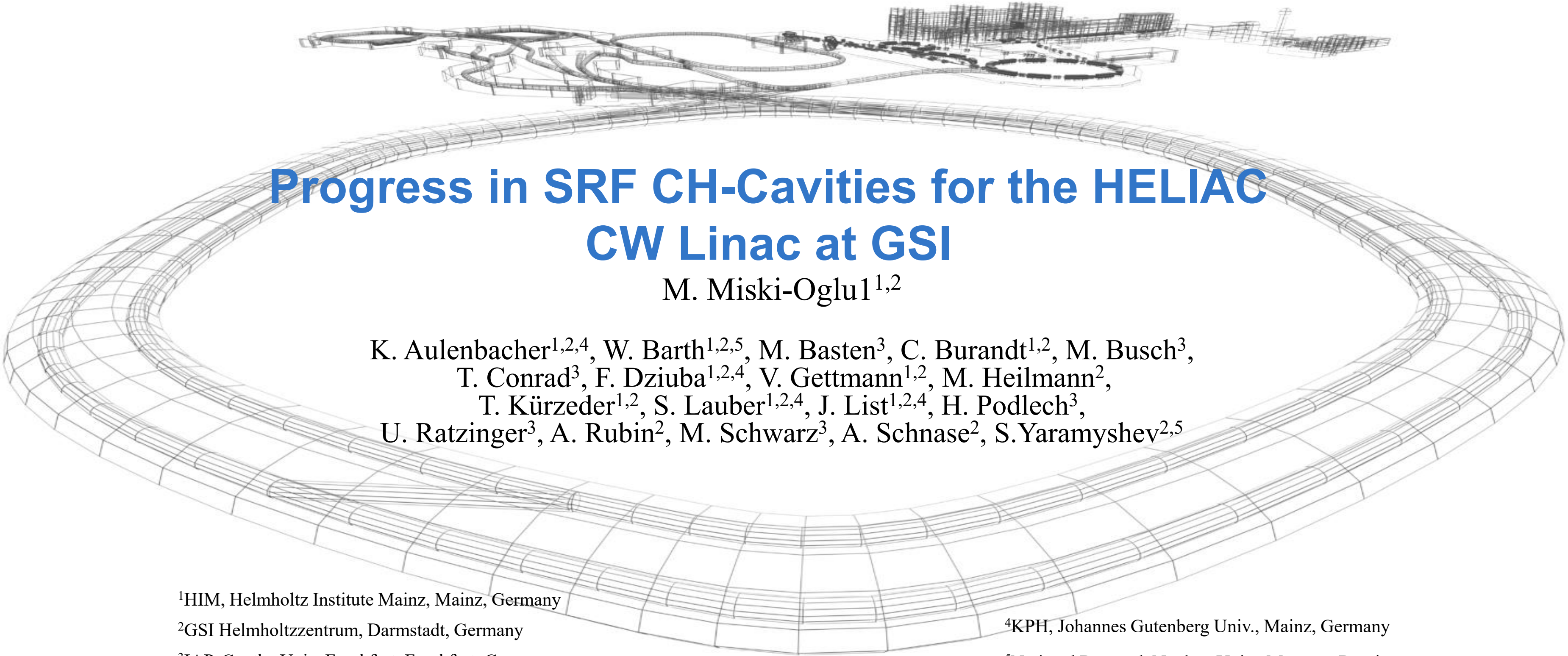


Progress in SRF CH-Cavities for the HELIAC CW Linac at GSI

M. Miski-Oglu1[1,2]

K. Aulenbacher[1,2,4], W. Barth[1,2,5], M. Basten[3], C. Burandt[1,2], M. Busch[3], T. Conrad[3], F. Dziuba[1,2,4], V. Gettmann[1,2], M. Heilmann[2], T. Kürzeder[1,2], S. Lauber[1,2,4], J. List[1,2,4], H. Podlech[3], U. Ratzinger[3], A. Rubin[2], M. Schwarz[3], A. Schnase[2], S.Yaramyshev[2,5]

[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

[5]National Research Nuclear Univ., Moscow, Russia

Requirements for FAIR and the SHE-Program

FAIR requirements:

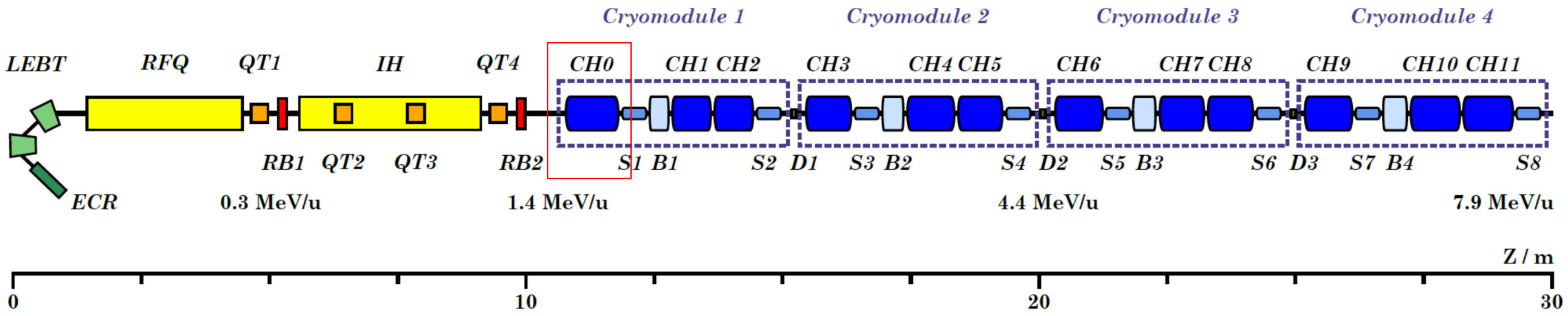
- high beam currents
- low repetition rate (max. 3 Hz)
- low duty factor (0.1 %, pulse length for SIS18 only 100 µs)

“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 at GSI**
- Heavy Ions (m > 200)
- High Beam Energy (up to 10 MeV/u)
- Continuous Beam Energy Variation (1.5 – 10 MeV/u)

Recent layout of the future superconducting cw HELIAC*

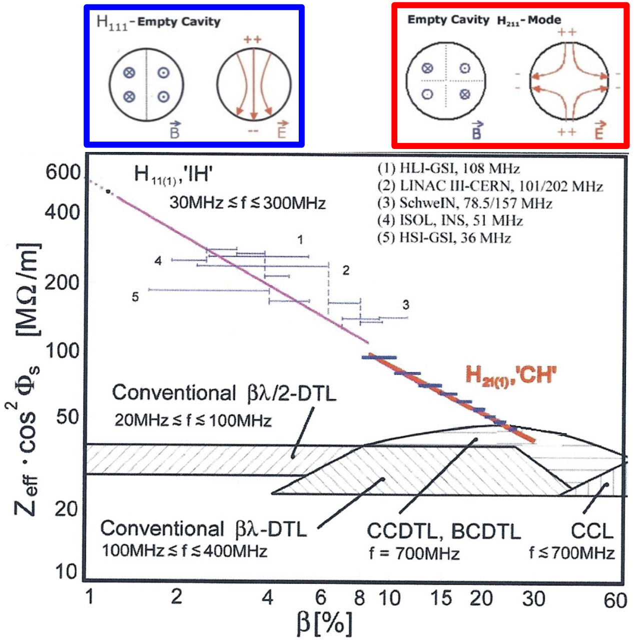


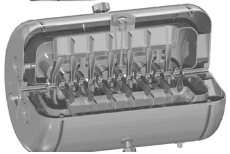
Design parameters sc cw-LINAC		
A/q		≤ 6
Frequency	MHz	216.816
Beam current	mA	≤ 1
Injection energy	MeV/u	1.4
Output energy	MeV/u	3.5–7.9
Length	m	20
CH cavities	#	12
Rebuncher	#	4
Solenoids	#	8

