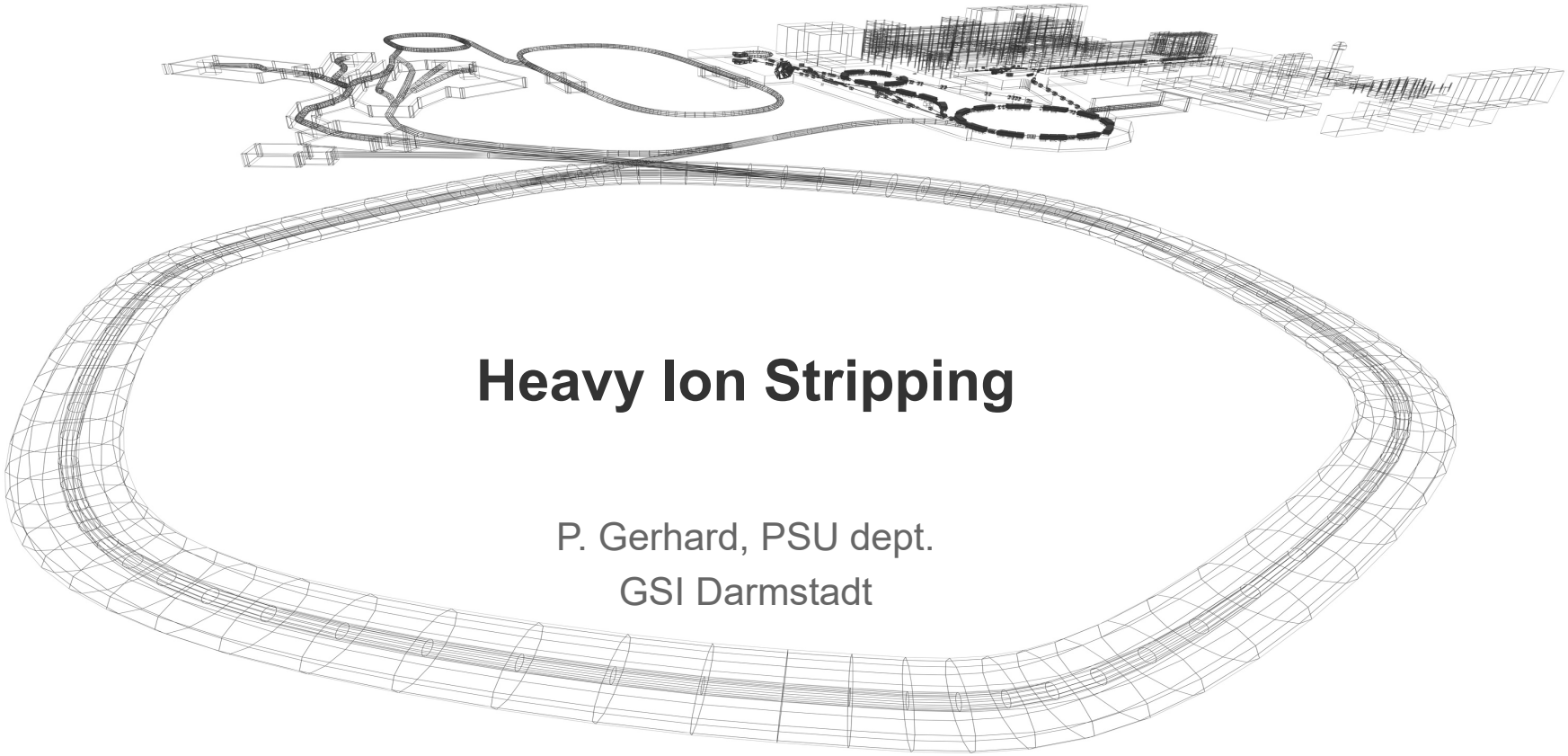
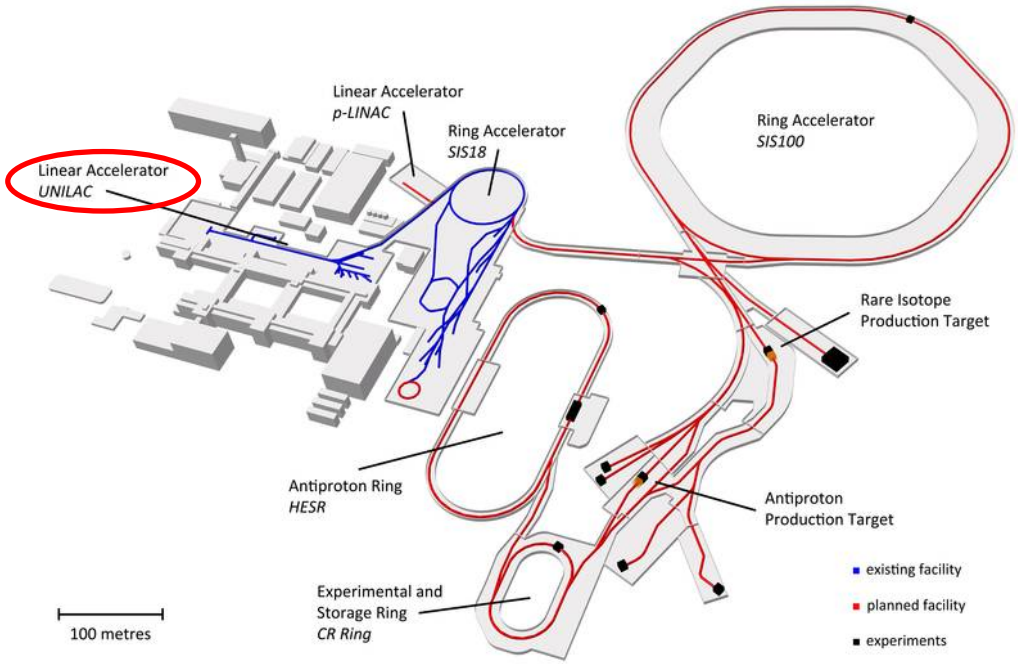


Heavy Ion Stripping

P. Gerhard, PSU dept.
GSI Darmstadt

Introduction



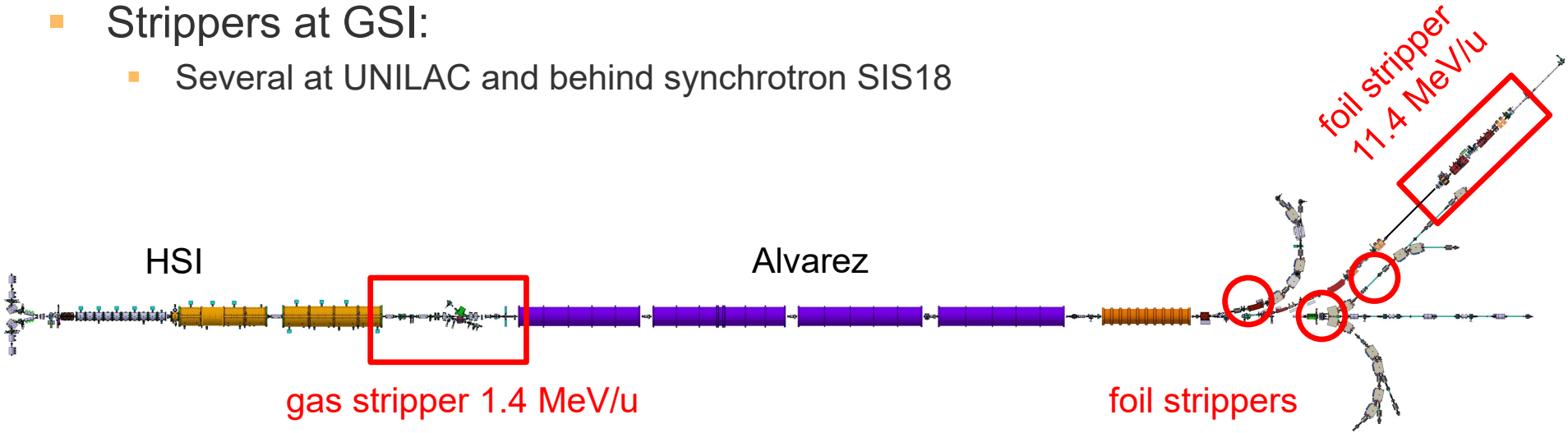
- GSI UNILAC and SIS18
  will serve as heavy ion injector for FAIR

- UNILAC reference for FAIR operation:
  ≥ 15 mA $^{238}U^{28+}$
  ≤ 100 µs pulse length
  ~ $3 \cdot 10^{11}$ U^{28+} per SIS18 injection

- $^{238}U^{28+}$ achieved until 2016:
  - 5.1 mA / 4.3mA
    behind UNILAC / in TK with H_2 gas stripper
  - $3 \cdot 10^{10}$ extracted from SIS18
    (with 2.5 mA injected from UNILAC)
  - Booster operation: First test May 2022
    4 x $2 \cdot 10^{10}$ extracted within 1.32 s

UNIversal Linear ACcelerator

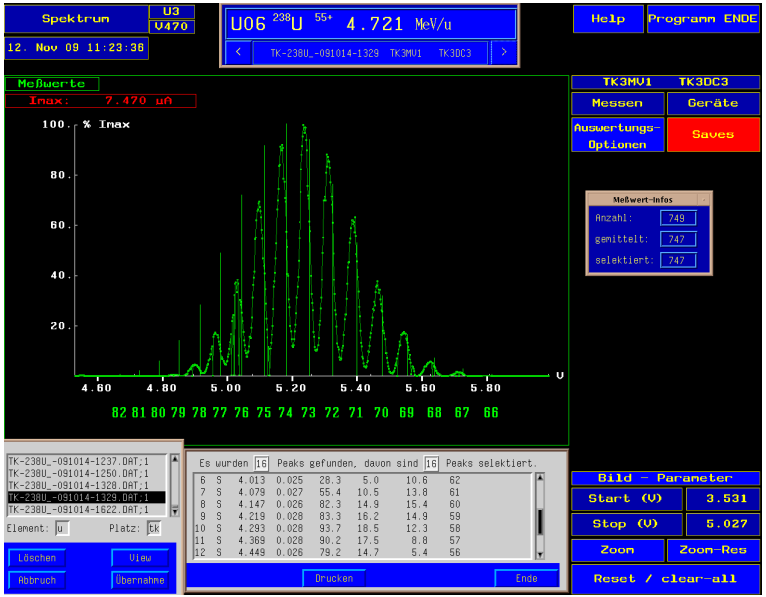
- Linac, commissioned 1975, all ion species from H^+ to U^{73+}
- Pulsed operation, different beams in parallel (time multiplexed)
  - Max. 5 ms pulses at 50 Hz for UNILAC users
  - Max. 200 µs pulses at 5 Hz for SIS18 / FAIR injection
- Strippers at GSI:
  - Several at UNILAC and behind synchrotron SIS18



Operating software

Stripper application

Spectrum application

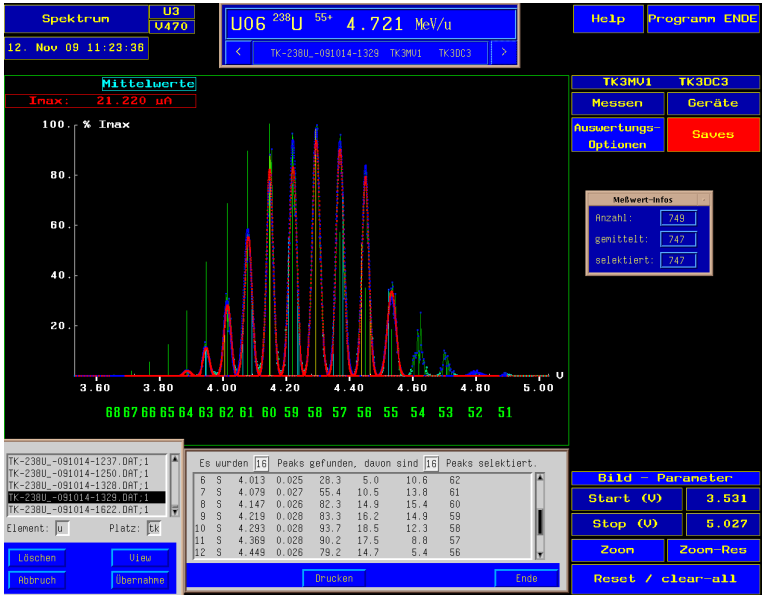


First version 1991

Operating software

Stripper application

Spectrum application



First version 1991

Outline

- Introduction
- Fundamentals
- Stripping at 1.4 MeV/u
  - GSI History
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- Stripping at 11 MeV/u
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- High Energy Foil Stripper
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Heavy Ion Stripping Fundamentals

- Heavy ion stripping: Charge transfer (both directions!) between beam ion and target atoms through collisions
  - Electron loss (L): Increase ion charge state, ionization
  - Electron capture (C): Reduce ion charge state
  - Stochastic processes, corresponding cross sections σ_L and σ_C
  - As target is traversed: Many collisions, ions approach equilibrium charge state distribution
  - Collisions: Associated energy loss and emittance blow up

