The Injector Systems for the FAIR Project

W. Barth, GSI - Darmstadt

1. FAIR - Project status
2. GSI Accelerator Facility – Injector for FAIR
3. Heavy Ion Linear Accelerator UNILAC
4. Unilac Upgrade Program
   - HSI Frontend
   - Stripper Sections
   - Alvarez Matching
   - Beam Diagnostics
5. Status of the Unilac High Current Performance & further Upgrade schedule
6. A Proton Linac for direct SIS-Injection
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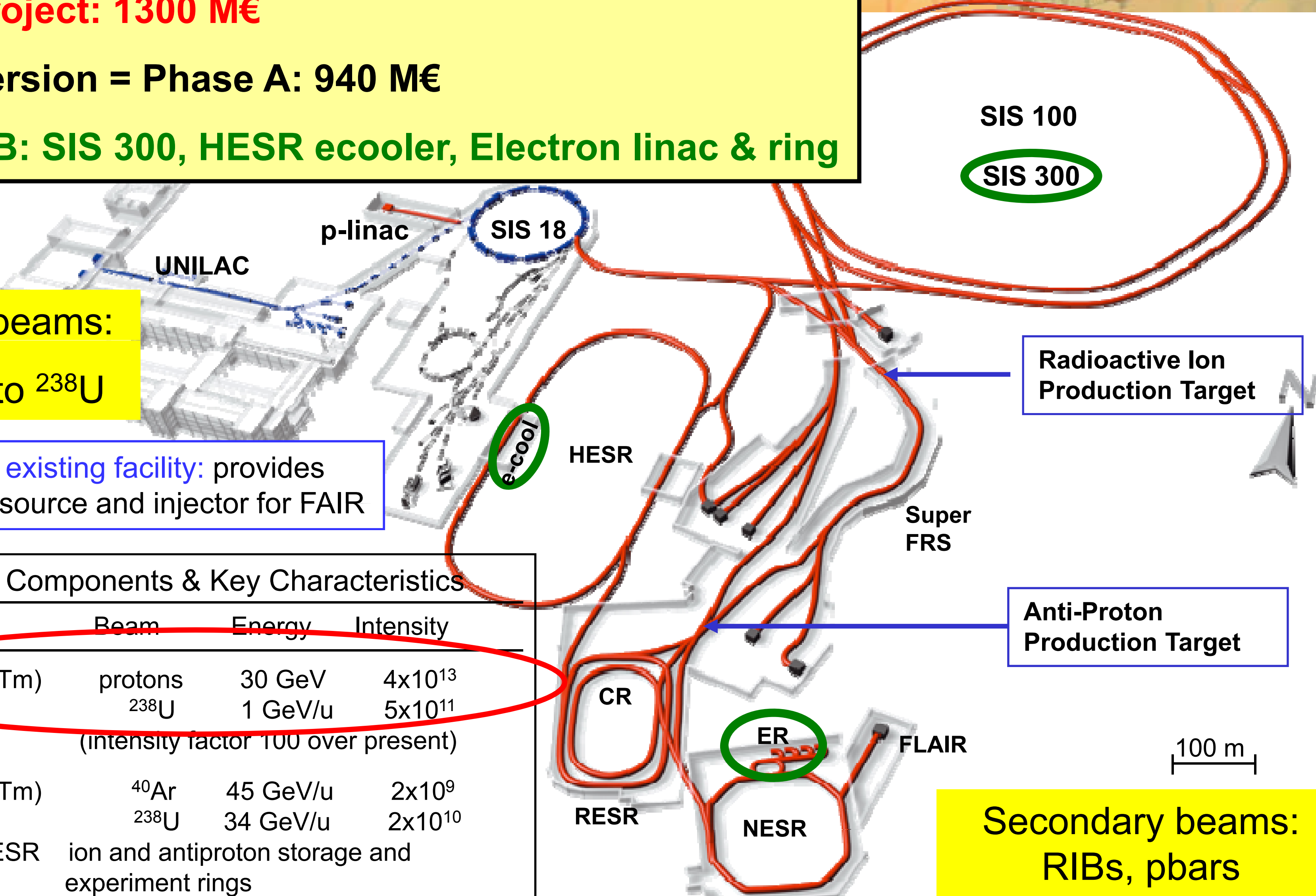
9. Summary

The FAIR Accelerator Complex

Total project: 1300 M€

Start Version = Phase A: 940 M€

Phase B: SIS 300, HESR ecooler, Electron linac & ring



Primary beams:

protons to ^{238}U

Upgraded existing facility: provides ion-beam source and injector for FAIR

Accelerator Components & Key Characteristics

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)		
SIS 300 (300Tm)	^{40}Ar	45 GeV/u	2×10^{9}
	^{238}U	34 GeV/u	2×10^{10}
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim 10^{11}$
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

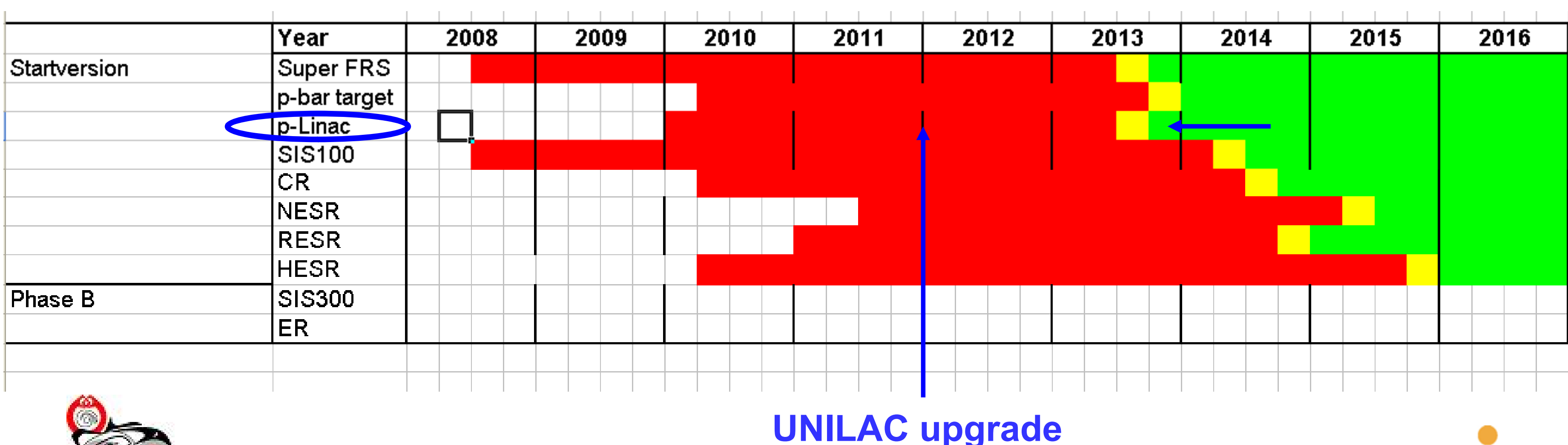
Secondary beams: RIBs, pbars

New future facility: provides ion and anti-matter beams of highest intensities and up to high energies

