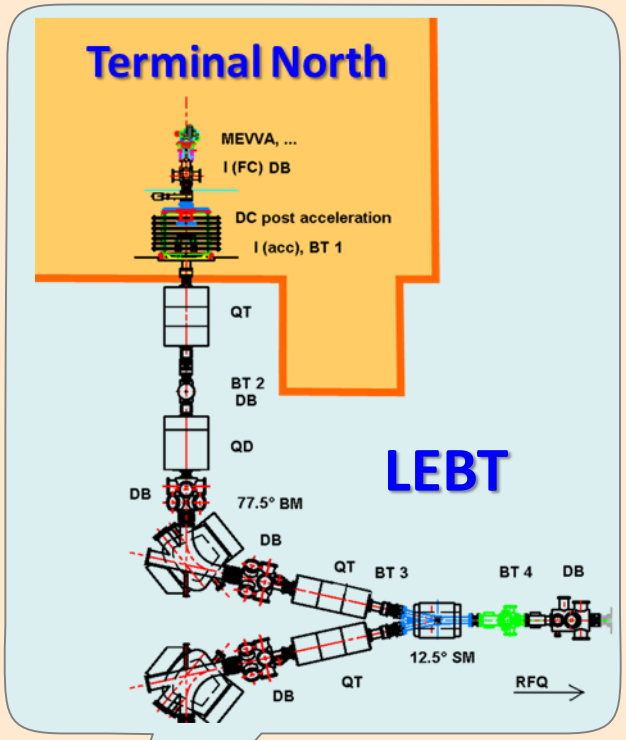
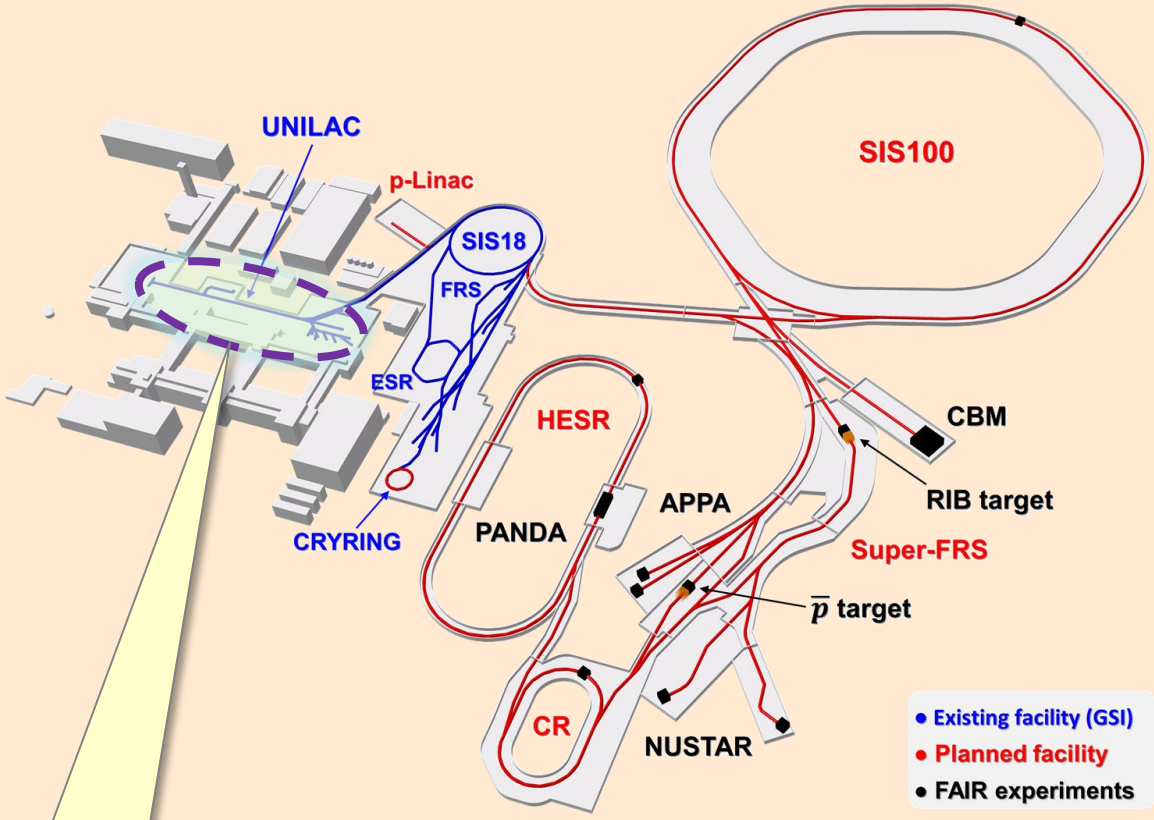
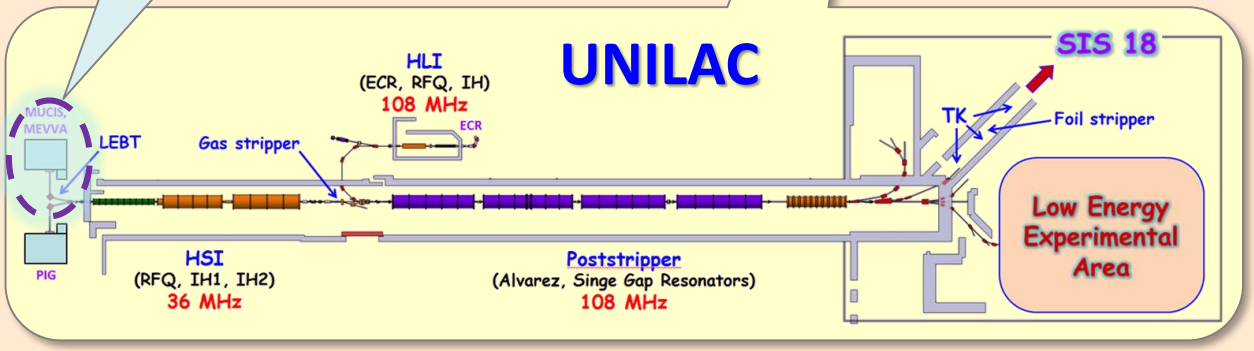
Towards Uranium intensities required for FAIR

Aleksey Adonin

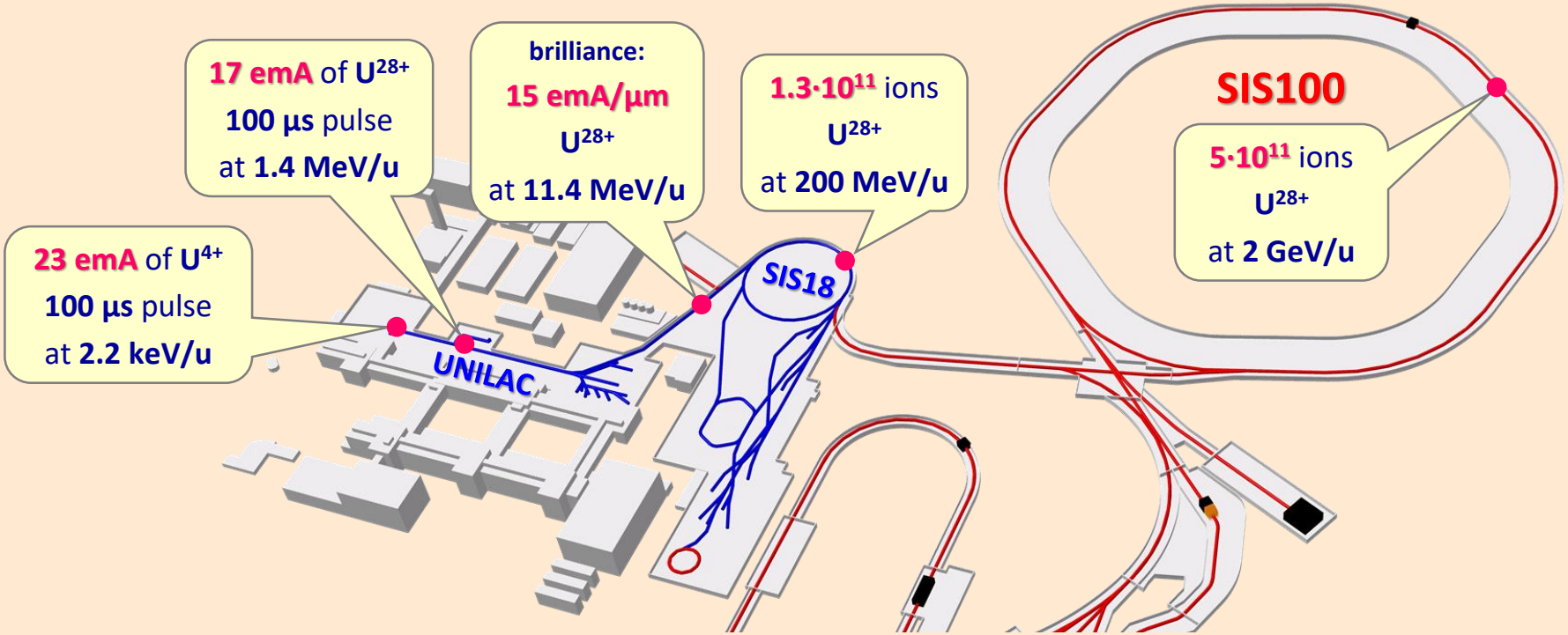
Ion Sources, GSI (Darmstadt, Germany)


Terminal North
MEVVA, ...
I (FC) DB
DC post acceleration
I (acc), BT 1
QT
BT 2
DB
QD
DB
77.5° BM
LEBT
DB
QT
BT 3
BT 4
DB
12.5° SM
QT
DB
RFQ


UNILAC
p-Linac
SIS18
FRS
ESR
SIS100
HESR
CBM
RIB target
APPA
PANDA
Super-FRS
CRYRING
$\overline{p}$ target
CR
NUSTAR
Existing facility (GSI)
Planned facility
FAIR experiments

