Heavy Ion Synchrotrons

Beam Dynamics Issues and Dynamic Vacuum Effects

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High Charge State Heavy Ions in Synchrotrons

AGS	BNL	5×10^9	Au^{77+}	11 GeV/ u
PS	CERN	1×10^9	Pb^{53+}	5.9 GeV/u
Nuclotron	JINR	1.5×10^7	Xe^{44+}	1.5 GeV/u
SIS18	**GSI**	4×10^9	U^{73+}	1 GeV/u
CSRm	**IMP**	1×10^9	U^{72+}	400 MeV/u
SPS	**CERN**	4×10^9	Pb^{82+}	177 GeV/u
LHC	**CERN**	4×10^{10}	Pb^{82+}	1380 GeV/u
RHIC	**BNL**	1.7×10^{11}	Au^{79+}	100 GeV/u

JPARC has just organize the first workshop on a potential heavy ion program.

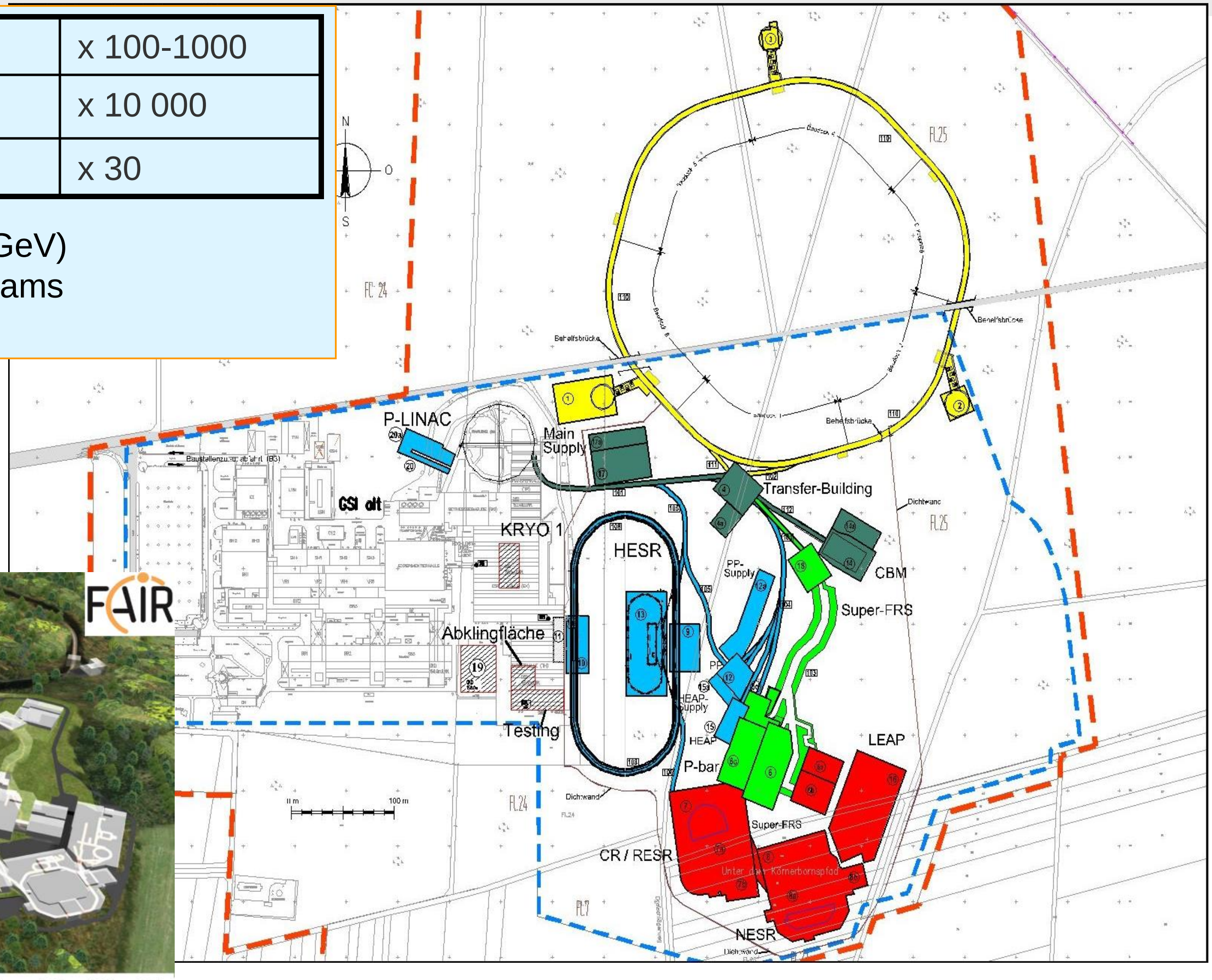
State of the art are 10^9 to 10^{10} heavy ions per cycle.

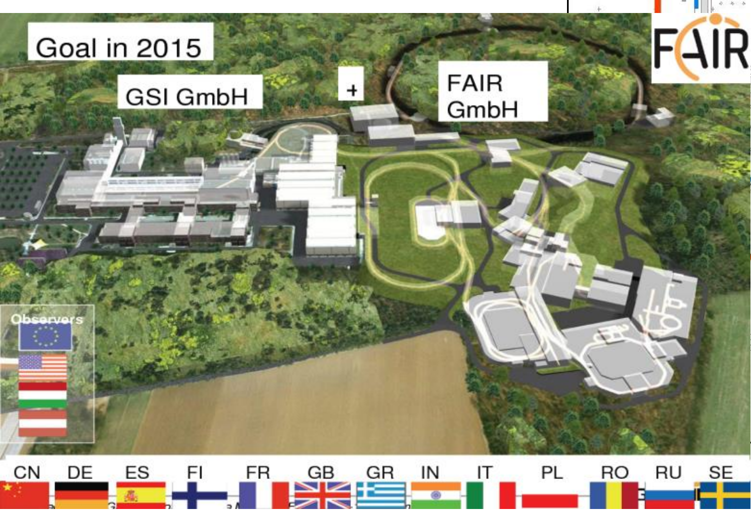
How to generate 10^{10} – 10^{12} heavy ions per cycle ?

FAIR Accelerator Facility Modul 0-6

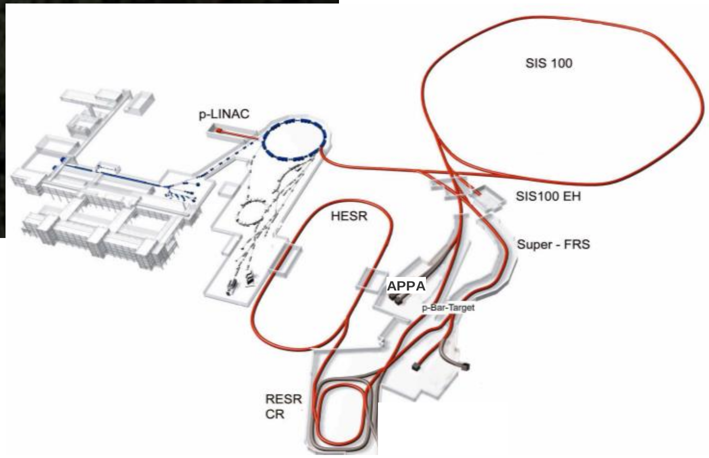
Primary Beam Intensity	x 100-1000
Secondary Beam Intensity	x 10 000
Heavy Ion Beam Energy	x 30

- New: Cooled pbar Beams (15 GeV)
- Intense Cooled Radioactive Beams
- Parallel Operation





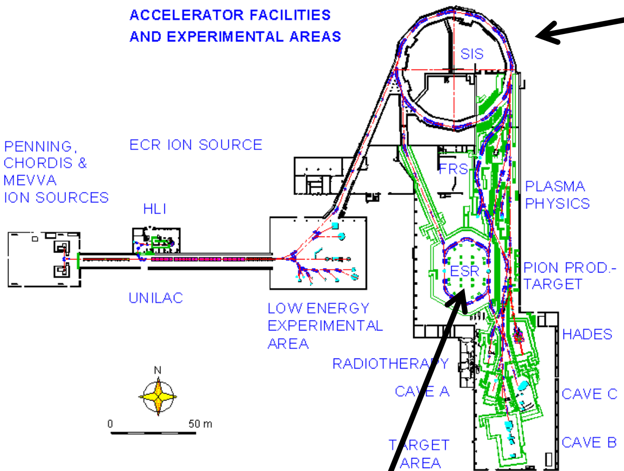
FAIR Construction Side

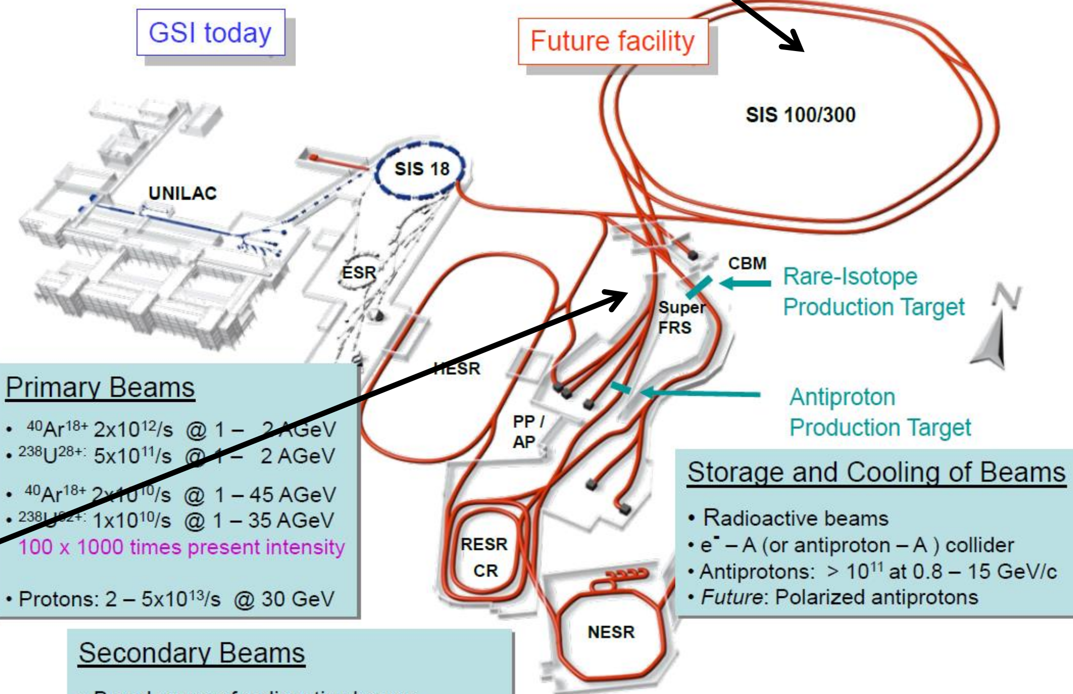


Primary Beams – Secondary Beams

FAIR is the big brother of GSI – the overall facility topology is identical

Primary Beams





Secondary Beams

Primary Beams

- $^{40}Ar^{18+}$ $2x10^{12}$/s @ 1 – 2 AGeV
- $^{238}U^{28+}$: $5x10^{11}$/s @ 1 – 2 AGeV
- $^{40}Ar^{18+}$ $2x10^{10}$/s @ 1 – 45 AGeV
- $^{238}U^{92+}$: $1x10^{10}$/s @ 1 – 35 AGeV

