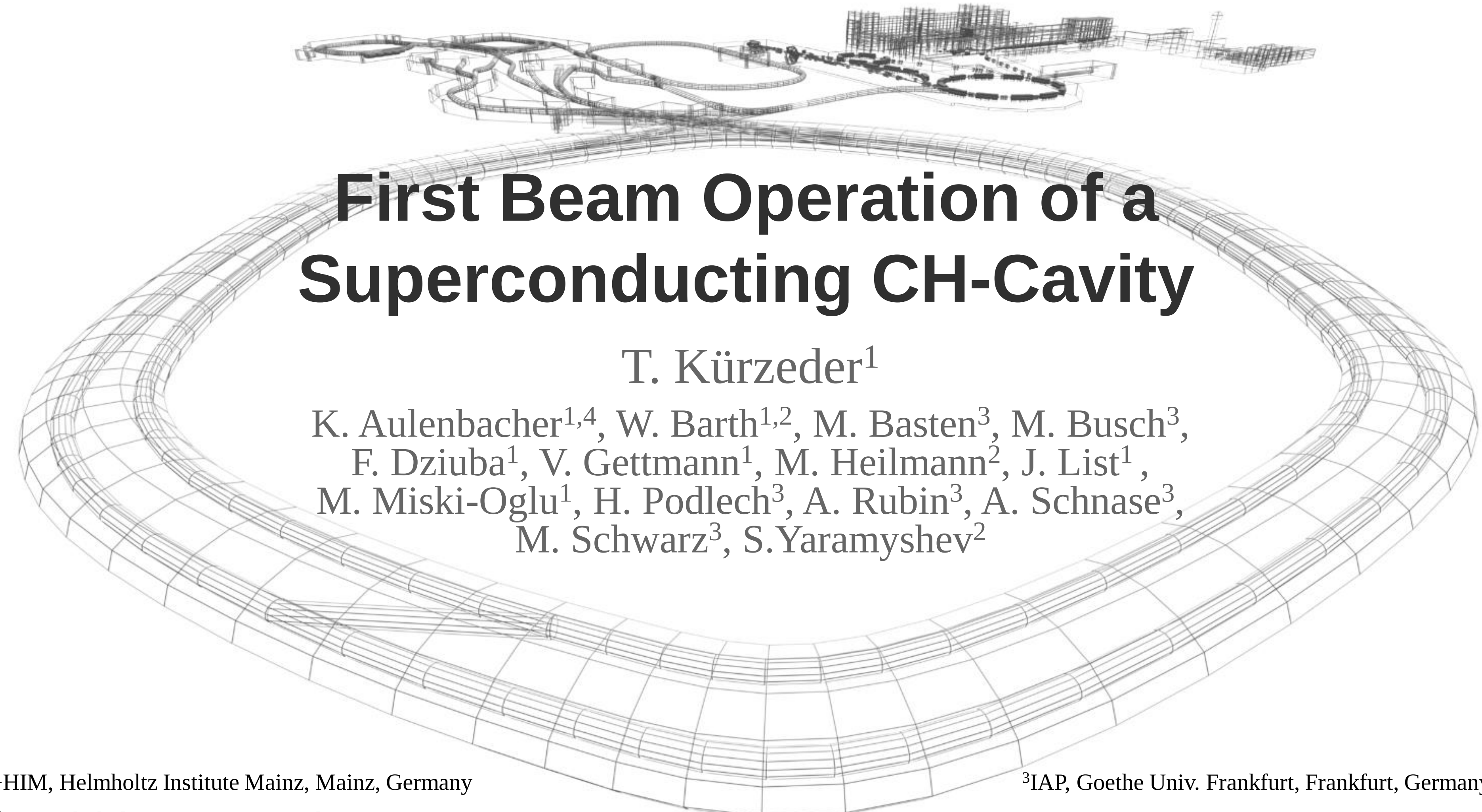


First Beam Operation of a Superconducting CH-Cavity

T. Kürzeder[1]

K. Aulenbacher[1,4], W. Barth[1,2], M. Basten[3], M. Busch[3], F. Dziuba[1], V. Gettmann[1], M. Heilmann[2], J. List[1] , M. Miski-Oglu[1], H. Podlech[3], A. Rubin[3], A. Schnase[3], M. Schwarz[3], S.Yaramyshev[2]

[1]HIM, Helmholtz Institute Mainz, Mainz, Germany

[2]GSI Helmholtzzentrum, Darmstadt, Germany

[3]IAP, Goethe Univ. Frankfurt, Frankfurt, Germany

[4]KPH, Johannes Gutenberg Univ., Mainz, Germany

Outline

- Motivation
- CH-cavity (design & tests)
- Beam acceleration (demonstrator)
- Next steps (advanced demonstrator)
- cw Linac design

cw-LINAC-Project: Motivation & Design parameters

- Reactions at the Coulomb-barrier → Production of SHE

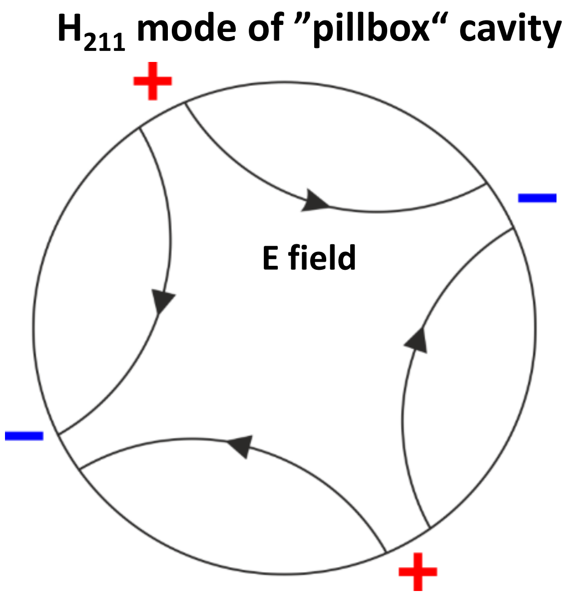
- Operation cw
- Mass / charge 6
- beam current ≤ 1 mA
- Injection energy 1.4 MeV/u
- Final energy 3.5 - 7.3 MeV/u

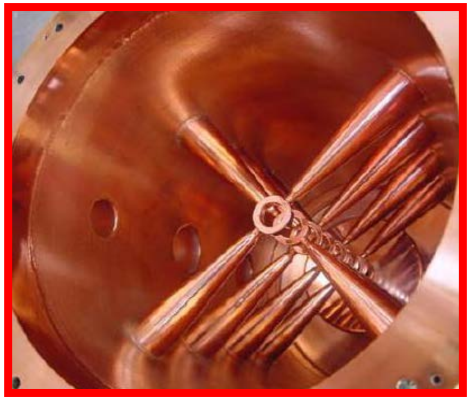
Production of Element $^{288}_{115}$uut, $^{289}_{115}$uut, $30\ events$

