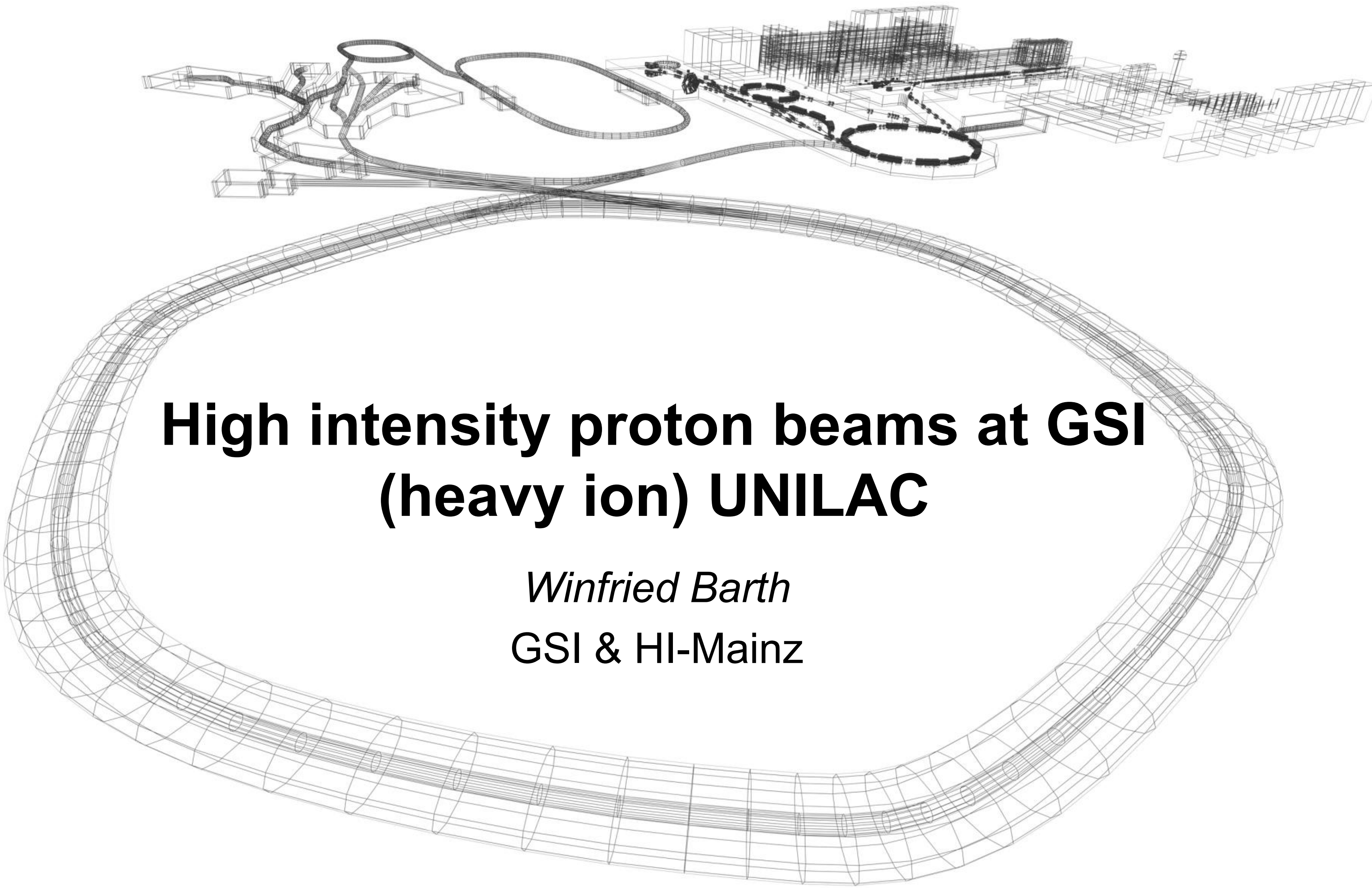


High intensity proton beams at GSI (heavy ion) UNILAC

Winfried Barth

GSI & HI-Mainz

High intensity proton beams at GSI (heavy ion) UNILAC

W. Barth[1,2,3]

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

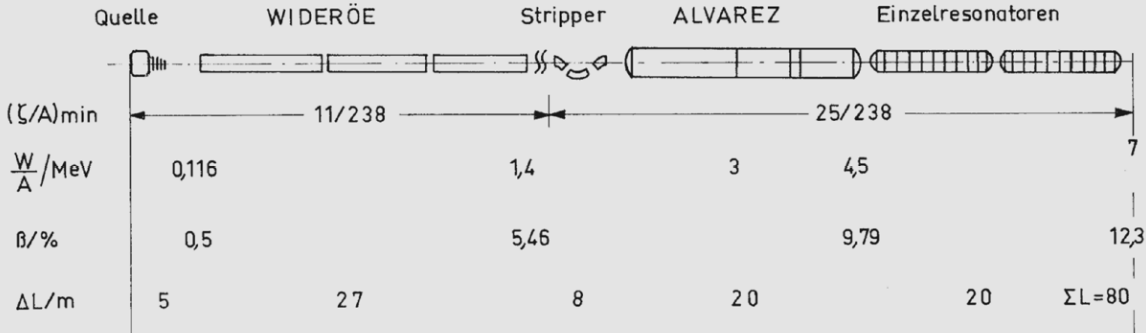
1. UNILAC – Linear accelerator for heavy ions
2. Proton beam acceleration at UNILAC
3. Proton operation at minimum synchronous phase
4. Parallel operation with (medium) heavy ion beams
5. Further UNILAC-options for high current-proton-operation

Requirements for a Universal Heavy Ion Accelerator (UNILAC)

- Accelerator for ions of **all** elements up to uranium
- Energy ≥7 MeV/u, threshold for nuclear reactions with any target atoms
- Independent rf-cavities with phase control allowing diff. velocity profiles
- Output energy variable in a wide range (2 to 10 MeV/u), stable within 10^{-3}
- Energy spread of the beam better than 10^{-3}
- No contamination from other energy components in the beam
- Beam intensity higher than 6×10^{12}/s
- Fast change of ion species possible

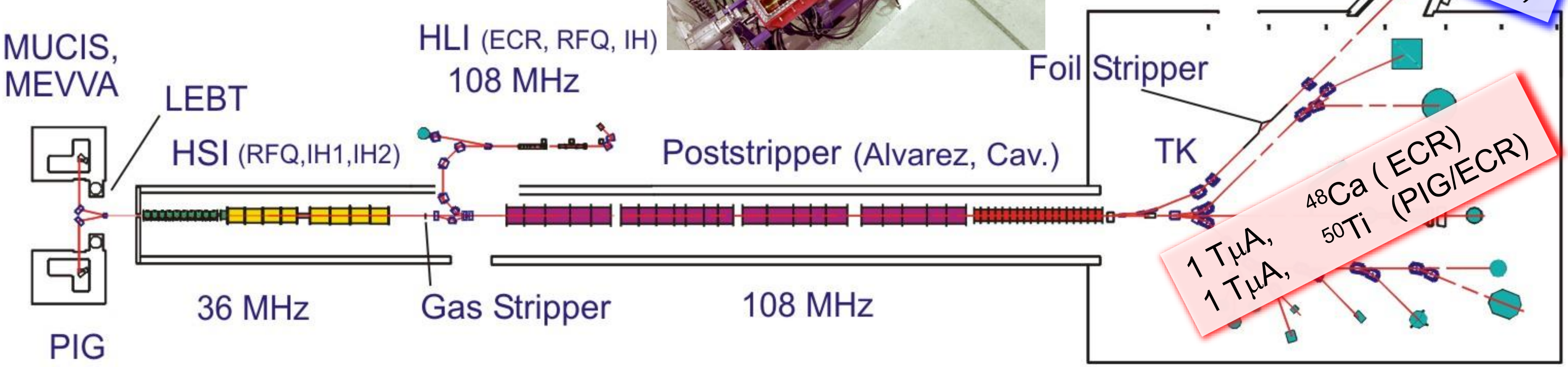
Prof. Christoph Schmelzer, first scientific director of GSI (1970 – 1978)