100 x 1000 times present intensity

- Protons: 2 – $5x10^{13}$/s @ 30 GeV

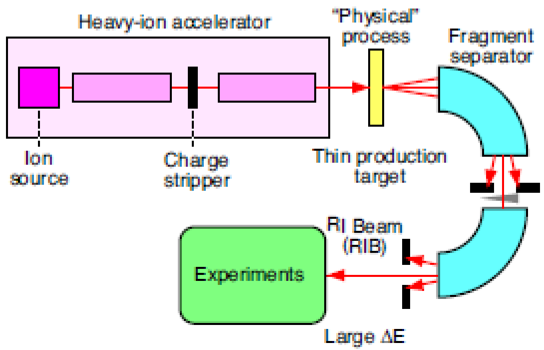
Storage and Cooling of Beams

- Radioactive beams
- e^- – A (or antiproton – A) collider
- Antiprotons: > 10^{11} at 0.8 – 15 GeV/c
- *Future*: Polarized antiprotons

Secondary Beams

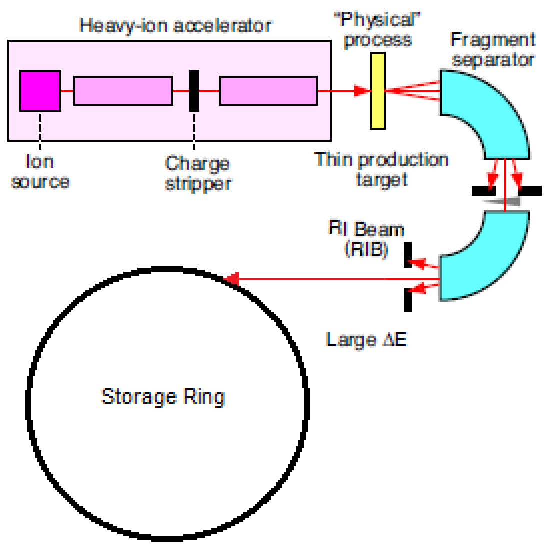
- Broad range of radioactive beams up to 1 – 2 AGeV
- RI- Intensities up to 10 000 over present
- Antiprotons

Primary Beams – Secondary Beams

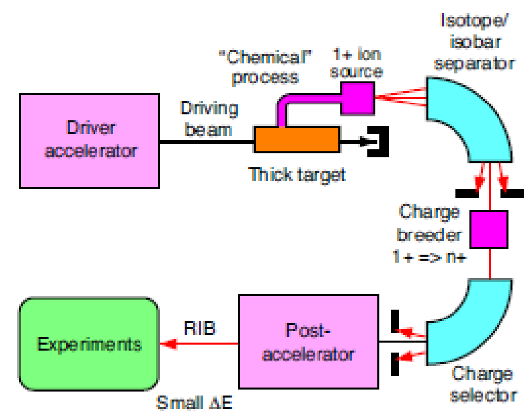


The FAIR user program requires intense, high energy bunched beams matched to the production targets and storage rings.

In average, CW linacs and cyclotrons provide the highest intensities.



In-flight RIB production

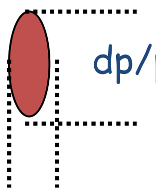


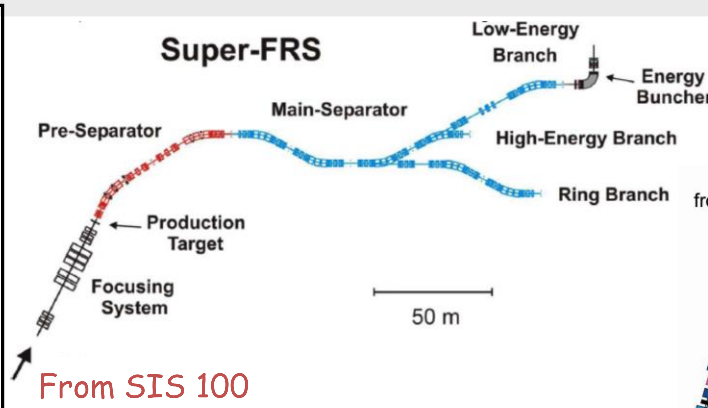
ISOL RIB production

RIB generation and pre-cooling

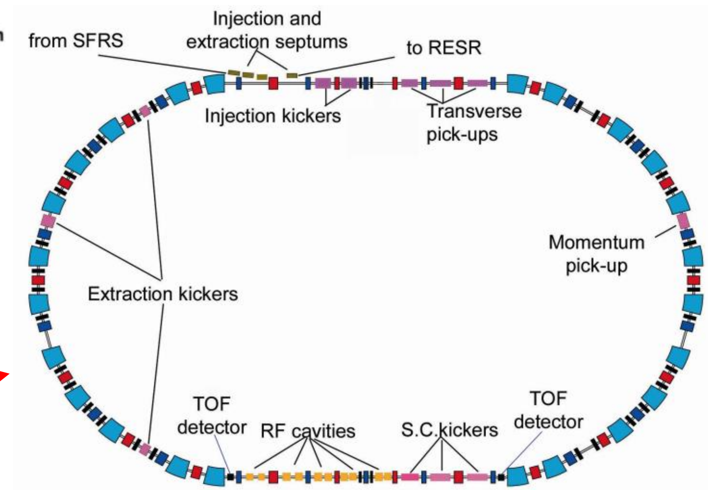
Target matching and fast bunch rotation in the CR

Short SIS 100 bunches:
- target matching
- RIB/pbar pre-cooling

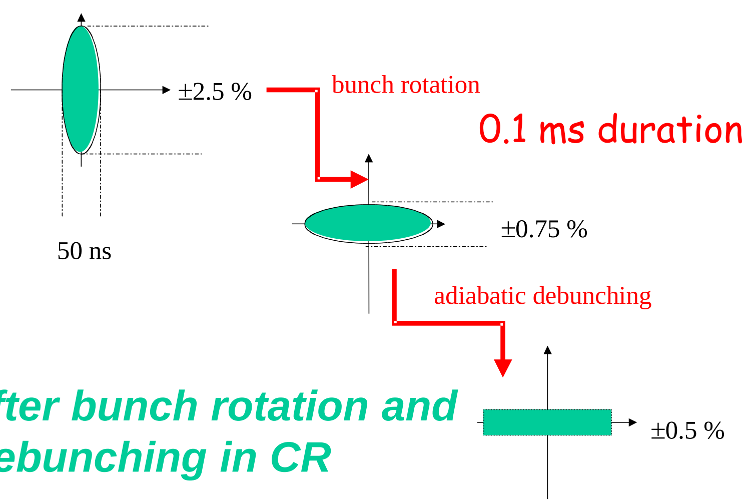




Collector Ring (CR)
circumference 212 m
rigidity 13 Tm



RF voltage in the CR: 200 kV (1.5 MHz)



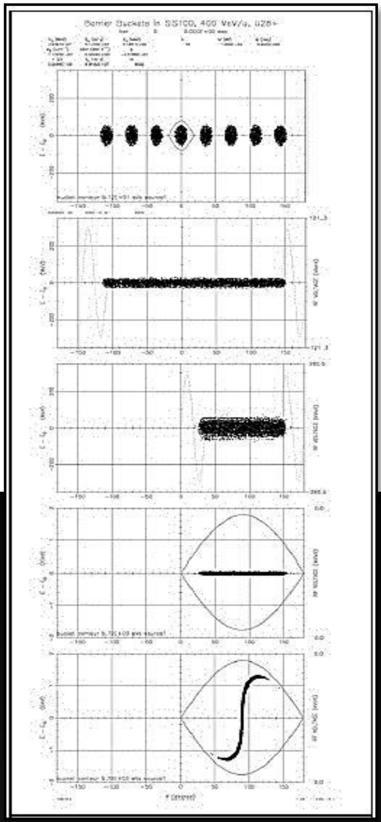
after bunch rotation and debunching in CR

CR ring properties:

	RIB	pbar
energy	740 MeV/u	3.0 GeV
mom. accept.	± 1.5 %	± 3.0 %
transv. accept.	200×10^{-6} m	240×10^{-6} m
Cooling down time	1.5 s	10 s

Production of Secondary Beams
Target and Storage Ring Matching

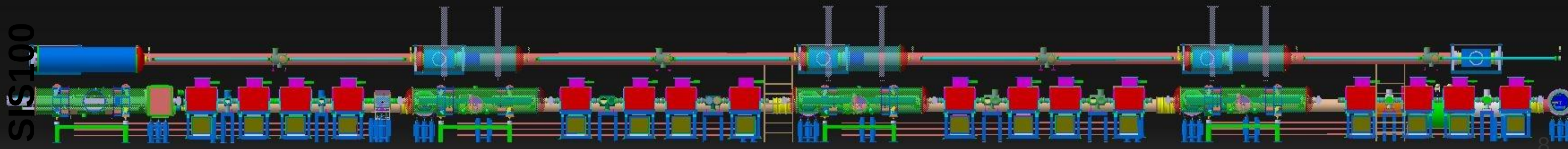
Short single bunches for optimum target matching and fast cooling in CR



Major bunch manipulations are required in the FAIR synchrotrons

- Acceleration
- Debunching in a barrier bucket
- Pre-compression in a barrier bucket
- Fast compression (phase space rotation)