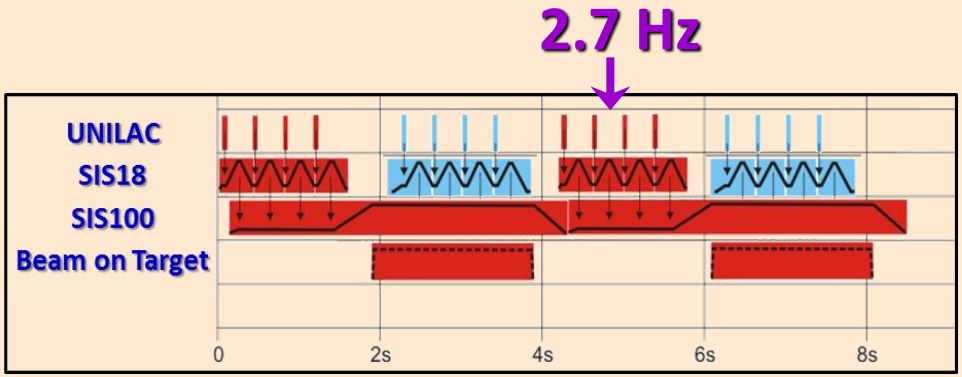

UNILAC
SIS 18
HLI
(ECR, RFQ, IH)
108 MHz
ECR
MUCIS
MEVVA
LEBT
Gas stripper
TK
Foil stripper
Low Energy
Experimental
Area
PIG
HSI
(RFQ, IH1, IH2)
36 MHz
Poststripper
(Alvarez, Singe Gap Resonators)
108 MHz

FAIR requirements for Uranium beams

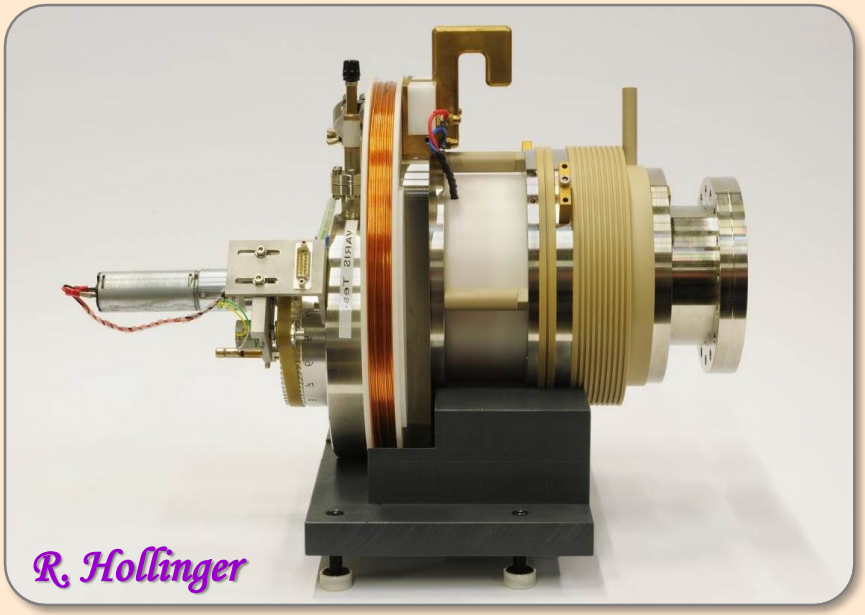


Requirements for U-source:

- U^{4+} beam at energy of 2.2 keV/u
- I_{Beam} = 23 emA inside ε = 220 π·mm·mrad
- operation with 2.7 Hz repetition rate



VARIS (Vacuum Arc Ion Source)



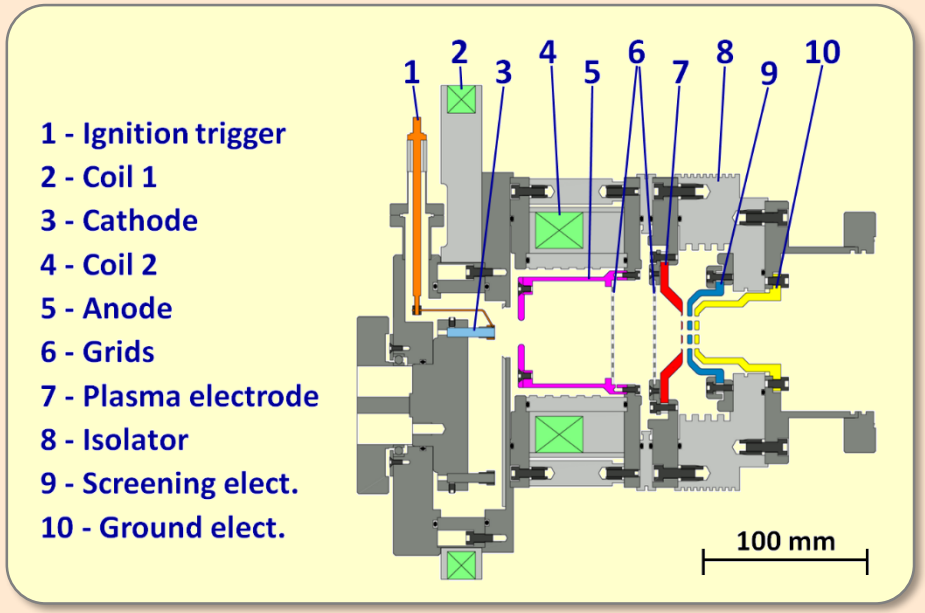
Technical data:

- Revolver with **17 Cathodes**
- 2 Solenoids: **0.1** and **0.2 Tesla**
- Extraction system: **Triode**; **7 x ø4 mm**
- Emission area: **0.88 cm²**
- Arc current: up to **1 kA**
- Typical duty cycle: **1 Hz / 0.5 ms**

Features:

- Optimized for Uranium: **67% of U^{4+}**
- High emission current density: **170 mA/cm²**
- NO water cooling is necessary
- Improved positioning of coils and grids
- Compact extraction system

R.Hollinger, M.Galonska, Nucl. Instr. and Meth. in Phys. Res. **B 239** (2005)

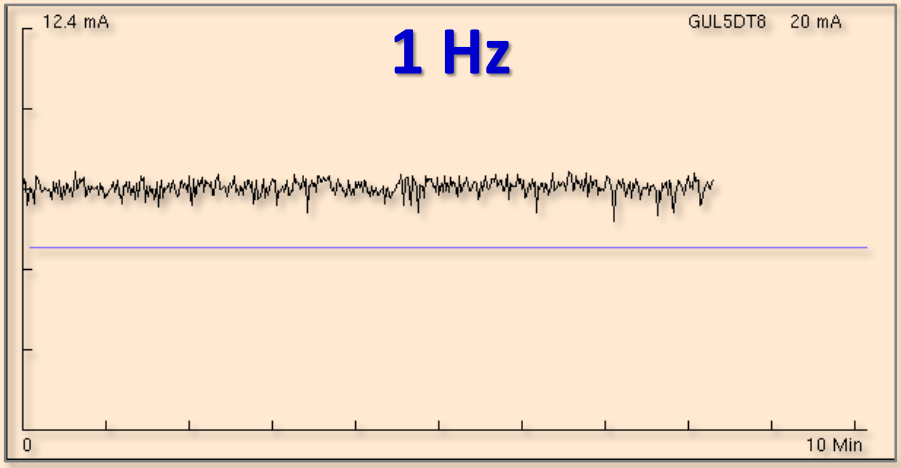


Recent situation

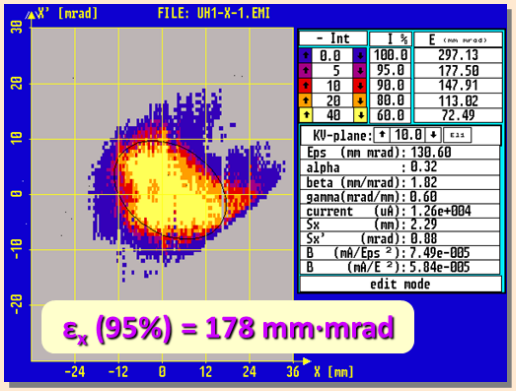
Well established operation with 1 Hz / 0.5 ms (pulse length)

- High production efficiency of U^{4+} ions (67% of U^{4+} in the spectrum)
- Proper beam pulse shape (with a flat top over 120 µs)
- Excellent pulse-to-pulse stability (intensity fluctuations < 12%)
- Beam current in front of the RFQ: up to 15 emA (2.3·10^{12} ions in 100 µs)

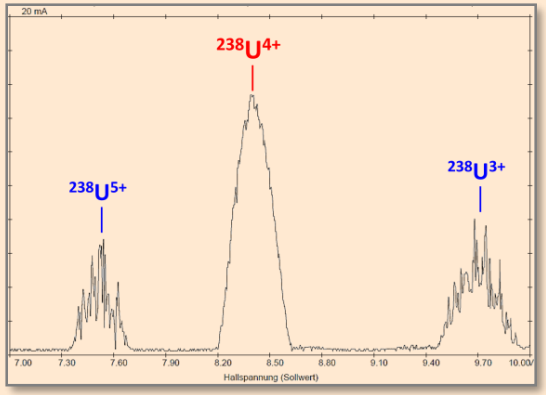
VARIS operation stability (pulse-to-pulse) with Uranium