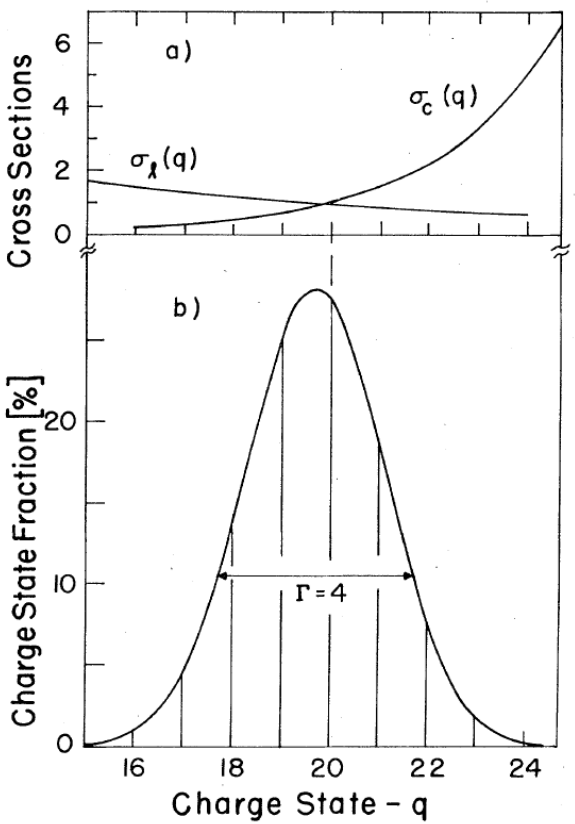
- Optimization ⇒ figures of merit:
  - High mean charge state (at equilibrium)
  - Stripping efficiency: Ion fraction with charge state of interest ⇔ width of distribution

Heavy Ion Stripping Fundamentals

- Cross sections σ_L and σ_C are functions of several parameters:
  - Ion charge state q
    - Additional contribution by shell effects
  - Ion velocity *v*, i. e. energy *E*
    - Capture depends strongly on velocity v_i of ion relative to target electrons
    - Capture highly suppressed for $v_i >> v_{1s}$ (velocity of 1s electrons)
    - Especially relevant for low *Z* targets since $v_{1s} \sim Z/137$
    - Energy loss of ion passing through target!
  - Ion atomic number *Z*
  - Target atomic number Z_T
  - Target density ρ: *Density effect*, gaseous $\Leftrightarrow$ solid state / liquid targets

- Target thickness: In order to reach equilibrium

Charge Transfer, Spectrum & Equilibrium Mean Charge State



- Charge transfer beam ion ↔ target:
  - Electron capture and loss
  - Cross sections $\sigma_L(q)$ and $\sigma_C(q)$: Functions of q
- Equilibrium charge state distribution
  - Equilibrium: $\sigma_L(q) = \sigma_C(q)$
  - Number of collisions must be sufficient ⇔ Target thickness
  - Mean charge state $\langle q \rangle$:

$$\langle q \rangle = \sum q\, F(q) \text{ with } \sum F(q) = 1$$

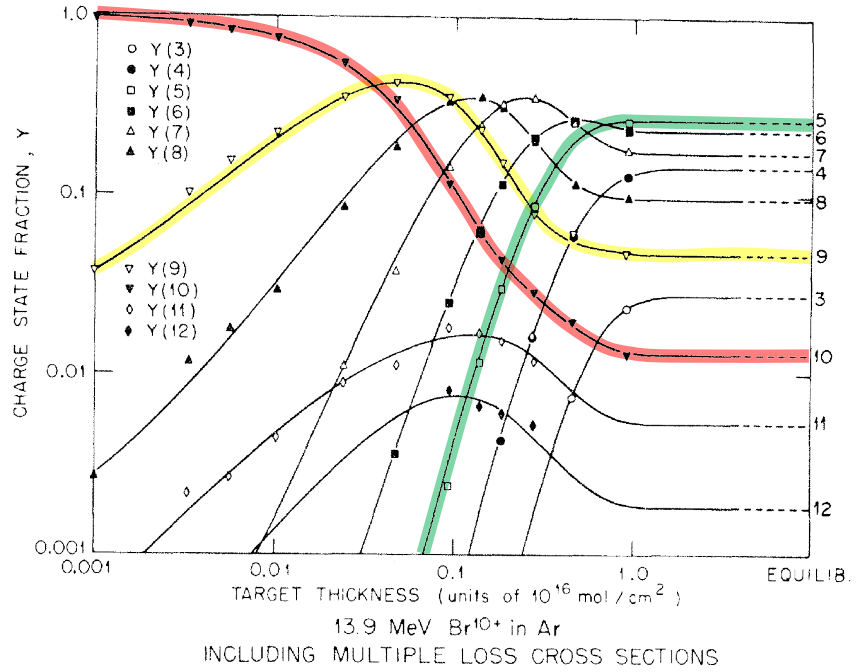
  - $F(q)$: Equilibrium charge state fraction with charge q

H. Betz, 1972, Reviews of modern Physics Vol. 44 Nr. 3

Target Thickness

Br^{10+} at 0.174 keV/u on Ar gas target

Symbols: Experimental data, Curves: Calculations

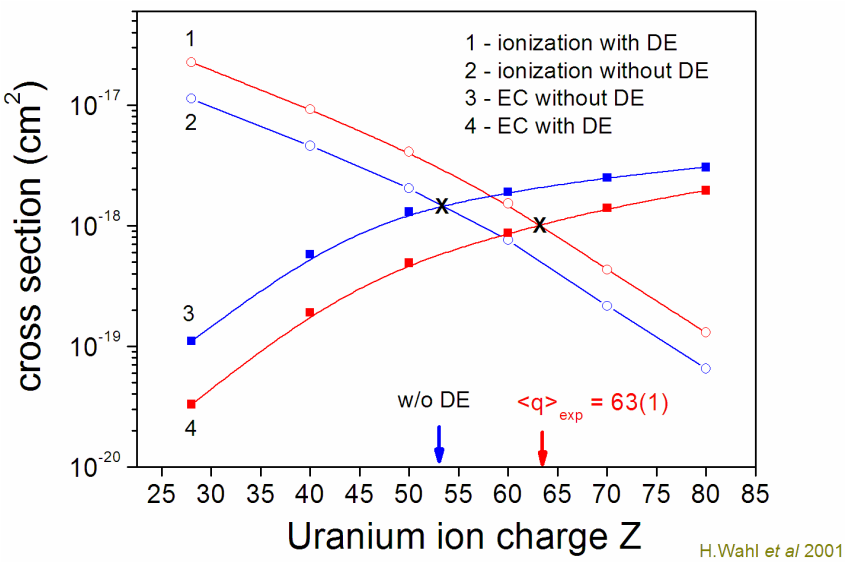


Datz et al., Phys. Rev. A 2, 430 (1970)

- Stable equilibrium above sufficient target thickness
- Independent of initial charge state
- Unusual:
  - Initial charge state q_{in} higher than $\langle q \rangle$
  - Intermediate maxima of charge state fractions possible

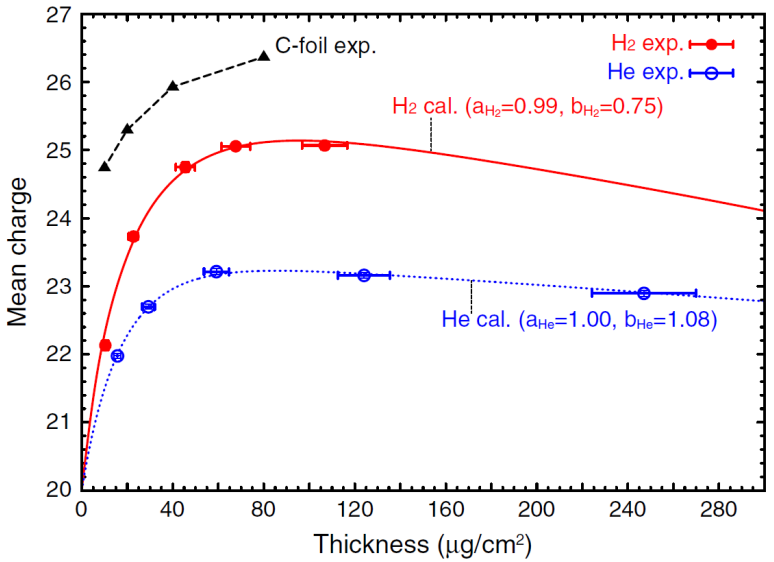
Density Effect & Low Z Targets

^{238}U beam at 10 MeV/u



H.Wahl *et al* 2001

^{86}Kr beam at 11 MeV/u



Kuboki et al., Phys. Rev. ST Accel. Beams 17, 123501 (2014)

- σ_L, σ_C depend on target density (Density Effect DE) and target Z
- Density Effect: Rate of charge transfer reactions increases with density, projectile excited states get ionized more likely ⇒ effective σ_C reduced
- Low Z targets: Electron capture suppressed due to velocity mismatch $v_i >> v_{1s}$

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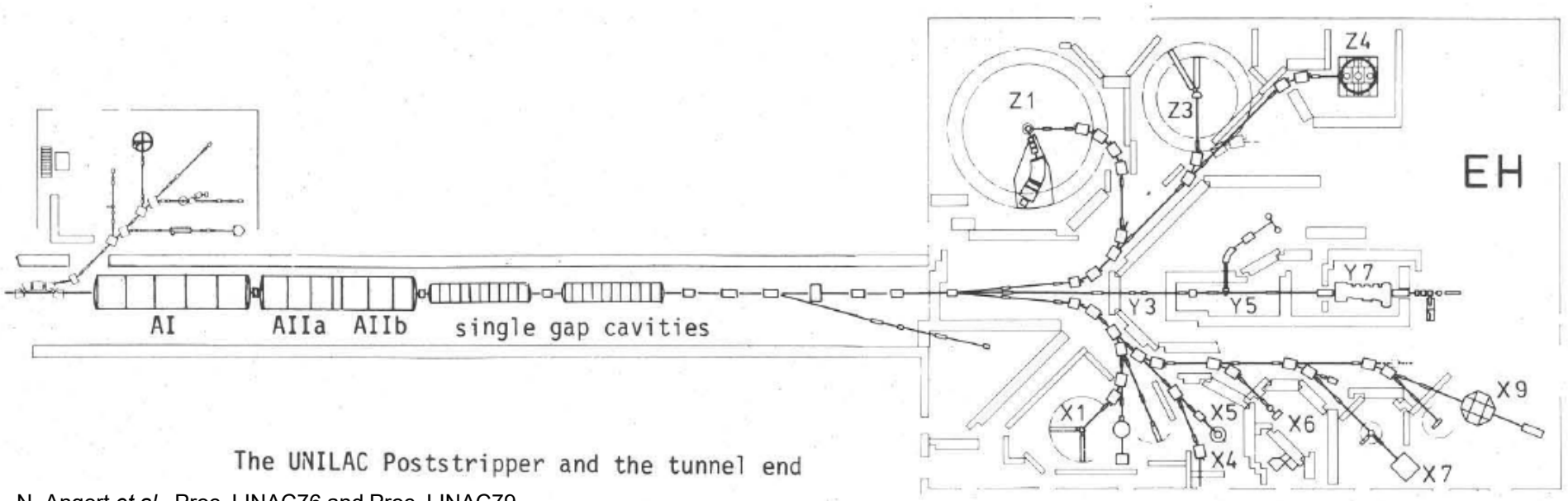
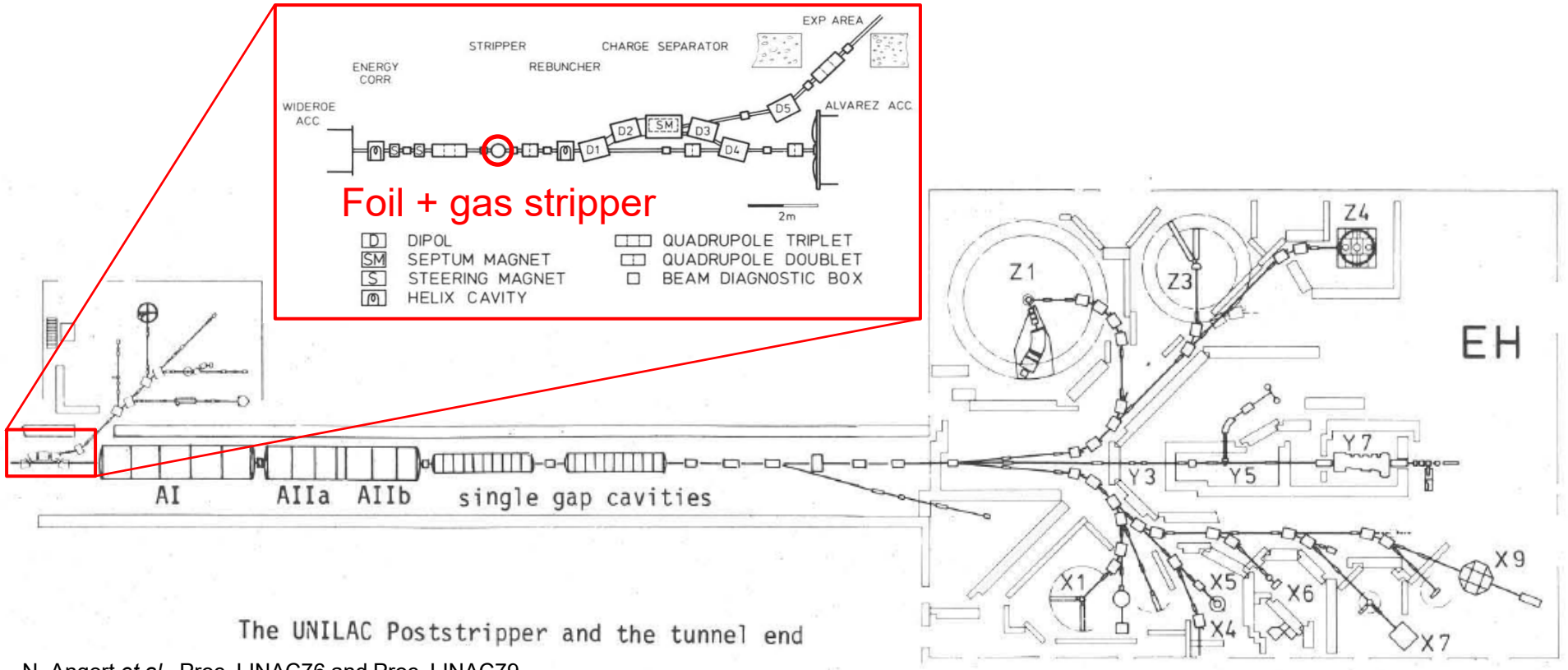
The beginnings of GSI



