Development of the Intensity and Quality of the Heavy Ion Beams at GSI

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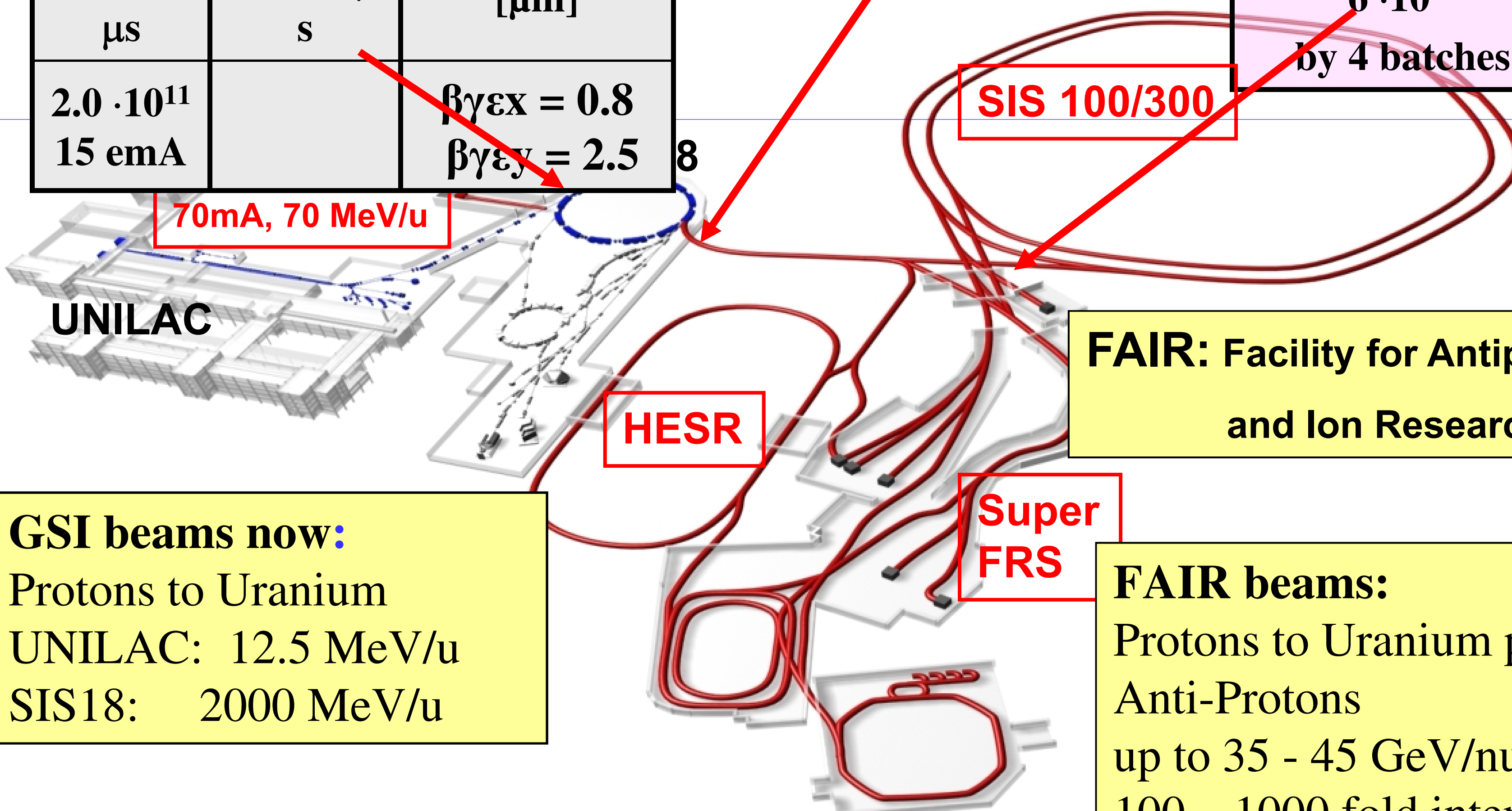
1. Accelerators and Beam Intensity Requirements
2. UNILAC: Upgrades and Beam Investigations
   - Front End Upgrades
   - 4th Order Resonances in the Alvarez Section
   - Emittance Transfer Experiment
3. SIS18: Beam Loss Reduction
   - Particle Losses by Ionization and Dynamic Vacuum
   - NEG Coating and Scrapers
   - New RF-Cavities, Faster Ramping
4. Conclusions

Envisaged Beam Intensities for an U28+ Beam

required ions/60 µs	measured ions/60µs	transverse emittances [µm]
$2.0 \cdot 10^{11}$ 15 emA		$\beta\gamma\varepsilon x = 0.8$ $\beta\gamma\varepsilon y = 2.5$

required ions/spill	measured ions/spill
$1.5 \cdot 10^{11}$	

required for SIS100 booster operation
$6 \cdot 10^{11}$ by 4 batches

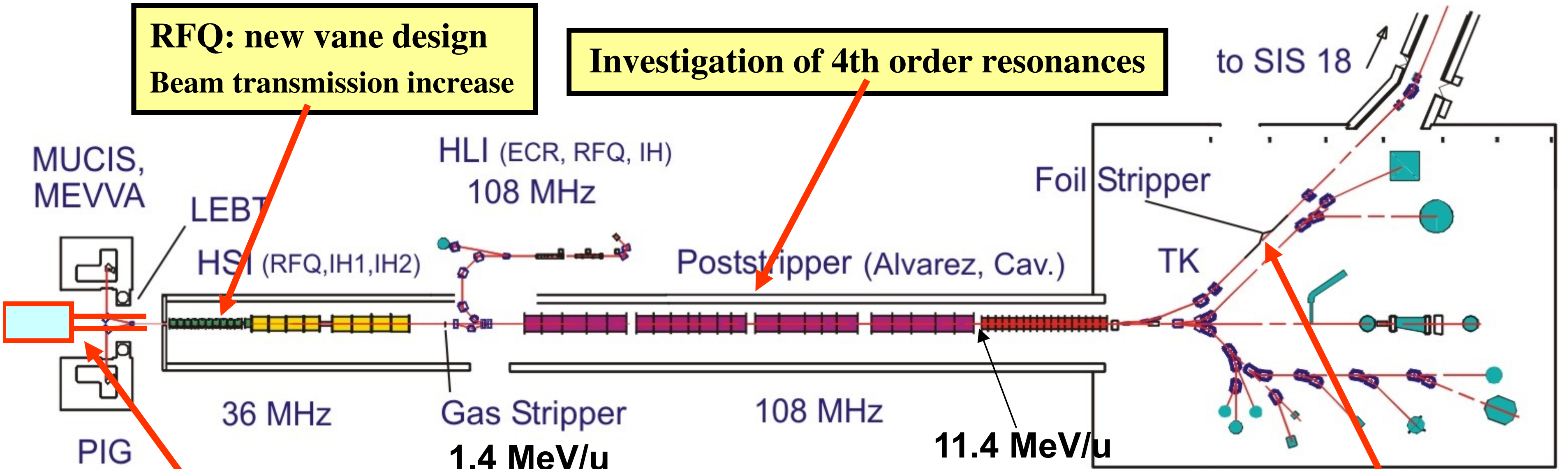


FAIR: Facility for Antiproton and Ion Research

GSI beams now:
Protons to Uranium
UNILAC: 12.5 MeV/u
SIS18: 2000 MeV/u

FAIR beams:
Protons to Uranium plus Anti-Protons
up to 35 - 45 GeV/nucleon
100 – 1000 fold intensity

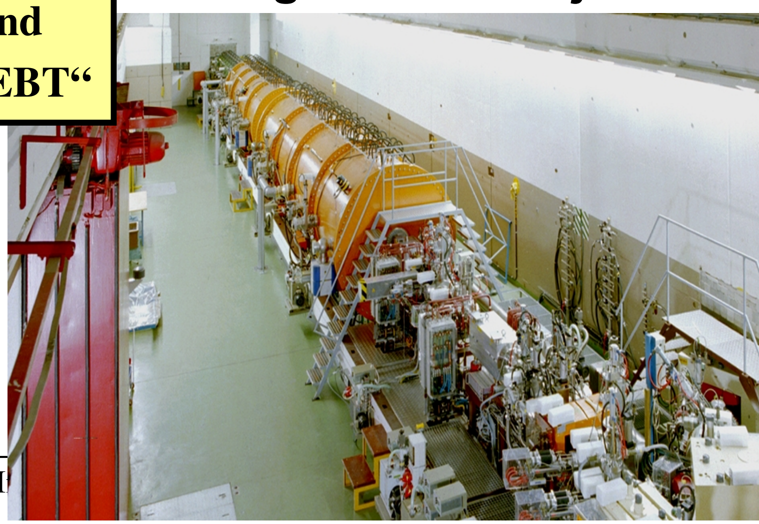
Beam Development at the UNILAC since 2009



