First Acceleration of Heavy Ion Beams with a Superconducting Continous Wave HIM/GSI-Linac

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1. Introduction
2. RF-cavity development
3. General Linac layout
4. R&D activities
5. Matching section and EQUUS beam dynamics
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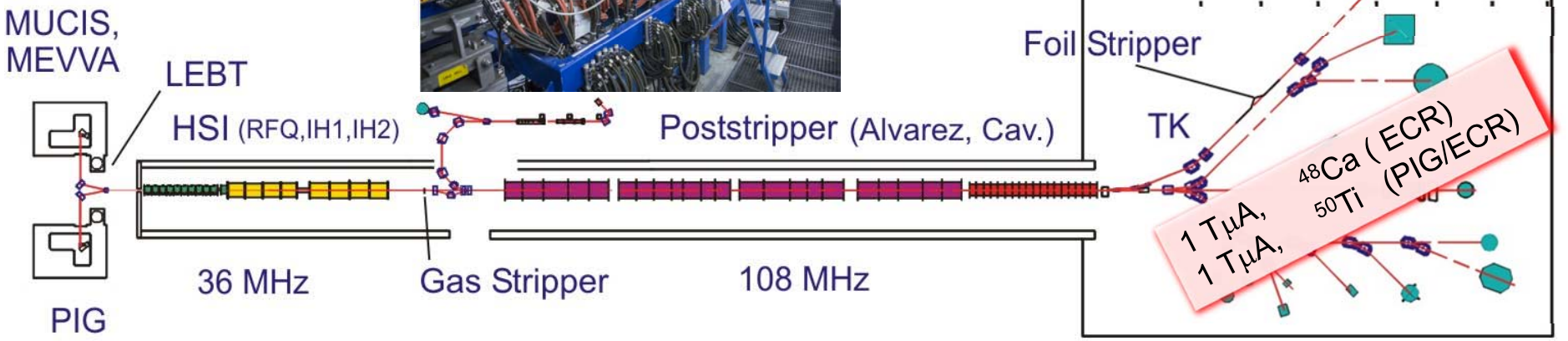
7. Systematic phase space measurements
8. Further R&D und Outlook

Introduction
GSI UNIversal Linear ACcelerator

HIM HELMHOLTZ Helmholtz Institute Mainz

High Charge State Injector (1991)

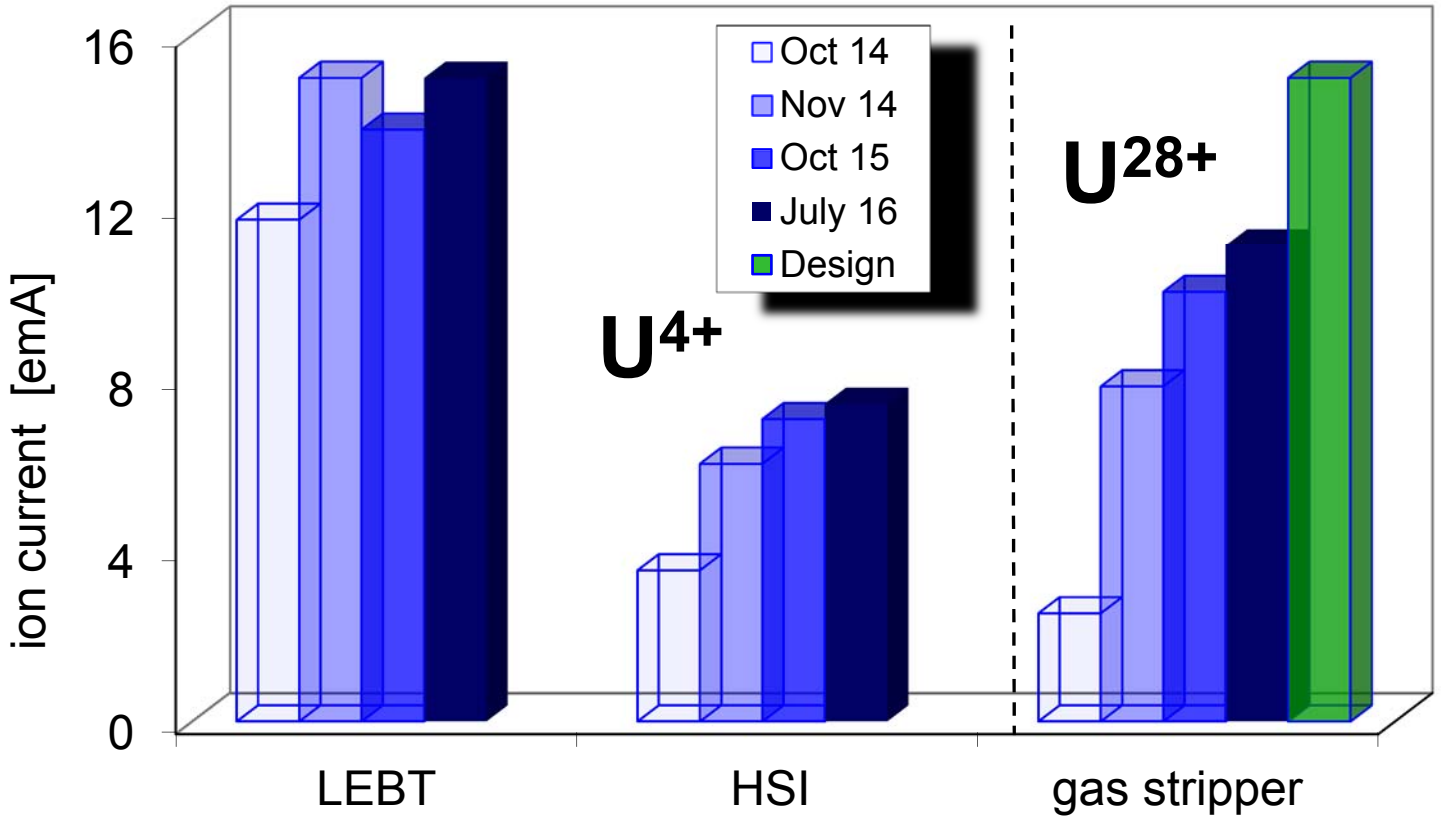


High Current Injector (1999)

Alvarez (1975)

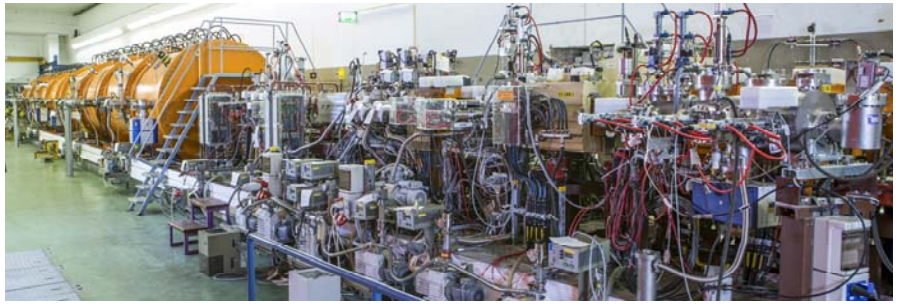
Single Gap Resonators (1975)

Status “UNILAC Uran-High Current”



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

see: P. Gerhard *et al.*, Invited Talk@LINAC2018, FR1A05



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 ≥ 200)
- High Beam Energy (up to 10 MeV/u)
- Continuous Beam Energy Variation (1.5 – 10 MeV/u)

cw-LINAC-project: Motivation

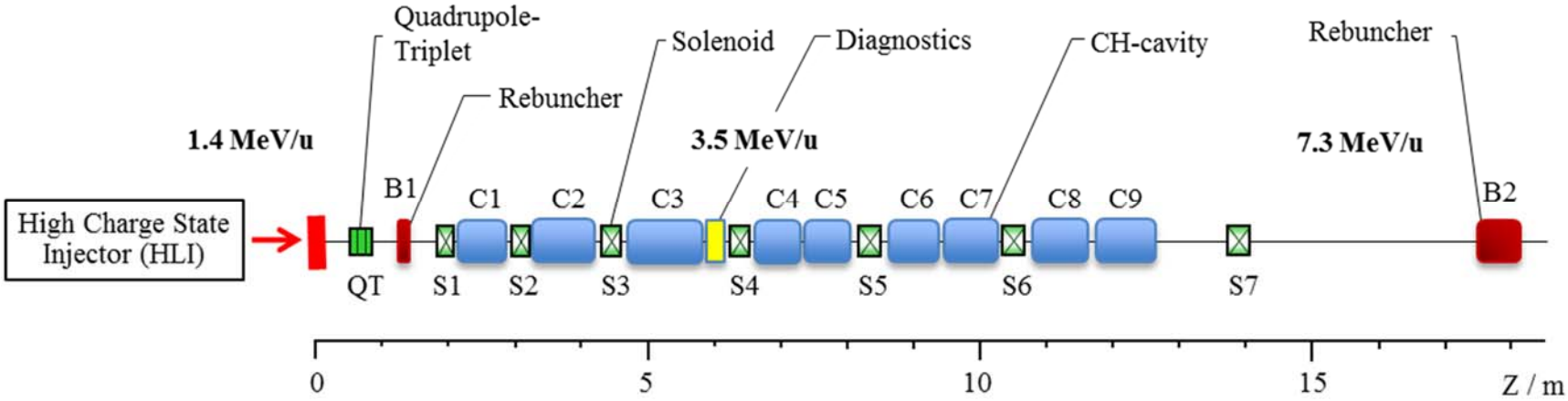
Nuclear reactions at the Coulomb-barrier→ production of Super Heavy Elements (SHE)

