Acceleration of Heavy Ion Beams with a Superconducting Continous Wave cw-Linac at GSI

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[3] Johannes Gutenberg-Universität Mainz, Mainz, Germany
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1. Introduction
2. General Linac layout and RF-cavity development
3. EQUUS beam dynamics and Matching section
4. Acceleration of heavy ion beams
   - First beam test with a sc CH-cavity
   - Systematic phase space measurements
5. Further R&D/Advanced Demonstrator Project
6. HELIAC* – preparation work
7. Outlook

* HElmoltz LInear ACcelerator

Introduction
GSI UNIversal Linear ACcelerator

HIM HELMHOLTZ Helmholtz Institute Mainz

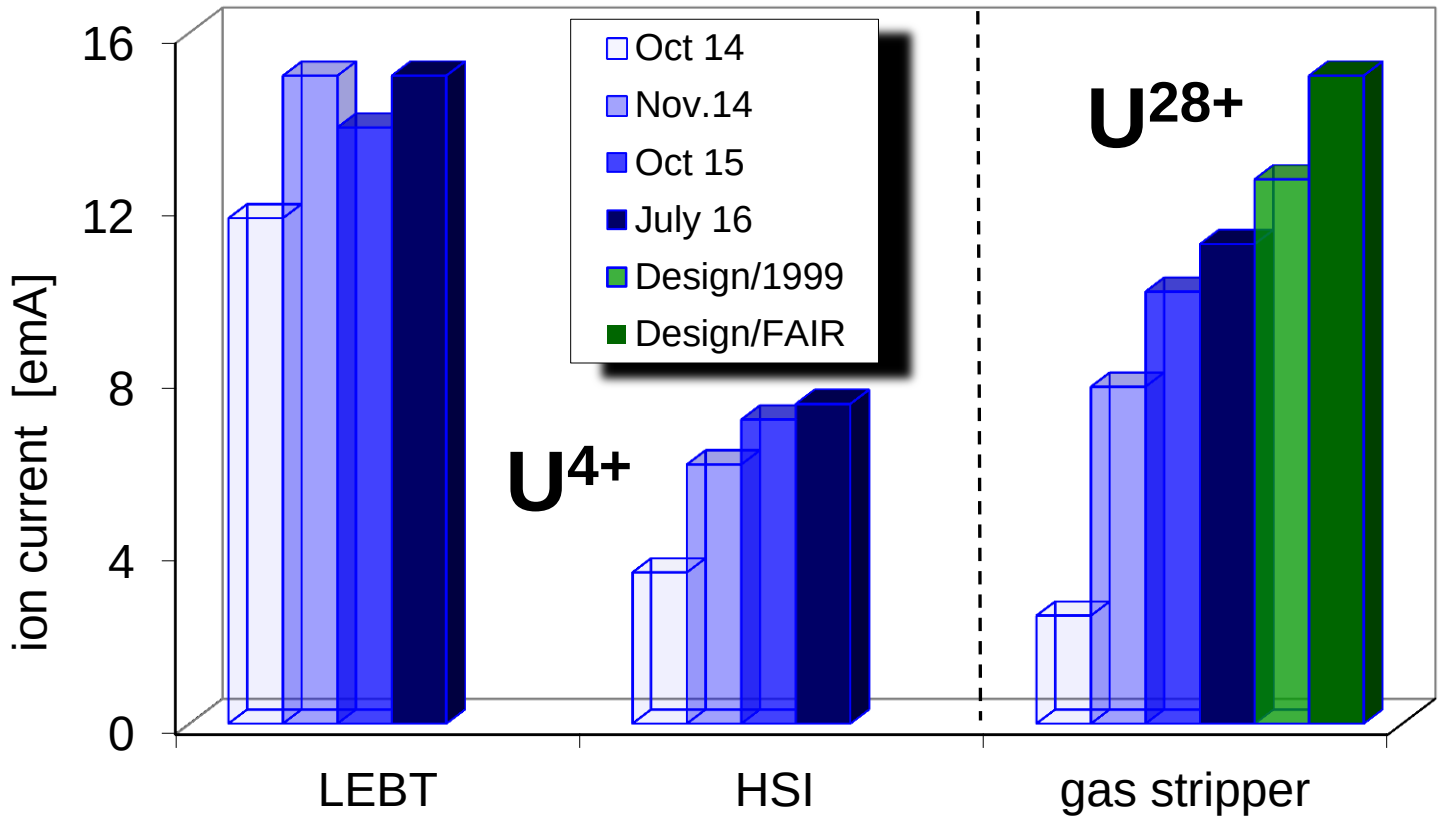
High Charge State Injector (1991)

High Current Injector (1999)

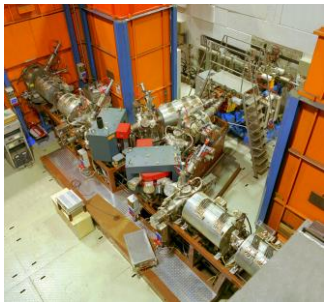
Alvarez (1975)

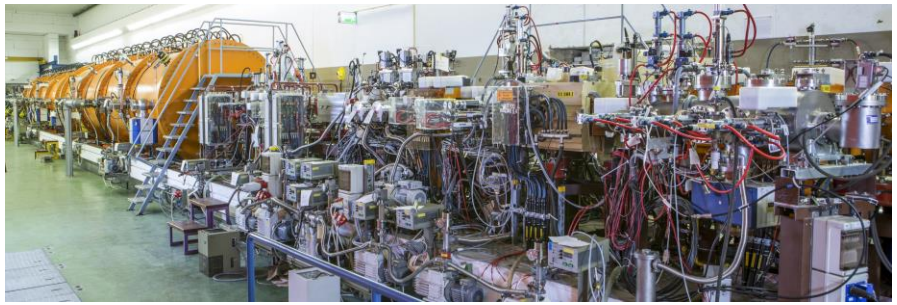
Single Gap Resonators (1975)

Uranium High Current Injector-Performance



W. Barth, et al., Phys. Rev. ST Accel. & Beams 20, 050101 (2017)





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-user program

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

Material Science at GSI-experimental hall

- Heavy Ions ($m \geq 200$)
- High Beam Energy (up to 10 MeV/u)
- Continuous Beam Energy Variation (1.5 – 10 MeV/u)

cw-LINAC-project: Motivation

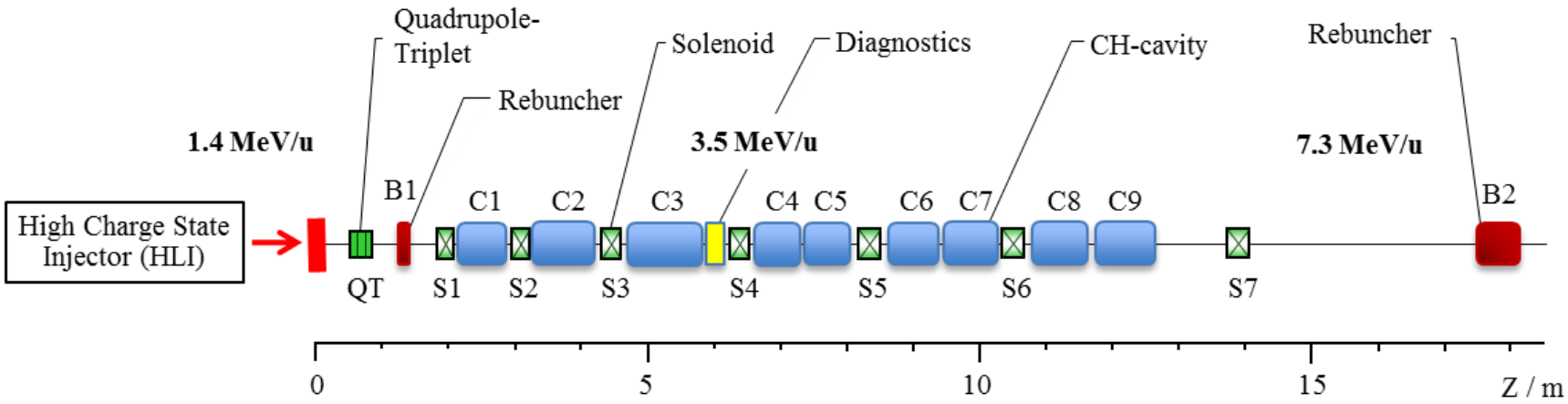
Nuclear reactions at the Coulomb-barrier→ production of Super Heavy Elements (SHE)

Production of Element $^{288}_{115}$uut, $^{289}_{115}$uut, 30 $events$

(D. Rudolph, Lund Univ., PRL 111, 112502 (2013))

	GSI- Unilac	cw-Linac
Beam intensity (particle/s)	$6 \cdot 10^{12}$	$6 \cdot 10^{13}$
Beam on target	3 weeks	2 days

General Heavy Ion cw-Linac layout

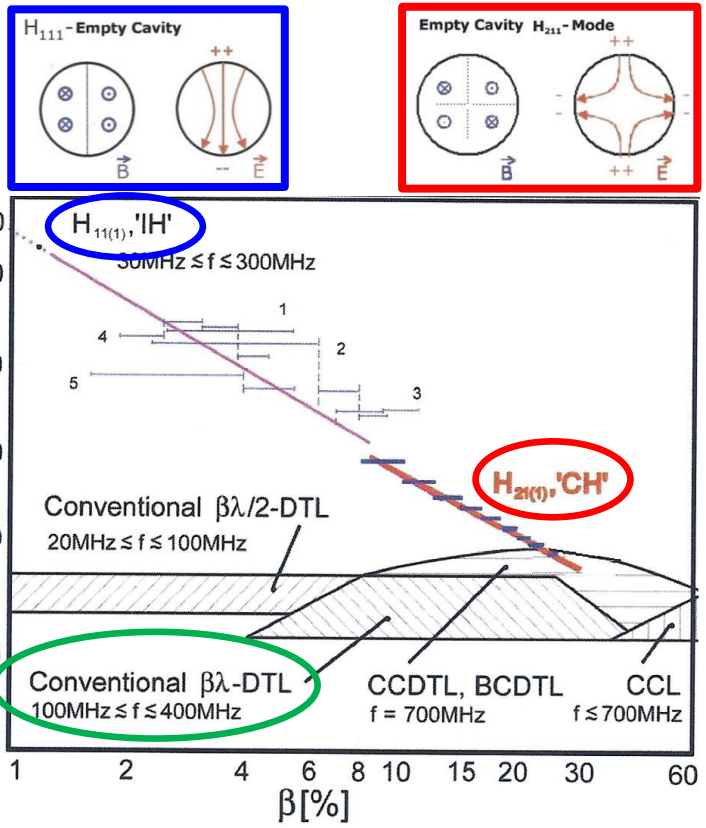


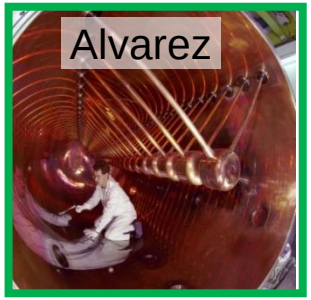
S. Minaev et al., Phys. Rev. ST Accel. Beams 12, 120101, (2009),

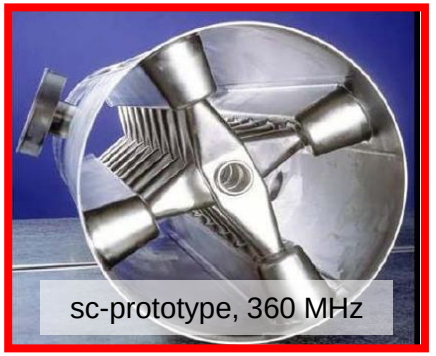
Mass/Charge		6
Frequency	MHz	216.816
Max. beam current	mA	1
Injection Energy	MeV/u	1.4
Output energy	MeV/u	3.5 – 7.3
Output energy spread	keV/u	±3
Length of acceleration	m	12.7
Sc CH-cavities	#	9
Sc solenoids	#	7

H-type Cavity developments

HELMHOLTZ Helmholtz Institute Mainz

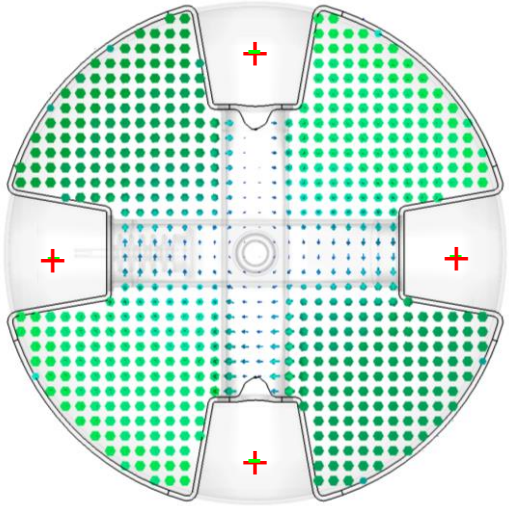




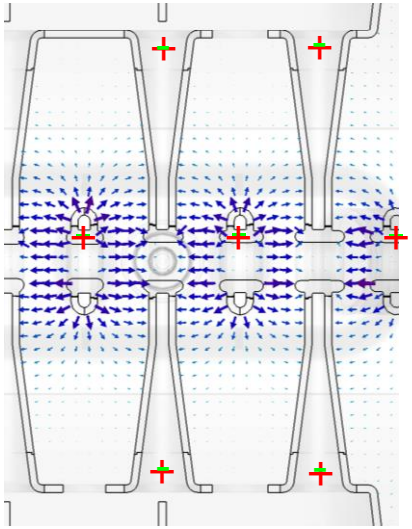


CH-cavity: Field profiles

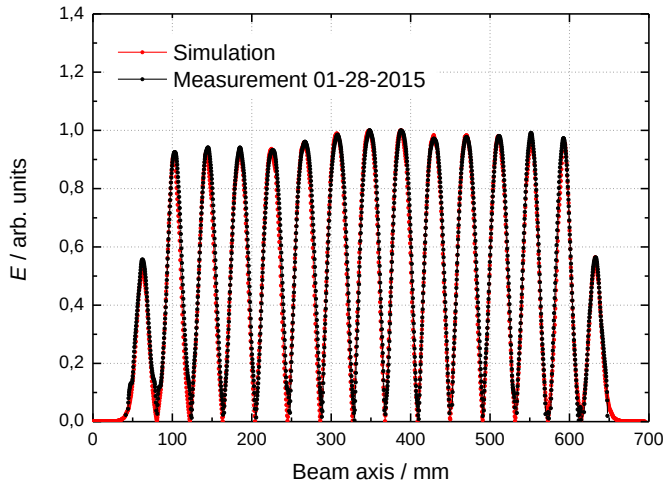
H field



E field



E field along beam axis



- Multigap drift tube cavity for the acceleration of protons and ions in the low and medium energy range
- Drift tubes are alternating connected to "+" and "-" potential
- **C**ross-bar-**H**-mode cavity → CH cavity
- Equidistant drift tubes length → special beam dynamics