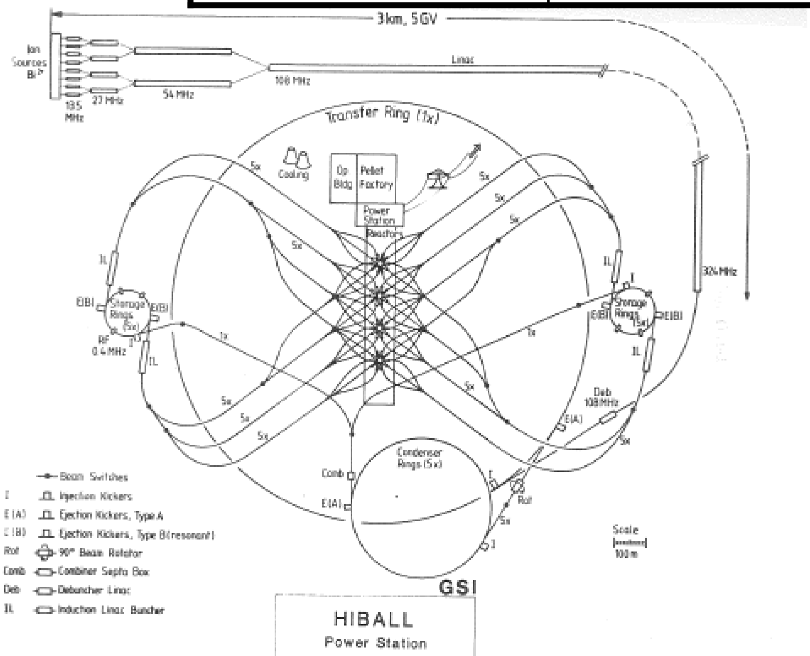
Arrangement of 16 MA loaded cavities for bunch compression



GSI – FAIR – HIBALL

Charge State and Intensity

Today	FAIR	HIBALL
U^{73+}	U^{28+}	U^{1+}
10^{9}	$\sim 10^{12}$	10^{15}



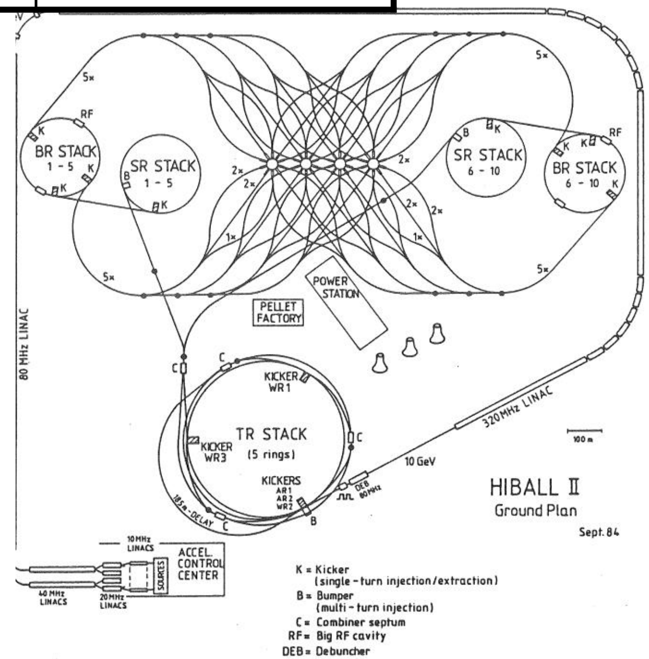


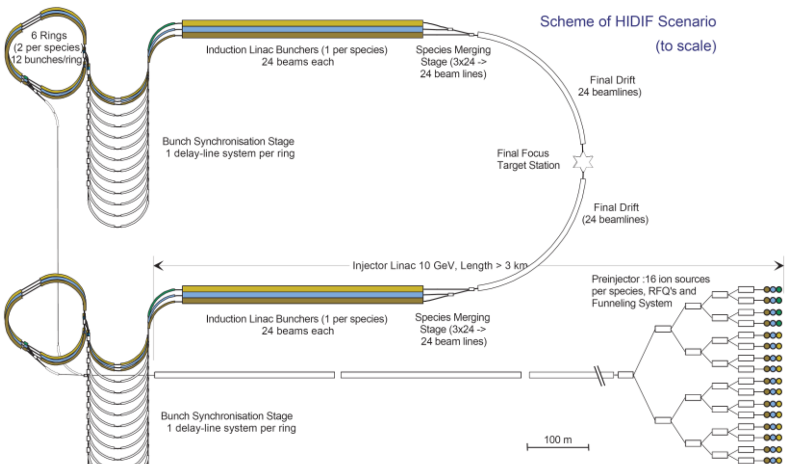
Fig. 1.2-1. HIBALL-II ground plan.

Ultimate intensity heavy ion beams in synchrotrons and storage rings require low charge states.

Space charge tune shift and beam loss in charge stripping processes restrict the maximum intensity.

Ultimate Heavy Ion Intensities
Final Energy Linacs and Storage Ring

Ultimate heavy ion intensities can be obtained only in the combination of a Main Linac accelerating to final energy and Storage Rings (no synchrotrons)

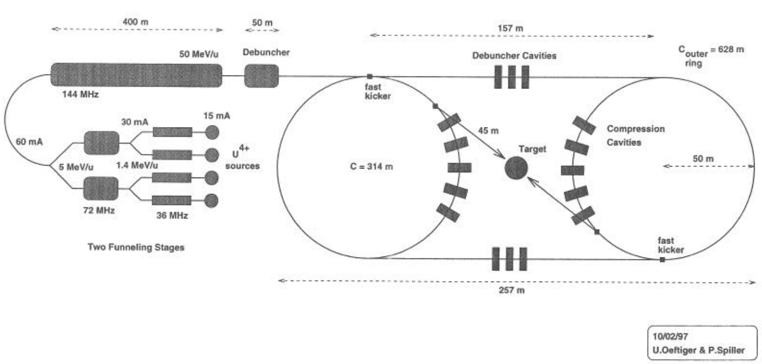


HIDIF (heavy ion driven ignition facility)

Linac for Bi^{1+} to 50 MeV/u

3 MJ Bi^{+}-ions for Ignition of an Indirectly Driven Target

Doppel-Ring-Anlage (DORA):



DORA (Doppelring Anlage)

(study group for futur accelerators at GSI 2000)

Linac for U^{4+} to 50 MeV/u

Final Energy Linac and Storage Ring

- Accelerating the low charge state ion beam to final energy assures the survival of the low charge state heavy ion beam, minimizes the overall cycle time and the integral cross section for charge exchange processes.

- Ultimate heavy ion linac currents enable short injection times into the subsequent rings (storage rings, synchrotrons) and help to minimize the pressure bump at injection.

But: Linacs for acceleration of low charge state heavy ions and energies relevant for nuclear structure physics become huge !

- Therefore, ultimate heavy ion beams from storage rings or synchrotrons with intensities above 10^{13} per cycle at energies relevant for nuclear structure physics will „never“ be available.

Proton Synchrotrons and Heavy Ion Beams

Although to a certain extent also used to accelerate heavy ions, most of the existing synchrotrons have been designed and developed for Proton acceleration. There is only a quite small number of synchrotrons which have been optimized for heavy ion operation.

In most cases heavy ion synchrotrons suffer from a missing powerful injector which enables the accumulation of intense heavy ion beams in a short time. Therefore, even the few deciated heavy ion synchrotrons are often operated only with light ions and Protons (e.g. the Nuclotron, JINR).

In general, the missing high injector current for heavy ion synchrotrons requires accumulation and stacking techniques, which make use of a large fraction of the machine acceptance and finally lead to beams with large emittances and filling factors.

Injector Requirements for FAIR

	required for FAIR
$^{238}U^{4+}$ Max. Beam Intensity I, (2.2 keV/u)	20 emA
I_{max}@beam power, (1.4 MeV/u)	18 emA@1500 kW
Transv. Emittance (LEBT) (90%, total)	120 π·mm·mrad
Macropulse Length	$\leq$150 μs
Beam loading (IH2)	710 kW (18 emA)
U^{28+}	
Max. Beam Current, (1.4 MeV/u)	15.0 emA
Max. Beam Intensity, 11.4 MeV/u, I_{max}@beam power Transfer to the SIS18 *Ions/100μs*	15.0 emA@1453 kW 3.3·10^{11}
Transv. Emittance (11.4 MeV/u) (90%, tot.)	7.0 π·mm·mrad
Pulse spread, Δp/p	0.001

Low Charge State Heavy Ion Injectors

Linac	Institute	Source type	Ion species	Injection energy [MeV/u]	Injection Current [pmA]
UNILAC >SIS	GSI	MEVVA/Varis, Chordis,	U^{28+}	11.4	0.5 (design) 0.18 (achieved)
>AGS Booster	BNL	EBIS	Au^{31+}	1	0.05 (design) 0.025 (achieved)
Linac 3 >LEIR	CERN	ECR	Pb^{27+}	25	0.007
HIAF Sc linac > ABR35 (proposed)	IMP	SECR	U^{34+}	25	0.025-0.05
(proposed)	JPARC	SECR	Au^{32+}	13	0.01 – 0.03

New intensity record in UNILAC:
7 emA of U^{28+} beam current reached by means of pulsed, high pressure gas (100 bar) stripper

"Lower" Charge States for FAIR

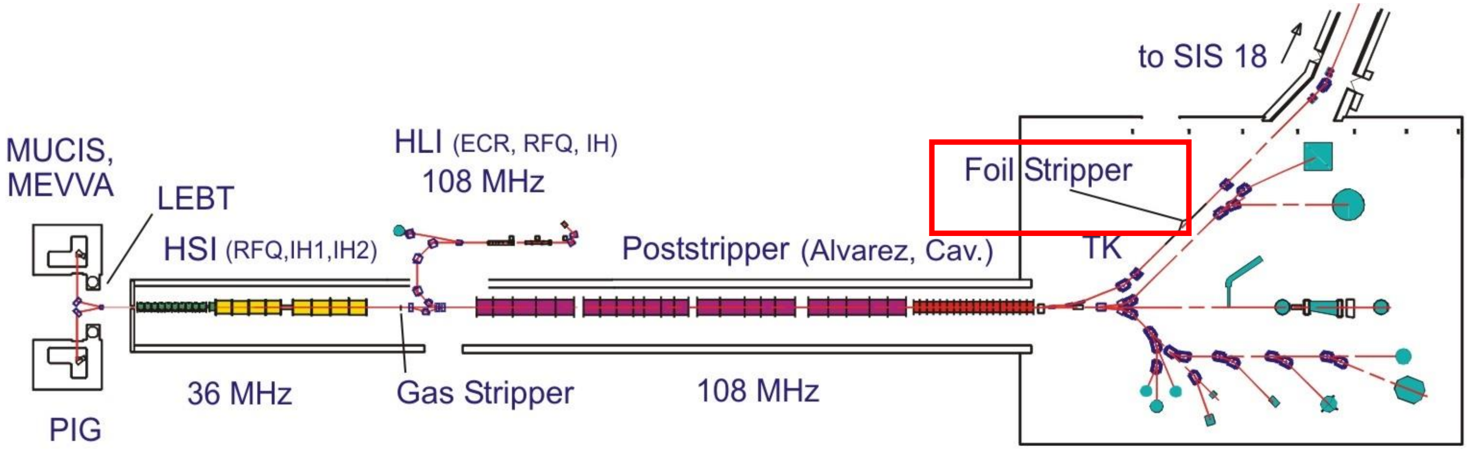
FAIR intensity goals can only be reached by lowering the charge states

