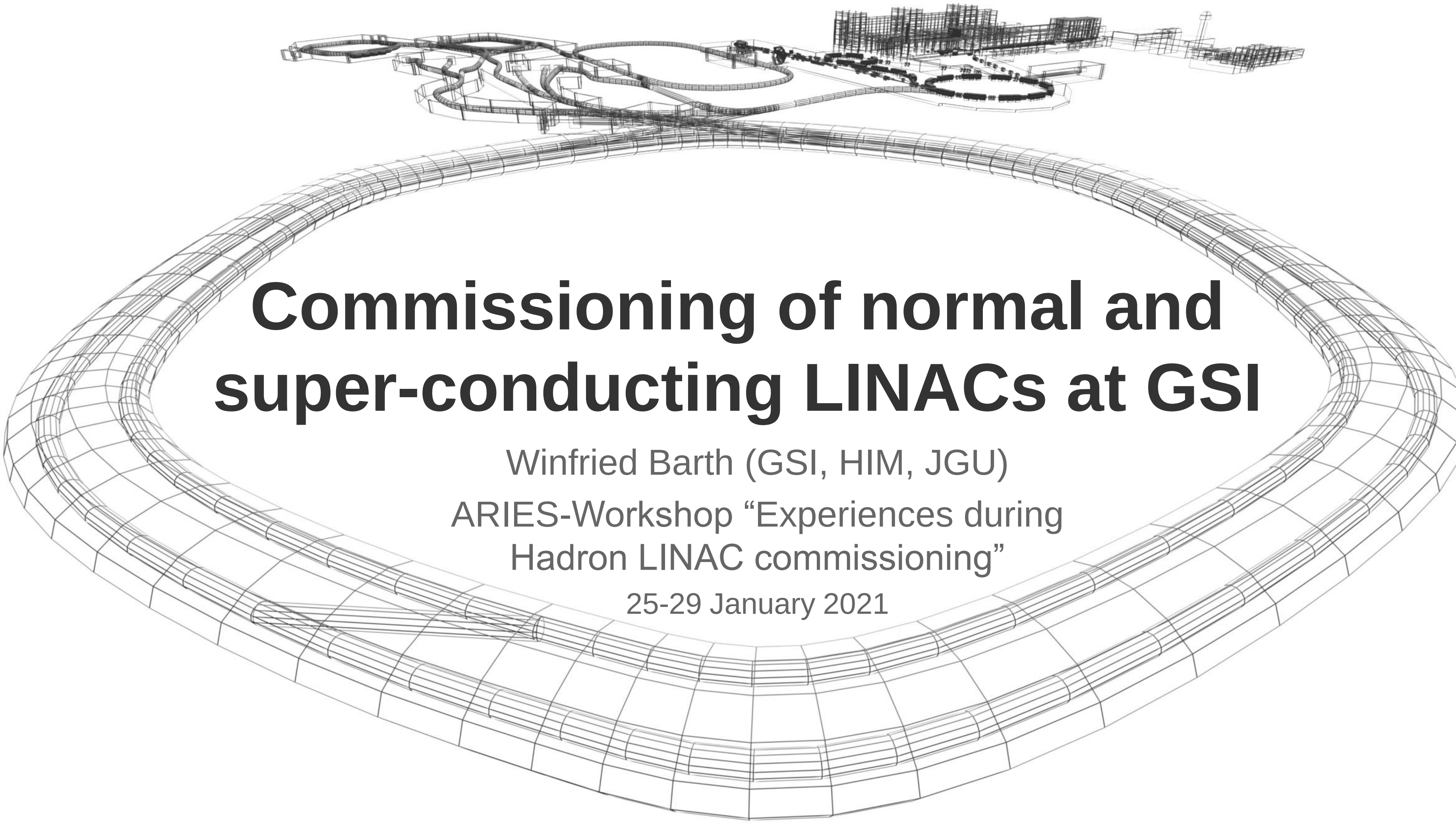


Commissioning of normal and super-conducting LINACs at GSI

Winfried Barth (GSI, HIM, JGU)

ARIES-Workshop “Experiences during Hadron LINAC commissioning”

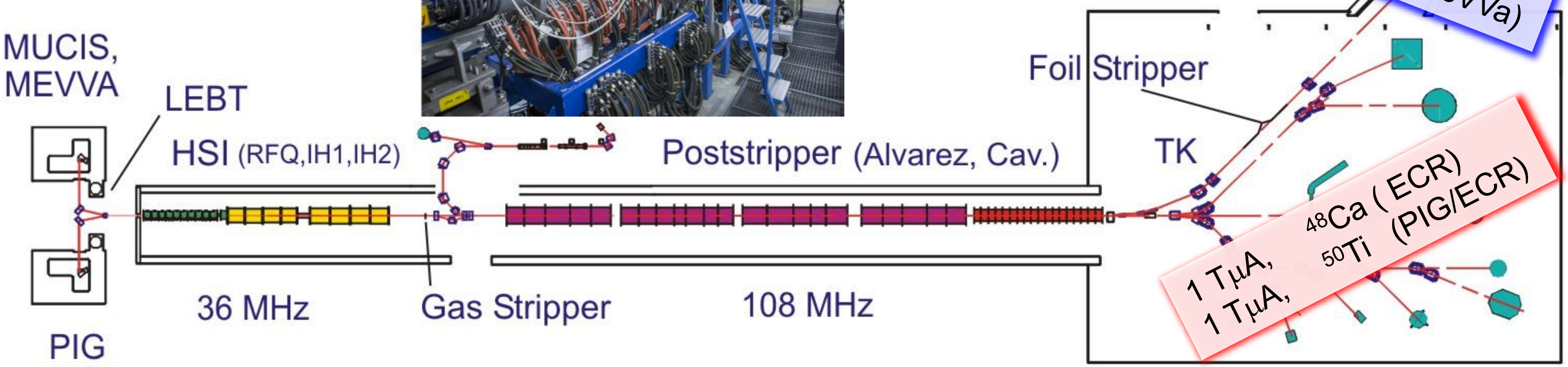
25-29 January 2021

Outline

1. GSI accelerator facility and Linac injector strategy
2. High Current Injector
   - Initial commissioning (1999)
   - Re-commissioning (2004, 2009, 2019)
3. 11.4 MeV/u charge separator commissioning
4. Commissioning steps of superconducting cw-Linac
   - Matching line to the cw-Linac-test area
   - Demonstrator cryomodule
   - Cryomodule I
5. Outlook

GSI UNIversal Linear ACcelerator

High Charge State Injector (1991)



High Current Injector (1999)

Alvarez (1975)

Single Gap Resonators (1975)

GSI/FAIR-Requirements

FAIR:

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

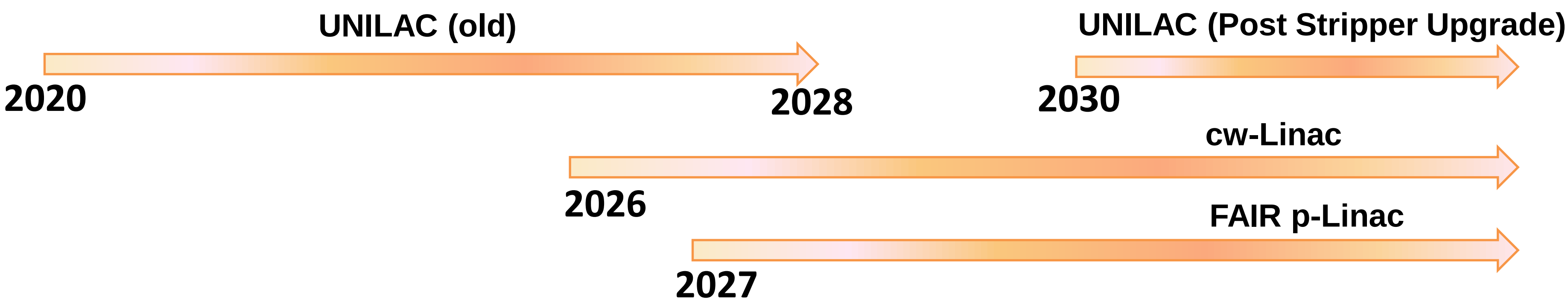
“Super Heavy Element”:

- 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)

Injector Linac schedule



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

- Poststripper-Rf-Upgrade => No more high duty factor operation =>cw-Linac

UNILAC, with replaced poststripper (≥2030)

- no availibilty during installation and commissioning phase ≥ 15 months)

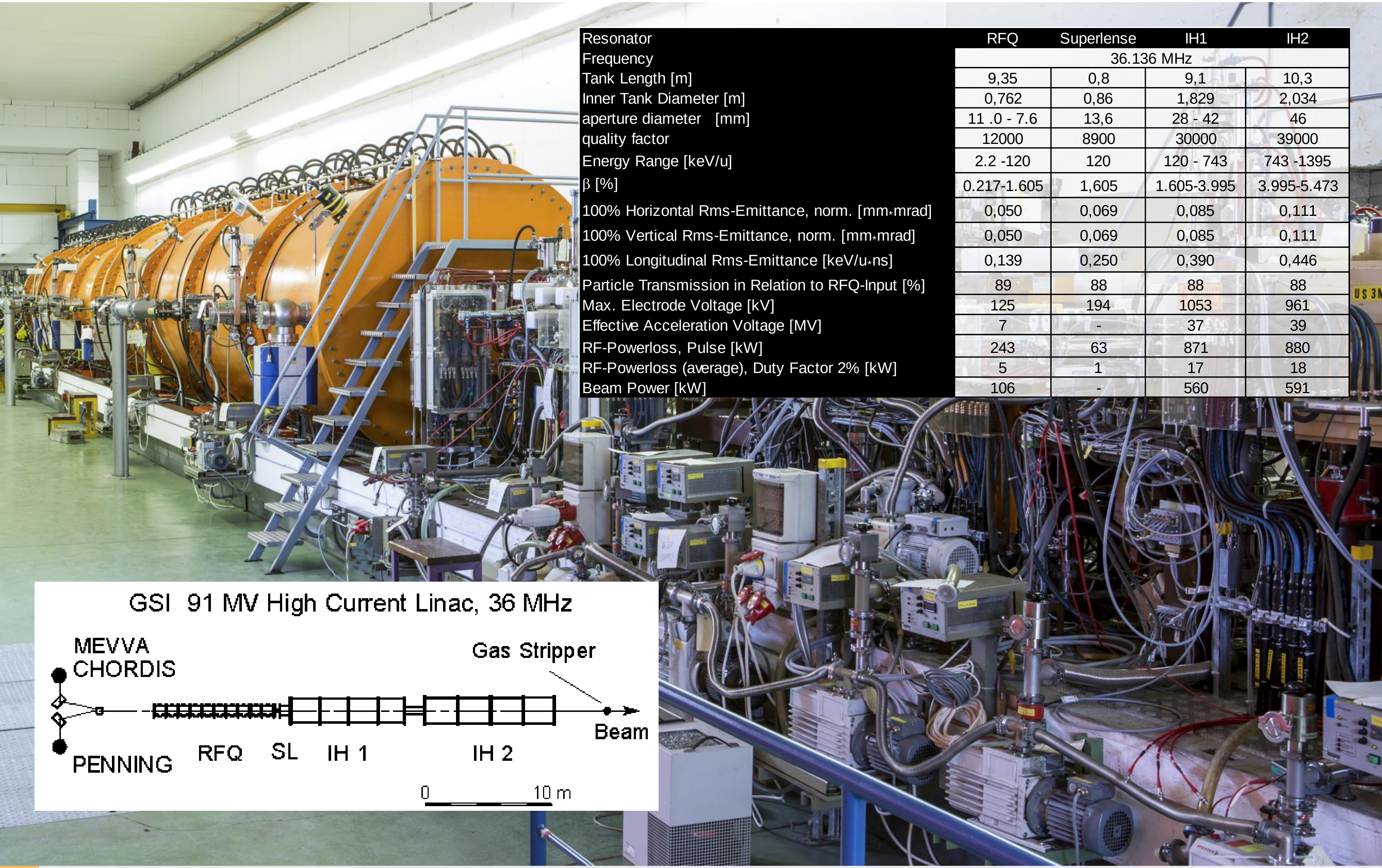
FAIR-p-Linac (≥2027)

- no availibilty during installation and commissioning phase (UNILAC as medium intensity injector Linac for proton beams)

cw-Linac (≥2026)

- no availibilty during installation and commissioning phase (UNILAC as high duty factor (25%) heavy ion Linac)

