION

- The new High Current Injector was mounted and commissioned with great success.
- The measured beam parameters, as energy, bunch width, energy spread after each commissioning step fits to calculation.
- No particle loss at beam currents up to 40% of the design intensity.
- The RFQ design current limit (for Ar^{1+}) was reached; significant particle loss at the space charge limit is not completely understood.
- Up to the highest beam intensities the transmission of the IH-DTL is as expected.
- The transverse emittance was measured along the whole Unilac – the emittance growth is close to the simulation.
- 10 mA (Ar^{10+}) were reached after the Alvarez-DTL
- 90% of the design rf-level was reached; stable operation with a U^{4+} beam (3 mA) in the HSI.
- HSI in routine operation (including dual beam operation) since November 1999.
- Outlook: filling the synchrotron up to the space charge limit for high mass numbers.

LINAC 2000

RFQ-Commissioning

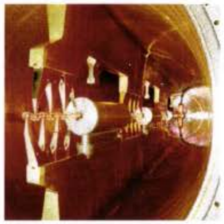


HSI-Conditioning

Rf conditioning of the HSI cavities


RFQ


Superlense

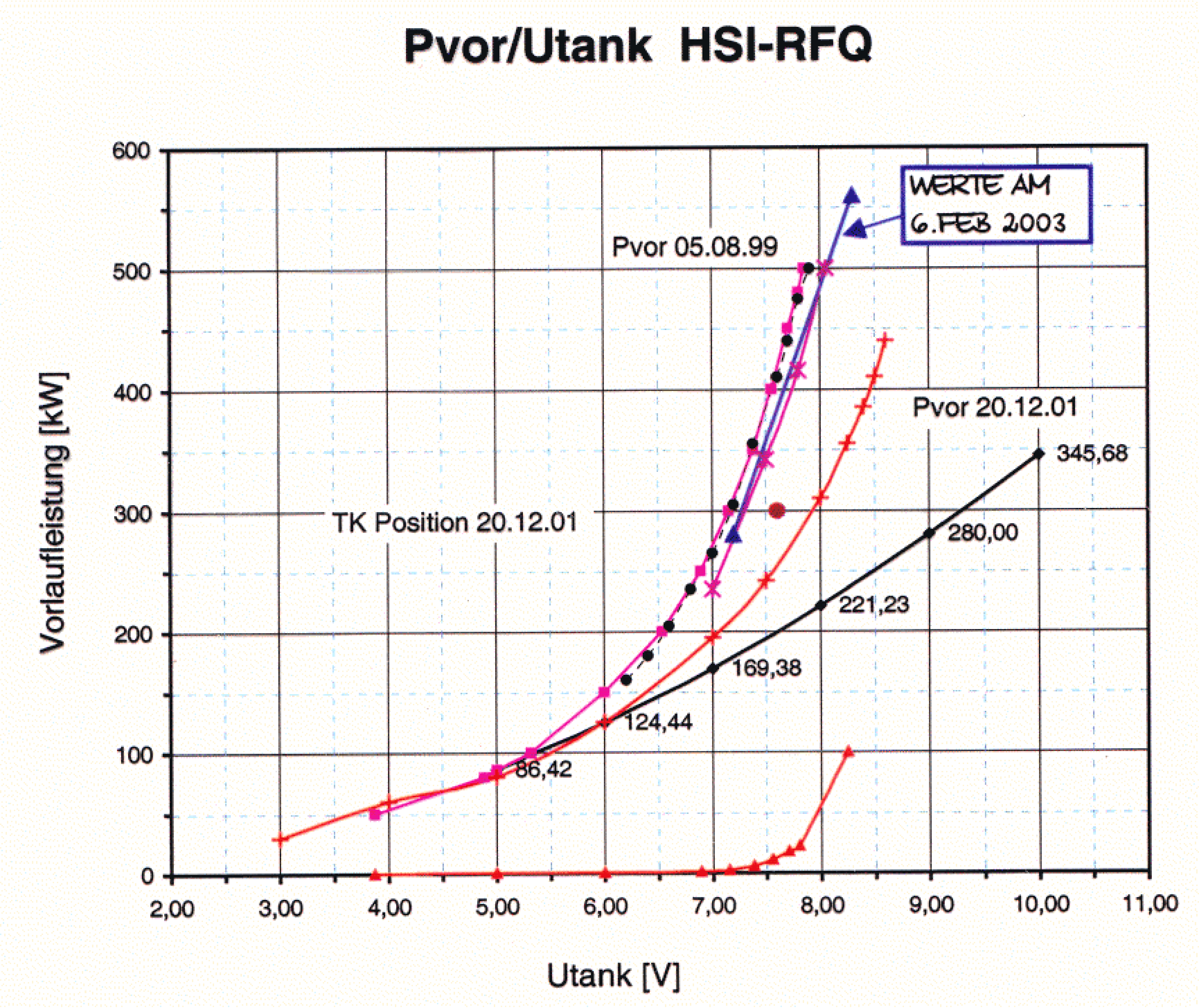

IH_1&IH_2

	TARGET ($^{238}U^{4+}$)	FEBRUARY 2000	AUGUST 2000	OCTOBER 2001*	DECEMBER 2001
RFQ	8.6 V	8.3 V	8.35 V	8.3 V	8.6 V
Superlense	8.3 V	7.95 V	7.0 V	7.55 V	7.6 V
IH_1	8.6 V	8.4 V	8.4 V	8.7 V	9.0 V
IH_2	8.3 V	8.75 V	8.8 V	8.7 V	9.0 V

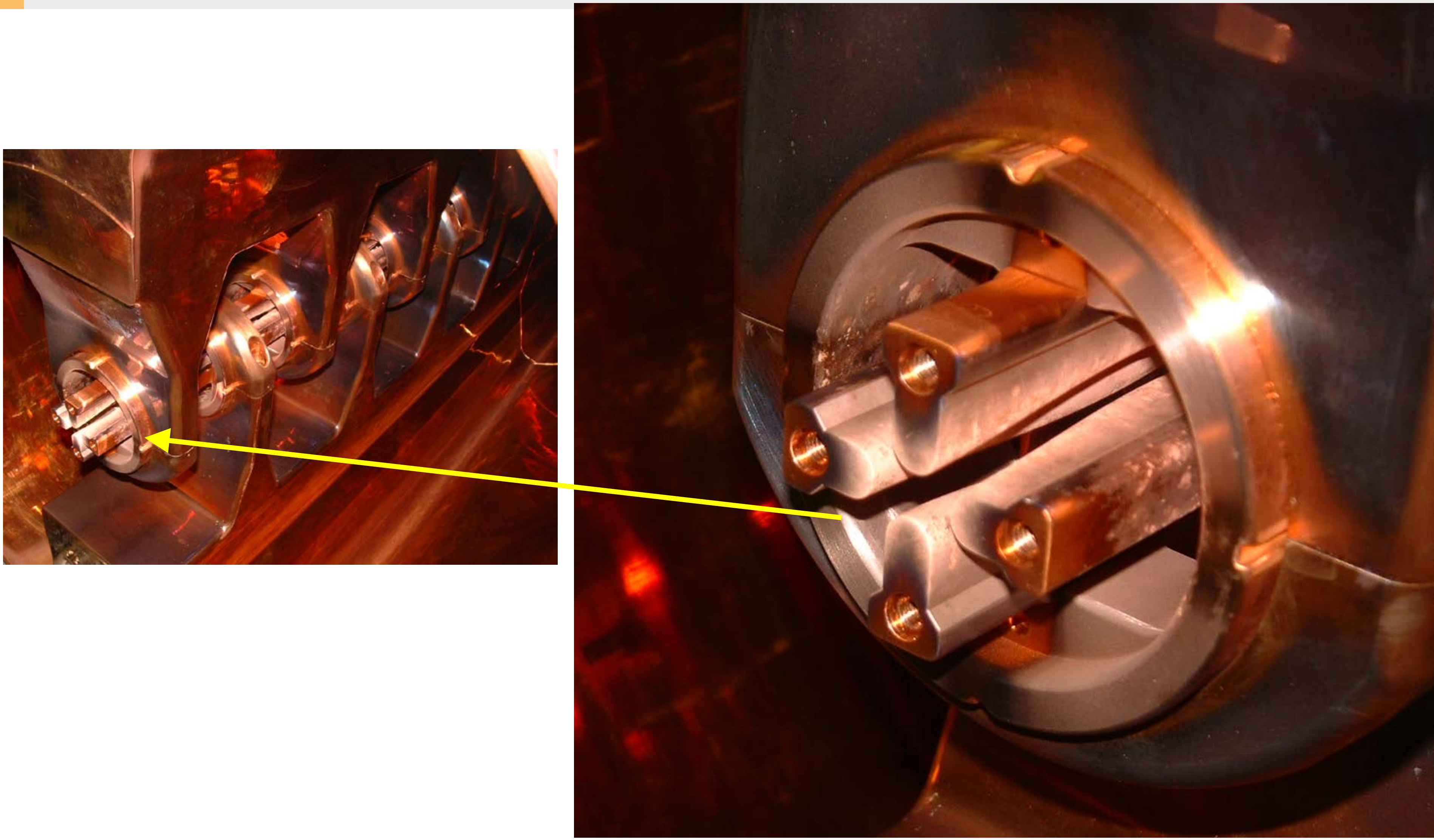
* routinely rf-conditioning with low duty cycle (3 Hz, 1ms) rf-pulses in a time sharing mode during beam time (50 Hz-mode) – leads to a high availability of rf-amplitudes for the U^{4+}-operation.