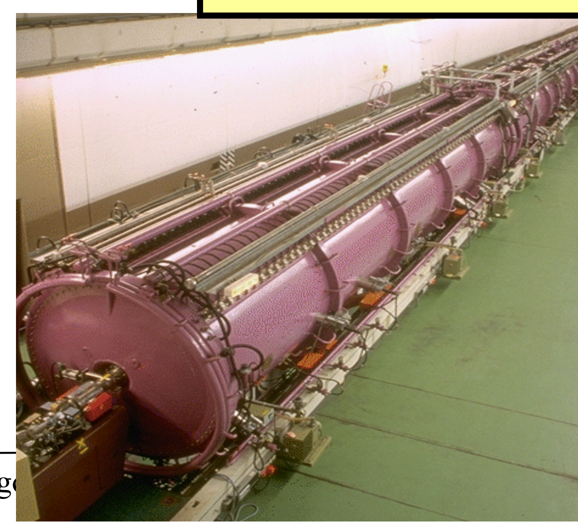
New ion source terminal and „Compact LEBT"

x/y emittance transfer, proof of priciple

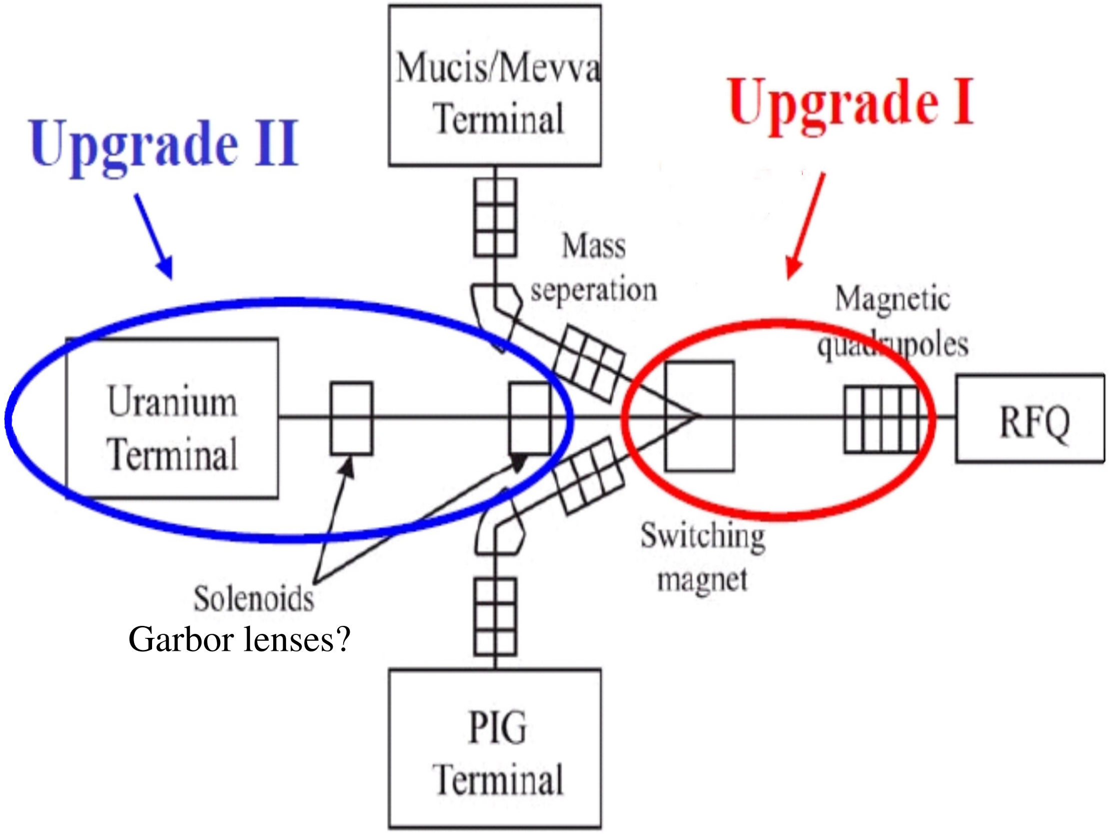
High Current Injector



Alvarez



Planned New IS-Terminal and Compact LEBT



Upgrade I

High current ion source test bench to develop highest beam brilliance.
Switching and quadrupole quartet magnets with increased aperture.

Upgrade II (Compact LEBT)

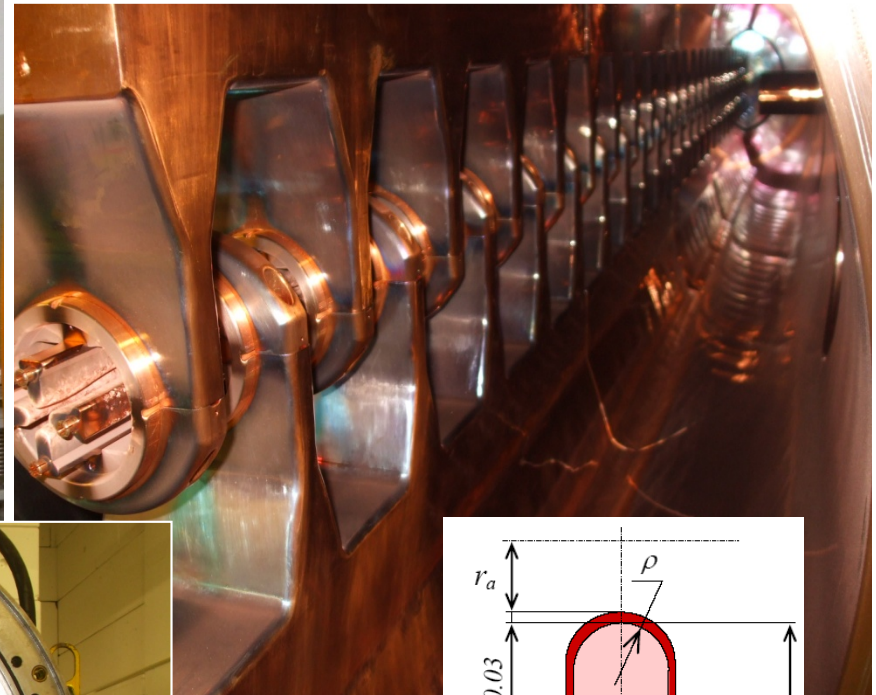
Sc solenoids or Garbor lenses for straight line injection of

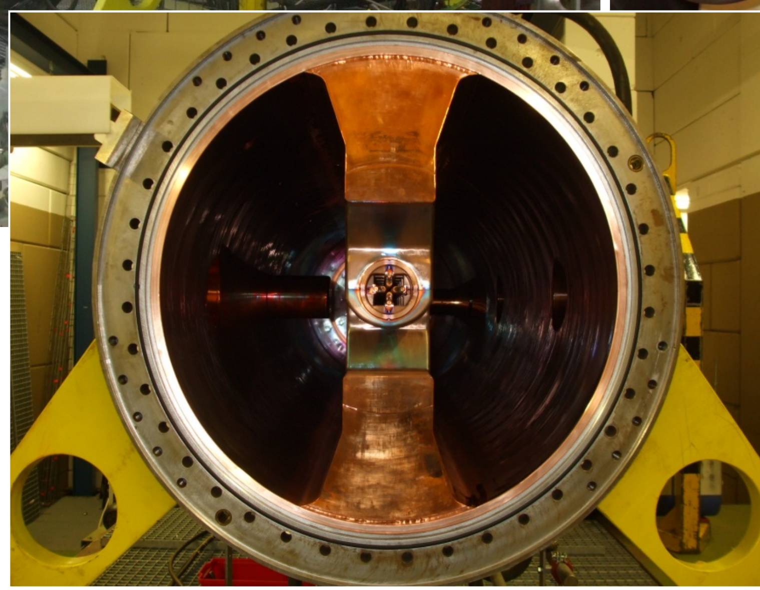
37 emA of U4+ beam

into the RFQ.

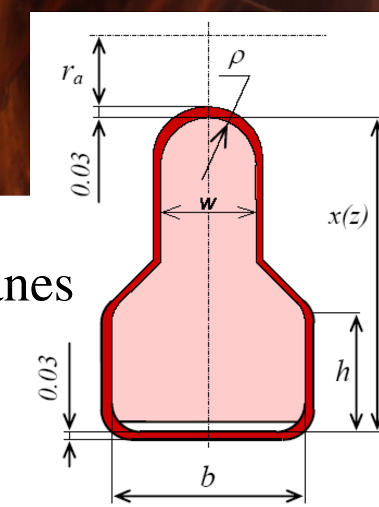
	MeVVa-ion source output	Entrance RFQ	Exit RFQ
Existing LEBT /RFQ	37 mA (U^{4+})	16.0 mA (U^{4+})	14.0 mA (U^{4+})
Compact LEBT	37 mA (U^{4+}) 18 mA (U^{3+})	37 mA (U^{4+}) 18 mA (U^{3+})	20.3 mA U^{4+} 1.6 mA U^{3+}