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

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

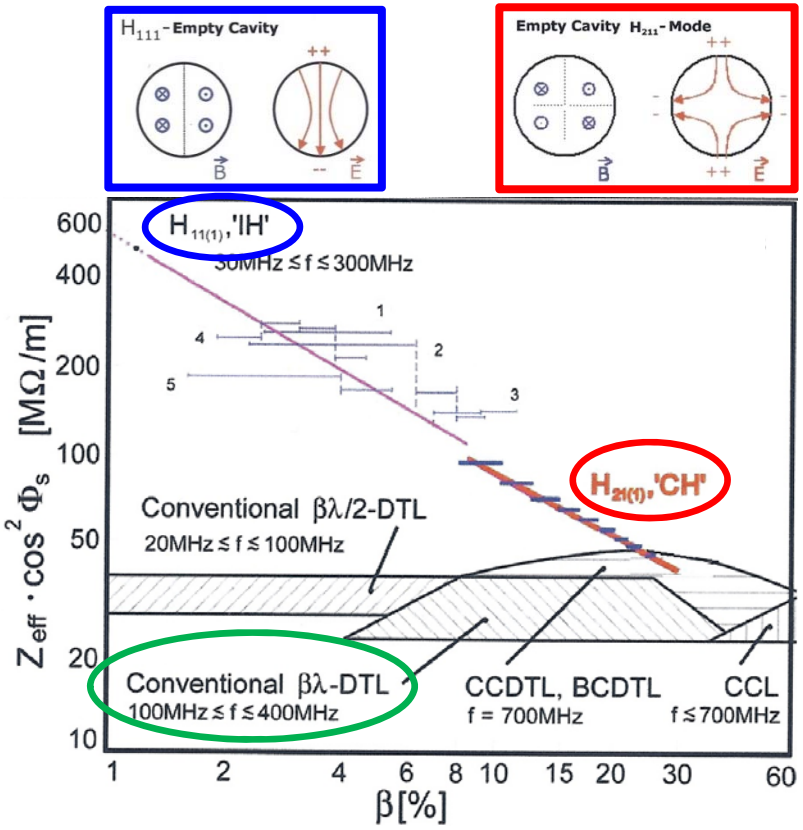
	GSI- Unilac	cw-Linac
Beam intensity (particle/s)	$6 \cdot 10^{12}$	$6 \cdot 10^{13}$
Beam on target	3 weeks	2 days

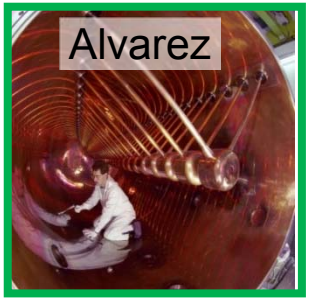
General Heavy Ion cw-Linac layout

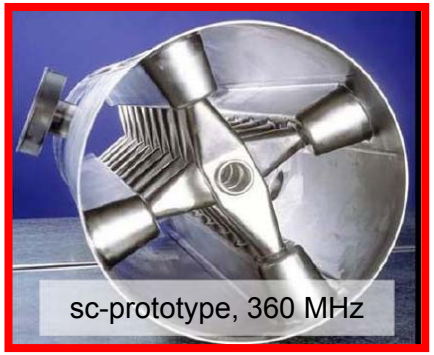


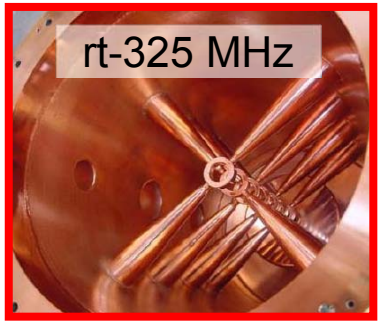
Mass/Charge		6
Frequency	MHz	216.816
Max. beam current	mA	1
Injection Energy	MeV/u	1.4
Output energy	MeV/u	3.5 – 7.3
Output energy spread	keV/u	±3
Length of acceleration	m	12.7
Sc CH-cavities	#	9
Sc solenoids	#	7

H-type Cavity developments



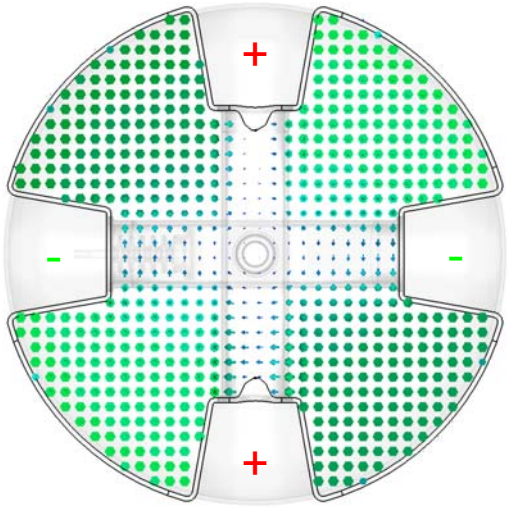




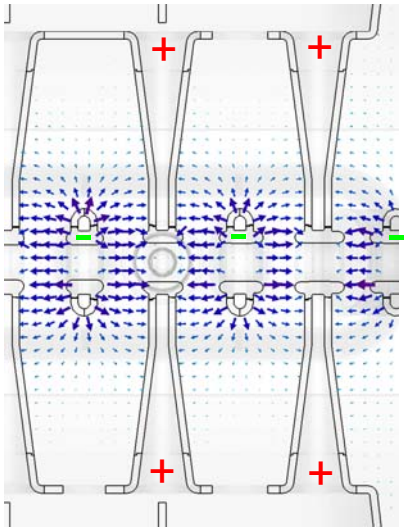


CH-cavity: Field profiles

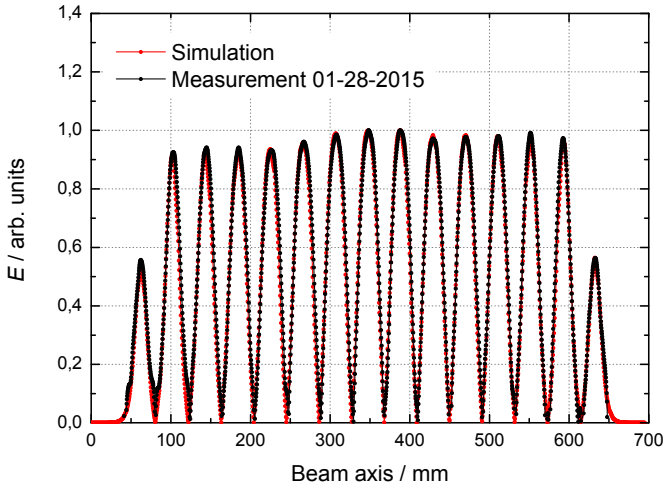
H field



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

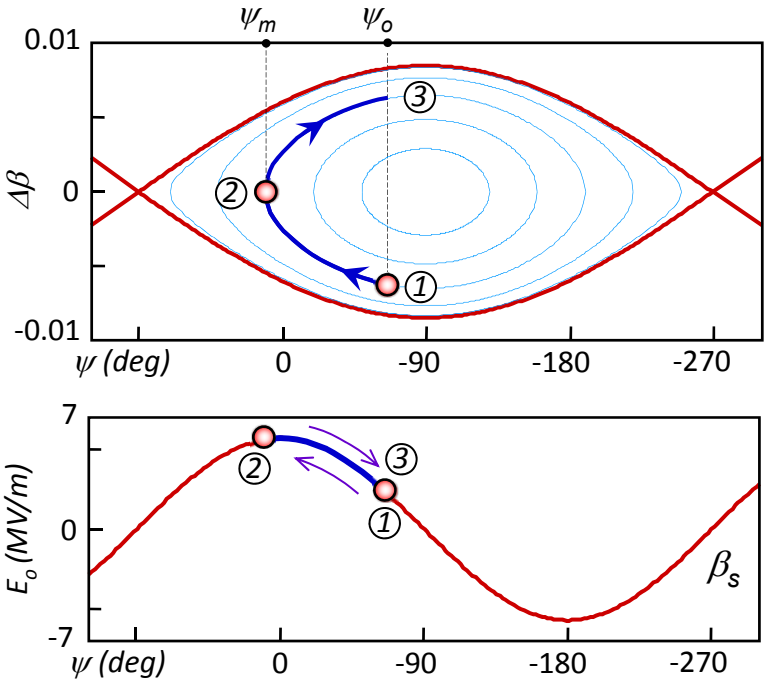
EQUUS - EQUidistant mUltigap Structure

① Particles too early → obtain less acceleration
→ longitudinal focussing

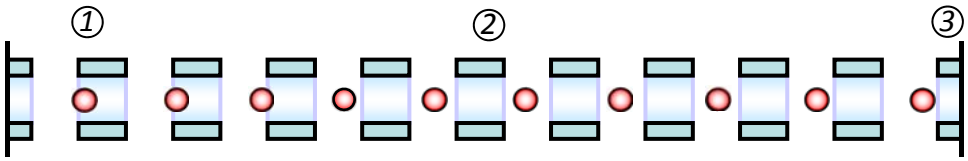
② Particles synchr. → reach max. acceleration
→ longitudinal defocussing

③ Particles too early → obtain less acceleration
→ longitudinal focussing

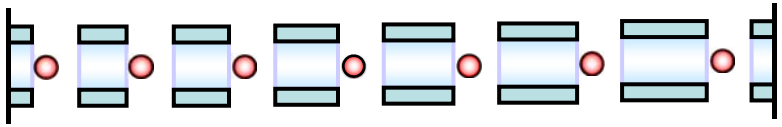
Longitudinal motion of an accelerated bunch in the constant-β-section