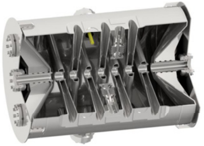
- Multigap CH cavities
- Cavities with short lengths (<1 m) and small transverse dimensions (<0.5 m)
- Modular construction with 4 cryomodules
- Each containing 3 CH cavities, 1 buncher, 2 solenoids
- E_a= 7.1 MV/m enables compact linac design
- R&D on Demonstrator Cavity

* HElmholz LInear ACcelerator

Motivation for Superconducting Multi Cell CH-Cavity





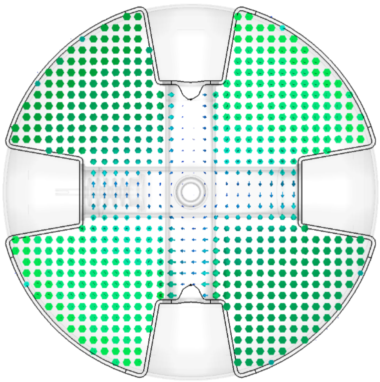


- Room temperature IH structures have unprecedented high efficiency with real estate gradients up to 4 MV/m (HSI IH-Injector @ GSI)
- Expectation on superconducting CH-structures: Mechanical stability, high accelerating voltage per cavity

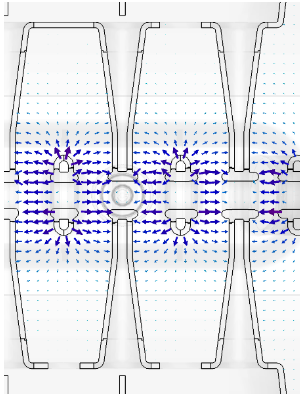
Field Profiles of CH-Cavity

H_{211} mode of "pillbox" cavity

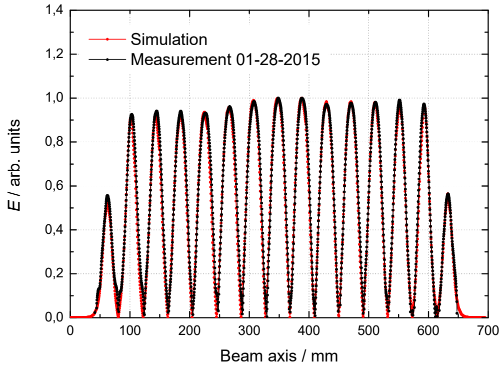
H field



E field



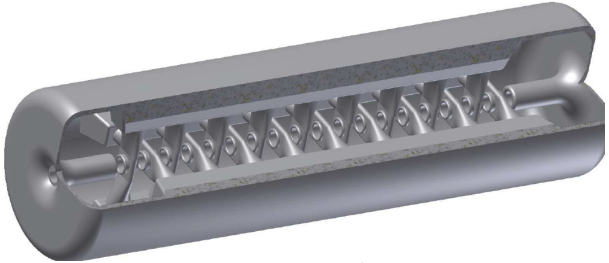
E field along beam axis



- Drift tubes are alternating connected to "+" and "-" potential
- **C**ross-bar-**H**-mode cavity → CH cavity
- Multigap drift tube cavity for the acceleration of protons and ions in the low and medium energy range (0.05<β<0.6)
- Accelerating voltage up to 6 MV

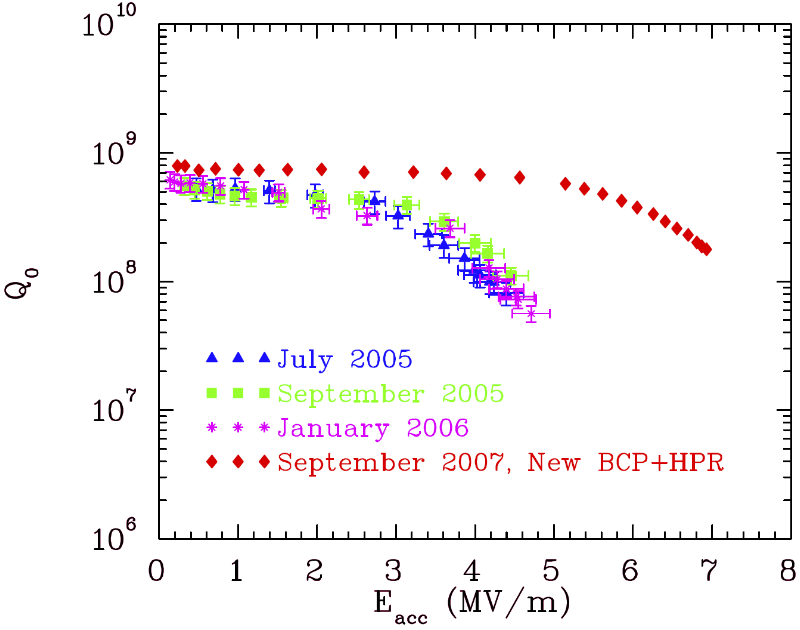
Main Patameters

- β=0.1
- f=360 MHz
- 19 gaps
- RRR=250
- length=1048mm
- diameter=277mm
- Ep/Ea=5.2
- Bp/Ea=5.7



Results

- Ea=7MV/m
- Ua=5.6
- Q_0=7x10^8
- Ep=36MV/m
- Bp=40mT



Next Steps

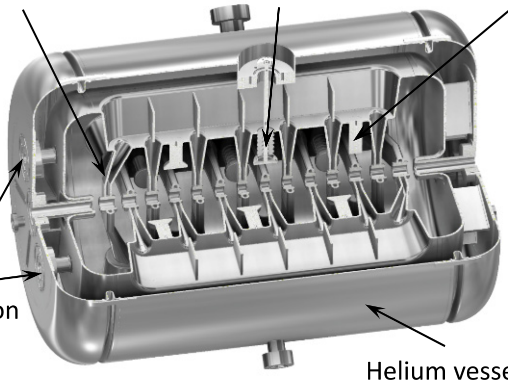
- 325 MHz, 7 cell, β=0.1
- 217MHz, 15 cell, β=0.059

RF Design of the Demonstrator Cavity CH0 (F. Dziuba)

(based on beam dynamic design by S. Mineav 2009)

Design Challenges

- 217MHz double frequency of HLI Injector
- β=0.059
- Small transverse dimensions
- Minimal peak fields
- Eacc=5.5MV/m (conservative)
- Mechanical stability
- Suppression of multipacting
- Frequency tuning
- Meet resonance frequency during manufacturing



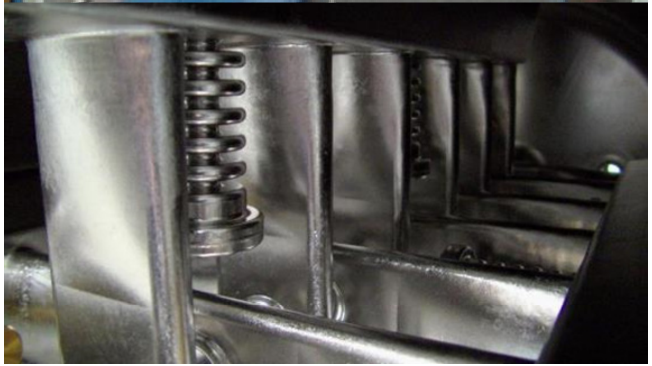
Parameters 217 MHz Cavity CH0		
β		0.059
Frequency	MHz	216.816
Accelerating cells		15
Effective length ($\beta\lambda$)	mm	612
Diameter (inner)	mm	409
Tube aperture	mm	18 / 20
Wall thickness	mm	4
df/dp^*	Hz/mbar	50
G	Ω	52
R_a/Q_0		3240
R_aR_S	kΩ^2	168
E_a (design)	MV/m	5.5
E_p/E_a		6.3
B_p/E_a	mT/(MV/m)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

*without He vessel

Manufacturing of Demonstrator/CH0 cavity (Research Instruments)

