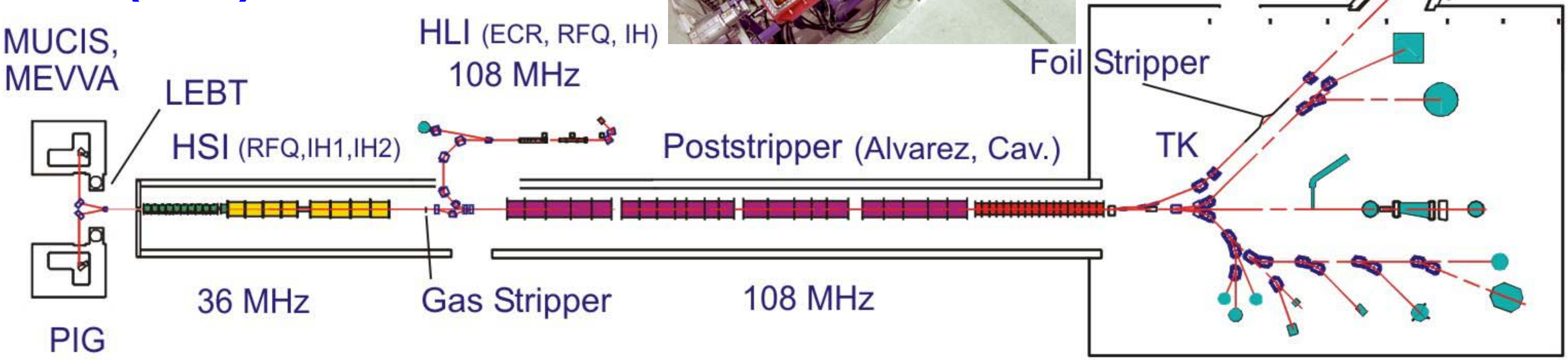
FAIR Bedarf: Injektoren

Winfried Barth (GSI Helmholtzzentrum für Schwerionenforschung GmbH)

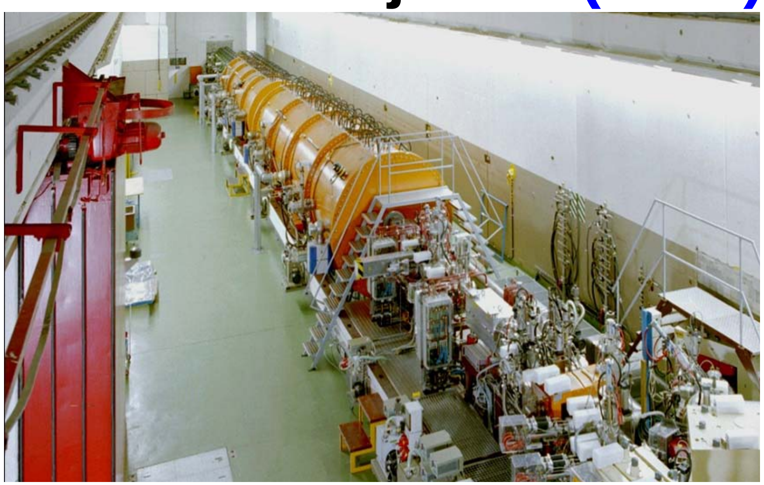
1. ***GSI-UNILAC***
2. **FAIR p-linac, FAIR-Upgrademaßnahmen, HE-LINAC-Projekt**
3. **Ionenquellen**
4. **Linearbeschleuniger**
5. **LINAC-HF**
6. **LINAC-Strahldiagnose**

GSI UNIversal Linear ACcelerator

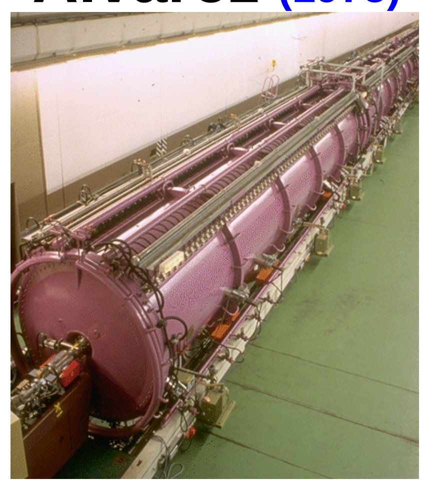
Hochladungsinjektor (1991)



Hochstrominjektor (1999)



Alvarez (1975)



Einzelresonatoren (1975)

GSI-HSI-LEBT Upgrade for FAIR

Upgrade 0

- High Current test stand measurements

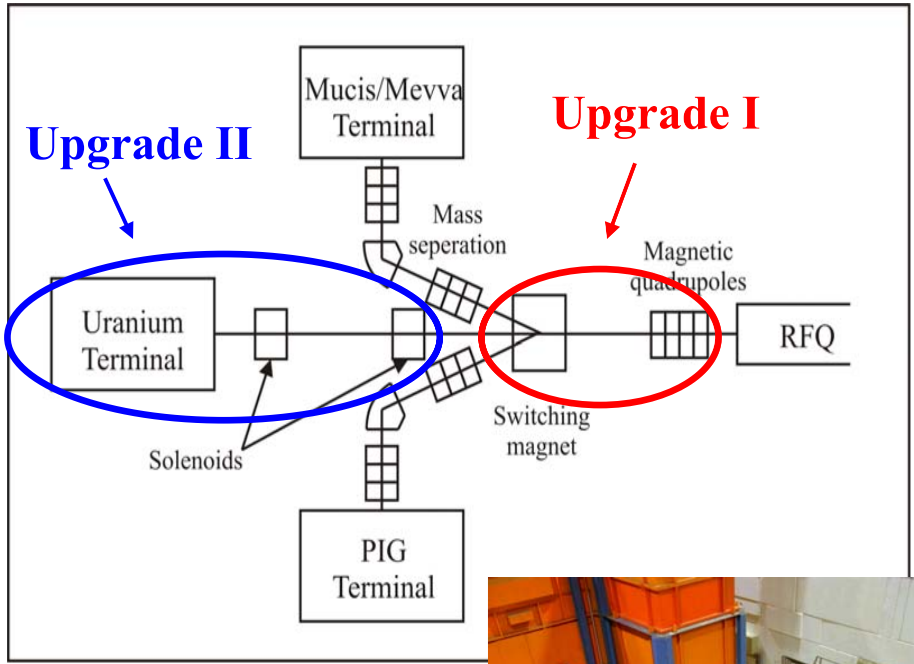
Upgrade I

- Switching magnet with increased aperture
- Quadrupole quartet (matching to the RFQ) with increased apertures (to be delivered)

Upgrade II (Compact LEBT)

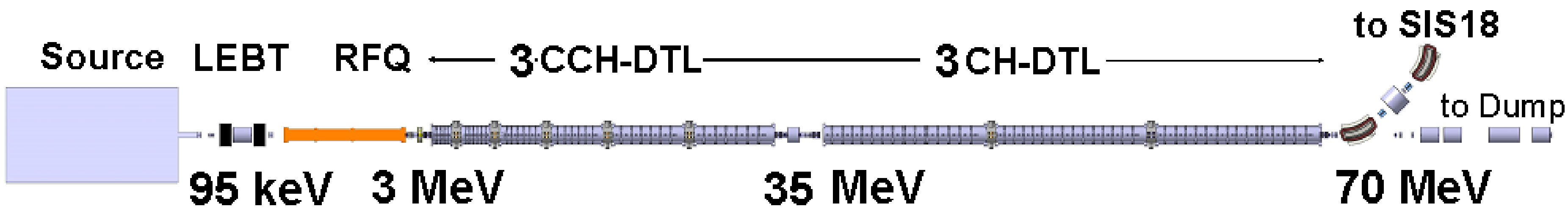
- Beam line with direct injection to the RFQ (integrated into the existing layout)

