Development for (heavy ion) injector linacs

W. Barth, GSI, HIM (G. Clemente, B. Schlitt, W. Vinzenz)

- Motivation
- Heavy ion high energy linac injector
- Key components (rf-structures, high power rf-amplifier)
  - nc IH-cavity
  - nc CH-cavity
- Linac injectors @ GSI
- Future options
- sc CH-DTL
- Outlook

Motivation

A Modern High Power Injector...

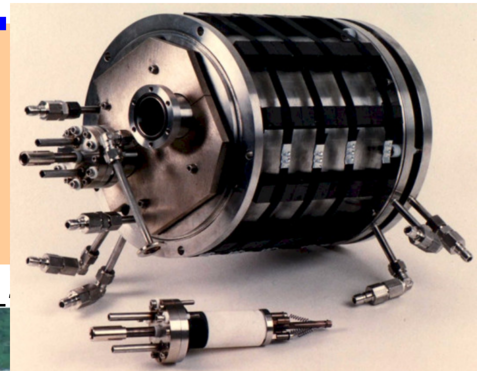
- should be...
  - compact
  - high efficient (rf-power consumption)
  - cost saving in production and operation
- should provide beam of...
  - High Intensity (minimum particle loss)
  - High Brilliance
- LINAC parameters (e.g. final beam energy, beam current and charge) should be fixed with respect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

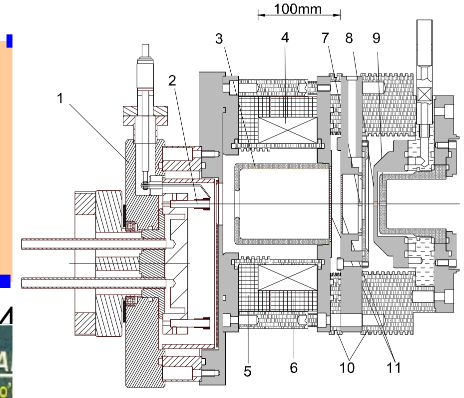
Heavy Ion High-Energy Linac Injector

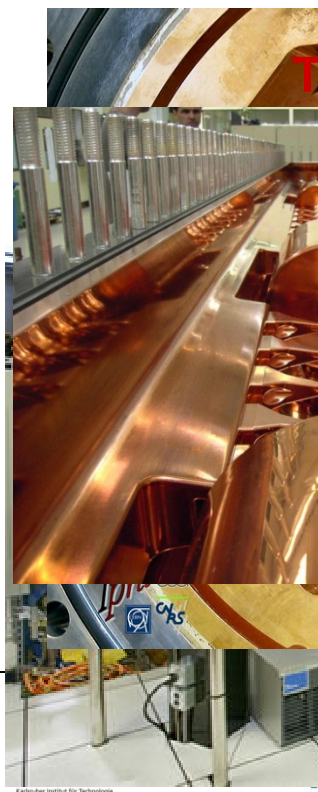
Typical Layout for a room temperature injector

ION SOURCE	RFQ
ECR (H+, heavy ions at higher charge states) MEVVA (metal) MUCIS (gas)	4-Vane 4-Rod

2-3 100- 4)

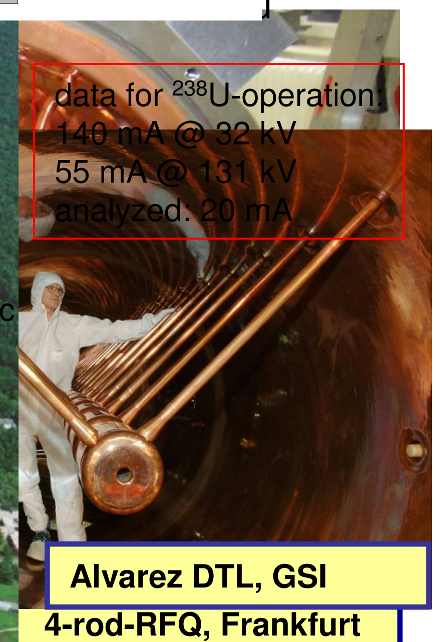






GSI-MUCIS
(Multi Cusp Ion Source)
ion source for gaseous ion production (emission current density up to 150 mA/cm²)

GSI-MEVVA
(Metal Vacuum Vapor Arc Ion Source)
Ionenquelle zur Erzeu-gung von Metallionen (Emissionsstromdichte bis 170 mA/cm²)



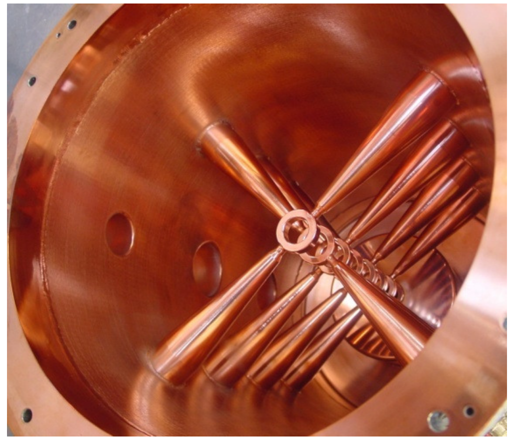
data for ^{238}U-operation:
140 mA @ 32 kV
55 mA @ 131 kV
analyzed: 20 mA

Alvarez DTL, GSI

4-rod-RFQ, Frankfurt

VENUS ECRIS BNL

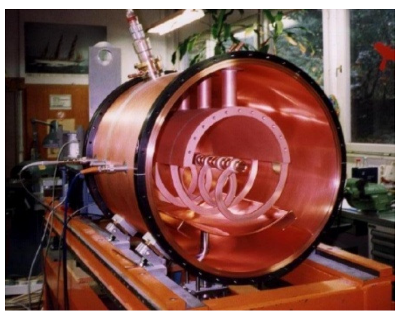
Room temperature DTL for low and intermediate energy



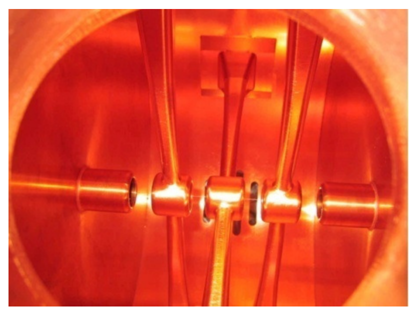
Goethe University Frankfurt/IAP

GSI

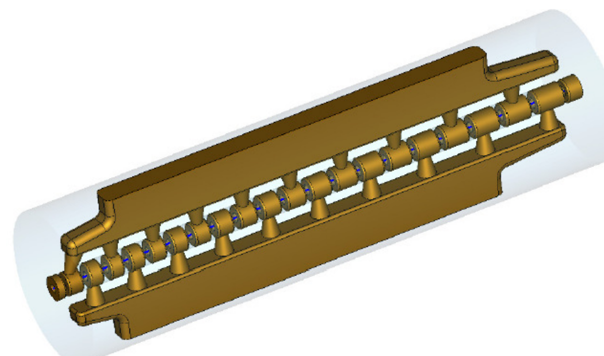
CERN



MPI-HD (7gap-res.)



FNAL (CH)



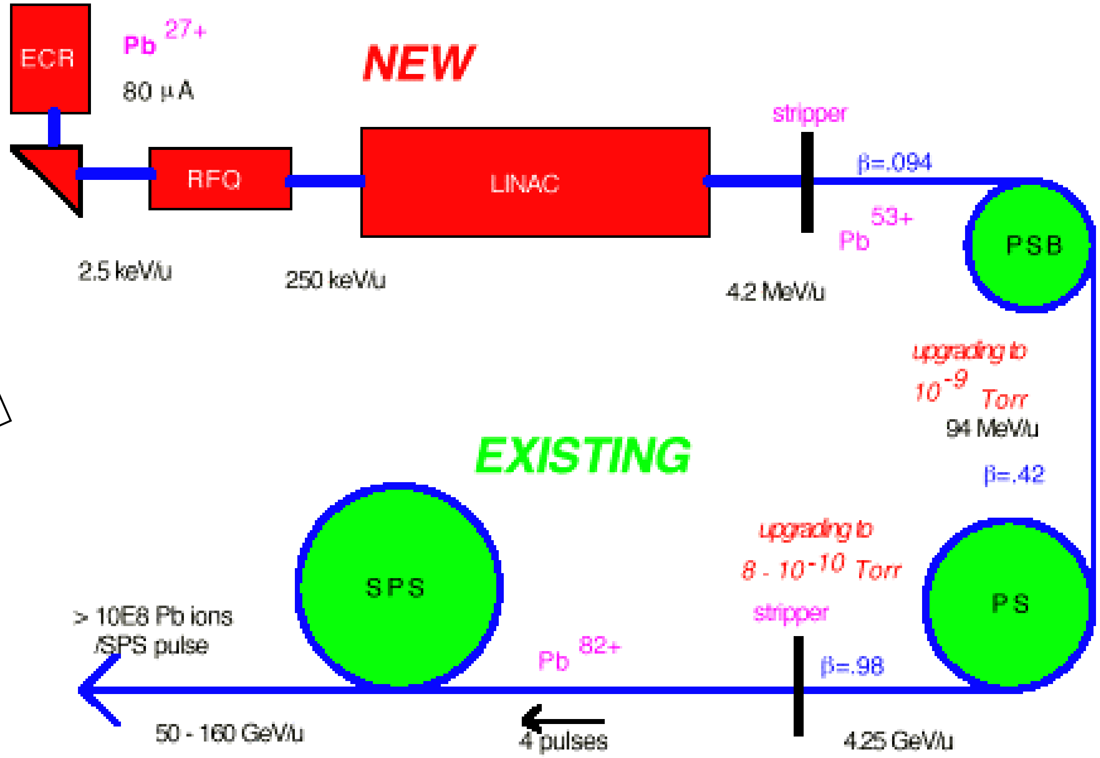
LANSCE (100 MeV-DTL)