Unilac layout 1968, 6a

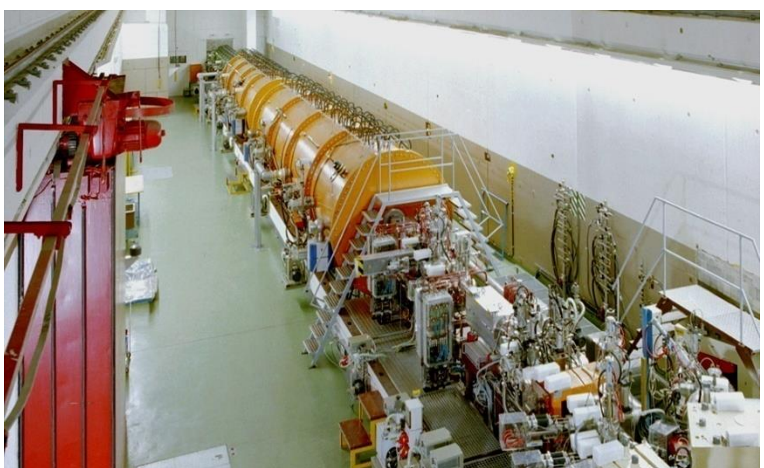


GSI UNIversal Linear ACcelerator

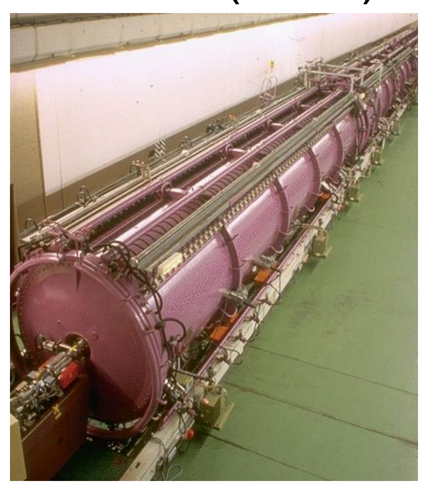
High Charge State Injector (1991)



High Current Injector (1999)



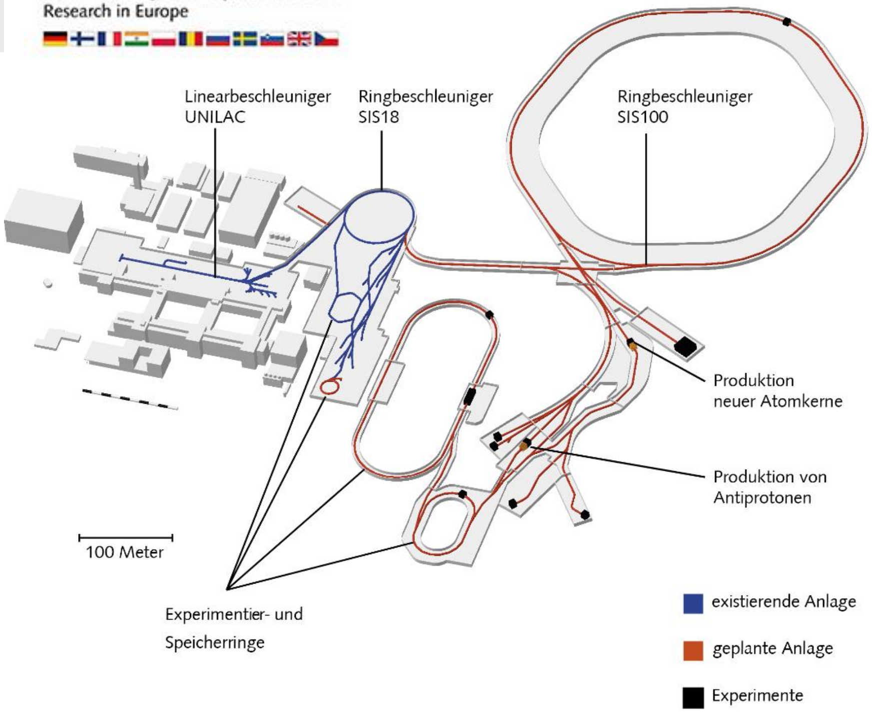
Alvarez (1975)



Single Gap Resonators (1975)

Facility for Antiproton and Ion Research

FAIR — Facility for Antiproton and Ion Research in Europe



FAIR-design uranium beam parameters at the UNILAC

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$
Elect. Current [mA]	25	18	15	15.0
Part./100µs pulse	$3.9\cdot10^{12}$	$2.8\cdot10^{12}$	$3.3\cdot10^{11}$	$3.3\cdot10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4
ΔW/W	-	$4\cdot10^{-3}$	$\pm1\cdot10^{-2}$	$\pm2\cdot10^{-3}$
$\varepsilon_{norm.,x}$ [mm mrad]	0.3	0.5	0.75	1.0
$\varepsilon_{norm.,y}$ [mm mrad]	0.3	0.5	0.75	2.5

protons???

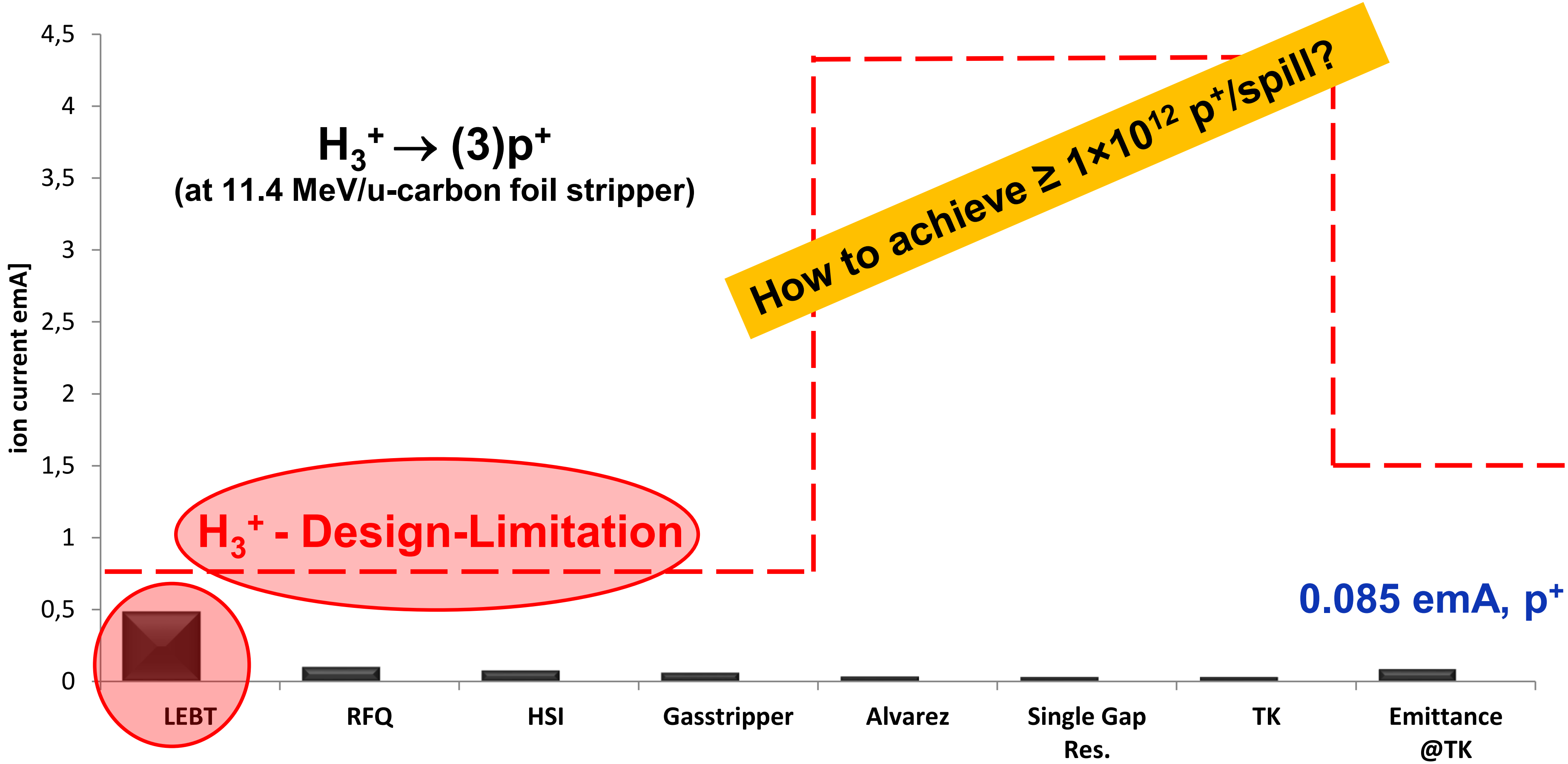
key parameters (^{238}U, p^{+})

