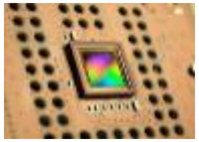
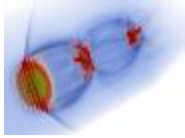
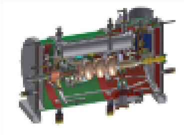
MATTER AND TECHNOLOGIES
HELMHOLTZ

FAIR — Facility for Antiproton and Ion Research in Europe

Overview on GSI

Heavy Ion Accelerator Facility

ARD ST3 Annual Meeting September 2022

HZB Berlin, *7th of September 2022*

Peter Forck, GSI

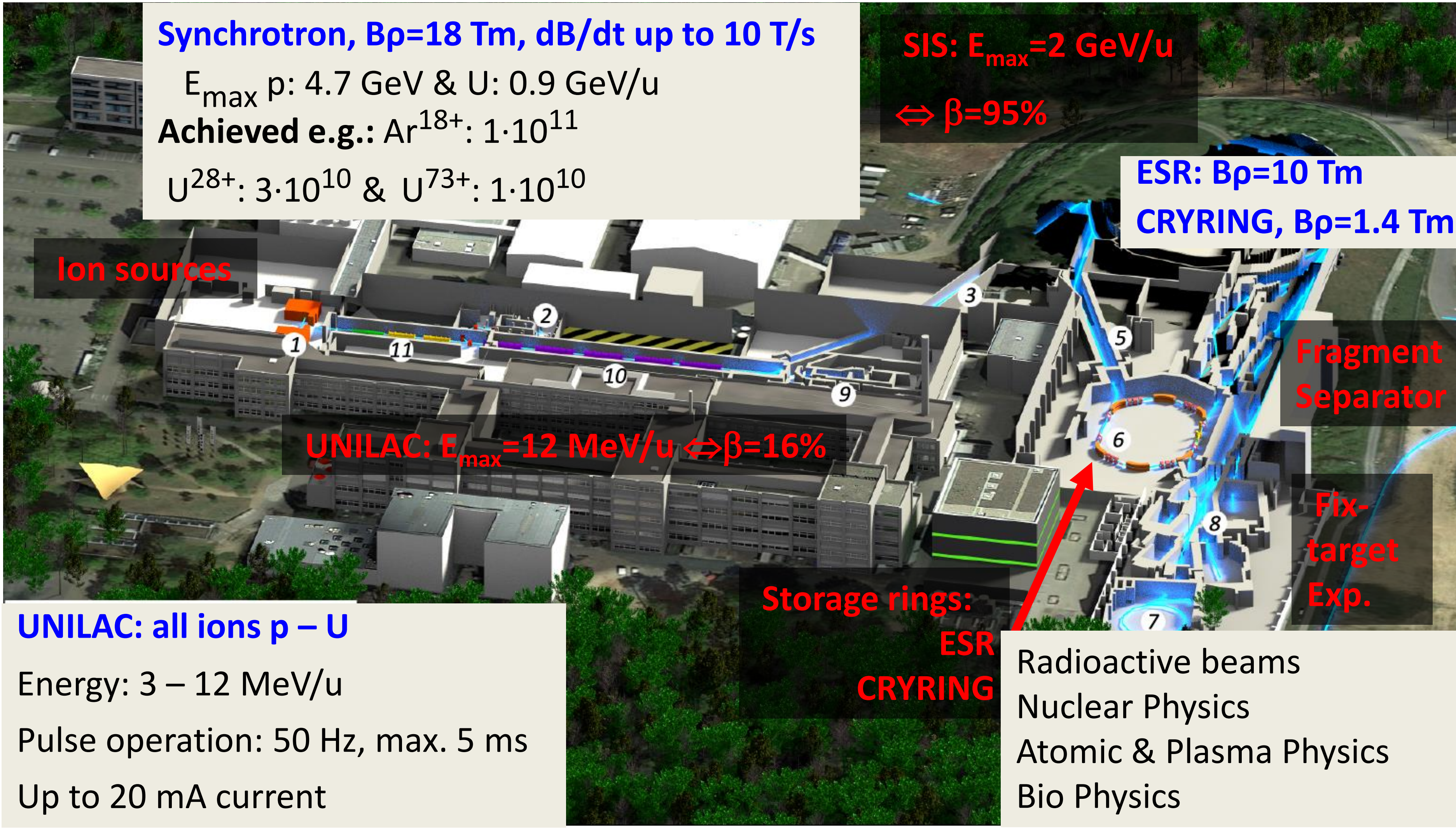
on behalf of the GSI Accelerator Department

For peace
and freedom

Solidarity
with Ukraine

HELMHOLTZ
ASSOCIATION

The GSI Accelerator Facility



UNILAC: all ions p – U

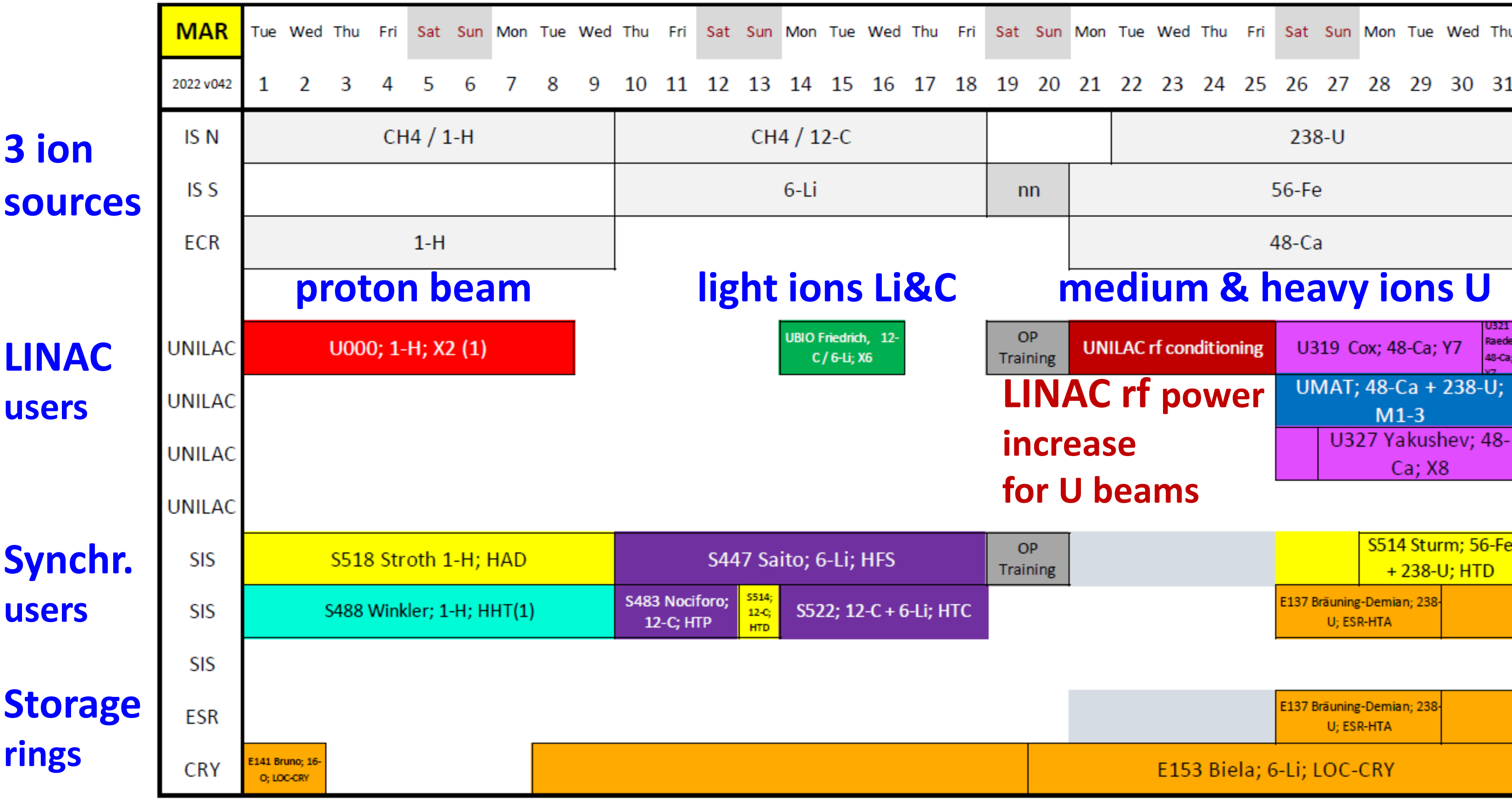
Energy: 3 – 12 MeV/u

Pulse operation: 50 Hz, max. 5 ms

Up to 20 mA current

Radioactive beams
Nuclear Physics
Atomic & Plasma Physics
Bio Physics

Beam Time Schedule Feb.-June 2022: Exemplarily for March



(1) only if parallel operation possible /// (2) only block mode

LINAC beam current in front of synchrotron

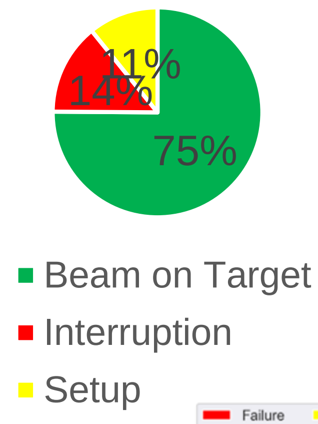
Ion	H	Li	C	O	Ar	Fe	Ni	Au	Pb	Bi	U
Current [mA]	1	0.005	0.045	1	3	0.05	0.025	0.025	0.5	0.015	0.5