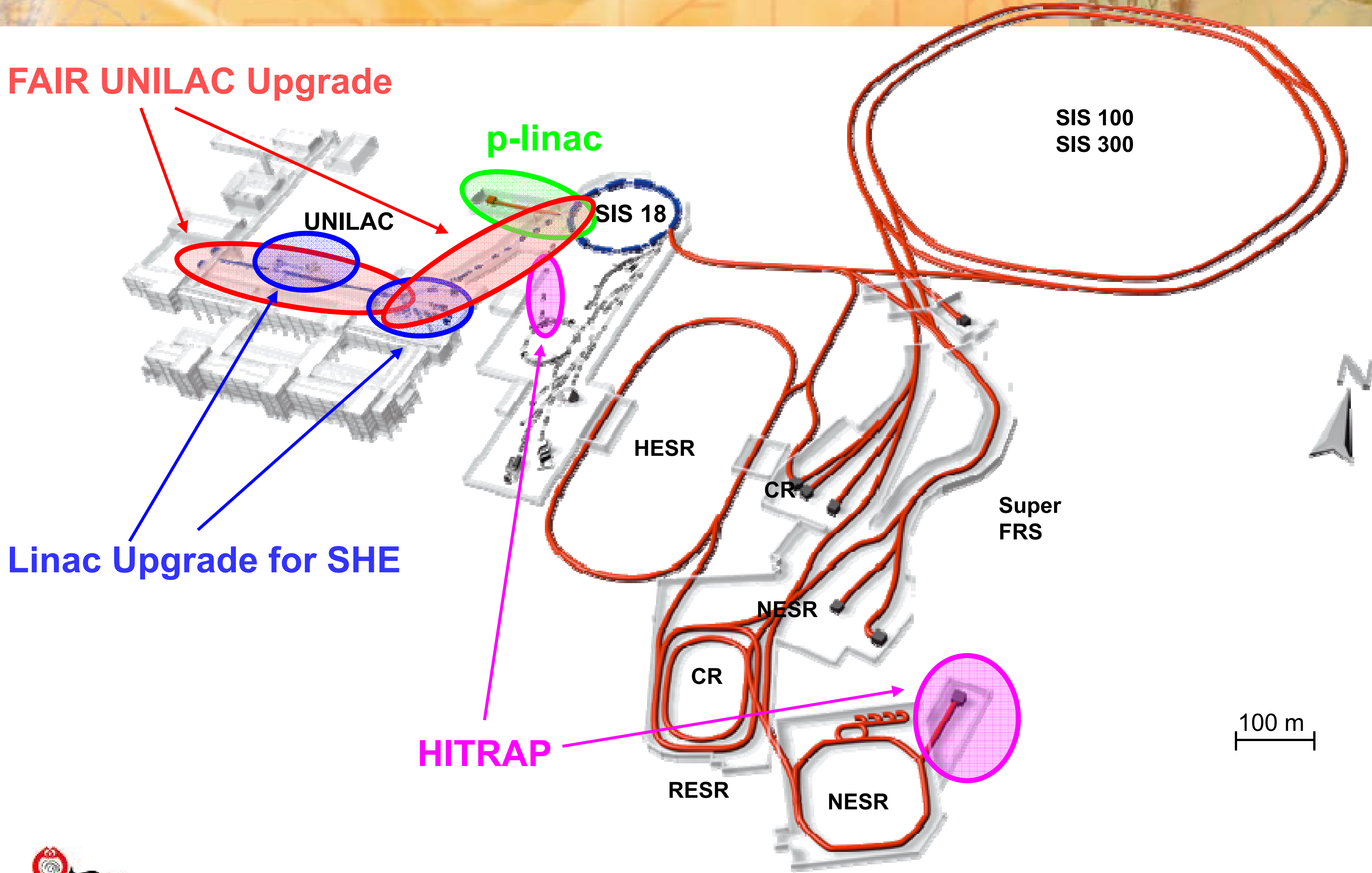
FAIR-schedule

- All legal documents being finalized (decision to be taken at next ISC meeting Oct. 1st)
- Aim: Signature of convention end of 2008
- Foundation of FAIR GmbH beginning of 2009
- First Experiments at Super-FRS 2014 (with beam from SIS18)

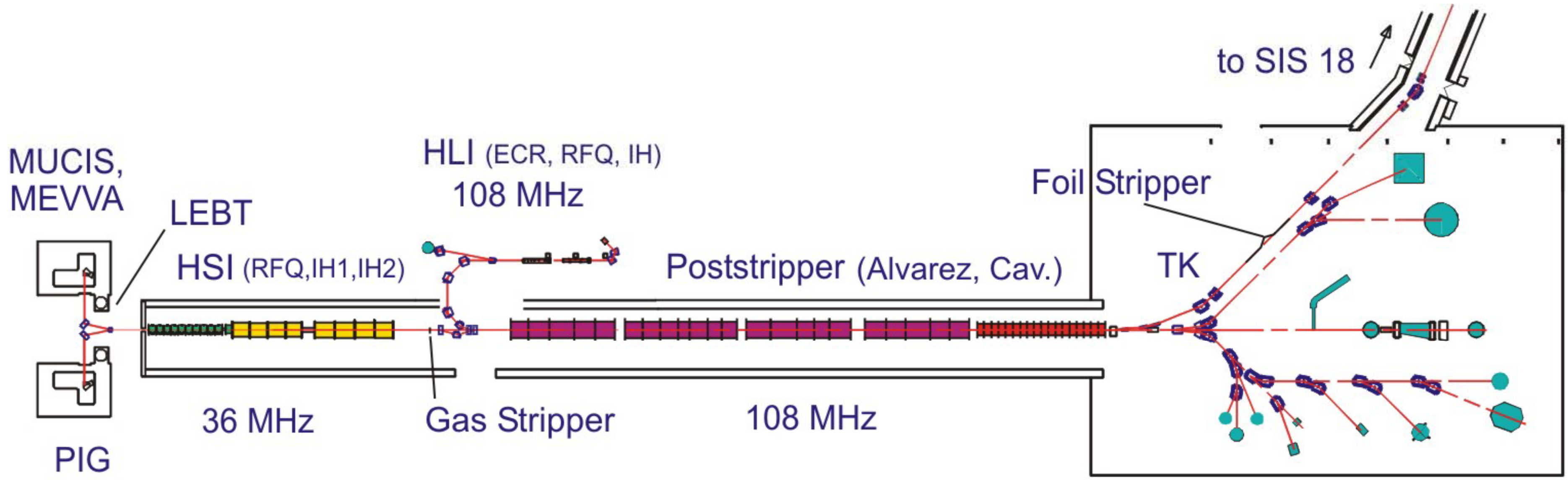
Schedule - Accelerators



FAIR related LINAC activities

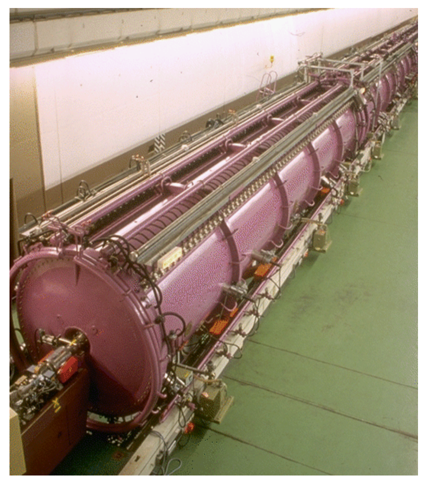


The GSI UNIversal Linear ACcelerator

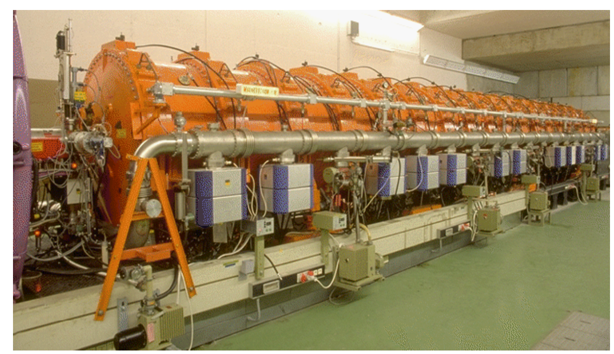


High Current Injector

Alvarez



Single Gap Resonators



UNILAC-Upgrade for FAIR

(FAIR-Technical Report 2005)

sub-project	***aim***
• High Current test bench → U^{4+}-ion source terminal for the High Current Injector • U^{4+}-Compact Low Energy Beam Transport	18 emA, U^{4+}, 1.4 MeV/u
• HSI-RFQ-Upgrade	
• Gasstripper	13% stripping efficiency for U^{28+}, 100 % transmission
• Power Supplies for 178 Alvarez-quadrupoles	σ_o = 55°, U^{28+} (improved beam quality)
• 11.4 MeV/u charge state separator	charge state separation for a 5 emA U^{73+} beam
• High Current beam diagnostics	Measurement of ion current, transmission, beam profile, position, energy, transverse and longitudinal emittance

HSI-LEBT Upgrade

Upgrade 0

- High Current test stand measurements

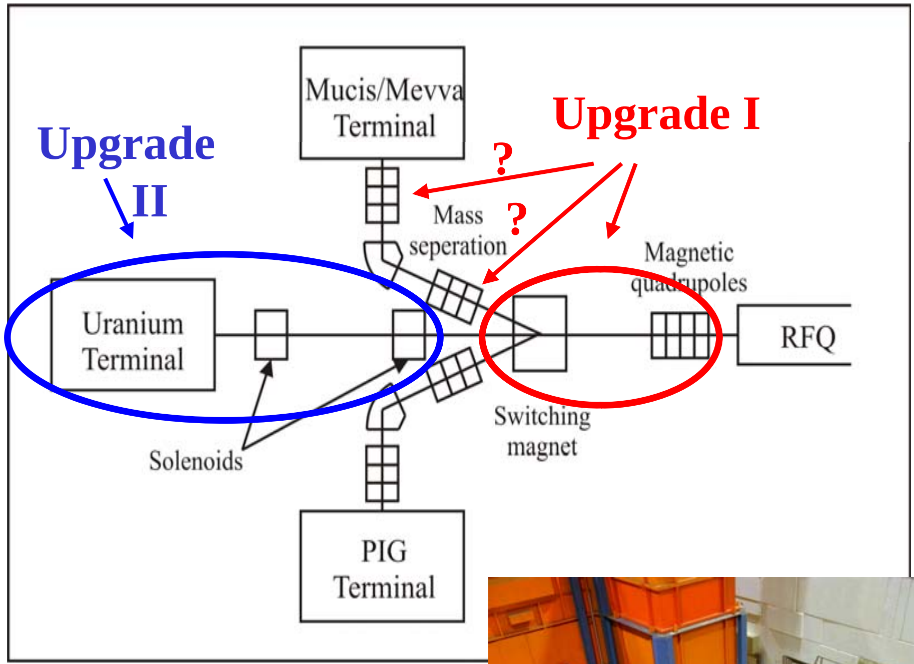
Upgrade I

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

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 !