Ring/Device	Beam	Energy	Intensity
SIS 100 (100Tm)	**protons**	**30 GeV**	**4×10^{13}**
	^{238}U	**1 GeV/u**	**5×10^{11}**

(intensity factor 100 over present)

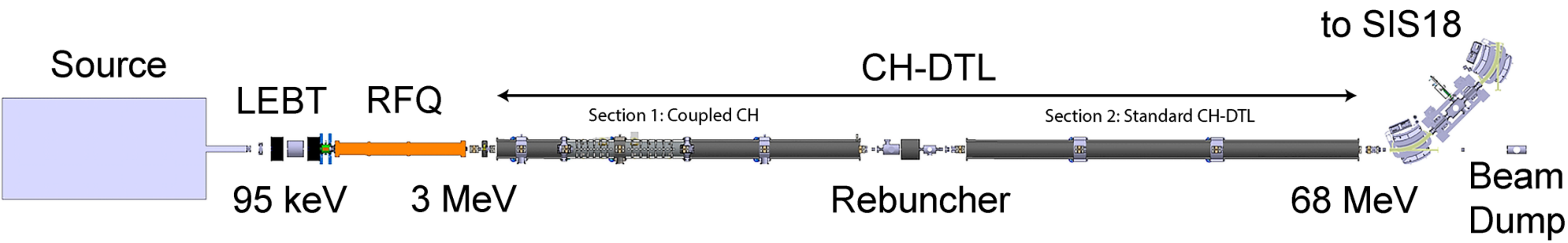
April 2014

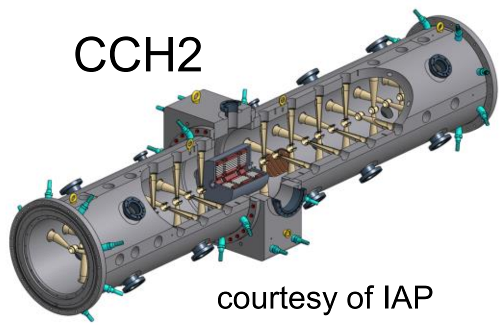
proton beam at GSI-UNILAC



=> 35 mA, p^+ (FAIR-proton Linac)

FAIR proton Linac





courtesy of IAP

Rf-Coupled Crossed-bar H-Cavities

- **reduce number of klystrons**
- **reduce place requirements**
- **profit from 3 MW klystron development**
- **avoid use of magic T's**
- **reduce cost for rf-equipment**

Beam Energy (MeV)	**68**
Beam Current (mA)	**35 - 70**
Beam Pulse (µs)	**36**
Repetition Rate (Hz)	**4 (2,7)**
Protons per pulse	**$7 \cdot 10^{12}$**
Frequency (MHz)	**325.224**
Norm. Emittance at output (µm)	***4.2***
Momentum Spread	**$\lesssim \pm 10^{-3}$**
Beam Loading (peak) (MW)	**4.9**
RF Power (peak) (MW)	**2.2**
Klystrons (3 MW Peak Power)	**7**
Solid State Amplifier (50 kW/180kW)	**3**
Total Length (RFQ + CH)	**≈ 27 m**

2.45 GHz ECR source generating 100 mA of 95 keV protons (CEA)

LEBT & diagnostics chamber:
faraday cup / allison scanner / wien filter (CEA)

ladder 4-Rod RFQ with chopper and a beam dump in front

Six normal conducting crossbar cavities of CCH and CH type aranged in two sections with intermediate diagnostic section (IAP)

HSI design parameters

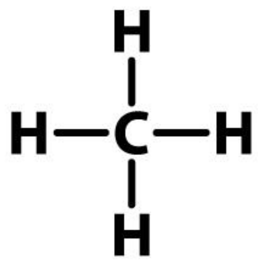
$$I_{design} = 0.25\ \text{emA} \times A/\xi$$

$^{238}U^{4+}$ (A/ζ = 59.5) — I_{design} = 15 emA				
Max. Electrode Voltage [kV]	125	194	1053	961
Effective Acceleration Voltage [MV]	7	-	37	39
RF-Powerloss, Pulse [kW]	243	63	871	880
RF-Powerloss (average), Duty Factor 2% [kW]	5	1	17	18
Beam Power [kW]	106	-	560	591
H_3^{1+} (A/ζ = 3 — I_{design} = 0.75 emA				
Max. Electrode Voltage [kV]	1,946	3,011	16,331	14,911
Effective Acceleration Voltage [MV]	0,109	-	0,575	0,606
RF-Powerloss, Pulse [kW]	1,267	0,328	4,544	4,588
RF-Powerloss (average), Duty Factor 2% [kW]	0,025	0,007	0,091	0,092
Beam Power [kW]	0,551	-	2,919	3,081

→ Acceleration of hydrocarbon compounds ($A/\xi \geq 15$)

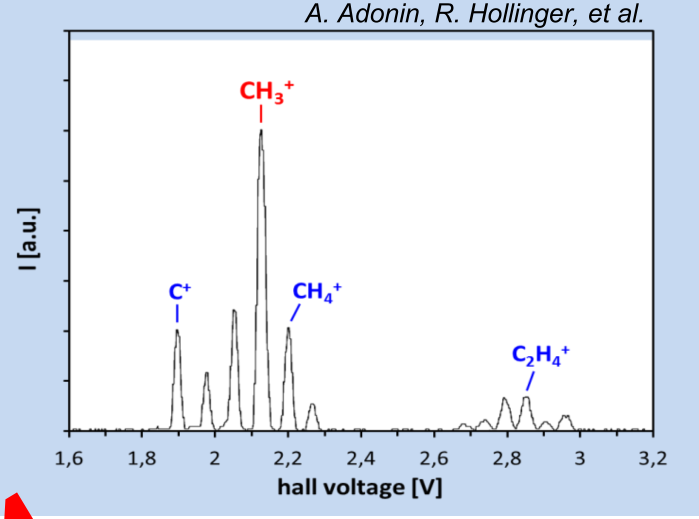
High intensity proton beams at GSI-UNILAC

How to use a heavy ion machine for acceleration of high intensity proton beams?