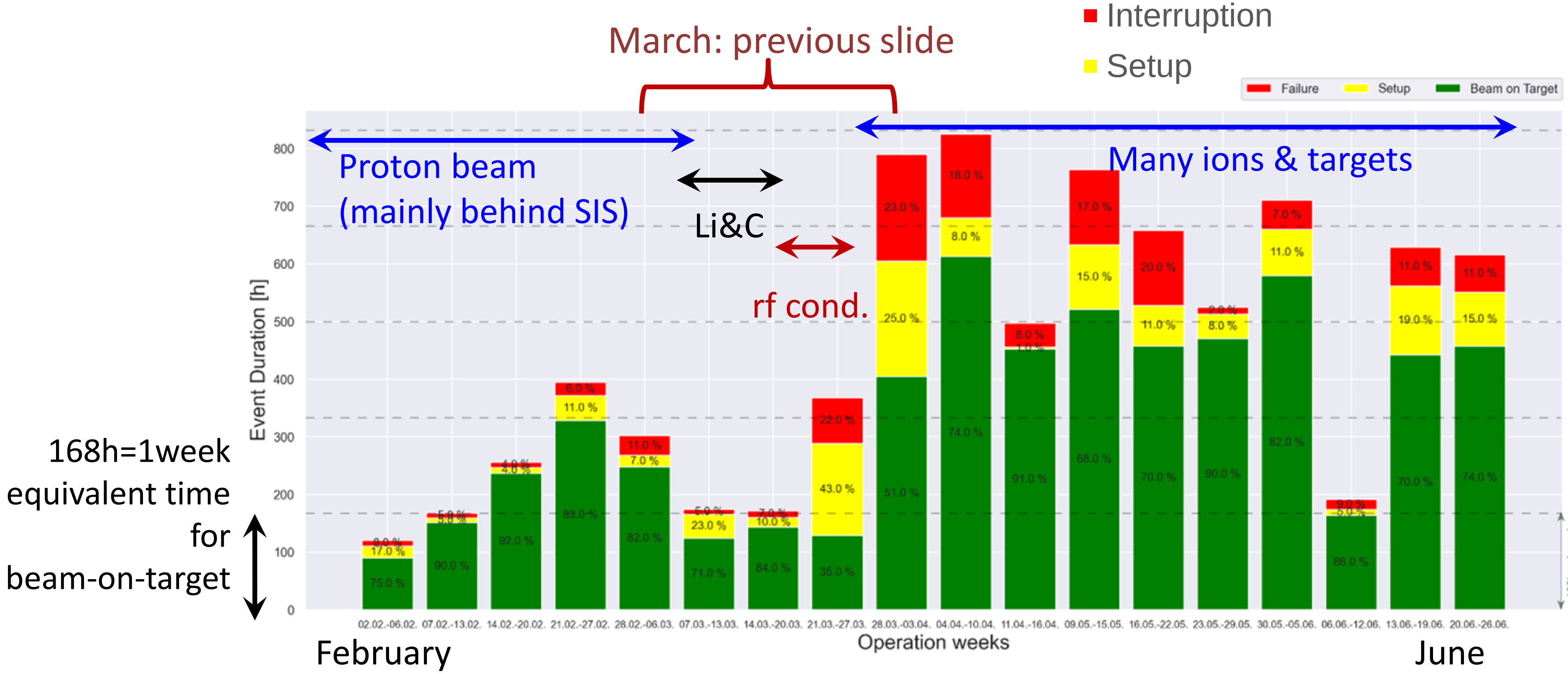
Beam Ability 2022

Features:

- LINAC with 50 Hz pulsing, max. pulse length 5 ms
- 'parallel' operation,
  i.e. each LINAC pulse can have different source and target
- Synch SIS18 is filled by LINAC, typical cycle time ≈ 3 s
- Storage ring might have hours storage times

Beamtime 2022

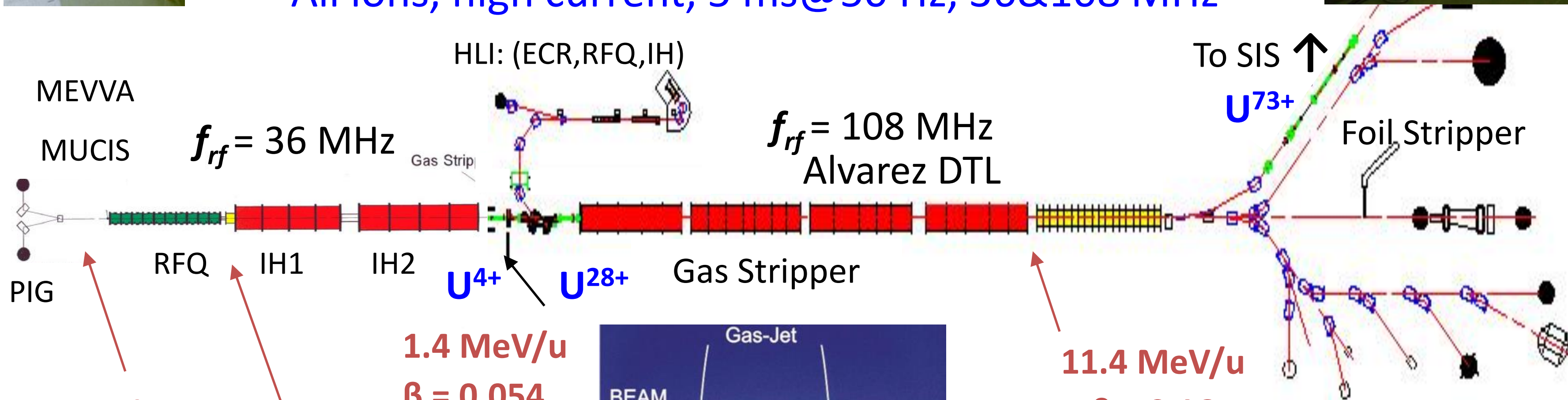


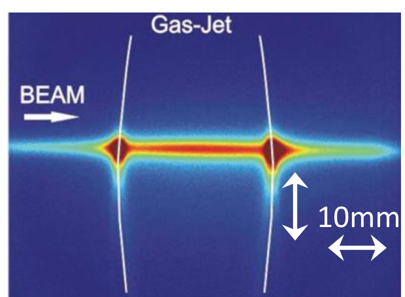


Operation weeks in 2022

UNILAC at GSI: Overview

All ions, high current, 5 ms@50 Hz, 36&108 MHz





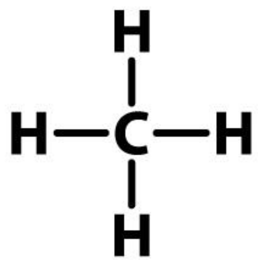
Constructed in the 70th, Upgrade 1999,

→ **Injector for FAIR ion operation**

Proton Generation by molecular Ions

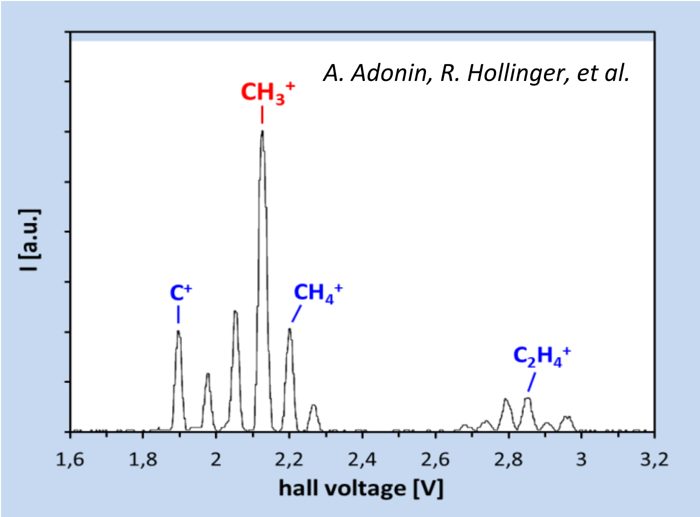
UNILAC: Built for heavy ion acceleration, e.g. 1st LINAC part $^{238}U^{4+}$ i.e. A/q=238/4=59.5

For **protons** $^{1}H^{+}$: Reduce of rf-voltage by factor ≈60, **But:** Outside of amplifier regulation