EQUUS beam dynamics concept

courtesy: F. Dziuba et al., Poster@LINAC2018, THPO073

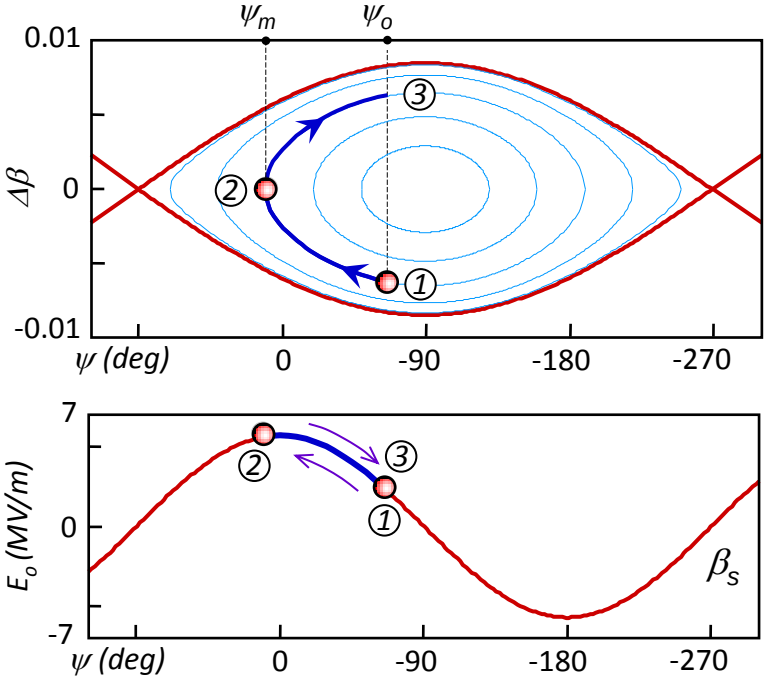
EQUUS - EQUidistant mUltigap Structure

① Particles too early → obtain less acceleration
→ longitudinal focussing

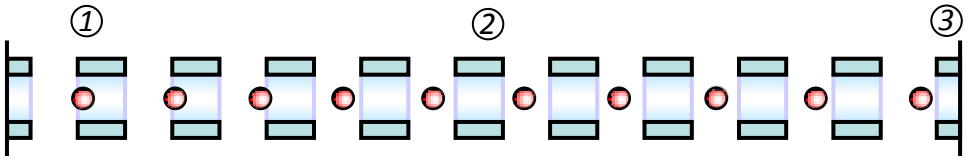
② Particles synchr. → reach max. acceleration
→ longitudinal defocussing

③ Particles too early → obtain less acceleration
→ longitudinal focussing

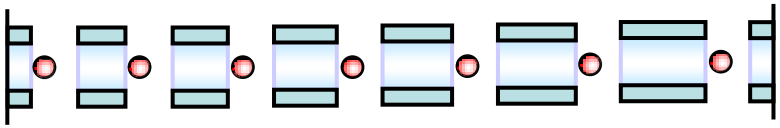
Longitudinal motion of an accelerated bunch in the constant-β-section



EQUUS

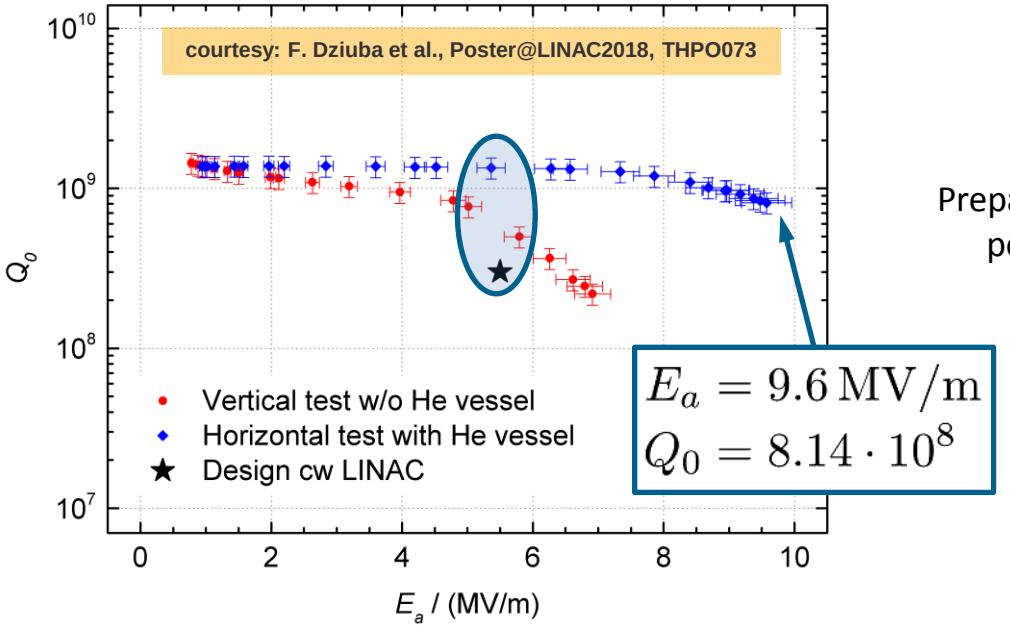


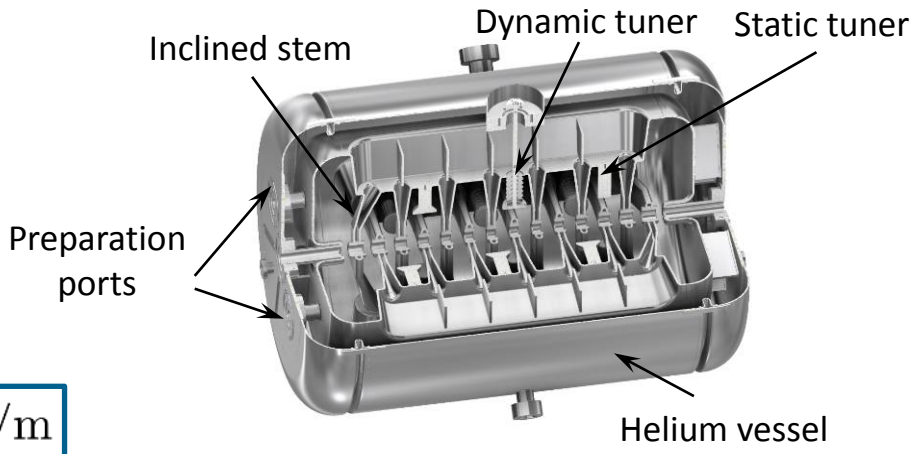
Resonant acceleration at φ = -30°



RF Testing of the CH-Cavity (10/2016)

RF test in a horizontal cryostat (@4.2°K)



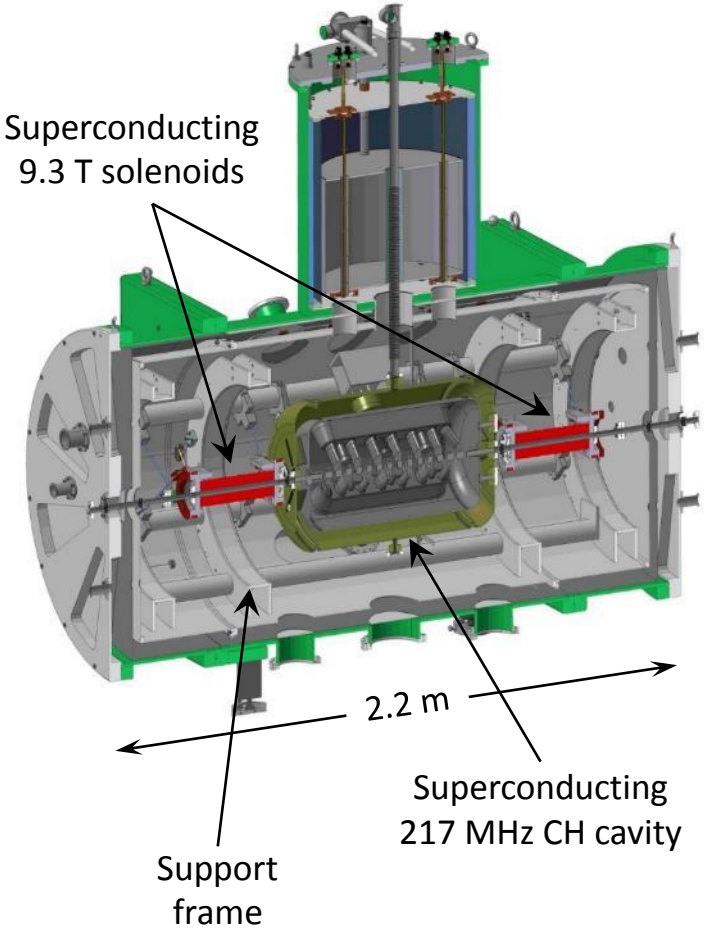


- Improved performance (add. HPR)
- Low field emission rate
- High field gradient
- Therm. quenching beyond 9.6 MV/m

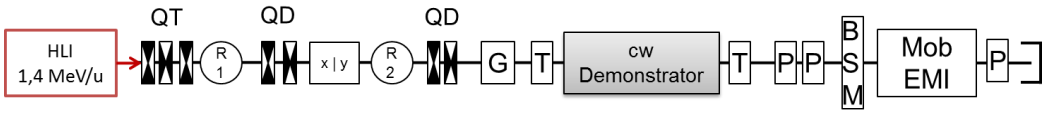
		Vertical test w/o He vessel	Horizontal test with He vessel
Q_0^{low}		$1.44 \cdot 10^9$	$1.37 \cdot 10^9$
R_S	nΩ	36	38
R_{BCS}	nΩ	15	15
R_{mag}	nΩ	9	12
R_0	nΩ	12	11
E_a	MV/m	6.9	9.6
Q_0		$2.19 \cdot 10^8$	$8.14 \cdot 10^8$
V_a	MV	4.2	5.9
E_p	MV/m	43	60
B_p	mT	39	55

Experimental setup of the demonstrator at GSI

Layout of the horizontal cryomodule

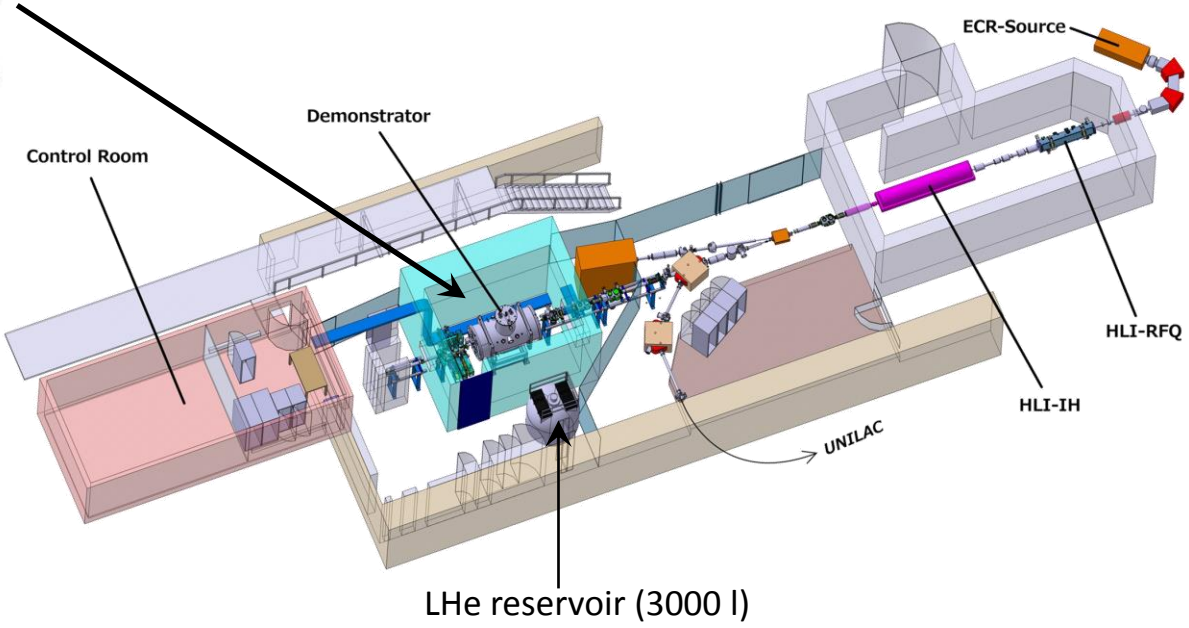


Matching line - demonstrator – test bench



- Steering magnets
- Rebuncher
- Quadrupole doublet
- Profile grids
- Phase probes for TOF measurement
- Beam current transformers
- Bunch shape monitor (Feschenko)
- Emittance measurement