Methan

Ion source

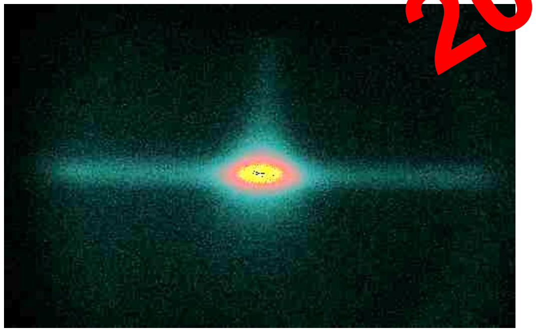


2014

CH_3^+ acceleration

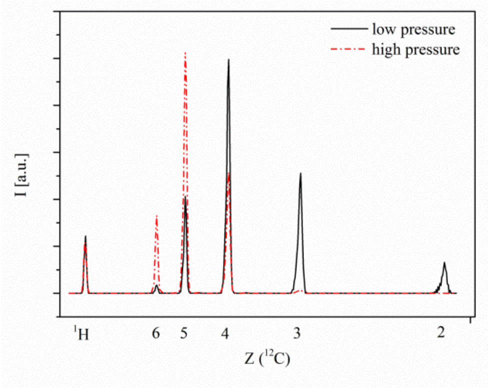
Use of HSI heavy ion beam capabilies to acclerate hydro-carbon compounds

gas target



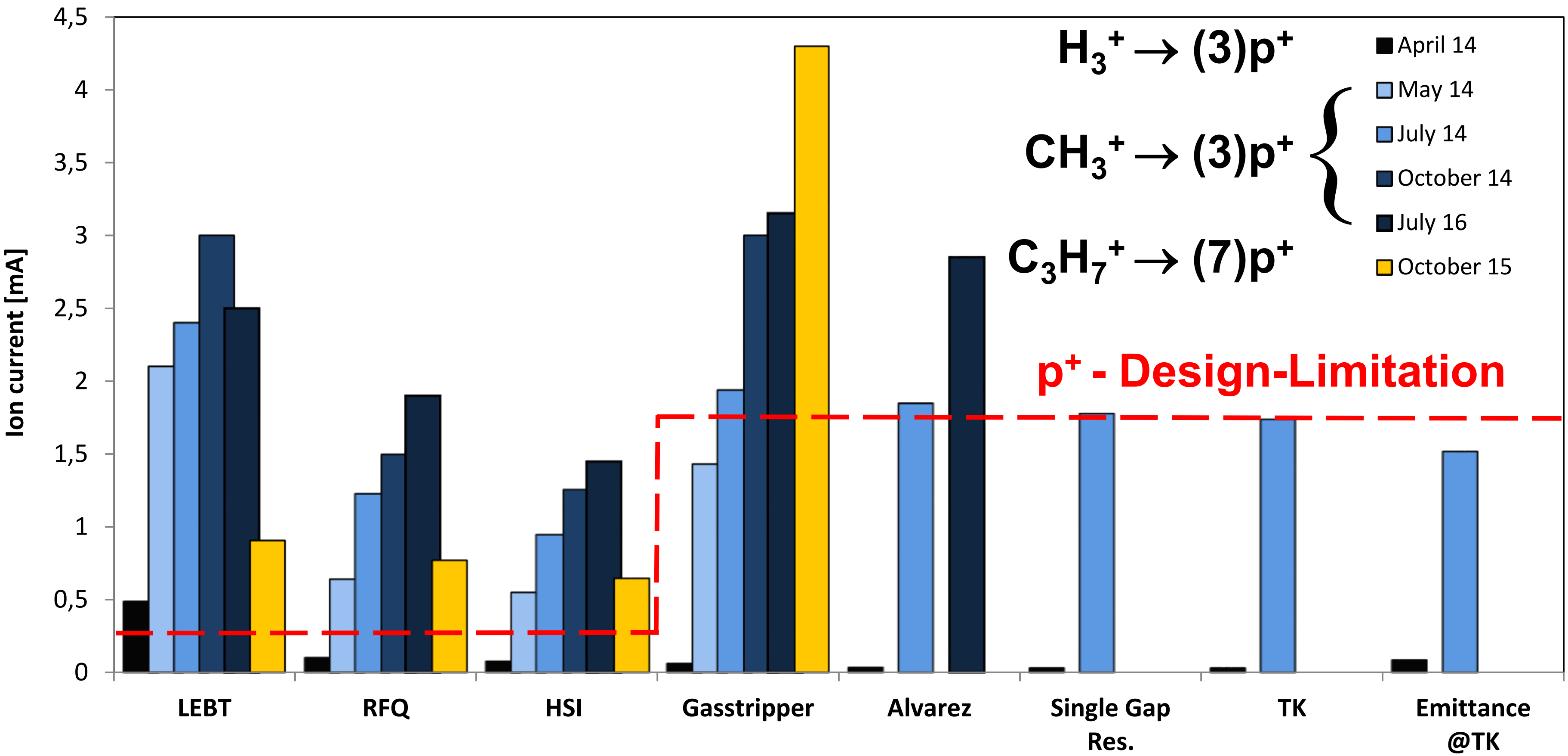
Cracking of CH-compounds
+ Stripping

C^{6+} acceleration (9 emA)



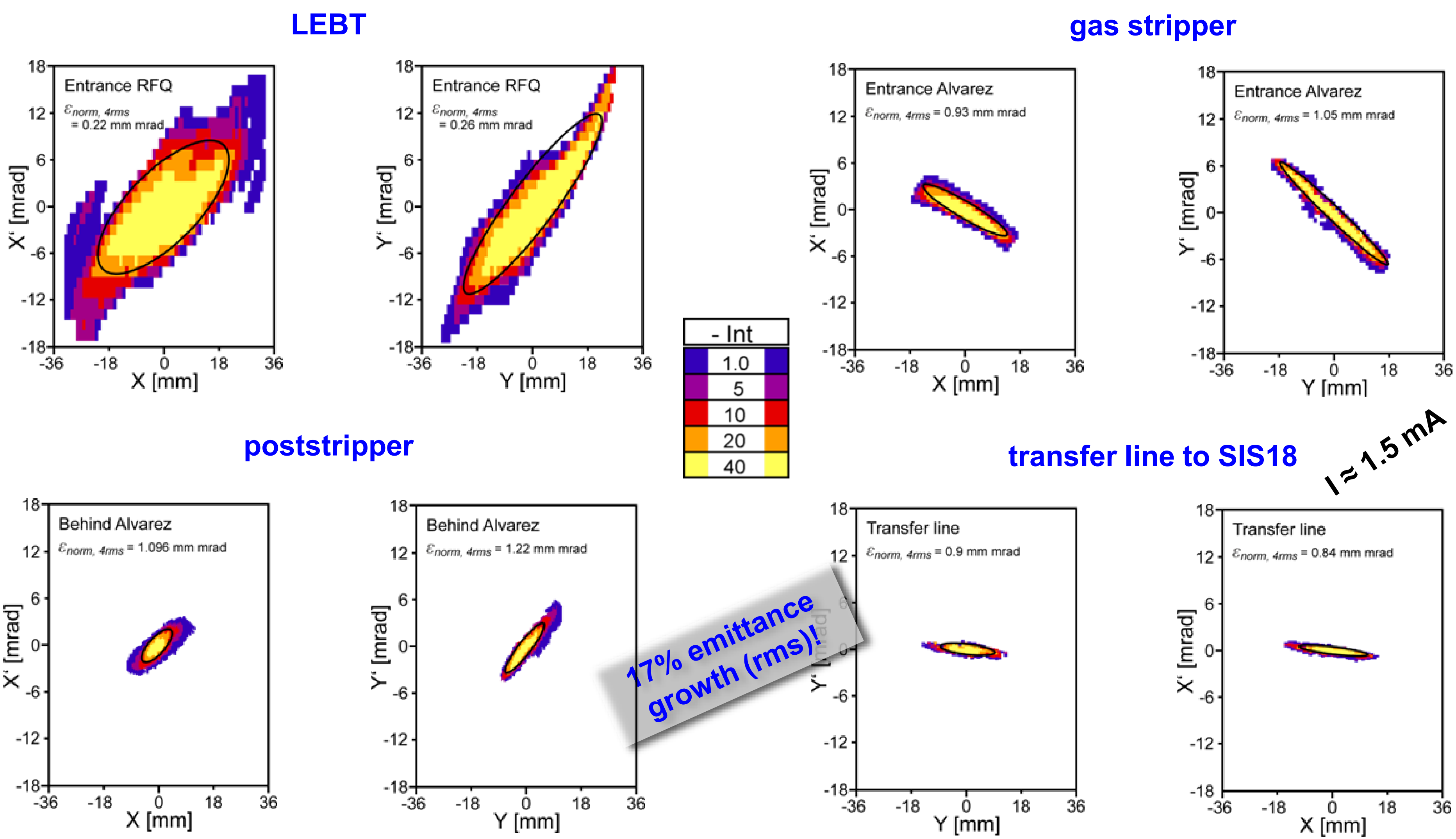
p^+ acceleration (3 emA)