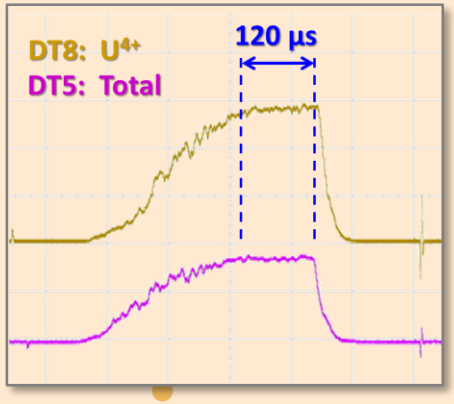
U^{4+} beam emittance in front of RFQ



Ion charge state distribution in plasma



Temporal profile of U^{4+} beam



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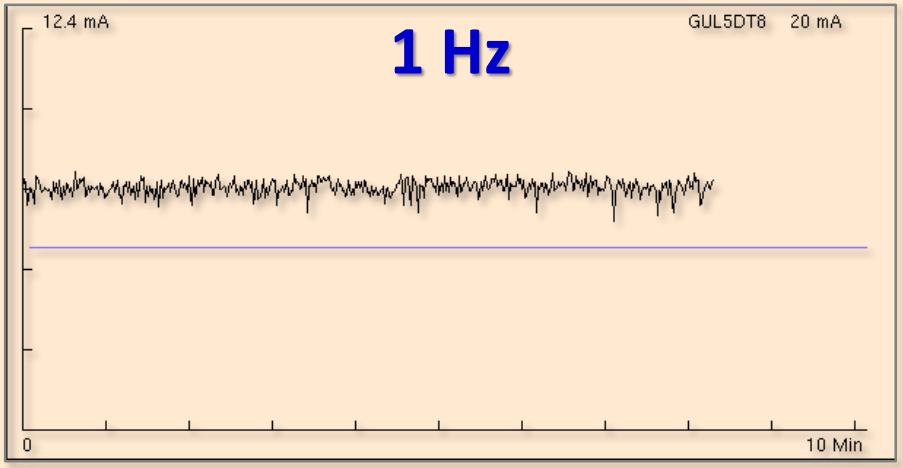
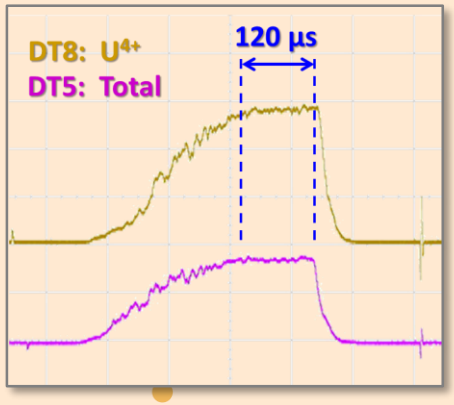


It is necessary to:

- increase the ion beam current: 15 emA → 23 emA
- keep the current inside: 220 π·mm·mrad
- increase operational repetition rate: 1 Hz → 2.7 Hz

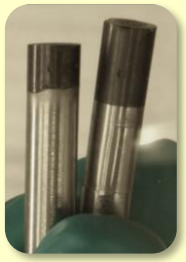
Temporal profile of U^{4+} beam

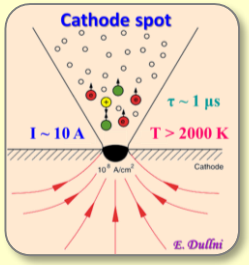


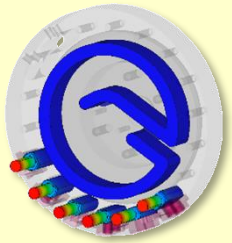
Directions of development

Directions of development of Uranium ion source and injector

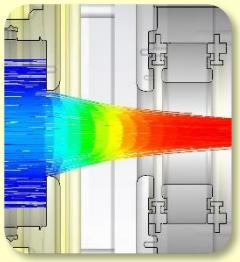
Increasing the repetition rate

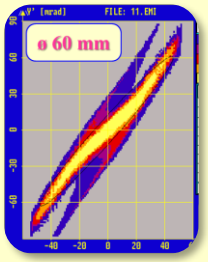


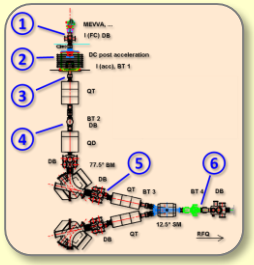




Increasing the beam brilliance and beam intensity in UNILAC







Increasing the repetition rate

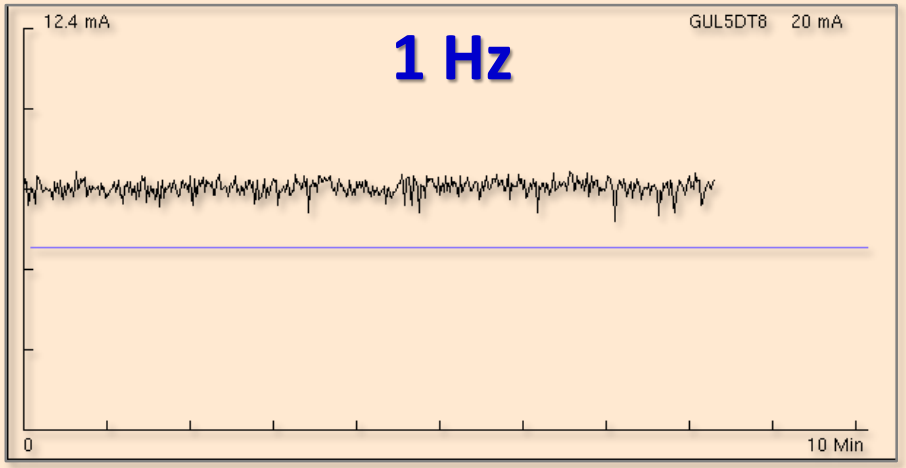
Repetition rate

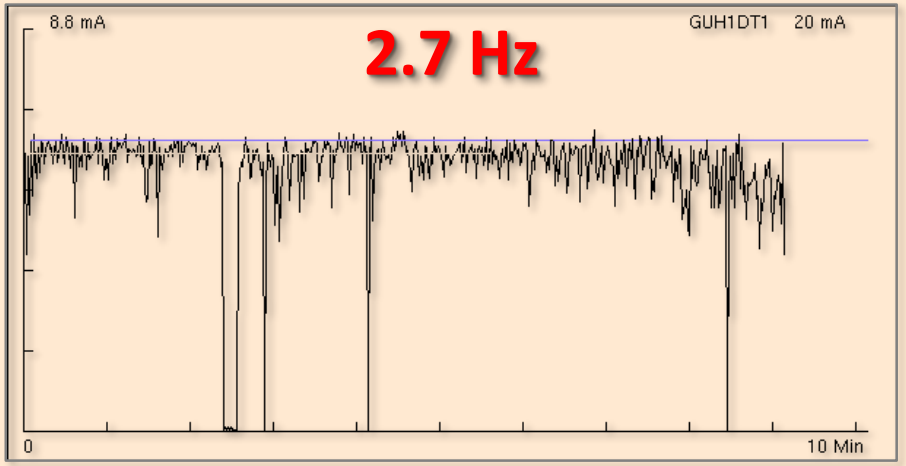
Increase repetition rate

from 1 Hz to 2.7 Hz (τ_{pulse} = 0.5 ms)

- Frequent **ignition failures** of cathodes
  - in average, every 4-th pulse fails
- Notably more **frequent breakdowns** in the extraction system
- **Instable operation** of the ion source
  - increased intensity fluctuations
- Attempts to stabilize the ion source results in **intensity drop** of U^{4+} beam

VARIS operation stability with Uranium

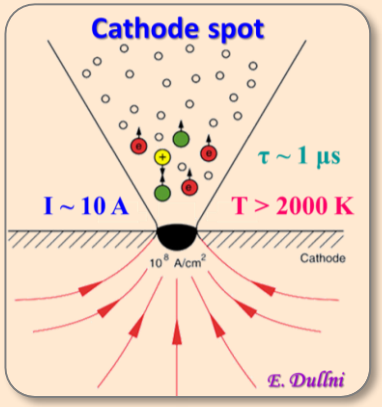


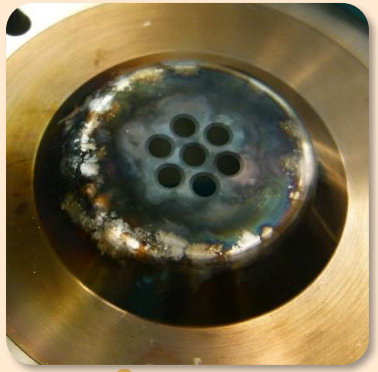


Repetition rate

Inhibiting factors:

- **Increased $T_{surface}$ of the cathode**
  → short circuit bridges → arc ignition failures
- **Higher flux of neutrals from the surface**
  → shifting the spectrum to the lower charge states
- **Increased T of extraction electrodes**
  → increased breakdown probability → sparking in the extraction system
- **Reduce discharge current**
  → reduced plasma density → lower beam current





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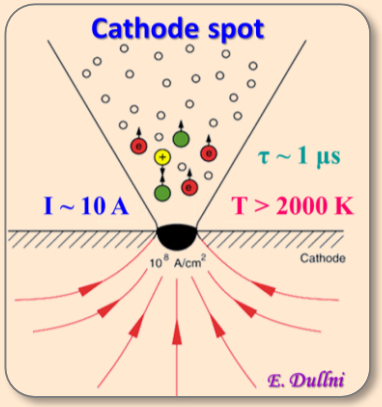
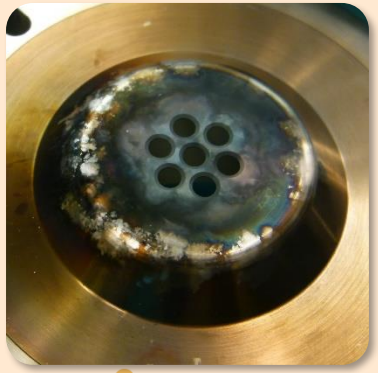


Possible solutions:

- **Enhance the physical properties of the cathode material**
  → use composite materials in cathodes instead of pure Uranium
- **Improve cooling of the cathode and the extraction system**
  → implement active water cooling for cathode revolver and extraction electrodes

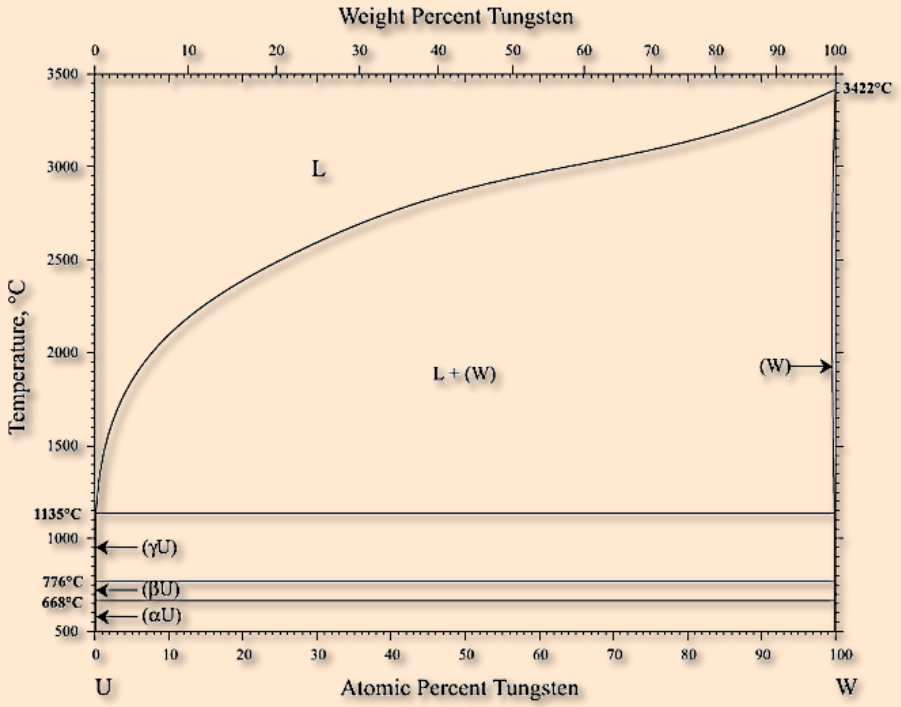


U-W composition

Enhancing material properties:

The **production of neutrals** during the discharge pulse can be reduced by **changing the physical properties** of the cathode material. This can be achieved by using an **alloy** or a **mixture** of the desired material with a **more refractory metal**.

