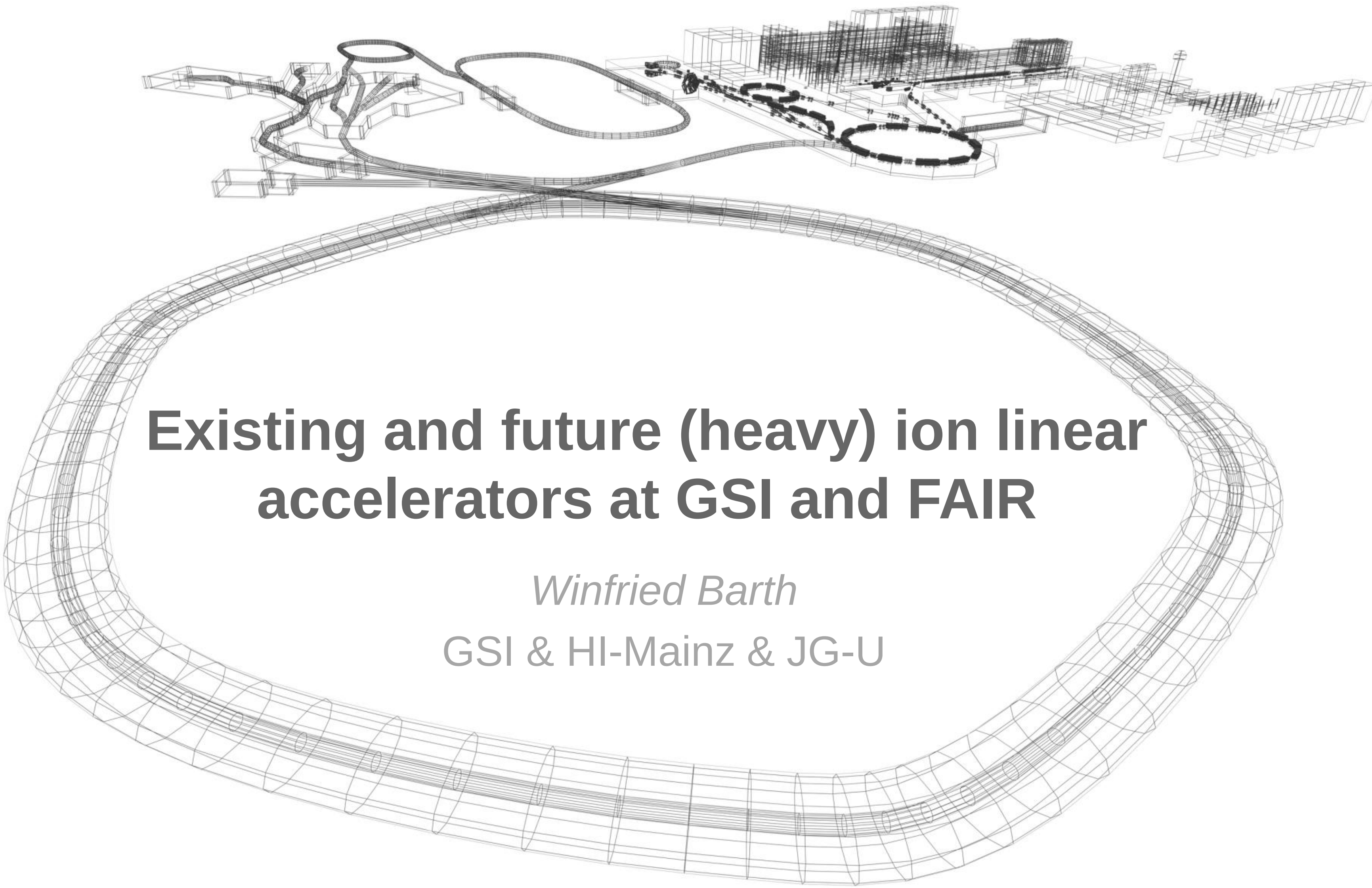


Existing and future (heavy) ion linear accelerators at GSI and FAIR

Winfried Barth

GSI & HI-Mainz & JG-U

Existing and future (heavy) ion linear accelerators at GSI and FAIR

W. Barth[1,2,3]

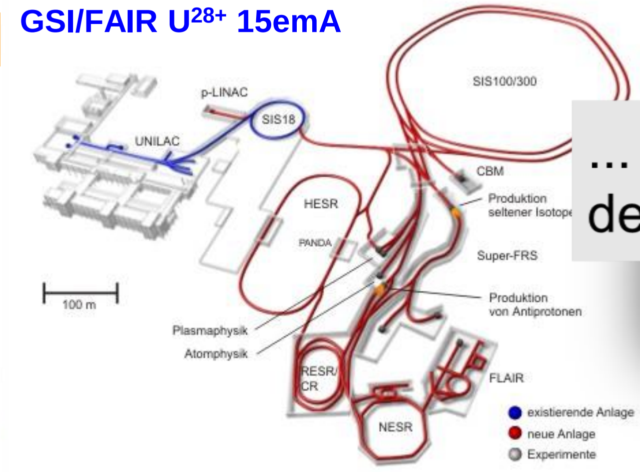
[1] Helmholtz Institute Mainz, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[3] Johannes Gutenberg University, Mainz, Germany

Introduction: Heavy Ion Linear Accelerators

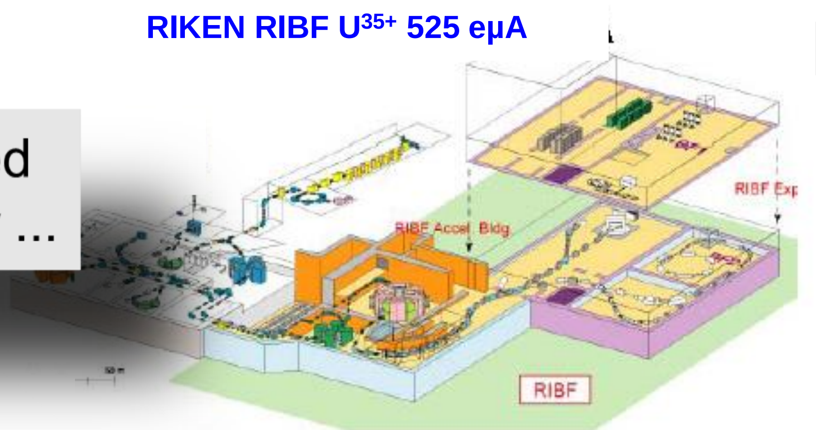
Delivery of the Heavy Ion Linear Accelerator (HILAC) poststripper tank; Cyclotron Road (Berkeley, 1956)

High power heavy ion accelerator facilities

GSI/FAIR U^{28+} 15emA

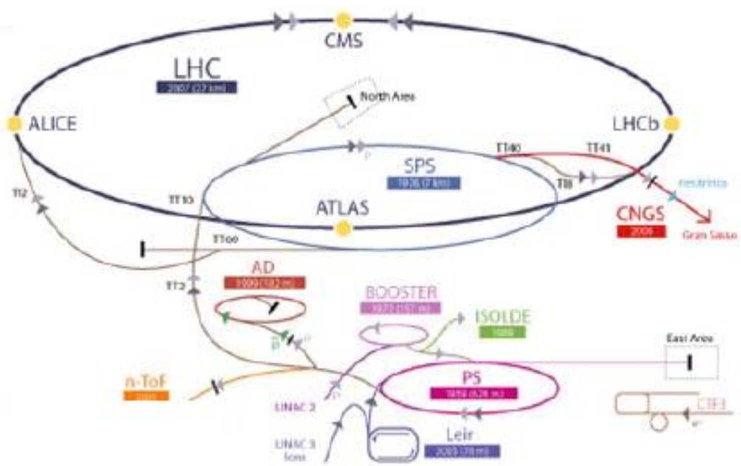


RIKEN RIBF U^{35+} 525 eµA

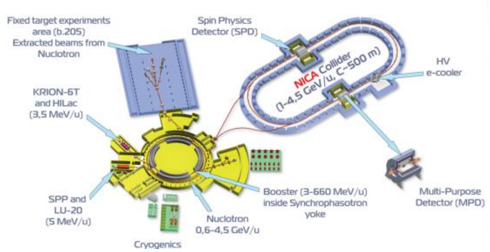


... non of them reached design intensity so far ...

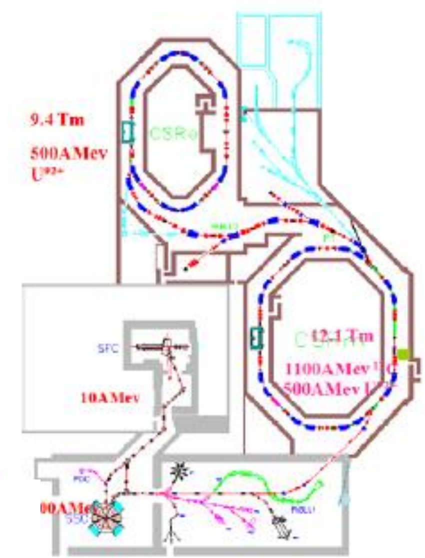
LHC Pb^{27+} 1 emA



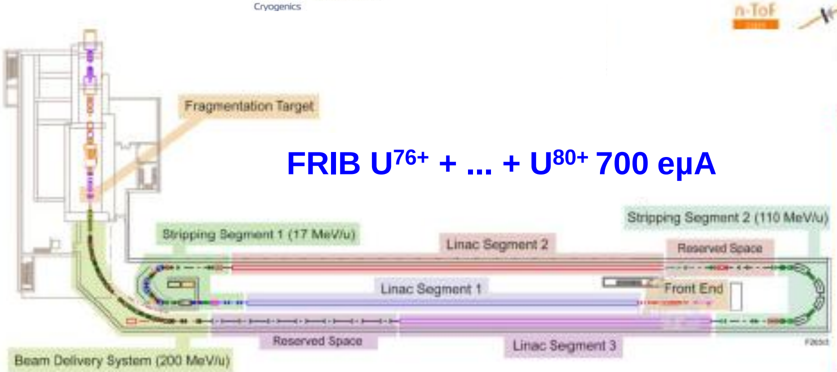
NIKA/HILAC Au^{31+} 10emA



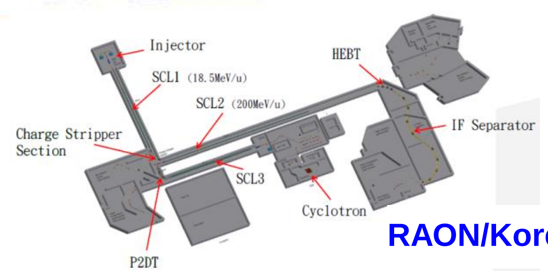
IMP HIRFL U^{41+} 100 eµA



FRIB U^{76+} + ... + U^{80+} 700 eµA



RAON/Korea U^{79+} 8.3 pµA (200 MeV/u)



Heavy Ion Accelerators in Germany Motivation and Proposal

- Increasing interest in experiments with heavy ions since the mid 1950s
- Nuclear shell model extrapolation suggested the existence of a stability island around Z = 120
- Proposals for appropriate accelerators in the USA, France and Soviet Union (cyclotron, synchotron, Tandem van de Graaff, and combinations)
- Schmelzer`s* proposal: UNIversal Linear ACcelerator begin of 1960s, UNILAC
- **Acceleration of ions of all elements up to uranium to energies of about 10 MeV/u**

**Prof. Christoph Schmelzer, first scientific director of GSI (1970 – 1978)*

Norbert Angert, GSI-FAIR Colloquium 15.05.2018

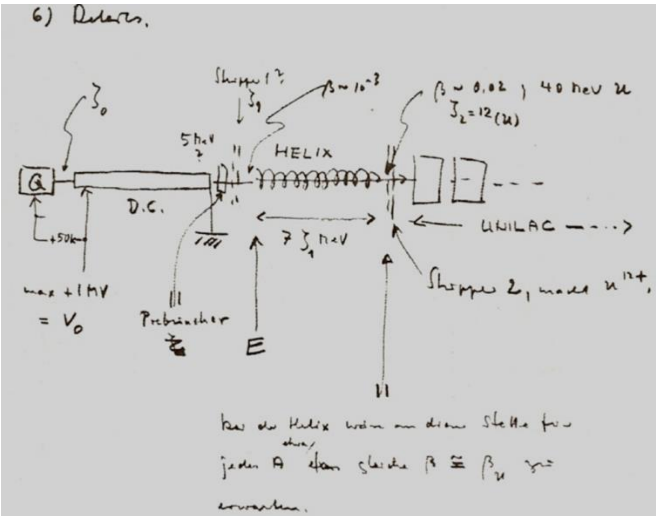
Requirements for a Universal Heavy Ion Accelerator