The UNILAC Poststripper and the tunnel end

N. Angert *et al.*, Proc. LINAC76 and Proc. LINAC79

The beginnings of GSI



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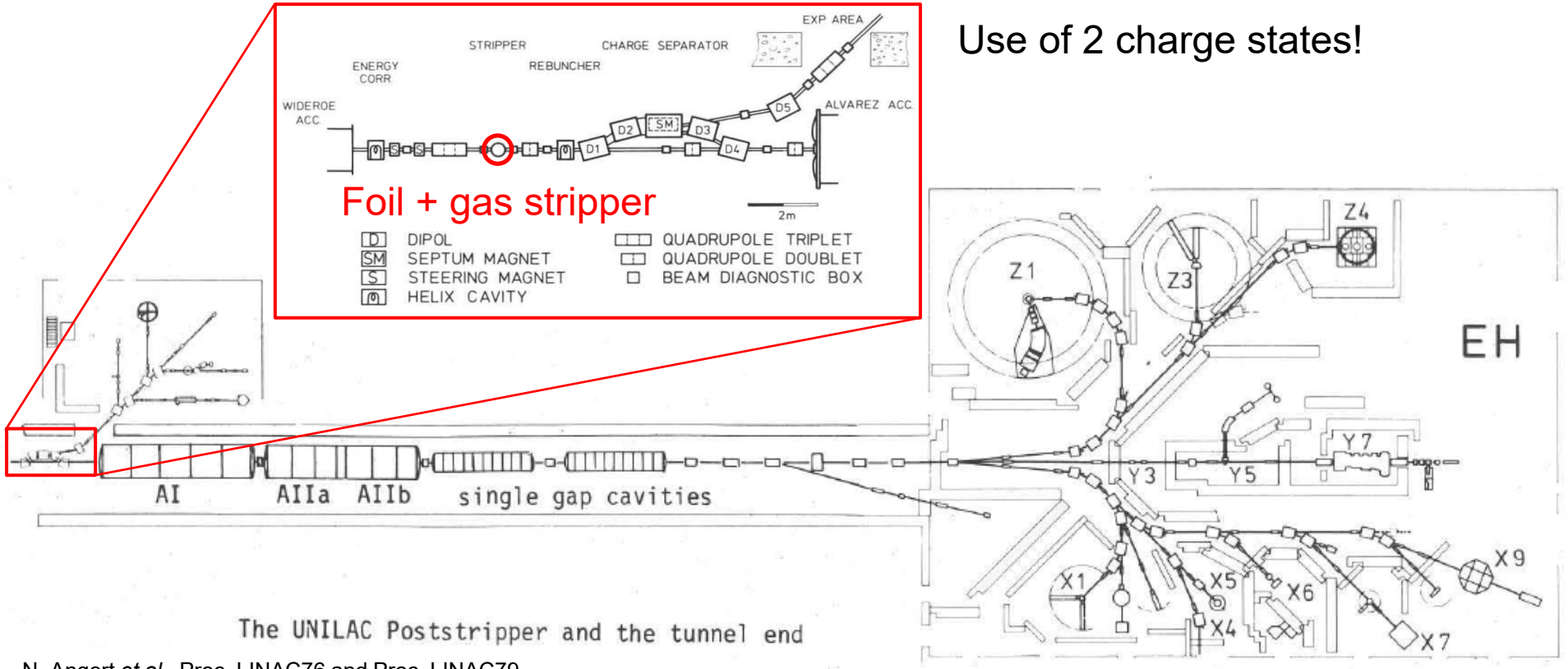
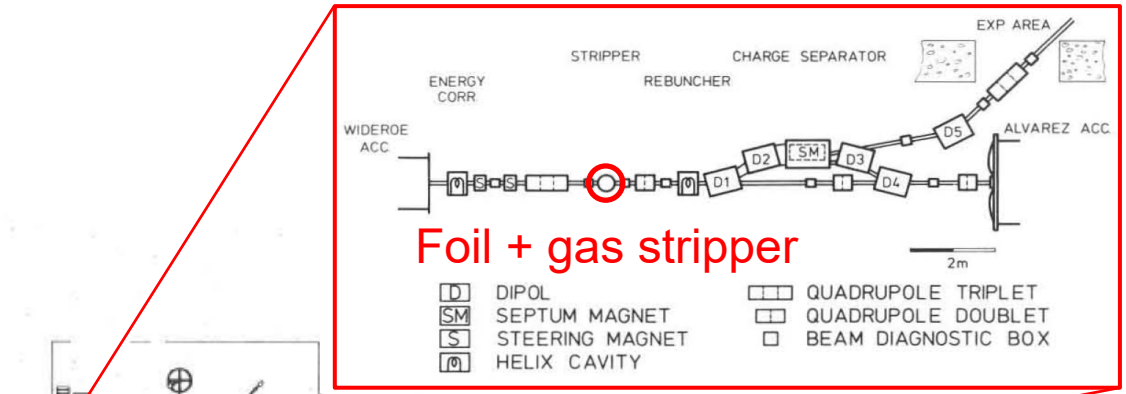
The beginnings of GSI



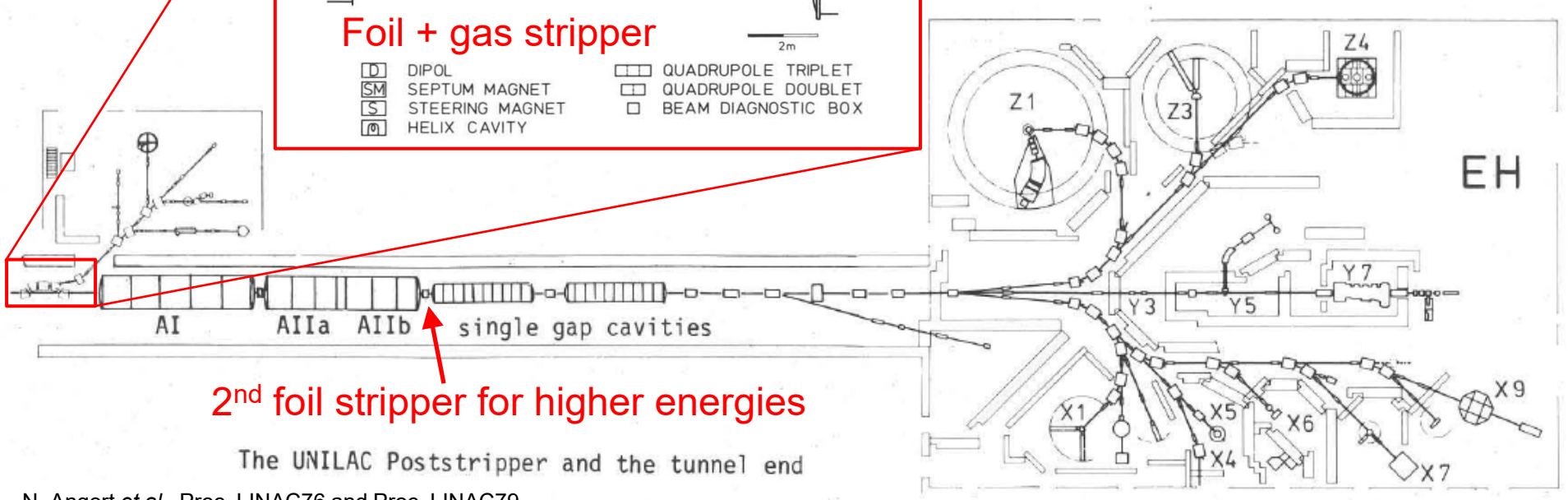
N. Angert *et al.*, Proc. LINAC76 and Proc. LINAC79

The beginnings of GSI



Foil + gas stripper

Use of 2 charge states!

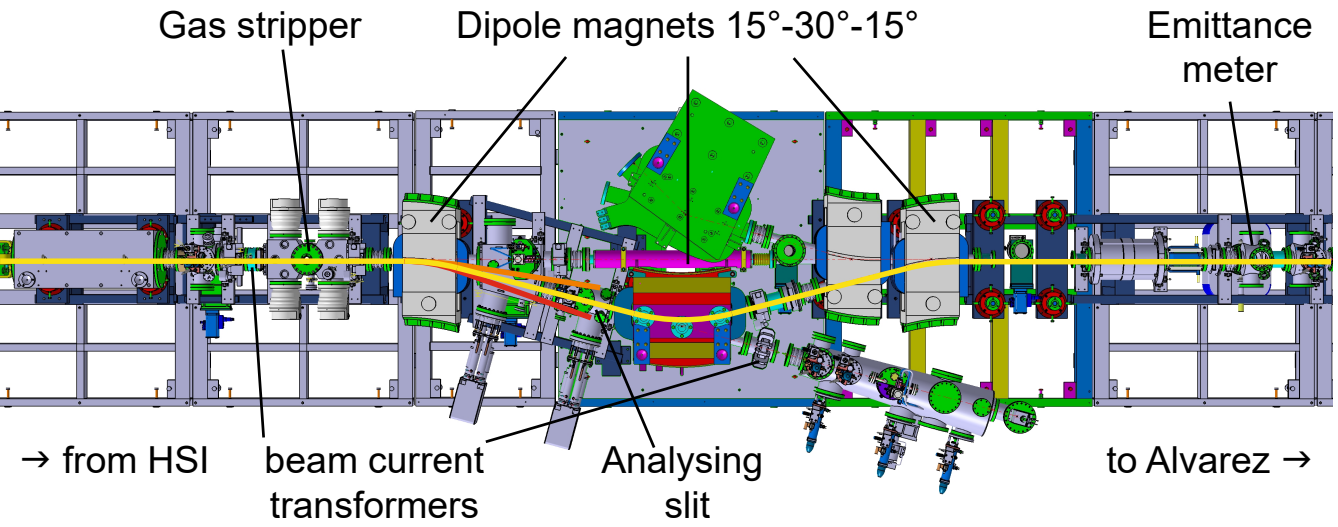


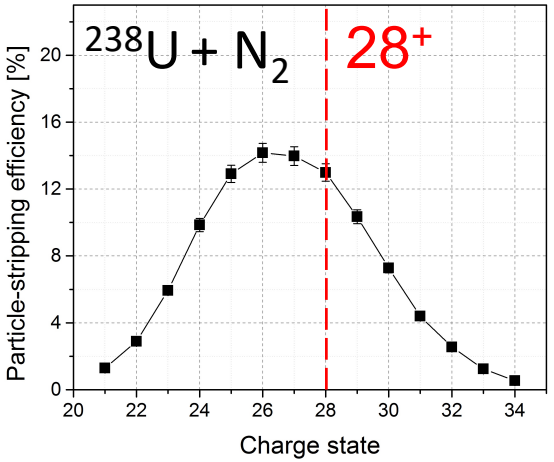
2nd foil stripper for higher energies

The UNILAC Poststripper and the tunnel end

N. Angert *et al.*, Proc. LINAC76 and Proc. LINAC79

Gas Stripper Section





- Situation after redesign 1999 in the course of the High Current Injector HSI installation
- Gas stripper: Continuously operated N_2 jet target with laval nozzle

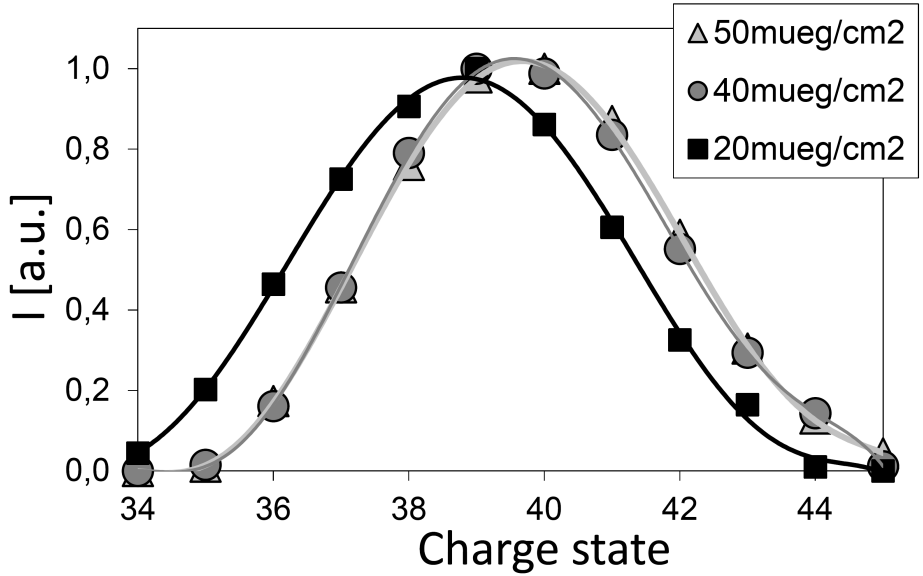
Back to the Future:
2010 Foil-Stripping of Heavy Ions at 1.4 MeV/u

before after

- Beam: U^{4+}, 1.4 MeV/u, 100 µs, 2 Hz
- Thickness: 20 to 50 µg/cm²
- Irradiation: ≈ 5 mA
- Lifetime: ≤ 10 h