HSI-RFQ upgrade (2009)

- Higher transverse acceptance and phase advance (keeping maximum field at the electrode surface)
- New Input Radial Matcher design → improved beam matching
- Improved beam dynamics for gentle buncher optimized for rapid and uniform separatrix filling
- Resonant frequency shift with increased average radius and reduced electrode thickness can easily be compensated
- Beam dynamics studied with DYNAMION& PARMTEQ-M
- Beam intensity at HSI-RFQ output (18 mA of U^{4+} ions) meets the FAIR requirement

	Final Design	Existing Design
Voltage, kV	155.	125.
Average radius, cm	0.6	0.5245 – 0.7745
Electrode width, cm	0.84	0.9 – 1.08
Maximum field, kV/cm	312.0	318.5
Modulation	1.012 – 1.93	1.012 – 2.09
Synch. Phase, degree	-90^0 - -28^0	-90^0 - -34^0
Aperture, cm	0.410	0.381
Min. transverse phase advance, rad	0.555	0.45
Norm. transverse acceptance, cm mrad	0.0856	0.73
Output energy, MeV/u	0.120	≈ 0.1185
Number of cells with modulation	394	343
Length of electrodes, cm	921.74	921.74

HSI End to end simulation

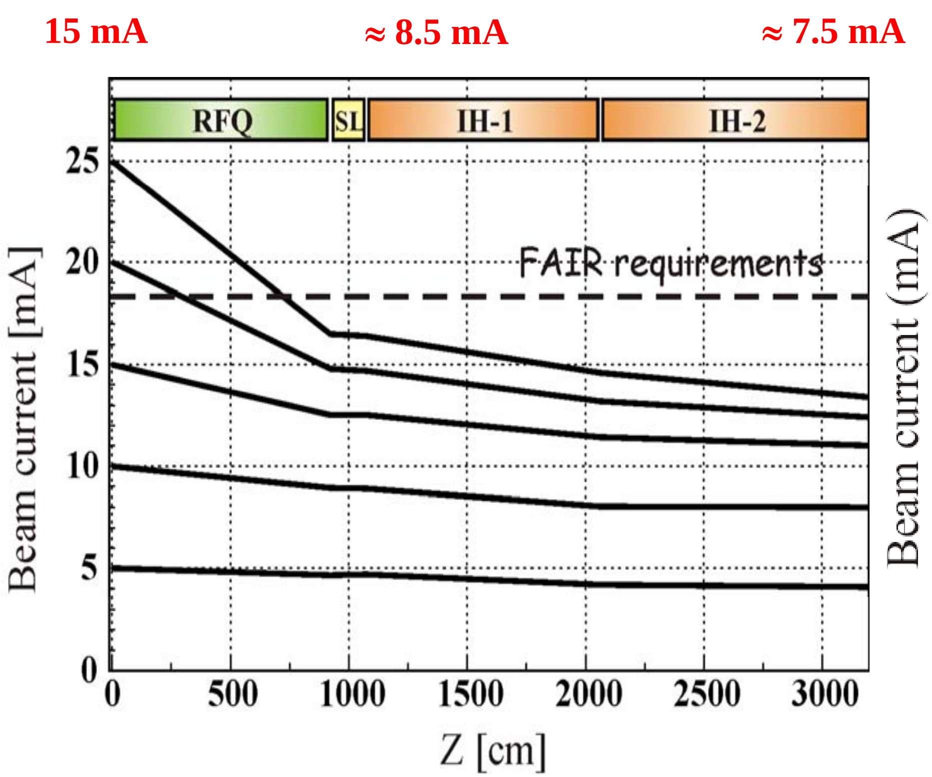
A. Kolomiets, MOP032

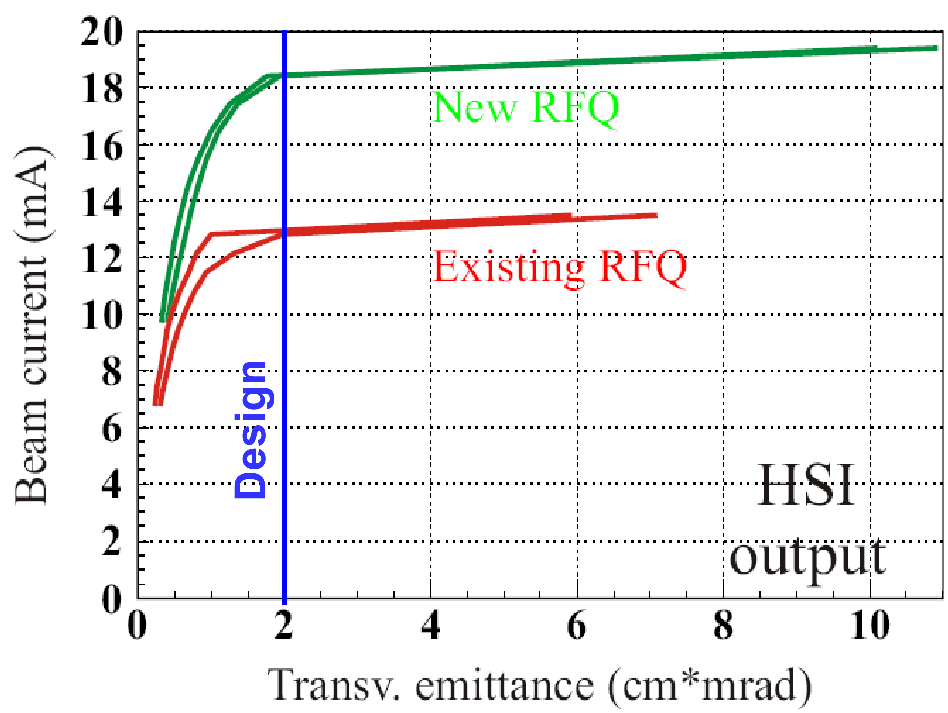
measurement for present RFQ :

DYNAMION (S. Yaramyshev, GSI)

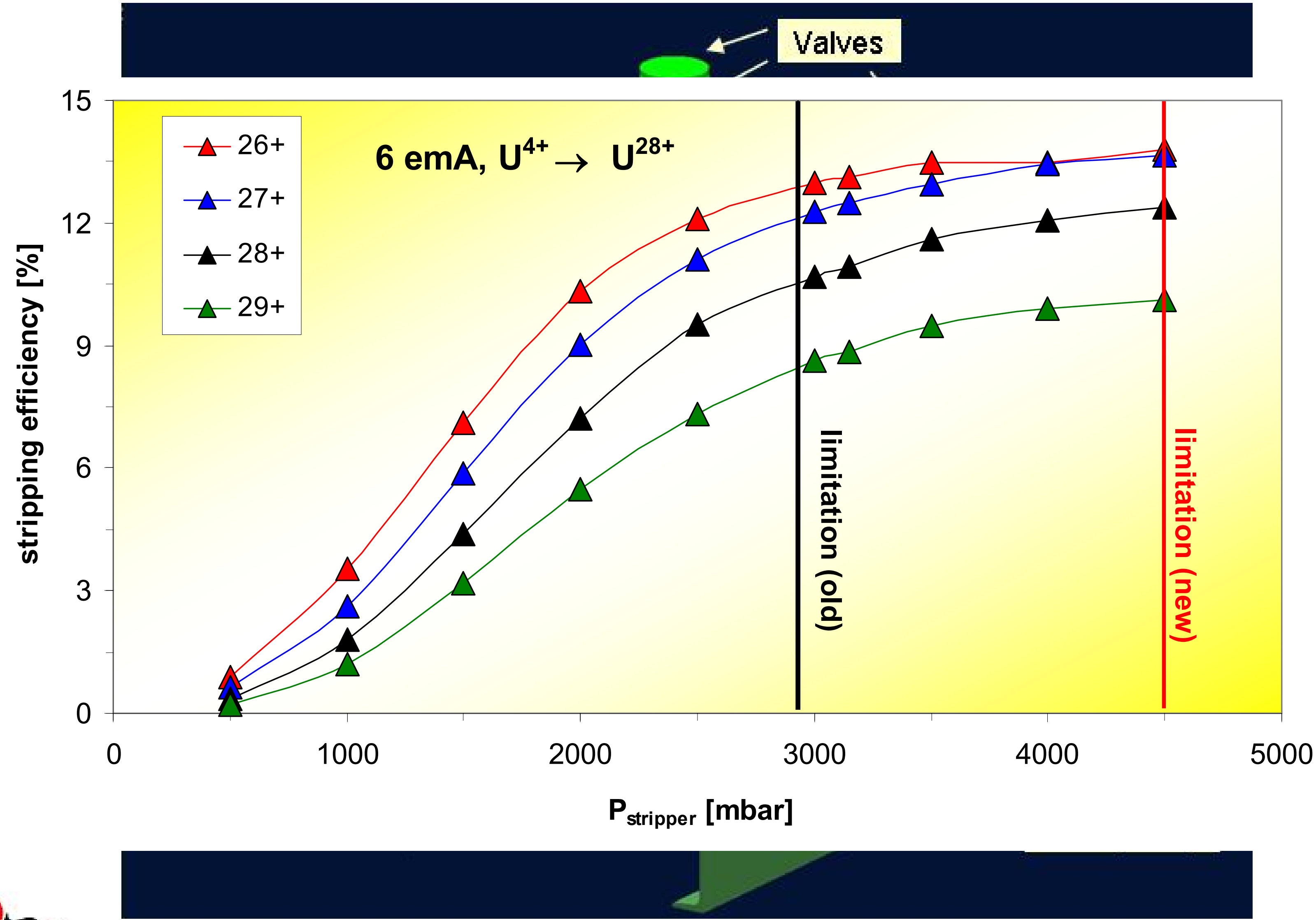
PARMTEQ (A. Schempp, Univ. Frankfurt)

LORASR (R. Tiede, Univ. Frankfurt)