GSI High Current Injetor



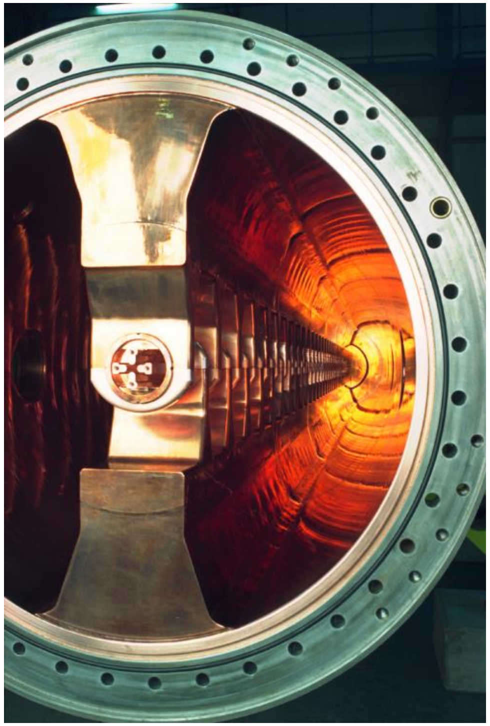
Resonator	RFQ	Superlense	IH1	IH2
Frequency	36.136 MHz			
Tank Length [m]	9,35	0,8	9,1	10,3
Inner Tank Diameter [m]	0,762	0,86	1,829	2,034
aperture diameter [mm]	11 .0 - 7.6	13,6	28 - 42	46
quality factor	12000	8900	30000	39000
Energy Range [keV/u]	2.2 -120	120	120 - 743	743 -1395
β [%]	0.217-1.605	1,605	1.605-3.995	3.995-5.473
100% Horizontal Rms-Emittance, norm. [mm*mrad]	0,050	0,069	0,085	0,111
100% Vertical Rms-Emittance, norm. [mm*mrad]	0,050	0,069	0,085	0,111
100% Longitudinal Rms-Emittance [keV/u*ns]	0,139	0,250	0,390	0,446
Particle Transmission in Relation to RFQ-Input [%]	89	88	88	88
Max. Electrode Voltage [kV]	125	194	1053	961
Effective Acceleration Voltage [MV]	7	-	37	39
RF-Powerloss, Pulse [kW]	243	63	871	880
RF-Powerloss (average), Duty Factor 2% [kW]	5	1	17	18
Beam Power [kW]	106	-	560	591

HSI-Linac comissioning strategy

- Prerequisite I
  - Installation in an existing Linac tunnel
  - no (major) additional TGA
  - Set up of an temporary shielding wall
  - Parallel (beam) operation at UNILAC-tunnel from 2nd. injector
- Prerequisite II
  - all Rf-amplifiers (and Rf-controls) installed and commissioned (on water load)
  - Dedicated beam diagnostics test bench for low and high intensity heavy ion beam operation
  - test bench individually adapted for each commissioning step
  - test bench components finally inegrated in gas stripper section
- step by step aproach
  - IQ&LEBT – RFQ – SL – IH1 –IH2&stripper section (6 weeks each)
  - set up – installations – controls - power supplies – vacuum commissioning – 10^{-7} mbar - beam diagnostics – Rf-conditioning until a certain theshold
  - 2 shift operation for all employees involved in the installation
  - 3 shift operation for the commissioning crew
  - On call service of all technical infrastructure expert groups
  - 2 weeks beam commissioning

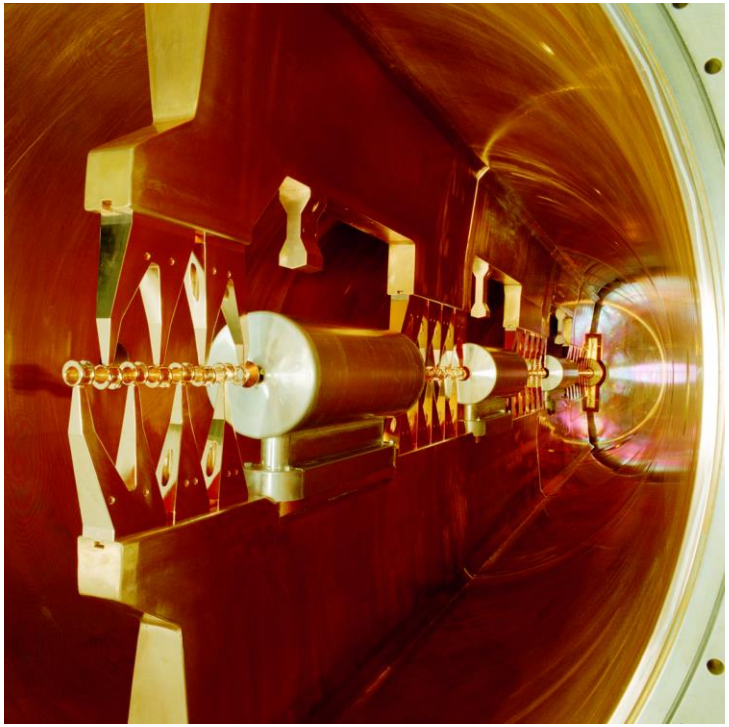
Rf-Conditioning of the HSI-Cavities

RFQ



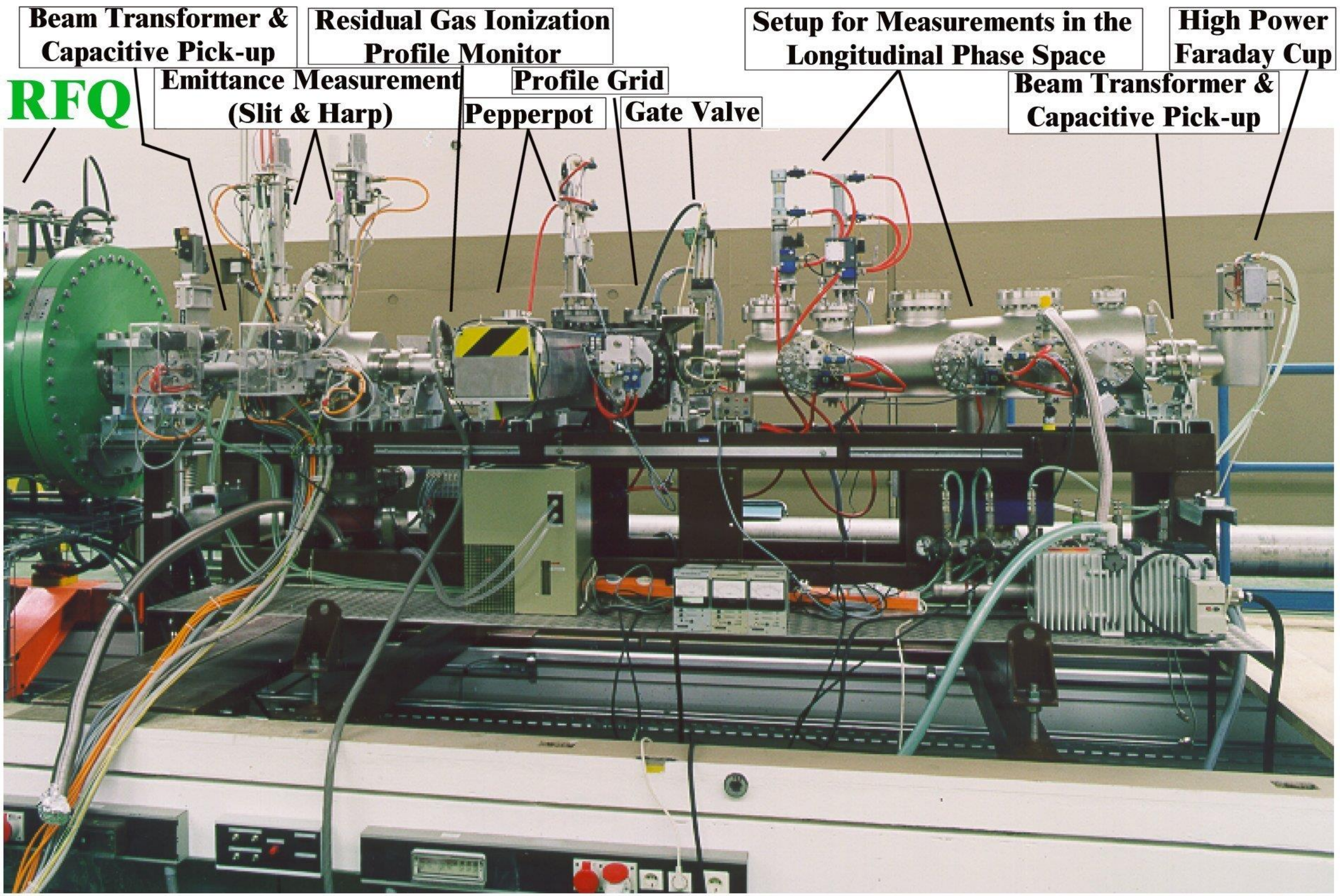
Super Lens

IH-DTL



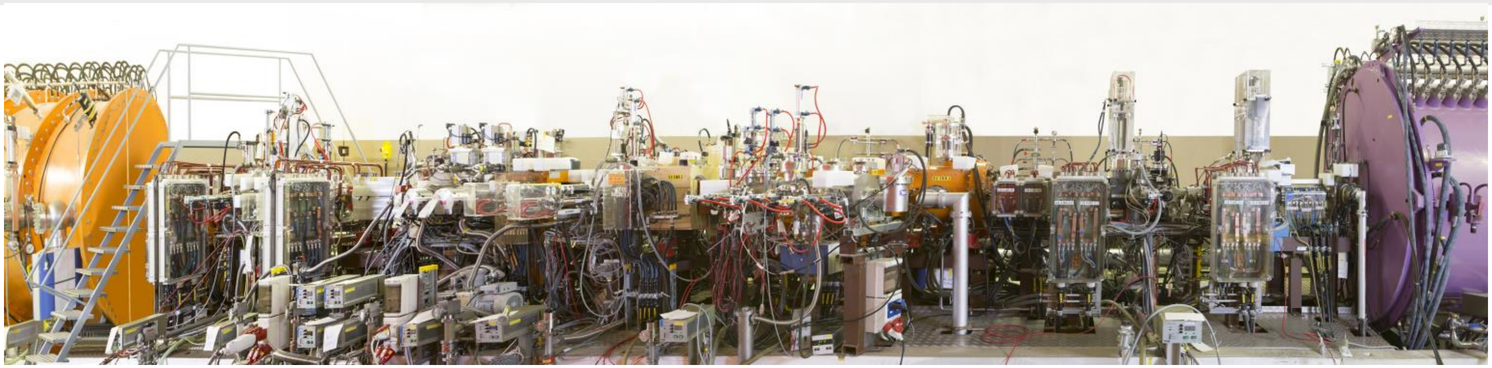
	Electrode Voltage (U^{4+})	Dec. 01	July 02
RFQ	125 kV	103 %	102 %
Super Lens	194 kV	92 %	110 %
IH1	1053 kV	105 %	100 %
IH2	961 kV	107 %	102 %