- Accelerator for ions of all elements up to uranium
- Energy at least 7 MeV/u, threshold for nuclear reactions with any target atoms
- Independent rf-cavities with phase control allowing different velocity profiles
- Output energy variable in a wide range (2 to 10 MeV/u), and stable within 10^{-3}
- Energy spread of the beam better than 10^{-3}
- No contamination from other energy components in the beam
- Beam intensity higher than 6×10^{12}/s
- Fast change of ion species possible

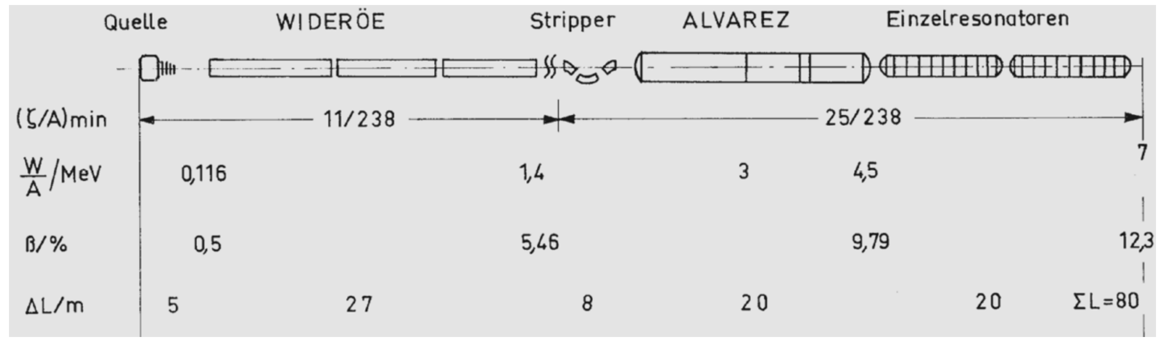
Norbert Angert, GSI-FAIR Colloquium 15.05.2018

UNILAC layout studies

Early studies at Heidelberg



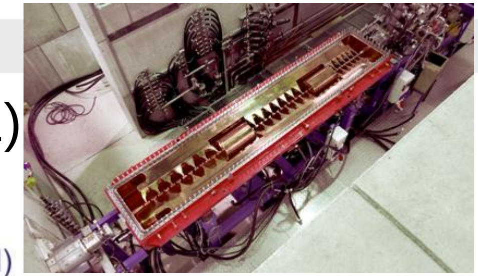
Unilac layout 1968, 6a

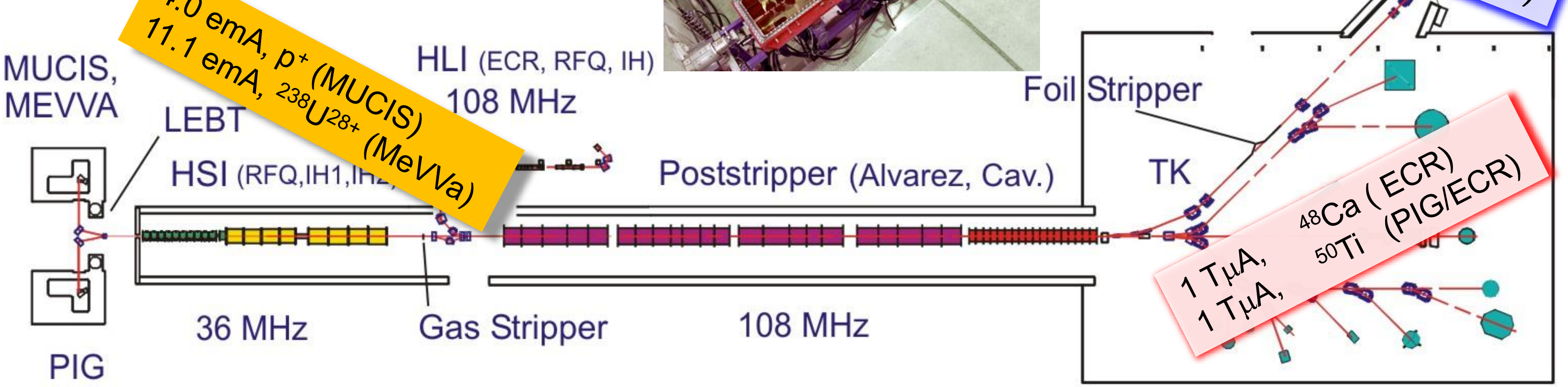


- Stripping data, average charge states
- Phase control of cavities
- Particle dynamics, phase stability during acceleration
- Focusing and filtering of wrong charge-to-mass particles
- Tolerances for acceleration and focusing system
- Low energy and injection section
- Ion sources for high charge states

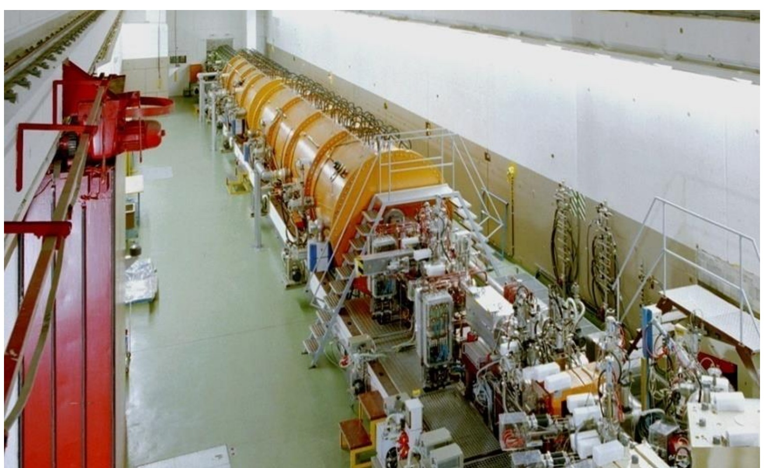
GSI UNIversal Linear ACcelerator

High Charge State Injector (1991)

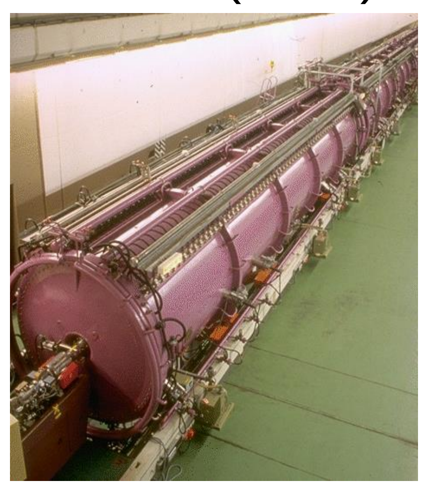




High Current Injector (1999)

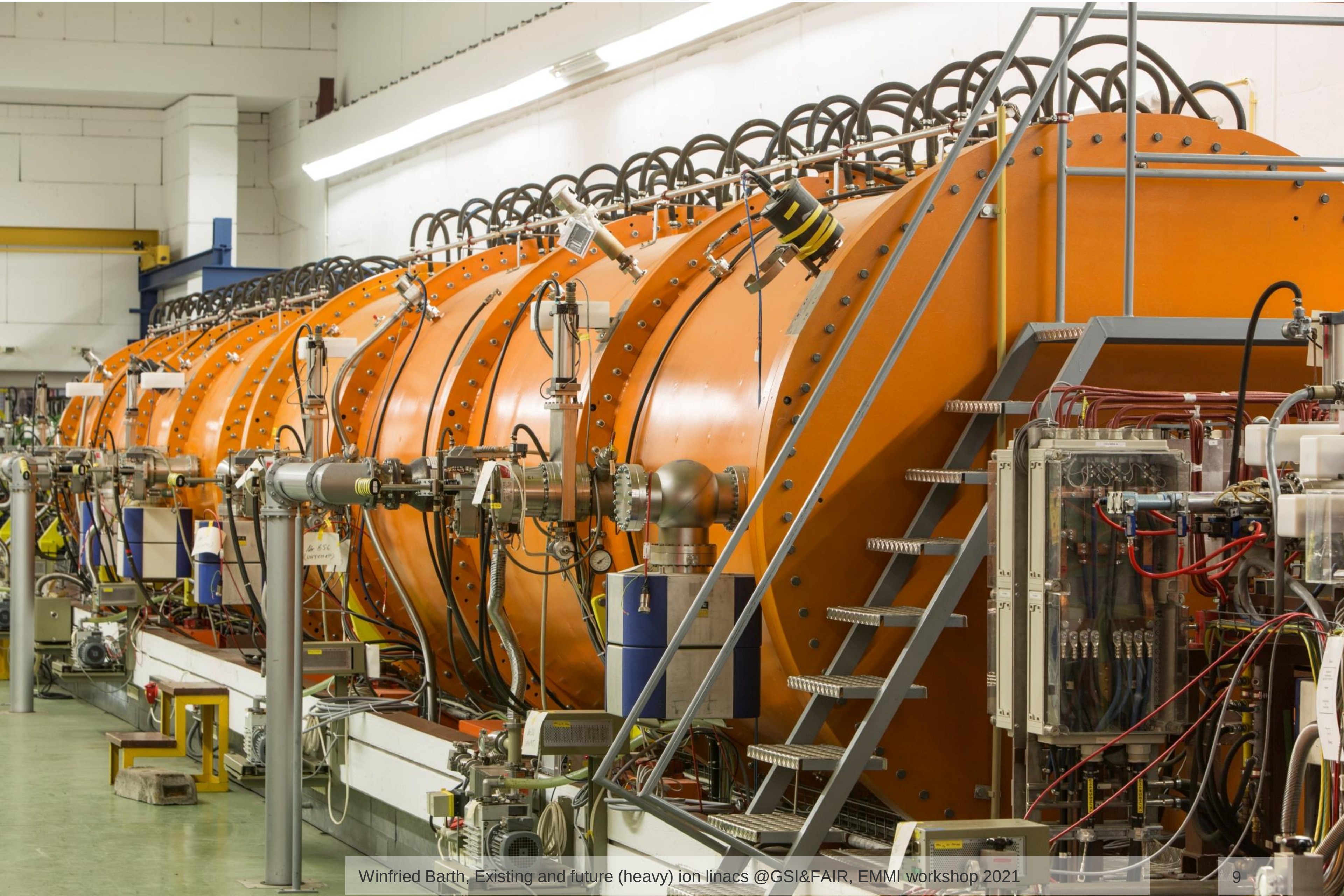


Alvarez (1975)



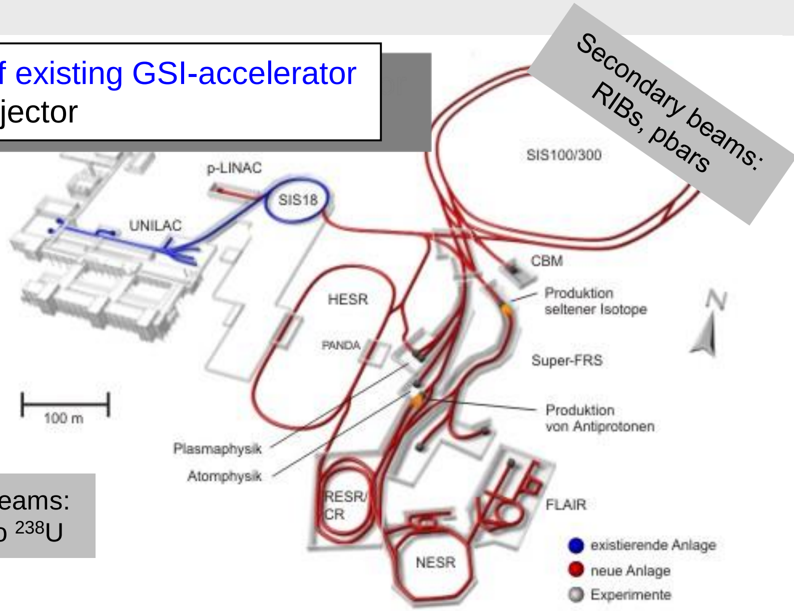
Single Gap Resonators (1975)

High Current Injector



Facility for Antiproton and Ion Research

Upgrade of existing GSI-accelerator as FAIR-Injector



Primary beams: protons to ^{238}U

Future FAIR-Facility: Ion- und anti-matter-beams of highest intensity and beam energy