Schematic layout of the LEBT

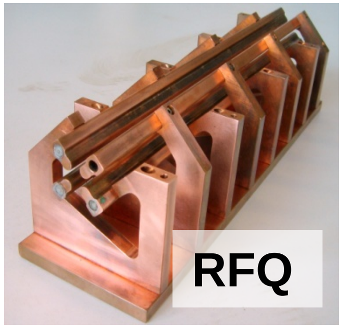


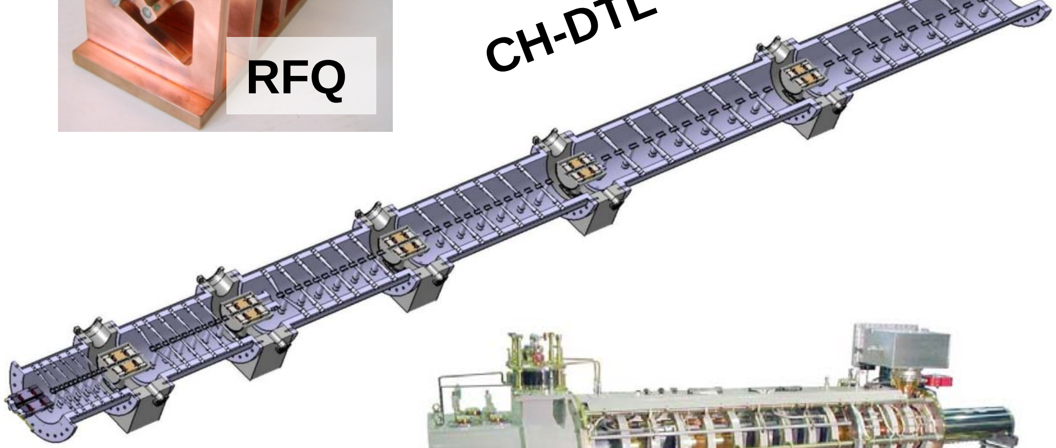
- Previous simulations: Compact LEBT + New RFQ → 20 mA behind RFQ !
- Fully designed
- sc solenoid in operation at test stand
- Quadrupoles (in house)

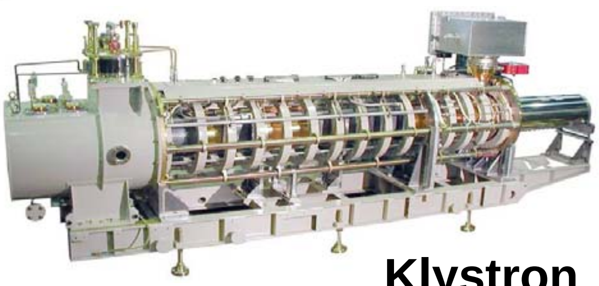
Future Option: The FAIR Proton Injector



Beam Energy	70 MeV
Beam Current (design/oper.)	70 / 35 mA
Beam Pulse	36 µs
Repetition Rate	4 Hz
Frequency	325.224 MHz
Norm. Emittance at output	2.1 / <u>*4.2*</u> µm
Momentum Spread	≤ ± 10^{-3}
Beam Loading (peak)	4.9 MW
RF Power (peak)	2.5 MW
Klystron (3 MW Peak Power)	7
Solid State Amplifier (50 kW)	3
Total Length (RFQ + CH)	≈ 27 m

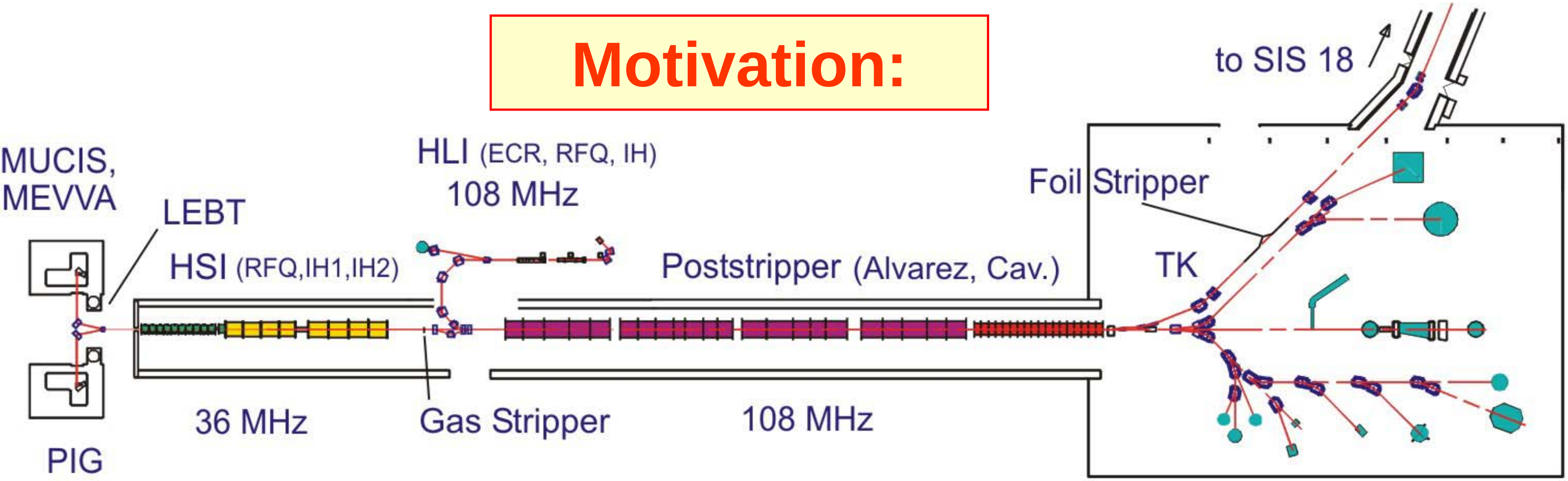






UNILAC-Future Operation modes

Motivation:



FAIR requirements:

- **extremely high pulse intensities**
- **low repetition rate (max. 3 Hz)**
- **low duty factor (0,1 %) (pulse length for SIS18 only 100 µs)**

SHE requirements:

- **(relatively) high pulse intensities**
- **high repetition rate (50 Hz)**
- **high duty factor (-> 100 %) (pulse length up to 20 ms)**

General Approach

A Modern High Power Injector...

- should be...
  - compact
  - high efficient (rf-power consumption)
  - cost saving in production and operation
- should provide beam of...
  - High Intensity (minimum particle loss)
  - High Brilliance
- LINAC parameters (e.g. final beam energy, beam current and charge) should be fixed with respect to the synchrotron design limits
  - Tune Shift
  - Life Time
  - Space charge limit

Ionenquellen

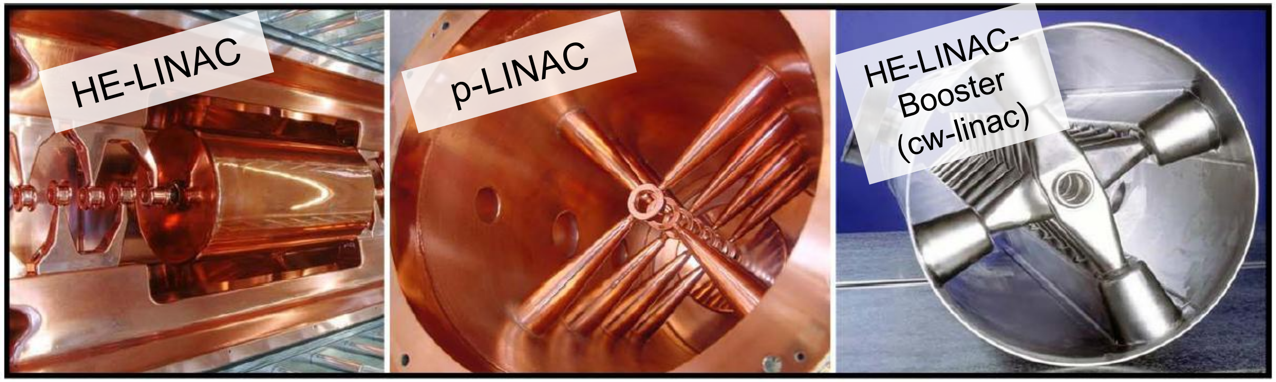
- Plasma-Linse (Compact-LEBT)
- Entwicklung/Extraktionssytem (FAIR p-linac)
- Max. Wiederholrate Hochstrom-Uranionenquellen-Betrieb für FAIR

LINAC

- rt- und sc-Kavitätenentwicklung
- Entwicklung von HF-Koppler und Tuner
- sc-325 MHz-Kavitätenentwicklung (HE-LINAC-Booster)
- 4d-Strahldynamik/analytisch
- Hochstrom-Ionenstripping (bei niedriger Ionenenergie)
  - Kohlenstoff-Folien
  - Gasstripping
  - Plasma-Stripper + Flüssig-Lithiumstripper

Further preparation activities for the injector linacs

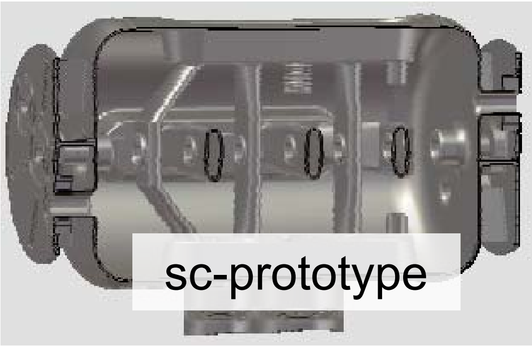
- FAIR-p-linac rf-teststand (325 MHz-CH-prototype, commissioning 2012)
- HGF-AcceleratorResearch&Development (prototyping HE&cw-LINAC key components)