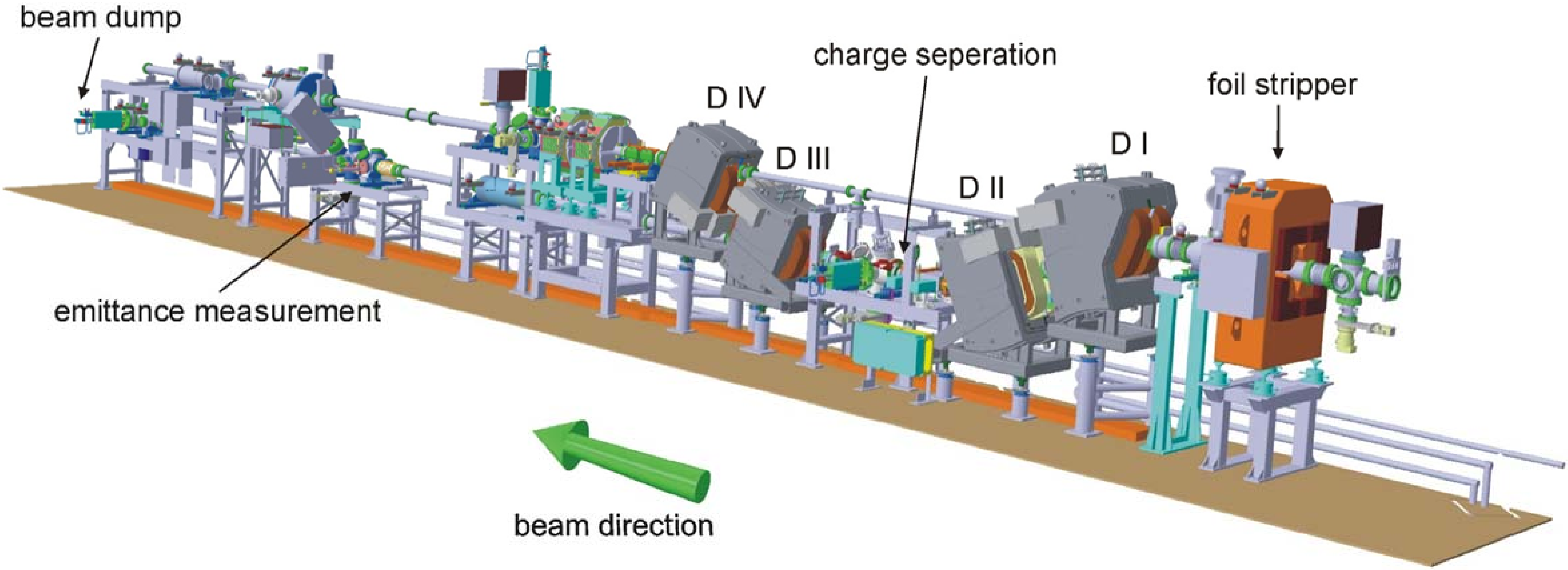
Increased Stripper Gas Density



Charge State Separator

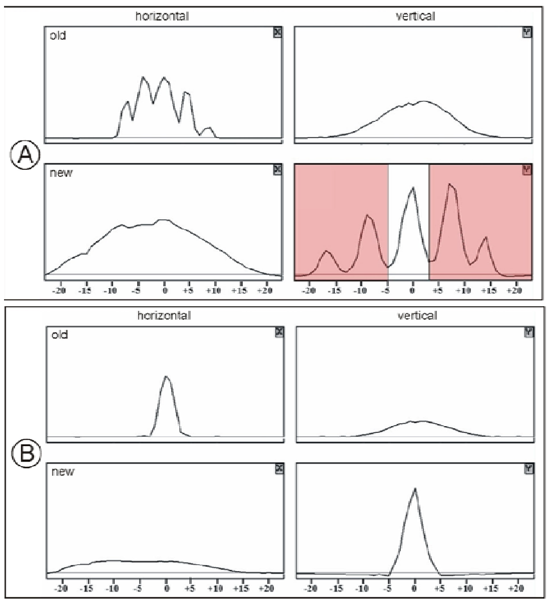
High Current operation (Uranium)

W. Barth, MOP046



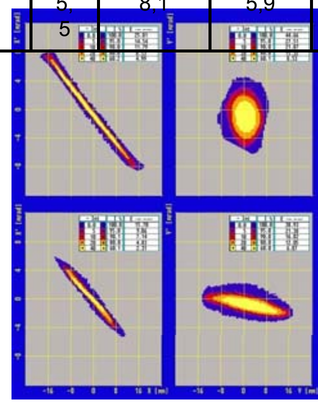
Beam commissioning of the Charge State Separator system

Charge Separation

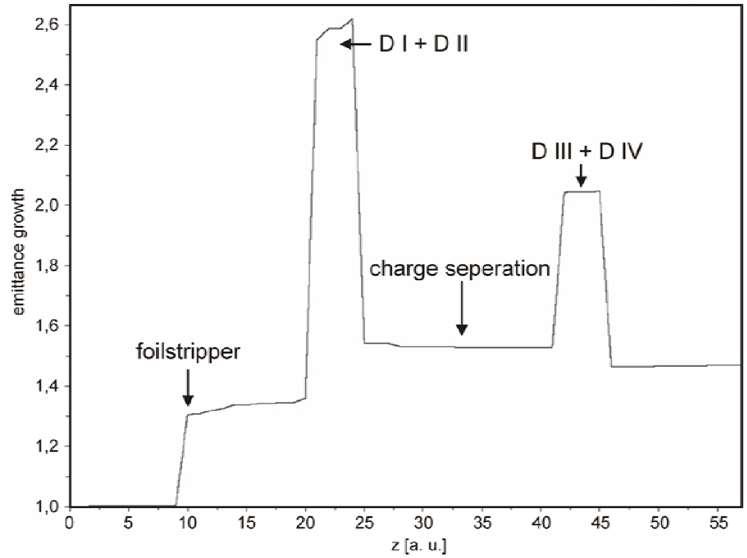


$^{40}AR^{18+}$-Beam Emittances (90 %)

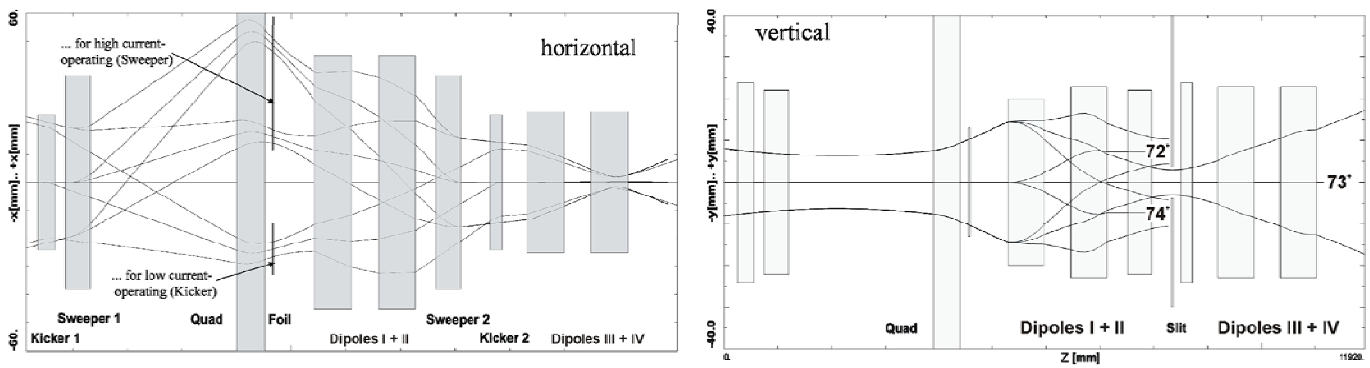
	high current		low current	
($4\cdot\varepsilon_{rms}$ [μm])	ho r.	vert.	hor.	vert.
behind D II	9,0	17,6	6,9	7,1
SIS injection	5,5	8,1	5,9	5,6