New Vanes for the 36MHz IH-type RFQ



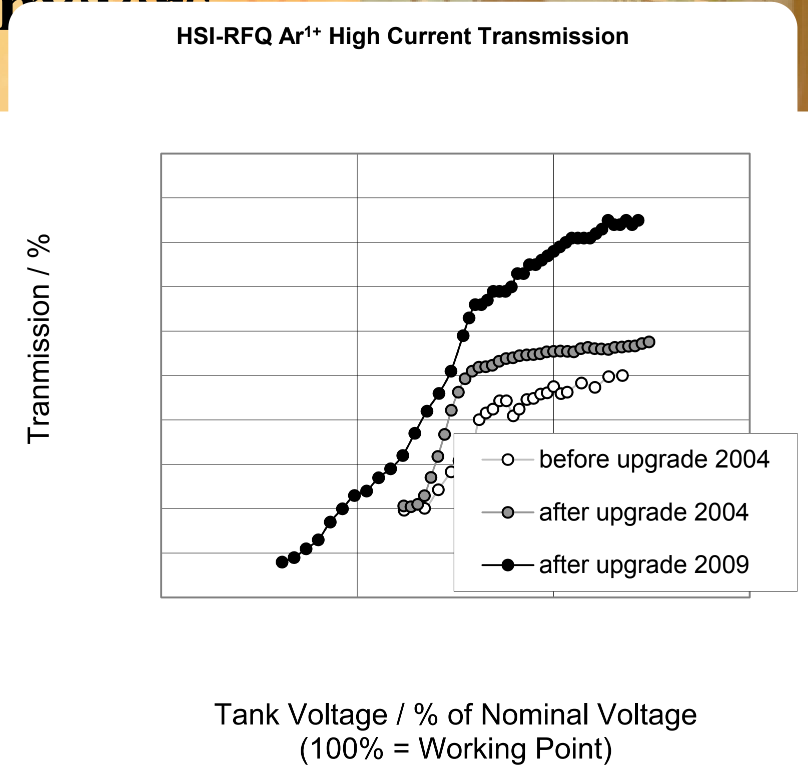


mini-vanes



New RFQ Parameters

	New Design	Old Design
Inter vane voltage, kV (U4+)	155	125
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, mm	4.10	3.81
Norm. transverse acceptance, mm mrad	0.856	0.73
Output energy, keV/u	120	118.5
Number of cells with modulation	394	343
Length of electrodes, mm	9217.4	9217.4



- Higher transverse acceptance and phase advance
- Improved input beam matching
- Gentle bunching for rapid and uniform separatrix filling
- Beam dynamics studied with DYNAMION & PARMTEQ-M

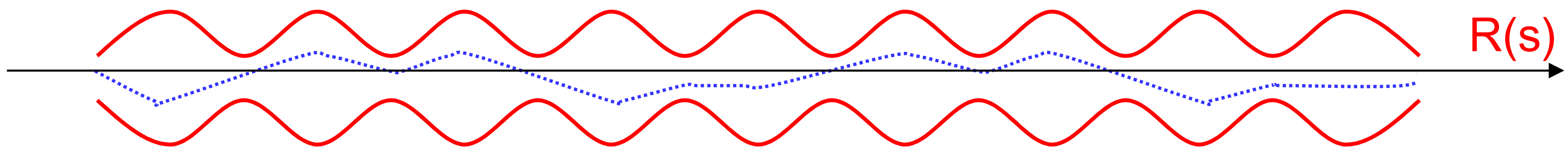
Simulations:

A. Kolomiets,

S. Yaramyshev,

R. Tiede

4th Order Space Charge Driven Resonances



- Given a periodically breathing beam envelope with phase advance σ_{env} and radial symmetry
- Single particles experience constant external magnet focussing and electric field of beam size

$$r'' + \sigma^2 r = a \cdot r^3 \cdot e^{i\sigma_{env} s}$$

depressed phase advance

approach : $r = e^{-i\sigma s}$

"New" oscillator equation : $r'' + \sigma^2 r = a \cdot e^{i(\sigma_{env} - 3\sigma)s}$

frequency of effective perturbation

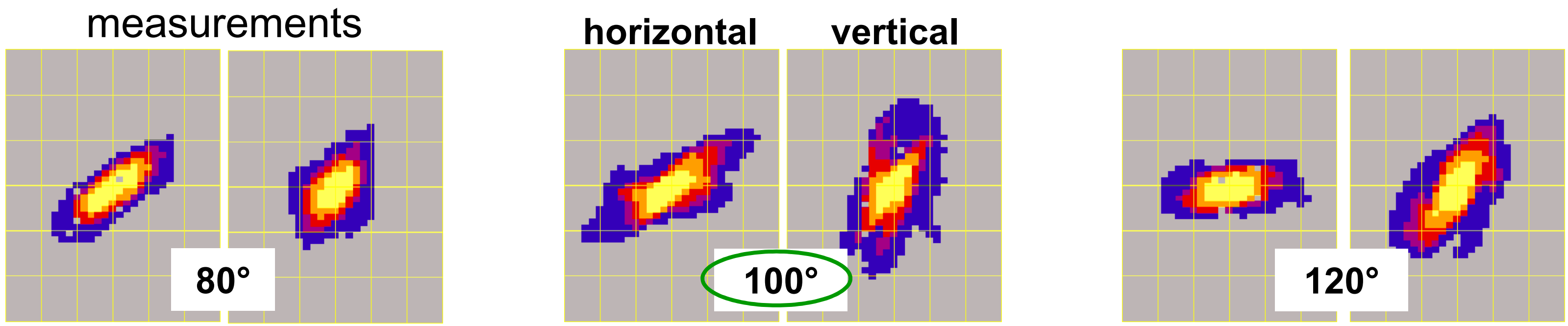
Resonance condition: $\sigma_{env} - 3\sigma = \sigma$ $\quad \sigma_{env} = 4\sigma$

envelope oscillates 4 times faster than single particle

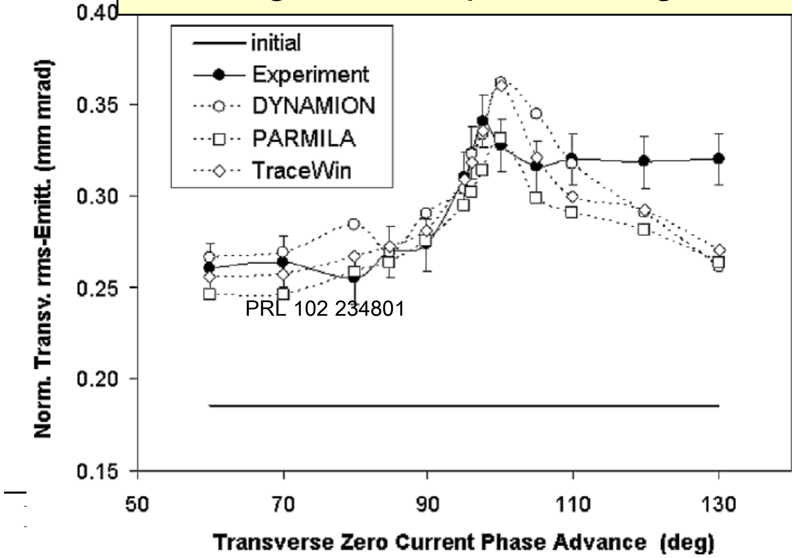
$\sigma_{env} = 360° \rightarrow \sigma = 90°$

4^{th} order resonance occurs at $\sigma = 90°$, i.e. $\sigma_o \geq 90°$

Proof for 4th Order Resonance in the UNILAC

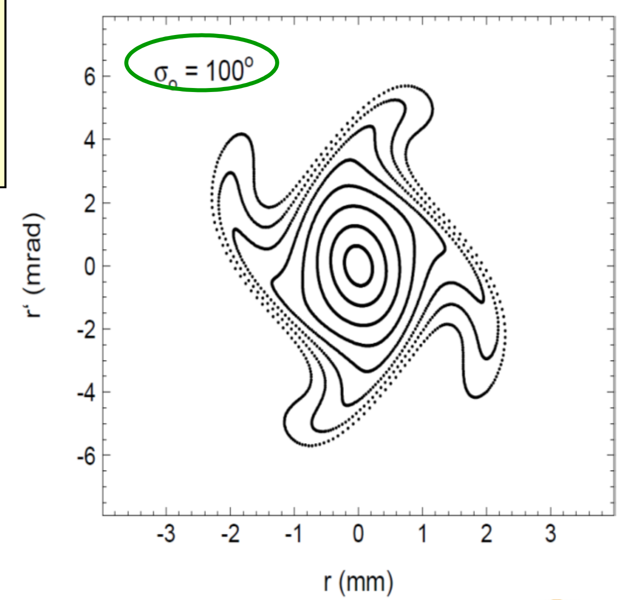


- DFFD periodic focussing channel with 180 quadrupoles
- Strong growth approaching $\sigma_o \approx 100°$
- Tune depression: $\sigma_o \approx 100° \rightarrow \sigma \approx 90° = 360° / 4$
- Good agreement with three simulation codes
- Strong hint for space charge driven 4th order resonance