Phase diagram of U-W system*



Material	Melting point (K)	Electrical resistivity (nΩ·m)	Thermal conductivity (W/m·K)	Temperature (K) for certain Vapor Pressure					
				1 Pa	10 Pa	100 Pa	1 kPa	10 kPa	100 kPa
U	1405	280	27.5	2325	2564	2859	3234	3727	4402
W	3695	52.8	173	3477	3773	4137	4579	5127	5823

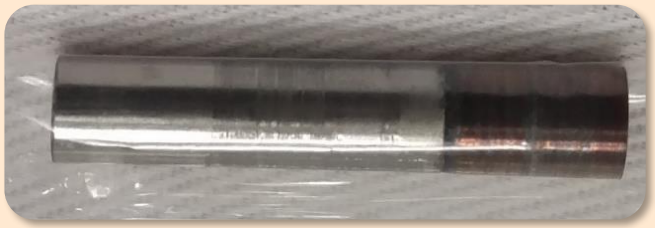
*T. B. Massalski, et al., "Binary Alloy Phase Diagrams", 2-nd Edition

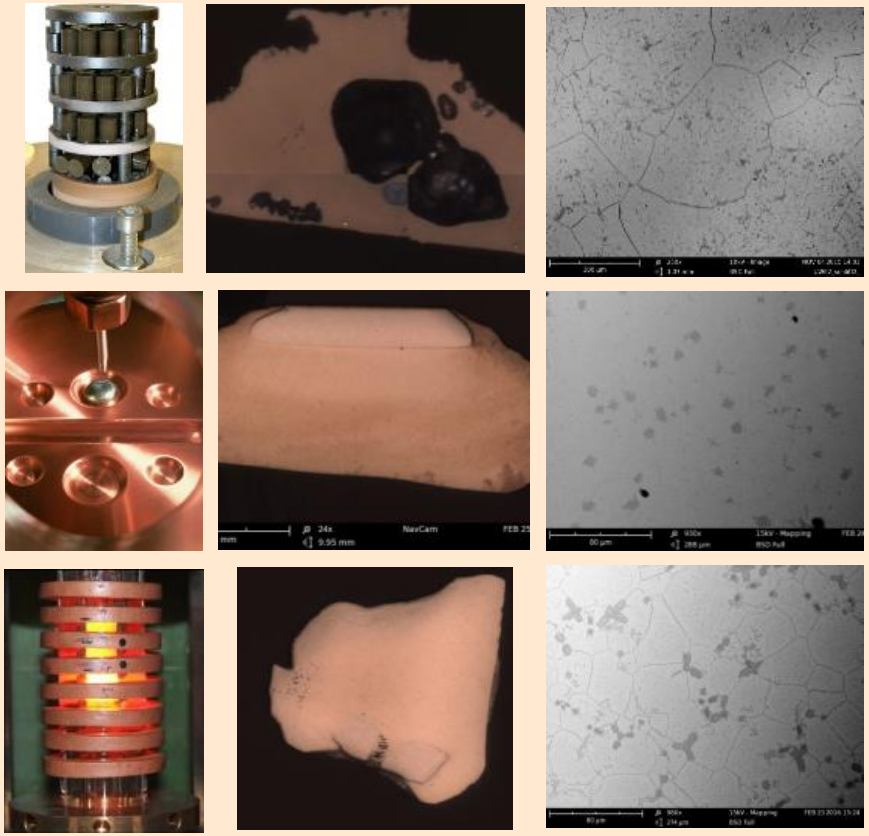
Manufacturing possibilities

Study of the production possibilities of the electrodes from **U-W composition** by **Framatome GmbH** (formal AREVA, Erlangen)

- Various methods of production of homoge-neous U-W mixture/alloy have been studied and tested:
  - **Equilibrium oven**
  - **Light arc oven**
  - **Induction oven**

- Sets of different prototype electrodes have been produced for tests at GSI:
  - **U-W (5% Wt.)** on **W**- and **Cu**-supporter
  - **U-W (12% Wt.)** on **W**- and **Cu**-supporter





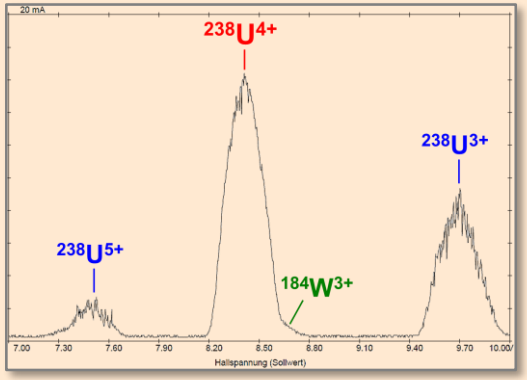
R. Bathelt
W. Schmid

U-W composite cathodes:

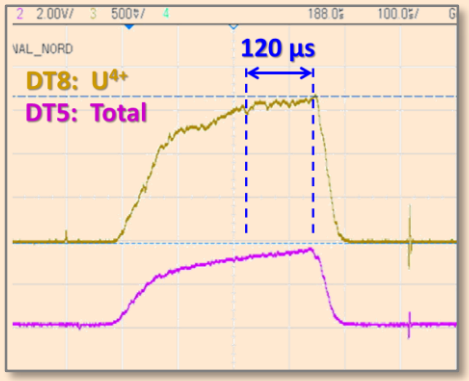
- **Main conclusion:**
  - Stable oper. with **2.8 Hz / 0.4 ms** is possible
  - No notable difference between **5%** and **12%**
- **Beam pulse shape:**
  - Flat top **over 120 µs**
  - Intensity noise **< 10%**
  - Rising edge **steeper** as for 1 Hz
- **Charge state distribution:**
  - Shifted in direction of 3^+
- **Beam current:** **up to 16 mA**
- **Stability:**
  - Pulse-to-pulse fluctuations **≤ 10%**
- **Conditioning time:**
  - **10-15 min** with 2.8 Hz

