End to End Simulation of the GSI Linear Accelerator Complex

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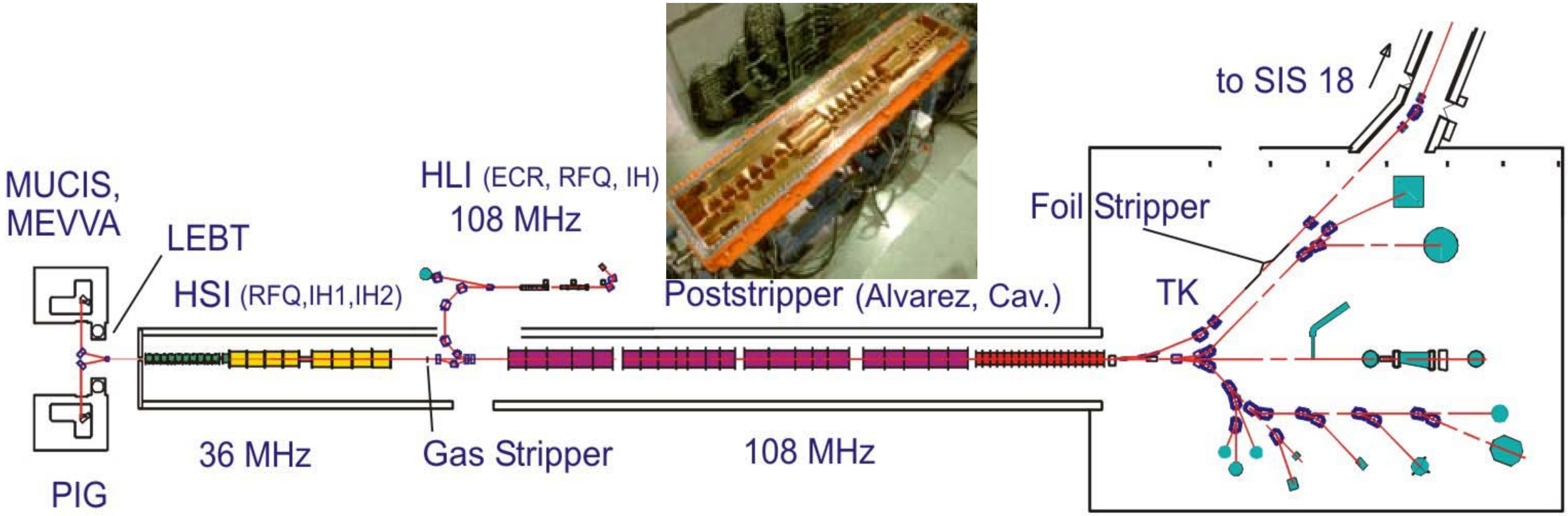
- **GSI Linear Accelerator Facility**
  - Heavy Ion Linear Accelerator UNILAC
- **From GSI to FAIR**
  - HSI Upgrade
- **The FAIR Proton Injector**
  - Cavity development at Frankfurt University
  - Beam Dynamics
  - Status of the Project
- **Commissioning of the HITRAP decelerator**
- **Summary and Outlook**

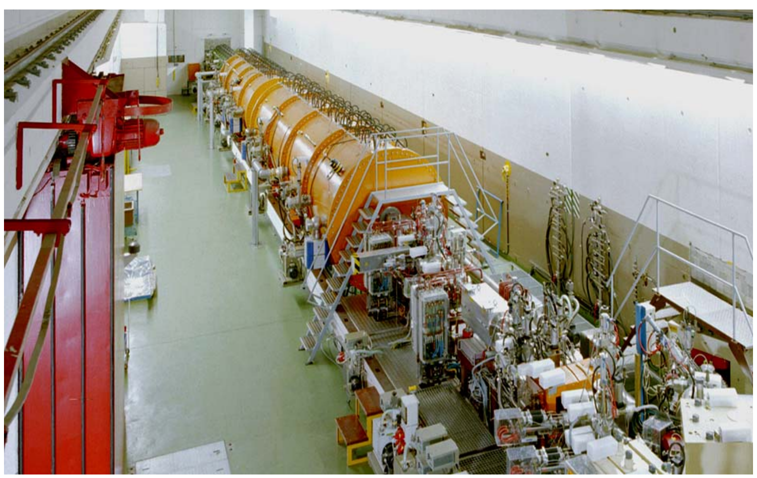
ICAP 2009

San Francisco, 3rd September 2009

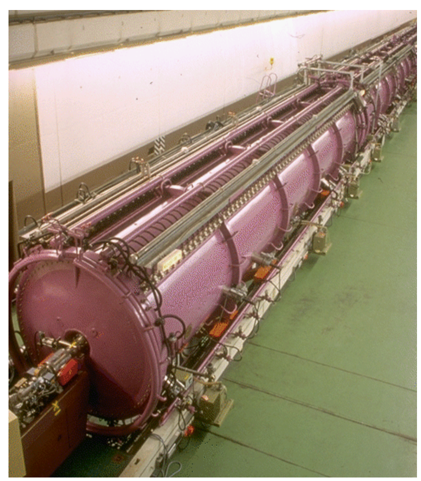
The GSI UNIversal Linear ACcelerator



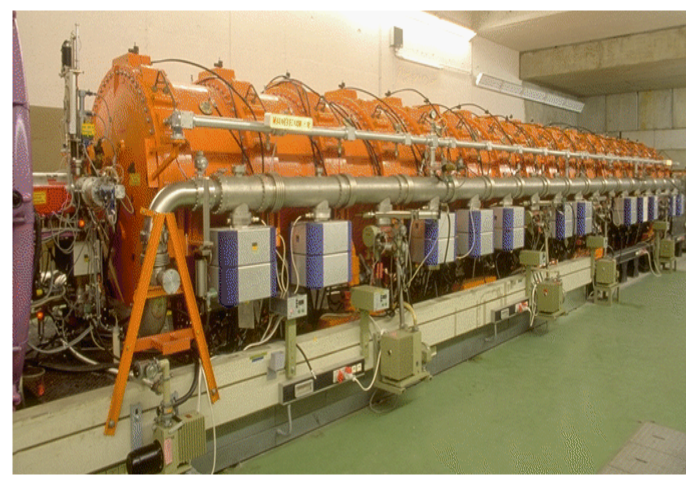
High Current Injector



Alvarez



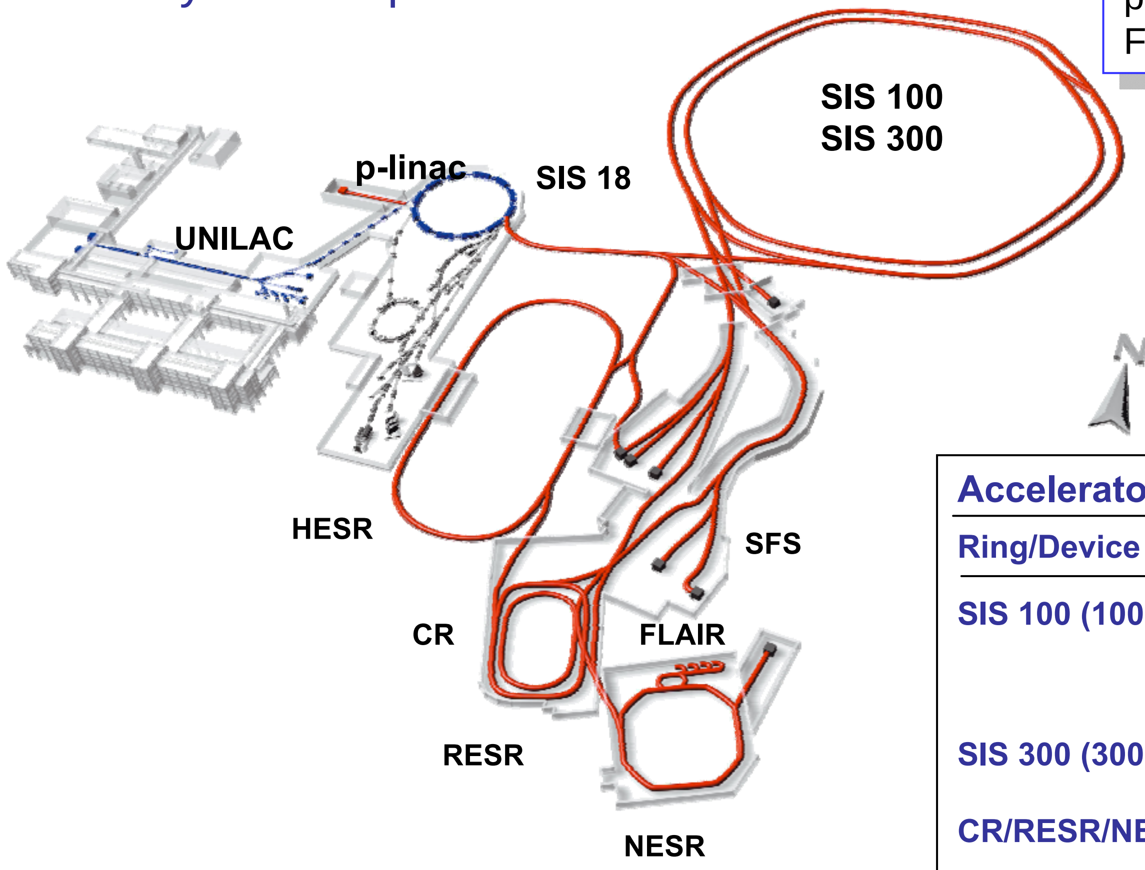
Single Gap Resonators



The FAIR Accelerator Complex

Primary beams: protons to ^{238}U

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



Accelerator Components & Key Characteristics

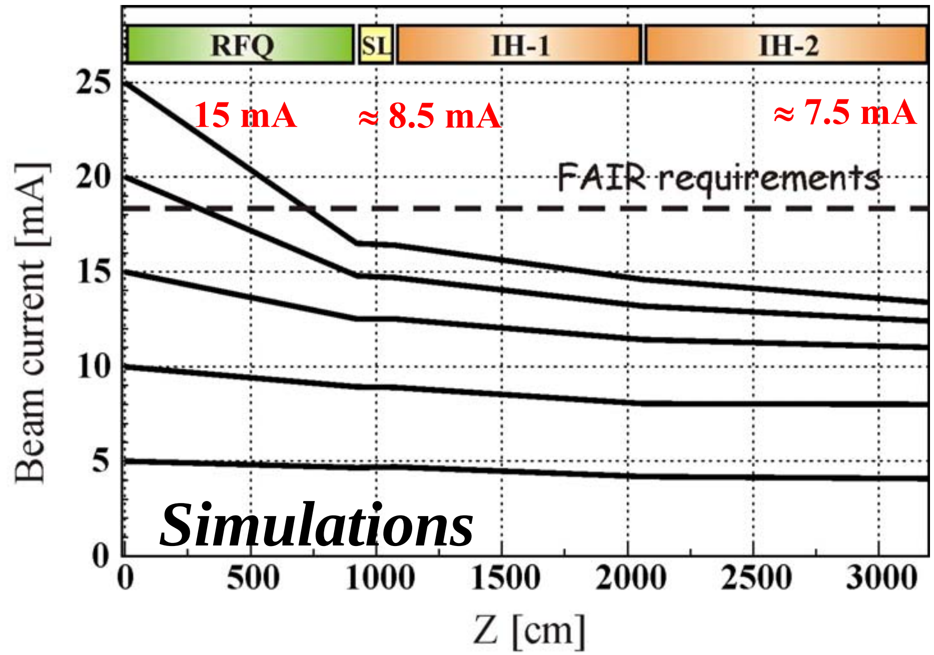
Ring/Device	Beam	Energy	Intensity
SIS 100 (100Tm)	protons	30 GeV	$4x10^{13}$
	^{238}U	1 GeV/u	$5x10^{11}$
	(intensity factor 100 over present)		
SIS 300 (300Tm)	^{40}Ar	45 GeV/u	$2x10^{9}$
	^{238}U	34 GeV/u	$2x10^{10}$
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim 10^{11}$
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