1/29/2002 W. Barth

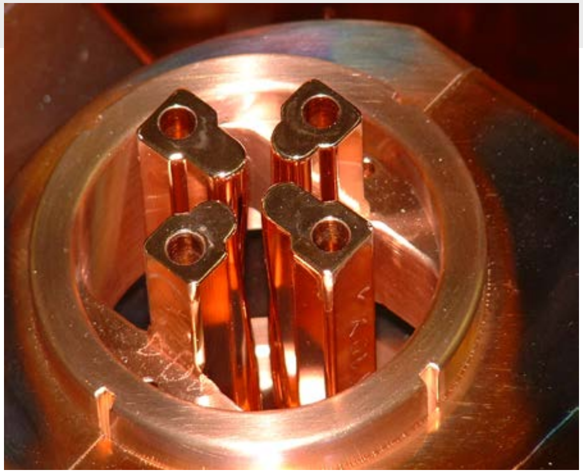
HSI-RFQ-RF-Conditioning (1999-2003)



RFQ-Upgrade I (2004)



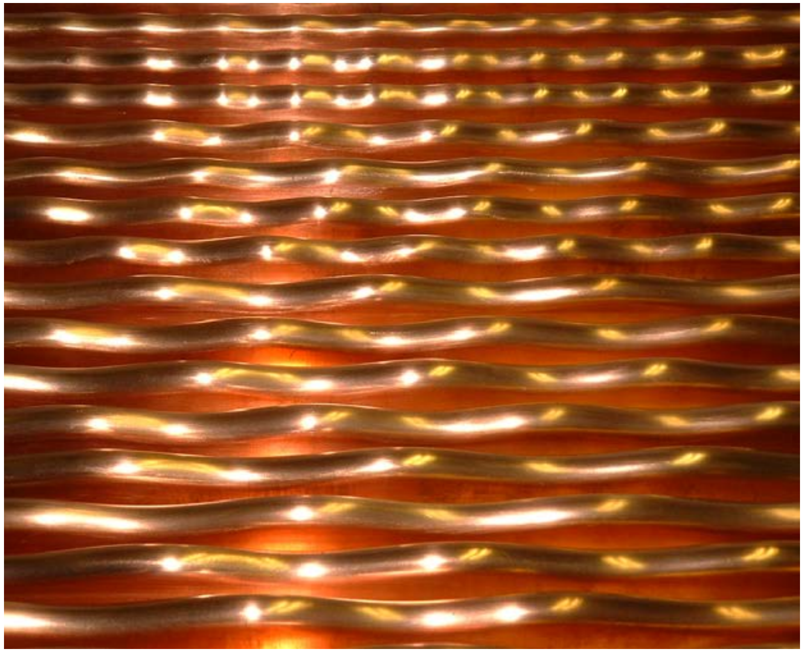
RFQ-Upgrade I: New electrodes



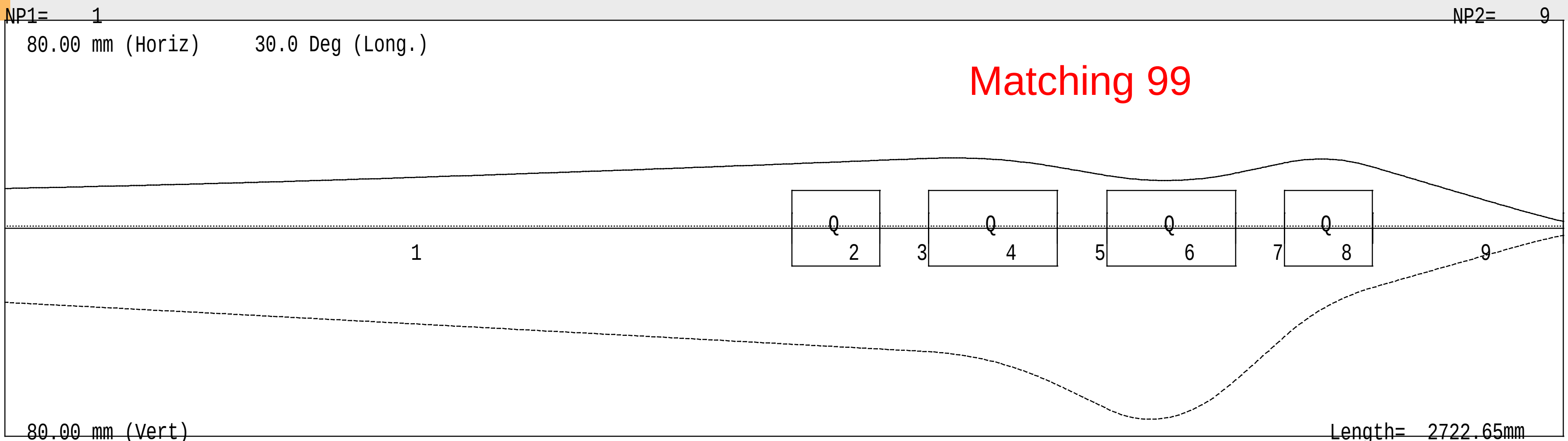
after assembly

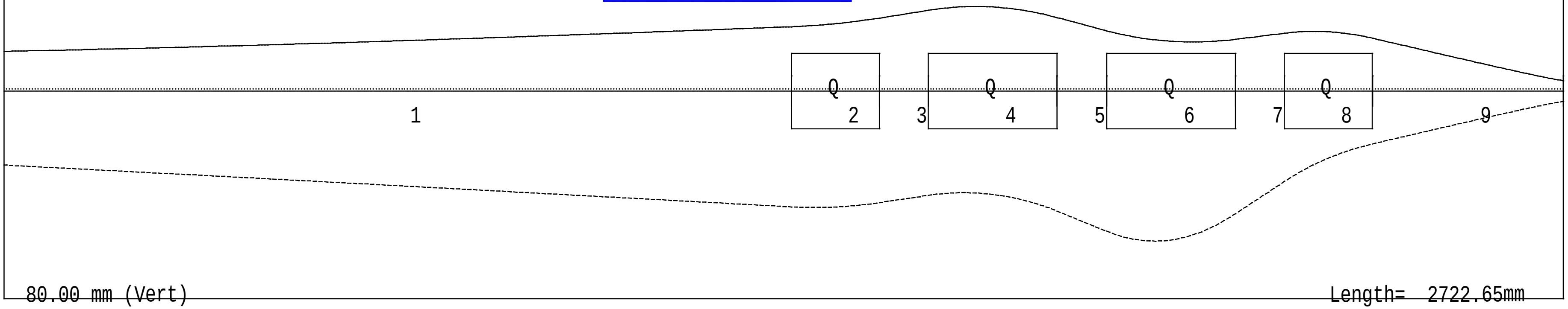
after disassembly

before copper plating

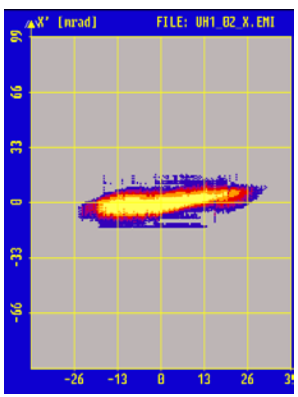


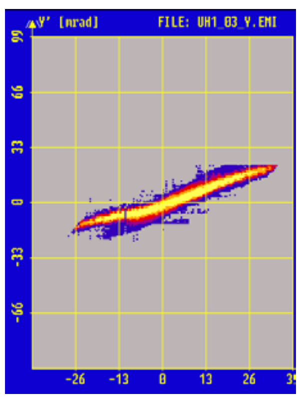
RFQ-Upgrade I: Modified IRM





LEBT-QQ Beam Measurements



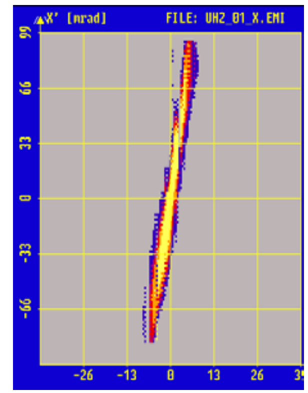


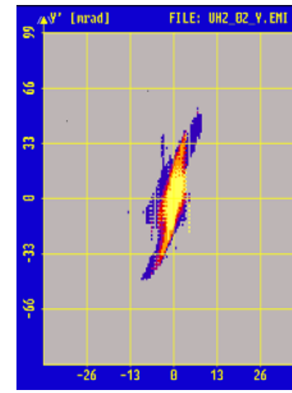
LEBT: $\varepsilon_{x,90\%}$ = 175 mm·mrad

