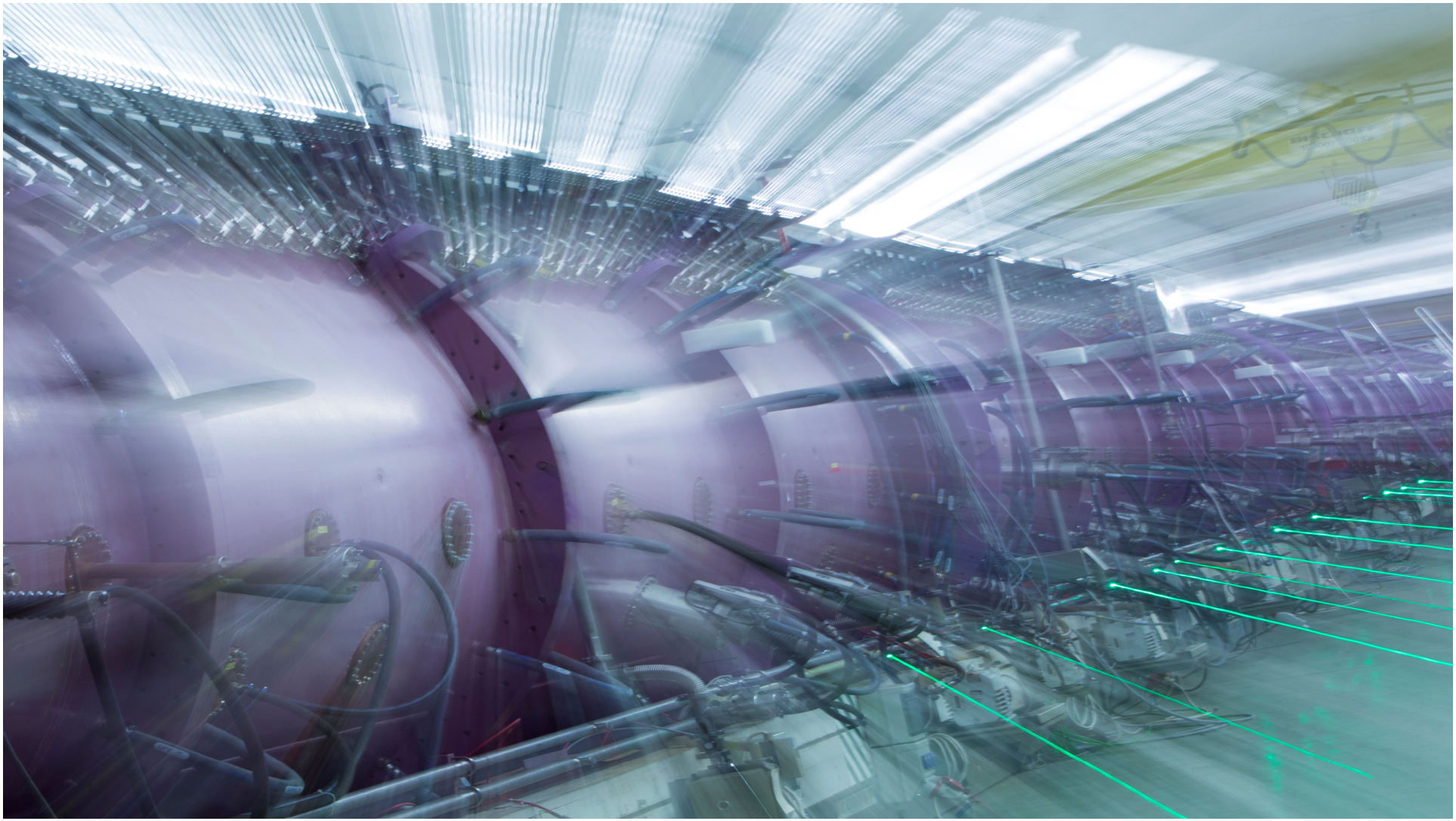


First Acceleration of Heavy Ion Beams with a Superconducting Continous Wave HIM/GSI-Linac

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

[1] Helmholtz Institut Mainz, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[3] Johannes Gutenberg-Universität Mainz, Mainz, Germany
[4] IAP Goethe-Universität Frankfurt, Frankfurt, Germany

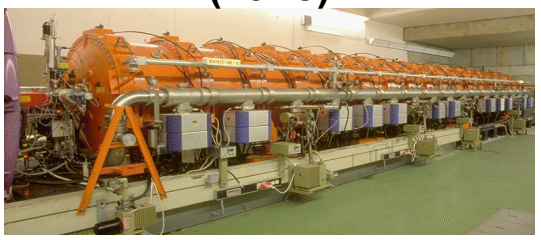
Introduction
GSI UNIversal Linear ACcelerator

High Charge State Injector (1991)

High Current Injector (1999)

Alvarez (1975)

Single Gap Resonators (1975)



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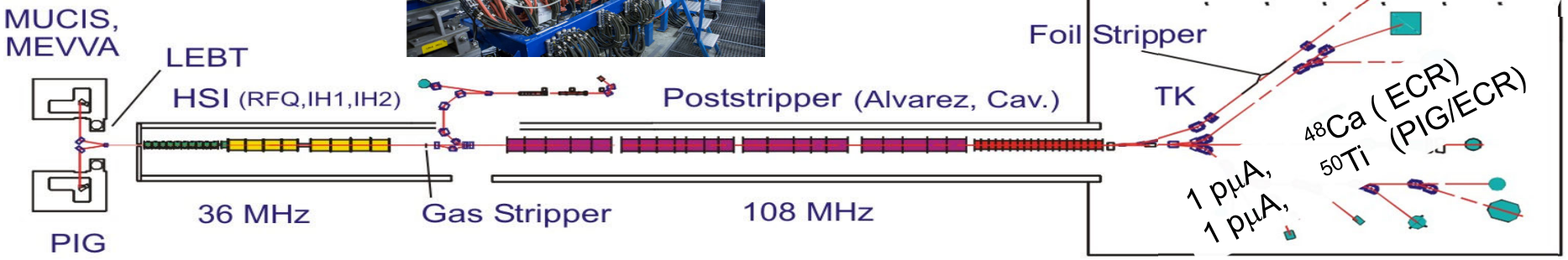

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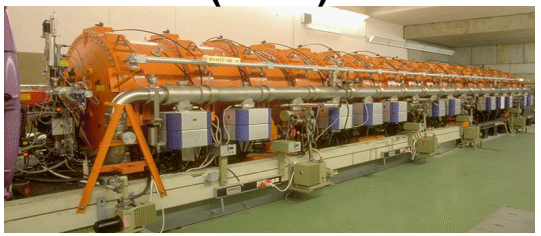
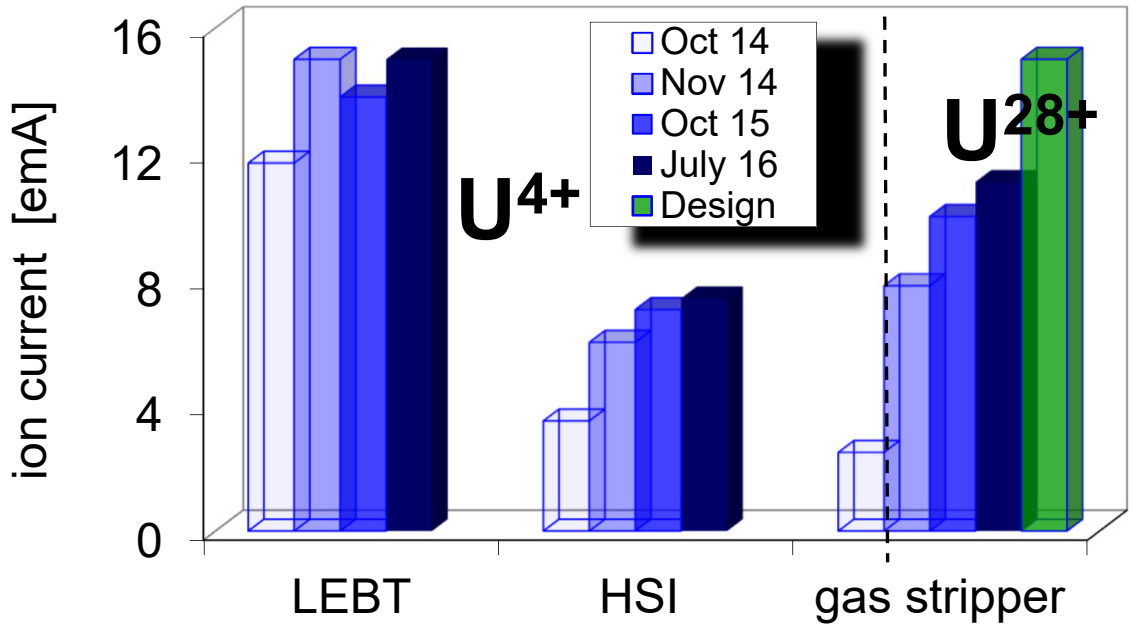
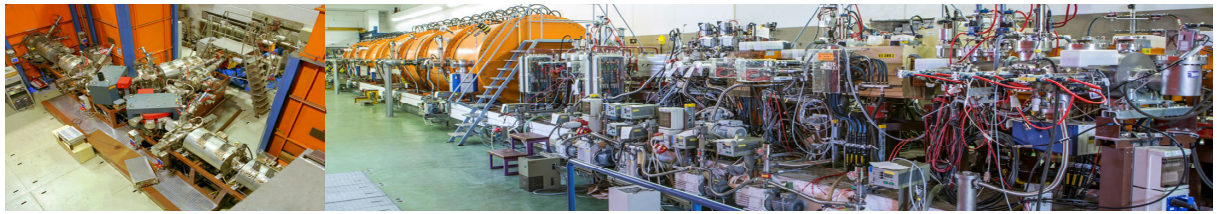


Status “UNILAC Uran-High Current”



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)

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- high repetition rate (50 Hz)
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“Super Heavy Element”:

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- high repetition rate (50 Hz)
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“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

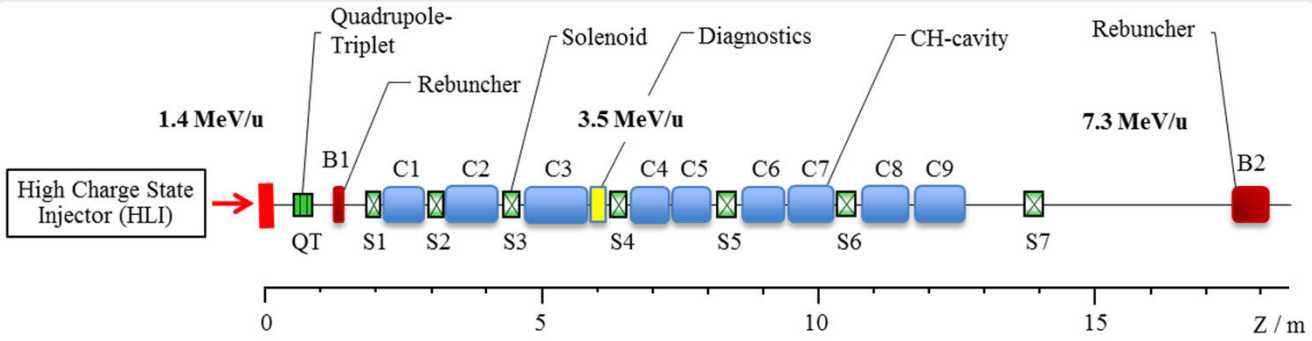
Nuclear reactions at the Coulomb-barrier→ production of Super Heavy Elements (SHE)