Methan

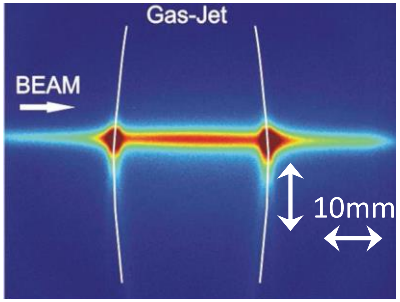
Ion source



Gas target at 1.4 MeV

CH_3^+ acceleration

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

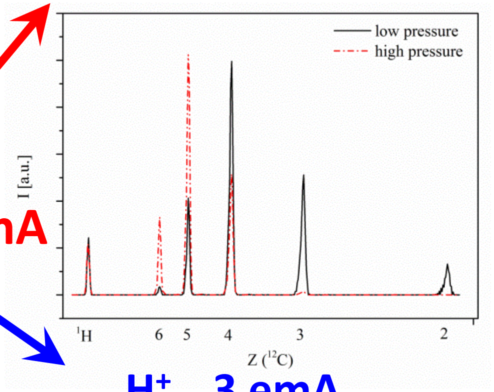


Dissociation of CH-compounds + stripping

C^{6+}, 6 emA

CH_3^+, 1 mA

H^+, 3 emA

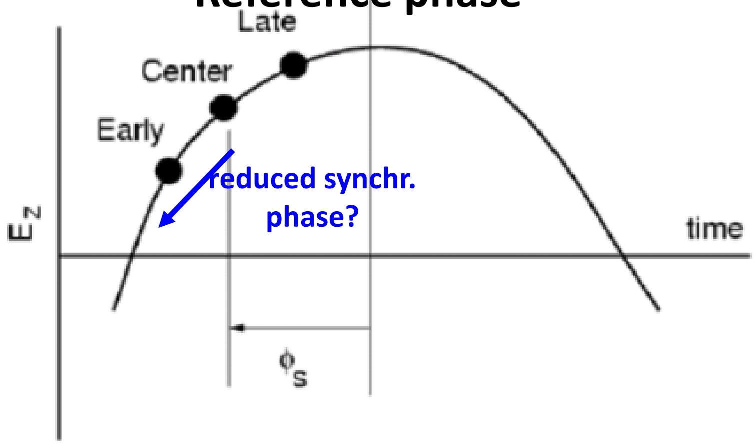


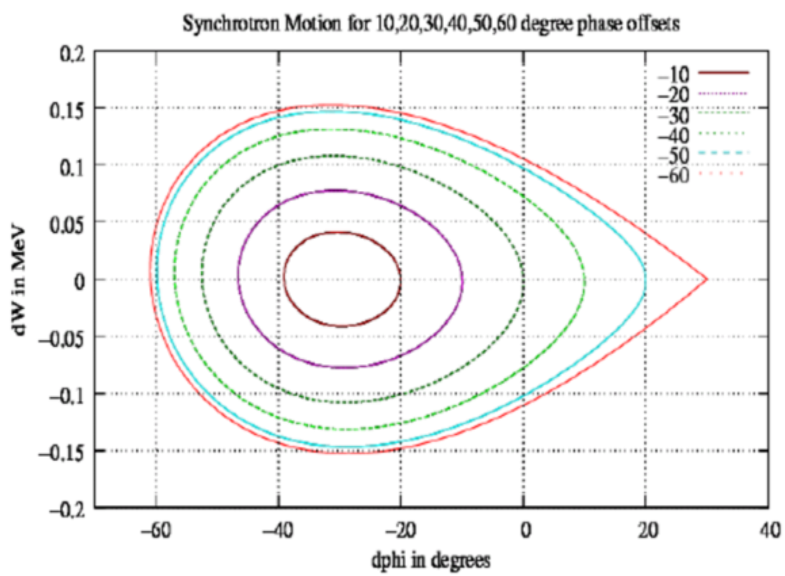
Proton Beam Dynamics with low Voltage & large Phase Offset

UNILAC: Built for heavy ion acceleration, e.g. 1st LINAC part $^{238}U^{4+}$ i.e. A/q=238/4=59.5

For **protons** $^{1}H^{+}$: Reduce of rf-voltage by factor 60, **BUT:** Outside of amplifier regulation

Reference phase





ALVAREZ Rf-voltage < 1V ($\Phi s \approx -30°$)?

- **$\Phi s \approx -57°$ ($U_{rf} \approx$ 1.5V)**
- **$\Phi s \approx -65°$ ($U_{rf} \approx$ 2.0V)**
- **$\Phi s < -65°$ ($U_{rf} >$ 2.0V)**

pros and cons of large negative phases:

- smooth rf-operation
- slightly reduced transmission
- emittance blow up
- longitudinal phase space?

Achievement:

- ≈3 mA before SIS18, sufficient for actual users
- Typical emittance reached

(High current ≈50 mA by planned proton LINAC)

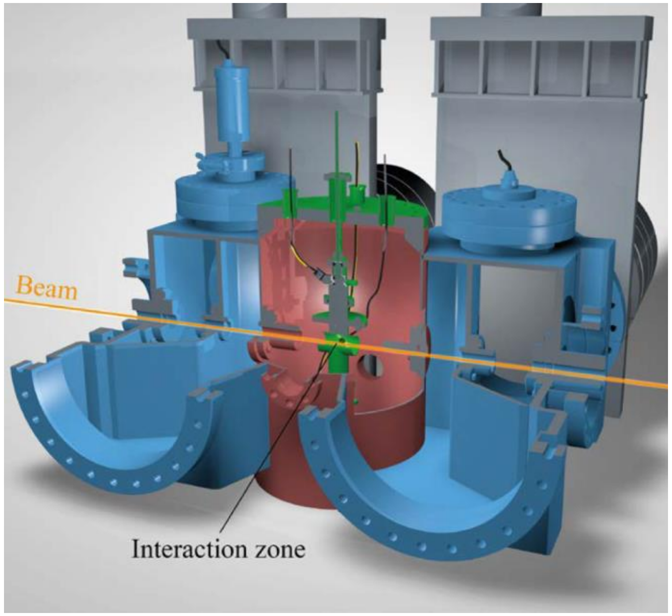
Gas Stripper for efficient Change of Charge State: Hardware

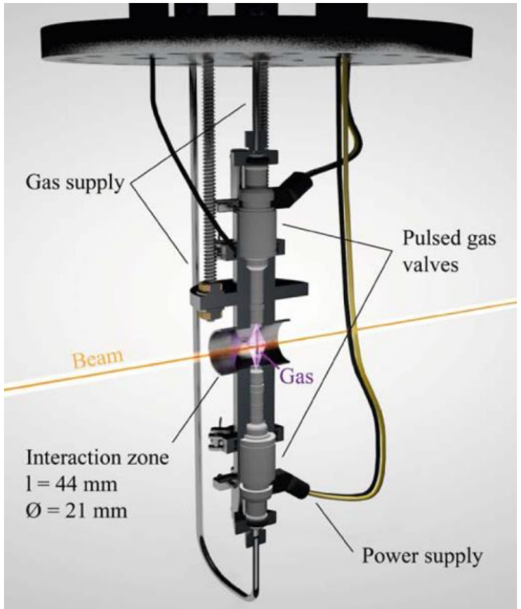
UNILAC: Ion source high current, low charge state e.g. $^{238}U^{4+}$

$\rightarrow$ 1st LINAC part $^{238}U^{4+}$ up to 1.4MeV/u (β=5.5%) $\rightarrow$ gas stripper $^{238}U^{4+} \rightarrow {}^{238}U^{28+}$

$\rightarrow$ 2nd part of LINAC $^{238}U^{28+}$ up to 11.4 MeV/u (β=15.5%)

However, only $\approx$ 15 % for q=28+ depending on gas and pressure





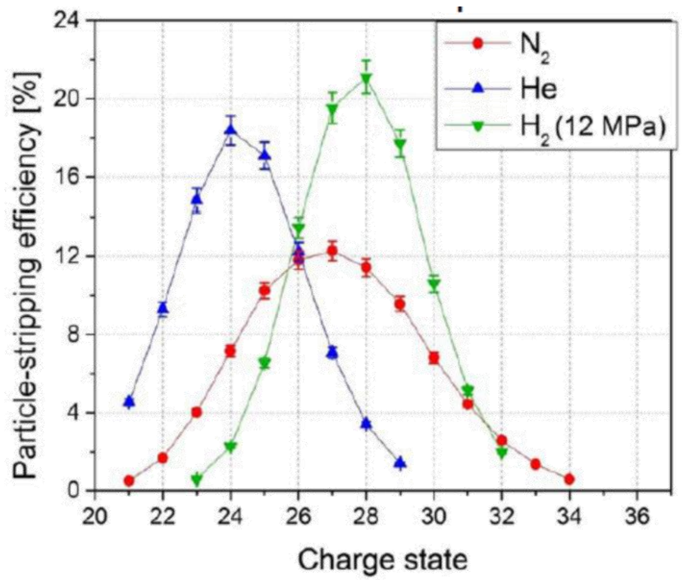
Automotive Gasoline Injector

- High pressure super-sonic gas jet required, inlet p = 120 bar, light molecules deliver small jet
- Contradictory requirements: high density $\rightarrow$ good stripping, low density $\rightarrow$ lower straggling
- Pulsed inlet to reduce gas load inn vacuum chamber

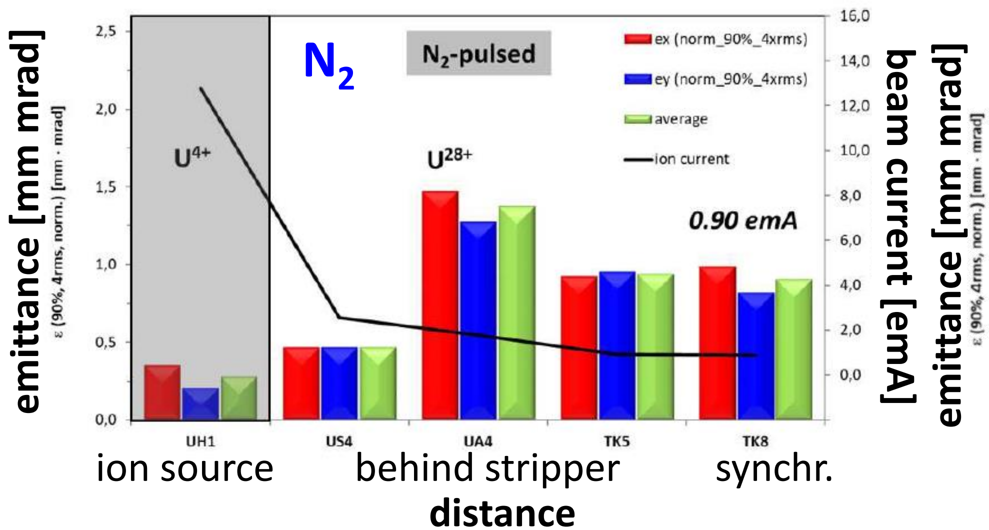
Gas Stripper for efficient Change of Charge State: Results

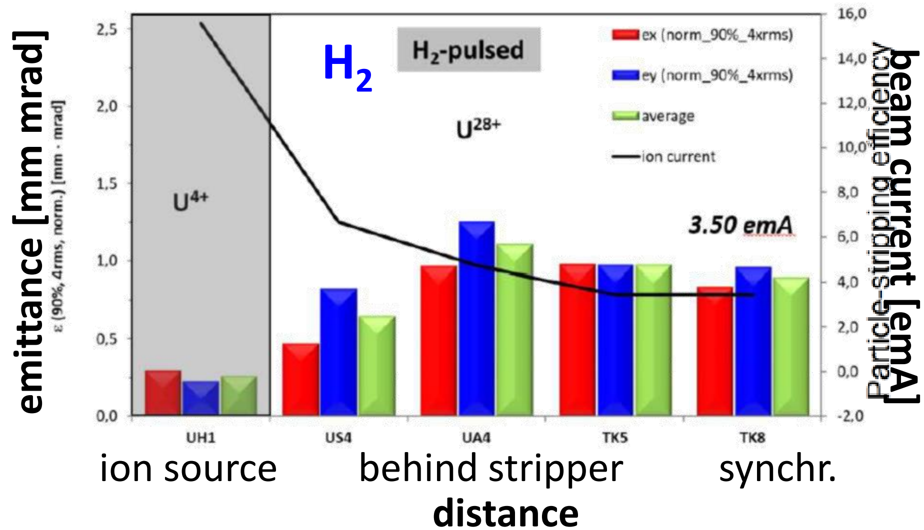
Results:

- Higher yield of $^{238}U^{28+}$ for pulsed H_2 jet
- Lower emittance due to lower straggling

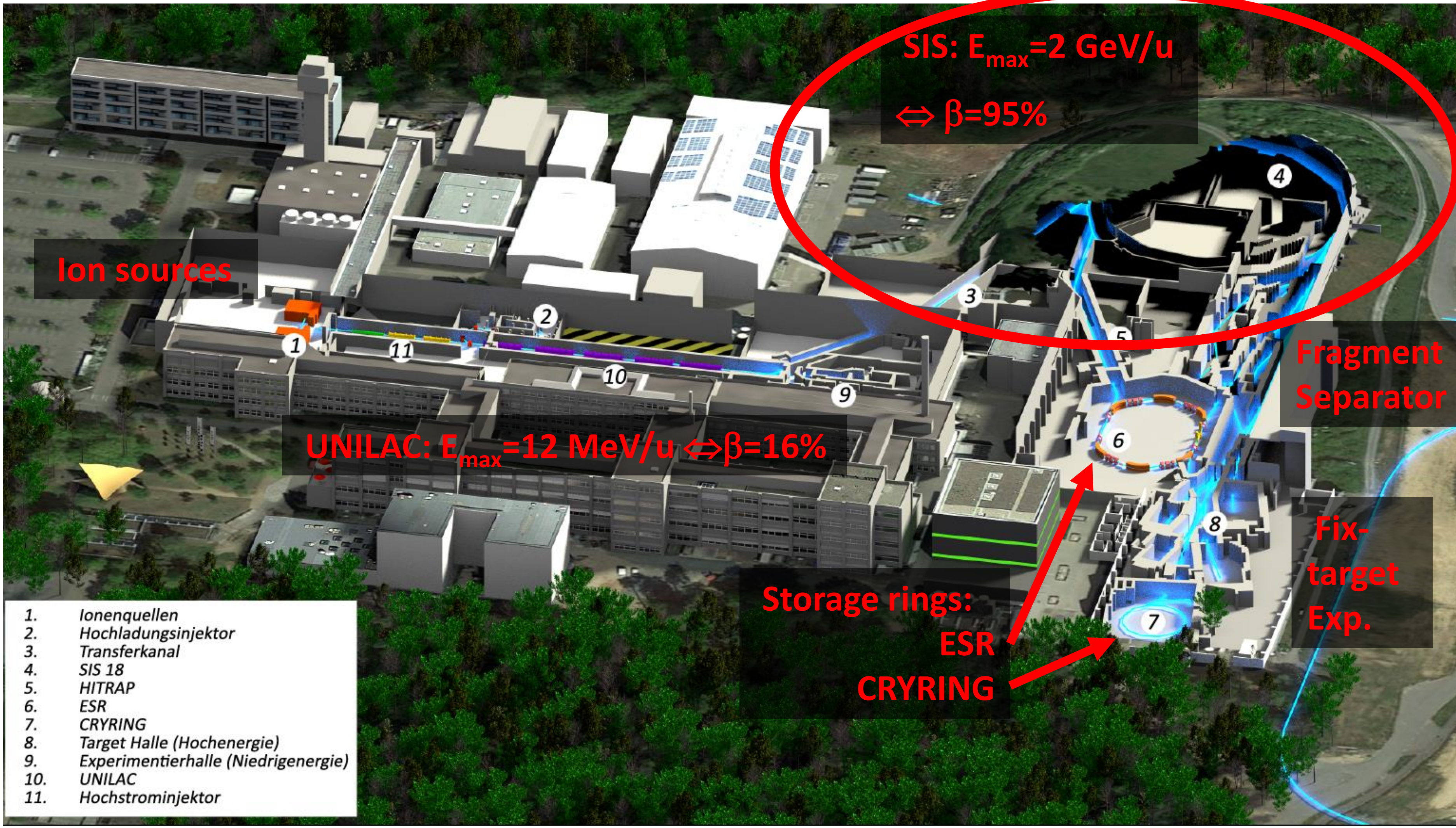


Talk by Simon Lauber: Novel beam dynamics for heavy ion acceleration

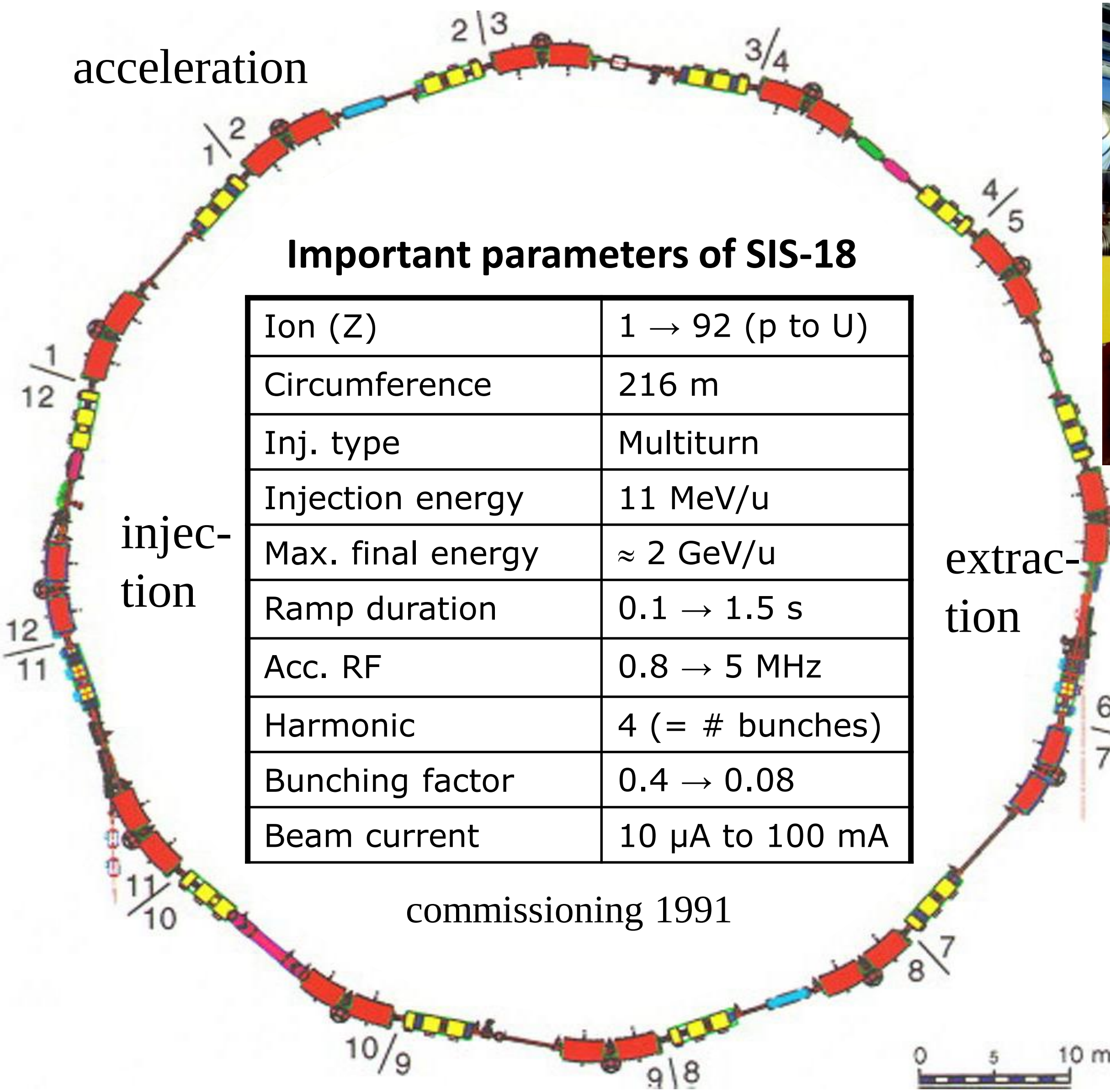




The GSI Accelerator Facility: Synchrotron



GSI Heavy Ion Synchrotron: Overview



Important parameters of SIS-18

Ion (Z)	1 → 92 (p to U)
Circumference	216 m
Inj. type	Multiturn
Injection energy	11 MeV/u
Max. final energy	≈ 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4 (= # bunches)
Bunching factor	0.4 → 0.08
Beam current	10 μA to 100 mA