(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

CH-cavities





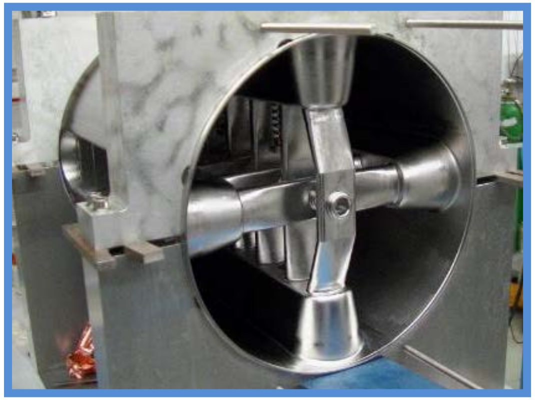
r.t. 340 MHz

GSI p-linac prototype

s.c. 360 MHz

Prototype

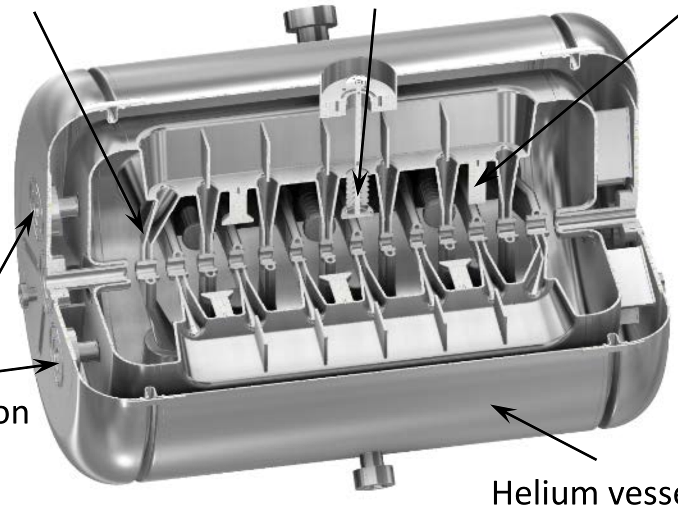
- Multigap drift tube cavity for the acceleration of protons and ions in the low and medium energy range (150 – 800 MHz, 1 – 150 MeV/u, β = 0.05 – 0.6)
- Drift tubes are alternating connected to "+" and "-" potential
- **C**ross-bar-**H**-mode cavity → CH-cavity

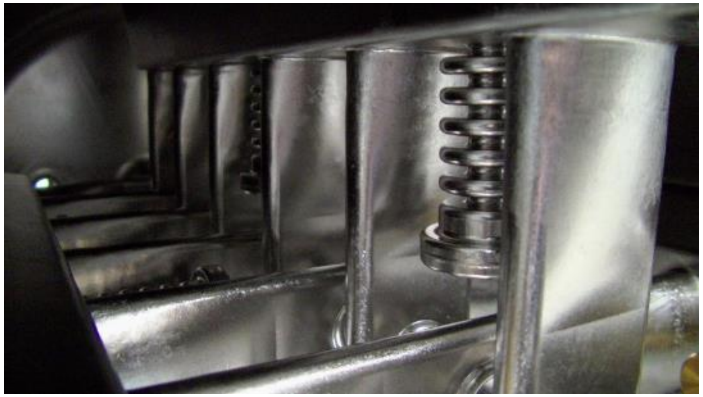


s.c. 217 MHz

Demonstrator cavity (CH0)

First CH-cavity for cw-Linac project (CH0)





Parameters 217 MHz Cavity CH0		
β		0.059
Frequency	MHz	216.816
Accelerating cells		15
Effective length ($\beta\lambda$)	mm	612
Diameter (inner)	mm	409
Tube aperture	mm	18 / 20
Wall thickness	mm	4
df/dp^*	Hz/mbar	50
G	Ω	52
R_a/Q_0		3240
R_aR_S	$\mathrm{k}\Omega^2$	168
E_a (design)	MV/m	5.5
E_p/E_a		6.3
B_p/E_a	mT/(MV/m)	5.7

*without He vessel

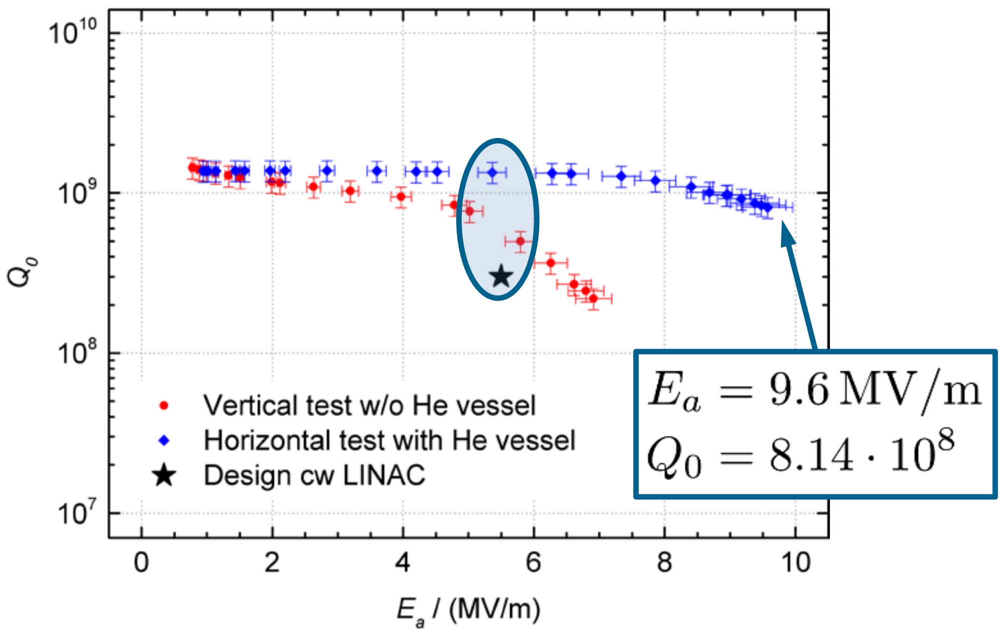
HIM Helmholtz-Institut Mainz

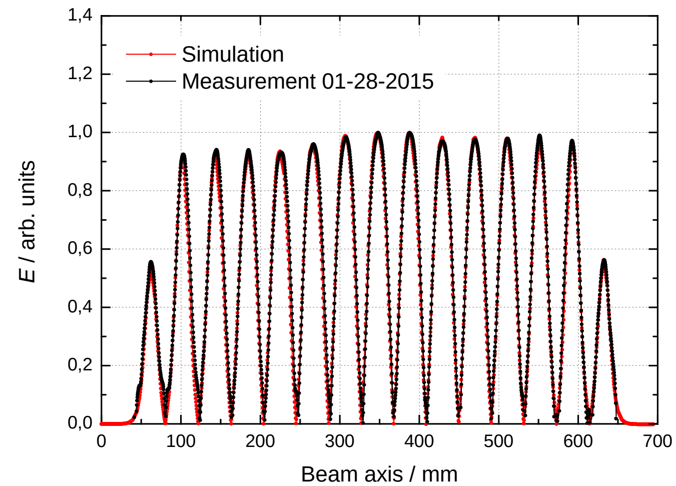
Cavity Performace at 4 K (in 2016)

F. Dziuba, et al., *First Cold Tests of the Superconducting cw Demonstrator at GSI, RUPAC2016, St. Petersburg, Russia, (2016)*

GSI

2. RF test in horizontal orientation with He vessel at GSI

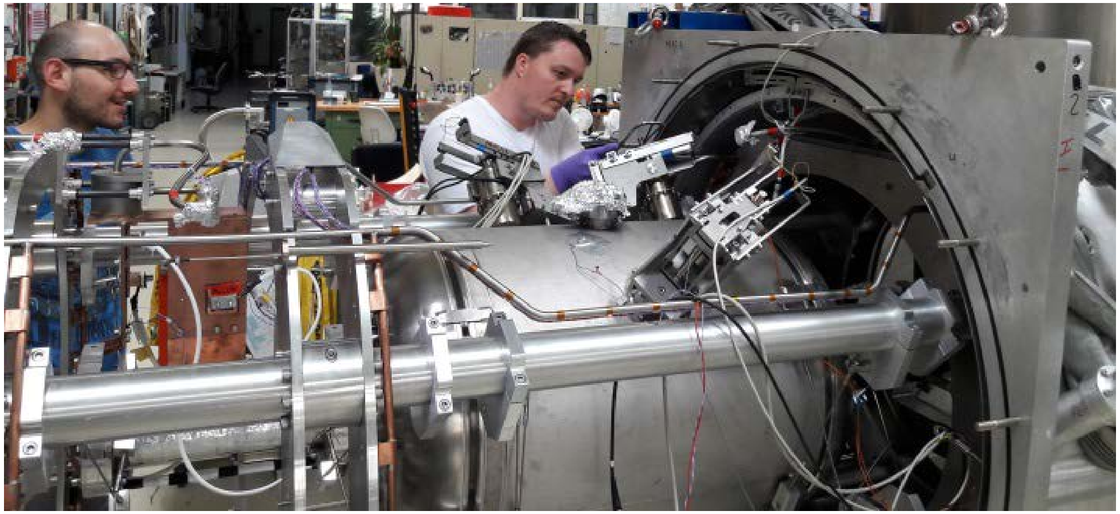




		Vertical test w/o He vessel	Horizontal test with He vessel
Q_0^{low}		$1.44 \cdot 10^9$	$1.37 \cdot 10^9$
R_S	nΩ	36	38
R_{BCS}	nΩ	15	15
R_{mag}	nΩ	9	12
R_0	nΩ	12	11
E_a	MV/m	6.9	9.6
Q_0		$2.19 \cdot 10^8$	$8.14 \cdot 10^8$
V_a	MV	4.2	5.9
E_p	MV/m	43	60
B_p	mT	39	55