Manufacturing Steps

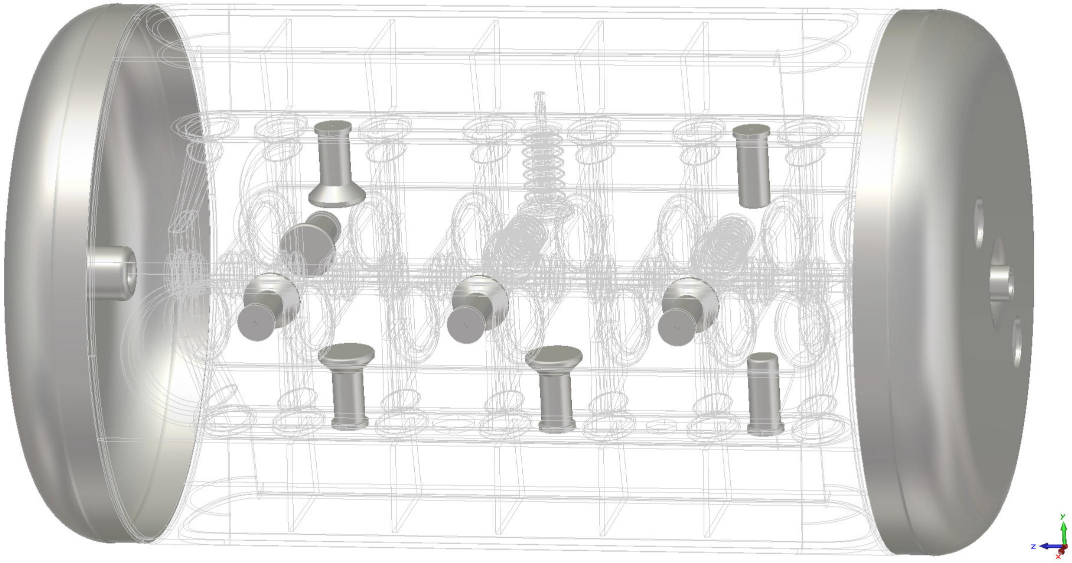
- Production of stems with tubes
- Welding of inner cross bar structure (girders, stems, bellow tuners)
- Welding of cylinder walls



Manufacturing of Demonstrator/CH0 cavity (Research Instruments)

Manufacturing Steps

- Production of stems with tubes
- Welding of inner cross bar structure (girders, stems, bellow tuners)
- Welding of cylinder walls
- Production of end caps
- Control of resonance frequency after each following steps with pressed end caps
- Trimming and welding of 4 static tuners
- Trimming and welding of left end cap
- Trimming and welding of next 3 static tuners
- Trimming and welding of right end cup
- 50 µm BCP treatment
- Trimming and welding of last 2 static tuners



Manufacturing of Demonstrator/CH0 cavity (Research Instruments)

Manufacturing Steps

- Production of stems with tubes
- Welding of inner cross bar structure (girders, stems, bellow tuners)
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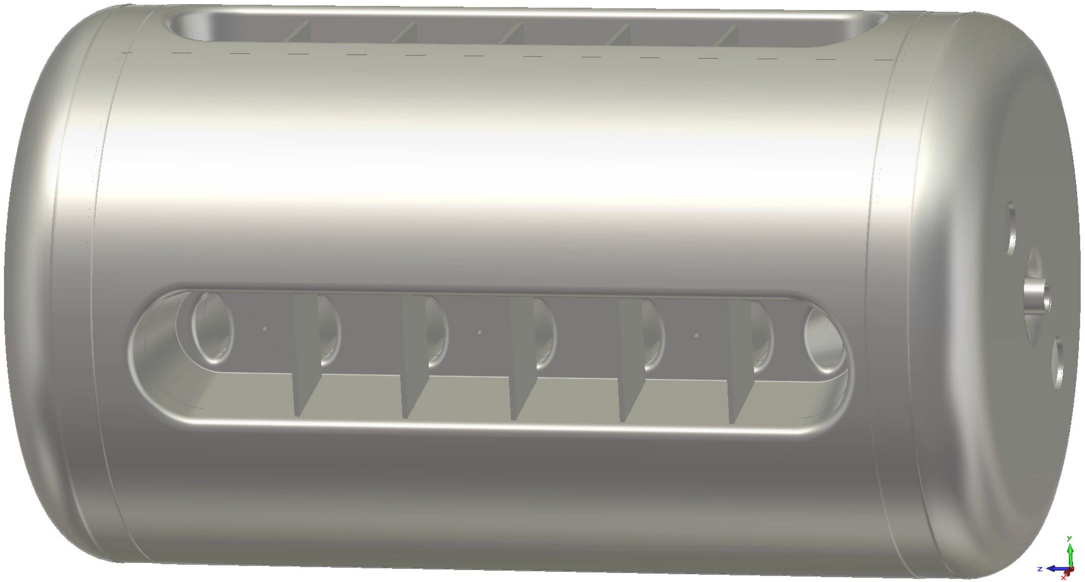
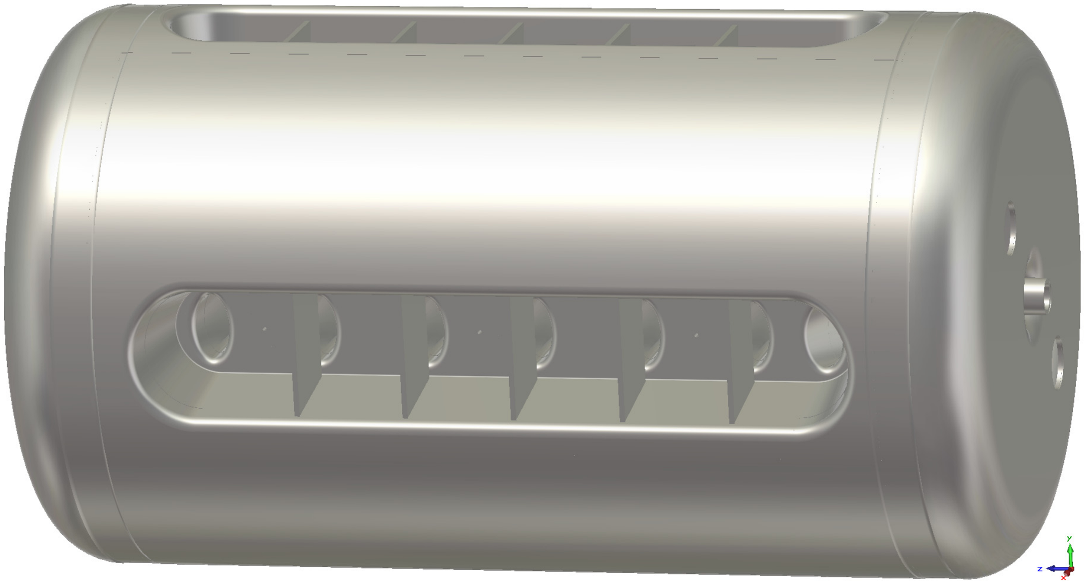
- Control of resonance frequency after each following steps with pressed end caps
- Trimming and welding of 4 static tuners
- Trimming and welding of left end cap
- Trimming and welding of next 3 static tuners
- Trimming and welding of right end cup
- 50 µm BCP treatment
- Trimming and welding of last 2 static tuners
- 25 µm BCP treatment



Manufacturing of Demonstrator/CH0 cavity (Research Instruments)