7.5 emA, Ar^{1+}

4 wings were observed



Proof for 4th Order Resonance in the UNILAC

• First direct measurement of a space charge driven resonance in an accelerator

• Rings: slit/grid emittance measurement is not possible

• UNILAC: so far resonances considered to be of no concern for operation

• Evidence for enveloped-matched operation of the UNILAC DTL

<u>Publications:</u>

D. Jeon et al., Prediction of 4th Order Transverse Resonances, PRST-AB 12 054204, (2009)

L. Groening et al., Experiment on 4th Order Transverse Resonances, PRL 102, 234801 (2009)

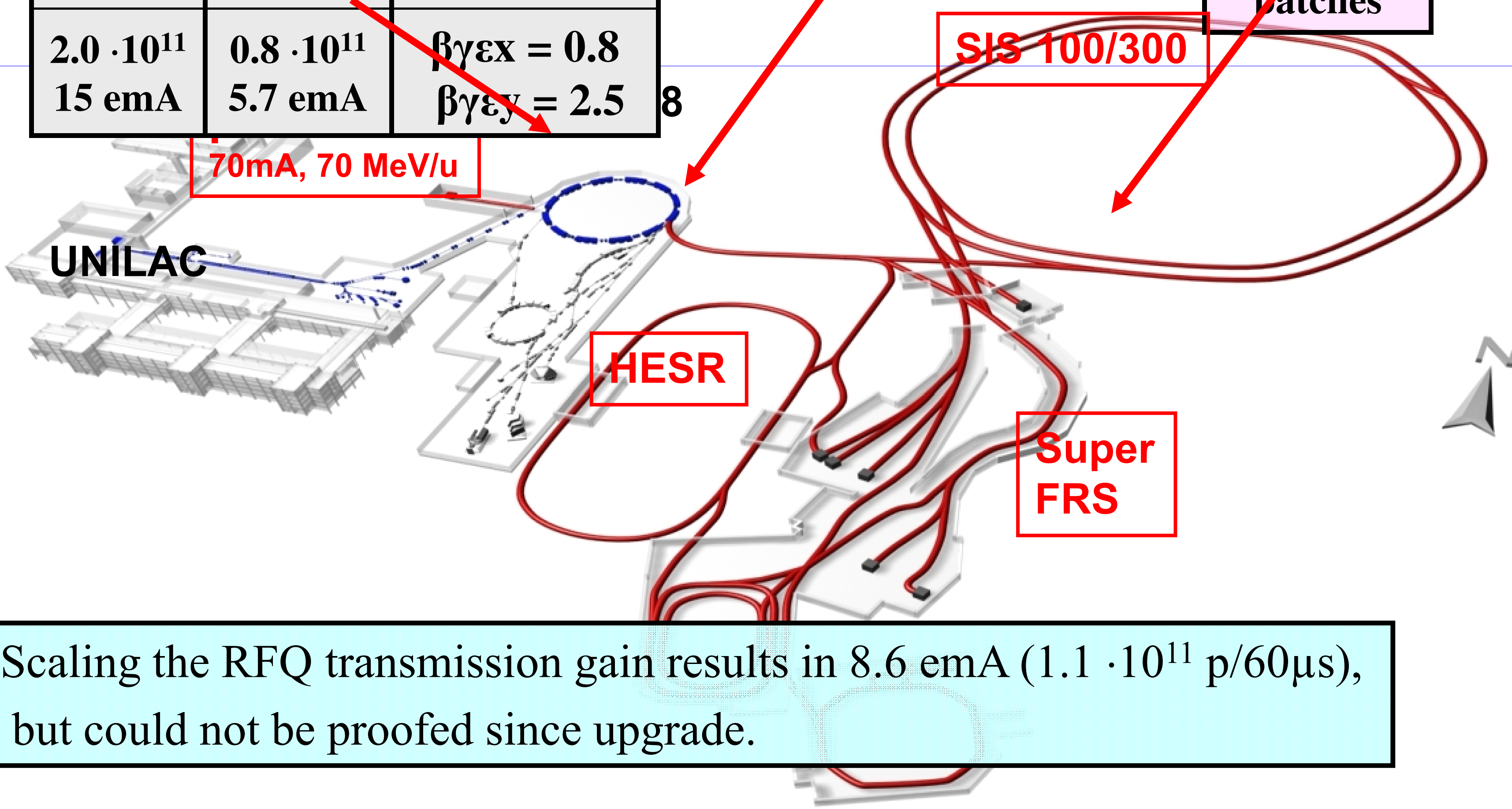
L. Groening et al., Parametric Resonance, PRL 103, 224801 (2009)

Beam Intensities for an U28+ Beam

require d ions/60 µs	measure d ions/60µ s	transverse emittances [µm]
$2.0 \cdot 10^{11}$ 15 emA	$0.8 \cdot 10^{11}$ 5.7 emA	$\beta\gamma\varepsilon x = 0.8$ $\beta\gamma\varepsilon y = 2.5$

required ions/spill	measured ions/spill
$1.5 \cdot 10^{11}$	

required
$6 \cdot 10^{11}$ by 4 batches



Scaling the RFQ transmission gain results in 8.6 emA ($1.1 \cdot 10^{11}$ p/60µs), but could not be proofed since upgrade.

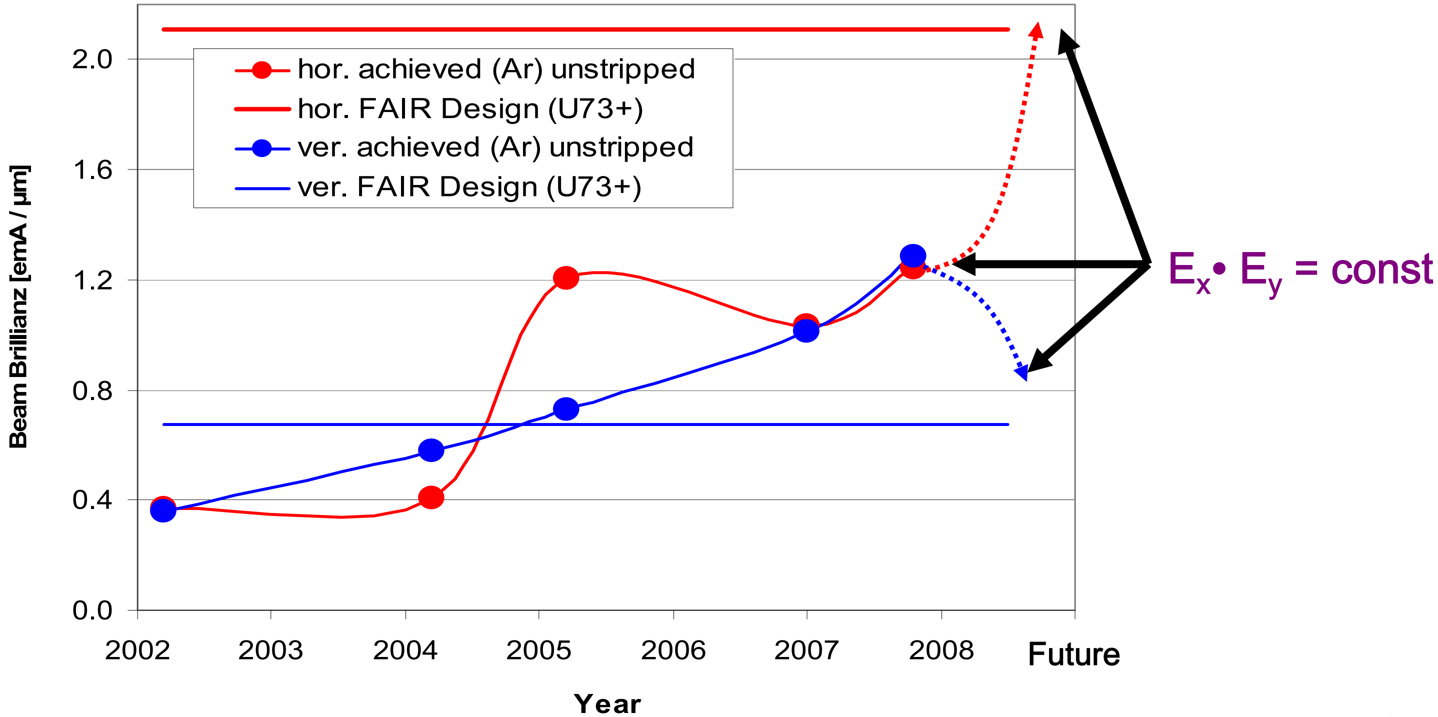
How to Meet Horizontal and Vertical Design Brilliances ?