VARIS performance with U-W composite cathodes

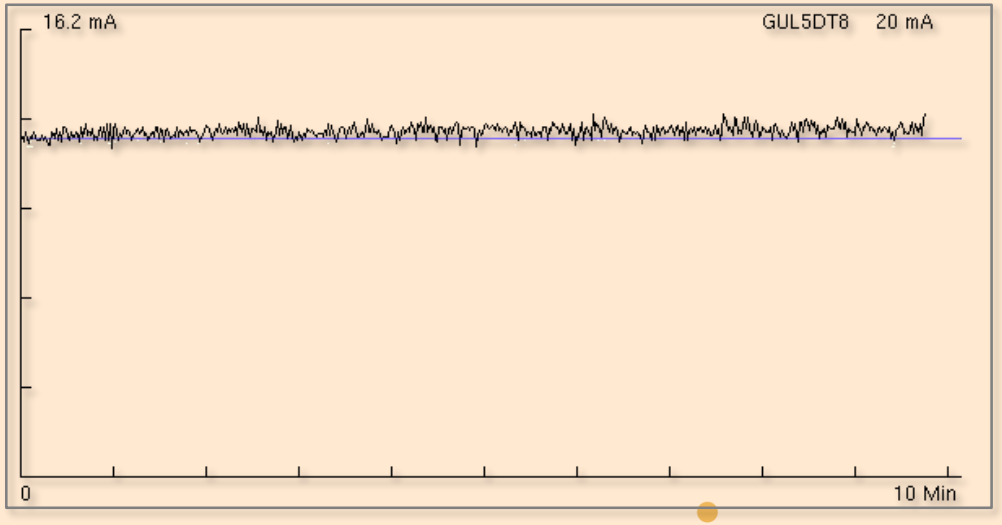
Ion charge state distribution for U



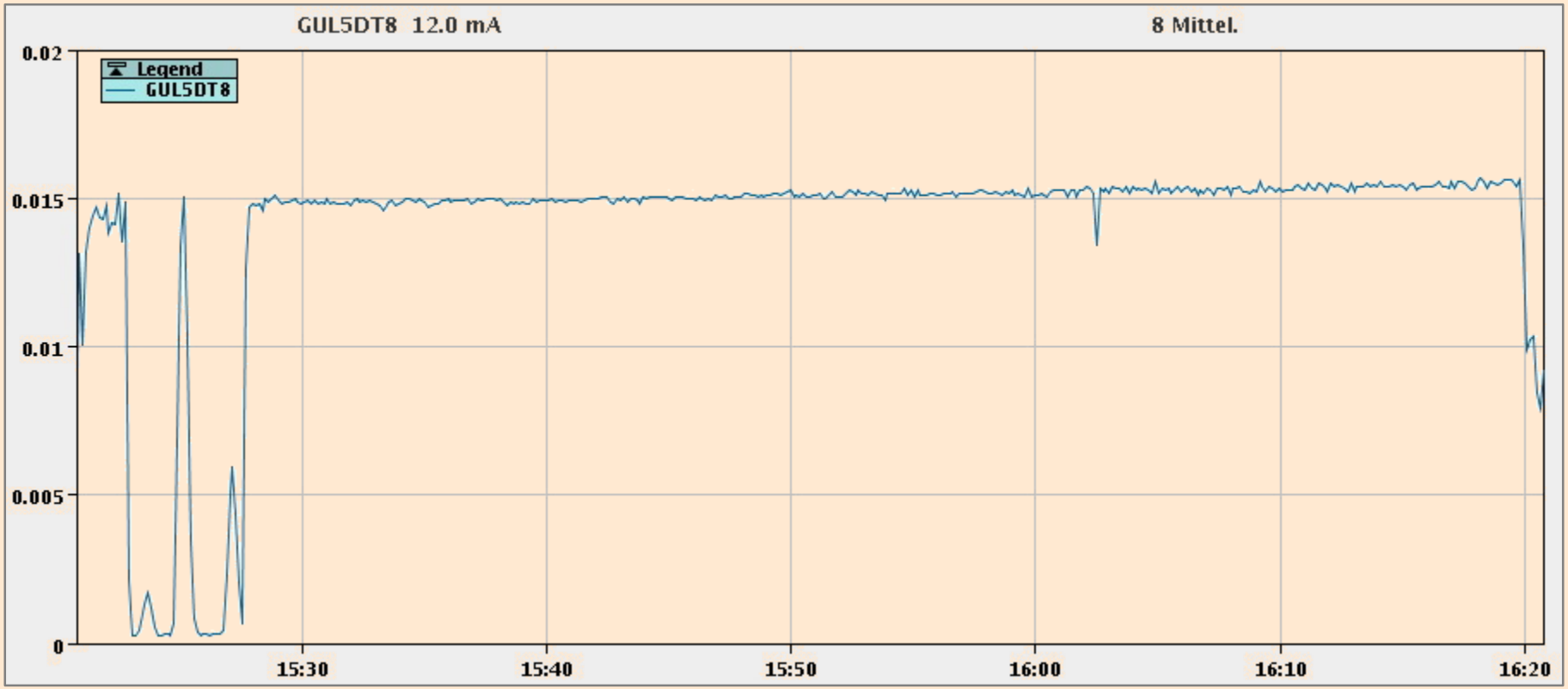
Temporal profile of U^{4+} beam



Operation stability (pulse-to-pulse) over 10 min



Operation stability over 1 hour



Actual problems:

- **"Bad phases" in cathode operation:**

→ ignition failures (**> 50%** of beam pulses are failed even with **P_{ZG} = MAX**)

→ very **unstable** arc discharge =>
=> very **noisy** beam pulse
(intensity fluctuations **up to 70%**)

→ no pulse-to-pulse stability

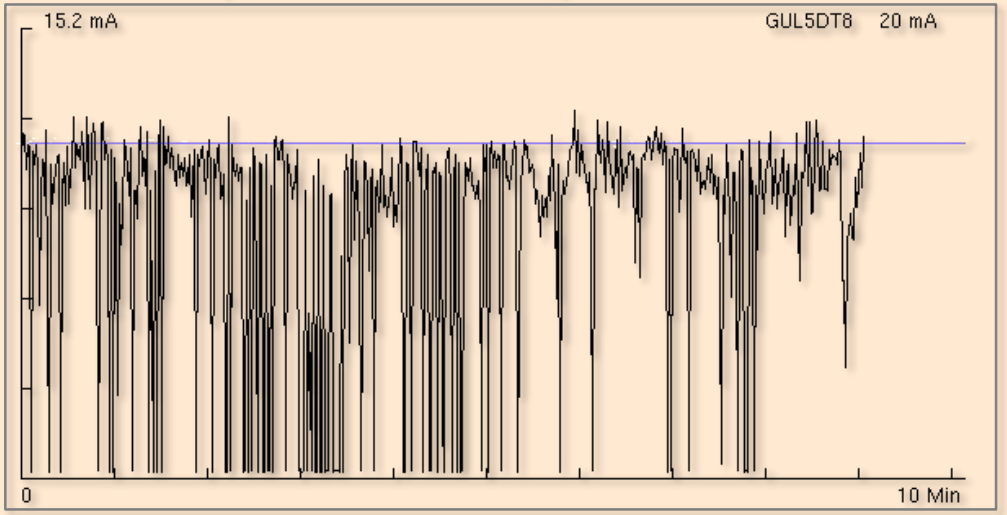
→ tuning the IS parameters doesn't help
=> it burns out by itself

→ "bad phase" can take **from 5 to 30 min**

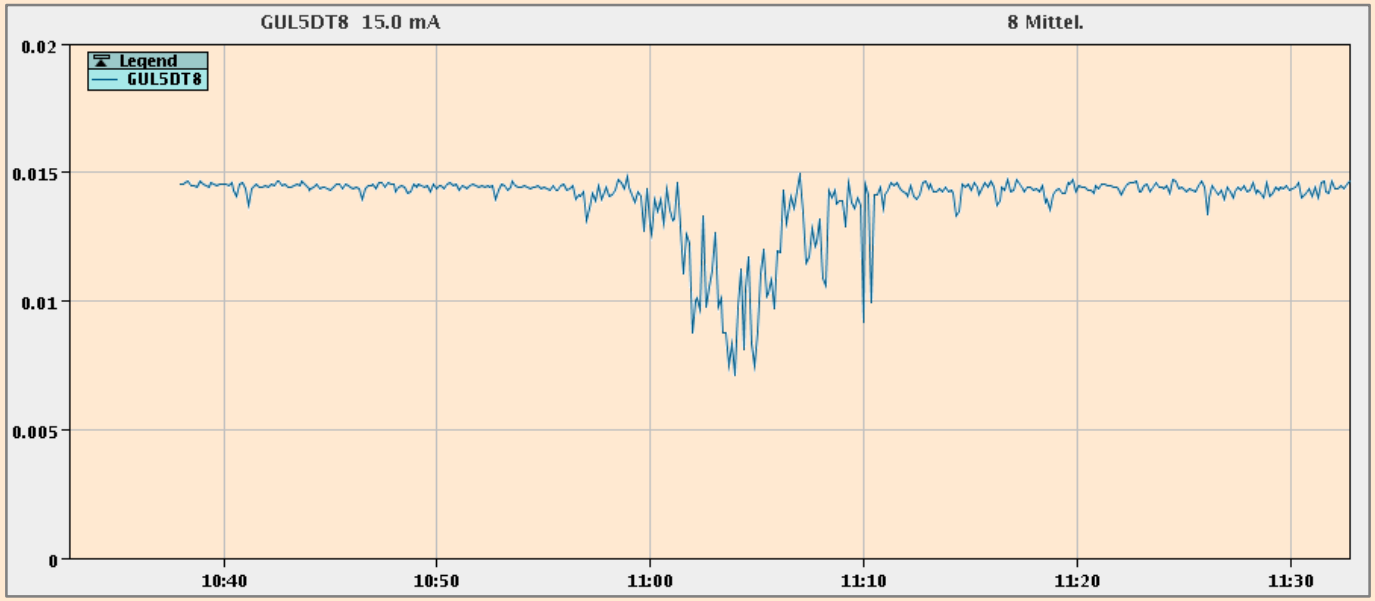
- **Lifetime of cathodes:**

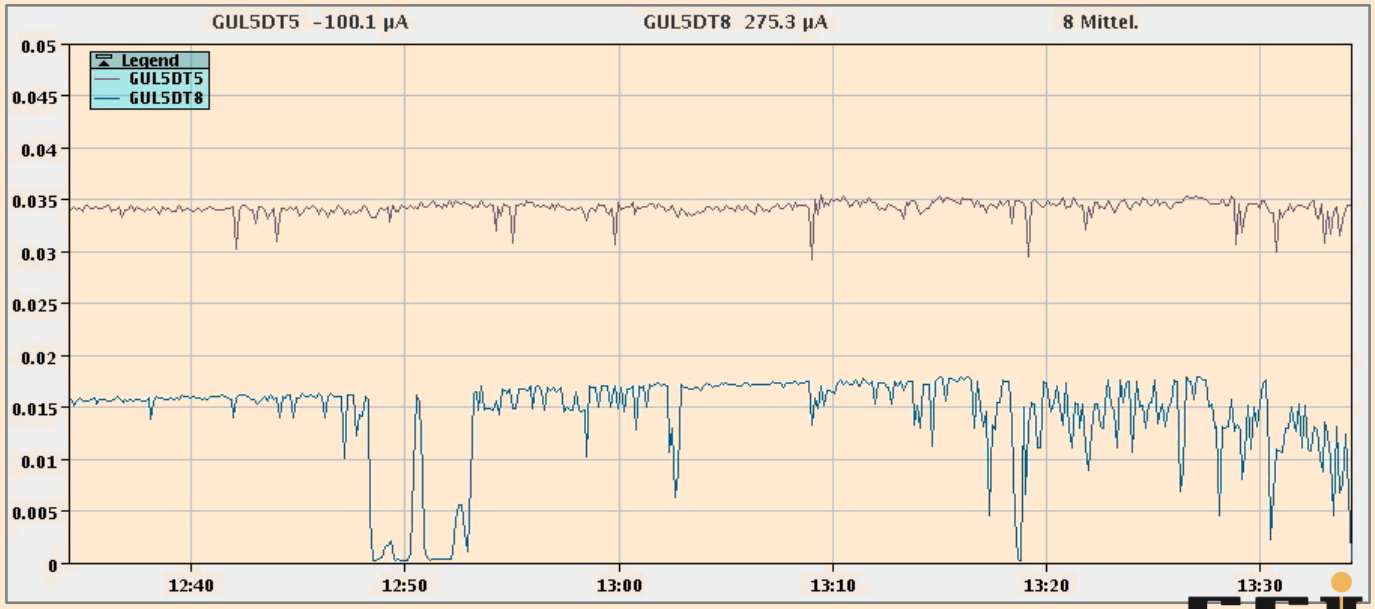
→ up to **7 hours** with 2.8 Hz
incl. total time of "BPh" **~1.5 hours**