Manufacturing Steps

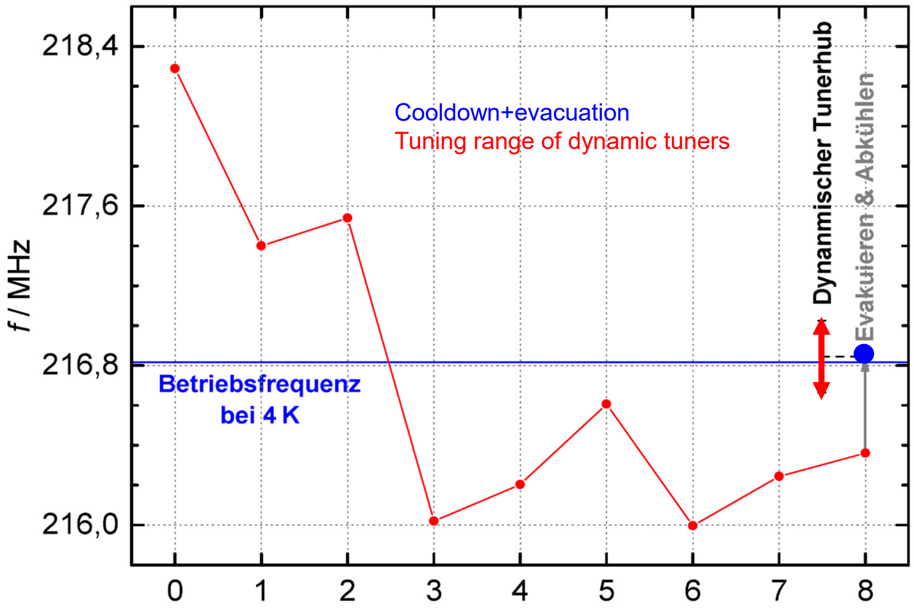
- Production of stems with tubes
- Welding of inner cross bar structure (girders, stems, bellow tuners)
- Welding of cylinder walls
- Production of end caps
- Control of resonance frequency after each following steps with pressed end caps
- Trimming and welding of 4 static tuners
- Trimming and welding of left end cap
- Trimming and welding of next 3 static tuners
- Trimming and welding of right end cup
- 50 µm BCP treatment
- Trimming and welding of last 2 static tuners
- 25 µm BCP treatment
- HPR
- 4K rf-test
- HPR
- Welding of He-Jacket



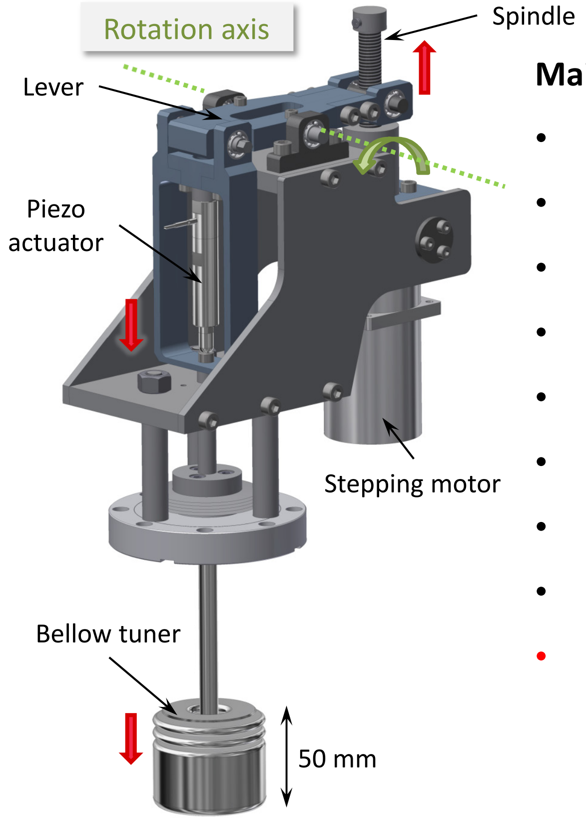
Resonance Frequency During Manufacturing

Manufacturing Steps

- Production of stems with tubes
- Welding of inner cross bar structure (girders, stems, bellow tuners)
- Welding of cylinder walls
- Production of end caps
- Control of resonance frequency after each following steps with pressed end caps
- Trimming and welding of 4 static tuners
- Trimming and welding of left end cap
- Trimming and welding of next 3 static tuners
- Trimming and welding of right end cup
- 50 µm BCP treatment
- Trimming and welding of last 2 static tuners
- 25 µm BCP treatment
- HPR
- 4K rf-test
- HPR
- Welding of He-Jacket

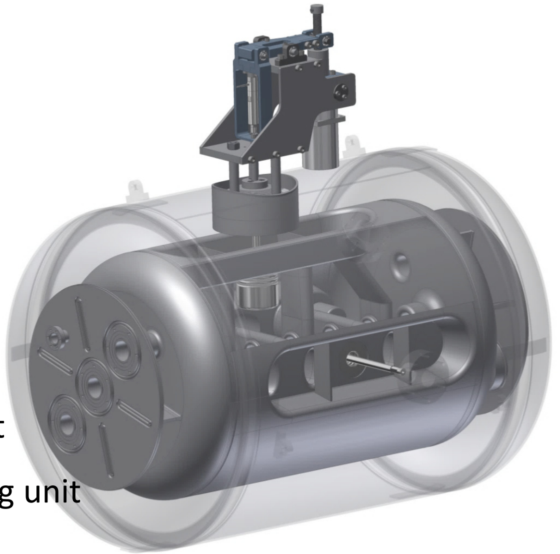


Cavity Tuning

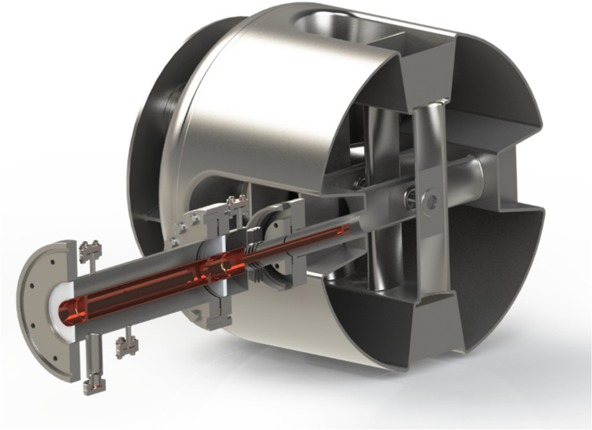


Main properties of the tuning system:

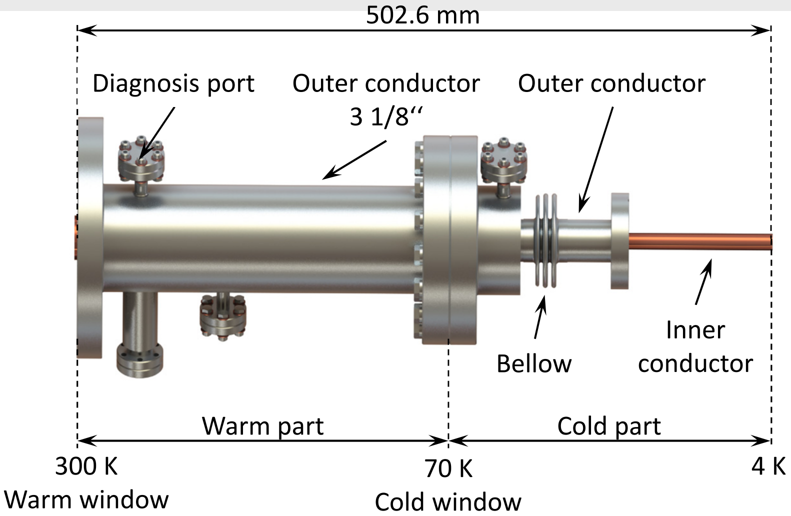
- Enables slow & fast frequency adjustment
- Capacitive bellow tuner
- Max. mechanical displacement ±1 mm (≈ ±60 kHz)
- Lever with pivot point ratio ≈ 2:1
- Stepping motor with gear reduction ratio 50:1
- 0.05 µm per step → very fine frequency adjustment
- Piezo actuator ‚connected in series' with slow tuning unit
- Required displacement of piezo ±6 µm (≈ ±360 Hz)
- All design goals have been achieved!