Secondary beams: RIBs, pbars

UNILAC-Upgrade for FAIR

Project	Target
High Current U^{4+} Primary beam	18 mA @ HSI output (1.4 MeV/u)
Gas Stripper	13 % Efficiency for U^{28+} 100 % Transmission
Alvarez Quadrupole Supplies	σ_0 = 55° for U^{28+}
Charge Separator	5 mA for U^{73+} beam
General Improvement of Diagnostics for high intensity	

Measurements



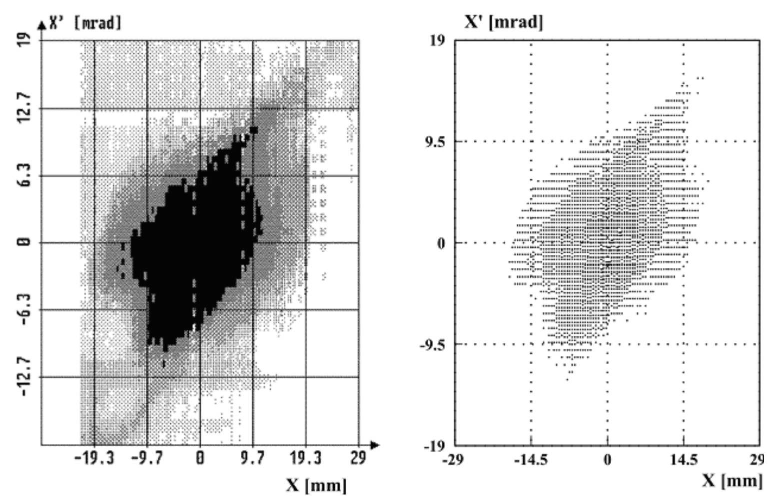
The HSI RFQ was upgraded in 2004

New electrodes were produced

Power consumption reduced from 620 kW to 380 kW

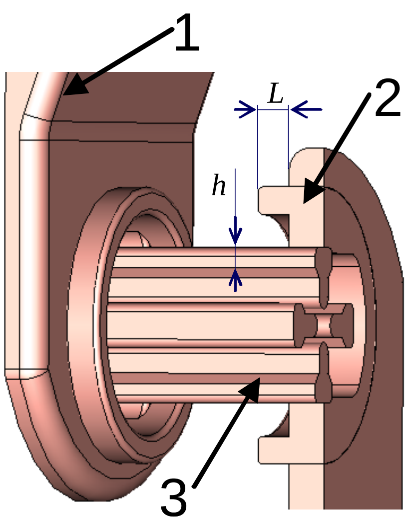
Simulations with generated particle distribution from measured emittance showed a bottleneck concerning the FAIR high current requirements

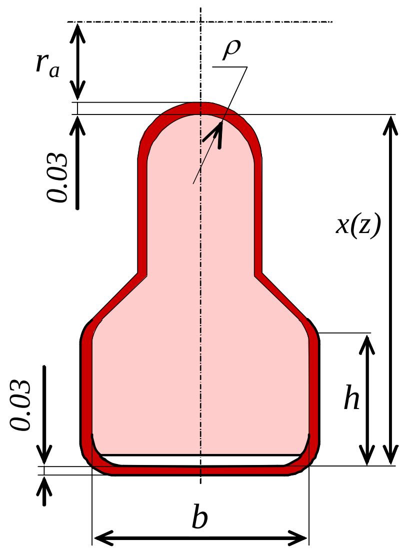
Results were confirmed by measurements



HSI-RFQ New Design 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





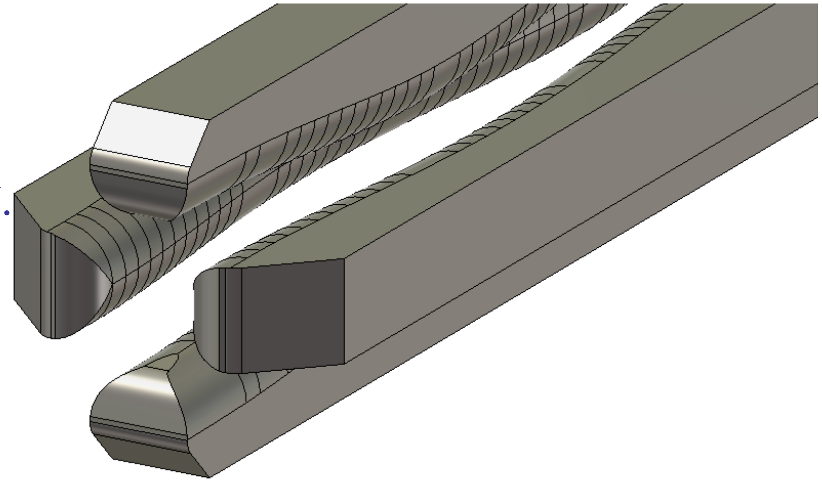
	2009 Design	2004Design
Voltage, kV	155.	125.
Average radius, cm	0.6	0.5245 – 0.7745
Electrode width, cm	0.84	0.9 – 1.08
Maximum field, kV/cm	312.0	318.5
Modulation	1.012 – 1.93	1.012 – 2.09
Synch. Phase, degree	-90^0 - -28^0	-90^0 - -34^0
Aperture, cm	0.410	0.381
Min. transverse phase advance, rad	0.555	0.45
Norm. transverse acceptance, cm mrad	0.856	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

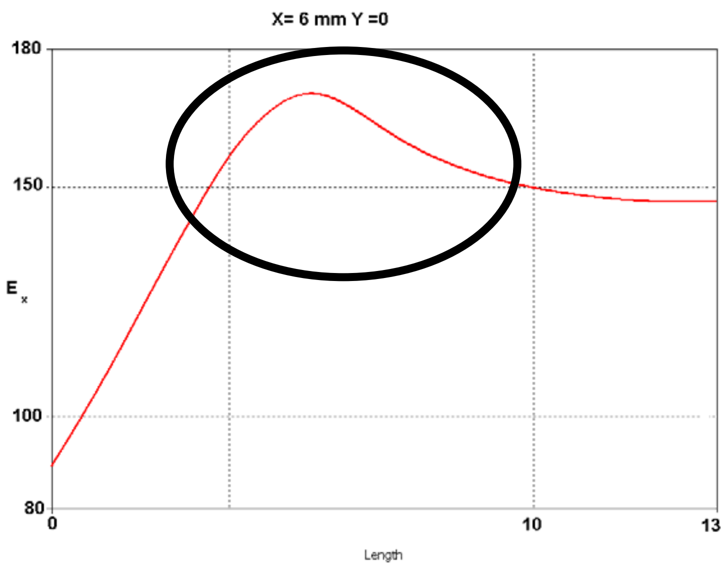
Beam dynamics studied with DYNAMION & PARMTEQ-M
IRM Designed with DESRFQ at ITEP

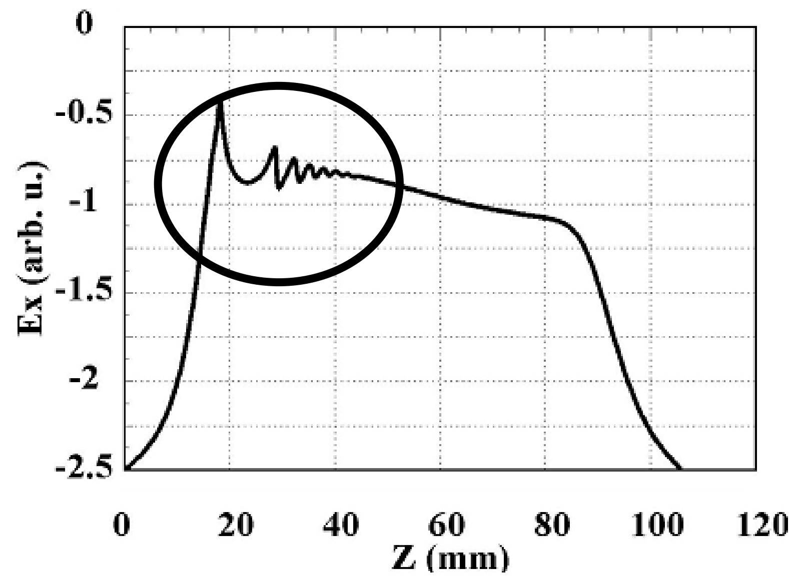
External EMS 3D Mapping of electrical field for

- RFQ matching out section
- Superlens

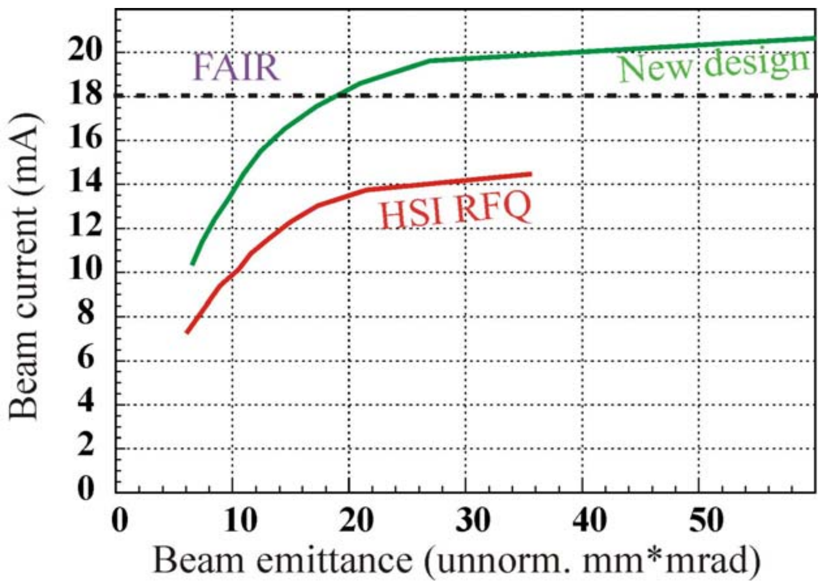
- Integration with the intrinsic 8 terms potential solver of DYN.
- Realistic description including details =>
- emittance orientation at the RFQ output
- exact final energy
- optimum synchronous phase in Superlense
- adjustment of the particle energy at IH entrance