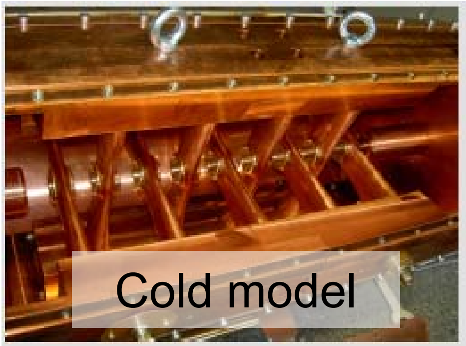


Room Temp. IH-DTL **Room Temp. CH-DTL** **Supercond. CH-DTL**

- Prototyping of a sc 325 MHZ-CH@GUF (HE-LINAC-Booster)

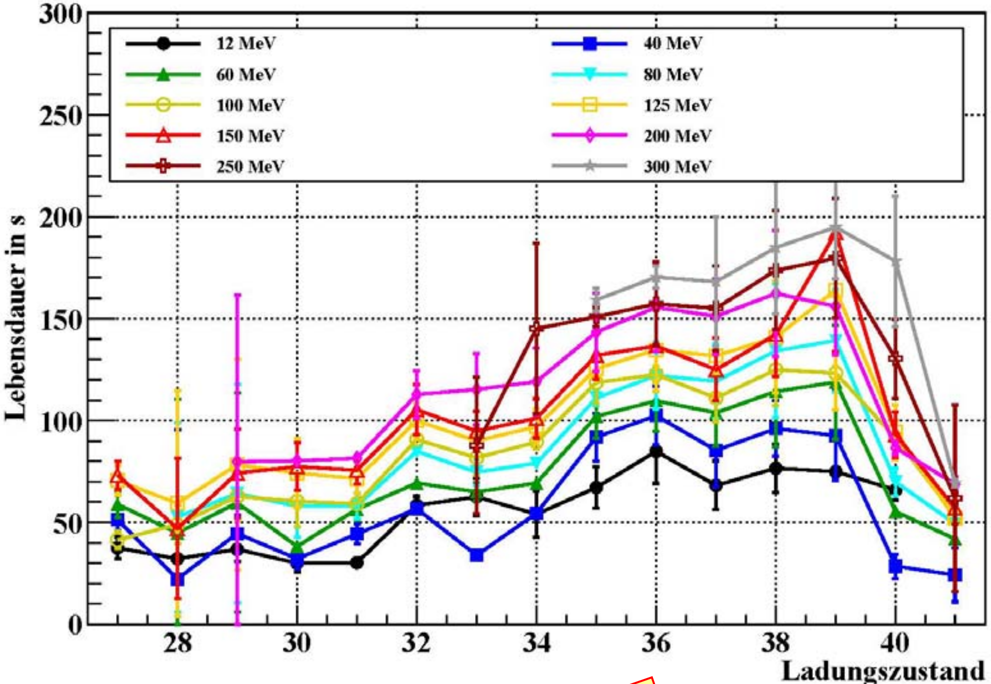
β	0.1565
frequency [MHz]	325.224
no. of cells	7
length ($\beta\lambda$-def.) [mm]	505
diameter [mm]	356
E_a [MV/m]	5
E_p/E_a	5.1
B_p/E_a [mT/(MV/m)]	13
G [Ω]	64
R_a/Q_0	1248
R_aR_s [Ω^2]	80000





Heavy ion High Energy-LINAC I

- Life time Increase by injection of higher charge state



preliminary!

- Space charge Limit and Tune shift

$$\Delta Q \propto N \cdot \frac{q^2}{A} \cdot \frac{1}{\beta^2 \gamma^3}$$

For the same injection energy:

$U^{28+} \rightarrow U^{38+} \Rightarrow \Delta Q \rightarrow +85\%$

Compensation through higher injection energy:

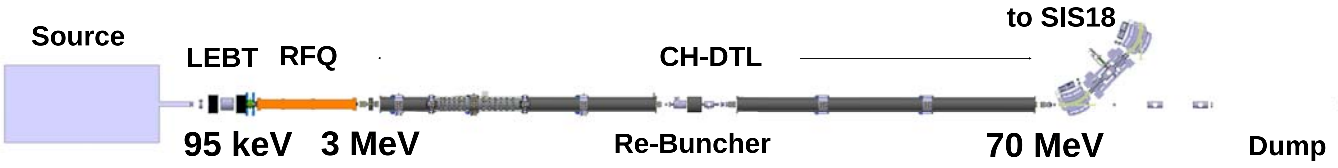
- **15 mA, U^{28+}, 11,4 MeV/u** **$\Delta Q \approx 0{,}51$**
- ***15 mA, U^{28+}, 15 MeV/u*** ***$\Delta Q \approx 0{,}39$***
- **20 mA, U^{38+}, 22 MeV/u** **$\Delta Q \approx 0{,}48$**

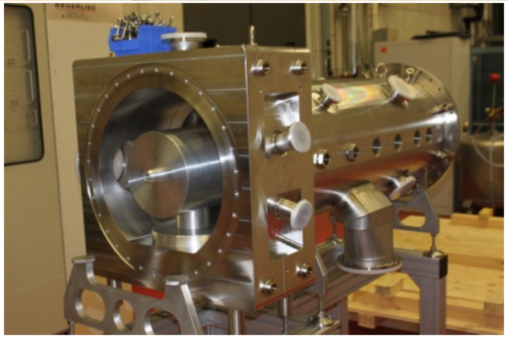
... for higher injection energy:

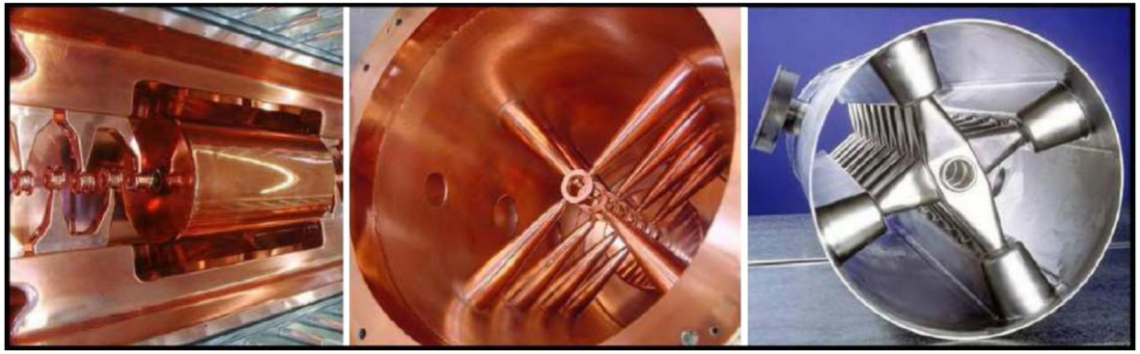
→ smaller emittance ($\propto 1/\beta$)
→ shorter injection pulse

FAIR Linacs: Kavitäten Entwicklung

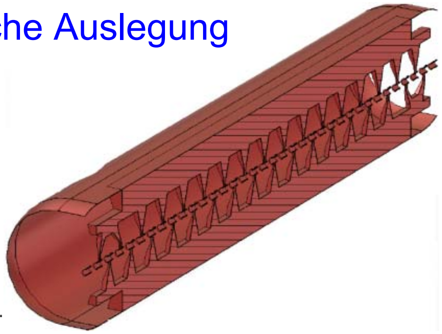
FAIR Protonen Linac



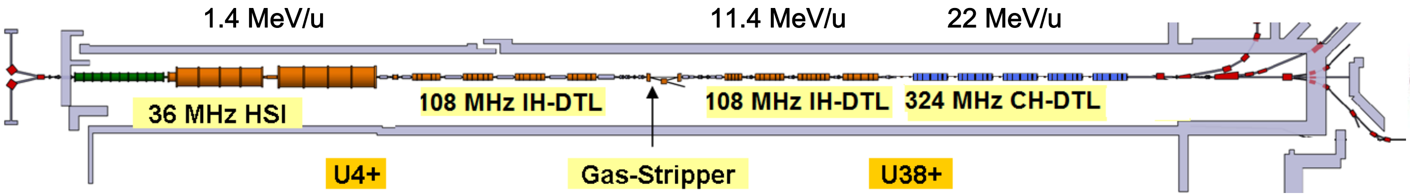




- Beschl. Kavitäten für HE-Linac
- Buncher für Protonen Linac
- alternative Oberflächen-Materialien
- RFQ-Entwicklung
- Hf-Simulationen
- mechanische Auslegung



Hoch-Energie Linac



CH-cavities

So far...