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

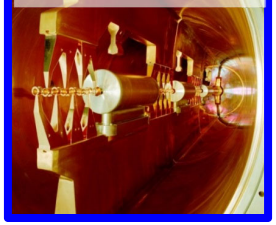
General Heavy Ion cw-Linac layout



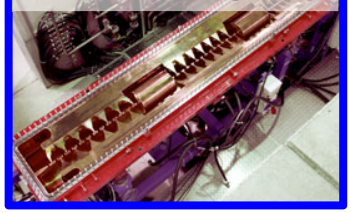
Mass/Charge		6
Frequency	MHz	216.816
Max. beam current	mA	1
Injection Energy	MeV/u	1.4
Output energy	MeV/u	3.5 – 7.3
Output energy spread	keV/u	±3
Length of acceleration	m	12.7
Sc CH-cavities	#	9
Sc solenoids	#	7

H-type Cavity developments

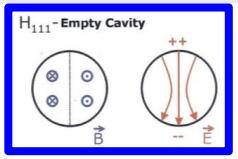
HSI 36 MHz@gsi

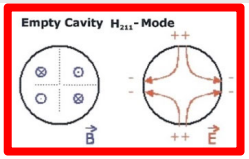


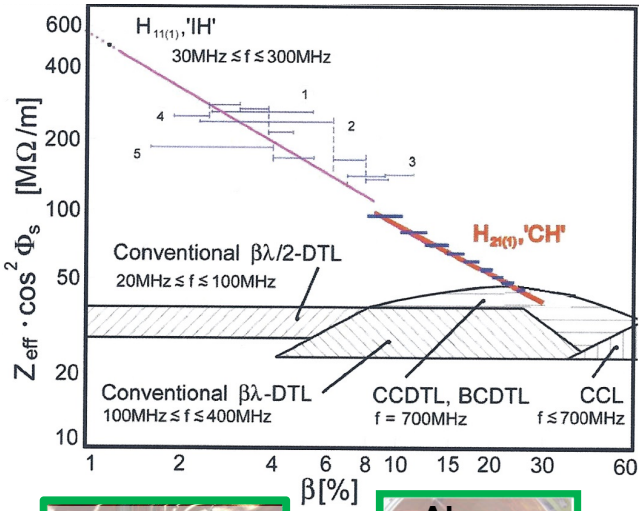
HLI 108 MHz@gsi



IH 216 MHz@HIT/Heidelberg

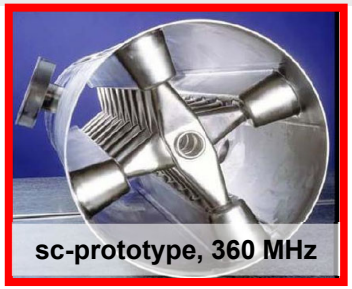






Wideröe

Alvarez



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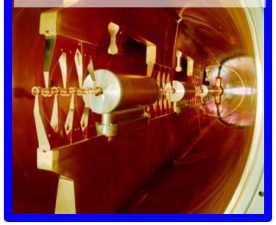

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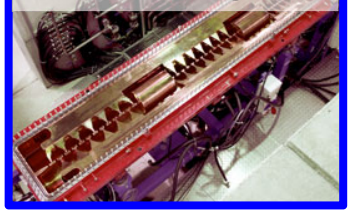

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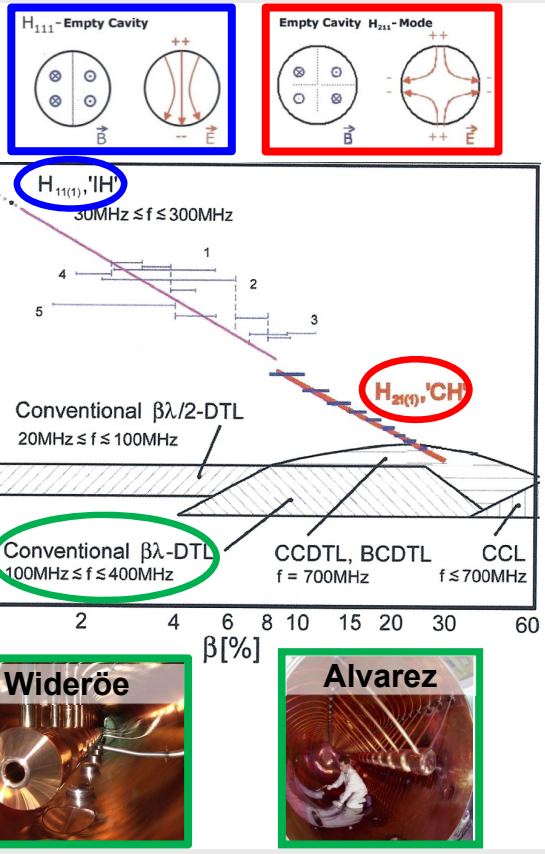
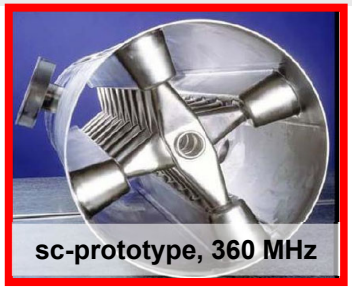


Wideröe

Alvarez

sc-prototype, 360 MHz

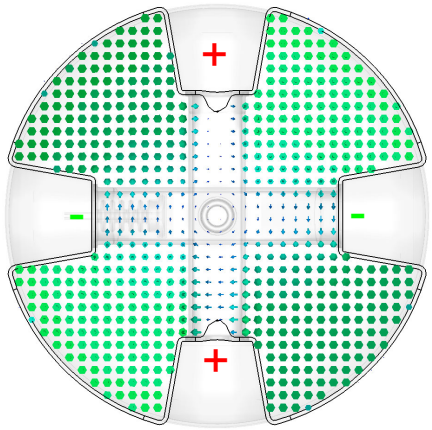


sc-booster cavity, 325 MHz

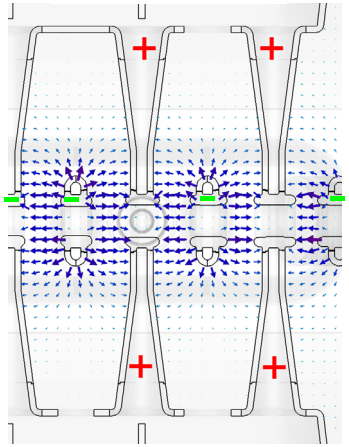
rt-325 MHz

CH-cavity: Field profiles

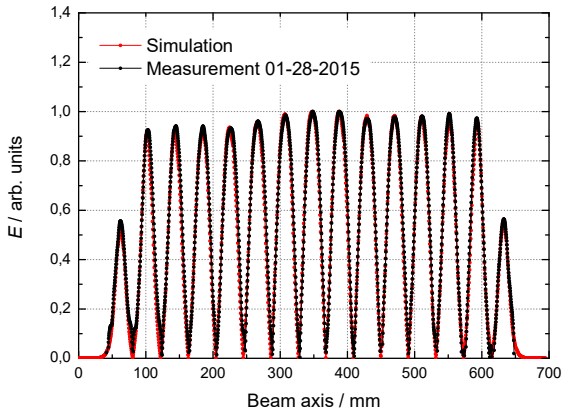
H field



E field



E field along beam axis

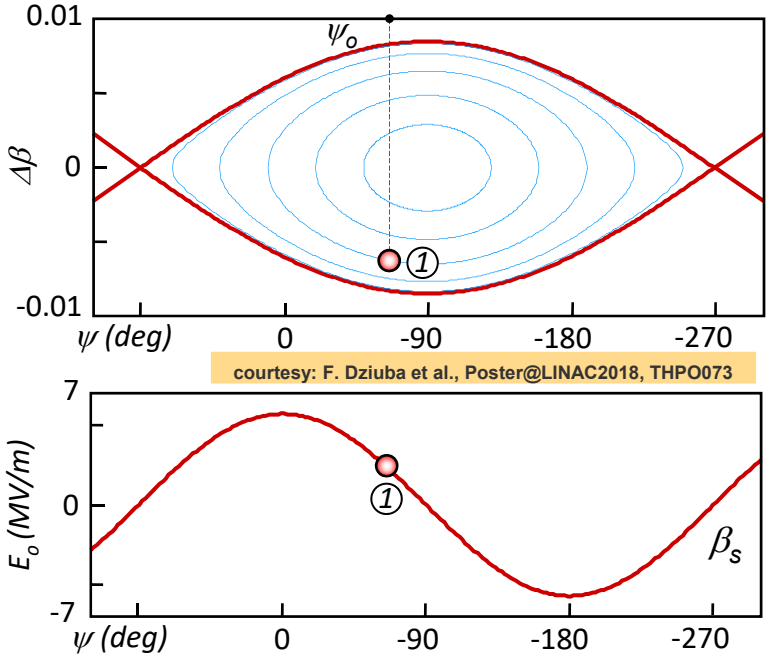


- Multigap drift tube cavity for the acceleration of protons and ions in the low and medium energy range
- Drift tubes are alternating connected to "+" and "-" potential
- **C**ross-bar-**H**-mode cavity → CH cavity
- Equidistant drift tubes length → special beam dynamics

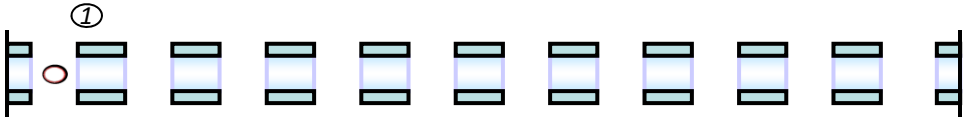
EQUUS beam dynamics concept

EQUUS - EQUidistant mUltigap Structure

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



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



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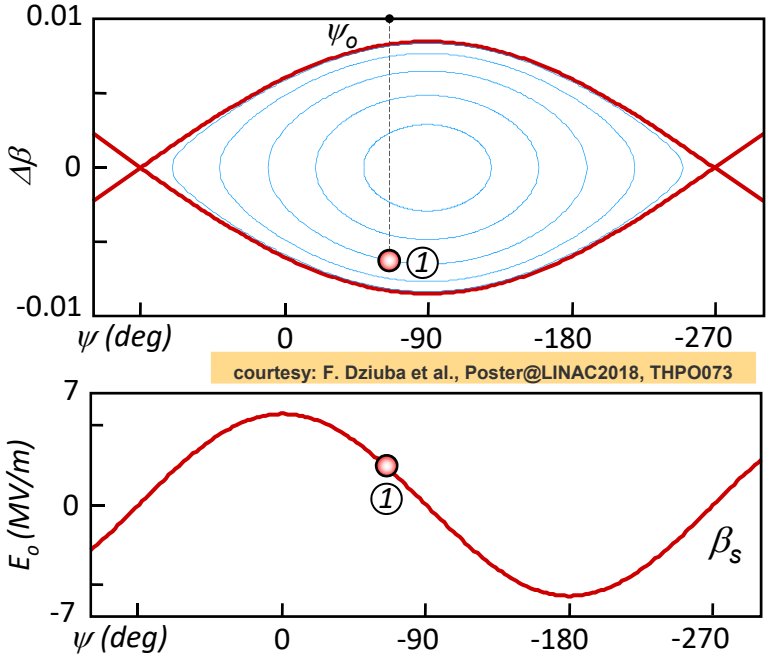