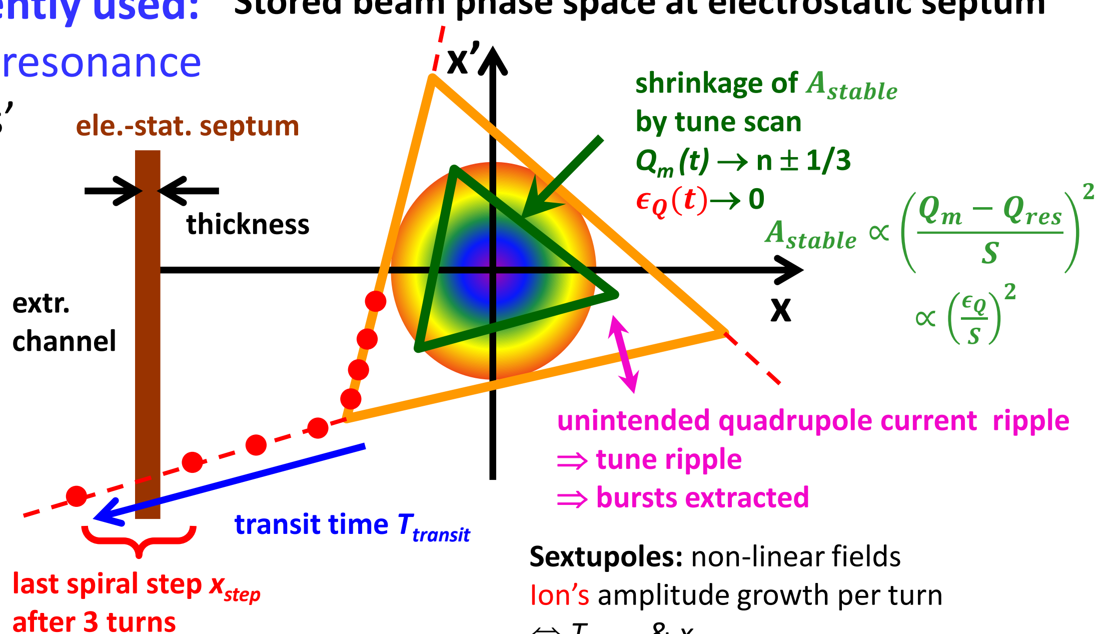
commissioning 1991

Slow Extraction: Principle and Micro-Structure

Slow extraction for t_{ex} = 1 … 10 s frequently used:
Gentle excitation of a beam **third** order resonance
Beam physics: Extraction as 'slow losses'
- Particle crosses stability-boarder sequentially
- Exponential amplitude growth $\approx$ 50 … 1000 turns reaching septum and is extracted

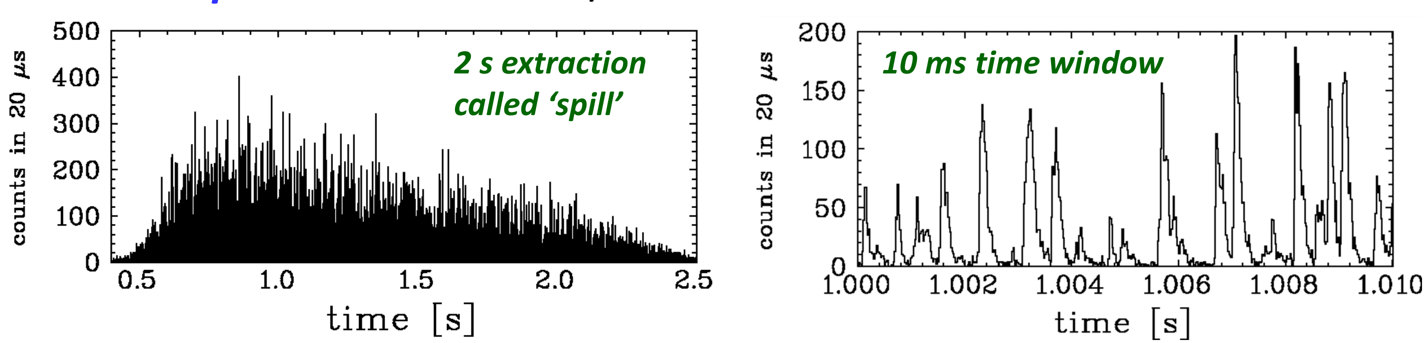
Problem: Sensitivity to any **unintended** resonance condition, e.g.:
Change of tune:
unintended quadrupole current ripples

Stored beam phase space at electrostatic septum



Sextupoles: non-linear fields
Ion's amplitude growth per turn
$\Leftrightarrow T_{transit}$ & x_{step}

Example: C^{6+} at 300 MeV/u at GSI



Spiky structure is one major problem for users as it increases the detector dead time

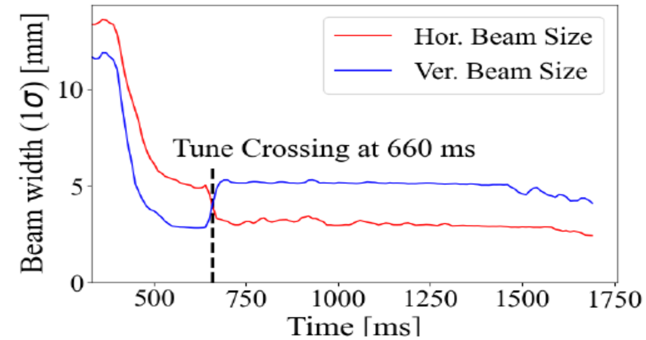
Slow Extraction: Micro-Structure Improvement

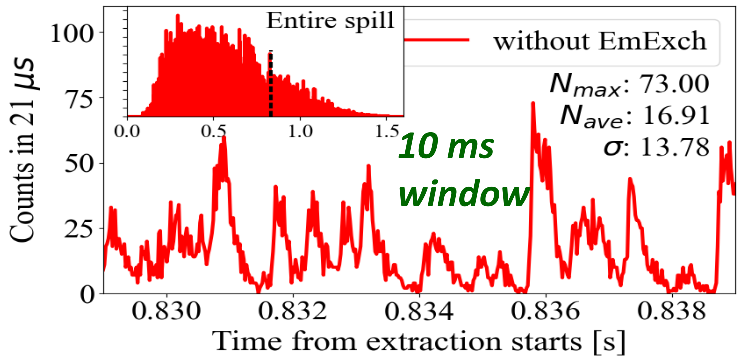
Possible mitigation:

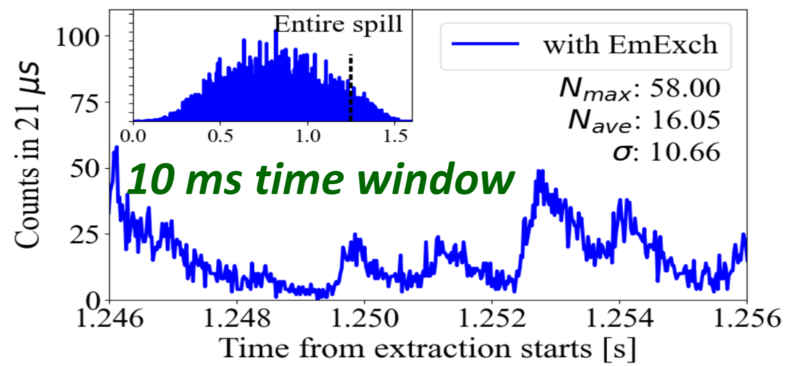
Smaller horizontal emittance by crossing shortly a coupling resonance $Q_x = Q_y + 1$

$\Rightarrow$ Significant improvement

Other methods also tested related to linear and non-linear beam dynamics

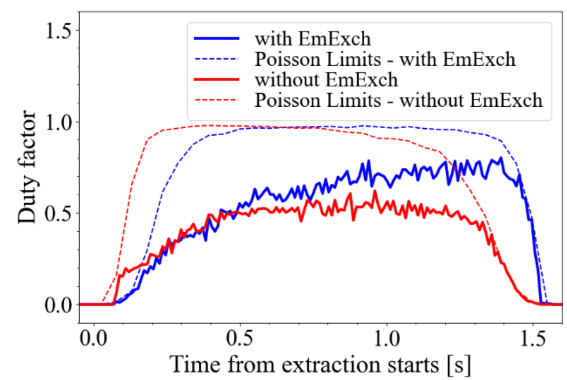






Duty factor, i.e. normalized fluctuations

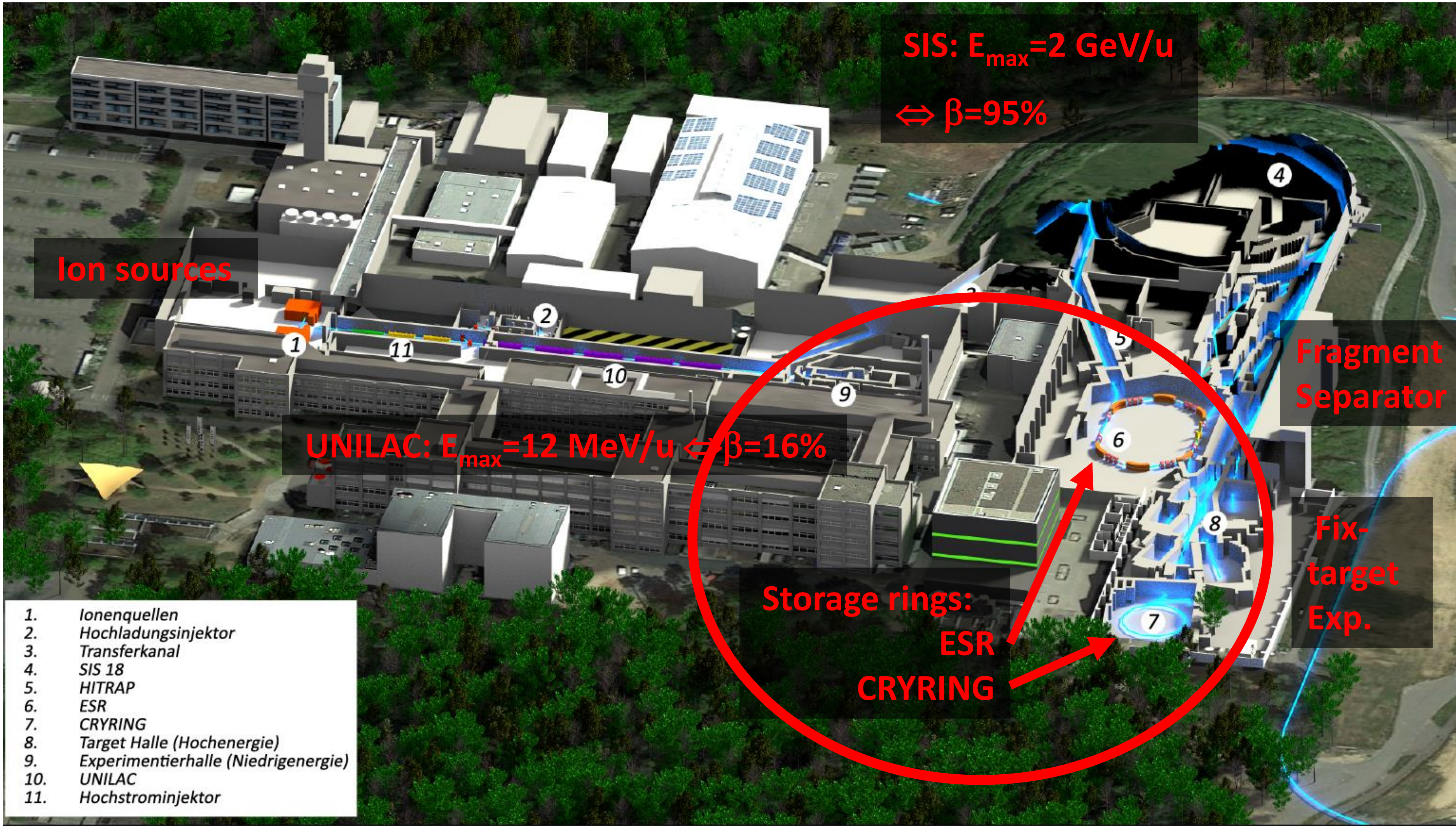
$$F_{\Delta t} \equiv \frac{c_{mean}^2}{c_{mean}^2 + \sigma_c^2} \equiv \frac{\langle c \rangle^2}{\langle c^2 \rangle}$$