- present measured UNILAC brilliances are similar in both transversal planes
- emittance transfer from horizontal to vertical plane should help
- transfer should preserve **Ex· Ey**

horizontally we are not ok

vertically we are ok

Brilliance Definition: $B_{x/y}$:= (q/A)*Current / $Emittance_{x/y}$



Emittance Splitting: Beam Dynamics

2d-rms-emittances

$$C_x = \begin{bmatrix} < xx > & < xx' > \\ < x'x > & < x'x' > \end{bmatrix}, \quad E_x^2 = \det C_x$$

$$C_y = \begin{bmatrix} < yy > & < yy' > \\ < y'y > & < y'y' > \end{bmatrix}, \quad E_y^2 = \det C_y$$

4d-rms-emittance

$$E_{4d}^2 = det \begin{bmatrix} < xx > & < xx' > & < xy > & < xy' > \\ < x'x > & < x'x' > & < x'y > & < x'y' > \\ < yx > & < yx' > & < yy > & < yy' > \\ < y'x > & < y'x' > & < y'y > & < y'y' > \end{bmatrix} = det\, C$$

two eigen-emittances $\varepsilon_{1/2}$

$$\varepsilon_1 = \frac{1}{2}\sqrt{-tr(CJ)^2 - \sqrt{tr^2(CJ)^2 - 16|C|}}$$
$$\varepsilon_2 = \frac{1}{2}\sqrt{-tr(CJ)^2 + \sqrt{tr^2(CJ)^2 - 16|C|}}$$

$$J := \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

- without x-y coupling: eigen-emittances = rms-emittances
- with x-y coupling: eigenemittances $\neq$ rms-emittances
- rotated, linear beam line elements, i.e. symplectic:
  - change rms-emittances through x-y coupling
  - do NOT change eigen-emittances !!!
- **eigen-emittances are preserved under symplectic („from a Hamiltonian") transformation**
- **all rotated, linear elements are „from Hamiltonian"**

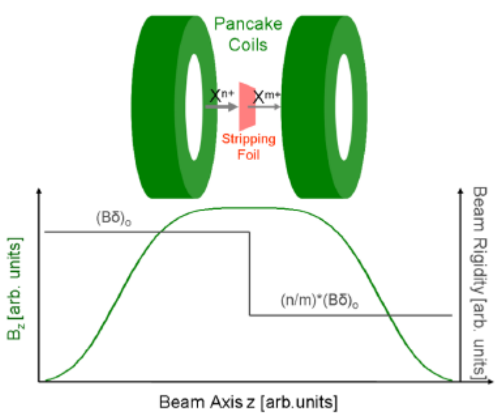
Concept for rms-Emittance Transfer

1. start from a x-y uncoupled beam with equal transv. rms-emittances = eigen-emittances

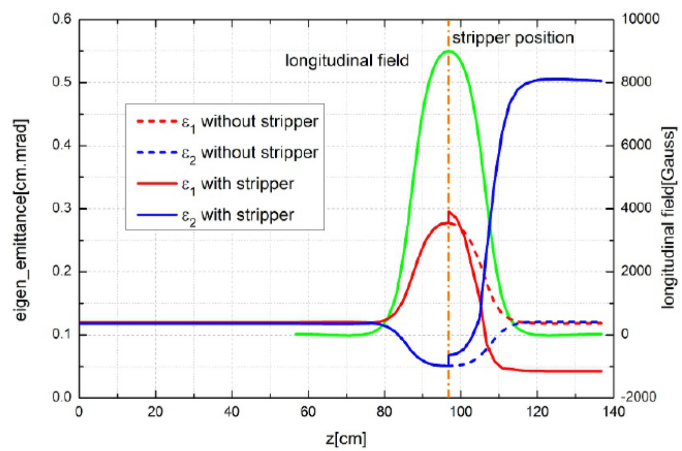
2. apply a non-Hamiltonian, x-y-coupling action :
    1. create x-y coupling
    2. change the eigen-emittances
    3. change the rms-emittances
    4. rms $\neq$ eigen !!!

3. apply a Hamiltionian x-y-coupling action to
    1. remove all x-y coupling
    2. re-optain rms = eigen
    3. remain with different transverse rms-emittances

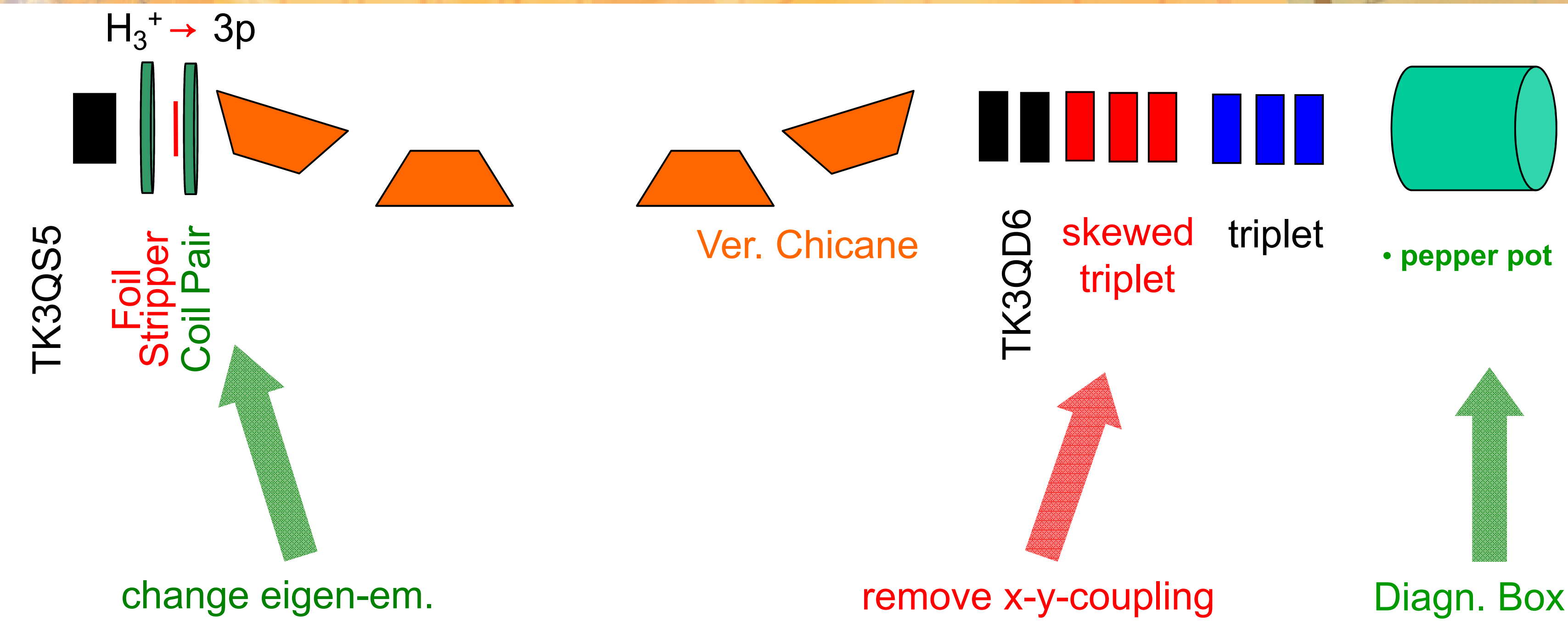
a skewed quad-triplet will do the job



change of charge state inside long. mag. field cannot be described by a Hamiltonian



Conceptual Layout of an Emittance Transfer Set-up



- set-up integrated around existing Charge State Separator
- comprises :
  - coil pair (B ≈ few T)
  - skew triplet + doublet or triplet
  - diagnostic box with pepper pot

Balance:

- Transmission: 100 %
- ΔE_x: - 42 %
- ΔE_y: +142 %
- ΔE_{4d}: + 42 %

Summary Emittance Transfer

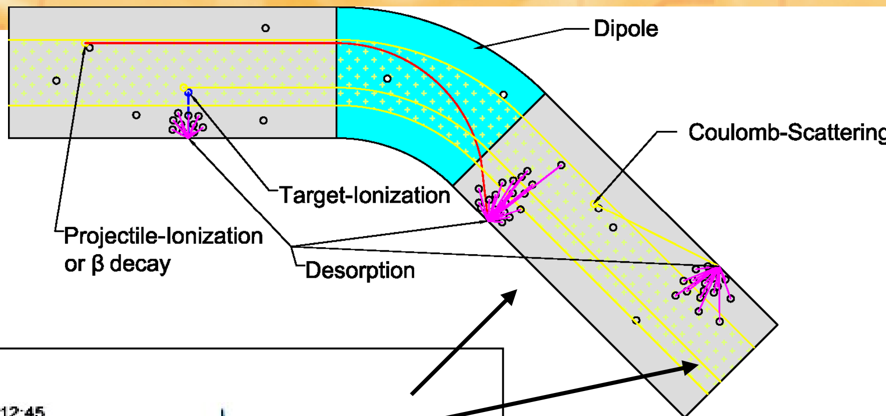
- Emittance splitting might improve synchrotron injection efficiency without primary beam current increase and beam collimation
- Simulations: hor. emitt. reduction by n·10% possible
- Experimental proof of principle using $H_3^+ \rightarrow 3p$ along UNILAC proposed