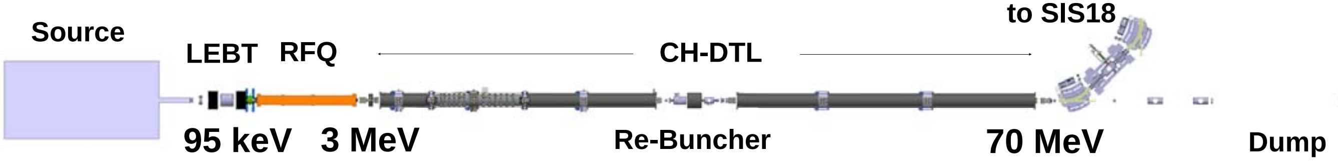
- sc energy variable linacs: 2 gap or 3 gap-cavities (spiral-, $\lambda/4$- $\lambda/2$-type)
- High flexibility in beam energies and q/m-ratios → altering rf-phase relations between cavities and matching the voltage amplitudes
- But: Relatively long lengths between accelerating sections and high total number of cavities including couplers, tuners, controls, and RF power amplifiers
- R.T. focusing elements → high number of separated cryostats accompanied by many cold-warm transitions

Multicell CH-cavities:

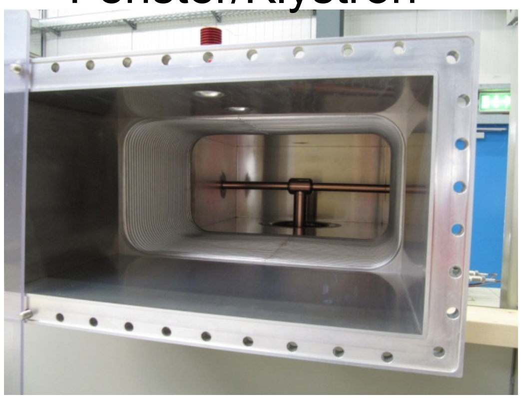
- 10 - 20 cell cavities + cold lenses (cryostat with several cavities and lenses)
- cavity length ≤ 1 m, cryostat length ≈ 5 m in length
- H-type cavities: Small transverse dimensions (at a certain frequency)
- A 19-cell 360 MHz prototype successfully developed and operated at Univ. of Frankfurt
- EQUidistant mUlti-gap Structure (EQUUS) + external focusing lenses → Negative initial and final rf-phases; acceleration around the crest of the wave along the middle part. → maximum in accelerating voltage between two neighboring focusing lenses
- EQUUS → eased manufacturing and rf-tuning (importance for sc structures)
- Comfortable beam dynamics layout

FAIR Linacs: Koppler und Tuner Entwicklung

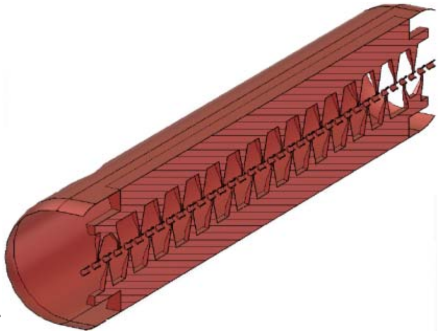
FAIR Protonen Linac



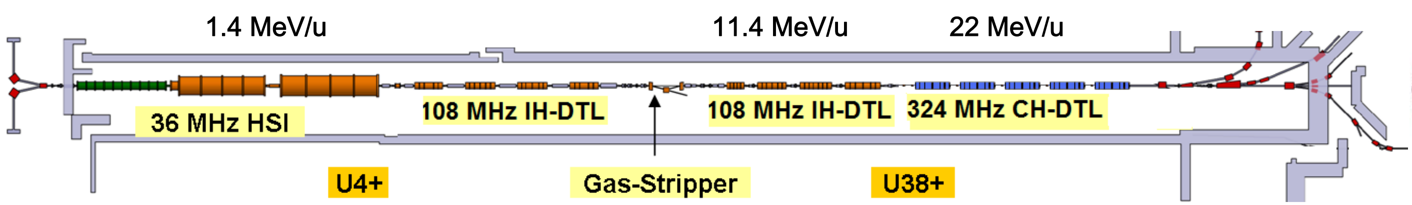
Blick ins Auskoppel-Fenster/Klystron



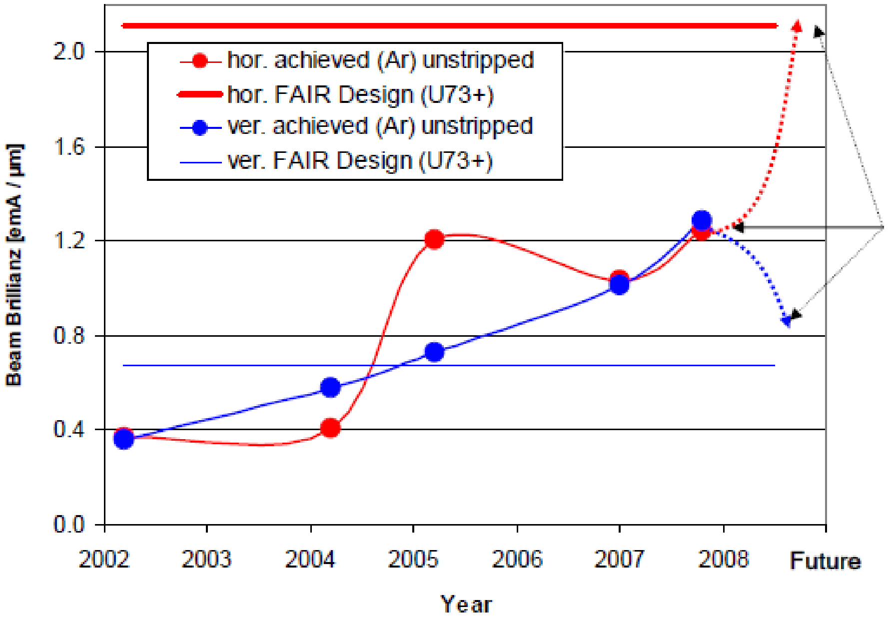
- **Entwicklung für beide Linacs**
- **Hf-Simulationen**
- **mechanische Auslegung**

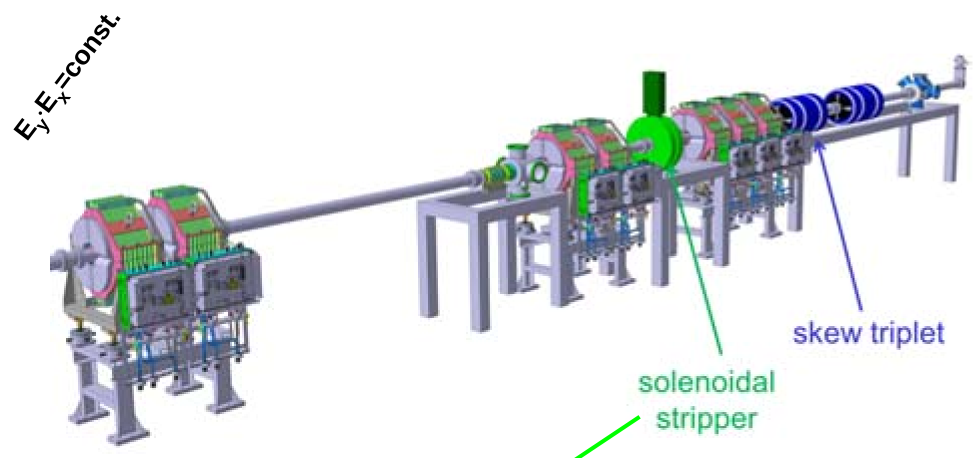


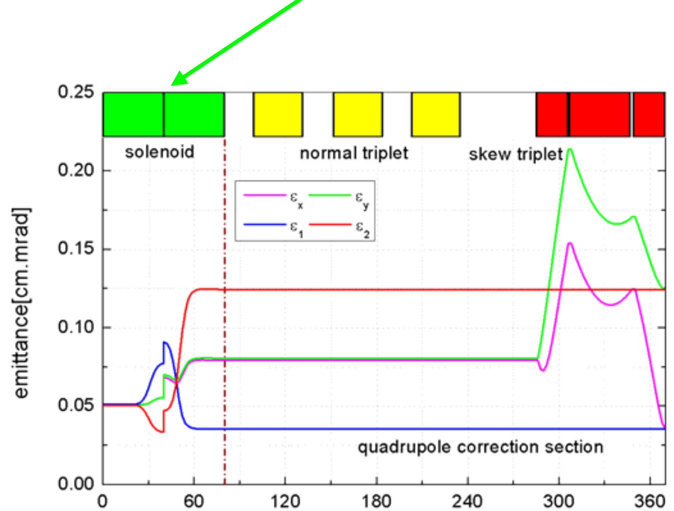
Hoch-Energie Linac



4d-Strahldynamik (analytisch)