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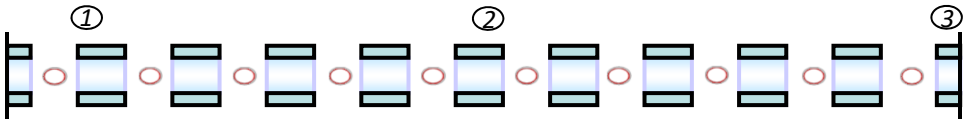

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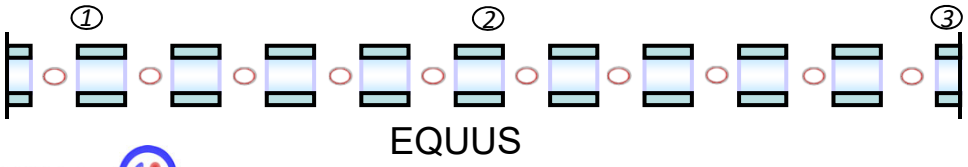

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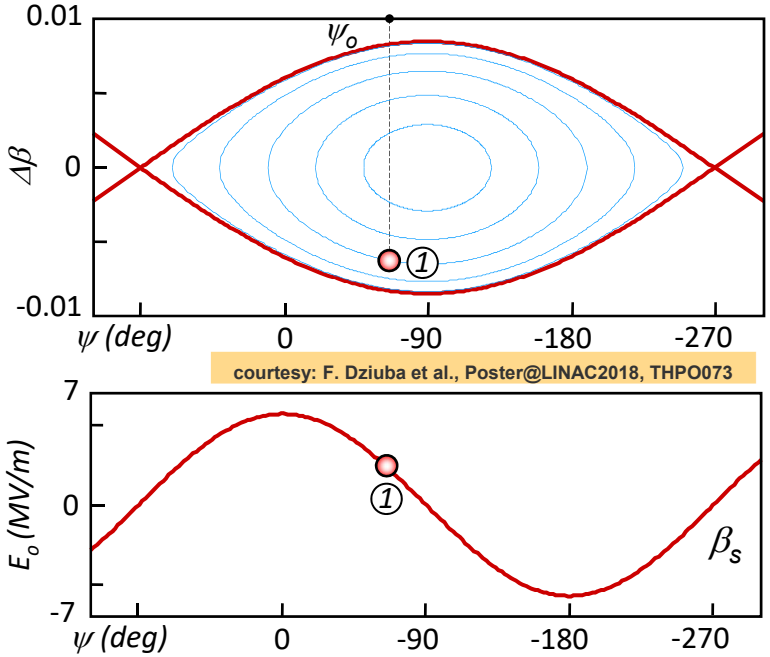

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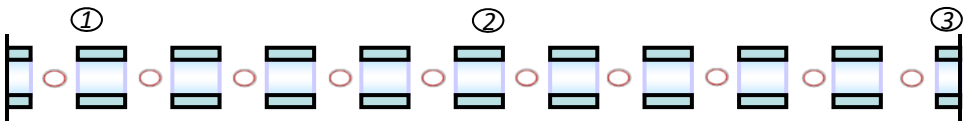

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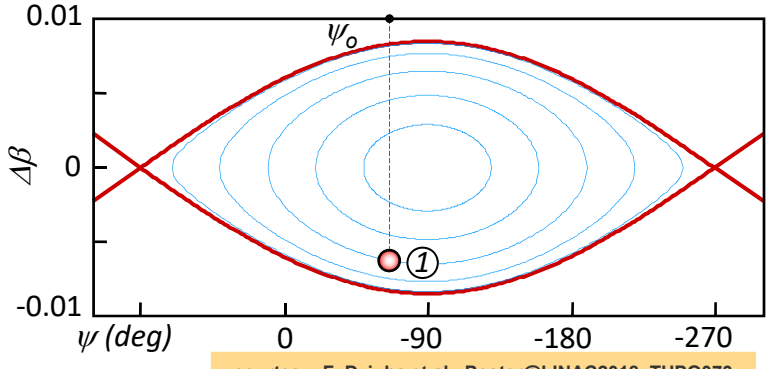

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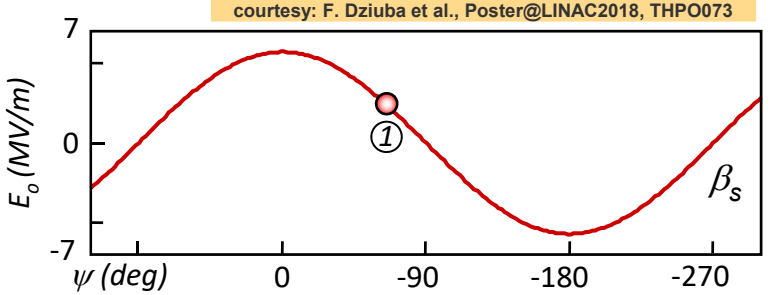

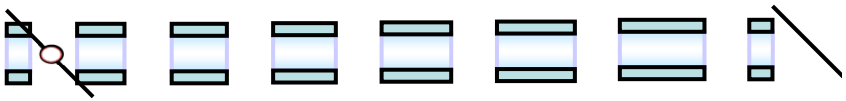

Resonant acceleration at φ=-30

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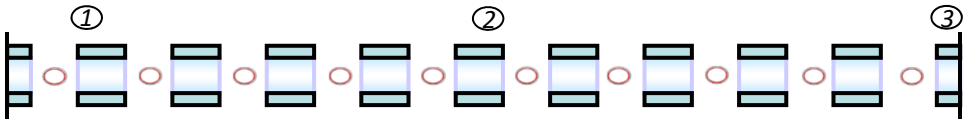

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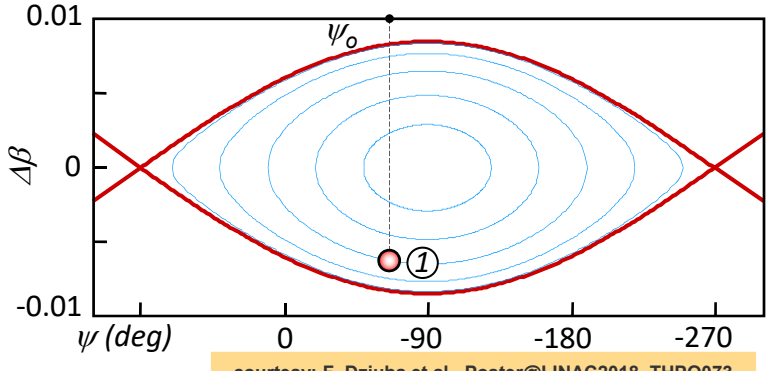

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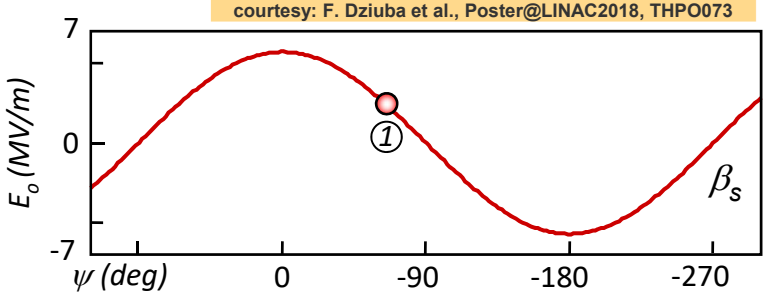

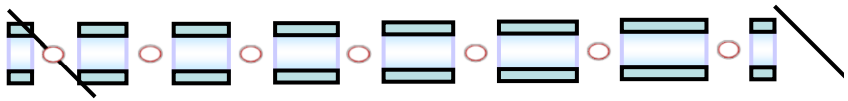

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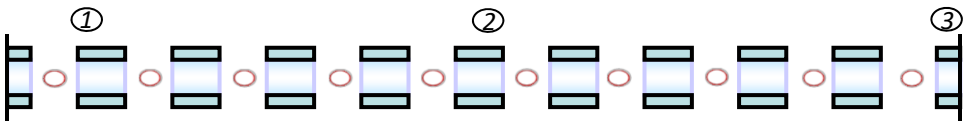

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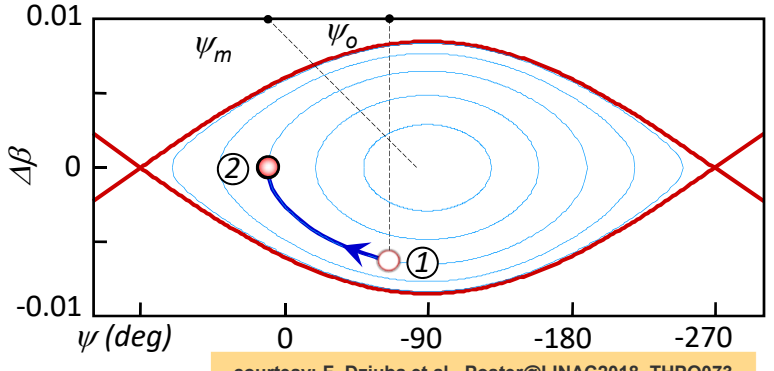

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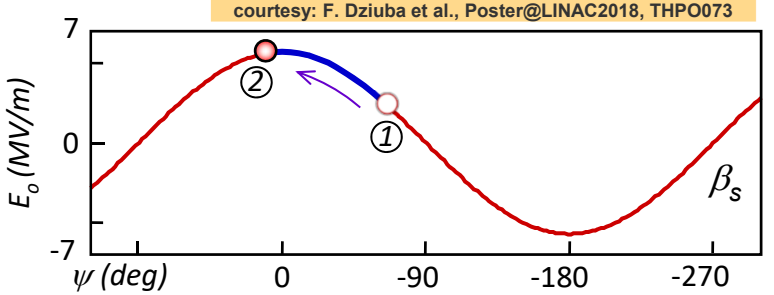

