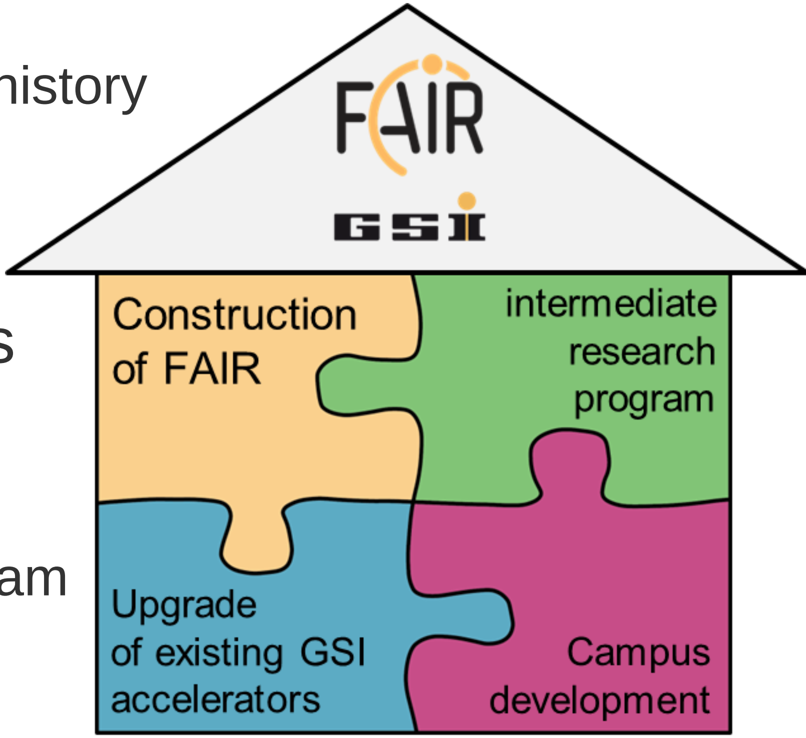
GSI Facility for FAIR Phase 0 and FAIR

M. Bai, GSI

on behalf of GSI Accelerator Operations Division

Outline

- Introduction
  - The GSI accelerator complex and brief history
  - FAIR and its science motivation
- Unique challenges and opportunities
  - Ongoing FAIR phase 0
  - Fit GSI for FAIR
  - Contribution of HFHF Accelerator Program
- Summary



Construction of FAIR

intermediate research program

Upgrade of existing GSI accelerators

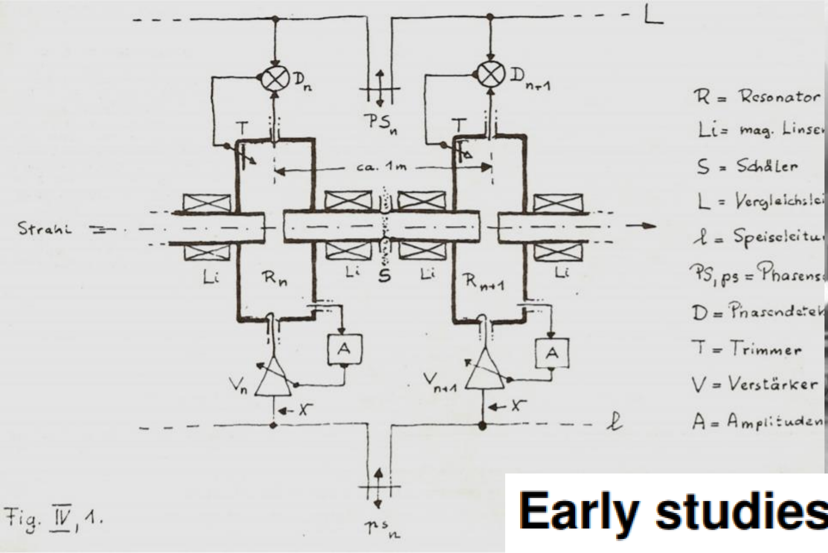
Campus development

Where do you find us?

Brief History

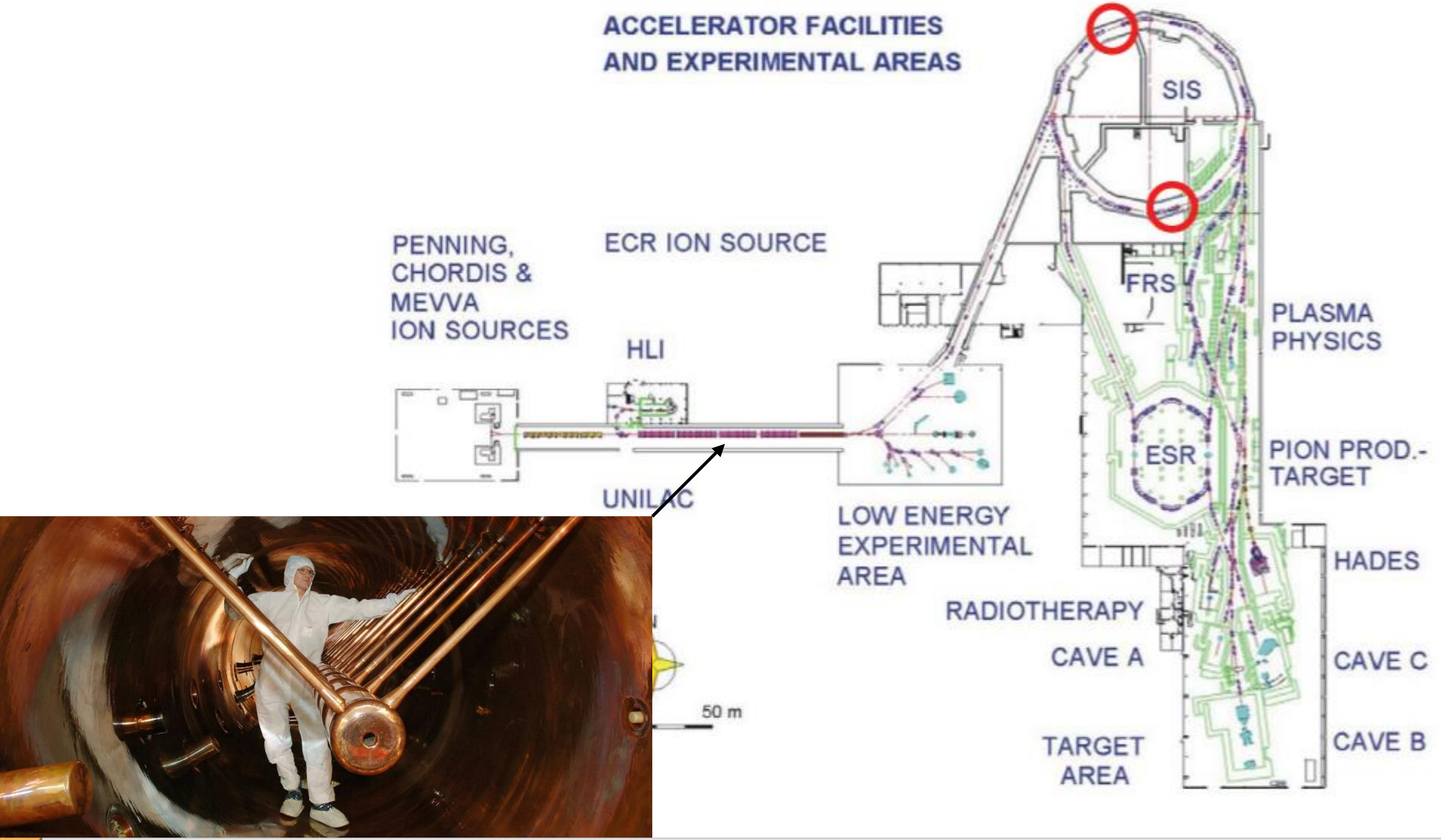
- “A Laboratory for Everyone” founded on Dec. 17, 1969
- **Founding director**: Prof. Dr. Ch. Schmelzer
- **Science motivation**: Nuclear shell model extrapolation suggested the existence of a stability island around Z = 120
- **Proposal**: a UNIversal Linear Accelerator to accelerate ions of all elements up to uranium to energies of about 10MeV/u
- UNILAC construction started 1971, First uranium beam 1976

N. Angert, The Story of GSI, https://indico.gsi.de/event/6978/material/slides/0.pdf

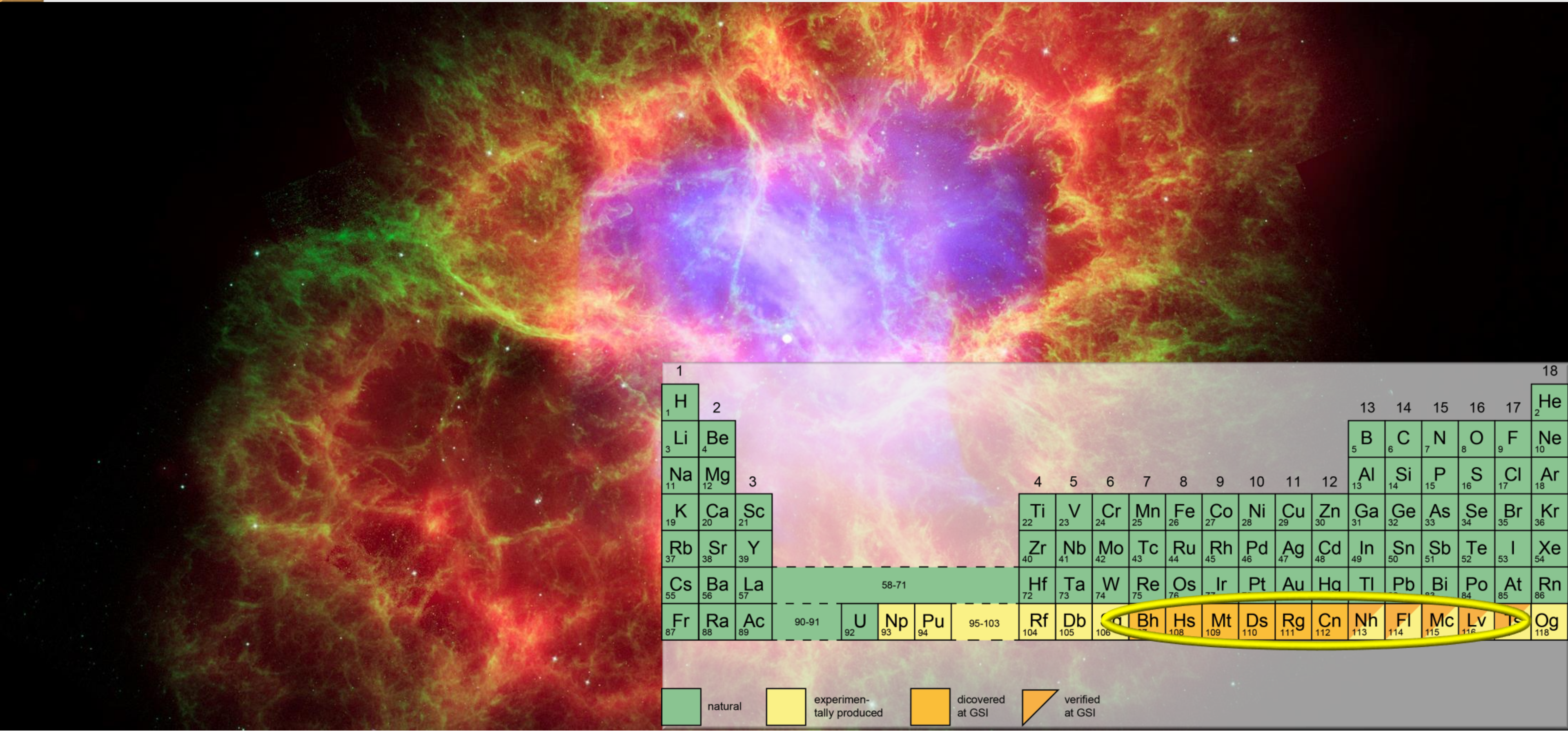


Early studies in Heidelberg

GSI facility

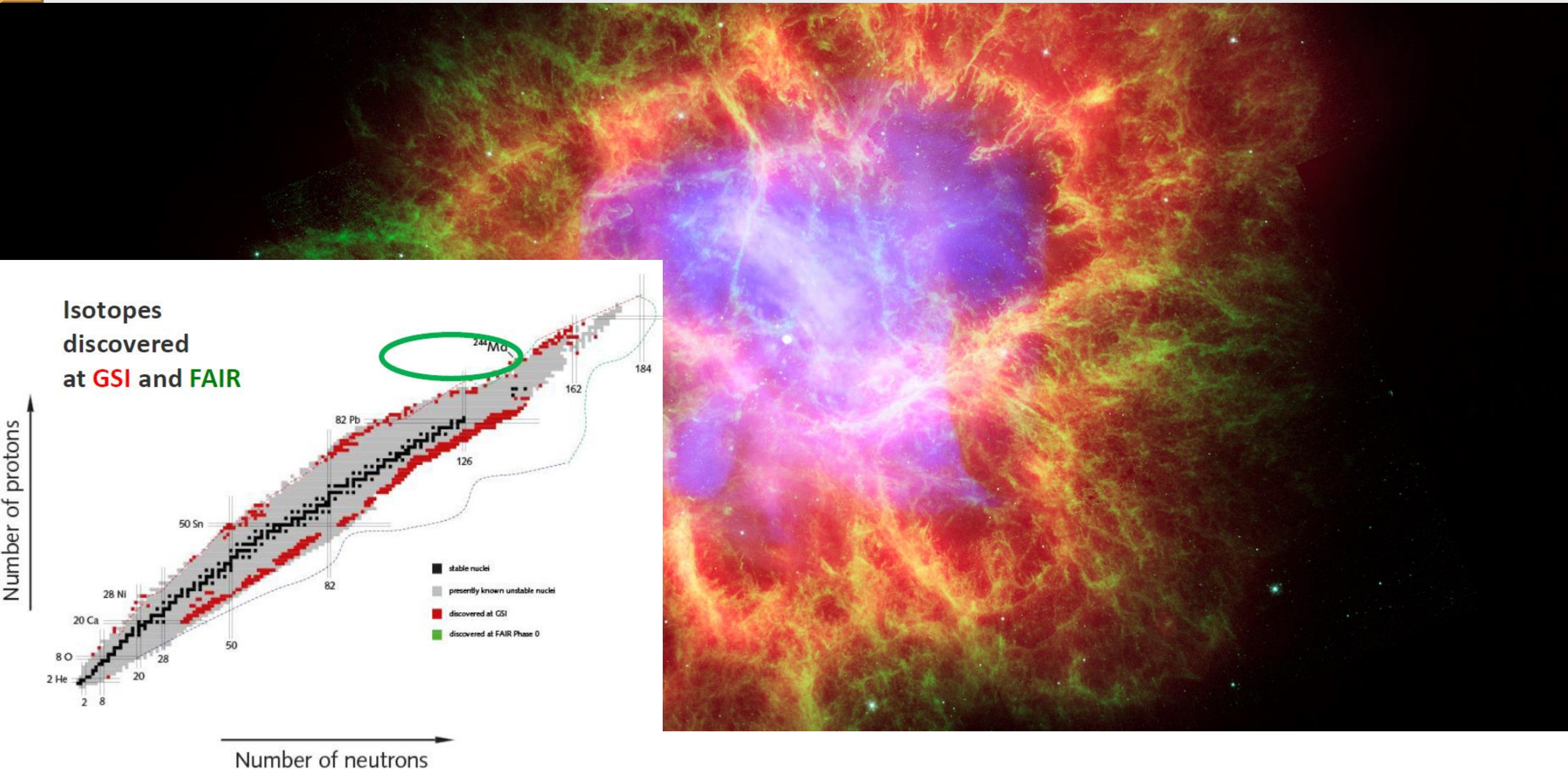


Major GSI Discoveries



- New chemical elements: **Bohrium, Hassium, Meitnerium, Darmstadtium, Roentgenium, Copernicium**

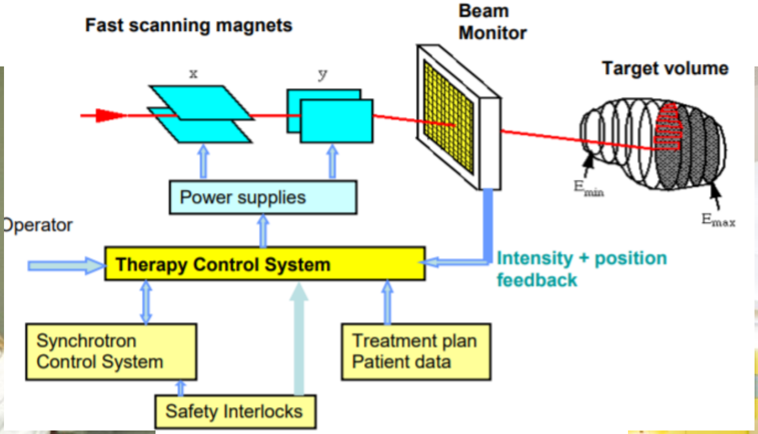
Major GSI Discoveries

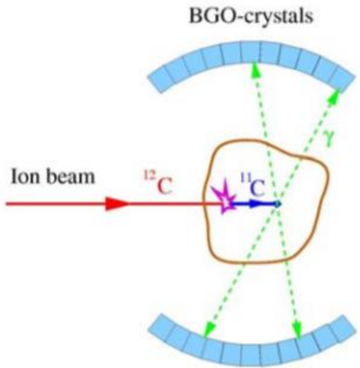


- Hundreds of new nuclear isotopes

Major GSI Discoveries

- Innovation in hadron cancer therapy
- 440 patients treated on campus before transfer to specialized clinics
  - **raster scanning:** pencil beam to paint a slice of the tumour
  - **In-beam PET**
  - etc…