EQUUS

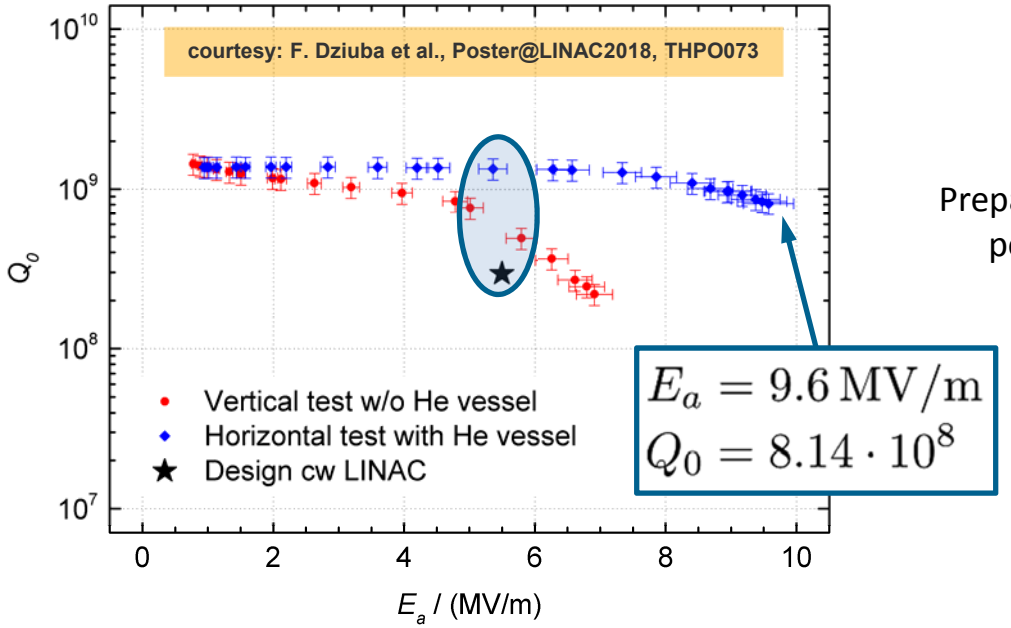


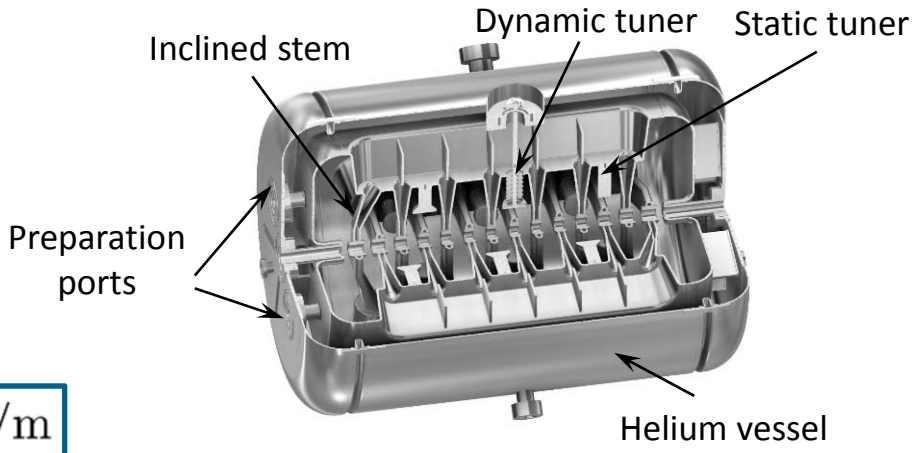
Resonant acceleration at φ=-30



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

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



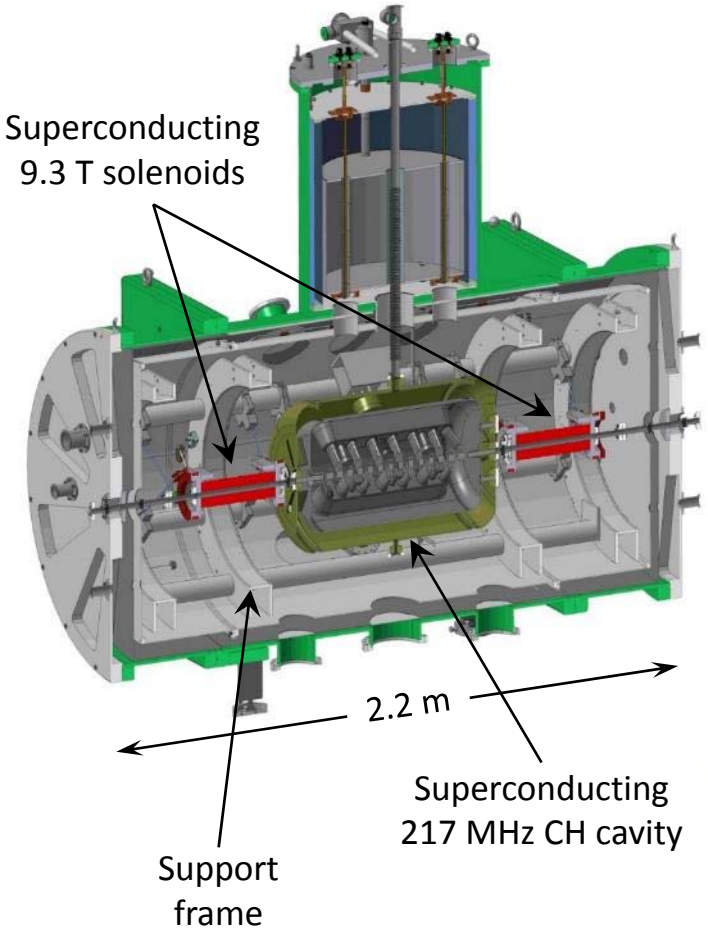


- Improved performance (add. HPR)
- Low field emission rate
- High field gradient
- Therm. quenching beyond 9.6 MV/m

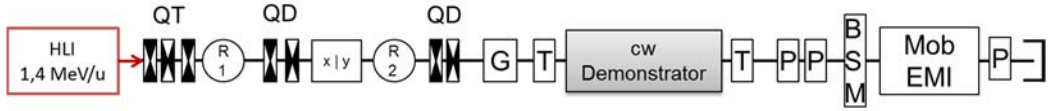
		Vertical test w/o He vessel	Horizontal test with He vessel
Q_0^{low}		$1.44 \cdot 10^9$	$1.37 \cdot 10^9$
R_S	nΩ	36	38
R_{BCS}	nΩ	15	15
R_{mag}	nΩ	9	12
R_0	nΩ	12	11
E_a	MV/m	6.9	9.6
Q_0		$2.19 \cdot 10^8$	$8.14 \cdot 10^8$
V_a	MV	4.2	5.9
E_p	MV/m	43	60
B_p	mT	39	55

Experimental setup of the demonstrator at GSI

Layout of the horizontal cryomodule

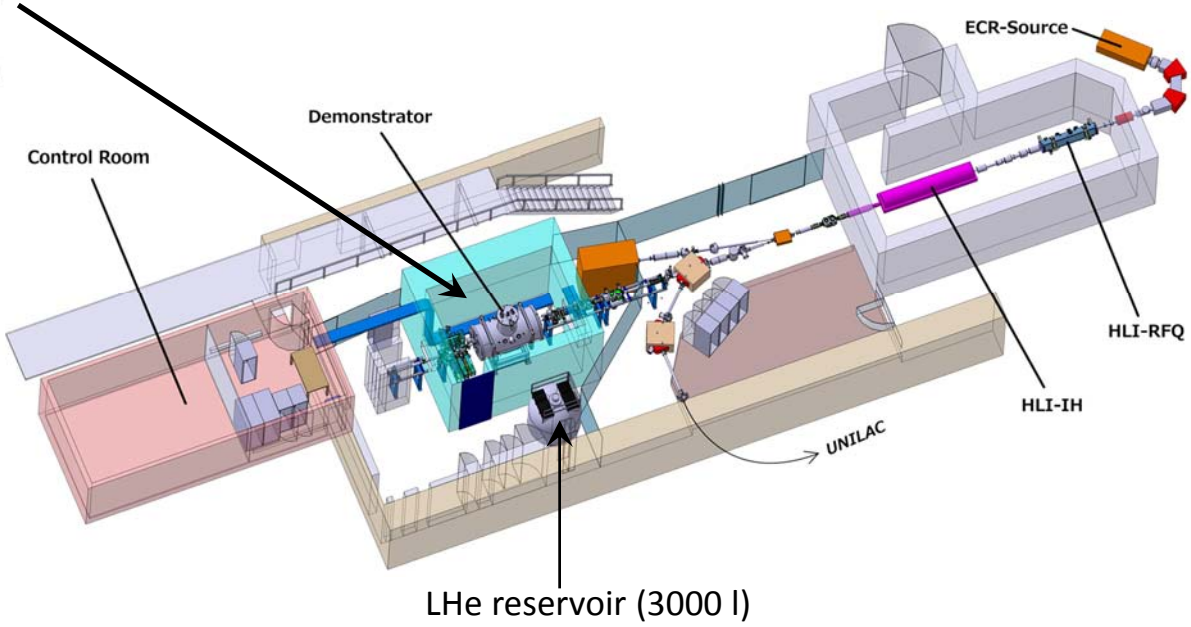


Matching line - demonstrator – test bench



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

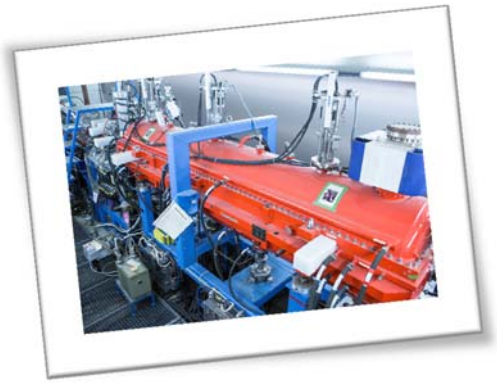
Demonstrator at GSI-High Charge State Injector (HLI)