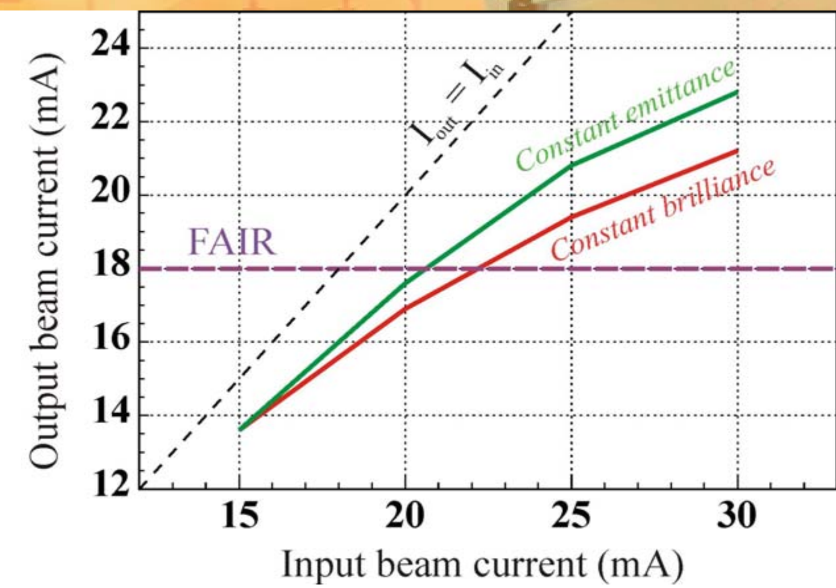


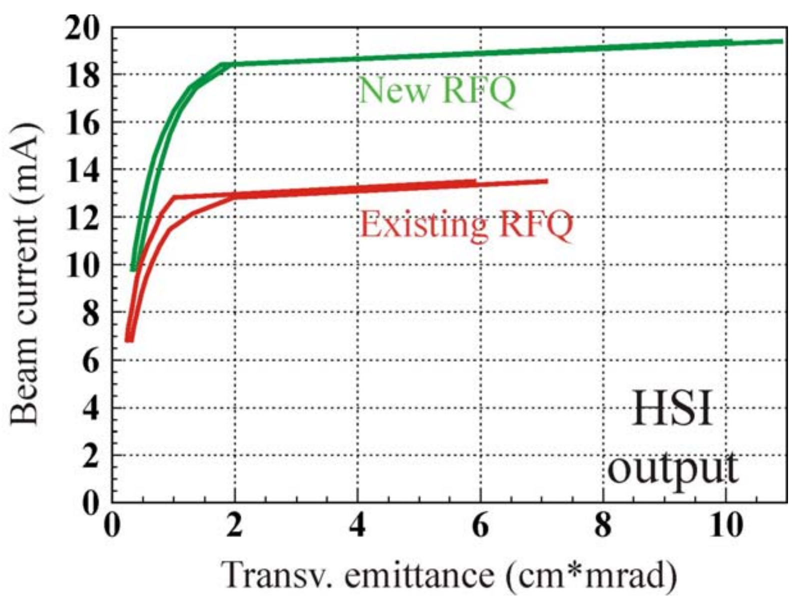


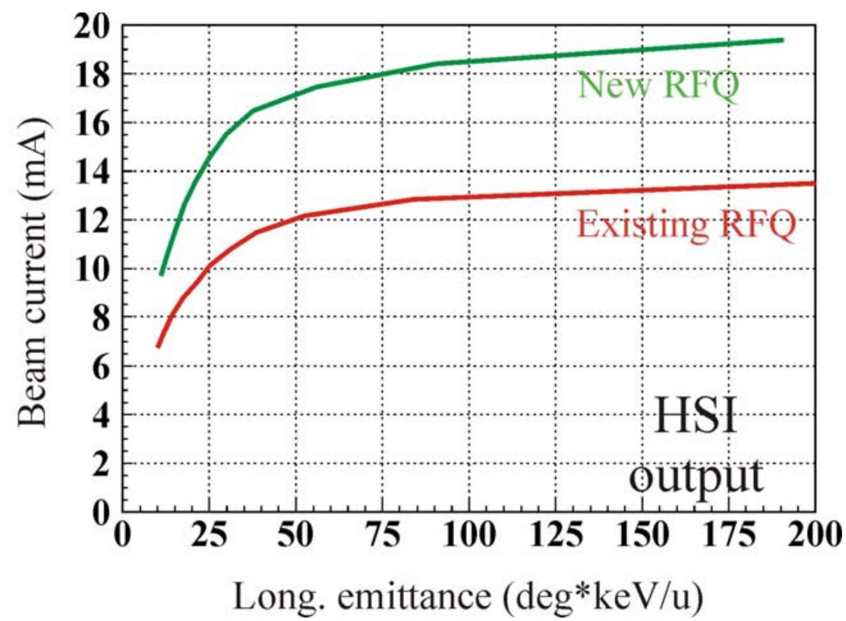


Beam brilliance at HSI-RFQ output









Topic

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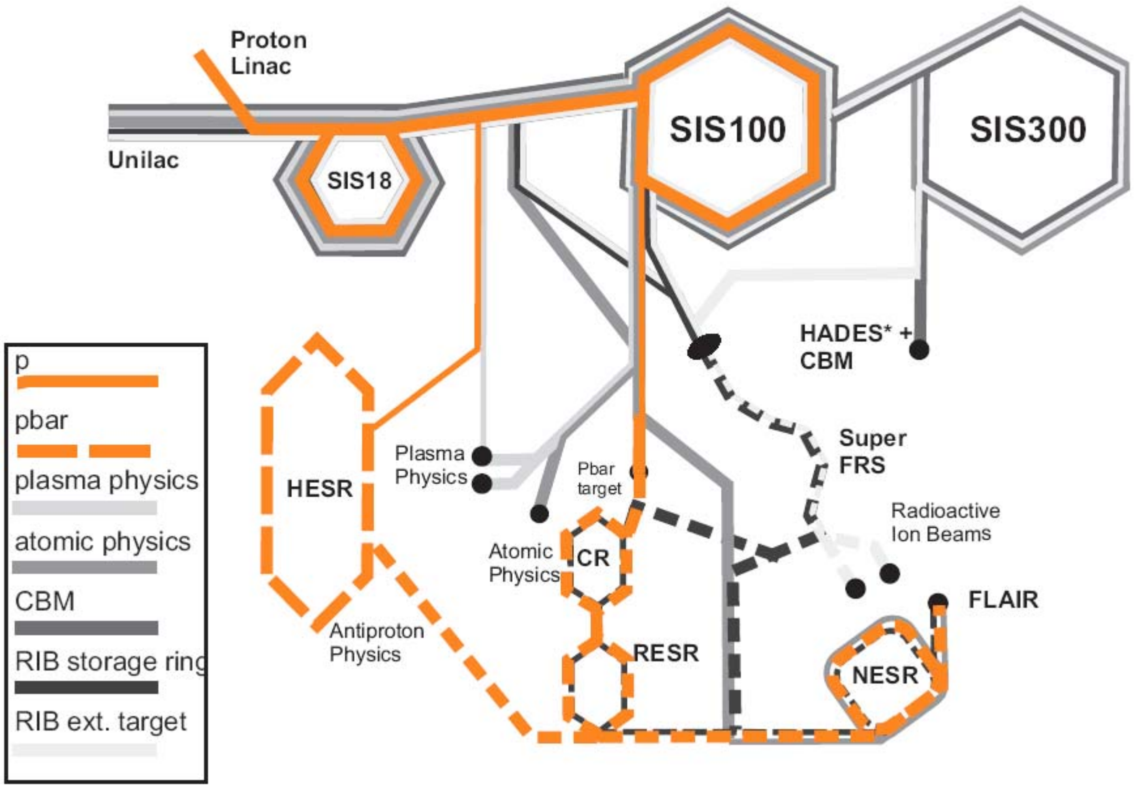
Accelerator Chain for Cooled Antiprotons



<=100 x :

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

or

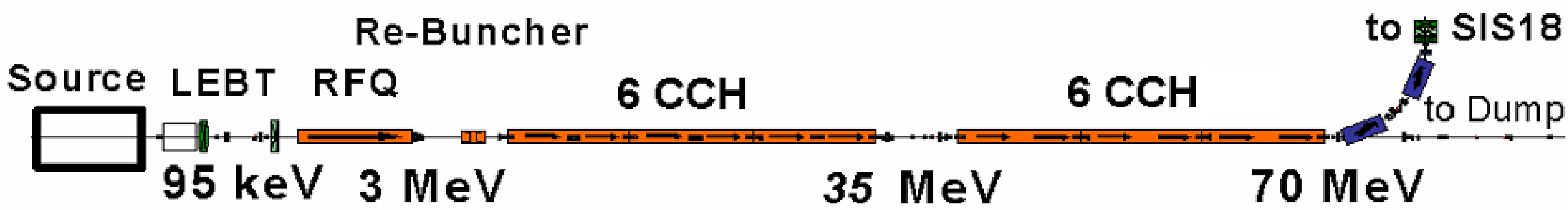
Deceleration in NESR to 30 MeV
Extraction to low energy pbar experiments

Multi-Turn Injection into SIS18 requires:

$$B_n := \frac{I}{(\beta\gamma)\epsilon_{tot}} = 63.6\,\frac{\mathrm{mA}}{\mu\mathrm{m}} \cdot \frac{(\beta\gamma)^2}{\eta_{MTI}}$$

η_{MTI} := MTI filling factor → 60%

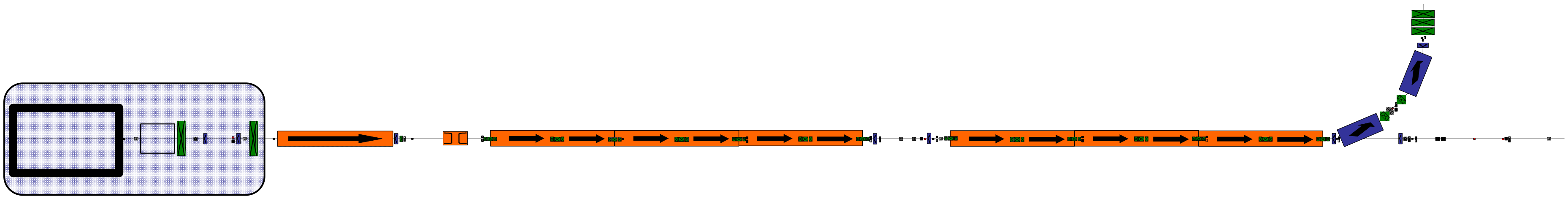
General Overview



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

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

Proton Source & LEBT



Requirements at LEBT exit:

P current	≥ 80 mA
$\beta\gamma\varepsilon_{tot}$ (transv.)	≤ 1.8 μm
High reliability	
High stability	

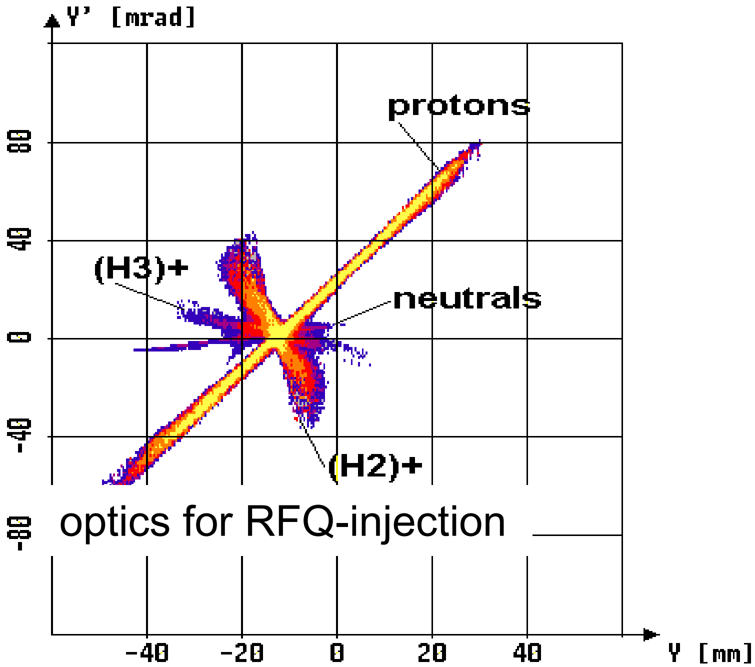
SILHI at CEA/Saclay: 95 keV, > 100 mA, dc

R. Gobin, CEA/Saclay

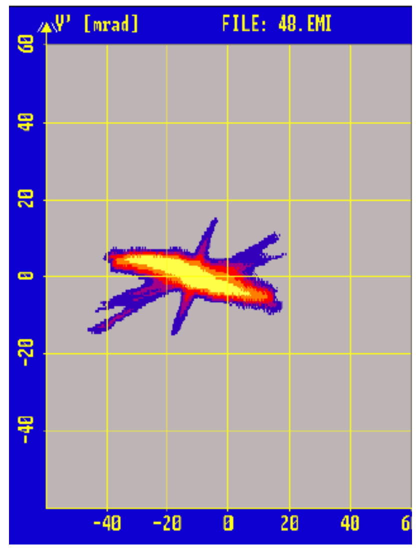
Beam Measurements at CEA/Saclay

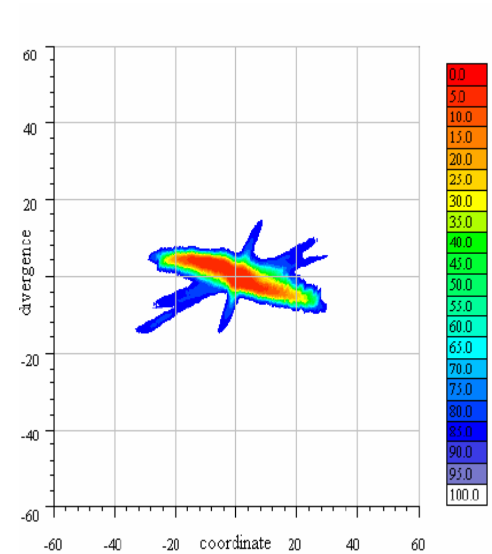
SILHI at CEA/Saclay:

95 keV, > 100 mA, dc



LEBT exit: two measurements using different electronics, separated by 4 days, intermediate opening of the plasma chamber:



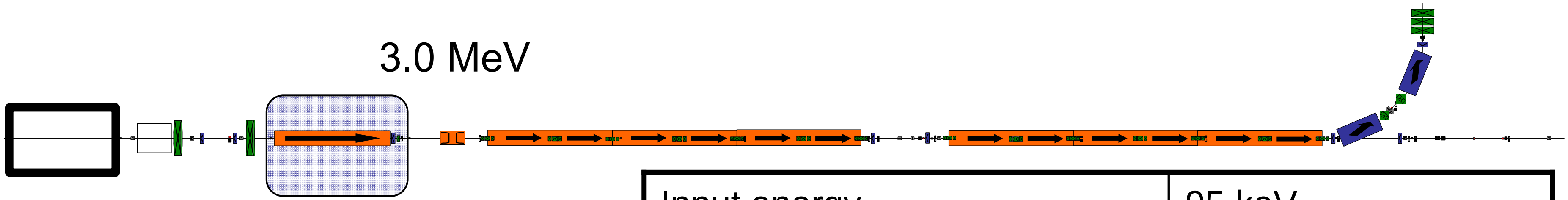


During 3 weeks of measurements :

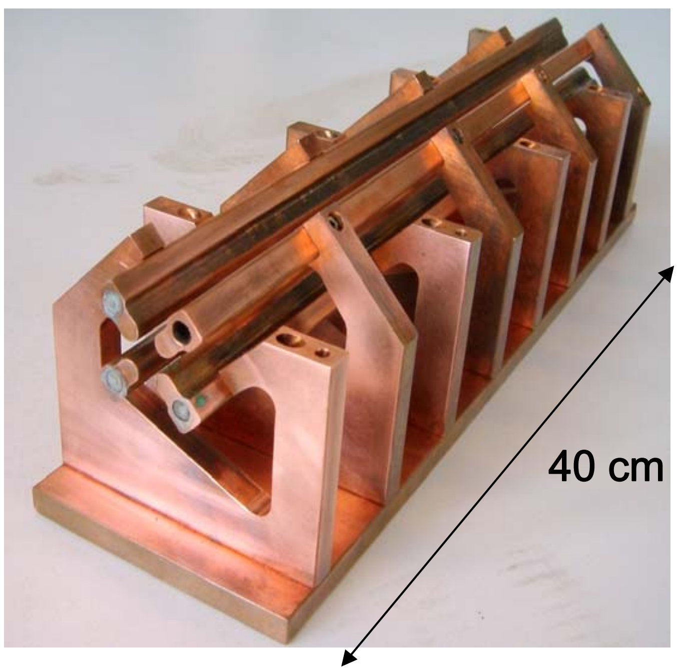
- **always reliable & stable 100 mA beam**
- **no single sparking of the HV**
- **no interruption due to any malfunction**

- **France submitted EoI to deliver operating set-up in-kind**
- **Set-up to be fully assembled and tested at CEA/Saclay**
- **Joint re-commissioning at GSI**

RFQ

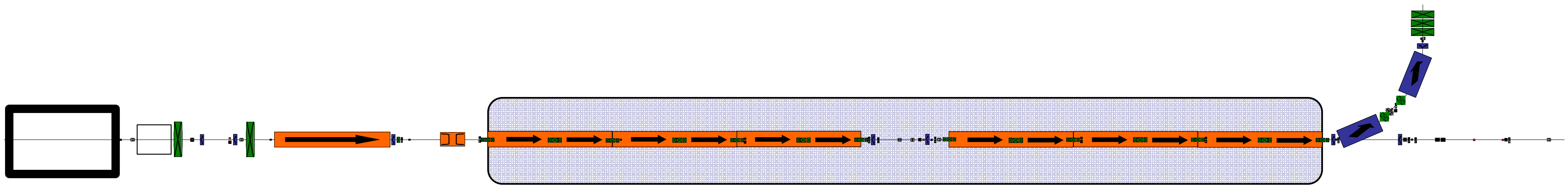


4-rod model (A. Schempp, Univ. Frankfurt)



Input energy	95 keV
Input Current	100 mA
Input emitt. (transv., norm.)	1.8 mm mrad
Frequency	325.224 MHz
Output energy	3.0 MeV
Accelerated current	98 mA
Output emitt. (transv., norm.)	2.1 mm mrad
Distance to closest mode	54 MHz
Rf – input power	0.74 MW
Electrode voltage	90 kV
Max. electric field strength	34.7 MV/m (1.94 E_k)
Aperture radius	2.4 – 3.8 mm
Length	3.2 m

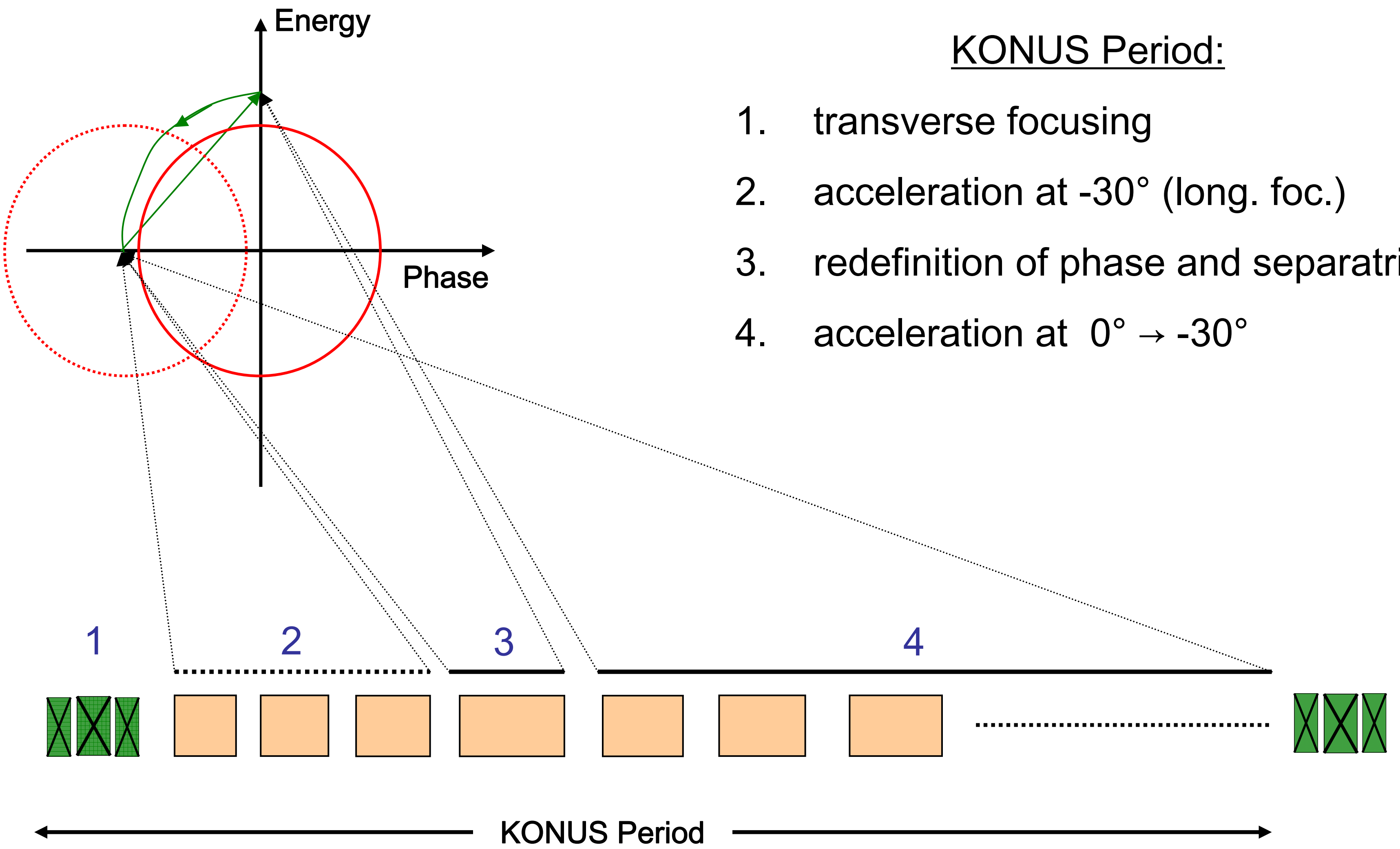
DTL



- state of the art: Alvarez type cavities (SNS, J-PARC), regular focusing:
  - acceleration at negative rf-phases, reducing real estate gradient, i.e. R_s
  - one quadrupole per drift tube → many quadrupoles to align, cool, etc ...
  - quadrupoles need space → further reduction of R_s

- KONUS beam dynamics (KOmbinierte NUll-Grad Struktur):
  - acceleration close to rf-crest
  - avoiding quadrupole in every drift tube
  - increase effective R_s