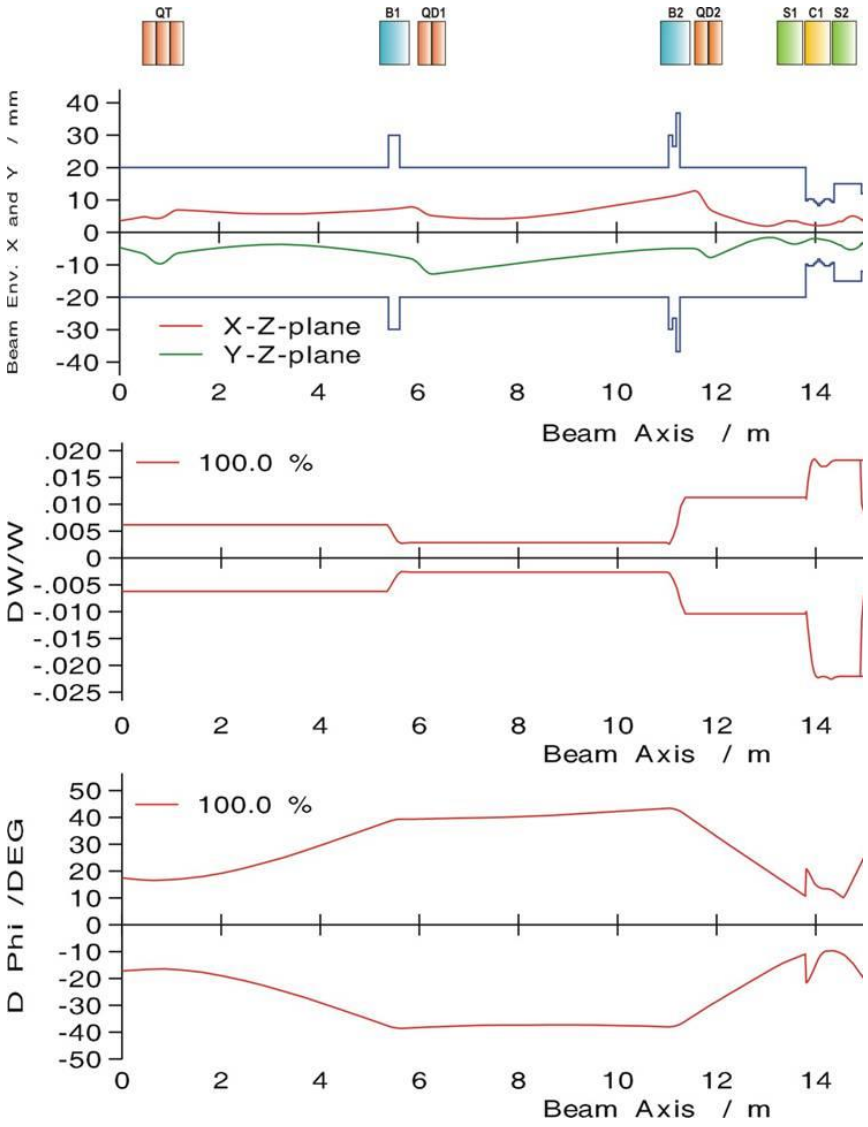
Demonstrator at GSI-High Charge State Injector (HLI)



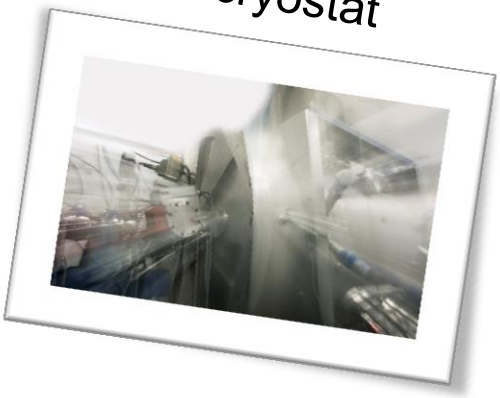

June 2017
First beam test

Matching the cw-Linac Demonstrator

HLI

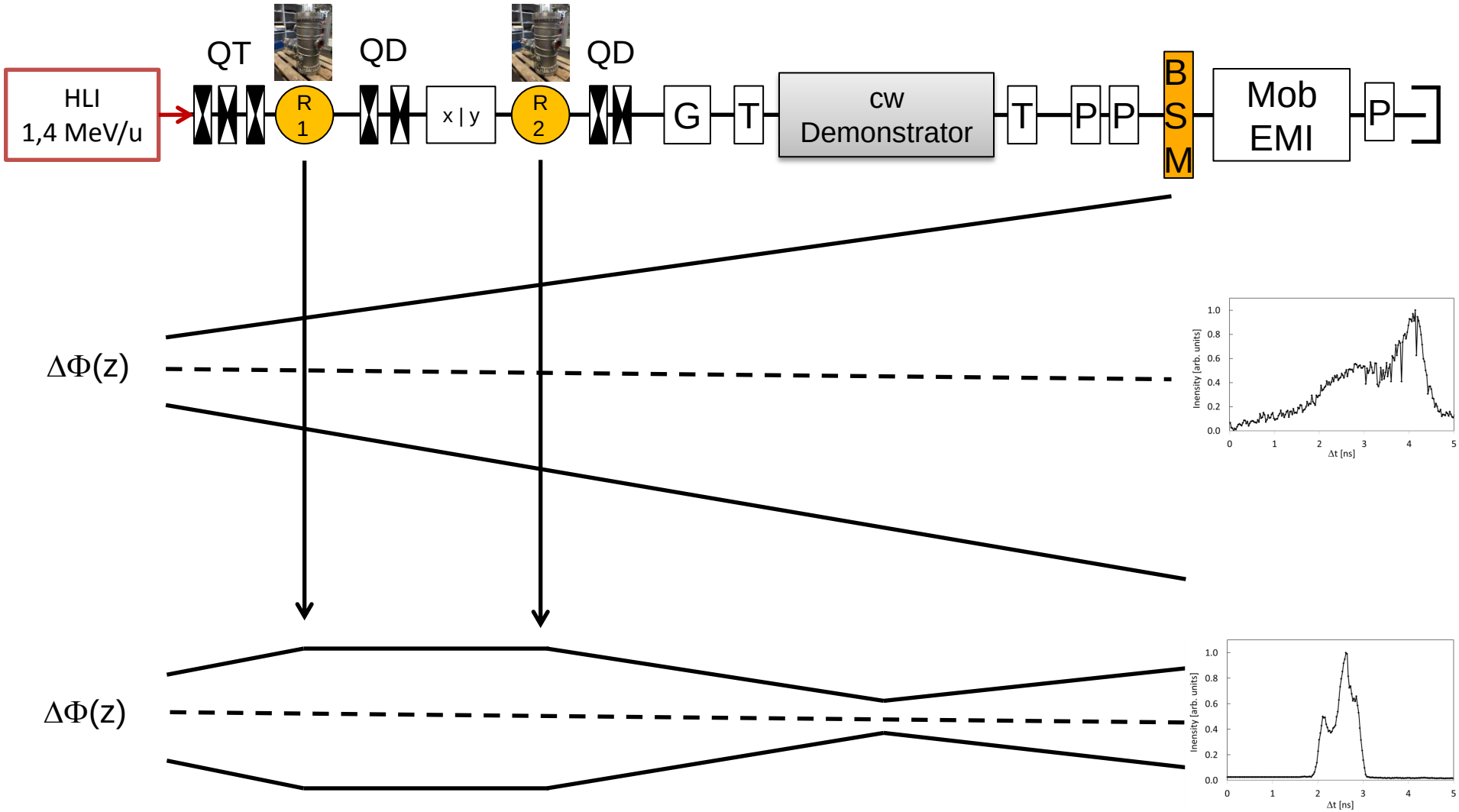


cryostat

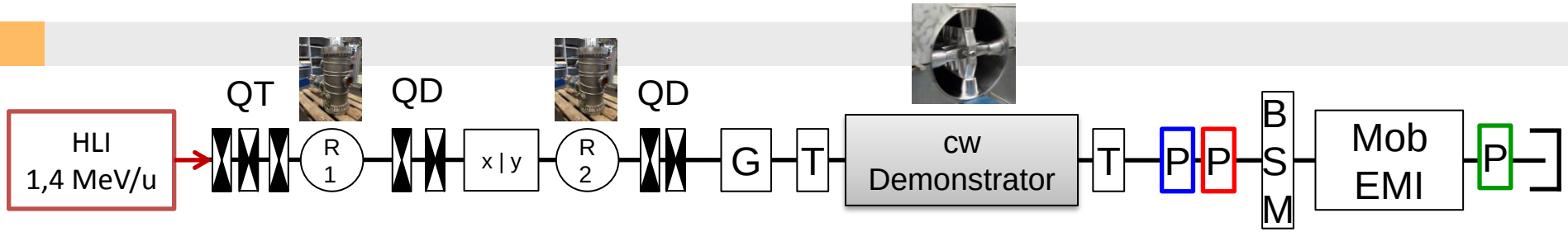


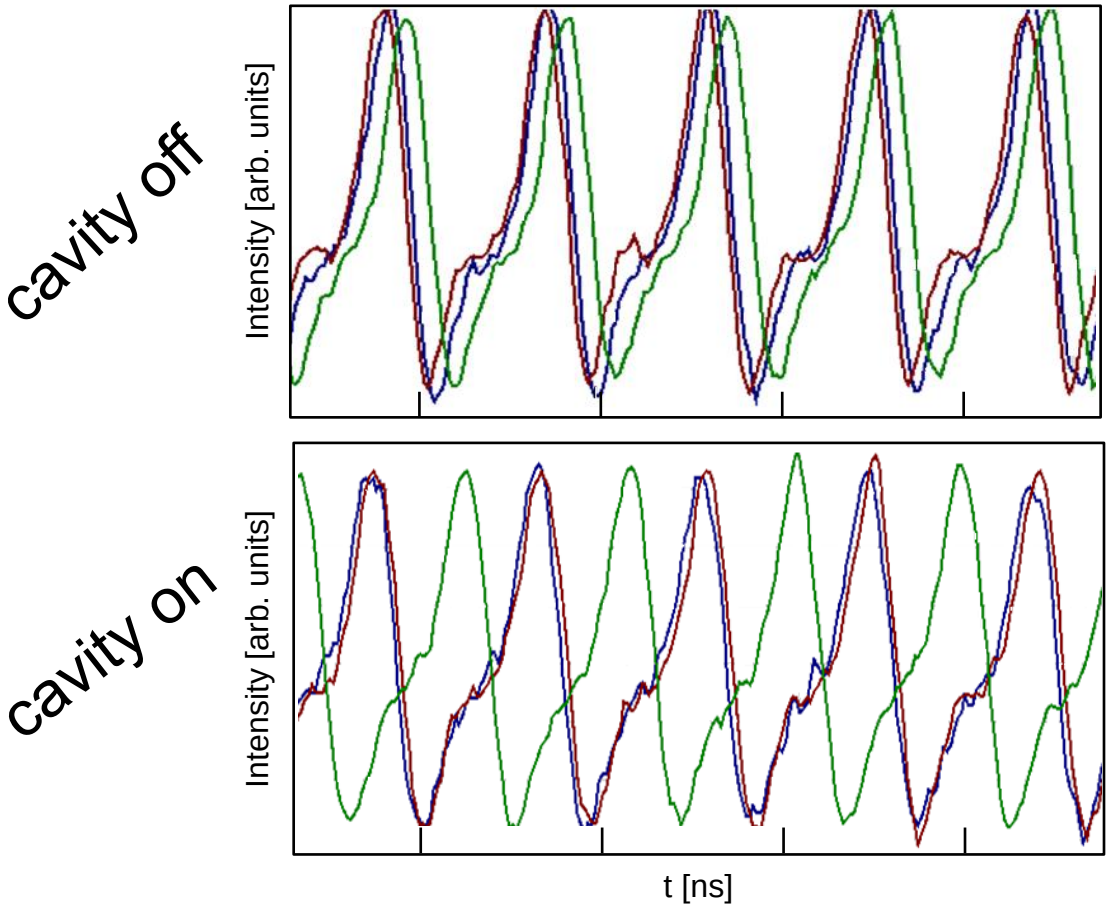
courtesy: A. Rubin, *Proc of IPAC'13*

Longitudinal matching



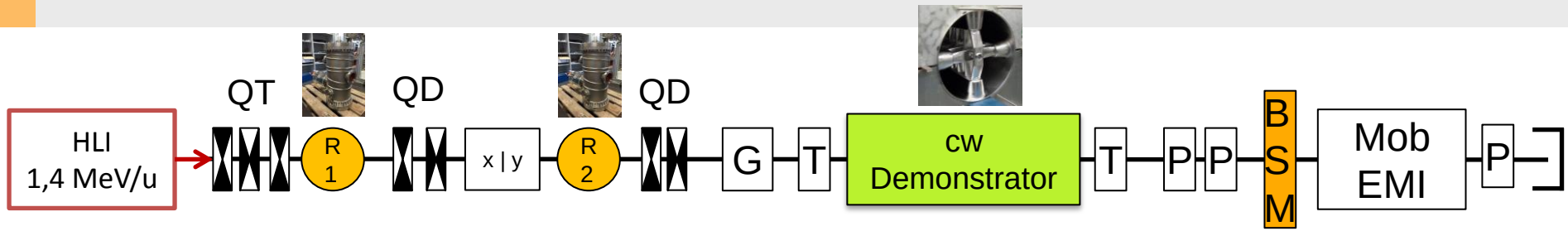
First Acceleration

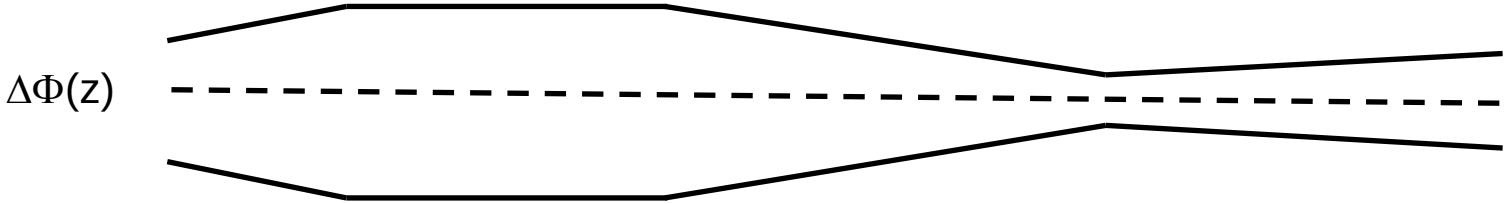




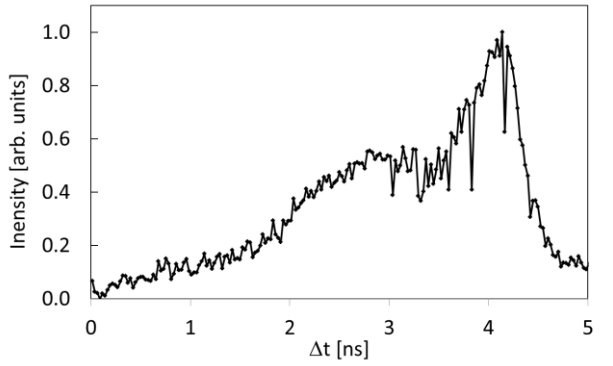
- Measurement of transient signal induced by traveling bunch
- Acceleration! Energy gain of 0.5 MeV/u
- → systematic scan of rf-phase and amplitude