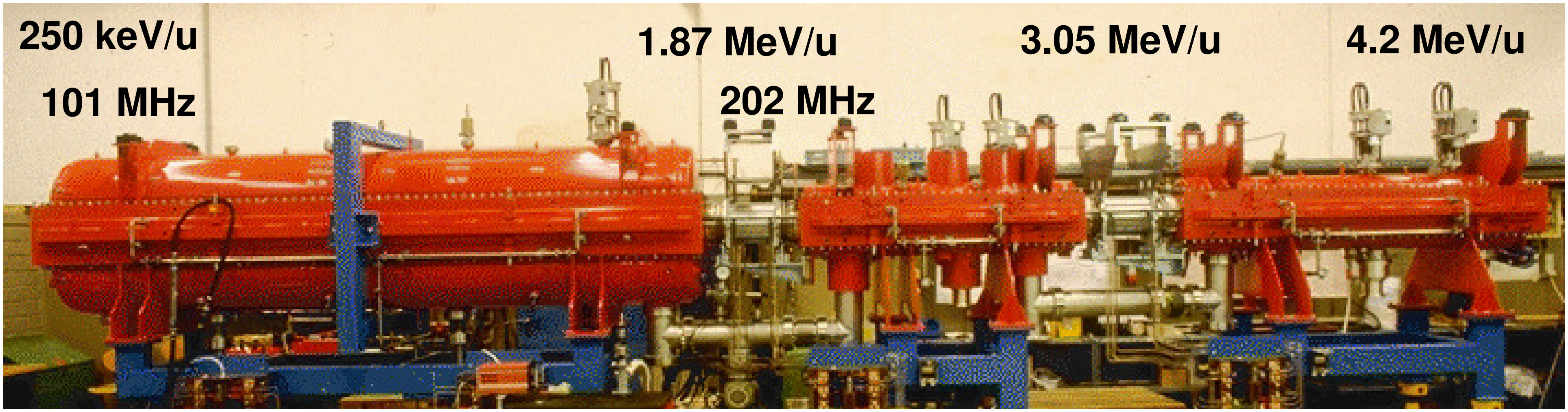
Example of a heavy ion linac injector

CERN LINAC 3:

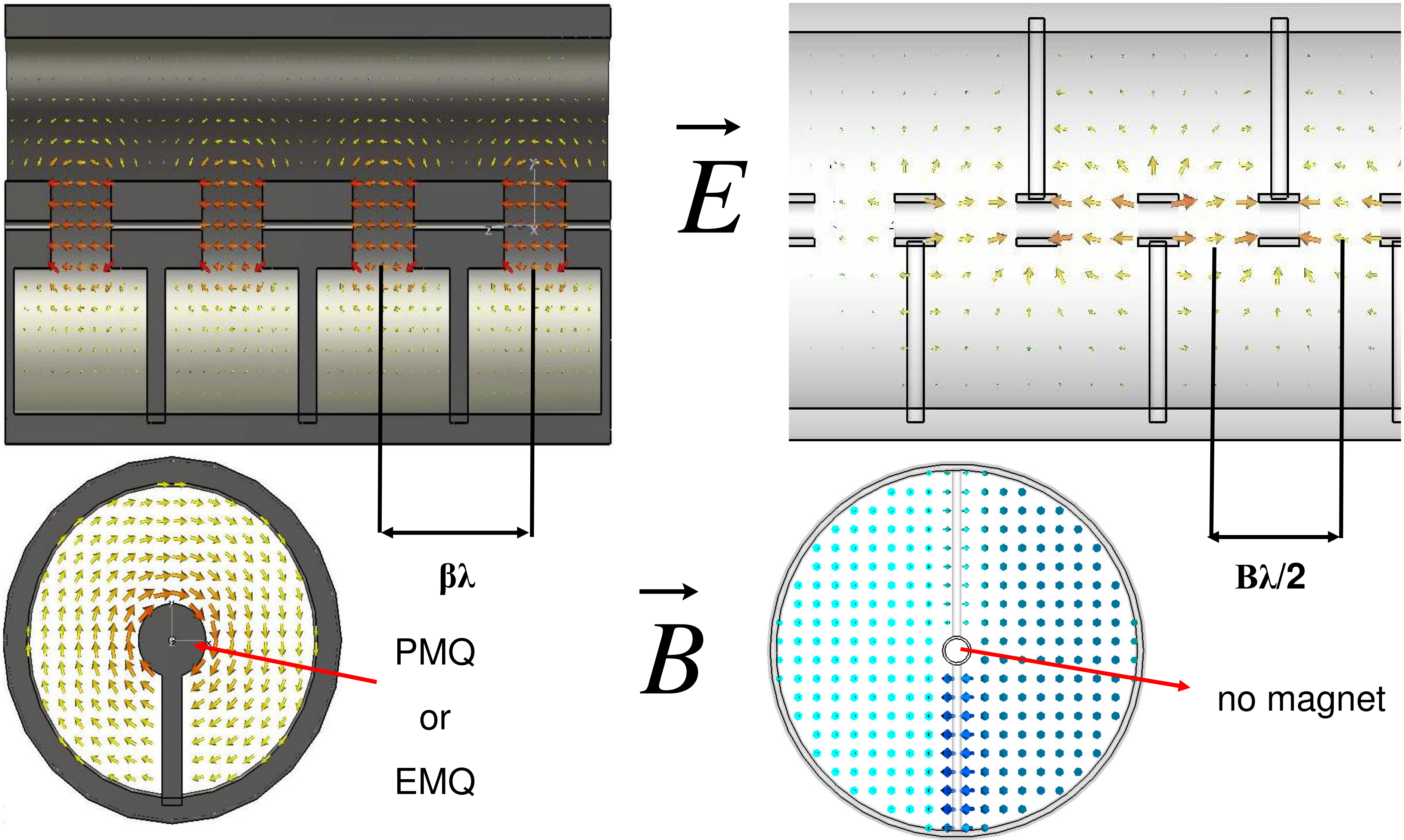
Pb^{27+} Injector for the PSB

RFQ+ IH Combination



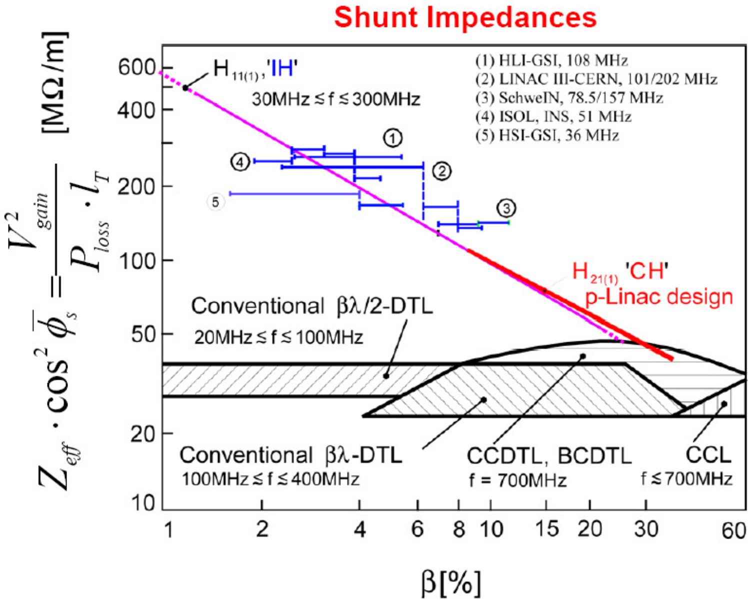


Key Component: E-Mode DTL vs H-Mode DTL

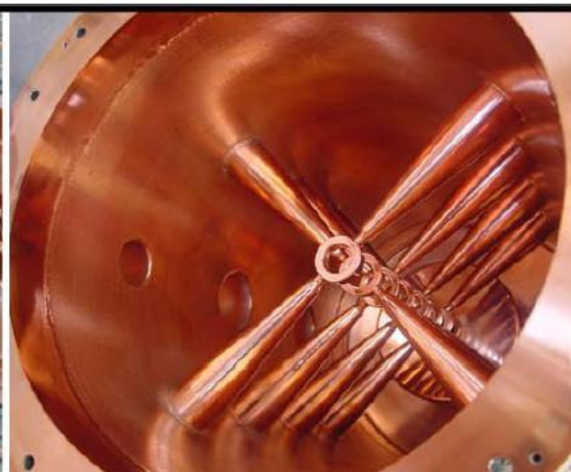


Key Component: H-Mode DTL

- Compactness
- Simplified Mechanical Design
- Reduced number of quadrupoles
- Higher RF efficiency and Stability
- No need of post-couplers
- Low construction and operational costs