Operation "instability" over 10 min



Results

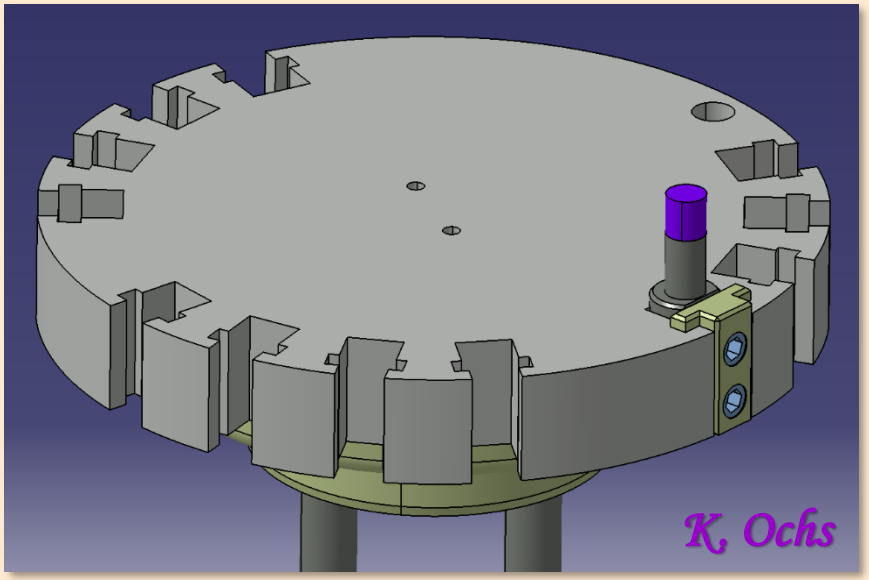

GUL5DT8 15.0 mA
8 Mittel.
Legend
GUL5DT8
0.02
0.015
0.01
0.005
0
10:40
10:50
11:00
11:10
11:20
11:30

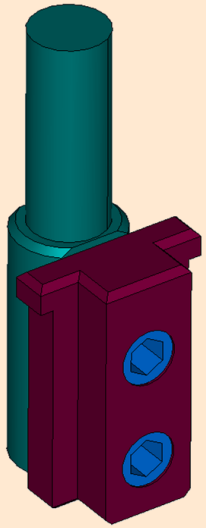

GUL5DT5 -100.1 µA
GUL5DT8 275.3 µA
8 Mittel.
Legend
GUL5DT5
GUL5DT8
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
12:40
12:50
13:00
13:10
13:20
13:30

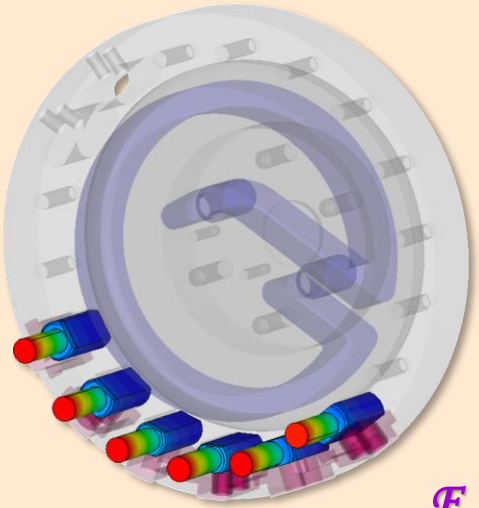
Active cooling of cathodes

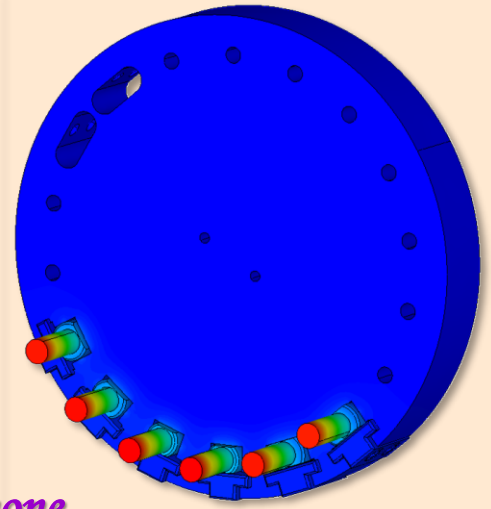
Concept:

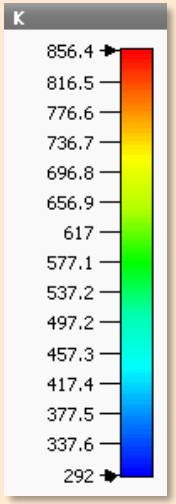
- Cathode revolver with water cooling
- Cathodes with improved heat dissipation:
  - **Uranium head** brazed on **Cu-supporter**
  - Special geometry of cathodes











F. Maimone

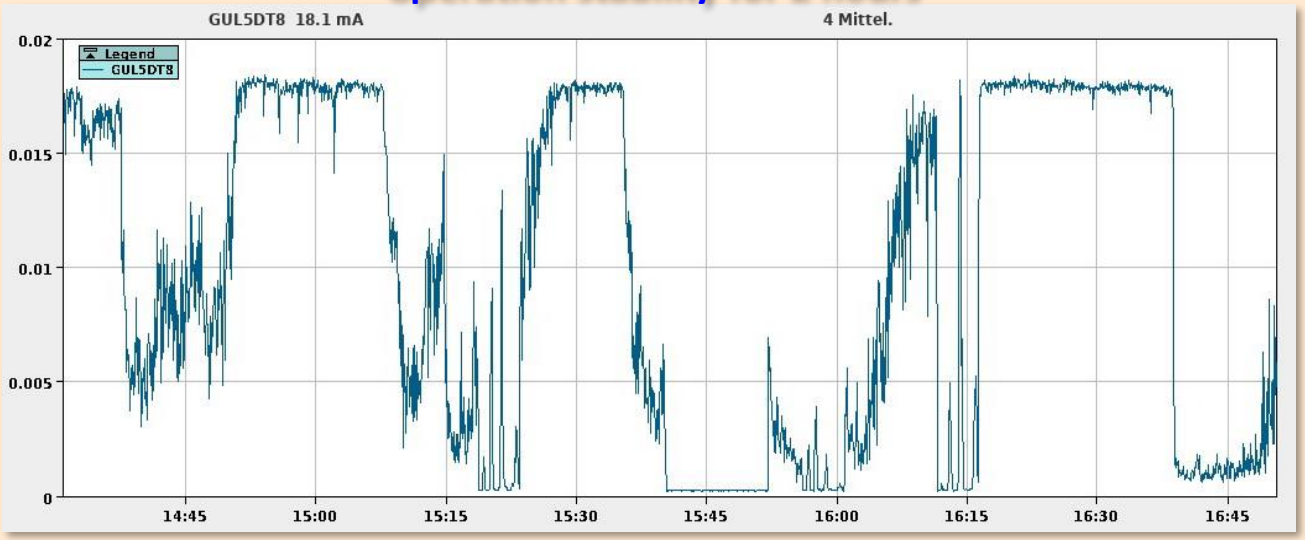
Active cooling of cathodes

1-st performance test:

- **4x** cathodes have been tested
- difficult to get a stable operation

  - about **40%** of operation time – **“bad phases”**
- no notable difference b/w **water ON** and **OFF**
- further tests needed…

Operation stability for 2 hours



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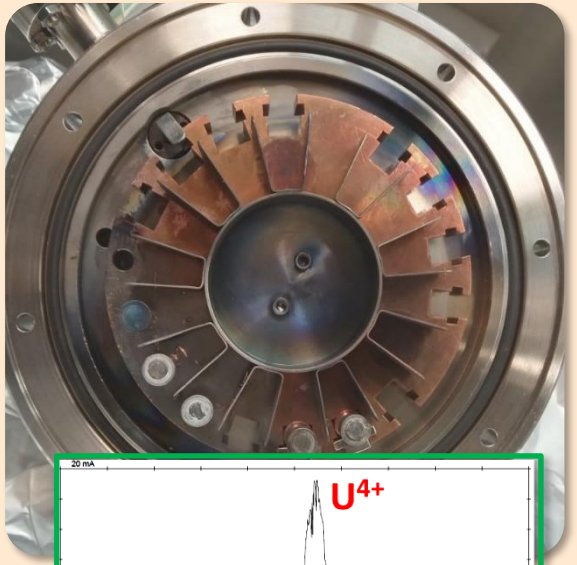
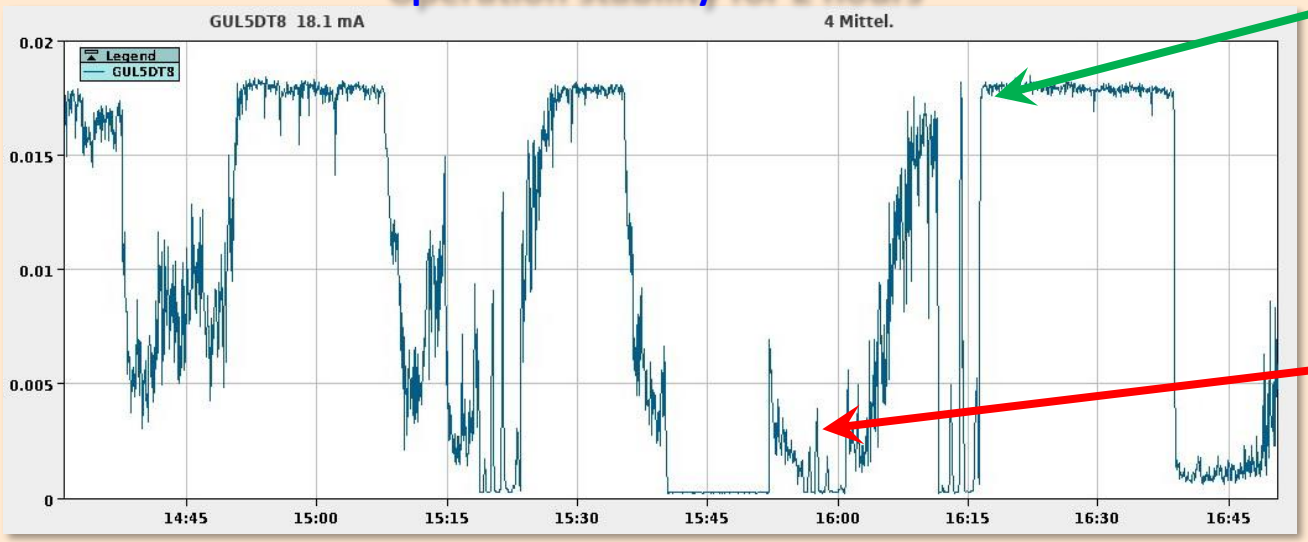
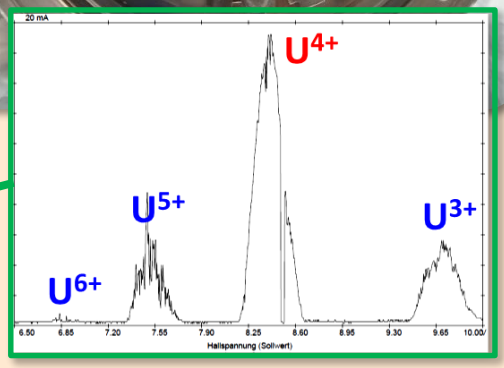
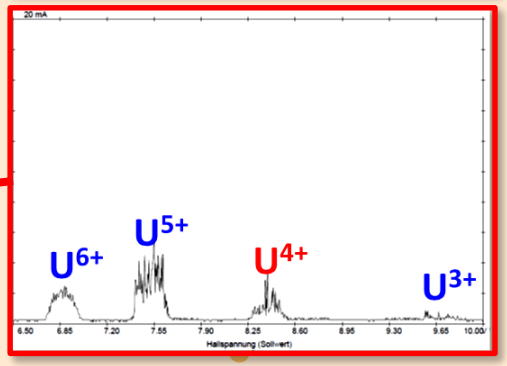