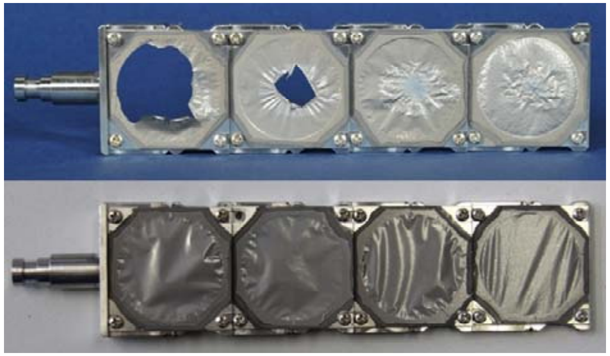




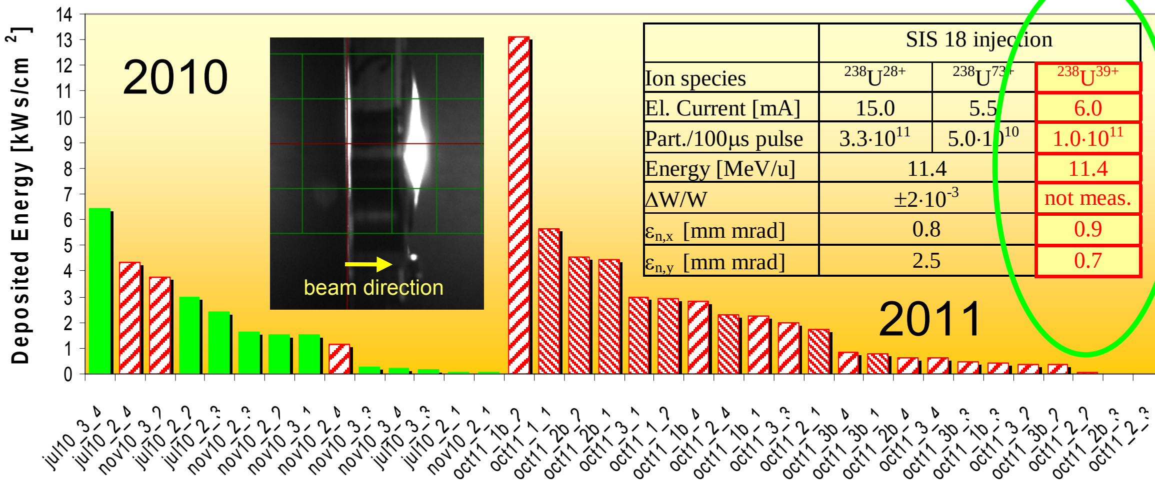
- 4d-Strahldynamik Untersuchungen zum Erreichen der FAIR-Anforderungen
- Simulationen vielversprechend, Exp. in Planung
- Besseres analytisches Verständnis angestrebt
- positiver Effekt bzgl. der Korrelation beobachtet, aber analytisch noch unverstanden
- Modellierung von Strahlführungen in 4d mit MAD-X Code

Hochstrom-Ionen-Stripping (Kohlenstoff-Folien)

1.4 MEV/U FIXED CARBON FOIL



Foil stripper before (bottom) and after (top) high current operation. For the second foil (top, from the right) 11 kJ of beam energy were deposited without any observed influence on the beam parameters.



3.6 MeV/u
rotating wheel

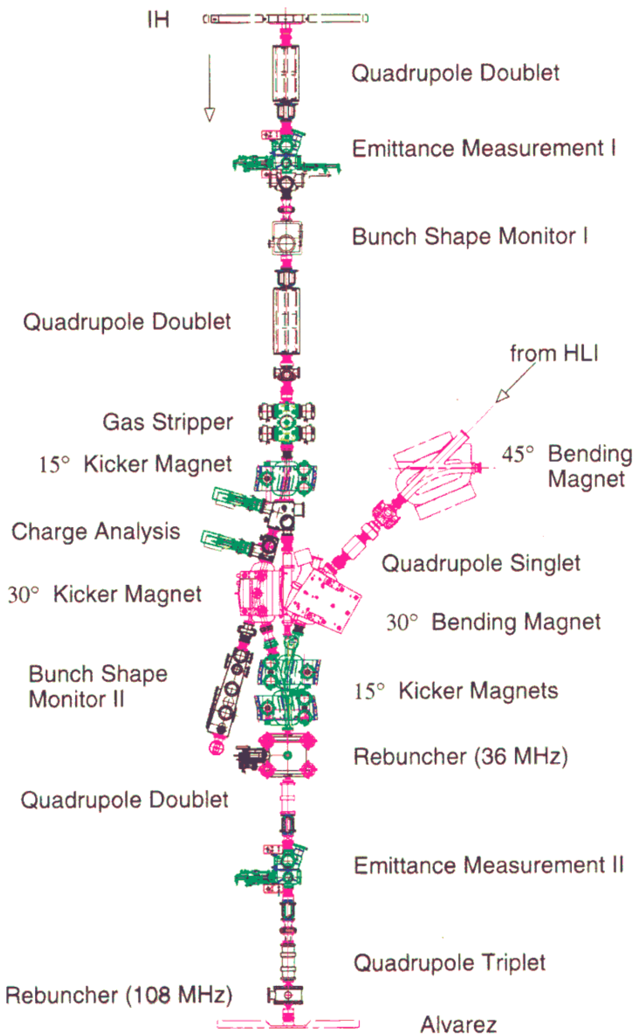
SHIP

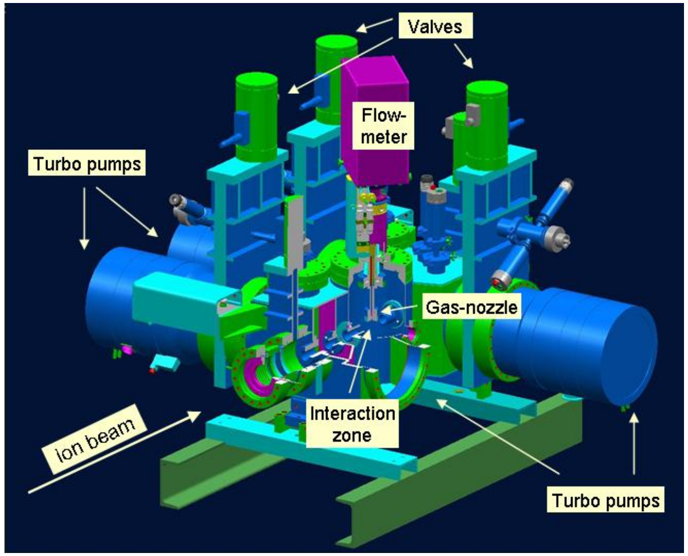
TASCA

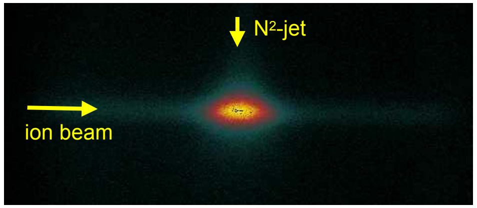
2012

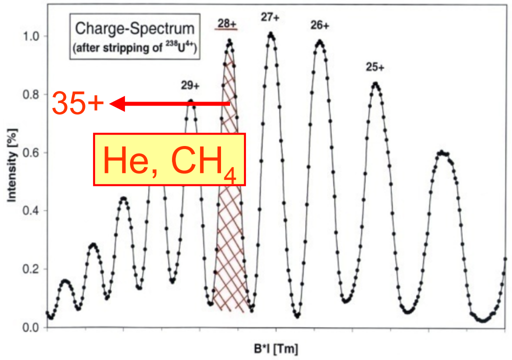
Experiment	SHIP 2012	TASCA 2012	Strippersection 2010
Energy	3,6MeV	3,6MeV	1,4MeV
foil density	20µ/cm²	30µg/cm² /20µg/cm²	20µg/cm²
Frequency	2Hz	50Hz	1Hz
ion species	U28+	Au25+	U4+
ion current	2,5emA	4eµA	5emA
pulse length	100µs	3ms	100µs
irradiation time	48h	24h	ca. 12h
beam size	3,14cm²	ca. 3cm²	3,14cm²
number of segments	8	4	4x1
particles/pulse	5,573E+10	2,996E+09	7,802E+11
particles/second	1,115E+11	1,498E+11	7,802E+11
particles/second and segment	1,393E+10	3,745E+10	7,802E+11
tot. intensity	3,16E+15	4,00E+15	3,464E+16
tot. intensity/segment	3,95E+14	1,00E+15	3,464E+16