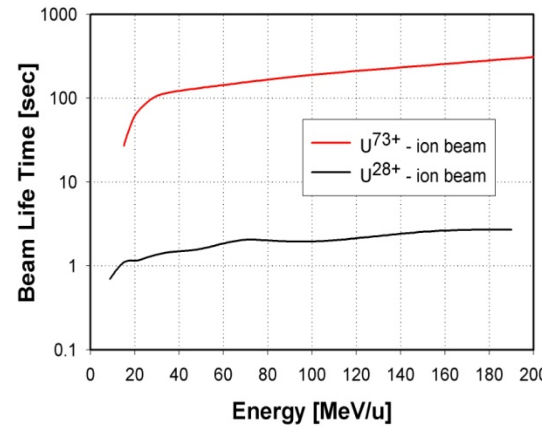
<u>Publications:</u>

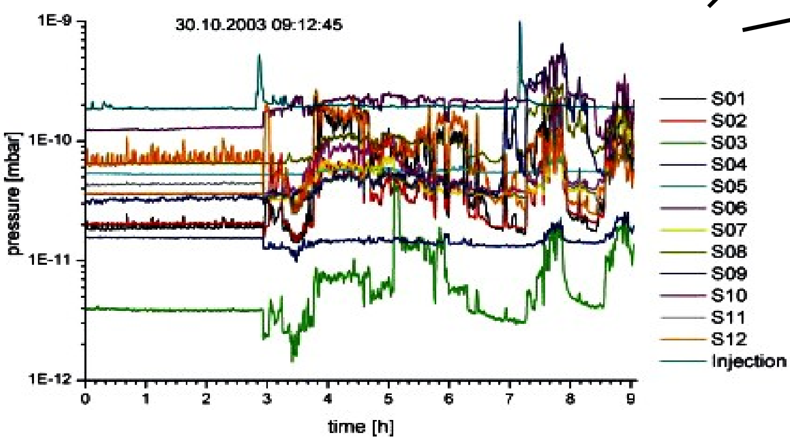
L. Groening, Transverse Emittance Transfer, PRST-AB 14, 069201 (2009)

X. Chen, Transverse Emittance Transfer, Internal Report IAP-DYNA-190412,
Goethe University Frankfurt, Institute of Applied Physics, Frankfurt, Germany (2012)

Ionization Beam Loss and Dynamic Vacuum in SIS18

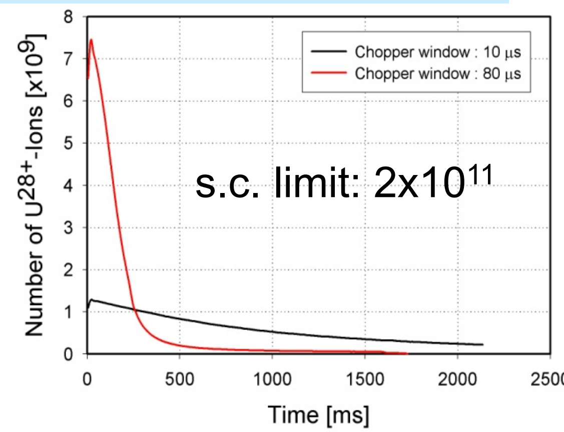






Ionization beam loss is by far the dominating loss process for intermediate charge states.

It begins much earlier as space charge and current dependent effects.



Main Issue of the Booster Operation:

- Life time of U^{28+} is significantly lower than of U^{73+}
- Life time of U^{28+} depends strongly on the residual gas pressure
- Ion induced gas desorption ($\eta \approx$ 10 000) increases the local pressure
- Beam loss increases with intensity (dynamic vacuum)

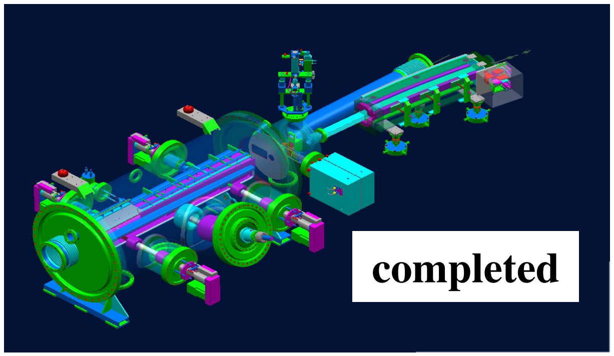
NEG Coating Facility

Goals:

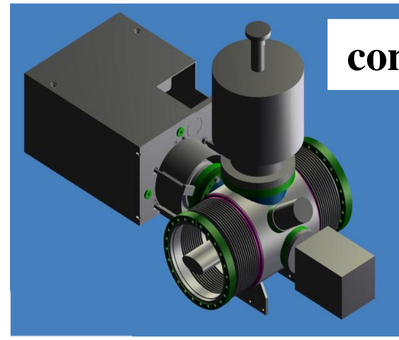
- Generation of extremly low static pressures of $p_0 < 5 \times 10^{-12}$ mbar and increased average pumping speed by up to a factor of 100
- Stabilization of dynamic pressure to $p(t)_{max} < 10^{-9}$ mbar

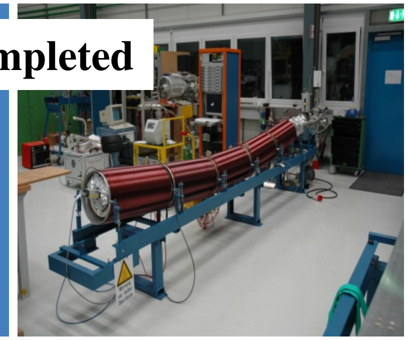
- NEG: Non-Evaporable Getter, thin film of Ti-Zr-V
- Replacement of all dipole- and quadrupole chambers by new, NEG coated chambers
- Improved bake-out system for operation up to 300K