Operation stability for 2 hours





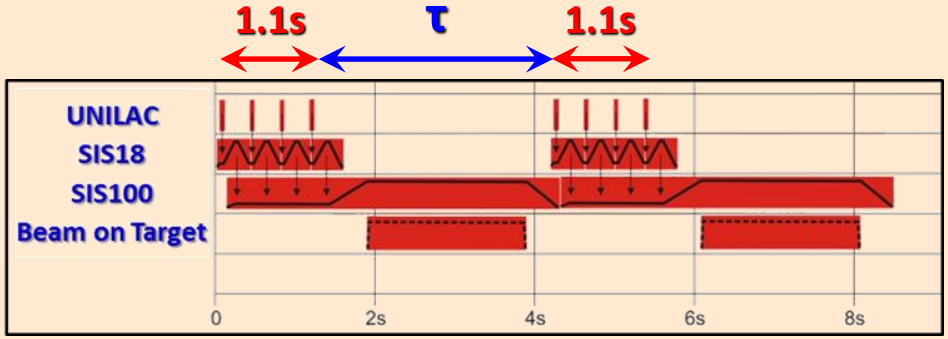


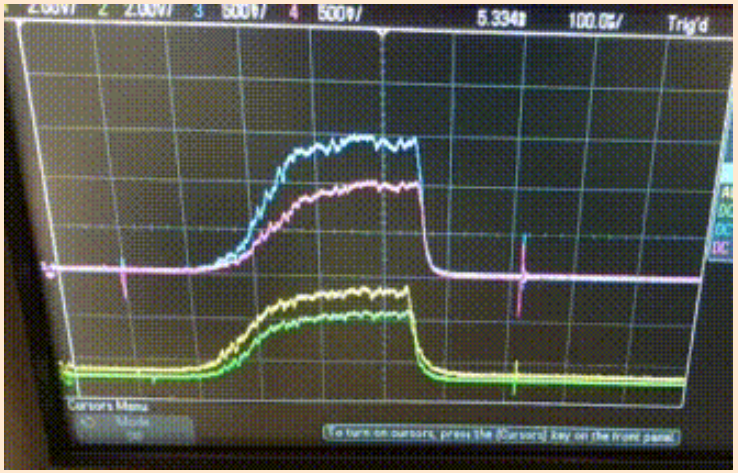
Uranium operation in "Booster-mode"

Test of booster mode for SIS18:

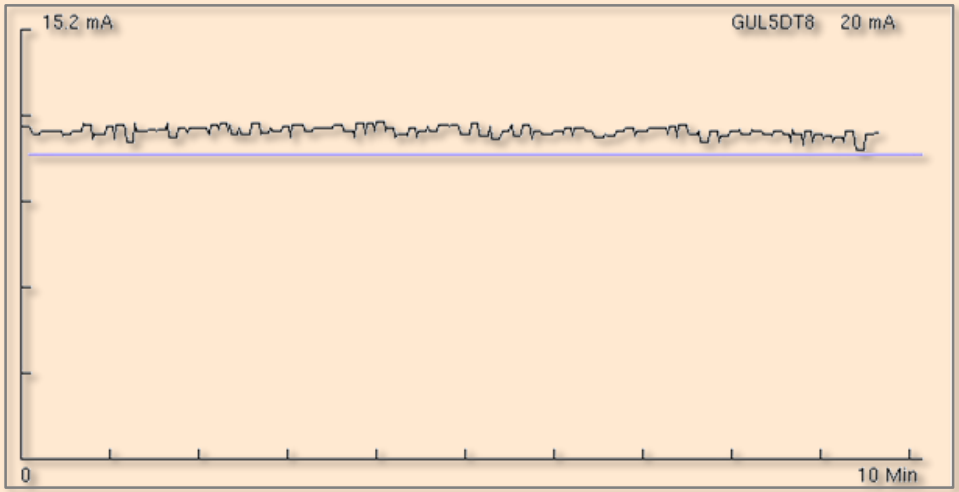
(short test during the last beamtime)

- **4 pulses** in **1.1 s** + delay (**τ = 3 ÷ 7 s**)
- Ion source timing:
  2.78 Hz / 0.45 ms, request mode
- Pulse-to-pulse stability at MAX performance:
  excellent; **<10%** intensity fluctuations



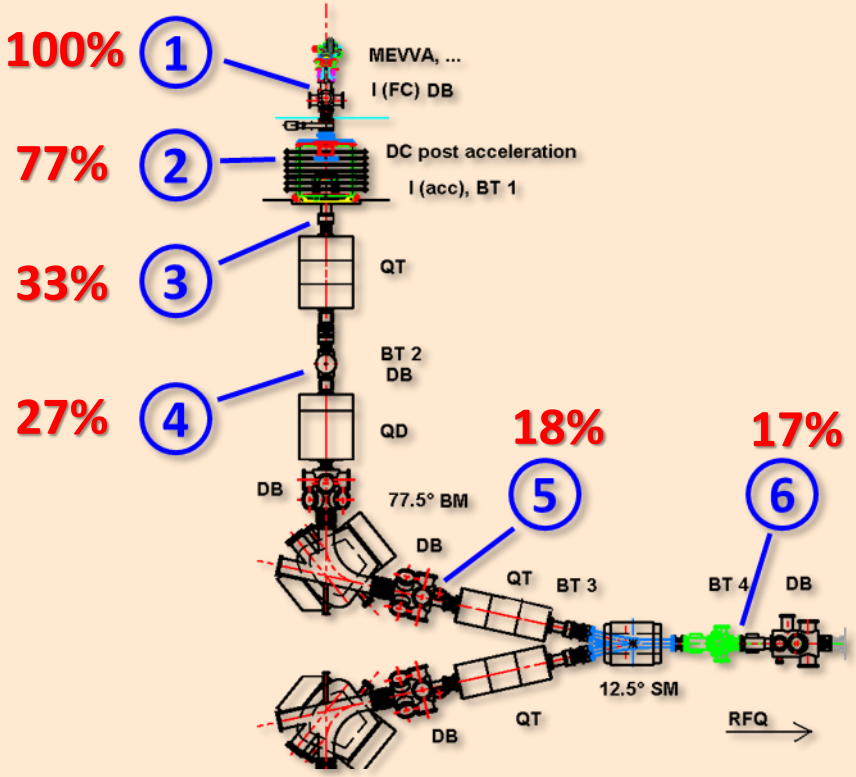


Operation stability in "Booster-mode"



Increasing the beam brilliance and beam intensity in UNILAC

Recent situation



Uranium transmission in LEBT:

1. Ion source extraction: **130 mA** (**90 mA** of U^{4+})
2. Ter. North – PA gap: **100 mA** (**70 mA** of U^{4+})
3. LEBT-UL4 (DT4): **43 mA** (**30 mA** of U^{4+})
4. LEBT-UL5 (DT5): **35 mA** (**24 mA** of U^{4+})
5. LEBT behind dipole: **16 mA** (U^{4+})
6. in front of HSI-RFQ: **15 mA** (U^{4+})

Reasons of low transmission:

- PA gap was designed for 300 kV ($^{238}U^{10+}$; 11 kV/u)
- designed for a “pencil-beam” from PIG source
- not optimized for high current beams
- beam emittance growth due to dispersion in dipole magnets
- too narrow chamber of the switching dipole => not optimal focusing for U-beam

Towards higher U-beam intensity

Increasing the beam intensity in UNILAC:

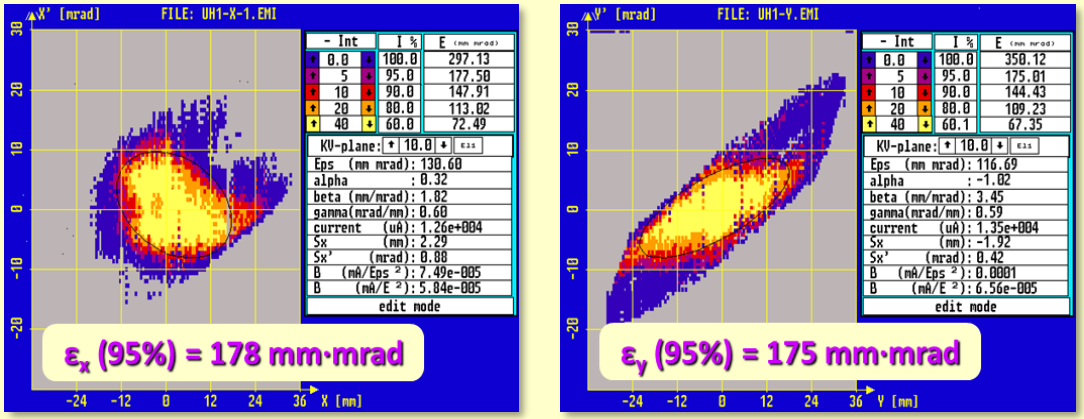
- Increase the beam brilliance from the ion source
- Optimize the post-acceleration system
- Reduce the beam losses between the ion source and RFQ
- Increase the stripping efficiency of the gas stripper