High intensity proton beams at GSI-UNILAC



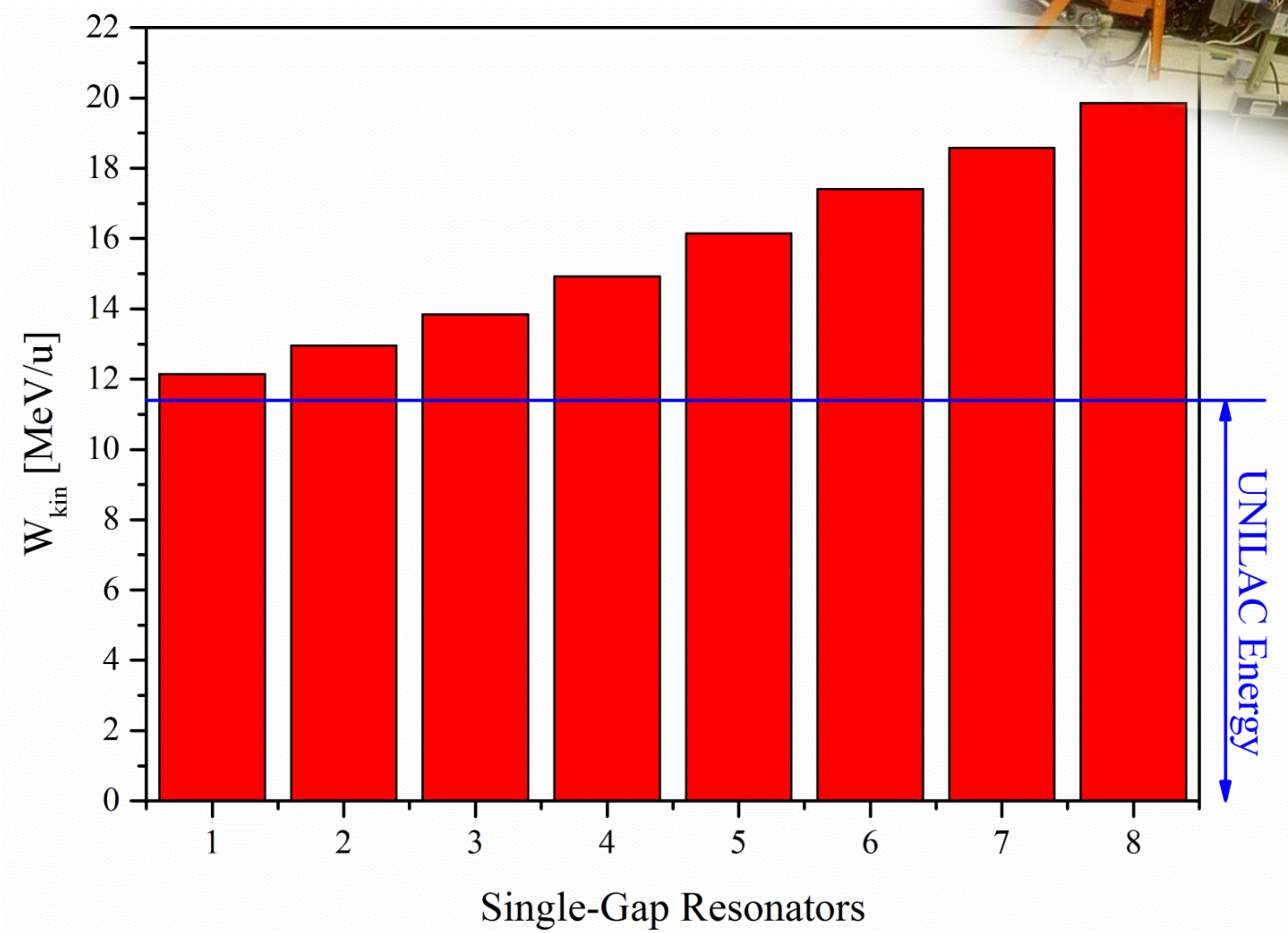
Front to end CH_3^+/p^+-emittance-measurements

W. Barth, et al., Phys. Rev. ST Accel. & Beams 18, 050102 (2015)



Energy booster operation

$\Delta W \approx 1$ MeV/SGR



Estimated intensities
FAIR proton injector options

HIAT 2022 | Darmstadt

S. Appel, GSI

	p-LINAC	UNILAC		
	design	**Measurement**		extrapolation
E [MeV]	70	**11.4**	**20**	20
I [mA]	35	**2**	**2**	**3**
$E_{x,y\ phys.}$ 4·rms [mm mrad]	7/8	**7/8**	**3/3**	3/3
SIS18 MTI output (N) *	5.8e12	8.2e11	9.7e11	1.5e12
Space charge limit (N)	5.8e12	8.7e11	1.5e12	1.5e12
SIS100 output (particles/cycle)	1.8e13	2.4e12	2.9e12	4.5e12
SIS100 output (relative)	100%	13.0%	16.0%	25.0%