Part of EU-project IFAST-REX with

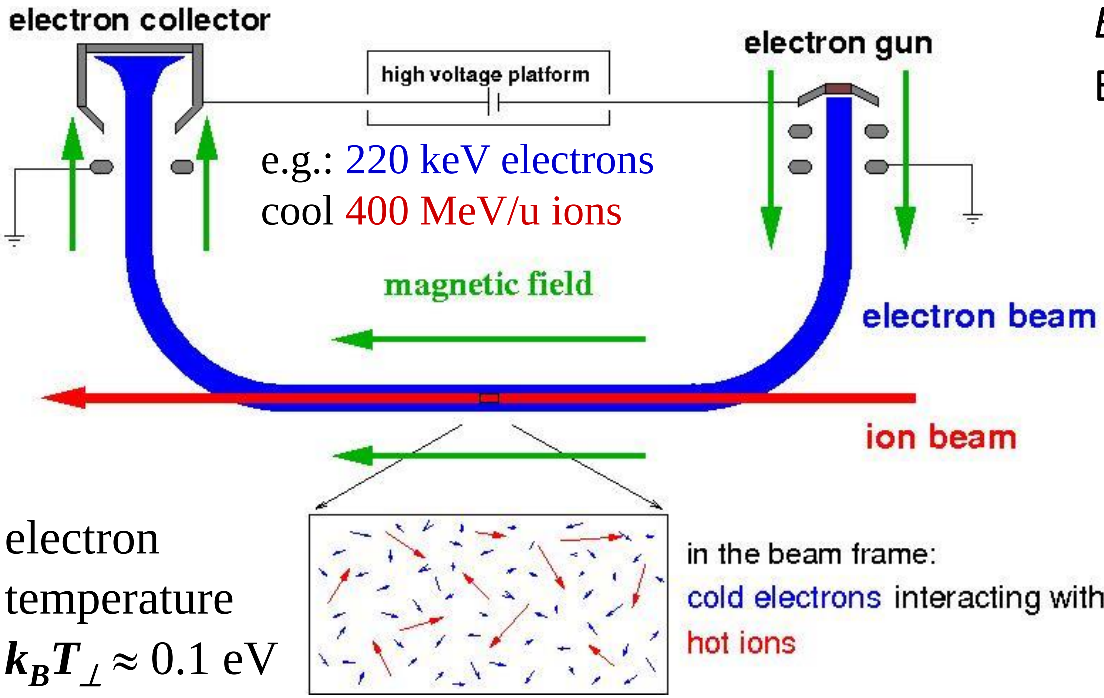
Collaboration: CERN, GSI, Medical Ion Therapy Centers

The GSI Accelerator Facility: Storage Rings



Electron Cooling: Improvement of Beam Quality

Electron cooling: Superposition ion and cold electron beams with the same



electron temperature

$k_B T_\perp \approx 0.1$ eV

$k_B T_\parallel \approx 0.1 - 1$ meV

Example:

Electron cooler at ESR U_{max} = 300 kV

Physics:

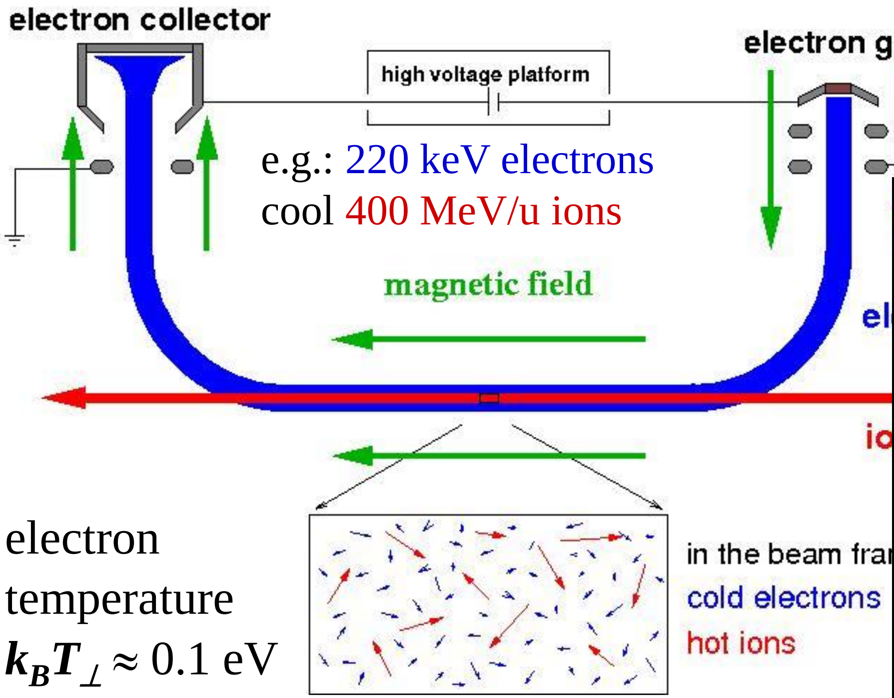
- Momentum transfer by Coulomb collisions
- Cooling force results from energy loss in the cold, co-moving electron beam

Cooling time: 0.1 s for low energy highly charged ions, 1000 s for high energy protons

Also Stochastic Cooling available at ESR

Electron Cooling: Improvement of Beam Quality

Electron cooling: Superposition ion and cold electron beams with the same



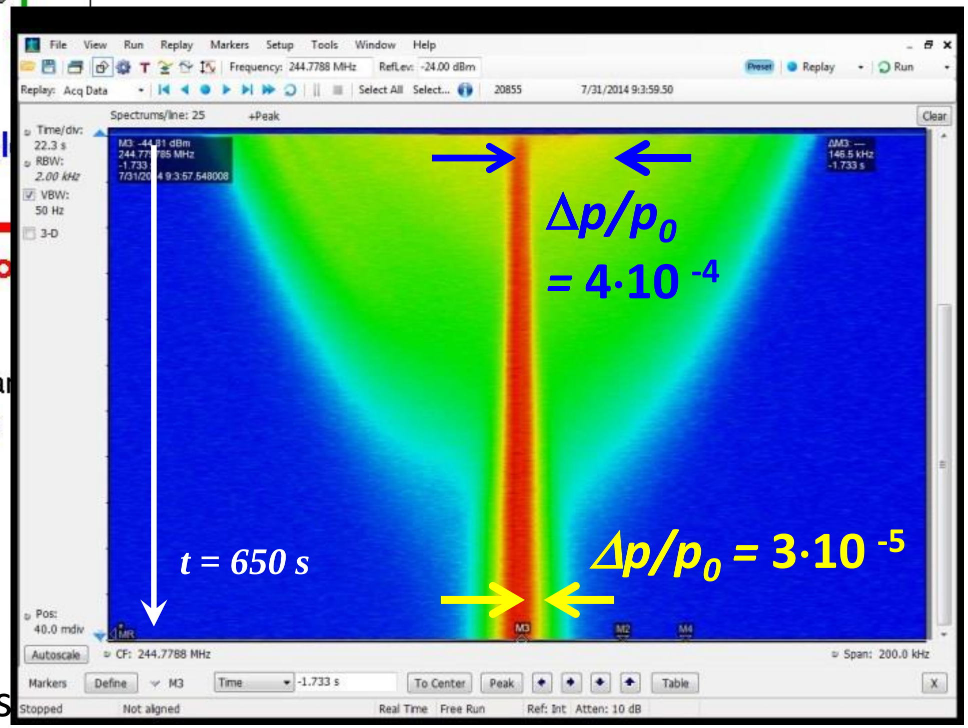
electron temperature

$k_B T_\perp \approx 0.1$ eV

$k_B T_\parallel \approx 0.1 - 1$ meV

Example:

Electron cooling at ESR: 10^8 proton at 400 MeV



Physics:

- Momentum transfer by Coulomb collisions
- Cooling force results from energy loss in the cold, co-moving electron beam

Cooling time: 0.1 s for low energy highly charged ions, 1000 s for high energy protons