$\varepsilon_{y,90\%}$ = 185 mm·mrad

horizontal **vertikal**

99

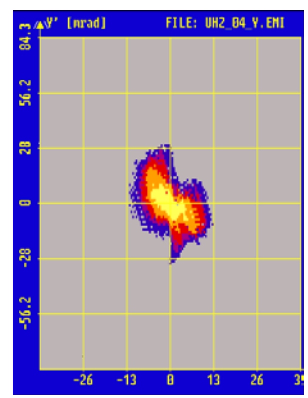


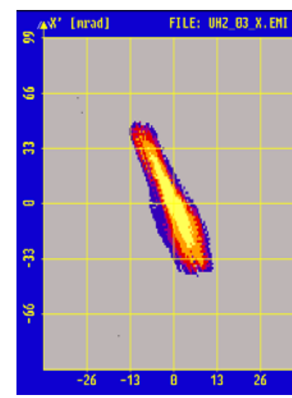


Emittanzwachstum:
-19 %/3 %

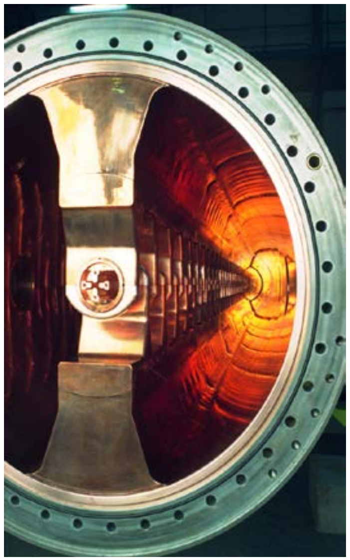
Transmission:
70 %/84 %

04





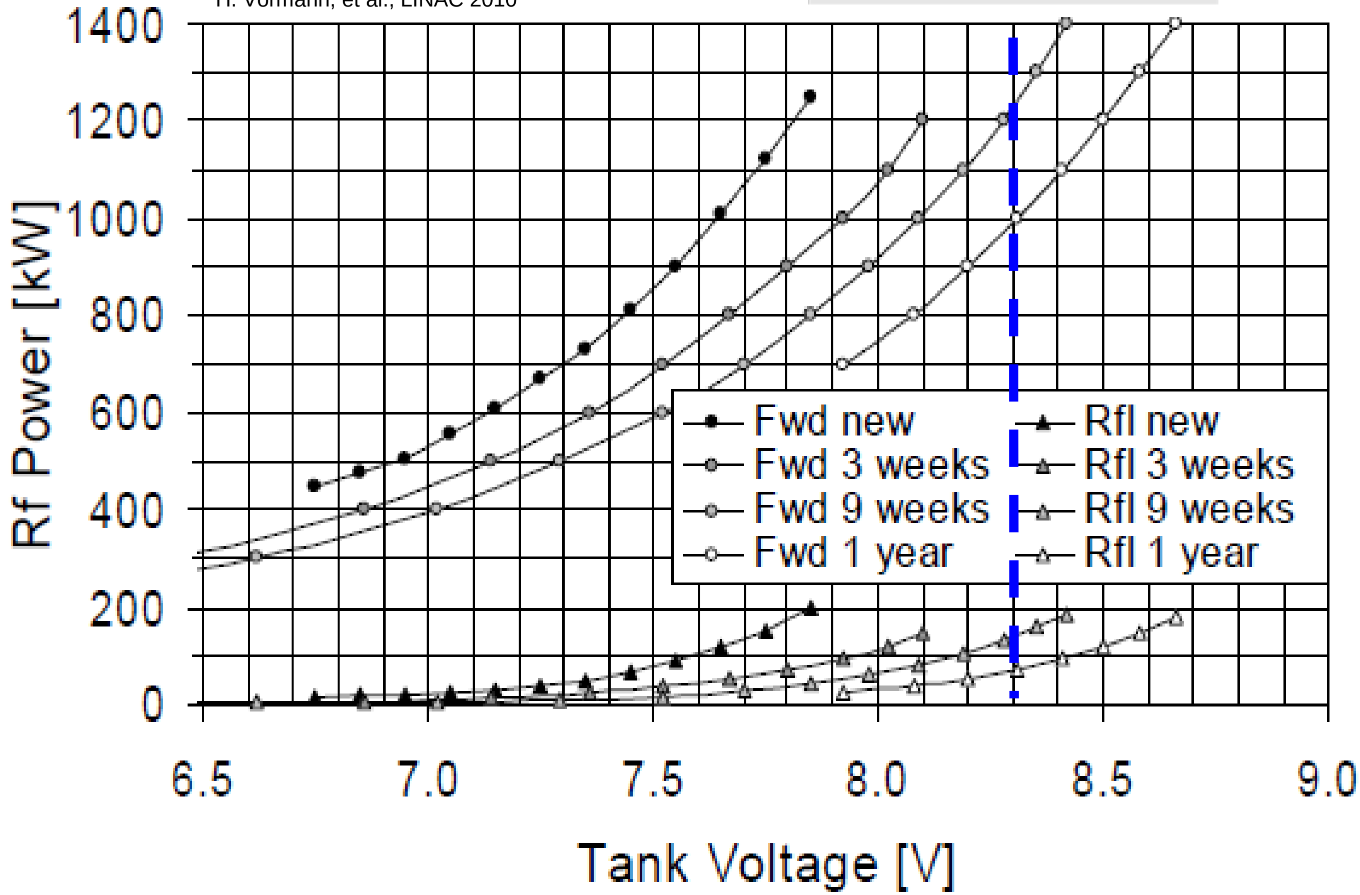
RFQ-Upgrade II (2009)



HSI-RFQ	New Design	Existing Design (up to 2008)
Electrode voltage / kV	155	125
Av. aperture radius / cm	0.6	0.54 – 0.52 – 0.77
Electrode width / cm	0.846	0.93 – 0.89 – 1.08
Maximum field / kV/cm	312.0	318.5
Modulation	1.012 – 1.93	1.00 – 2.09
Min. transv. phase advance / rad	0.555	0.45
Synch. Phase, degrees	-90^0 - -28^0	-90^0 - -34^0
Min. aperture radius, cm	0.410	0.381
Norm. transv. acceptance / µm	0.856	0.73
Number of cells with modulation	394	343
Length of electrodes, cm	921.74	921.74

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

H. Vormann, et al., LINAC 2010



RFQ Upgrade II: Beam commissioning

H. Vormann,
MOP040,
Linac 2010

Table 4: HSI maximum high current transmission

	U^{4+}		Ar^{1+}	
Beam current/ Transmission	before upgrade	2010 (2009)	before upgrade	2009
Before QQ	12.4 mA	7 mA (11)	13.5 mA	12.5 mA
Behind RFQ	7.9 mA	6.6 mA (7.5)	7.6 mA	9.5 mA
Transm. RFQ	64 %	95 % (70%)	56 %	85 %
Behind HSI	6.6 mA	5.1 mA (6.0)	5.9 mA	8.5 mA
Transm. HSI	50 %	72 % (60%)	44 %	56 %

100% HSI-beam transmission for low current beams from PIG ion source (long term operation)!

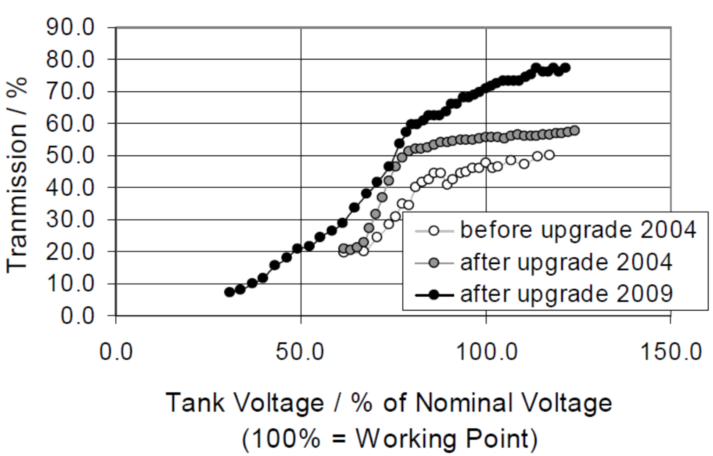


Figure 6: Measured Ar^{1+} high current transmission of the HSI-RFQ (Input 16 mA).

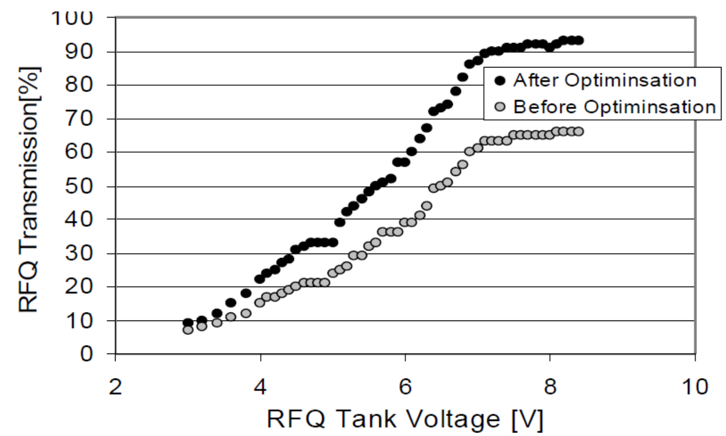
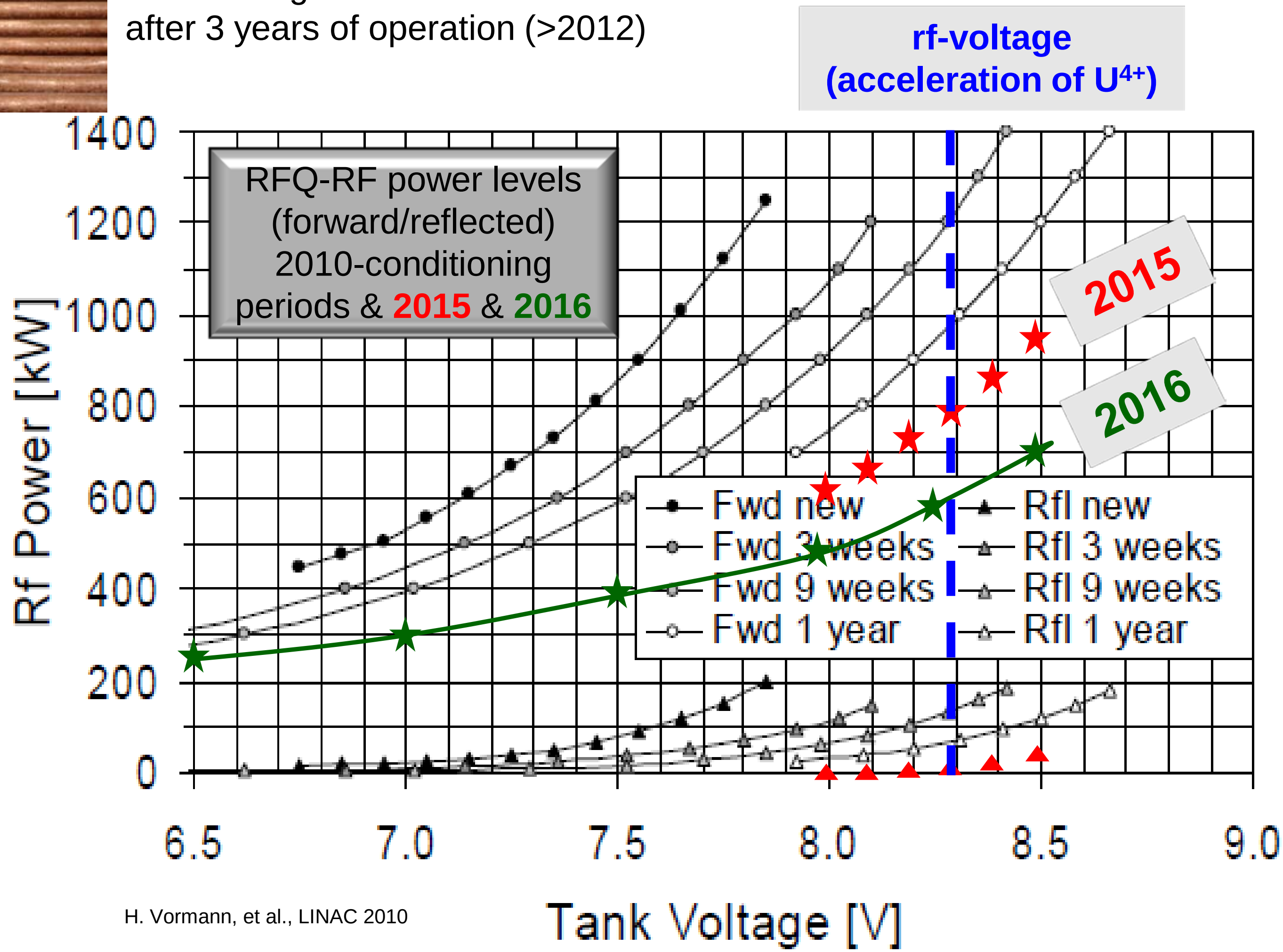


Figure 8: U^{4+} transmission (7 mA).

