Towards the High Intensity Limit in the FAIR Project - Present Status and Future Challenges

Peter Spiller

HB2010

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Low Charge State Heavy Ion Beams

- High intensities and high currents are not rigidly linked at heavy hons > charge state can be changed if the current becomes to high.
- So far, to save acceleration and bending power typical heavy ion accelators were designed for the highest possible charge state.
- Now, with the need to increase intensities, charge states are lowered.

Heavy ion accelerators and projects based on intermediate charge state heavy ions:

AGS Booster	BNL	Au32+
LEIR	CERN	Pb54+
NICA Booster	JINR	Au32+
SIS18	GSI	U28+
SIS100	FAIR	U28+

SIS100 - Heavy Ion Beams for FAIR

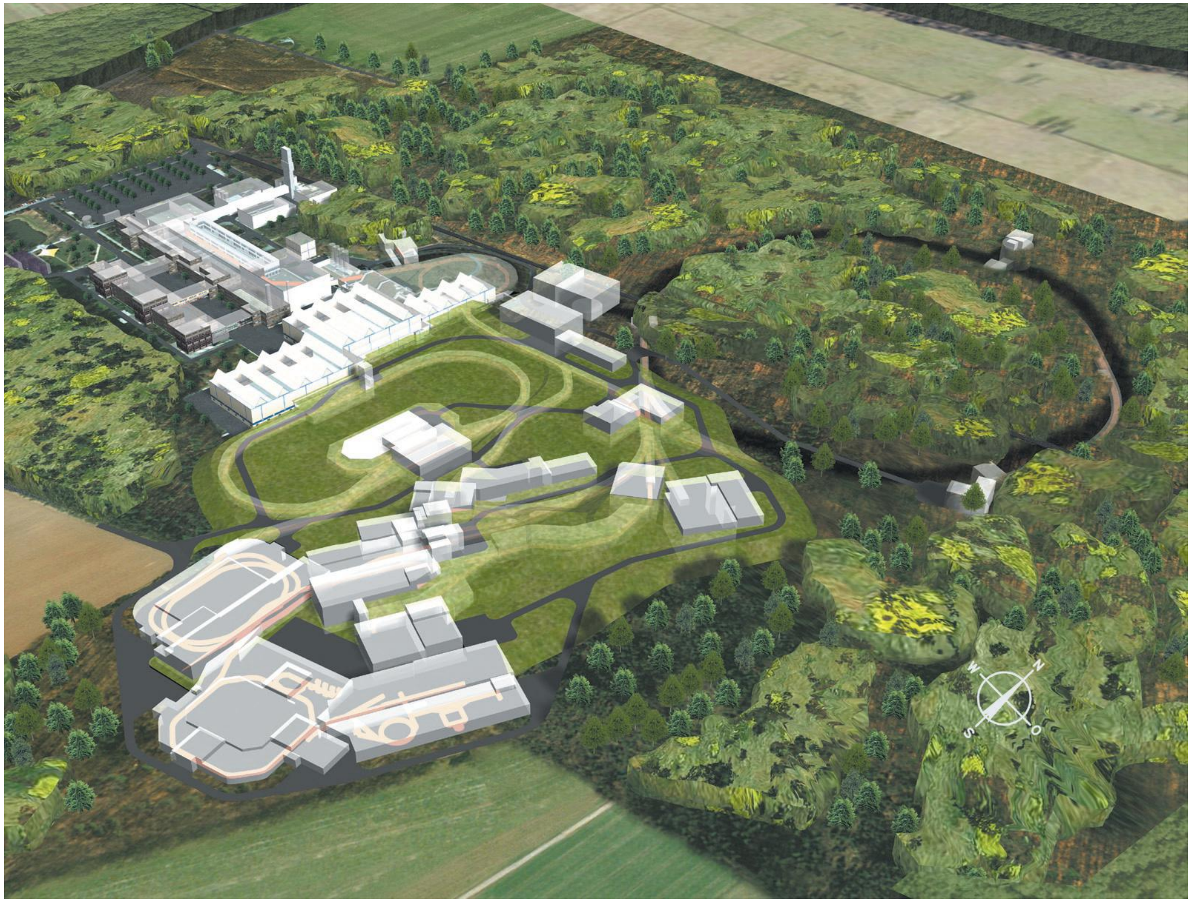
SIS100 beam parameters:

Species: U^{28+} -ions (e.g.)

N: 5×10^{11} /cycle

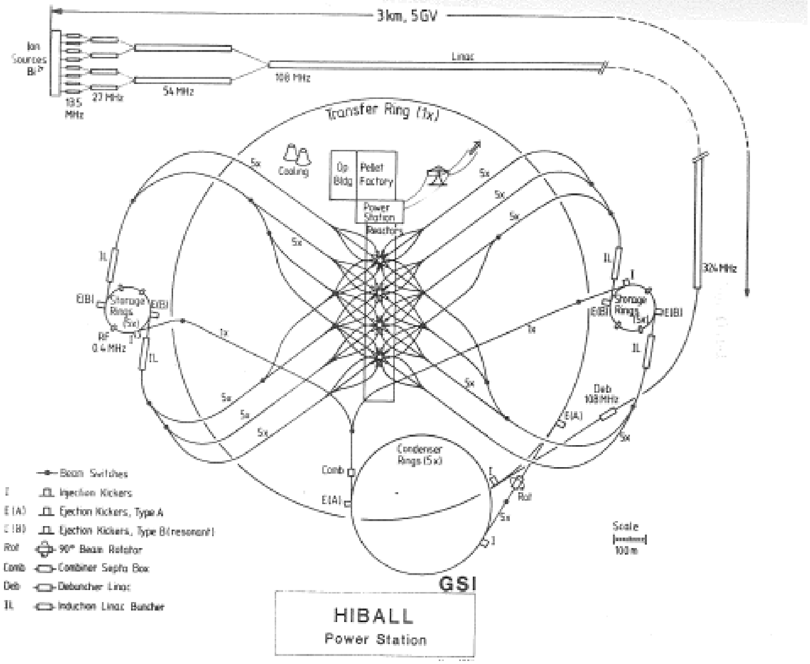
Rep. rate: 0.5 Hz

Energy: 400–2715 MeV/u



GSI – FAIR - HIBALL

Today	FAIR	HIBALL
U73+	U28+	U1+
10^9	$\sim 10^{12}$	10^{15}



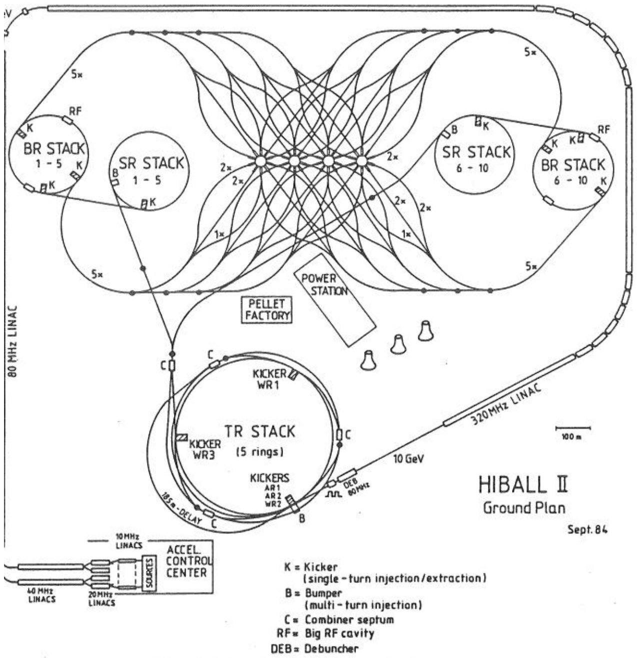
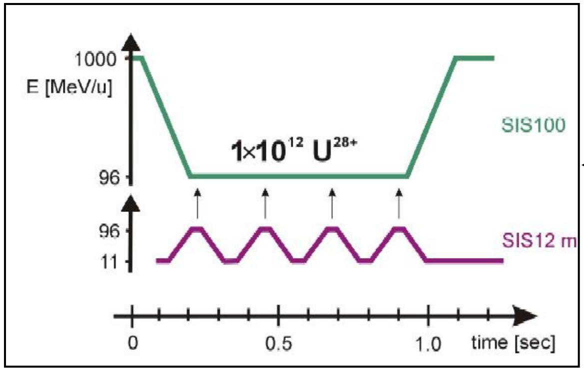


Fig. 1.2-1. HIBALL-II ground plan.

Goal: Energy Production 8 GW - 4.8 MJ Bi^{1+} / Bi^{2+}-ions

Intensity Requirements in SIS18 for FAIR

Fair Stage	Today	Stage 0 (Existing Facility after upgrade)	Stage 1 (Existing Facilty supplies Super FRS, CR, NESR)	Stage 2 (SIS100 Booster)
Reference Ion	U^{73+}	U^{73+}	U^{73+}	U^{28+}
Maximum Energy	1 GeV/u	1 GeV/u	1 GeV/u	0.2 GeV/u
Maximum Intensity	4×10^{9}	2×10^{10}	2×10^{10}	2×10^{11}
Repetition Rate	0.3 - 1 Hz	1 Hz	1 Hz	2.7 Hz



Intermediate Charge States for FAIR

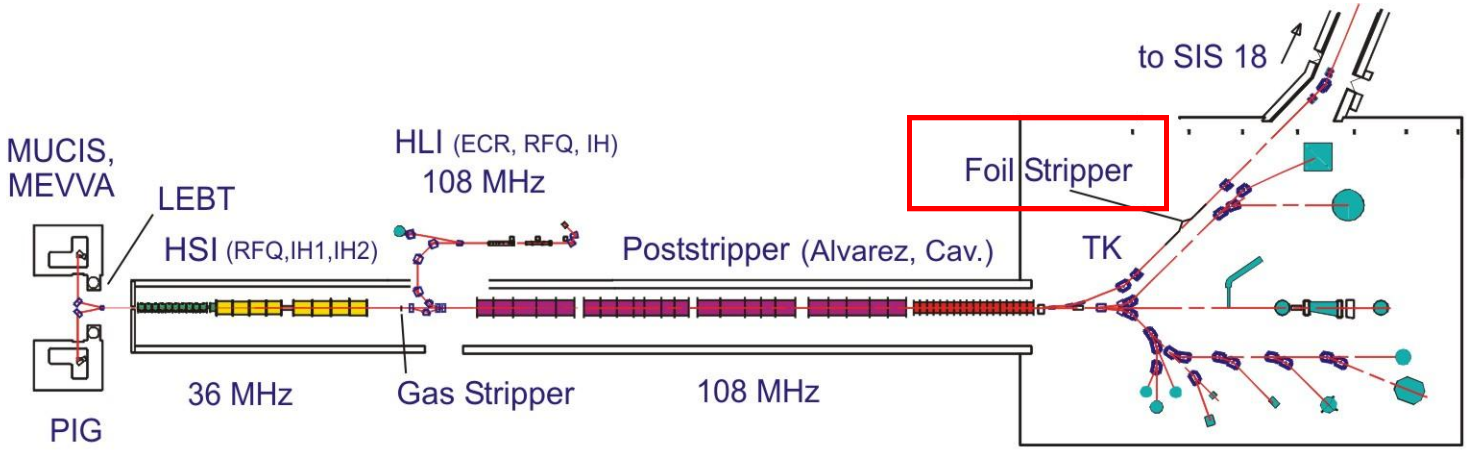
FAIR intensity goals can only be reached by lowering the charge states