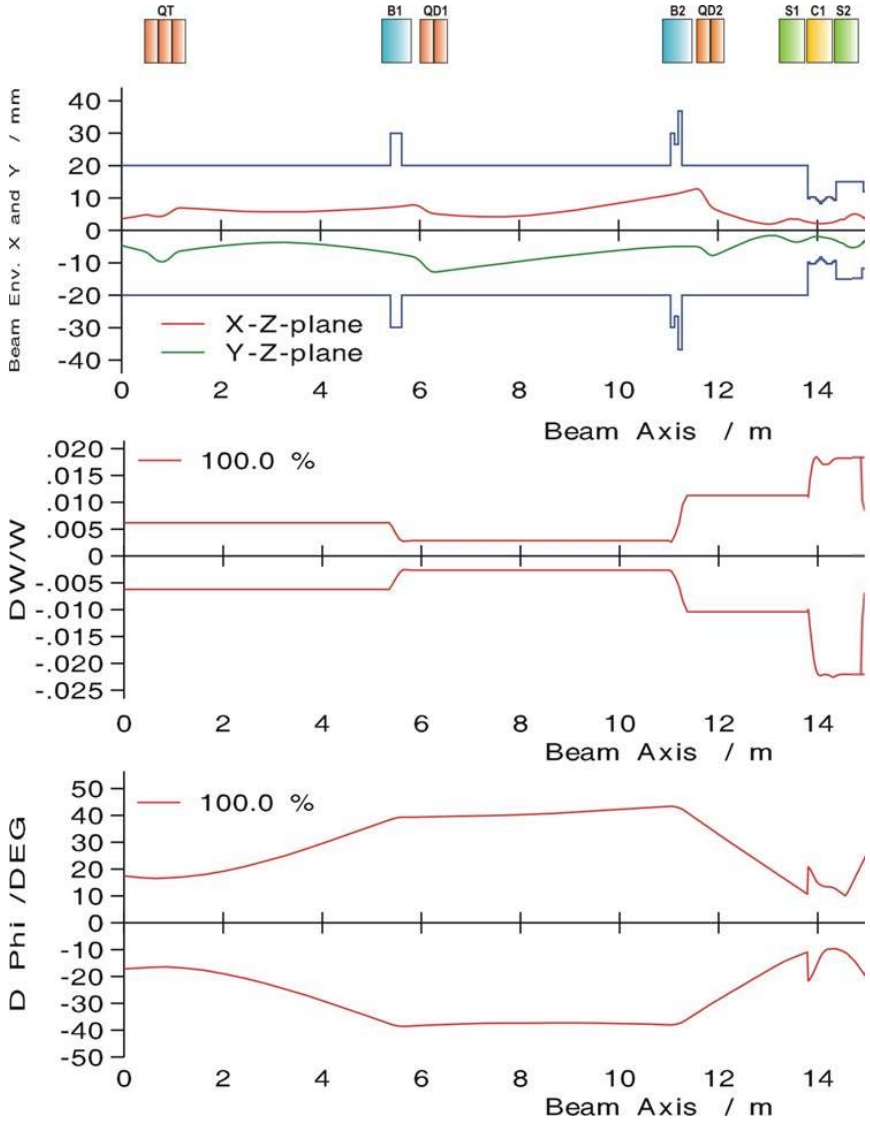



J. List *et al.*, THPO107 & SWPR025
M. Schwarz, et al., TUPO084 & SWPR034
M. Basten et al., THPO072 & SPWR010
F. Dziuba, et al., THPO073
June 2017
First beam test