Bunch structure measurement

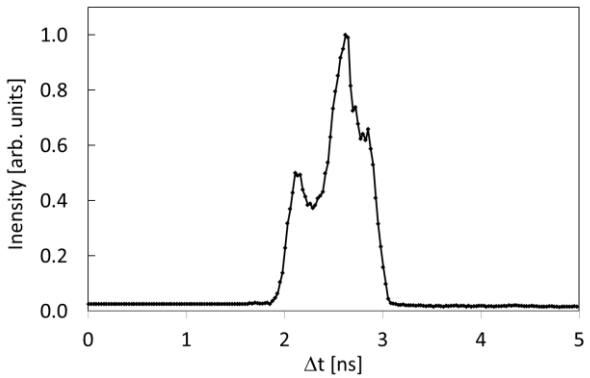




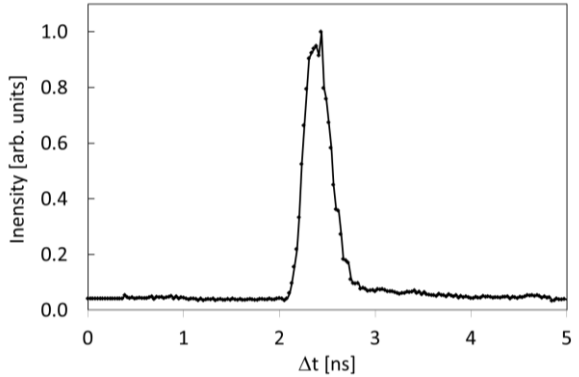
cavities off



R1 + R2



R1 + R2 + CH0

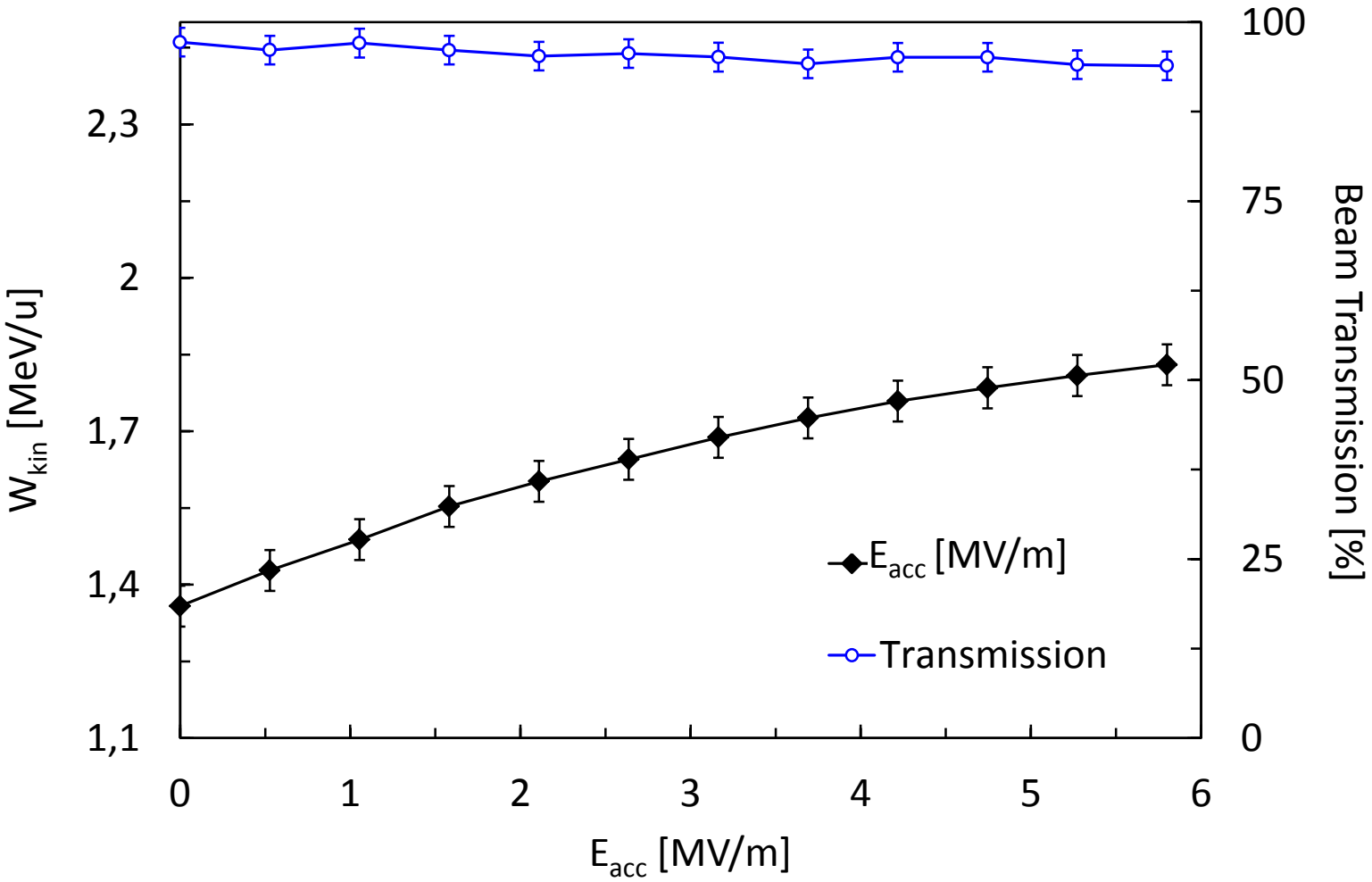


RF-parameter (matched case)

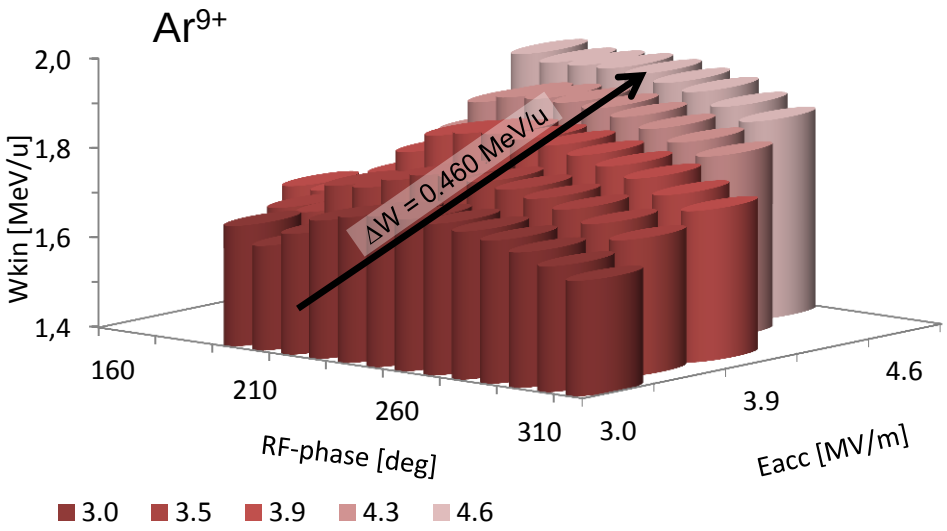
	He^{2+}	Ar^{11+}	Ar^{9+}	Ar^{6+}
A/q	*2.0*	*3.6*	*4.4*	*6.7*
$U_{Reb1,eff.}$ [kV]	8.3	15.0	18.3	27.9
$U_{Reb2,eff.}$ [kV]	22.7	40.8	49.9	75.9
$E_{acc,CH}$*[MV/m]	1.8	3.2	3.9	5.9
U_0 [MV]	1.2	2.2	2.7	4.0

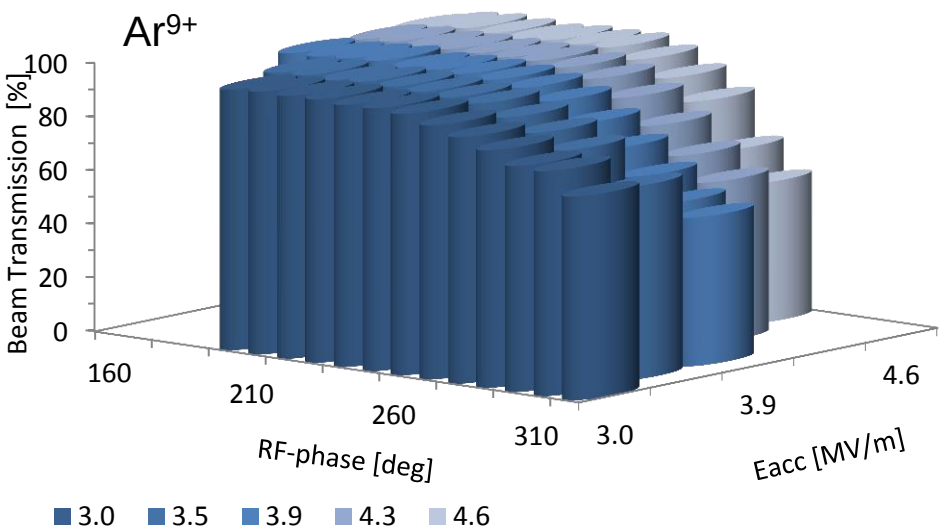
* E_{acc} = *transit time factor* × *total accelerating voltage*/($n \times 0.5 \times \beta\lambda$)

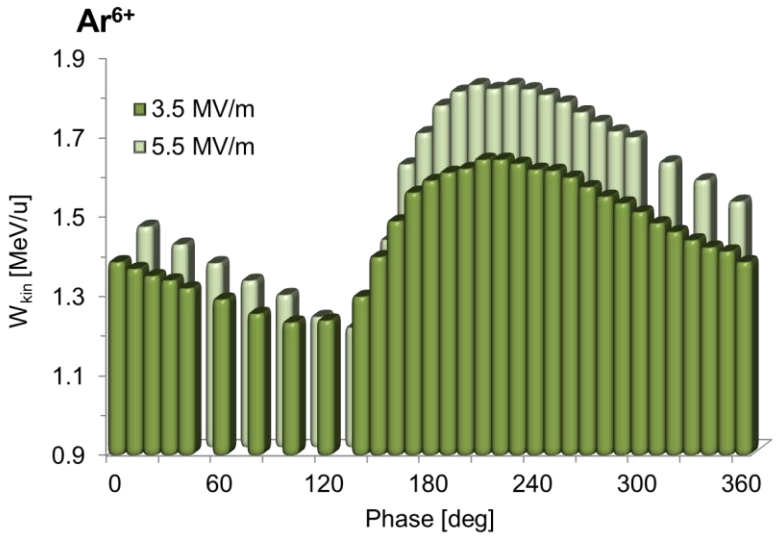
Amplituden-scan

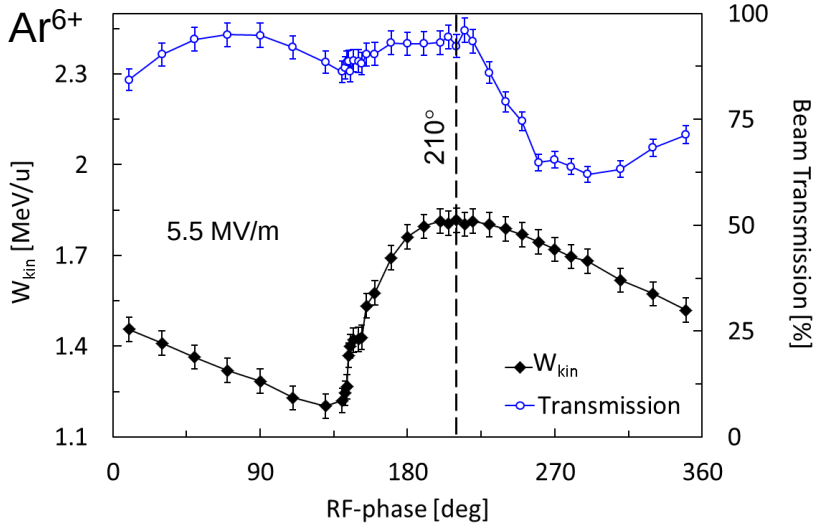


Systematic Scans (RF-phase/-amplitude)