High Current Emittance Growth



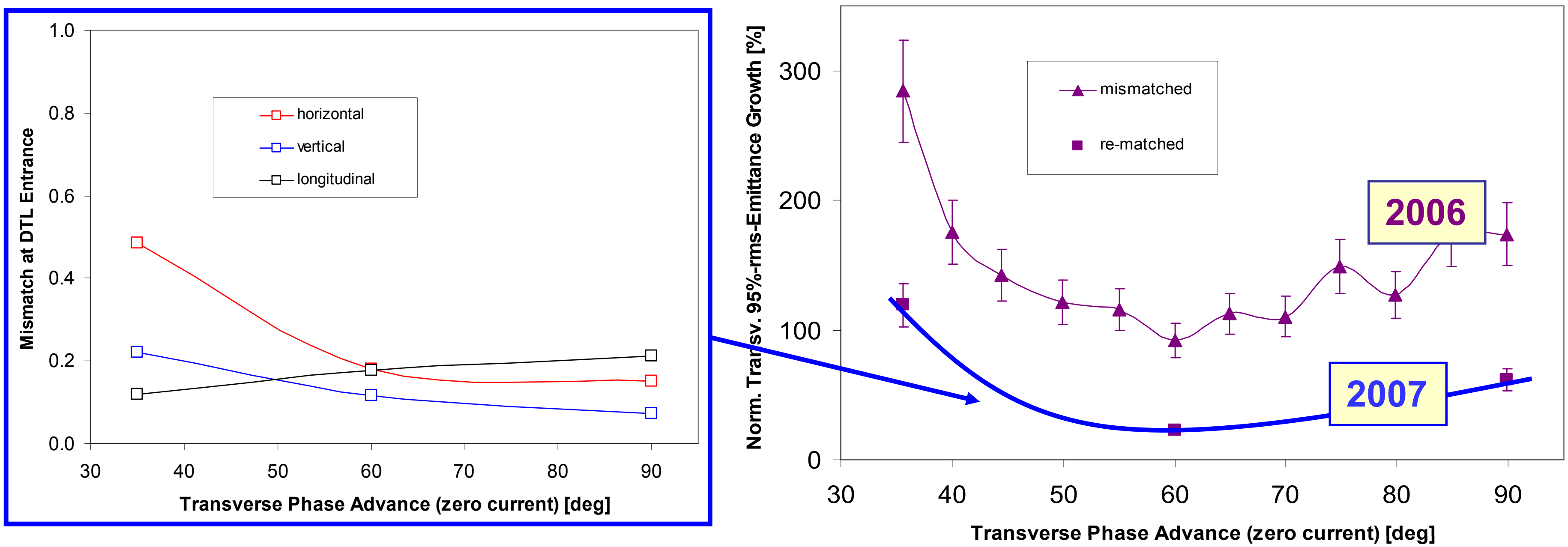
Beam Dynamics



Reduction of Mismatch

L. Groening, MOP075

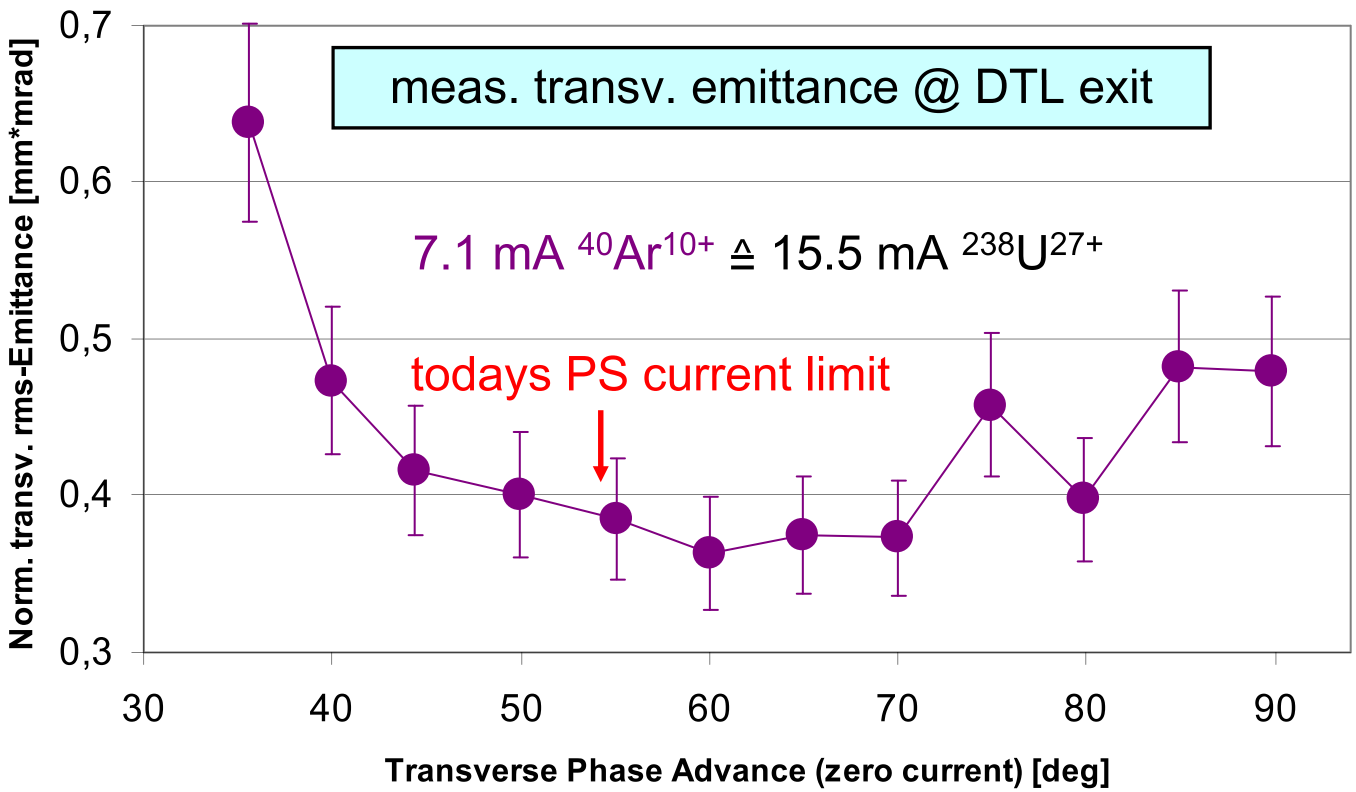
- new algorithm used to rms-match a (measured) initial distribution to periodic DTL
- test of matching by re-measuring emittance growth



- significant reduction of emittance growth by rms-matching including space charge

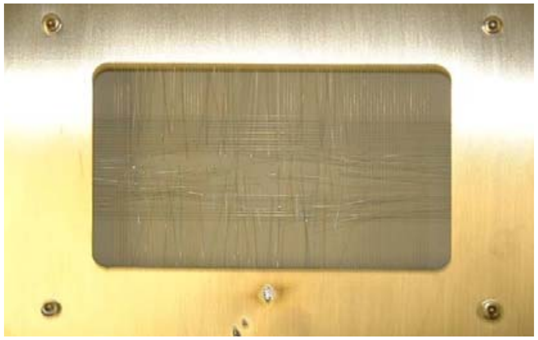
New Power Supplies for the UNILAC Alvarez dc-Magnets

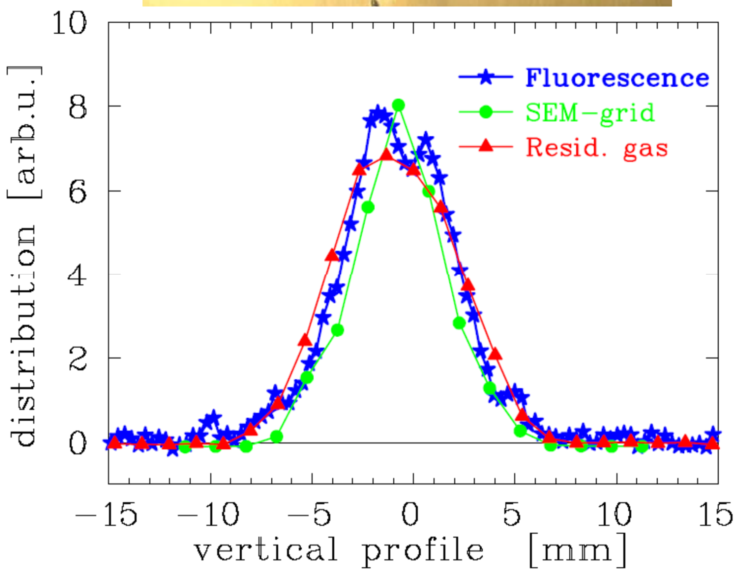
- The achieved ratio current / rms-emittance at DTL exit is too low for FAIR
- Design: 15.5 mA / 0.25 µm;   Achieved: 4.4 mA / 0.43 µm
- One measure of improvement → reduction of emittance growth along DTL
- Exp. and simulation: possible by increasing DTL quad strengths