Incoherent tune shift limits the maximum intensity in SIS18

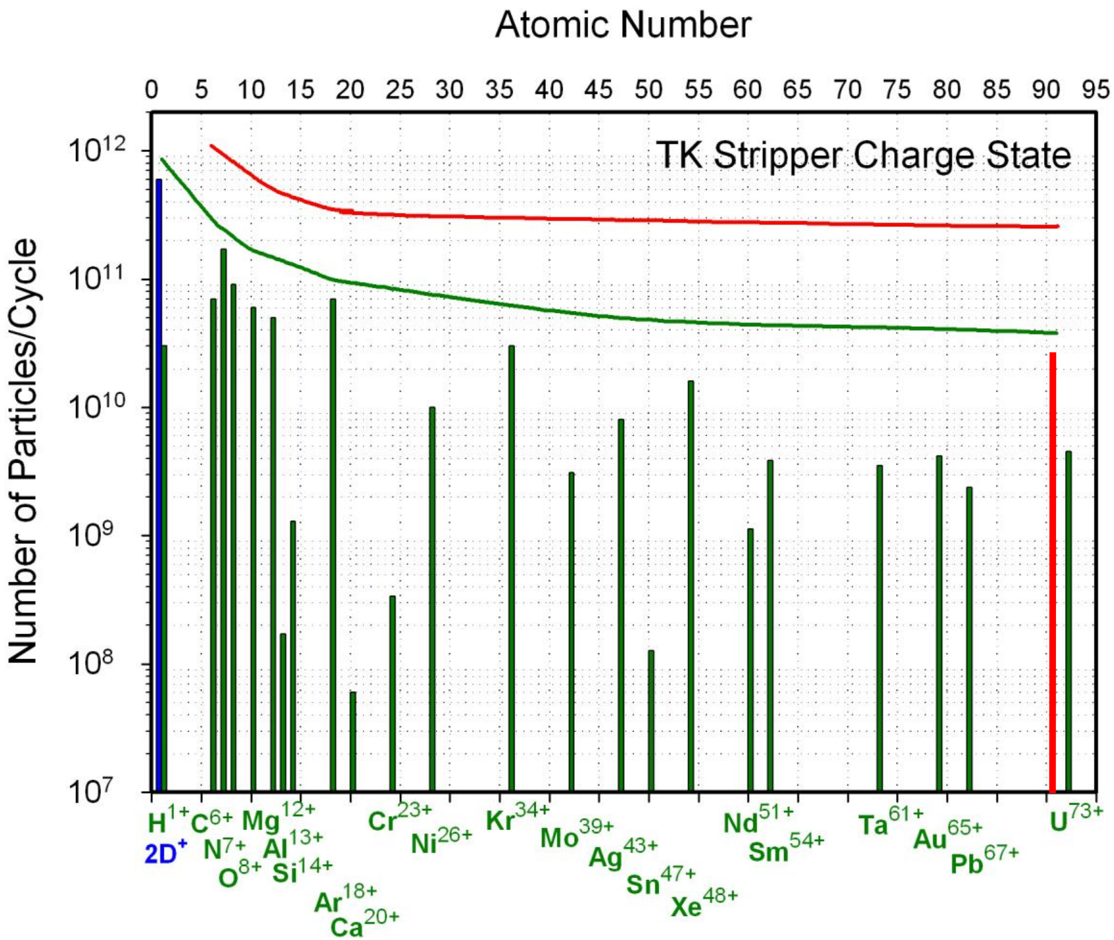
$-dQ \propto Z^2/A$ > Poststripper charge states will be used

(e.g.: Ar^{18+} > Ar^{10+}..........U^{73+} > U^{28+})

No stripping loss (charge spectrum) in the transfer channel ($N_{uranium}$ x7) !



Intensities - Status and Goals



– Space charge limit for intermediate chage state ions (without TK stripper)

– Space charge limit for high charge state ions (with TK stripper)

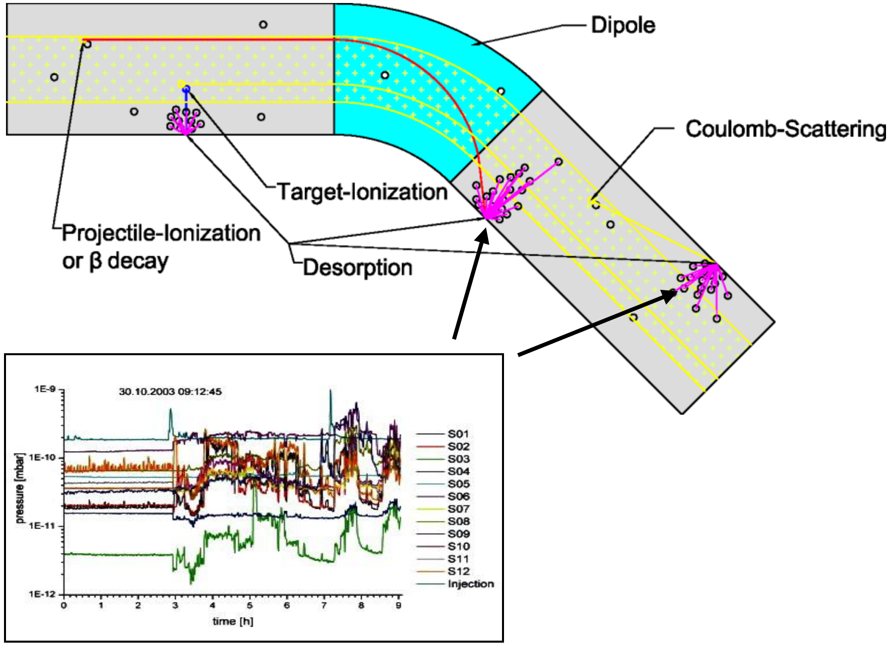
About one order of magnitude enhanced space charge limit by lower charge state.

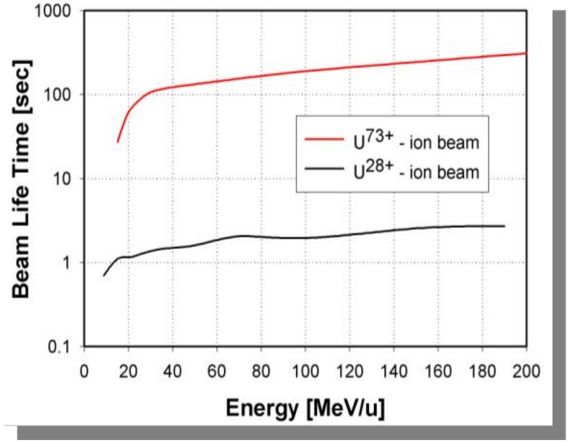
Equilibrium Charge States

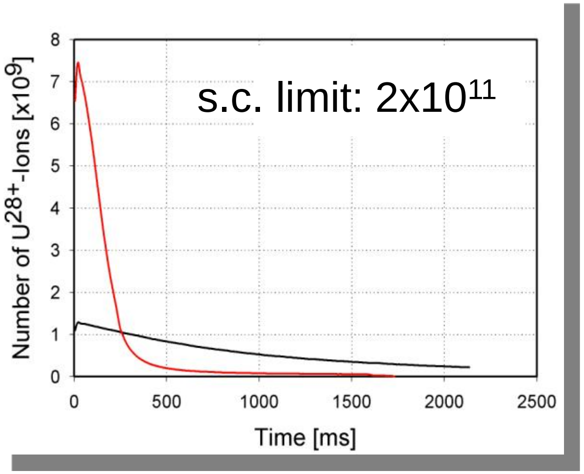
Ion	charge states with/ without TK stripper	equilibrium charge state SIS18 inject.	equilibrium charge state SIS18 extract.	equilibrium charge state SIS100 extrac.
$^{20}_{10}Ne$	7+	10+ (0,0114)	10+ (1,22)	10+ (9,50)
	10+	10+ (0,0114)	10+ (1,99)	10+ (13,95)
$^{40}_{18}Ar$	10+	17+ (0,0114)	18+ (0,75)	18+ (6,63)
	18+	17+ (0,0114)	18+ (1,76)	18+ (12,60)
$^{58}_{28}Ni$	14+	25+ (0,0114)	28+ (0,69)	28+ (6,27)
	26+	25+ (0,0114)	28+ (1,72)	28+ (12,37)
$^{84}_{36}Kr$	16+	31+ (0,0114)	36+ (0,49)	36+ (4,87)
	34+	31+ (0,0114)	36+ (1,65)	36+ (11,99)
$^{132}_{54}Xe$	21+	42+ (0,0114)	54+ (0,36)	54+ (3,95)
	48+	42+ (0,0114)	54+ (1,31)	54+ (10,06)
$^{181}_{73}Ta$	24+	51+ (0,0114)	72+ (0,26)	73+ (3,15)
	61+	51+ (0,0114)	73+ (1,17)	73+ (9,21)
$^{197}_{79}Au$	24+	54+ (0,0114)	78+ (0,22)	79+ (2,83)
	64+	54+ (0,0114)	79+ (1,11)	79+ (8,85)
$^{238}_{92}U$	28+	59+ (0,0114)	90+ (0,20)	92+ (2,71)
	73+	59+ (0,0114)	92+ (1,02)	92+ (8,30)

energy in brackets

Ionization Beam Loss and Dynamic Vacuum



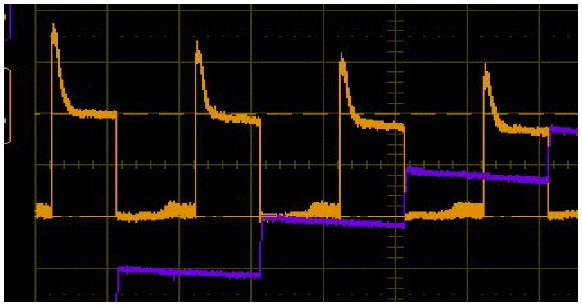




Main Issue of the Booster Operation:

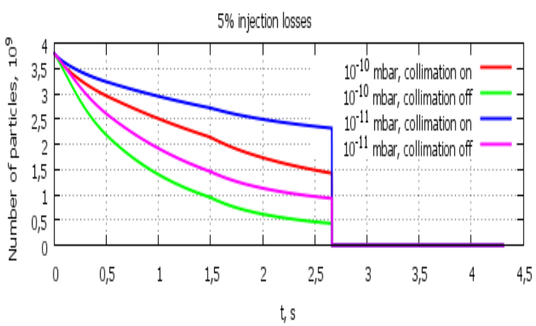
- Life time of U^{28+} is significantly lower than of U^{73+}
- Life time of U^{28+} depends strongly on the residual gas pressure
- Ion induced gas desorption ($\eta \approx$ 10 000) increases the local pressure
- Beam loss increases with intensity (dynamic vacuum)

Intermediate Charge State Operation and Beam Loss

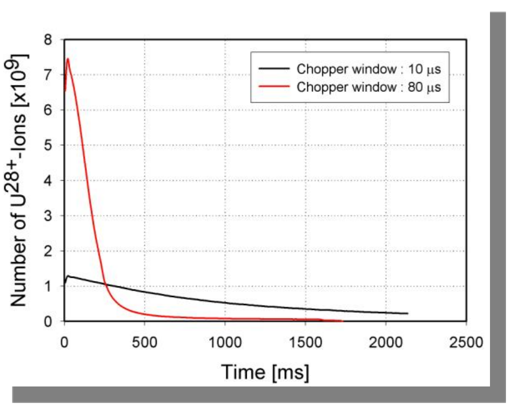


AGS booster (measured)

Intermediate charge state operation suffers from severe charge exchange loss. Ionization beam loss is by far the dominating loss process and begins much earlier the space charge and current dependent effects.



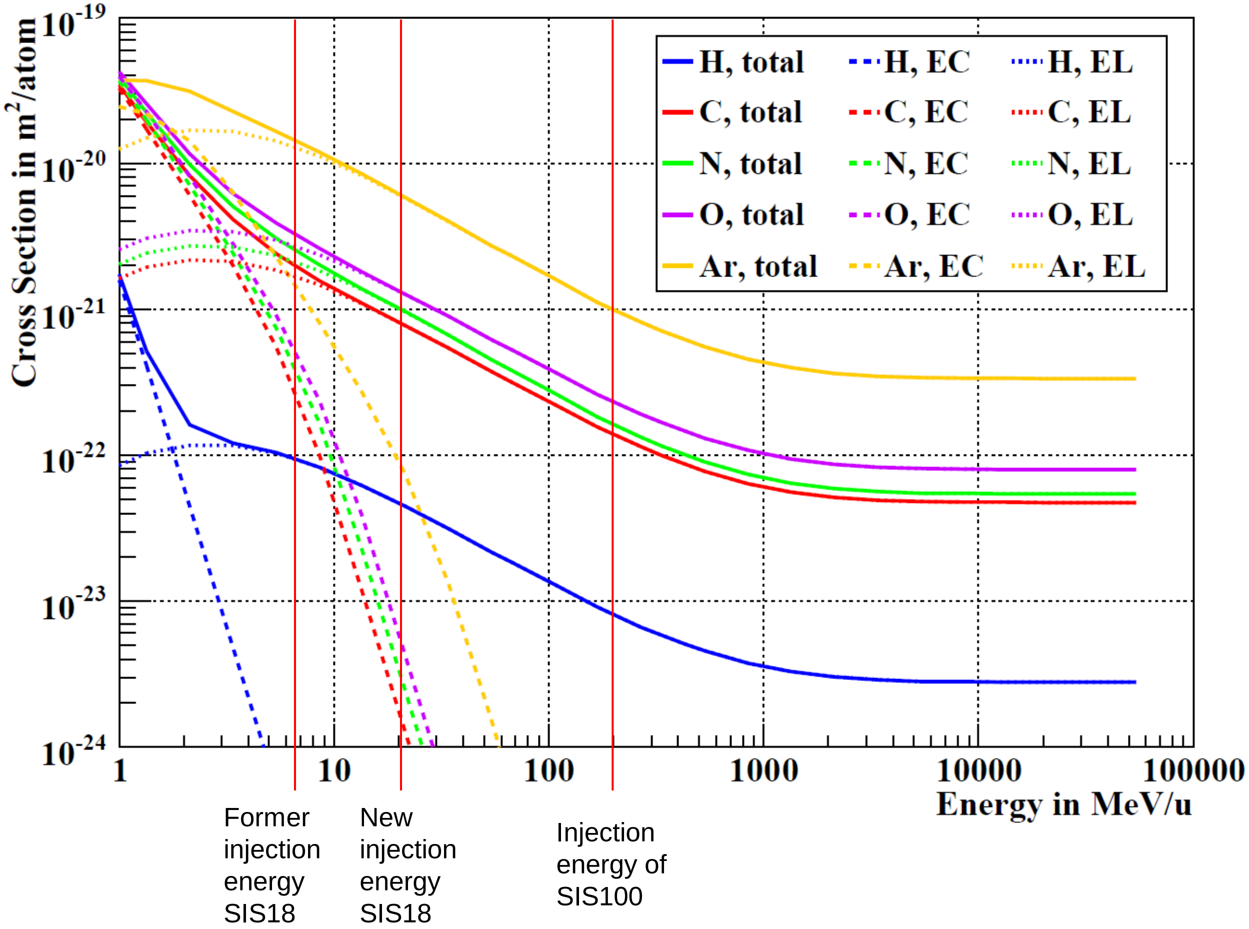
NICA booster (predicted)