- Improved performance due to second HPR
- Low field emission activity
- Very high gradient
- Thermal quenching above 9.6 MV/m

Assembly of Acceleration String at GSI (2017)



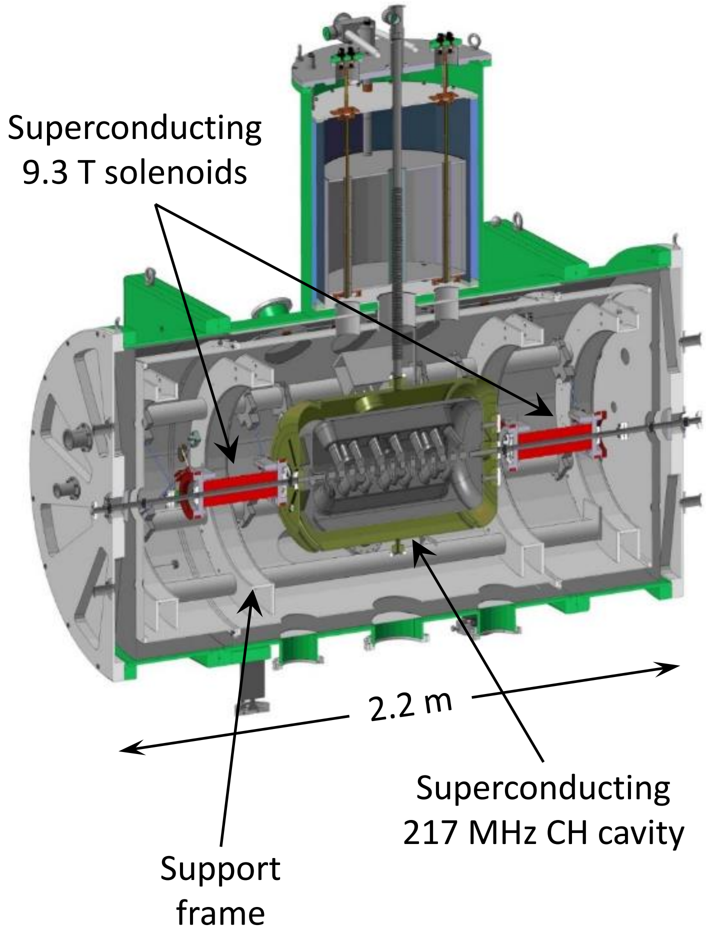
Upgrade of clean room

- Outer space: ISO-8 → ISO-6
- Inner space: ISO-4

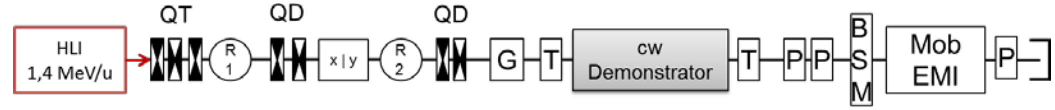
Integration into Cryostat

Demonstrator Beam Commissioning Environment

Layout of the horizontal cryomodule

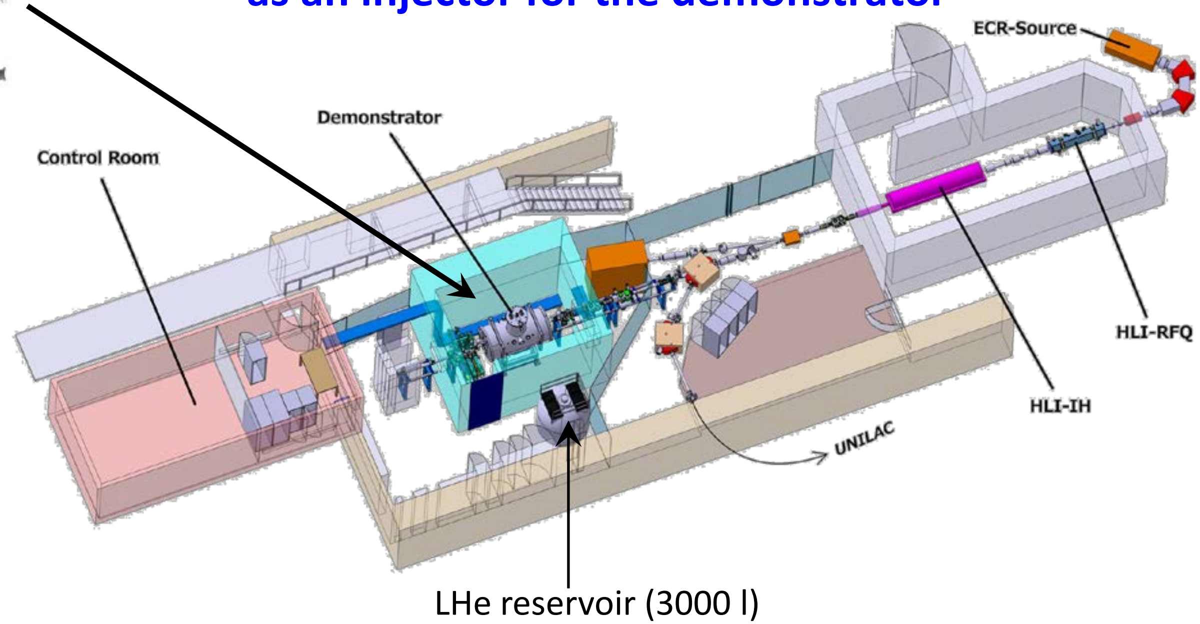


Matching line - demonstrator – test bench

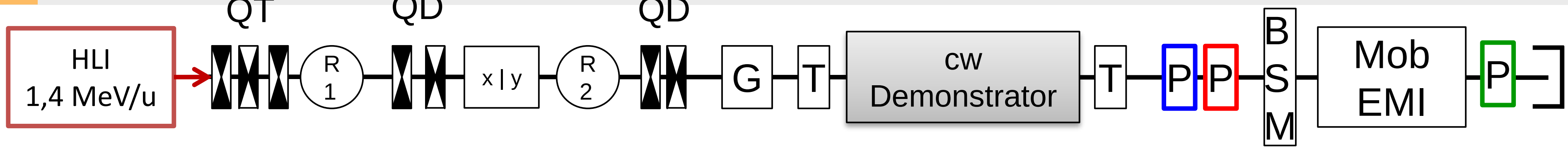


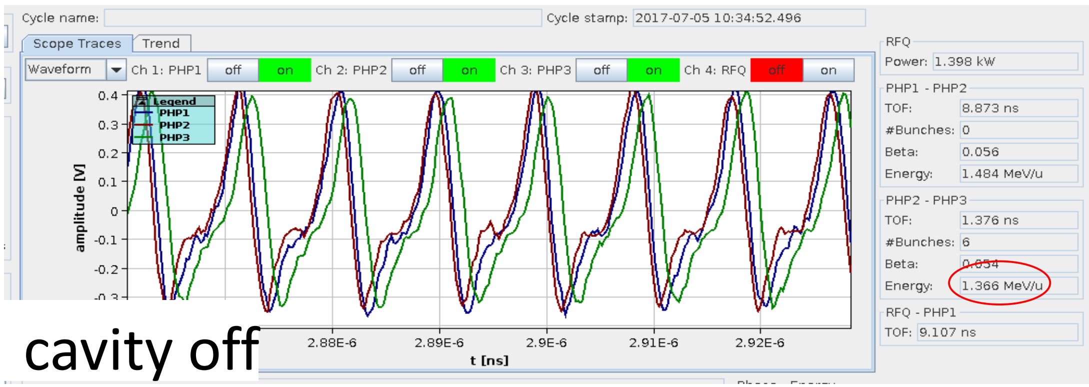
- Steering magnets
- Rebuncher
- Quadrupole doublet
- Profile grids