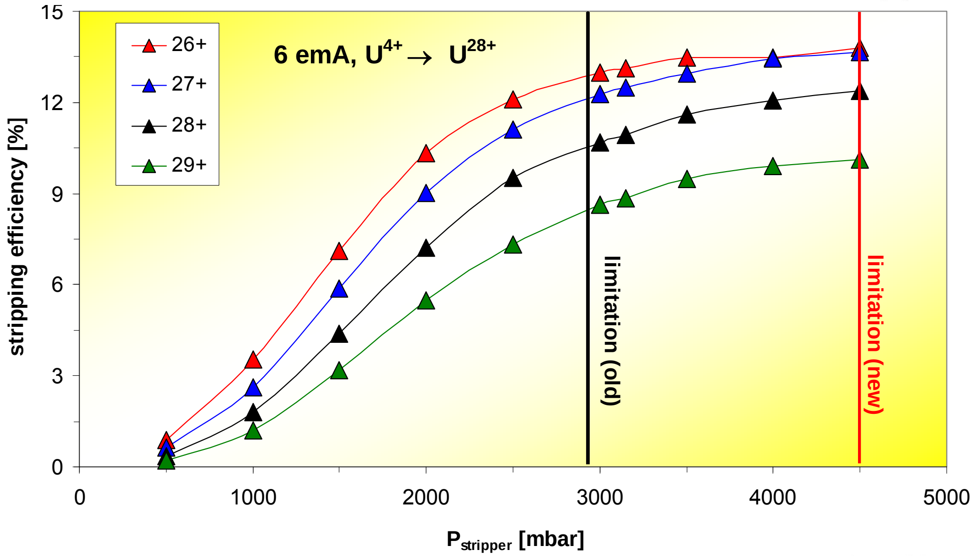
gas stripping (1.4 MeV/u)





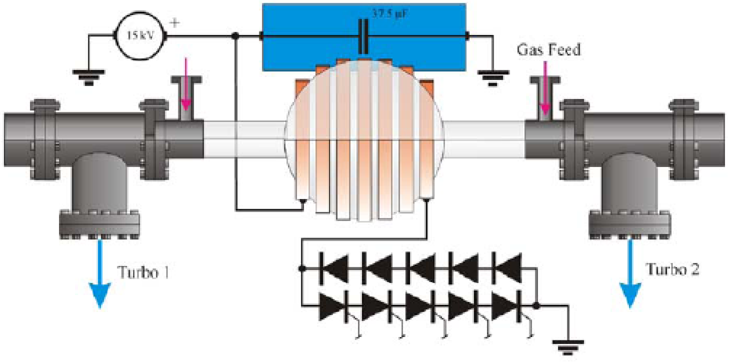




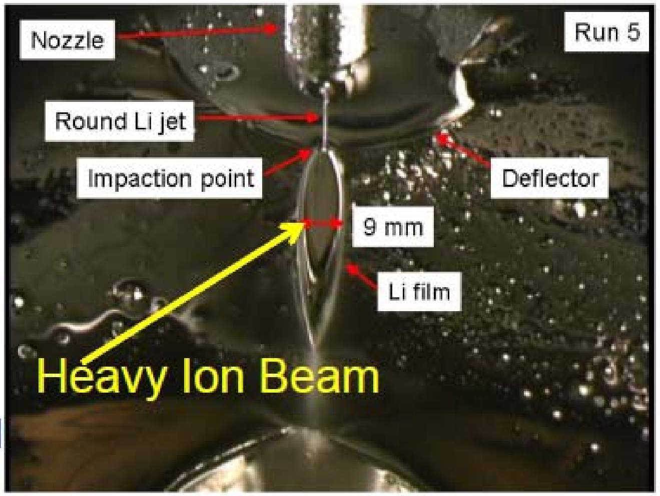


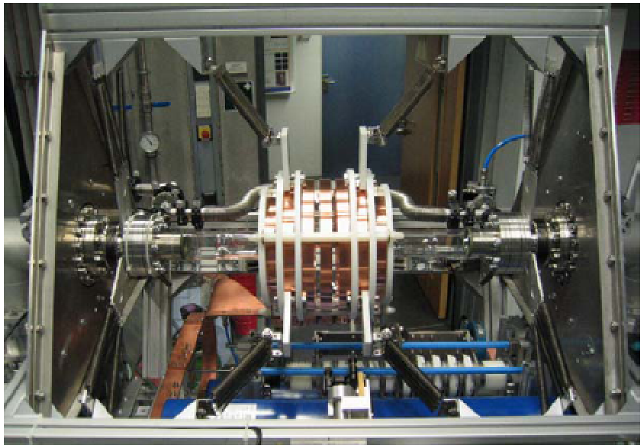
Plasma-Ionen-, Flüssig-Lithium-Stripping

- Limitierung der erreichbaren Ladungszustandes durch Rekombination mit Elektronen des Mediums
- Rekombinationsrate deutlich verringert, falls diese Elektronen frei sind, z.B. in einem Plasma
- Plasma-Stripper sind evtl. Alternative zu existierenden Medien
- Untersuchungen erforderlich



Flüssiges Lithium

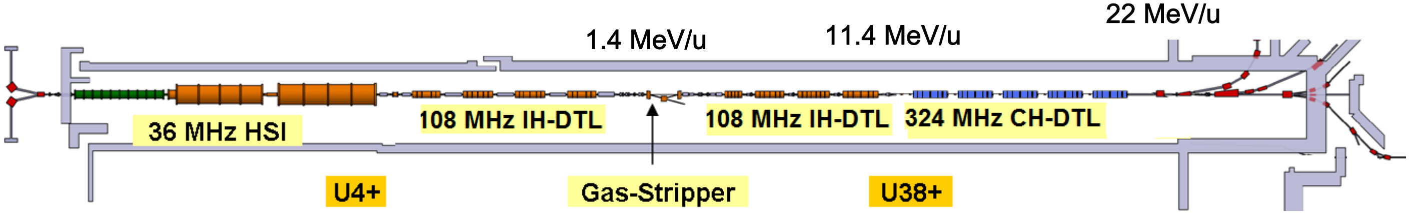




LINAC-HF

- Entwicklung 2 MW-HF-Endstufe (HE-LINAC)
- Erneuerung 108 MHz-Phasenachse

HF-Sender Prototyp, 108 MHz, 1.8 MW



High Energy Linac

- Entwicklung eines HF-Hochleistungssender für HE-Linac (2 MW)
- Prototype (-komponenten) teilweise beauftragt
- Systematische Tests, Verbesserungen, ...
- Darauf aufbauend:
  - Vorbereitung der Serienbeschaffung
  - Auslegung einer neuen HF-Gallerie

Hochfrequenz

Design-Ion	$^{238}U^{28+}$	
A / q	8,5	
Eingangsenergie	1,4	MeV/u
Endenergie	ca. 11,4 – 12	MeV/u
Ionenstrom	15	mA
Transv. Strahlemittanz am Ende, normiert	1	π mm mrad
Gesamte Beschleunigungsspannung	ca. 85 – 90	MV
Anzahl IH-Beschleunigungstanks	ca. 6	
Tanklängen IH-Tanks	1,6 – 3,5	m
Max. Beam Loading pro IH-Kavität	ca. 300	kW
Max. HF-Verlustleistung pro IH-Kavität	≤1,2	MW
Strahlpuls-Wiederholrate	4	Hz
Strahlpulsdauer	100	µs
Betriebsfrequenz	108,408	MHz
HF-Pulswiederholrate	≥4	Hz
HF-Pulsdauer	1	ms
HF-Tastverhältnis	≤1	%
HF-Pulsleistung	1800	kW
Mögliche Verstärkerröhre	TH 558 SC	

TU Darmstadt

Master Oszillator UNILAC HF 108,408 MHz

Erneuerung der UNILAC Phasenachsen
108 und 36 MHz auf DDS Basis

Begründung:
Die derzeitig betriebene Hardware zur Erzeugung der beiden Betriebsfrequenzen 108 MHz und 36 MHz in PLL Technik hat zeitweise Synchronisationsprobleme.