SIS18 (measured in 2001)

Space charge limit: $2x10^{11}$

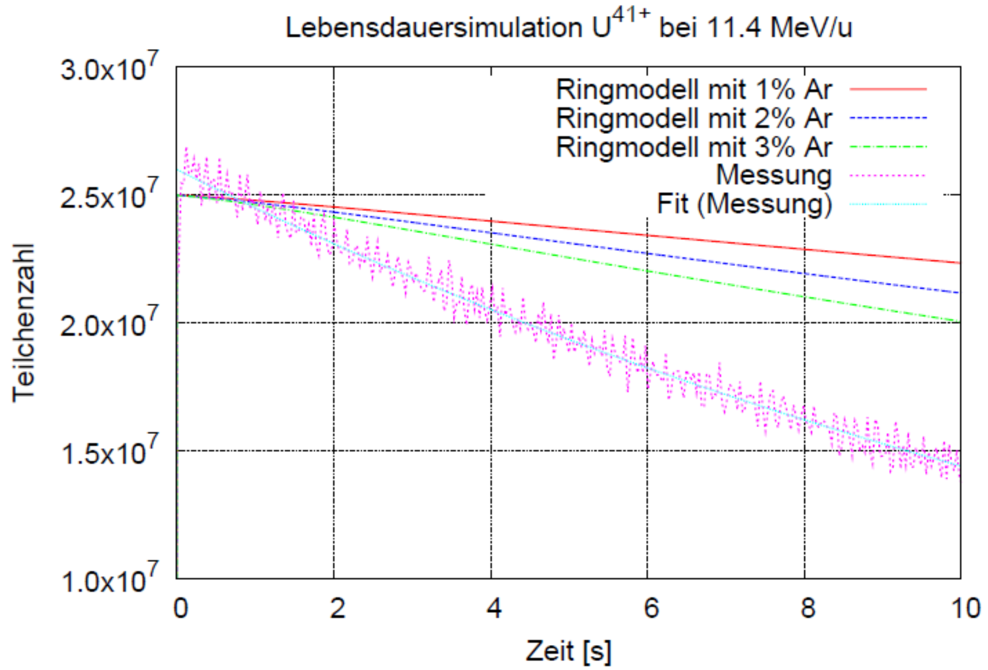
Ionization and Capture Cross Sections



Calculated V. Shevelko

Beam Life Time and Ionization Cross Sections

Close collaboration with atomic physics department concerning ionization and capture cross sections



Surprised not excluded:

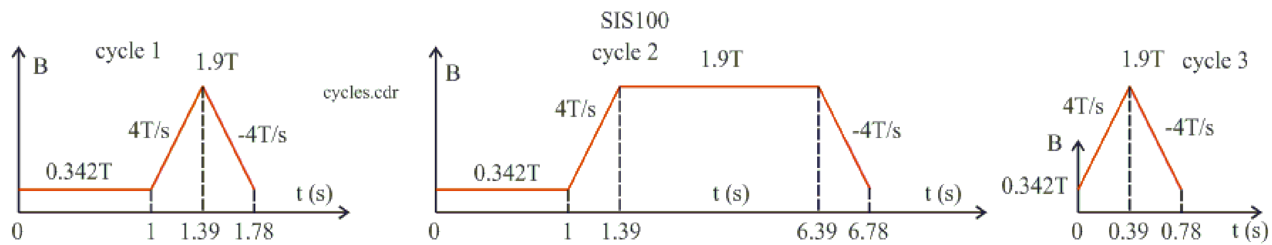
The recently measured beam life times for U^{39+} and U^{40+} were unexpected low and consequently the corresponding ionization cross section seem to be unexpected high.

Atomic physics process at intermediate charge state region not completely understood ?

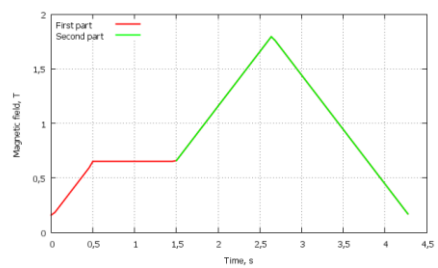
Or mistakes done at life time measurements ?

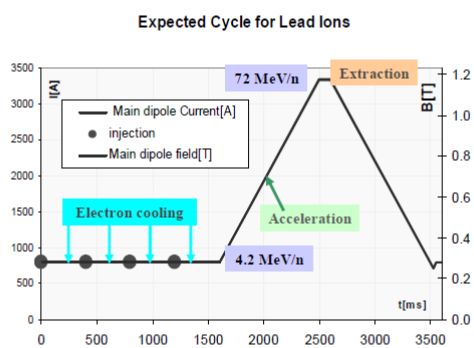
Machine Cycles and Integral Cross Section

SIS100 cycles



NICA booster cycle





LEIR cycle

σ_{int} depends on the specific machine cycle

$\sim \int \sigma(E(t))\, dt$

Strength of Charge Exchange and Dynamic Vaccum

Charge exchange loss and dynamic vacuum scale with : [N x σ_{int}] x f_{rep}

Accelerator	Institut	Ion species	Total integ. cross section	Number of ions	N x σ_{int}	Rep. rate [Hz]	N x σ x frep
AGS Booster	BNL	Au31+	4.5E-21	5x109	2.2E-11	5	1.1E-10
LEIR	CERN	Pb54+	5.5E-20	1x109	5.5E-11	0.25	1.4E-11
NICA Booster	JINR	Au32+	4.9E-21	4x109	1.9E-11	0.25	4.7E-12
SIS18	GSI	U28+	8.7E-22	1.5x1011	1.3E-10	3	3.9E-10
SIS100	FAIR	U28+	1.8E-21	6x1011	1.1E-9	0.5	5.5x-10

Pressure Stabilization - Recipe

- Short cycle times and short sequences

  SIS18: 10 T/s - four batch sequence for SIS100 injection

  (new power connection, power converters and Rf system)

- Enhance pumping power (UHV upgrade)

  (NEG-coating - local and distributed)

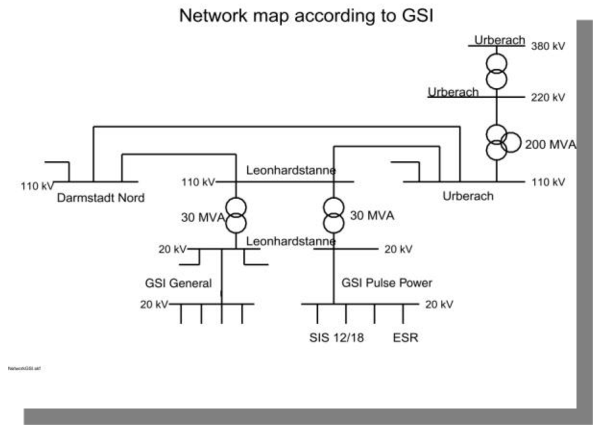
  (new magnet chambers, improved bake out system)

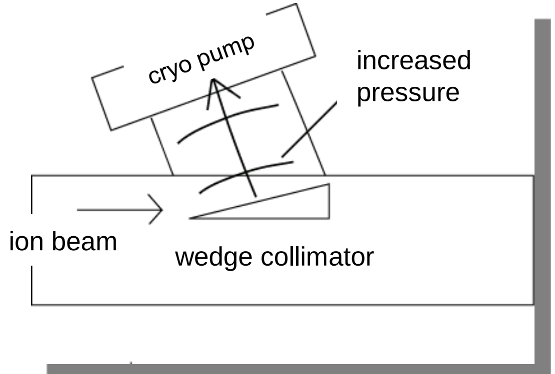
- Localizing beam loss and controle/suppression of desorption gases

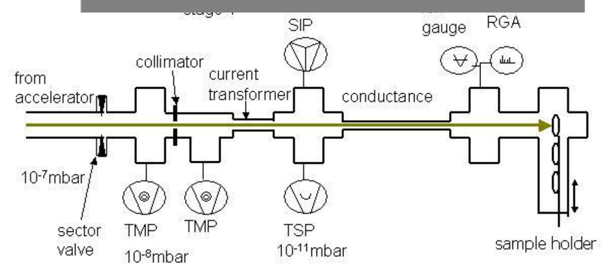
  (Catcher system, Lattice design)

- Materials with low desorption yields

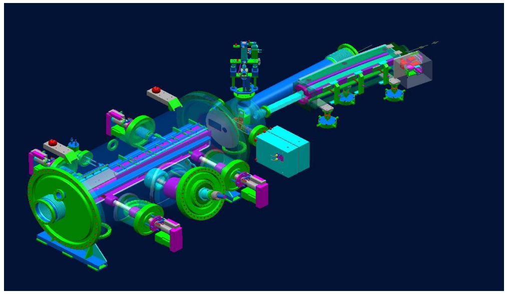
  η-Teststand, ERDA measurements,



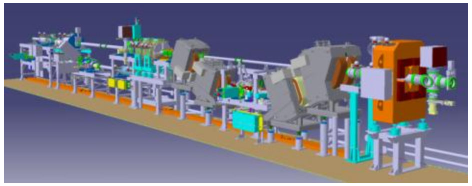




SIS18upgrade Program

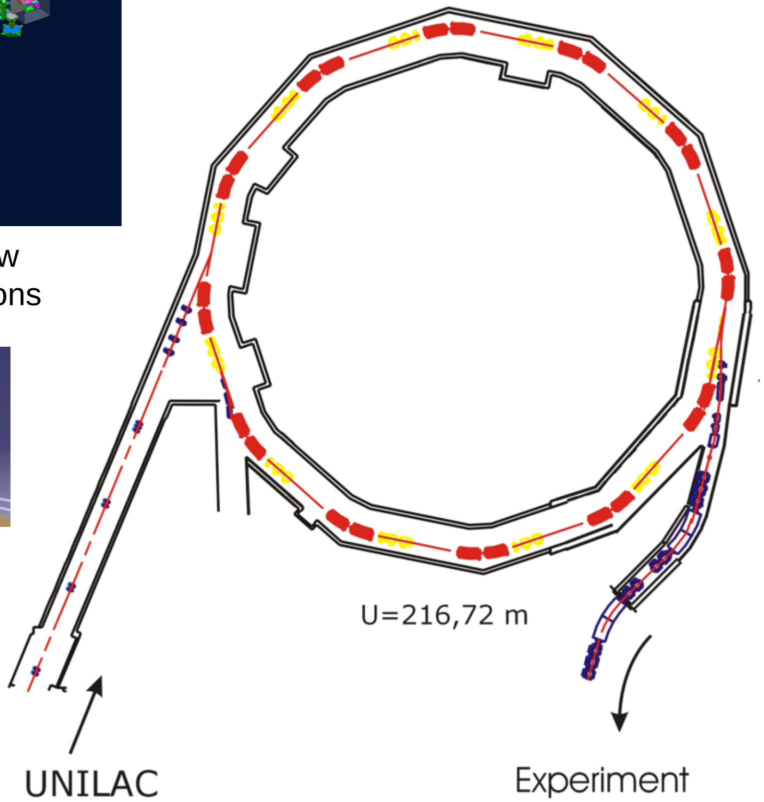


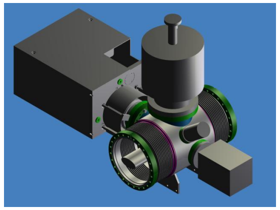
Injection system for low charged state heavy ions



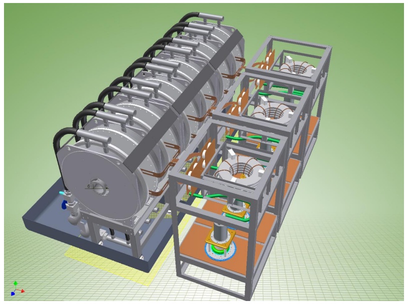
Charge separator for higher intensity and high quality beams

Power grid connection





Scrapers and NEG coating for pressure stabilization



h=2 acceleration cavity for faster ramping

The SIS18upgrade program: Booster operation with intermediate charge state heavy ions