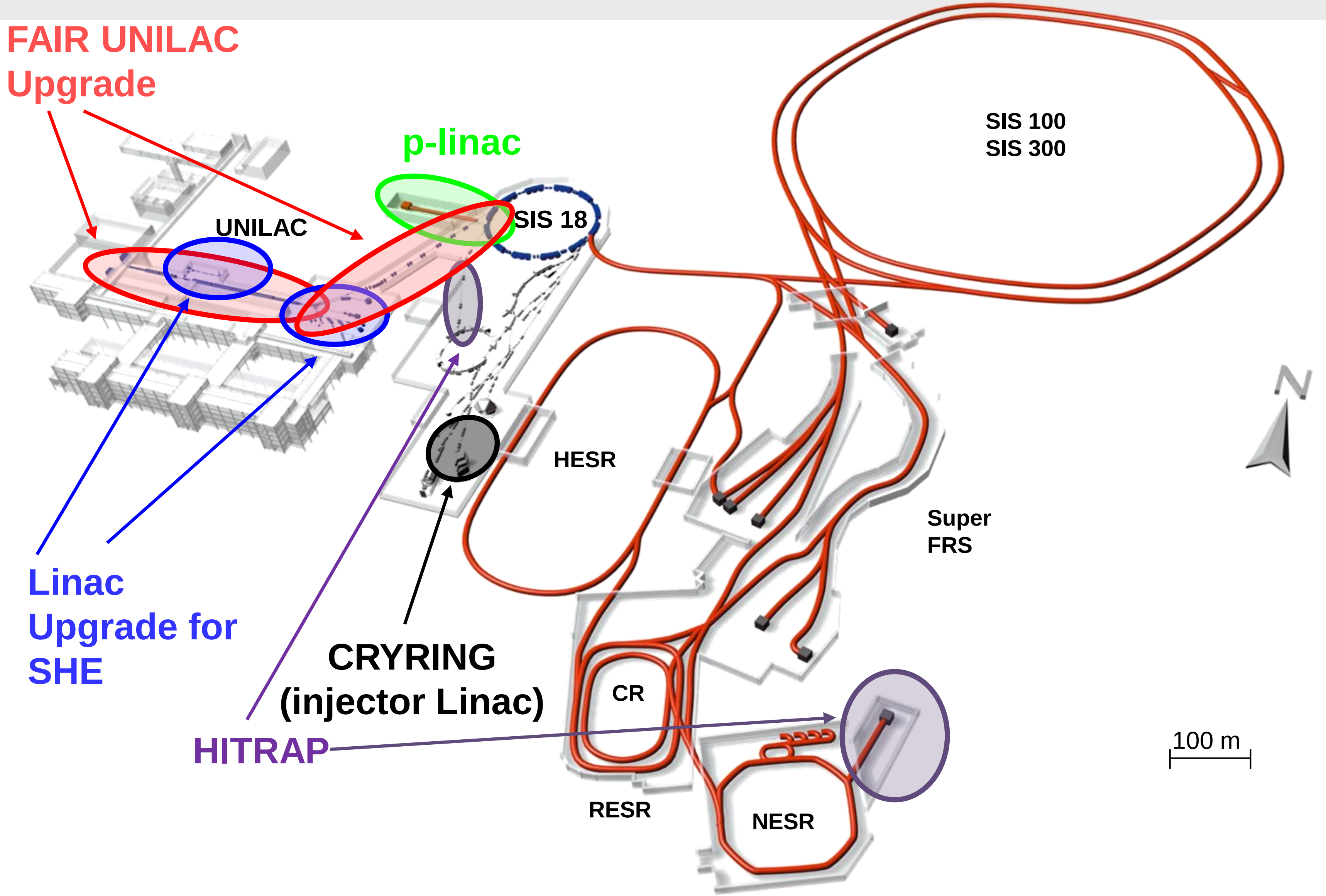
Hauptkomponenten & Schlüsselparameter

Ring/Device	Beam	Energy	Intensity
SIS 100 (100Tm)	protons	30 GeV	$4x10^{13}$
	^{238}U	1 GeV/u	$5x10^{11}$
	(intensity factor 100 over present)		
SIS 300 (300Tm)	^{40}Ar	45 GeV/u	$2x10^{9}$
	^{238}U	34 GeV/u	$2x10^{10}$
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim 10^{11}$
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

FAIR-design uranium beam parameters at the UNILAC

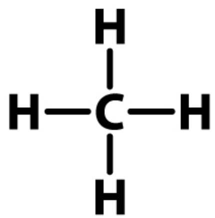
	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$
Elect. Current [mA]	25	18	15	15.0
Part./100µs pulse	$3.9 \cdot 10^{12}$	$2.8 \cdot 10^{12}$	$3.3 \cdot 10^{11}$	$3.3 \cdot 10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4
$\Delta W/W$	-	$4 \cdot 10^{-3}$	$\pm 1 \cdot 10^{-2}$	$\pm 2 \cdot 10^{-3}$
$\varepsilon_{norm.x}$ [mm mrad]	0.3	0.5	0.75	1.0
$\varepsilon_{norm.y}$ [mm mrad]	0.3	0.5	0.75	2.5

FAIR related LINAC projects



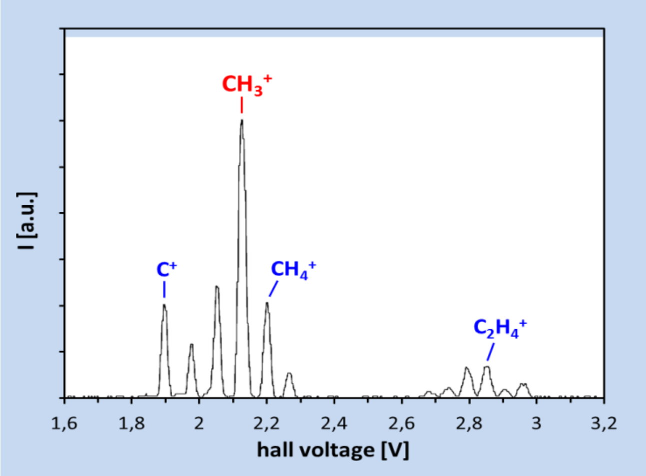
High intensity proton beams at GSI-UNILAC

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



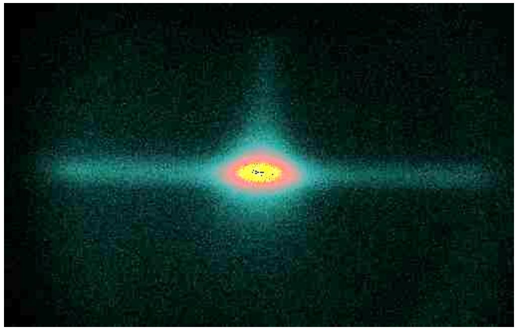
Methan

Ion source



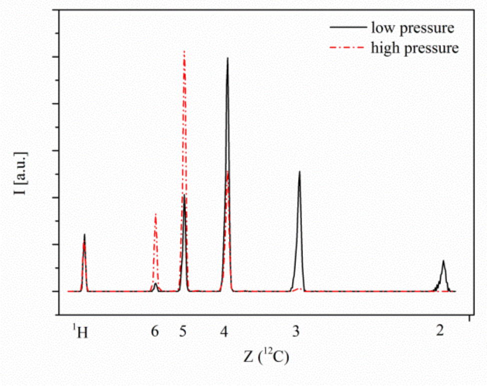
CH_3^+ acceleration

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



Cracking of CH-compounds + stripping

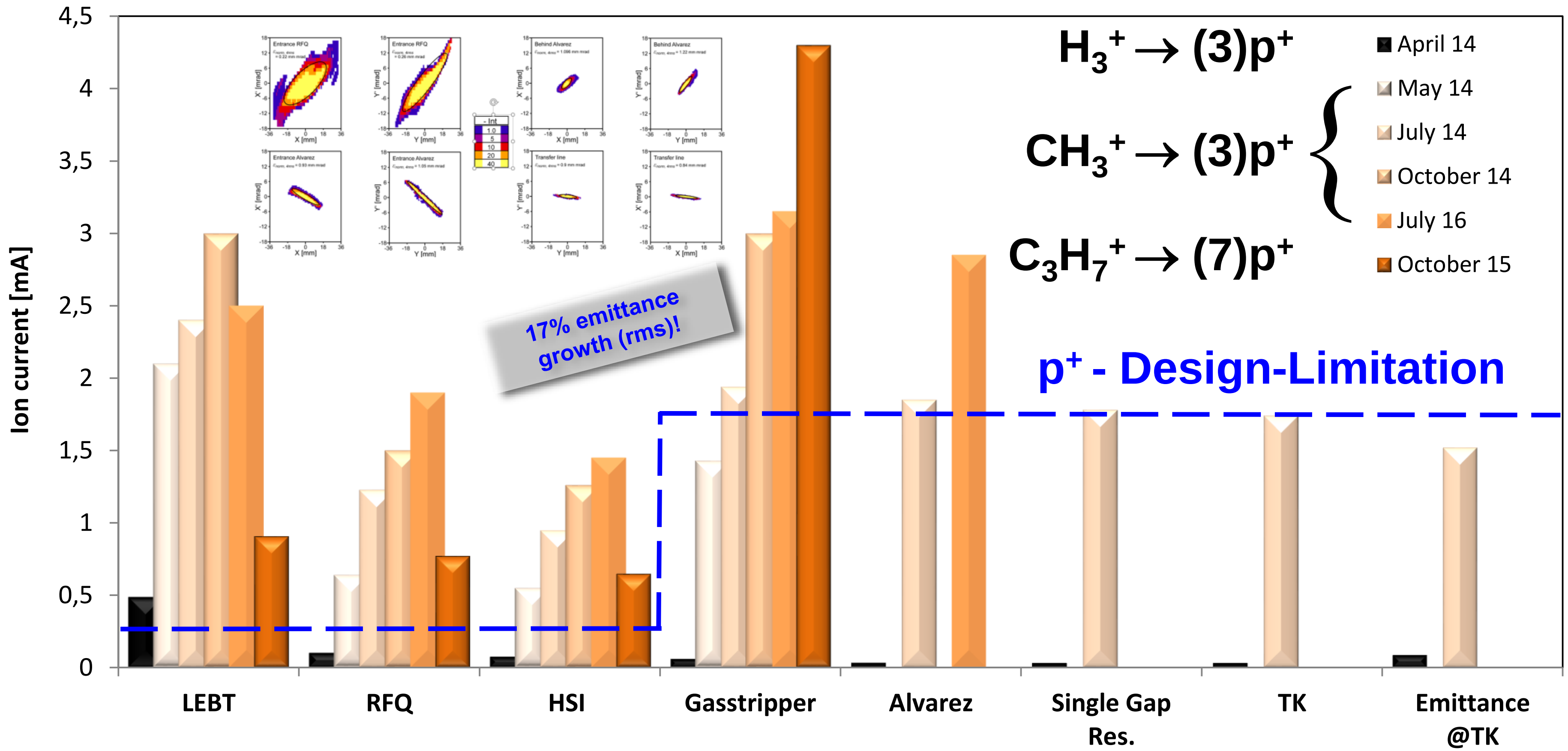
C^{6+} acceleration (9 emA)



p^+ acceleration (3 emA)

High intensity proton beams at GSI-UNILAC

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



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

High current-p⁺-beam@FAIR

S. Appel, GSI

$$\Delta Q_x^{sc} = -\frac{r_p}{\pi}\frac{Z^2}{A}\frac{N}{\beta^2\gamma^3}\frac{g_f}{B_f}\frac{1}{\epsilon_x + \sqrt{\epsilon_x \epsilon_y}}$$

	FAIR p-LINAC	GSI-UNILAC				
E [MeV]	70	11.4	11.4	20	20	
I [mA]	35	1	2	1	2	3emA
$e_{x,y\ (4\cdot rms)}$ [mm mrad]	7/8	7/8	7/8	3/3	3/3	
γ	1.07	1.01	1.01	1.02	1.02	
β	0.37	0.15	0.15	0.2	0.2	
$\beta^2\cdot\gamma^3$	0.17	0.02	0.02	0.04	0.04	
Space charge limit (N)	5.8e12	8.6e11	8.6e11	1.5e12	1.5e12	
SIS100 (part./cycle)	1.7e13	1.2e12	2.3e12	1.5e12	2.8e12	
SIS100 (relative)	100%	7.1%	13.5%	8.5%	16.7%	25%
SIS18 MTI (N)	6.0e12	4.1e11	8.2e11	5.1e11	1.0e12	1.5e12

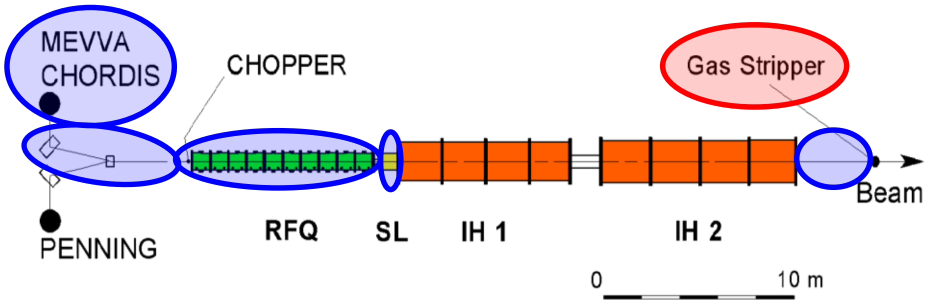
2.1e11 (measured)