Room Temperature IH-DTL



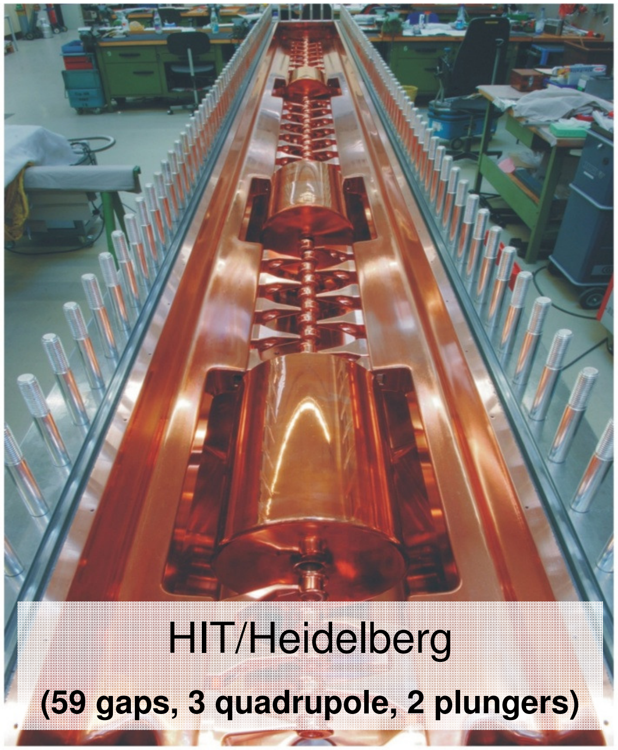
Room Temperature CH-DTL

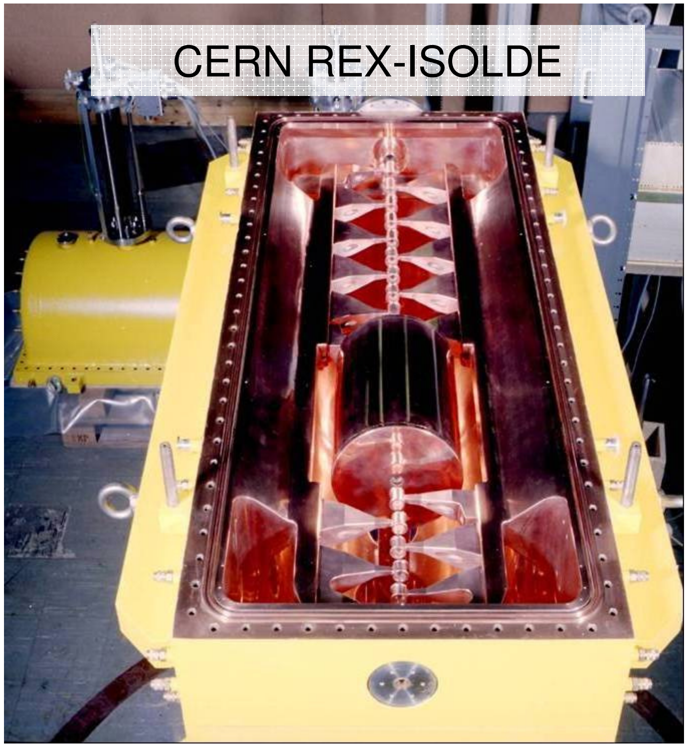
Superconducting CH-DTL

Room Temperature IH-DTL

Range of Operation: $0.01 \leq \beta \leq 0.2$, $30\ \text{MHz} \leq f \leq 220\ \text{MHz}$

- **Established as standard solution for heavy ion acceleration**
- **For $\beta \leq 0.1$ even competitive with s.c. structure at identical accelerator length**
- **In operation at GSI, CERN, BNL, TRIUMPH, HIMAC, HIT, CNAO**
- **High Current operation demonstrated at the HSI at GSI**
- **Limited number of RF tuners (1-2 per cavity) No postcouplers required**

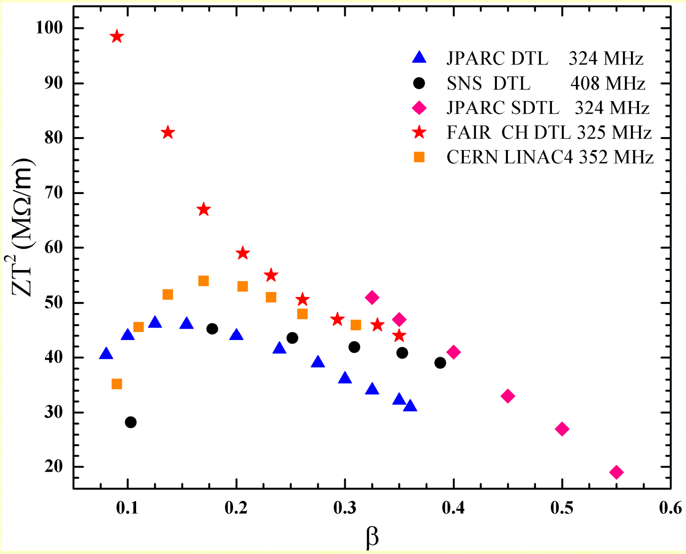

HIT/Heidelberg
(59 gaps, 3 quadrupole, 2 plungers)


CERN REX-ISOLDE

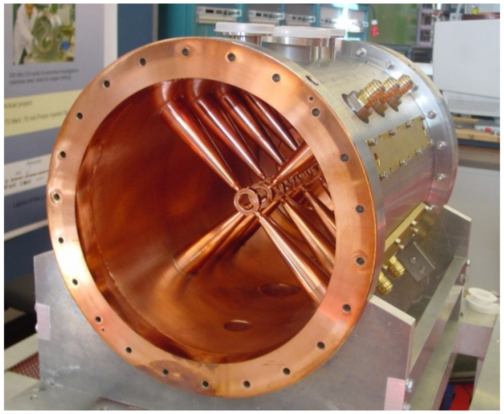
Room Temperature CH-DTL

Range of Operation: 0.08 ≤ β ≤ 0.45, f ≥ 170 MHz

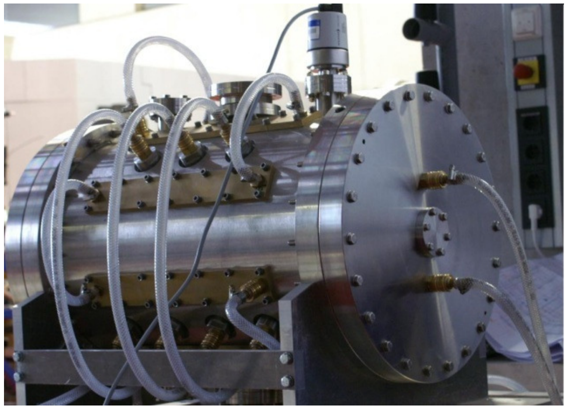
- Higher RF efficiency for β ≤ 0.2
- Possibility of Coupled Structure at low β
- Very long lens-free section for β ≥ 0.25
- Intensive R&D performed at IAP and GSI
- Adopted at FAIR, Project-X and LANSCE
- First Coupled Structure in production
- High Power RF test foreseen in 2012 at GSI



Successful copper plating

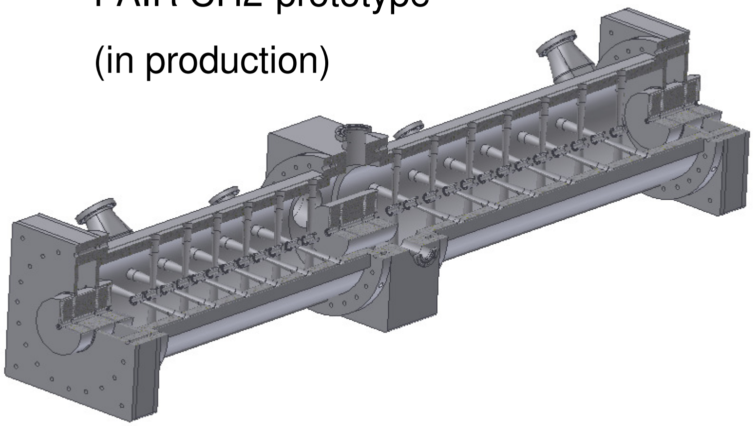


2 kW (cw)-test at IAP



FAIR CH2-prototype

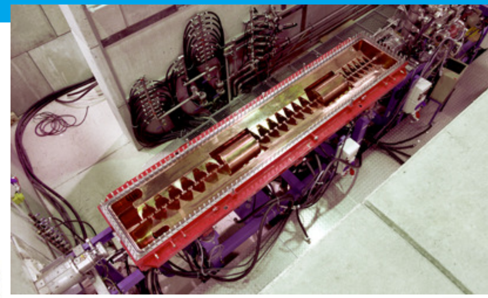
(in production)