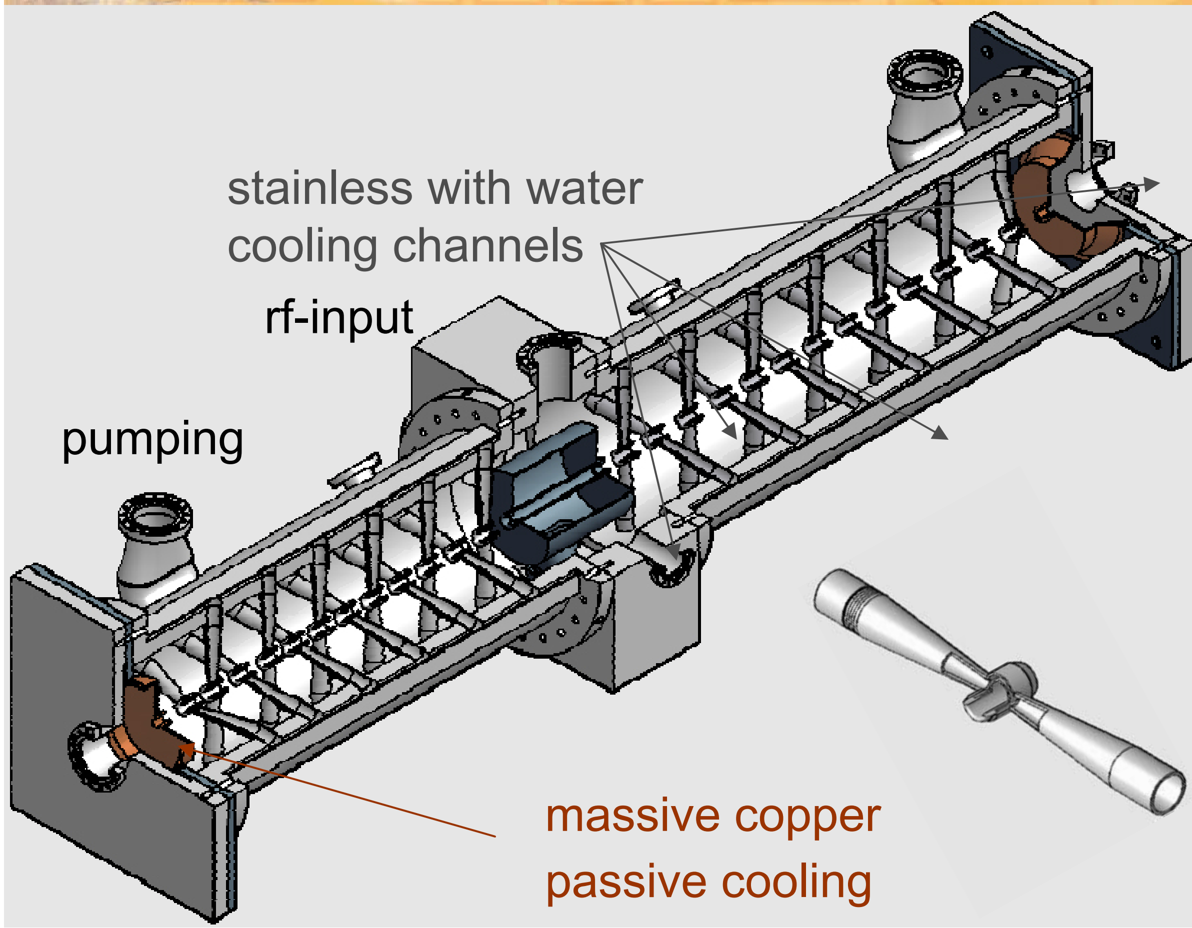
DTL: Longitudinal Dynamics

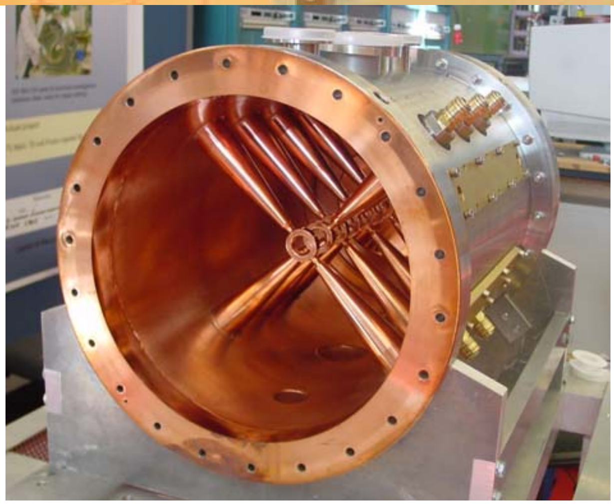


KONUS Period:

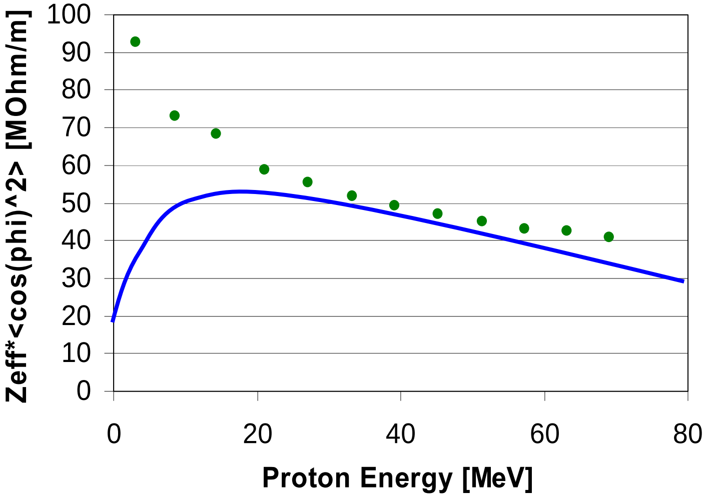
1. transverse focusing
2. acceleration at -30° (long. foc.)
3. redefinition of phase and separatrix
4. acceleration at 0° → -30°

Production of Prototype Cavity





model successfully
copper-plated at GSI



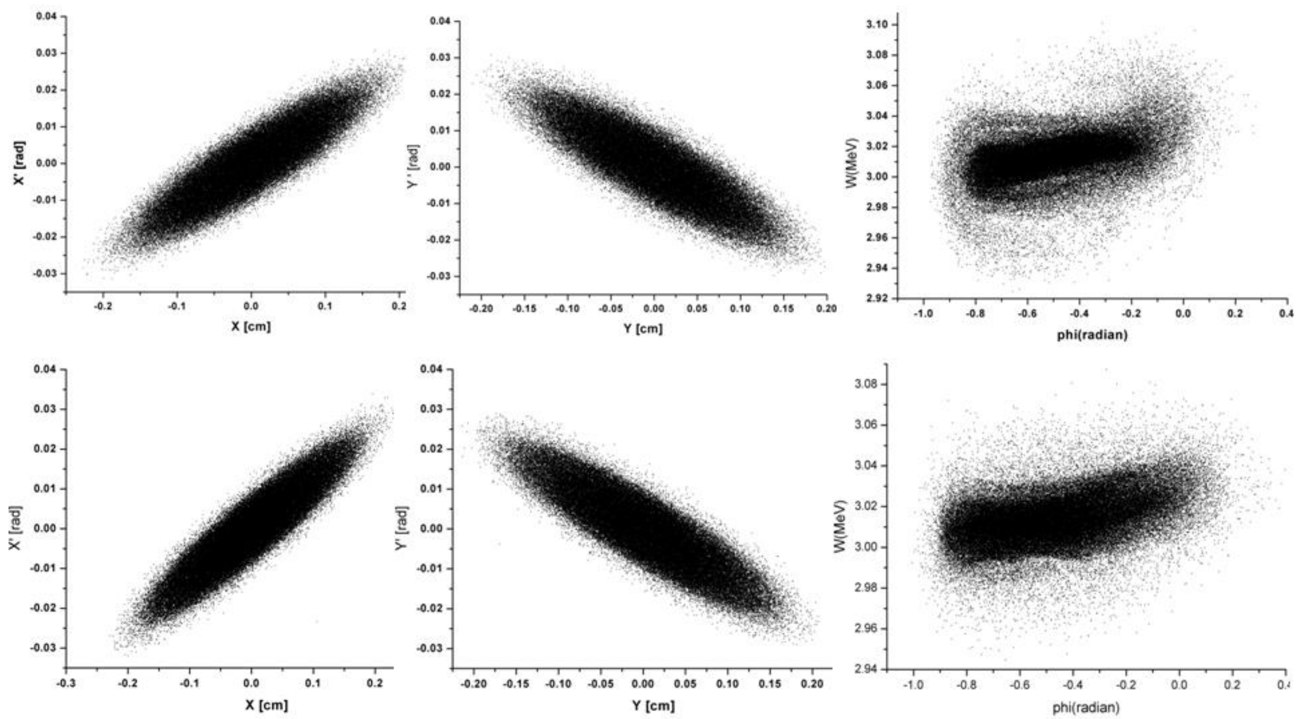
cavity accelerating from 11.6 to 24.1 MeV under production

Beam Dynamics

RFQ Output distribution generated with PARMTEQ

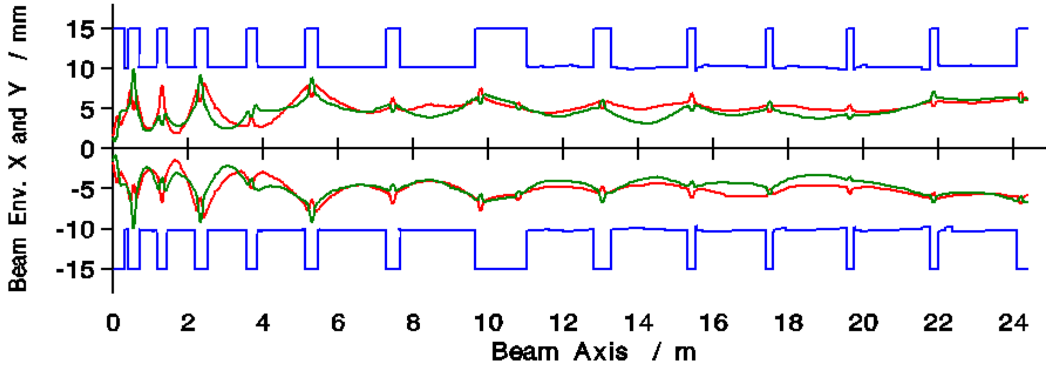
45 mA

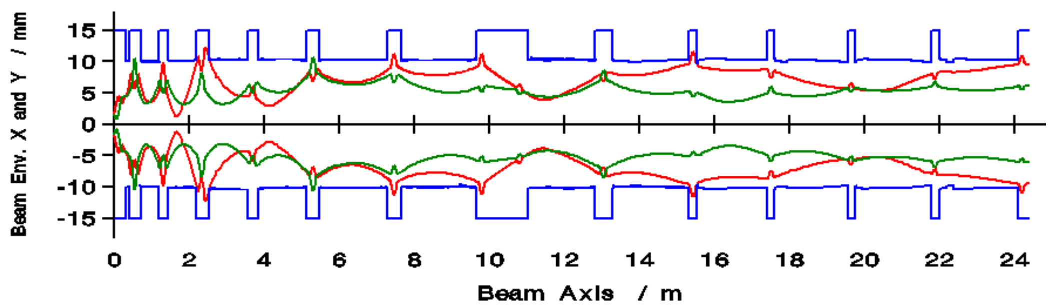
100 mA

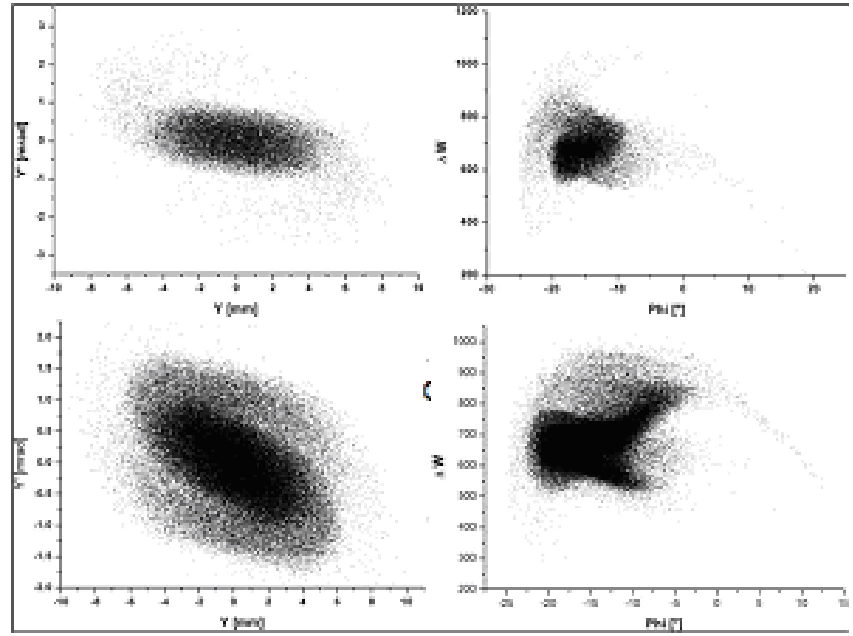


	45 mA	100 mA
RMS ε norm hor	**0.26**	**0.25**
RMS ε norm ver	**0.26**	**0.25**
RMS ε norm Δϕ ΔW	**1.29**	**1.25**

Beam Dynamics







PARAMETER	45 mA	100 mA
RMS ε norm X-X' mm mrad	0.40	0.70
RMS ε normY-Y' mm mrad	0.44	0.58
RMS ε normΔΦ- ΔW keV/ ns	2.09	2.45