UNILAC-Upgrade:
Aims for FAIR-0 and beyoned

- Serving FAIR-0 user program in the most reliable way
- Mitigating risks of substantial failure (in particular at ALVAREZ-DTL)
- Providing for nominal beam parameters (e.g. 2e9 U^{73+} per cycle)
- Ramp up for (intitial) FAIR-Uranium beam parameters
- Serving FAIR-commissioning/day 1-user program with heavy ions until PSU is installed
- Providing for high intensity proton beam until p-Linac is in operation
- Serving UNILAC high duty cycle user program (SHIP, TASCA, U-Mat, U-Bio, …)

Pushing the limits for uranium beam operation (2014 – 2016)

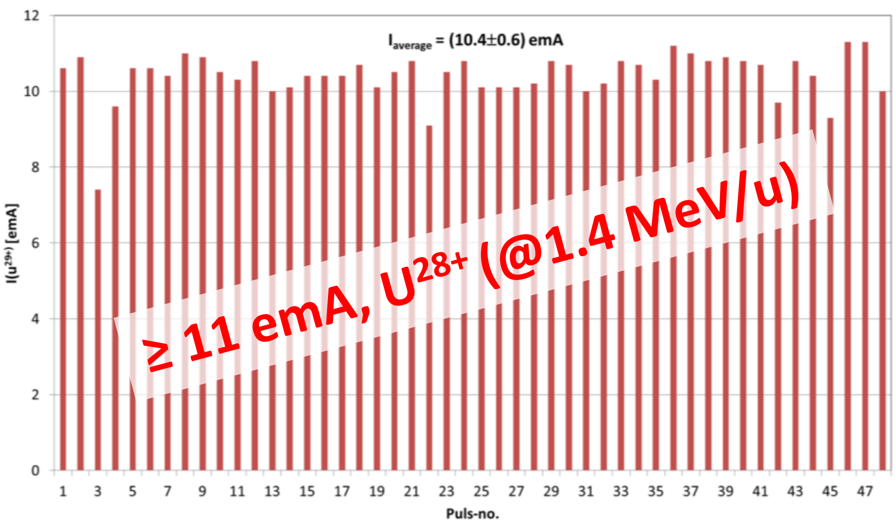
High Current Injector



- **Ion Source:** Applying a multi-aperture (7-hole) extraction system at the VARIS ion source → Increased U^{4+}-intensity and improved primary beam brilliance
- **Low Energy Beam Transport:** Improved LEBT-performance and RFQ-Matching using high brilliance Uranium beam from the VARIS → 75% RFQ-Transmission
- **RFQ:** RF optimization by adjusting plunger positions at the HSI RFQ tank and extensive rf-conditioning → Reduction of forwarded rf-power, yielding for reliable high-current uranium beam operation
- **MEBT:** Optimizing the between RFQ and IH DTL by increasing the transverse and longitudinal focusing strength (3%) → Reduction of beam loss, stable high current operation.
- **1.4 MeV/u-Transport Line:** Adapting the quadrupole channel (matching the gas stripper) → 90% beam transmission, U^{4+} beam current of 7.6 emA available for heavy ion stripping.
- **Gas Stripper:** H_2-pulsed gas stripper prototype => ≥11 emA, U^{28+}, 0.5 mm·mrad (hor.)
- **Reliable high current beam operation!**

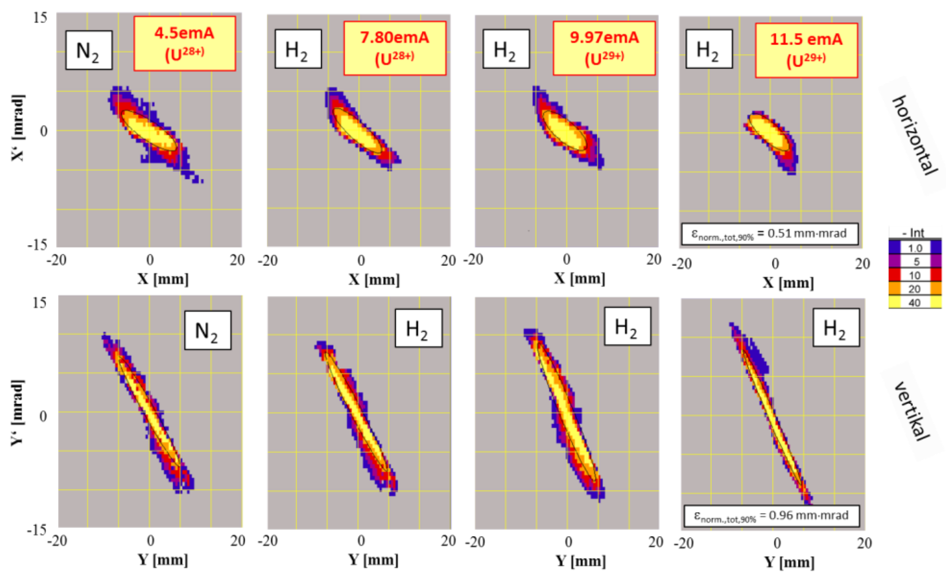
U^{28+} high current (brilliance) beam measurements (2014-2016)

beam current



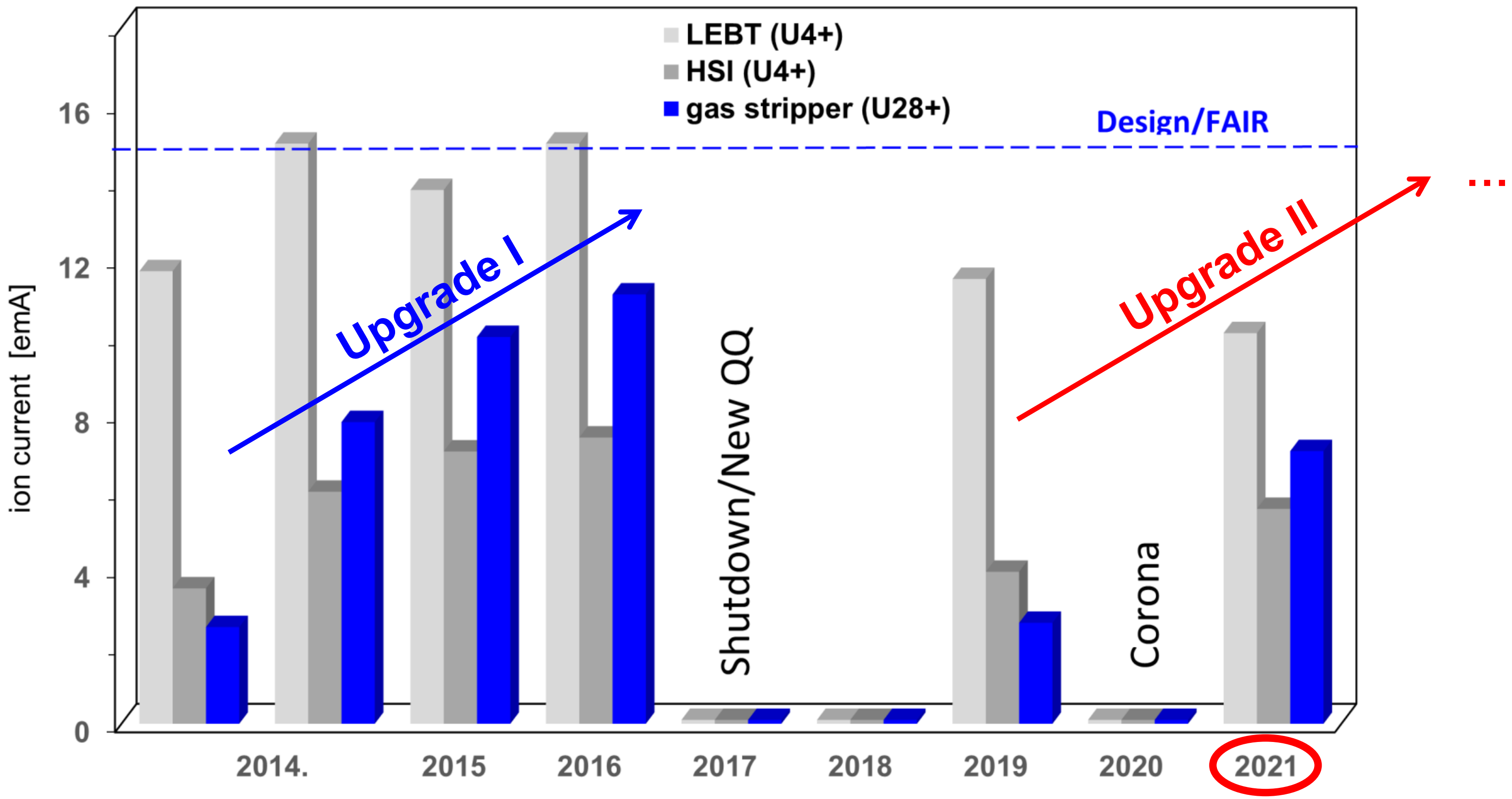
beam emittance

$\varepsilon_{90\%,tot} \approx$ 0.5 µm



$\varepsilon_{90\%,tot} \approx$ 1.0 µm

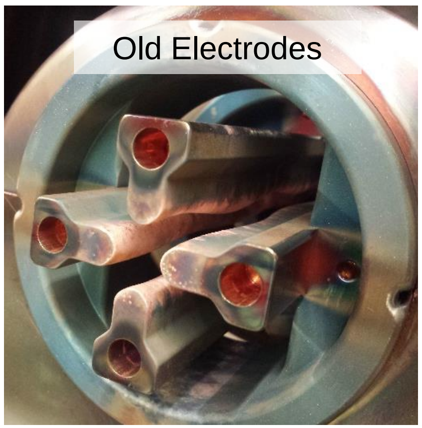
HSI-Uranium-intensities

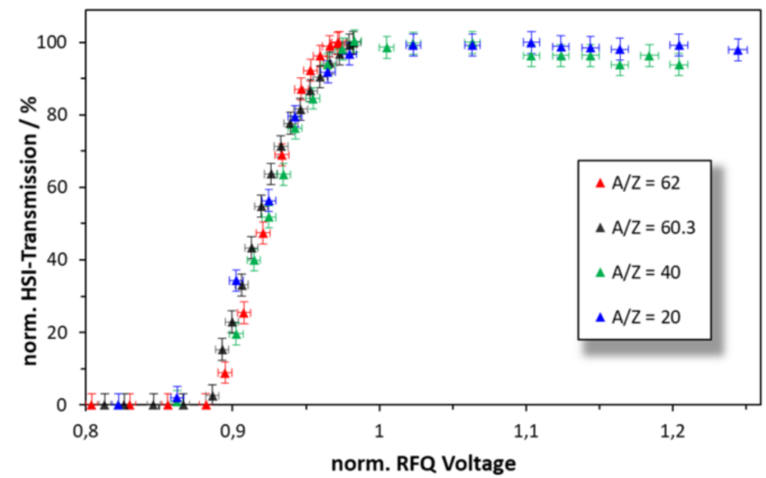


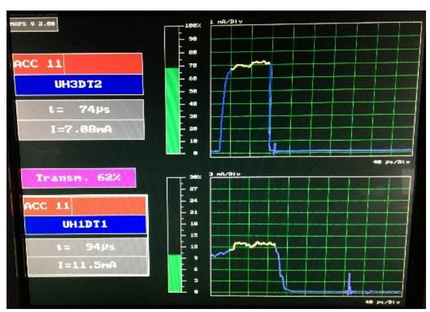
← no Uranium beam user operation →

HSI-RFQ-Upgrade (2019)

- **New (longer) Quadrupole Quartett (2017/18)**
- **HSI-RFQ: New electrodes (2019) installed (2018: Rf-level limited to max. 74% of design)**