Status: nicht begonnen

LINAC-Strahldiagnose

- Development of pepperpot emittance measurement device; Advantage: Single shot measurement, Coupling between horizontal & vertical plane detectable, Investigations of screen materials, simulations concerning straggling and resolution
- Screen investigations for profile measurement and pepperpot emittance; Investigations: Beam based tests for various screen materials and beam properties; physical understanding of related processes incl. radiation hardness, evaluation of most suited material
- Bunch shape determination with particle detectors; investigations: Best suited detector type, experimental and theoretical tests for timing properties of detector

Emittance Measurement: Pepper-Pot Method

Advantage:

1. Single-pulse device → shorter measurement time

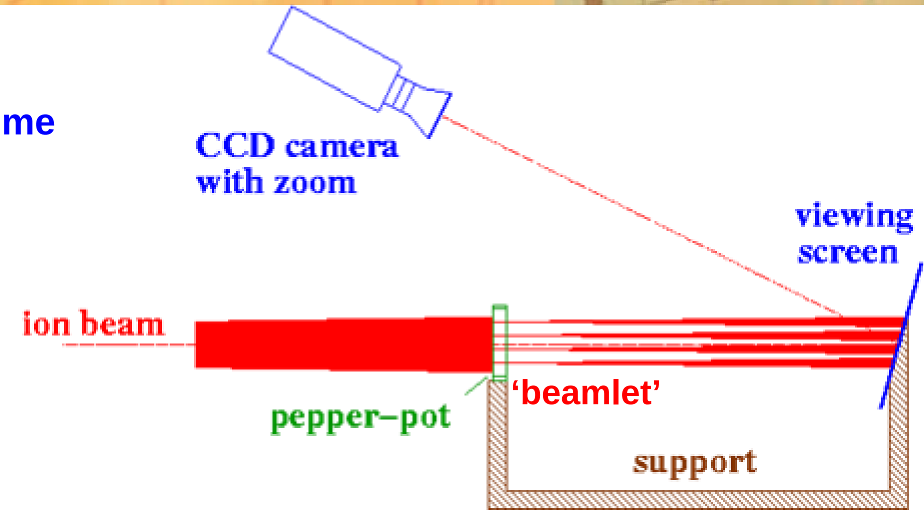
2. Horizontal – vertical coupling detectable!

Pepper-Pot:

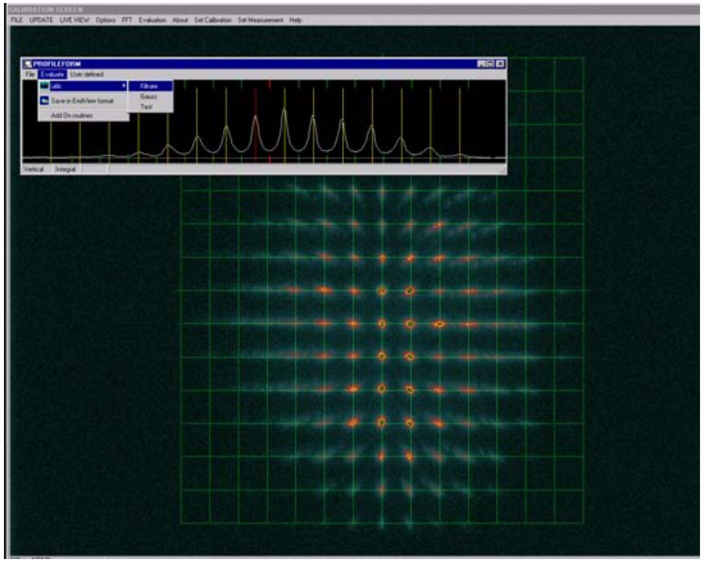
48x48mm² Cu-plate, 15x15 holes Ø0.1mm

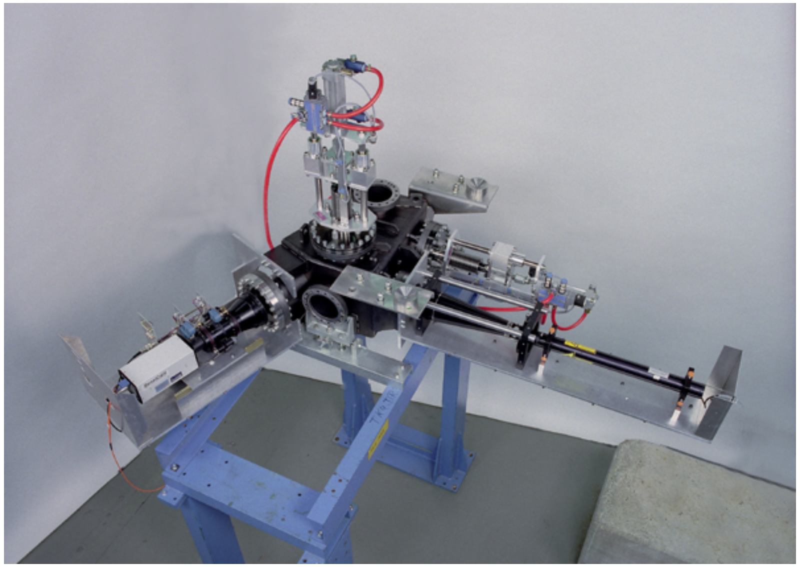
For high current operation

careful R&D concerning scintillation-screens!



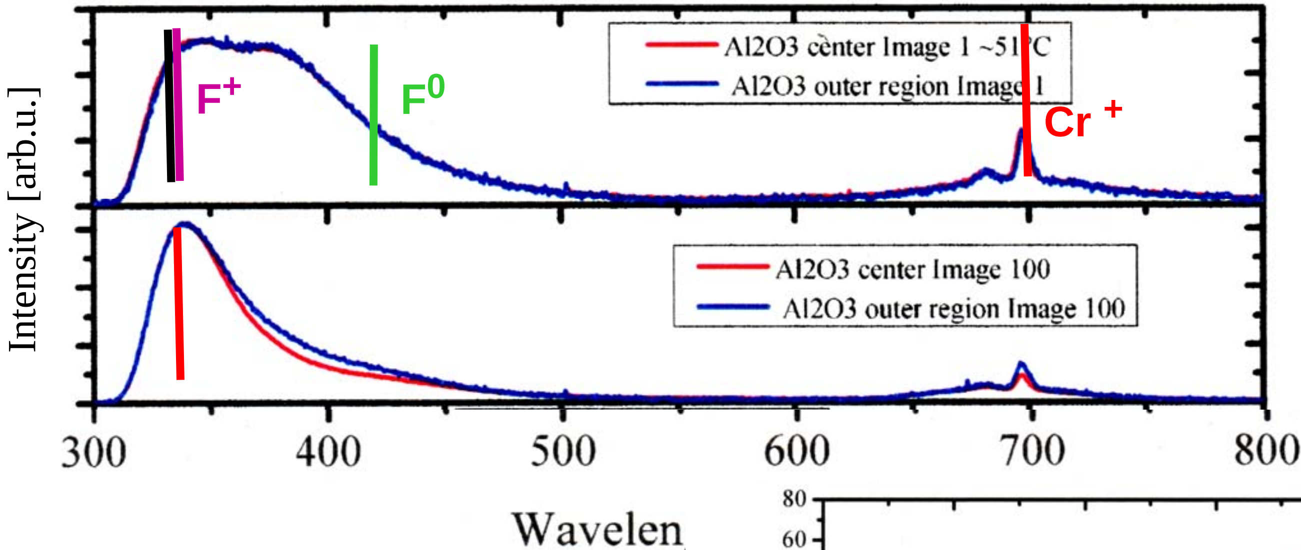
Example: Ar^{1+} at 1.4 MeV/u





Example of Screen Investigations for Pepper-Pot

Example for investigations: Wavelength spectra and image reproduction for Al_2O_3



Beam parameter:

30 μA Ca^{10+}, 4.8 MeV/u

5×10^{10} ppp, P_{peak}=0.6 kW

duration 3.3 ms, 30 μA

Spectrum influenced by:

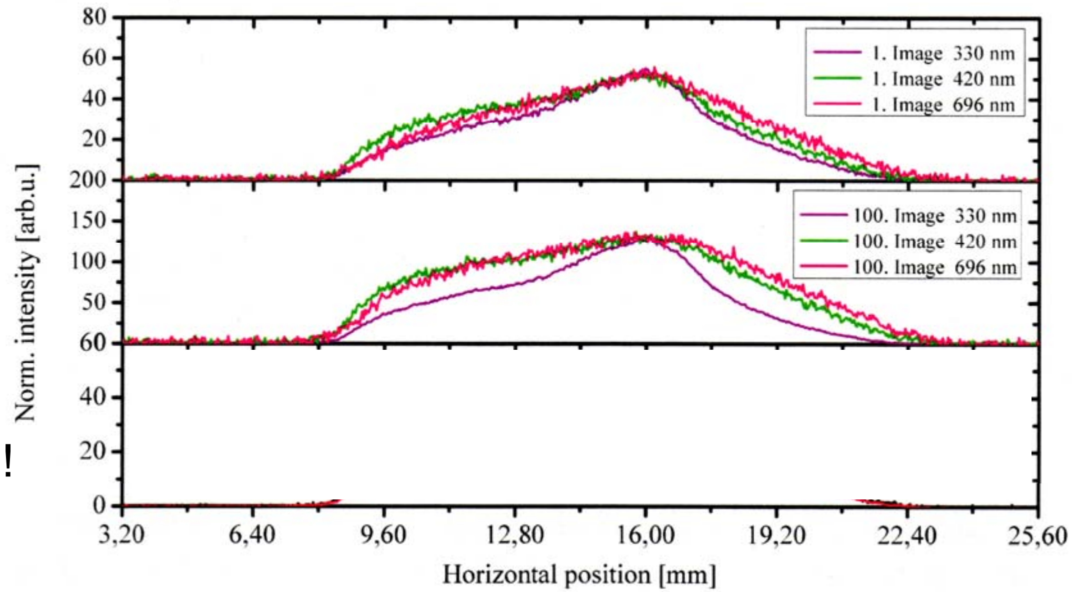
- Temperature
- Material modification by ions

Unexpected:

Some transitions are less sensitive

Here: color center F^+ with τ=2ns

Goal: Find right wavelength interval!