High Power Coupler

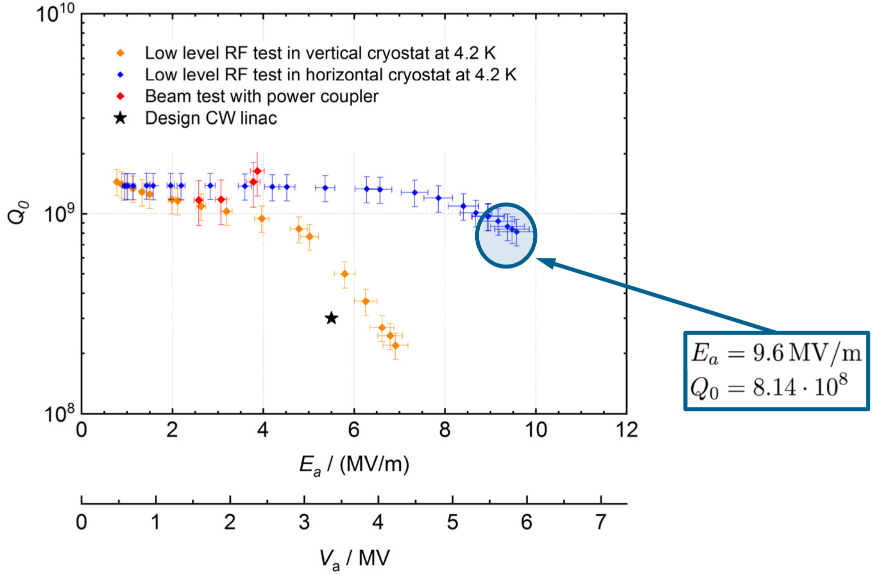


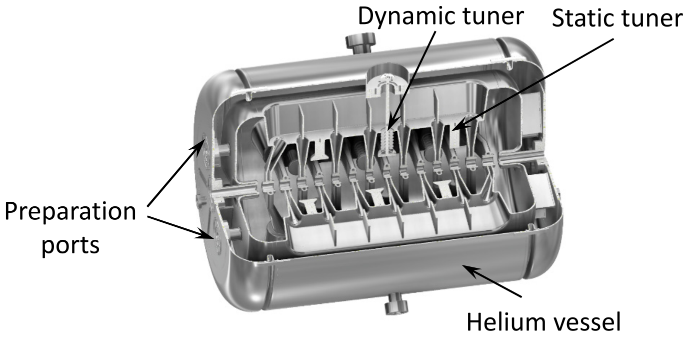
Coupler design based on the work of S. Kazakov, Fermilab



- Capacitive coupling of RF power
- Devided into cold & warm part by 2 ceramic windows (Al_2O_3), TiN coated
- 5 kW cw operation, cold window connected to LN_2 supply
- 216.816 MHz operation frequency with 33 MHz bandwidth

RF Tests of the Cavity at IAP and GSI

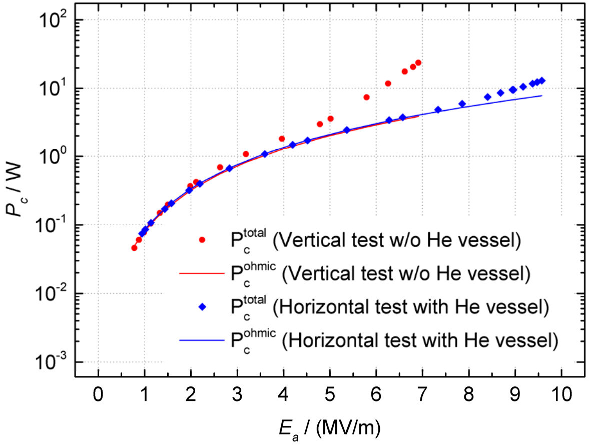


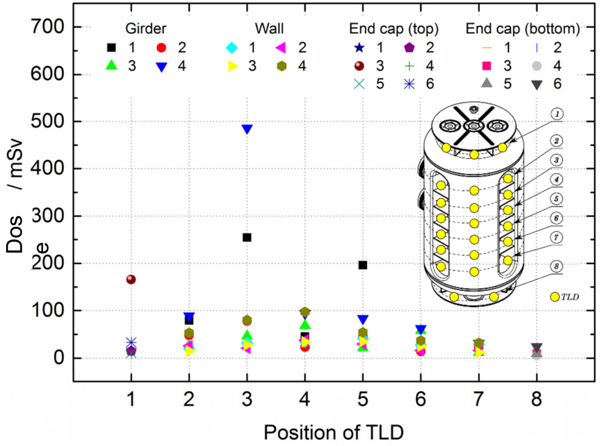


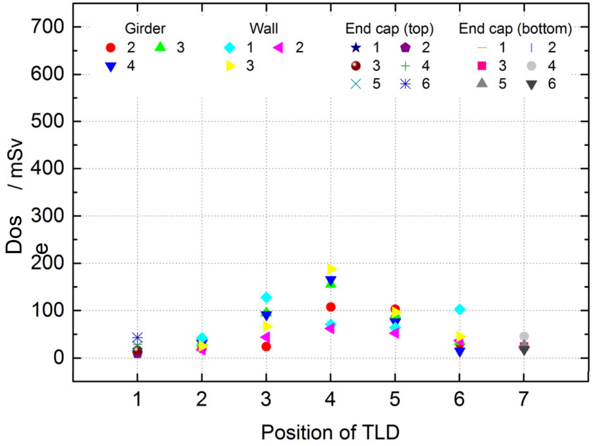
		Vertical test w/o He vessel	Horizontal test with He vessel
Q_0^{low}		$1.44 \cdot 10^9$	$1.37 \cdot 10^9$
R_S	nΩ	36	38
R_{BCS}	nΩ	15	15
R_{mag}	nΩ	9	12
R_0	nΩ	12	11
E_a	MV/m	6.9	9.6
Q_0		$2.19 \cdot 10^8$	$8.14 \cdot 10^8$
V_a	MV	4.2	5.9
E_p	MV/m	43	60
B_p	mT	39	55

- Improved performance due to an additional HPR
- Low field emission activity
- High accelerating gradient
- Acceleration of ions over design up to A/q = 12
- R&D for further improvement of rf-performance

Field Emission







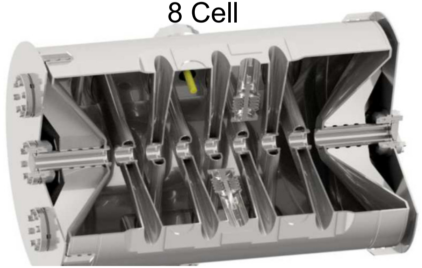
- Rapidly increase of total losses @ E_a = 5 MV/m (E_p = 32 MV/m)
- Strong indication for field emitter activation
- Reduced total losses after anew HPR
- Minor deviation of total losses from Ohmic law @ E_a = 7.8 MV/m (E_p = 49 MV/m)
- Field emission is reduced due two anew HPR!

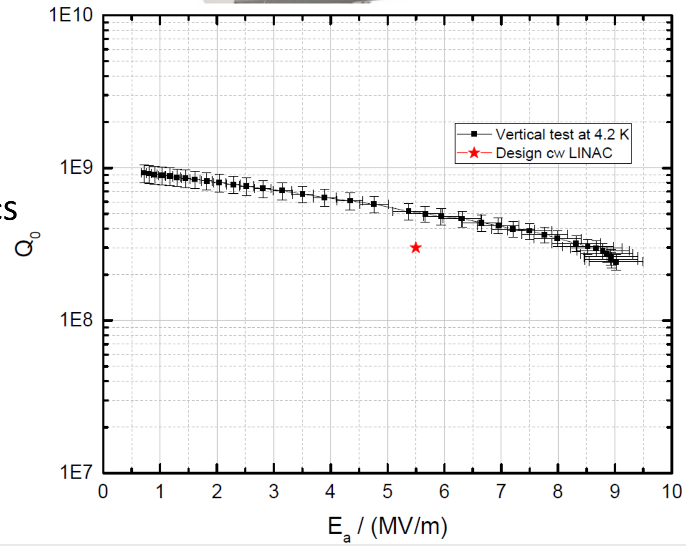
Series Cavty

Design goals

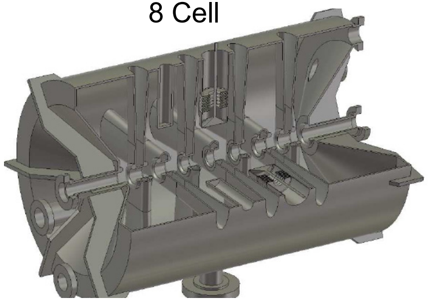
- Easier manufacturing
- Less static tuner
- 2 dynamic tuners
- Higher mechanical stability
- Minimal peak fields
- Less gaps⟶ flexible beam dynamics
- Two identical cavities
- β=0.07
- Ea=5.5MV/m