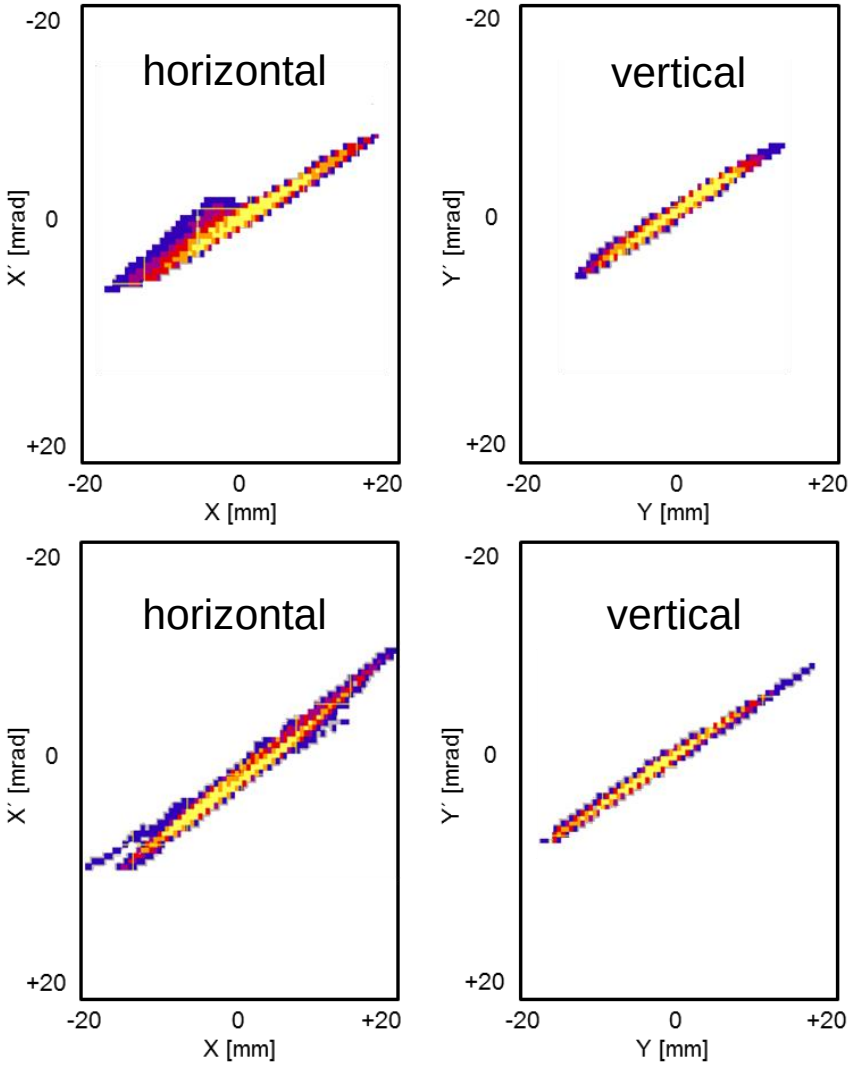








Emittance measurement



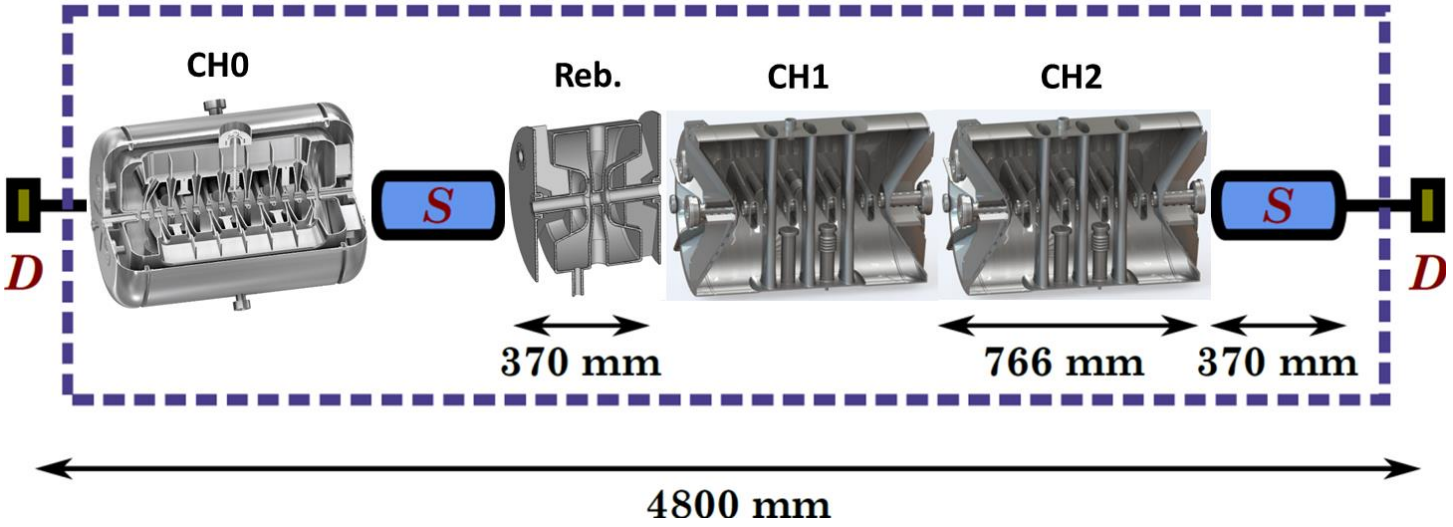
1.40 MeV/u

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

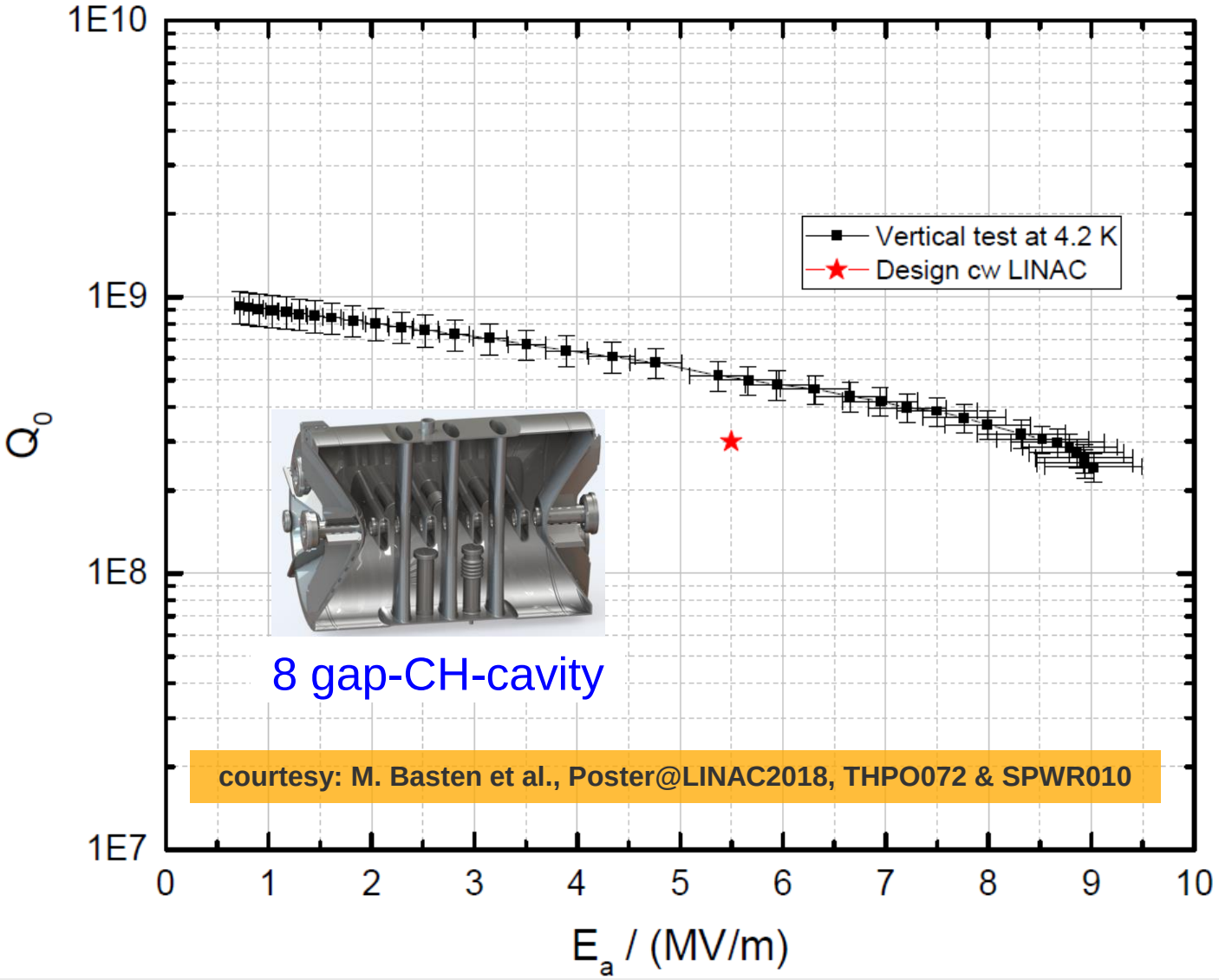
Advanced Demonstrator

Standard cryomodule layout



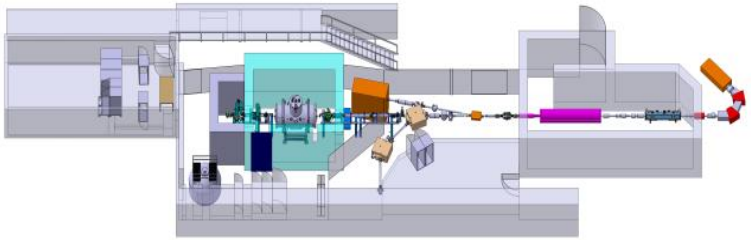
- New cryo module layout containing demonstrator CH cavity, 2 short CH cavities, 1 buncher and 2 solenoids
- Simplified cavity design (easier manufacturing & surface processing)
- CH1 & CH2 are already in production (delivery at 4th quarter of 2019)
- Ordering of cryostat at 1rd quarter of 2019
- Tendering process for rebuncher, solenoids, rf-amplifiers and high power couplers ongoing
- Moderate increase of design gradient $\rightarrow$ more compact linac design or higher A/q

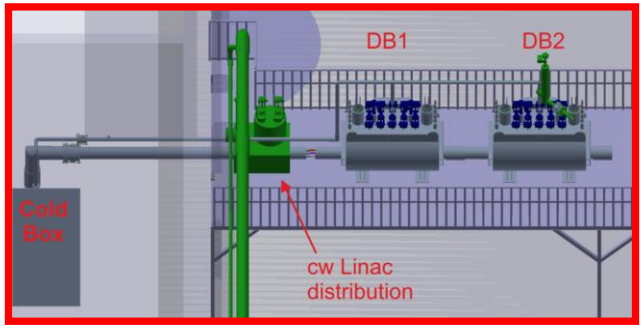
First RF-measurement for CH1 in a vertical cryostat



Extension of test cave and Link to helium supply system (GSI-STF) (2019)

2018



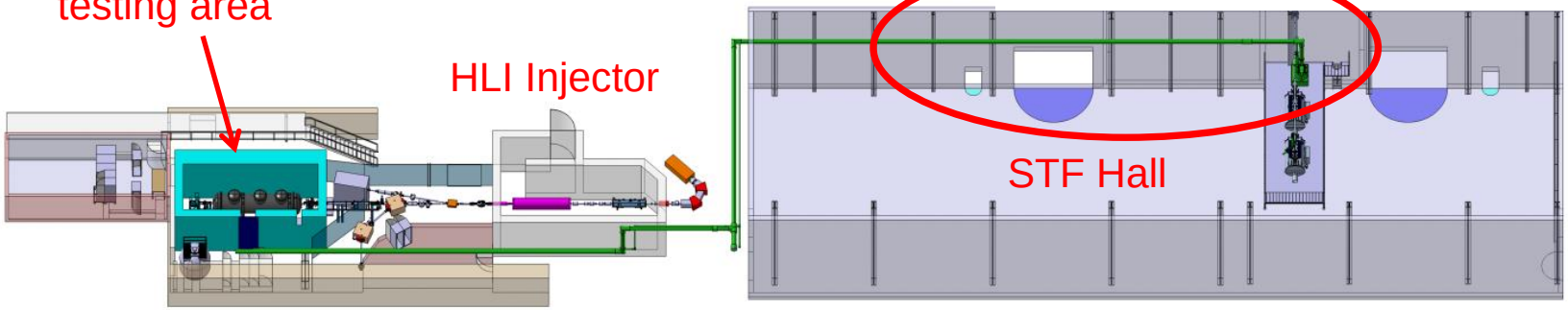


>2018

Advanced demonstrator testing area

Tie In + 20m transfer line installed !

HLI Injector

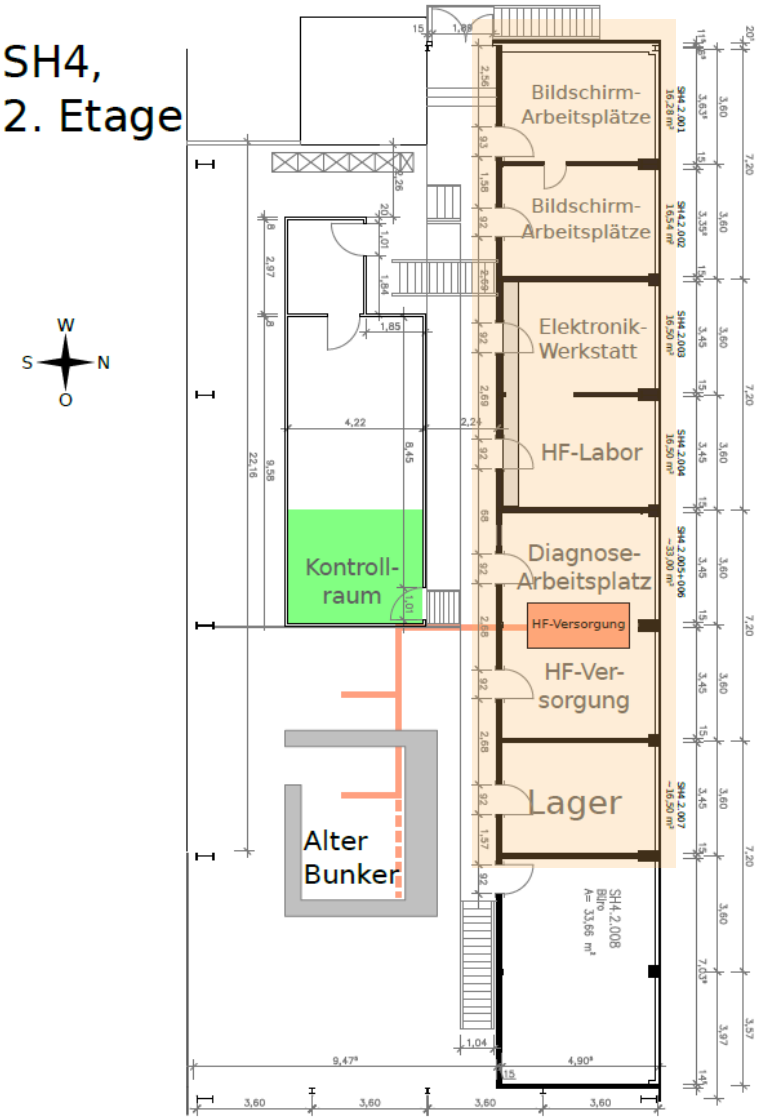


- Radiation protection shelter take whole available space
- No access to fill 3000l Dewar with mobile LHE cans

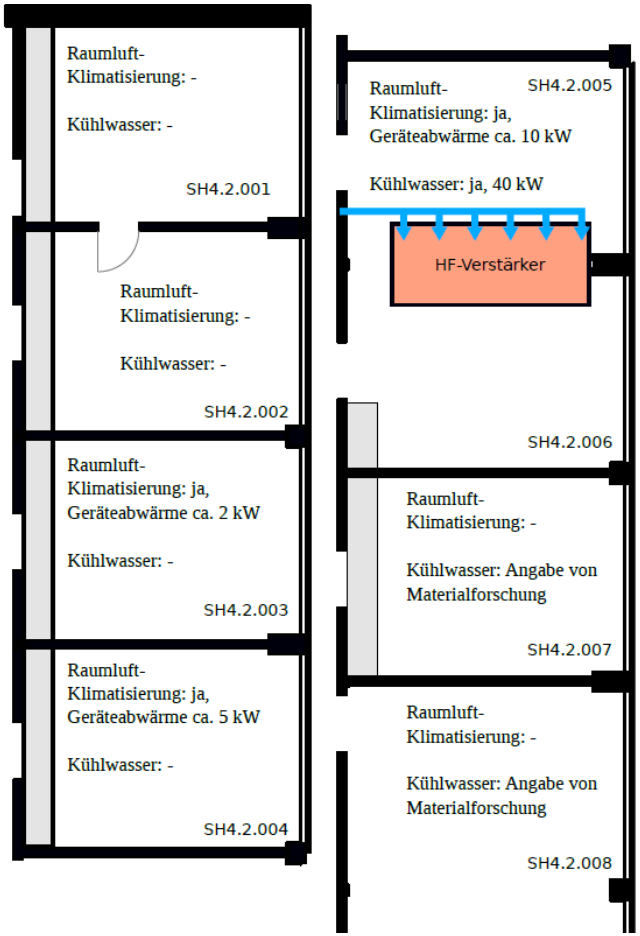
Access to the test area

New local control room, rf-gallery, ...