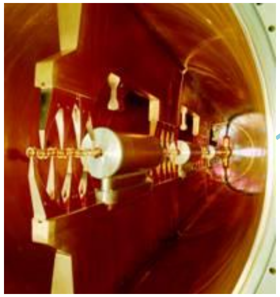


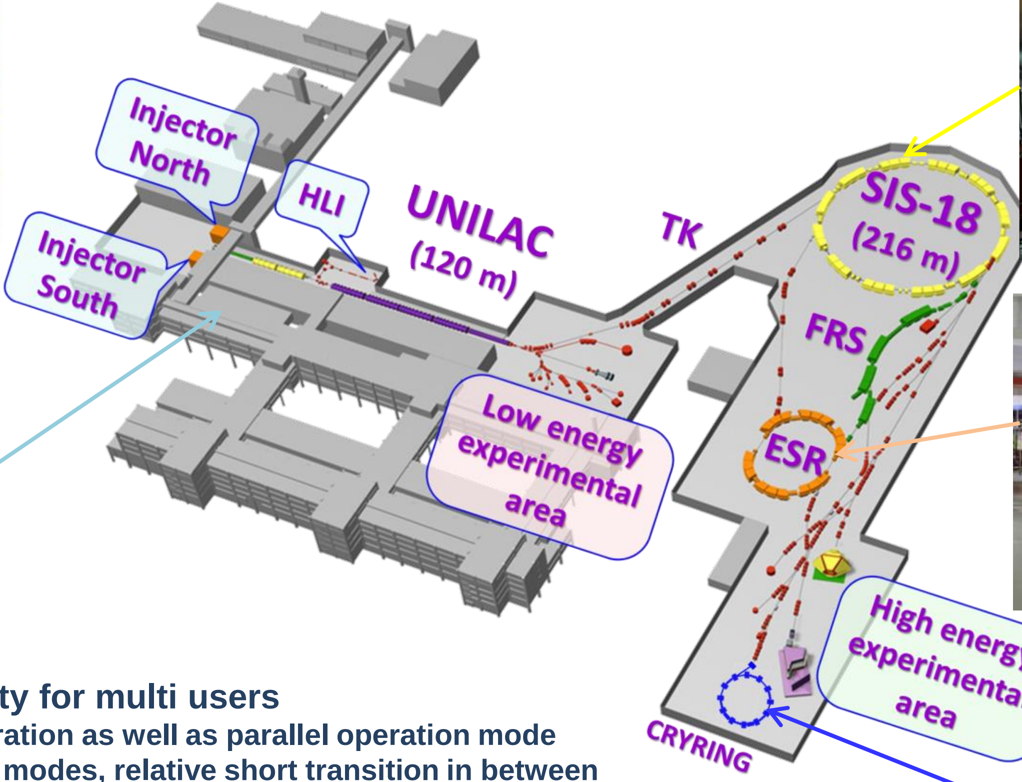
D. Schardt et al, Tumor Therapy with Heavy Ions at GSI Darmstadt

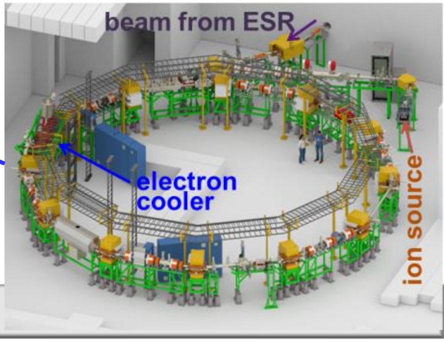
GSI Accelerator Complex Today

- One of the 18 Helmholtz research centers dedicated to fundamental research in understanding the matter and universe using energetic ion beams.

Ion sources



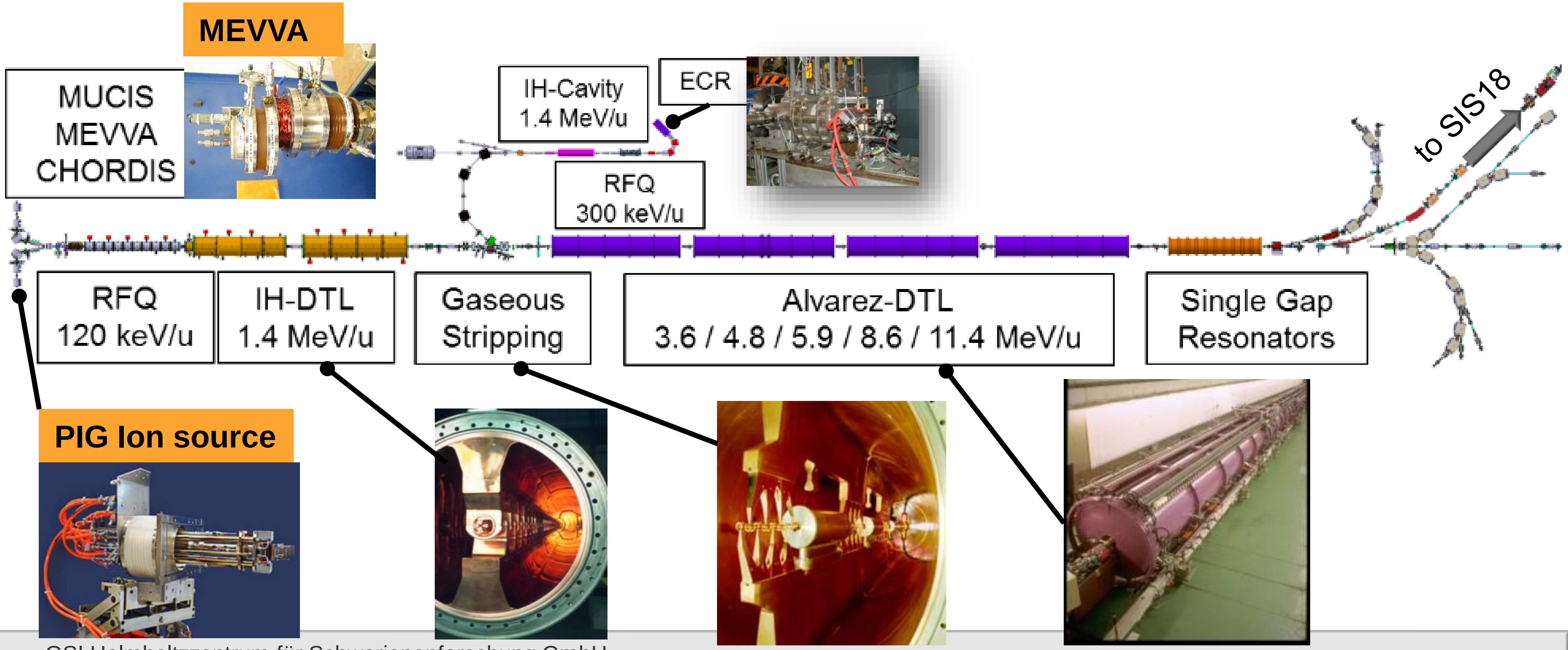




- Unique hadron facility for multi users
  - both dedicated operation as well as parallel operation mode
  - variety of operation modes, relative short transition in between
- Ultra high vacuum technique to reach highest intensity uranium beam!
- Comprehensive beam cooling to enable precision experiments at storage rings

UNILAC Overview

- High current ion sources and ECRIS for high charge state
  - ions: 14N, 16O, 18O, 50Ti, 40Ar, 48Ca, 107Ag, 124Xe, 208Pb, 238U
  - p+ and 12C from molecular beams (isobutane)
- High intensity and bright uranium beams!



MEVVA

MUCIS
MEVVA
CHORDIS

IH-Cavity
1.4 MeV/u

ECR

RFQ
300 keV/u

to SIS18

RFQ
120 keV/u

IH-DTL
1.4 MeV/u

Gaseous
Stripping

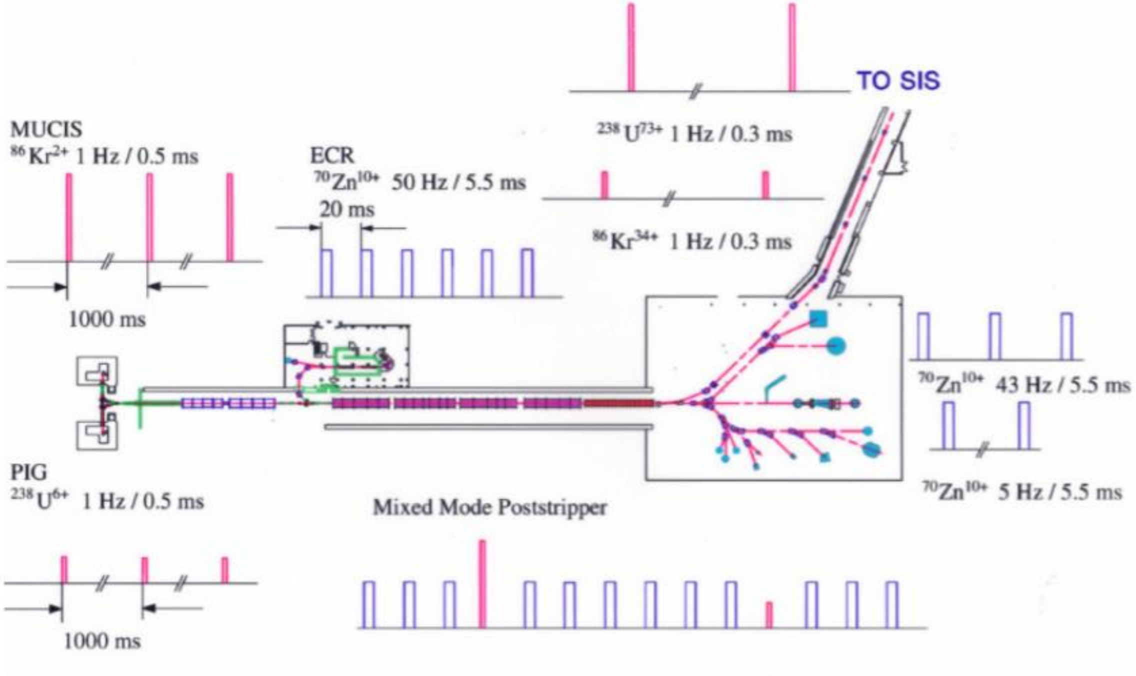
Alvarez-DTL
3.6 / 4.8 / 5.9 / 8.6 / 11.4 MeV/u

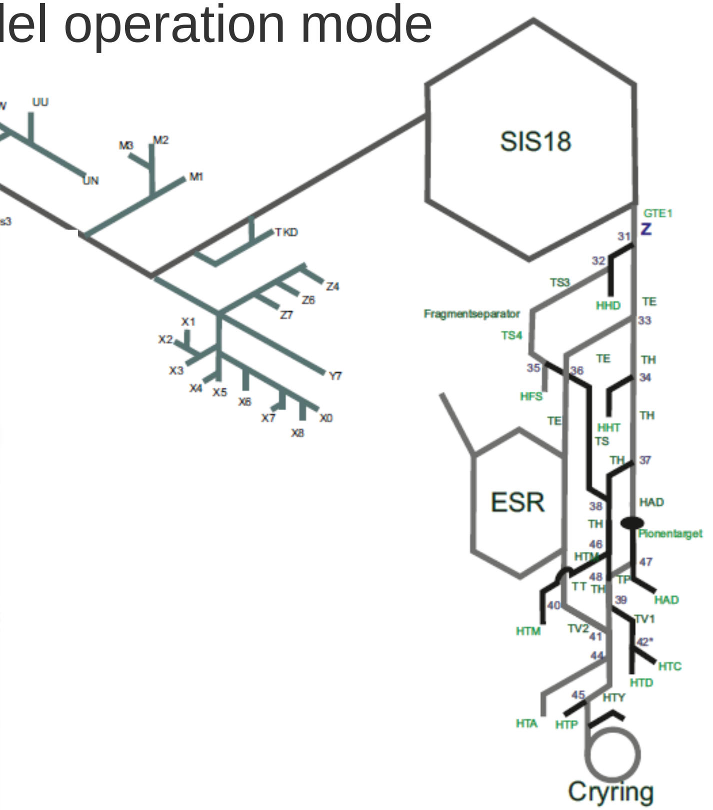
Single Gap
Resonators

PIG Ion source

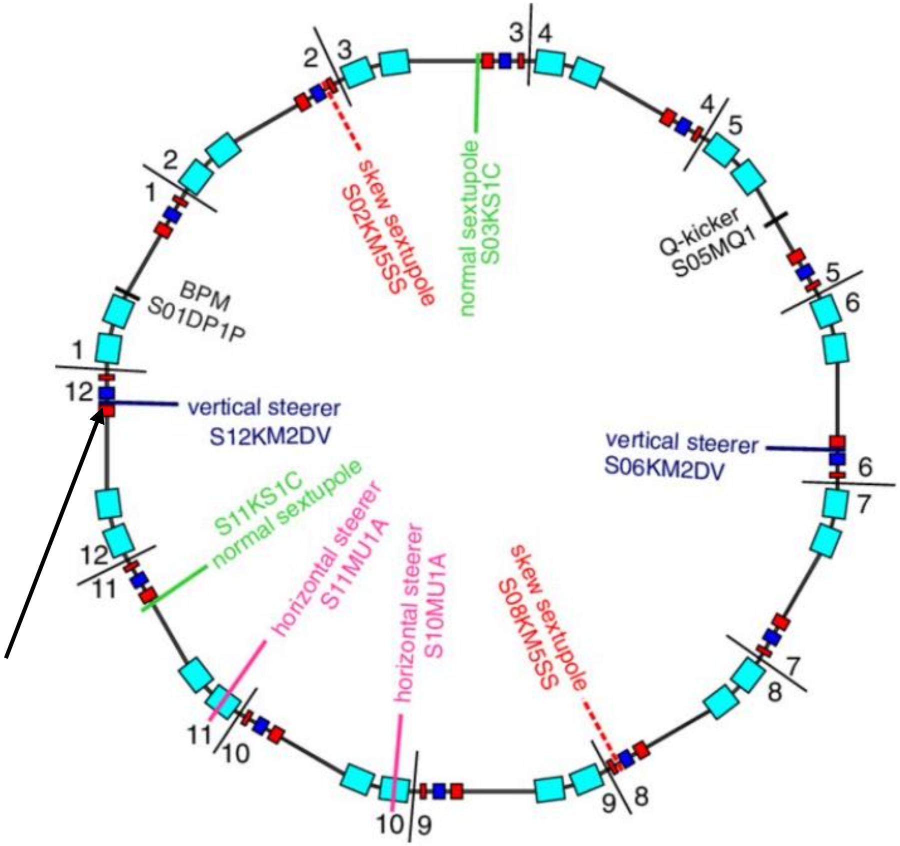
GSI Facilities uniqueness

- versatileness and flexibilities
  - unique hadron facility for multi users
  - both dedicated operation as well as parallel operation mode
    - variety of operation modes
    - relative short transition in between





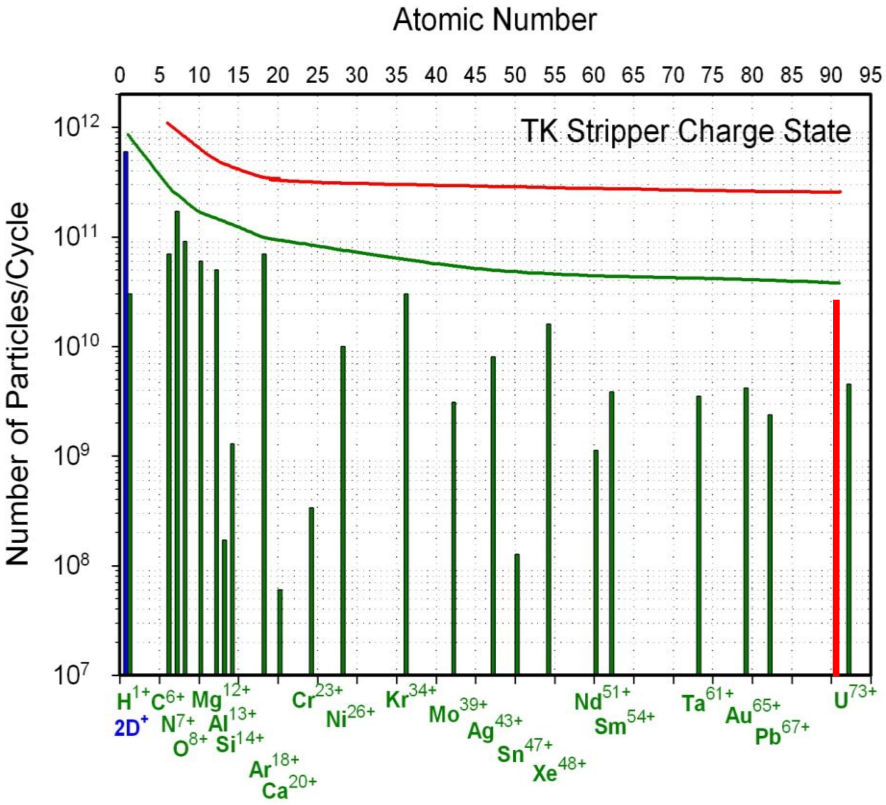
SIS18: the heavy ion driver

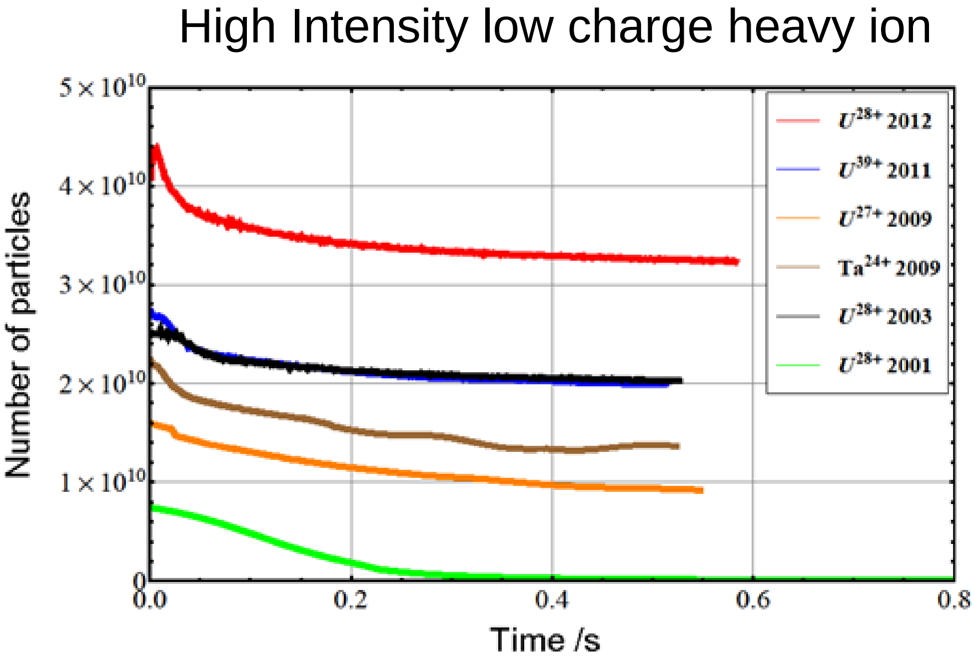


- 216 m synchrotron with maximum bending strength of 18 Tm
- Cycling rate 1 Hz
- Consists of 24 dipoles and 12 triplets
- Ramp rate 4 T/s to 10 T/s
- Flexible triplet and doublet optics
- Multi-turn injection
- Equipped with electron cooler for multi-multi-turn injection
- UHV ring for accelerating low to medium charged heavy ions
- Slow extraction to various fixed target experiments
- Fast extraction for FRS as well as feeding in ESR