Upgrade dedicated to pressure stabilization

Supported by EU Construction contract:

- **RF System (fast acceleration – short cycle time)**
  New h=2 acceleration cavity and bunch compresion system for FAIR stage 0, 1
  (2012)

- **Replacement of Main Dipole Power Supplies (fast acceleration – short cycle time)**
  Operation with 10 T/s up to 18 Tm
  (2012)

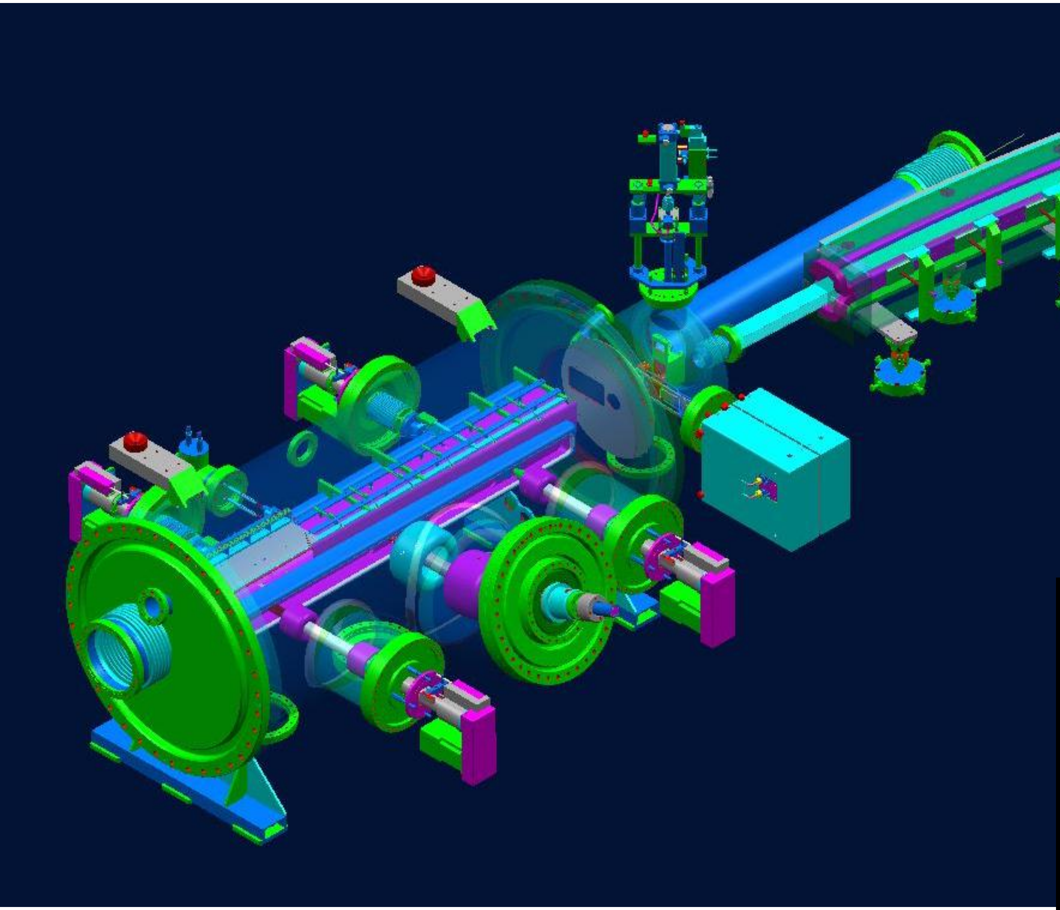
- **UHV System (high distributed pumping power) - completed**
  New, NEG coated dipol- and quadrupole chambers
  (2009)

- **Insertions (low desorption materials, local pumping power) - completed**
  Set-up of a „low-desorption“ scraper system
  (2009)

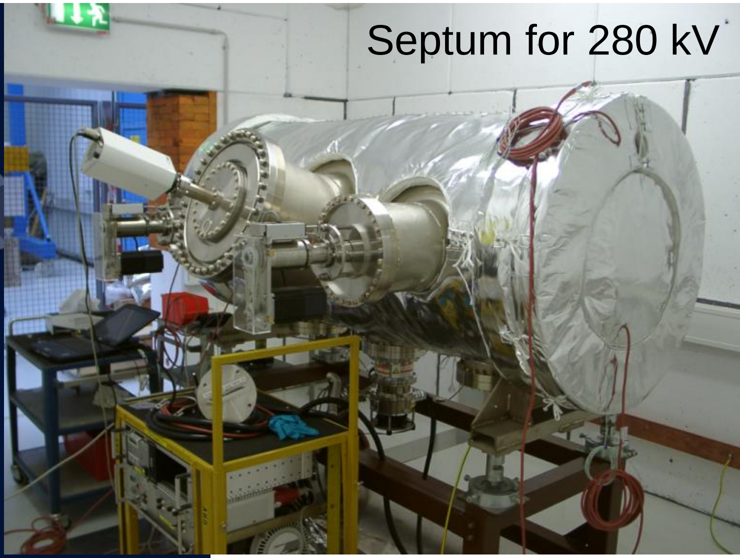
- **Injection / Extraction Systems (higher injection energy) - completed**
  New, large acceptance injection system plus HV power suppy

- **Power Grid Connection - completed**
  Dedicated 110 kV power connection and transformer for fast ramping

Injection System Upgrade



Final design of the new injection system



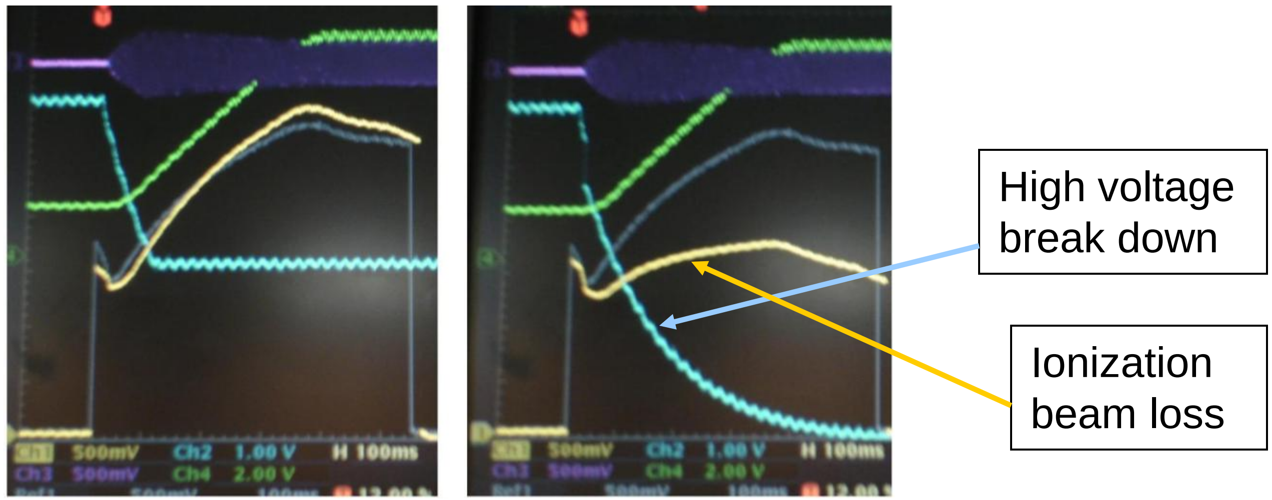
Septum for 280 kV

- Increased acceptance
- Injection of U^{28+} at reference energy
- Protection of septum electrodes (1.5 MW beam power)
- Position and profile verification
- Aim for reduced gas production

Project completed

Minimization of Initital Pressure Bumps

Injection of a MW heavy ion beam.



Gas desorption in the injection channel of the injection septum results in HV voltage break downs which again generates pressure bump and ionizes a large fraction of the beam after injection.

Stronger pumping is needed in the injection septum.
NEG panels are prepared for the next shut down.

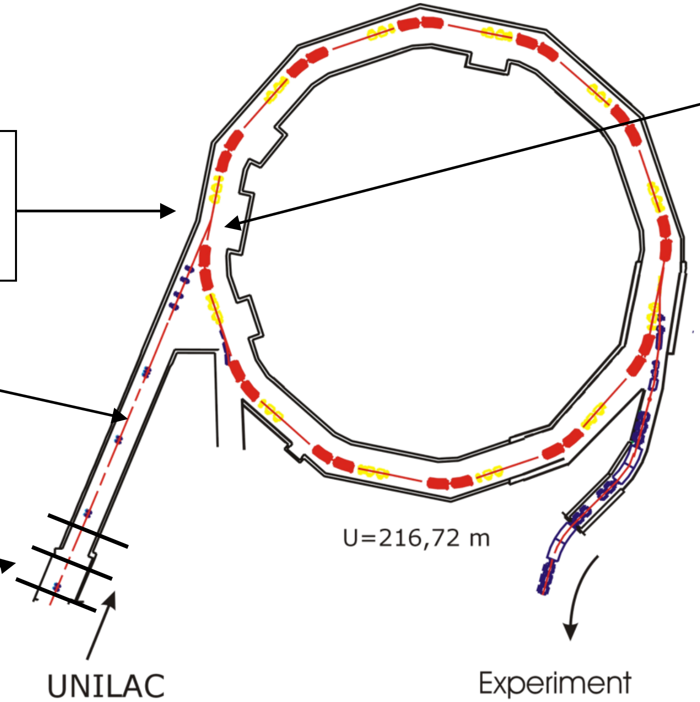
Injection of a Sharp Edge Beam

1. Image plane

(Injection channel)

Imaging optical system

Object plane (Three Collimators)



2. Image plane

(Backside injection septum)

Imaging system from the collimator up to the injection channel and the backside of the septum

Fast Ramping

High average beam intensity requires fast short cycle times with fast ramping.

- Shortening of cycle time (intermediate charge states)
- Higher repetition rate (booster operation 2.7)
- Increased average intensity (x 2-9)

Present Operation:
dB/dt = 1.3 T/s – 1/3 Hz

A. SIS18 Modus

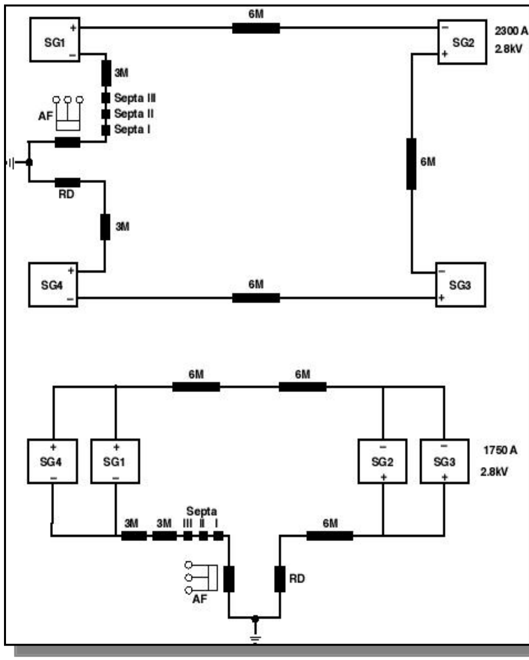
B_{max}= 1.8 T - dB/dt = 4 T/s
I_{max} = 3500 A - V_{max} = 5.5 kV
2 groups each 2 parallel power converters
2 groups each 12 Dipole

$P_{\mathbf{max}}$ = +19/-17 MW

B. SIS12 Modus

B_{max} = 1.2 T - dB/dt = 10 T/s - I_{max} = 2300 A - V_{max} = 11.2 kV
4 in power converters in series supply 4 groups each 6 dipols

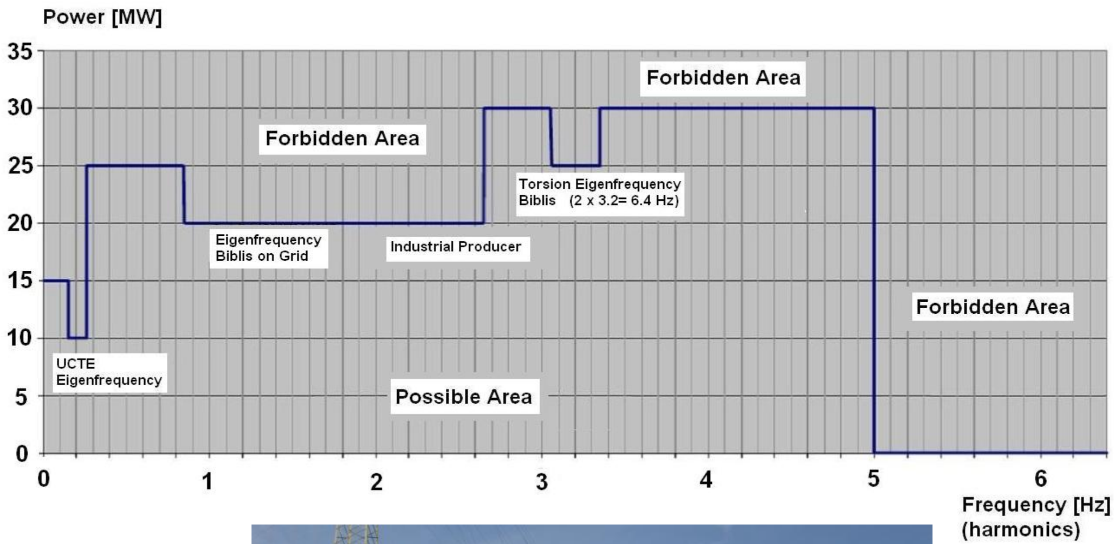
$P_{\mathbf{max}}$ = +26/-23 MW



(U^{73+} : E_{max} = 512 MeV/u)