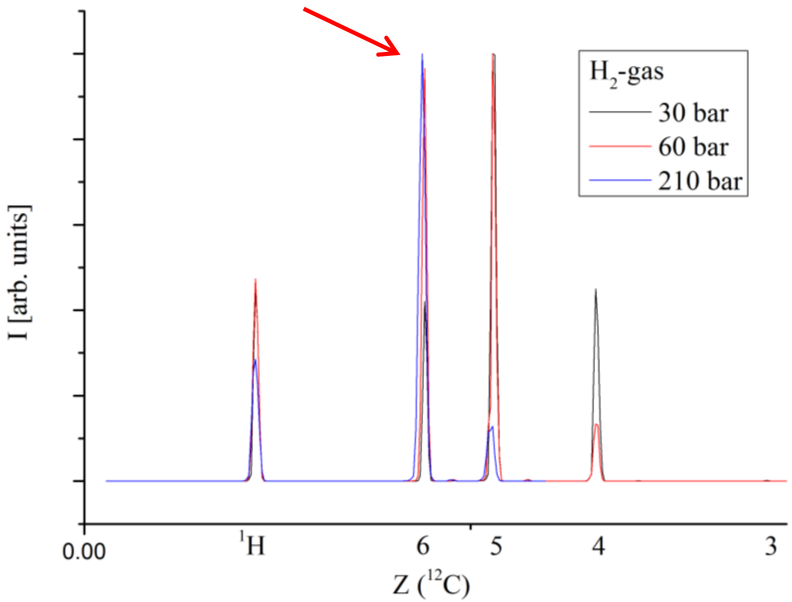
*** 2.1e11 (measured)**

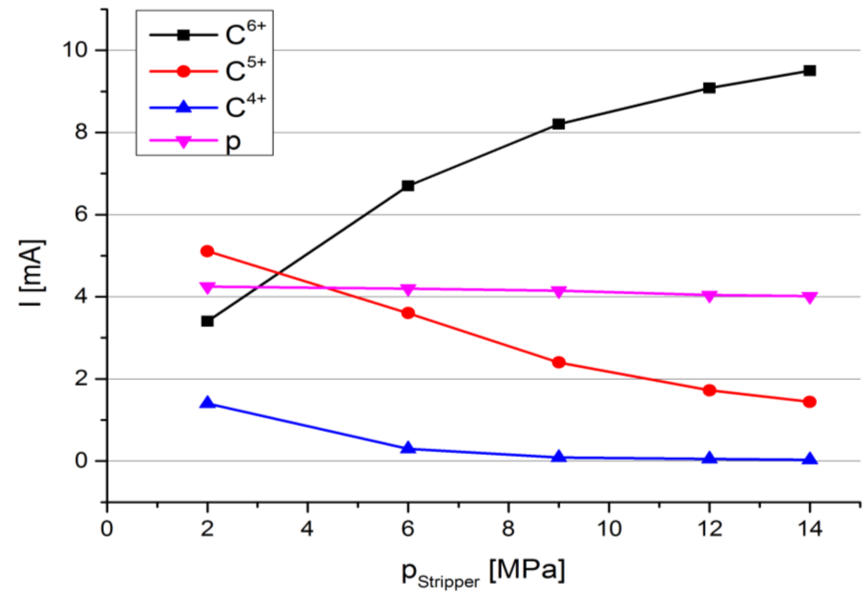
Hydrogen gas stripper: $CH_3^+ \rightarrow p^+/C^{6+}$

HIAT 2022 | Darmstadt

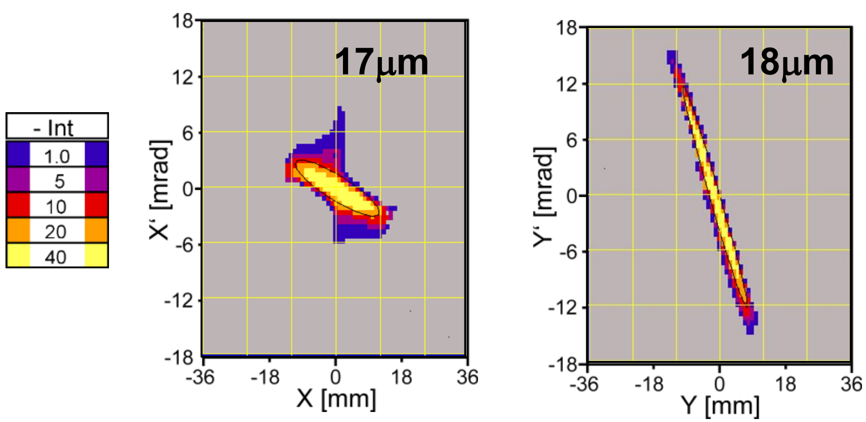
$^{12}C^{6+}$, I ≈ 9 emA

M. Heilmann, W. Barth





Proton beam emittance (I = 3.5 emA)

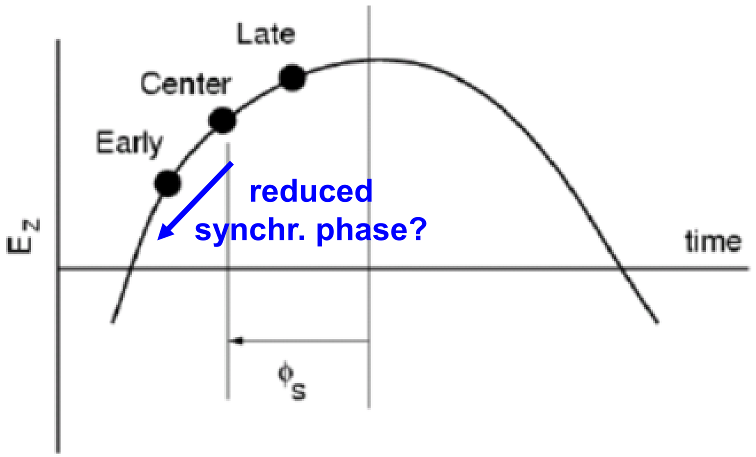


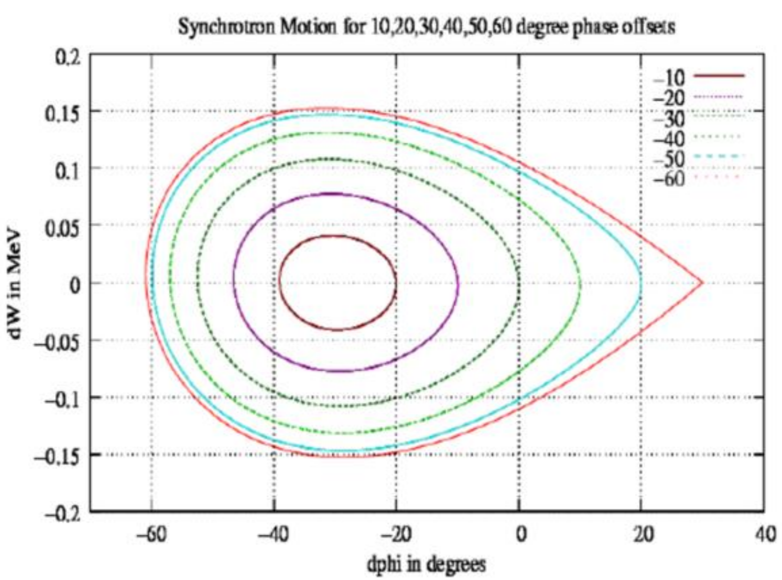
- **Clean charge spectrum**
- **High brilliance proton beam**
- **High brilliance carbon beam**
  - $^{12}C^{2+}$
  - $^{12}C^{3+}$
  - $^{12}C^{4+}$
  - $^{12}C^{5+}$
  - $^{12}C^{6+}$
- **(parallel) poststripper operation???**

Light ion beam studies: p+

U. Scheeler, H. Vormann, M. Vossberg, S. Yaramyshev, W. Barth

Resonance acceleration





ALVAREZ Rf-voltage < 1V ($\Phi s \approx -30°$)?

- $\Phi s \approx -57°$ ($U_{rf} \approx$ 1.5V) 👍
- $\Phi s \approx -65°$ ($U_{rf} \approx$ 2.0V) 👍
- $\Phi s < -65°$ ($U_{rf} >$ 2.0V) 👎

pros and cons ?

- smooth Rf-operation 👍 👍
- slightly reduced transmission 👍
- emittance blow up 👎
- longitudinal phase space? 👎

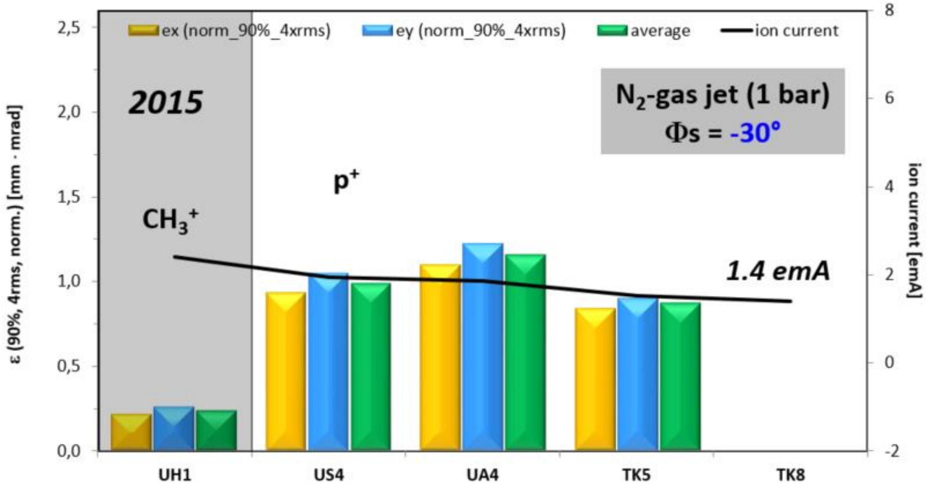
see also: *A. Rubin, et al.*

Brilliant beam acceleration at longitudinal phase advances far beyond 90°, LINAC 2020