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

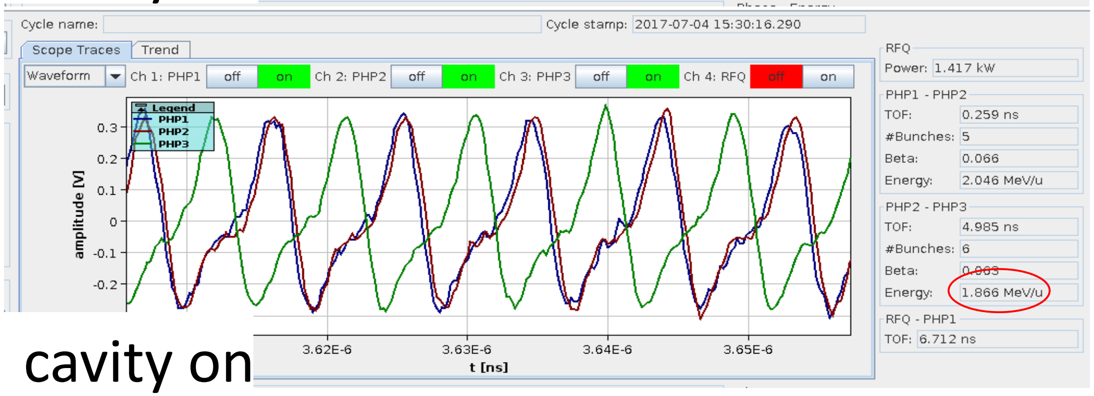


Time of Flight Measurements Ar^{9+}





cavity off



cavity on

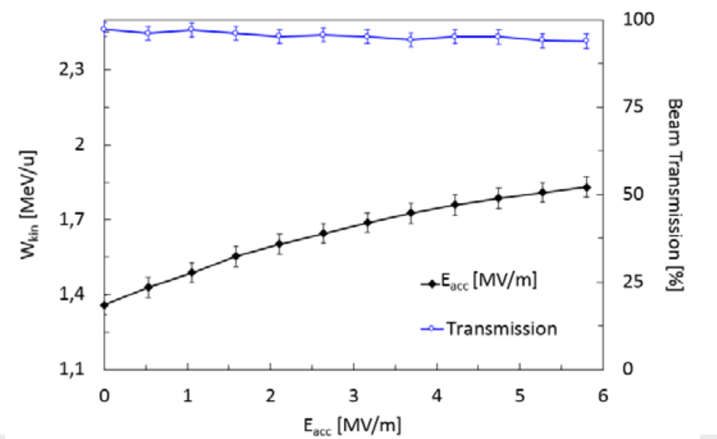
- Measurement of transient signal induced by traveling bunch
- Acceleration! Energy gain of 0.5 MeV/u
- → systematic scan of rf-phase and amplitude

Beam input parameter

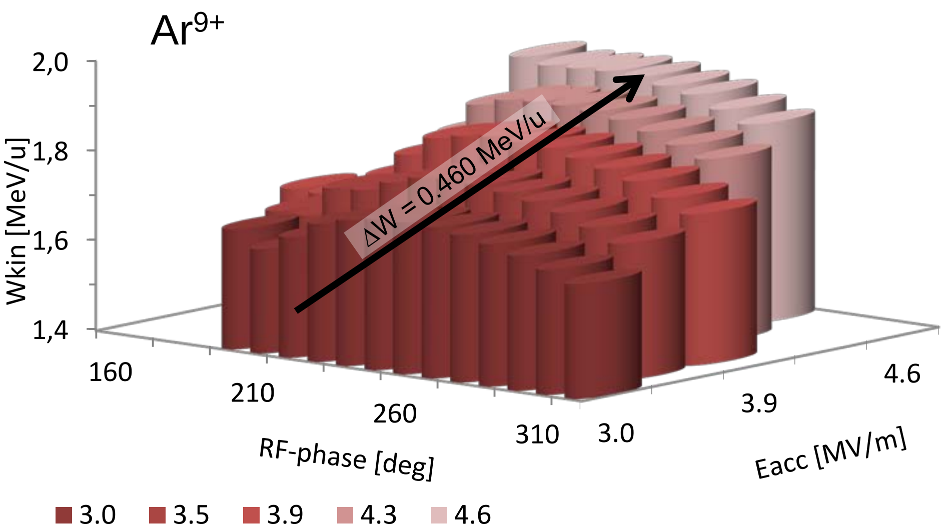
- 50 Hz, 5 ms (25% beam duty)
- cw (RF duty)
- 1.5pμA (particle current)

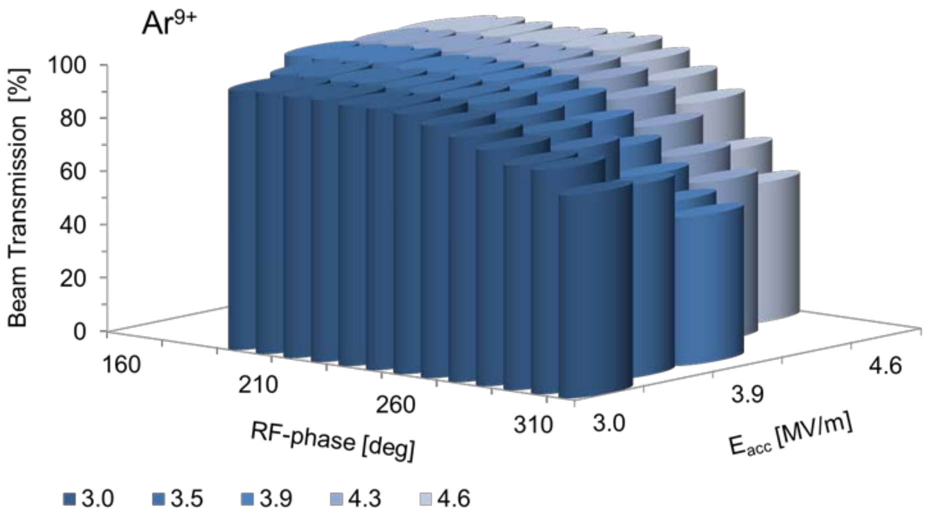
Beam output parameter

- Design energy of 1.86 MeV/u
- 95% of beam transmission
- 15% of trans. emittance growth
- 0.25 ns bunch length (Δϕ = 20°)



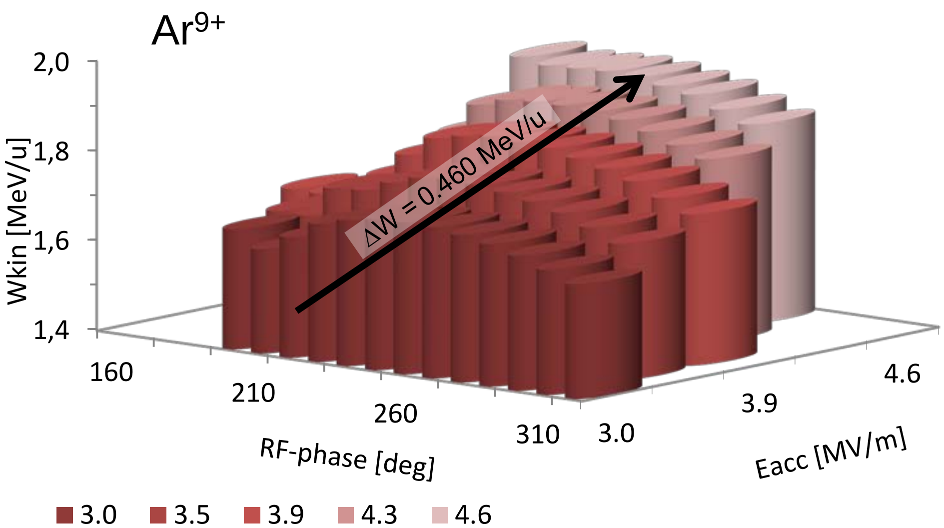
Systematic scans (RF phase/amplitude)