Power converter upgrade for 10 T/s up to 18 Tm

New 110 kV Power Connection



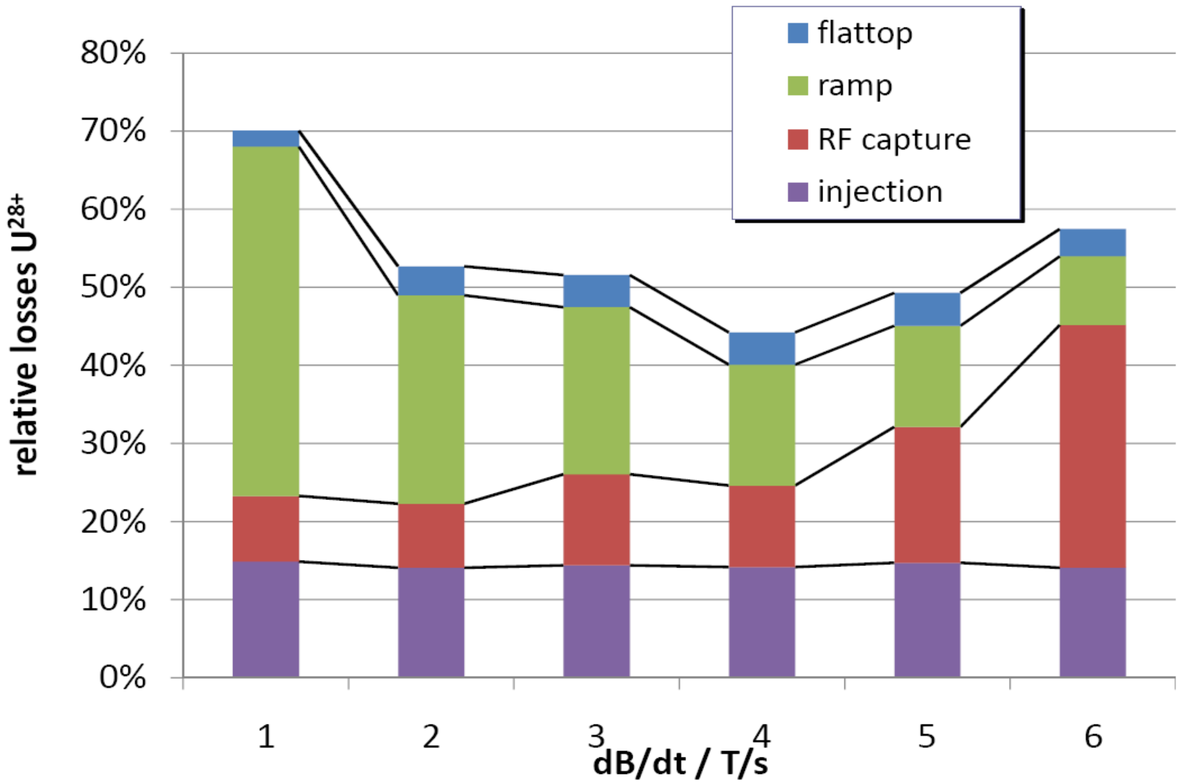
	Pulse Power	Field Rate
SIS18	5 MW	1.3 T/s
SIS12	+26 MW -17 MW	10 T/s
SIS18	+ 42 MW	10 T/s
SIS100	± 26 MW	4 T/s
SIS300	± 23 MW	1 T/s

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

Project completed

> H. Ramakers

U^{28+} - Beam Loss at High Ramp Rates



- Ionization loss decreases with ramp rate
- RF capture loss increases with ramp rate

Fractional loss of different mechanisms during fast ramping

New h=2 Acceleration System

- Sufficient Rf voltage for fast ramping with low charge state heavy ions

  U^{73+} acceleration with 4 T/s (2x10^{10} ions)

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

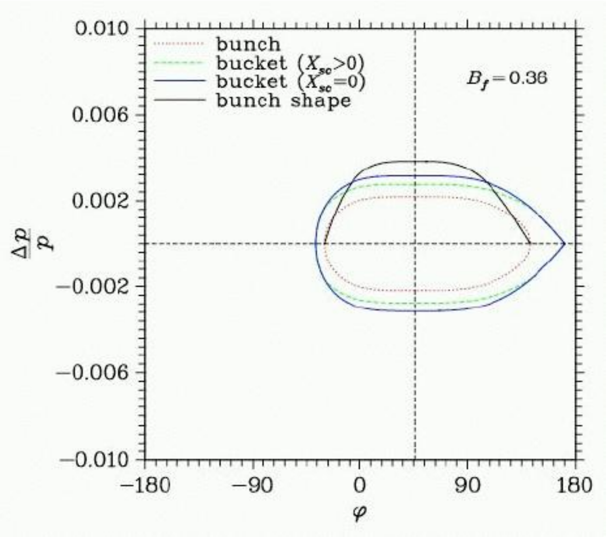
- Sufficient bucket area for loss free acceleration

  (30 % safety)

- Flat bunch profile (high Bf) for lower inc. tune shift

  two harmonic acceleration

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

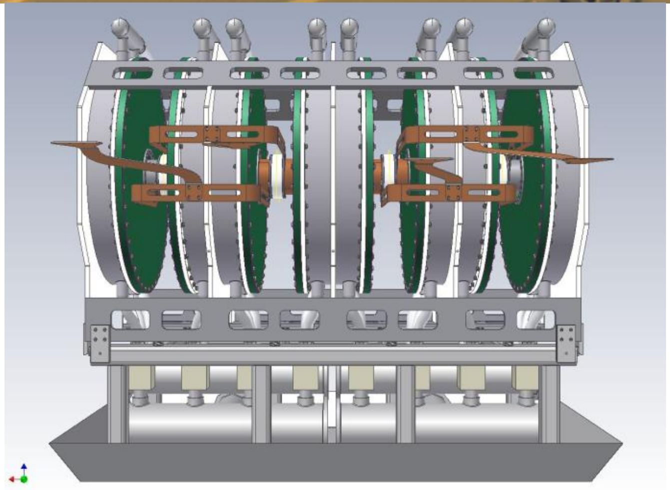


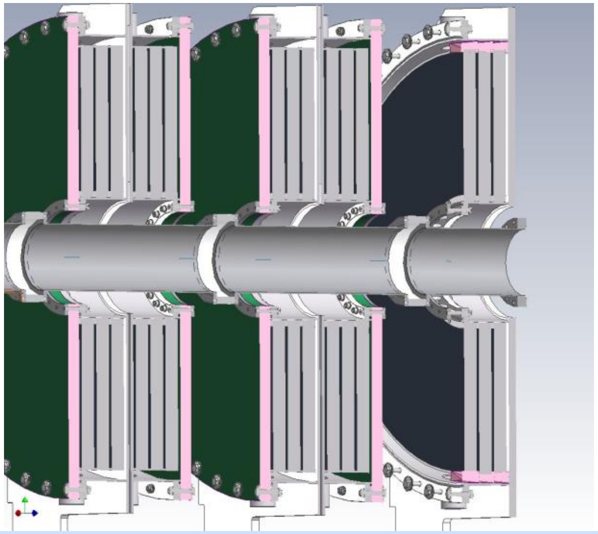
- Compatible with SIS100 RFcycle

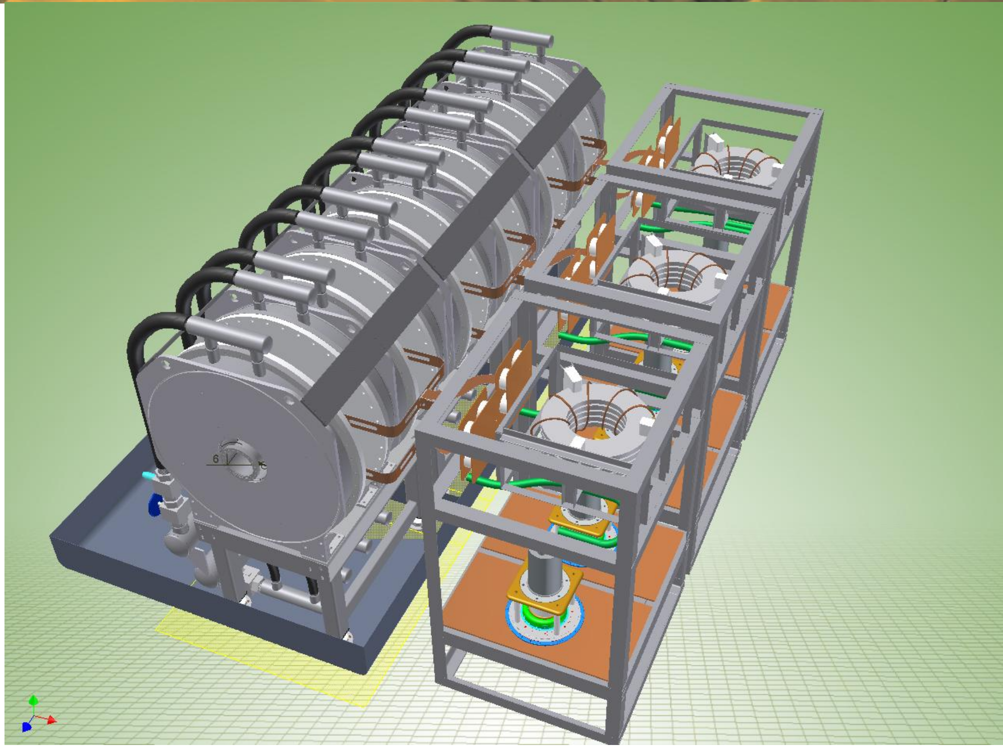
  (Transition from two-harmonics to one harmonic during ramping at constant dB/dt)

- 50 kV – high power requirements – additional space provided in tunnel

New h=2 Acceleration System





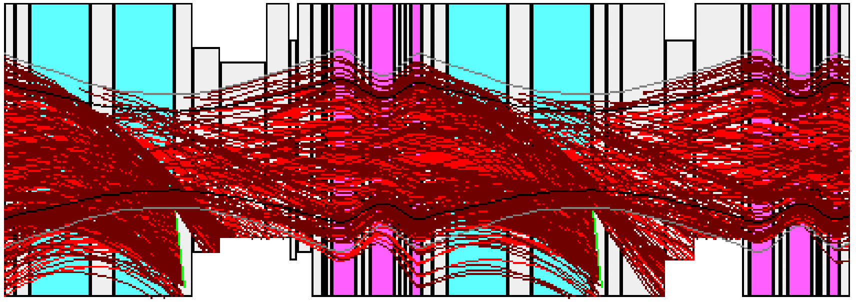


Installation end of 2012

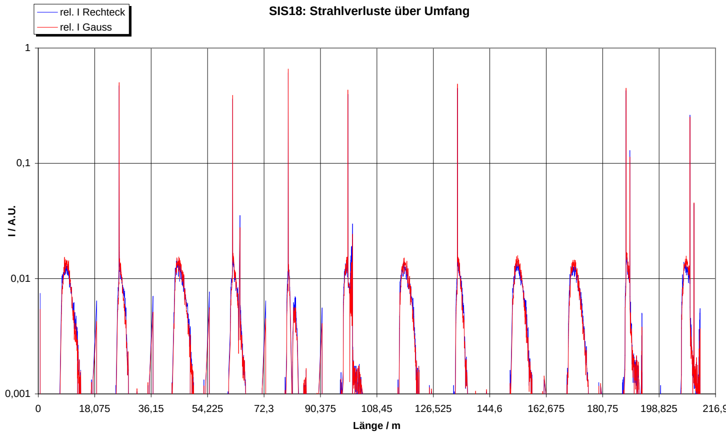
P. Hülsmann,
H. Klingbeil

Design studies for the new, high duty cycle MA loaded, h=2 acceleration cavities (0.5 MHz - 50 kV)