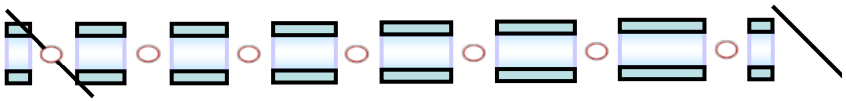

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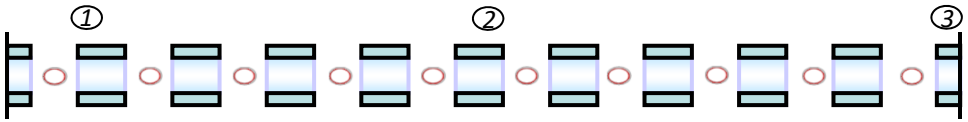

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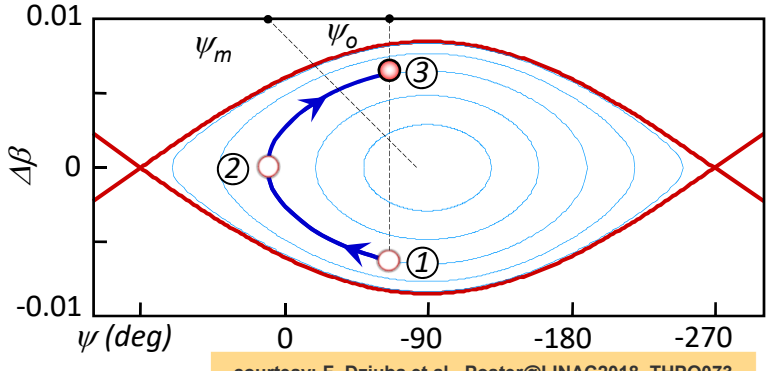

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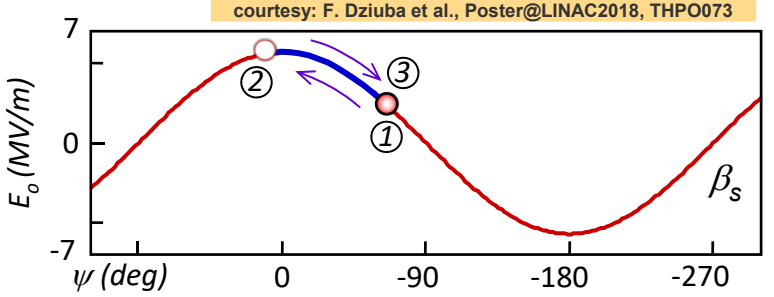
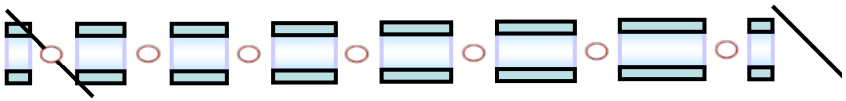


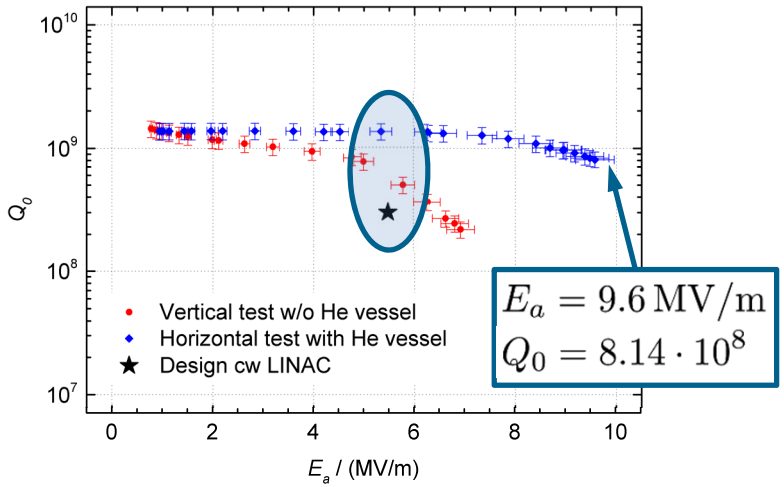


Resonant acceleration at φ=-30

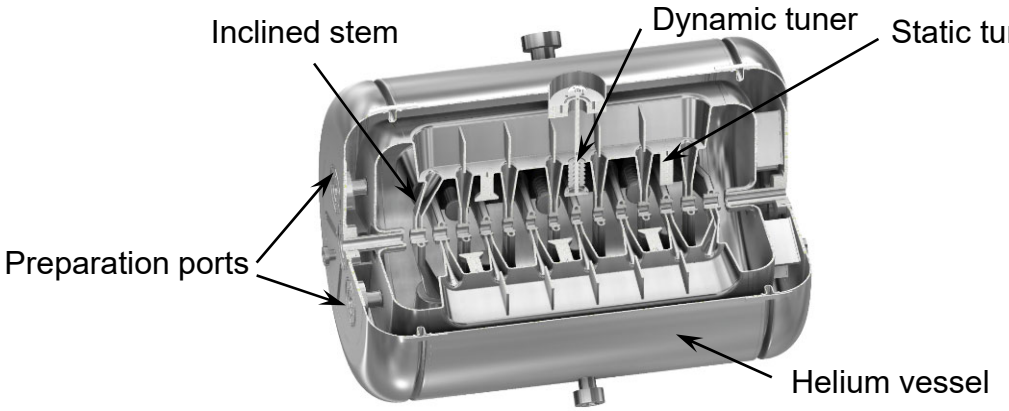
RF Testing of the CH-Cavity (10/2016)

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

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



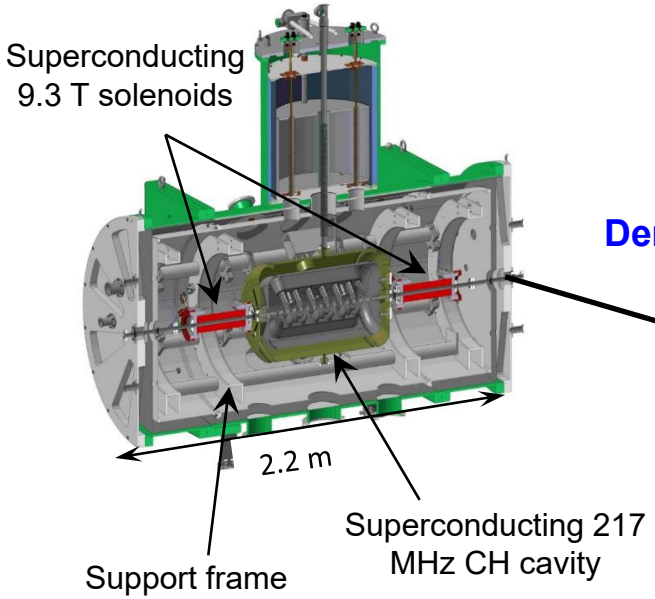
- Improved performance (add. HPR)
- Low field emission rate
- High field gradient
- Therm. quenching beyond 9.6 MV/m



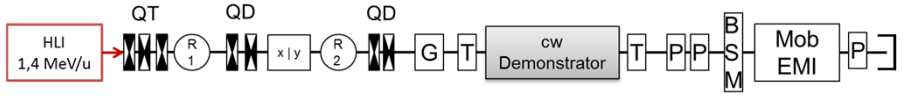
		Vertical test w/o He vessel	Horizontal test with He vessel
Q_0^{low}		$1.44 \cdot 10^9$	$1.37 \cdot 10^9$
R_S	nΩ	36	38
R_{BCS}	nΩ	15	15
R_{mag}	nΩ	9	12
R_0	nΩ	12	11
E_a	MV/m	6.9	9.6
Q_0		$2.19 \cdot 10^8$	$8.14 \cdot 10^8$
V_a	MV	4.2	5.9
E_p	MV/m	43	60
B_p	mT	39	55

Experimental setup of the demonstrator at GSI

Layout of the horizontal cryomodule



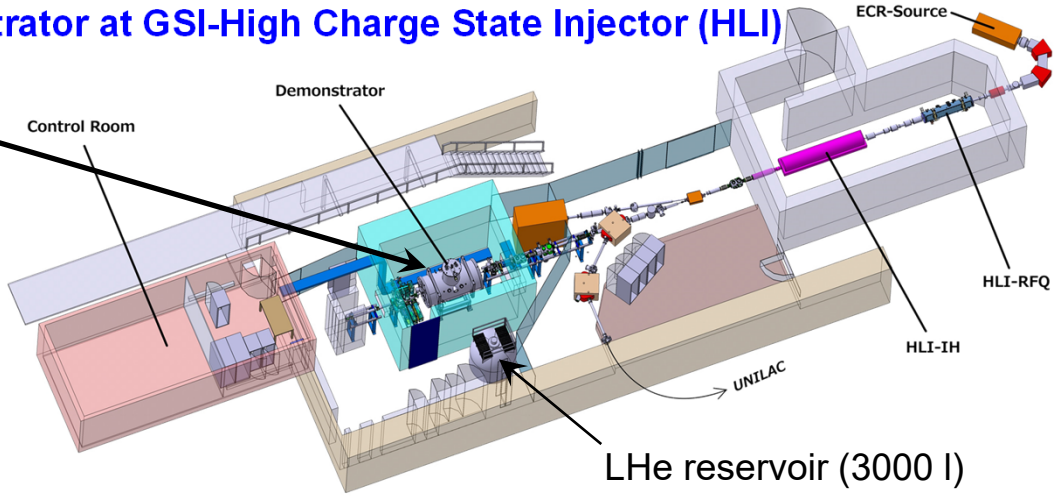
Matching line - demonstrator – test bench



- Steering magnets
- Rebuncher
- Quadrupole doublet
- Profile grids

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

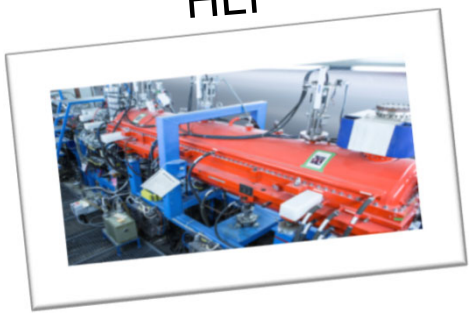
Demonstrator at GSI-High Charge State Injector (HLI)