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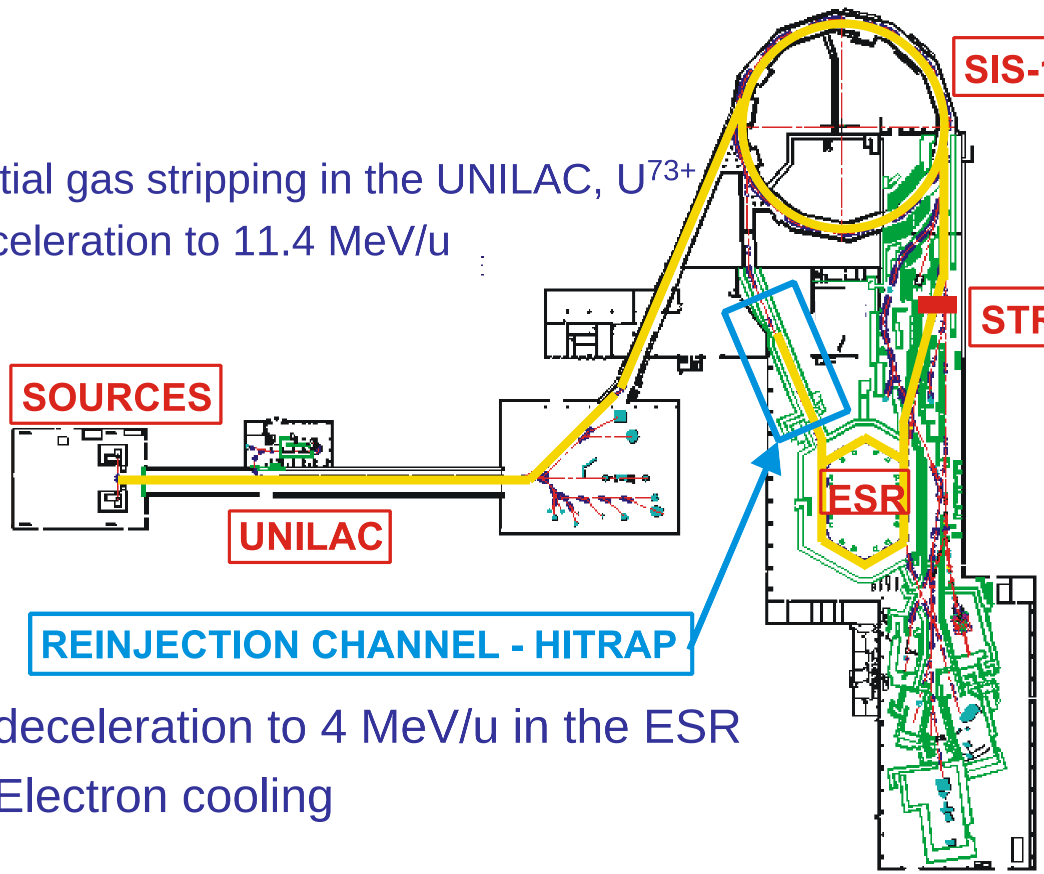
The Accelerator Chain to HITRAP

•acceleration to 400 MeV/u in the SIS18

•partial gas stripping in the UNILAC, U^{73+}

•Acceleration to 11.4 MeV/u

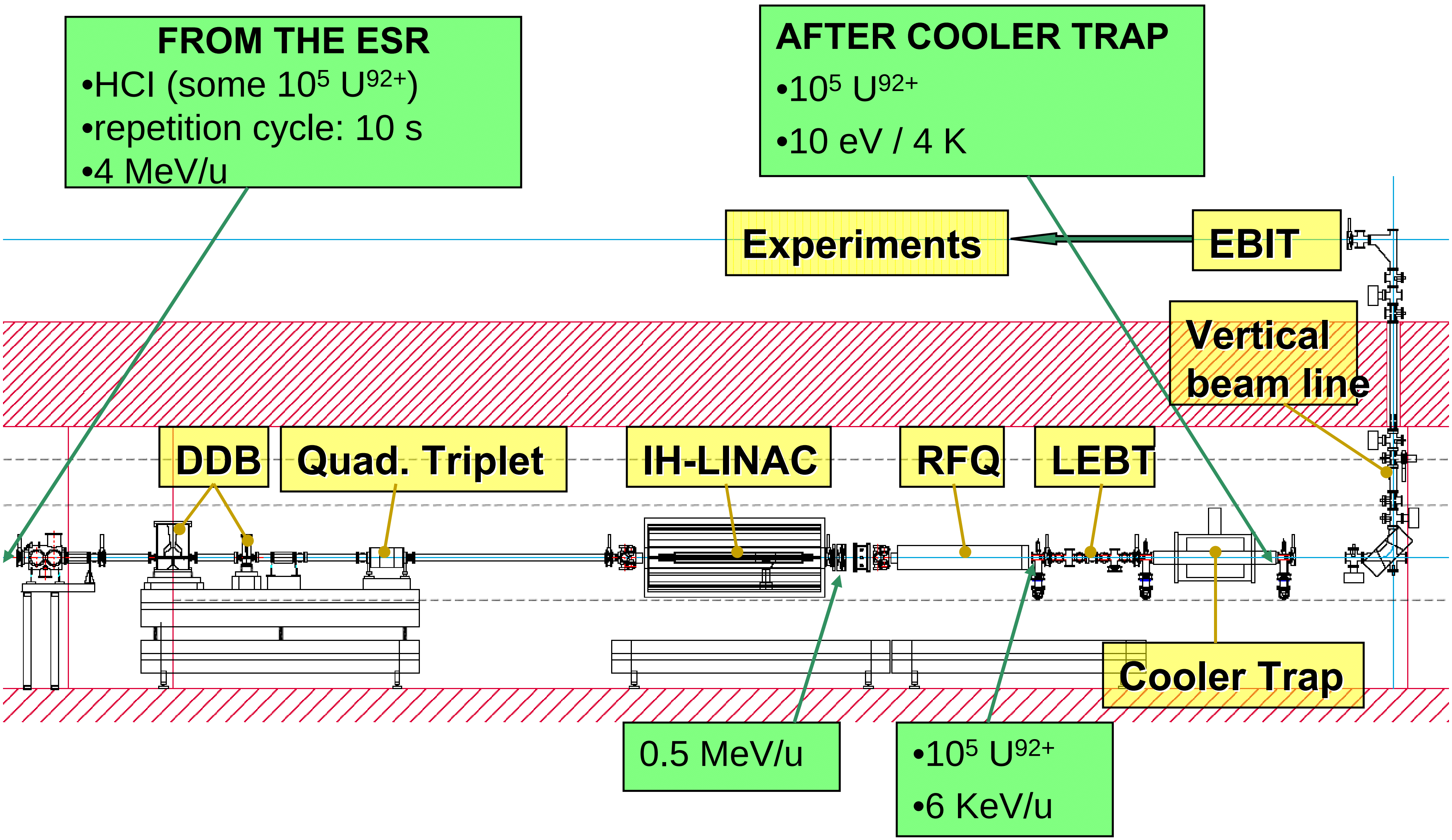


Solid target stripping (U^{92+})

•deceleration to 4 MeV/u in the ESR

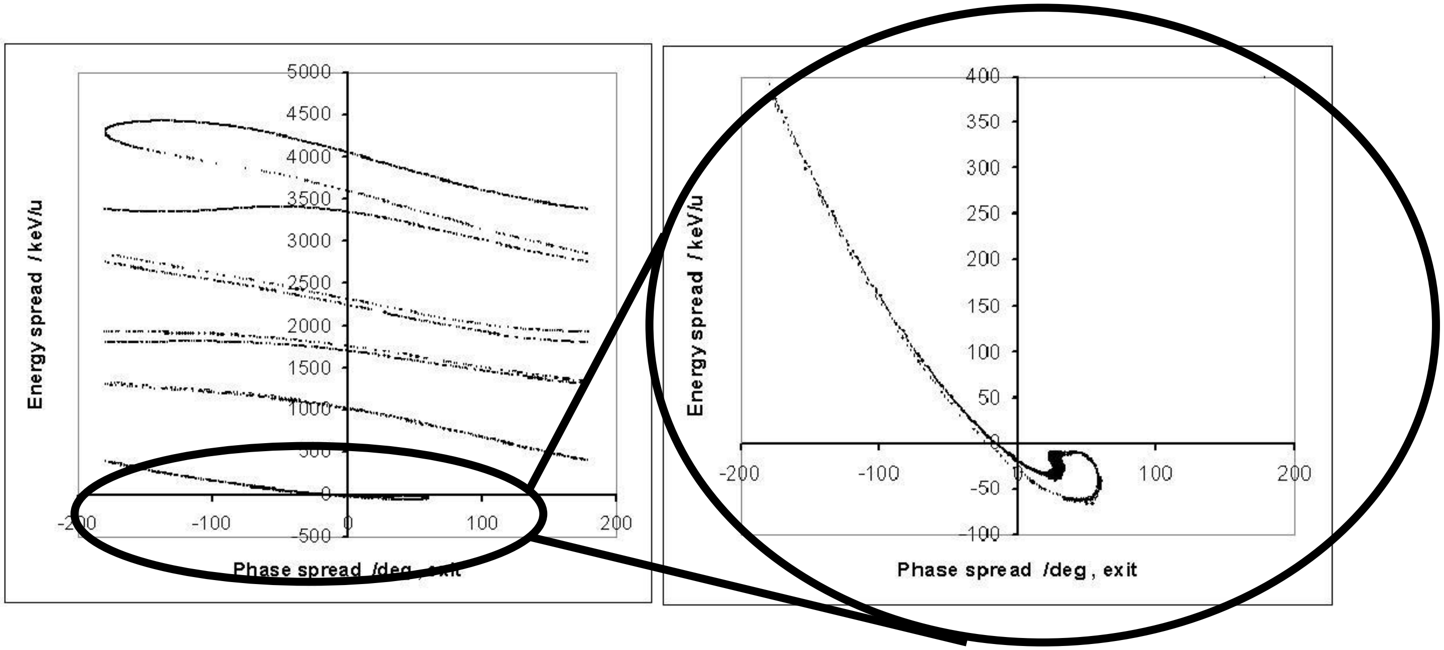
•Electron cooling

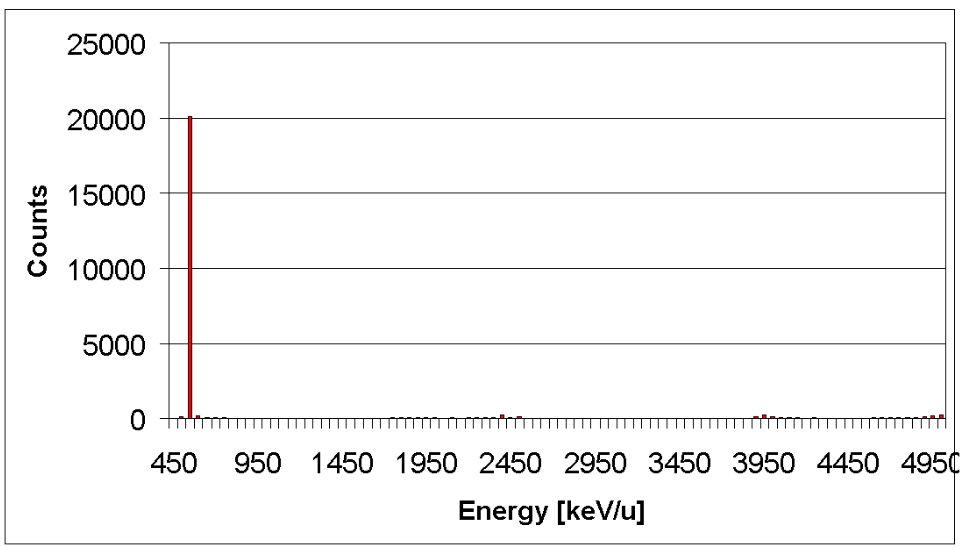
HITRAP

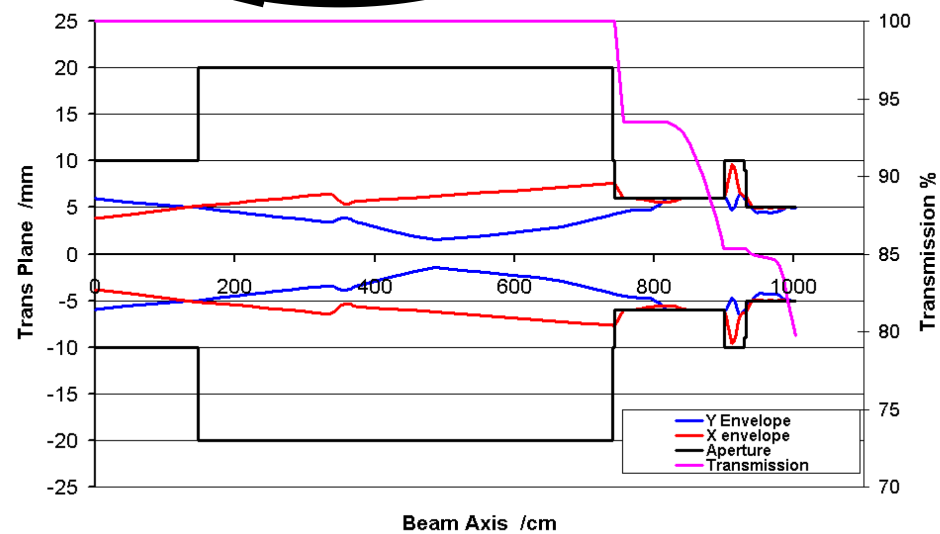


FROM THE ESR
•HCI (some 10^5 U^{92+})
•repetition cycle: 10 s
•4 MeV/u
AFTER COOLER TRAP
•10^5 U^{92+}
•10 eV / 4 K
Experiments
EBIT
Vertical beam line
DDB
Quad. Triplet
IH-LINAC
RFQ
LEBT
Cooler Trap
0.5 MeV/u
•10^5 U^{92+}
•6 KeV/u