Charge Catcher System



Ionization beam loss in section 11,12

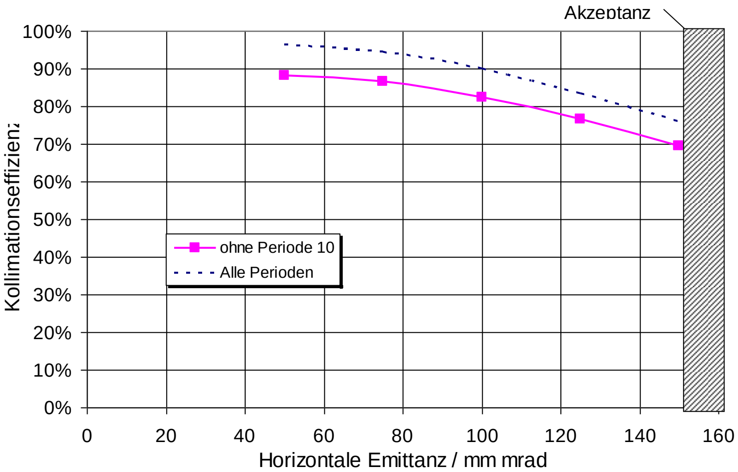


Beam loss distribution U^{29+}

- Developed for heaviest ions (highest ionization cross sections)

- Triplet/ doublet structure is suitable but: bending power of dipoles to high

  > Limited catching efficiency depending on emittance (70 %)

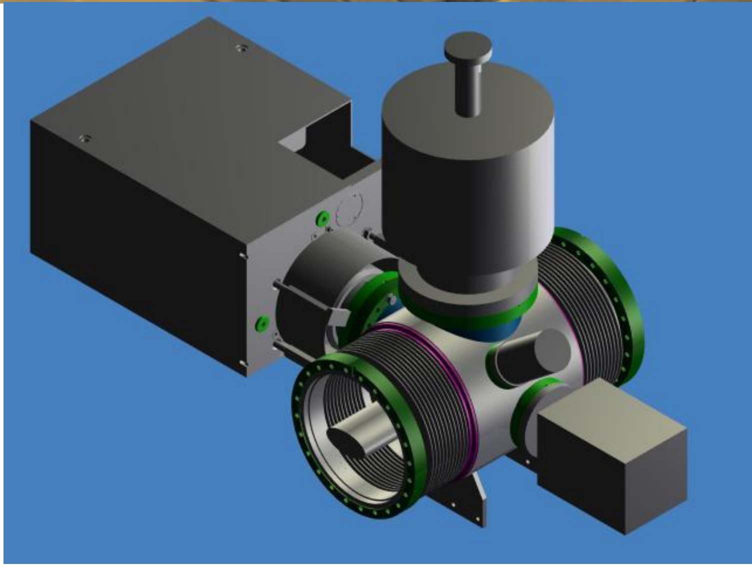


Catching efficiency U^{29+}

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

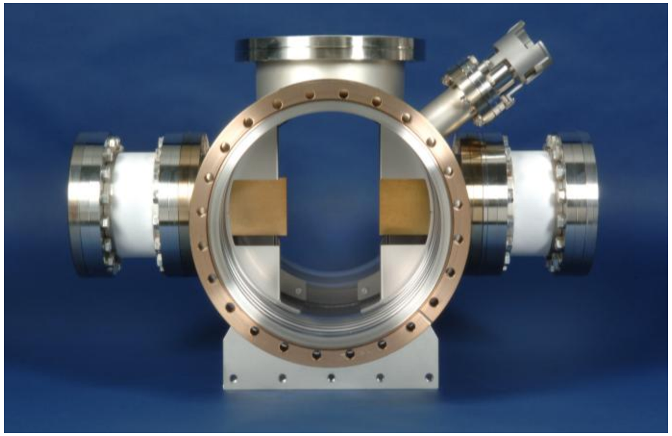
Two prototypes succesfully tested in 2007 shut down

Significantly reduced desorption yield

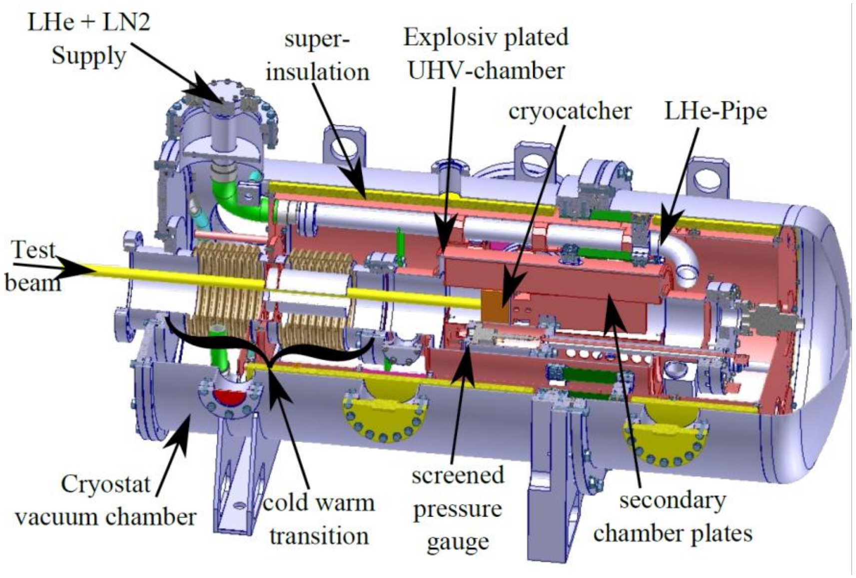
Installation of series (10 catchers) completed.

Development of Low Desorption Catcher Systems

Control of Ionisation Beam Loss (and Dynamic Vacuum) by Dedicated Ion Catcher Systems (warm and cold)

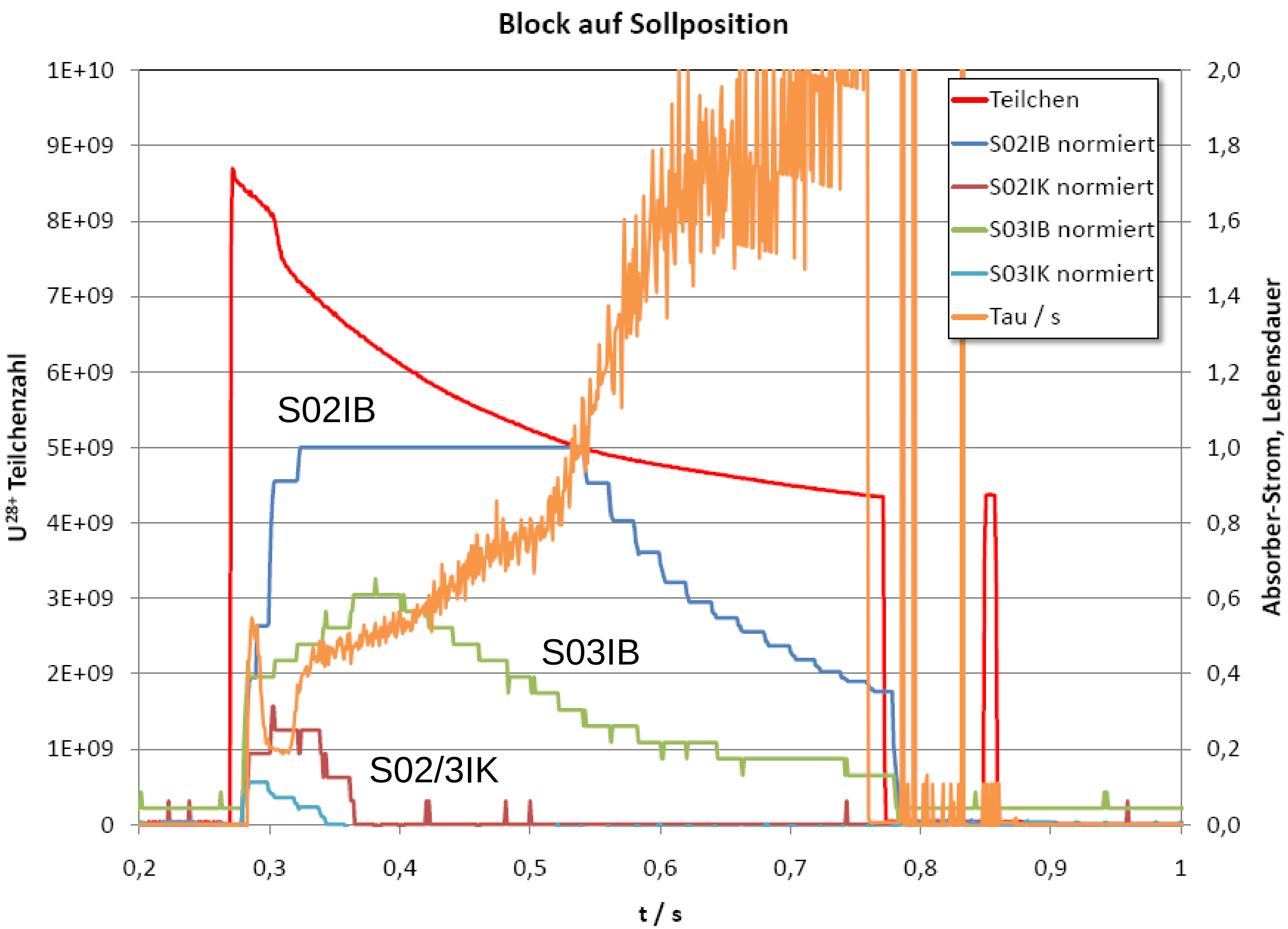


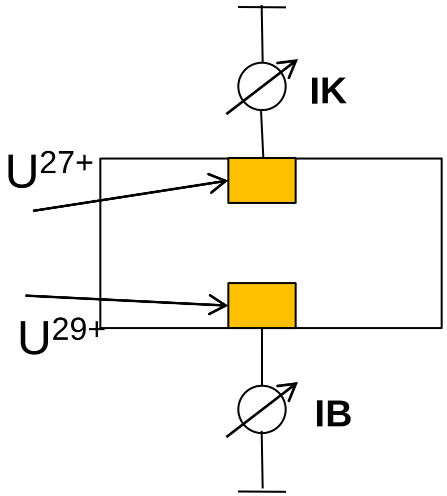
SIS18 warm, low desorption ion catcher



SIS100 cold, low desorption ion catcher (prototype)

Measurement of Ionisation and Capture Loss



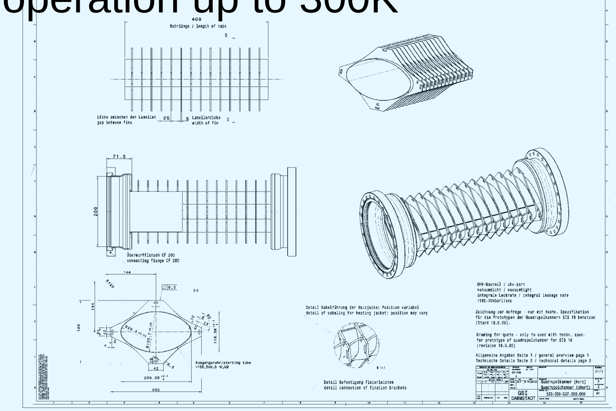


UHV system upgrade

Goals:

- Generation of extremly low static pressures of $p_0 < 5x10^{-12}$ mbar and increased average pumping speed by up to a factor of 100
- Stabilization of dynamic pressure to $p(t)_{max} < 10^{-9}$ mbar
- Removement of contamination with heavy residual gas components

- Replacement of all dipole- and quadrupole chambers by new, NEG coated chambers
- Improved bake-out system for operation up to 300K



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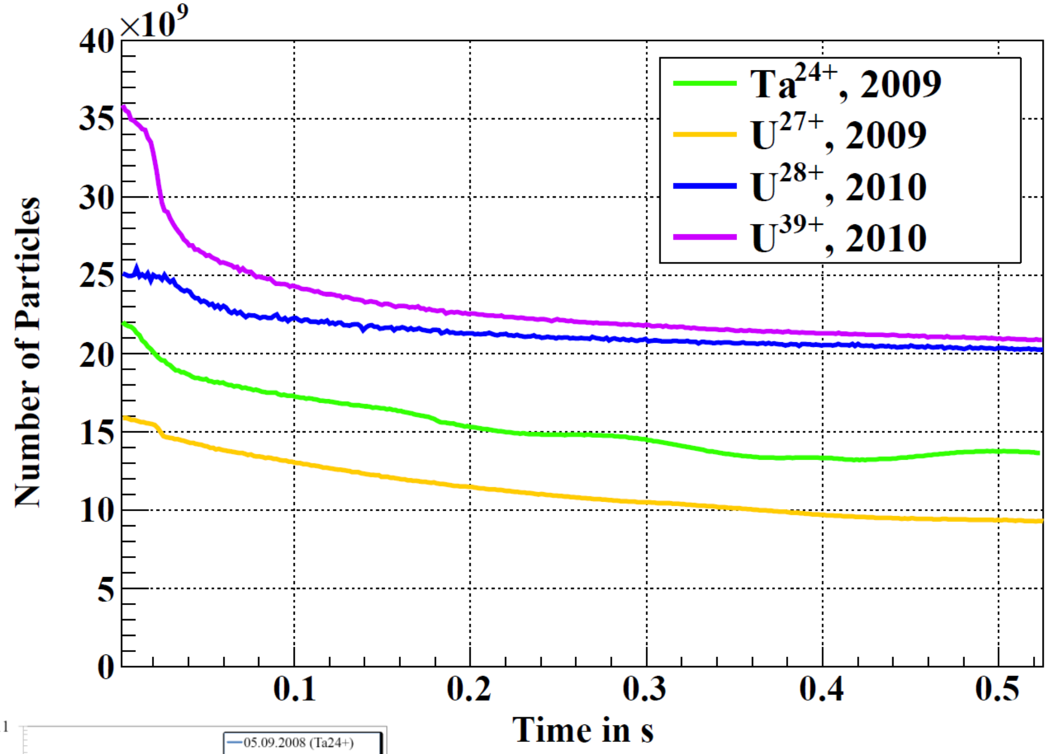
UHV system upgrade