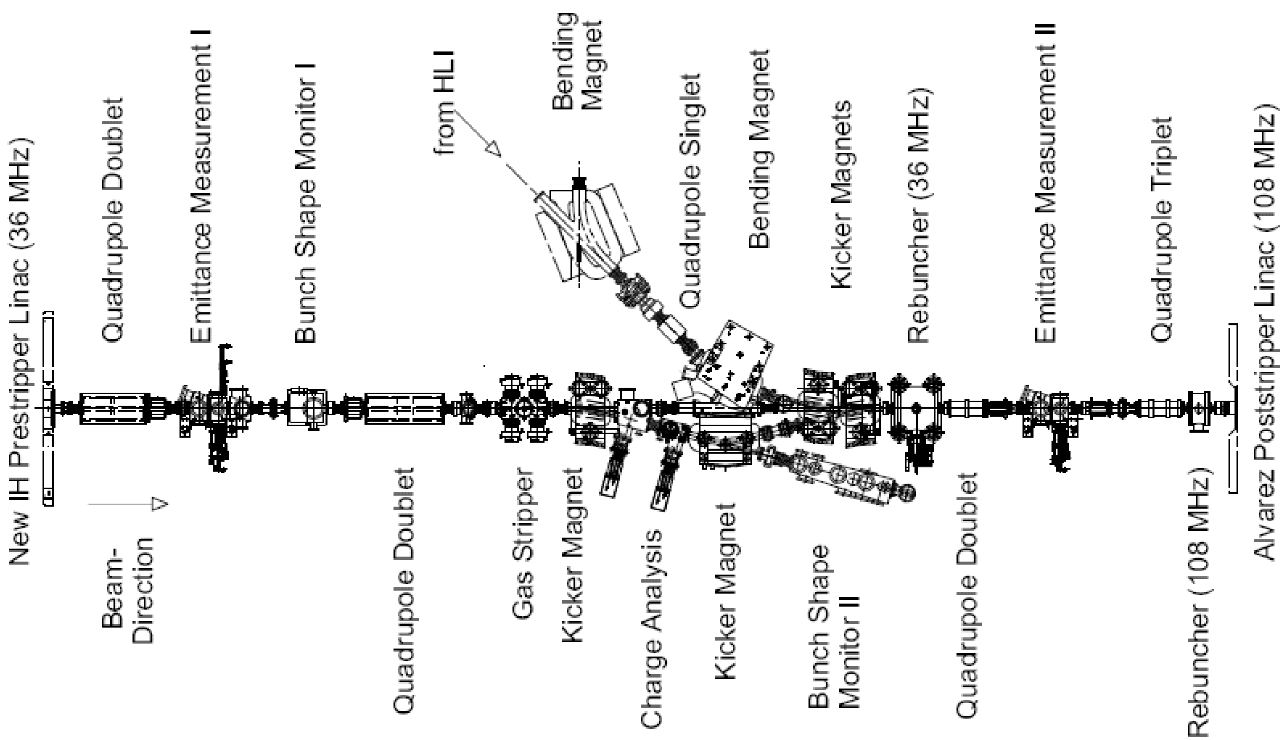
Beam Diagnostics Test Bench



P. Forck, LINAC200

Commissioning of 1.4 MeV/u gas stripper section

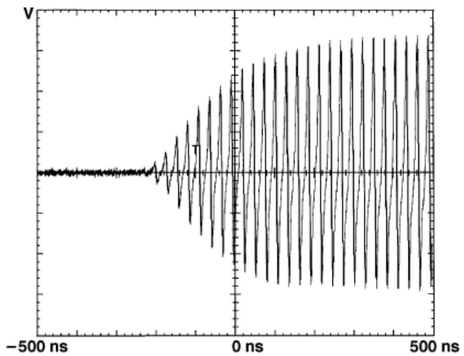




W. Barth, LINAC200

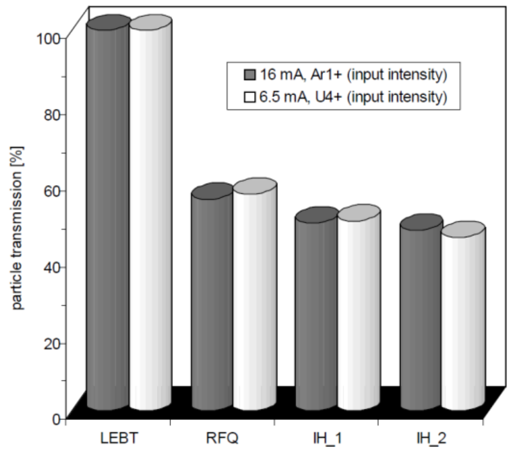
HSI-commissioning results

Rise Time of phase probe signal

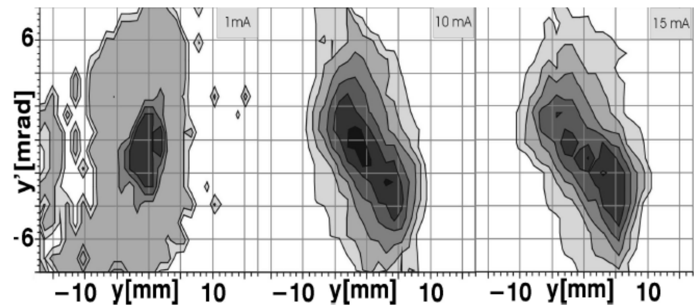


Rise time of the phase probe signal after RFQ

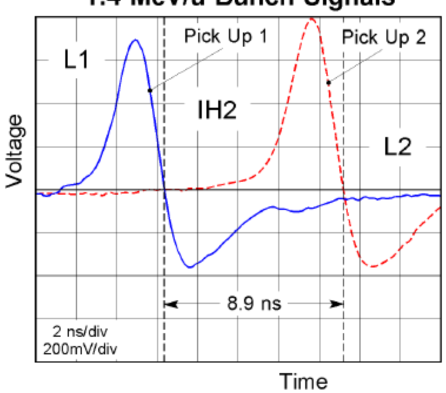
Beam Transmission



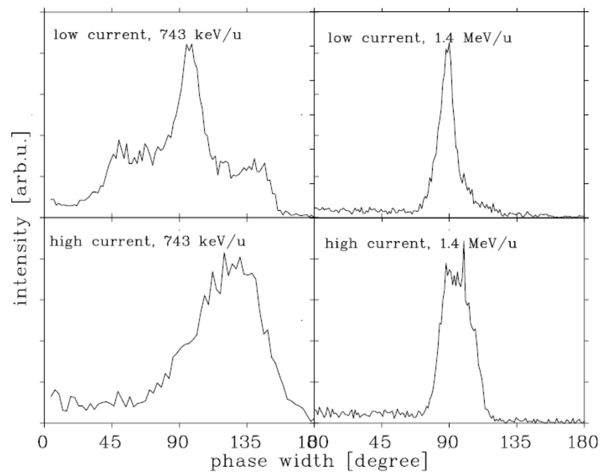
Pepper Pot Emittance measurement (Ar^{1+})



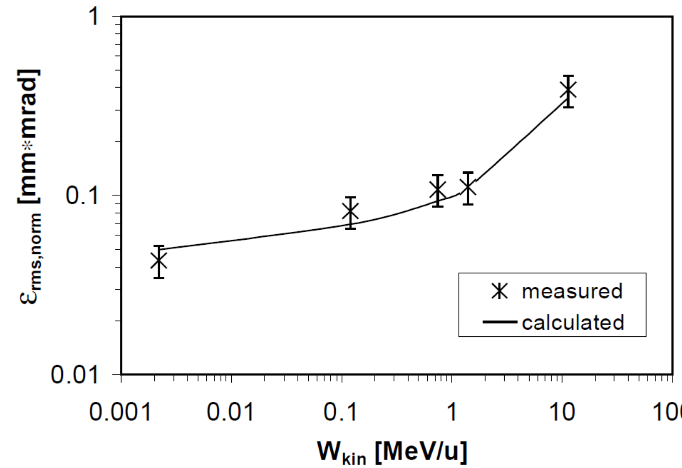
TOF Measurement
1.4 MeV/u Bunch Signals



Bunch Shape



Slit-Grid Emittance measurement



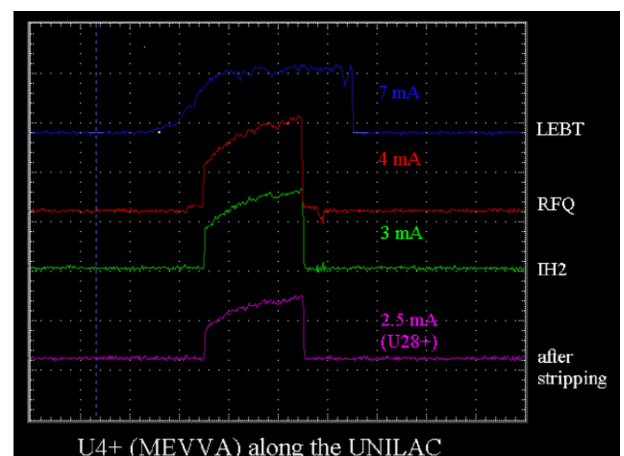
W. Barth, LINAC200

Commissioning Time Schedule

Dec. 98	Last operation-shift with Wideröe injector
Jan.-Feb. 99	Disassembly of Wideröe and rf, installation of LEBT section
March 99	Successful commissioning of LEBT
April-May 99	Mounting IH-RFQ and first acceleration up to 120 keV/u
June 99	Beam tests with Superlens, achieving 10 mA Ar^{1+} at RFQ exit
July 99	Assembly of IH1, verification of beam accelera-tion up to 743 keV/u

August 99	Completing HSI with IH2 and stripper Section
2.Sept. 99	Proof of acceleration up to 1.4 MeV/u, further on: 90% IH-transmission for highest argon intensities (8 mA)
October 99	Upgrade of transfer line to SIS and mounting of matching section to Alvarez
November 99	Establishing three beam operation, complete Alvarez transmission at highest current
Since Nov. 99	HSI in routine operation
February 2000	Achievement of the 90%-rf levels, first 1.4 MeV/u U^{4+} beam (3 mA)

First U^{4+} beam (Feb. 2000)



W. Barth, LINAC200

RFQ-Recommissioning

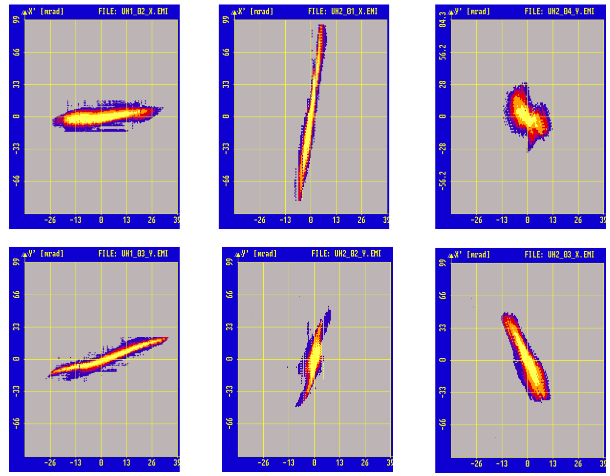
- 2004
  - surface degradation
  - new IRM
  - no change of electrode profile
- 2009
  - surface degradation
  - new electrode profile
- 2019
  - surface degradation
  - copper acet formation due to moisture absorption
  - no change of electrode profile

Exchange of RFQ-Electrodes (2004)

LEBT

RFQ-matching

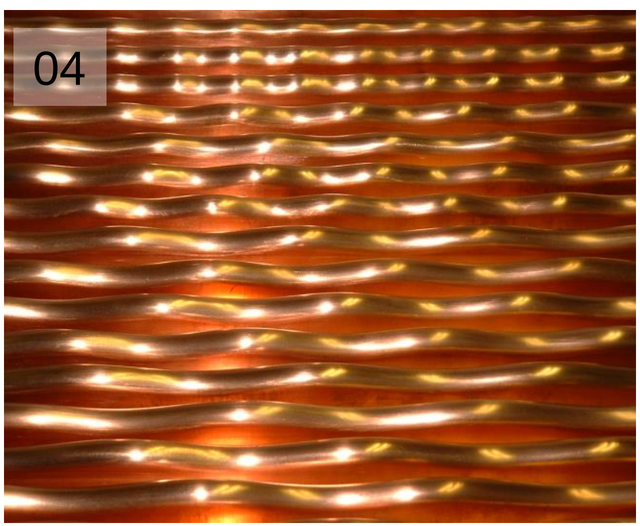
99 04



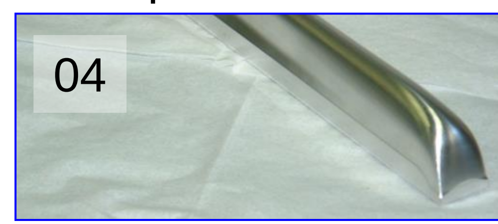
horizontal

vertical

Emittance Growth:	-19 % / 3 %
Beam Transmission:	70 % / **84 %**



Improved IRM

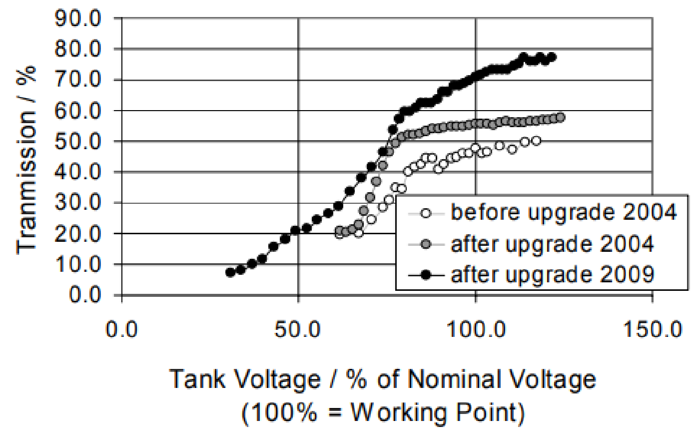


Two slit grid emittance measurement devices @LEBT and @QQ
=> emittance growth effects

RFQ-Upgrade (2009)

H. Vormann, et al., MOP040 Proceedings of Linear Accelerator Conference LINAC2010, Tsukuba, Japan

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



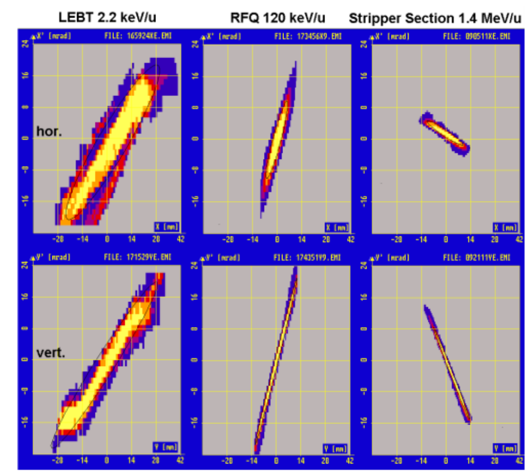


Figure 7: Measured Ar^{1+} high current HSI-emittance.