Table 4: HSI maximum high current transmission

Further RFQ RF-Optimization (2014-2016)

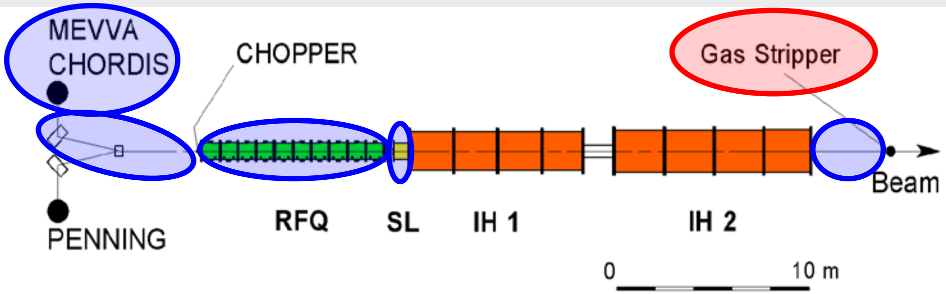
surface degradation observed
after 3 years of operation (>2012)



H. Vormann, et al., LINAC 2010

3. Pushing the limits for uranium beam operation

High Current Injector



- **Ion Source:** Applying a multi-aperture (7-hole) 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 → 75% RFQ-Transmission (I_{out} = 11.25 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 7.6 emA available for heavy ion stripping.

Particle Stripping Efficiency

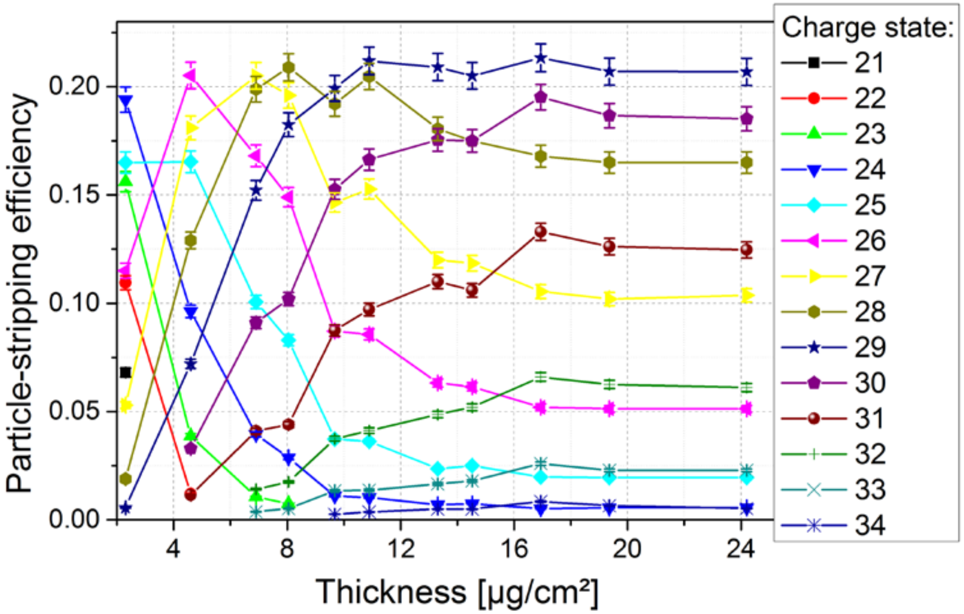
Beam Parameters:

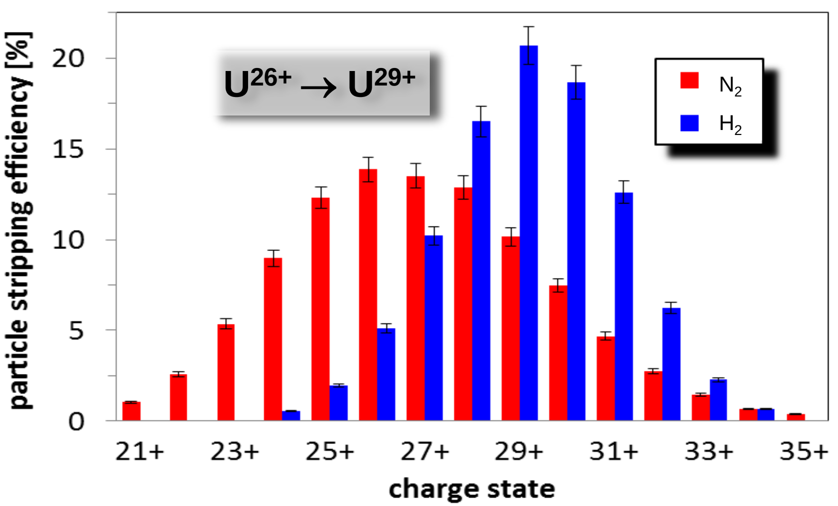
	N_2-gas jet [8]	H_2- gas cell (pulsed)
Back-pressure	0.4 MPa	12.0 MPa
U^{4+}-current (HSI)	6.0 emA	7.4 emA
Stripping charge state	28+	29+
Stripping efficiency	12.7±0.5%	21.0±0.5%
Energy loss	14±5 keV/u	60±5 keV/u
Max. current	4.5 emA	11.5 emA
ε_x (90%, tot.) norm.	0.76 µm	0.51 µm
ε_y (90%, tot.) norm.	0.84 µm	0.96 µm
Hor. brilliance (90%)	5.32 mA/µm	20.29 mA/µm

average: 4.65 mA/µm **18.37 mA/µm**

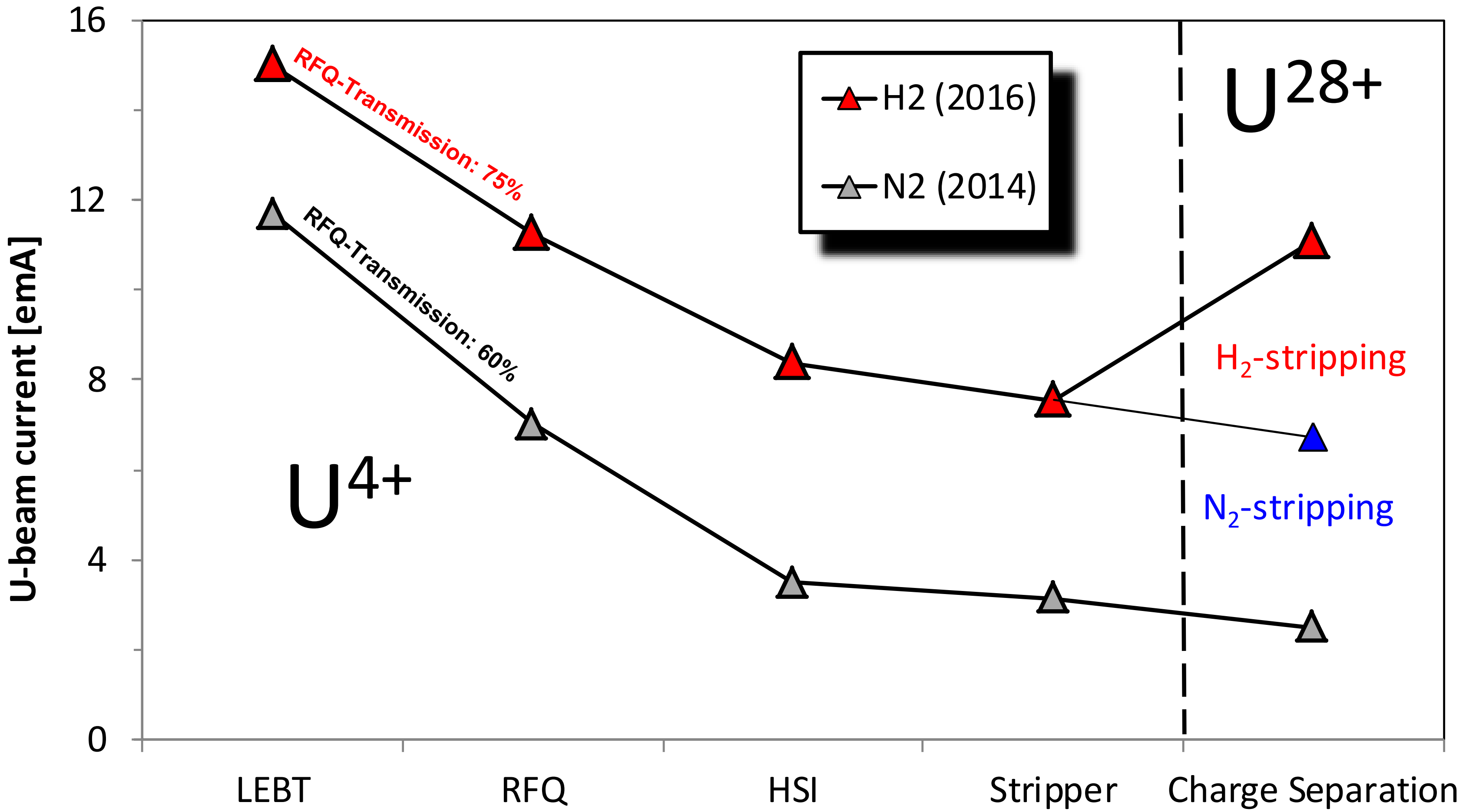
Beam Energy Loss:

U^{28+}	N_2-jet (max.)	**14±5 keV/u**
U^{28+}	Pulsed H_2-stripper cell (7.5 MPa)	**35±5 keV/u**
U^{29+}	Pulsed H_2-stripper cell (12.0 MPa)	**60±5 keV/u**