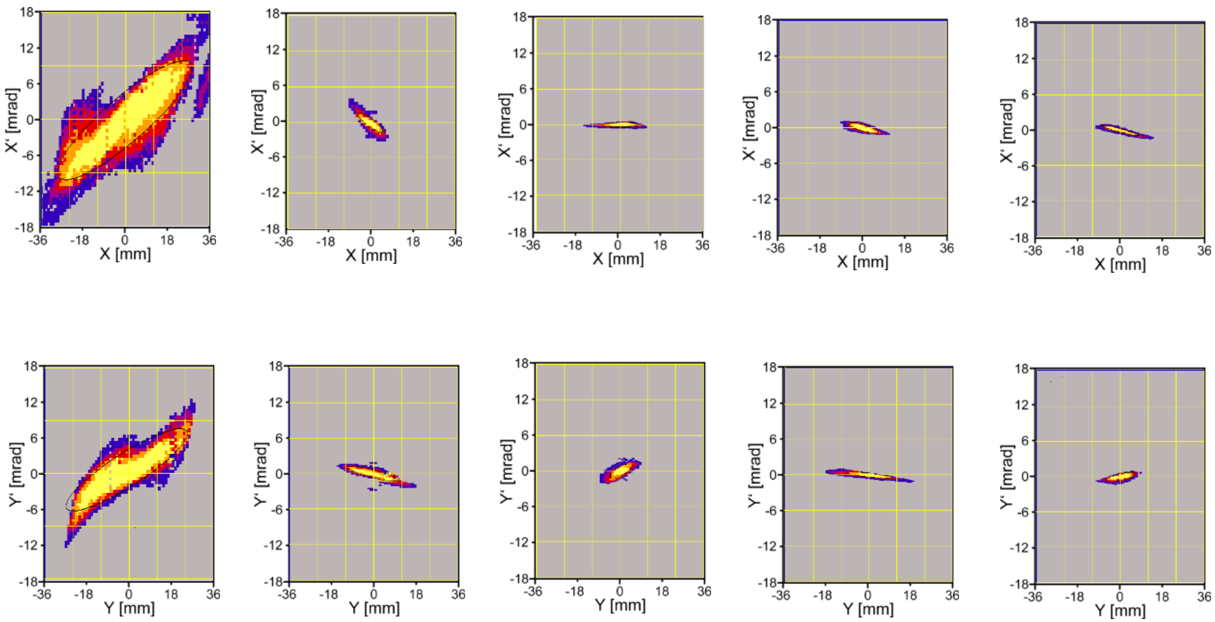




- **90% of the design Rf-level applied successfully**
- **redefinition of RFQ-working point**
- **Sufficient U^{4+}-RFQ-operation ($^{124}Xe^{2+}$; A/q = 62)**
- **60% of best HSI-performance (2016)**
- **U^{4+} => U^{28+} => U^{73+} (11.4 MeV/u)**

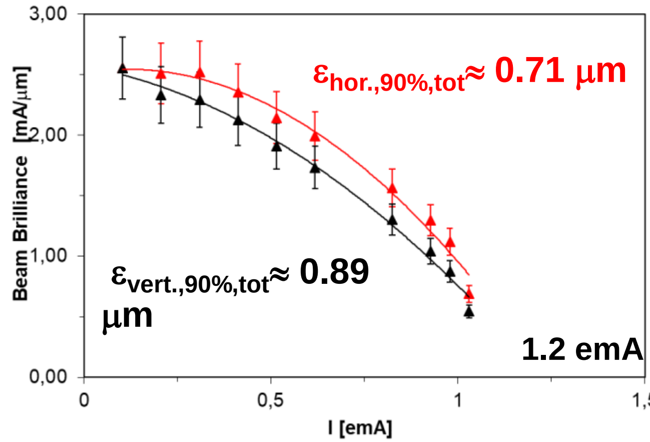
UNILAC-heavy ion beam studies: U^{4+} => U^{73+}
(further improvements with N_2-gas jet stripper: 4/2021)

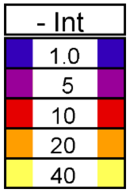
LEBT	N_2-gas stripper	poststripper	TK5	TK8
2.2 keV/u	1.4 MeV/u	11.4 MeV/u	11.4 MeV/u	11.4 MeV/u



11.0 emA	5.0 emA	4.0 emA	1.5 emA	1.2 emA

≈1e10 U^{73+}-particles/100µs





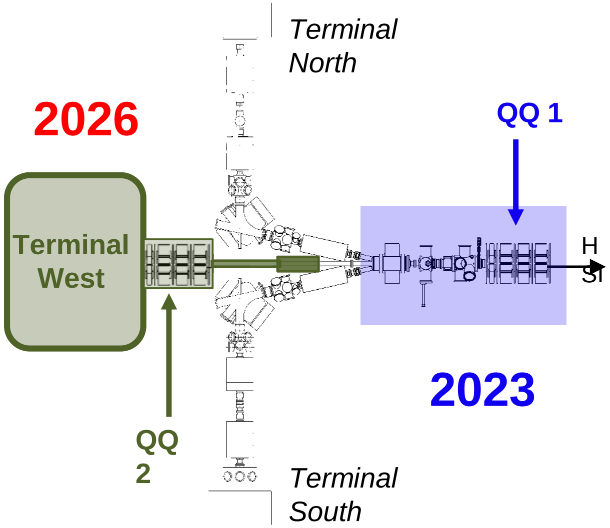
UNILAC machine parameter campaign 2020/2021

>80%
>15%
<15%

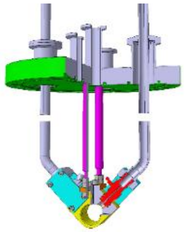
gas stripper	charge	ion species (FAIR)	I [emA] (FAIR)	measured I/1 mm*mrad (hor.) [emA/mm*mrad]	[%]
N2	28	U	15,0	0,80	5,3
H2	28	U	15,0	2,90	19,3
N2	73	U	5,8	0,30	5,2
N2	73	U (-QQ)	5,8	1,20	20,9
H2	73	U	5,8	1,10	19,1
N2	26	Bi	14,2	1,00	7,0
H2	28	Bi	13,2	2,70	20,5
N2	68	Bi	5,4	0,53	9,8
H2	68	Bi	5,4	1,10	20,3
N2	-	Ta	-	-	-
N2	-	Xe	-	-	-
N2	10	Ar	7,1	5,50	77,9
N2	18	Ar	3,9	4,00	102,0
N2	6	C	3,5	0,50	14,2
N2	1	H (-30deg)	1,8	1,30	73,7
N2	1	H (-57deg)	1,8	1,00	56,7

Further UNILAC-Upgrade I

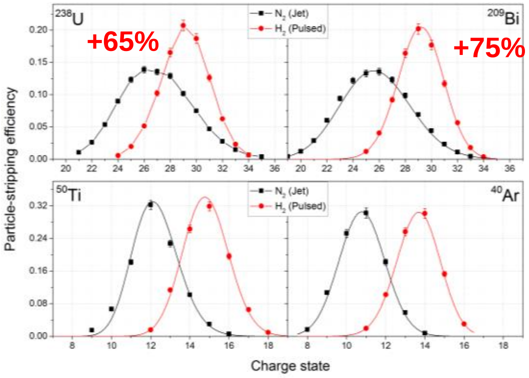
PRe Injector DEdicated for Uranium operation (PRIDE)



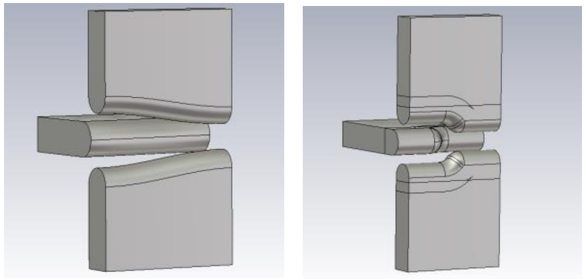
Pulsed H_2-Gasstripper
2024



Heavy ions (U, Bi):
- more narrow distribution
- increased stripping efficiency
- higher beam intensity



High intensity heavy ion RFQ with high reliability



M. Vossberg, R. Brodhage, M. Kaiser, F. Maimone, W. Vinzenz, S. Yaramyshev, GSI, Darmstadt, Germany,
DESIGN STUDIES FOR THE PROTON-LINAC RFQ FOR FAIR, IPAC'15 (2015)

Schedule
- 2019: Exchange of RFQ-electrodes
- 2020: Advanced Rf-conditioning
- 2020: U^{4+}-operation
- 2022: Exchange of LEBT-QQ (back to 2016)
- **≥2023**: Improved RFQ-electrode design (FAIR-req.)
  - lower RF-voltage (RF-power)
  - higher acceleration efficiency

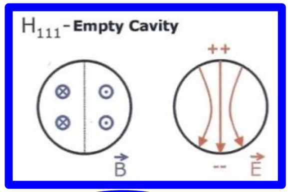
FAIR: 15 mA U^{28+} at 11.4 MeV/u:

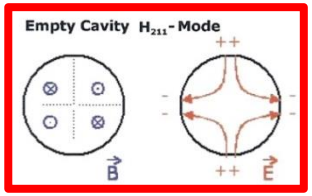
Required at RFQ entrance: **20 mA U^{4+} (inside 250 μm)**

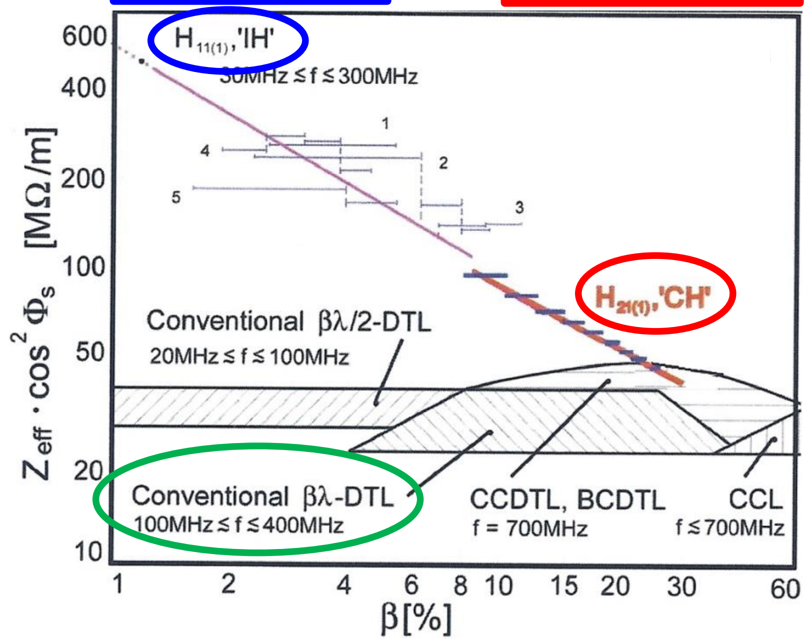
Low Z-gas stripping witth improved heavy ion stripping efficiency: **+65% => 15 mA U^{28+} (inside 1 μm)**

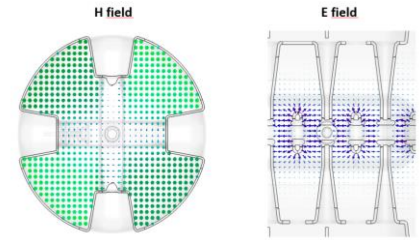
H-Mode cavity-development

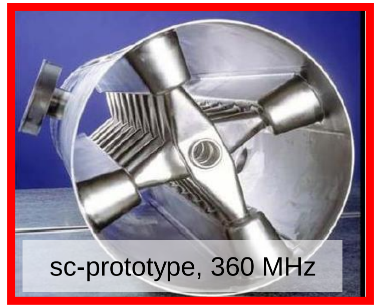
Drift tubes are alternating connected to “+” and “-” potential











cw-Linac@GSI/Motivation

FAIR:

– high beam currents
– low repetition rate (max. 3 Hz)
– low duty factor (0.1 %, pulse length for SIS18 only 100 µs)

"Super Heavy Element":

– relatively low beam currents
– high repetition rate (50 Hz)
– high duty factor (100 %, pulse length up to 20 ms)

"Material Science":

– Heavy Ions ($m \geq 200$)
– High Beam Energy (up to 10 MeV/u)
– high repetition rate (50 Hz)
– Continuous Beam Energy Variation (1.5 – 10 MeV/u)

Poststripper Rf-upgrade for FAIR

FAIR:

– high beam currents
– low repetition rate (max. 3 Hz)
– low duty factor (0.1 %, pulse length for SIS18 only 100 µs)

~~**"Super Heavy Element":**~~

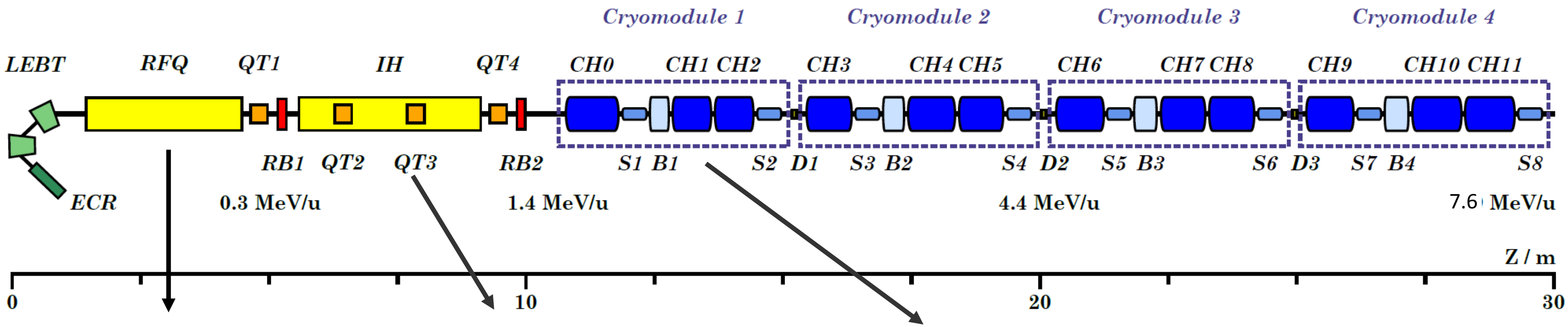
– relatively low beam currents
~~– high repetition rate (50 Hz)~~
~~– high duty factor (100 %, pulse length up to 20 ms)~~