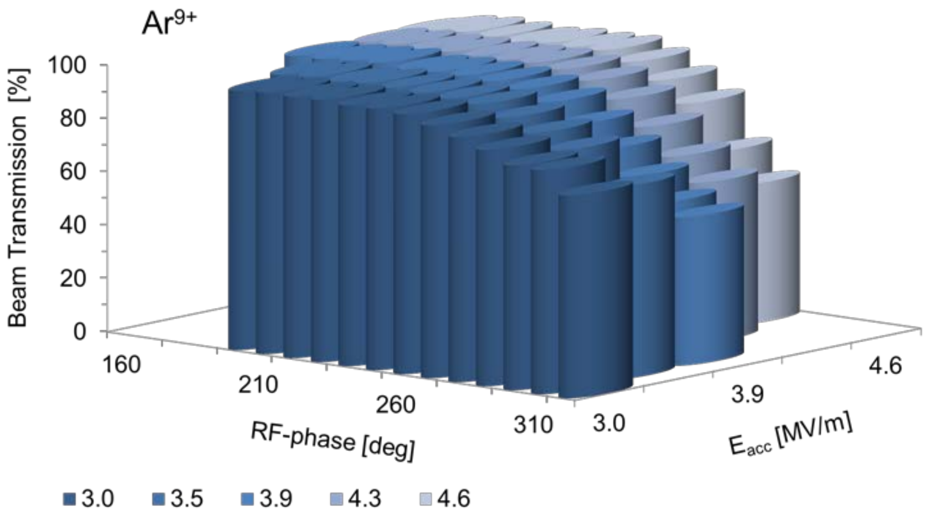




- Variation of phase and amplitude of RF power
- Beam transmission is high for most of RF phases
- 2.2 MeV/u reached at 830 W of forward power
- Energy variation 1.2 - 2.2 MeV/u → Feature of EQUUS beam dynamics

Systematic scans (RF phase/amplitude)

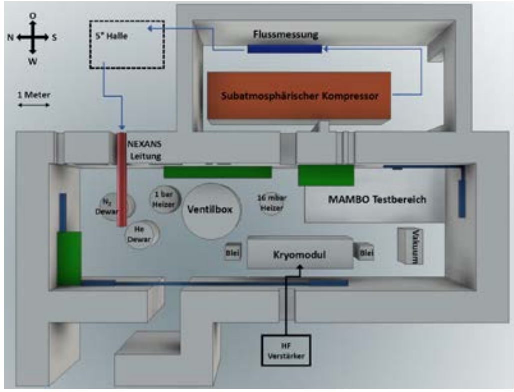




- Variation of phase and amplitude of RF power
- Beam transmission is high for most of RF phases
- 2.2 MeV/u reached at 830 W of forward power
- Energy variation 1.2 - 2.2 MeV/u $\rightarrow$ Feature of EQUUS beam dynamics

Overall we accelerated different Ar and He ions for 12 days (2 < A/Z < 7). Measuring energy, transmission, bunch profiles and emittances. Matching the beam with r.t. bunchers was very succesful and ensured excellent beam quality in a wide range of applied rf parameters.

Cavity Assembly, Preparation and Testing at HIM

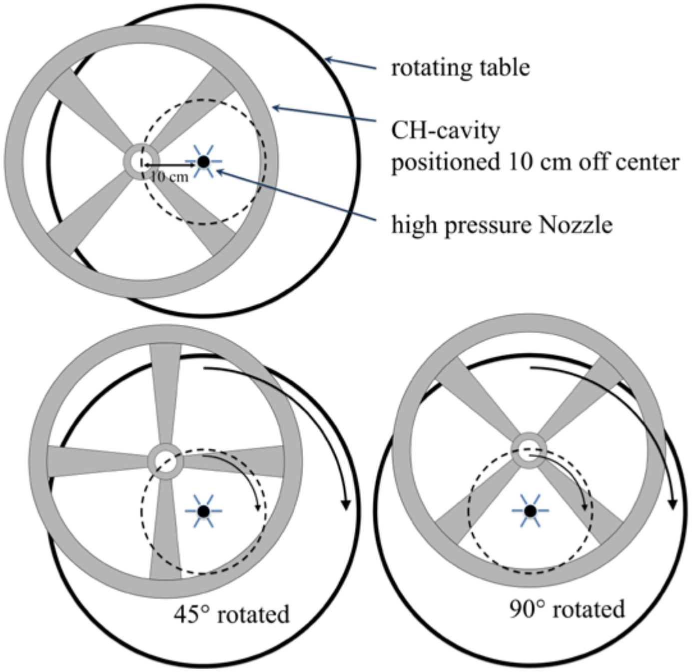


Infrastructure in Mainz:

- Clean room environment
- High Pressure Rinsing
- Further improvement of cavity performance
- Cavity bakeout
- Setup for cavity RF testing at 4 K & 2 K

Cavity Assembly, Preparation and Testing at HIM

Special HPR Cabinet

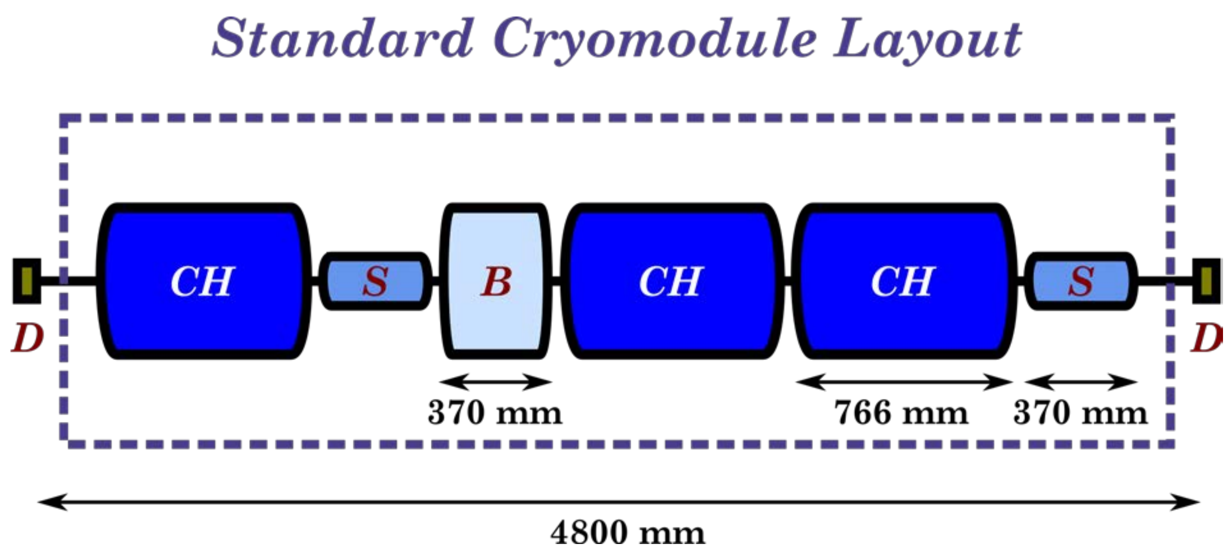


Infrastructure in Mainz:

- Clean room environment
- High Pressure Rinsing
- Further improvement of cavity performance
- Cavity bakeout
- Setup for cavity RF testing at 4 K & 2 K