- Various investigations on lifetime

- No option for FAIR



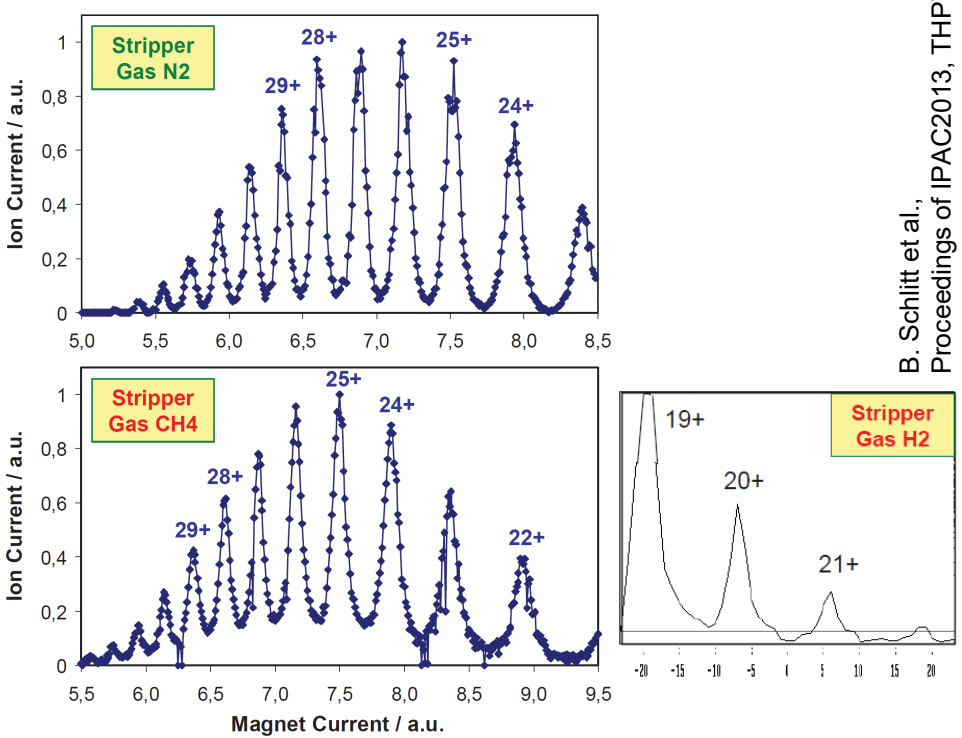
W. Barth et al., Proceedings of LINAC2010, Tsukuba, Japan, 154-156

Jet Stripper With Other Gas Targets

- 2012: Replace N_2 by CH_4 and H_2
- CH_4 no advantage to N_2:
  - Mean charge state 25+ vs. 27+
  - U^{28+} stripping efficiencies 7% vs. 12%
  - Separation deteriorated for CH_4
  - No potential for improvement seen
- H_2 far away from equilibrium
  - max. charge state reached 21+
  - **low target thickness, high gas load**

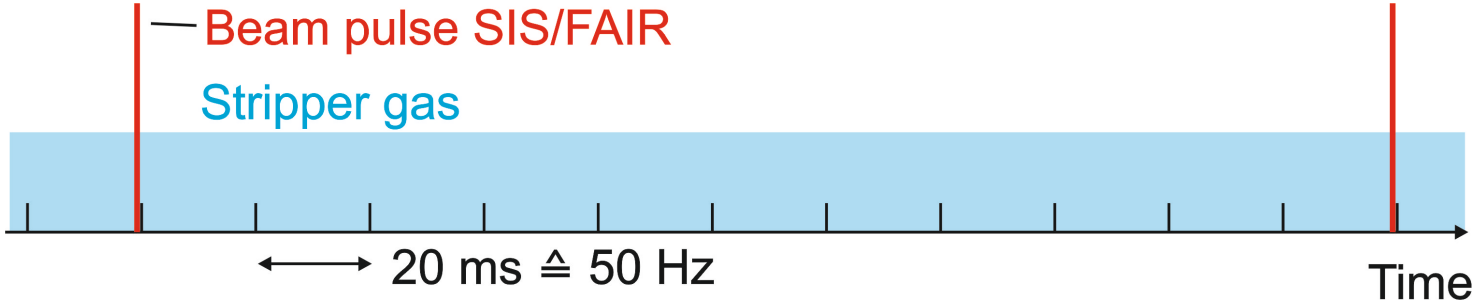
- Substantial modifications of stripper setup necessary

U charge spectra



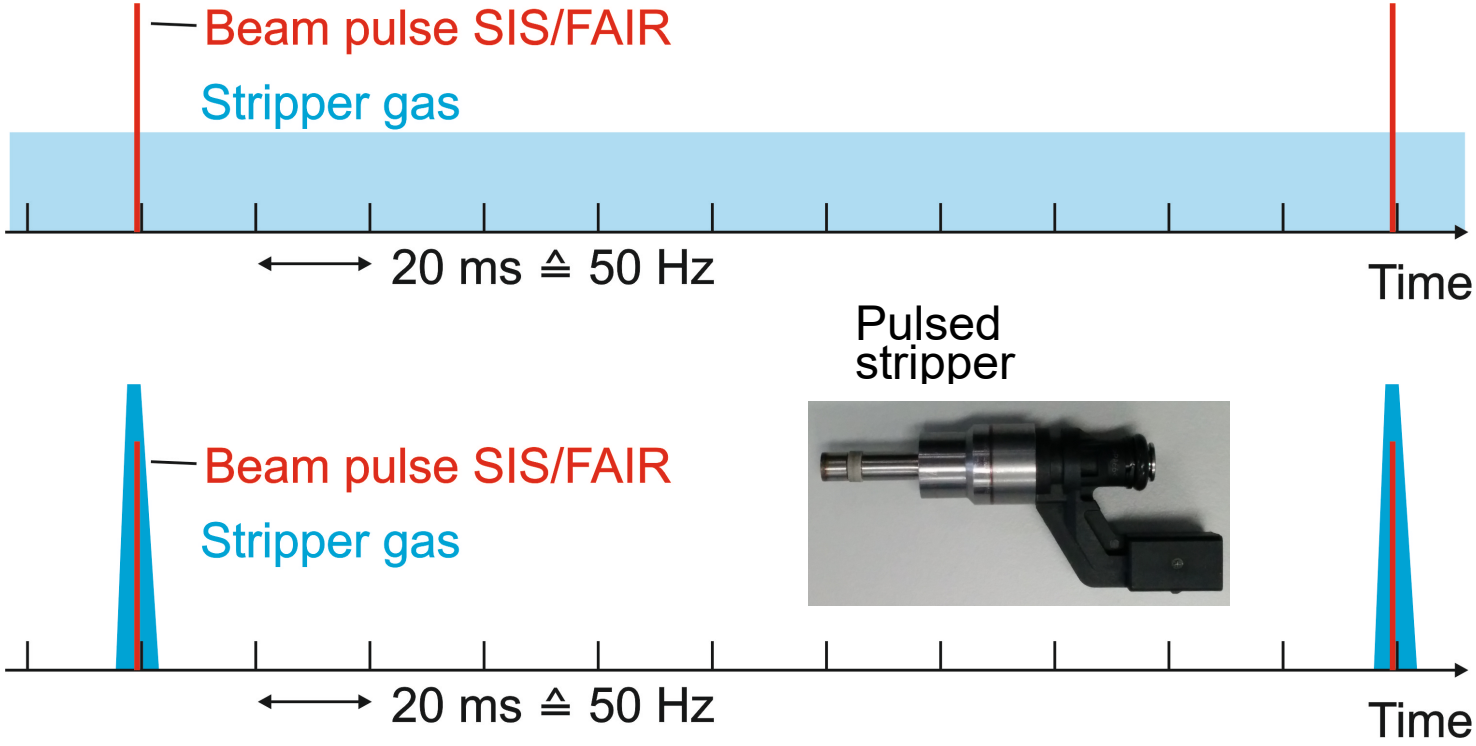
B. Schlitt et al., Proceedings of IPAC2013, THPWO010