SIS18: the heavy ion driver

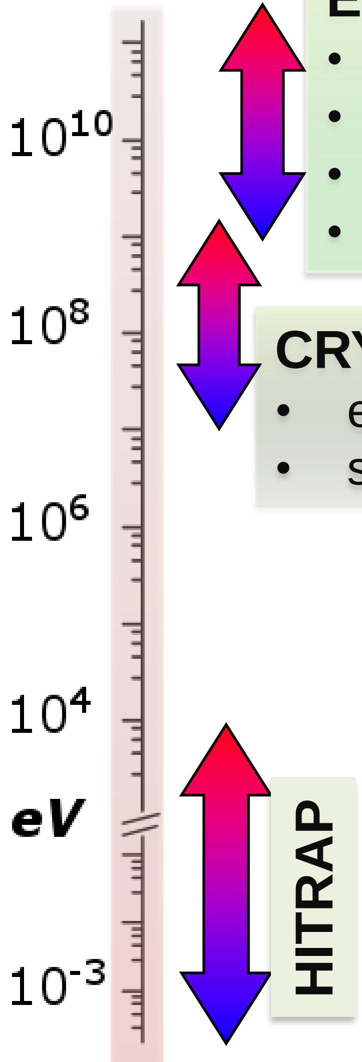
- For most highly charged ions, beam intensity limitation is dominated by space charge
- For low charge heavy ions, dynamic vacuum due to beam loss is the leading intensity limitation





Courtesey of P. Spiller

Storage, deceleration and trapping of ion beams

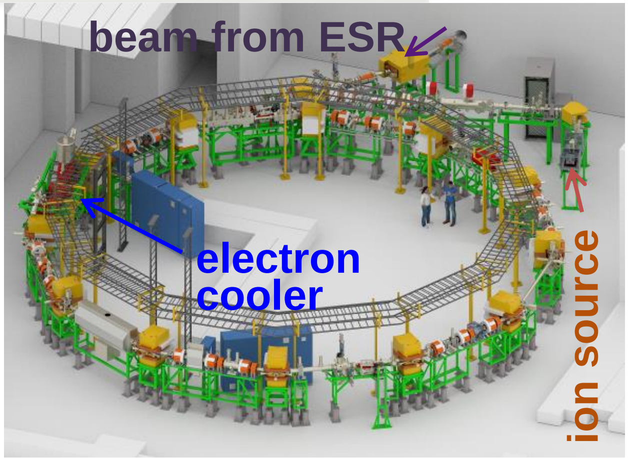


Experimental Storage Ring

- stable ions and RIBs
- multi-charge state
- beam accumulation
- fast/slow extraction

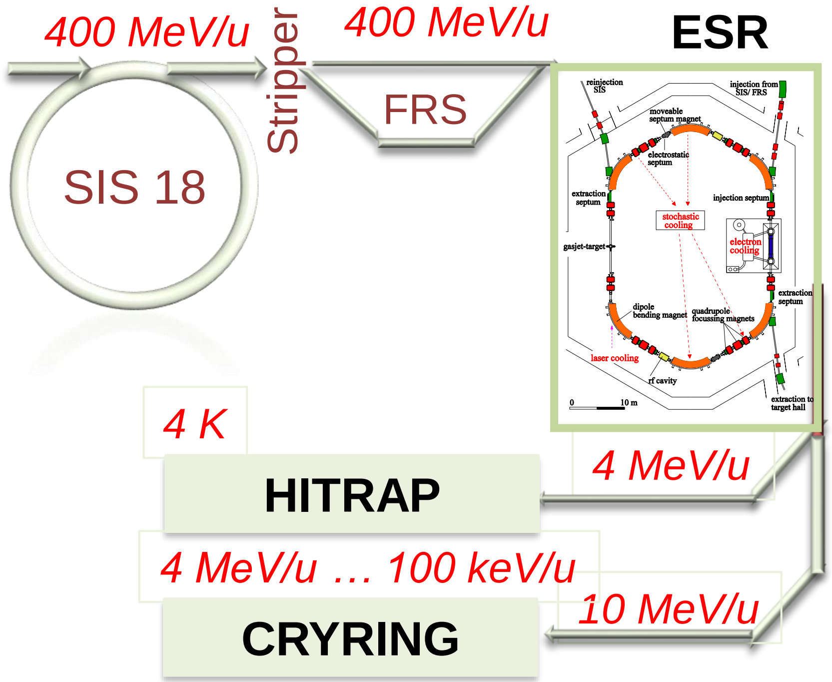
CRYRING

- electron cooling
- stand-alone operation



ESR R&D Highlights

- Comprehensive beam cooling
- Isochronous mode
- high precision Schottky spectrometry for single particle detection



Comprehensive beam cooling

- Stochastic cooling and electron cooling to facilitate the internal target experiment at the storage rings
  - compensate energy loss due to internal target
  - reduce the momentum spread, as well as transverse emittance

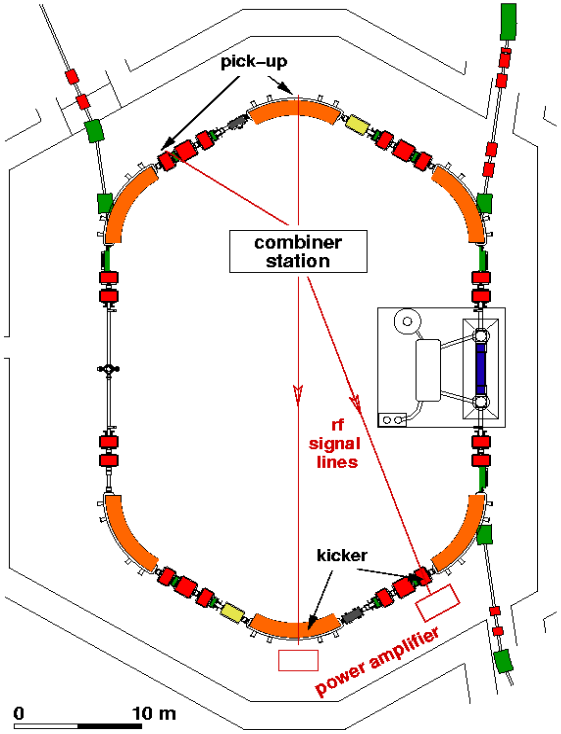
- R&D in developing laser cooling for heavy ions

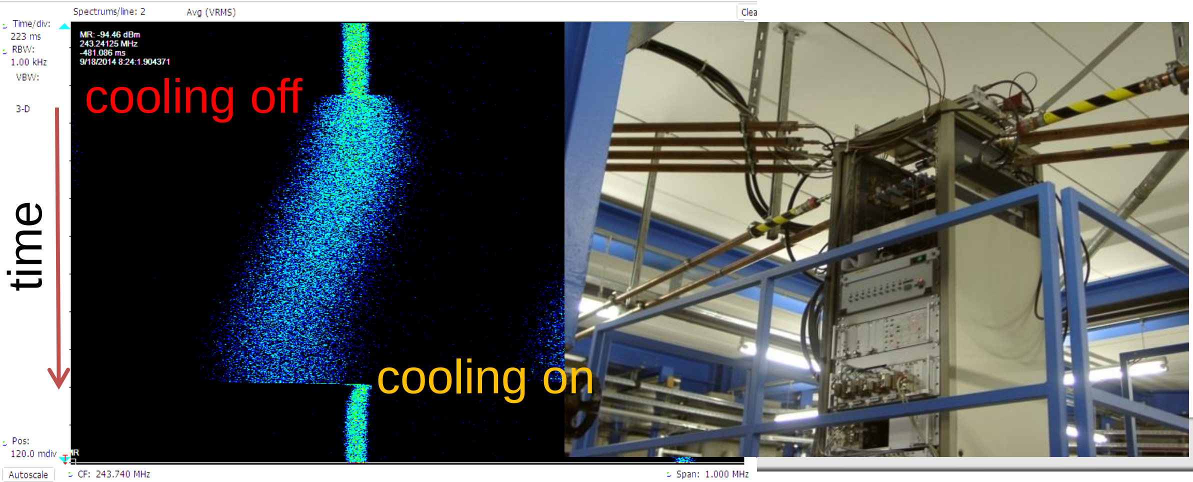
Stochastic cooling at ESR

energy 400 (-550) MeV/u
freq range 0.9-1.7 GHz)

$\delta p/p = \pm 0.35\ \% \rightarrow \delta p/p = \pm 0.01\ \%$

$\varepsilon = 10 \times 10^{-6}\ \mathrm{m} \rightarrow \varepsilon = 2 \times 10^{-6}\ \mathrm{m}$

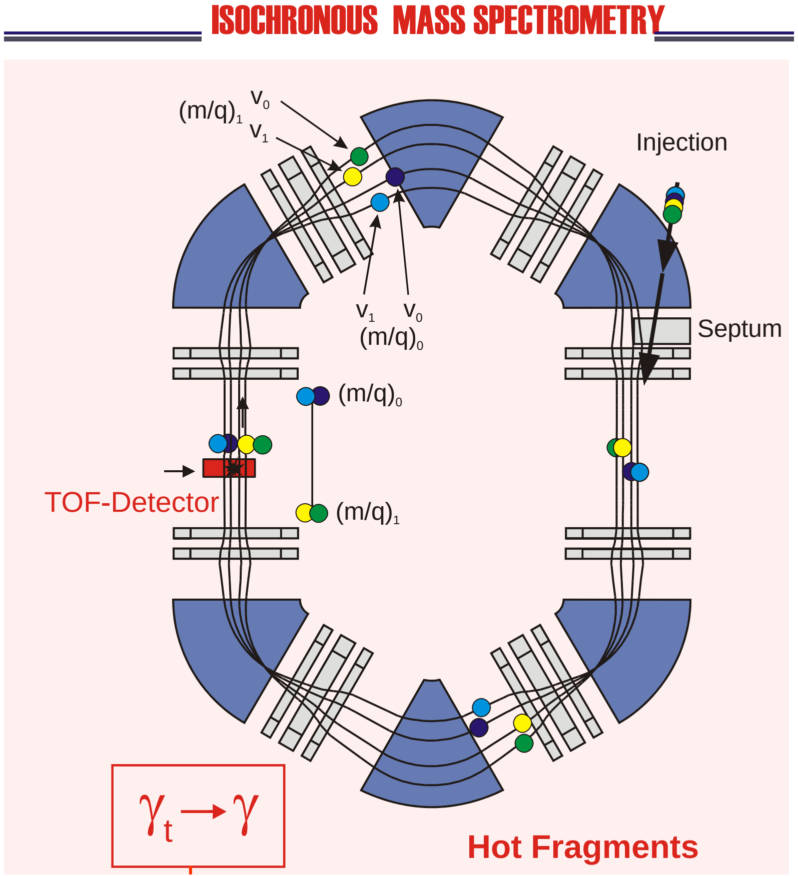


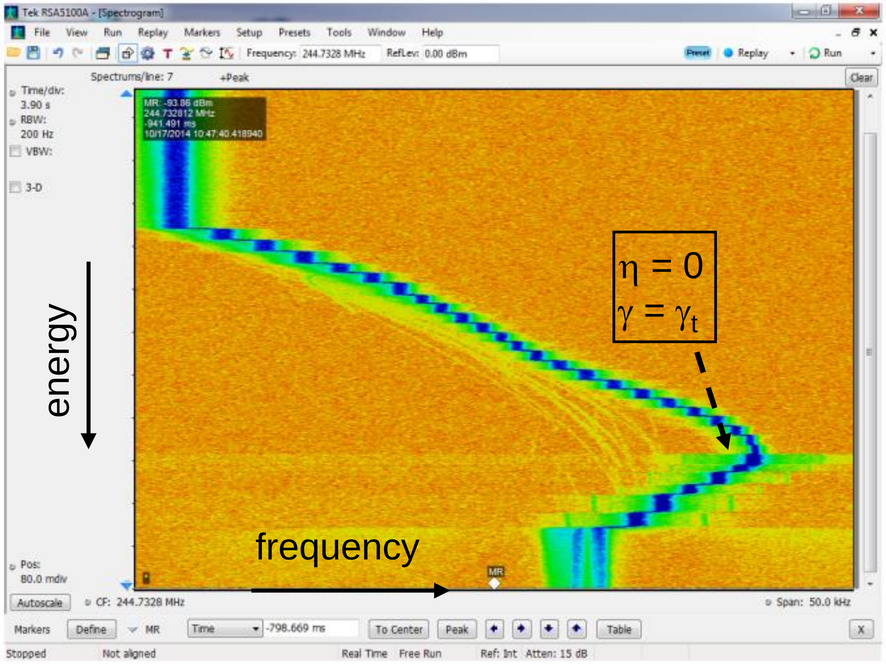

Spectrums/line: 2
Avg (VRMS)
Time/div: 223 ms
RBW: 1.00 kHz
VBW:
3-D
MR: -94.46 dBm
243.24125 MHz
-481.086 ms
9/18/2014 8:24:1.904371
Pos: 120.0 mdiv
CF: 243.740 MHz
Span: 1.000 MHz

High precision mass spectrometer

- Isochronous mode

$$\frac{\Delta f}{f} = -\frac{\Delta T}{T} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} - \cancel{\left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}} \quad (= 0 \text{ ,if } \gamma = \gamma_t)$$

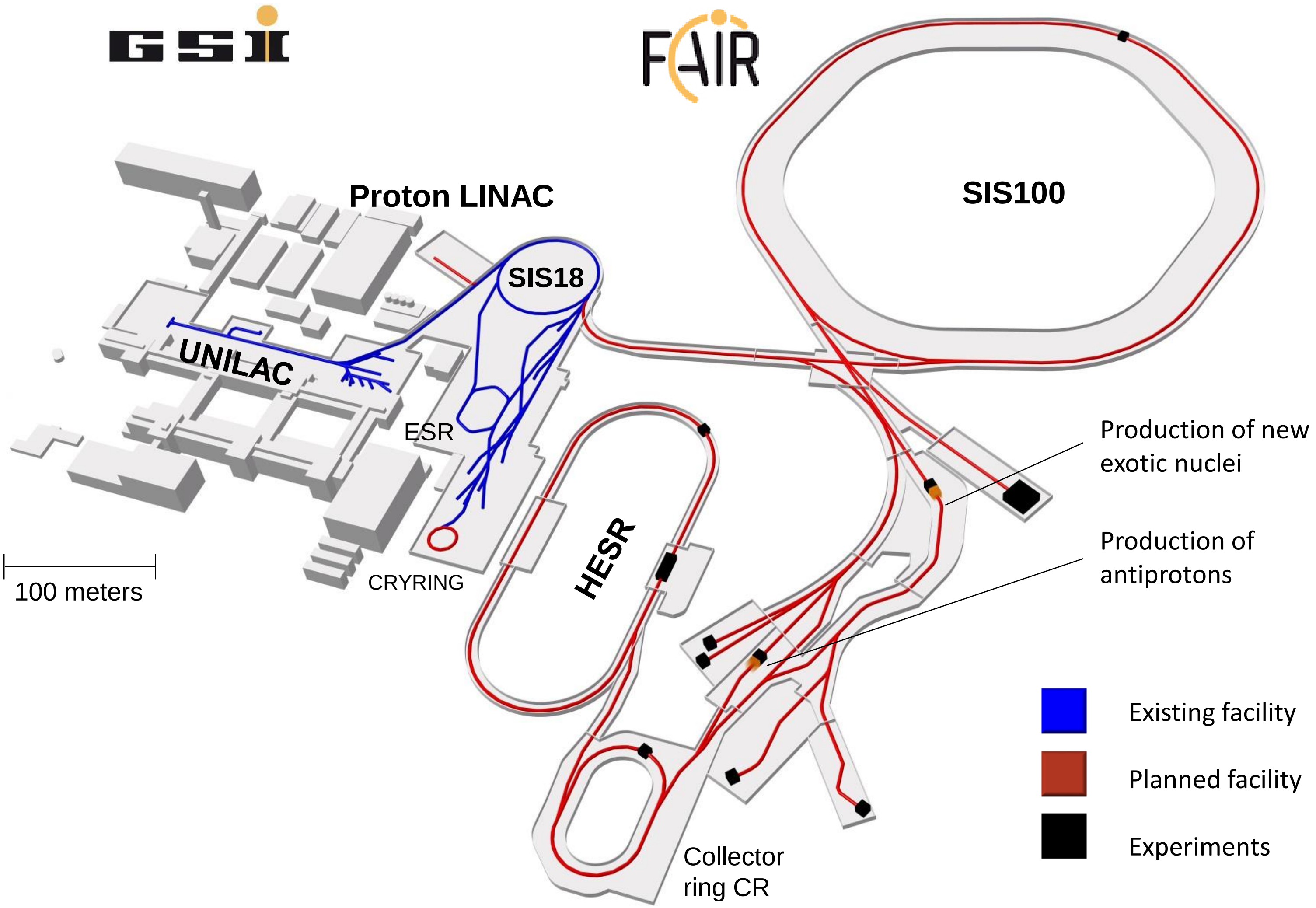




Frequency: 244.7328 MHz
RefLev: 0.00 dBm
Spectrums/line: 7 +Peak
Time/div: 3.90 s
RBW: 200 Hz
☐ VBW:
☐ 3-D
MR: -93.86 dBm
244.732812 MHz
-941.491 ms
10/17/2014 10:47:40.418940
Pos: 80.0 mdiv
CF: 244.7328 MHz
Span: 50.0 kHz
Time -798.669 ms
Stopped Not aligned Real Time Free Run Ref: Int Atten: 15 dB