SIS18 Upgrade Program for U28+ Booster Operation



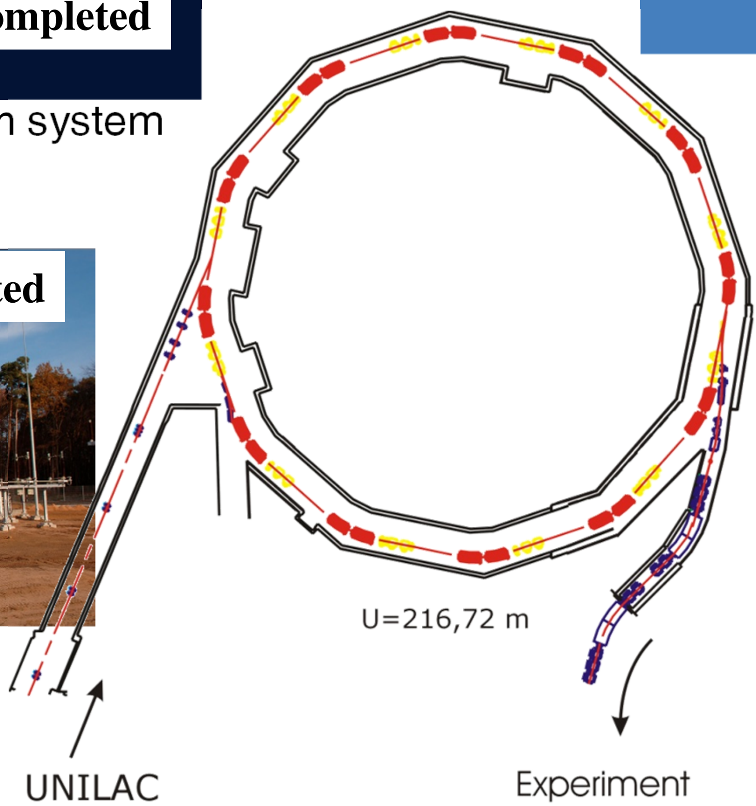
NEG coated injection system

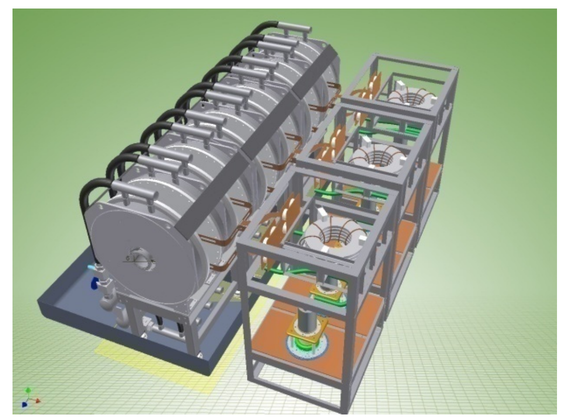




Scrapers and NEG coating for pressure stabilization

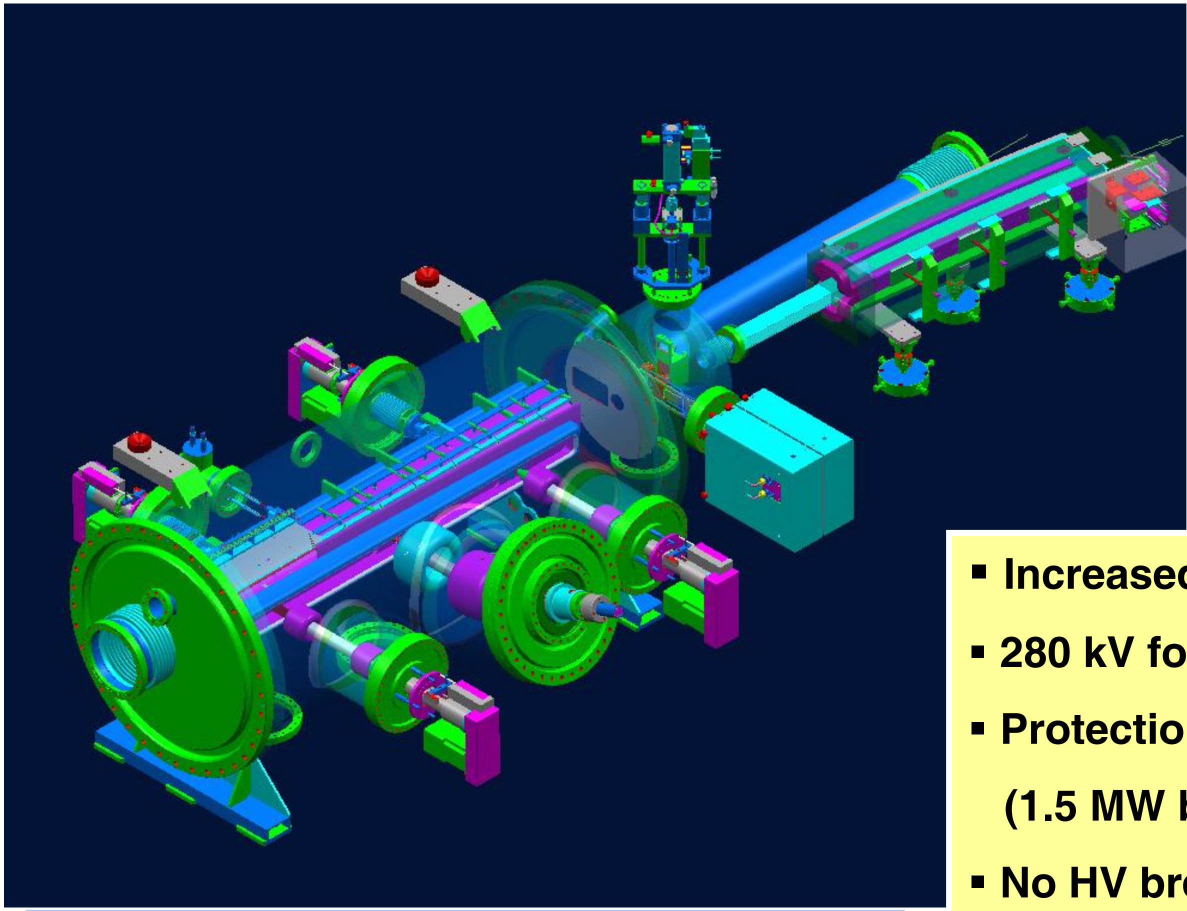
110 kV Power grid connection



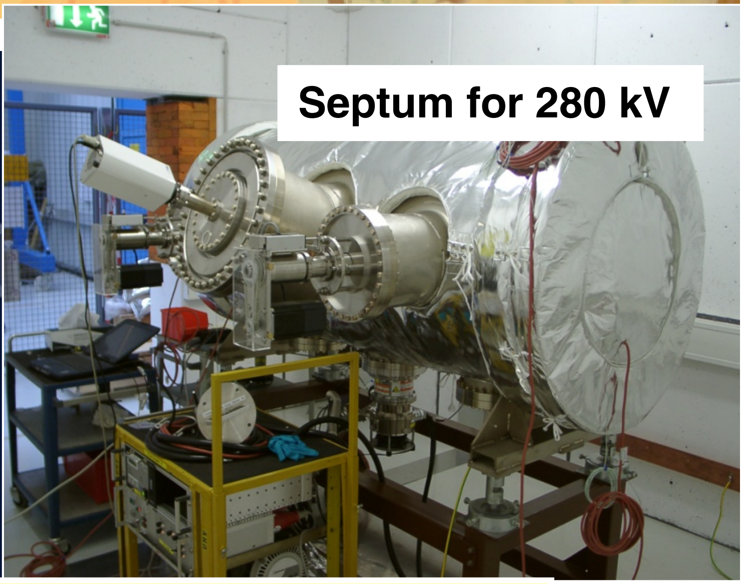


h=2 acceleration cavity for faster ramping/cycling

Injection System Upgrade



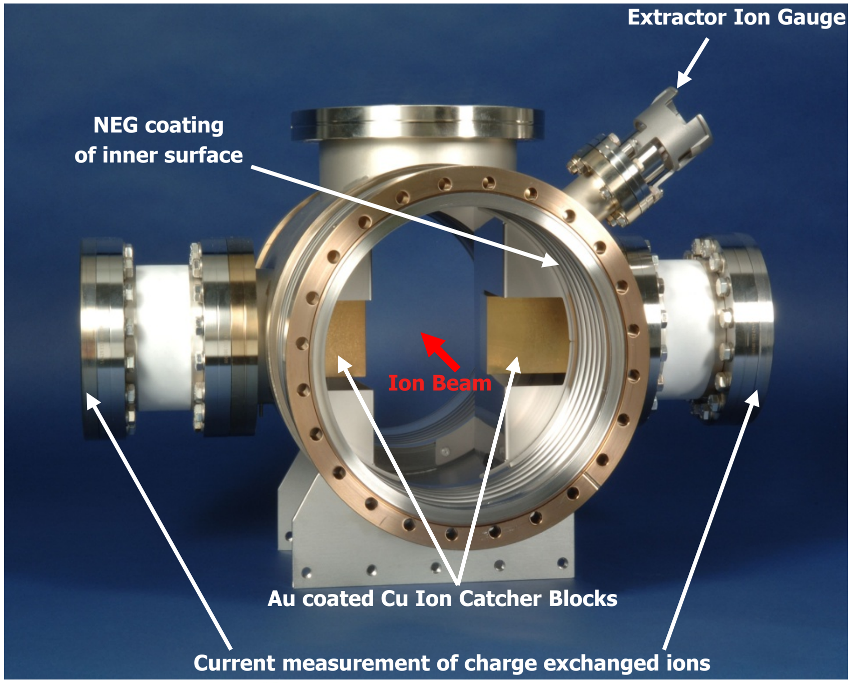
Final design of the new injection system



- Increased acceptance
- 280 kV for U^{28+} at 11.4 MeV/u
- Protection of septum electrodes (1.5 MW beam power)
- No HV break downs
- Reduced ionization beam loss
- Aim for reduced gas production

Project completed

Charge Catcher System - Technology



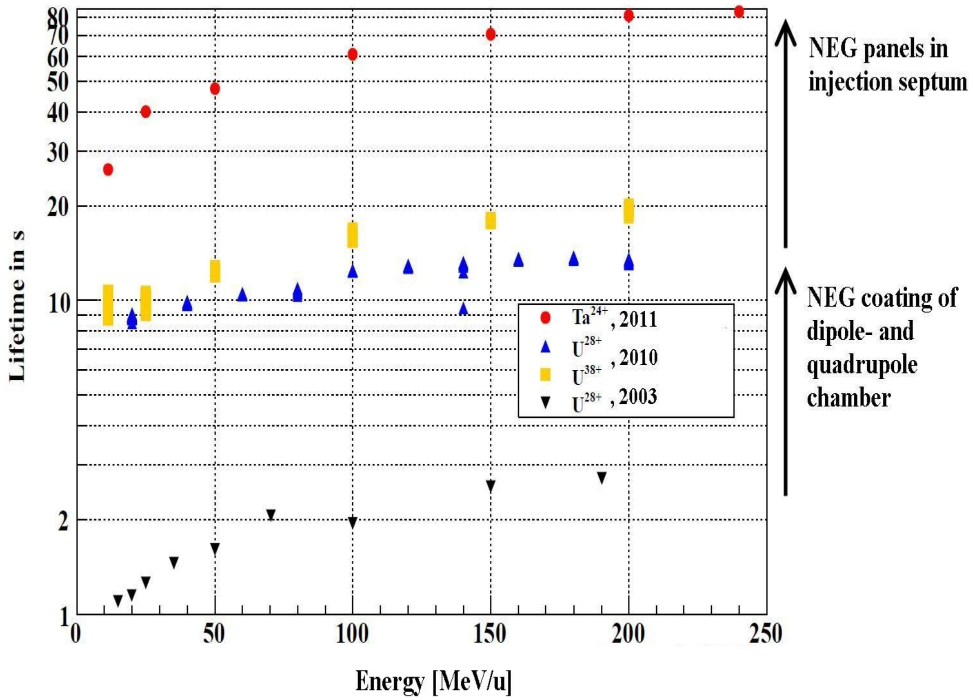
Goals:

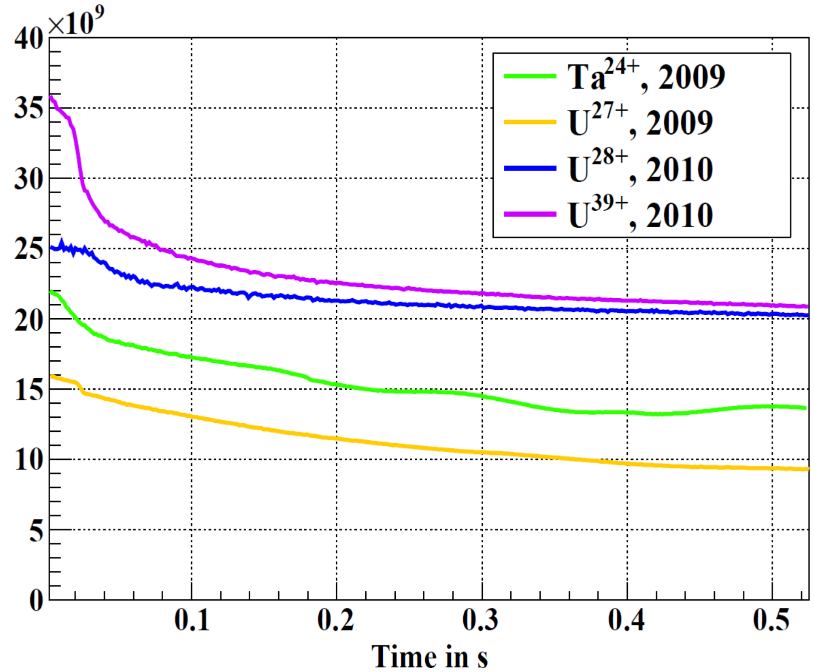
- Minimization of desorption gas production
- Capture and removal of desorbed gas
- Stabilization of the dynamic pressure