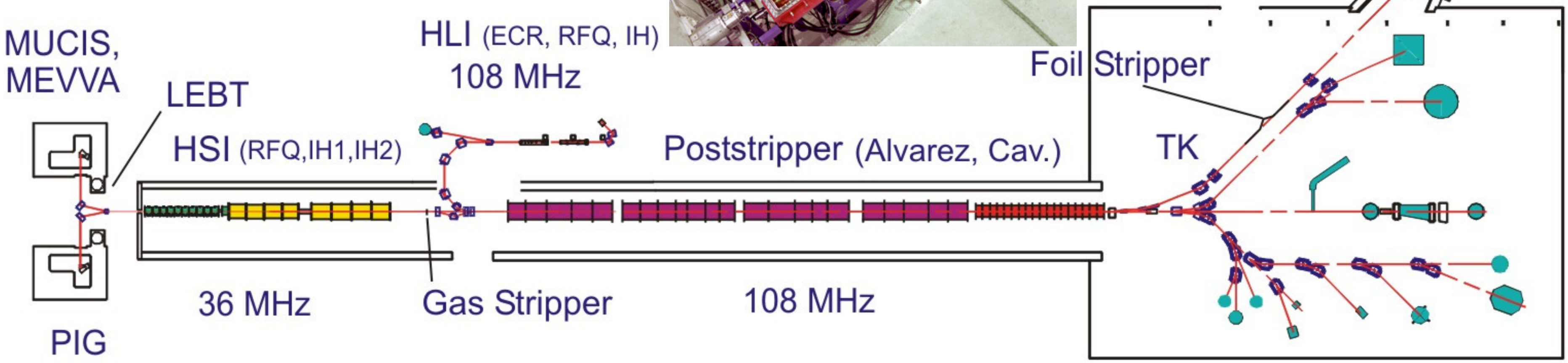


DESY KIT GSI HZDR HZB Helmholtz Zentrum Berlin HELMHOLTZ GEMEINSCHAFT

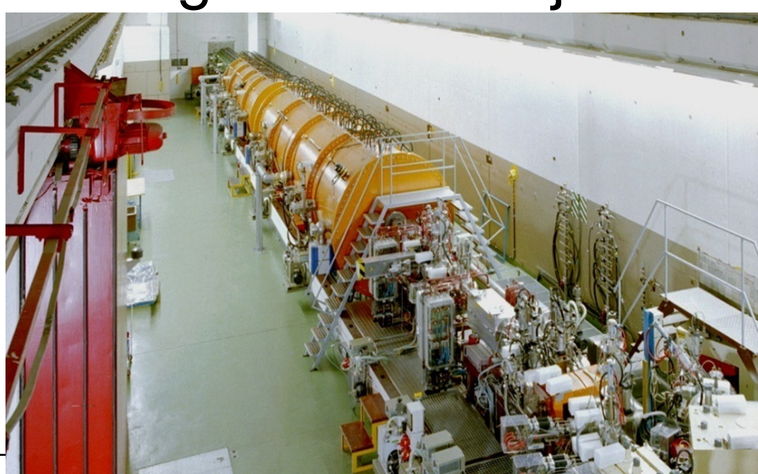
GSI UNIversal Linear ACcelerator

High Charge State Injector

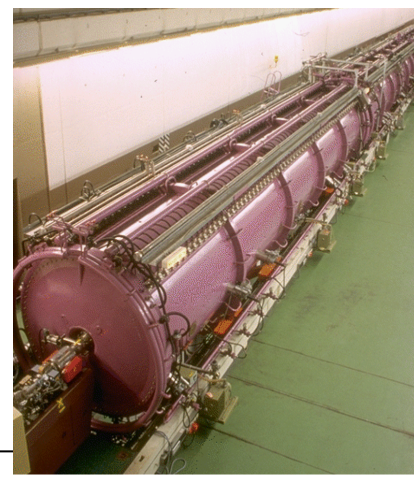




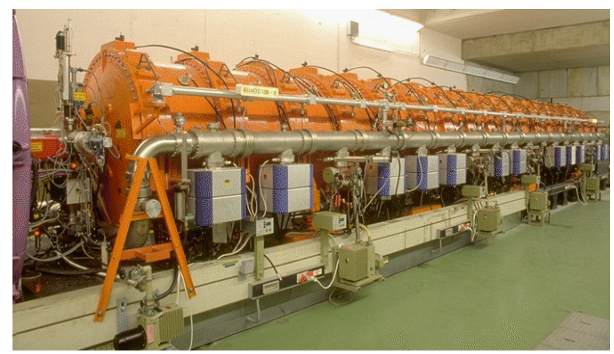
High Current Injector



Alvarez



Single Gap Resonators

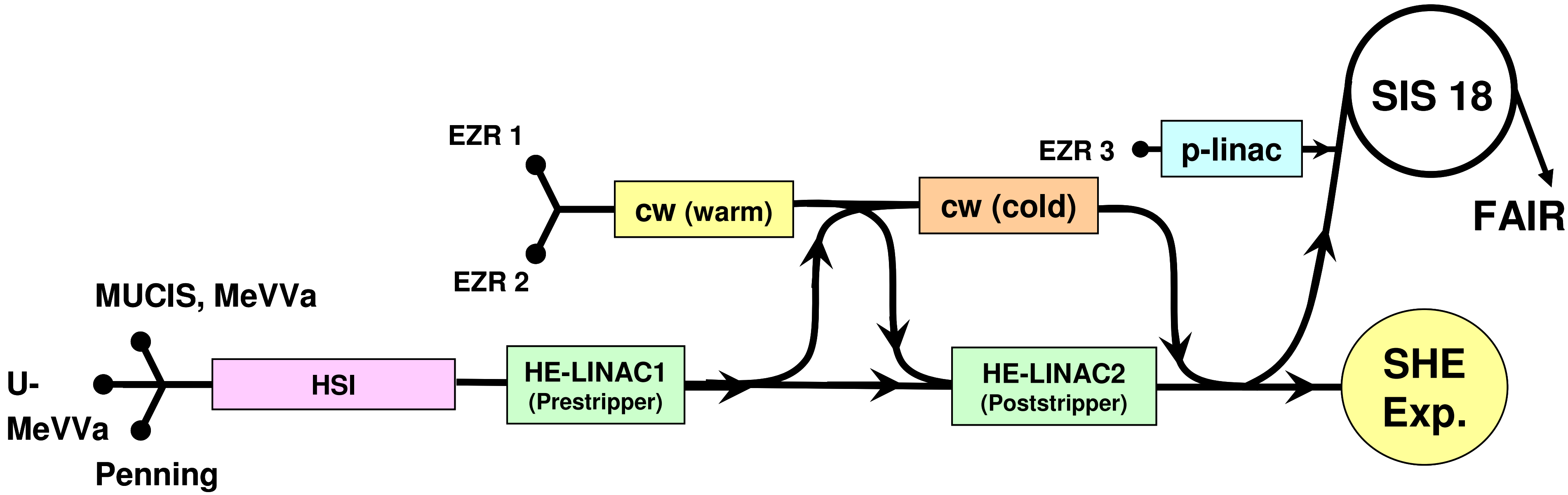


Requirements for FAIR-linac injector operation

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection	SIS 18 injection (FAIR)
ION SPECIES	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$	$^{238}U^{28+}$
El. Current [mA]	16.5	15	12.5	8.4*	15
Part. per 100µs pulse	$2.6\cdot10^{12}$	$2.3\cdot10^{12}$	$2.8\cdot10^{11}$	$1.9\cdot10^{11}$*	$3.5\cdot10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4	11.4
$\Delta W/W$	-	$\pm4\cdot10^{-3}$	$\pm2\cdot10^{-3}$	$\pm2\cdot10^{-3}$	$\pm2\cdot10^{-3}$
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8	0.8-1.1
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5	-

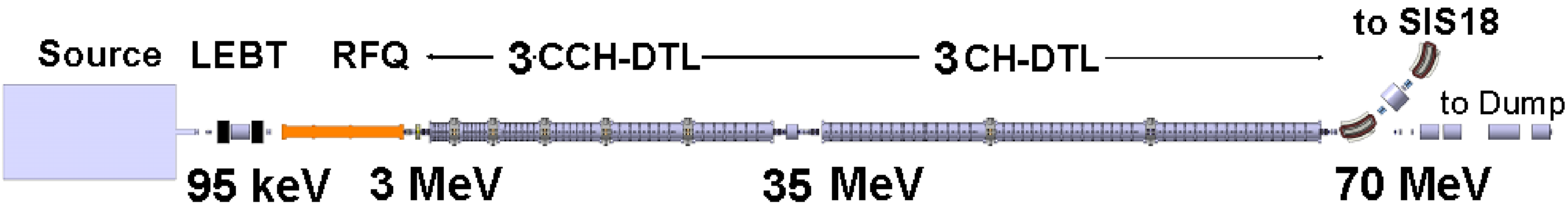
* in SIS-acceptance, as expected from multiparticle calculation