Experimentally realized at ESR

From GSI to FAIR



Production of new exotic nuclei

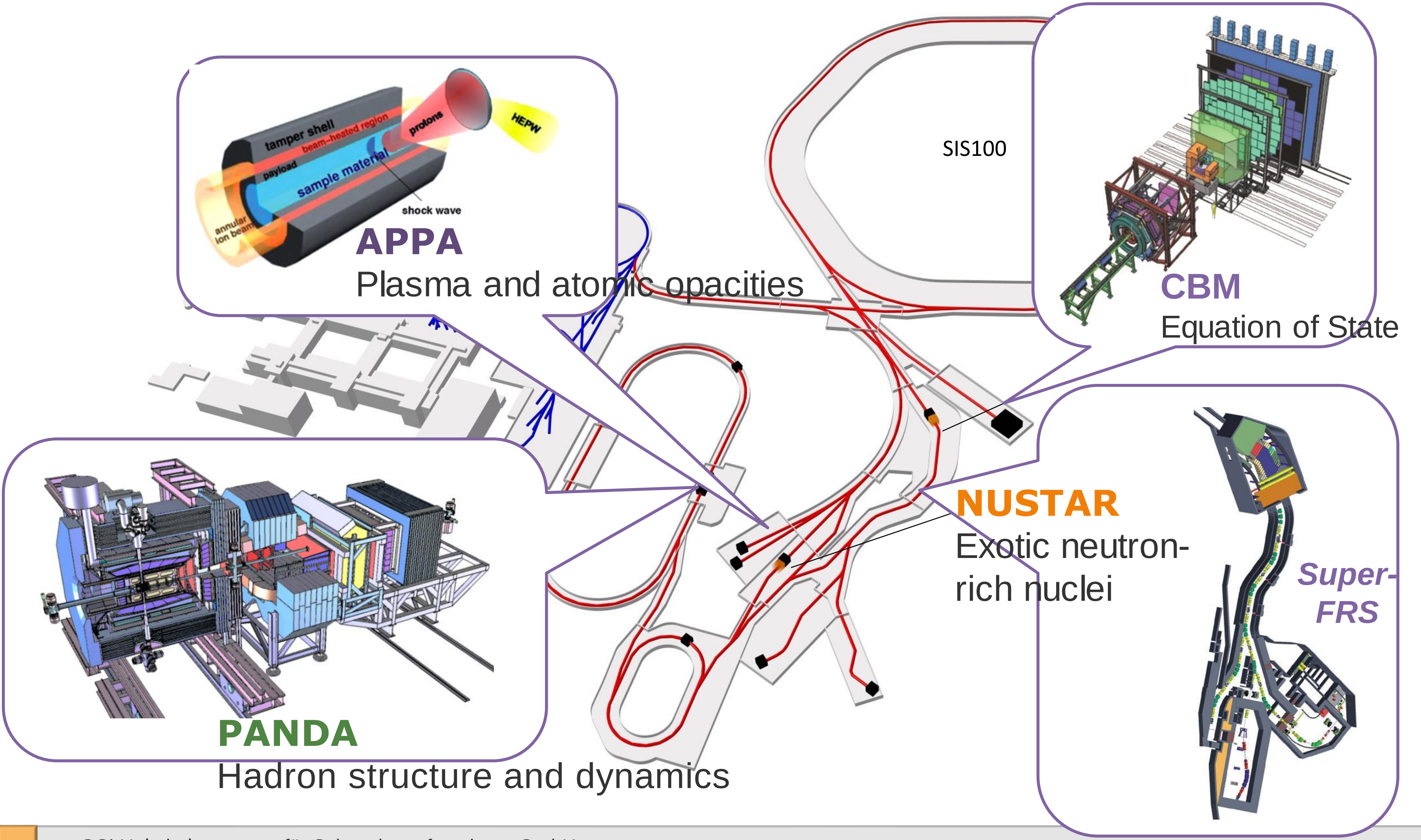
Production of antiprotons

🟦 Existing facility

🟥 Planned facility

⬛ Experiments

FAIR – universe in the laboratory



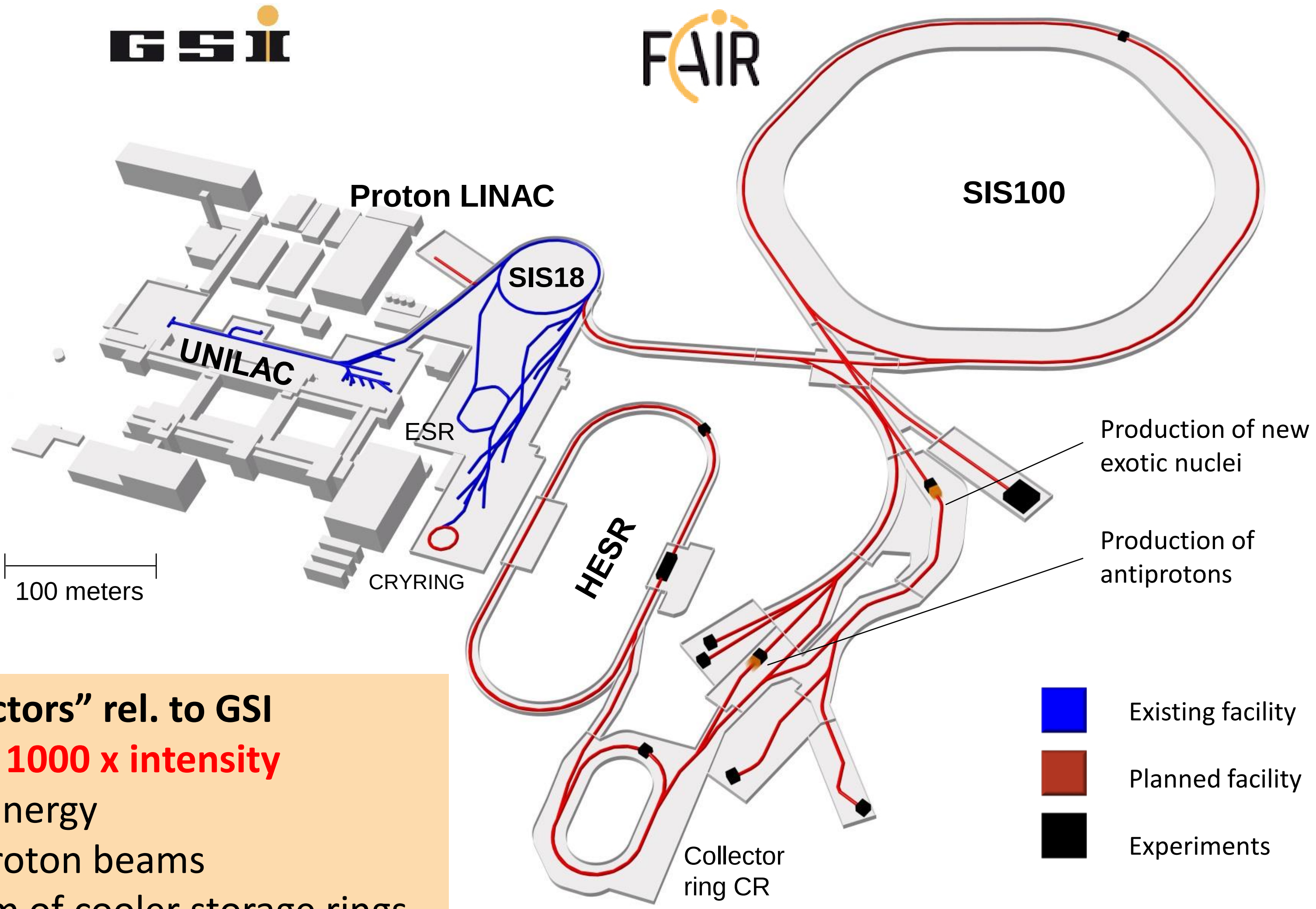
APPA
Plasma and atomic opacities

CBM
Equation of State

NUSTAR
Exotic neutron-rich nuclei

PANDA
Hadron structure and dynamics

Challenges in Accelerator Science & Technology

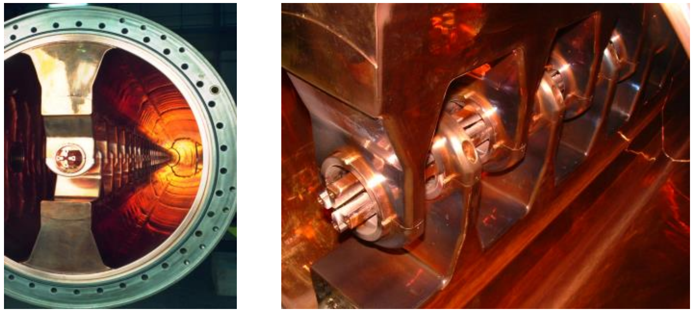


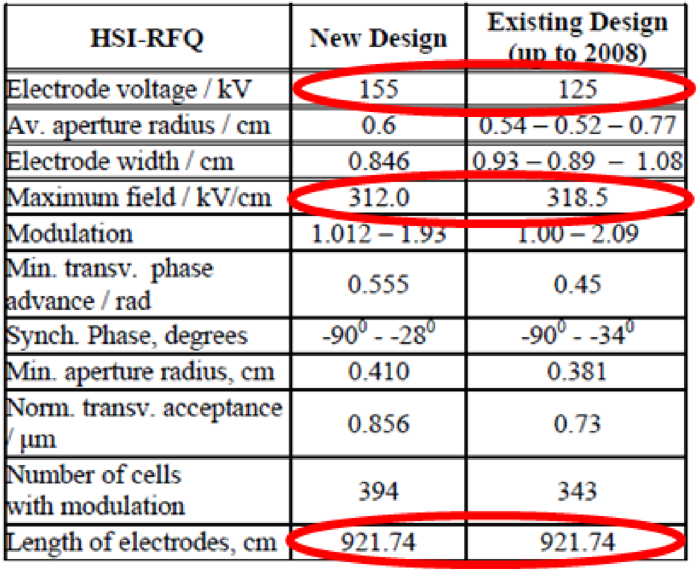
“Gain factors” rel. to GSI

- **100 – 1000 x intensity**
- 10 x energy
- antiproton beams
- system of cooler storage rings

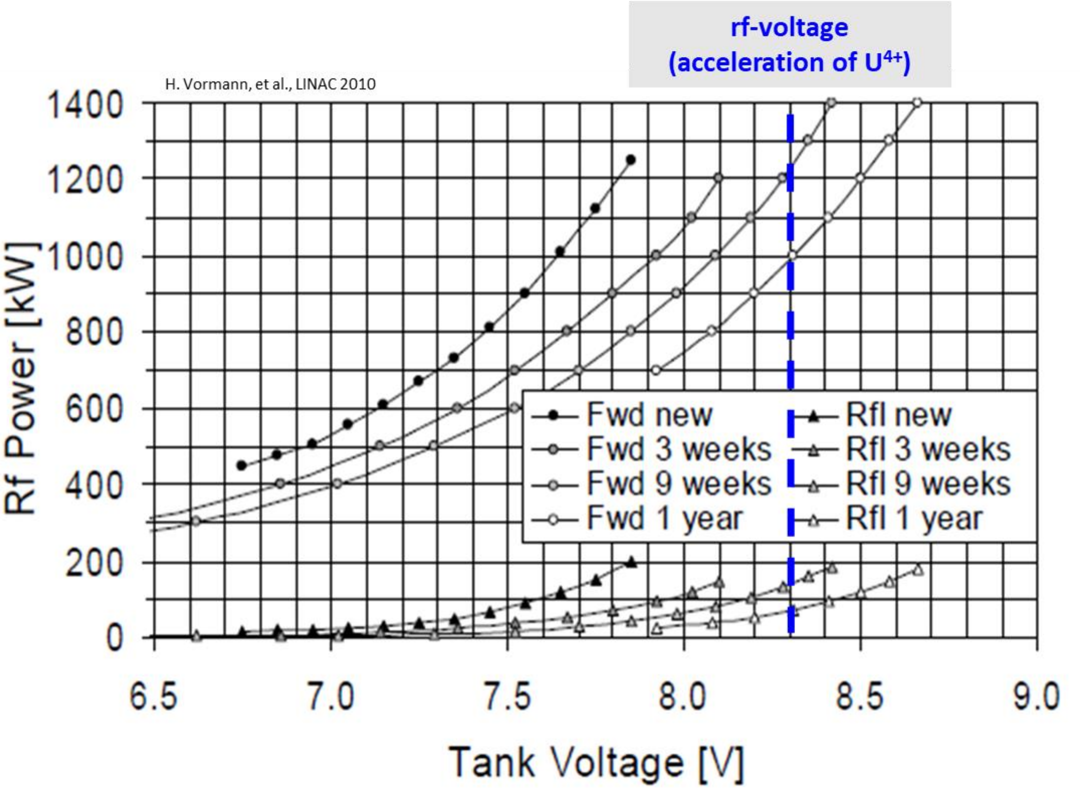
Unique challenges: High intensity RFQ (HSI RFQ)

- 4-rod design
- Very high peak field is required for accelerating U4+





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

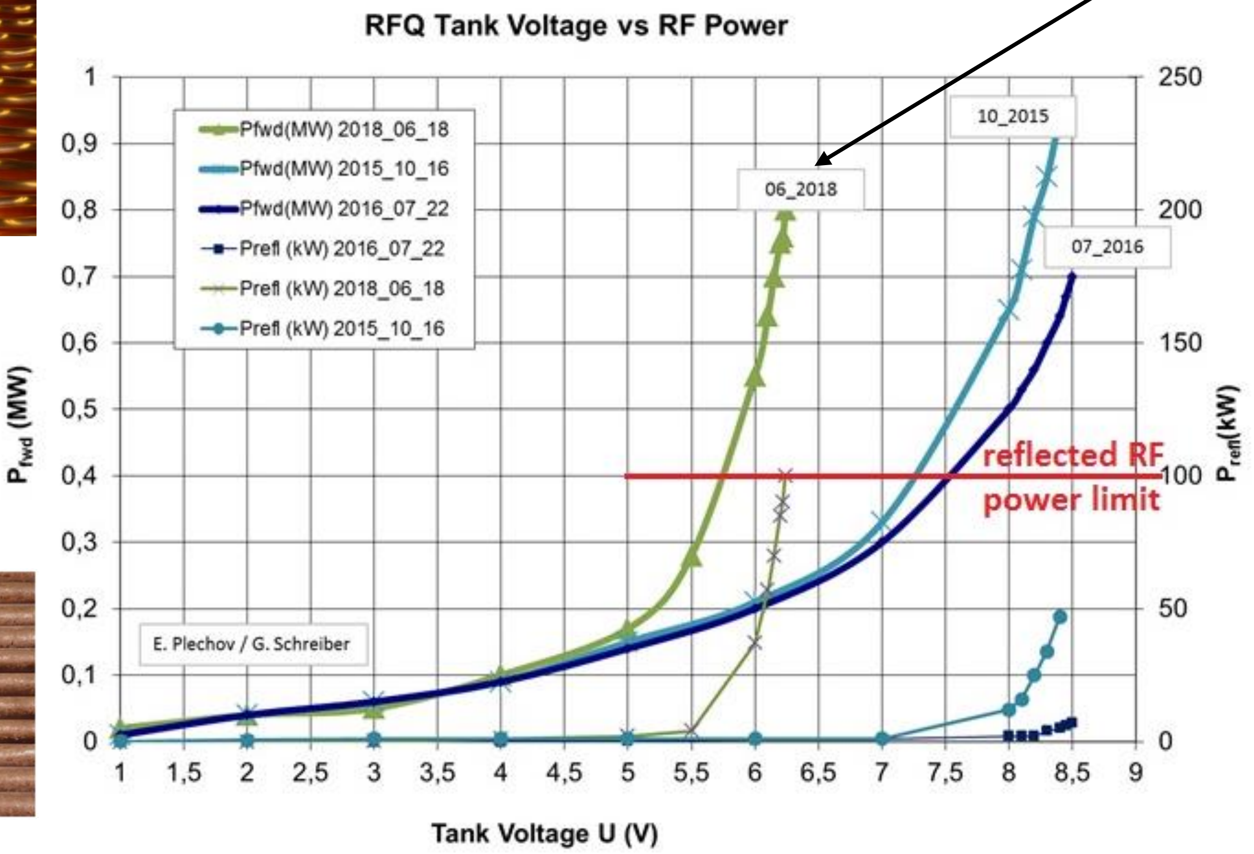


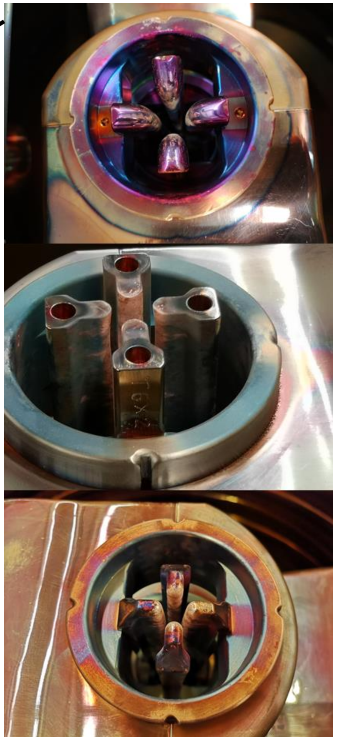
rf-voltage (acceleration of U^{4+})