S. Yaramyshev 2009

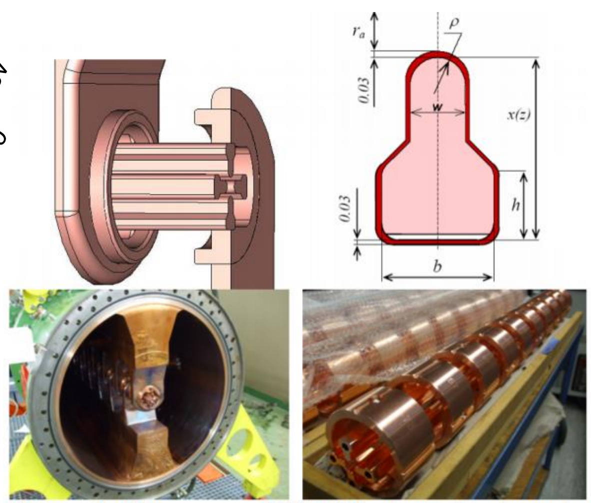
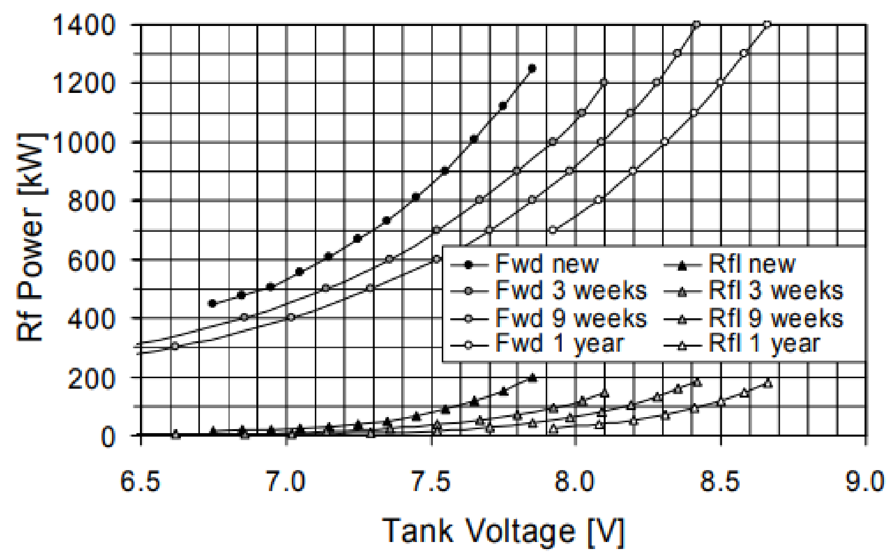


Figure 4: Upper row: HSI-RFQ electrode channel and geometry; lower row: RFQ tank opened during assembly works; pre-assembled electrode cage.



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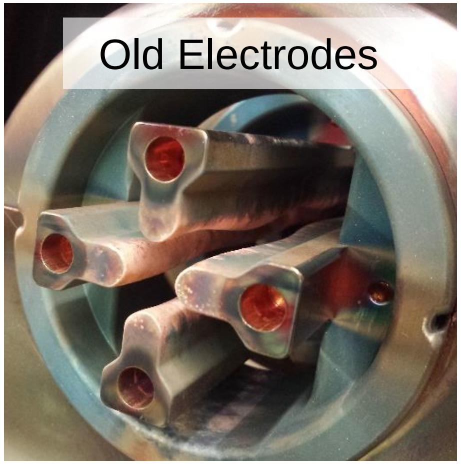
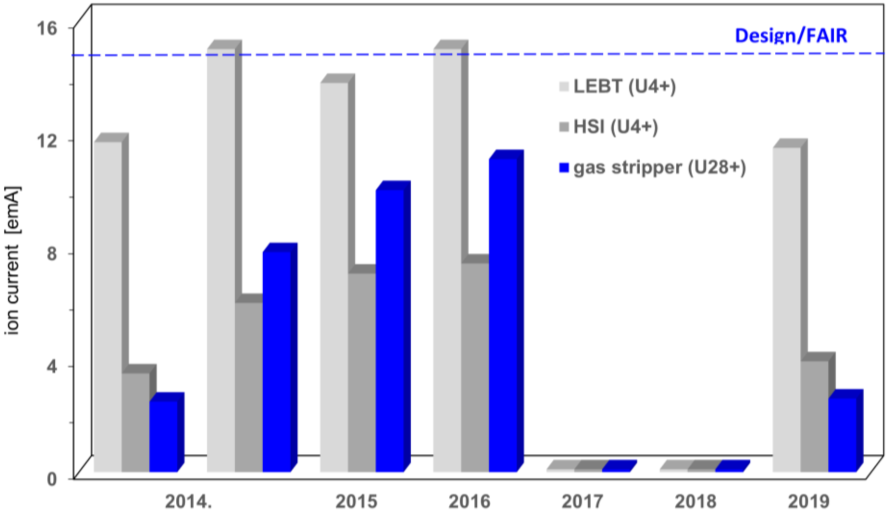
Exchange of RFQ-Electrodes (2019)



- **90% of the design Rf-level applied successfully**
- Sufficient U^{4+}-RFQ-operation
- 50% of best HSI-performance (2016)
- U^{4+} => U^{28+} => U^{68+} (8.6 MeV/u)
- **For SIS18-injection: 1.1 +/-0.1 emA**

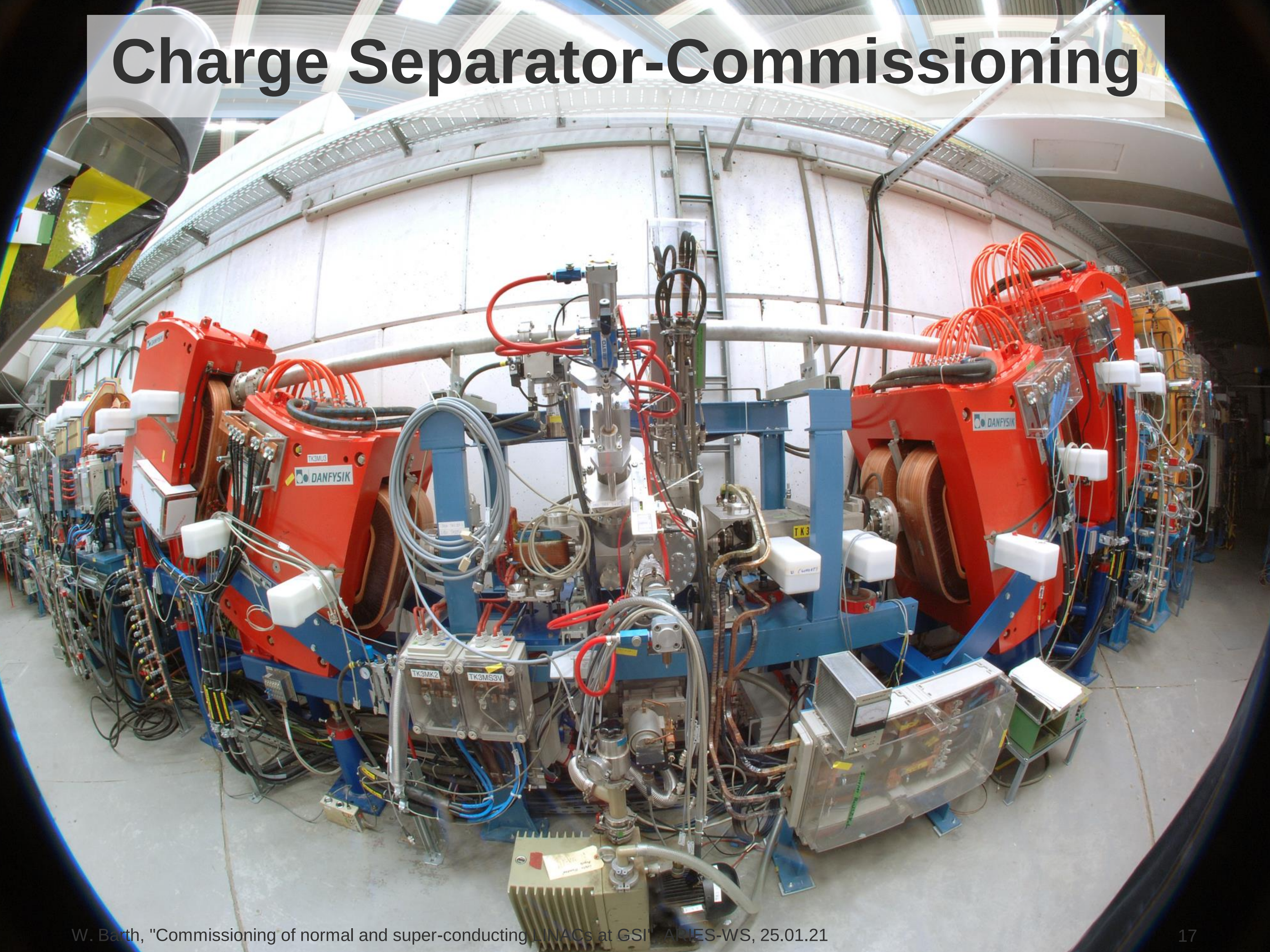


Schedule

2019:	Exchange of RFQ-electrodes 👍
2020:	RFQ-machine investigations 👍
2021:	Advanced Rf-conditioning/U^{4+}-operation
2022:	Exchange of LEBT-QQ (1)
≥2023:	Improved SL/RFQ-electrode design (2)
	– lower RF-voltage (RF-power)
	– higher acceleration efficiency

W. Barth
FAIR-MAC23-report (2020)

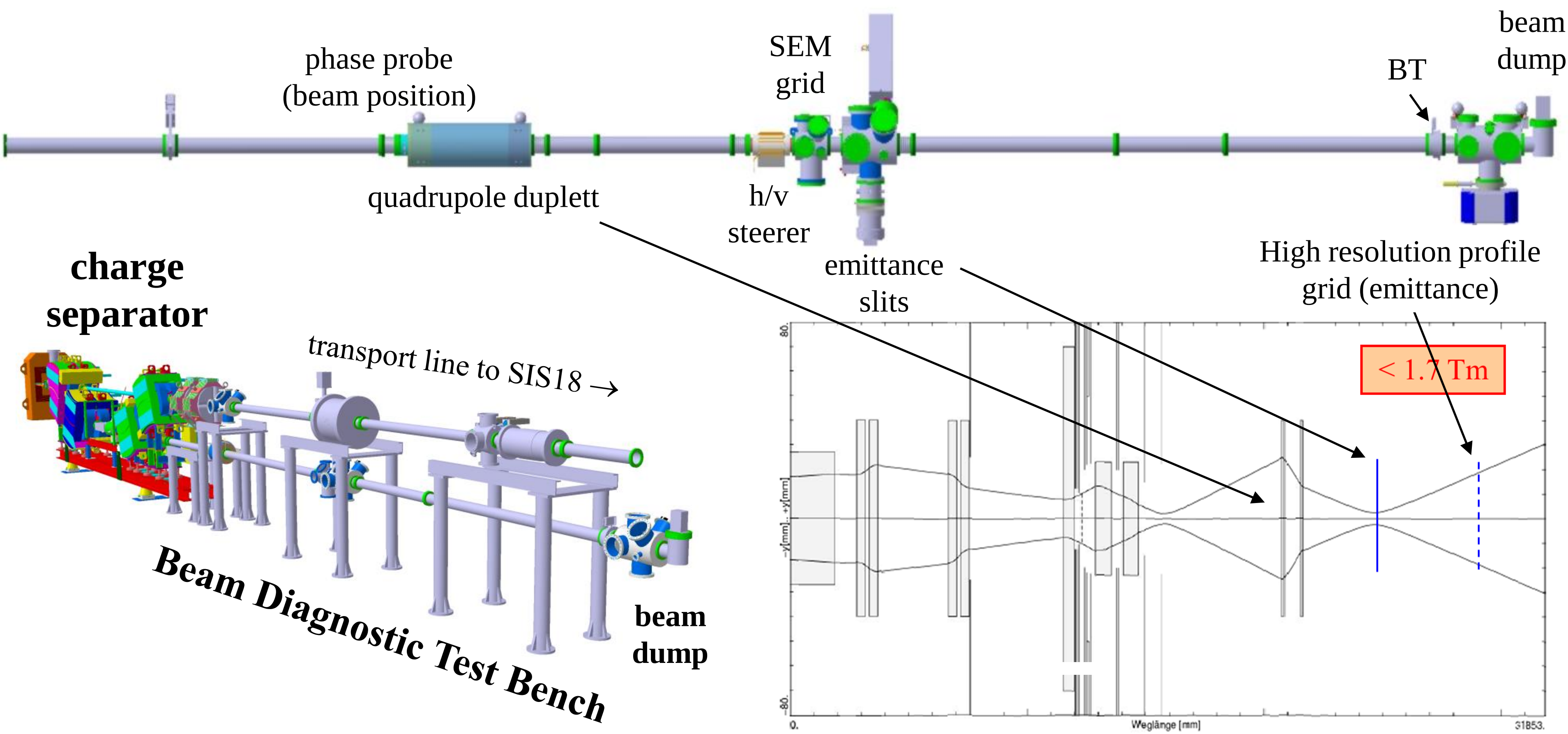
Charge Separator-Commissioning



Charge Separator-Concept

- Compact (6m) system of four vertical 35°-1.6 T-dipole magnets (field homogeneity ≤ 1.5 %)
- Sufficient for pulse operation: 3 Hz pulsed mode, 5 Hz demand mode
- Dipole chamber with low eddy currents in pulse operation, copper walls and apertures for low radioactivity from the impact of unwanted charge states, cooling and protection from thermal stress
- Stripper-system integrated
- Short (space charge dominated) beam transport (multi charge state beam): 1m
- less emittance growth
- Intensity gain inside SIS-acceptance ≈ 20%
- Charge-resolution ≤ 1%
- Improved beam operating

Beam diagnostics test bench



- ion current
- beam profile
- beam position (and correction)
- beam emittance
- bunch shape (non destructive)
- beam energy (ToF)