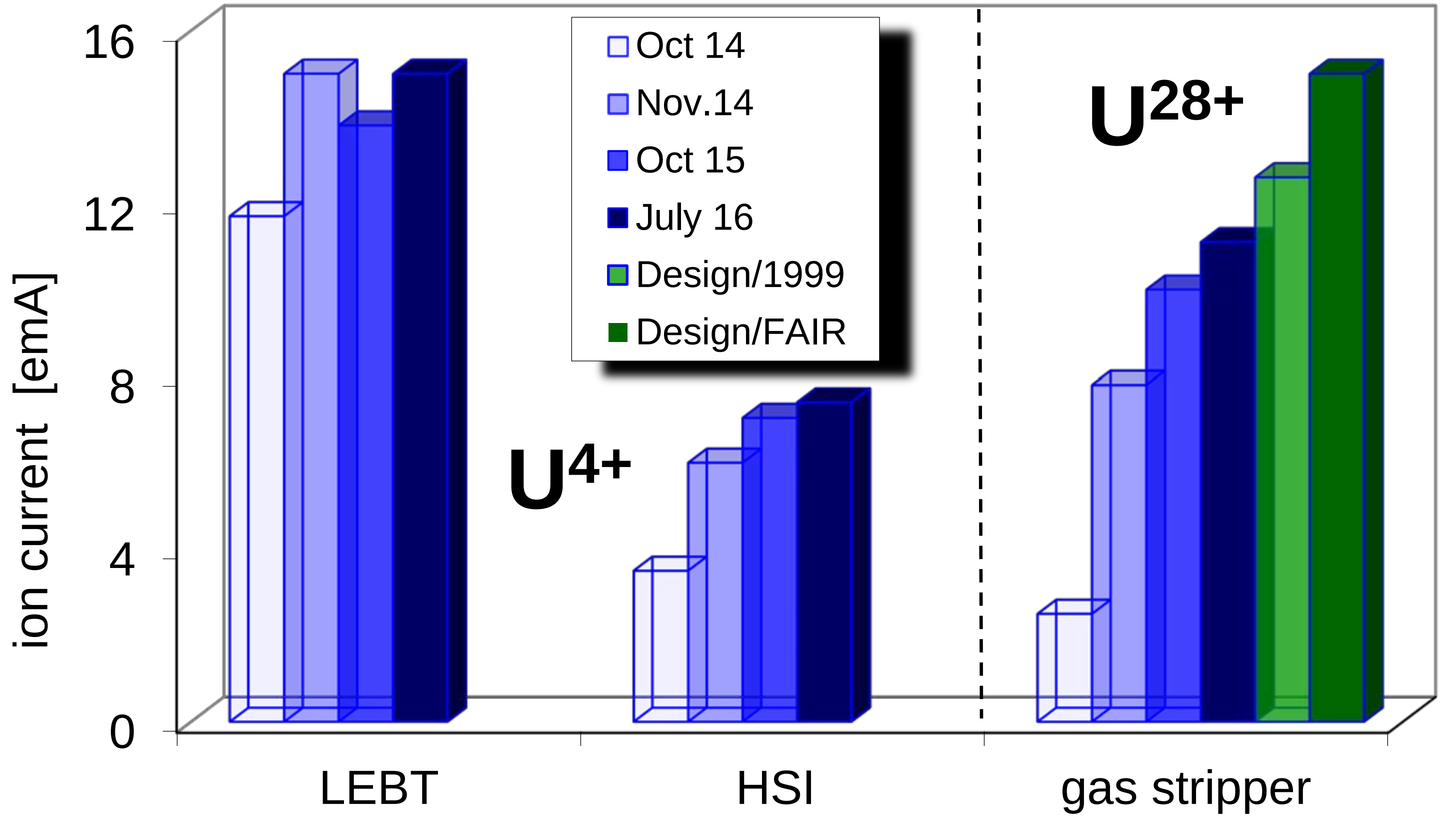


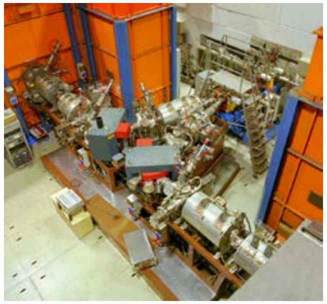


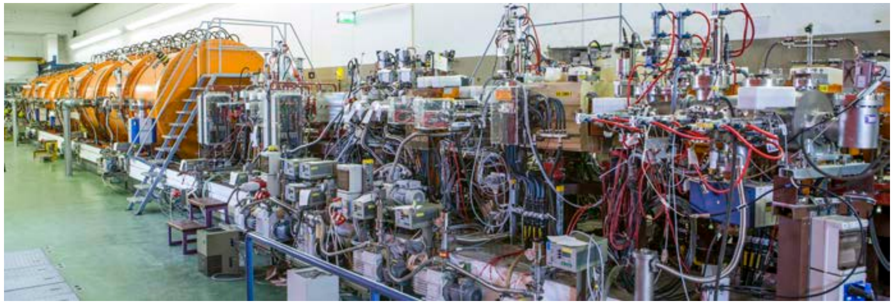
Comparison of HSI-Transmission



Uranium High Current Injector-Performance

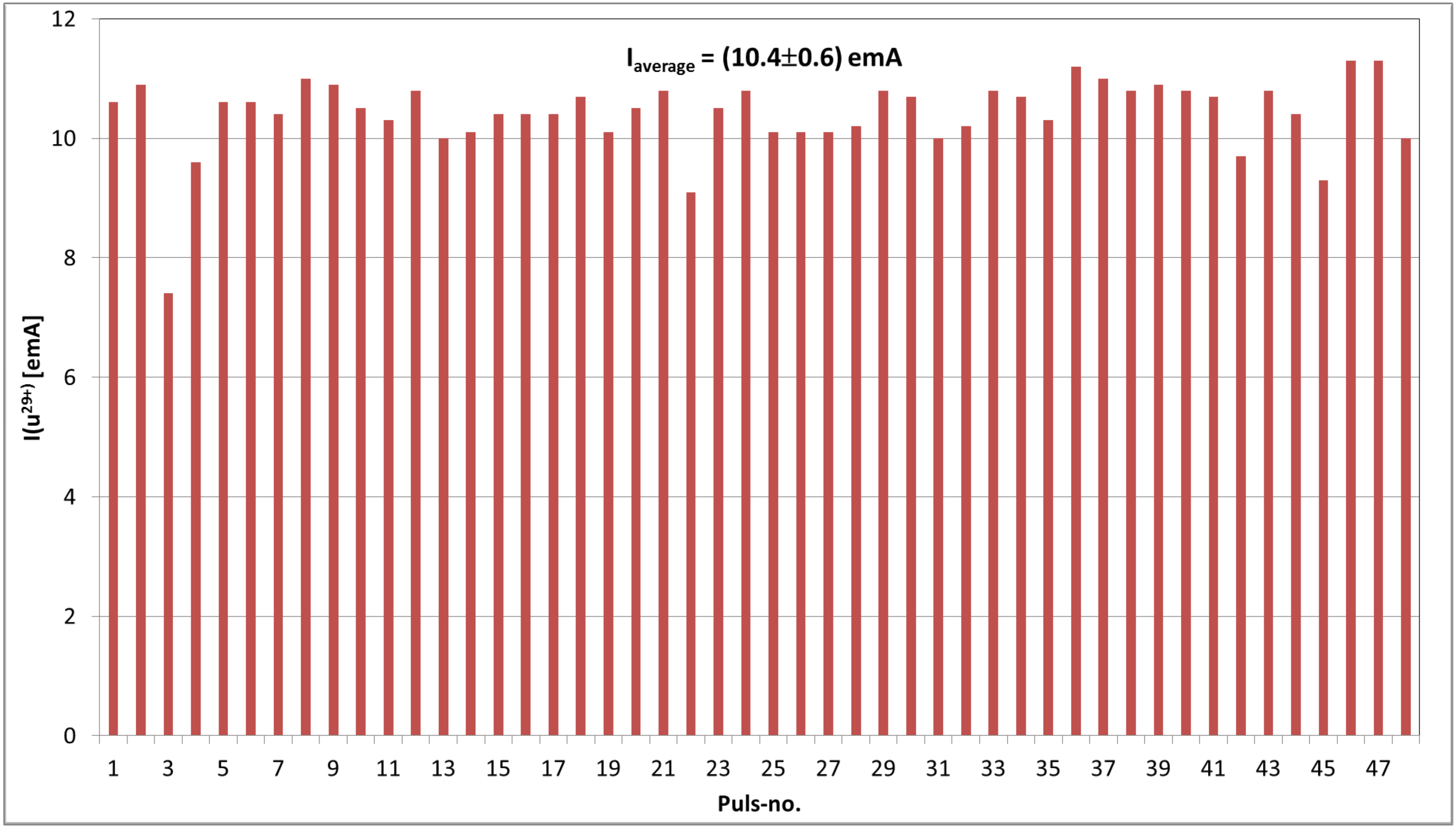




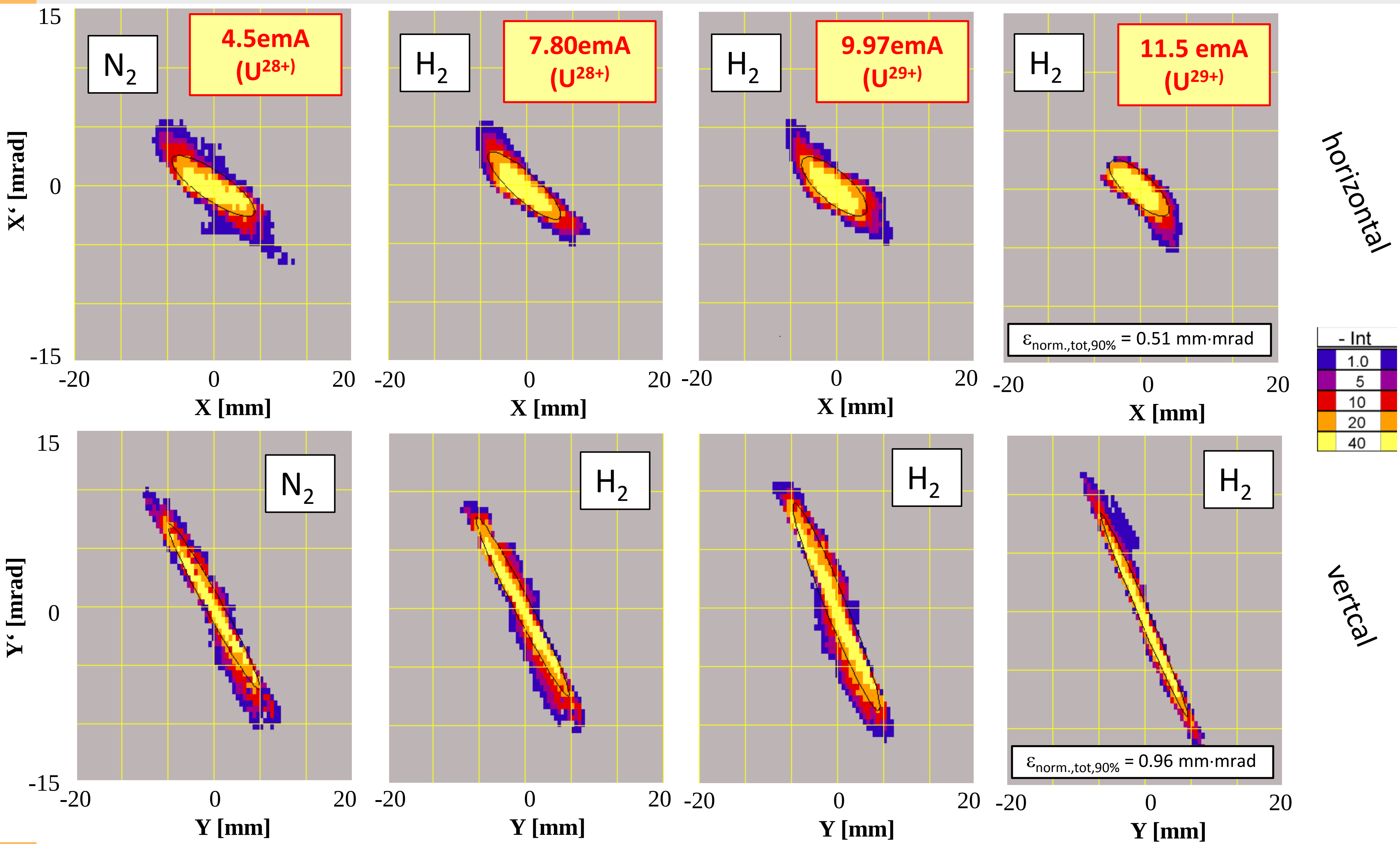


W. Barth, et al., Phys. Rev. ST Accel. & Beams 20, 050101 (2017)

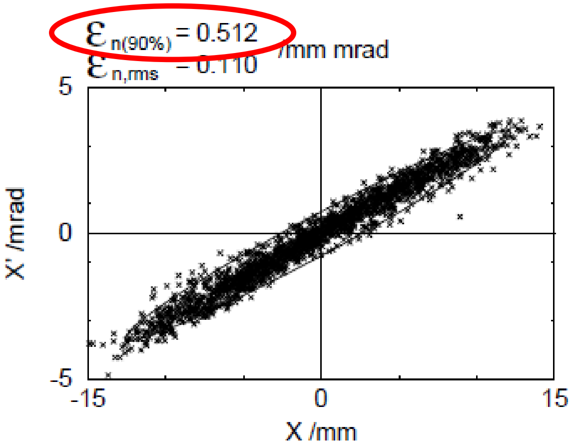
$^{238}U^{29+}$-Current Measurements at 1.4 MeV/u