Also Stochastic Cooling available at ESR

Deceleration of Highly Charged Ions

Slow, highly charged ions

- Stripping at high energy

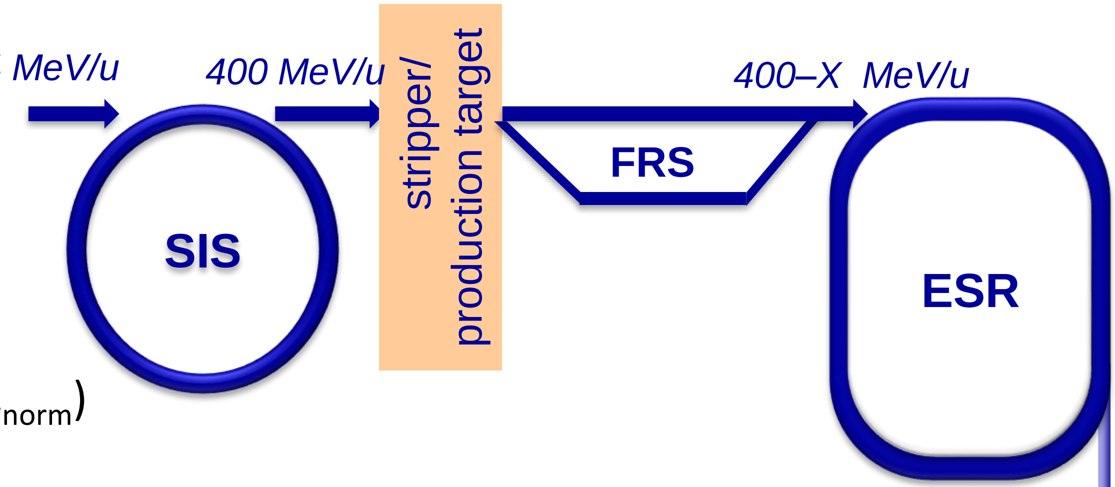
to provide sufficient collisional energy

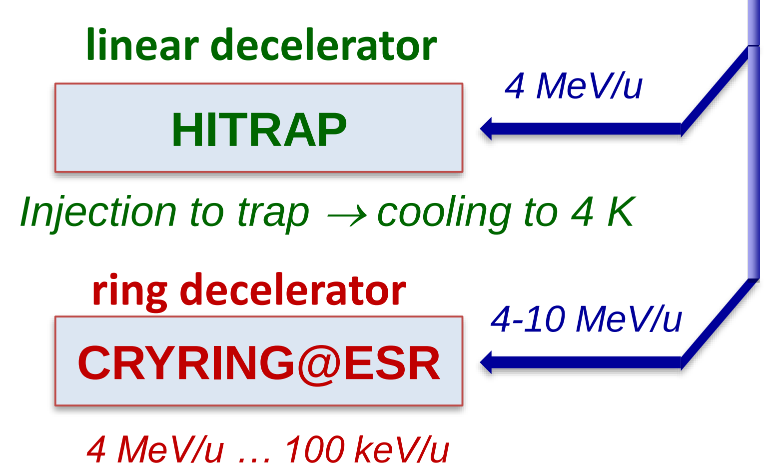
- Deceleration: Emittance increase

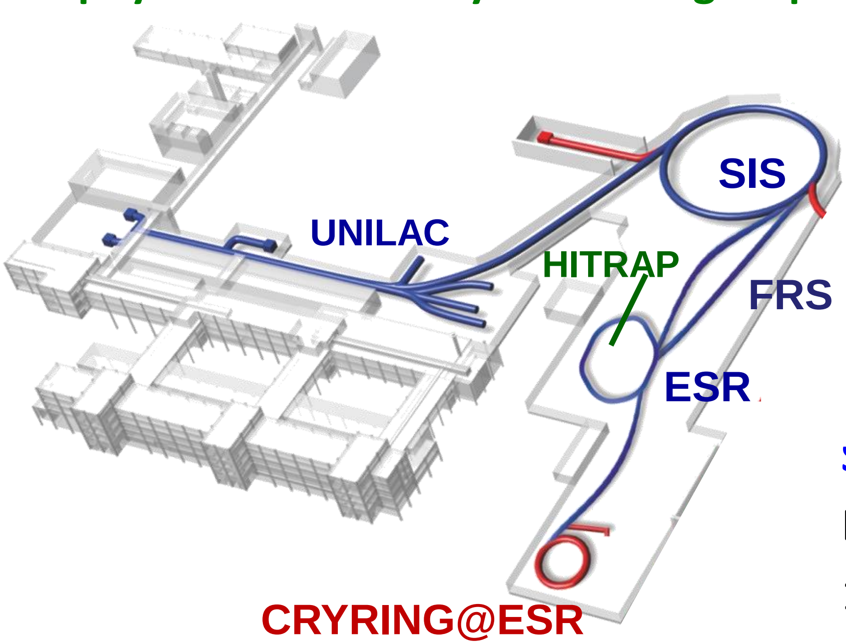
(Ideally: Conservation of **normalized** ε_{norm})

$\Rightarrow$ **Cooling required**

Atomic physics: Ion far away from charge equilibrium







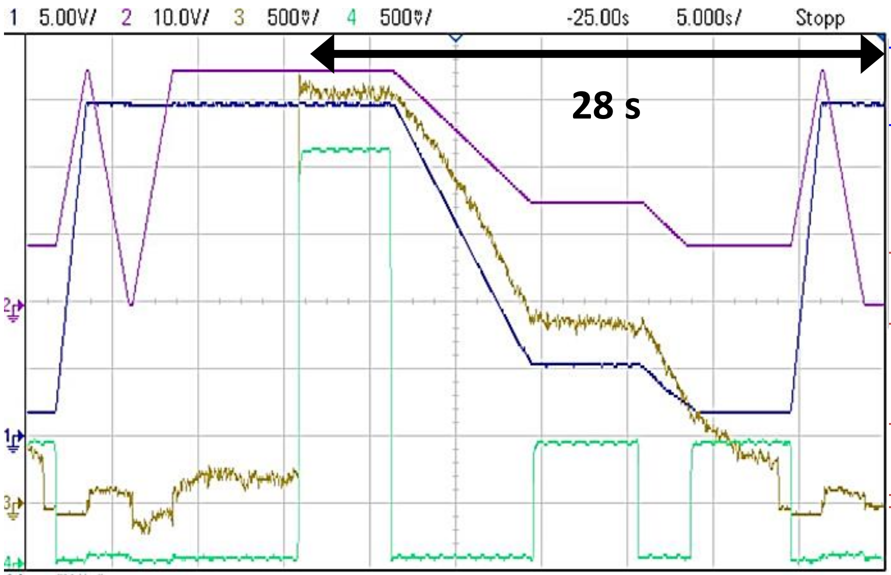
Slow ions are stored and well controlled

Energy range 10 MeV/u to sub eV/ion

10^5 to 10^7 highly charged ions. e.g. U^{91+}

ESR Deceleration Cycle 2022

Deceleration: Au^{78+}: 145 → 30 → 10 MeV/u followed b fast transfer to CRYRING



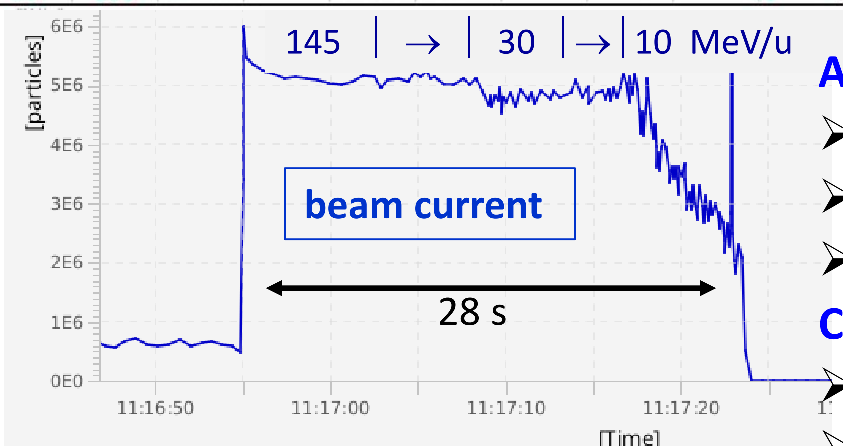
high voltage of electron cooler (electron energy)

electron cooling is applied at all three plateaus

dipole field strength

beam current

electron current (300/100 mA)



Achievements:

- Optimization of complex beam manipulation
- Intensity below 10^7
- Particle loss less than 20 % from 145 to 10 MeV/u

Challenges:

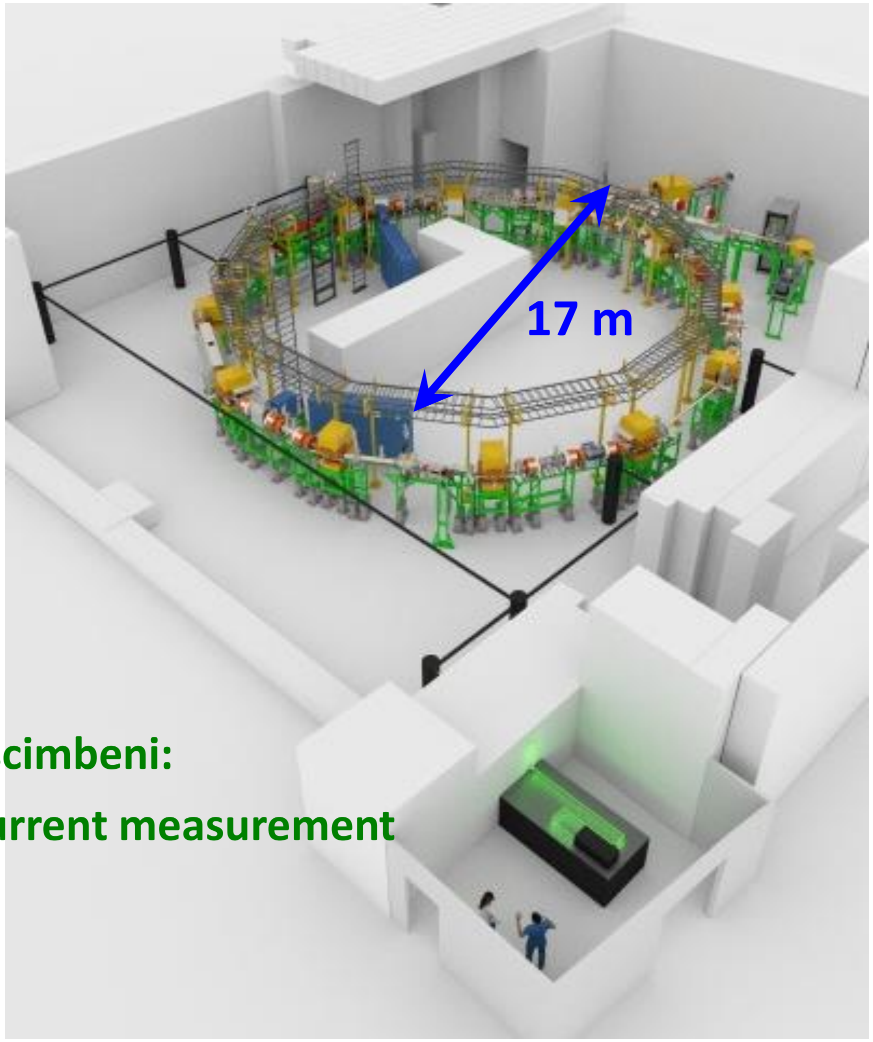
- Beam instabilities by large space charge
- Lifetime limit by residual gas coll. ($p=10^{-11}$ mbar)