GSI-Future Option

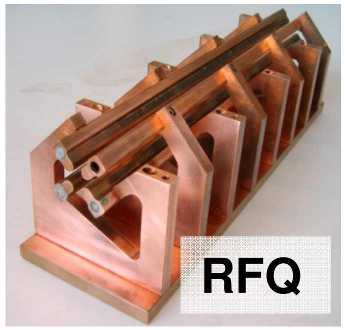


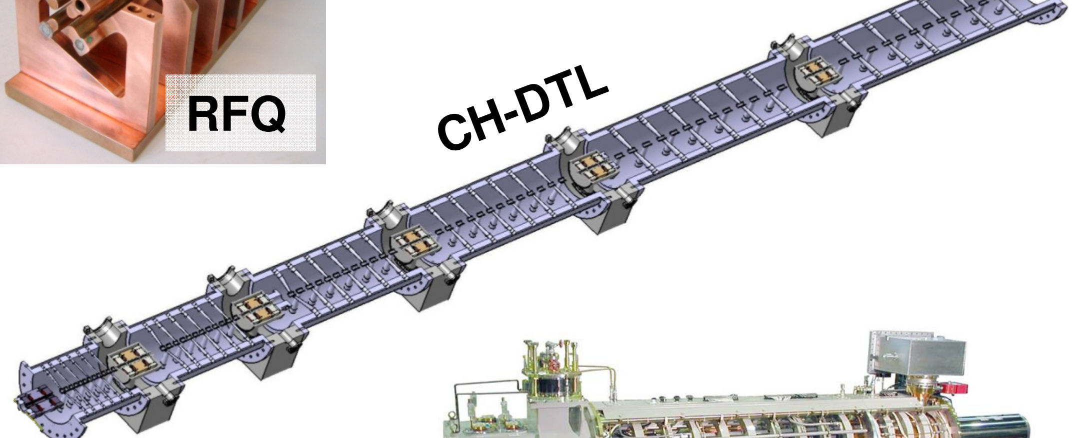
- **Proton linac-injector for FAIR**
  - 70 MeV, 70 mA, 325 MHz, 0.1% duty factor
- **High Energy injector linac (replacement of Alvarez DTL)**
  - 22 MeV/u, 18 mA, 108 MHz, 1% duty factor
  - 100 MeV/u 18 mA, 325 MHz, 1% duty Factor
- **sc-cw-linac (for Super Heavy Element program)**
  - 3.5 – 7.5 MeV/u, 1 mA, 217 MHz, 100 % duty cycle

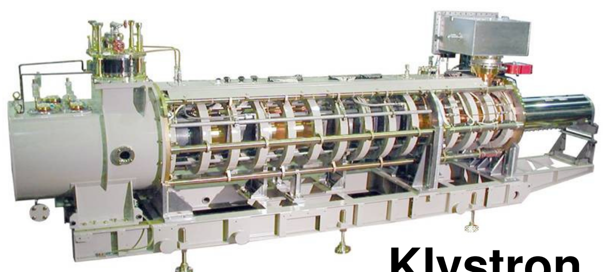
Future Option: The FAIR Proton Injector



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 / *4.2* 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







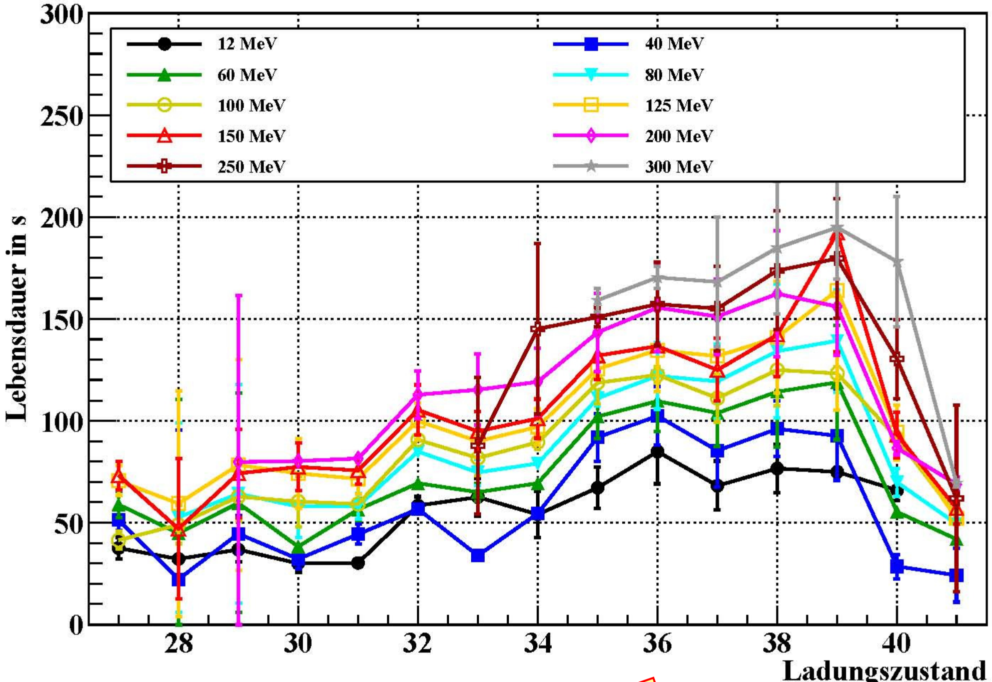
Future Option: High Energy LINAC

- **Heavy Ion Injector for FAIR:**
  - Short pulse operation (100 µs)
  - Low duty factor (< 1%)
  - Very high beam current
  - High beam rigidity
  - Multiple beam operation
- **Present Status Of UNILAC**
  - Most of the Alvarez-tank and all Single Gap Resonators in operation since 1975
  - Issues on machine reliability and maintenance ⇒ substitution of the DTL cavities
  - Operation of quadrupoles only in dc-mode
  - Limited flexibility for multibeam operation
  - Less effective for short pulse operation because of high power, high duty factor operation
    - Injection of U^{28+} (Gas-Stripper):
    - Beam losses in SIS due to charge interaction with the residual gas ⇒ Increasing of the injection energy
    - High acceleration gradient in the Alvarez DTL required ⇒ Use of H-mode DTL
    - Limited beam current for High SIS Energy due to the second stripping process ⇒ Increasing of charge state

MASSIVE INJECTOR-UPGRADE REQUIRED !

Future Option: The HE-LINAC

- 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:

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

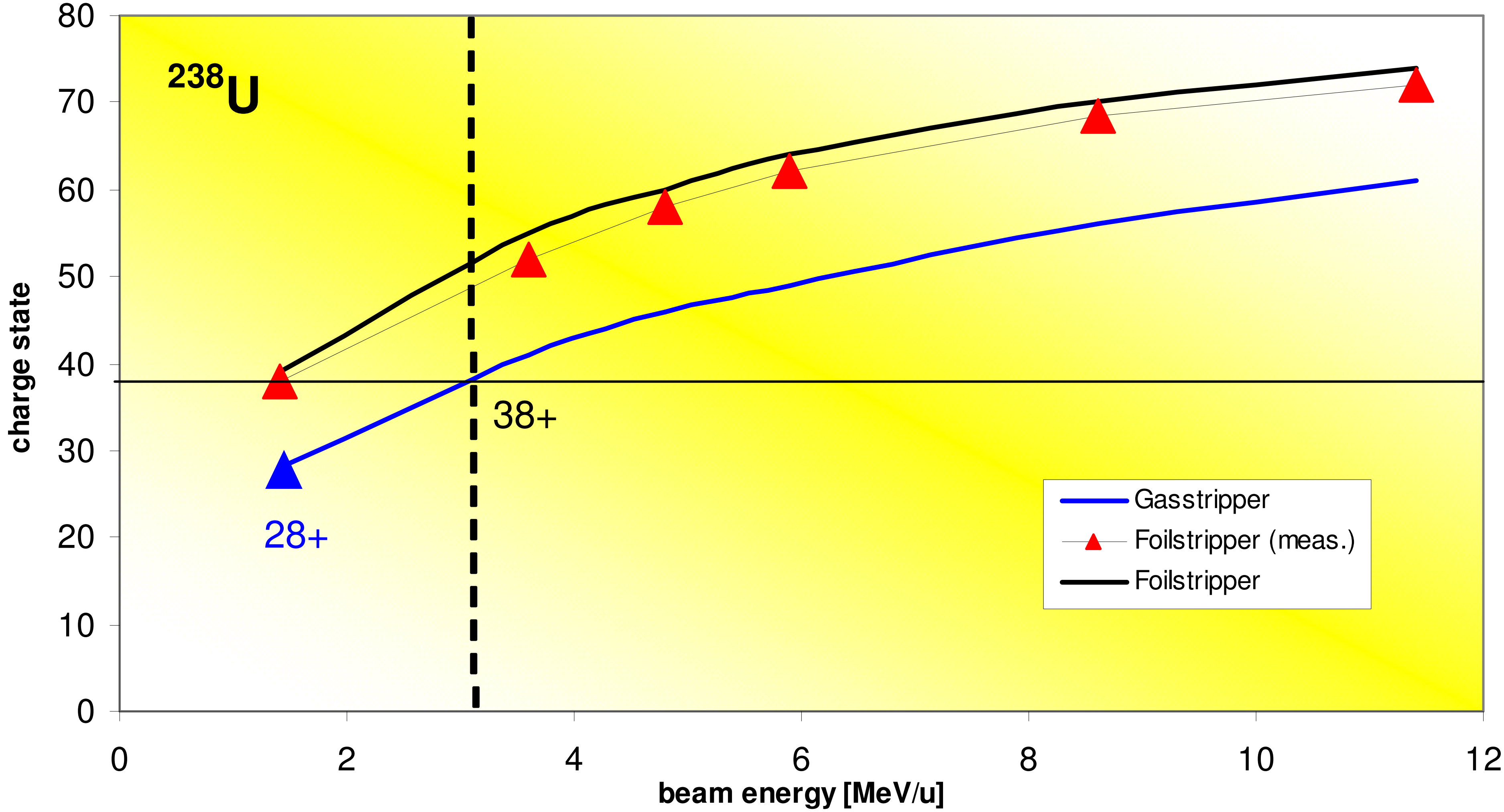
Compensation through higher injection energy:

- **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** **$\Delta Q \approx 0{,}48$**

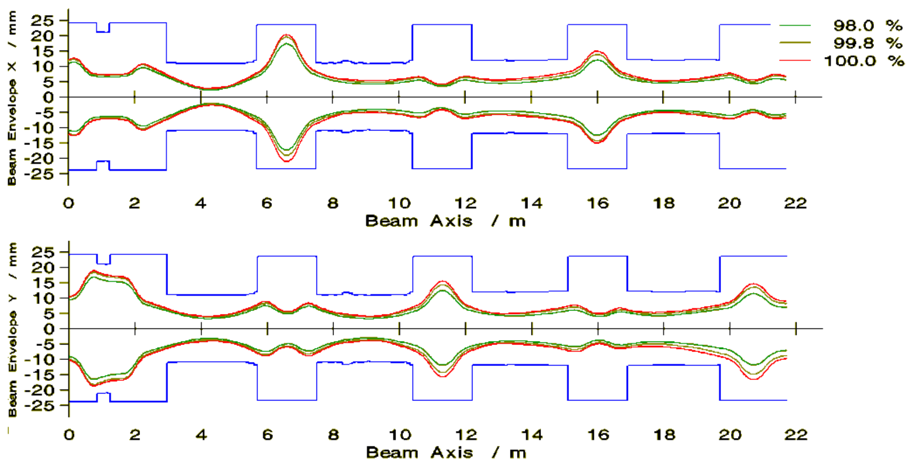
... for higher injection energy:

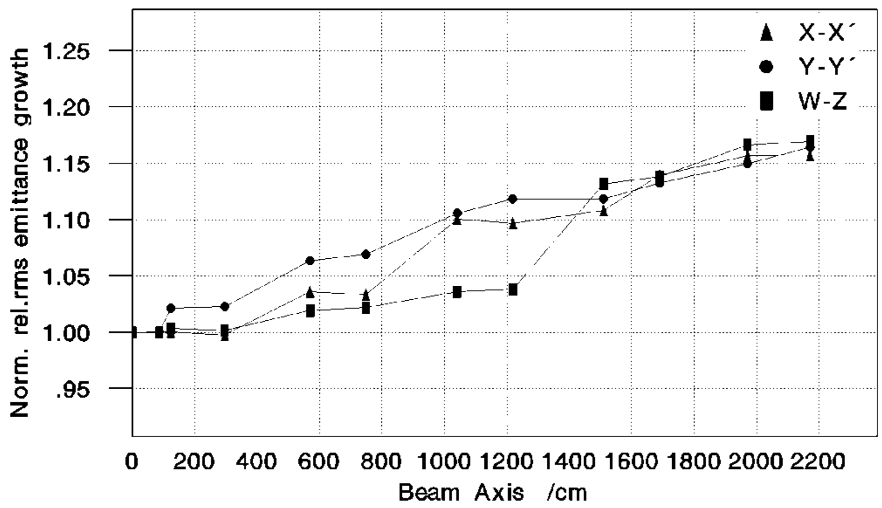
→ smaller emittance ($\propto 1 / \beta$)
→ shorter injection pulse

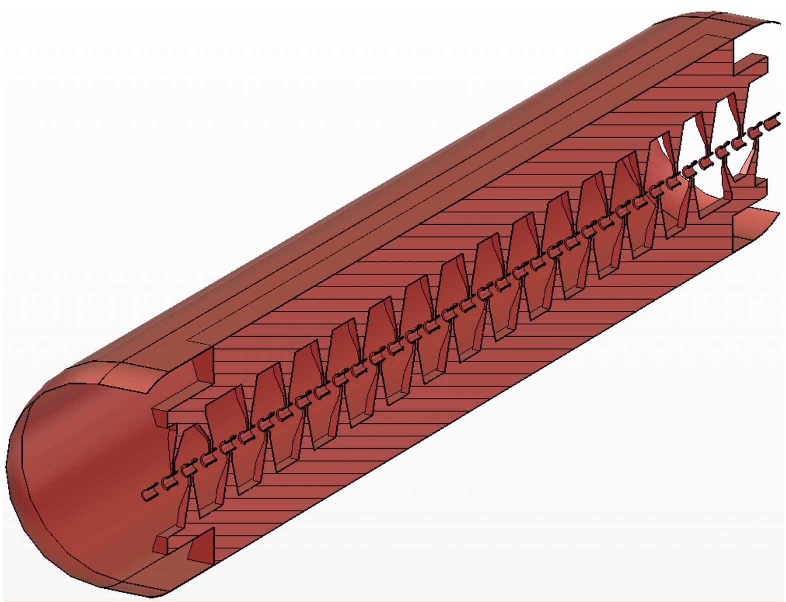
Future Option: The FAIR HE Linac



Future Option: The FAIR High Energy-Linac



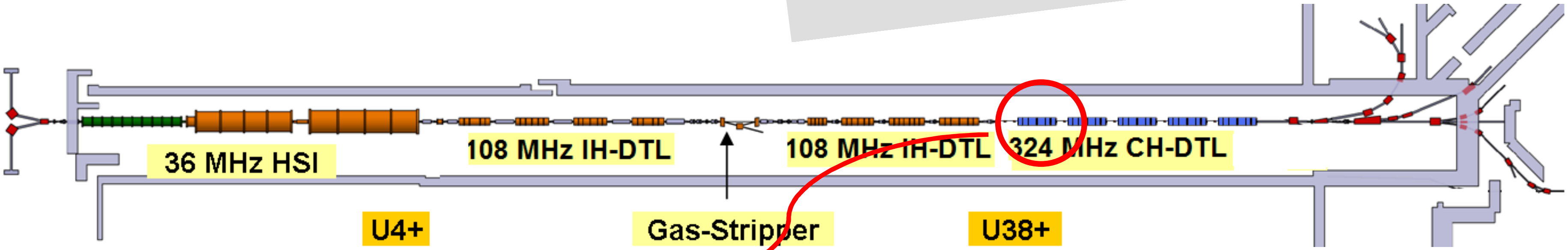




DTL	ΔW (keV/u)	P_{beam} (kW)	P_{loss} (MW)	V_{eff} (MV)	Length (m)
IH3	426	511	≤ 1.1	26.7	~ 2.9
IH4	445	534	≤ 1.1	28.7	~ 3,1
IH5	408	490	≤ 1.1	25.8	~ 3.0
IH6	336	403	≤ 1.1	23.9	~ 3.0

325 MHZ-sc-CH-prototype

Progress in Superconducting CH-Cavity Development
M. Busch - U. Ratzinger - H. Podlech - F. Dziuba
IAP - Uni Frankfurt

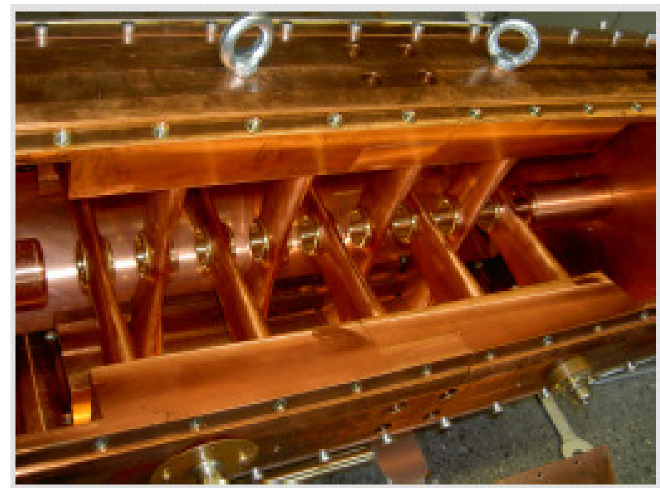


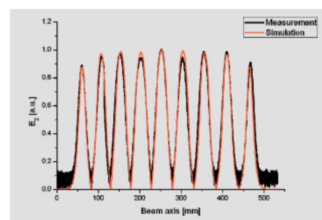
Prototype

- Inclined stems (short total length)
- Improved field distribution
- Fast/slow membrane tuners
- Cavity in fabrication!