H. Vormann, et al., LINAC 2010

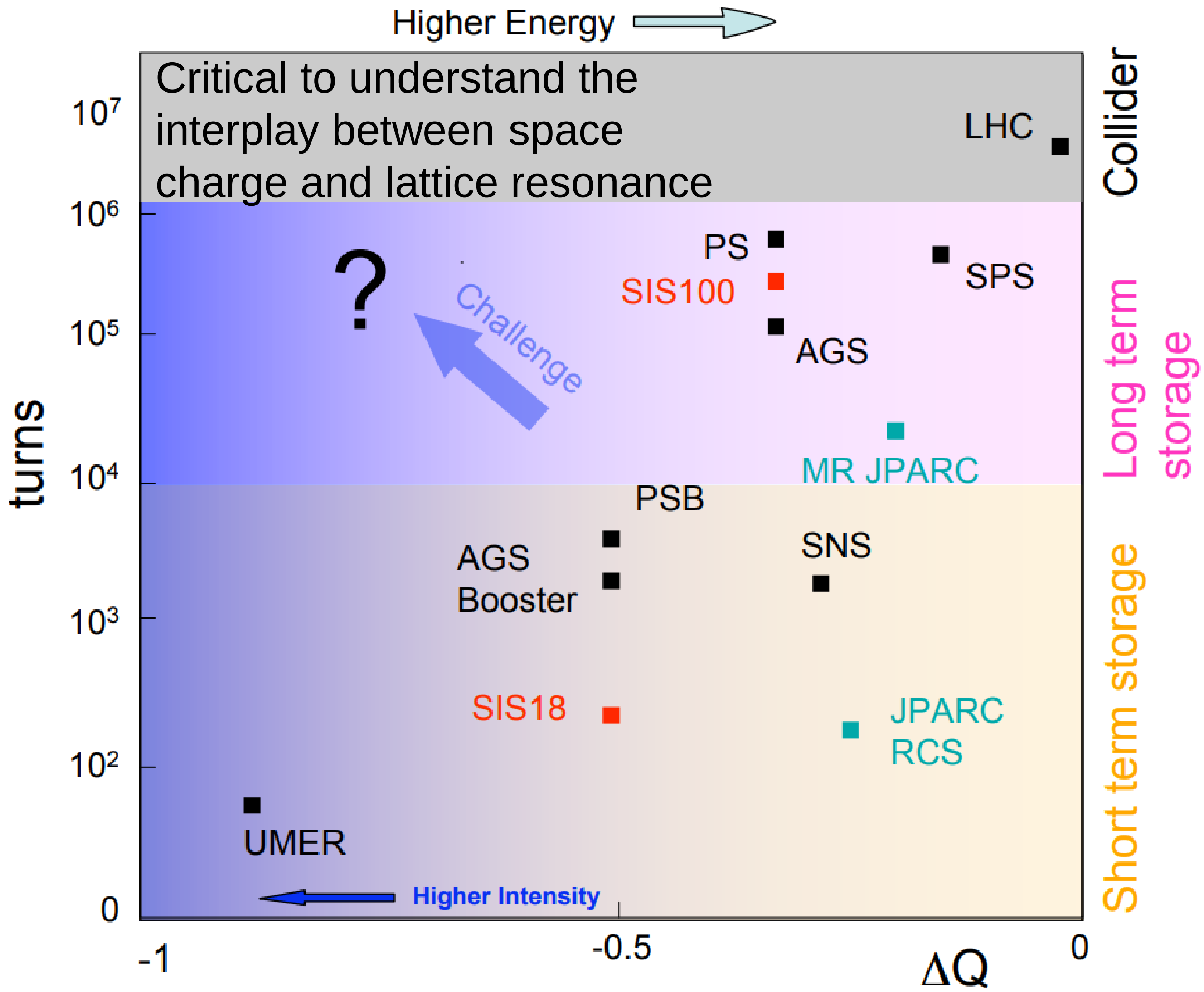
Unique challenges: High intensity RFQ (HSI RFQ)

- Reach the require high field reliably





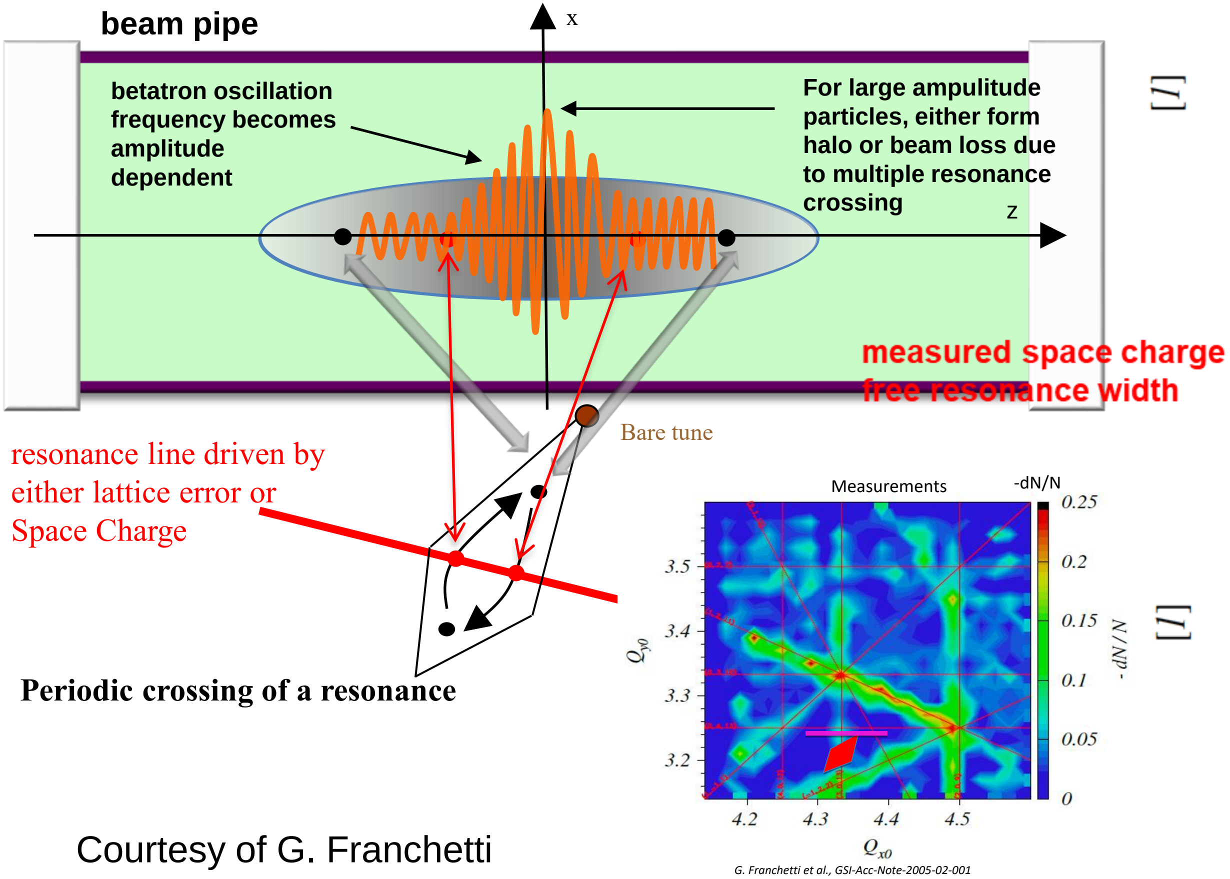
Unique challenges: high intensity heavy ion beams



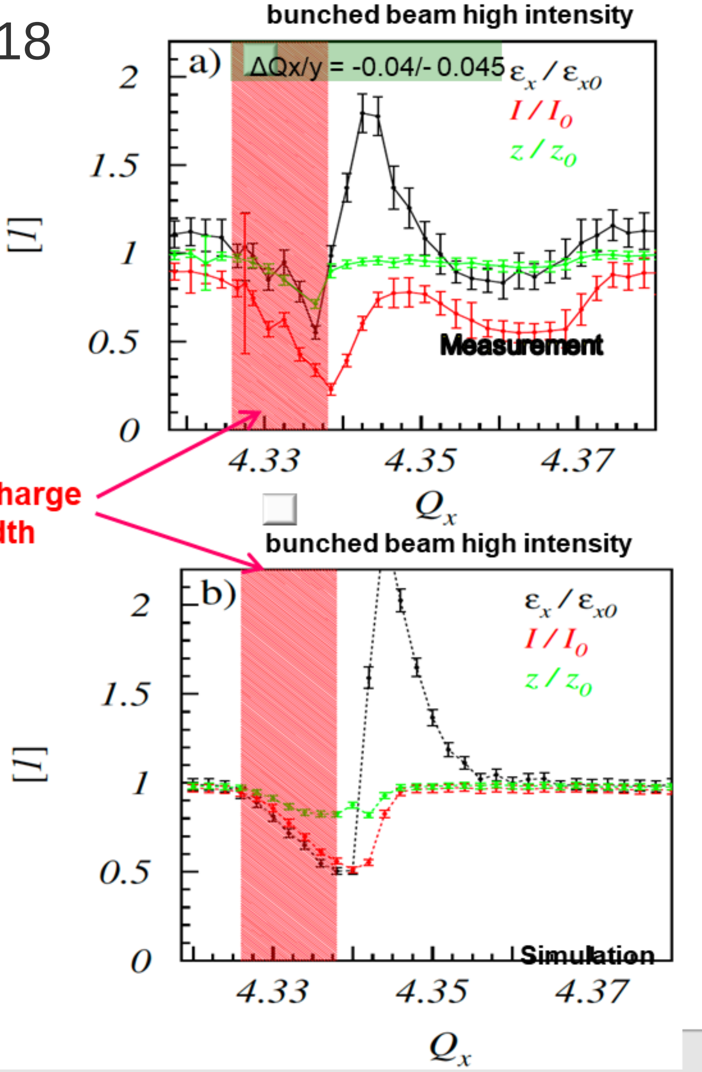
Courtesey of G. Franchetti

Space charge dominated beam dynamics

- coupling of space charge with lattice resonances
  - complete experimental confirmation at SIS18



G. Franchetti et al., GSI-Acc-Note-2005-02-001

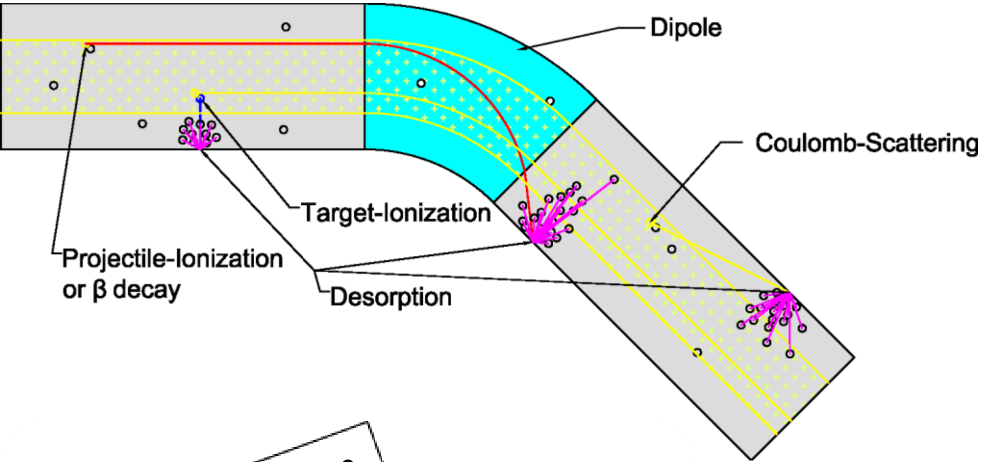


Courtesy of G. Franchetti

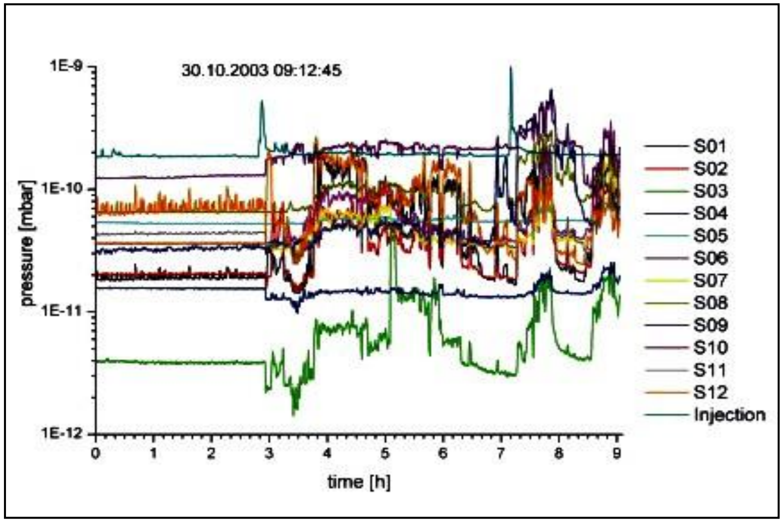
Unique challenges: low charge state heavy ions

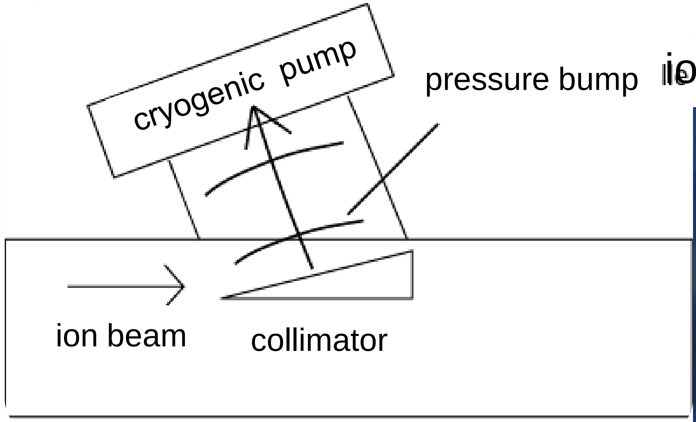
- mitigating the dynamic vacuum instability

beam induced desorption

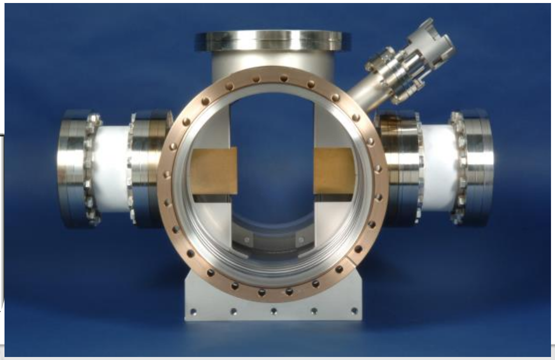


SIS18 vacuum during high intensity operation





ion catcher



Recipe for Mitigating Dynamics Vacuum Instability

- Short cycle times, short sequences and short injection plateau

  Fast ramping (SIS18: 10 T/s, SIS100: 4 T/s)

  (power connection, power converters, Rf system,

  fast ramped (superconducting) magnets)

- XHV and huge pumping power

  (NEG-coating, cryo pumping - local and distributed)

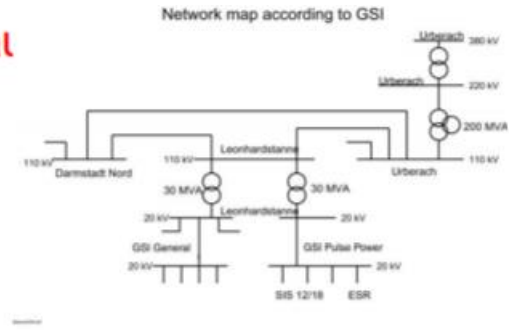
- Localizing beam loss and controle/suppression of desorption gases

  (Ion catcher system with low desorption yield surfaces,

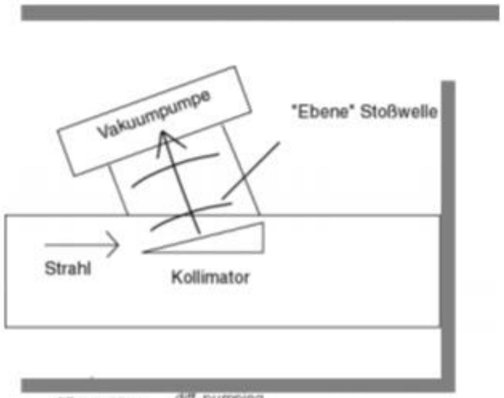
  Synchrotron optics and lattice design)