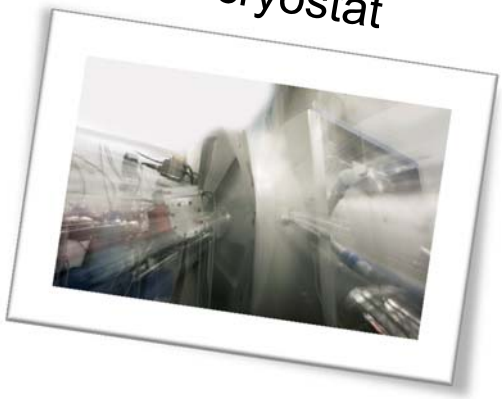
Matching the cw-Linac Demonstrator

HLI



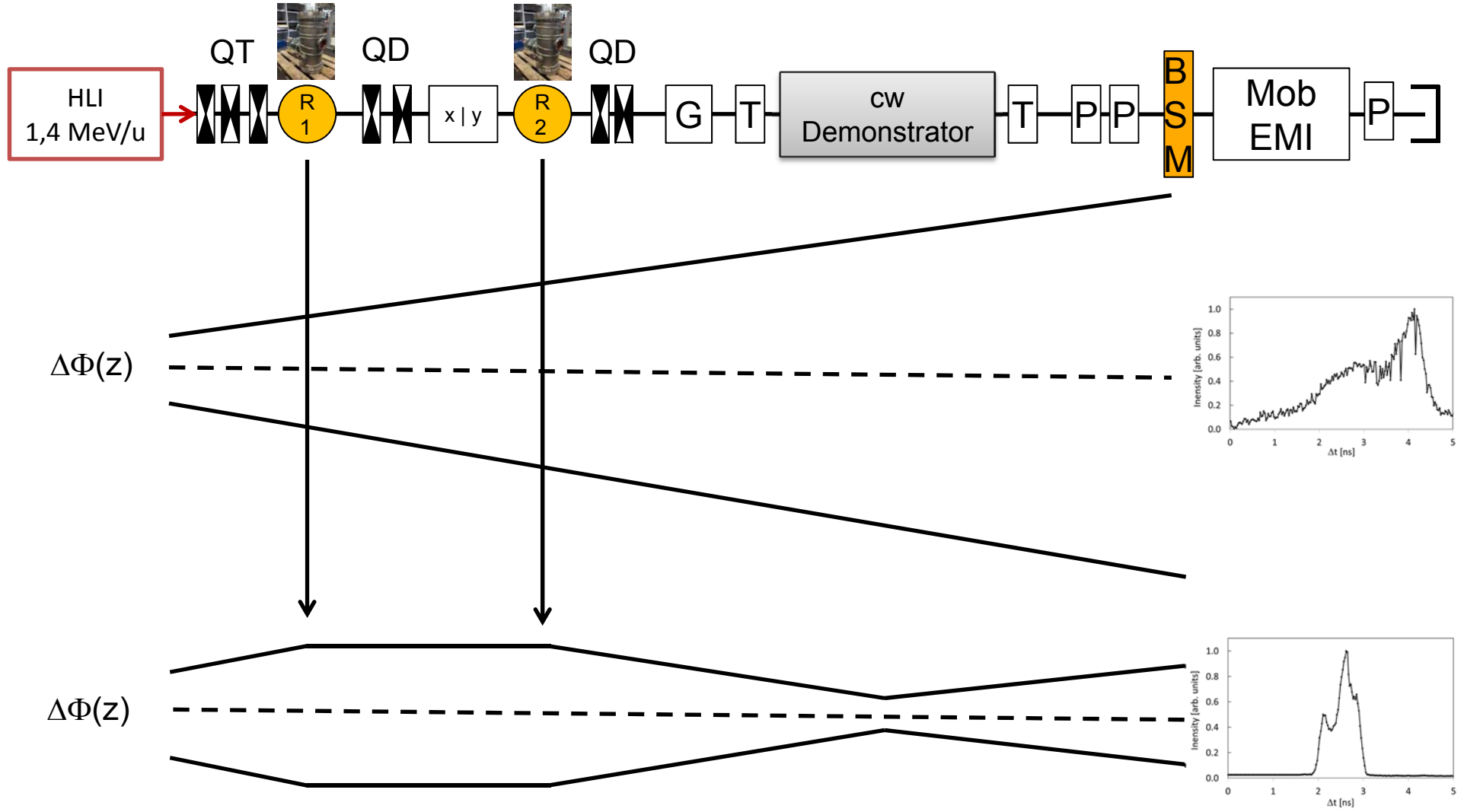


cryostat

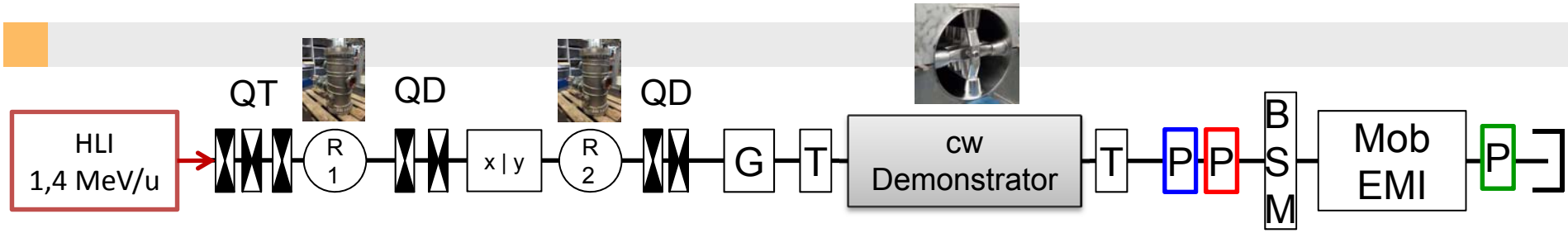


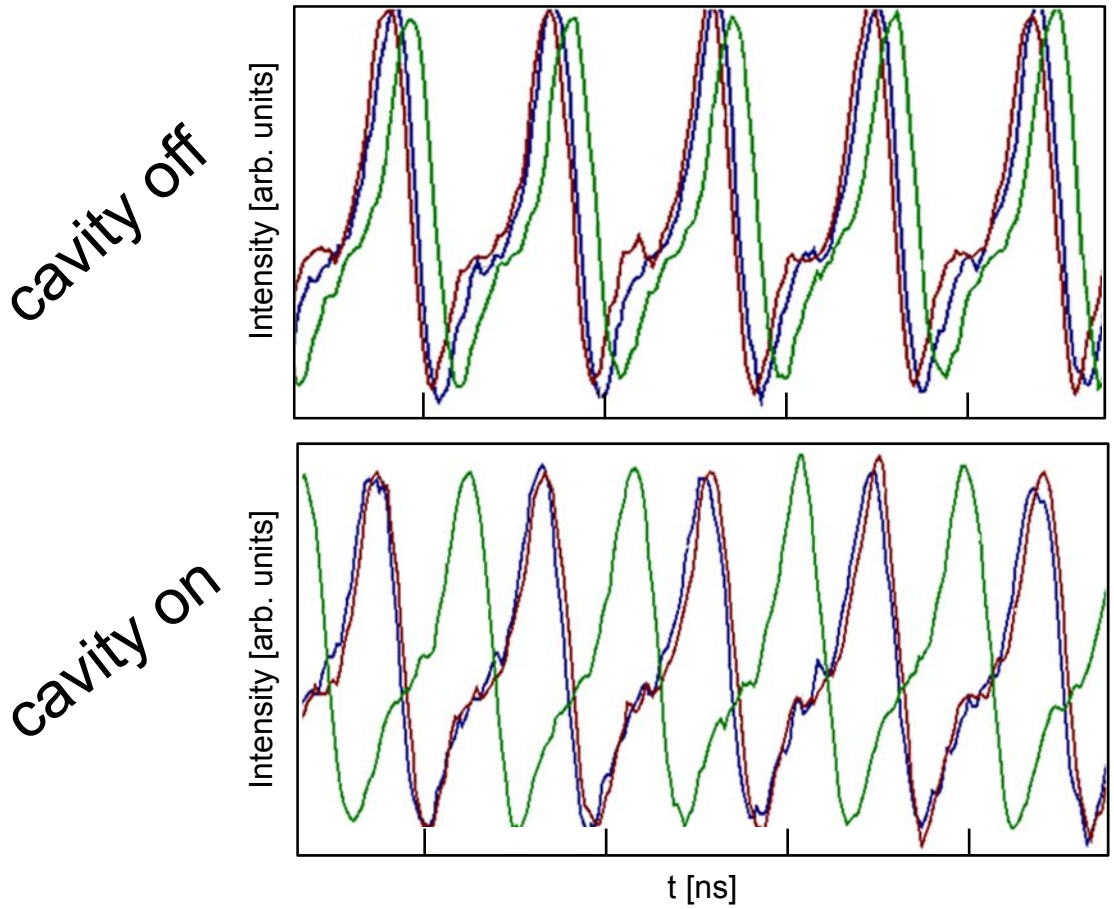
courtesy: A. Rubin, *Proc of IPAC'13*

Longitudinal matching



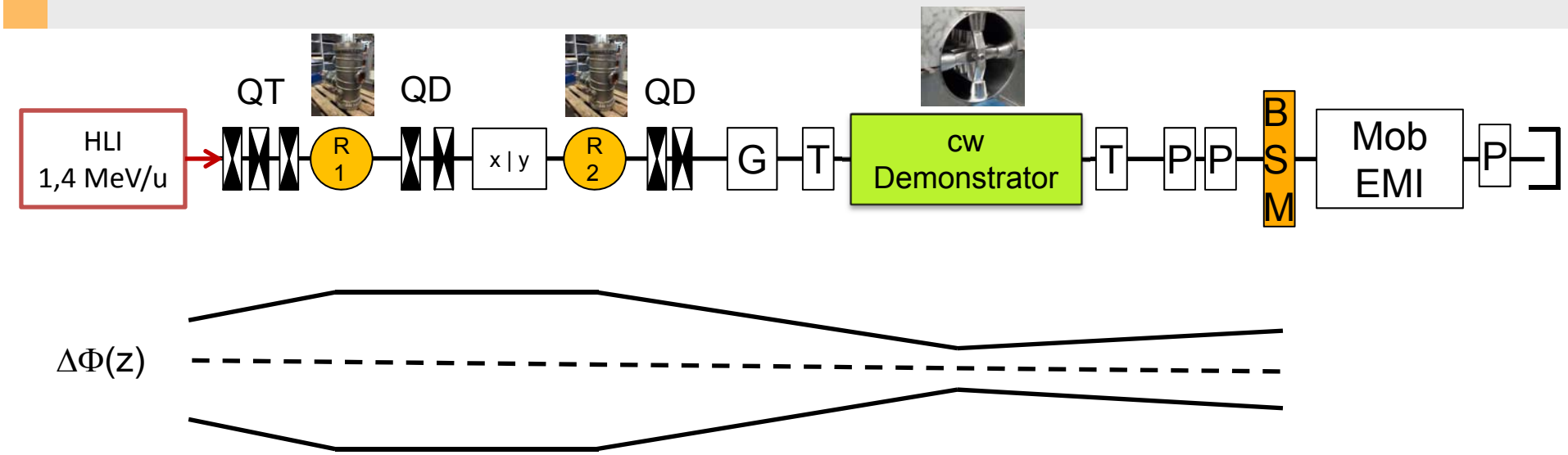
First Acceleration



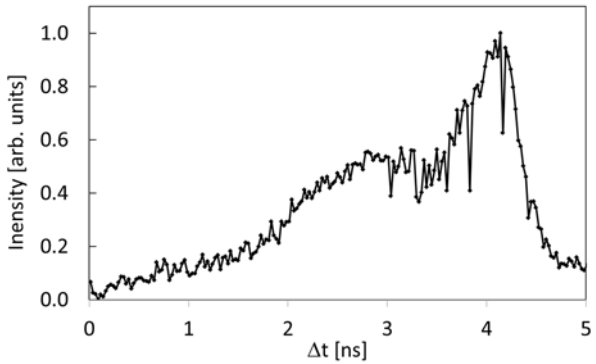


- Measurement of transient signal induced by traveling bunch
- Acceleration! Energy gain of 0.5 MeV/u
- → systematic scan of rf-phase and amplitude

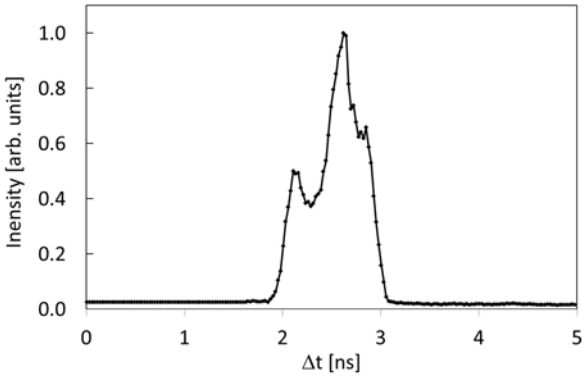
Bunch structure measurement



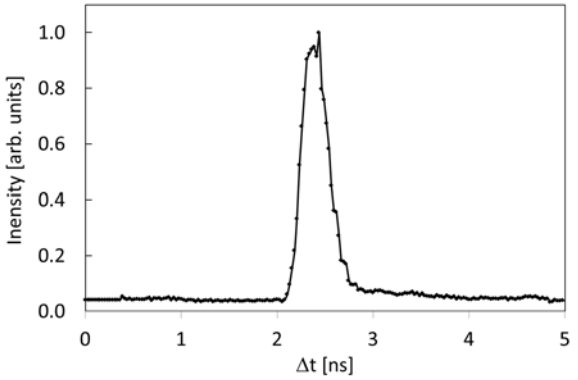
cavities off



R1 + R2



R1 + R2 + CH0

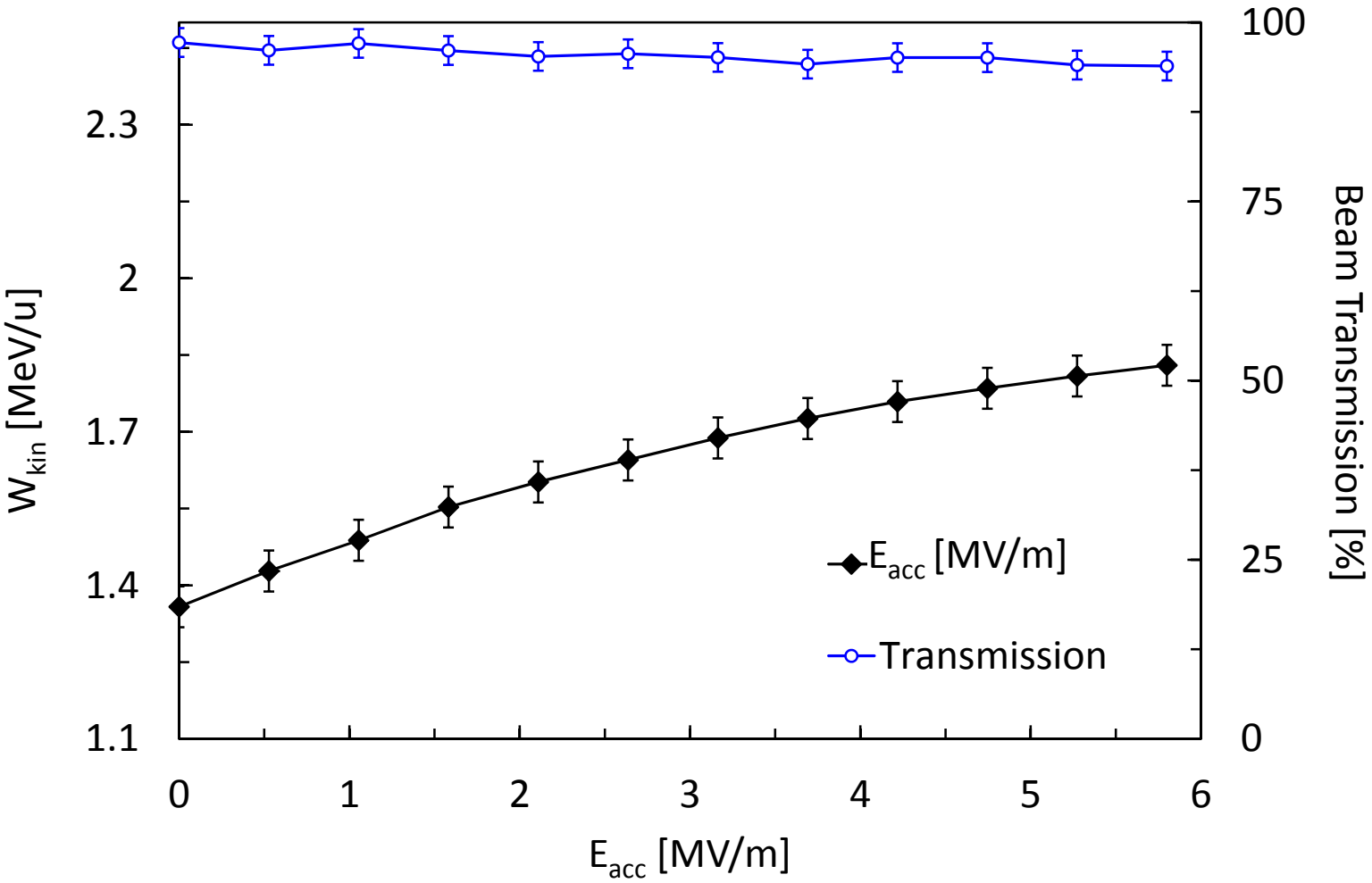


RF-parameter (matched case)