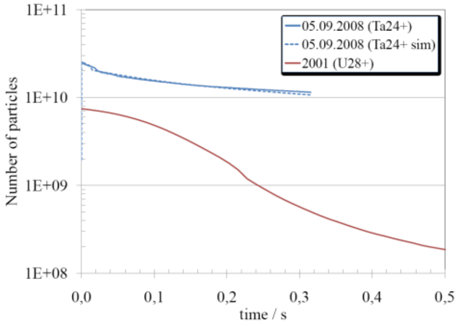
Project Status

- NEG coating facility successfully commissioned at GSI

  NEG coating know-how acquired
- Manufacturing of new dipole chambers completed
- Upgrade of bake-out system for a temperature of 300°C completed
- Replacement of dipole and quadrupole chambers completed

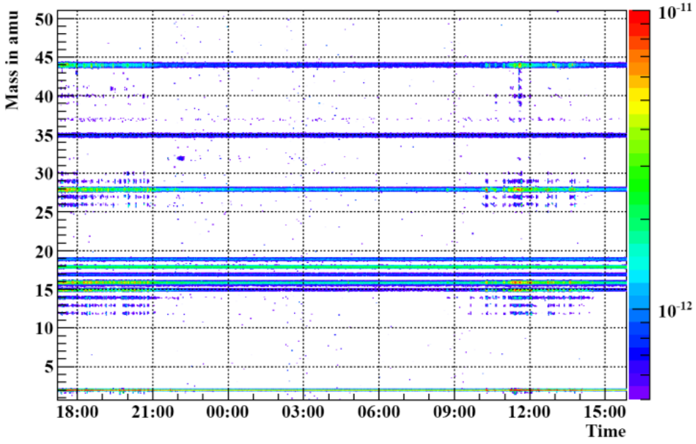
SIS18 Intensity Records with Intermediate Charge States

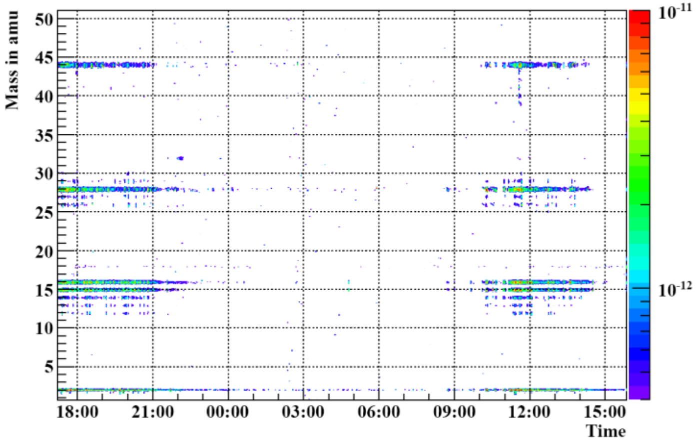




Intensity enhancement has been achieved by:

- Increased injection energy (11.4 instead of 7.1 MeV/u and therefore lower cross sections
- Brakes of 1-8 s between the cycle to accomodate for the low insufficient effective pumping power
- Carefull machine setting with minimized systematic loss
- Low desorption ion catcher system with local (strong, high conductivity) NEG pumping.
- NEG coating of all magnet chambers.





Residual gas component	Relative amount for outgassing	Relative amount for desorption
Hydrogen	88 %	40 %
Nitrogen	0 %	0 %
Oxygen	0 %	0 %
Argon	1 %	0 %
Water	4 %	0 %
Carbonmonoxide	2 %	25 %
Carbondioxide	1 %	10 %
Methan	4 %	25 %

Dynamic Vacuum – STRAHLSIM Code

Linear beam optics

Loss pattern due to charge change
Collimation efficiency
Reads and writes many formats (AML, MIRKO, MAD-X, WinAGILE)

Static Vacuum

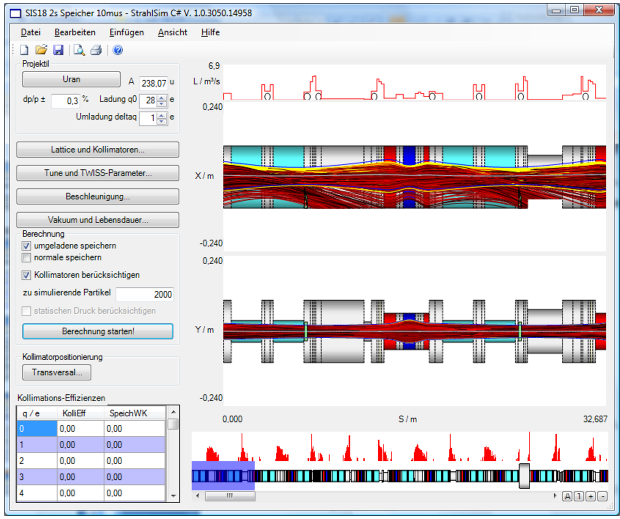
p_0, S_{eff}, Vacuum-conductances, NEG coating, cryogenic surfaces,
Static residual gas components

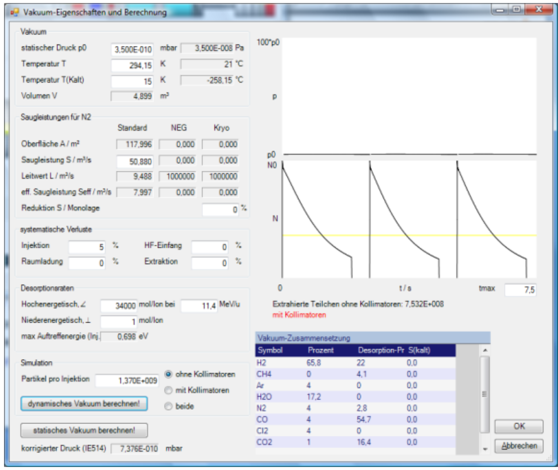
Dynamic (Source of beam losses)

- Synchrotron cycle
- $S_{eff,cold}(p, T)$: analytic model, incl. saturation
- $S_{eff,NEG}(p, t)$: Saturation
- Systematic losses (injection, RF capture)
- Projectile ionisationand capture $s_{pi}(E, Dq, Z)$
  from Shevelko, Olson work in conjunction with AP
- Coulomb scattering
- Target ionisation
- Intra beam scattering

Ion stimulated desorption

- Desorption rate η scaled with $(dE/dx)^2$
- Beam scrubbing included

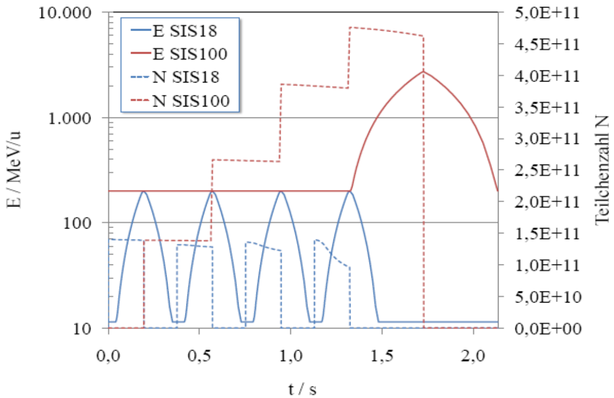




Benchmarked with many machine experiments (and at other accelerators)

Multi-Cycle and Long Term Studies

Multi-cycle Studies

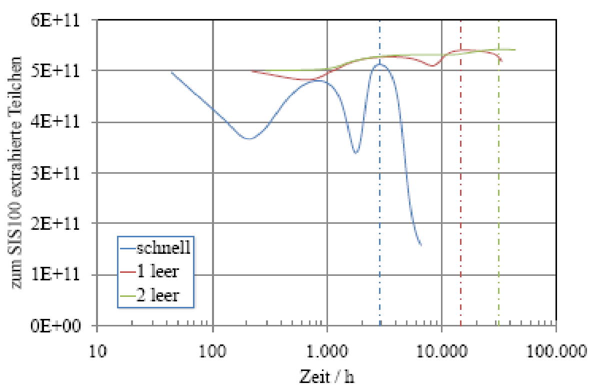


Ionization loss during stacking and acceleration in SIS18 and SIS100

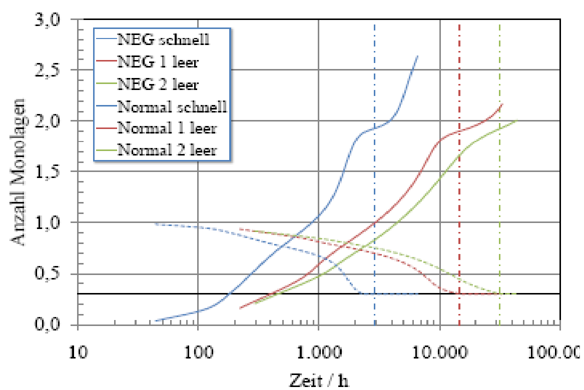
- The pressure at the end of the first cycle is the pressure at the beginning of the second cycle > Relaxation of the peak pressure over many cycles
- Modulation of the intensity in the booster cycles may lead to highes average numbers
- Pumping power of NEG depends on number of monolayers

(decreas of half an order per monolayer)

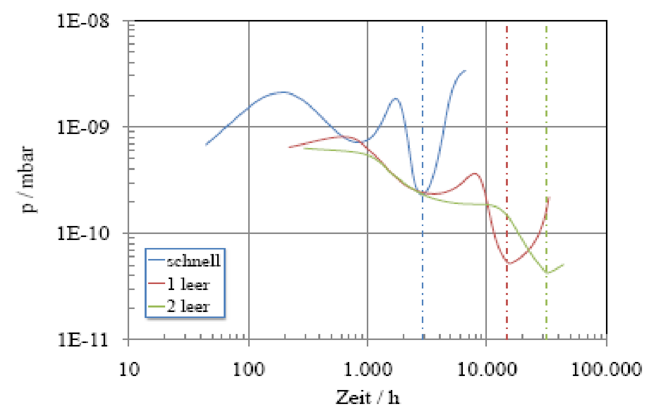
Long Term Studies



Accumulated ions over months



Number of monolayers over months



Pressure over months

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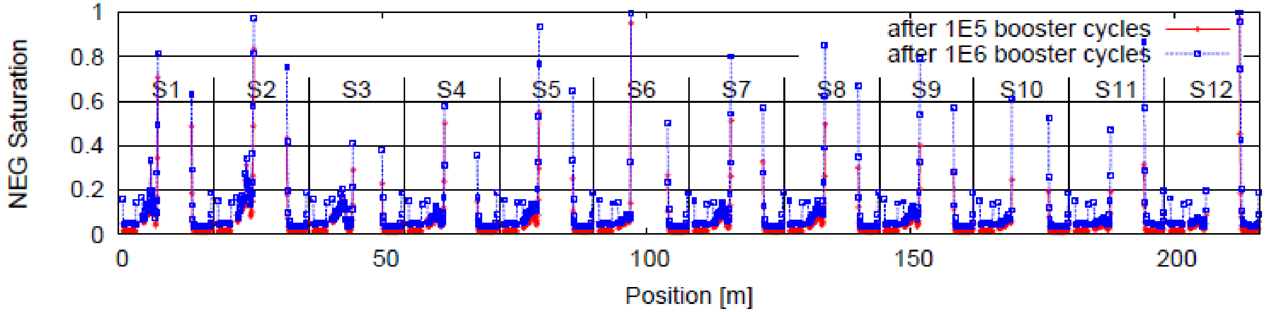
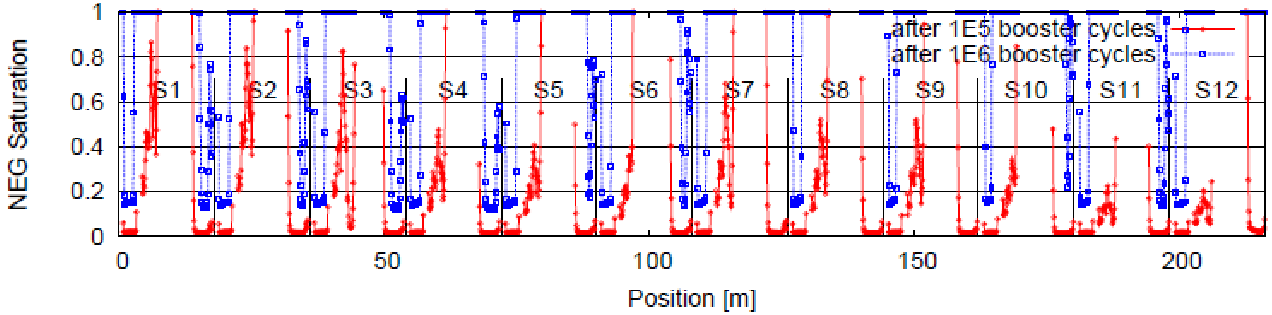
2nd Generation of STRAHLSIM Code

- Spatial and Time Resolved Simulation of Dynamic Vacuum and Charge Exchange Beam Loss
- Better modelling of localized effects (no conductivity averaging over the circumference)
- Self determined static vacuum depending on the UHV system and machine layout.
- Long term stability (transmission) and NEG saturation depends on the beam scrubbing.