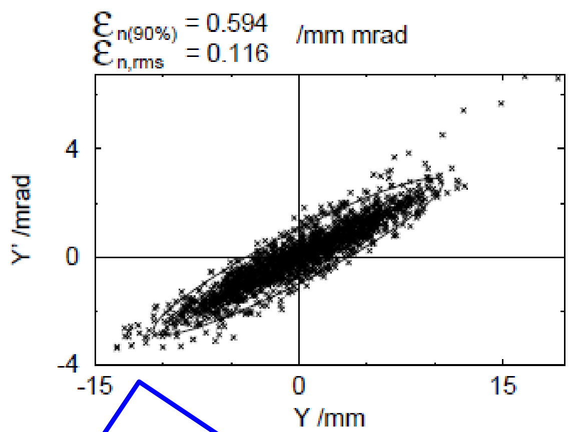


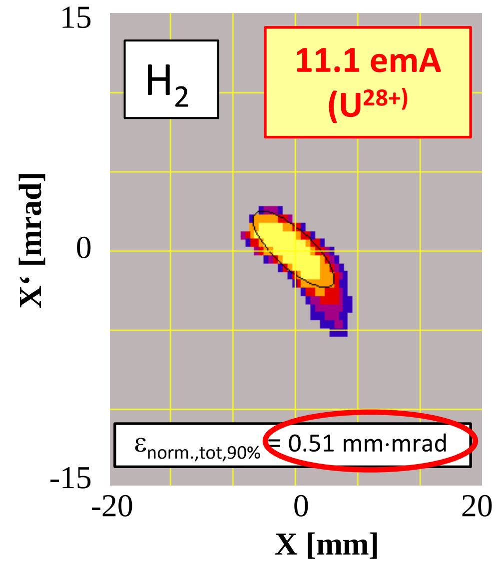
U^{28+} beam emittance at 1.4 MeV/u

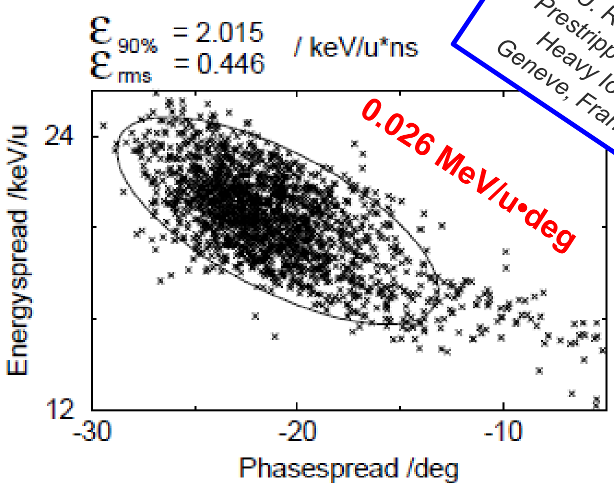


HSI-IH2-Simulationen









Exit particle distribution immediately behind of IH tank 2 at the design current of 16.5 emA and A/q = 65. The 90 % emittance values correspond to the plotted ellipses ; N_{tot}= 1768 particles.

U. Ratzinger, „The New GSI Prestripper Linac for High Current Heavy Ion Beams", LINAC96, Geneve, France, p. 288-292 (1996)

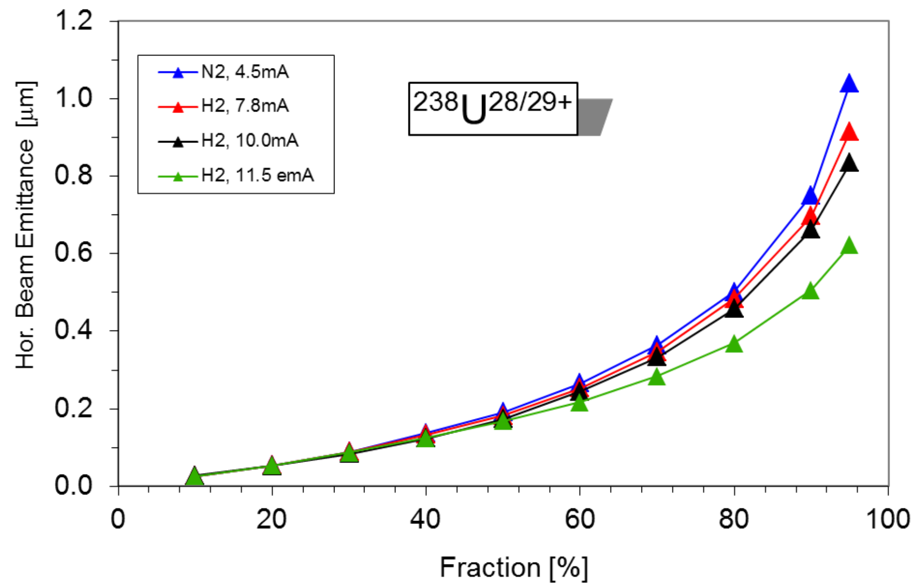
LINAC2000

Table 1: Specified beam parameters at … SIS injection, exemplary for a uranium bea…

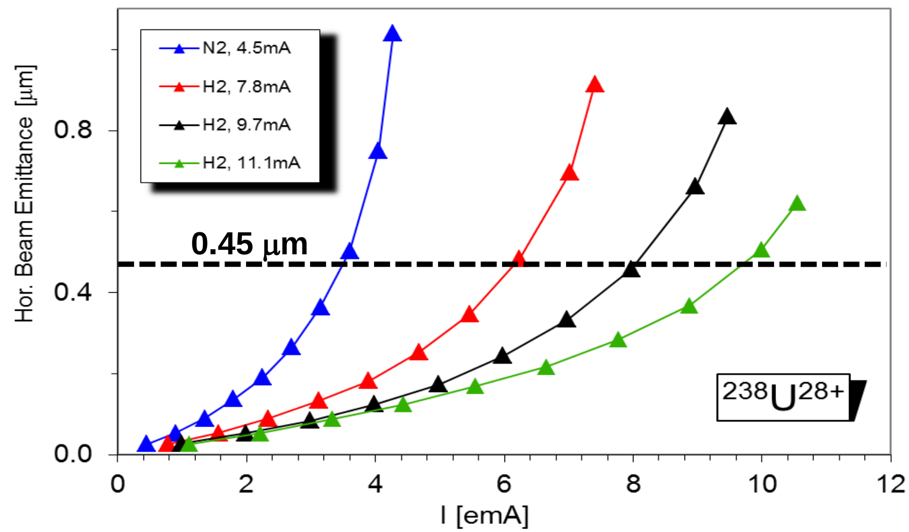
	HSI entrance	HSI exit	Alvarez entrance	SIS injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{73+}$
El. Current [mA]	16.5	15	12.5	4.6
Part. per 100µs pulse	$2.6\cdot10^{12}$	$2.3\cdot10^{12}$	$2.8\cdot10^{11}$	$4.2\cdot10^{10}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4
$\Delta W/W$	-	$\pm4\cdot10^{-3}$	$\pm2\cdot10^{-3}$	$\pm2\cdot10^{-3}$
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5