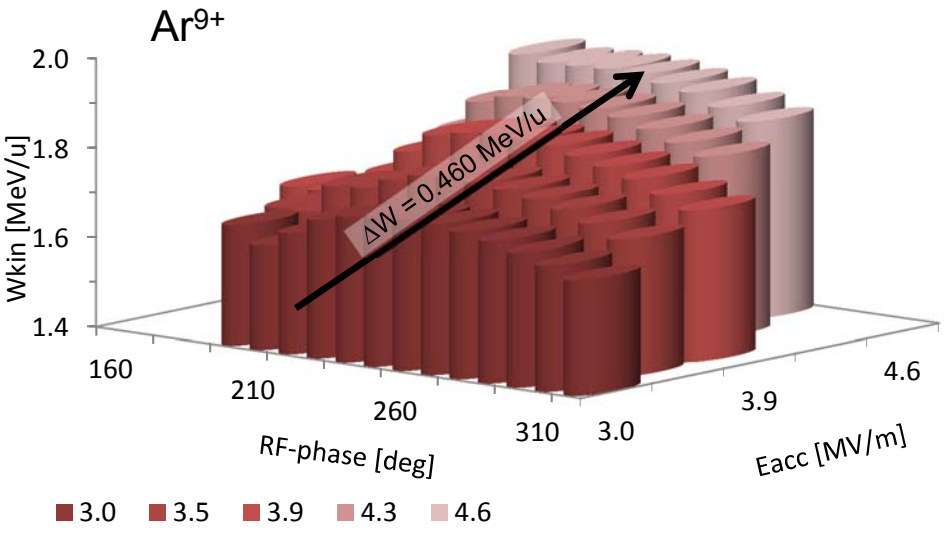
	He^{2+}	Ar^{11+}	Ar^{9+}	Ar^{6+}
A/q	*2.0*	*3.6*	*4.4*	*6.7*
$U_{Reb1,eff.}$ [kV]	8.3	15.0	18.3	27.9
$U_{Reb2,eff.}$ [kV]	22.7	40.8	49.9	75.9
$E_{acc,CH}$*[MV/m]	1.8	3.2	3.9	5.9
U_0 [MV]	1.2	2.2	2.7	4.0

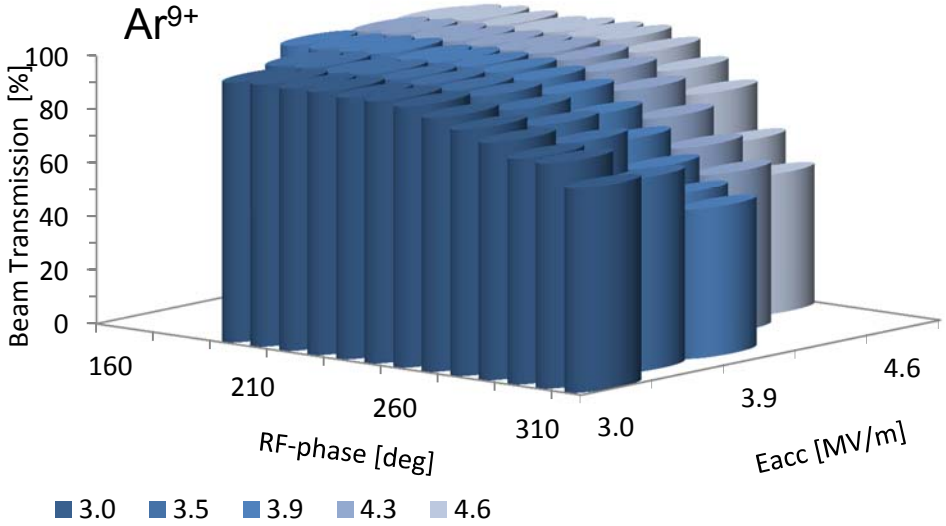
* E_{acc} = *transit time factor* × *total accelerating voltage*/($n \times 0.5 \times \beta\lambda$)

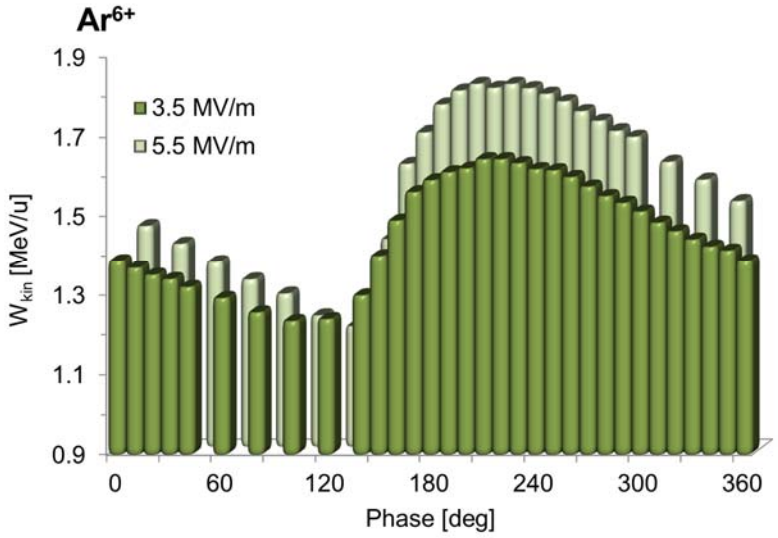
Amplituden-scan

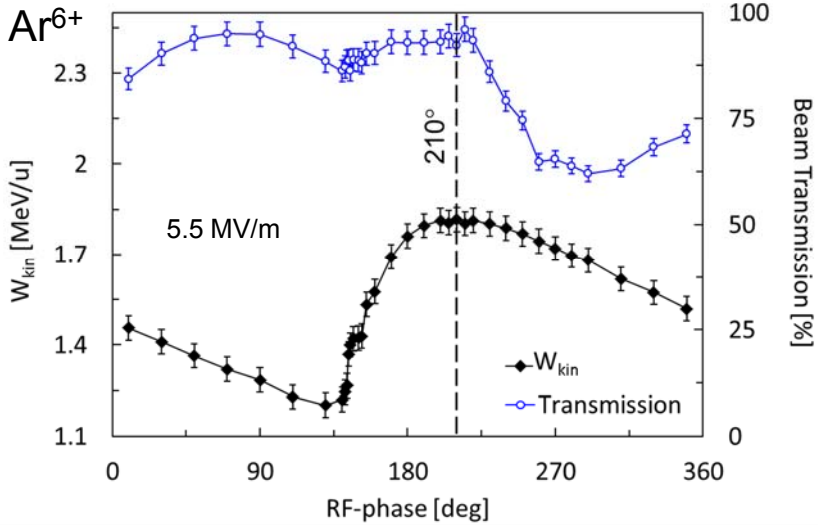


Systematic Scans (RF-phase/-amplitude)