Incoherent tune shift limits the maximum intensity in SIS18

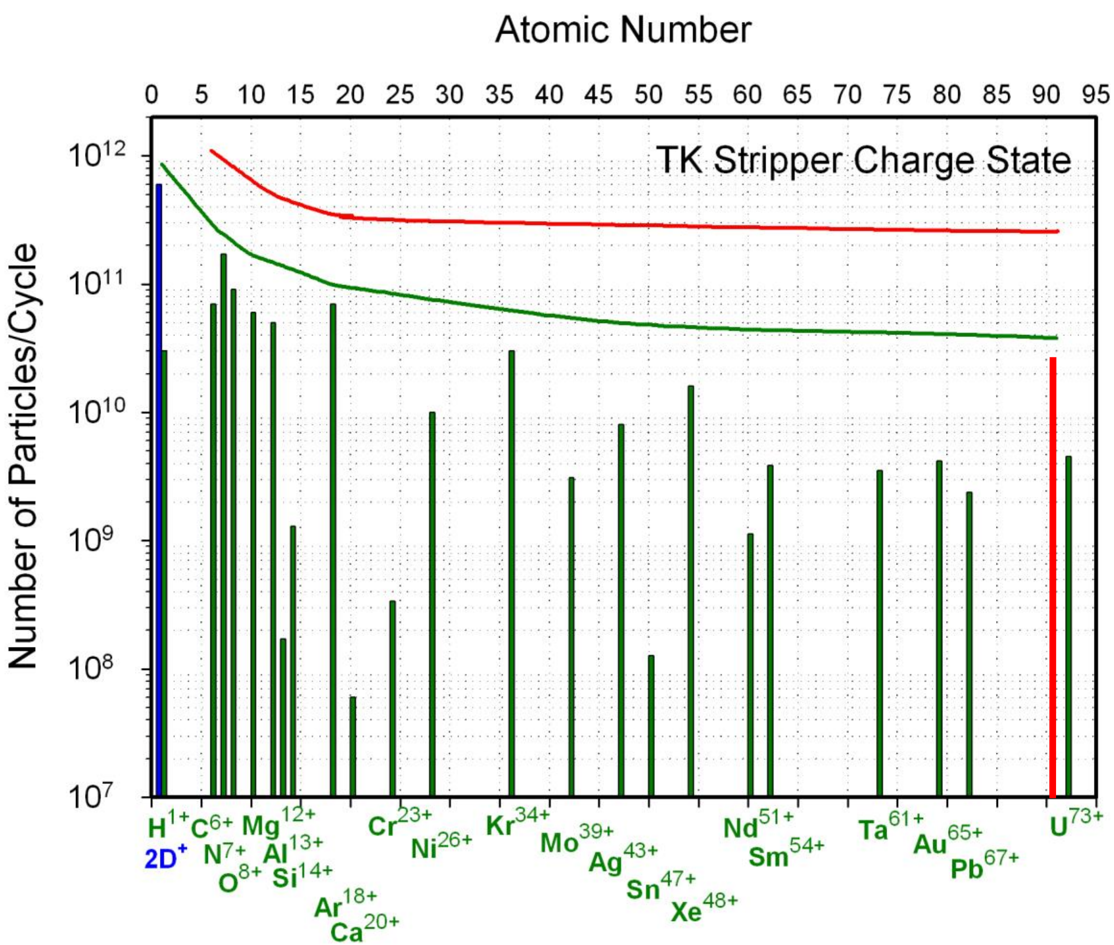
$-dQ \propto Z^2/A$ > Poststripper charge states will be used

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

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



SIS18 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.

Proton and Heavy Ion Synchrotrons
Context of SIS100

- Low charge state heavy ion operation was so far restricted to (fast) low energy, booster synchrotrons AGS Booster, PS Booster. Typical booster cycles are short (and the intensities limited), which enables low charge state operation.

- Most synchrotrons presently operated with heavy ions have been designed for Proton operation (AGS Booster, AGS, PS booster, PS, SPS..). For the „slow ramping“ main rings, charge states had to be enhanced by stripping. Low charge state heavy ion beam can not be accelerated in the typical Proton Synchrotrons AGS, PS...

- Proton synchrotrons suffer from a poor residual gas pressure (10^{-8} -10^{-9}mbar) and long cycle times which does not allow high intensity heavy ion operation with LOW CHARGE STATES.

- LOW CHARGE STATE heavy ion operation requires residual gas pressures in the range of 10^{-11}-10^{-12} mbar.

- Consequently, due to the high charge state, the maximum intensity per cycle is restricted.

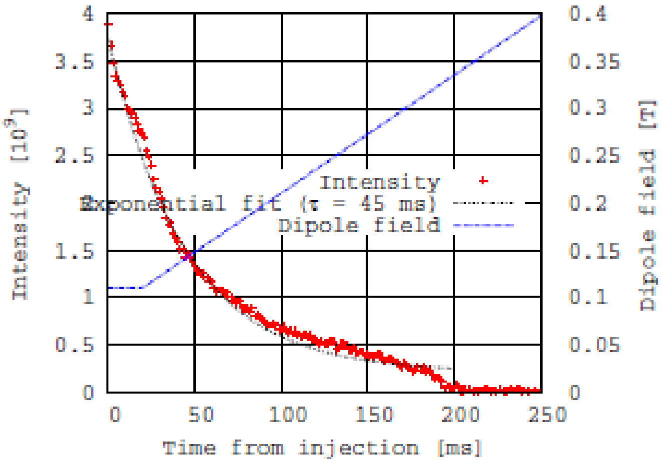


Figure 3: Acceleration of Au^{31+} beam from an energy of E_{kin} = 100.8 MeV/nucleon with a ramp rate of 1.25 T/s.

Proton and Heavy Ion Synchrotrons
Context of SIS100

- So far, there was no dedicated **heavy** ion synchrotron beside SIS18.
- SIS100 will be the first synchrotron optimized for very high number of heavy ions.
- SIS100 is the first synchrotron developed to boost the operation with low charge state heavy ions to higher energies, relevant for nuclear structure physics etc.
- The „longer“ cycle times in SIS100 (SIS100: 2 s instead of SIS18: 0.3 s) require special effort to achieve a desired residual gas pressure suitable for low charge state operation.
- The main feature of SIS100 is:

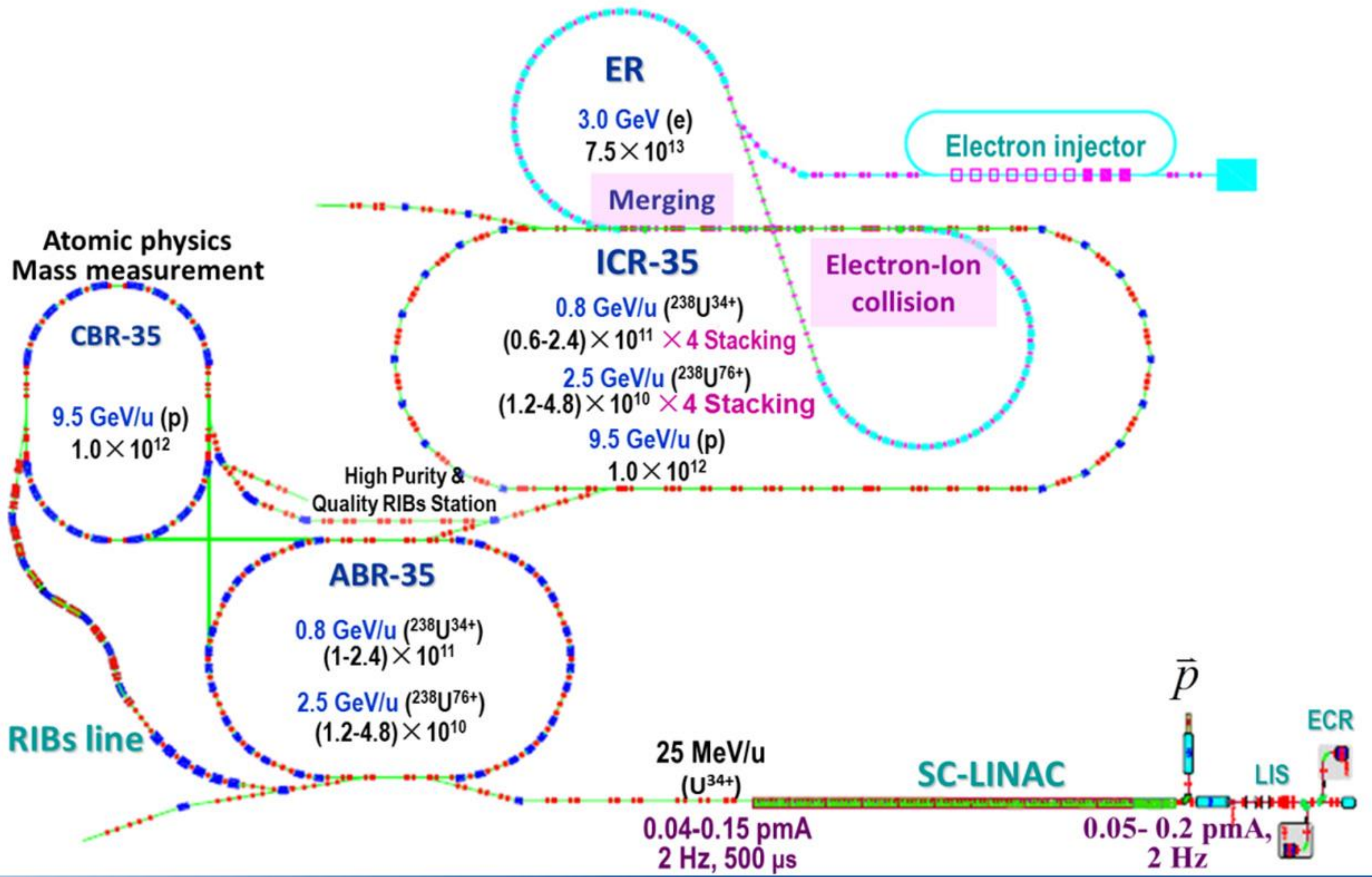
SIS100 is a superconducting synchrotron with powerful cryopumping.