Increasing the beam brilliance

New extraction system for VARIS

- Multi apertures: **7 holes, ø 4 mm**
- Plasma - Scr. distance: **4 mm**
- Aspect ratio: **S = 0.5**
- MAX ext. voltage: **42 kV**
- Emission area: **88 mm²**

Beam emittance in front of the RFQ



A.Adonin and R.Hollinger, Review of Scientific Instruments, **89**, art. no. **052304** (2018)

Result:

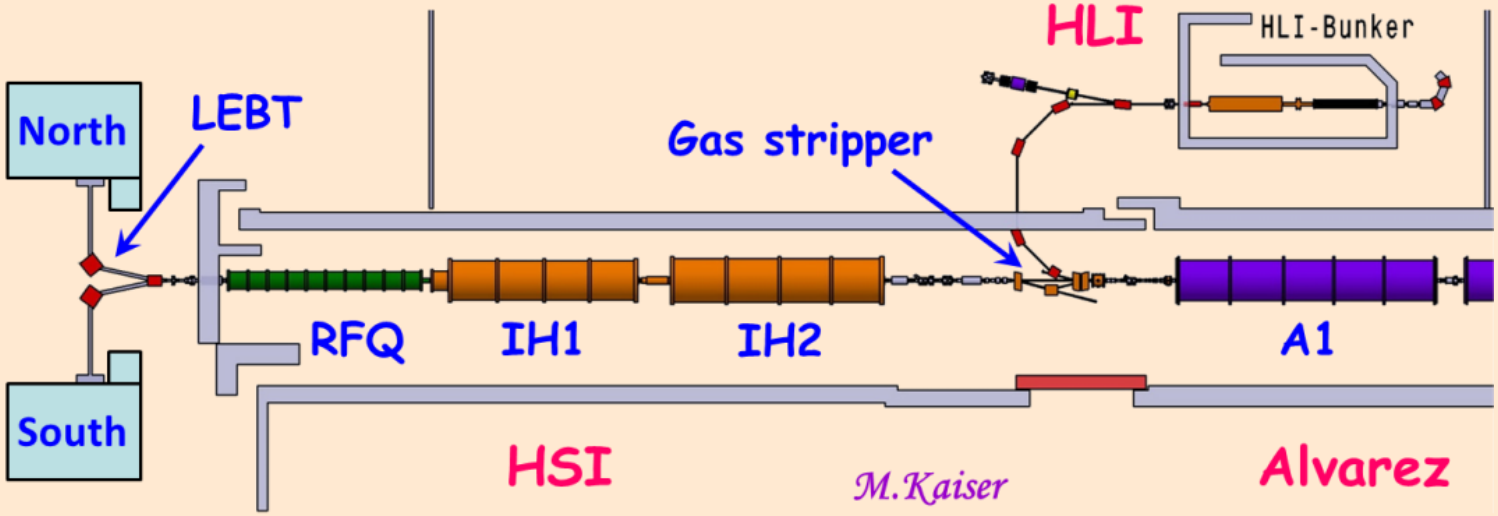
- Improved transmission in UNILAC
- Record intensity behind high current injector:
  7.5 emA of U^{4+}
  $1.2 \cdot 10^{12}$ part. (in 100 µs)

Increasing the stripping efficiency

New H_2 pulsed gas stripper:

(performance tests in 2016)

- Higher gas target densities as with **N_2-jet** stripper
- Increased stripping efficiency for Uranium ($U^{4+} \rightarrow U^{28+}$):
  12.5 % → **21 %**
- New intensity record for U^{28+}:
  11 emA (**$2.4 \cdot 10^{11}$** part. in **100 µs**)



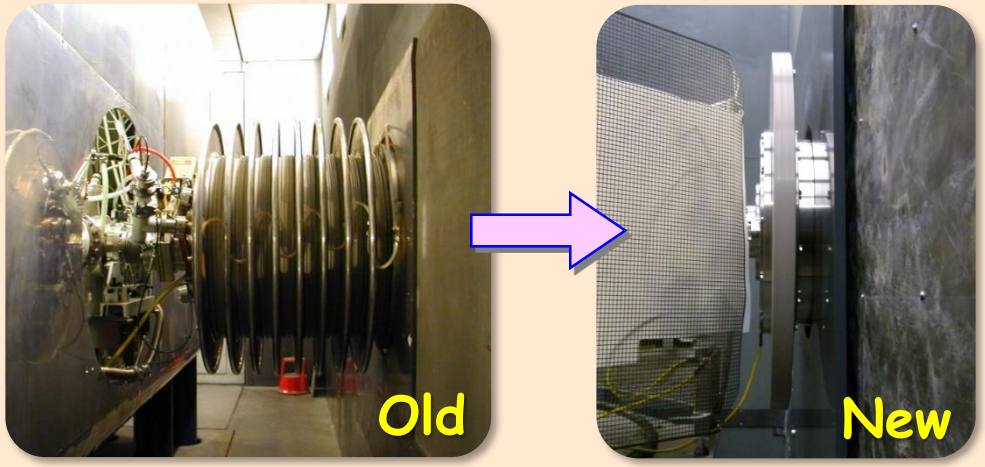
W.Barth et al., Phys. Rev. AB, **20 (5)**, art. no. **050101** (2017)

Optimization of the PA-system

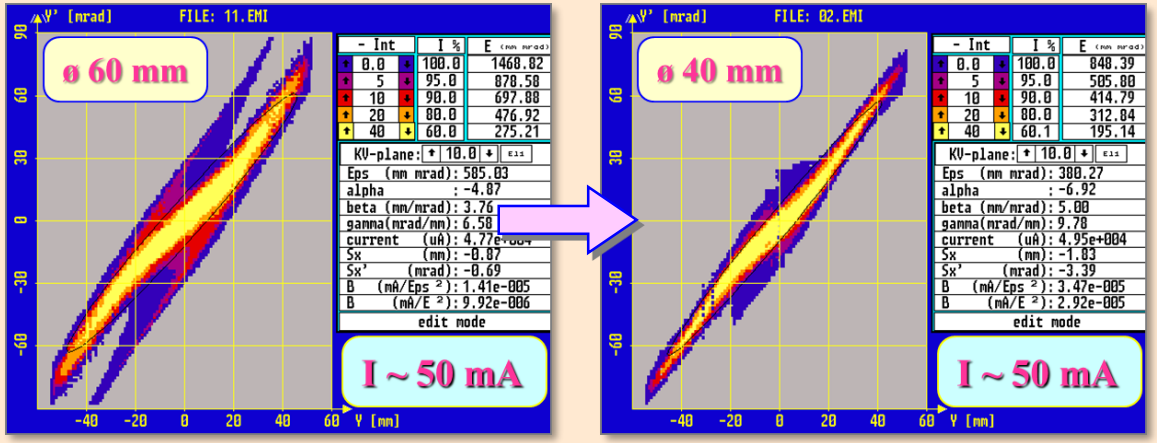
Post acceleration system:

- Optimization of the setup to reduces distances:
  Ion source → PA gap → 1-st magnet
- Reduce ion beam losses between the source and 1-st magnet in the LEBT
- Optimization of electrodes geometry in PA gap → electrostatic beam compression

Optimization of the setup



Electrostatic beam compression (Ta-beam)



A.Adonin, R.Hollinger, Rev. Sci. Instrum. **85 (2)**, 02A727 (2014)

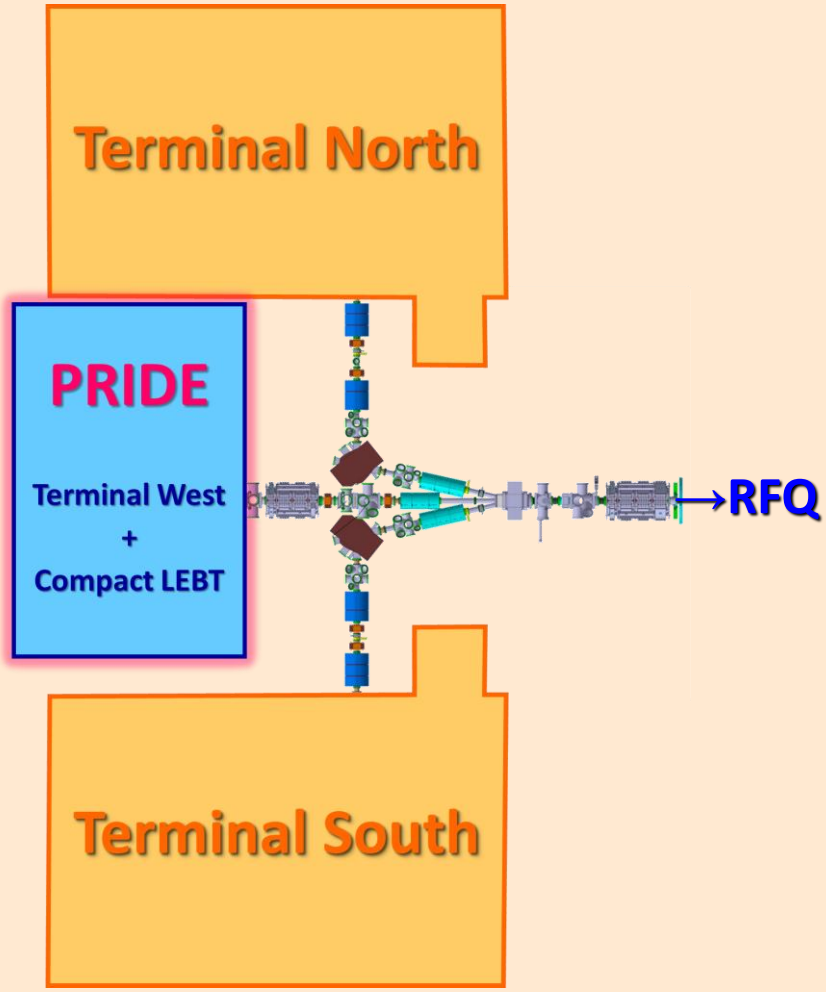
PRIDE – PRe-Injector DEdicated for uranium operation

Terminal West:

- Uranium operation only
  => no cross-contamination risk
- Optimized post-acceleration gap

Compact LEBT:

- 9.9 m long straight beam transfer line design for U^{4+} beams
- No beam emittance growth due to dispersion in dipole magnets
- Ion charge states separation by focusing on tunable iris
- Higher transmission efficiency for U^{4+} ions



FAIR is comming…

Thank you very much for your attention