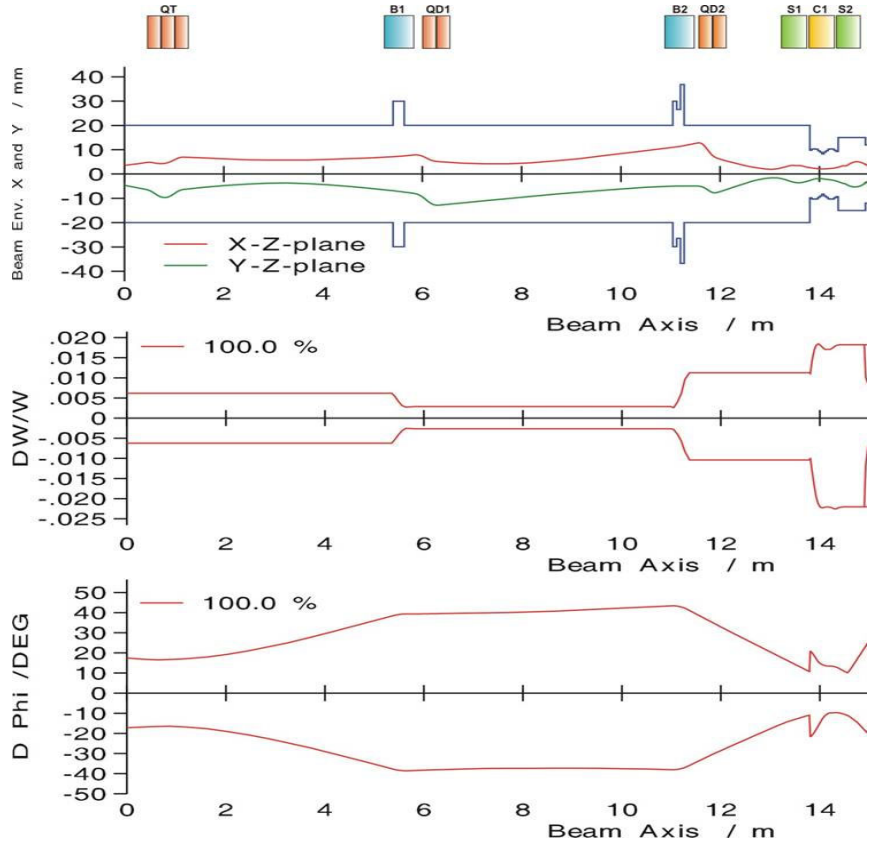



June 2017
First beam test
DOI: 10.1103/PhysRevAccelBeams.21.020102

Matching the cw-Linac Demonstrator

HLI

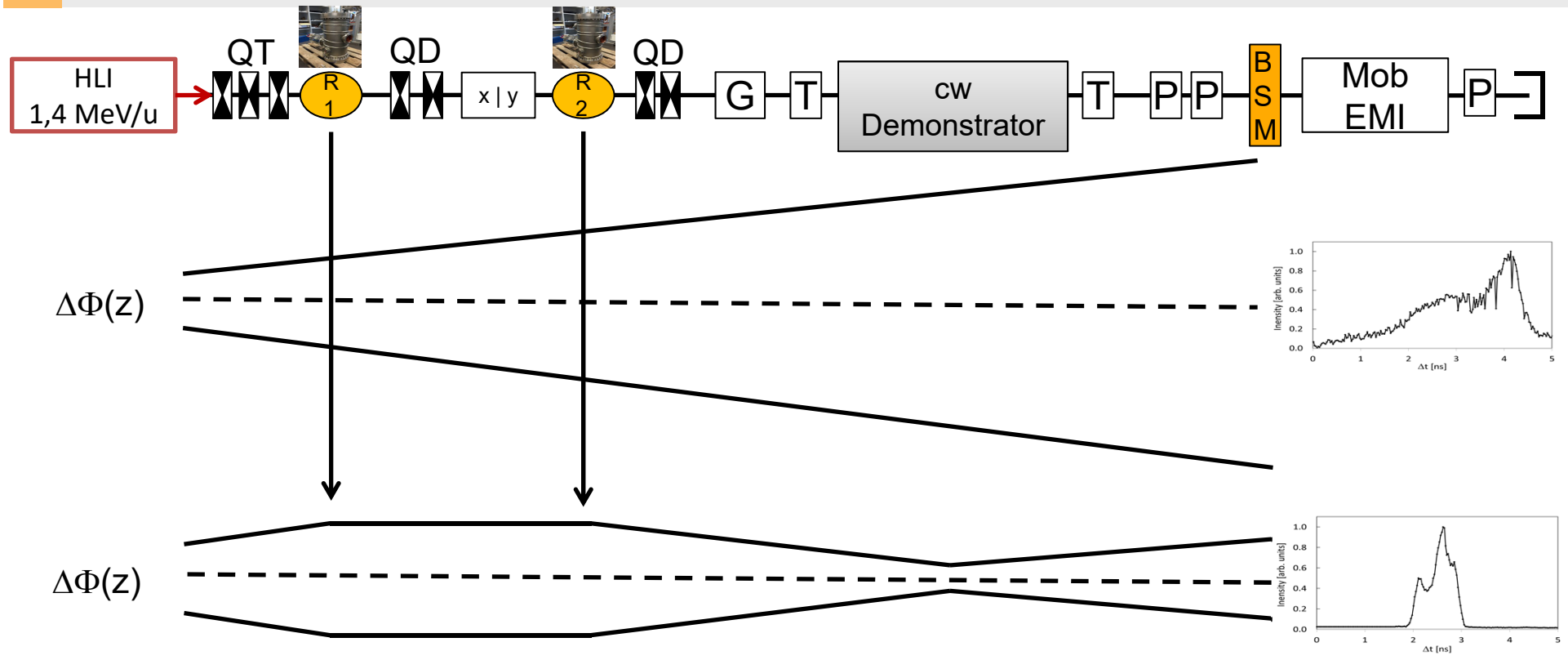




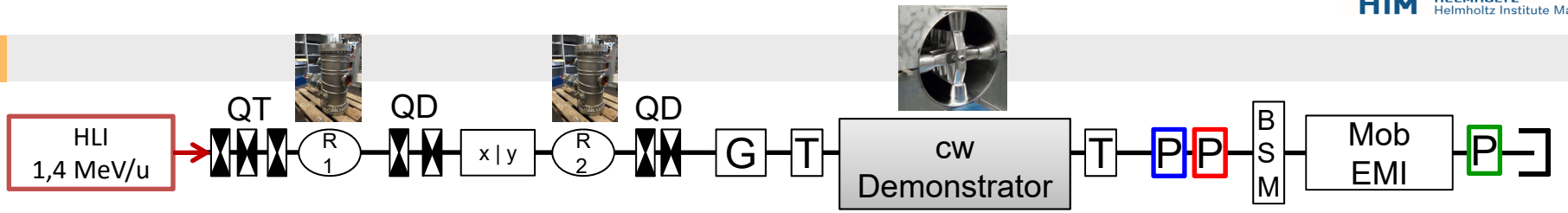
cryostat

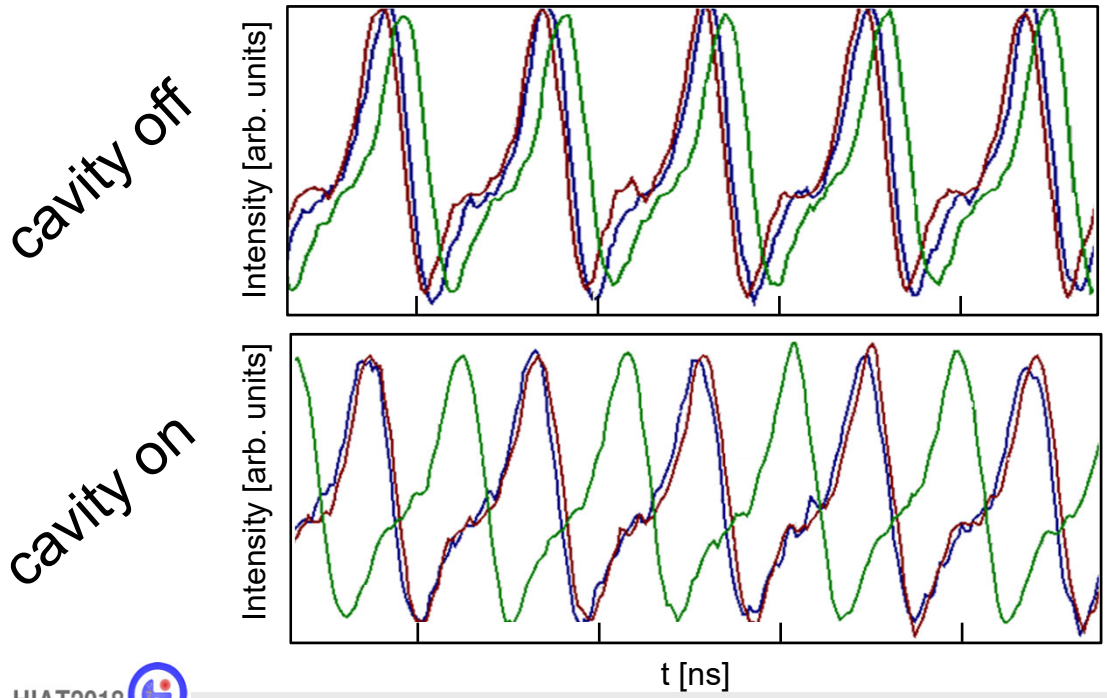
courtesy: A. Rubin, *Proc of IPAC'13*

Longitudinal matching



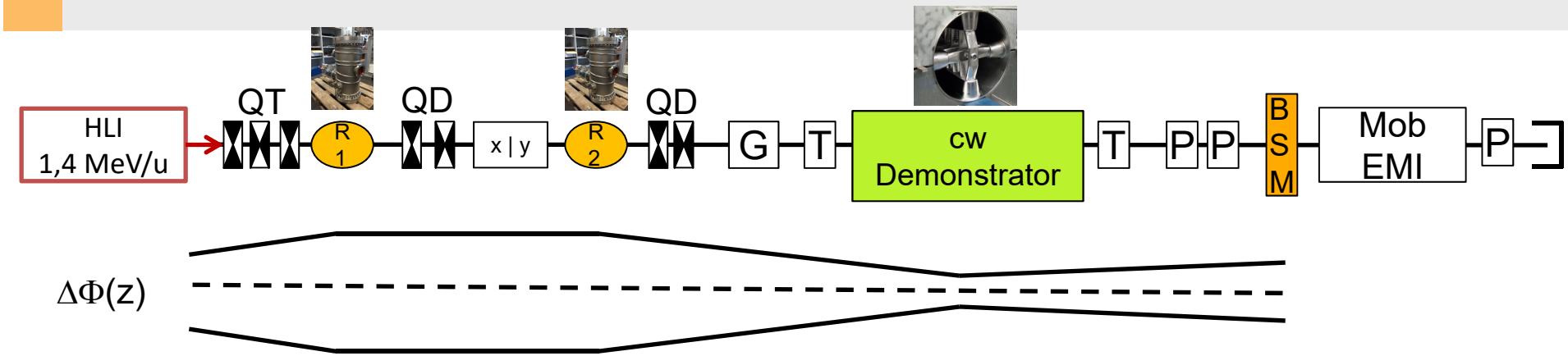
First Acceleration



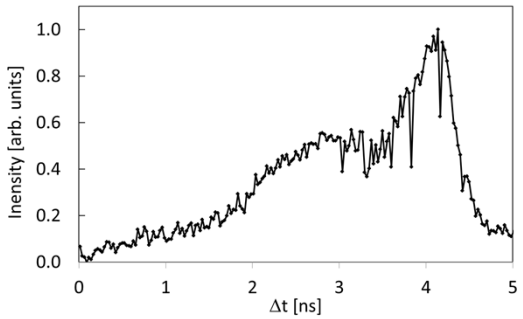


- Measurement of transient signal induced by traveling bunch
- Acceleration! Energy gain of 0.5 MeV/u
- → systematic scan of rf-phase and amplitude