From Continuous to Pulsed Operation



N_2 jet stripper

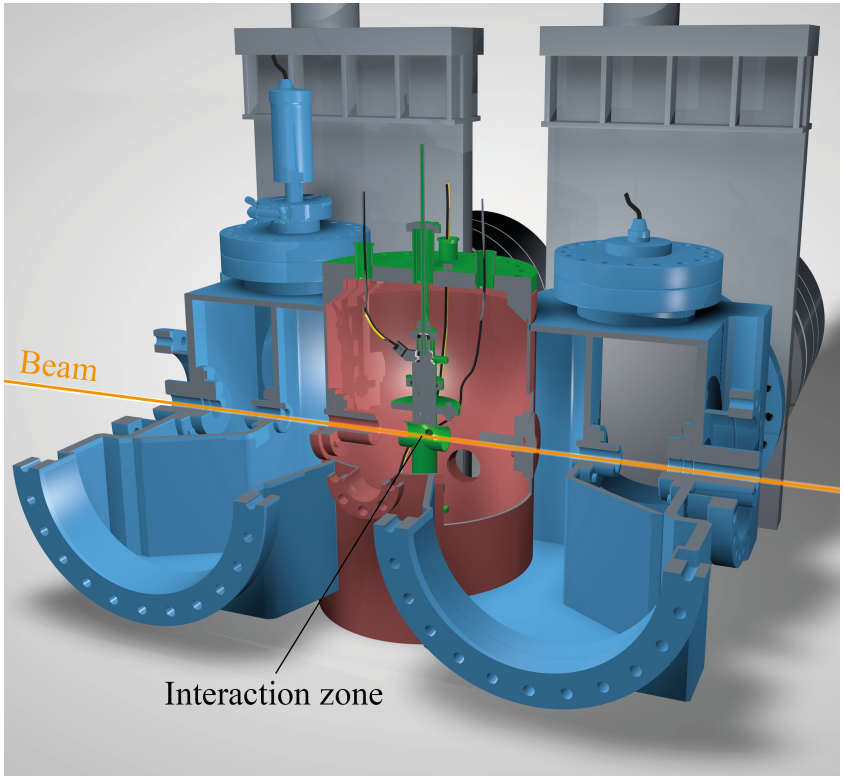
From Continuous to Pulsed Operation

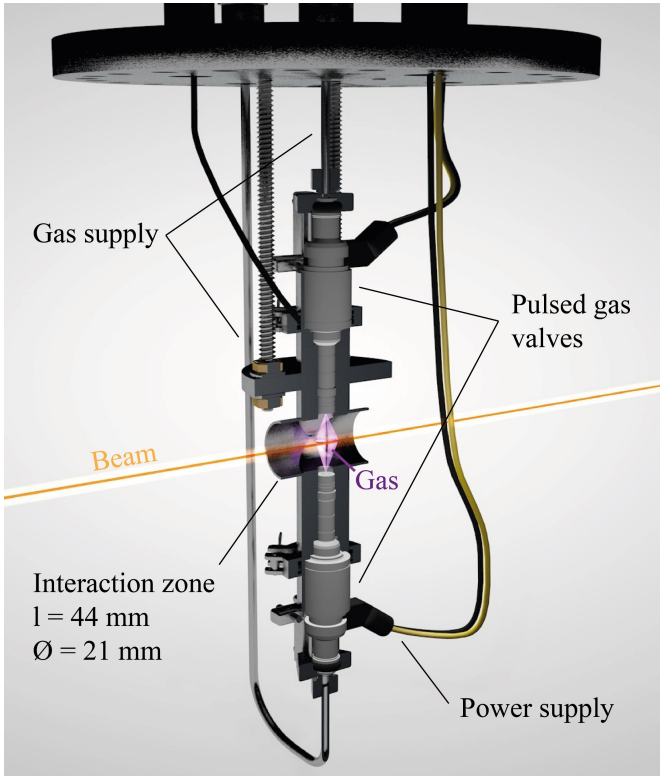


N_2 jet stripper

Pulsed stripper

Gas Stripper Chamber and Pulsed Setup



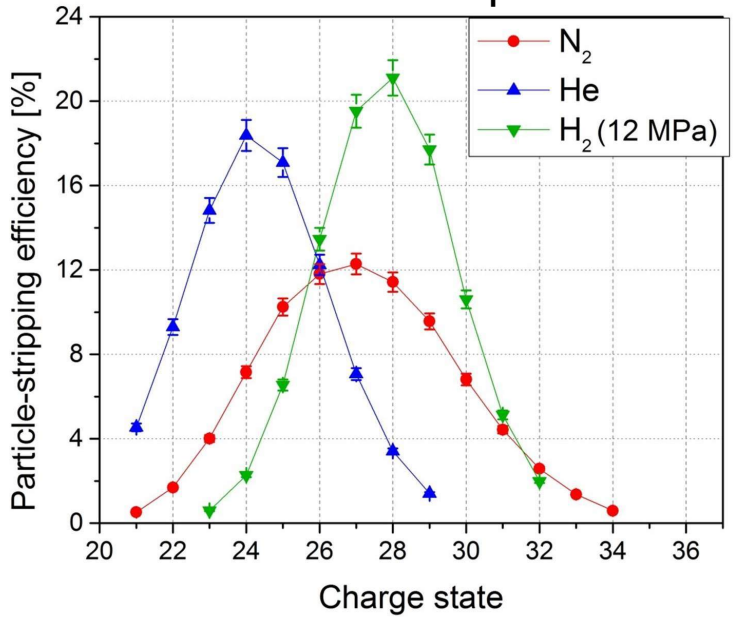


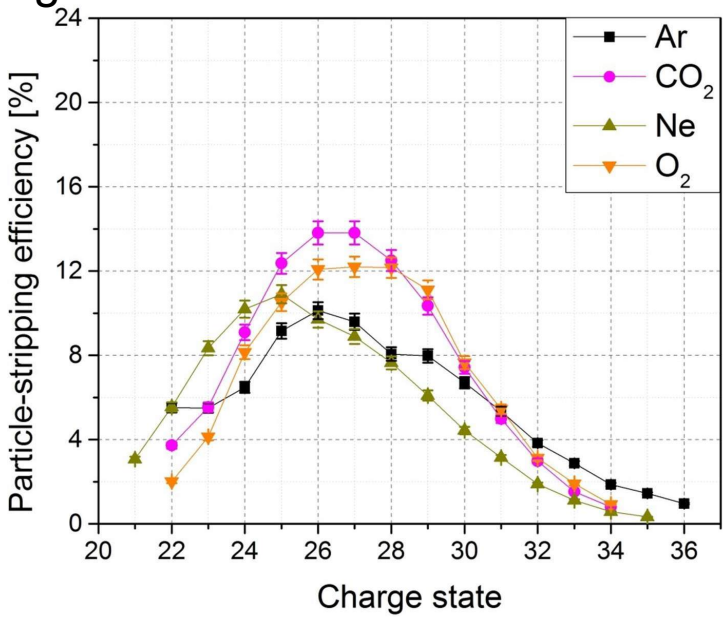
Automotive Gasoline Injector

Status 2016

Gas Target Investigations

Uranium equilibrated charge state distributions*





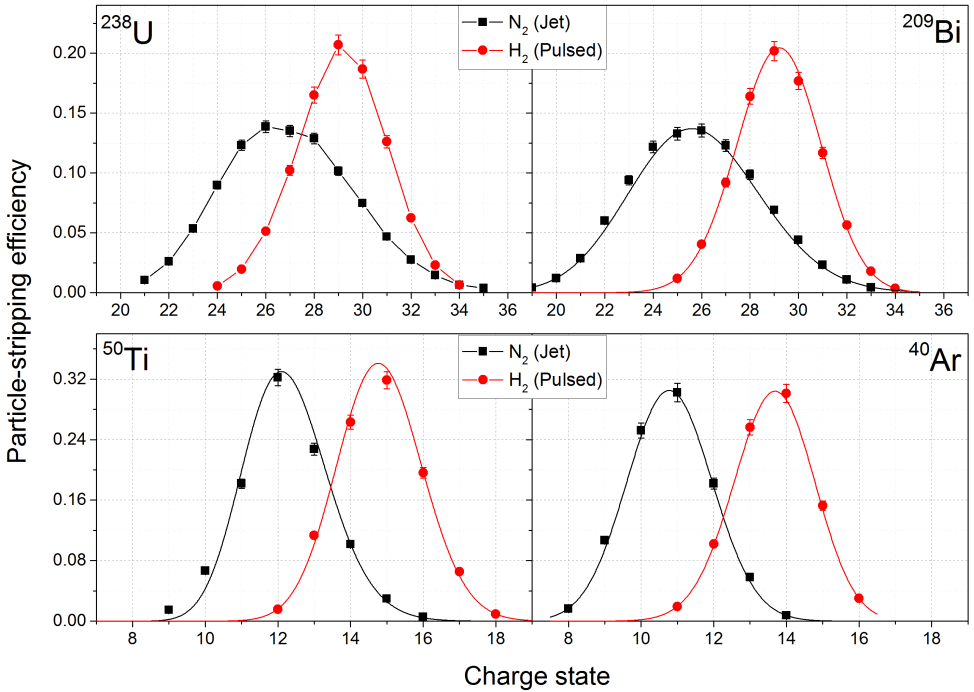
Light gas targets → narrow distribution → increased stripping efficiency

*: First setup, non-equilibrium distribution for H_2

P. Scharrer et al., Proc. HIAT15, TUA1C01

Projectile Investigations

Measured charge state distributions with highest <q>

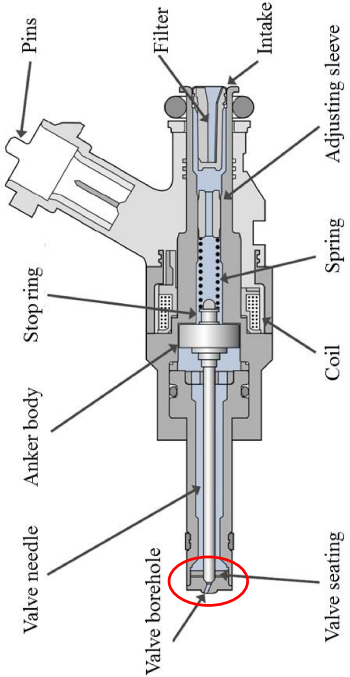


P. Scharrer et al., Proc. LINAC16, TUOP03

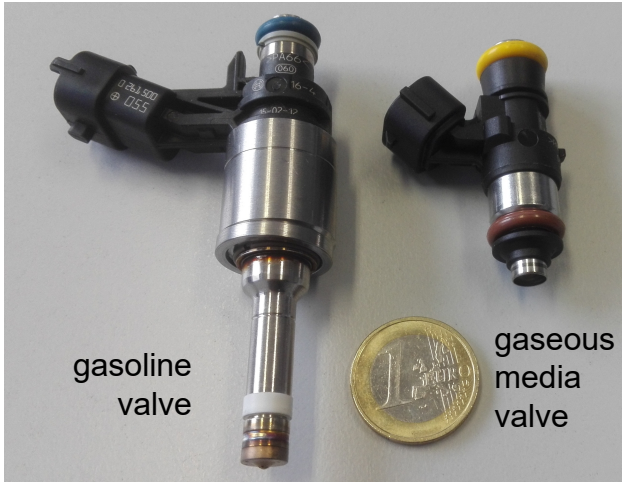
- Heavy ions (U, Bi):
  - more narrow distribution
  - increased stripping efficiency
  - higher beam intensity
- All ions:
  - higher average charge state
  - less rf power
  - higher energy in SIS18

Pulsed Gas Stripper for Routine Operation

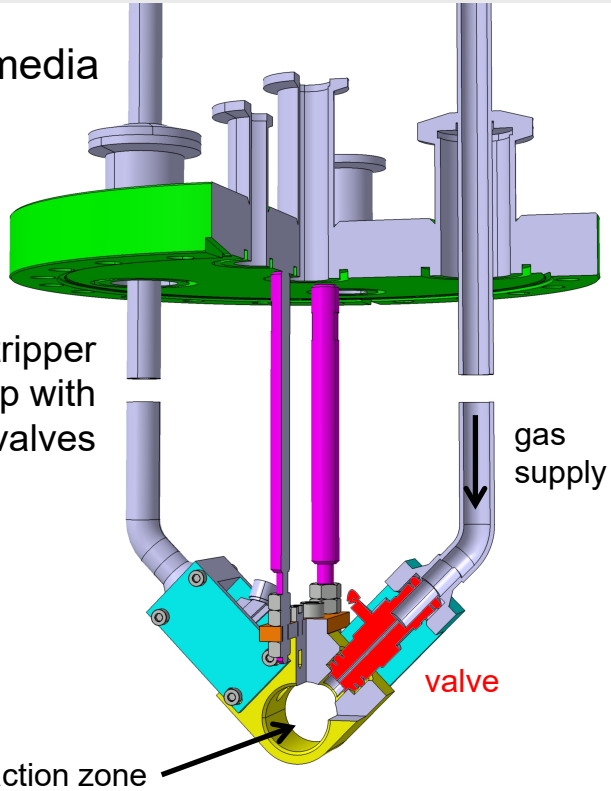
Gasoline valve not suitable for long term operation with gaseous media
New valve type for gaseous media, requires less back pressure



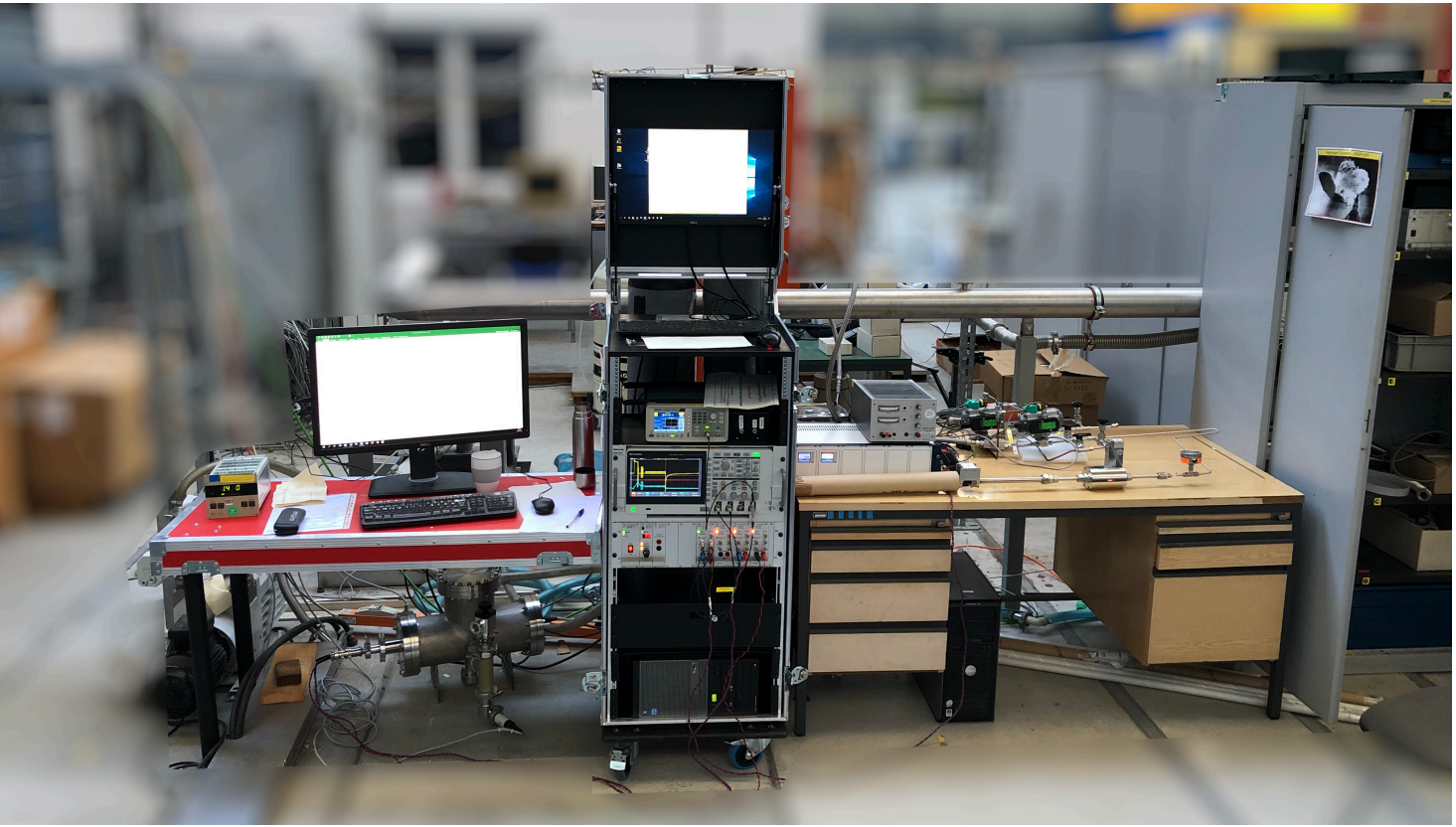
BOSCH Automotive Berufsschulinfo, 2003/4