217 MHz CH1/CH2
8 Cell





217 MHz CH3/CH4/CH5
8 Cell

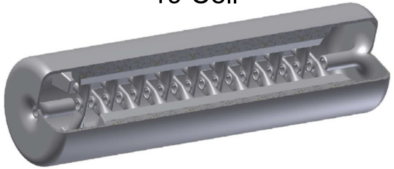


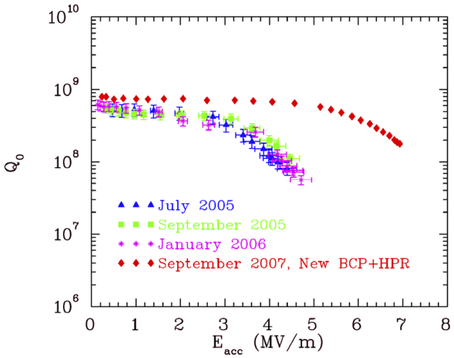
Design goals

- Ea=7.1 MV/m
- Unified stem geometry across CH3/CH4/CH5 “series”
- Individual β

Performance of “series”

360MHz
Prototype
19 Cell

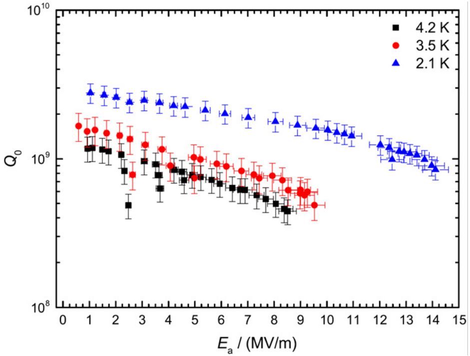




$E_p = 36MV/m$

$B_p = 40mT$

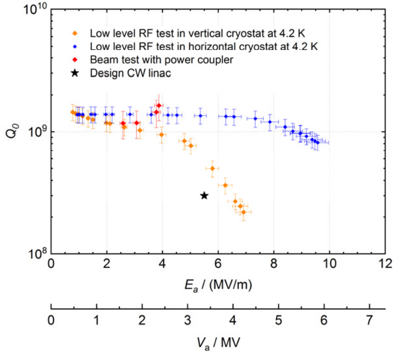
325 MHz CH
7 Cell



$E_p = 42$ MV/m (70.5 MV/m)

$B_p = 110$mT (182mT)

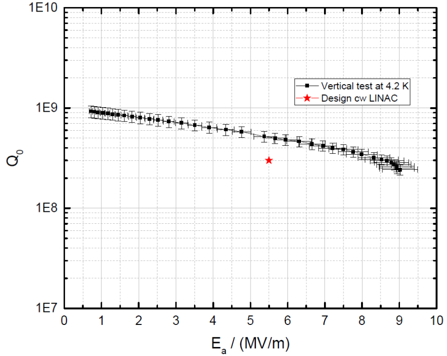
217 MHz
Demonstrator/CH0, 15 Cell



$E_p = 60$MV/m

$B_p = 54$ mT

217 MHz CH1/CH2
8 Cell



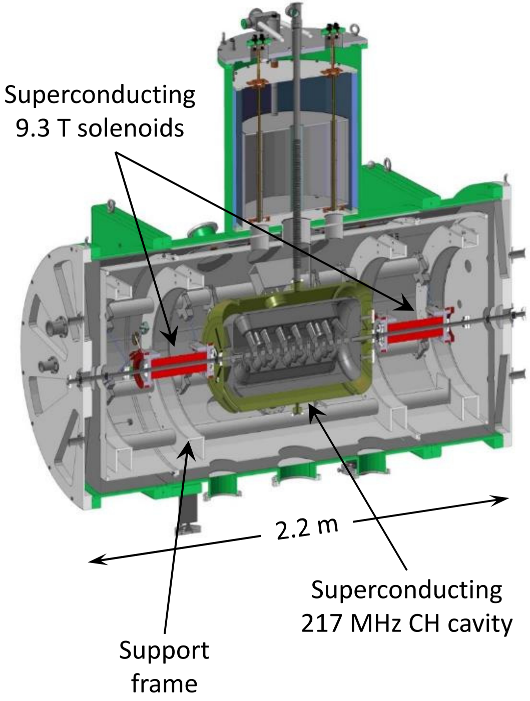
$E_p = 54$ MV/m

$B_p = 90$mT

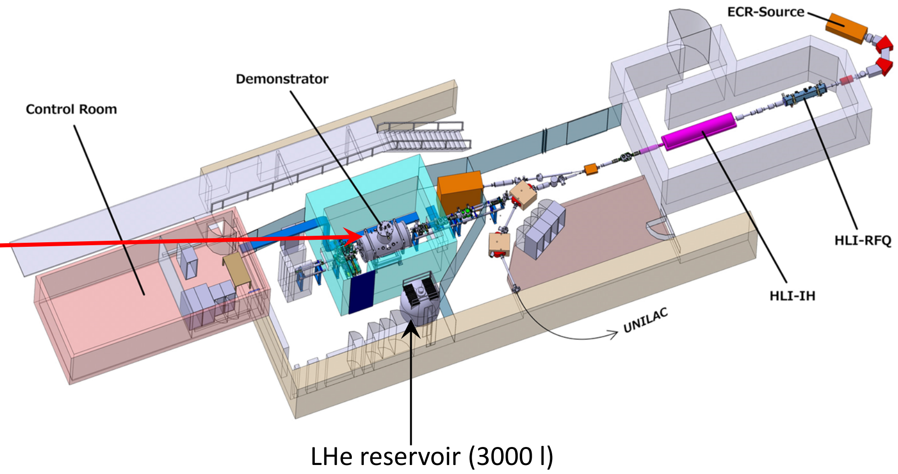
- All cavities at 4K are limited by surface peak electric field Ep.
- Multipacting induced quench?

Experimental setup of the demonstrator at GSI

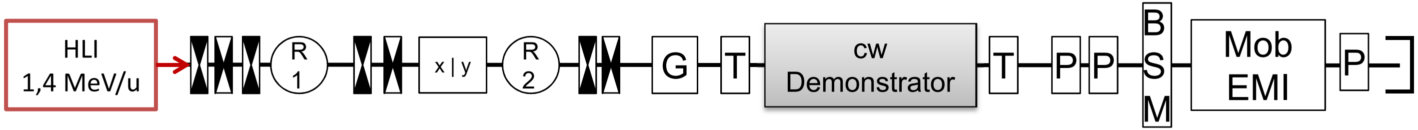
Layout of demonstrator cryomodule



Demonstrator at GSI-High Charge State Injector (HLI)