Rinsing off axis

Advanced Demonstrator

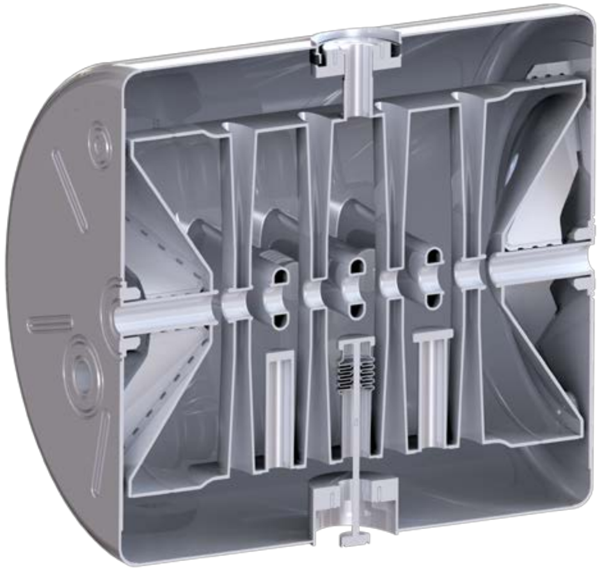


- New cryo module layout containing demonstrator CH cavity, 2 short CH cavities, 1 buncher and 2 solenoids
- Simplified cavity design (easier manufacturing & surface processing)
- CH1 & CH2 are already in production (delivery at 4th quarter of 2018)
- Tendering for cryostat at 3rd quarter of 2018

Short CH-Cavity Design

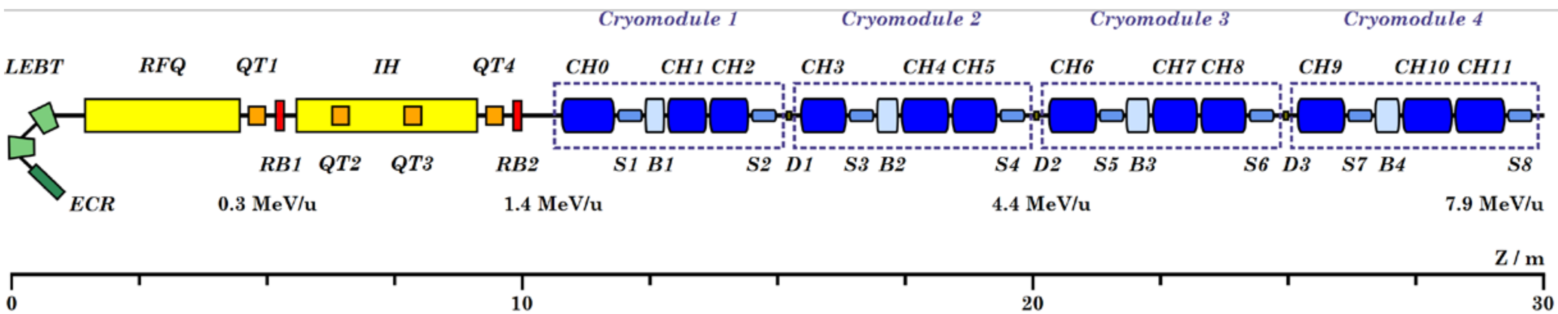
Design parameters of short CH cavities CH1 & CH2

β		0.069
Frequency	MHz	216.816
Cell number	#	8
Length (βλ-definition)	mm	381.6
Cavity diameter (outer)	mm	400
Cell length	mm	47.7
Aperture diameter	mm	30
Dynamic bellow tuner	#	2
Wall thickness	mm	3-4
Accelerating gradient	MV/m	5.5
df/dp	Hz/mbar	-13
E_p/E_a		5.2
B_p/E_a	mT/(MV/m)	<10
G	Ω	50
R_a/Q_0		1070



PhD thesis of M. Basten, IAP, Frankfurt University

New cw-Linac Layout



- Total of 12 CH cavities
- Each cryo module contains 3 CH-cavities + Re-Buncher + 2 solenoids
- Variable end energy 3.6 - 7.6 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

Acknowledgements

Thank you very much for your attention!

June 2017:
First beam test

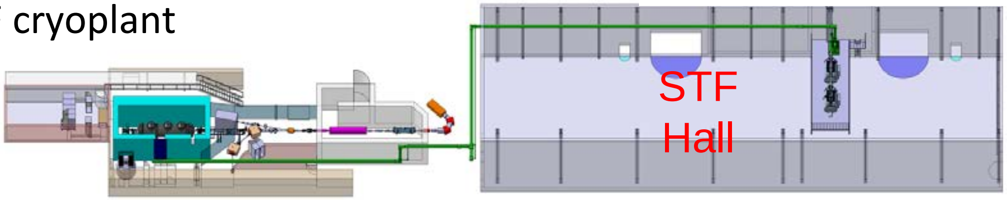
Collaboration partners

GSI *HIM/JGU Mainz* *IAP/JGU Frankfurt*

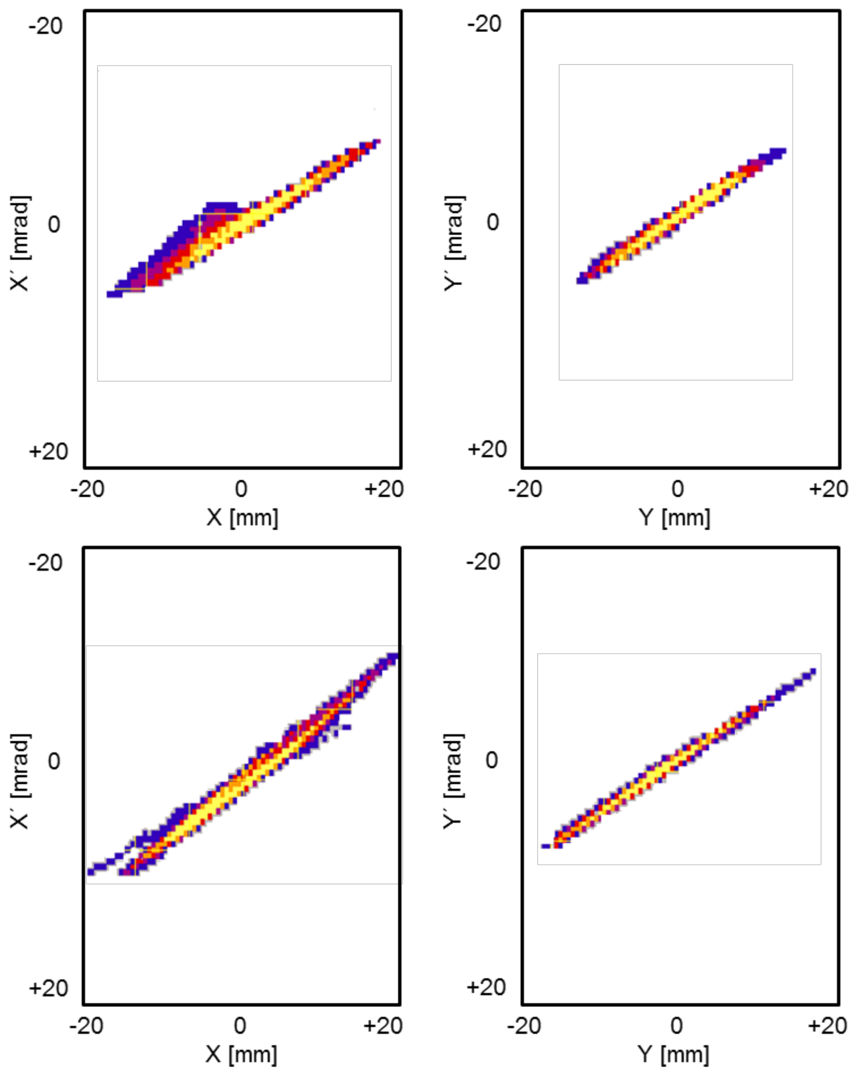
EXTRA slides

Timeline of Advanced Demonstrator Project

02/2015	Start POF3
09/2016	Ordering of two short CH-cavities
02/2018	Link of testing area to STF cryoplant
10/2018	Tendering of cryostat
11/2018	Delivery of short cavities
02/2019	Modification of radiation protection shelter @GSI
11/2019	Delivery of cryostat
02/2020	Assembly of cryomodule @ HIM
10/2020	**Beamtest @ GSI**
>12/2020	User Operation