The low Energy Storage Ring CRYRING

CRYRING: Significant improved ring from University Stockholm

Injection from ESR or local source, acceleration and deceleration, electron cooling

Parameter	Value
Circumference	54.17 m (ESR/2)
Vacuum pressure	10^{-11}-10^{-12} mbar
Ion energy	< 300 keV/u - 14 MeV/u
Rigidity for ions	0.054 - 1.44 Tm
Magnet ramping	1 T/s (4 T/s, 7 T/s)
Stand-alone operation	local ion beam (300 keV/u, q/A > 0.25)
Beam injection	multiturn and fast
Beam extraction	slow and fast



Beam time 2022:

- Beams from ESR
- Beam from local source
- Atomic physics and material investigations
- Extracted beams

Talk by Lorenzo Crescimbeni:

Extreme sensitive current measurement

The FAIR Facility

Future Facility for Anti-proton and Ion Research FAIR:

→ **Brilliant future as Brillance = Beam Current / Emittance**

SIS100:

Low charge states e.g. U^{28+}

⇒ factor 10 more ions

High energies e.g. for U^{92+}

Radioactive beam production:

100-fold better trans.& separation

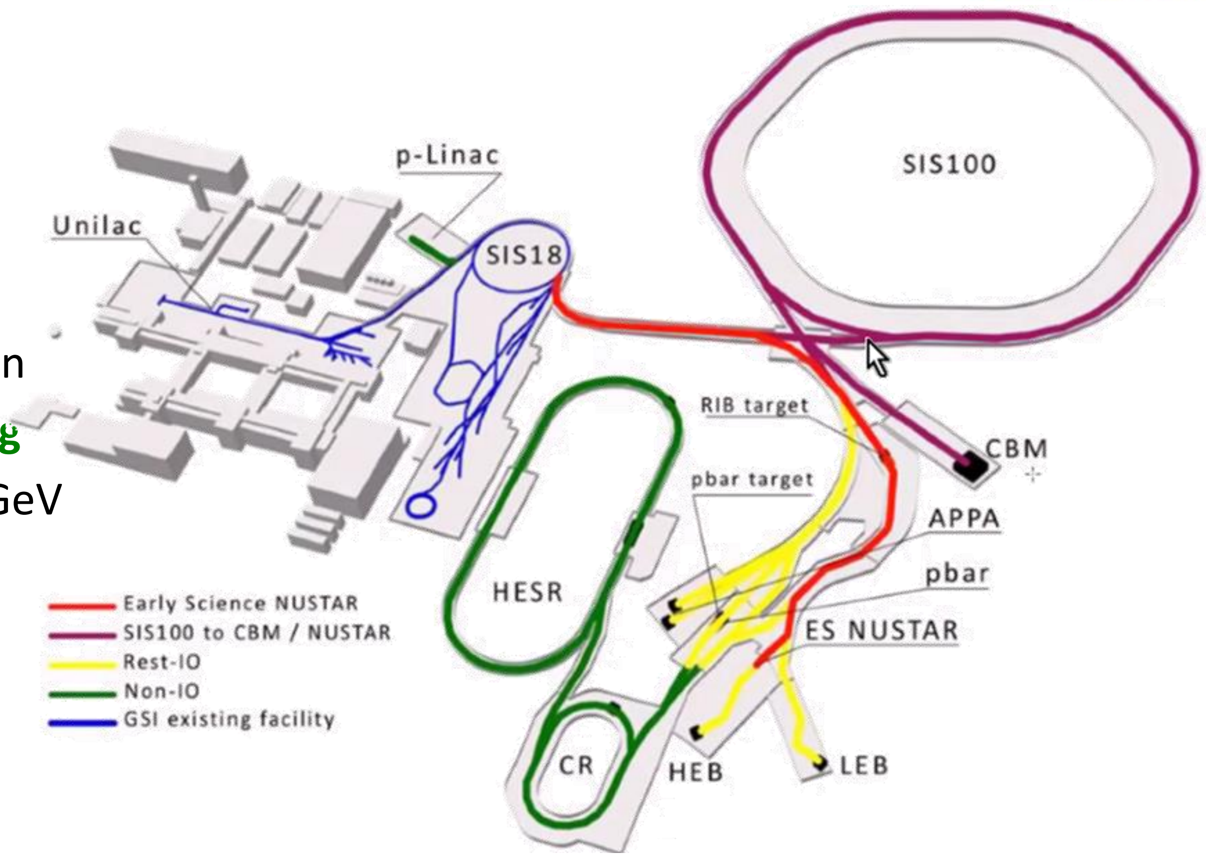
Anti-proton production & cooling

Novel investigation for up to 30 GeV

Fix targets:

Nuclear-, atomic-, plasma-,

bio-physics & & material science



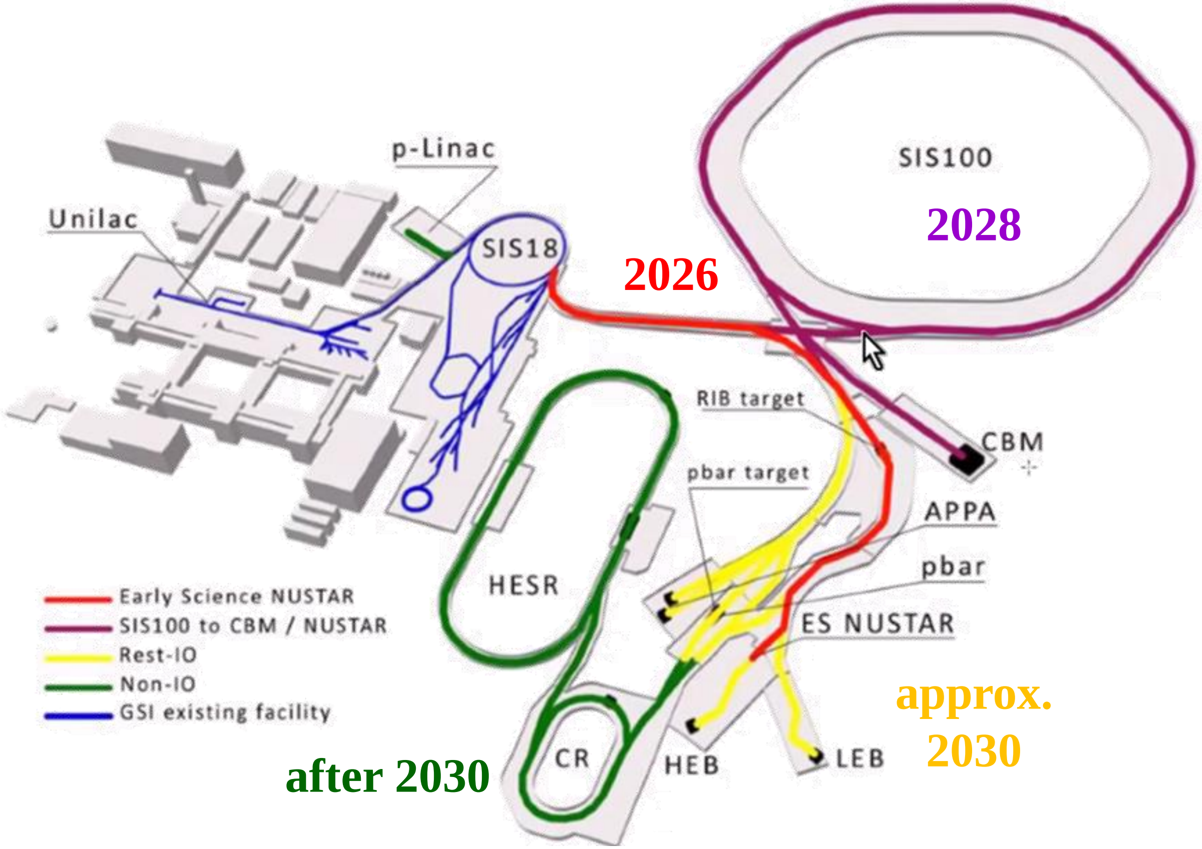
The FAIR Facility

Future Facility for Anti-proton and Ion Research FAIR:

→ **Brilliant future as Brillance = Beam Current / Emittance**

Problems due to sanctions against Russia (financial and in-kind)

⇒ Significant delays expected (under considerations….)



The FAIR Facility: Present Status

Conclusion:

- GSI: One of the most versatile accelerator facilities in the world
- Challenging operation with interesting accelerator physics and technologies
- FAIR as a ‘natural’ extension in progress

Thank you for your attention! Do you have questions?