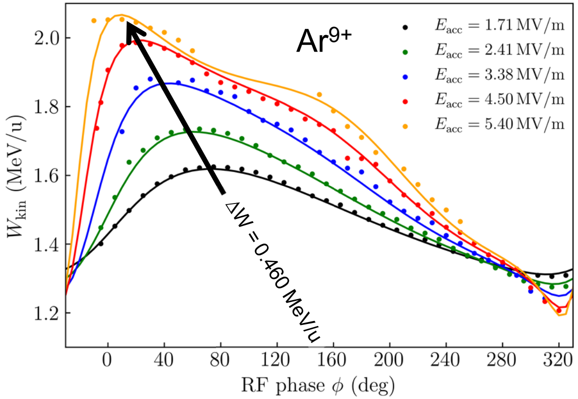


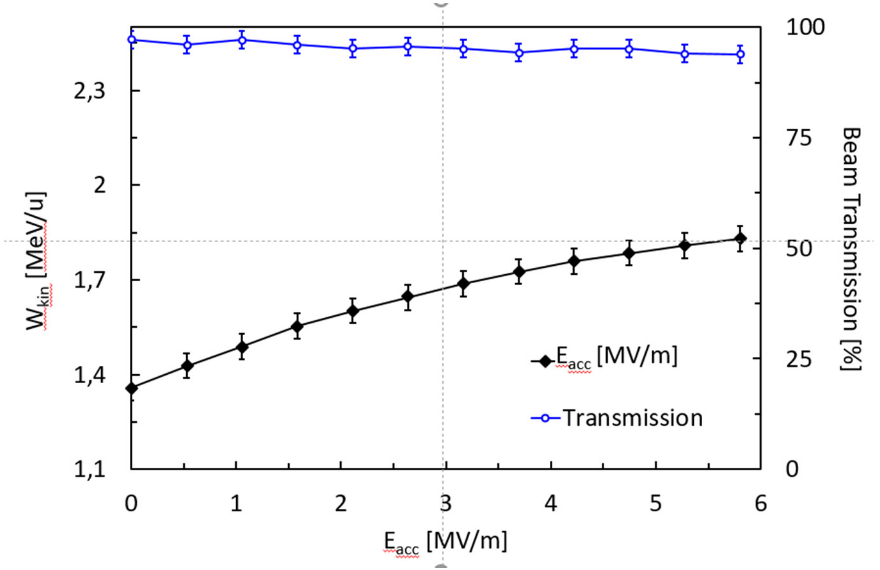
Matching Line for the Beam Test



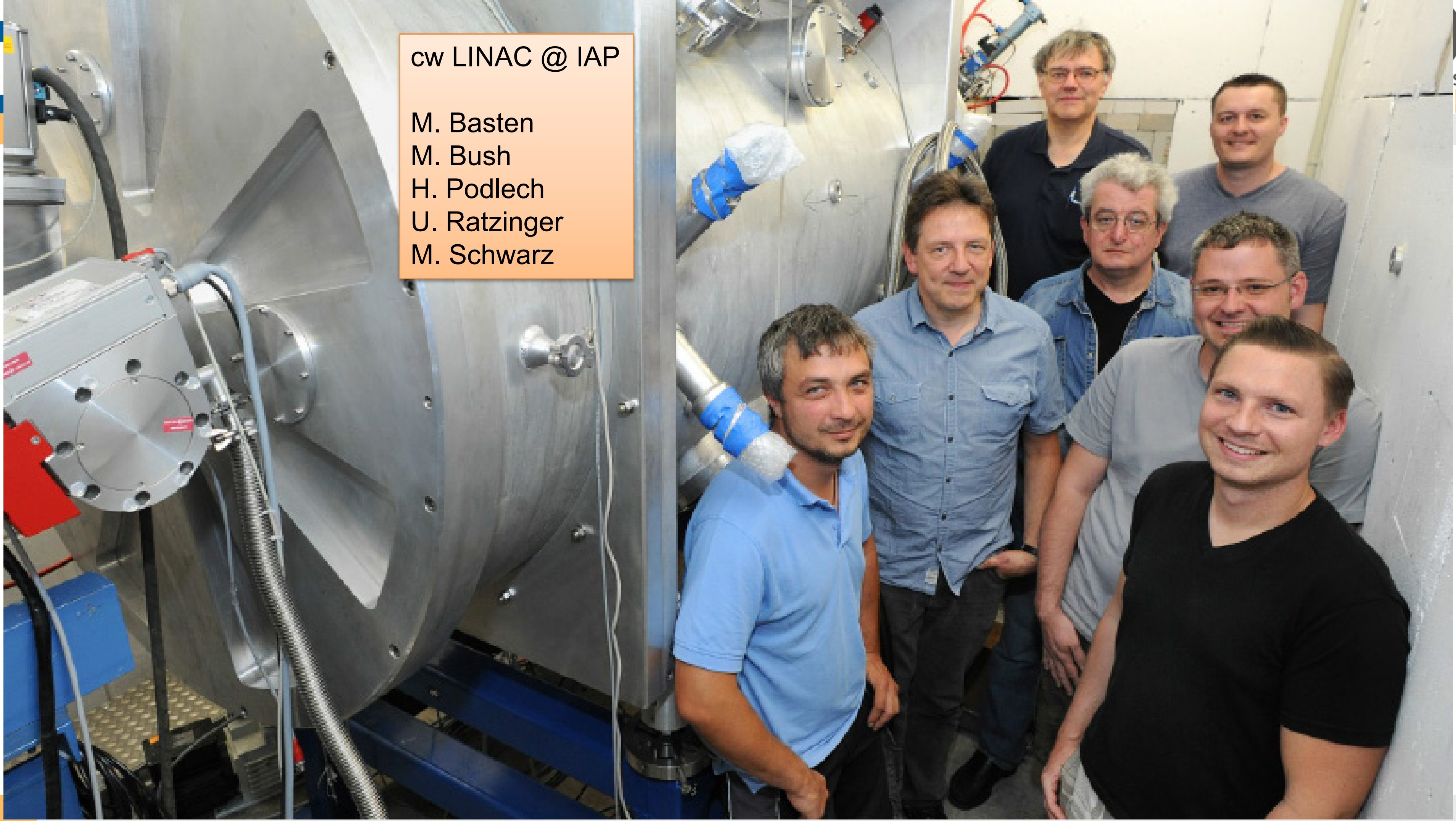
- HLI provides Ar^{11+}, Ar^{9+}, Ar^{6+}, He^{2+} @ 1,4 MeV/u
- Steering magnets
- Additional Re-Buncher
- Quadrupole doublet
- Profile Grid
- Phase probes for TOF measurement of beam energy (also as BPM)
- Beam current transformers for transmission measurement
- Bunch shape monitor (Feschenko monitor)
- Slit-Grid emittance measurement device
- 6d characterization of the beam
- Test Bench of components and procedures for future HELIAC

Beam Energy vs. RF-Phase and -Amplitude





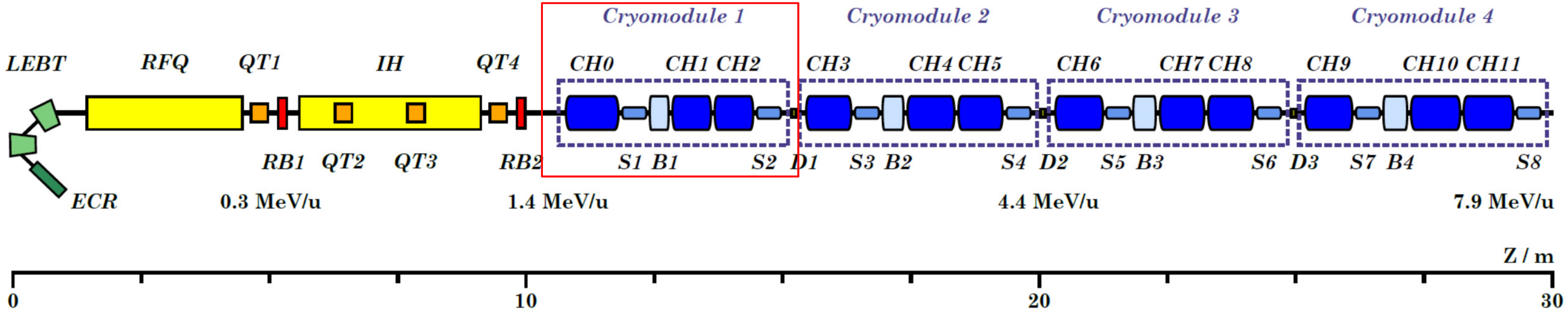
- Beam energy measured by TOF
- Independent rf-calibration of pick-up
- Accelerating field calculated by CST
- Amplitude of the field scaled according rf-calibration
- Energy gain calculated by tracking of particles in E-field
- Agreement between measurement and calculation
- Smooth energy variation
- High beam transmission



cw LINAC @ IAP

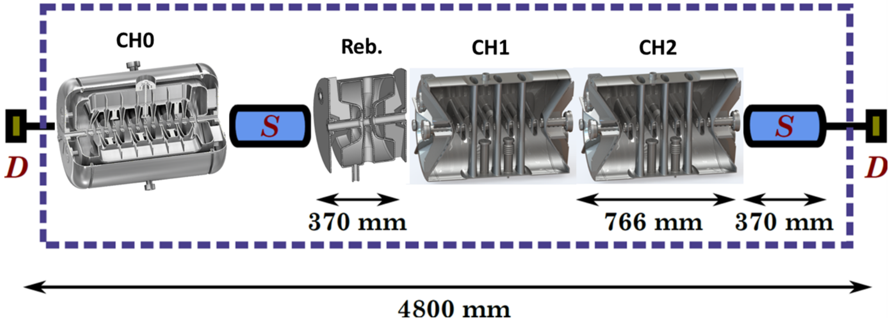
M. Basten
M. Bush
H. Podlech
U. Ratzinger
M. Schwarz