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

Cold model





Field distribution with optimised β-profile

β	0.1 (var.)
Frequency [MHz]	332
No. of cells	10 (var.)
Length [mm]	570 (var.)
Diameter [mm]	330
Q-value [measured]	6500
Material	Copper

GSI sc-cw-LINAC-project

Motivation:

Element 120, <0.1 pb (1pb <-> 1 event/week)

	GSI-UNILAC	cw-LINAC
Beam Intensity (particles/sec) *(S. Hofmann et al, EXON 2004)*	$3 *10^{12}$	$6 *10^{13}$
Beam on target	10 weeks	4 days

UNILAC is not dedicated to SHE, nearly not obtainable to keep SHE @ GSI competetive: Increase of Beam Intensity and Detection Efficiency

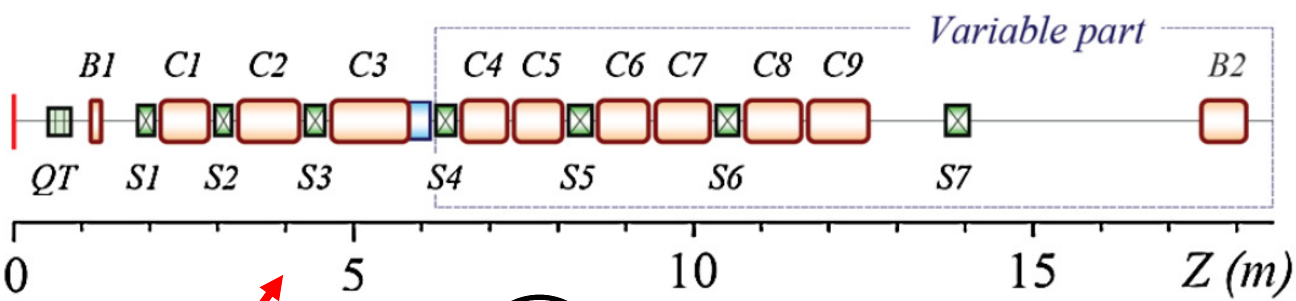
General parameters

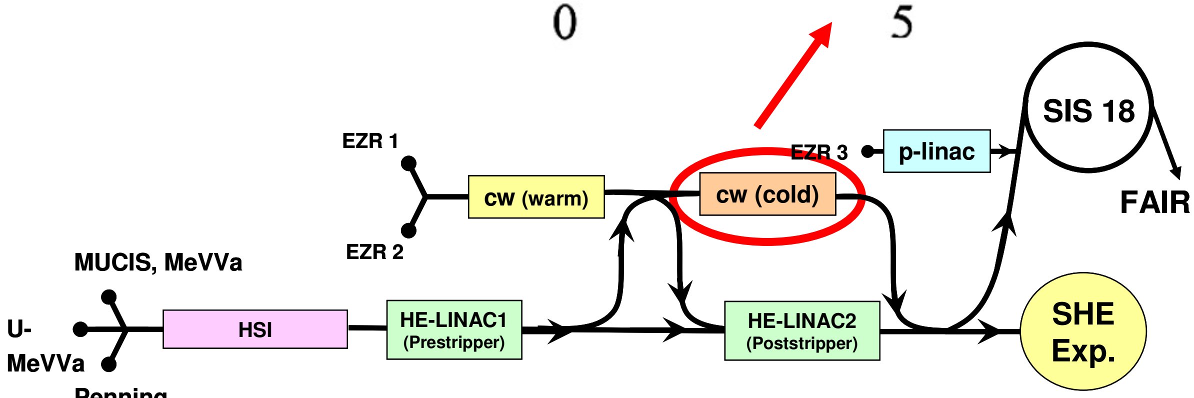
Mass/Charge		1/6
Frequency	MHz	217
max. beam current	mA	1
Injection Energy	MeV/u	1.4
Output energy	MeV/u	3.5 – 7.5
Output energy spread	keV/u	+- 3
Length of acceleration	m	12.7
Sc CH-cavities		9
Sc solenoids		7

Multicell sc-CH-cavity

- Small number of rf cavities (gap numbers from 10 to 20)
- acc. gradient of 5 MV/m → compact linac design
- Cold solenoids in the inter-tank sections
- Several cavities, solenoids per cryostat
- Cavity lengths range up to around 1 m
- Cylindrical cryostats is typically <6 m long
- At a given frequency: CH-type cavities has very small transverse dimensions

conceptual layout of the cw-LINAC

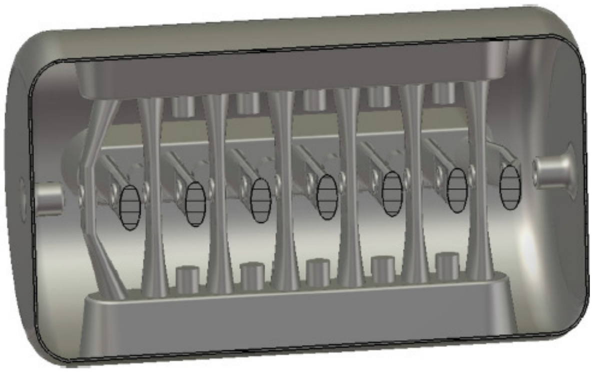




Future GSI-injector environment

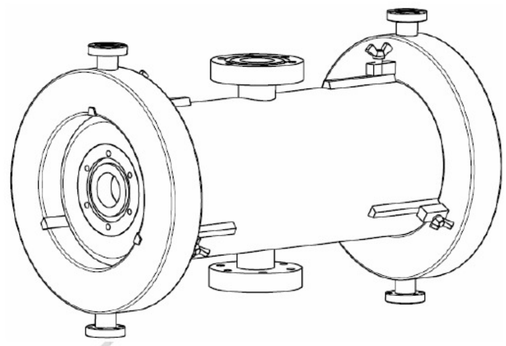
216 MHz-CH-Protype

216 MHz-CH-cavity
(Goethe Univ. Frankfurt)



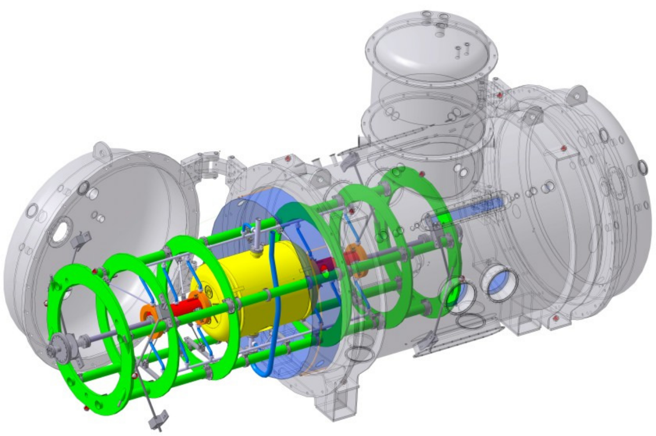
Parameter	Unit	CH-1
Beta		0.059
Frequency	MHz	217
Gap number		15
Total length	mm	690
Cavity diameter	mm	420
Cell length	mm	40.82
Aperture	mm	20
Effective gap voltage	kV	225
Voltage gain	MV	3.13
Accelerating gradient	MV/ m	5.1
E_p/ E_a		6.5
B_p/ E_a	mT/ (MV/m)	5.9
R/ Q	Ω	3540
Static tuner		9
Dynamic bellow tuner		3