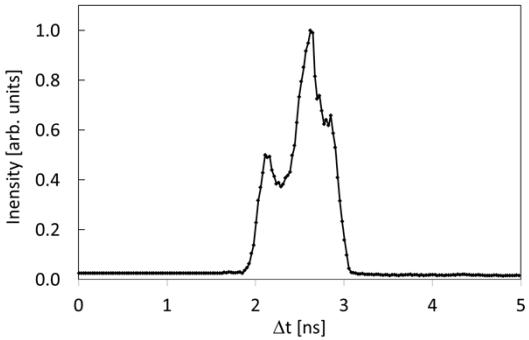
Bunch structure measurement



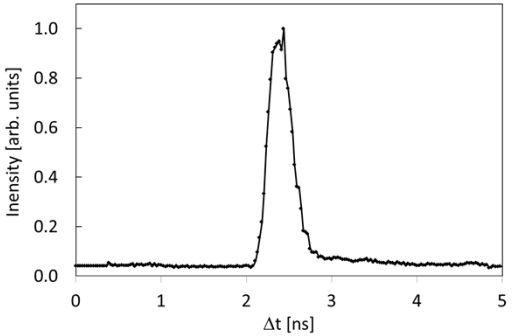
cavities off



R1 + R2



R1 + R2 + CH0

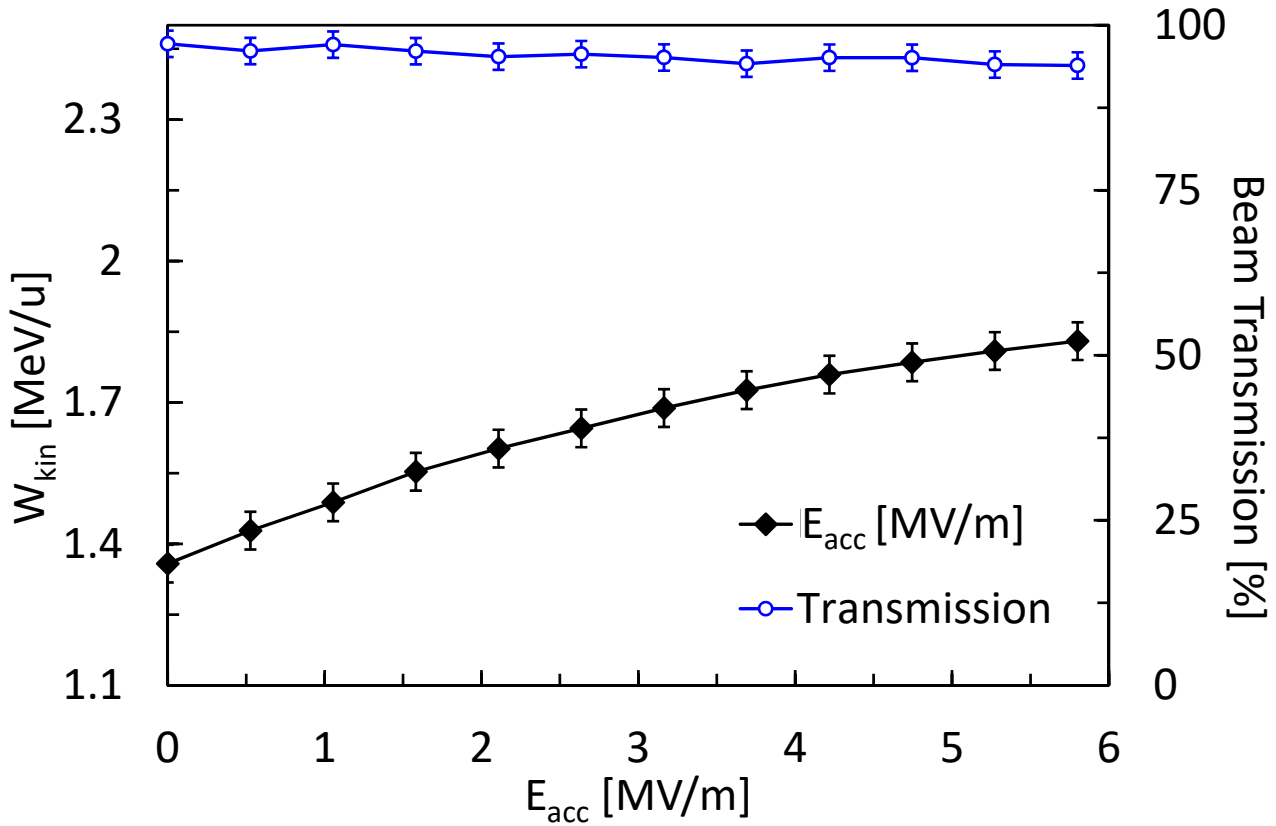


RF-parameter (matched case)

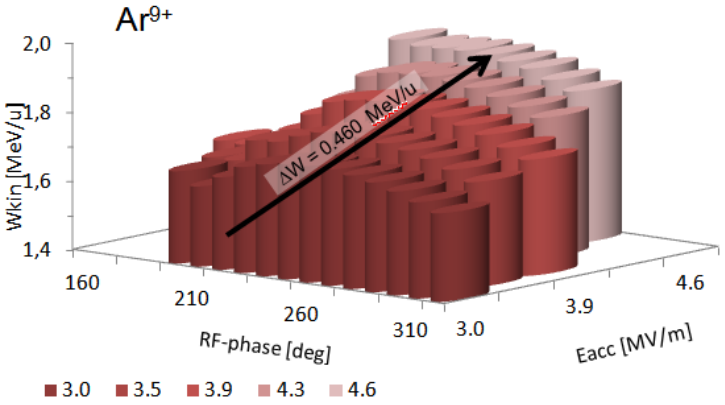
	He^{2+}	Ar^{11+}	Ar^{9+}	Ar^{6+}
A/q	*2.0*	*3.6*	*4.4*	*6.7*
$U_{Reb1,eff.}$ [kV]	8.3	15.0	18.3	27.9
$U_{Reb2,eff.}$ [kV]	22.7	40.8	49.9	75.9
$E_{acc,CH}$*[MV/m]	1.8	3.2	3.9	5.9
U_0 [MV]	1.2	2.2	2.7	4.0

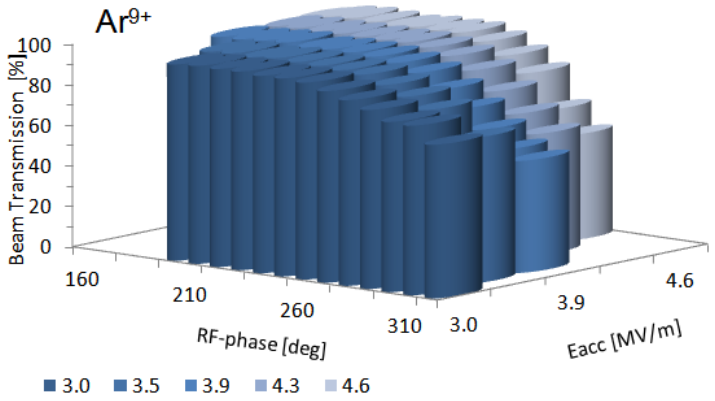
* E_{acc} = *transit time factor* × *total accelerating voltage*/($n \times 0.5 \times \beta\lambda$)

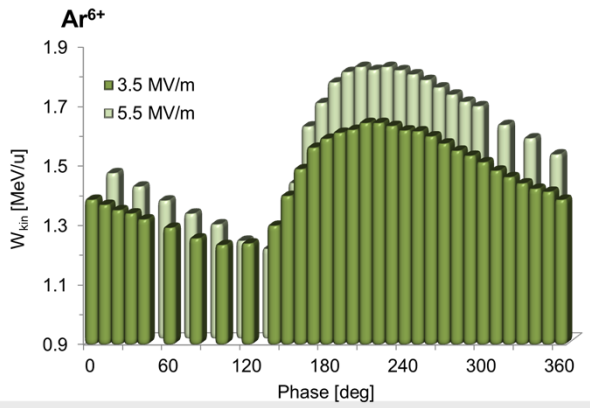
Amplituden-scan

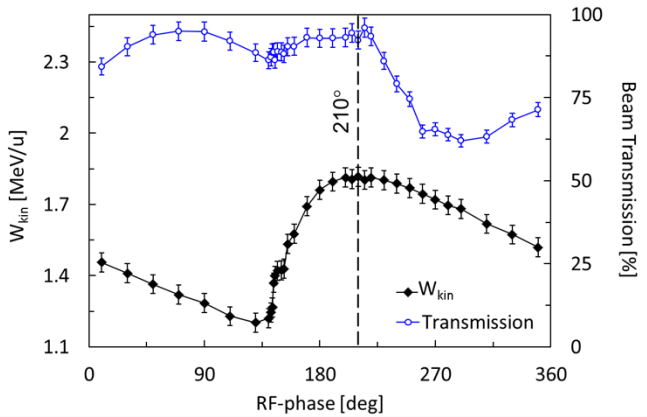


Systematic Scans (RF-phase/-amplitude)