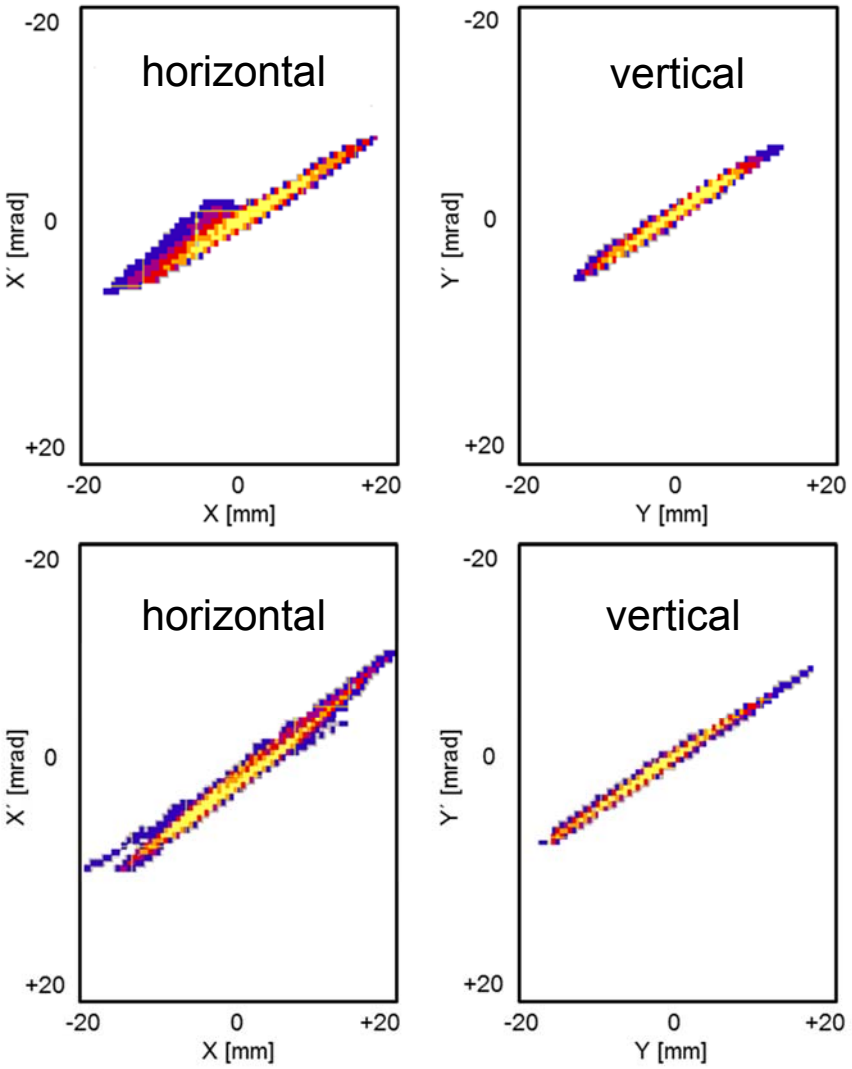








Emittance measurement



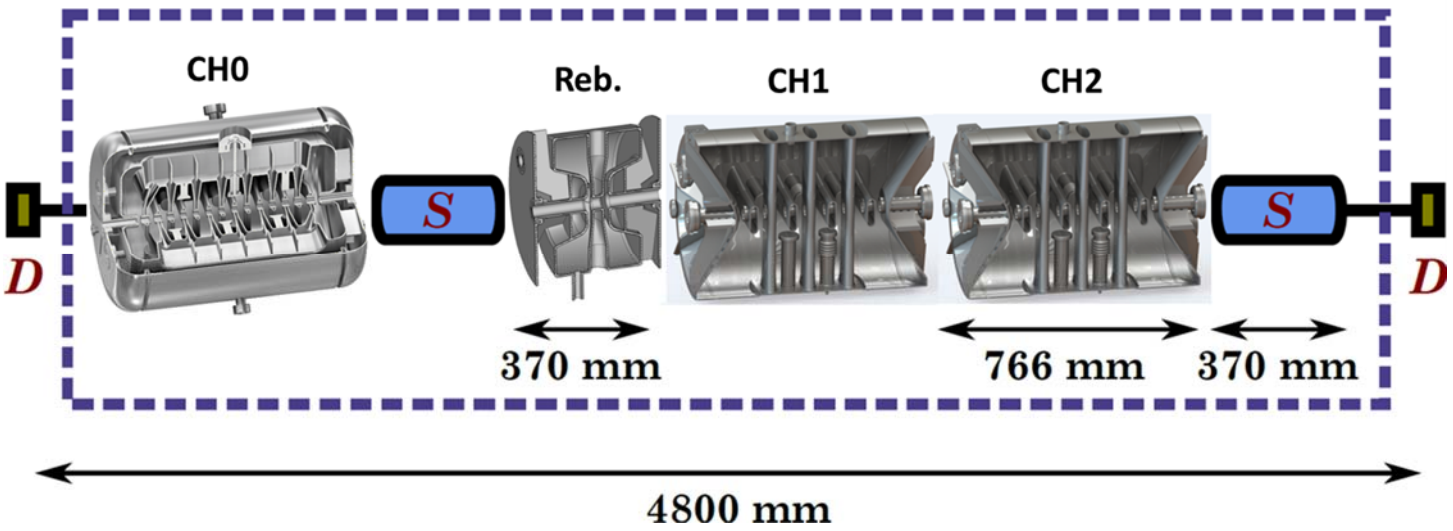
1.40 MeV/u

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

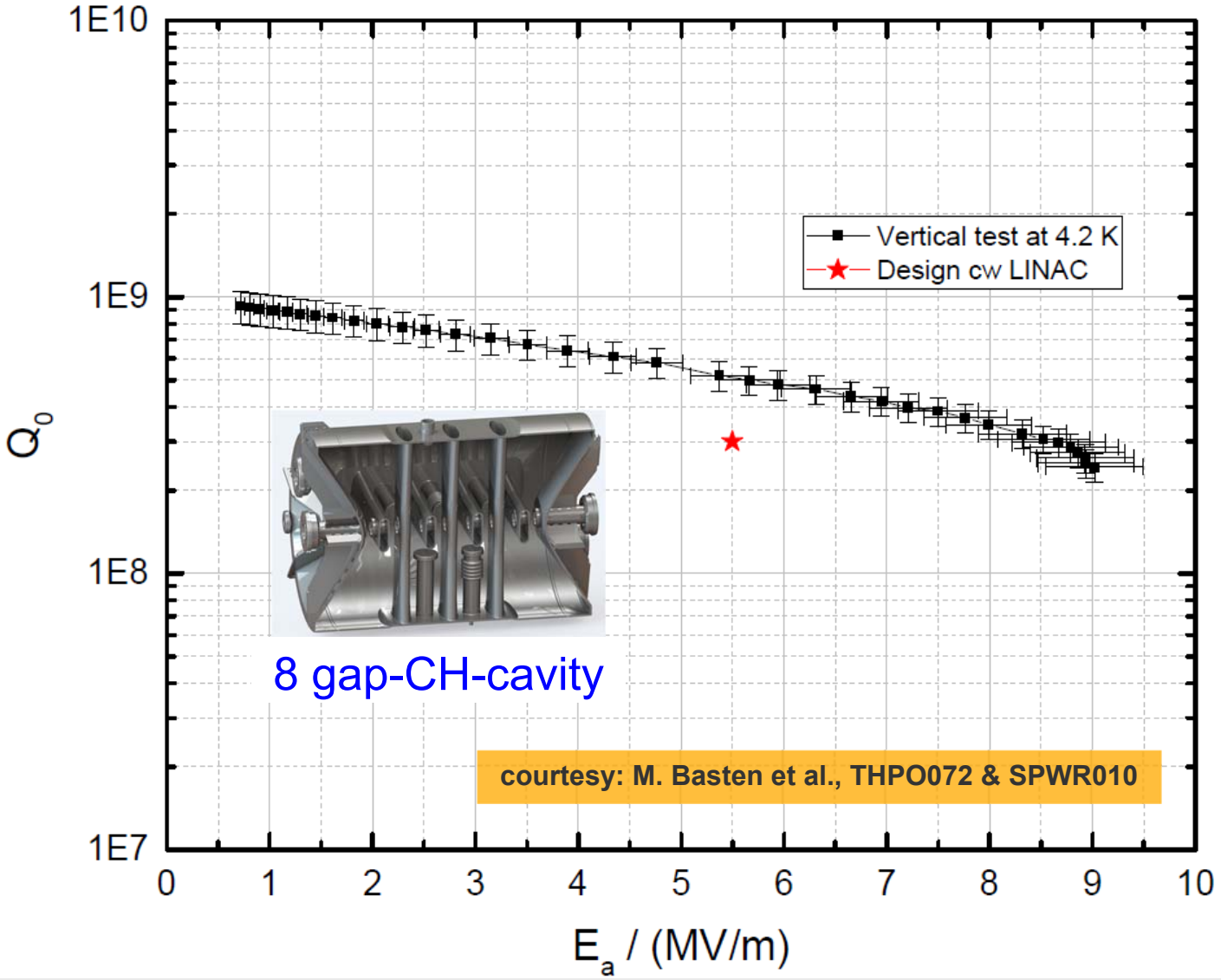
Advanced Demonstrator

Standard cryomodule layout

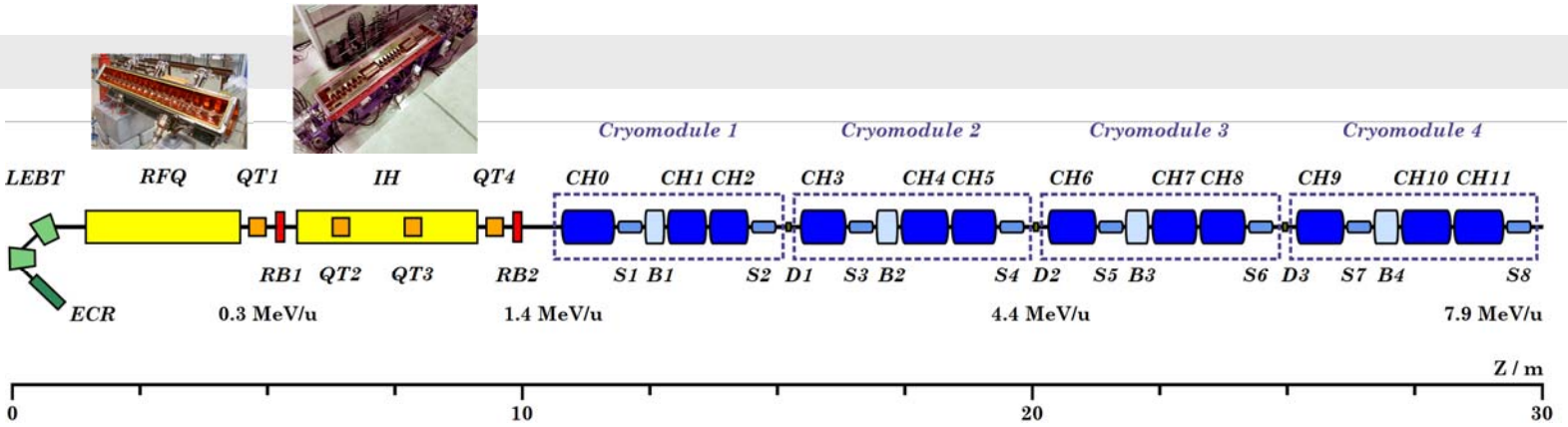


- New cryo module layout containing demonstrator CH cavity, 2 short CH cavities, 1 buncher and 2 solenoids
- Simplified cavity design (easier manufacturing & surface processing)
- CH1 & CH2 are already in production (delivery at 4th quarter of 2018)
- Tendering for cryostat at 3rd quarter of 2018
- Moderate increase of design gradient → more compact linac design or higher A/q

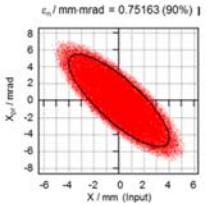
First RF-measurement for CH1 in a vertical cryostat