$$\Delta B = B_{gem}/B_{design} = 1.18$$

Beam emittance analysis

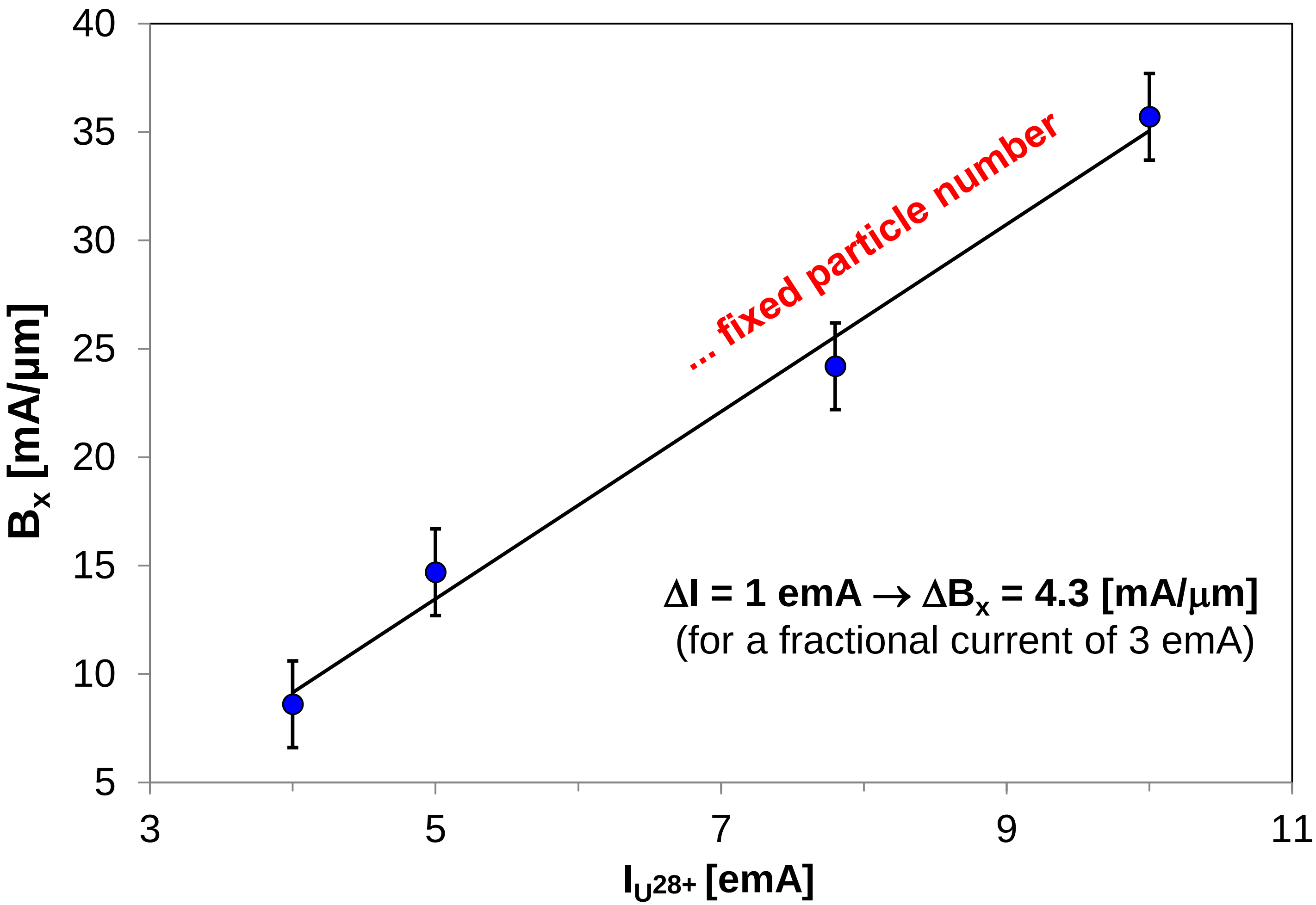


... fixed relative fraction

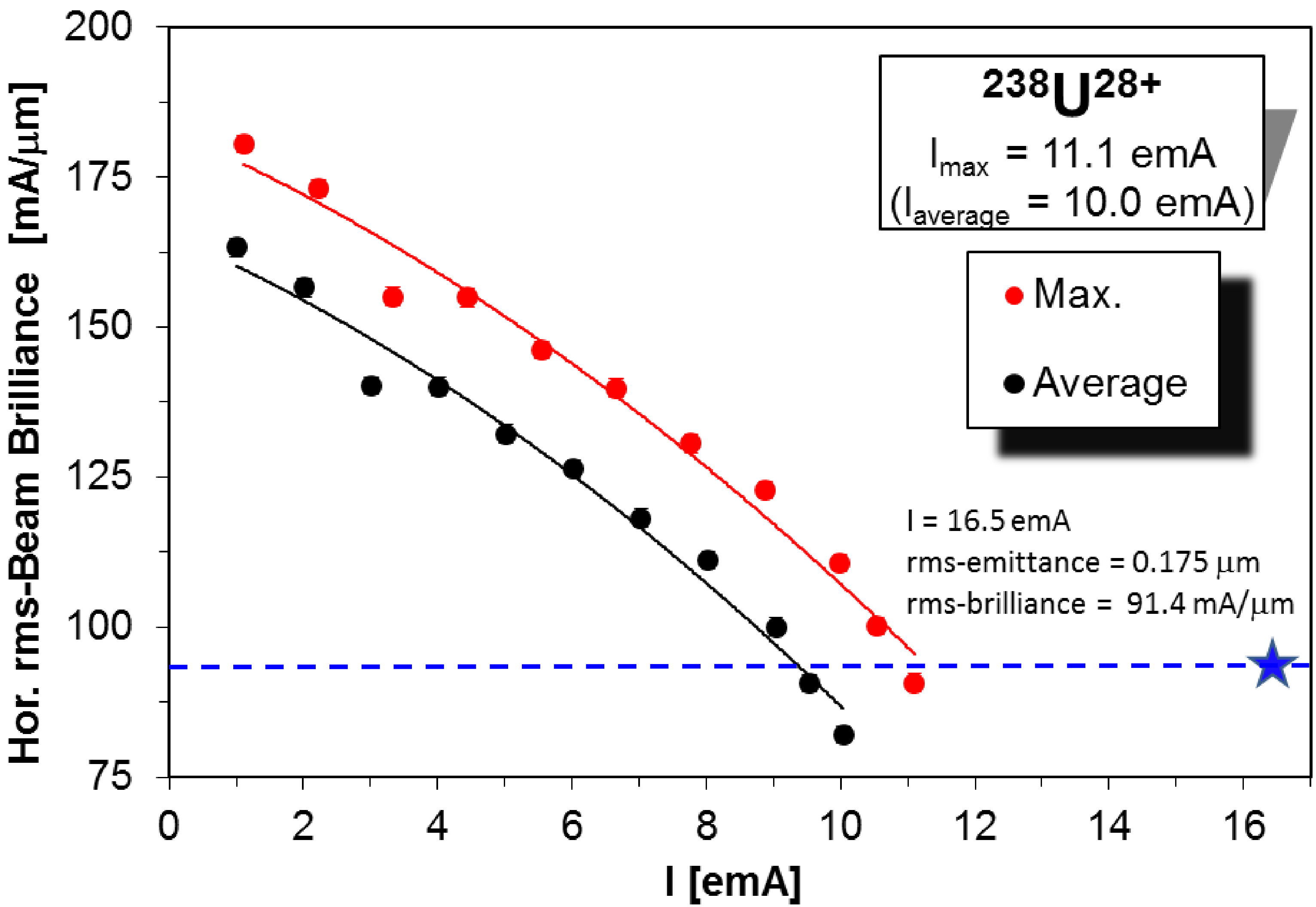


... fixed particle number

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

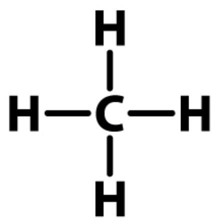


Beam Brilliance analysis



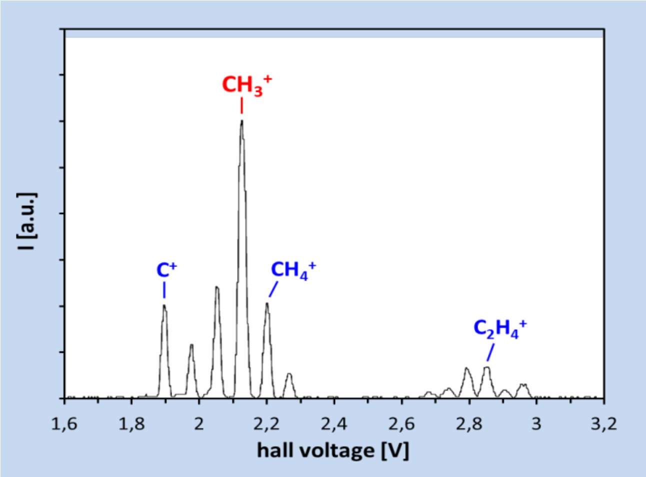
High intensity proton beam acceleration at GSI UNILAC

How to use a heavy ion machine for acceleration of high intensity proton beams?