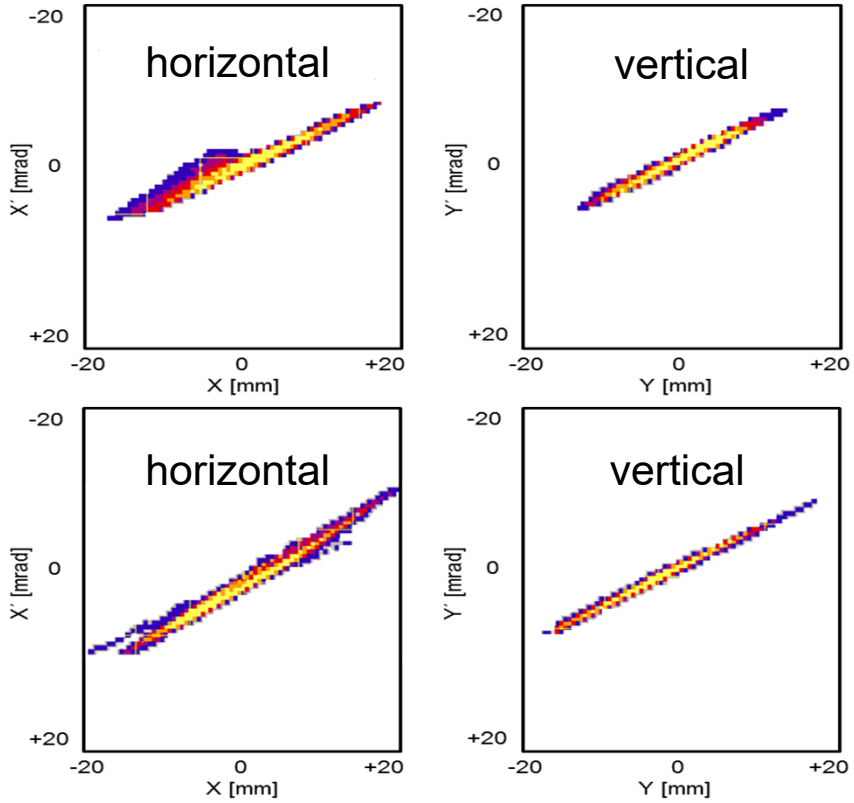








Emittance measurement



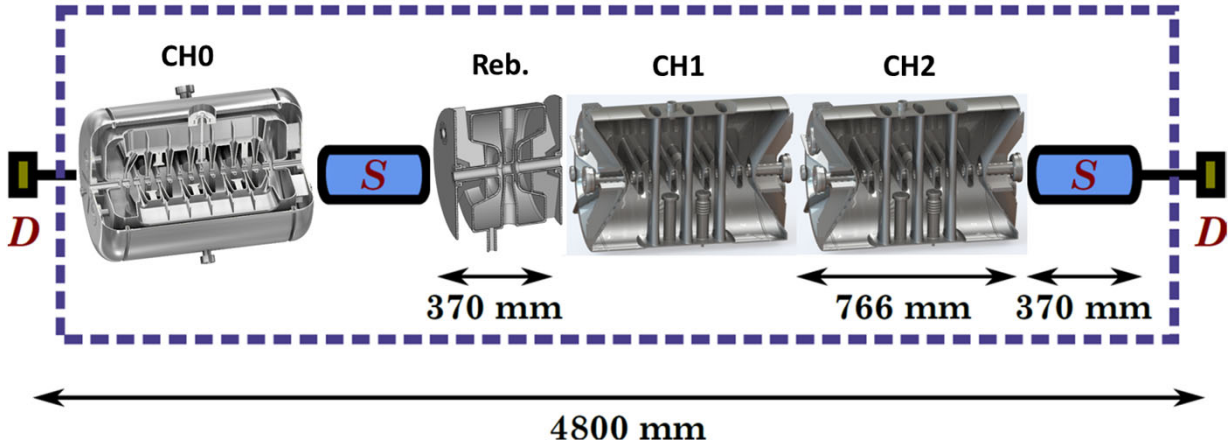
1.40 MeV/u

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

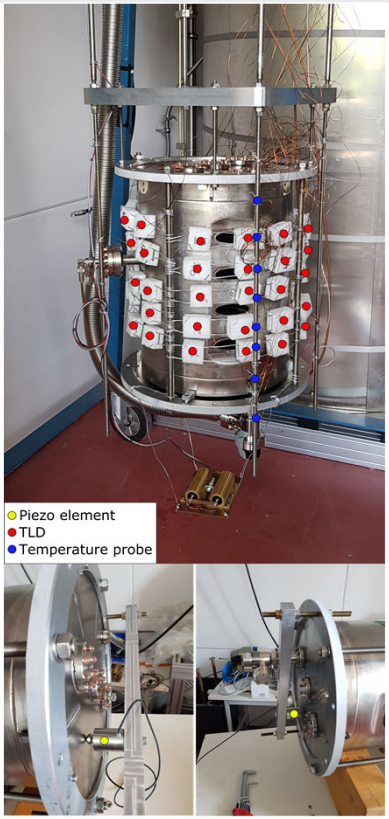
Advanced Demonstrator

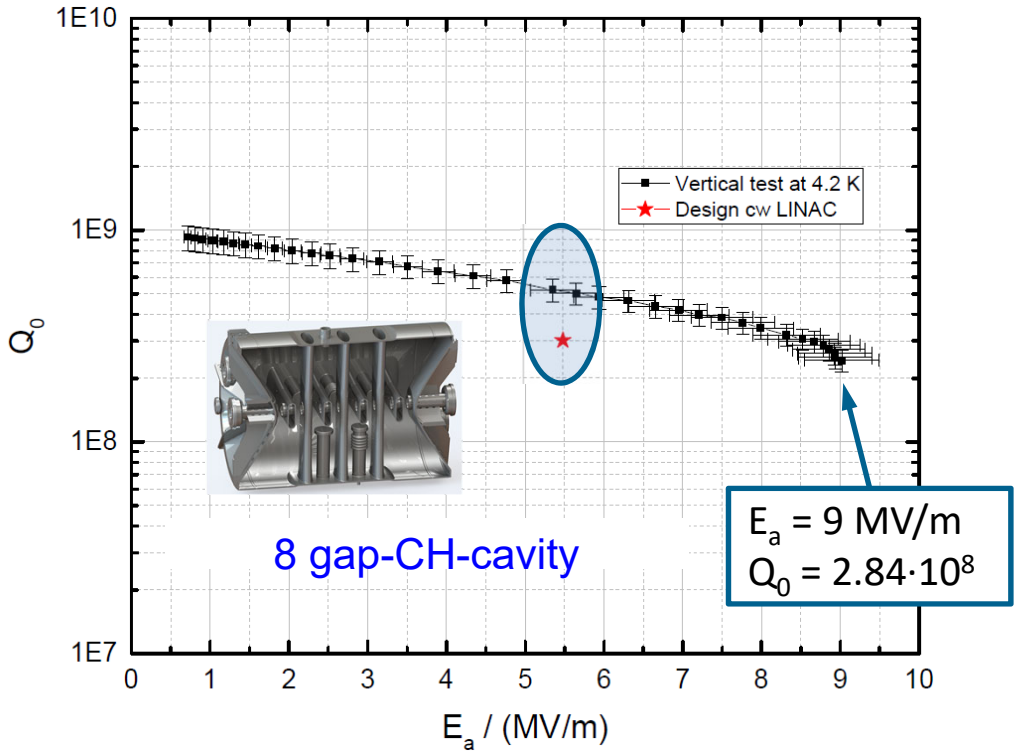
Standard cryomodule layout



- 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 produced and the first one has already been tested in the middle of 2018
- Tendering for cryostat at 3rd quarter of 2018
- Moderate increase of design gradient → more compact linac design or higher A/q

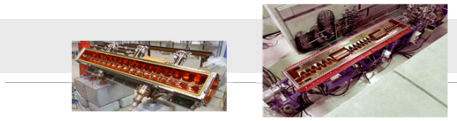
First RF-measurement for CH1 in a vertical cryostat

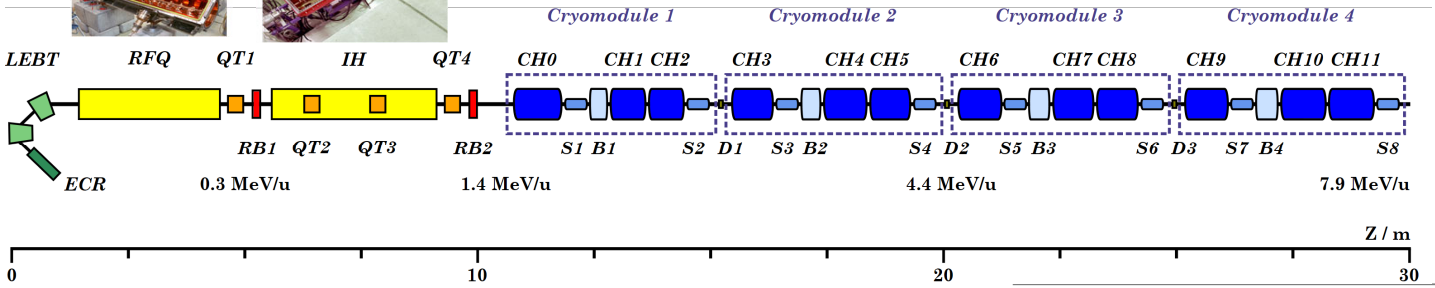




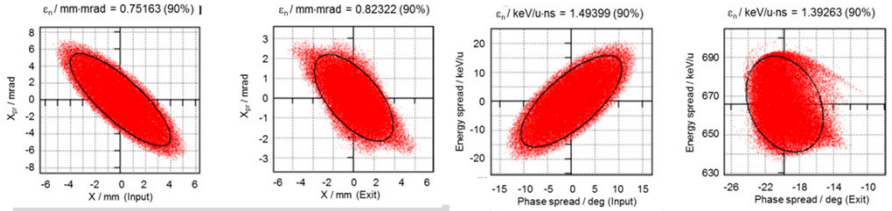
courtesy: M. Basten et al., Poster@LINAC2018, THPO072

Current cw-Linac Layout





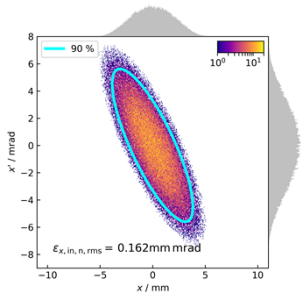
Input CM1 Output CM4

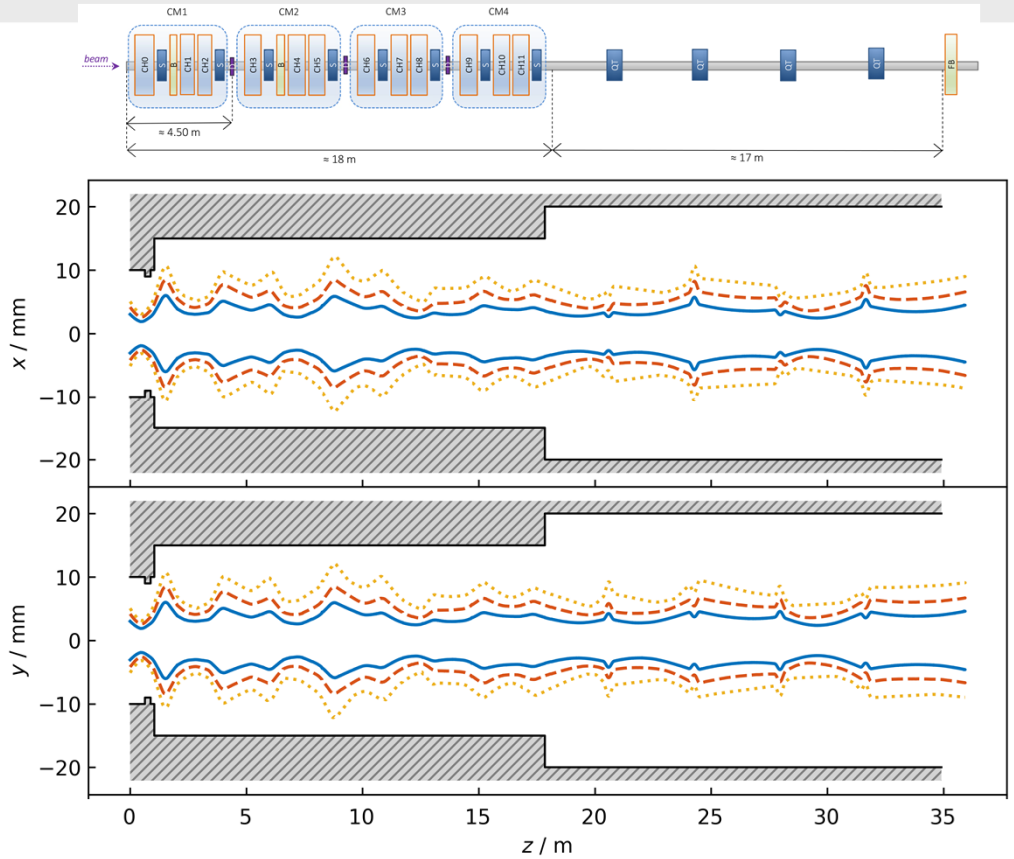


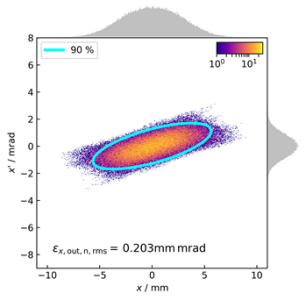
- Total of 12 CH cavities
- Each cryo module contains 3 CH cavities + 1 rebuncher + 2 solenoids
- Variable beam energy 3.6-7.5 MeV/u