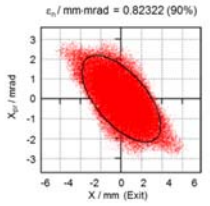


Current cw-Linac Layout

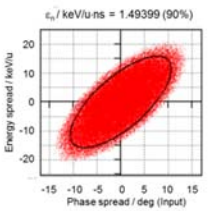


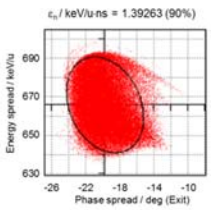
Input CM1





Output CM4

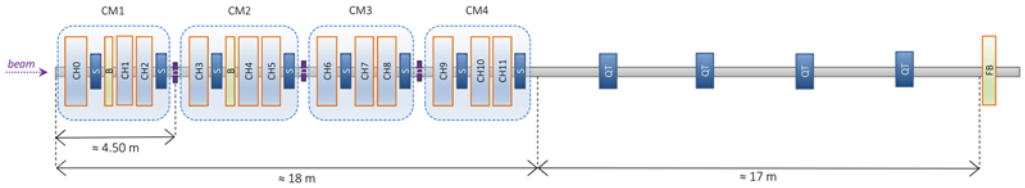


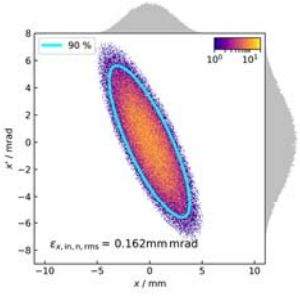


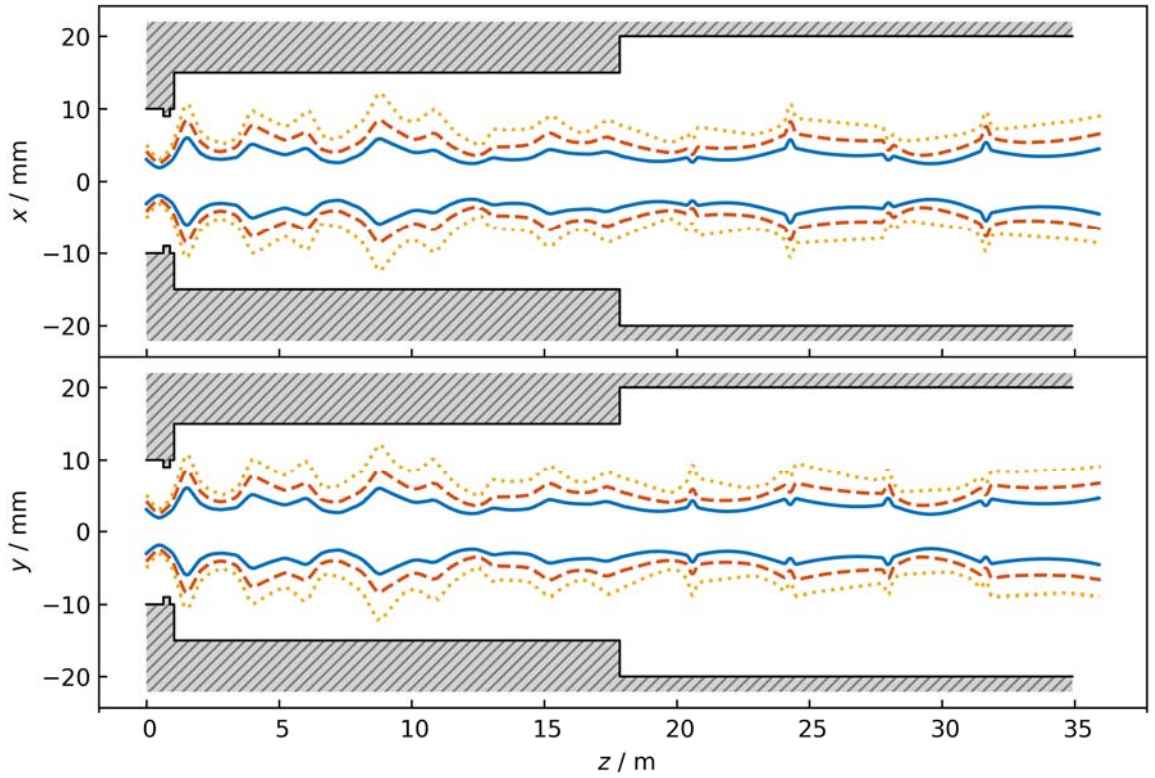
- Total of 12 CH cavities
- Each cryo module contains 3 CH cavities + 1 rebuncher + 2 solenoids
- Variable beam energy 3.6-7.5 MeV/u

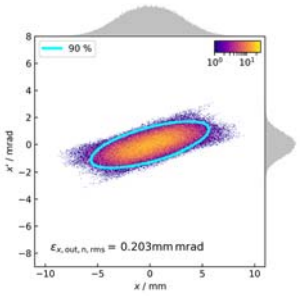
Cryo Module	Cavity	Output energy (MeV/u)		
		A/Z=6	*A/Z=3*	*A/Z=1*
	HLI	*1.4*	*1.4*	*1.4*
CM1	CH0	2.1	2.2	3.0
	CH1	2.6	3.0	4.2
	CH2	2.9	3.6	4.6
CM2	CH3	3.4	4.3	5.7
	CH4	3.8	4.8	6.3
	CH5	4.2	5.5	7.7
CM3	CH6	4.7	6.2	8.6
	CH7	5.2	7.0	9.9
	CH8	5.8	7.8	10.9
CM4	CH9	6.4	8.7	12.3
	CH10	7.0	9.5	13.2
	CH11	7.6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

Transversal beam dynamics cw-Linac layout



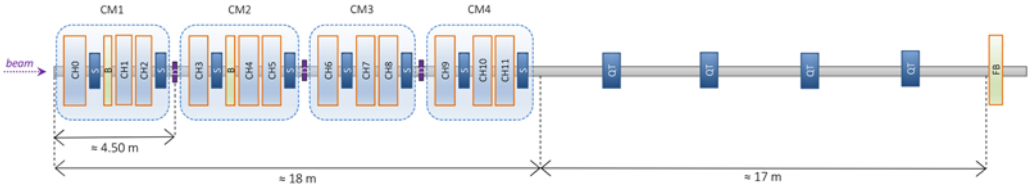


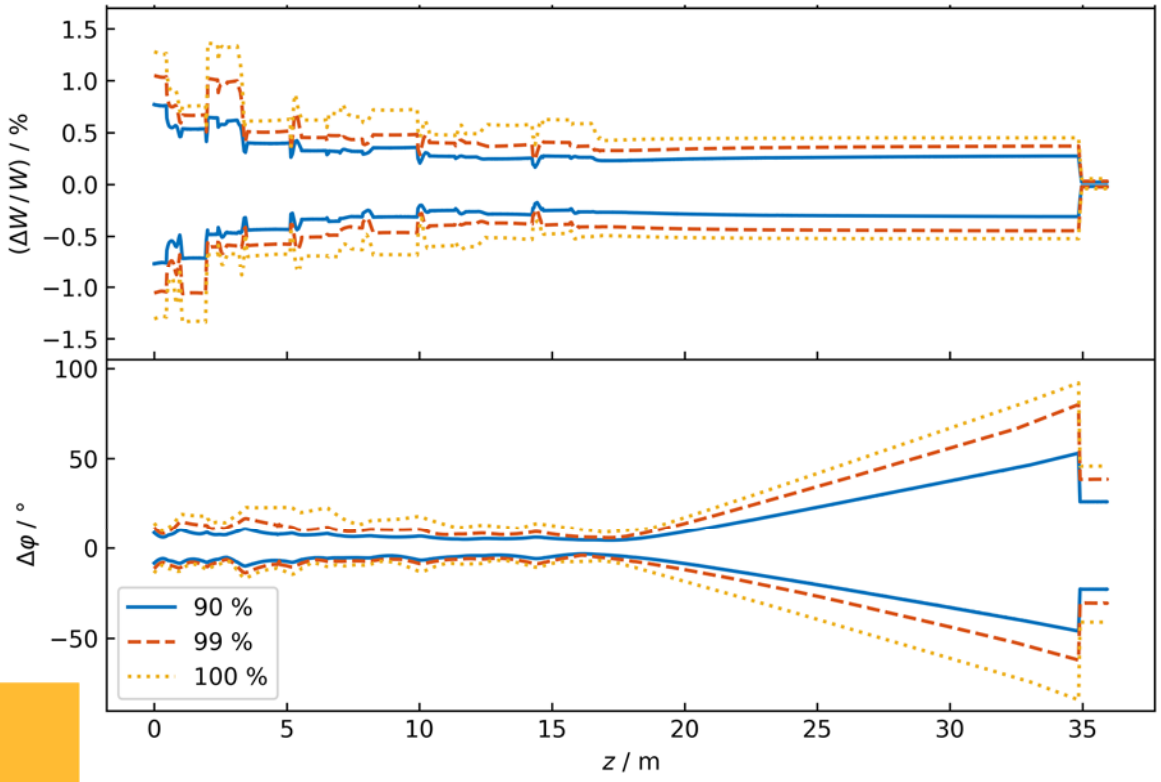




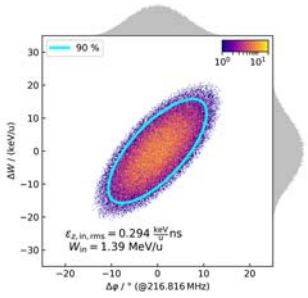
courtesy:
M. Schwarz, et al.,
TUPO084 & SWPR034

Longitudinal beam dynamics cw-Linac layout

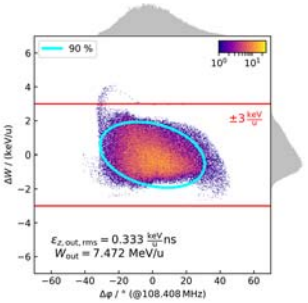




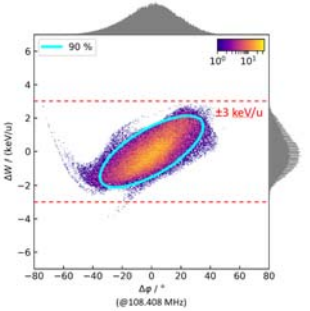
1.4 MeV/u



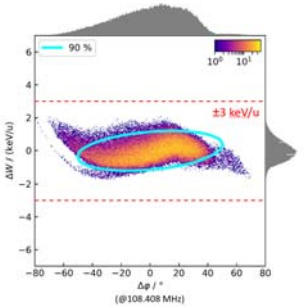
3.5 MeV/u



5.0 MeV/u



7.5 MeV/u



courtesy:
M. Schwarz, et al.,
TUPO084 & SWPR034

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

Thank You for Your attention!