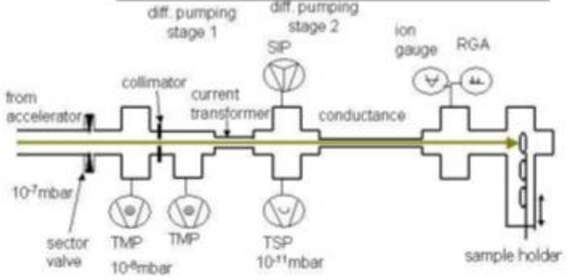
- Minimum „effective“ initial beam loss

  (TK halo collimation, low desorption yield surfaces)



Network map according to GSI





Courtesey of P. Spiller

Roadmap towards FAIR

Upgrade the UNILAC for high intensity operation

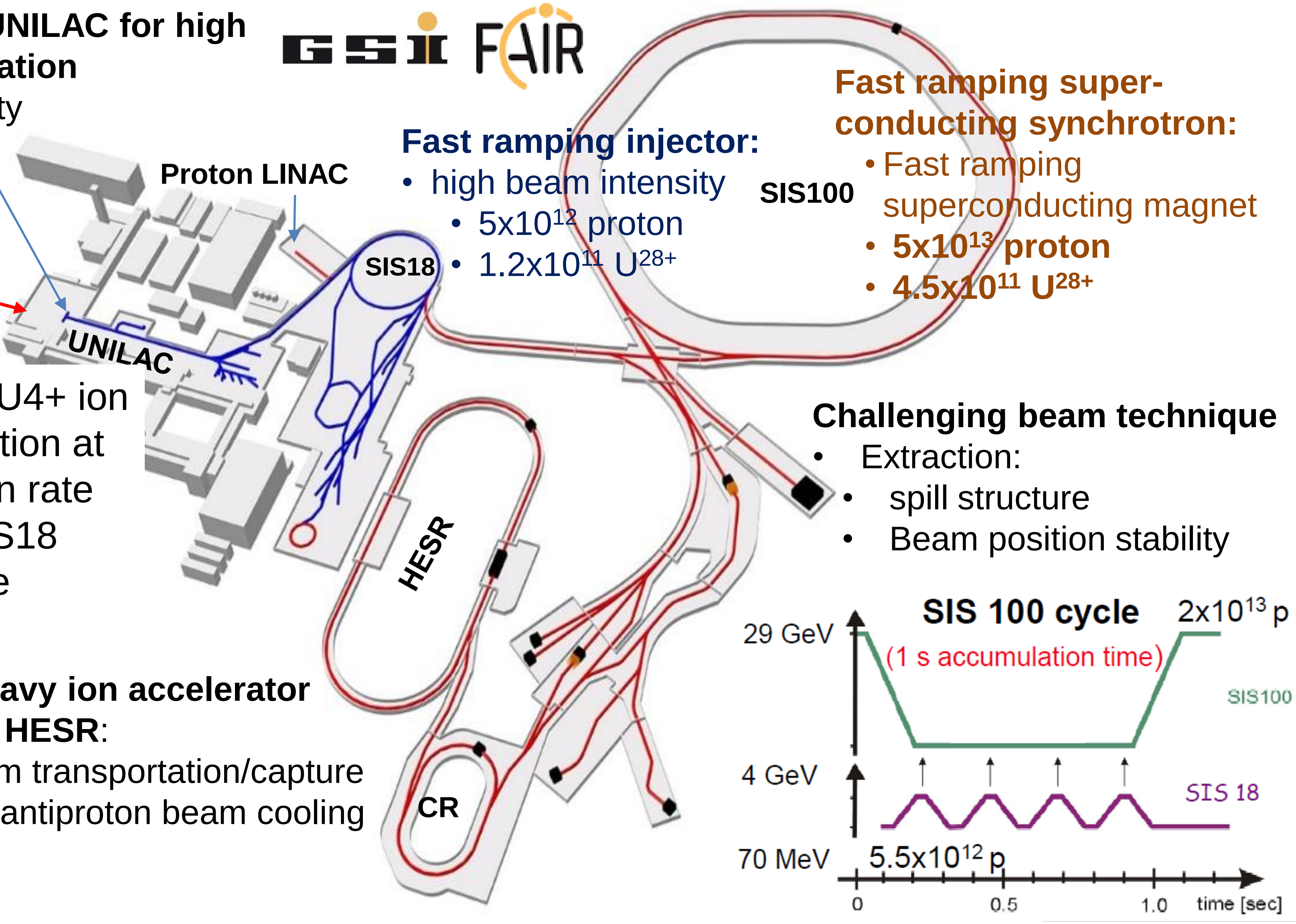
- beam intensity
- reliability

Ion sources

High current U4+ ion source operation at high repetition rate **2.7 Hz** for SIS18 booster mode

Antiproton/heavy ion accelerator chain CR and HESR:

- Efficient beam transportation/capture
- High energy antiproton beam cooling



Fast ramping injector:

- high beam intensity
  - 5x10^{12} proton
  - 1.2x10^{11} U^{28+}

Fast ramping super-conducting synchrotron:

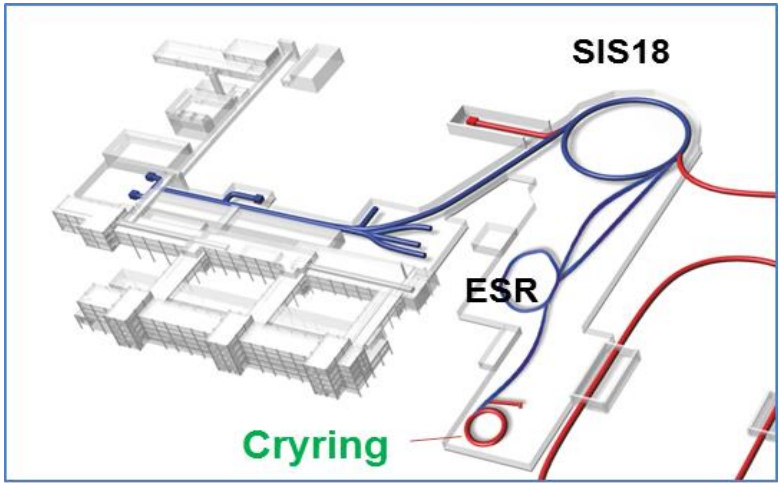
- Fast ramping superconducting magnet
- **5x10^{13} proton**
- **4.5x10^{11} U^{28+}**

Challenging beam technique

- Extraction:
  - spill structure
  - Beam position stability

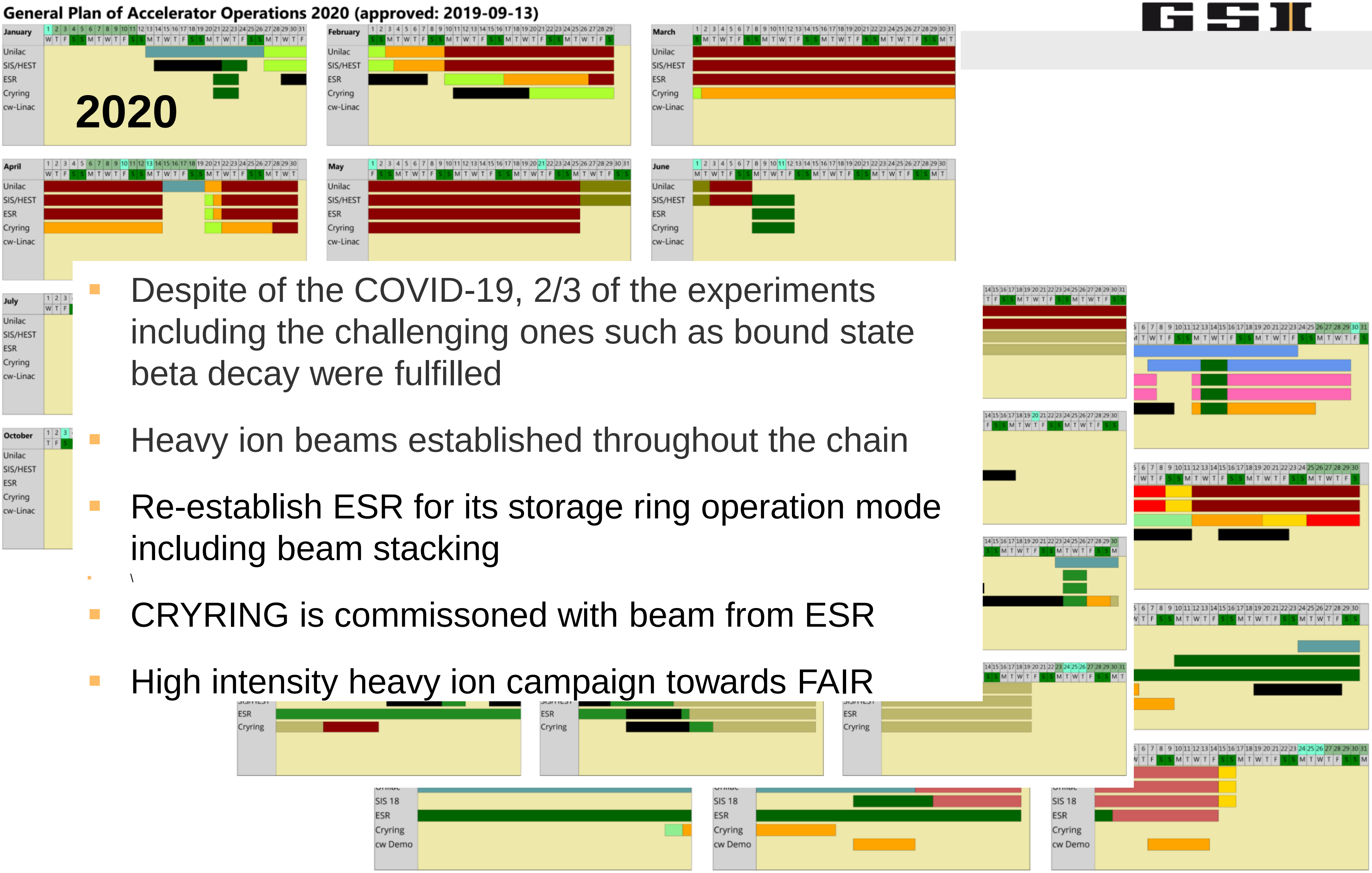
FAIR Phase-0
intermediate research program

- Objectives:
  - Forefront research by employing and testing new FAIR detectors
  - Exploiting upgraded GSI accelerator facilities incl. the newly installed CRYRING
  - Education of young scientists
  - Maintain and extend skills and expertise
  - Serve national and international user community



- requires careful techn. preparation:
  - full re-commissioning of the UNILAC/SIS18/ESR complex incl. new controls
  - gradual implementation of the intensity increase to avoid any damage and activation

Beamtime for FAIR Phase 0



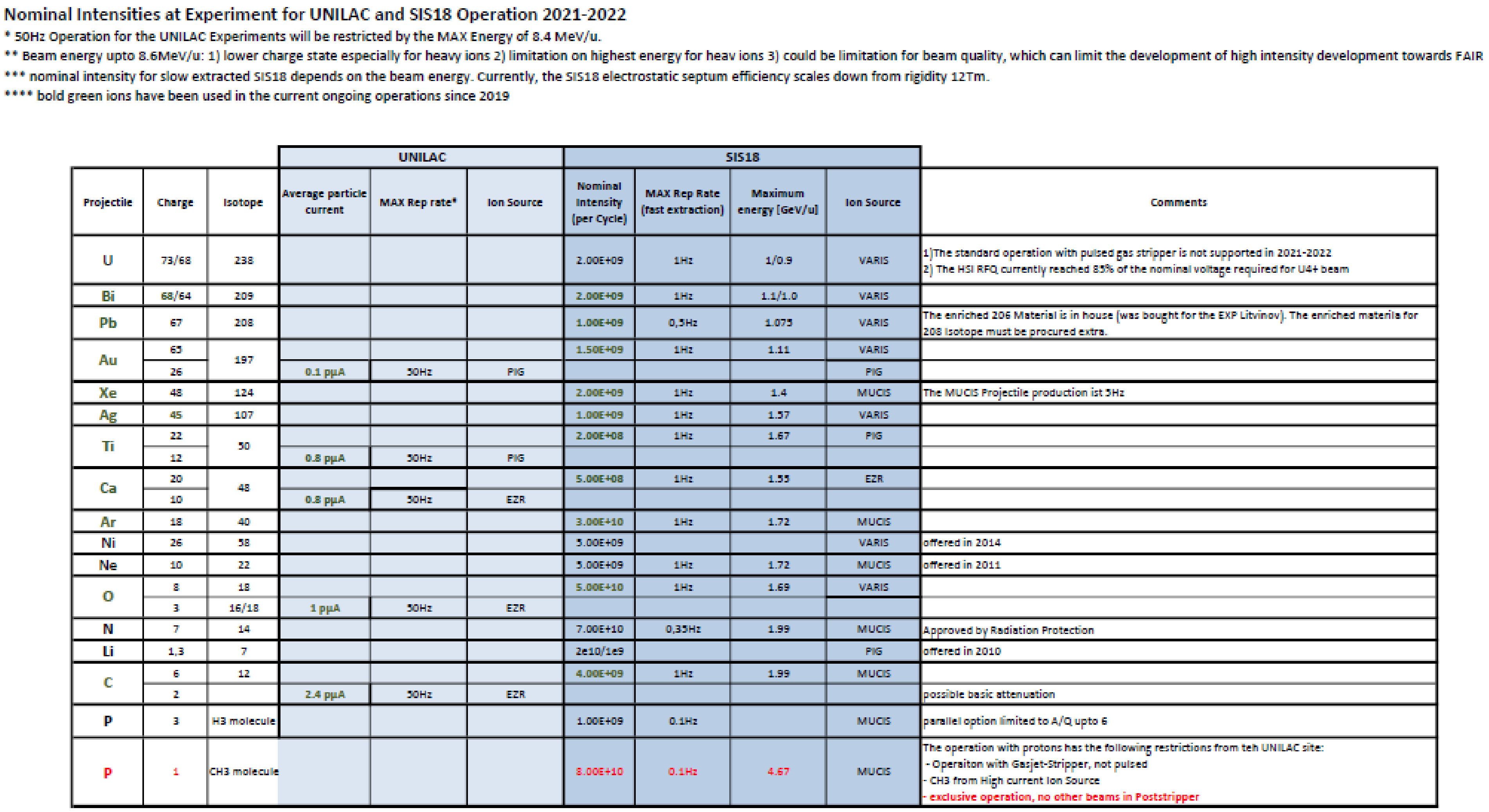
General Plan of Accelerator Operations 2020 (approved: 2019-09-13)

2020

- Despite of the COVID-19, 2/3 of the experiments including the challenging ones such as bound state beta decay were fulfilled
- Heavy ion beams established throughout the chain
- Re-establish ESR for its storage ring operation mode including beam stacking
- CRYRING is commissoned with beam from ESR
- High intensity heavy ion campaign towards FAIR

Current nominal performance for FAIR Phase 0

- https://www.gsi.de/work/beschleunigerbetrieb/betrieb.htm



Nominal Intensities at Experiment for UNILAC and SIS18 Operation 2021-2022

* 50Hz Operation for the UNILAC Experiments will be restricted by the MAX Energy of 8.4 MeV/u.

** Beam energy upto 8.6MeV/u: 1) lower charge state especially for heavy ions 2) limitation on highest energy for heav ions 3) could be limitation for beam quality, which can limit the development of high intensity development towards FAIR

*** nominal intensity for slow extracted SIS18 depends on the beam energy. Currently, the SIS18 electrostatic septum efficiency scales down from rigidity 12Tm.