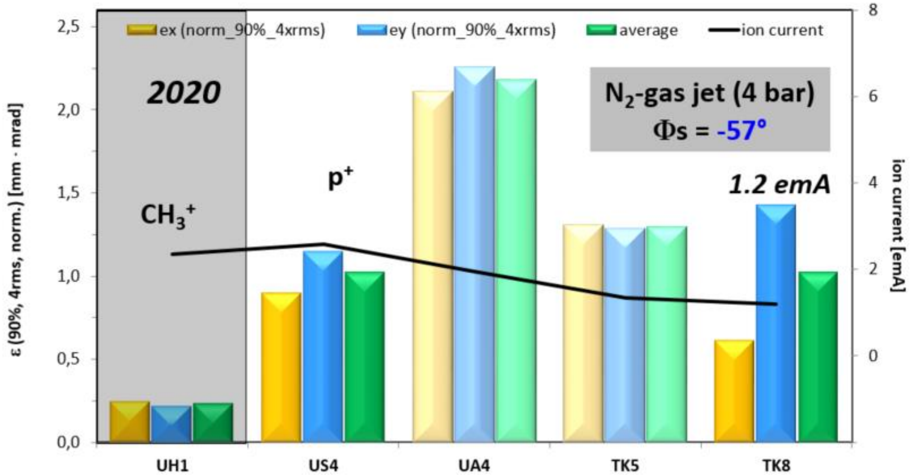
Simulations on operation of the new UNILAC post-stripper with intense proton beams: longitudinal phase advances below and beyond 90°. Acc. Sem., GSI, 2020

UNILAC-p^+-operation

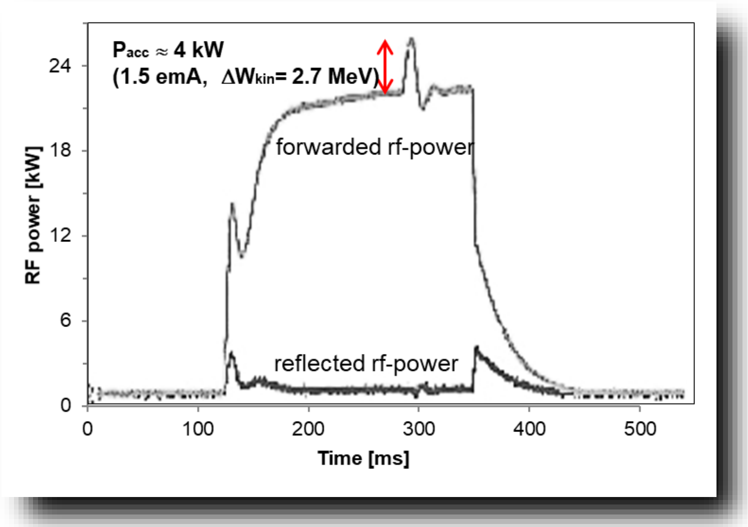
$\Phi s \approx -30°$ ($U_{rf} \approx$ 1.0V)



$\Phi s \approx -57°$ ($U_{rf} \approx$ 1.5V)



Beam Load measurement
Forward and reflected Rf power

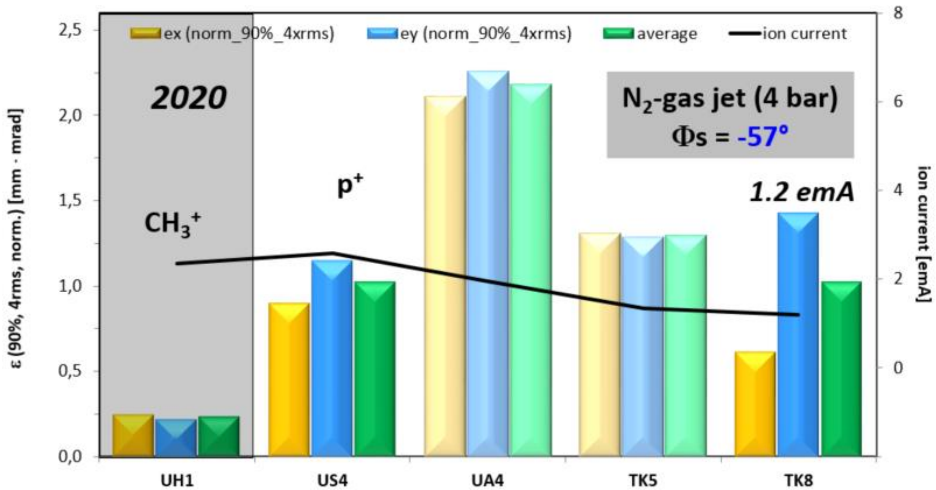


→ more than two times increased Rf-power!

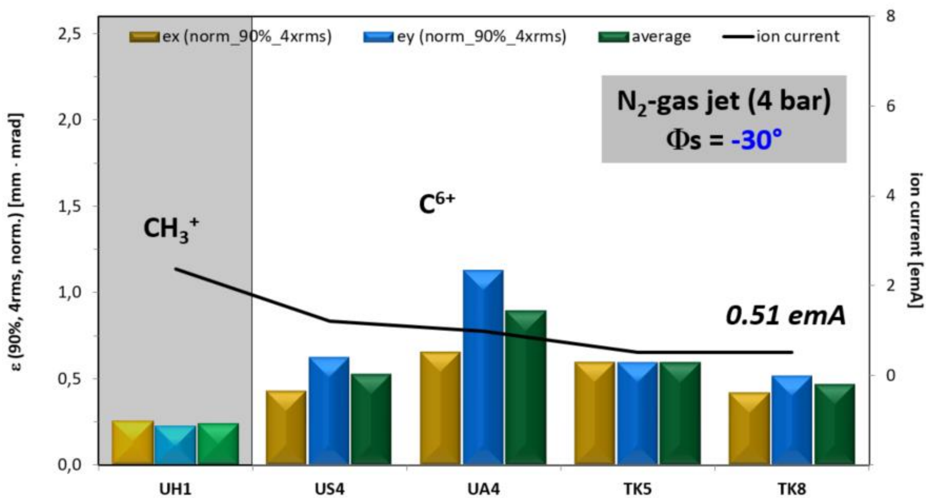
UNILAC-parallel Operation

Parallel operation (quad focussing/average A/ξ = 1.35)

p^+
(A/ξ = 1.0)



$^{12}C^{6+}$
(A/ξ = 2.0)