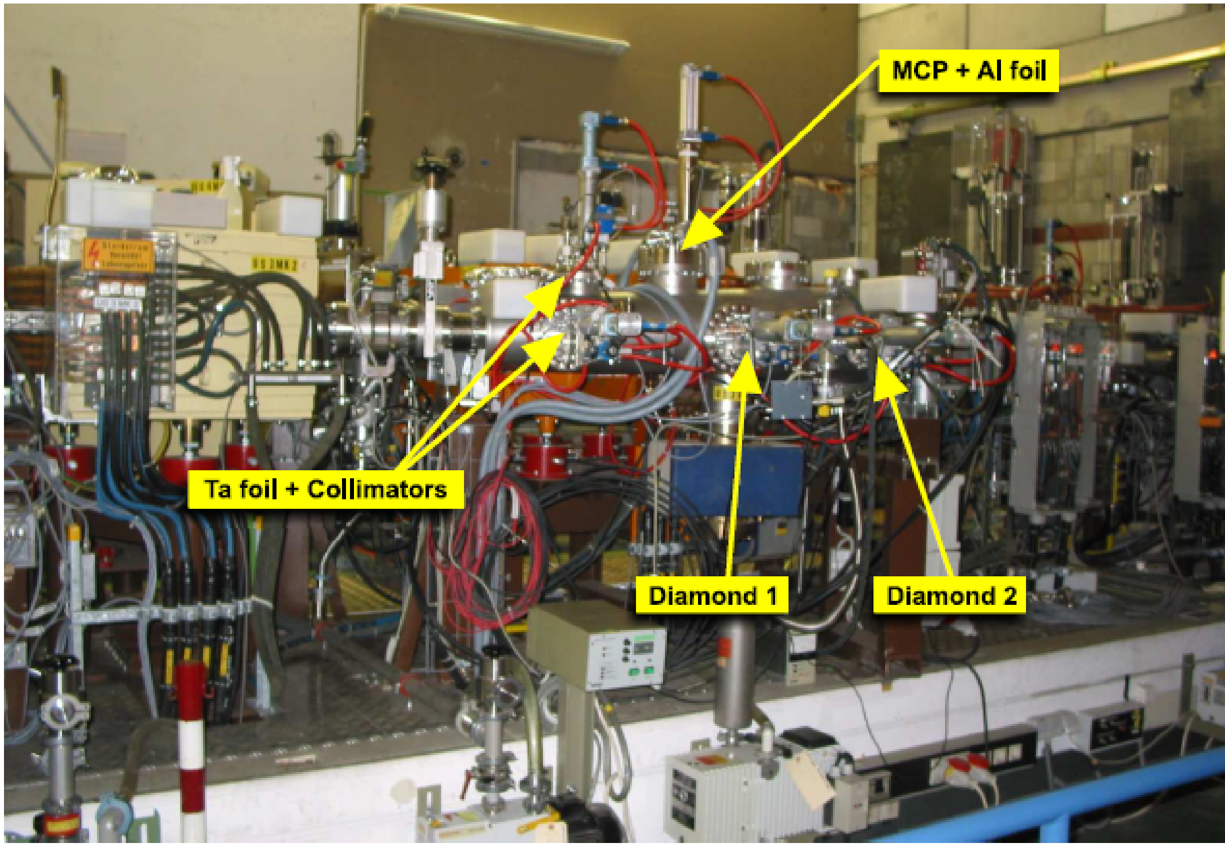


Collaboration with TU-Darmstadt **et al.**

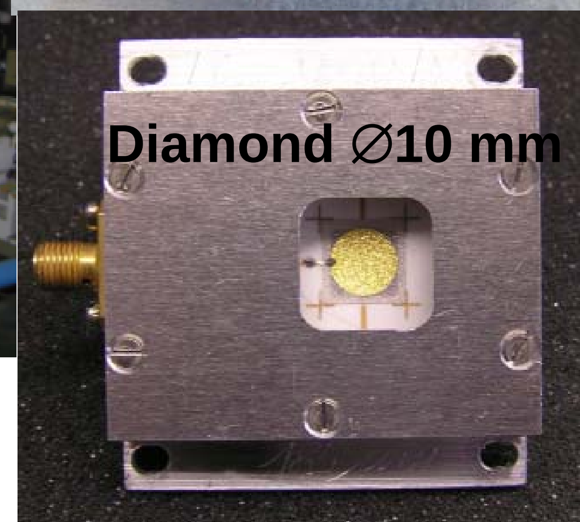
E. Gütlich (GSI) et al., Proc. DIPAC‘11

Precursor Installation at UNILAC

◄ RFQ, IH1, IH2 @ 36 MHz **Beam** ► Alvarez @ 108 MHz ►



MCP ∅18 mm



T. Milosic (GSI) et al., Proc. DIPAC'09

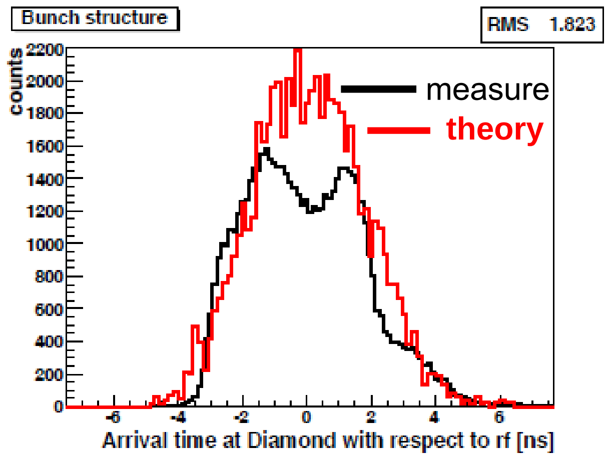
Example of Measurement for longitudinal Emittance

Phase space measurement:

Particle detection, ≈10 min

Result:

- Non-Gaussian bunch shape,
- Gaussian energy distribution
- Comparison to theory:
- Too low correlation α

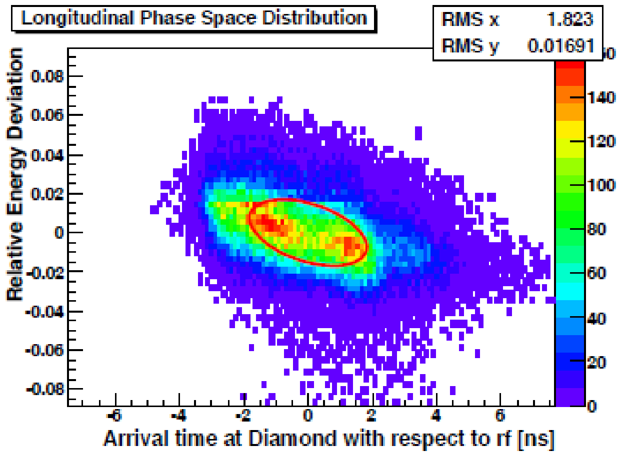


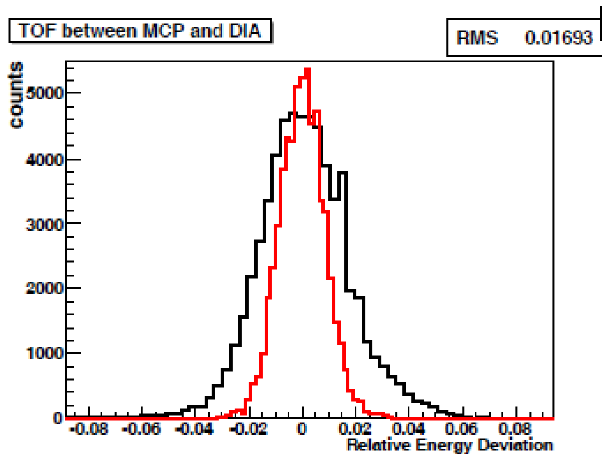
Beam parameter:

Ar $^{11+}$, 1.4 MeV/u

Resolution:

- Very good for bunch shape
- Sufficient for total energy
- In-sufficient for phase space
- Energy-/Time-res. to be optimized
- Improvements possible
  by new detector materials





T. Milosic (GSI) et al., Proc. DIPAC'09