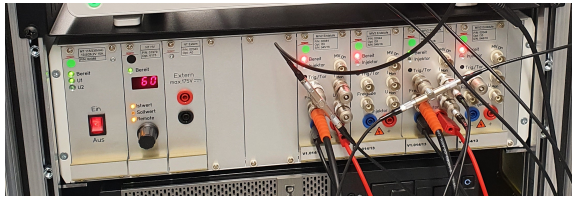
New stripper setup with two gas valves



Test stand



Fast Valve Operation: Probing the Gas Target

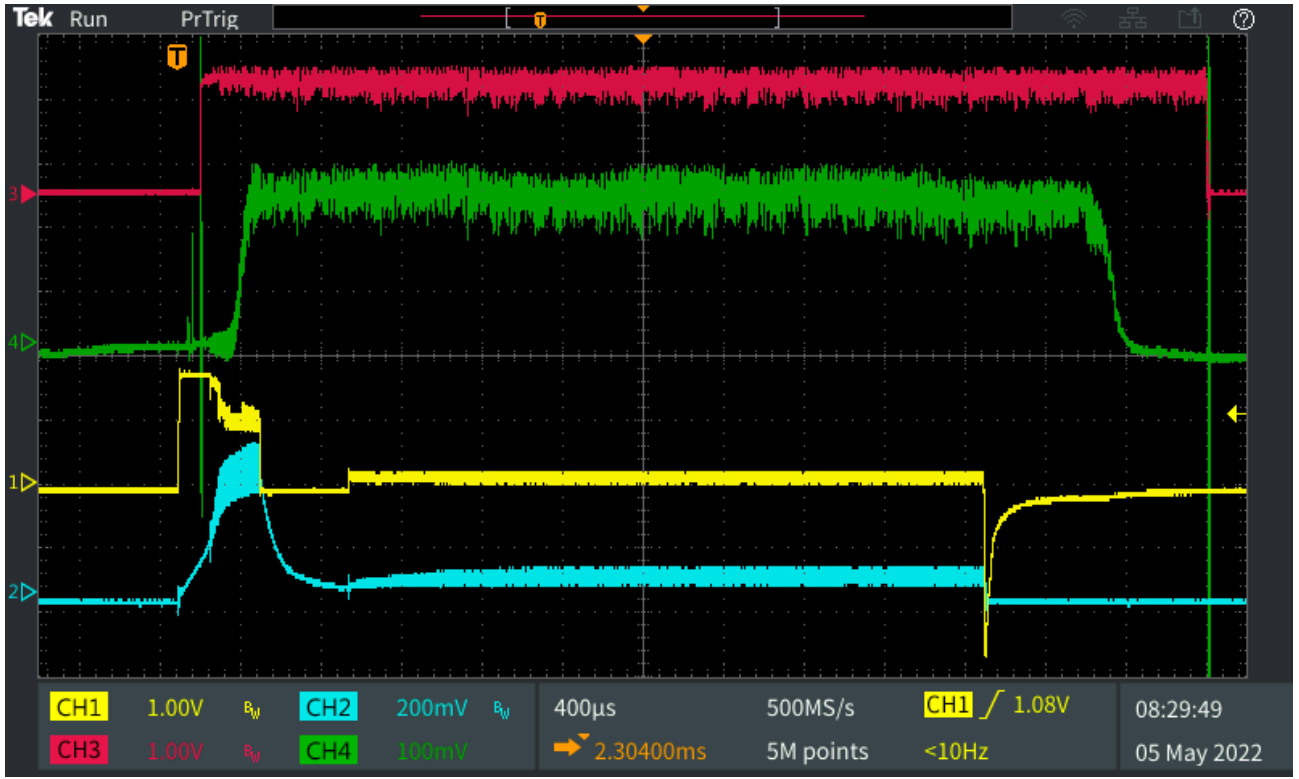


Beam current unstripped

Beam current stripped

Valve coil voltage

Valve coil current



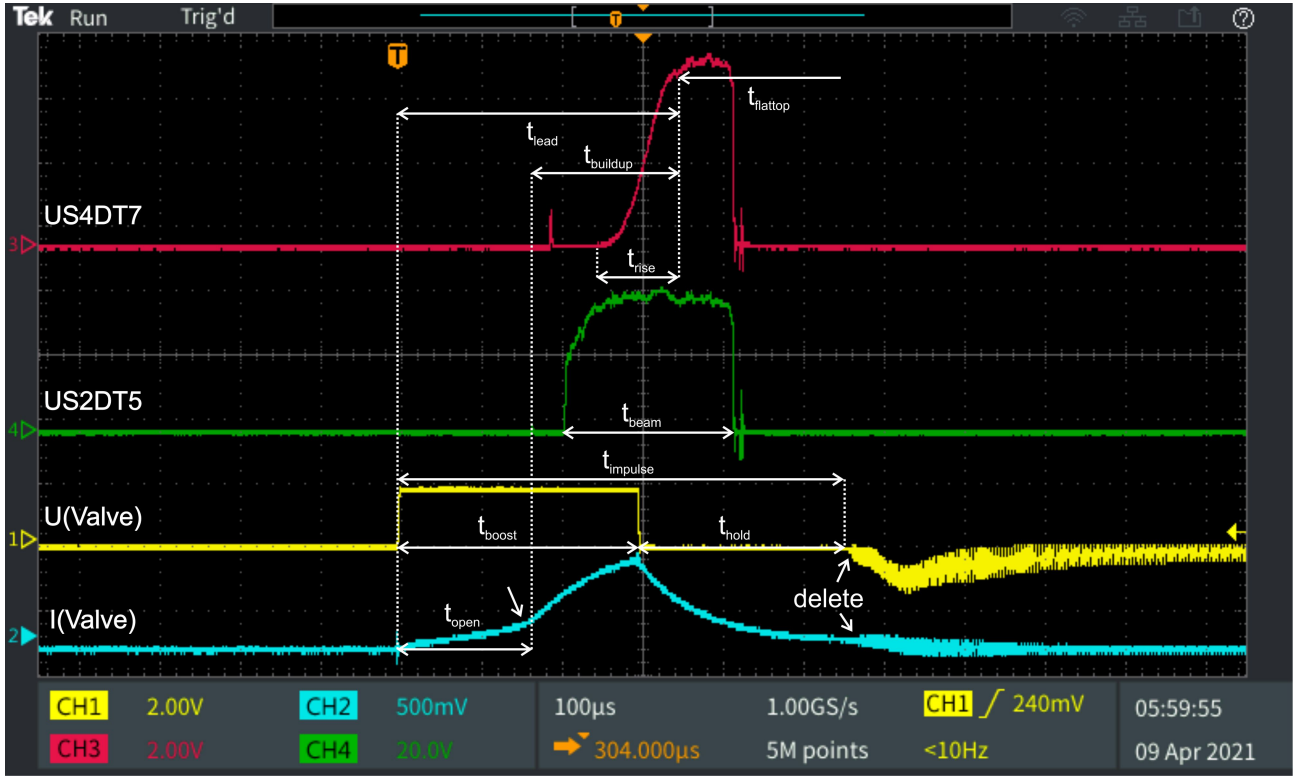
Fast Valve Operation: Parameters

Beam current stripped

Beam current unstripped

Valve coil voltage

Valve coil current



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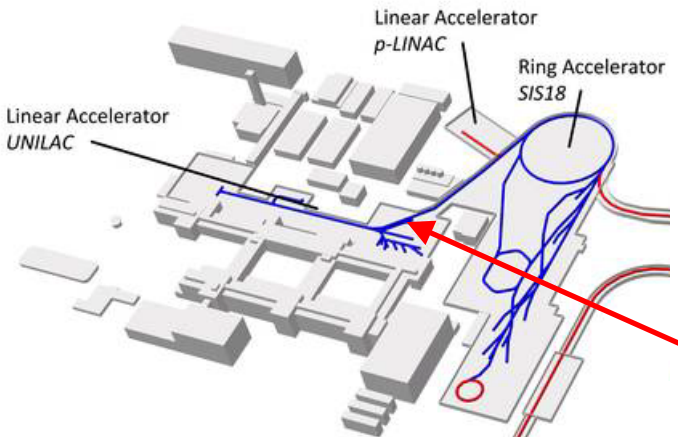
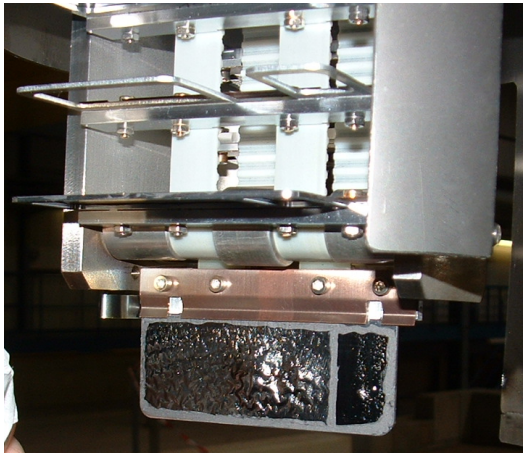
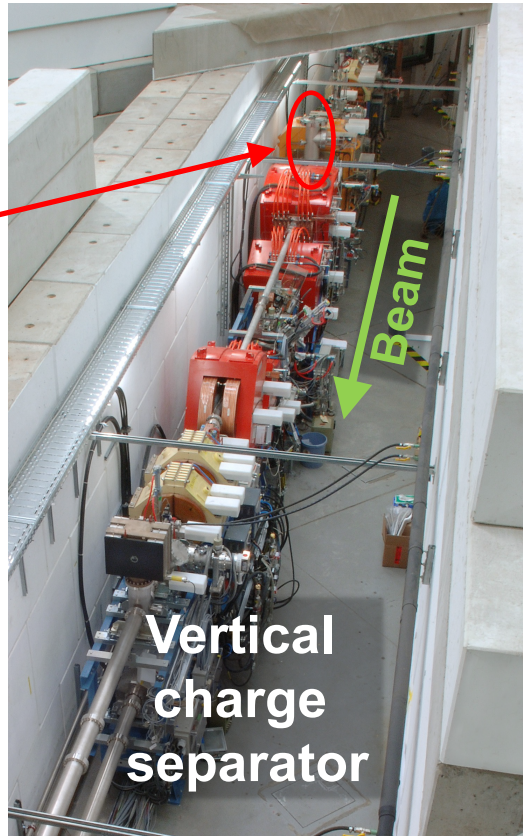
Multiple Foil Stripper @11.4 MeV/u



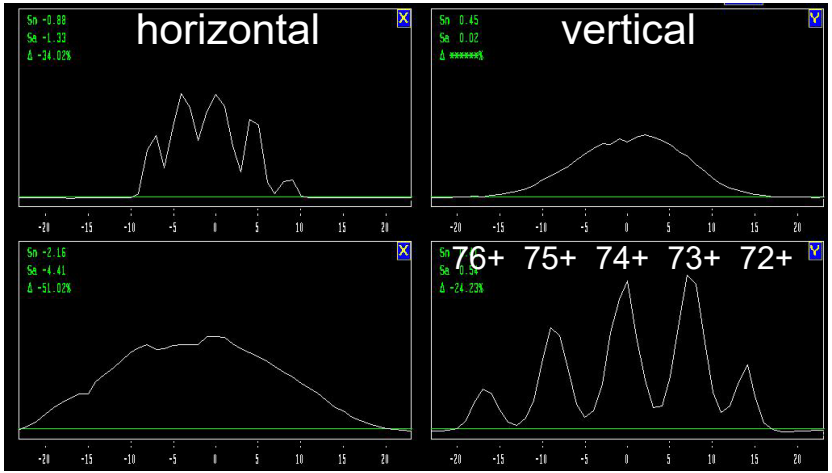




41 frames, 2 **carbon** foils each

µg/cm²	200	400	600
typ. Ion	C^{12+}	Ar^{18+}, Xe^{48+}	U^{73+}
E_{Loss} /MeV/u	0.1	0.2	0.3