NEG saturation with scrubbing



NEG saturation without scrubbing

See poster Patrick Puppel

Summary

▪ Six major upgrade measures (big investments) have been defined and are partly completed to prepare SIS18 for the booster operation with high intensity, intermediate charge state heavy ions

▪ Major progress has been achieved in the understanding and simulations of the dynamic vacuum, gas desorption and beam loss by charge changes and it long term behaviour under influence of saturating NEG surfaces and beam scrubbing effects.

▪ An important simulation and measurement campaign is running adressing the high current and high space charge operation

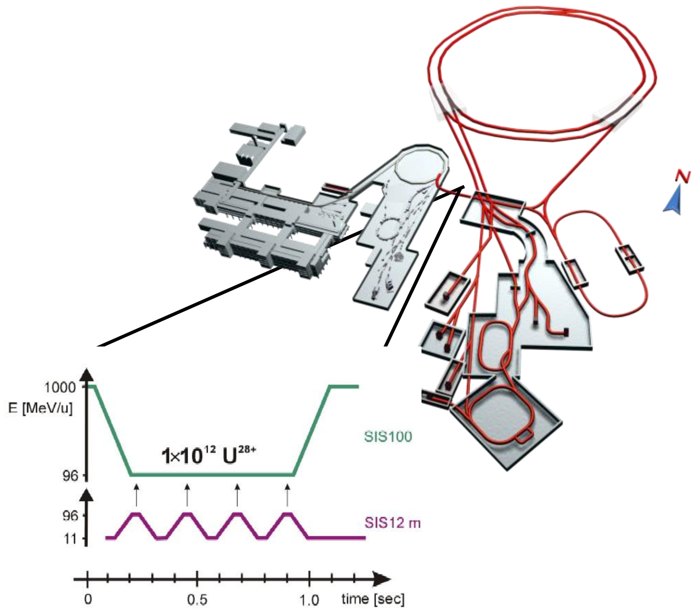
▪ It is known, that a number of "minor" issues, especially related to initial systematic beam loss have to be adressed in parallel to the six major measures. The dynamic vacuum simulations indicate that a succesful completion of these minor measures is a preconditions for the booster operation.

▪ Major progress has already been achieved in the unique acceleration of high intensity, intermediate charge state heavy ions.

▪ For FAIR a factor of 10 in intensity per cycle and a factor of 30 in intensity per second is missing.

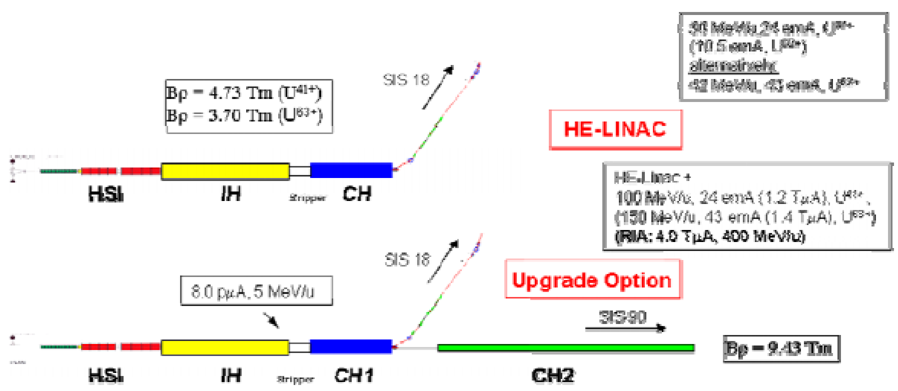
Alternative Injection Schemes for SIS100

- U^{28+}, U^{39+} ions directly injected into SIS100 (bypassing SIS18) by means of a new Linac replacing the ALVAREZ structures.



FAIR reference injection scheme

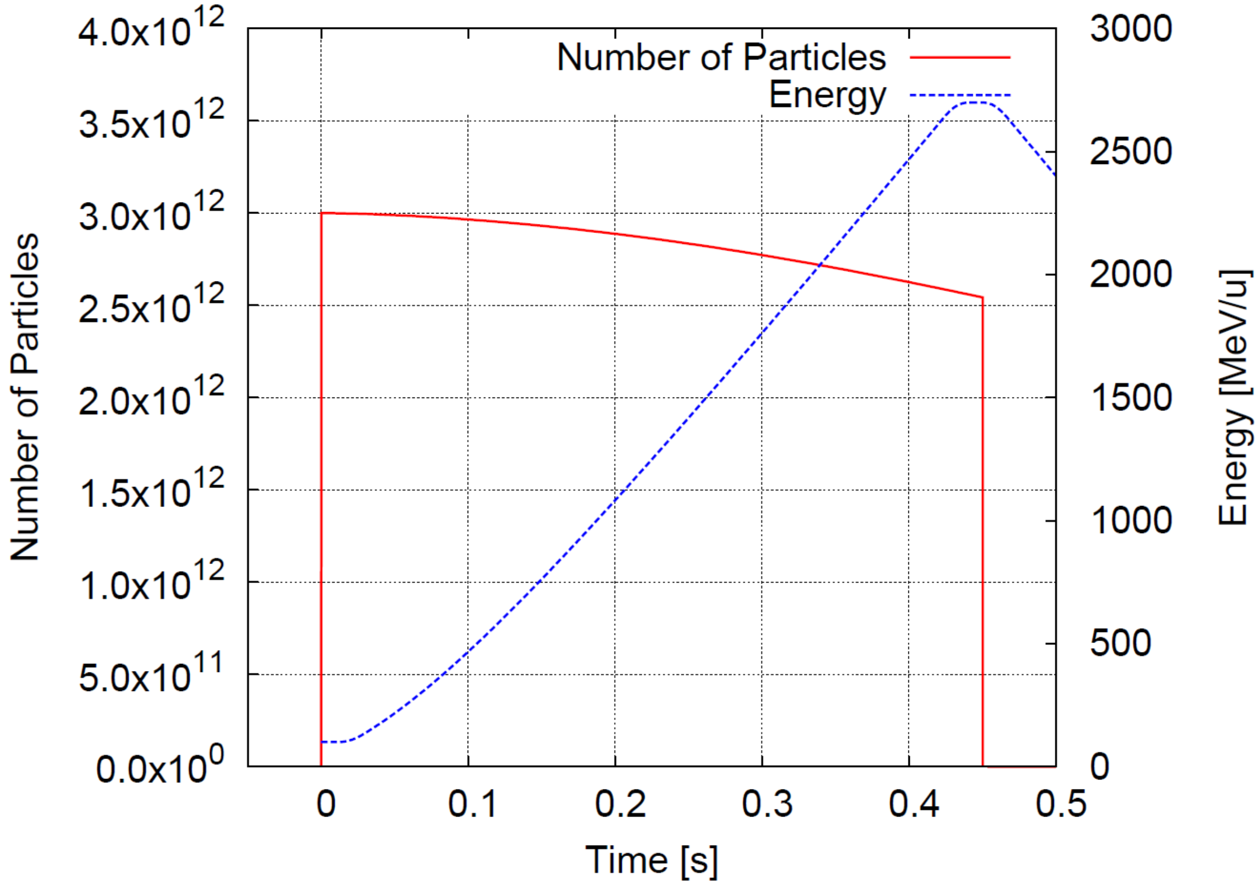
(longitudinal stacking)



W. Barth et.al, Proc. of Linac06

Advantage of multi turn injection: Short stacking time (2 ms instead of 1 s), lower beam loss.

Vaccum Stability and Ionization Beam Loss

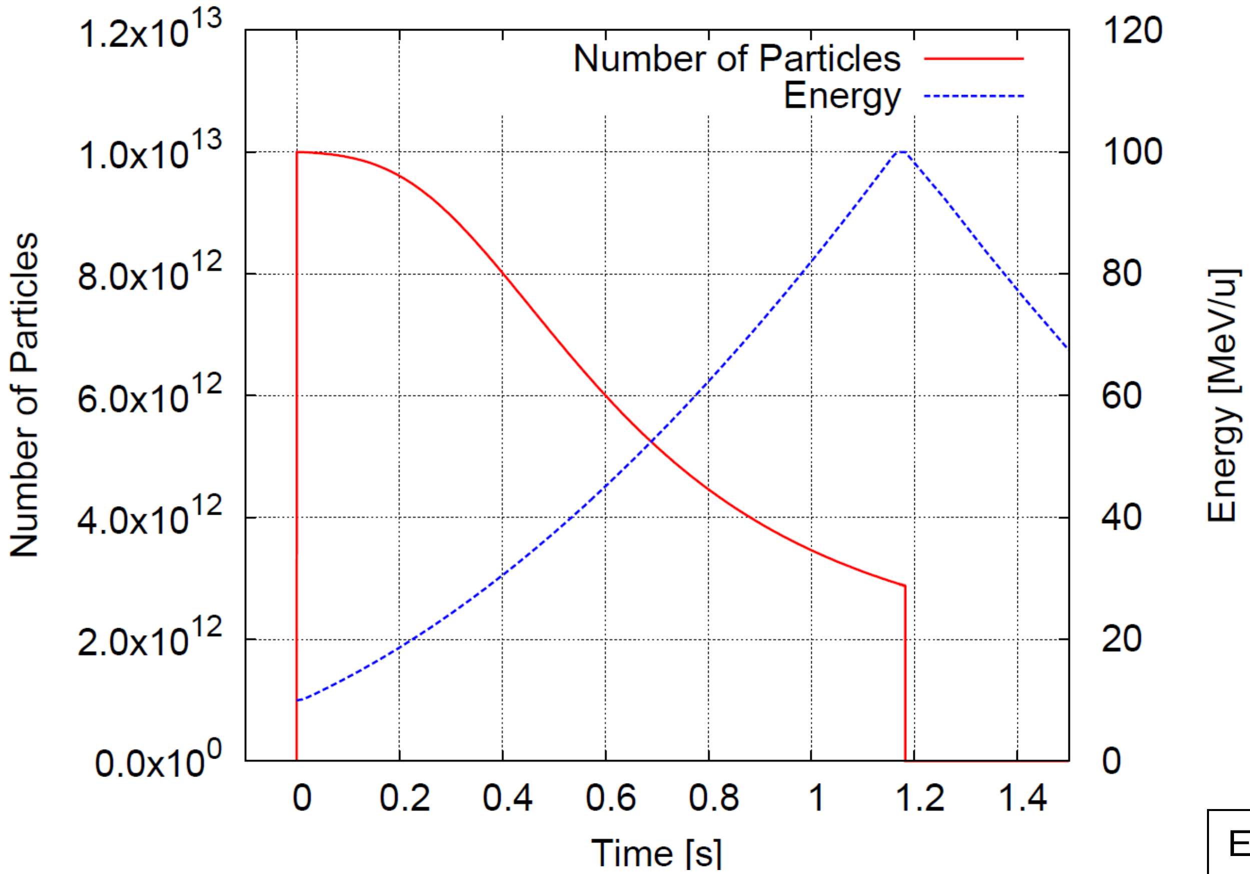


Eta= 25000

E= 100 MeV/u

Ionization Beam Loss for U^{28+}

Vaccum Stability and Ionization Beam Loss



Eta=50 assumed

E= 50 MeV/u

Ionization Beam Loss for U^{4+}

Conclusions System Studies

- Operation of intermediate charge state (e.g. U^{28+}) heavy ions with high intensities (~ $5x10^{12}$) in SIS100 with its „long“ cycle time is feasible with the technologies developed for FAIR and with stable dynamic vacuum conditions.

- By means of a new high energy (100 MeV/u) linac for U^{28+}, the intensities in the FAIR SIS100 may be significantly increased by means of multi turn injection and linear coupling

- Operation with low charge state heavy ions e.g. U^{4+} in synchrotrons seems very difficult in synchrotrons and requires severe technical developements – may work in storage ring with short storage time.

with regards to P. Puppel and L. Bozyk

4th of october foundation of the FAIR GmbH and official project start