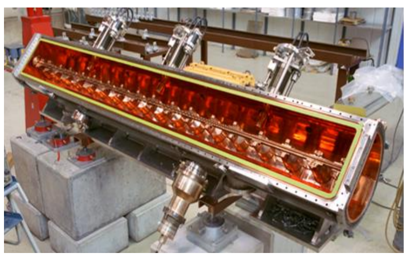
~~**"Material Science":**~~

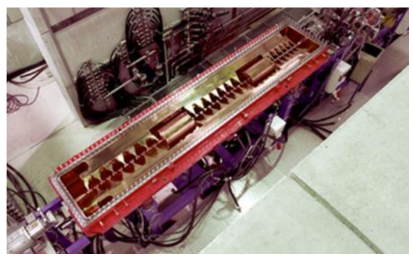
– Heavy Ions (m ≥ 200)
– High Beam Energy (up to 10 MeV/u)
~~– high repetition rate (50 Hz)~~
~~– Continuous Beam Energy Variation (1.5 – 10 MeV/u)~~

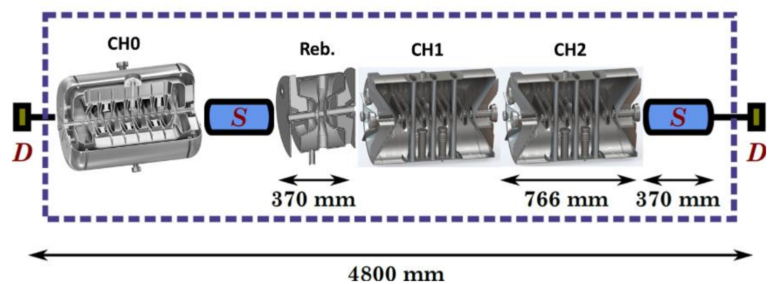
Layout of the future superconducting cw HELIAC*

* HElmholz LInear ACcelerator









Design parameters sc cw-LINAC		
A/q		≤ 6
Frequency	MHz	216.816
Beam current	mA	≤ 1
Injection energy	MeV/u	1.4
Output energy	MeV/u	3.5-7.6
Length	m	20
CH cavities	#	12
Rebuncher	#	4
Solenoids	#	8

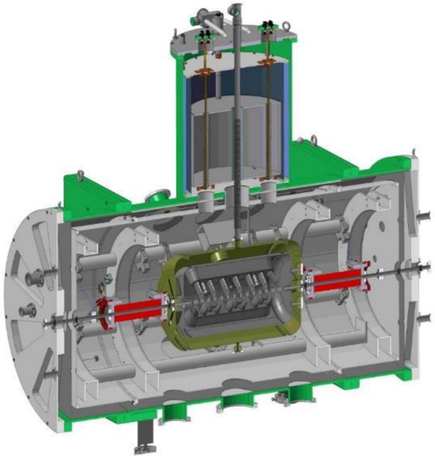
Layout properties

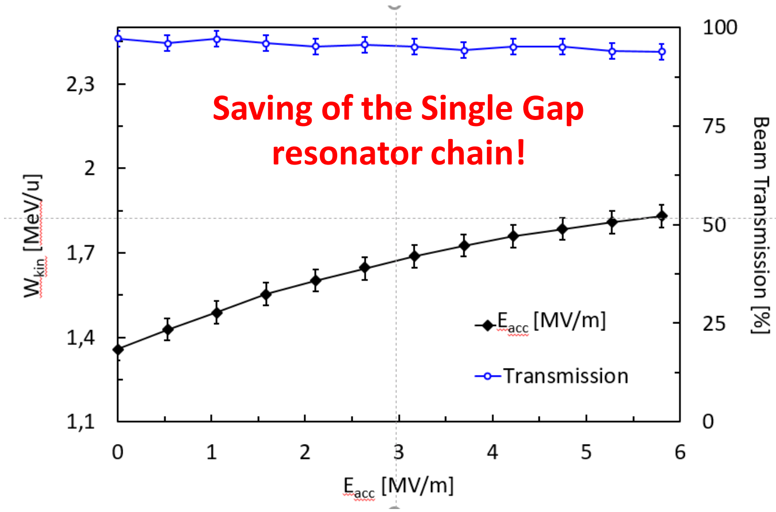
- Short multigap CH cavities: length <1 m), transverse dimensions <0.5 m
- Modular construction: 4 cryomodules each with 3 CH, 1 buncher, 2 solenoids
- Compact Linac design ($E_a \geq 7.1$ MV/m)

Maximum energy per CM

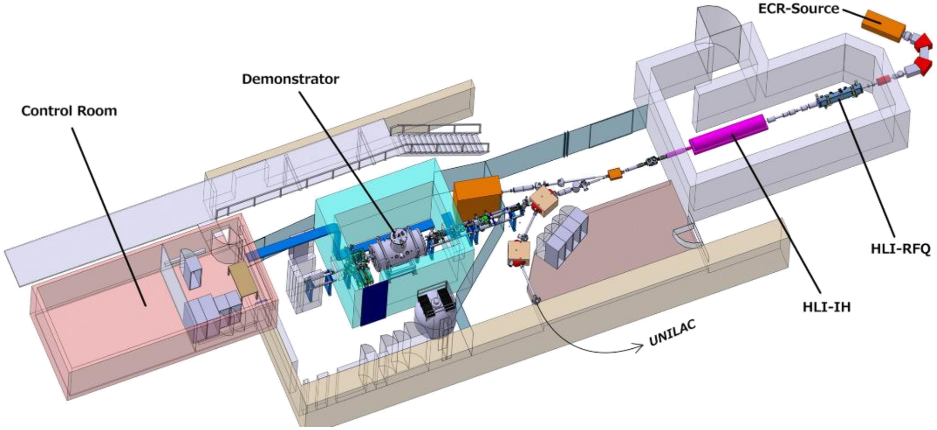
Cryo Module	Output energy (MeV/u			
	A/Z=8.5	A/Z=6	A/Z=3	A/Z=1
CM1	2.6	2.9	3.6	4.6
CM2	3.5	4.2	5.5	7.7
CM3	4.5	5.8	7.8	10.9
CM4	5.55	7.6	10.5	14.6
CM4 + CH12	6	8	11.4	15.6

Former cw-Linac R&D



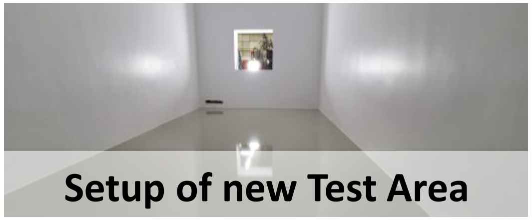


- First superconducting 217 MHz-CH-Cavity
- High E_{acc}-gradient up to 10 MV/m
- High quality factor → low RF-dissipation (<10W)
- Equidistant gaps → **continuous energy variation**
- 2017: Successful beam commissioning at GSI



Demonstrator at GSI-High Charge State Injector

cw-Linac-Infrastructure



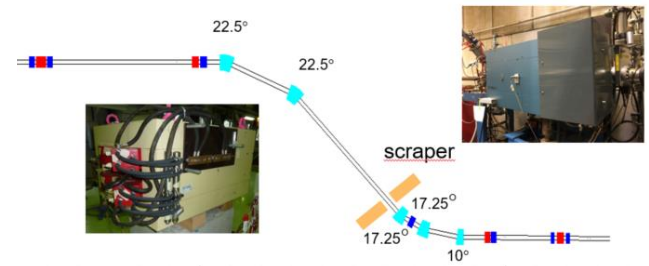
Setup of new Test Area

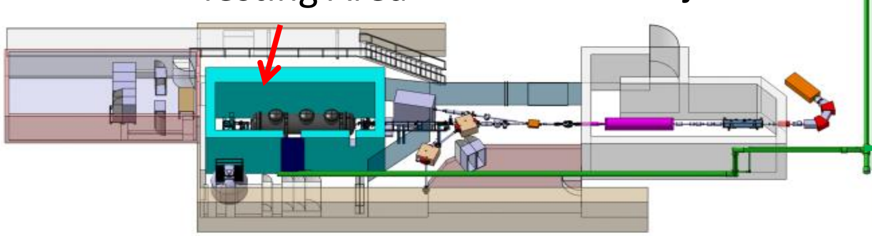
Link to STF (SeriesTest Facility)

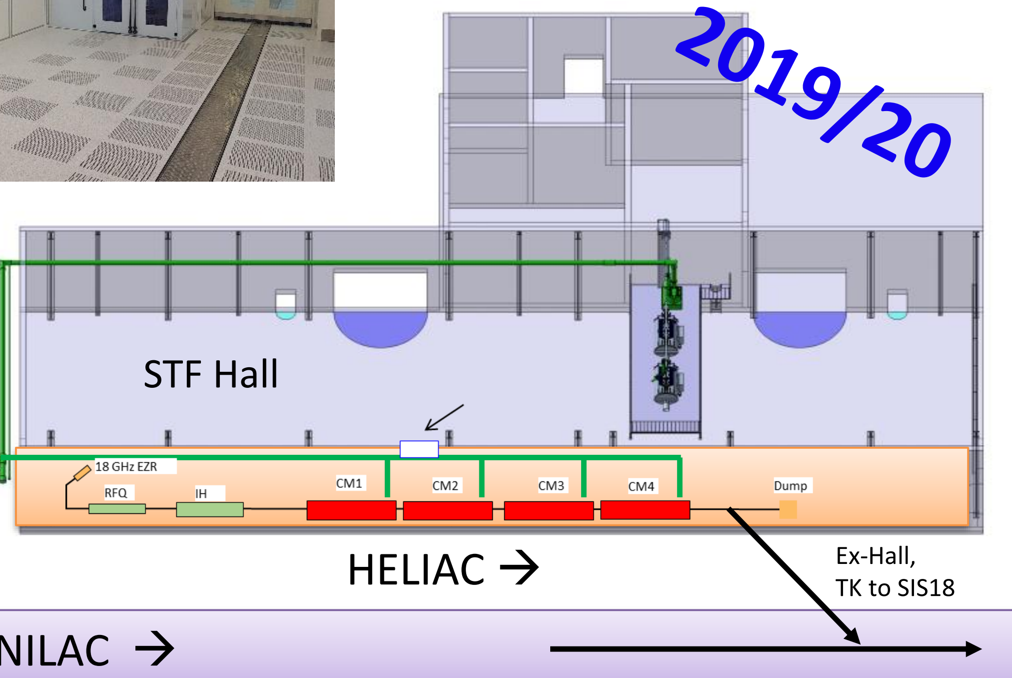
Infrastructure in Mainz:

- Clean room environment
- High Pressure Rinsing
- Rf-test bunker

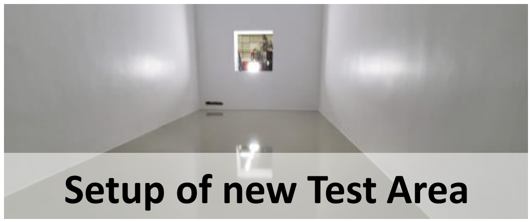
HEBT to UNILAC







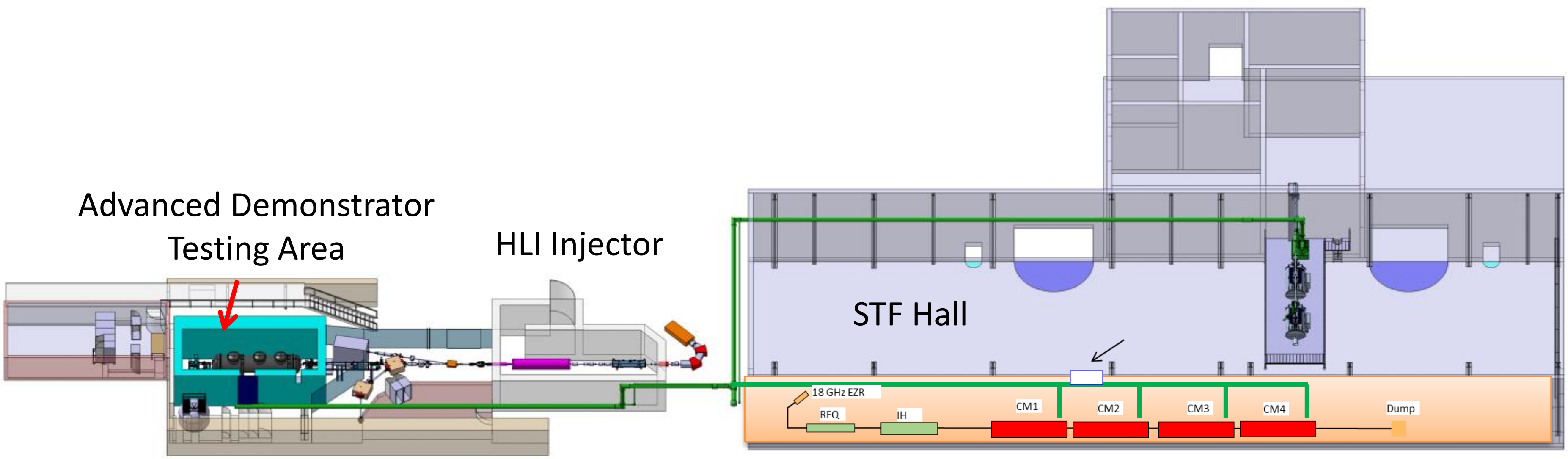
cw-Linac-Infrastructure



Infrastructure in Mainz:

- Clean room environment
- High Pressure Rinsing
- Rf-test bunker

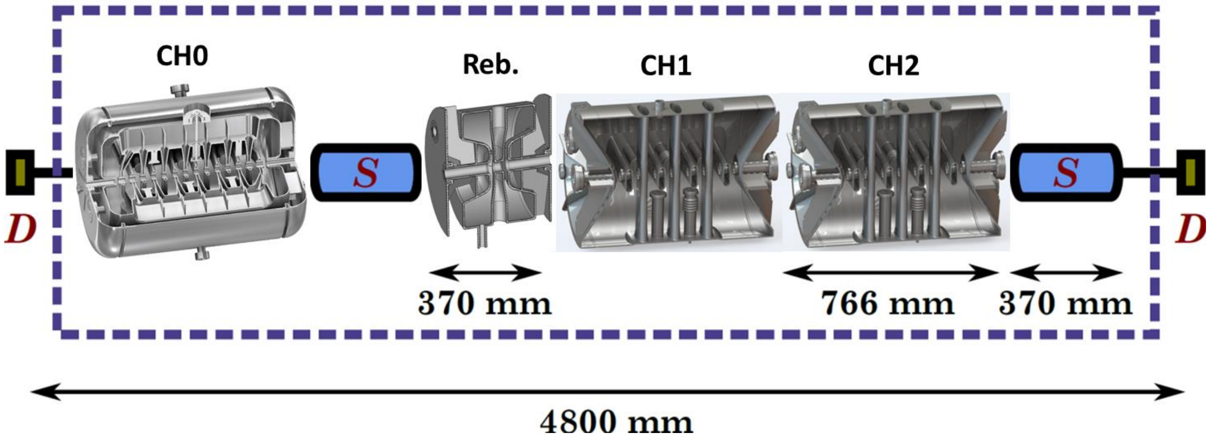
HEBT to UNILAC

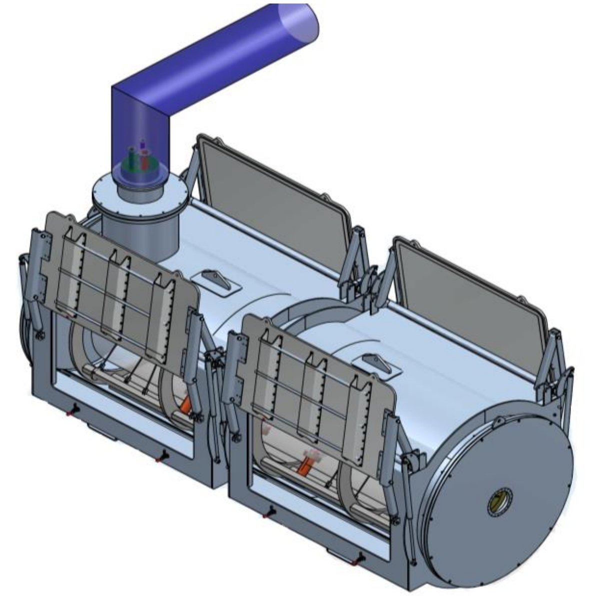


HELIAC →

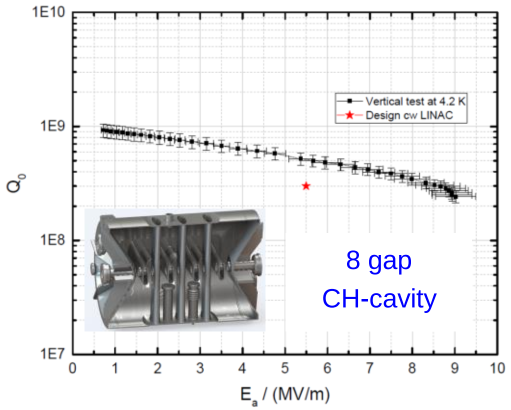
cw-Linac-Prototyping: Advanced Demonstrator

Standard cryomodule layout



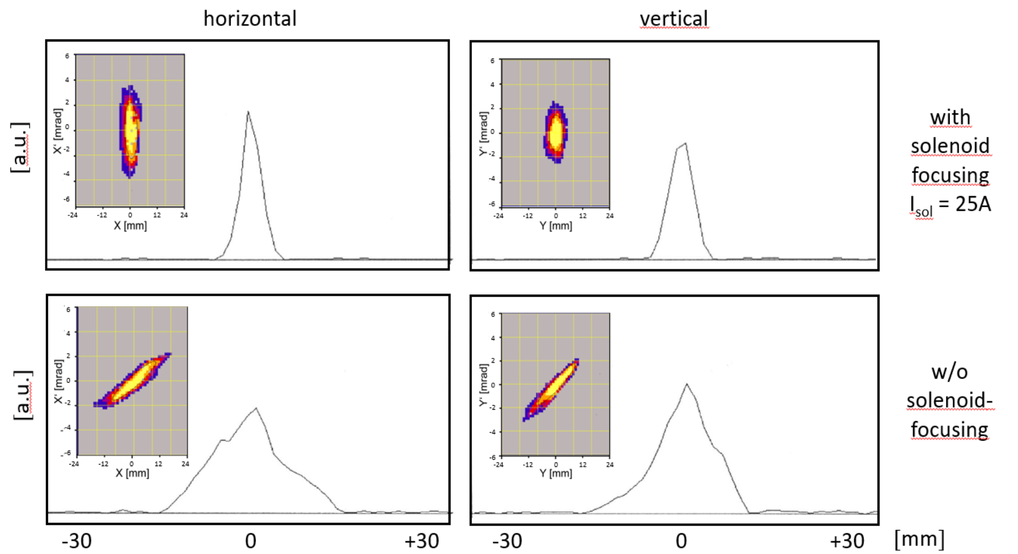


- New cryo module layout containing demonstrator CH cavity, 2 short CH cavities, 1 buncher and 2 solenoids
- Simplified cavity design (easier manufacturing & surface processing
- CH1 & CH2 are already produce and tested
- cryostat delivery Q2/2021
- compact linac design for or higher A/q (=8.5)



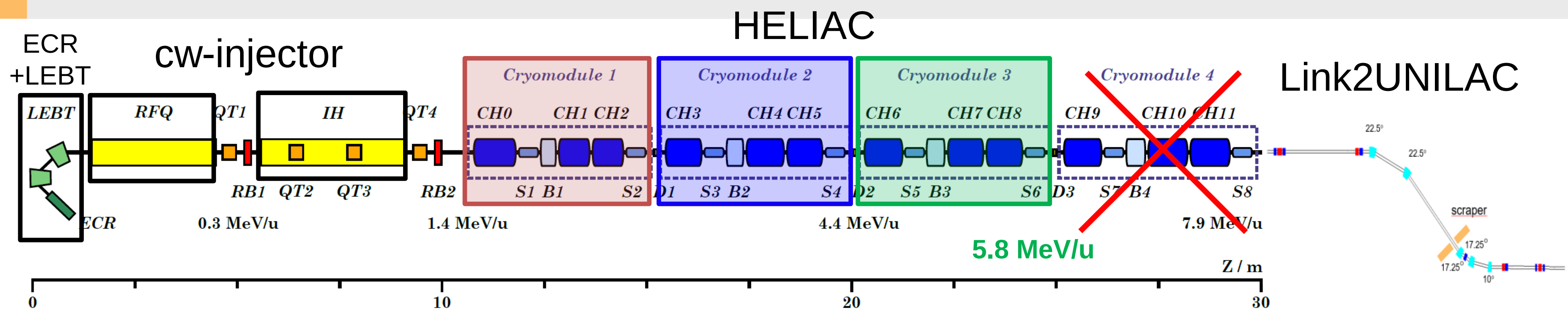
Test of cw-Linac Advanced Demonstrator
- first HELIAC cryomodule -

Ar^{8+}-beam commissioning of superconducting solenoids



July 2021

cw-LINAC „basic approach“



2026

normal conducting 25%-injector Linac

- **ECR + LEBT**
  - 18 GHZ-ECR
  - LEBT (prelim. layout)
- **cw-RFQ**
  - former HLI-RFQ
- **cw-IH-DTL (tendering: Q1 2021)**
- **transport sections, etc.**
  - MEBT, Matching Line, HEBT (Quads, Dipole)
  - cw-Rebuncher, debuncher
- **High power Rf-ampl.** (RFQ, IH, buncher) (reused)
- **Other supply systems**
  - Power supplies (LEBT, MEBT, HEBT)
  - beam diagnostics, vacuum system, controls

superconducting cw-Linac

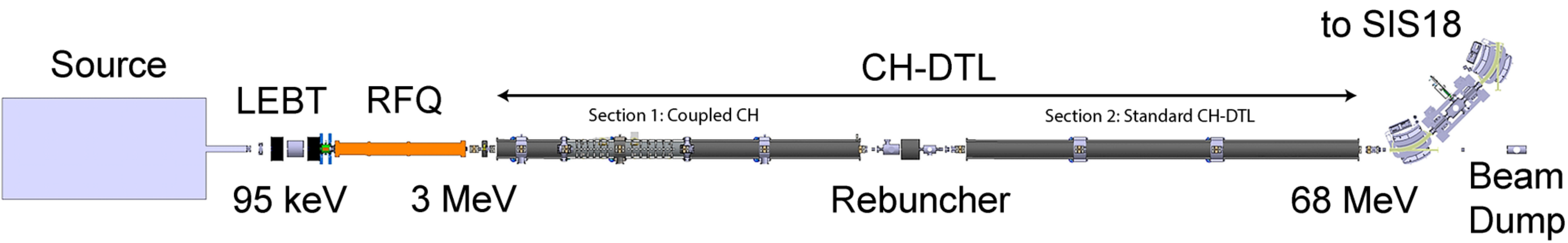
- **CM1 (PoF3)**
  - CH1 tested & CH2 tested
  - Rebuncher cavity ordered
  - Cryostat ordered
  - Solenoids ordered
  - 4 rf amplifiers ordered
  - aux. comp. (couplers, tuner, BPM, LLRf)
- **CM2 (PoF4)**
  - CH3-5 specified, ordering (tendering/Q3 2021)
  - Re-buncher cavity ordered
  - Cryostat ordered
  - Solenoids, rf Amplifiers, aux. components
- **CM3 (BmBF)**
  - CH6-8 specified, ordering (tendering/Q2 2021)
  - Re-buncher, Cryostat, Rf Amplifiers, …
  - Solenoids

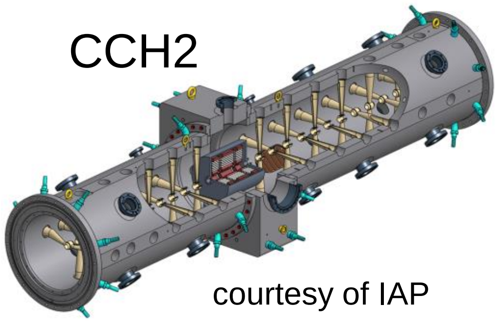
cw-Linac: Timeline

Q4/2022	CM1 (Advanced Demonstrator) beam test at Test Area
Q2/2024	**Linac-Tunnel (@SH2/3) ready for installation of components**
Q3&4/2024	ECR and LEBT commissioning @ Linac-tunnel
Q4/2024	CM2 beam test at Test Area
Q1/2025	RFQ commissioning @ Linac tunnel
Q2/2025	cw-IH-DTL commissioning @ Linac tunnel
Q3/2025	Matching Line & CM1 commissioning
Q4/2025	CM2 commissioning (and CM3 beam at Test Area)
Q1/2026	**CM3 & HEBT to UNILAC commissioning**

@Additional schedule for test activities at HI-Mainz

FAIR proton Linac





courtesy of IAP

Beam Energy (MeV)	**68**
Beam Current (mA)	**35 - 70**
Beam Pulse (µs)	**36**
Repetition Rate (Hz)	**4 (2,7)**
Protons per pulse	**$7 \cdot 10^{12}$**
Frequency (MHz)	**325.224**
Norm. Emittance at output (µm)	***4.2***
Momentum Spread	**$\leq \pm 10^{-3}$**
Beam Loading (peak) (MW)	**4.9**
RF Power (peak) (MW)	**2.2**
Klystrons (3 MW Peak Power)	**7**
Solid State Amplifier (50 kW/180kW)	**3**
Total Length (RFQ + CH)	**≈ 27 m**