Intermediate Charge State Heavy Ions

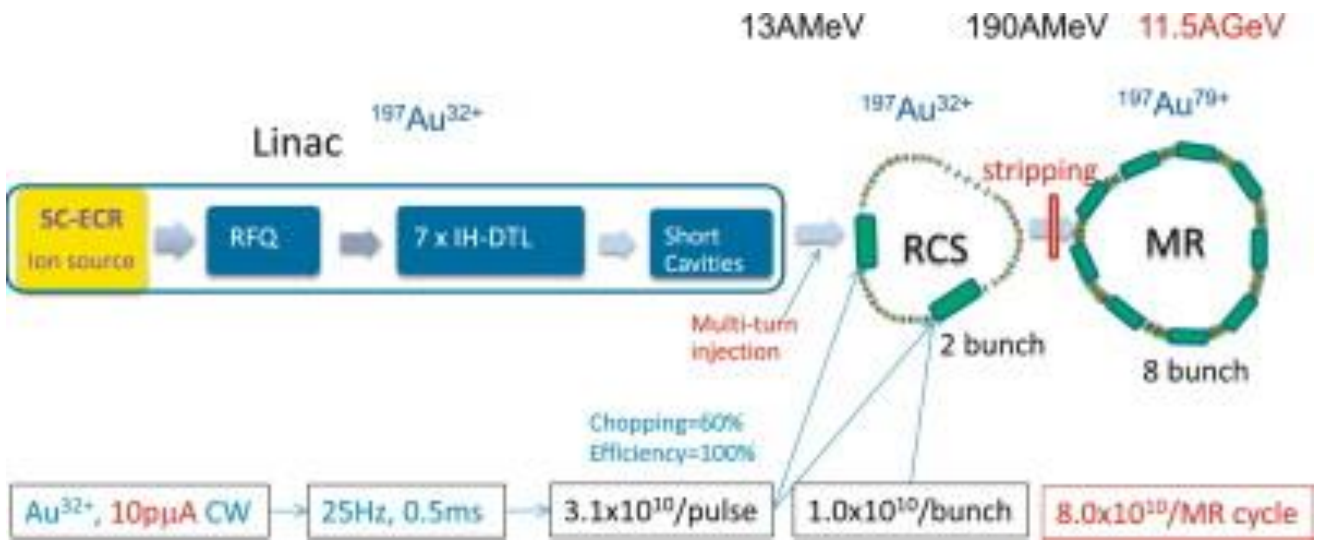
Existing and planned heavy ion synchrotrons operated with intermediate charge states

Existing	**Institute**	**Number of ions / cycle**	**Ion species**
AGS Booster	BNL	$5x10^{9}$	Au^{32+}
LEIR	CERN	$1x10^{9}$	Pb^{54+} (quite high q)
SIS18	GSI/FAIR	$4x10^{10}$ (reached) - $1.5x10^{11}$	U^{28+}
Under Construction			
SIS100	FAIR	$5x10^{11}$	U^{28+}
NICA Booster	JINR	$4x10^{9}$	Au^{32+}
Proposed			
HIAF	IMP	$1x10^{12}$	U^{34+}
RCS	JPARC	$3x10^{10}$	Au^{32+}

New Intermediate Charge State Heavy Ion Proposal HIAF / IMP

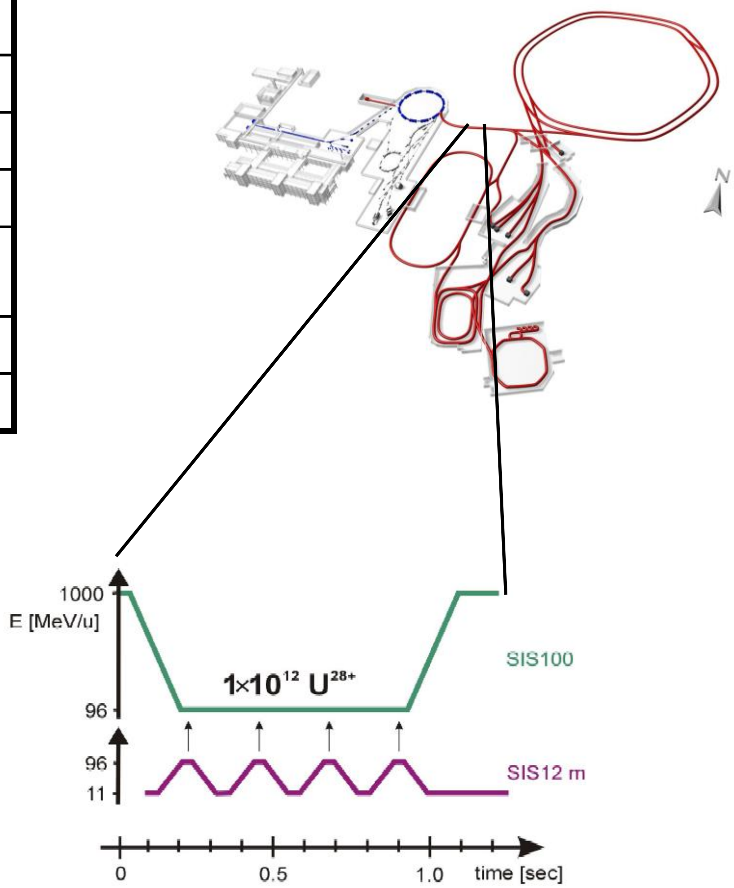


New Intermediate Charge State Heavy Ion Proposal JPARC



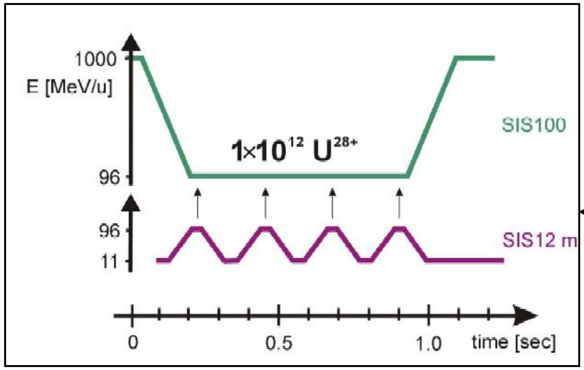
Beam Parameters SIS100

SIS100	**Protons**	**Uranium**
Number of injections	4	4
Number of ions per cycle	2.5x 10^{13} ppp	5 x 10^{11}
Maximum Energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.7 Hz	0.7 Hz



SIS18 FAIR Booster Mode

	Today	FAIR Booster	Today	FAIR Booster
Reference Ion	U^{73+}	U^{28+}	P	P
Maximum Energy	1 GeV/u	0.2 GeV/u	4 GeV	4 GeV
Maximum Intensity/Cycle	4×10^{9}	1.5×10^{11}	5×10^{10}	2.5×10^{12}
Repetition Rate	0.3 - 1 Hz	2.7 Hz	0.3 – 1 Hz	2.7 Hz



SIS18 has served over ten years as a test facility for the development of

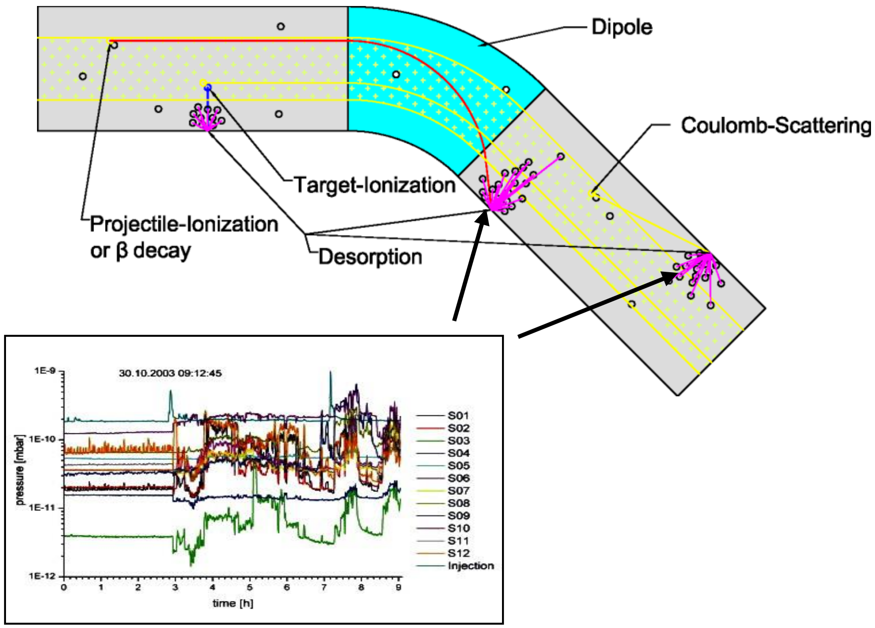
- new accelerator concepts
- new technologies and
- the understanding

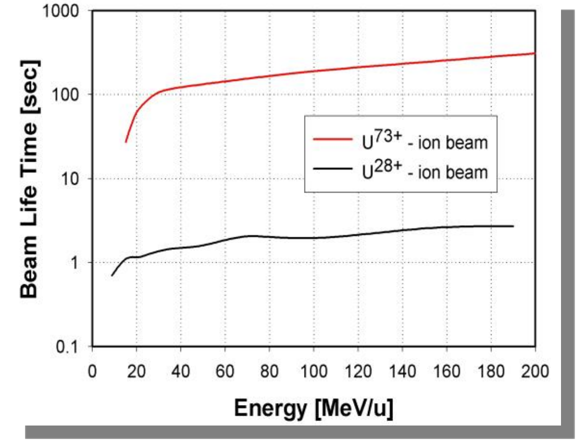
... to overcome vacuum instabilities and ionization beam loss at high intensity heavy ion operation.