Next Phase: Advanced Demonstrator



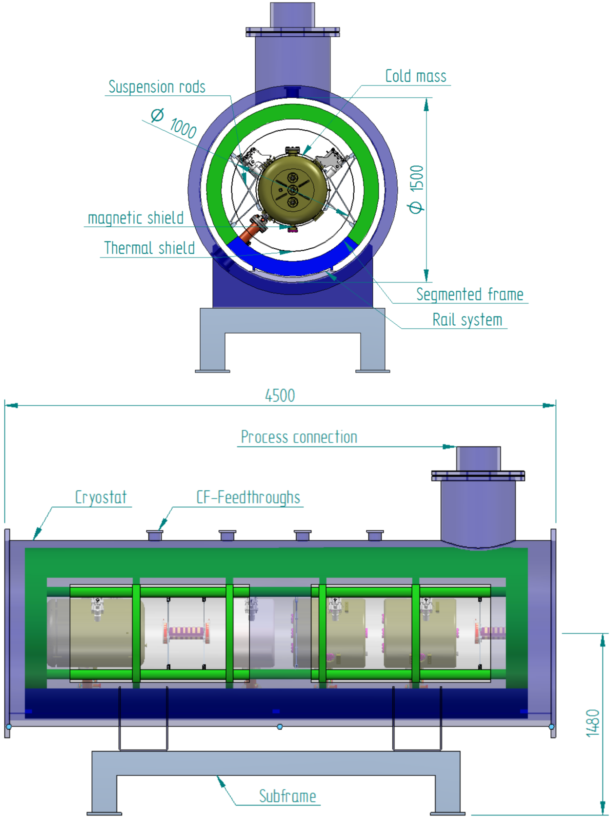
Next Phase: Advanced Demonstrator

Standard cryomodule layout



- New cryo module layout containing demonstrator CH cavity, 2 short CH cavities, 1 re-buncher and 2 solenoids
- Simplified cavity design (easier manufacturing & surface processing)
- CH1 & CH2 are already in testing (delivery at 4th quarter of 2019)
- Re-buncher cavity is designed and Nb material is ordered
- Cryostat is ordered, expected delivery Q2 2020
- Solenoids are tendered
- 4 rf Amplifiers are tendered
- R&D on single aux. components is in advanced stadium
  - Rf-power couplers
  - Tuner mechanics
  - cold BPM
  - low level rf
  - New radiation protection shelter
- Connection to cryoplant

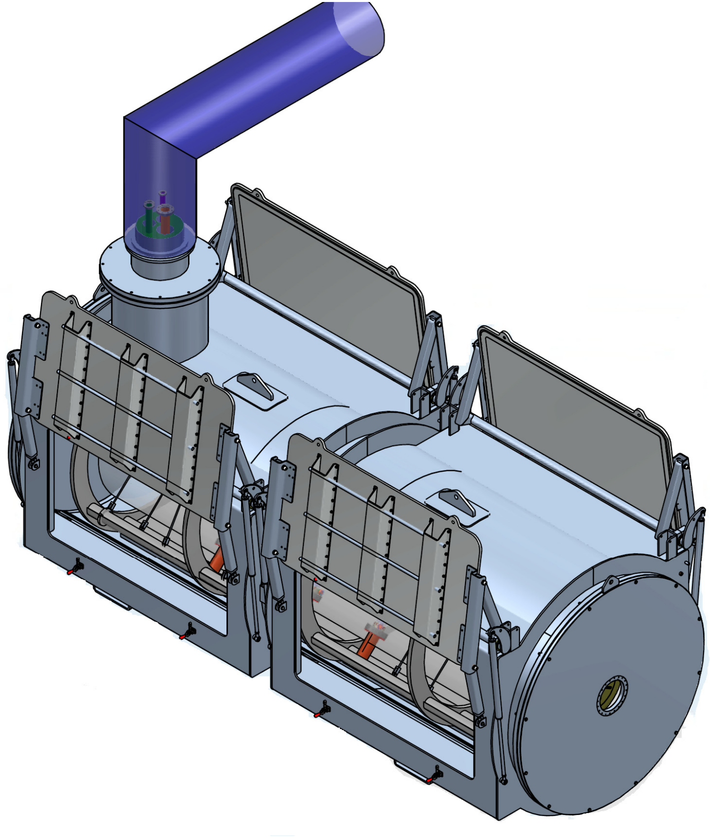
New Cryomodule Layout



Design features & improvements

- 4 rectangular service doors
- On site alignment of each component to the beam line with a laser tracker
- Assembly of RF power couplers and solenoid current leads through the doors
- Nuclotron suspension of single components
- Segmented support frame, mechanically and thermally coupled to outer tank (300 K)
- Thermal shield inside of support frame
- Segmented frame standing on dedicated points of the bottom of the cryostat
- Deformations of outer vessel during evacuation do not affect the position of the frame
- Trans. position of each component will be preserved within ± 0.1 mm during cool down

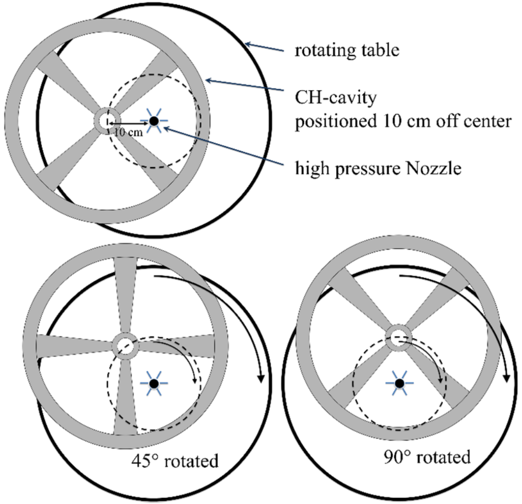
New Cryomodule Layout



- Already ordered, expected delivery in 04/2020
- Built by Cryoworld, Advanced Cryogenic, Netherlands

CRYOMODULE CM1		
Inner length	mm	4500
Inner diameter	mm	1500
Material vessel		Stainless steel 1.4404
Insulating vacuum	mbar	$< 1 \cdot 10^{-6}$
Max. system pressure	bar	< 0.5
Operating temperature	K	4.2
Temperature thermal shield	K	40
Max. static losses (stand by)	W	< 5

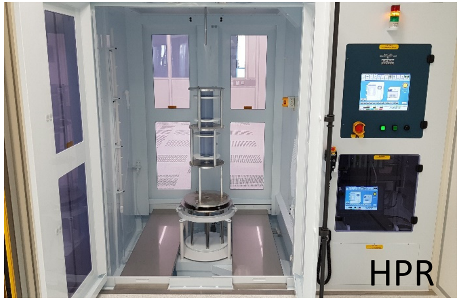
Infrastructure @ HIM



Infrastructure in Mainz:

- Clean room environment
- Cavity bakeout 120°C
- High Pressure Rinsing
- Rail system for string assembly
- Setup for cavity RF testing at 4 K and 2 K
- Further improvement of cavity performance

Rinsing off axis



Outlook

02/2015	Funding of the Advanced Demonstrator within POF3
09/2016	Ordering of two short CH-cavities
11/2018	Tendering of cryostat
05/2019	Modification of radiation protection shelter @GSI
10/2019	Delivery of short cavities
12/2019	Link of testing area to STF cryoplant
04/2020	Delivery of cryostat
04/2021	Assembly of cryomodule @ HIM
10/2021	Beamtest @ GSI

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