**** bold green ions have been used in the current ongoing operations since 2019

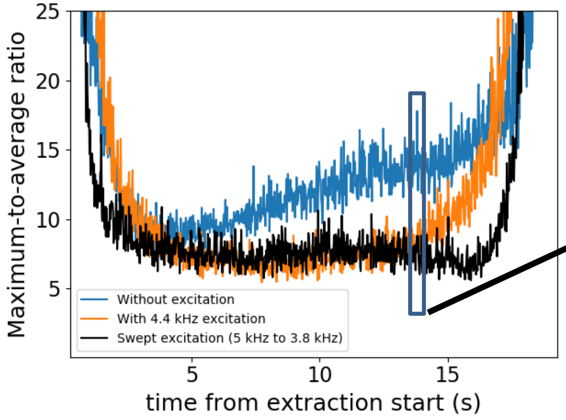
			UNILAC			SIS18				
Projectile	**Charge**	**Isotope**	**Average particle current**	**MAX Rep rate***	**Ion Source**	**Nominal Intensity (per Cycle)**	**MAX Rep Rate (fast extraction)**	**Maximum energy [GeV/u]**	**Ion Source**	**Comments**
U	73/68	238				2.00E+09	1Hz	1/0.9	VARIS	1)The standard operation with pulsed gas stripper is not supported in 2021-2022 2) The HSI RFQ currently reached 85% of the nominal voltage required for U4+ beam
Bi	68/64	209				2.00E+09	1Hz	1.1/1.0	VARIS	
Pb	67	208				1.00E+09	0,5Hz	1.075	VARIS	The enriched 206 Material is in house (was bought for the EXP Litvinov). The enriched materila for 208 Isotope must be procured extra.
Au	65	197				1.50E+09	1Hz	1.11	VARIS	
	26		0.1 pµA	50Hz	PIG				PIG	
Xe	48	124				2.00E+09	1Hz	1.4	MUCIS	The MUCIS Projectile production ist 5Hz
Ag	45	107				1.00E+09	1Hz	1.57	VARIS	
Ti	22	50				2.00E+08	1Hz	1.67	PIG	
	12		0.8 pµA	50Hz	PIG					
Ca	20	48				5.00E+08	1Hz	1.55	EZR	
	10		0.8 pµA	50Hz	EZR					
Ar	18	40				3.00E+10	1Hz	1.72	MUCIS	
Ni	26	58				5.00E+09			VARIS	offered in 2014
Ne	10	22				5.00E+09	1Hz	1.72	MUCIS	offered in 2011
O	8	18				5.00E+10	1Hz	1.69	VARIS	
	3	16/18	1 pµA	50Hz	EZR					
N	7	14				7.00E+10	0,35Hz	1.99	MUCIS	Approved by Radiation Protection
Li	1,3	7				2e10/1e9			PIG	offered in 2010
C	6	12				4.00E+09	1Hz	1.99	MUCIS	
	2		2.4 pµA	50Hz	EZR					possible basic attenuation
P	3	H3 molecule				1.00E+09	0.1Hz		MUCIS	parallel option limited to A/Q upto 6
P	1	CH3 molecule				8.00E+10	0.1Hz	4.67	MUCIS	The operation with protons has the following restrictions from teh UNILAC site: - Operaiton with Gasjet-Stripper, not pulsed - CH3 from High current Ion Source - exclusive operation, no other beams in Poststripper

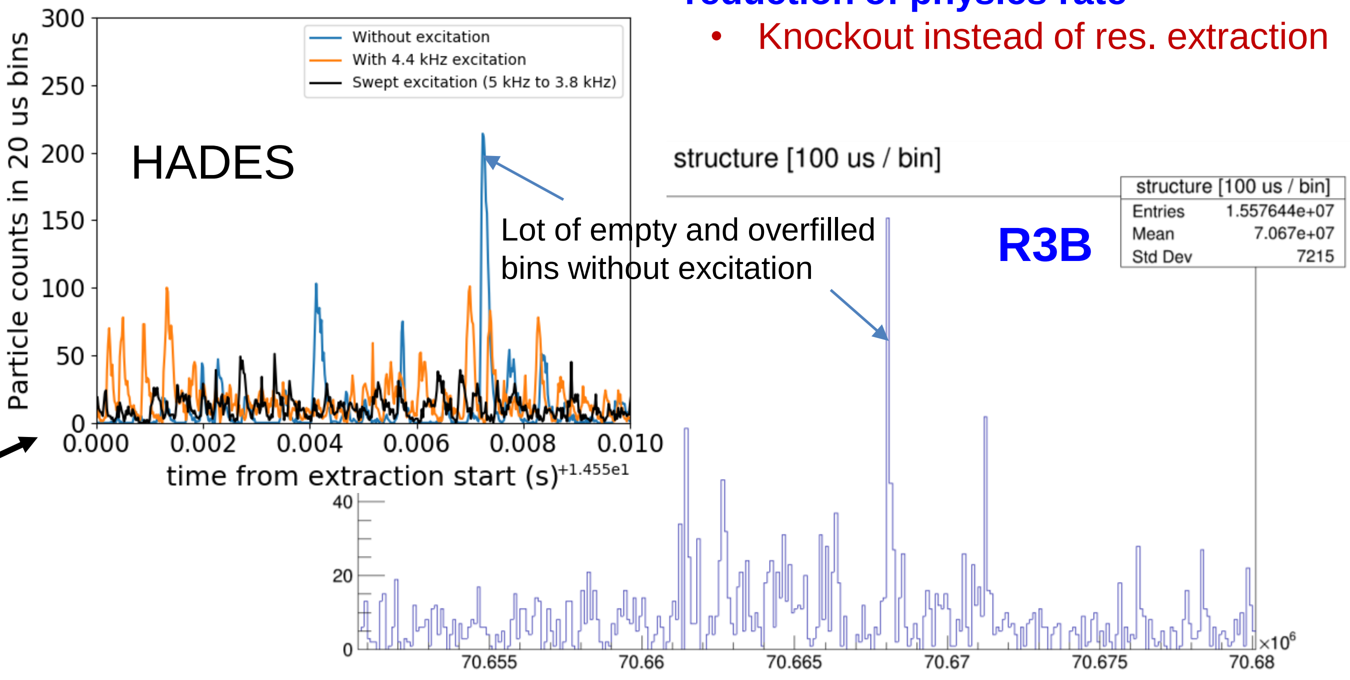
Highlights: SIS18 slow extraction

- sporadic spill structure
  - Not yet comprehensive measurements to ping down the smoking gun(s)
  - Cause deadtime on the detectors

- **Deadtime resulted a factor of 5 reduction of physics rate**
  - Knockout instead of res. extraction

Significant improvement of extraction beam quality w.r.t that HADES!





HADES

Lot of empty and overfilled bins without excitation

R3B

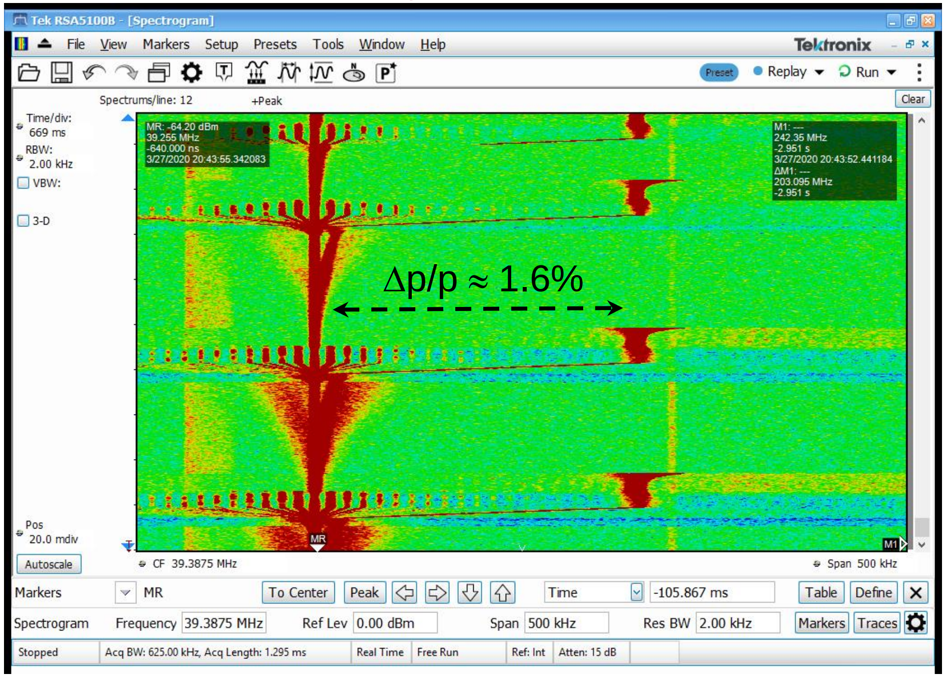
R. Singh et al, PHYSICAL REVIEW APPLIED **13,** 044076 (2020)

Highlights: Beam Accumulation in the ESR

- Beam stacking is now operational with FAIR control
- Pb beam decelerated, and extracted to CRYRING

stack orbit (electron cooling)

injection orbit (stochastic cooling)



Spectrums/line: 12 +Peak

MR: -64.20 dBm
39.255 MHz
-640.000 ns
3/27/2020 20:43:55.342083

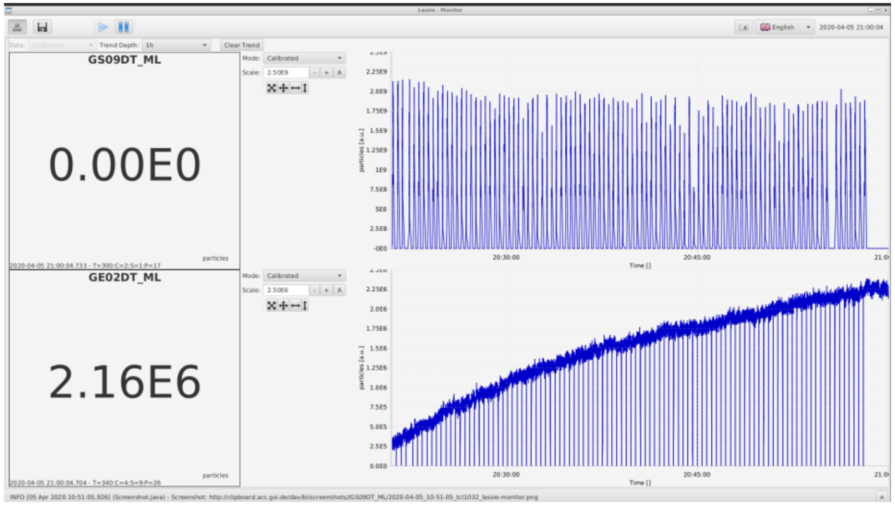
M1: ---
242.35 MHz
-2.951 s
3/27/2020 20:43:52.441184
ΔM1: ---
203.095 MHz
-2.951 s

CF 39.3875 MHz
Span 500 kHz

Markers: MR | To Center | Peak | Time: -105.867 ms | Table | Define

Spectrogram: Frequency 39.3875 MHz | Ref Lev 0.00 dBm | Span 500 kHz | Res BW 2.00 kHz | Markers | Traces

Stopped | Acq BW: 625.00 kHz, Acq Length: 1.295 ms | Real Time | Free Run | Ref: Int | Atten: 15 dB



GS09DT_ML
0.00E0
particles

GE02DT_ML
2.16E6
particles

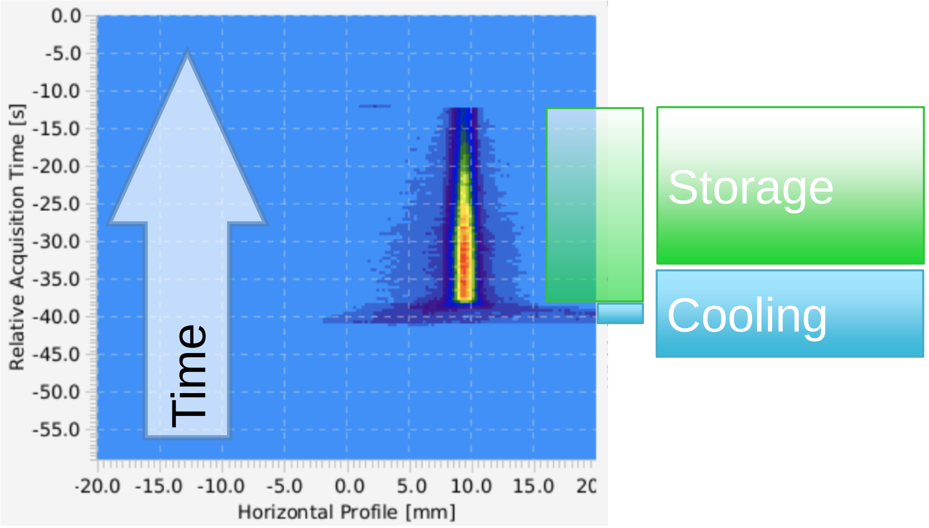
62 injections: $2{\times}10^6$ $^{205}\mathrm{Tl}^{81+}$ ions (exceeding the proposal intensity by a factor 2)

M. Steck, GSI 3rd beam time retreat

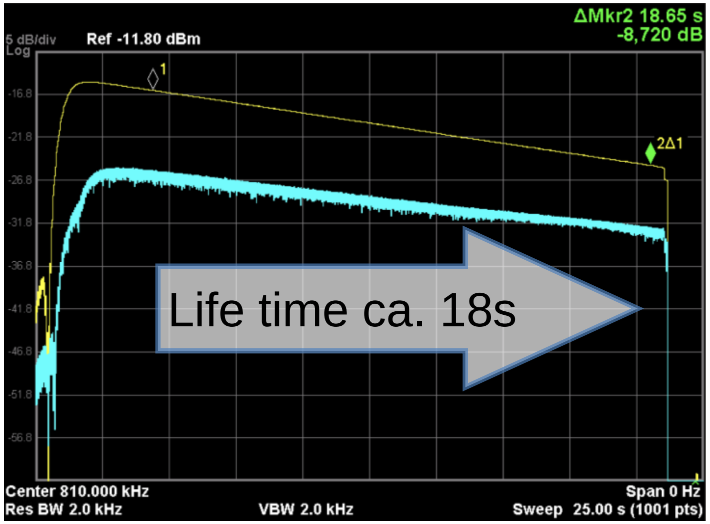
Highlights: CRYRING

- Captured, Stored and Cooled Pb^{78+} and Pb^{82+} (bare)
  - 6 x 10^{6} particles delivered from ESR at 10 MeV/nucleon
  - 3 x 10^{5} particles available for experiments in CRYRING@ESR after cooling
  - Ion beam deceleration to 4 MeV/nucleon has been successfully tested
- Lifetimes measured for different energies and ions
  - Pb^{82+} lives between 10 and 20 seconds

Electron Current	Lifetime Measured / s	Lifetime beamcalc / s	@10 MeV/u
12 mA	24(1)	33	Pb78+
22 mA	8(1)	28	Pb78+
12 mA		23	Pb82+
12 mA		18	U92+
			@4 MeV/u
0 mA	5(1)	7.5	Pb78+