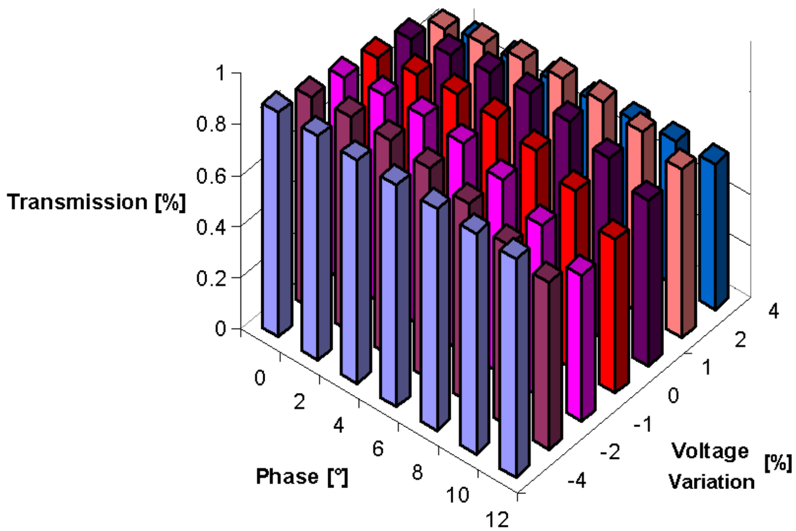
IH Beam Dynamics: Nominal case

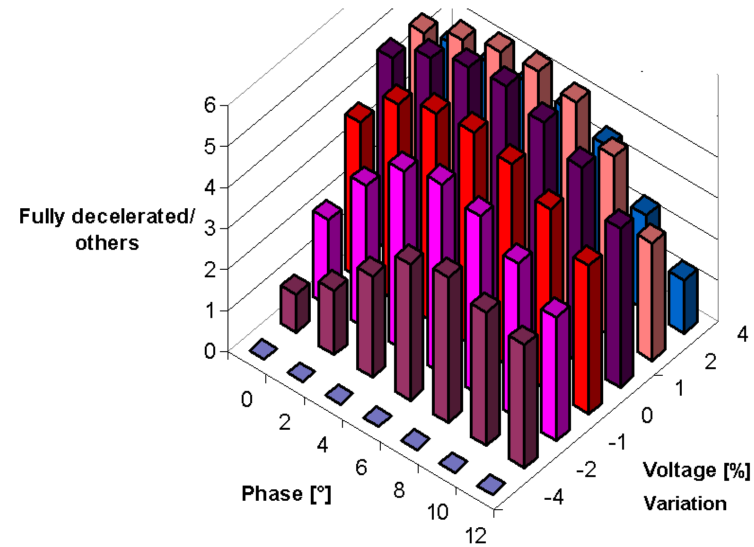






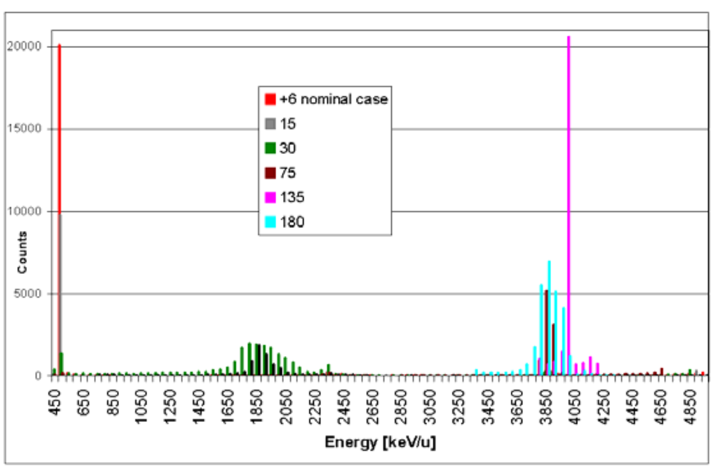
IH Beam Dynamics: IH Working Point



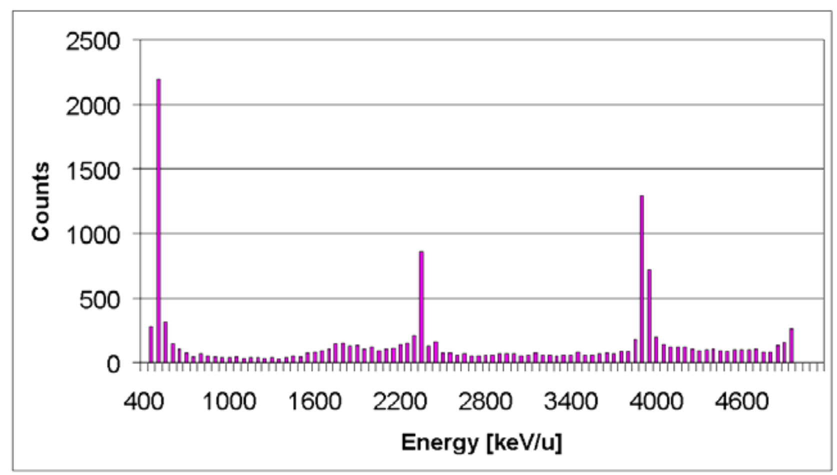


WP of the DDB+IH has to be carefully selected according to the energy of the ESR

Example of wrong Phase settings of IH

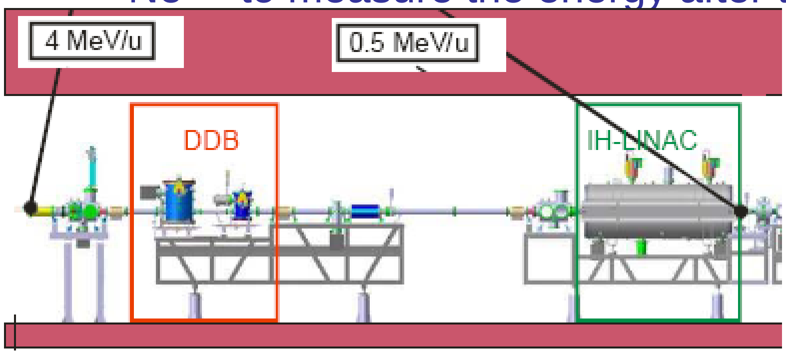


Energy with 4.04 MeV/u from the ESR



First Beam Commissioning: Energy from ESR 4.04 MeV/u

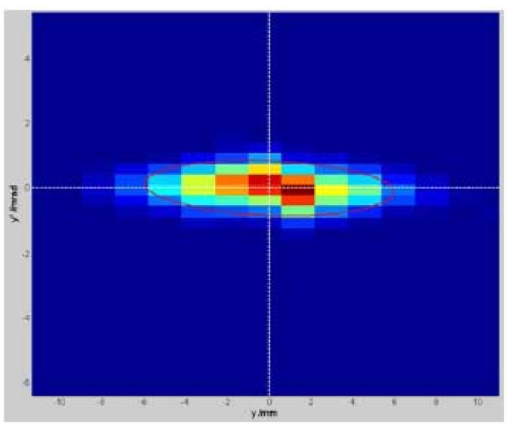
- In August and October first beams available to commission the Bunchers-IH beam line
- No fine tuning of the IH was possible
- $^{64}Ni^{28+}$ to measure the emittance after the buncher
- $^{10}Ne^{20+}$ to measure the energy after the IH



Steerers + vertical diamonds detector array after the IH: signals proportional to ions energy

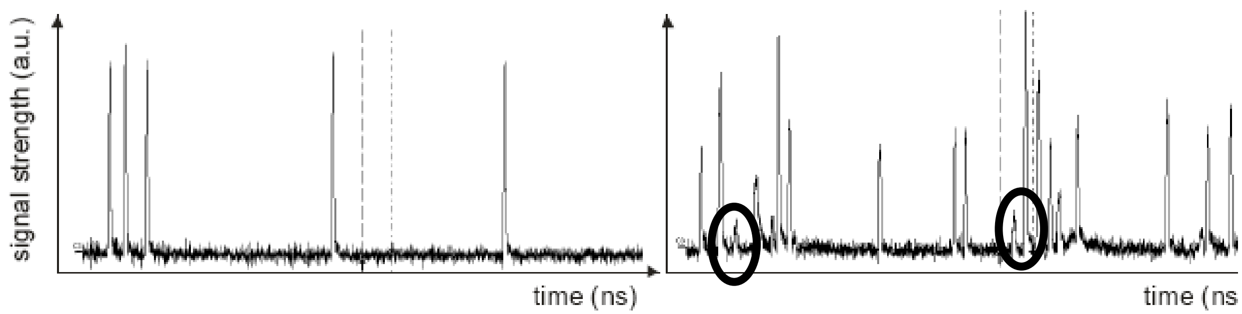
Evidence of decelerated ions with major fraction of the beam at ~ 2.3 MeV/u, 4 MeV/u and even more

Pepper pot single shot emittance scanner after DDB: RMS Emittance for 88 % 1,23 π mm mrad