Emittance measurements

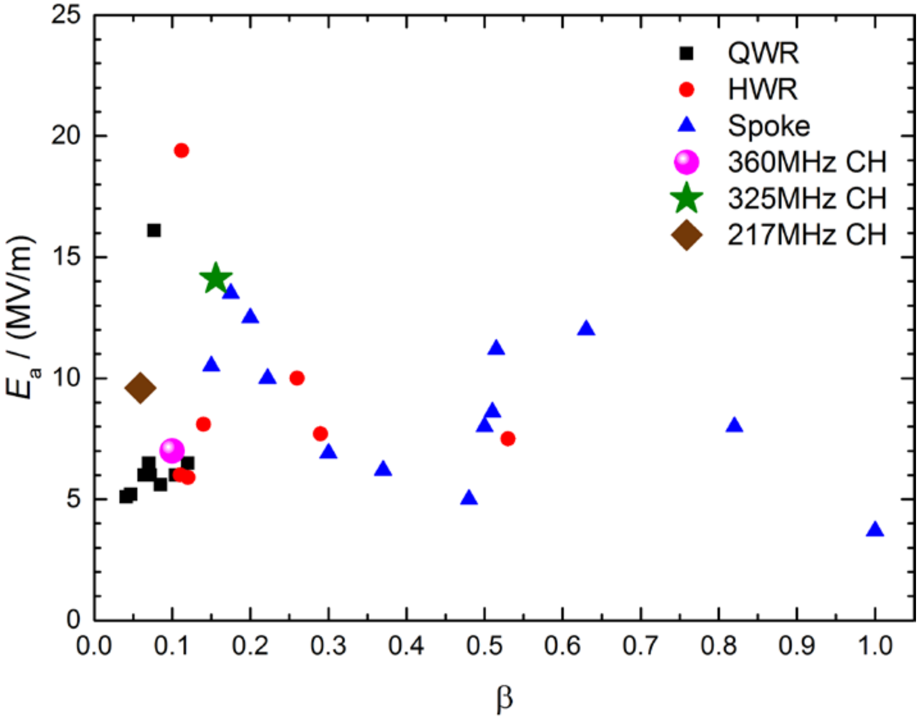


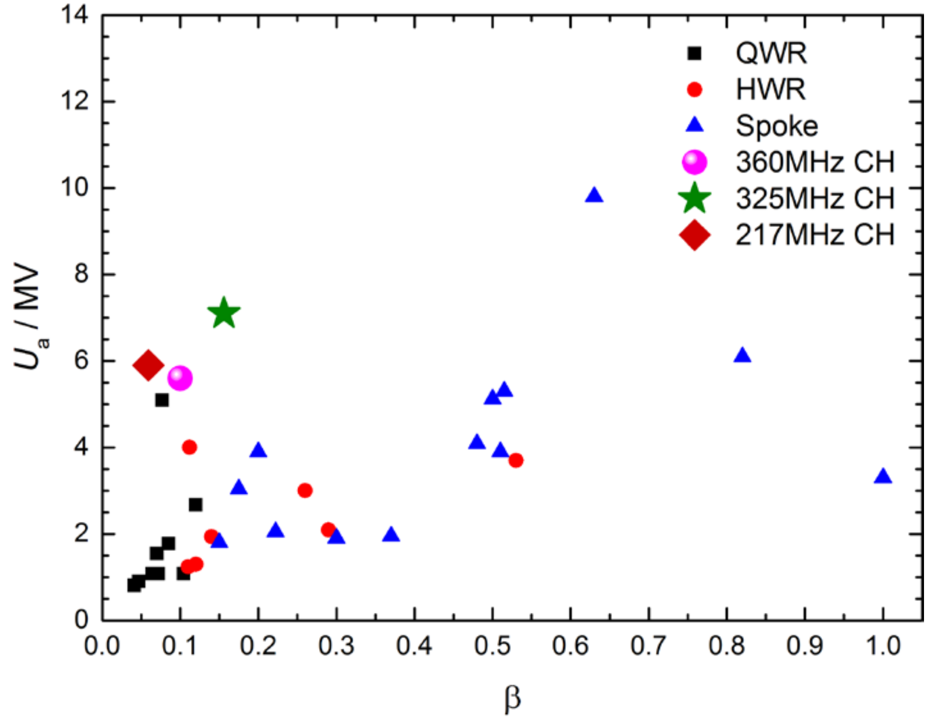
1.41 MeV/u

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

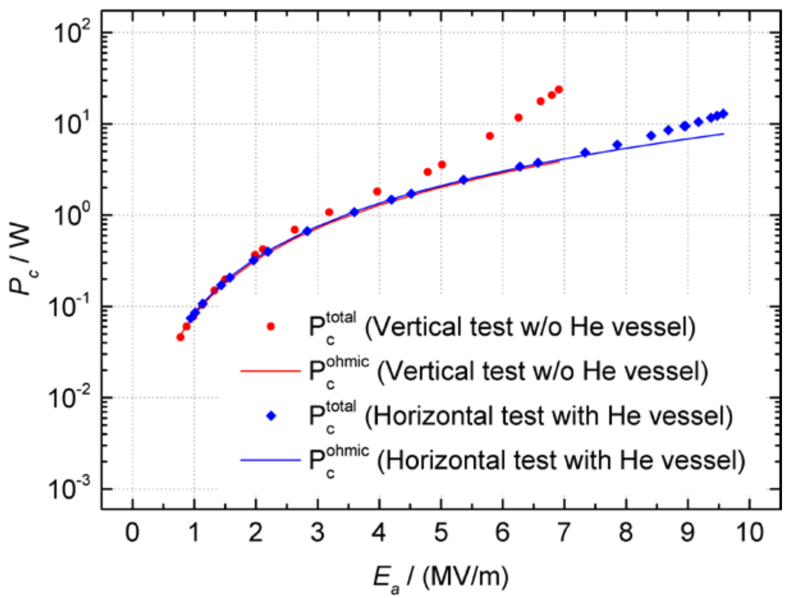
What is the advantage of a sc CH Cavity?