Horizontal beam profile over time

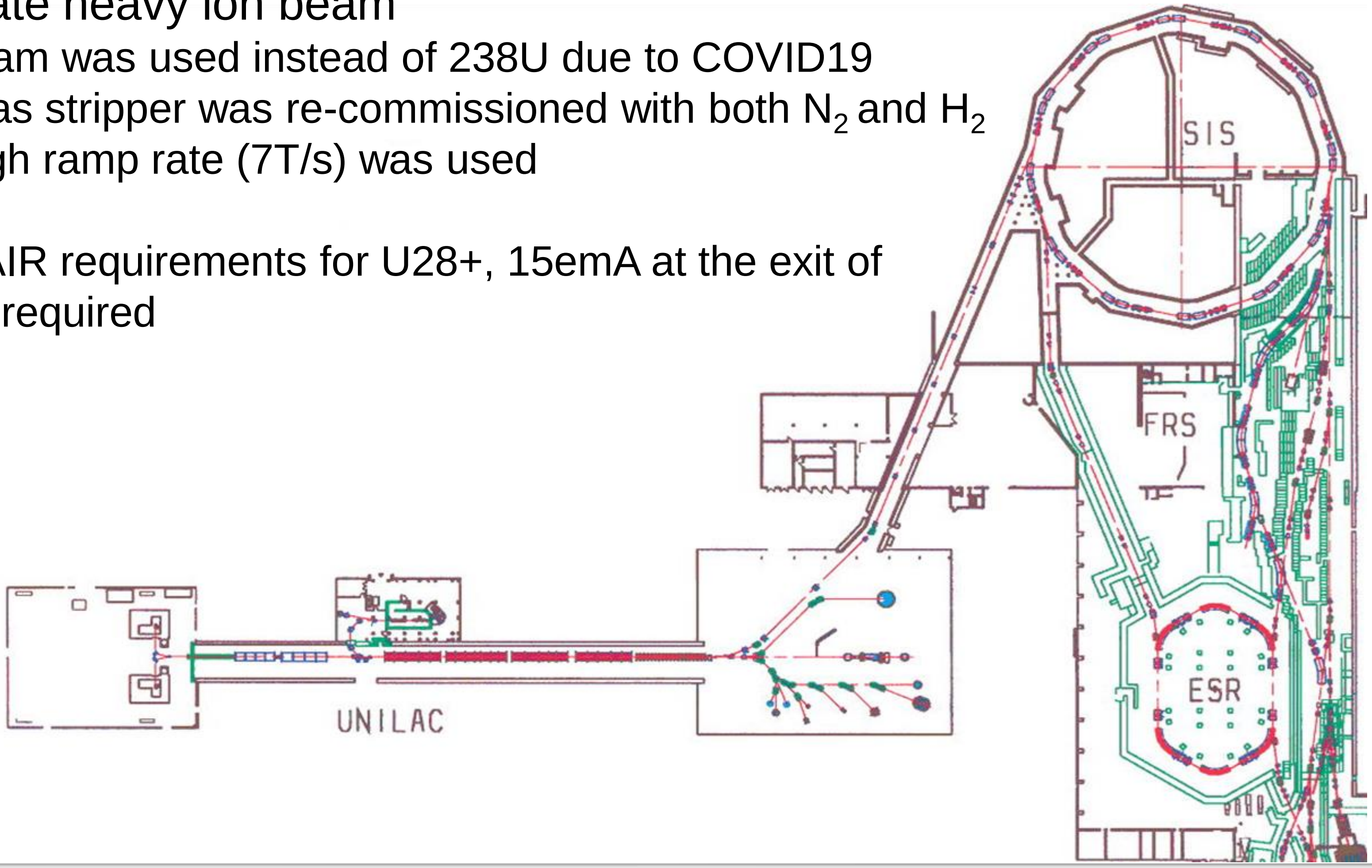


Lifetime, i.e. time for a signal drop of 8 dB

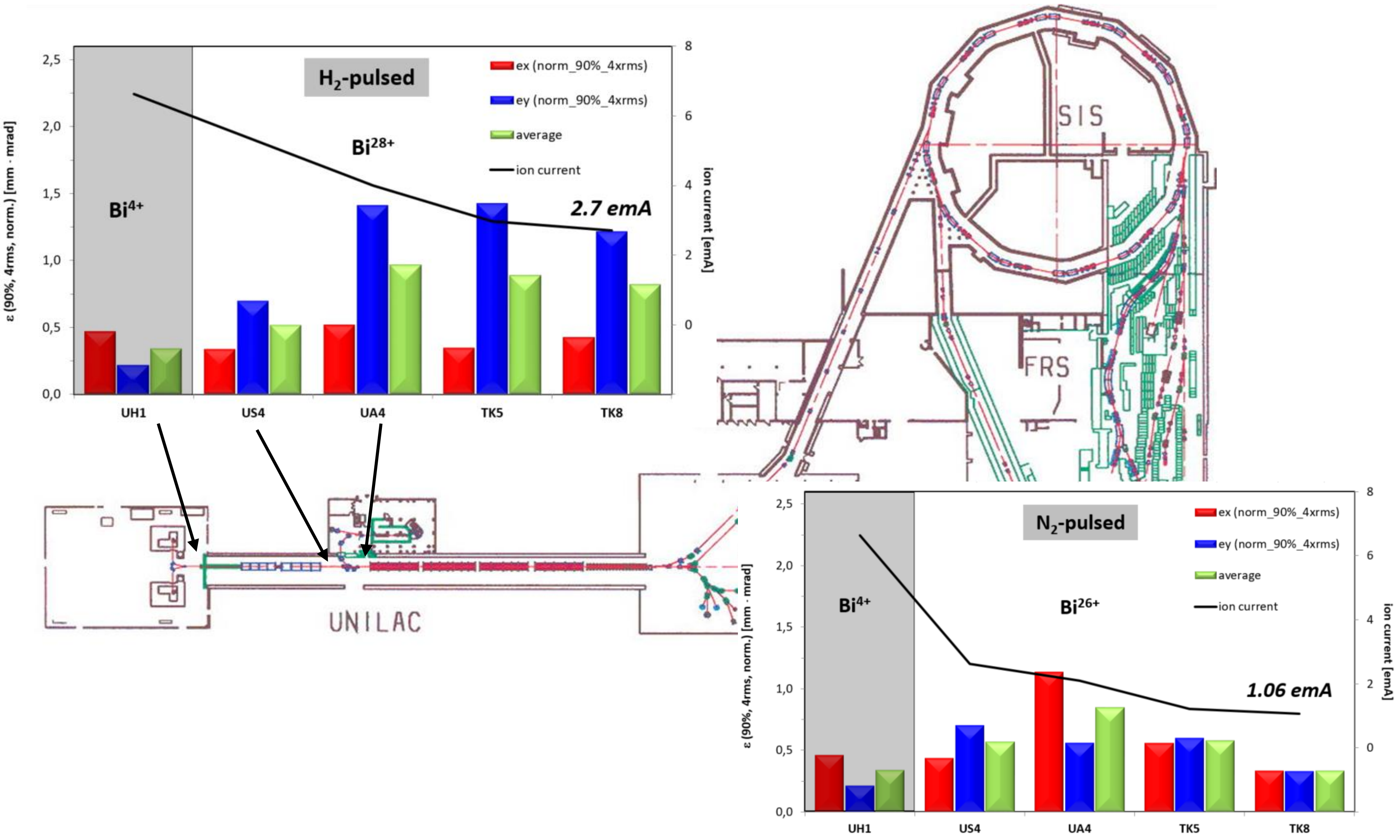
High Intensity Heavy Ion Campaign in 2020

- Dedicated 5 days of beam time to re-establish low charge state heavy ion beam
  - 209Bi beam was used instead of 238U due to COVID19
  - Pulsed gas stripper was re-commissioned with both N_2 and H_2
  - SIS18 high ramp rate (7T/s) was used

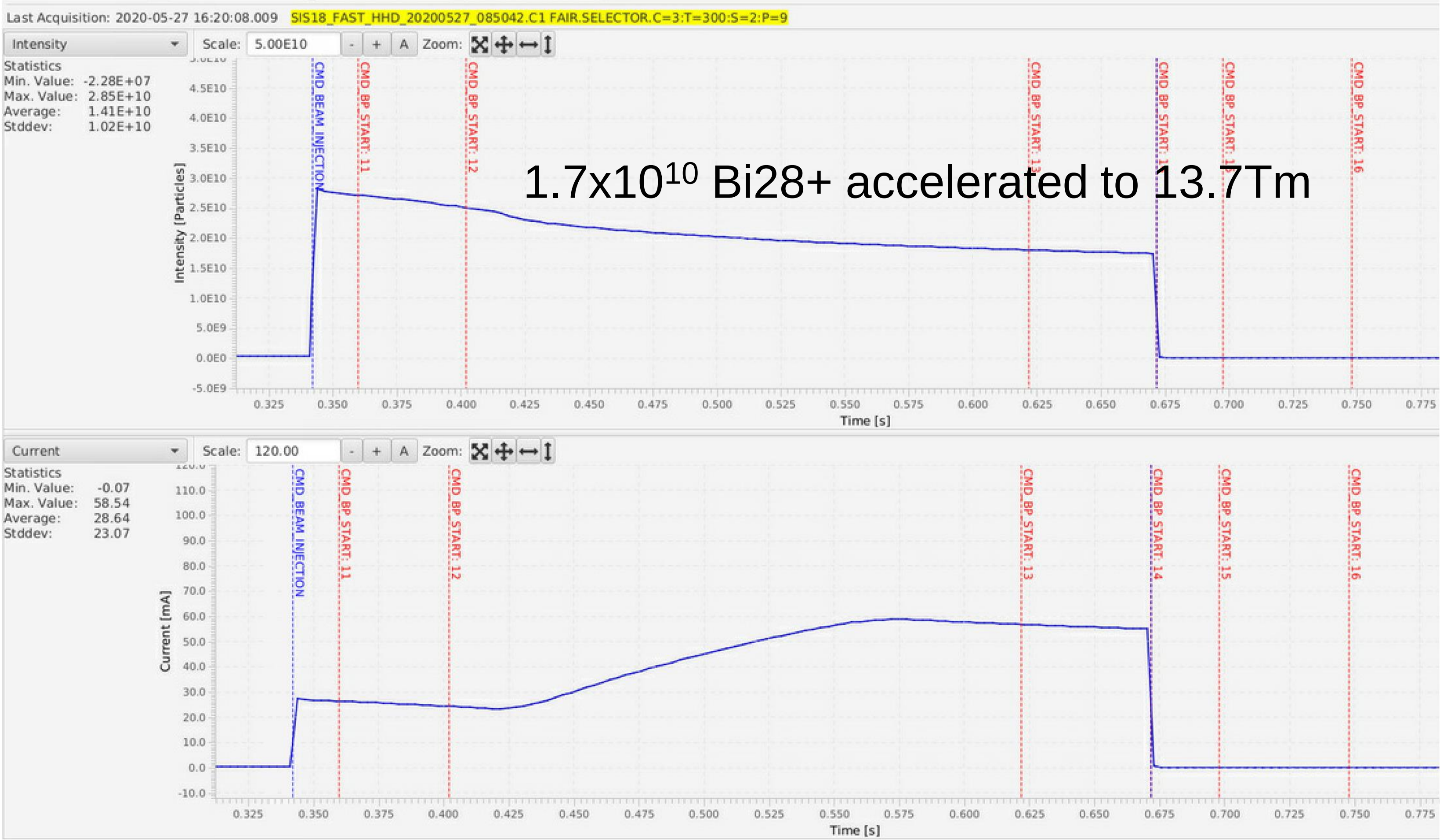
- To meet FAIR requirements for U28+, 15emA at the exit of UNILAC is required



High Intensity Heavy Ion Campaign in 2020



High Intensity Heavy Ion Campaign in 2020



Last Acquisition: 2020-05-27 16:20:08.009 SIS18_FAST_HHD_20200527_085042.C1 FAIR.SELECTOR.C=3:T=300:S=2:P=9

Intensity Scale: 5.00E10

Statistics
Min. Value: -2.28E+07
Max. Value: 2.85E+10
Average: 1.41E+10
Stddev: 1.02E+10

Current Scale: 120.00

Statistics
Min. Value: -0.07
Max. Value: 58.54
Average: 28.64
Stddev: 23.07

1.7×10^{10} Bi28+ accelerated to 13.7Tm

Achieved Beam Performance w.r.t FAIR requirement

Updated: Oct. 2020

High intensity U28+ beam is one of the flagships of FAIR

Design: Uranium28+ **2020 Bi28+**	**Cycle rate[Hz]**	**Ramp rate[T/s]**	**Intensity**		**ϵ_x[mm-mrad]**		**ϵ_y[mm-mrad]**		**Bunch area eVs/u**	
	Design||reached	**Design||reached**	Design	Reached	Design	Reached	Design	Reached	design	reached
IQS	2.7 || 1	--	--	--	--	--	--	--	--	--
Entrance of HSI RFQ (U4+/Bi4+)	--	--	--	11emA 6.3emA*	--	0.35 0.5*	--	0.31 0.25*	--	--
Entrance of Post-stripper (U28+/Bi28+)	--	--	--	5.4emA 5.5emA*	--	0.84 0.4*	--	0.8 0.75*	--	--
UNILAC TK8 (U28+/Bi28+)	--	--	15 emA	4.3emA 2.7emA*	1.0	0.60 0.4*	--	0.64 1.3*	$\frac{\delta p}{p} \pm 1e\text{-}3$ $4.5ns$	N/A
SIS18 Inj. (U28+/Bi28+)	2.7 || 1 || 1*	10 || 4 || 7*	2e11	4.5e10 3e10*	23.5	N/A N/A	7.8	N/A N/A	0.1	N/A N/A
SIS18 flat top (U28+/Bi28+)	2.7 || 1 || 1*	10 || 4 || 7*	1.2e11	3.2e10 1.7e10*	5.5	N/A N/A	2.4	N/A N/A	0.15	N/A N/A

Note:

[1] Transverse emittances in the table are normalized 4 times rms emittance. SIS18 design bunch area is based on 2/3 of bucket area

[2] Uranium data were from 2012 for SIS18, and 2016 for UNILAC during which N2 gas stripper was also used

* for 2020 high intensity campaign, Bi28+ was used instead of U28+ due to COVID-19 crisis, and pulsed H2 gas stripper used

Measures for meeting FAIR requirements

	Upgrade measures	Status	Timeline
Ion source	2.7 Hz high current uranium source	ongoing	2018 to 2023
	dedicated uranium terminal	planned	2020 to 2026
UNILAC	HSI RFQ upgrade Redesign of RFQ beam dynamics and matching to subsequent pre-stripper, LEBT, RFQ dynamics, MEBT	proposed	• Corresponding details will be formed after carefully evaluating the systematic high intensity heavy ion beam performance during the upcoming operations • Implementation of the measures depends on the budget availability
	HSI MEBT upgrade	proposed	Similar as above
SIS18	mitigate the dynamic vacuum instability: control of systematic beam loss and cryo pumps	proposed	Similar as above
	Advanced techniques to address beam intensity limitations	Under investigation	Similar as above
	Systematic evaluation of beam parameters including 6D emittance	ongoing	**Q4 2019 to FAIR commissioning**
CRYRING	Upgrade of RF and vacuum	Planned	Depending on budget and resource availability

HFHF Accelerator Program

- HFHF: The Helmholtz Forschungsakademie Hessen für FAIR
  - Continue the excellent torch of HIC4FAIR with more focus on addressing the scientific challenges for FAIR phase 0 towards FAIR
  - Accelerator program is part of the Accelerator physics and scientific computing, one of the 5 scientific programs
  - Currently 4 members with research topics to address

HLI upgrade and innovative RF techniques

Prof. Dr. H. Podlech

- Address the technical challenges for reliable operation of high duty cycle RFQ for heavy ions
- Investigate the automation of RF conditioning and develop and event prediction system

High intensity ion LINACs

Prof. Dr. Uli Ratzinger

- Ion source including LEBT and beam formation improvement
- Investigate cavity field limitation
- Innovative RFQ beam dynamics, reduced longitudinal emittance
- Gas stripper investigations
- Efficient heavy ion linac acceleration for a substantial Unilac energy upgrade in the longer future

Extreme beams and complex systems

Pv. Dr. G. Franchetti, Prof. Dr. Mei Bai

- WP 1 – comprehensive dynamics modeling of extreme beams
- WP 2 – Application of AI/ML in the optimization of beam and operation performance in an accelerator complex system

Roadmap towards FAIR

High intensity ion LINACs

Prof. Dr. Uli Ratzinger

Upgrade the UNILAC for high intensity operation

- beam intensity
- reliability

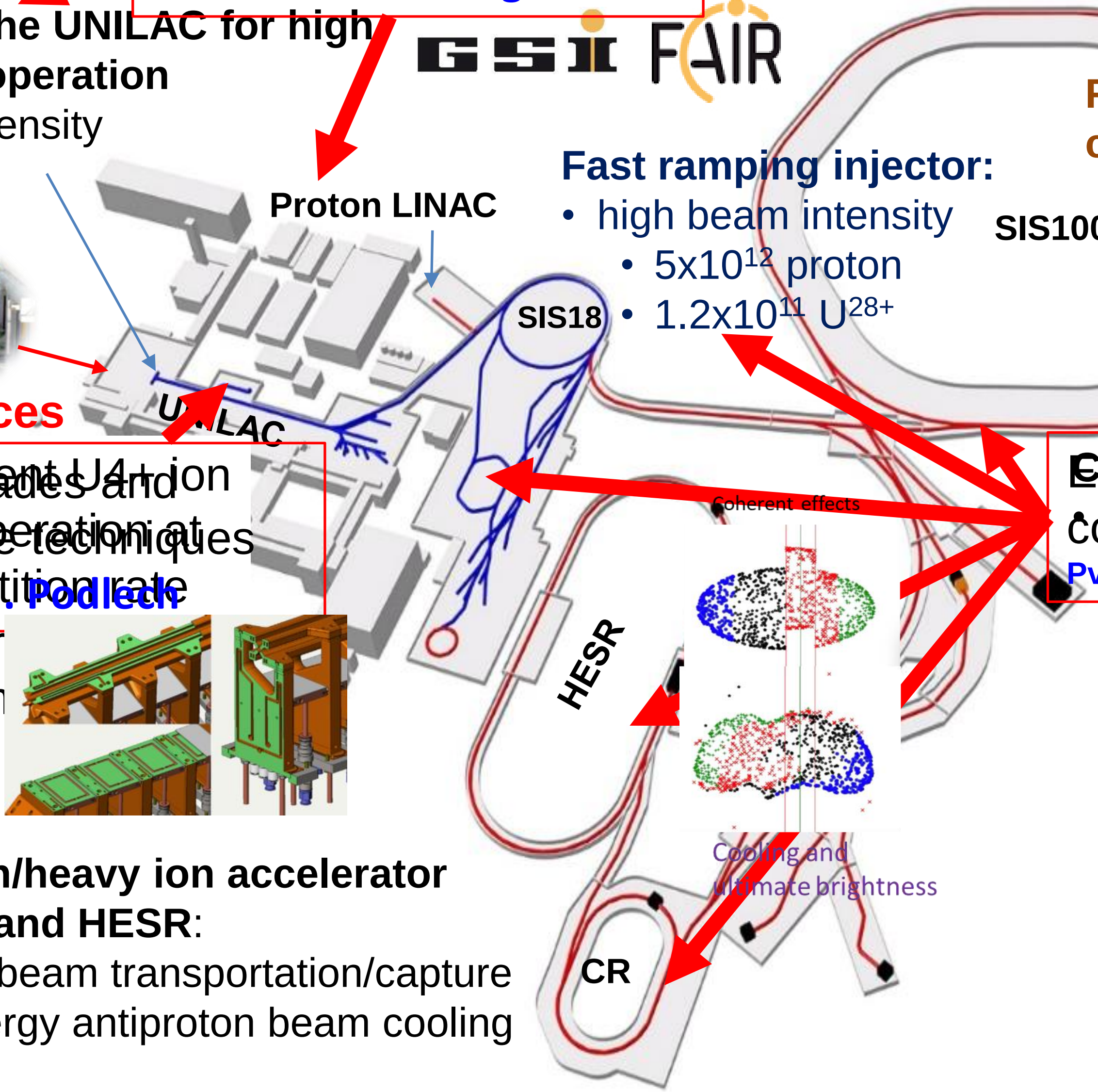
Ion sources

High current U4+ ion source operation at high repetition rate

HLI upgrades and innovative techniques

Prof. Dr. H. Podlech

2.7 Hz for booster m



Fast ramping injector:

- high beam intensity
  - 5×10^{12} proton
  - 1.2×10^{11} U^{28+}

Fast ramping super-conducting synchrotron:

- Fast ramping superconducting magnet
- **5×10^{13} proton**
- **4.5×10^{11} U^{28+}**

Challenging beam technique

- Extraction:
- spill structure

Extreme beams and complex systems

Pv. Dr. G. Franchetti, Prof. Dr. Mei Bai

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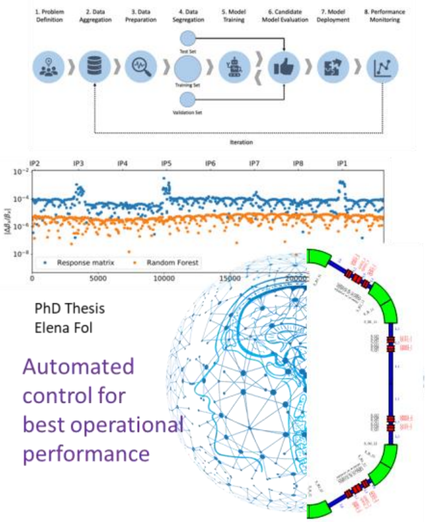

PhD Thesis
Elena Fol

Automated control for best operational performance

Antiproton/heavy ion accelerator chain CR and HESR:

- Efficient beam transportation/capture
- High energy antiproton beam cooling

FAIR 2025

Thank You!