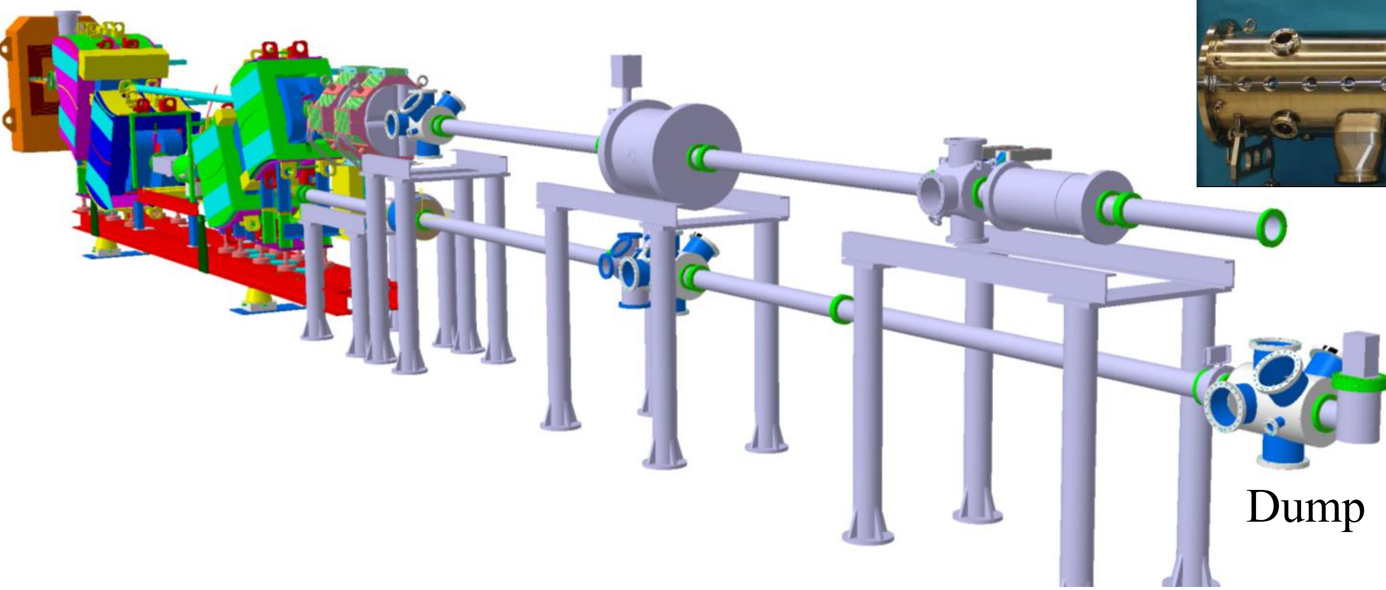
pulsed gas stripper
=> increased yield!

Summary

- UNILAC serves as heavy ion accelerator since 1975
- 2014/15: R&D-program: High intensity proton beams at ion source and UNILAC
- 2016: High intensity proton beam available
- UNILAC can provide for up to 3 emA (high brilliance p^+-beam) at ≥ 20 MeV
- UNILAC may help to bridge the time until FAIR-p-Linac is available
- Advanced (simplified) UNILAC-proton operation with $\Phi_s \approx -57°$
- ≥ 2020: High intensity proton beam for user operation
- Parallel operation: high intensity p^+- and C^{6+}-beam from a single ion source!
- Outlook: Pulsed (hydrogen stripper): p/C-parallel operation at max. intensity!

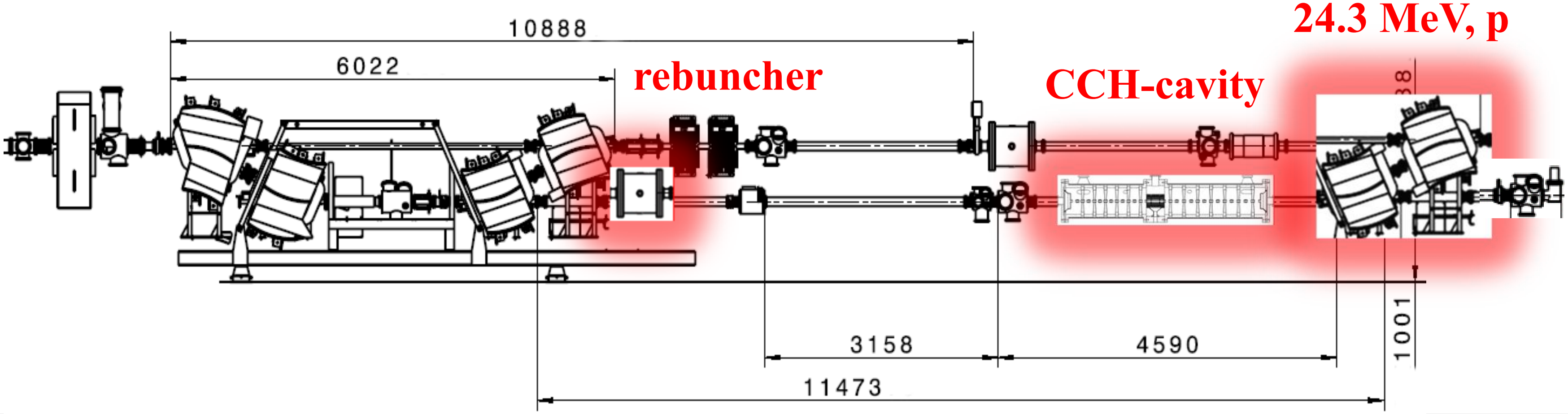
Outlook: Post acceleration of UNILAC p^+-beam

Beam Diagnostic Test Bench



p-LINAC-prototype (tested 2015)

no. of gaps	13 + 14 = 27
frequency [MHz]	325.2
energy range [MeV]	11.7 - 24.3
beam loading [kW]	882.6
heat loss [MW]	1.35
total power [MW]	2.2
Q_0-value	15300
effective shunt impedance [MΩ/m]	60
average E_0T [MV/m]	6.4 - 5.8
Kilpatrick factor	2.0
coupling constant [%]	0.3
aperture [mm]	20
total inner length [mm]	2800



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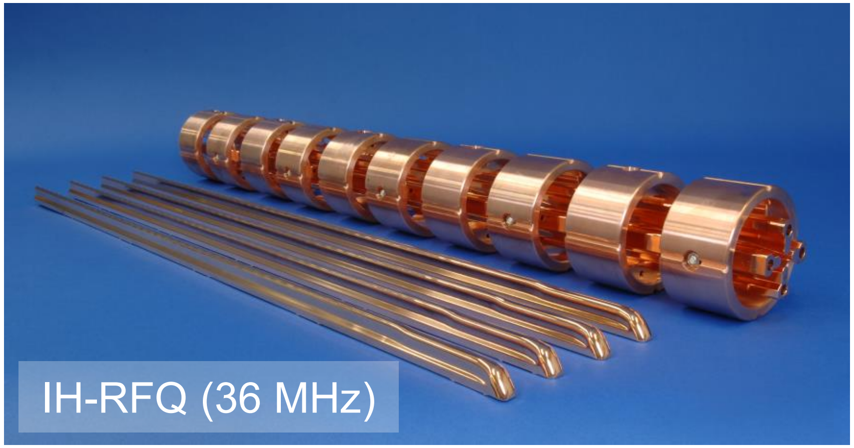

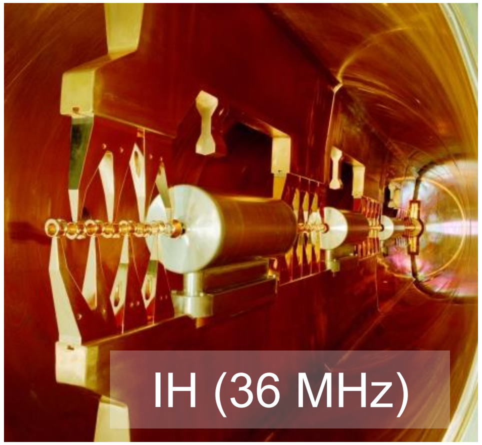

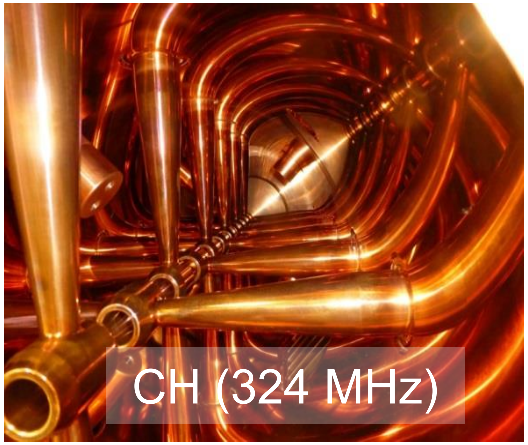

My thanks go to all the collaborators and colleagues who contributed to the proton beam developments of the last years; especially to Wolfgang Vinzenz, who passed away much too early, without whose expertise and optimism we would never have started...