High Current Beam Diagnostics: Beam Induced Fluorescence Monitor

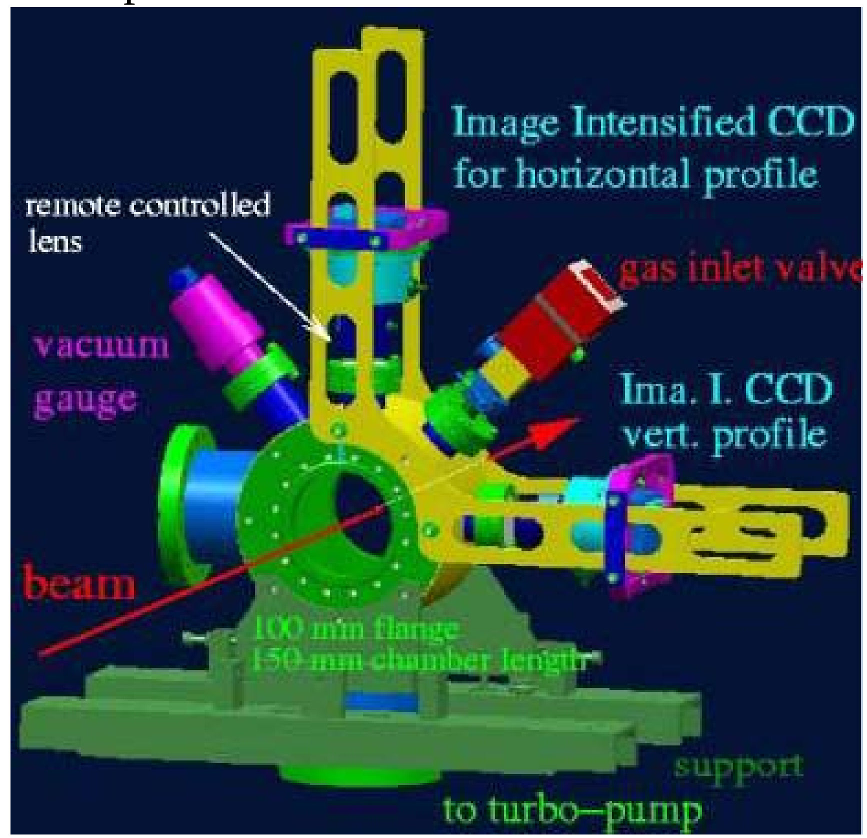
Damaged SEM-Grid





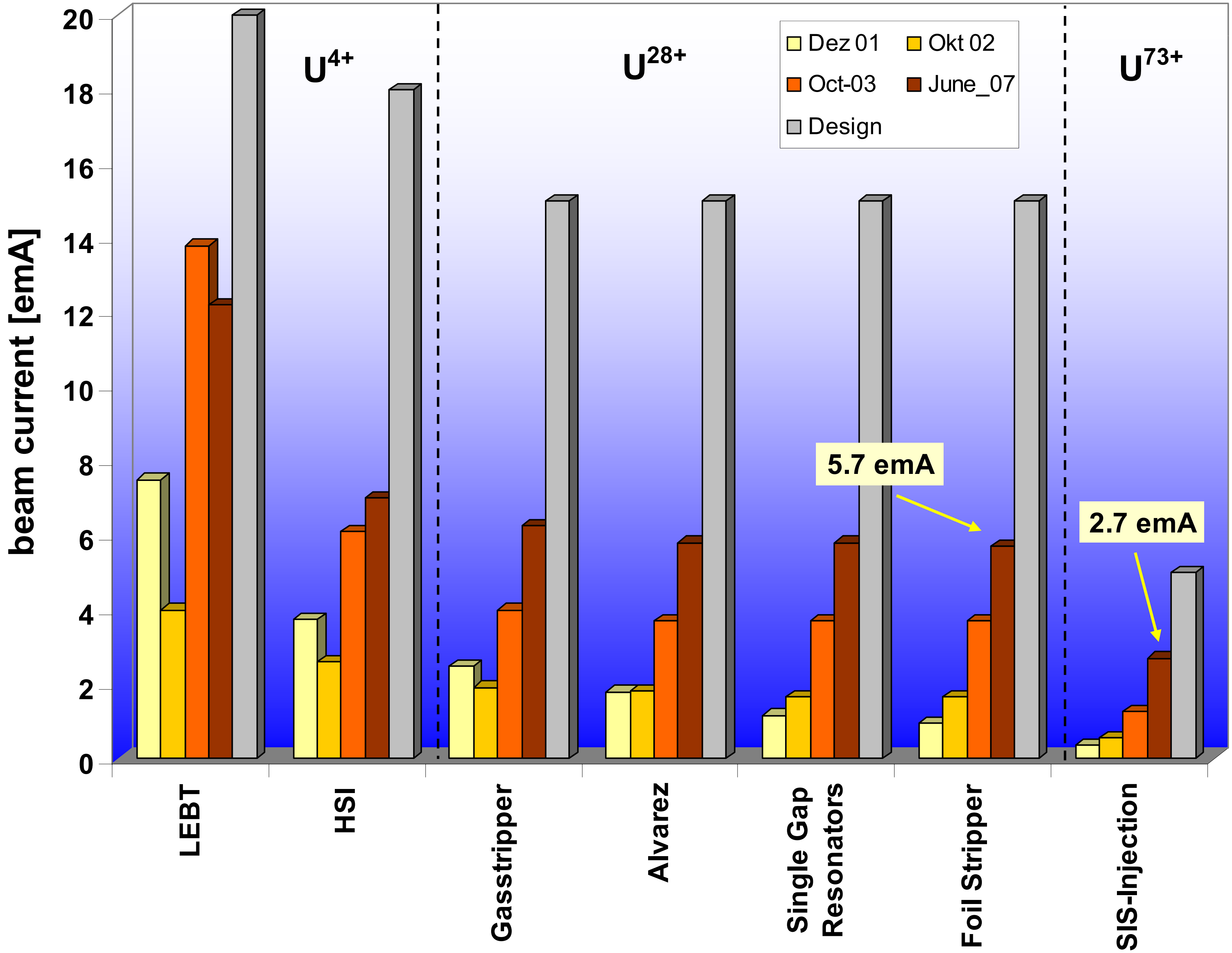
4.7 MeV/u Ar^{10+} beam
I=2.5 mA equals to 1011 particle
One single macro pulse of 200 μs
Vacuum pressure: p=10-5 mbar (N2)

Compact chamber with 150 mm insertion:



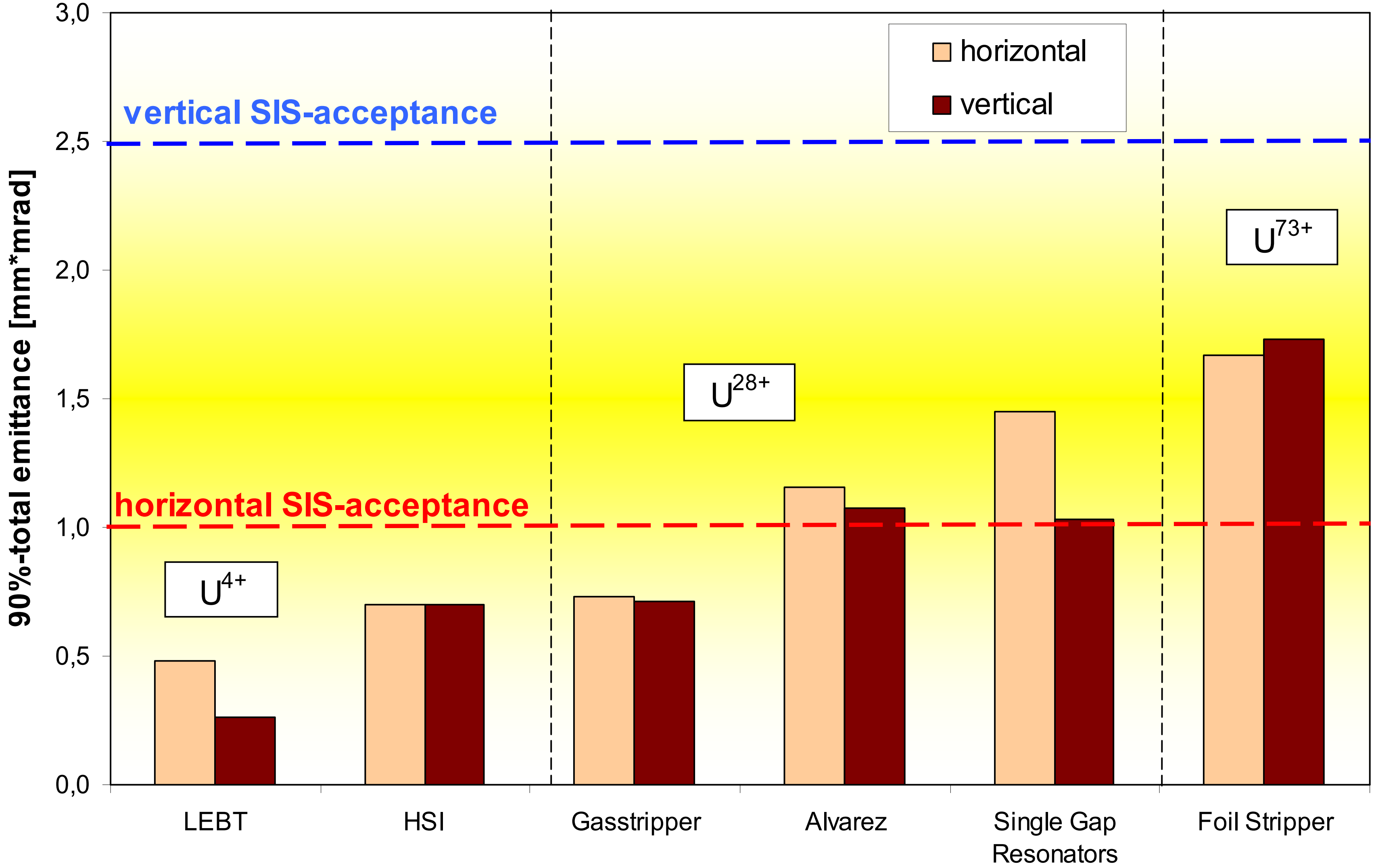
Large beam power → Non-intercepting method:
⇒ Beam Induced Fluorescence BIF
N_2 + Ion → $(N_2^+)^*$+ Ion → N_2^+ + γ + Ion
With single photon detection scheme
⇒ installation.of seven BIF-stations

Status Quo



beam current [emA]
0
2
4
6
8
10
12
14
16
18
20
U4+
U28+
U73+
Dez 01
Okt 02
Oct-03
June_07
Design
5.7 emA
2.7 emA
LEBT
HSI
Gasstripper
Alvarez
Single Gap Resonators
Foil Stripper
SIS-Injection