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

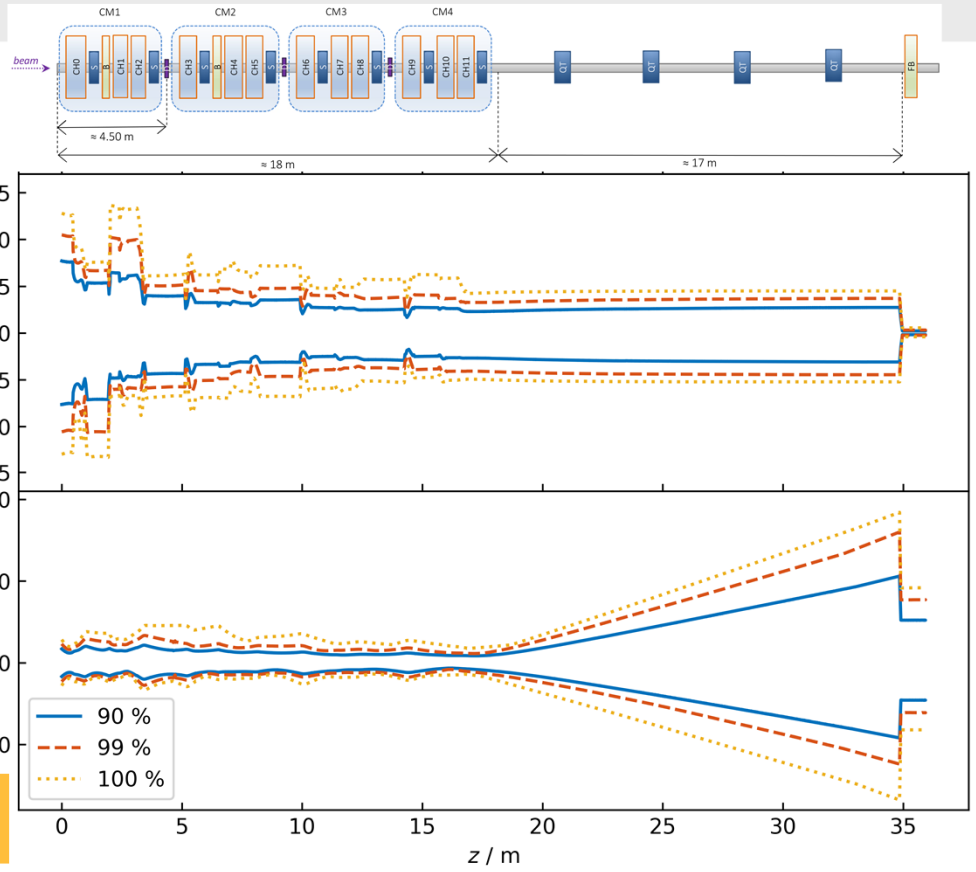




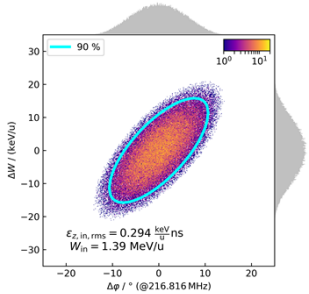


Courtesy: M. Schwarz, et al., Poster@LINAC2018, TUPO084

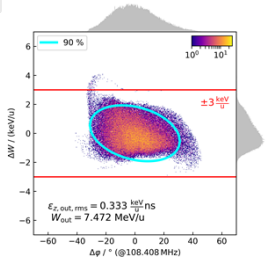
Longitudinal beam dynamics cw-Linac layout



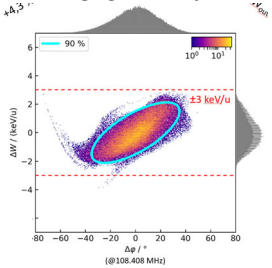
1.4 MeV/u



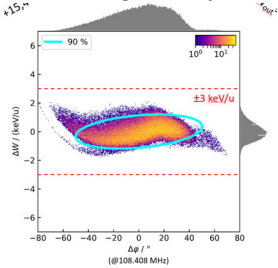
3.5 MeV/u



5.0 MeV/u



7.5 MeV/u



Courtesy: M. Schwarz, et al., Poster@LINAC2018, TUPO084

Summary&Outlook

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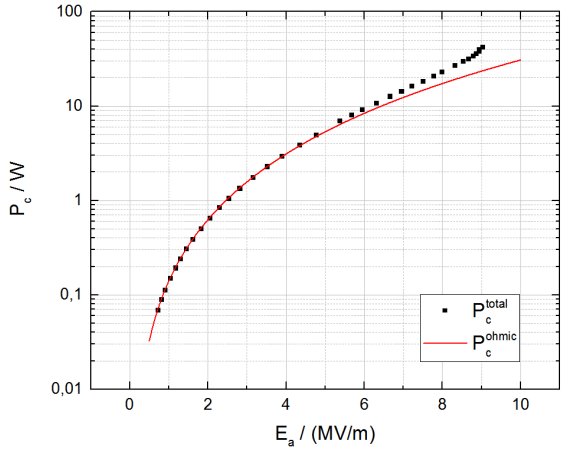
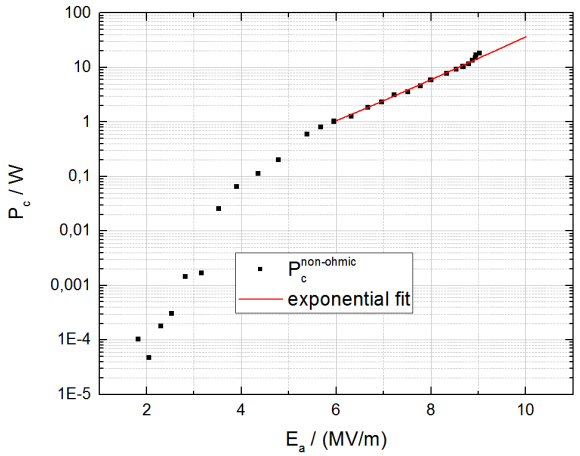
- Advanced cw-Linac layout based on four cryomodules, each equipped with three CH-cavities and a sc-rebuncher demonstrates the high capabilities due to energy variation preserving the beam quality
- New design could provide beam acceleration for a wide range of different ions (protons to uranium) above the design beam energy, featuring the ambitious GSI-user program, while the GSI-UNILAC is upgraded for short pulse high current FAIR-operation

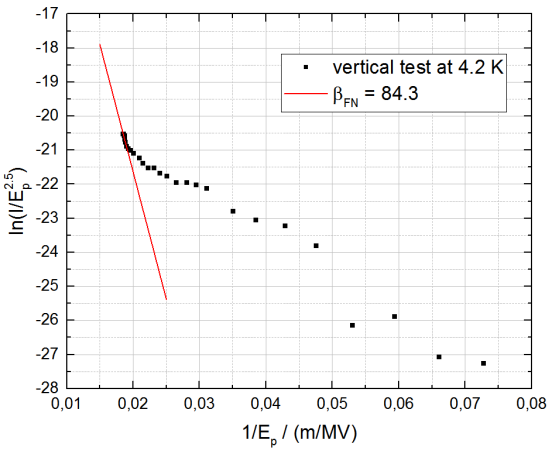
First RF-measurement for CH1 in a vertical cryostat



Total & pure ohmic losses inside the cavity depending on E_a



Non-ohmic losses inside the cavity depending on E_a

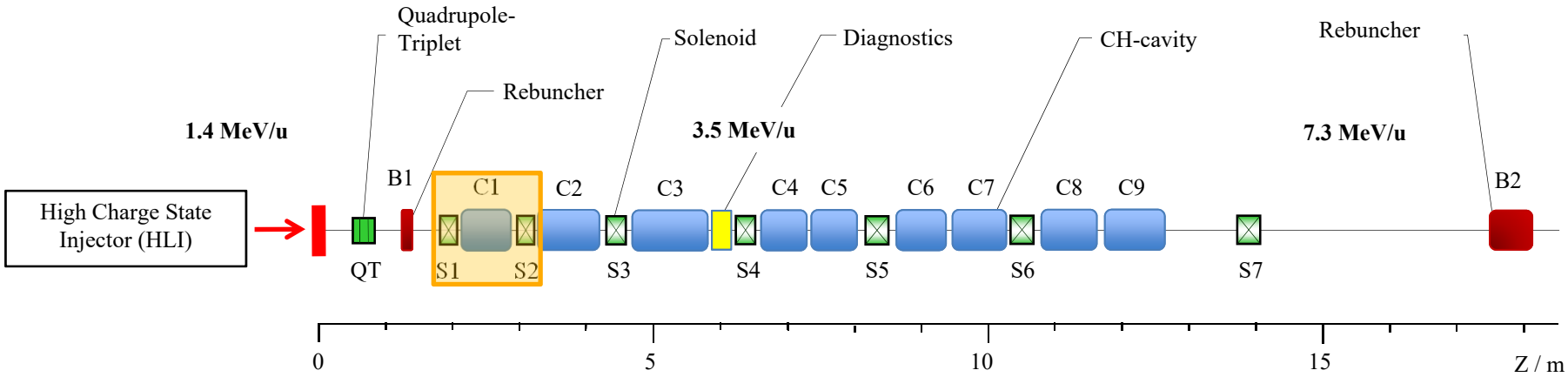


Fowler-Nordheim plot for the first vertical test at 4.2 K

courtesy: M. Basten et al., Poster@LINAC2018, THPO072

Thank You for Your attention!

Superconducting cw-Linac layout
(S. Minaev, 2009)



- Multigap CH-cavities
- Small number of rf cavities and short cavity lengths (up to 1 m)
- acc. gradient of 5 MV/m → compact LINAC design
- Several cavities and solenoids per cryostat
- Small transverse cavity dimension
- First step →Demonstrator project

cw-Linac-Strahlenschutztunnel (>2021)