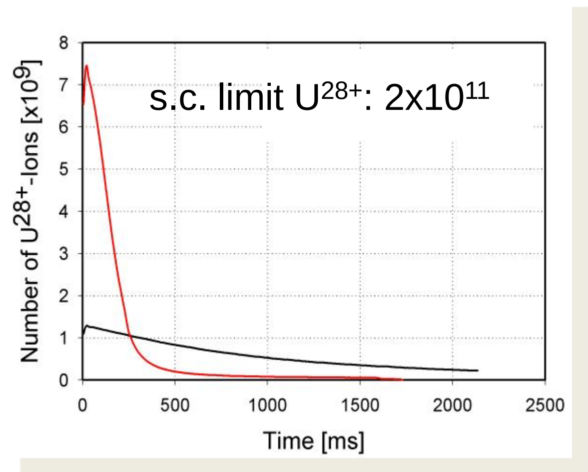
Ionization Beam Loss and Dynamic Vacuum determines

the system layout and the accelerator technologies of SIS18 and SIS100

Ionization Beam Loss and Dynamic Vacuum



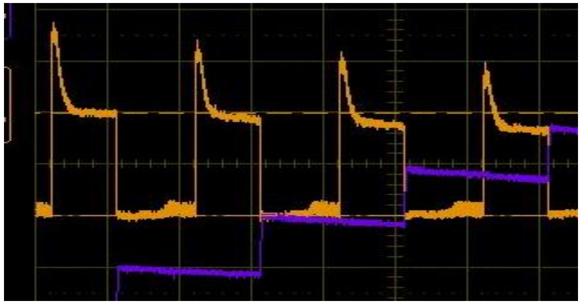




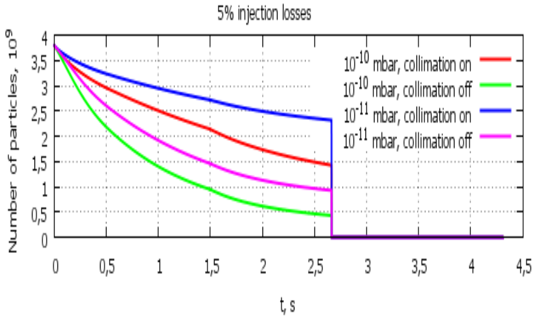
Dynamic Vacuum: Main Issue of the FAIR Booster Operation

- Life time of U^{28+} is significantly lower than of U^{73+}
- Life time of U^{28+} depends strongly on the residual gas pressure and its mass spectrum
- Ion induced gas desorption ($\eta \approx$ 10 000) increases the local pressure
- Beam loss increases signficantly with intensity (dynamic vacuum) and becomes critical far below any space charge and current limits

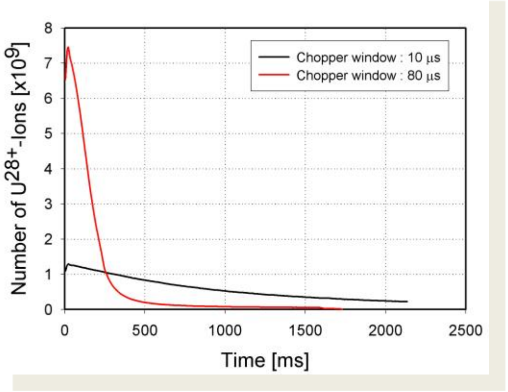
Intermediate Charge State Operation and Charge Exchange Beam Loss



AGS booster (measured)



NICA booster (predicted)



SIS18 (as measured in 2001)

Space charge limit: 2x10^{11}

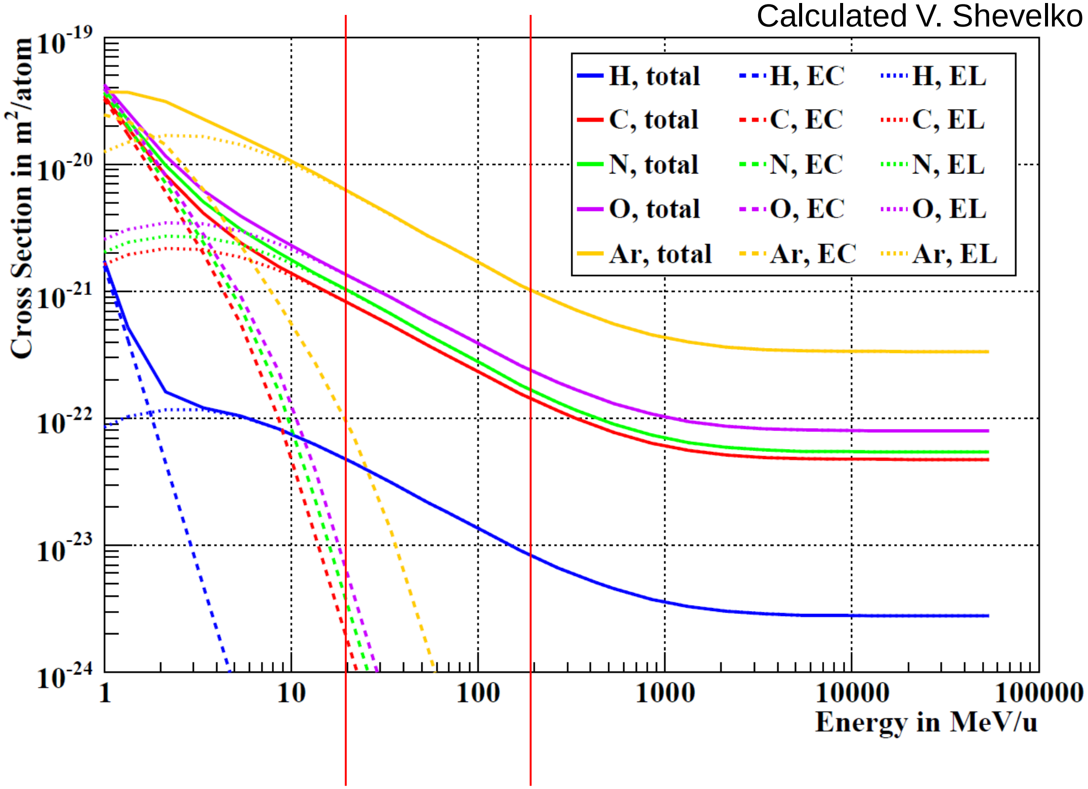
Ionization and Capture Cross Sections

Intense and unique collaboration with the GSI atomic physics department on cross sections for

- projectile ionization and multiple ionization
- electron capture
- target specific cross sections
- energy dependency
- target ionization

All data are summarized in a data base for the STRAHLSIM dynamic vacuum code.

Calculated V. Shevelko

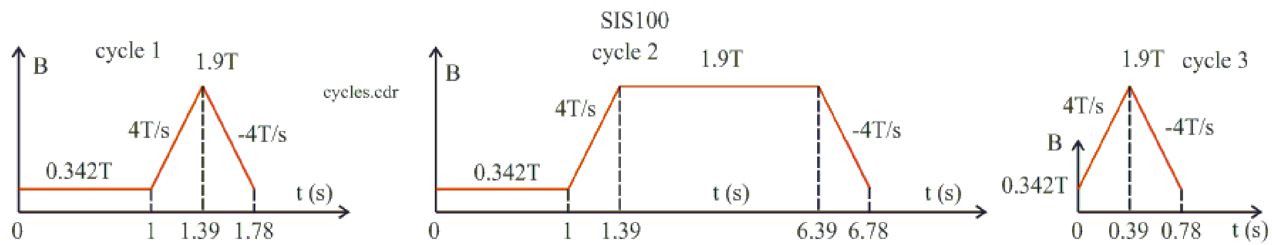


New injection energy SIS18

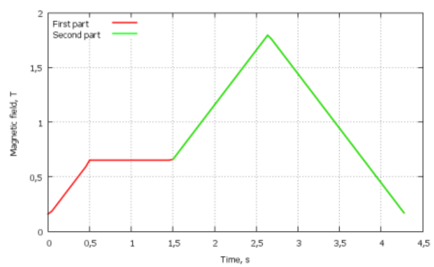
Injection energy of SIS100

Machine Cycles and Integral Cross Section

SIS100 cycles

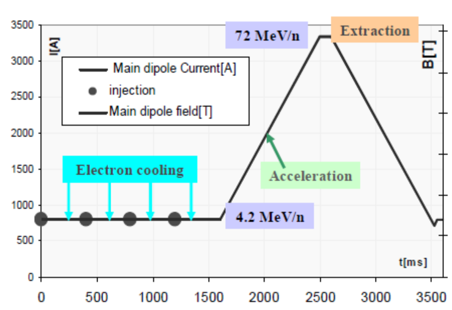


NICA booster cycle



LEIR cycle

Expected Cycle for Lead Ions



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	Au^{31+}	4.5×10^{-21}	5×10^{9}	2.2×10^{-11}	5	1.1×10^{-10}
LEIR	CERN	Pb^{54+}	5.5×10^{-20}	1×10^{9}	5.5×10^{-11}	0.25	1.4×10^{-11}
NICA Booster	JINR	Au^{32+}	4.9×10^{-21}	4×10^{9}	1.9×10^{-11}	0.25	4.7×10^{-12}
SIS18	GSI	U^{28+}	8.7×10^{-22}	1.5×10^{11}	1.3×10^{-10}	3	3.9×10^{-10}
SIS100	FAIR	U^{28+}	1.8×10^{-21}	6×10^{11}	1.1×10^{-9}	0.5	5.5×10^{-10}
Bring	HIAF	U^{34+}	2.5×10^{-21}	5×10^{11}	1.25×10^{-9}	0.09	1.1×10^{-10}

Initial Pressure Bump and Beam Loss During Injection

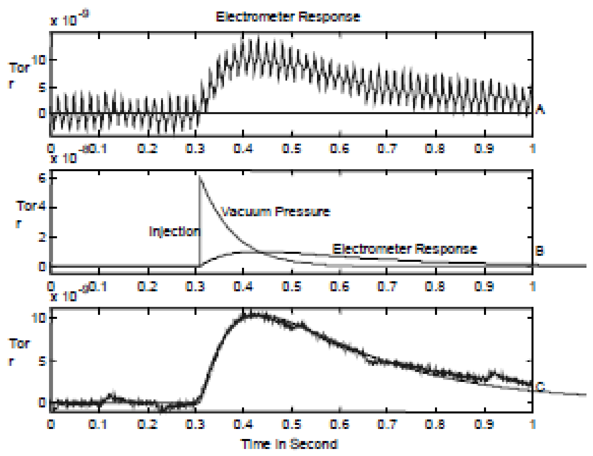
- The lack of injector current for heavy ion beams requires beam accumulation at injection into the synchrotron, e.g. horizontal multi-turn injection, horizontal and vertical multi-turn injection, multi-multi-turn injection with cooling.