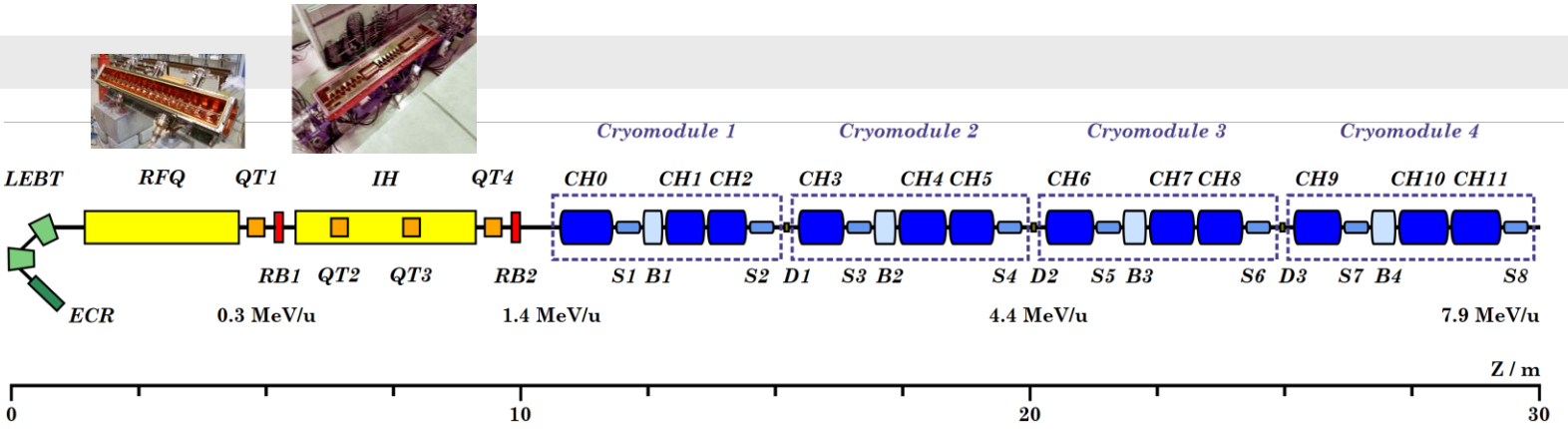
SH4,
2. Etage



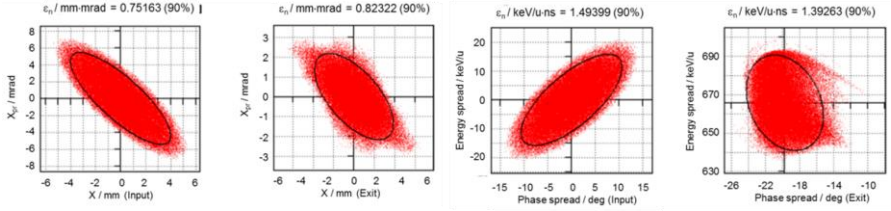
Air conditioning



Current cw-Linac Layout



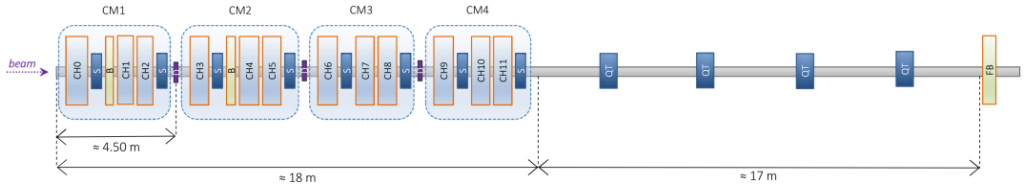
Input CM1 Output CM4

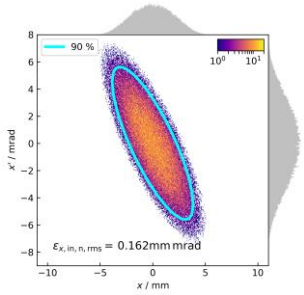


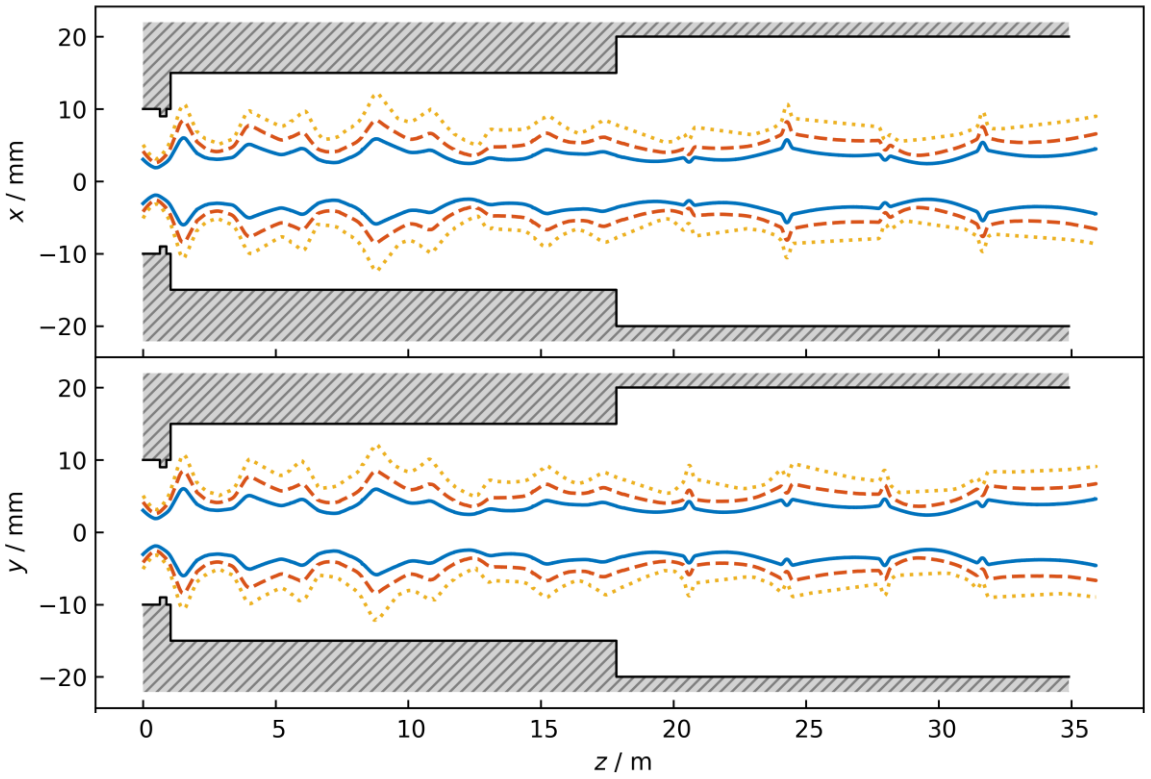
- Total of 12 CH cavities
- Each cryo module contains 3 CH cavities + 1 rebuncher + 2 solenoids
- Variable beam energy 3.6-7.5 MeV/u

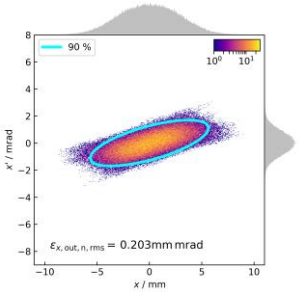
Cryo Module	Cavity	Output energy (MeV/u)		
		A/Z=6	*A/Z=3*	*A/Z=1*
	HLI	*1.4*	*1.4*	*1.4*
CM1	CH0	2.1	2.2	3.0
	CH1	2.6	3.0	4.2
	CH2	2.9	3.6	4.6
CM2	CH3	3.4	4.3	5.7
	CH4	3.8	4.8	6.3
	CH5	4.2	5.5	7.7
CM3	CH6	4.7	6.2	8.6
	CH7	5.2	7.0	9.9
	CH8	5.8	7.8	10.9
CM4	CH9	6.4	8.7	12.3
	CH10	7.0	9.5	13.2
	CH11	7.6	10.5	14.6

Transversal beam dynamics cw-Linac layout



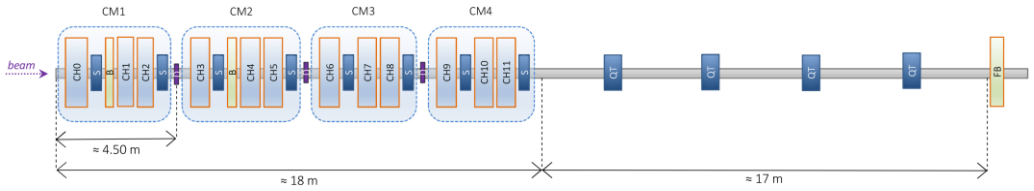


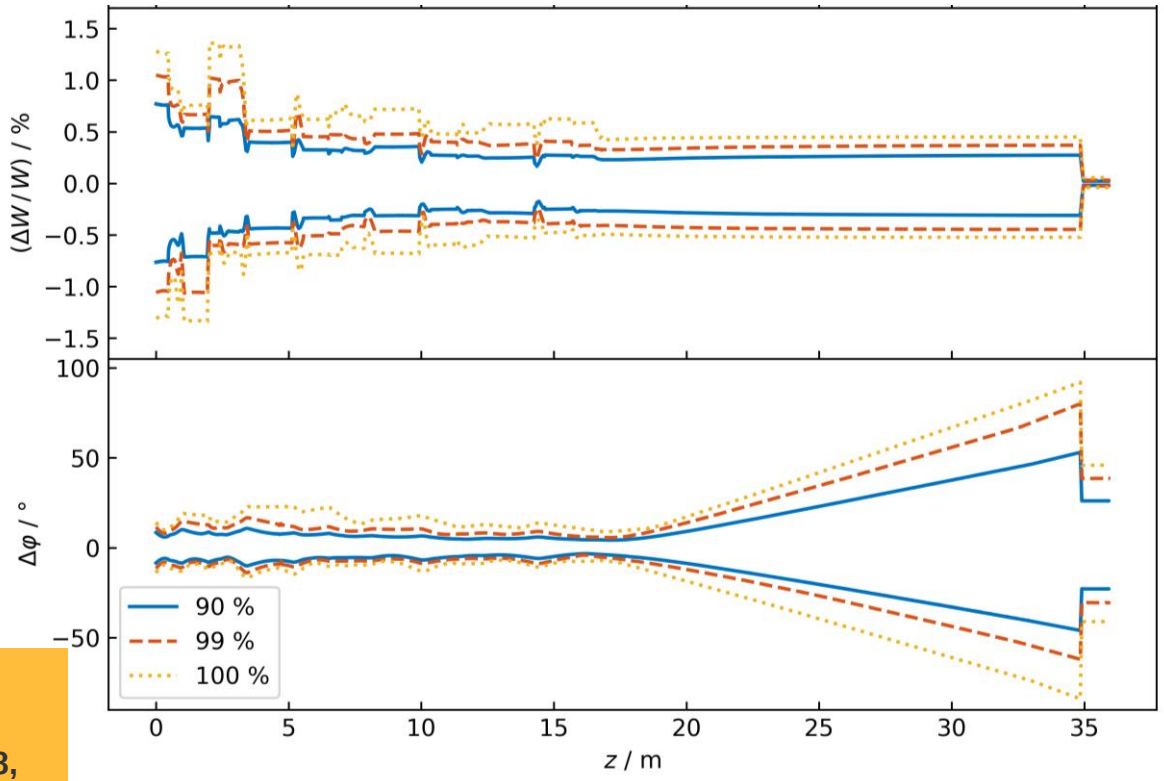




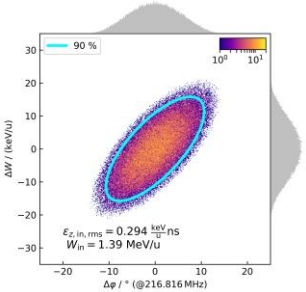
courtesy:
M. Schwarz, et al., Poster@LINAC2018, TUPO084 & SWPR034