Beam Commissioning (^{238}U) Charge Separator

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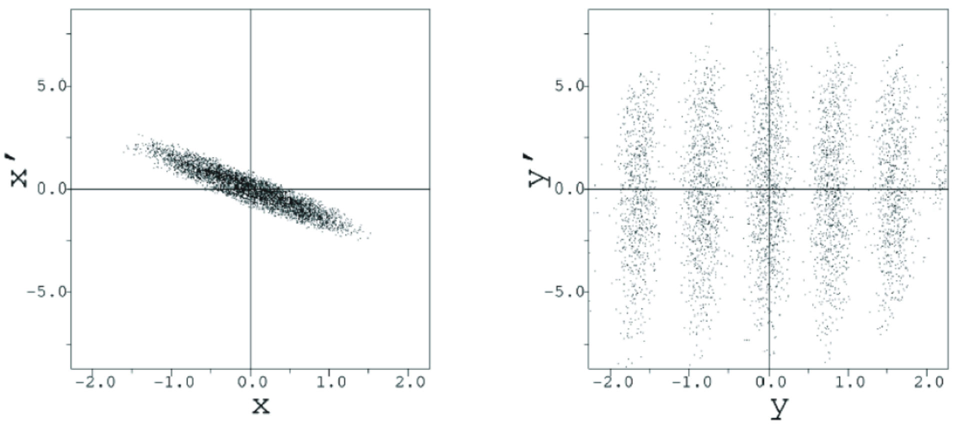
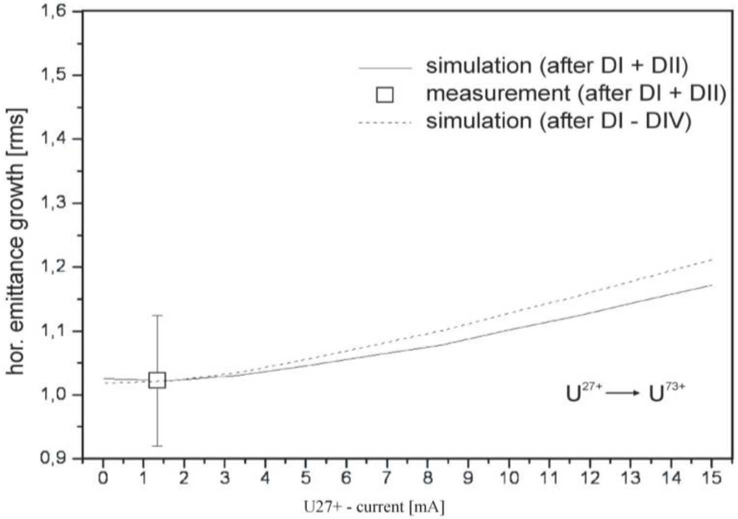
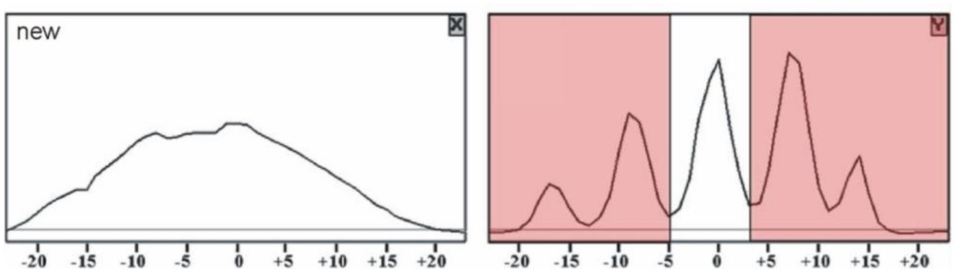
PARMILA-Transport



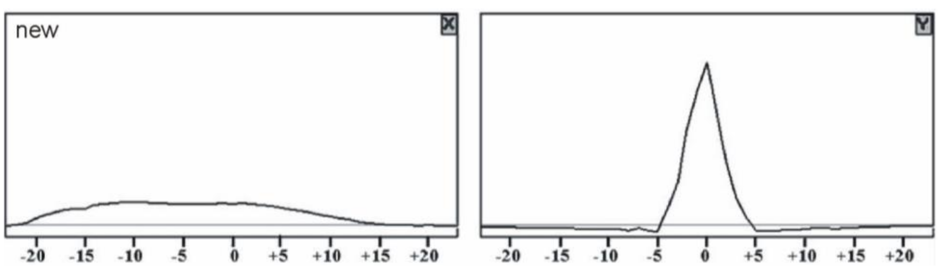


Open separation slit



hor. vert.

Charge separation of $^{238}U^{73+}$



hor. vert.

Superconducting cw-linear accelerator HELIAC* for heavy ion beams

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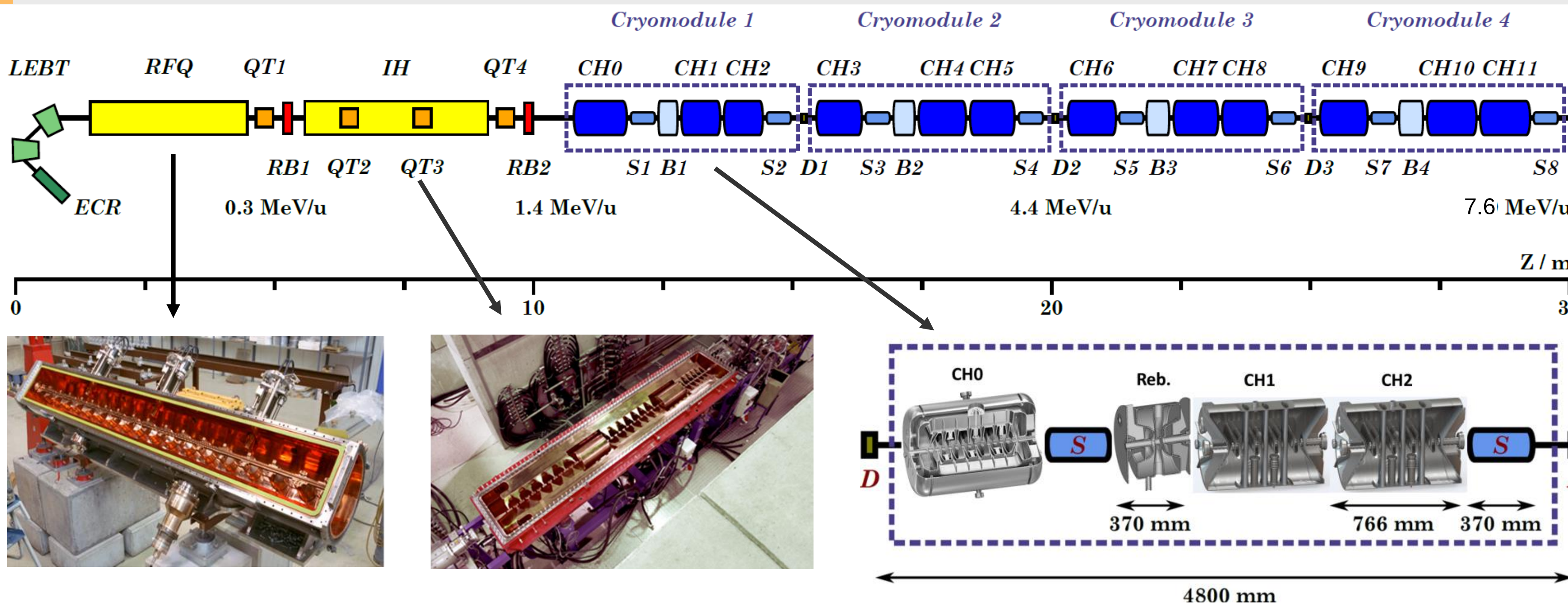
HIM HELMHOLTZ Helmholtz Institute Mainz

*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

Main properties

- short Crossbar H-Mode-Kavitäten
- modular set up: 4 cryomodules, each with 3 CHs, 1 buncher, 2 solenoids
- compact Linac design ($E_a \geq 7.1$ MV/m)

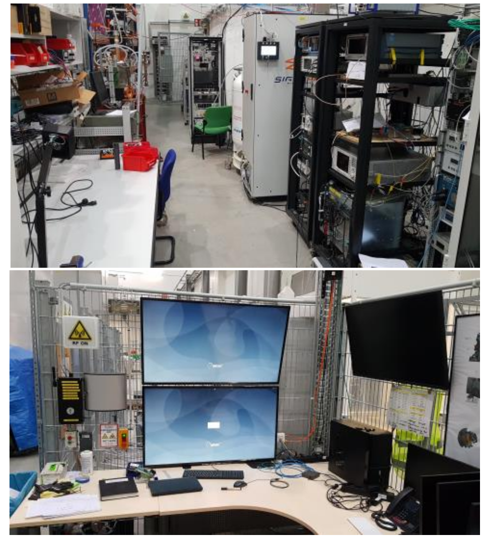
Max. beam energy per cryomodule

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

SRF-Lab at JGU-campus

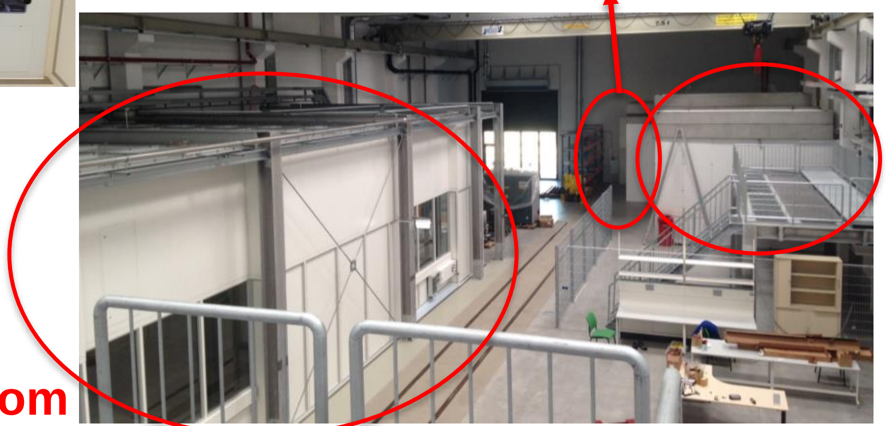
clean area: ISO-class 4

High Pressure Rinsing at clean room



Rf-test area

Test cryostat with superconducting cavity at test bunker



clean room

test bunker

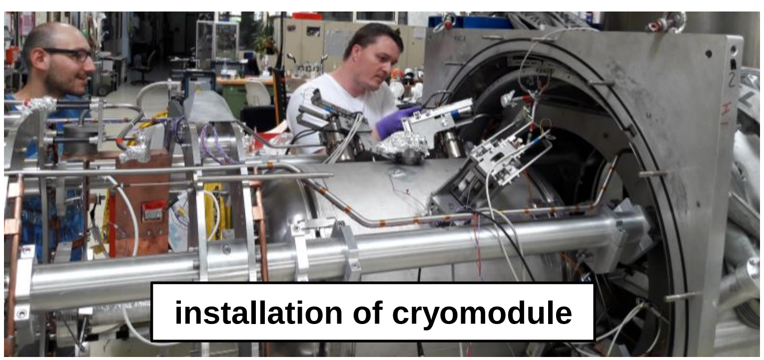
Experimental hall at HI Mainz

cw-Linac-demonstrator beam test@GSI

2017

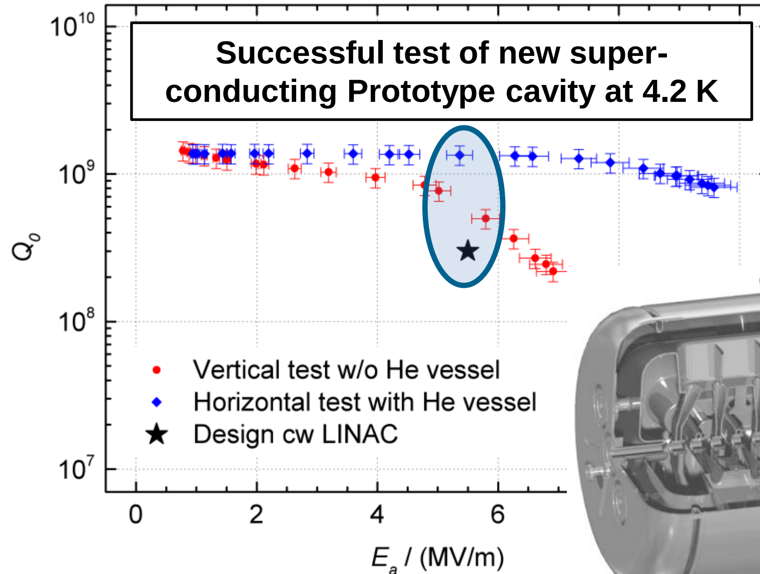
RF-conditioning of high power coupler

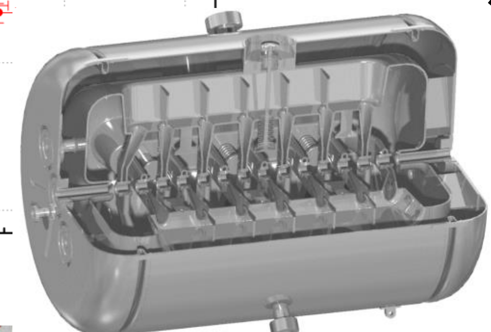
superconducting cavity@new cleanroom



installation of cryomodule

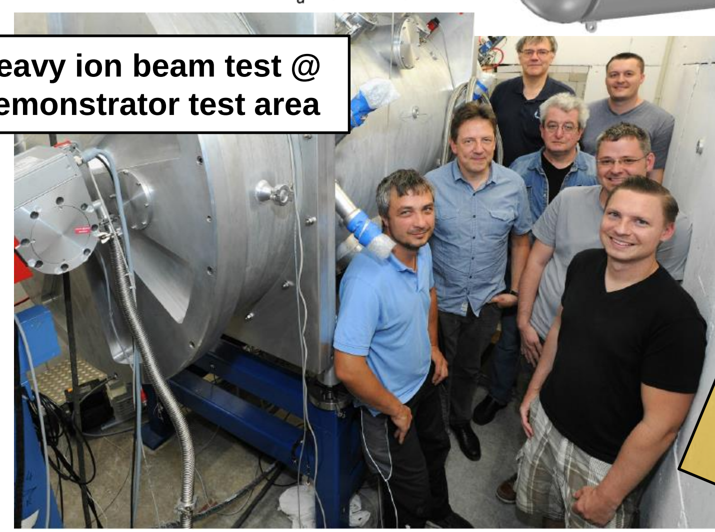
2016





Measured: 9.6 MV/m !!!
(Design: 5.1 MV/m)