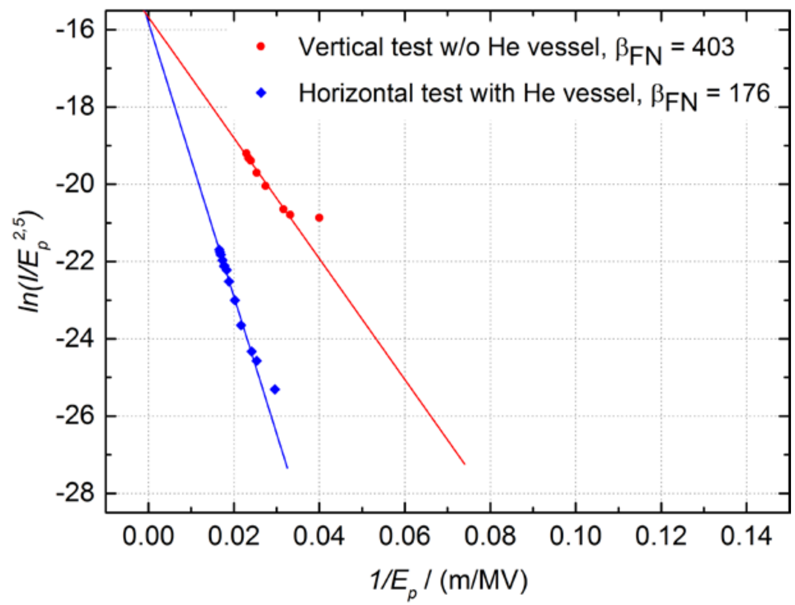
Power Consumption & Emitter Current

Total losses inside the cavity



Fowler-Nordheim plot

for 2 different surface qualities



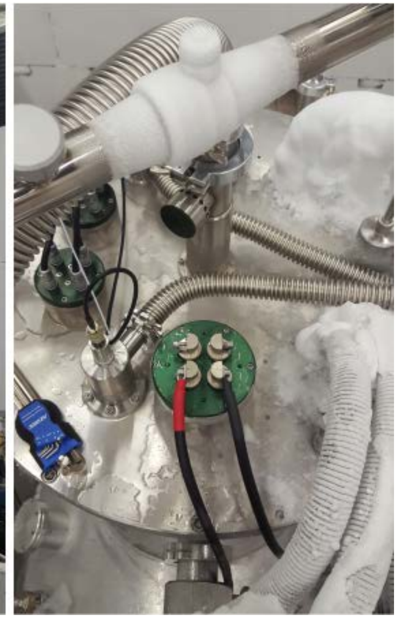
After 1. RF test

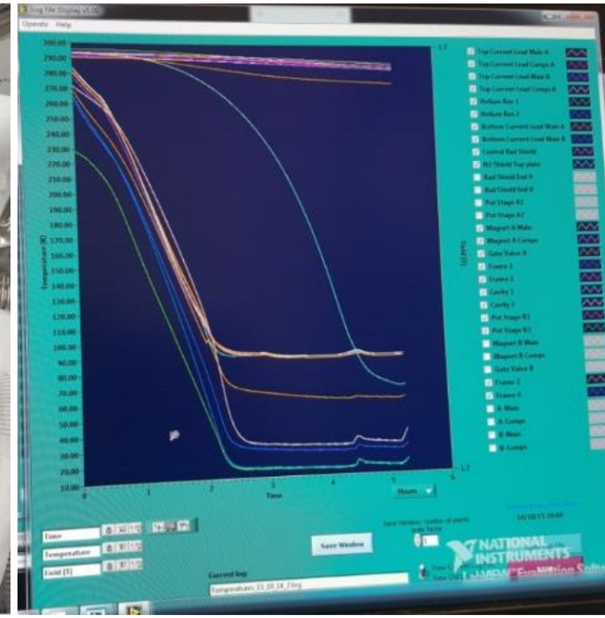
- Rapidly increase of total losses at E_a = 5 MV/m (E_p = 32 MV/m)
- Activation of field emitters

After 2. RF test (advanced HPR)

- Extremely reduced total losses
- Minor field emitter activation at E_a = 7.8 MV/m (E_p = 49 MV/m)

Commissioning of Cryomodule and Solenoids





- Superconducting solenoids were ramped at 9.3 T (0.2 A/s)
- Standby losses of cryostat 3 W
- Transversal drift of components during cooldown ±0.15 mm (tolerance: ±0.2 mm)

Surface Preparation

Before assembly of He vessel (before 1st cold test):

- 1. BCP - 50 µm
- 2. BCP - 25 µm (after welding of static tuners)
- 3. BCP - 3 µm
- HPR for 2 h, 12 h drying, assembly of antennas
- HPR for 12 h (from both sides repectively), 12 h drying

After assembly of He vessel (after 1st cold test):

- HPR for 12 h (from both sides repectively), 12 h drying
- Final welding of He vessel

HPR only along beam axis!

Requirements for FAIR and the SHE-Program

FAIR requirements:

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

“Super Heavy Element” requirements:

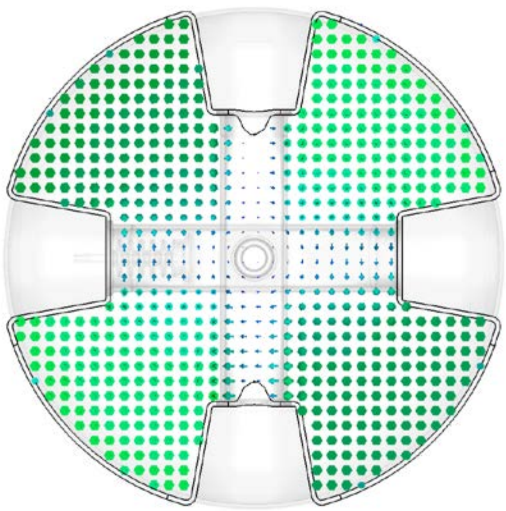
- relatively low beam currents
- high repetition rate (50 Hz)
- high duty factor (100 %, pulse length up to 20 ms)

“Material Science” additional requirements:

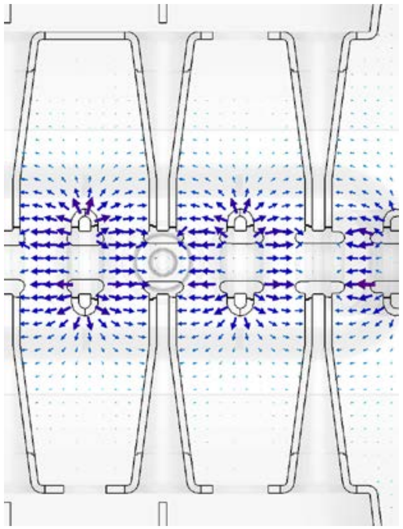
- Heavy Ions ($m \geq 200$)
- High Beam Energy (up to 10 MeV/u)
- Continuous Beam Energy Variation (1.5 – 10 MeV/u)

EXTRA slides

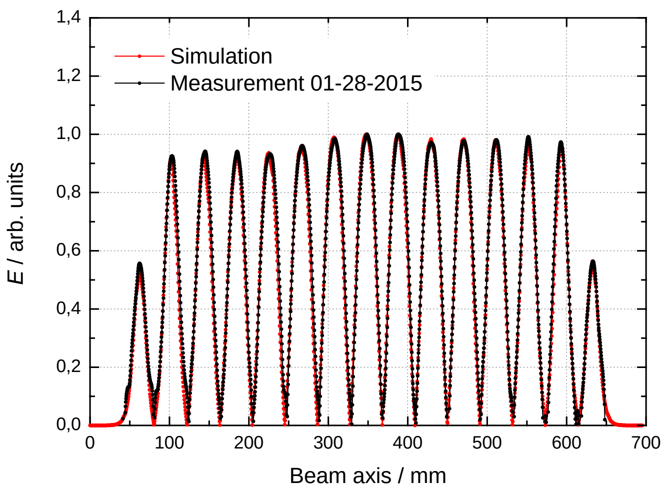
H field



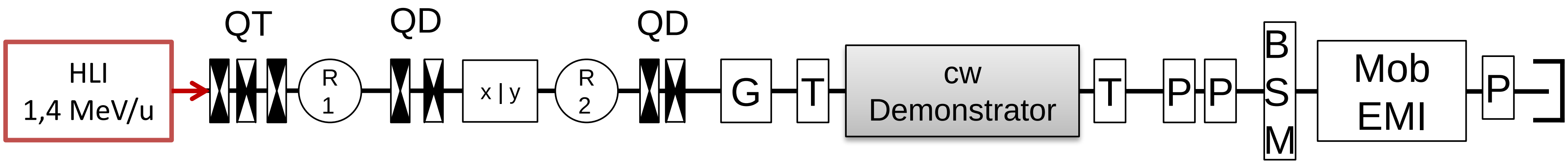
E field



E field along beam axis



Matching line – demonstrator – beam diagnostics test setup



- HLI provides Ar^{11+}, Ar^{9+}, Ar^{6+}, He^{2+} @ 1,4 MeV/u
- Steering magnets
- Additional Re-Buncher
- Quadrupole doublet
- Profile Grid
- Phase probes for TOF measurement
- Beam current transformers for transmission measurement
- Bunch shape monitor (Feschenko monitor)
- Slit-Grid emittance measurement device
- Transversal matching is measured in 2015
- 6d characterization of the beam
- $\rightarrow$ Matching in 6d