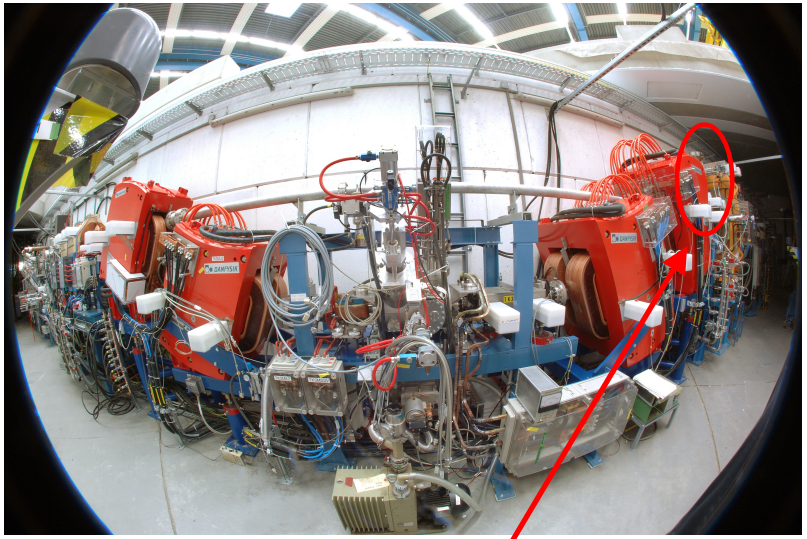
Charge State Separation of U^{73+}

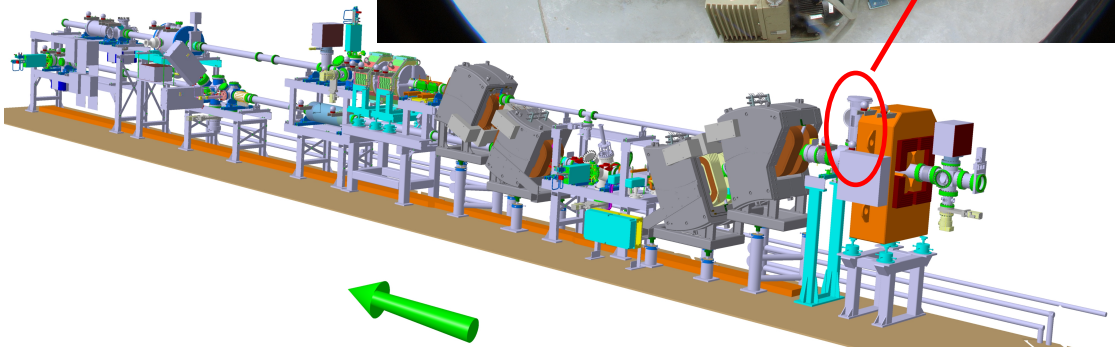


old

new

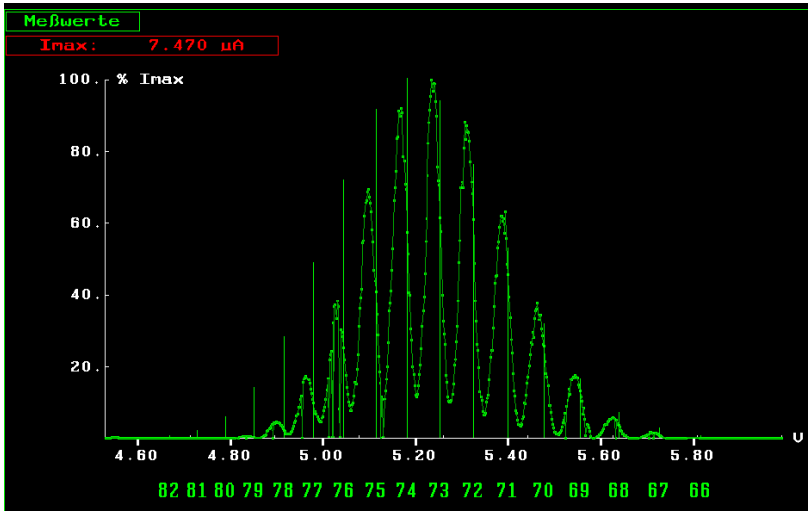
SEM grids at charge separation

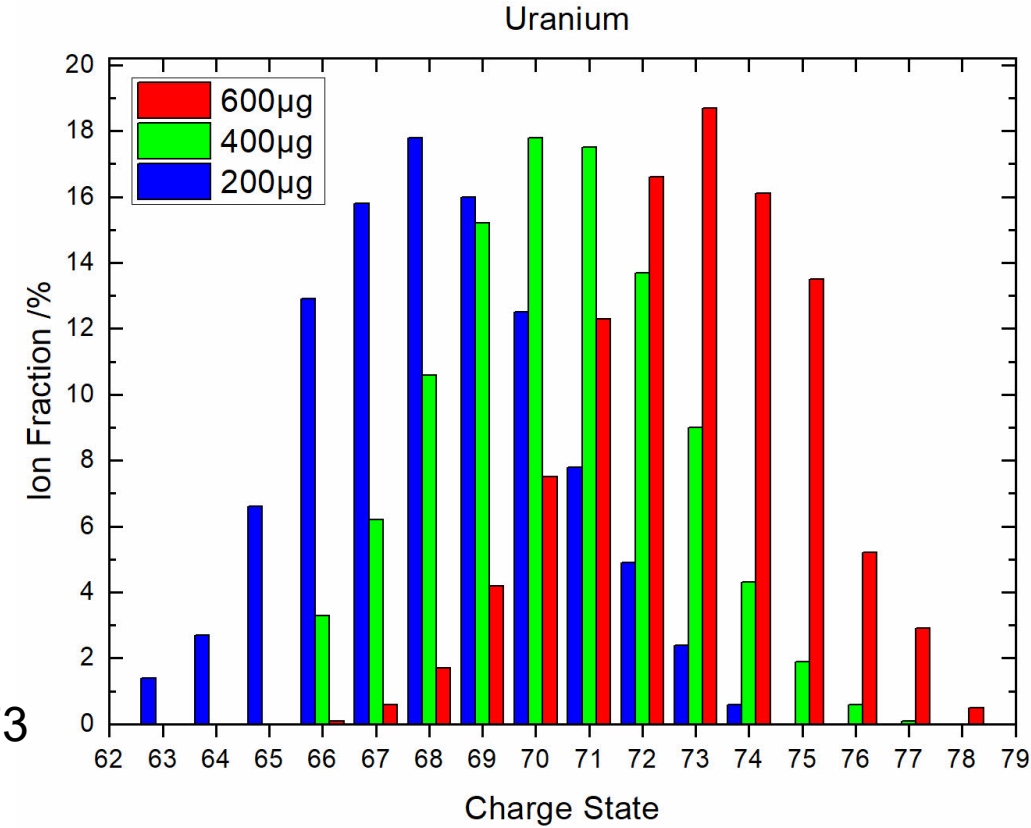




Uranium spectra @11.4 MeV/u

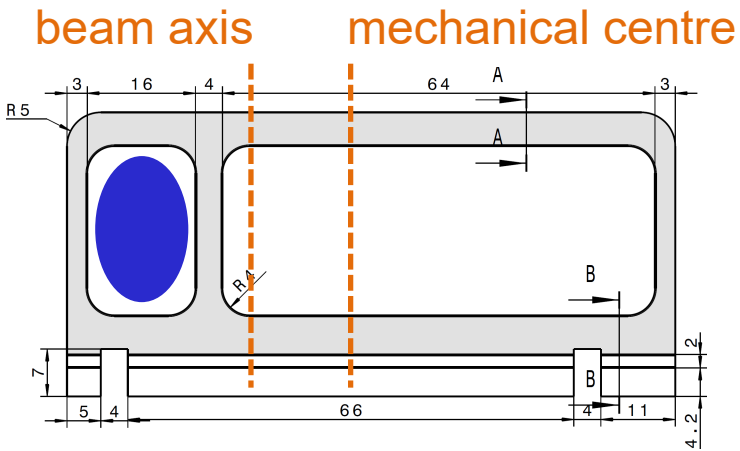
Measured spectrum (screenshot)



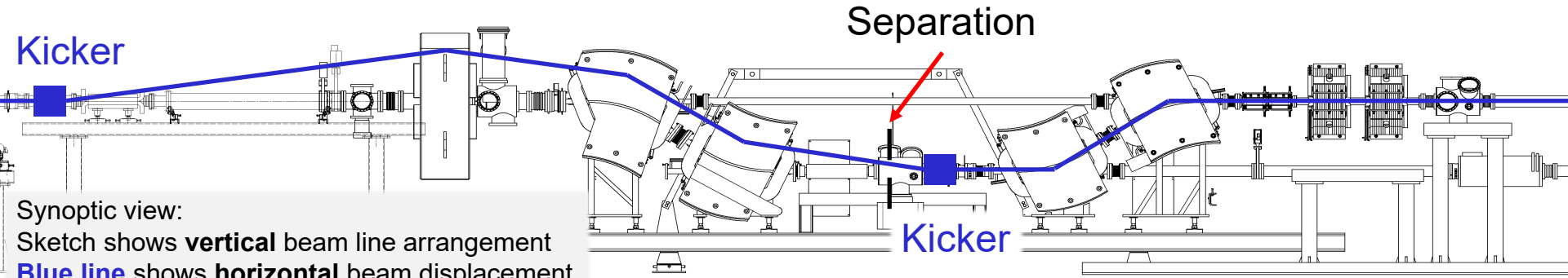


Different foil thickness:
Same efficiency, but <q>= 68, 70.5 and 73

Stripping Modes: Kicker Left

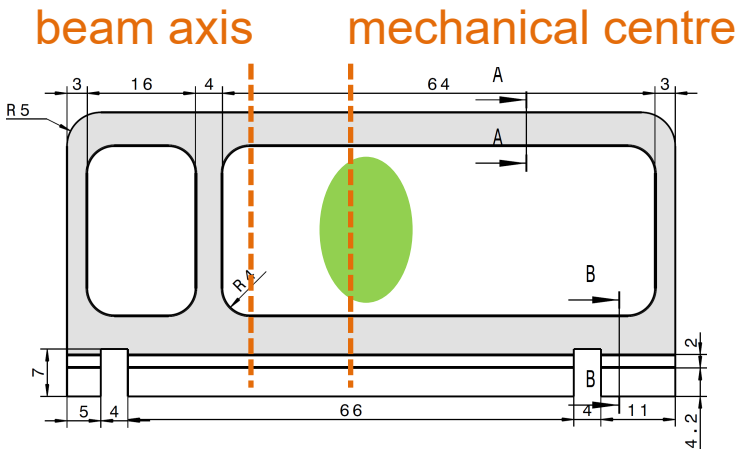


Use small foil for
low current beam
⇒ optimum foil for two
different ion species

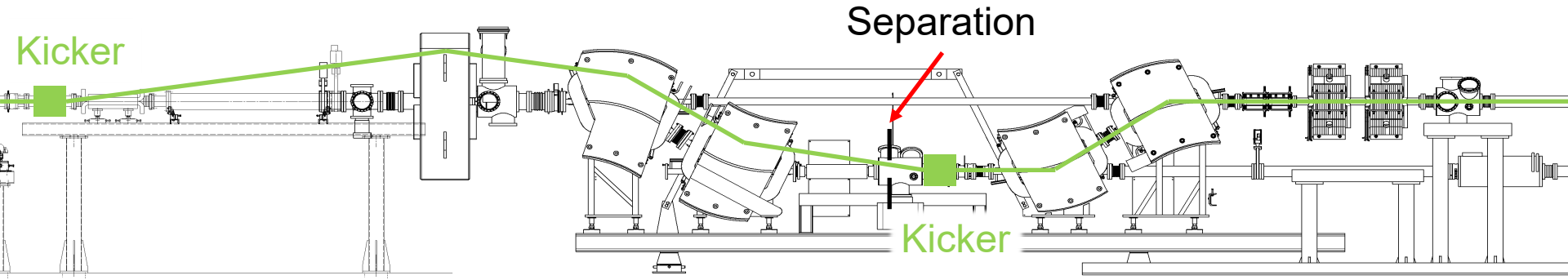


Synoptic view:
Sketch shows **vertical** beam line arrangement
Blue line shows **horizontal** beam displacement

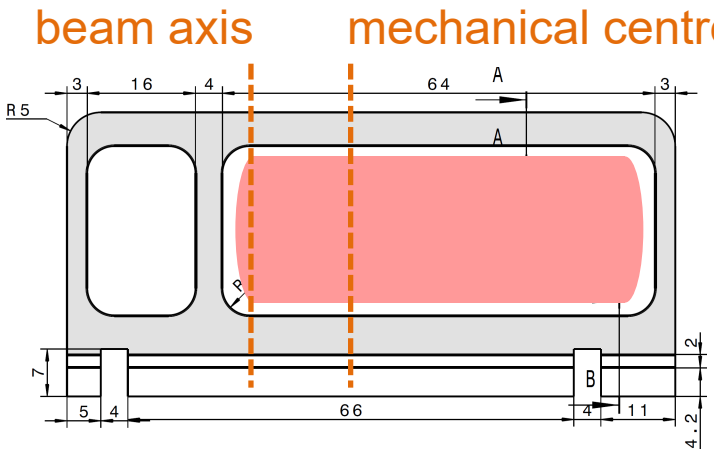
Stripping Modes: Kicker Right



Use large foil for
low current beam
without sweeping
⇒ easier setup

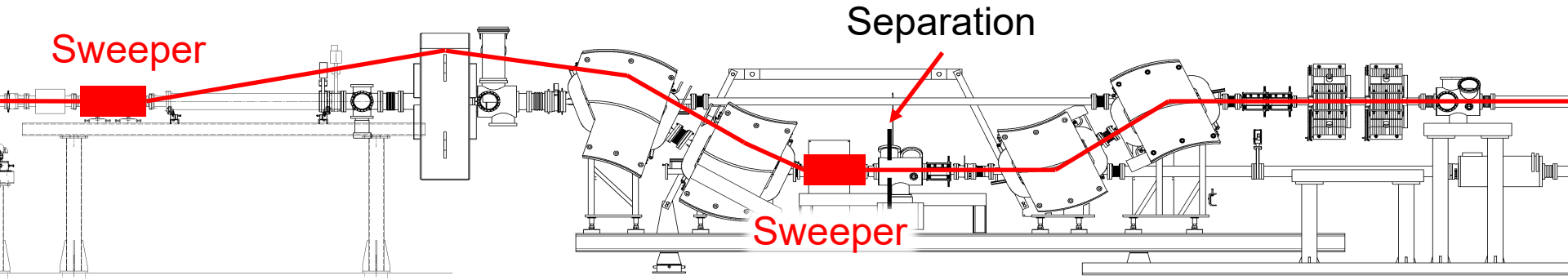


Stripping Modes: Sweeper

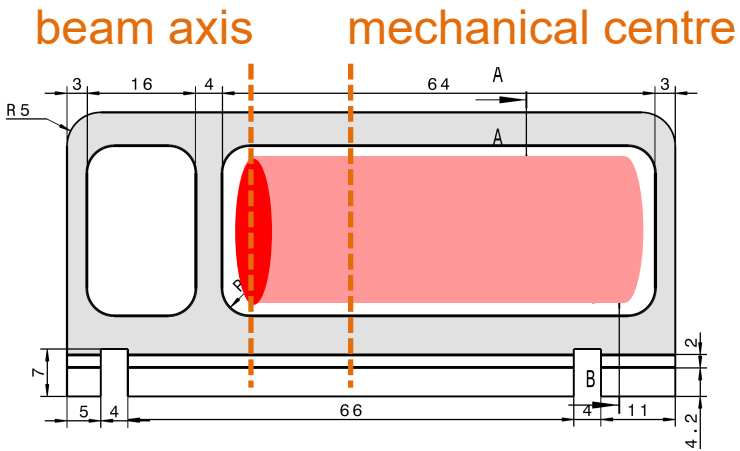


- Double-click for video

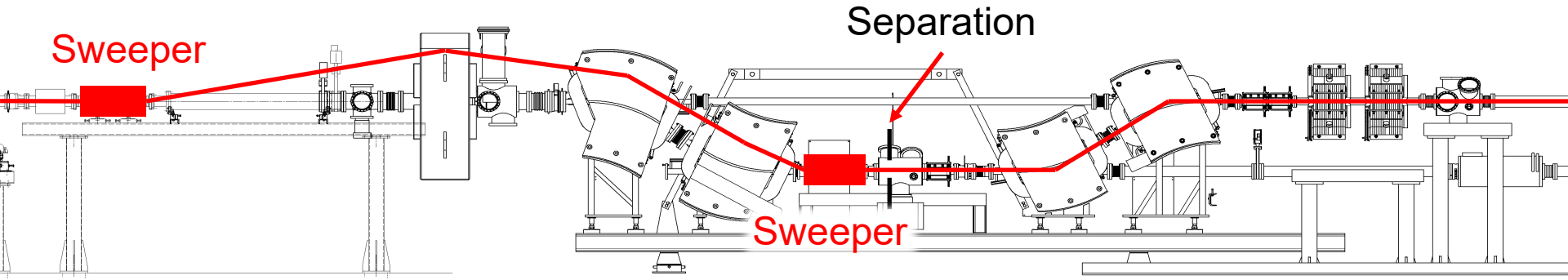
Reduce foil damage due to stripping of high current beams