Rf-Coupled Crossed-bar H-Cavities

- **reduce number of klystrons**
- **reduce place requirements**
- **profit from 3 MW klystron development**
- **avoid use of magic T's**
- **reduce cost for rf-equipment**

2.45 GHz ECR source generating 100 mA of 95 keV protons (CEA)

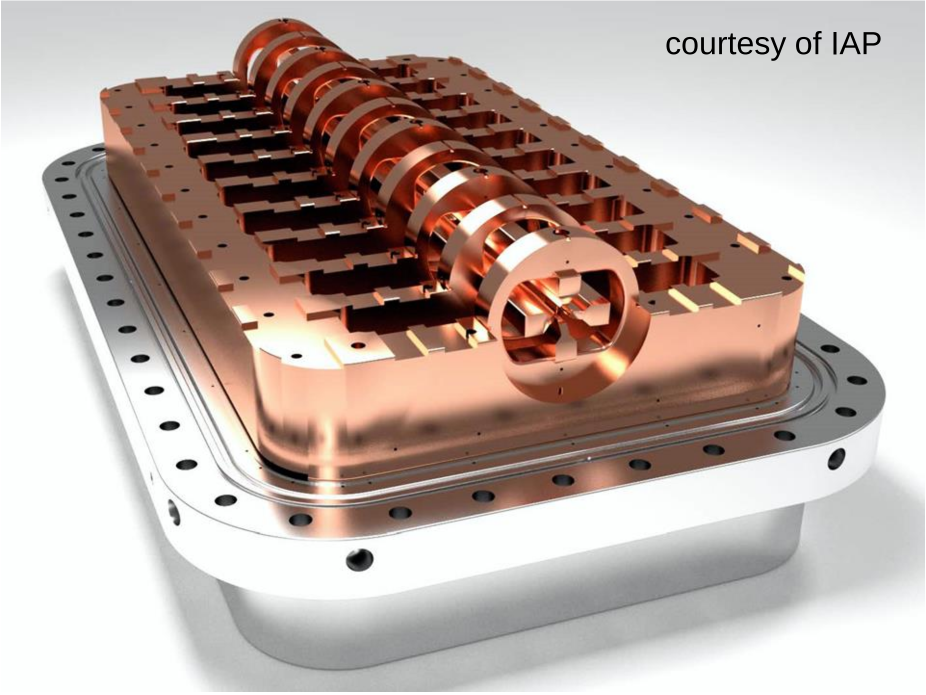
LEBT & diagnostics chamber:
faraday cup / allison scanner / wien filter (CEA)

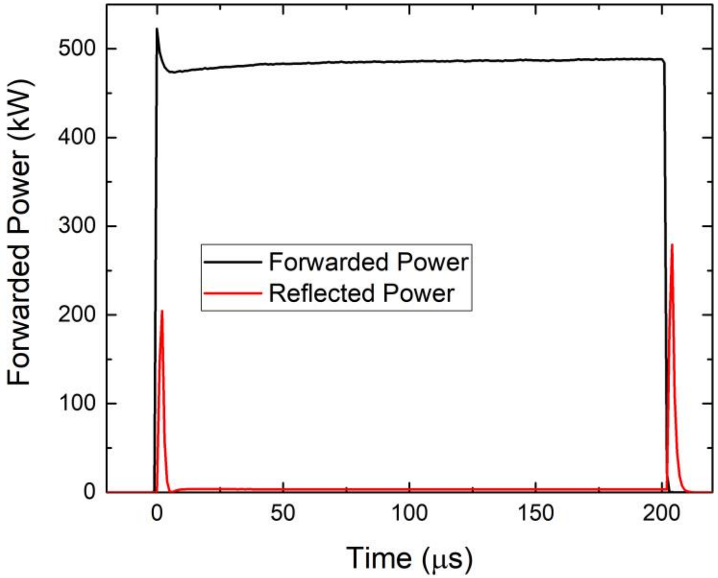
ladder 4-Rod RFQ with chopper and a beam dump in front

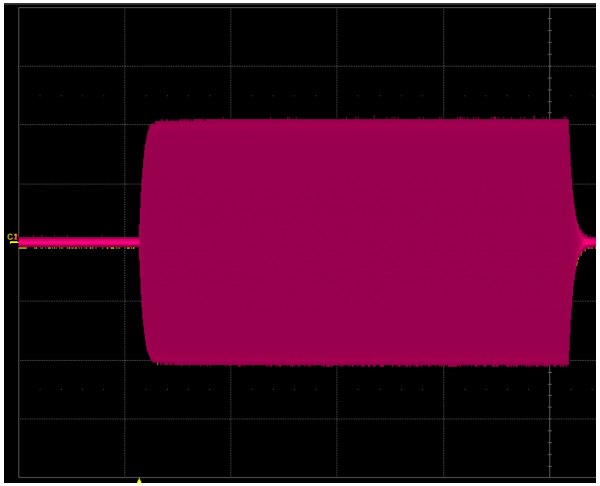
Six normal conducting crossbar cavities of CCH and CH type aranged in two sections with intermediate diagnostic section (IAP)

Ladder RFQ *prototype*

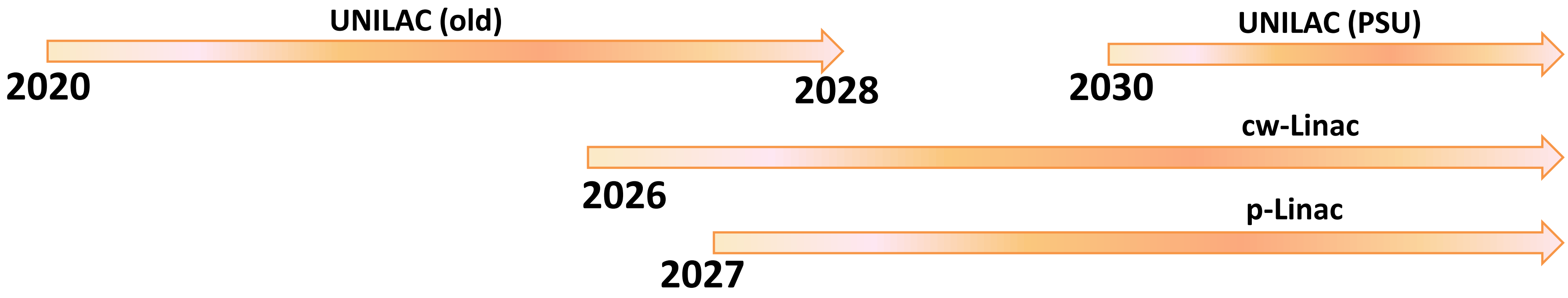
05/2016 – high power tests@GSI
500 kW @ 2 Hz / 200 µs







Injector Linac schedule



UNILAC, essentially as it is currently available (≤2028)

- **No high duty factor operation at UNILAC after…**
  - Poststripper-Rf-Upgrade => **cw-Linac ≥2026**

UNILAC, with replaced poststripper (≥2030)

- **no availability during installation and commissioning phase (≥18 months)**

FAIR-p-Linac (≥2027)

- **no availability during installation and commissioning phase**
  - UNILAC as medium intensity injector Linac for proton beams

cw-Linac (≥2026)

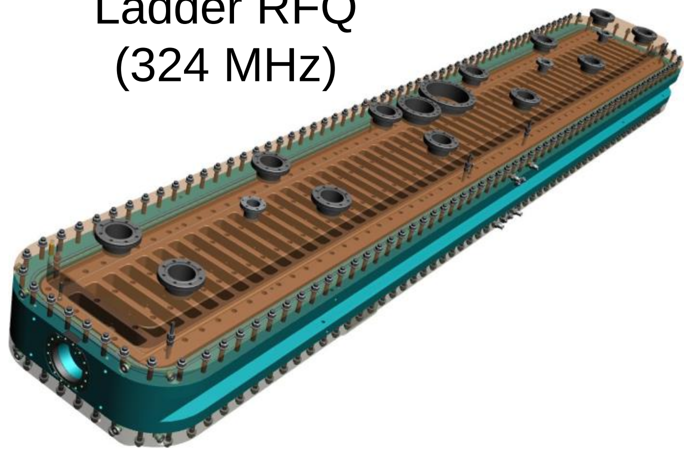
- **no availability during installation and commissioning phase**
  - UNILAC as high duty factor (25%) heavy ion Linac (FAIR-0)

Summary&Outlook

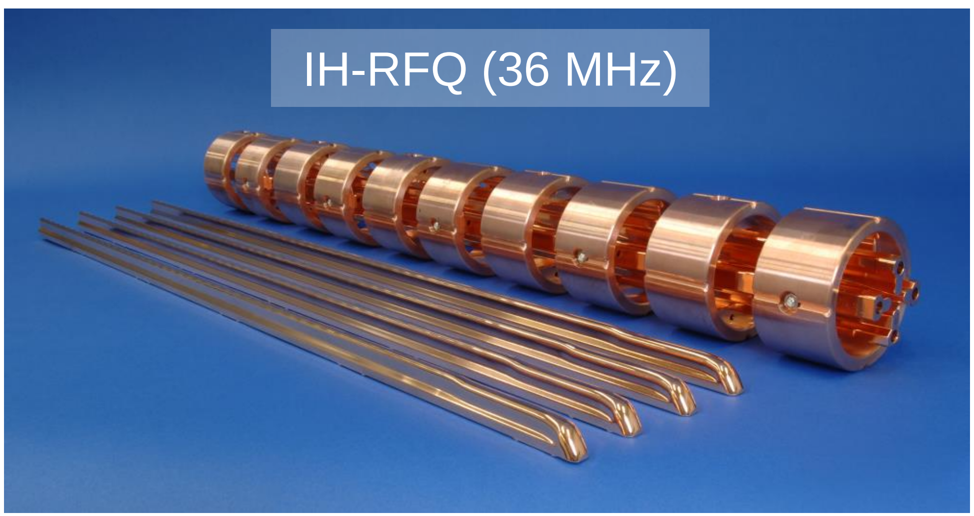
- Development of modern and efficient H-mode Rf-cavities contribute decisively to the reduction of size and costs of HI-Linacs
- In collaboration with Goethe University Frankfurt (IAP) various HI-Linac projects (e.g. GSI-HSI-Linac, HIT-, MIT-Linac, …) have been successfully carried out at GSI over the last 30 years on the basis of these developments.
- FAIR-UNILAC-Upgrade I (2014-2016): 11 emA, U^{28+} at 1.4 MeV/u
- FAIR-UNILAC-Upgrade II (2019 - 2026) : Aiming for 15 emA, U^{28+} at 11.4 MeV/u
- The GSI UNILAC provides for high current proton beam in routine operation (≈1.5 emA)
- Normal conducting C(C)H cavities, as well as novel ladder RFQ are applied in the FAIR p^{+}-Linac (68 MeV, 35 emA)
- After start of PSU-installation (new short pulse operated ALVAREZ-DTL): No high duty factor beam available anymore!
- cw-Linac R&D: Design acceleration gain was achieved with heavy ion beams even above the design mass to charge ratio at full transmission and maximum available beam intensity
- Beam quality was measured as excellent in a wide range of different beam energies, confirming advanced beam dynamics design
- New HELIAC-design could provide beam acceleration for a wide range of different ions (protons to uranium), featuring the ambitious GSI-user program, while the GSI-UNILAC is upgraded for short pulse high current FAIR-operation
- A basic cw-Linac approach (3 CM each with 4 CH-cavities, limited to 25% duty factor) is envisaged to be built and commissioned until 2026

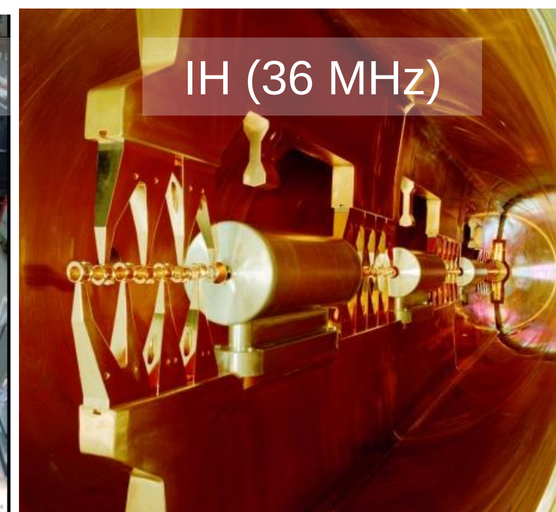
Thank you for your attention

Ladder RFQ
(324 MHz)



superconducting
CH (216 MHz)





My thanks go to all collaborators and colleagues who have contributed to the far-reaching developments of the last years, especially from GSI (accelerator area), HIM and Goethe University Frankfurt (Institute of Applied Physics).