Solenoids

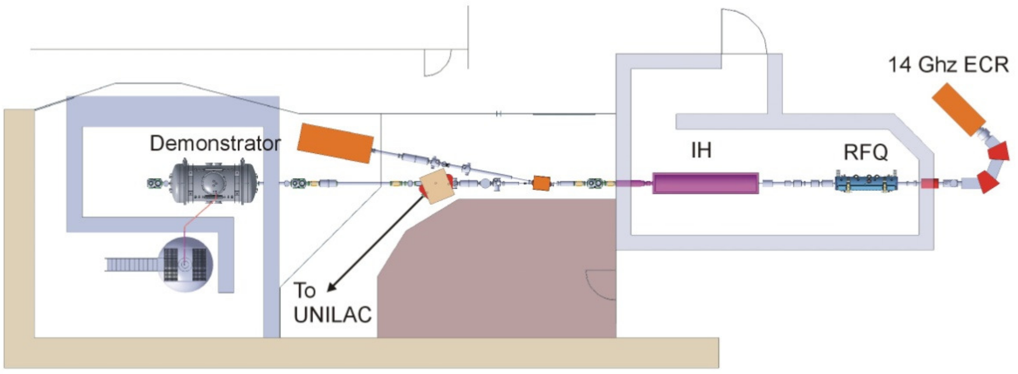


Bmax	9,323T
B*L	2,635 Tm
L	0,28 m
Aperture	30 mm

Cryostat:



Demonstrator Project (HIM, GSI)



HELMHOLTZ GEMEINSCHAFT

Outlook I

- H-mode structure are established as a standard solution for heavy ion injectors
- For injection energies lower than 20 MeV/u a RFQ+IH-DTL is the most reliable solution
- For higher beam energies (up to 120 MeV/u) CH-DTL is a considerable option
- GSI Injector upgrade:
  - Substitution of the Alvarez DTL with IH-CH Combination up to 22 MeV/u
  - Increase of the injection energy into the SIS18
  - Reduced beam losses inside the SIS18
  - In a long term perspective injection energy could be increased up to 100 MeV/u
- In parallel a dedicated s.c. LINAC is under development for the SHE program

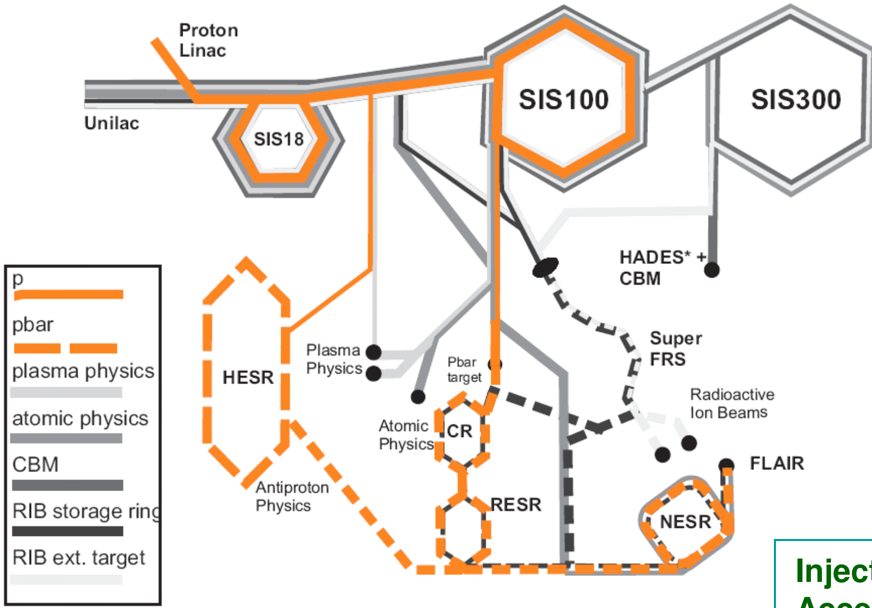
Outlook II

- 108 MHz, 2 MW rf-amplifier (duty factor 1%) ?
- R&D for a nc CH-cavity as a key component for acceleration of heavy ion (β> 0.2)*
- Prototyping for a nc 325 MHZ-CH-cavity*
- Prototyping for a sc 325 MHZ-CH-cavity
- High power rf-testing at the GSI-klystron test stand*
- advanced beam dynamics layout of the High Energy linac
- Conceptual layout $\rightarrow$ design report
- Technical layout $\rightarrow$ design report

*covered by ARD!

Backup

Future Option: FAIR Proton Linac



<=100

4 x
Injection of protons into SIS18
Acceleration to 2 GeV
Injection into SIS100

Acceleration to 29 GeV
Impact on target → hot pbars
Stoch. pbar cooling in CR
Injection into in RESR

↓ Injection into HESR
Acceleration to 14.5 GeV

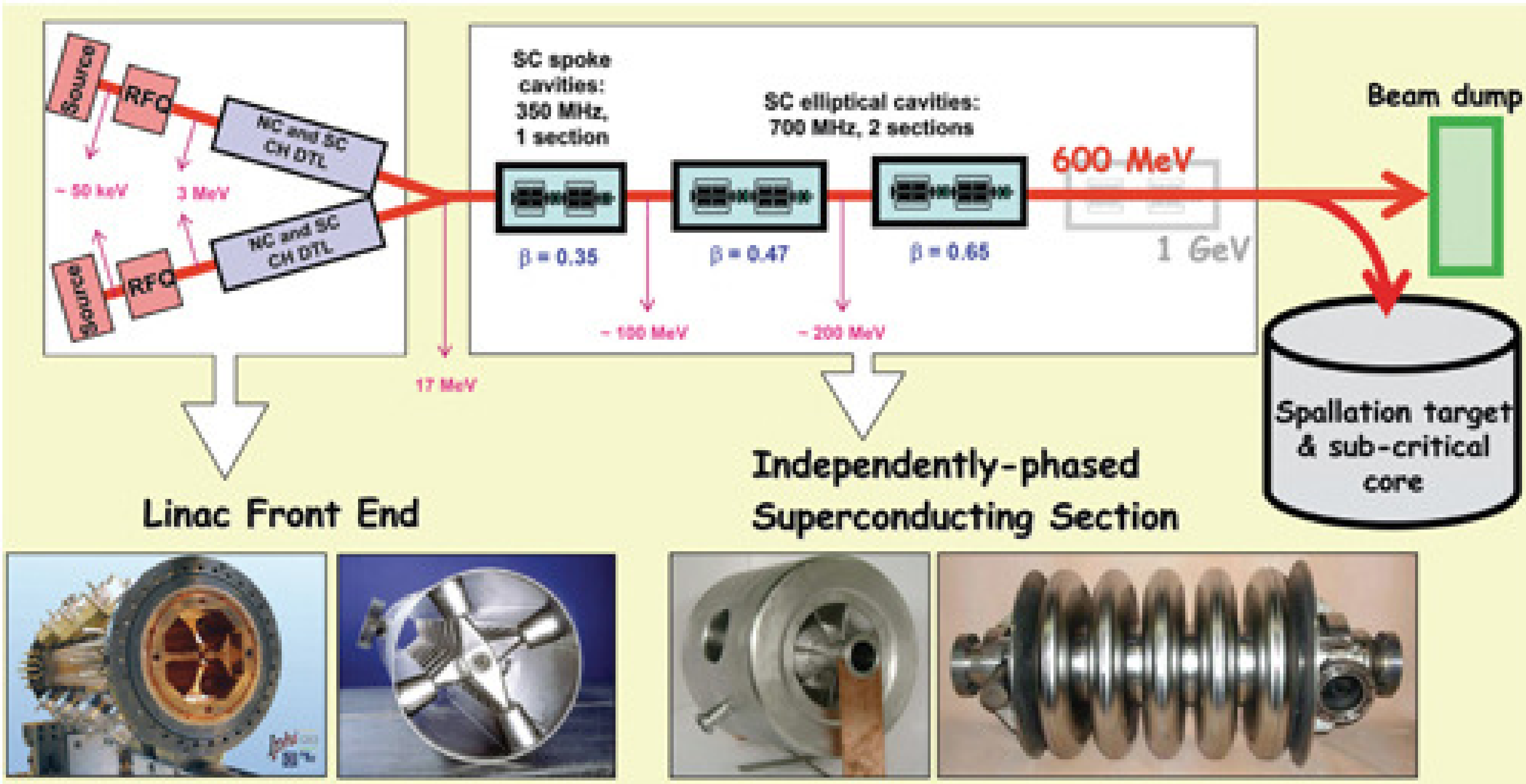
↓ Deceleration in NESR to 30 MeV
Extraction to low energy pbar experiments

Multi-Turn Injection into SIS18 requires:

$$B_n := 63.6 \frac{\text{mA}}{\mu\text{m}} \cdot \frac{(\beta\gamma)^2}{\eta_{MTI}} \rightarrow 16.5 \text{ mA / µm} \quad \rightarrow \quad I = 35 \text{ mA}, \beta\gamma\varepsilon_x = 2.1 \text{ µm}$$

η_{MTI} := MTI filling factor → 60%

XADS



Source
RFQ
NC and SC CH DTL
~ 50 keV
3 MeV
17 MeV
SC spoke cavities: 350 MHz, 1 section
SC elliptical cavities: 700 MHz, 2 sections
β = 0.35
β = 0.47
β = 0.65
~ 100 MeV
~ 200 MeV
600 MeV
1 GeV
Beam dump
Spallation target & sub-critical core
Linac Front End
Independently-phased Superconducting Section