- **Wedge and block shaped beam stopper made of low desorption yield material tested**
- **Secondary chamber for confinement of desorption gases**
- **NEG coated chamber walls (high conductivity)**
- **Integration of UHV diagnostics and current measurement**
- **Two prototypes succesfully tested in 2007 shut down**
- **Significantly reduced desorption yield**
- **Installation of series (10 catchers) completed.**

Beam stopper

SIS18 Intensity Records with Intermediate Charge States





Beam intensity at SIS18 injection: $0.30 \cdot 10^{11}$ p/60µs

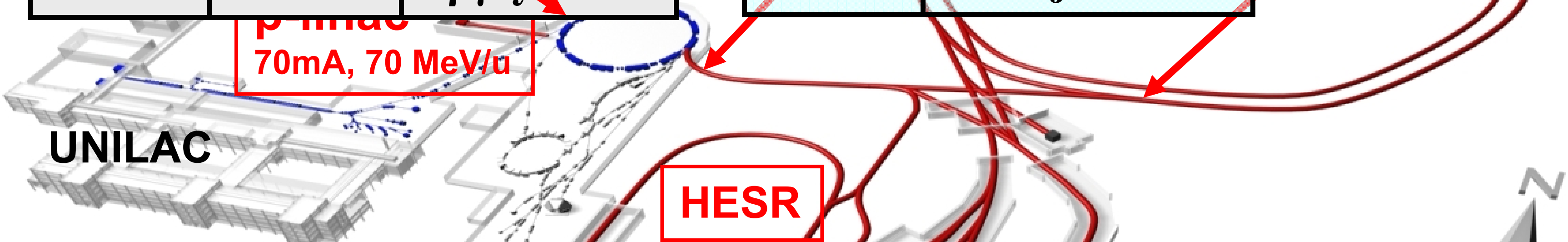
at SIS18 extraction: $0.21 \cdot 10^{11}$ p/spill

Beam Intensities for an U28+ Beam

required ions/60 µs	measured ions/60µs	transverse emittances [µm]
$2.0 \cdot 10^{11}$ 15 emA	$0.8 \cdot 10^{11}$ 5.7 emA	$\beta\gamma\varepsilon x = 0.8$ $\beta\gamma\varepsilon y = 2.5$

required ions/spill	measured ions/spill
$1.5 \cdot 10^{11}$	$0.21 \cdot 10^{11}$ only 2 emA injected

required
$6 \cdot 10^{11}$ by 4 batches



UNILAC-intensity 2007: 5.7 emA

2009: 8.6 emA scaled, but not proofed yet!

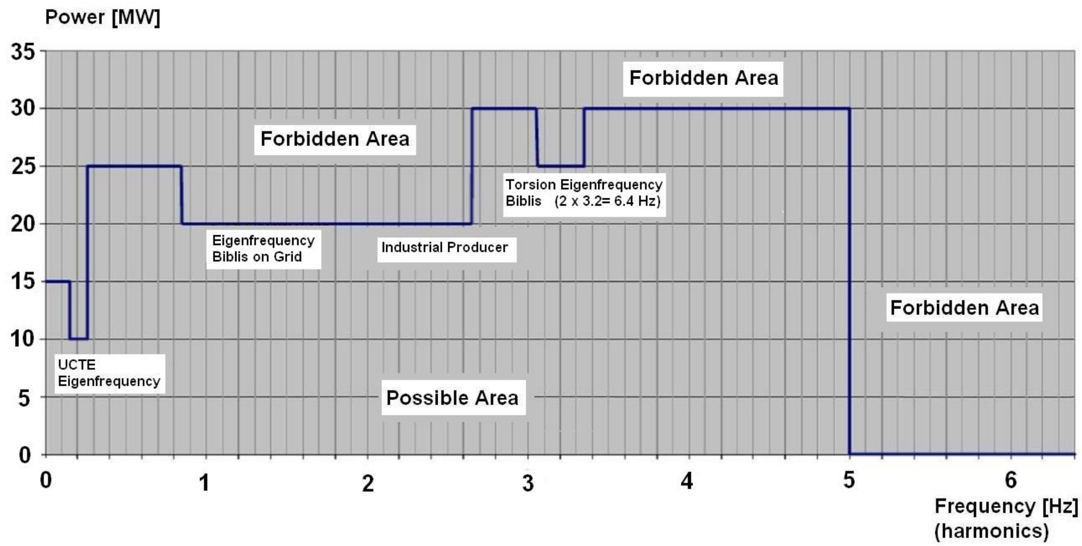
=> ~ 57 % of required 15 emA.

SIS18: 2.0 emA from UNILAC, achieved in **2010**: $0.21 \cdot 10^{11}$ ions/spill.

Scaling linearly UNILAC max intensity, SIS18 extracts $0.9 \cdot 10^{11}$ ions/spill.

=> ~60 % of required $1.5 \cdot 10^{11}$ ions/spill.

New 110 kV Power Connection



	Pulse Power	Field Rate
SIS18	+5 MW	1.3 T/s
SIS18	+ 42 MW	10 T/s
SIS100	± 26 MW	4 T/s
SIS300	± 23 MW	1 T/s

- Study of electromechanical resonance (damping) of Biblis B generator shaft
- Measurements of torsion and power oscillation in the grid

Replacement of main dipole power supplies for f_{rep} = 2.7 Hz (2014)

New h=2 Acceleration System

- Rf voltage for fast ramping

  U^{28+} acceleration with 10 T/s ($2x10^{11}$ ions)

- Bucket area for loss free acceleration

  (30 % safety)

- *two harmonic acceleration*

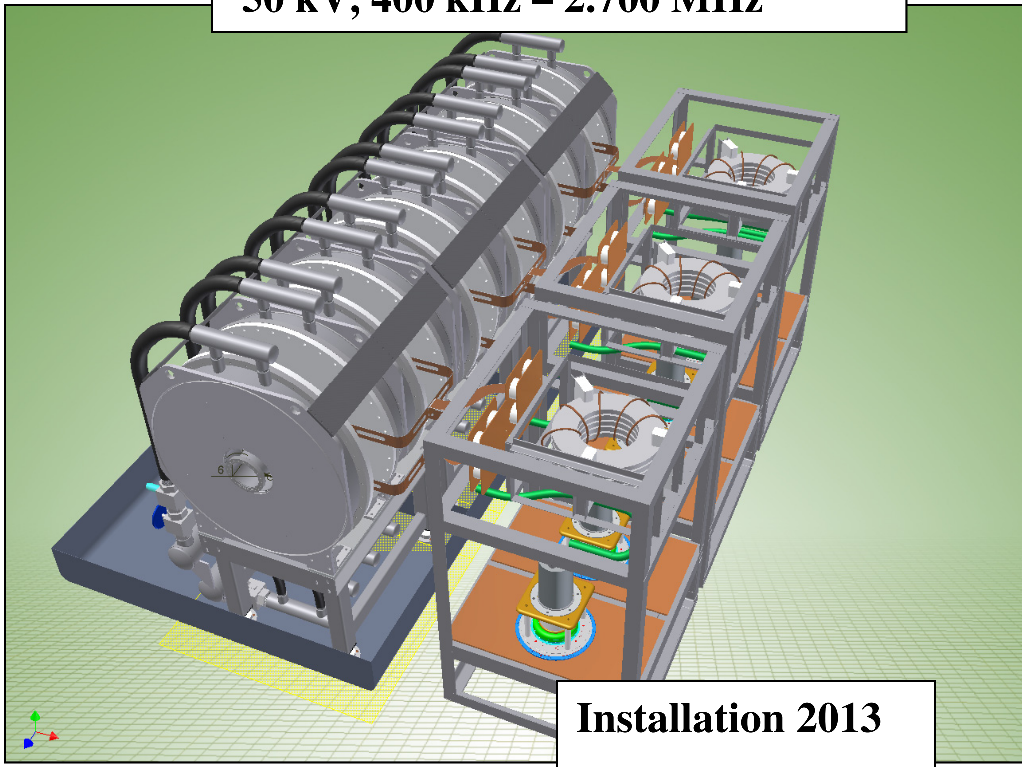
  h=4 (existing cavity) and new h=2

- Compatible with SIS100 Rfcycle

- 50 kV – high power requirements

- Power consumption 1.6 MW

50 kV, 400 kHz – 2.700 MHz



Installation 2013

f_{rep} = 2.7 Hz

Thank You

Winfried Barth
Cristina Bellachioma
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Oliver Kester
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Jens Stadlmann
Hartmut Vormann
Chen Xiao
Stepan Yaramishev