Heavy ion beam test @ demonstrator test area



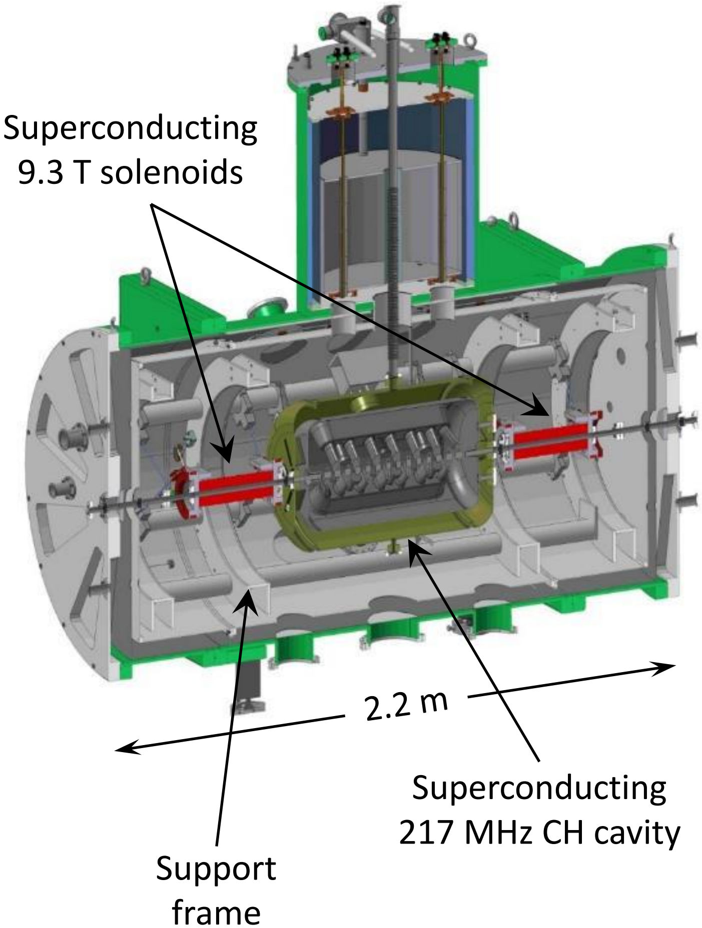
June/July 2017

cw-test/schedule

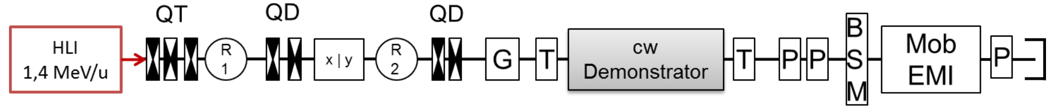
582	68		95%	**CW-Linac**	**255 Tage**	**Mon 18.07.16**	**Fre 07.07.17**	
583	69		0%	cw Demonstrator ready for operation	0 Tage	Fre 07.07.17	Fre 07.07.17	
584	754	✓	100%	**Bunker Abschirmung CW-LINAC schließen**	**194 Tage**	**Mon 19.09.16**	**Don 15.06.17**	
585	916	✓	100%	*Fenster im Bunker zusetzen*	*1 Tag*	*Mon 19.09.16*	*Mon 19.09.16*	
586	755	✓	100%	*Decke CW-CAVE schließen*	*3 Tage*	*Mon 17.10.16*	*Mit 19.10.16*	*GA_Bau*
587	516	✓	100%	*Decke CW-CAVE öffnen*	*1 Tag*	*Mon 05.12.16*	*Mon 05.12.16*	*GA_Bau*
588	428	✓	100%	*Wände L-förmig, U-förmig schließen, Tür mit mobilen Steinen am BEAM-STOP zusetzen, Decke CW-CAVE + CW-BEAM-STOP schließen*	*5 Tage*	*Fre 09.06.17*	*Don 15.06.17*	
589	479	✓	100%	**Reinraum**	**9 Tage**	**Mon 18.07.16**	**Don 28.07.16**	
596	510	✓	100%	**Re Buncher 108 MHz, gepulst**	**91 Tage**	**Fre 09.09.16**	**Mon 06.02.17**	
605	518	✓	100%	**Kavität: Test ohne Strahl ohne Koppler**	**0 Tage**	**Mon 12.09.16**	**Mon 12.09.16**	
607	528	✓	100%	**Koppler Teststand**	**144 Tage**	**Don 15.09.16**	**Fre 28.04.17**	
608	529	✓	100%	LieferungHF Leistungskoppler	0 Tage	Don 15.09.16	Don 15.09.16	
609	1314	✓	100%	217MHz Verstärker Betriebsbereit	24 Tage	Mit 08.02.17	Mon 13.03.17	
610	533	✓	100%	Test Leistungskoppler	23 Tage	Mon 27.03.17	Fre 28.04.17	CW LINAC;LORF
611	535		91%	**Kavität: Test mit Strahl**	**115 Tage**	**Mon 23.01.17**	**Fre 07.07.17**	
612	537	✓	100%	Reinigung der Solenoide und Bälge	35 Tage	Mon 23.01.17	Fre 10.03.17	CSTI;CW LINAC
613	520	✓	100%	Aufbau und Test der Tuner	55 Tage	Mon 23.01.17	Fre 07.04.17	CW LINAC
614	1036	✓	100%	Lieferung Langloch Flansch mit Durchführungen für Koppler	0 Tage	Mon 20.03.17	Mon 20.03.17	CSTI
615	1037	✓	100%	String im Reinraum montieren	84 Tage	Mit 25.01.17	Fre 26.05.17	CW LINAC
616	538	✓	100%	Einbau in Cryostat	5 Tage	Mon 29.05.17	Fre 02.06.17	CSTI;CW LINAC
617	1315	✓	100%	Transfermessung	1 Tag	Die 06.06.17	Die 06.06.17	
618	1038	✓	100%	Transport und Einbau in Strahlführung	1 Tag	Mit 07.06.17	Mit 07.06.17	
619	539	✓	100%	Justage im Bunker	1 Tag	Don 08.06.17	Don 08.06.17	ENMA
620	1039	✓	100%	Vakuum bis auf 1e-9 anpumpen	2 Tage	Fre 09.06.17	Mon 12.06.17	
621	540		0%	Kalttest / HF-Leistungstests mit Hochleistungskoppler	9 Tage	Die 13.06.17	Fre 23.06.17	CW LINAC;LORF
622	541		0%	Test mit Strahl: braucht Quelle, Medien, Schicht, Rufbereitschaften	10 Tage	Mon 26.06.17	Fre 07.07.17	CW LINAC;LORF

Experimental setup of the demonstrator at GSI

Layout of the horizontal cryomodule



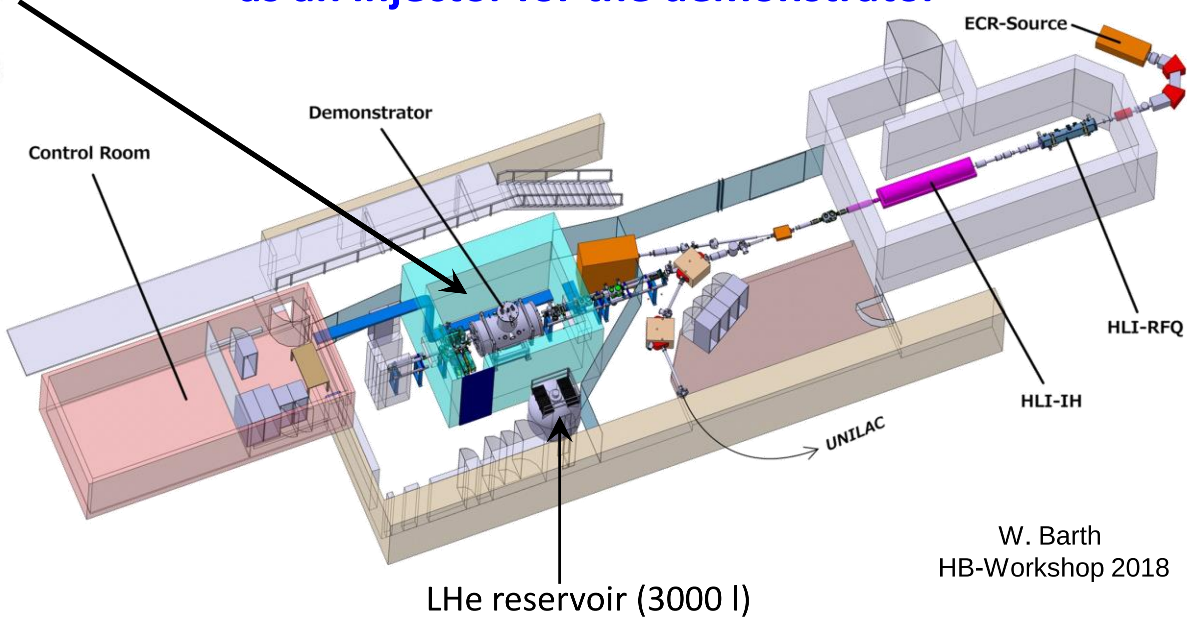
Matching line - demonstrator – test bench



- Steering magnets
- Rebuncher
- Quadrupole doublet
- Profile grids

- Phase probes for TOF measurement
- Beam current transformers
- Bunch shape monitor (Feschenko)
- Emittance measurement

The High Charge State Injector (HLI) at GSI serves as an injector for the demonstrator



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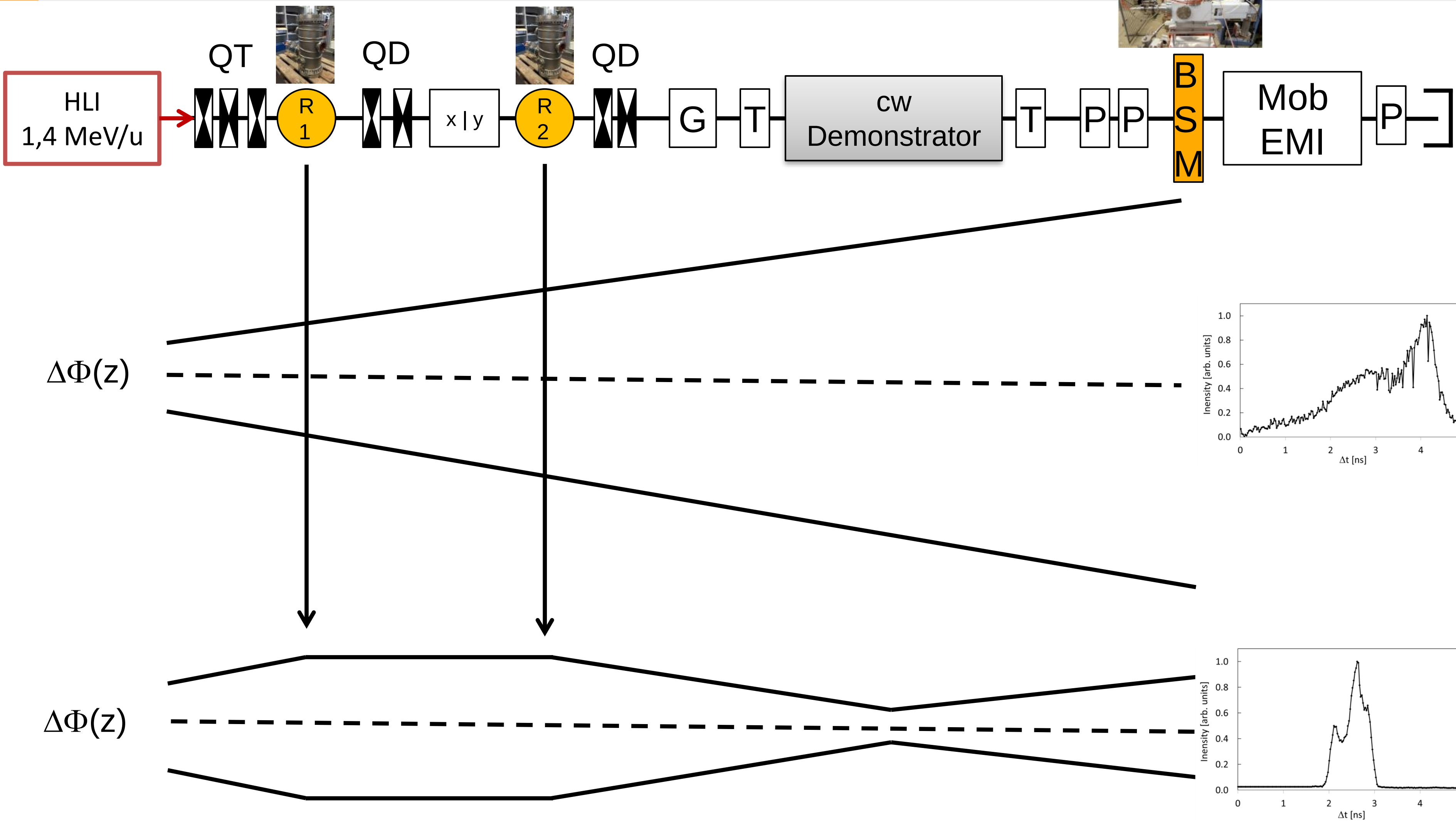
Beam Line commissioning: Longitudinal matching