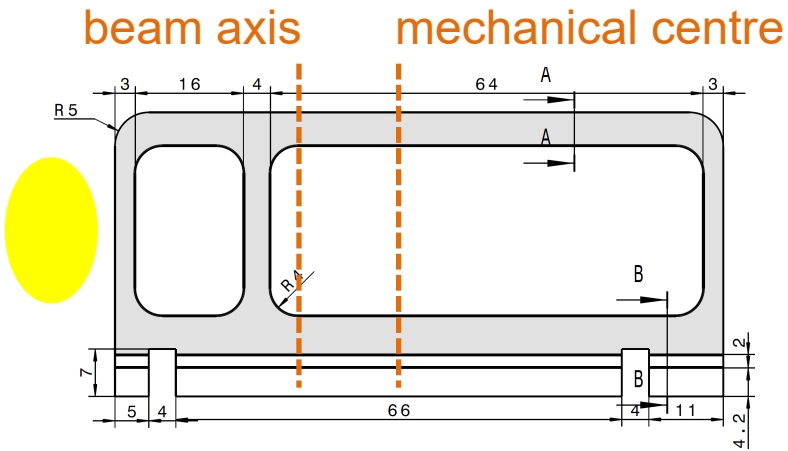
Stripping Modes: Sweeper



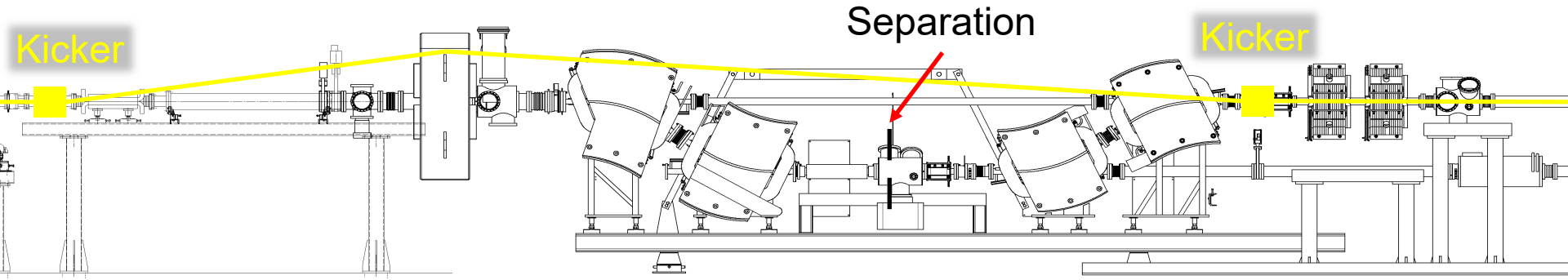
Reduce foil damage due
to stripping of
high current beams



Stripping Modes: Kicker Unstripped

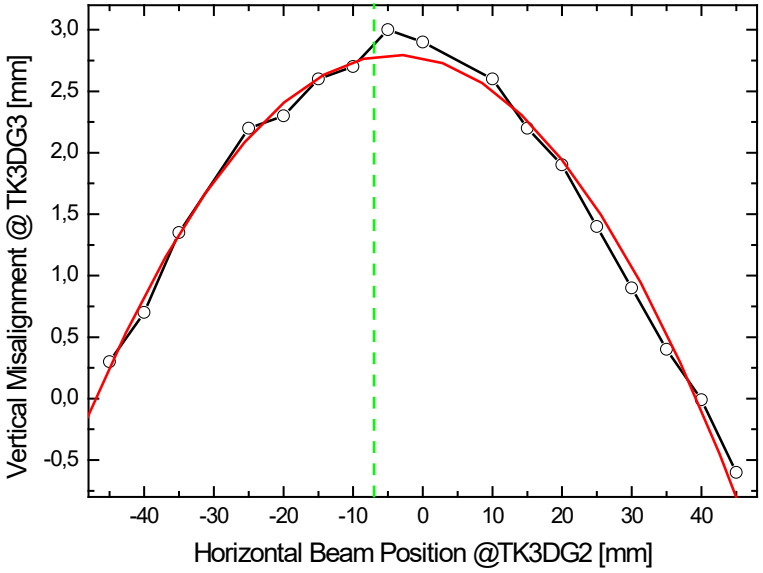


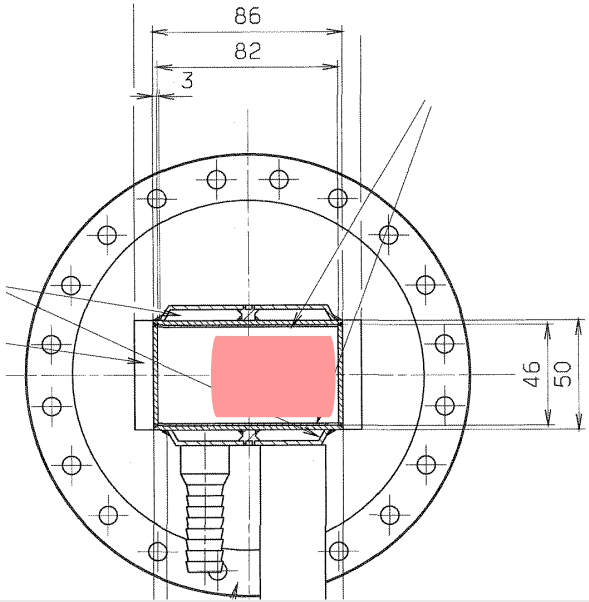
Transport beams at medium charge state without stripping
⇒ higher intensities



Sweeper Mode Trouble

- Unfortuantely, **horizontal sweeping** is converted into **vertical sweeping** at the vertical separation slits by the main separator dipoles
- Dipole field changes by 2‰ from beam axis to vicinity of yoke; spec was 1.5‰
- Solution: Skew sweepers and quadrupole 1-2 mrad



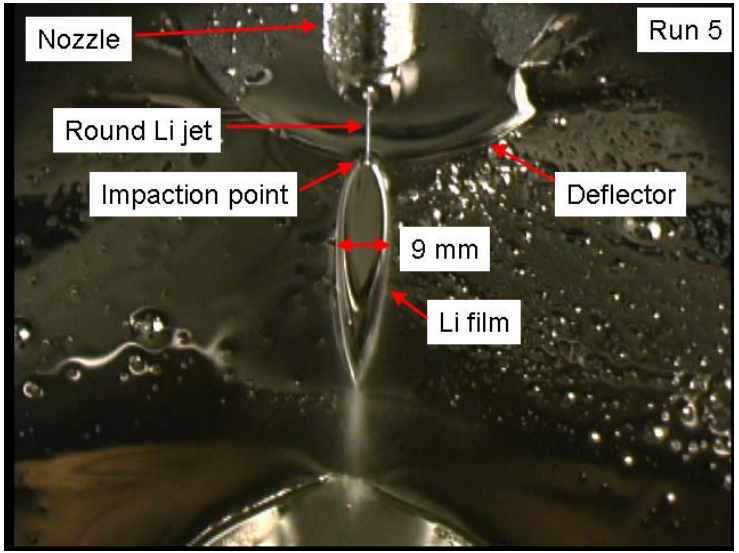


Liquid targets

- Talk by Takuji Kanemura, MSU/FRIB

  “Liquid Lithium Charge Stripping Commissioning with Heavy Ion Beams”

  next session



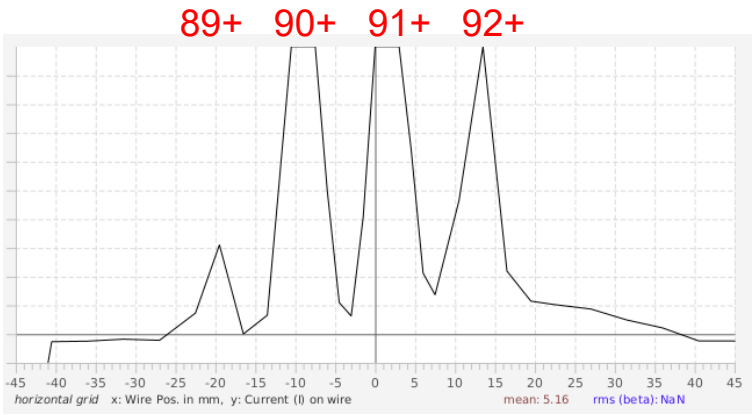
F. Marti *et al.*, DEVELOPMENT OF A LIQUID LITHIUM CHARGE STRIPPER FOR FRIB, Proceedings of HIAT2015

Outline

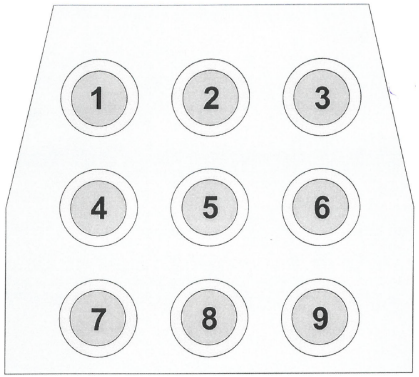
- Introduction
- Fundamentals
- Stripping at 1.4 MeV/u
  - GSI History
  - Recent Gas Stripper Development
- Stripping at 11 MeV/u
  - GSI Multiple Foil Stripper
  - Liquid Targets
- High Energy Foil Stripper
- Summary

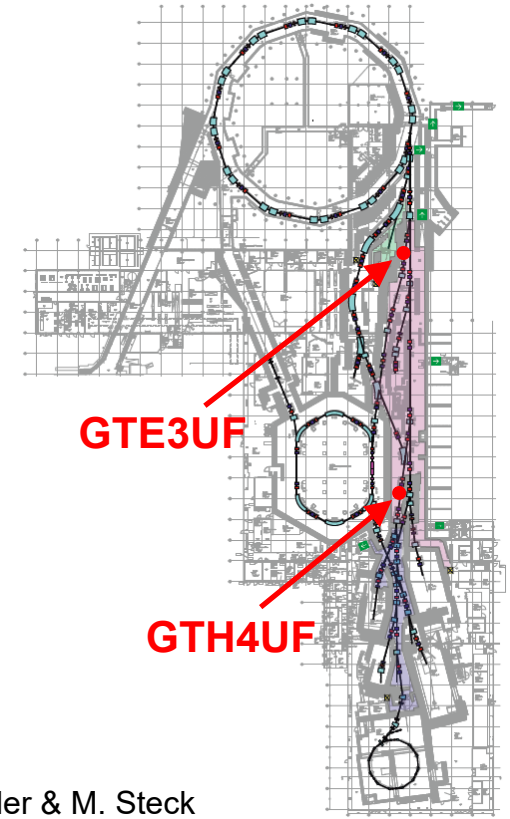
High Energy Foil Strippers

- GTE3UF in beam line towards ESR:
  - 9 foil targets (Cu, Ta, C, Be; 5-100 mg/cm²) arranged in 3x3 matrix
  - Highly charged (e.g. hydrogen-like) uranium beams or simple fragments (1 cm Be target)



U on 40 mg/cm² Cu @300 MeV/u



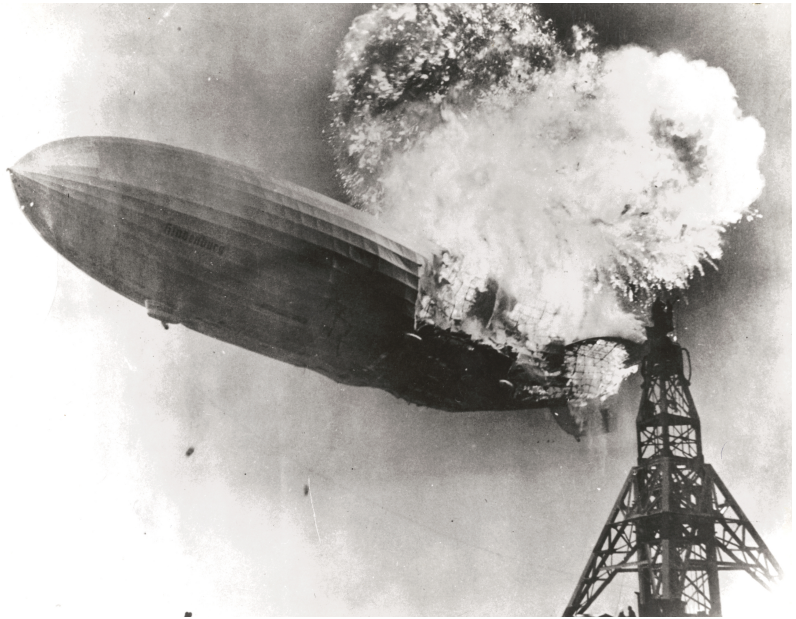


Courtesy of C. Hessler & M. Steck

Summary

- Stripping is an essential technology for operating heavy ion accelerator facilities efficiently
- Several flavours of such devices exist and are still in further development
- GSI has a rich history of stripping devices and applications, operates a number of different strippers today
- GSI development efforts are focused on beam intensity for FAIR
  - For heavy ions ~60% increase will be reached by introducing H_2 at the gas stripper
  - Making it available for routine operation is more difficult than expected, mostly due to safety requirements

The End!



Acknowledgments

- Paul Scharrer for choosing the gas stripper as his PhD thesis topic, and for several slides & figures
- All colleagues from GSI, HIM, and others who contributed to this talk

F. Marti, HEAVY ION STRIPPERS, Proceedings of LINAC2012, Tel-Aviv, Israel, FR1A01