Longitudinal beam dynamics cw-Linac layout

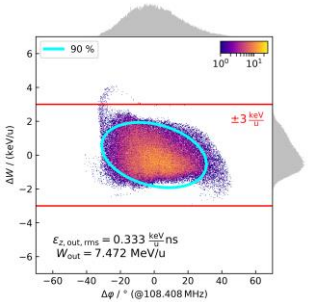




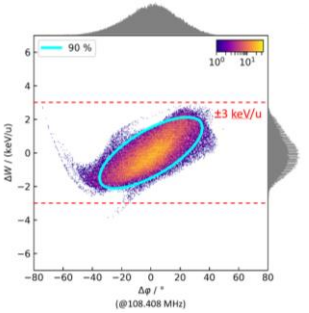
1.4 MeV/u



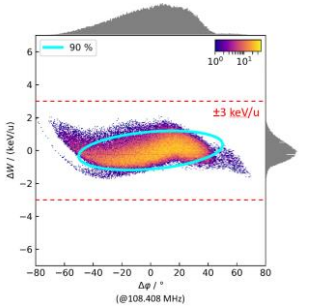
3.5 MeV/u



5.0 MeV/u

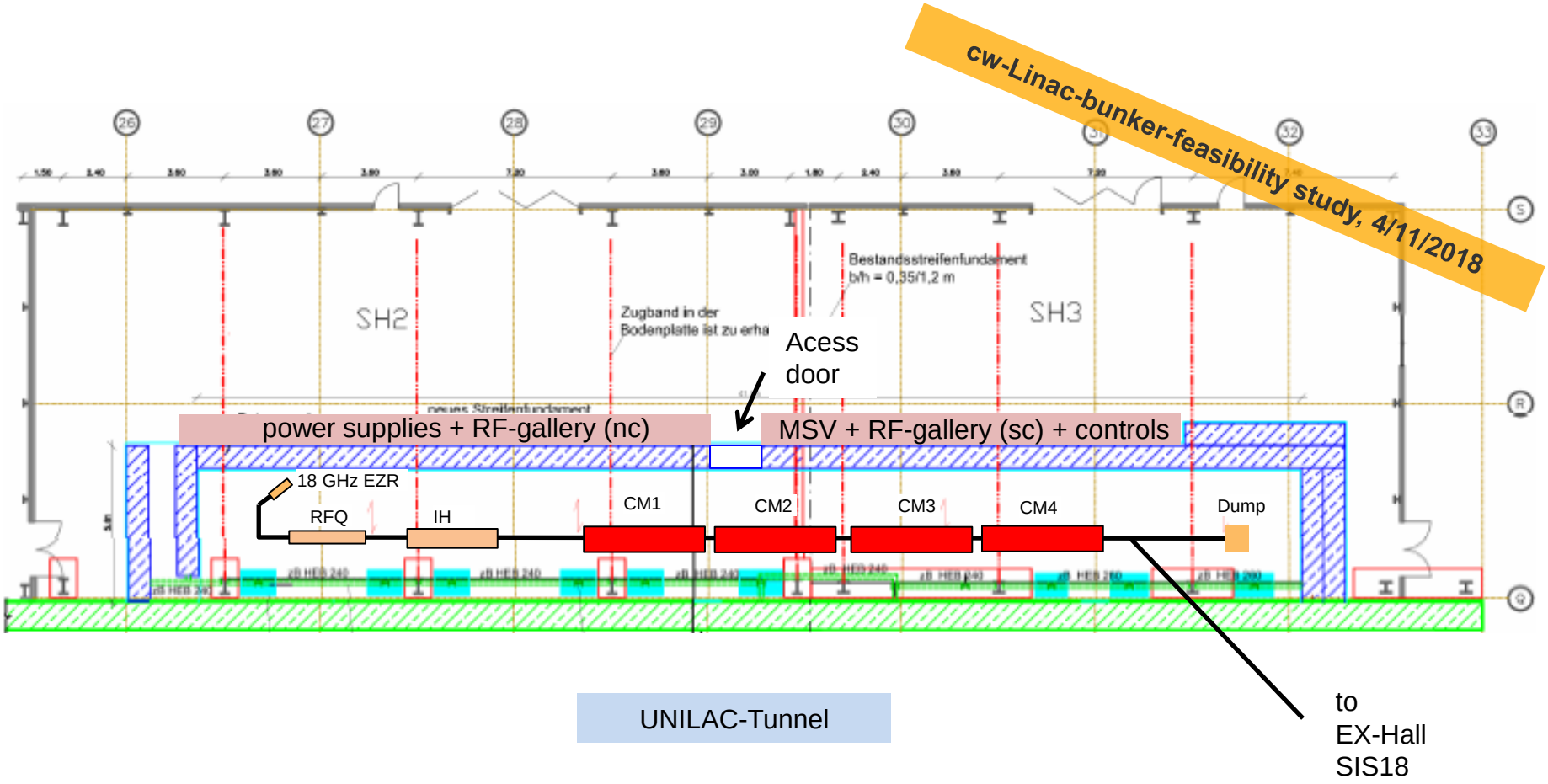


7.5 MeV/u



courtesy:
M. Schwarz, et al., Poster@LINAC2018, TUPO084 & SWPR034

HELIAC-preparation: cw-Linac-bunker (>2021)



Crossection of the Linac-Tunnel

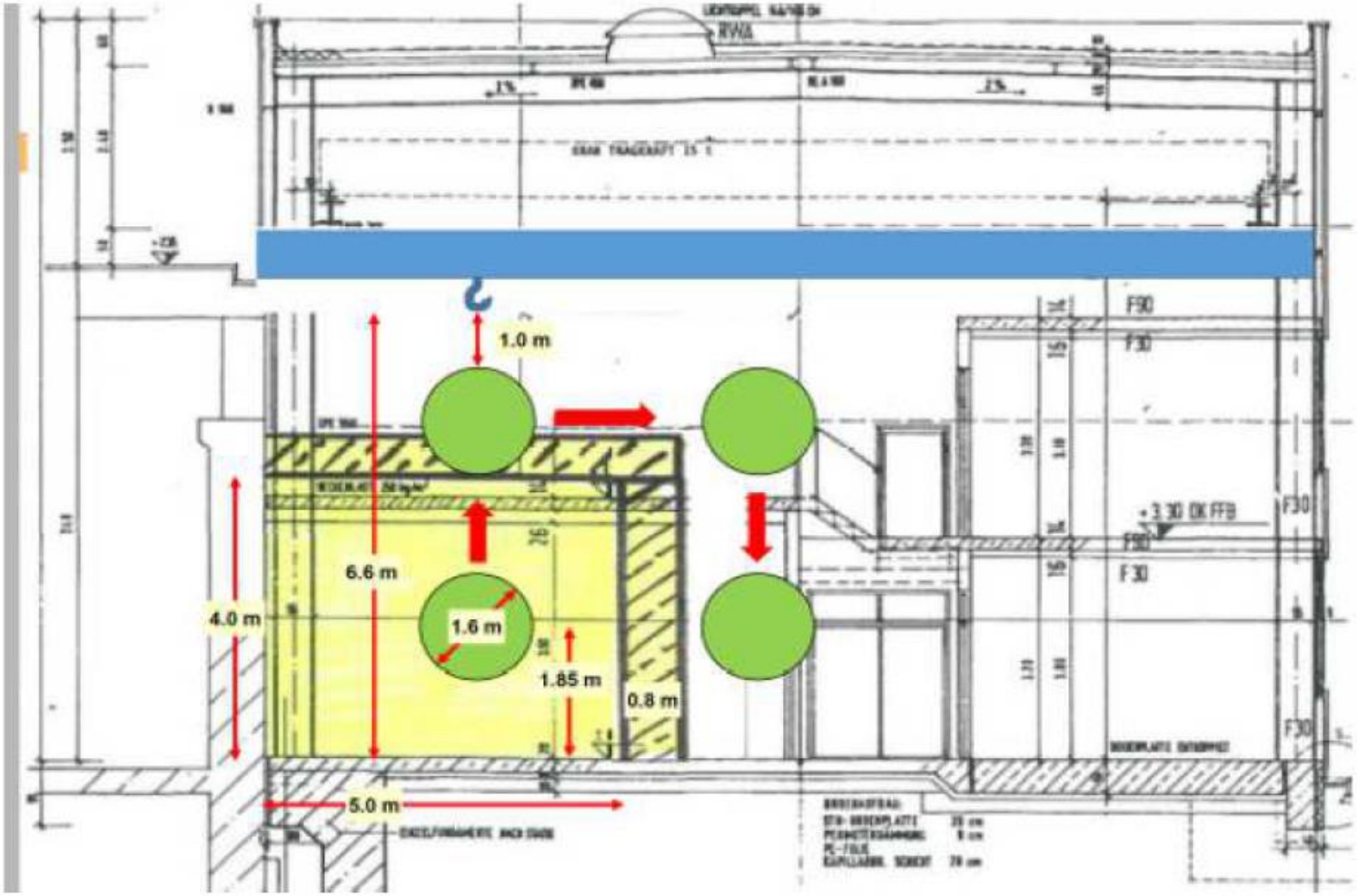
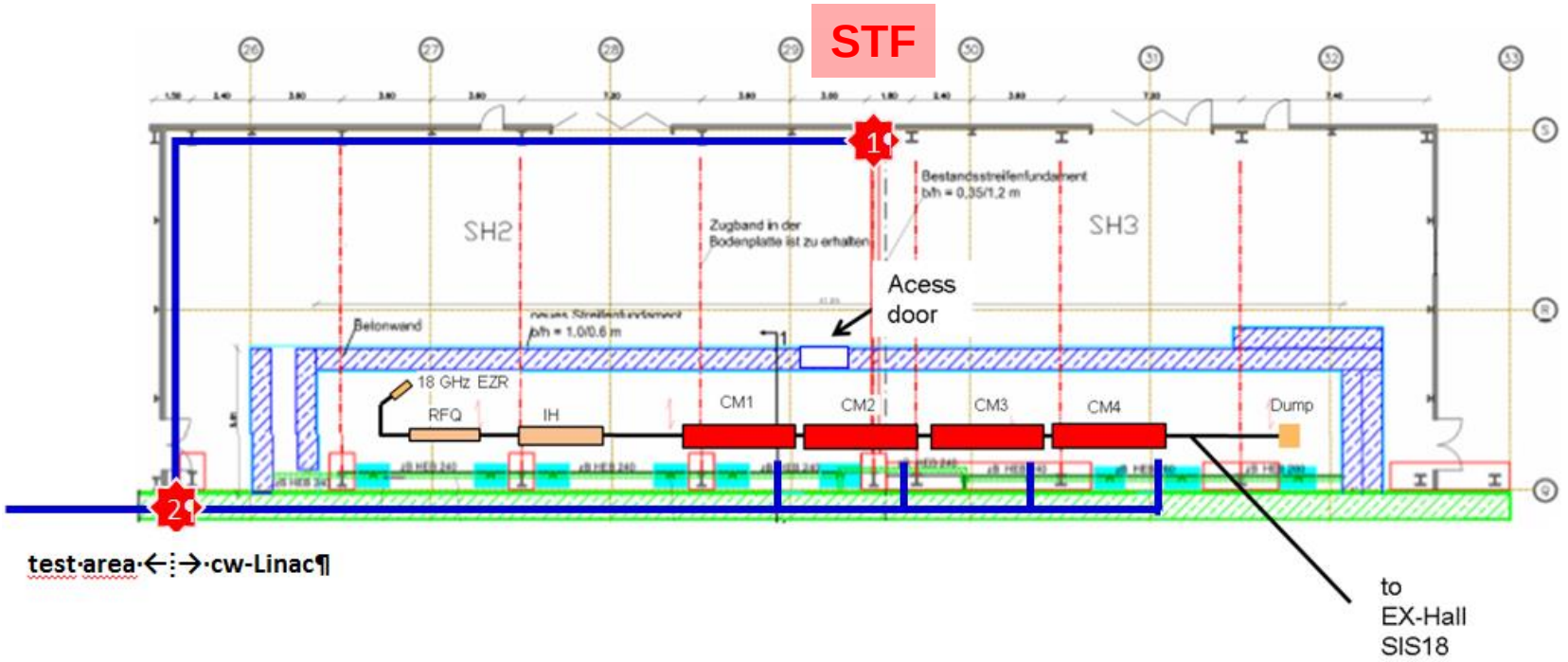


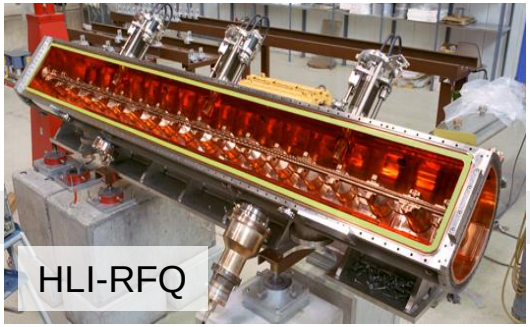
Abb. 4: Querschnitt mit Darstellung der geplanten Betonabschirmung

Link to the STF (LHe-supply system at SH5)

- ... (STF, ① in the figure above) has been installed during regular shutdown of STF in December 2018
- LHe-transfer line to the bifurcation point ② and from bifurcation point to the test area cave will be both completed in 2019
- Short transfer line from the bifurcation point to the LHe-supply system of the cw-Linac tunnel will be finalized after setup of the tunnel

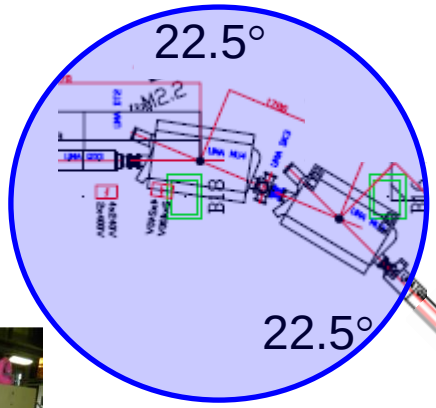


Synergies...



- Second use of SH2/3
- HLI-RFQ (Version 1) stored at JGU-Mainz => 25% duty factor (first setup)
- Second use of STF
- RF-switch for joined use of 200kW-high power RF-amplifiers (first setup)
- Second use of beam line elements (Quads, steerer, dipole magnets)

from cw-LINAC
→

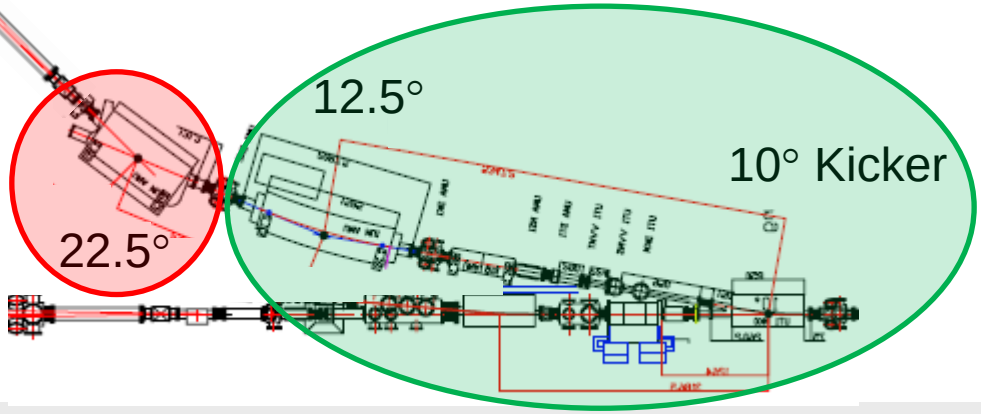


back from CERN, renewed and stored at GSI

scraper

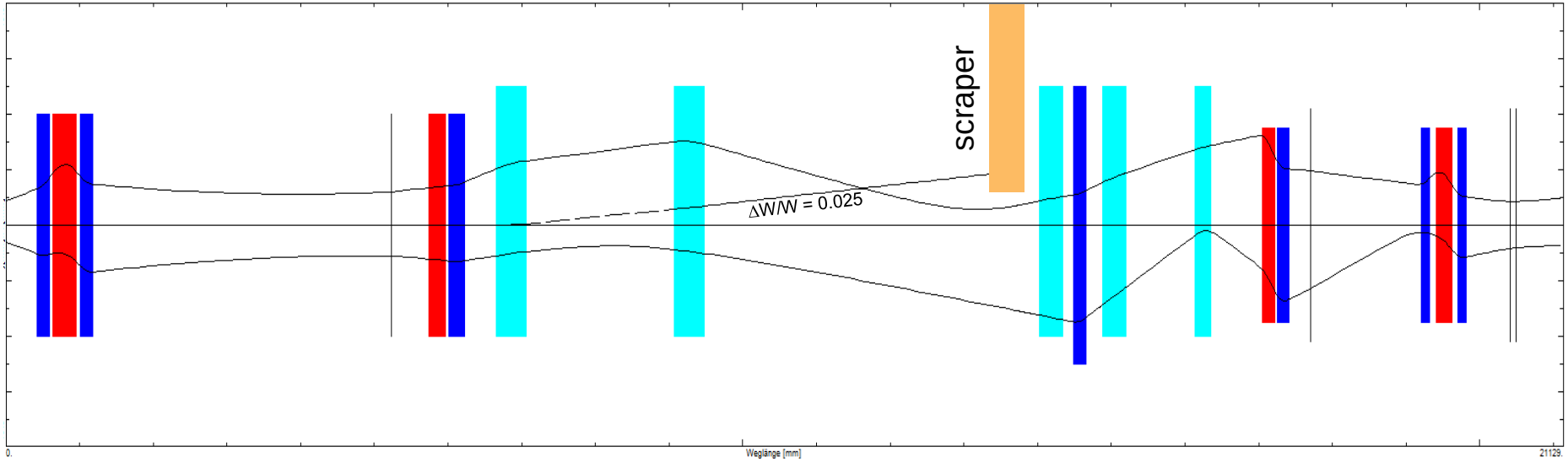
GSI-design (Link to M-branch)