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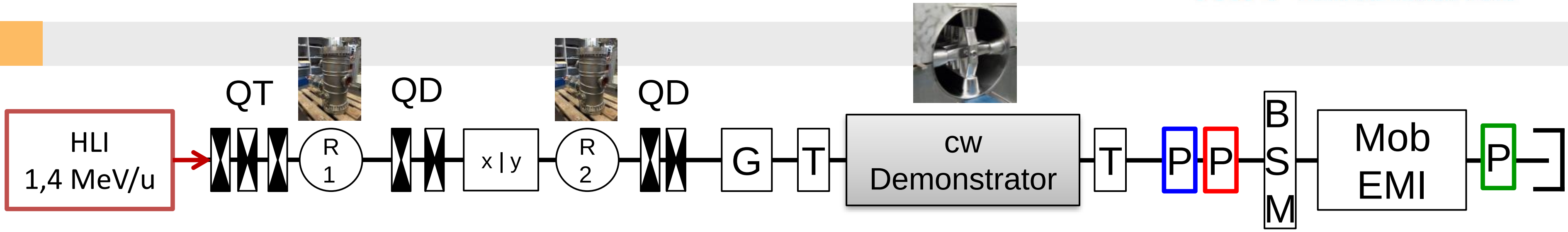
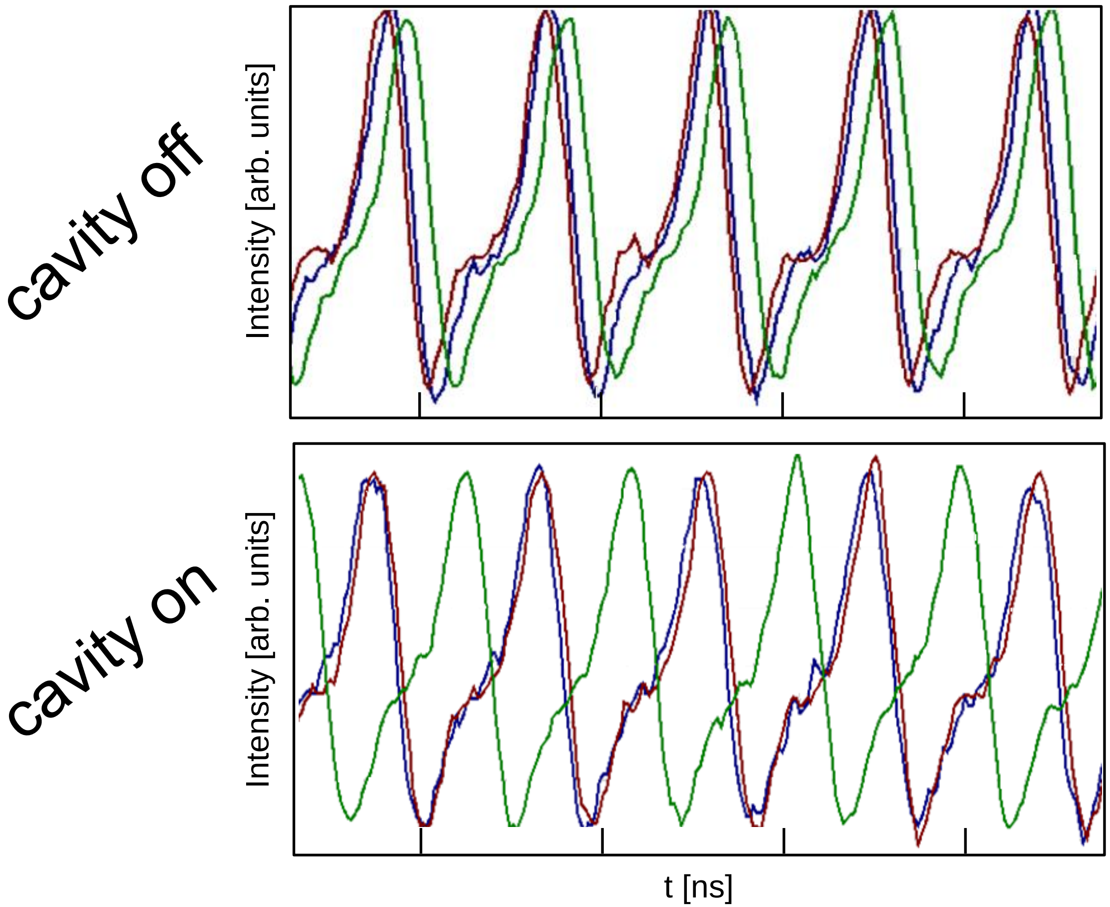
First Acceleration





- Measurement of transient signal induced by traveling bunch
- Acceleration! Energy gain of 0.5 MeV/u
- → systematic scan of rf-phase and amplitude

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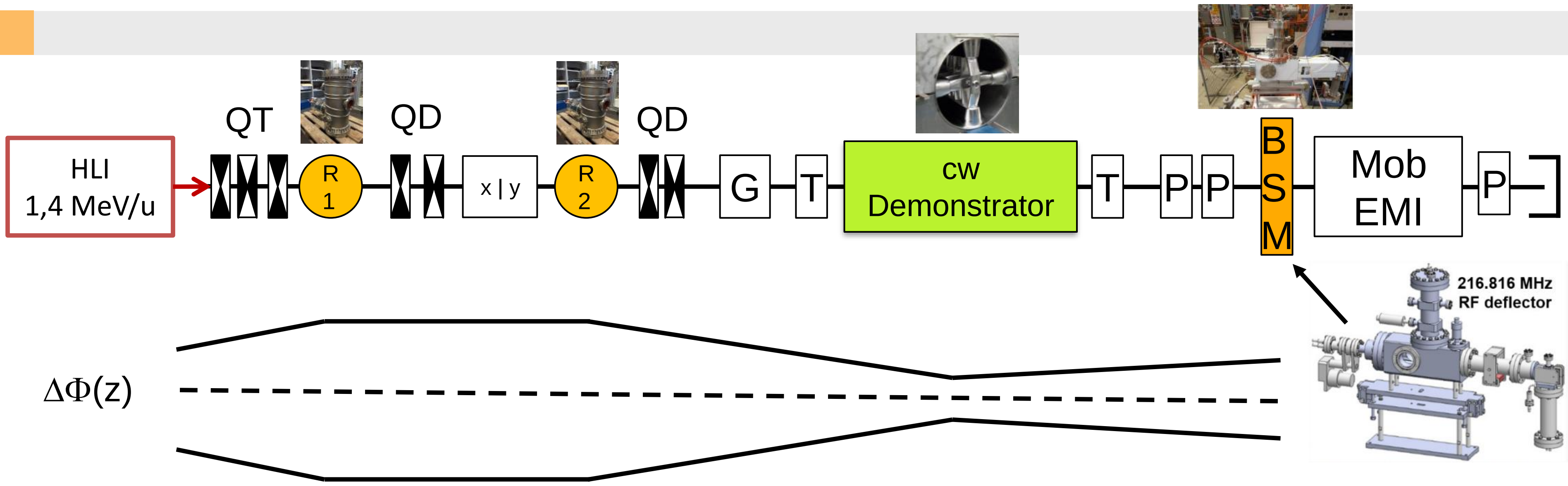
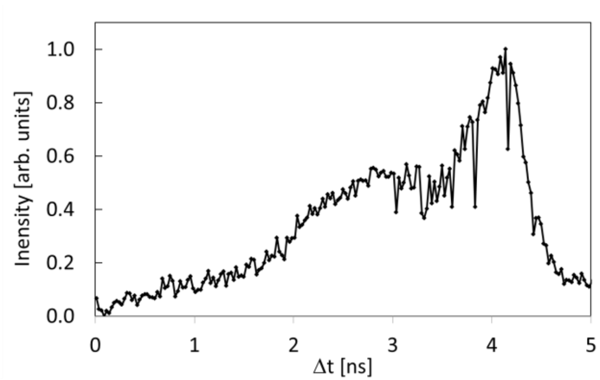
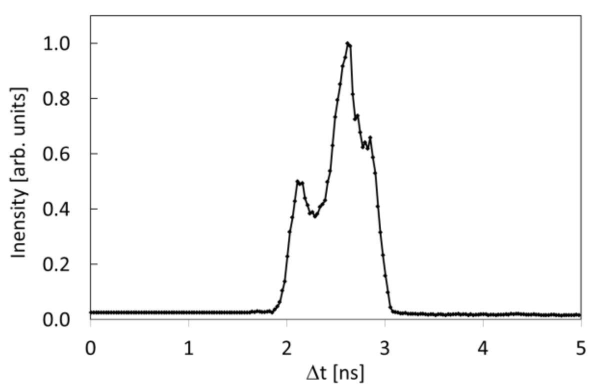
Bunch shape measurement



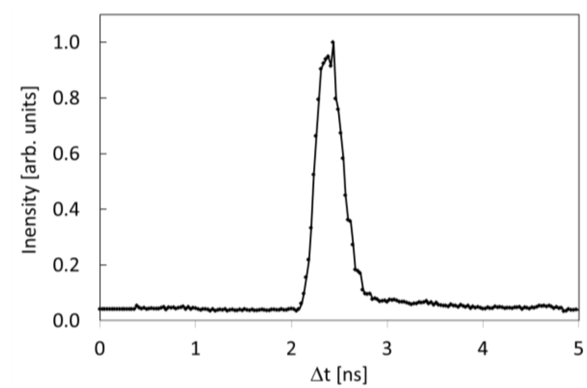
cavities off



R1 + R2



R1 + R2 + CH0



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RF-parameter (matched case)

	He^{2+}	Ar^{11+}	Ar^{9+}	Ar^{6+}
A/q	*2.0*	*3.6*	*4.4*	*6.7*
$U_{Reb1,eff.}$ [kV]	8.3	15.0	18.3	27.9
$U_{Reb2,eff.}$ [kV]	22.7	40.8	49.9	75.9
$E_{acc,CH}{}^{*}$[MV/m]	1.8	3.2	3.9	5.9
U_0 [MV]	1.2	2.2	2.7	4.0

$^{*}E_{acc} = \text{transit time factor} \times \text{total accelerating voltage}/(n \times 0.5 \times \beta\lambda)$

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Systematic Scans (RF-phase/-amplitude)