Status Quo



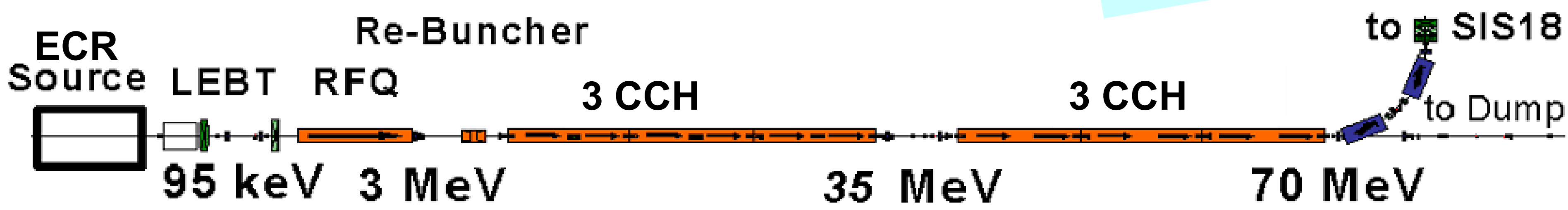
3,0
2,5
2,0
1,5
1,0
0,5
0,0
90%-total emittance [mm*mrad]
vertical SIS-acceptance
horizontal SIS-acceptance
horizontal
vertical
U4+
U28+
U73+
LEBT
HSI
Gasstripper
Alvarez
Single Gap Resonators
Foil Stripper

Status of the UNILAC Uranium-Performance

	Measured	Design (1999)	required for FAIR
$^{238}U^{4+}$ Max. Beam Intensity I, (2.2 keV/u)	16 emA	16 emA	20 emA
I_{max}@beam power, (1.4 MeV/u)	6.5 emA @587 kW	15 emA@1250 kW	18 emA@1500 kW
Transv. Emittance (LEBT) (90%, total)	140 π·mm·mrad	120 π·mm·mrad	120 π·mm·mrad
Macropulse Length	150 μs	150 μs	150 μs
Reproducibility/Transversal Emittance	±4.5%	-	-
Beam loading, 7emA (IH2)	350 kW	590 kW (15 emA)	710 kW (18 emA)
U^{28+}			
~~Max. Beam Current, (1.4 MeV/u)~~	6.25 emA	~~12.6 emA~~	15.0 emA
Max. Beam Intensity, 11.4 MeV/u, I_{max}@beam power Transfer to the SIS18 *Ions/100μs*	5.7 emA@567 kW *$1.3 \cdot 10^{11}$*	12.6 emA@1221 kW *$2.8 \cdot 10^{11}$*	15.0 emA@1453 kW $3.3 \cdot 10^{11}$
U^{73+} Max. Beam Intensity, 11.4 MeV/u, *Ionen/100μs*	2.7 emA *$2.3 \cdot 10^{10}$*	4.6 emA *$3.9 \cdot 10^{10}$*	3.5 emA $3.0 \cdot 10^{10}$
Transv. Emittance (11.4 MeV/u) (90%, tot.)	11.0 π·mm·mrad	5.0 π·mm·mrad	7.0 π·mm·mrad

The proton Linac

W. Vinzenz, THP078
H. Podlech, THP011



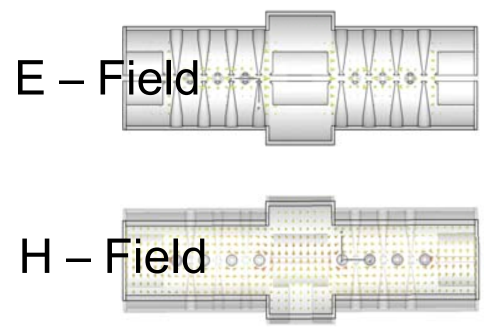
- **ECR proton source & LEBT**
- **RFQ (4-rod)**
- **6 Pairs of Coupled CH-DTL**
- **2 Bunchers**
- **48 Quads**
- **5.1 MW of beam loading (peak), 710 W (average)**
- **11 MW of total rf-power (peak), 1600 W (average)**
- **41 beam diagnostic devices**

Crossed-bar H-Cavity (CH)

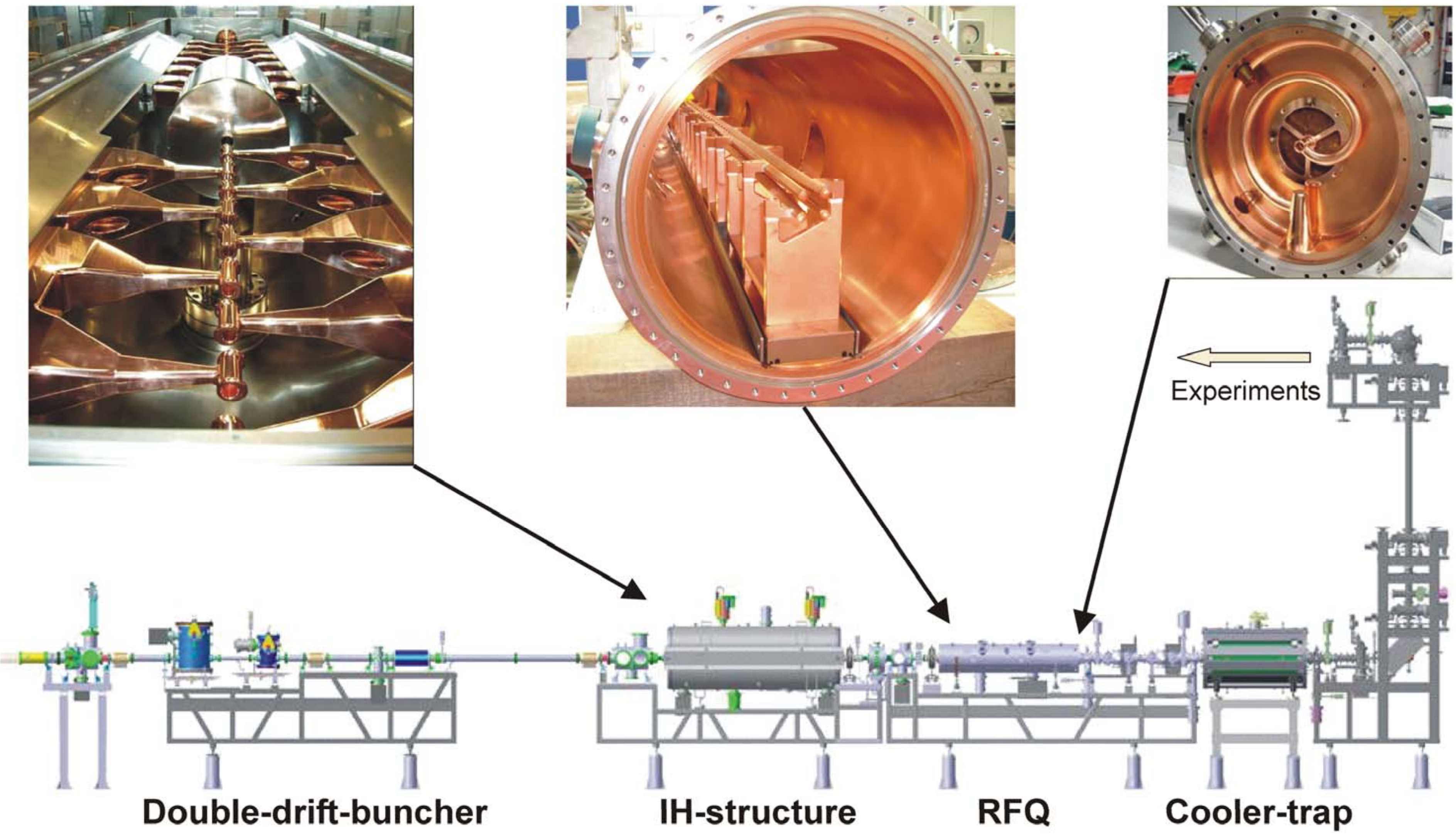
Beam energy	70 MeV
Beam current (op.)	35 mA
Beam current (des.)	*70 mA*
Beam pulse length	36 µs
Repetition rate	4 Hz
Rf-frequency	325.224 MHz
Tot. hor emit (norm.)	2.1 / *4.2* µm
Tot. mom. spread	$\leq \pm 10^{-3}$
Linac length	≈ 35 m

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**



HITRAP Decelerator

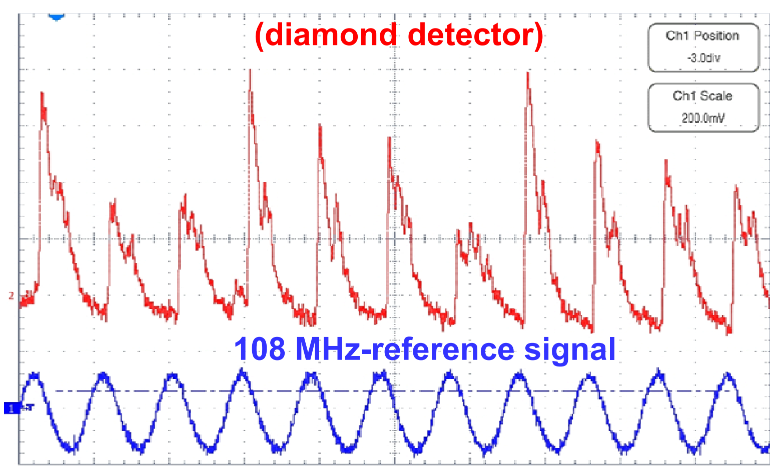


HITRAP-Commissioning

L. Dahl, MOP019
J. Pfister, TUP074

	ion species	installations	commissioning goal
May 2007	$^{64}Ni^{28+}$	ESR extraction beam line and DDB section	optimized beam transfer, system acceptance test, compilation of magnet settings, emittance measurements
August 2007	$^{20}Ne^{10+}$	DDB amplifiers working	bunch shape optimization, determination of DDB working points, emittance measurements,
August 2008	$^{197}Au^{79+}$	IH tank including 200kW amplifier, matching section	IH tank transport and deceleration and determination of the working point, optimized beam parameters behind the matching section, beam energy
October 2008	$^{64}Ni^{28+}$		beam energy measurements (behind IH), phase + amplitude calibration of DDB and IH tank
November 2008		installation of the RFQ tank	
2009	not defined yet	HITRAP decelerator completed inclusive cooler trap	phase and amplitude + calibration of rebuncher, RFQ and debuncher, deceleration to 6 keV/u (RFQ), energy measurements, beam quality optimization