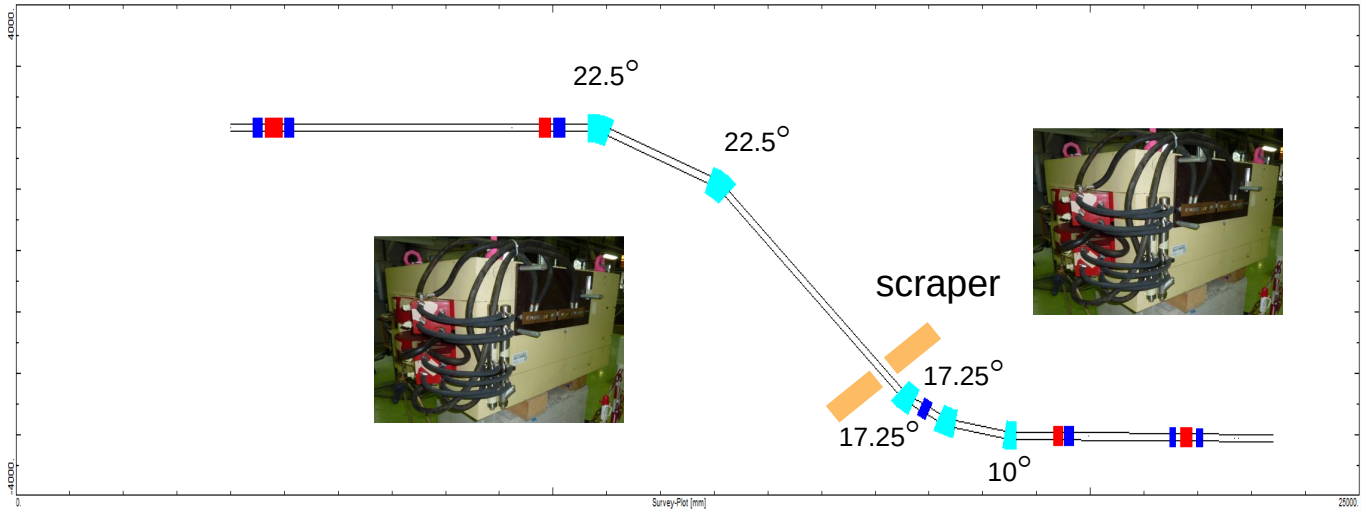
Reuse of Z-branch dipole(s), Quad(s), rebuncher



from UNILAC →

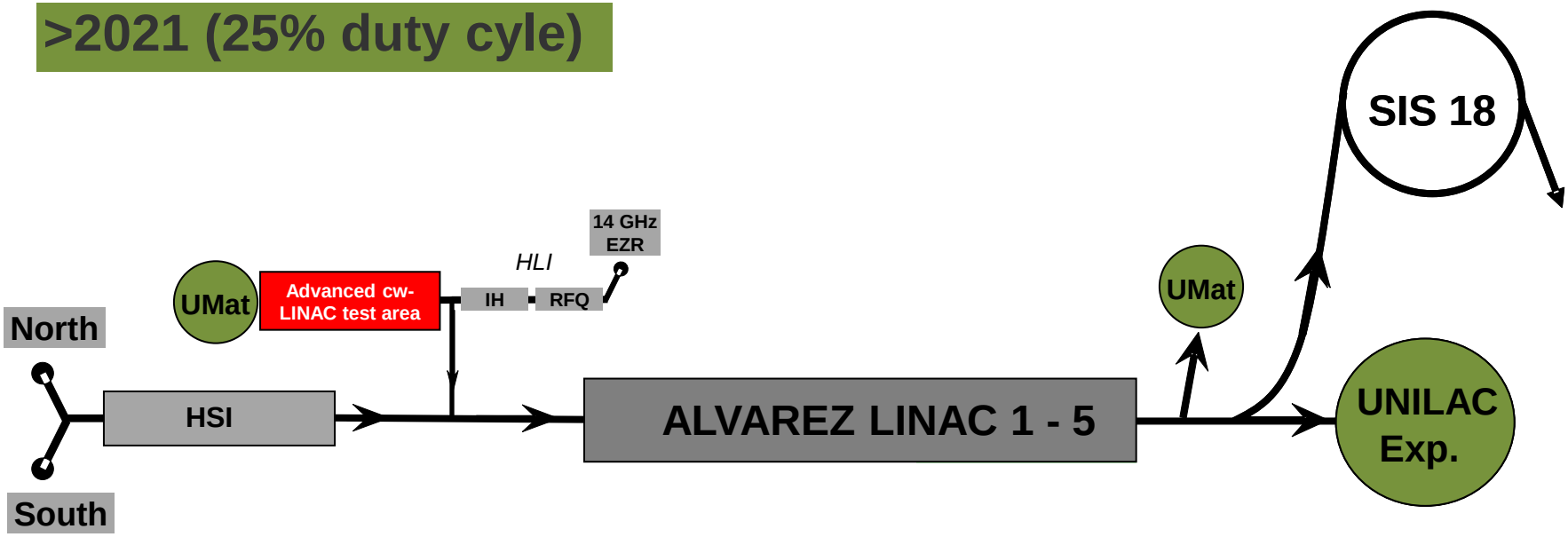
Beam Transport Line cw-Linac to UNILAC





Maximum cw-Linac beam energy

>2021 (25% duty cyle)



Cryo Module	Cavity	Output energy (MeV/u)		
		A/Z=6	*A/Z=3*	*A/Z=1*
	HLI	*1.4*	*1.4*	*1.4*
CM1	CH0	2.1	2.2	3.0
	CH1	2.6	3.0	4.2
	CH2	2.9	3.6	4.6

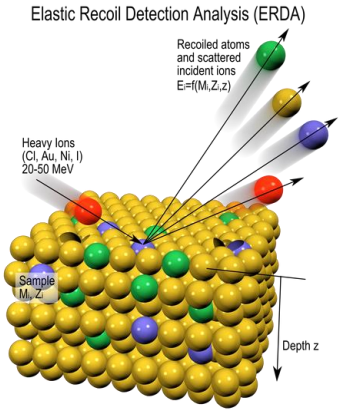
← @advanced cw-Linac test area

Opportunities (2021+)
Material Science (4-8 weeks per year)
Biology (2-3 weeks per year)

“High Energy” Ion Beam Analytic ERDA

Elastic **R**ecoil **D**etection **A**nalysis (ERDA)

Requires:
heavy ions (Xe – Au)
duty cycle > 25 %

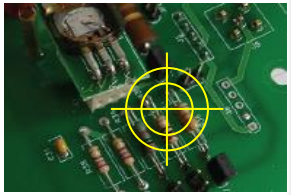


Experimental benefits:

- 2 MeV/u allows depth analysis up to several µm
- Worldwide unique UHV-ERDA setup available
- Existing detector systems →detection of H
- Resolution 1 nm

Microprobe

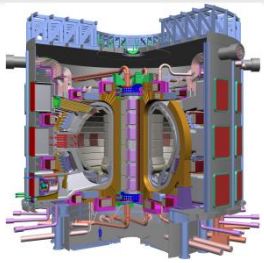
Microprobe with frequent beam access for targeted irradiations
– electronic devices
– biological objects

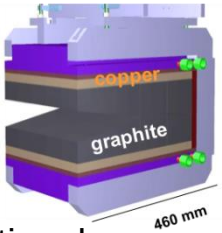


material modification/ damage studies

Advantages

- high-duty cycle
- low heat load
- high-dose accumulation
- no activation - energy below Coulomb barrier





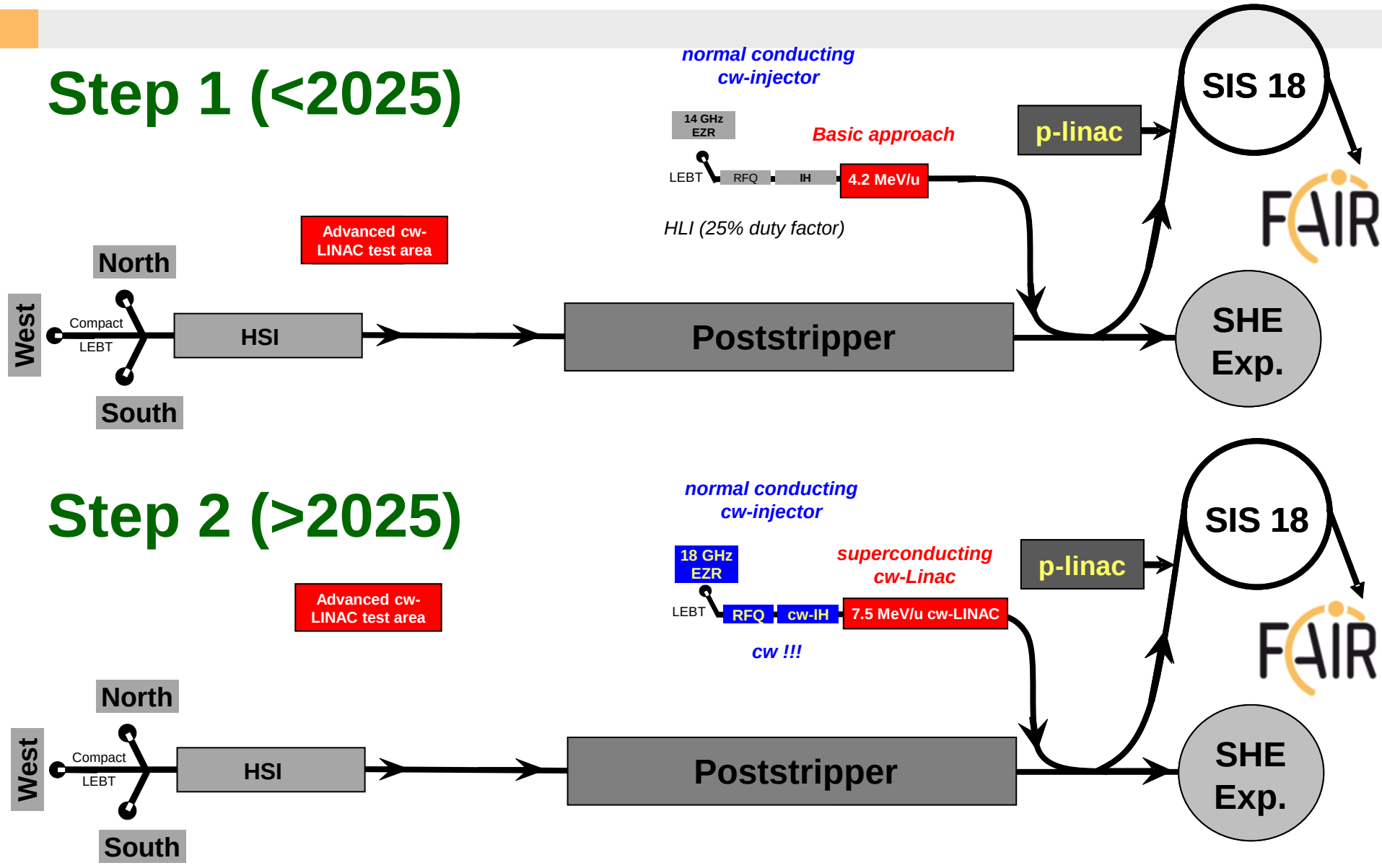
Experimental benefits

- radiation hardness tests of functional materials for accelerator, fusion and fission applications
- testing electronic devices (ESA)
- simulate effects of fission fragments (geosciences)

Biology

- cell irradiation
- Online microscopy
- high duty factor (He, Ne, Ar, Kr)

cw-Linac@SH2/3)



Summary&Outlook

- Demonstrator beam commissioning is a major milestone paving the way to the GSI/HIM-cw-Linac
- 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 EQUUS beam dynamics design
- Advanced cw-Linac layout based on four cryomodules, each equipped with three CH-cavities and a sc-rebuncher demonstrates the high capabilities due to energy variation preserving the beam quality
- New design could provide beam acceleration for a wide range of different ions (protons to uranium) above the design beam energy, featuring the ambitious GSI-user program, while the GSI-UNILAC is upgraded for short pulse high current FAIR-operation
- Test area commissioning planned for 2021, user operation at test area (2022+)
- Basis approach set up after SIS100-dipole magnet testing is finalized (<2025)
- cw-Linac full aproach as upgrade option (>2025)

Thank You for Your attention!

Abstract

At June 2017, after successful RF-testing of the sc RF-cavity in 2016, set up of the matching line to the demonstrator and a short commissioning and ramp up time of some days, the Crossbar H-Mode cavity CH0 of the cw-Linac accelerated first time heavy ion beams (Ar^{11+}) with full transmission up to the design beam energy. The design acceleration gain of 3.5 MV inside a length of less than 70 cm has been verified with heavy ion beam of up to 1.5 pmA. The measured beam parameters show an excellent beam quality. The machine commissioning with beam was a milestone of the R&D work of Helmholtz Institute Mainz (HIM) and GSI in collaboration with IAP Goethe-University Frankfurt in development of the superconducting heavy ion cw-Linac. In autumn 2018 two additional machine runs have been successfully executed, confirming the strong capabilities of heavy ion beam acceleration with CH-cavities. Further R&D efforts, as well as preparatory work for the future Linac will be presented.