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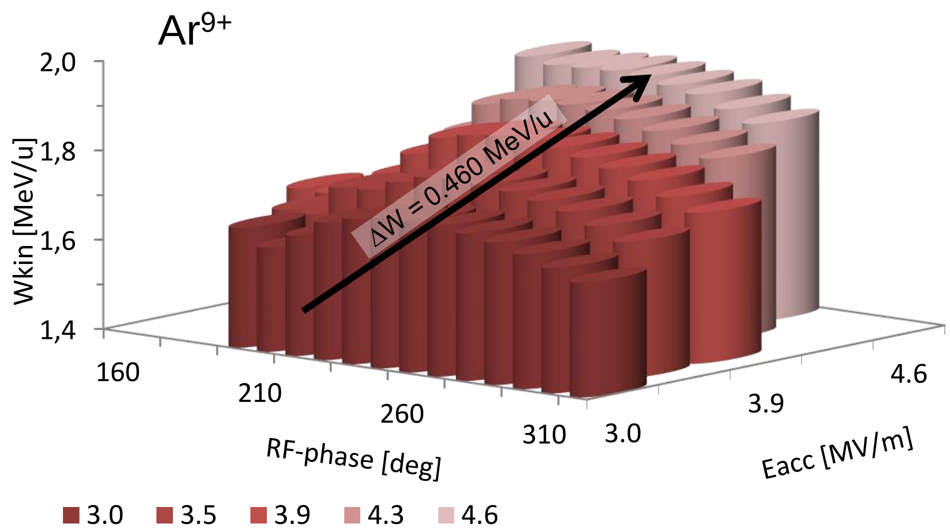
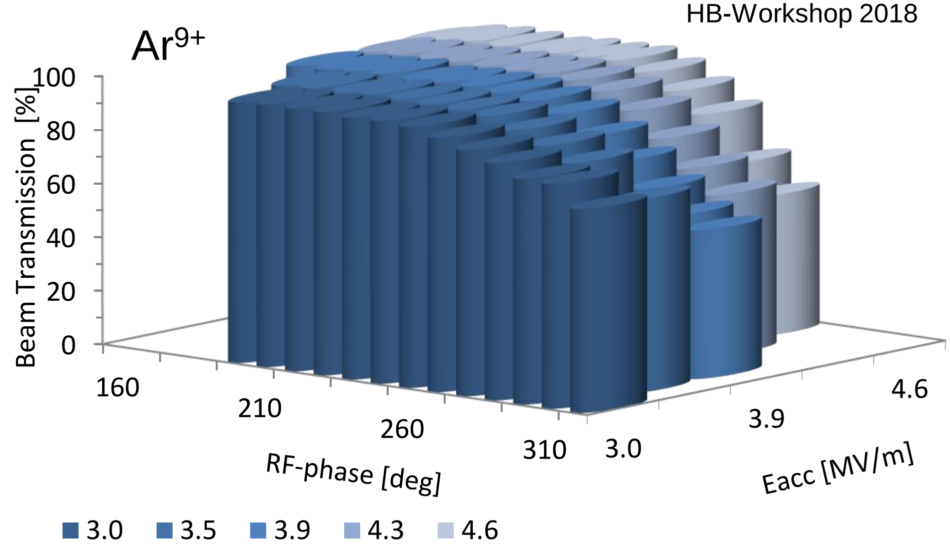
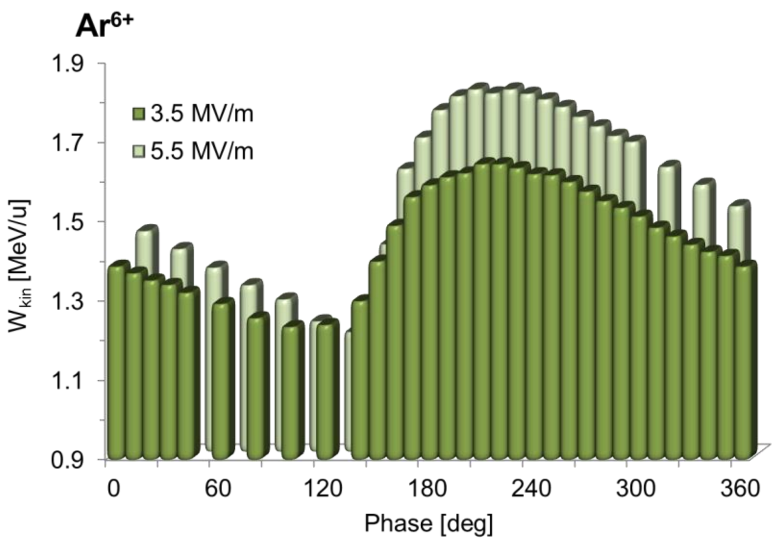
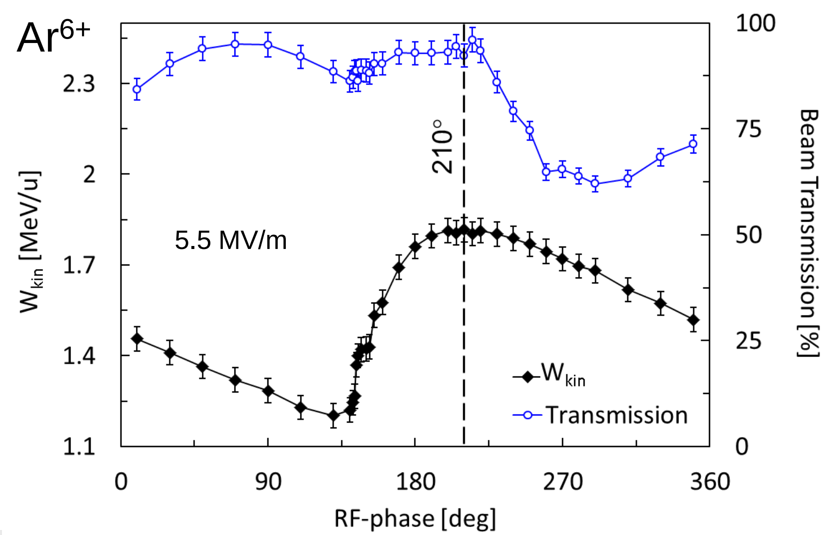
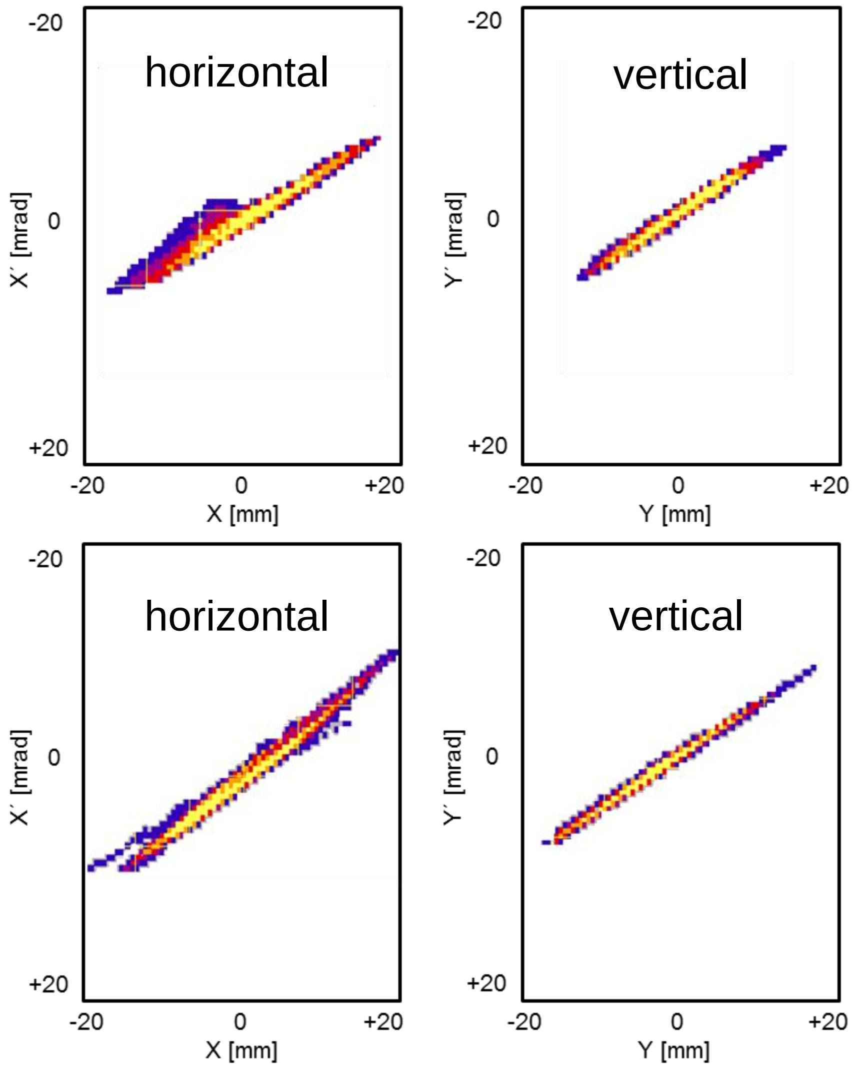








Emittance measurement



1.40 MeV/u

Ion species: $^{40}Ar^{11+}$, $^{40}Ar^{9+}$, $^{40}Ar^{6+}$ (A/q=6.7),
50 Hz, 5ms, 25% beam duty, cw (rf duty), 1.5pμA (particle current),
≈95% (beam transmission), 0.460 MeV/u (ΔW),
transv. emittance growth ≈12%

1.86 MeV/u

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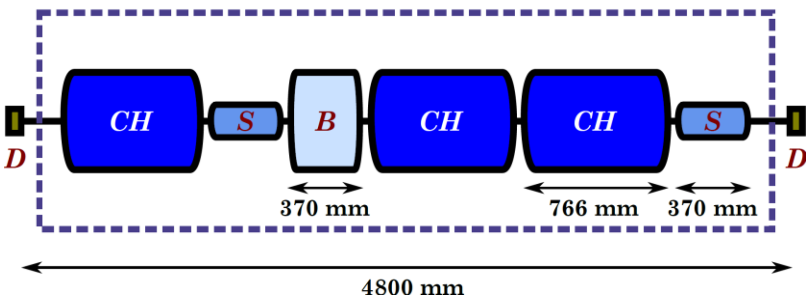
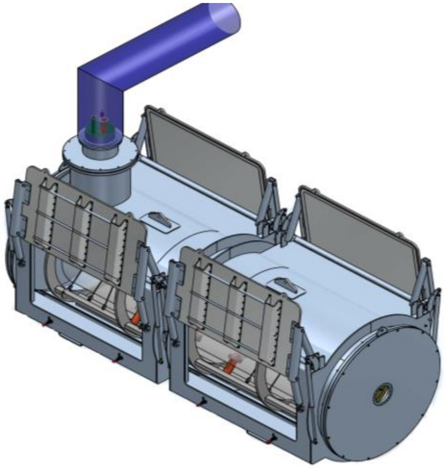
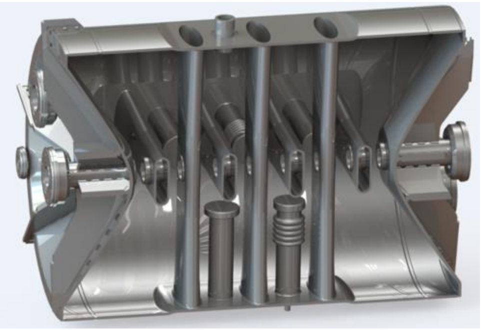
Cryomodule I

Standard cryomodule layout





(8 gap)-CH-cavity



- 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 ready for final Rf-testing
- cryostat in production
- Moderate increase of design gradient $\rightarrow$ more compact linac design or higher A/q

Outlook: cw-Linac protyping and beyoned

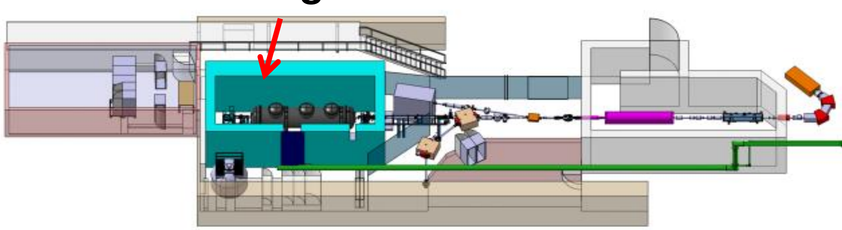
Setup and commissioning of new test area

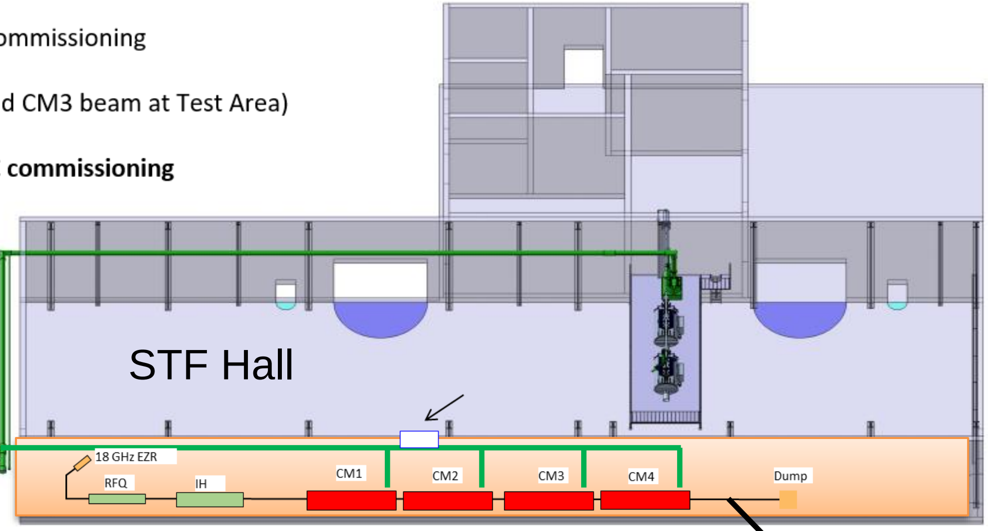
Q4/2022	CM1 (Advanced Demonstrator) beam test at Test Area
Q2/2024	**Linac-Tunnel (@SH2/3) ready for installation of components**
Q3&4/2024	ECR and LEBT commissioning @ Linac-tunnel
Q4/2024	CM2 beam test at Test Area
Q1/2025	RFQ commissioning @ Linac tunnel
Q2/2025	cw-IH-DTL commissioning @ Linac tunnel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

Link to STF (SeriesTest Facility)

Advanced Cryomodule Testing Area

HLI Injector





HELIAC →

Ex-Hall, TK to SIS18

UNILAC →

Thank You for Your attention!