IH OFF

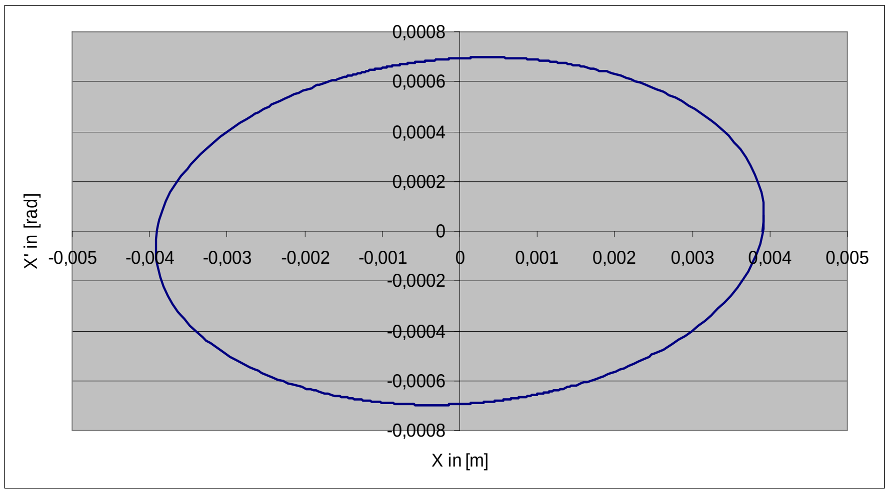
IH On

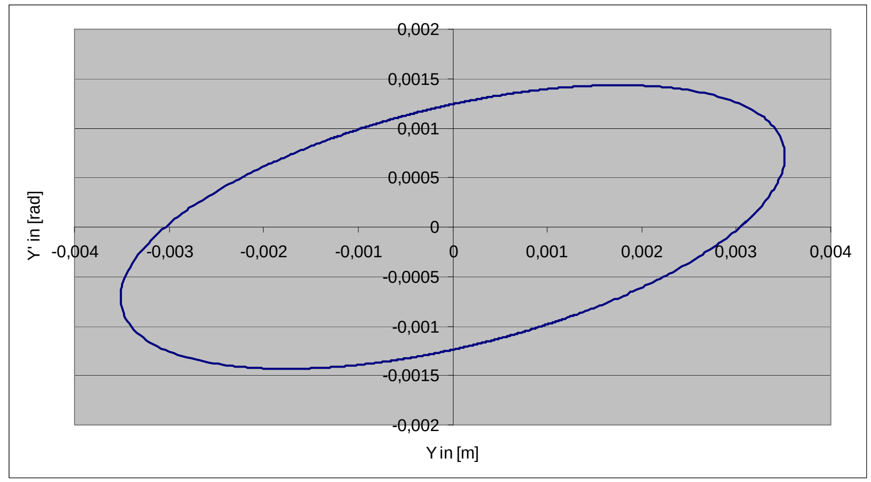


500 keV/u

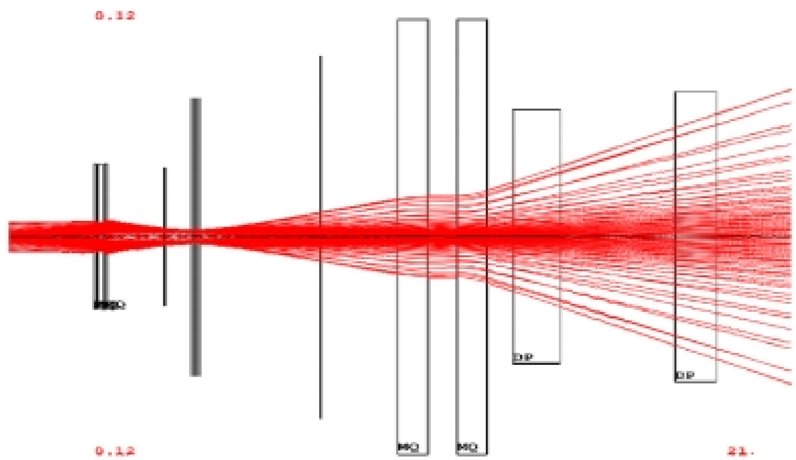
Results: Emittance measurements

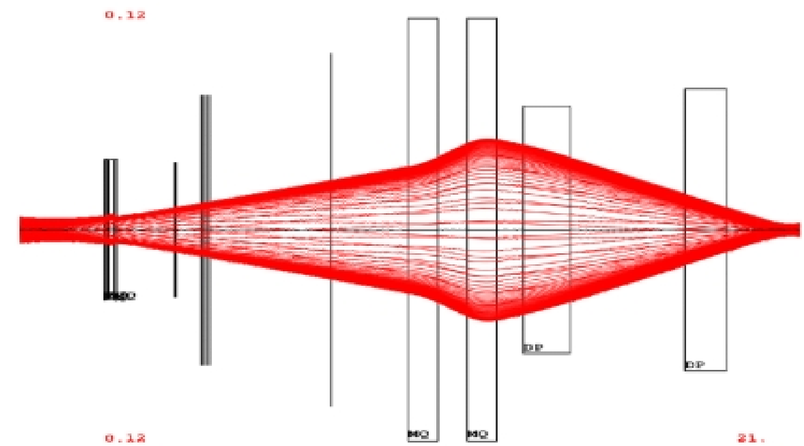
Emittance in front of IH using the emittance evaluation with beam profiles in dependence of lens variation





beam tracked from IH input back to ejection of ESR: results in agreement with previous simulations





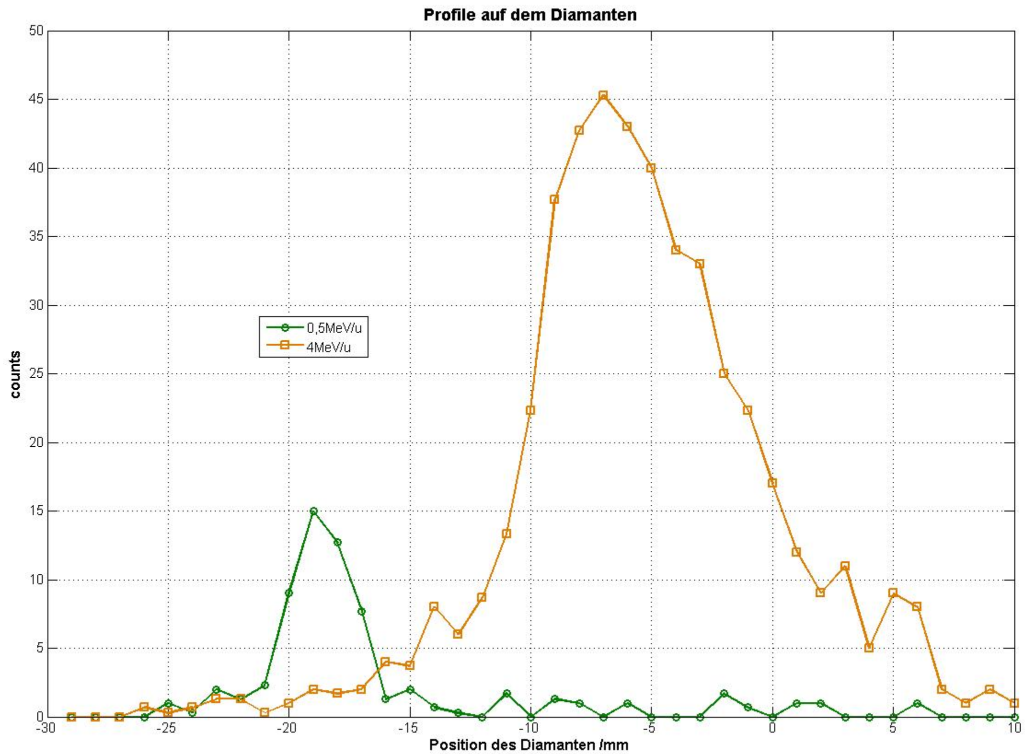
Results from Diamond detector

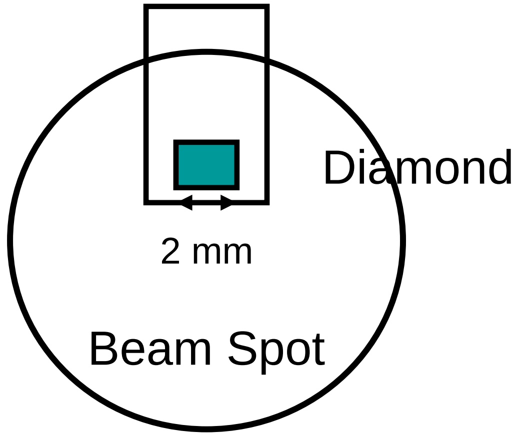
beam profile separation of 0.5 and 4 MeV/u beam on diamond

Triplet used to focuse the beam on vertical plane

Steeres used to separate different energies

Huge uncertainty since only a fraction of the beam is seen





ratio between fully decelerated and other transmitted ions

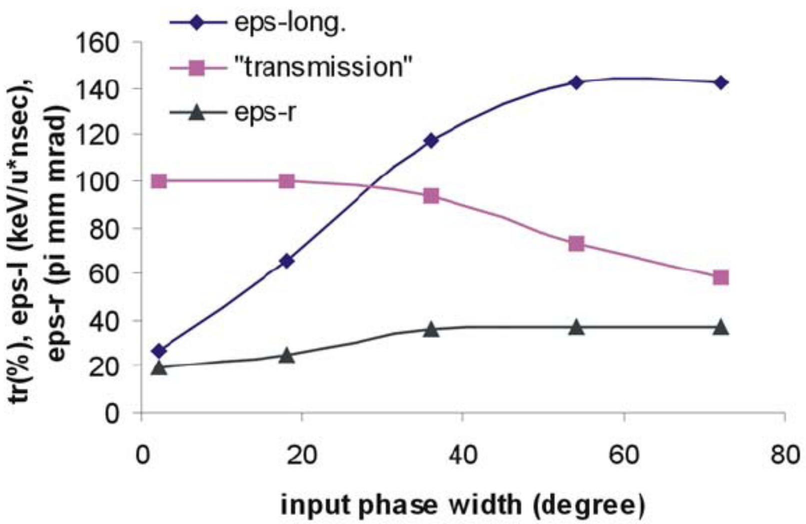
1:7.22

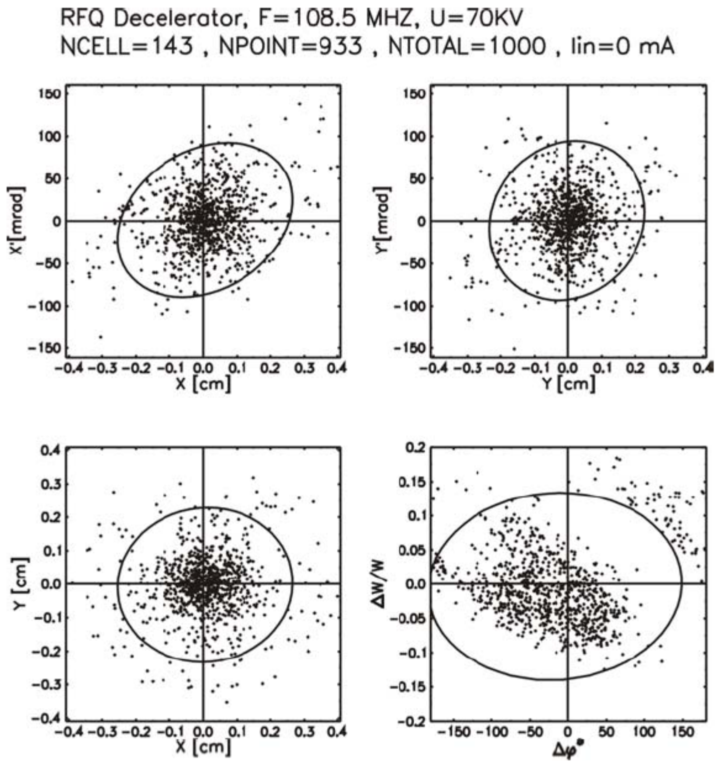
=

13% of ions @ 500keV/u (seen 1-dimensional)

RFQ DESIGN and Beam Dynamics

Input phase width / energy spread	± 9° / ± 10 keV/u	± 9° / ± 5 keV
Injection energy / output energy	500 keV/u / 6 keV/u	
Charge-to-mass ratio q/A	> 1/3	
Operation frequency	108.408 MHz	
Electrode voltage	70 kV	
Modulation	2.44	
Phase range	−18° – −70°	
RFQ length	1.9 m	
Aperture	4 mm radius	
Input emittance (normalized)	0.24 π mm mrad	
Output energy spread	± 0.5 keV/u (8.3 %)	± 0.38 keV/u (6.3%)
Longitudinal input emittance	23 nsec .keV/u	11.5 nsec keV/u
Longitudinal output emittance (80 %)	10 nsec keV/u	5.6 nsec keV/u
Longitudinal output emittance (100 %)	23 nsec keV/u	9.0 nsec keV/u
Radial output emittance (normalized)	0.37 π mm mrad	0.25 π mm mrad
Transmission	93%	100%
Power consumption	80 kW	





Outlook and Summary

•FAIR requirements pushed towards a new design of the HSI-RFQ
•The new design was commissioned in July 2009 matching the FAIR requirements
•Primary proton beam intensities will be increased by a new proton linac (to be commissioned in 2013).
•First RF coupled cavity in construction
• In the frame of atomic and nuclear physics at GSI the decelerator facility HITRAP is being commissioned.