  All these stacking processes create beam loss and require time.

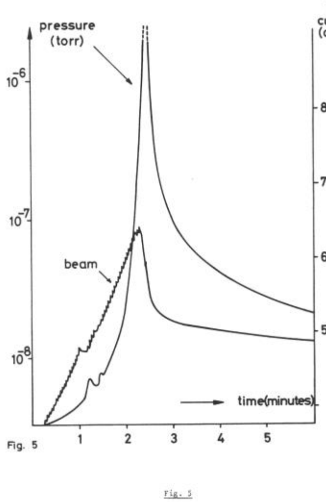
- High injector linac currents enable short injection times and immediate acceleration with fast decay of charge exchange cross sections. Long storage times at low energy, especially in the pressure peak generated by injection losses, have to be avoided.
- Most facilities have no powerful heavy ion injector linacs and therefore long injection or accumulation times.

The 40 years old UNILAC is still the most powerful heavy ion linac worldwide.

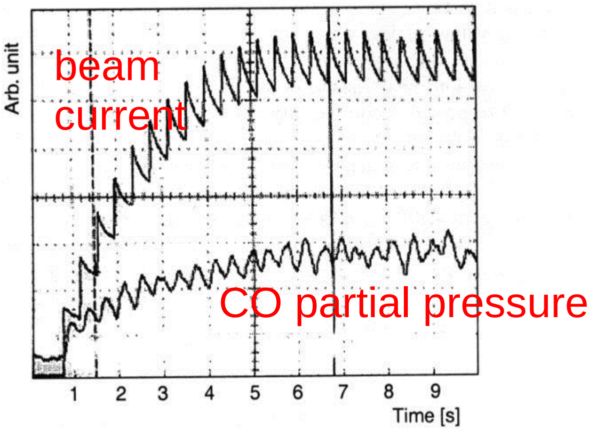
Initial Pressure Bump and Beam Loss During Injection



Measurements in AGS Booster indicate peak pressure rise up to 10^{-7} Torr estimated (1999).

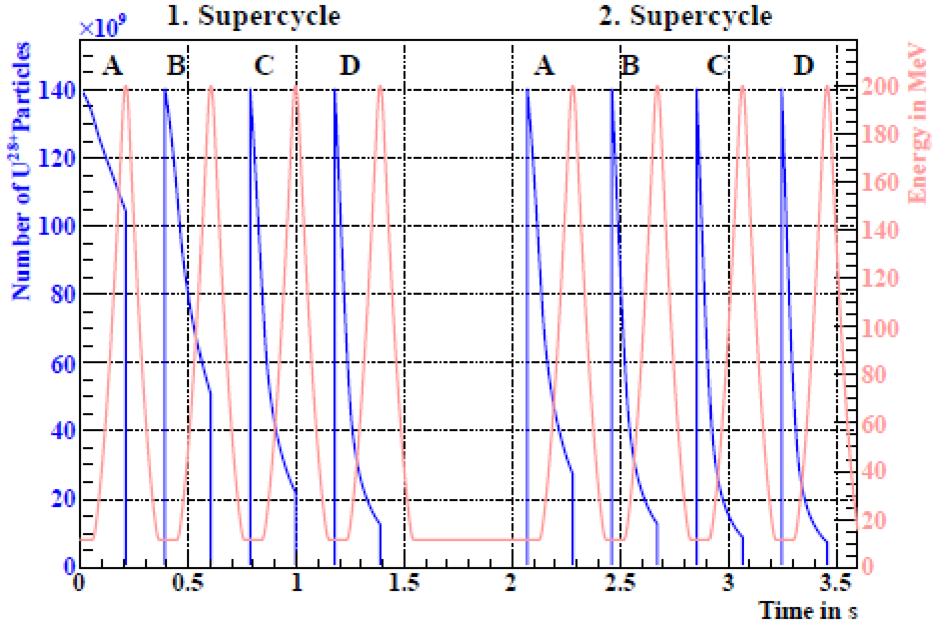


Pressure bump in ISR (1973)



Multiturn injection and stacking in the LEAR ring (1999)

Initial Pressure and Fast Repetition



Dynamic vacuum simulation for the SIS18 booster cycles:

The extracted number of particles is significantly reduced by the initial pressure bump and by the degraded vacuum conditions at the beginning of the subsequent cycles.

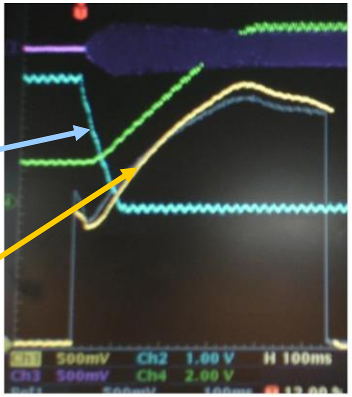
Pressure Bump
by High Voltage Break Through

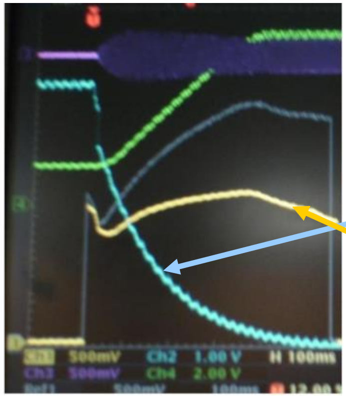
Injection of a MW heavy ion beam.

Beam loss in electrostatic injection septum drives HV break downs

Voltage of electrostatic injection septum

Beam current over acceleration





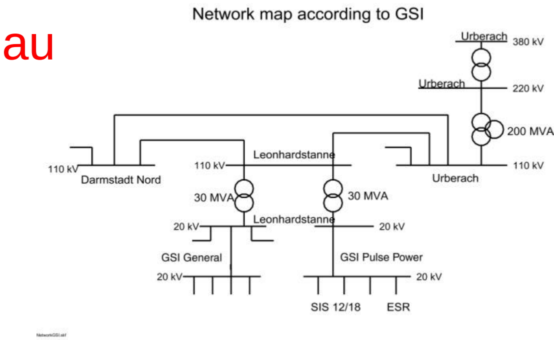
High voltage break down

Beam current under the influence of pressure bump

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.

Strong pumping is needed in the injection septum. NEG panels installed.

Low Charge State Synchrotron Recipe for High Intensity Heavy Ion Synchrotrons



1. Short cycle times, short sequences and short injection plateau

Fast ramping (SIS18: 10 T/s, SIS100: 4 T/s)

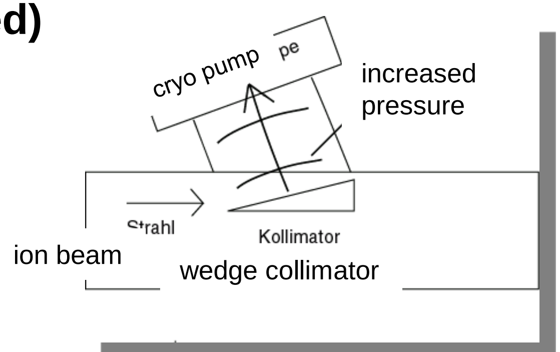
(implication on power connection, power converters, Rf system, fast ramped (superconducting) magnets, injector current)

2. XHV and huge pumping power

(NEG-coating, NEG panel, cryo pumping local and distributed)

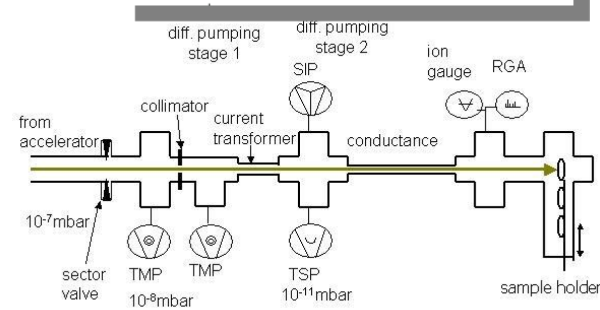
3. Localized beam loss and controle/suppression of gases desorption and pressure bumps

(Ion catcher system with low desorption yield surfaces, Synchrotron optics and lattice design)



4. Minimum „effective“ initial beam loss

(TK halo collimation, low desorption yield surfaces)



1. Short cycle times, short sequences and short injection plateau

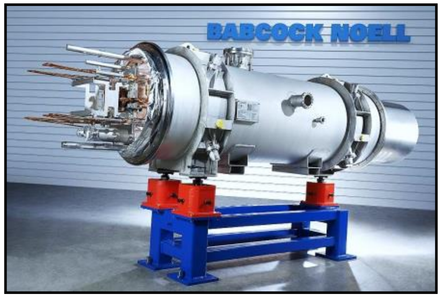
SIS18

New main dipole power converter for ramping with 10 T/s

New MA Rf acceleration cavities providing 50 kV

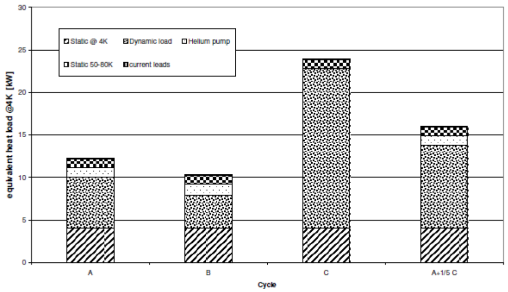
Dedicated power grid connection for 50 MW pulse power

SIS100

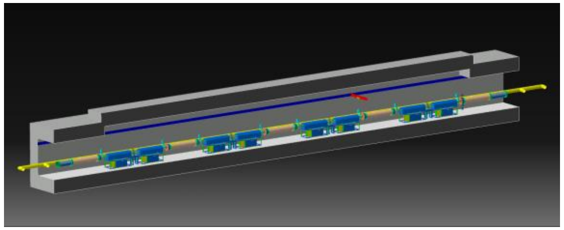


Fast ramped s.c. magnets with „low“ AC loss and restricted aperture (overall pulse power, AC loss)