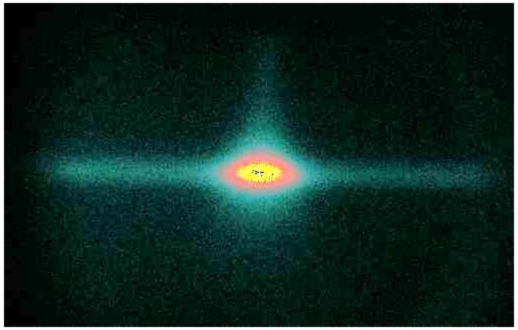
Methan

Ion source



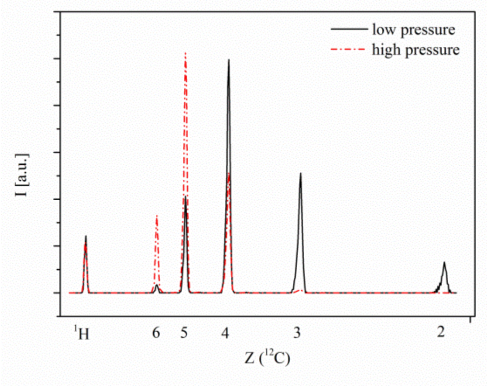
CH_3^+ acceleration

Use of HSI heavy ion beam capabilities to acclerate hydro-carbon compounds



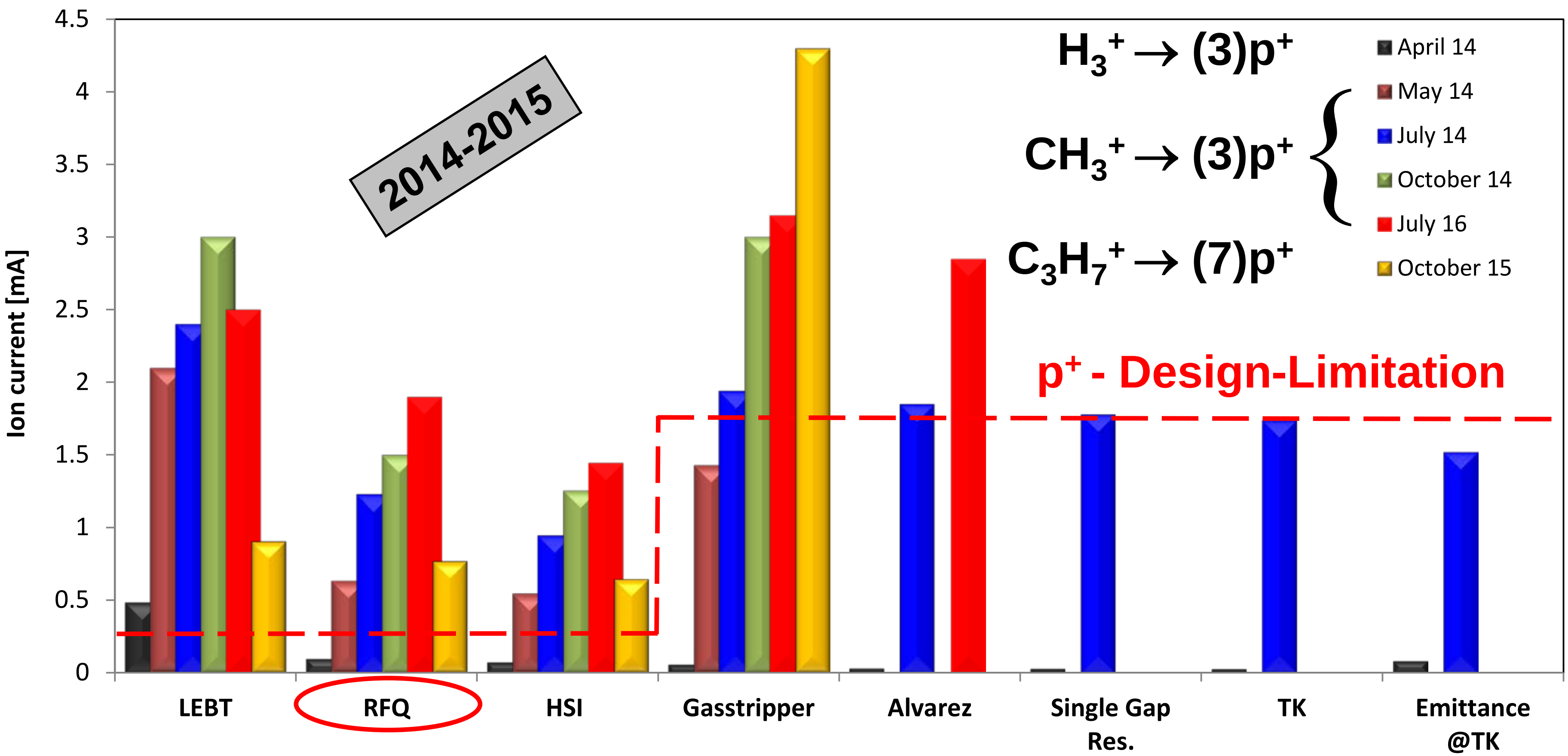
Cracking of CH-compounds + Stripping

C^{6+} acceleration (9 emA)



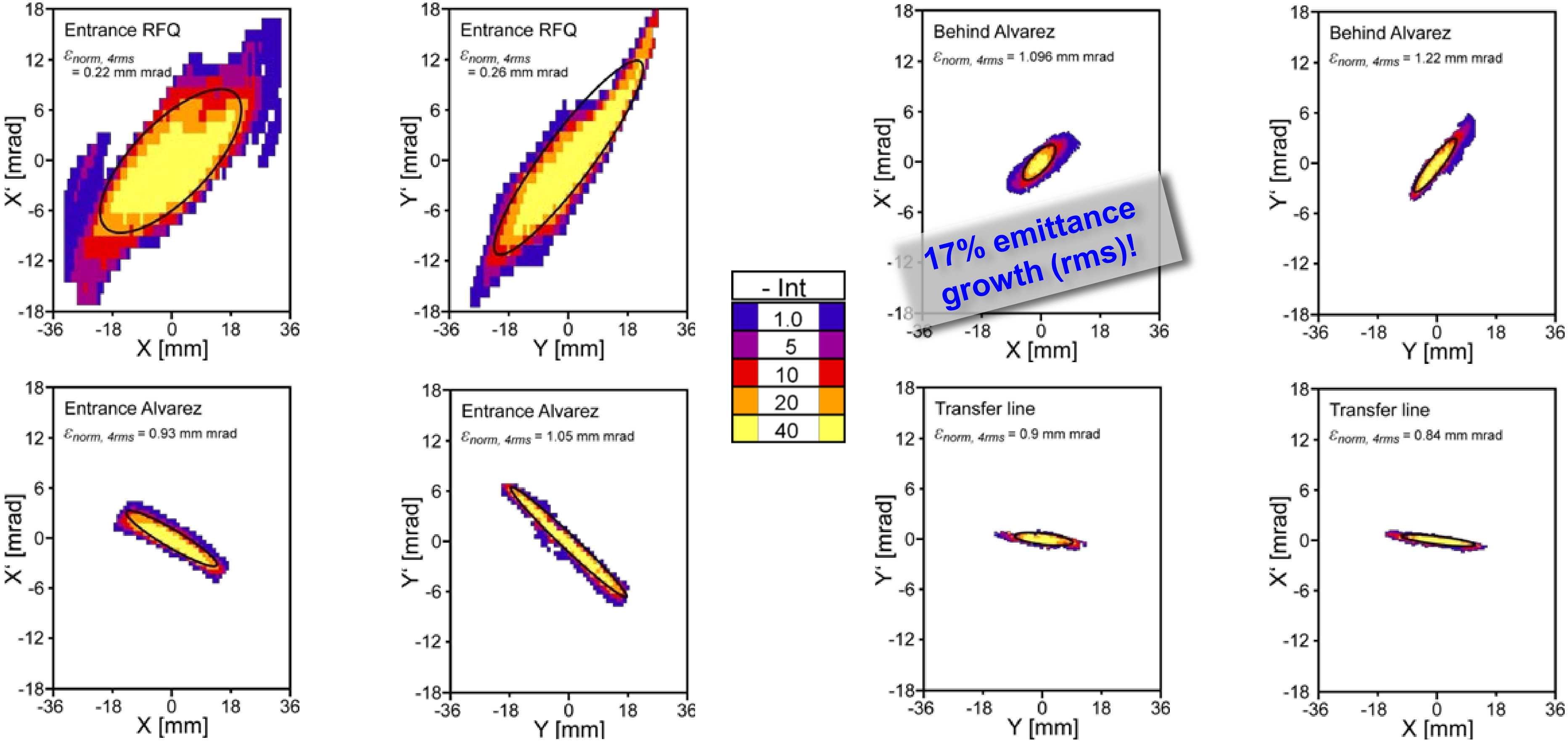
p^+ acceleration (3 emA)

High intensity proton beams at GSI-UNILAC



3 mA, p+ (UNILAC) => 1.5e12 (SIS18) => 25% of FAIR-requirement

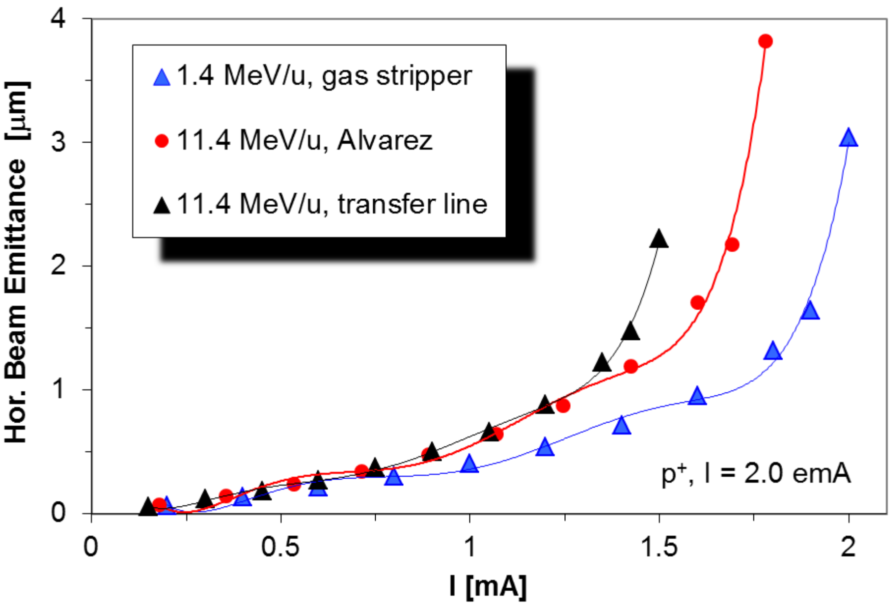
Front to end emittance-measurements



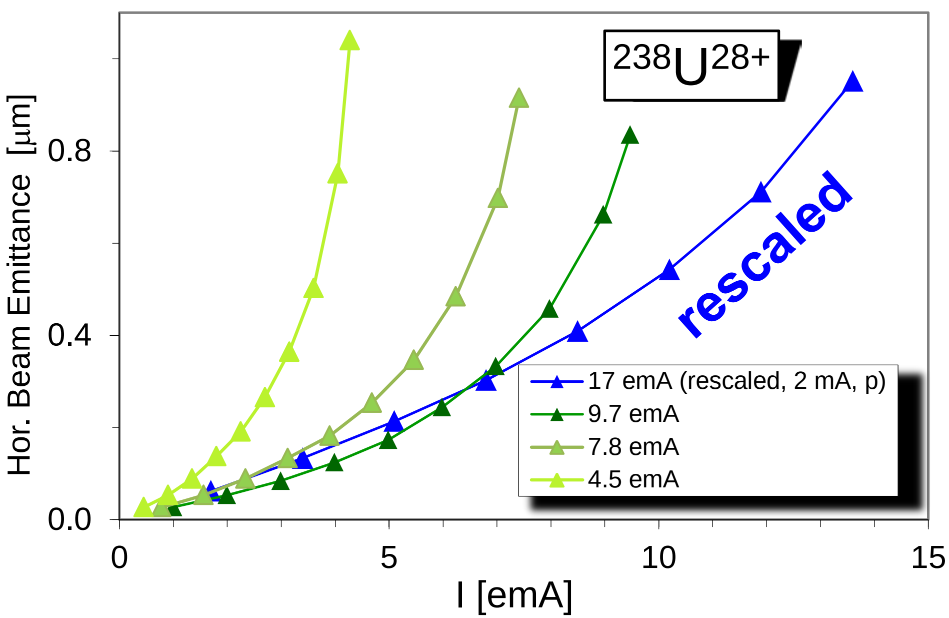
W. Barth, et al., Phys. Rev. ST Accel. & Beams 18, 050102 (2015)

Emittance Beam Analysis

Proton beam emittance



Uranium beam emittance



Summary

- RFQ-commissioning (1999) successfully accomplished with high current argon beam
- First uranium (4+) beam commissioning in 2000 after careful rf-conditioning
- RFQ-Upgrade I (2004) after significant surface degradation during 5 years operation; newly designed IRM; increased beam transmission
- RFQ-Upgrade II (2009) after again significant surface degradation during 5 years operation; copper plated electrodes; new electrode design with increased rf-voltage and aperture and slightly reduced max. field; increased beam transmission
- No electrode exchange since 10 years! Almost 18 months of shutdown (2016 - 2018).
- Despite further surface degradations the RFQ RF-performance could be dramatically improved: 600kW forwarded power at U^{4+} voltage level.
- As a result a new record RFQ high current Uranium beam intensity (11.25 emA) at sufficiently high beam transmission (75%) has been achieved in 2016.
- The horizontal Uranium 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
- World record U^{28+} beam intensity (11.1 emA) at low emittance (1.4 MeV/u)
- The conducted high current proton beam emittance measurement throughout the UNILAC shows a loss of horizontal beam brilliance of 23%
- Remark: Beam intensity attenuation concept (LEBT-QQ) => permanent particle loss inside RFQ during beam operation!

Thank You for Your Attention!