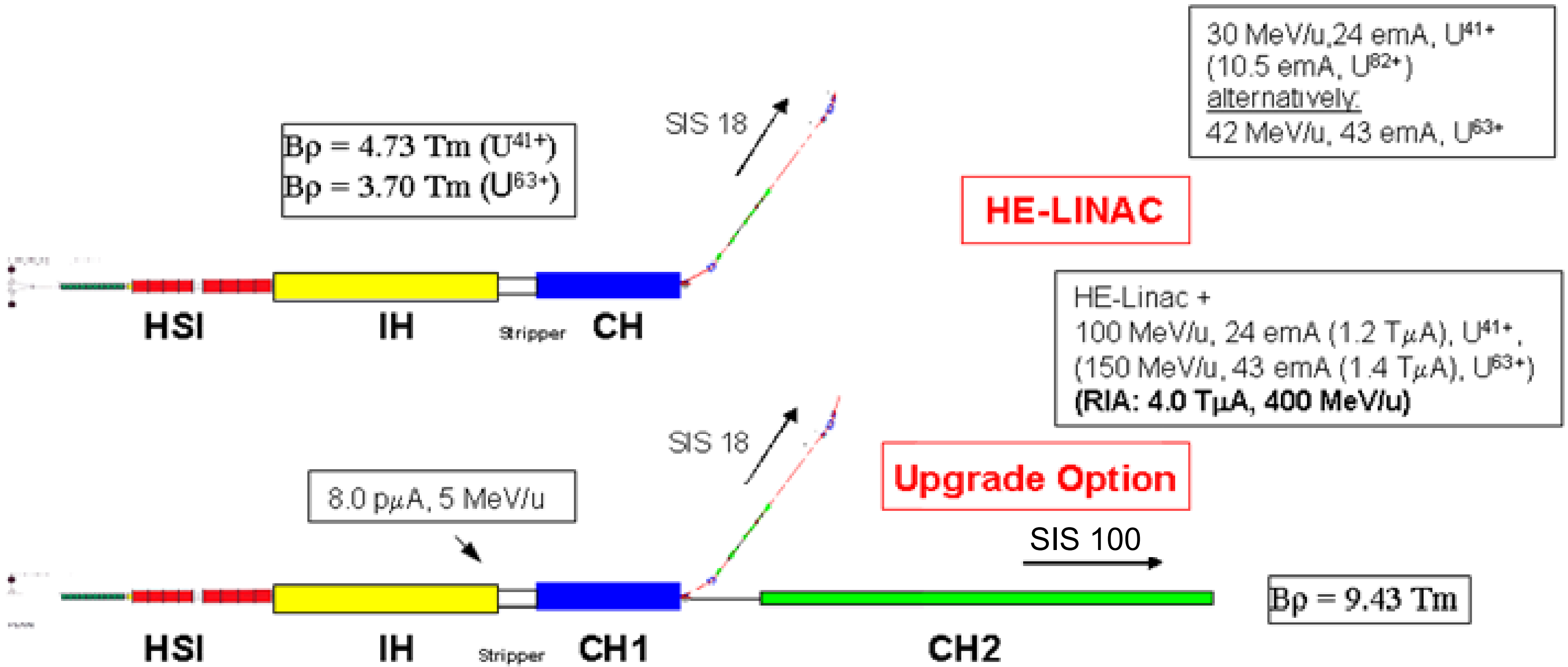
Bunch measurement 4 MeV/u neon-beam



Beam Parameters

HITRAP Section	Energy [MeV/u]	ΔT/T	$\varepsilon_{x,n}$ (= $\varepsilon_{y,n}$) [π·mm· mrad]	ε_x (=ε_y) [π·mm·mrad]	total Transmission	particles/ spill
ESR	5.0	$4.8 \cdot 10^{-4}$	0.093	0.9		$1 \cdot 10^6$ measured
	4.0		0.1	1.0	100%	($6 \cdot 10^5$) estimated
	3.0	$2 \cdot 10^{-4}$	0.06	0.7		$2 \cdot 10^5$ measured
Entrance Prebuncher	4.0	$4.8 \cdot 10^{-4}$	0.2	2.2	100 %	$6 \cdot 10^5$
Entrance IH	4.0	$\pm 1.3 \cdot 10^{-2}$	0.2	2.2	28 %	$1.7 \cdot 10^5$
Exit IH / Entr. RFQ	0.5	$\pm 2 \cdot 10^{-2}$	0.24	7.3	28 %	$1.7 \cdot 10^5$
Exit RFQ	0.006	$\pm 7 \cdot 10^{-2}$	0.37	100	26 %	$1.5 \cdot 10^5$
LEBT, entrance of trap	0.006	$\pm 7 \cdot 10^{-2}$	0.37	100	21 %	$1.2 \cdot 10^5$

Longterm Perspective for the FAIR-LINAC injectors

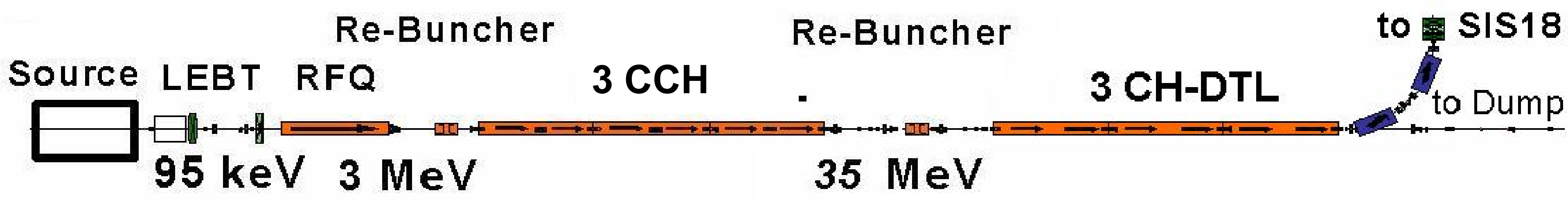


Summary

- An extended upgrade program in the UNILAC in combination with machine investigations resulted in a uranium beam intensity of up to 5.7 emA (28+) for the injection into the synchrotron SIS 18.
- High Current UNILAC-Upgrade: Mainly the improved ion source performance, the increased stripper gas density, the improved DTL-performance, and the use high current beam diagnostics devices were responsible for the successful development program.
- FAIR-requirements: The UNILAC-upgrade will be continued with the upgrade of a new front end for U^{4+} (ion source terminal – LEBT –RFQ), stronger power supplies for the Alvarez quads, the charge state separator system and beam diagnostics devices, sufficient for the operation with megawatt heavy ion beams (until 2011).
- Primary proton beam intensities will be increased by a new proton linac (to be commissioned in 2013).
- The commissioning of the decelerator for the HITRAP will be finished in 2009.
- The UNILAC (since more than 35 years in operation) will serve as an high current injector for FAIR at first - long term perspective: substitution by a more effective high heavy ion linac used as synchrotron injector.

p-Linac: Alternative Layout

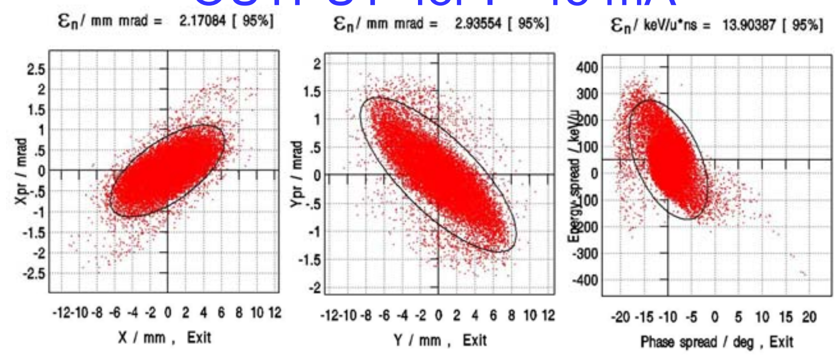
USE of KONUS ⇒ Long section without triplet



OUTPUT for I= 45 mA

3 Pairs of Coupled CH-DTL's
followed by 3 longer standard CH-DTL's

- 11 magnetic triplet required instead of 14
- Simplified RF and Mechanical Design
- A rebuncher needed after the diagnostics section



- **The GSI Proton injector will be based on H-Mode cavities in combination with the KONUS Beam Dynamics**
- **Design is based on RFQ-Output distributions up to 70 mA**
- **Two designs are under discussions and they are comparable in terms of beam quality**
- **Error Studies indicated that both designs are robust enough against fabrication errors and power supplies oscillations**
- **Tolerances are comparable with the ones of other High Intensity linacs such as LINAC 4 or SNS**
- **Fabrication of the first RF Prototype (Coupled CH 3 and 4 in preparation)**