Thin-wall (0.3 mm) magnet chambers (eddy currents)



Cryoplant dominated by AC loss



High acceleration gradients and linac-like straights (many cold warm transitions)

2. XHV and Huge Pumping Power

SIS18

NEG coating of magnet chambers and beam pipes

NEG panels in injection and extraction device

Bake-out system for 300°C

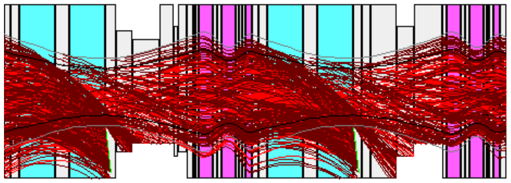
SIS100

Cryopumping, LHe cooled, thin wall magnet chambers

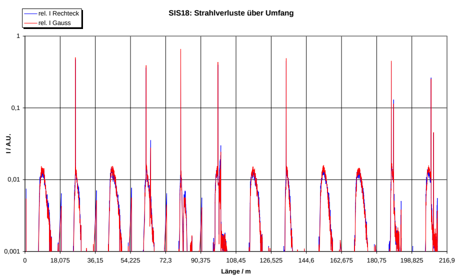
Cryo-adsorption pumps for pumping of H and He residual gas

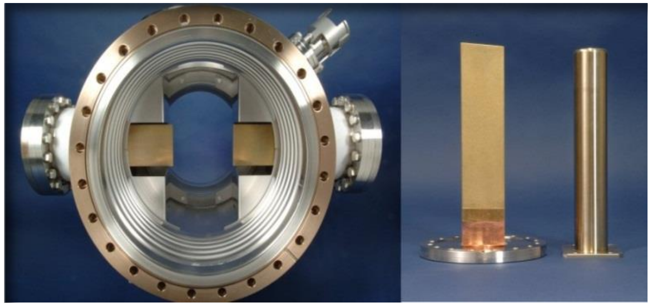
3. Localized beam loss and controle/suppression of gases desorption and pressure bumps

SIS18



Triplett lattice provides
70% catching efficiency

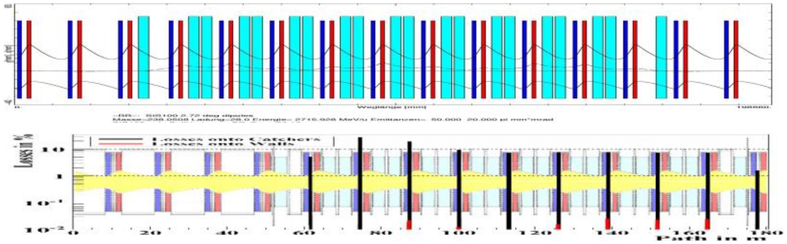




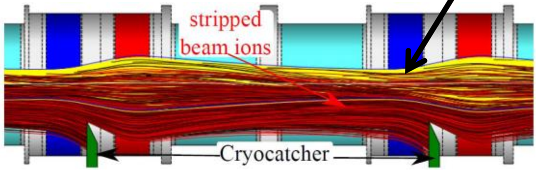
Room temperature ion-catchers
with low desorption yield surfaces
and NEG coated chamber

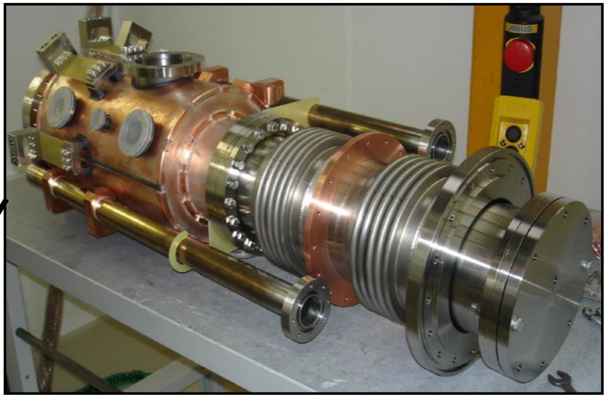
SIS100

Charge separator lattice



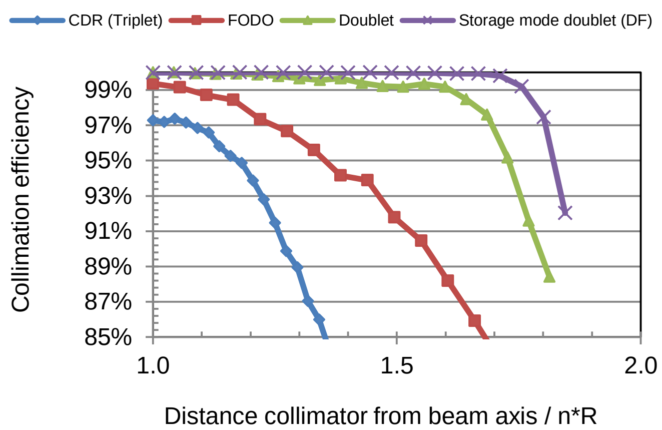
Charge separator lattice provides
100% catching efficiency

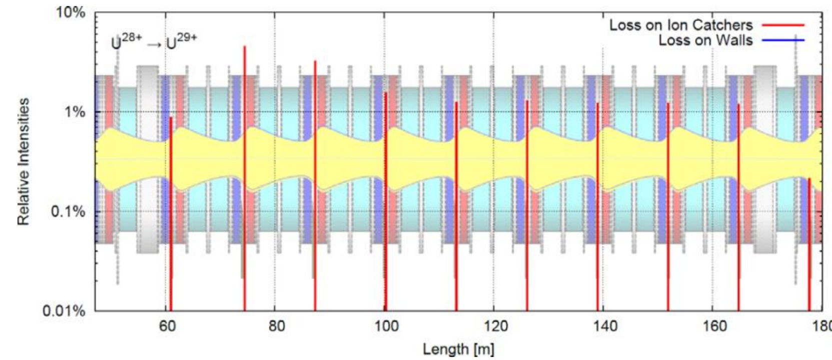




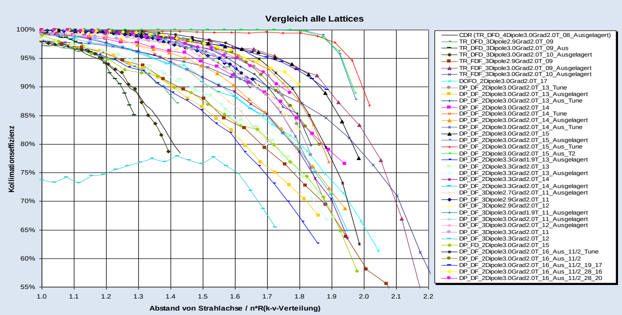
Cryogenic ion-catchers with low
desorption yield surfaces and cryo-
pumping chamber

Lattice for Low Charge State Heavy Ions

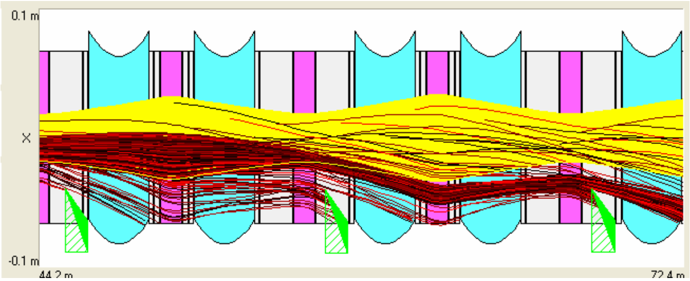




Peaked distribution of ionization beam loss in SIS100.



Ion catching efficiency has been studied for SIS100 for many different lattice types



FODO lattices do not provide a peaked loss distribution for ionization beam loss.

Only good in one cell and bad in the next.

Ion catcher system shall not define the machine acceptance

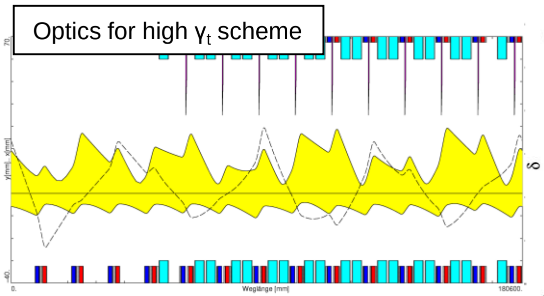
SIS100 Proton Operation

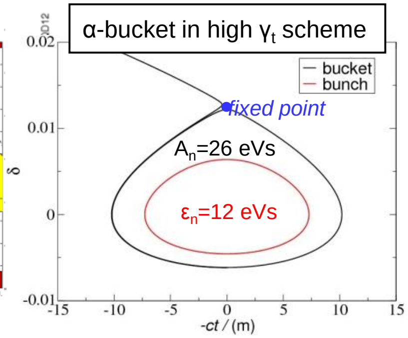
SIS100 faces same problem as PS and AGS:
How to escape transition?

- SIS100 optimized for heavy ions
  - Charge separator function for dynamic vacuum
  - Strong focusing, large chromaticities
  - Acceptance limitation due to collimators

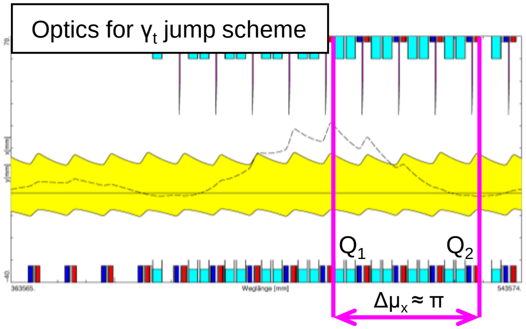
	SIS100	PS	AGS
#protons/cycle	$2\cdot10^{13}$	$2\cdot10^{13}$	10^{14}
Circumference [m]	1083.6	628.3	807.0
Lattice type	Dublet	AG	AG
Gamma range	5.3 – 32.0	2.5 – 29.0	2.7 – 27.0
Gamma transition	15.5	6.1	8.5
Q_h/Q_v	**18.9/18.8**	6.2/6.3	8.8/8.7
$Q_{h,v}/L$ [1/100m]	**1.7**	1.0	1.1
C_h/C_v (nat.)	**-22.6/-22.6**	-5.0/-6.3	-9.0/-9.0

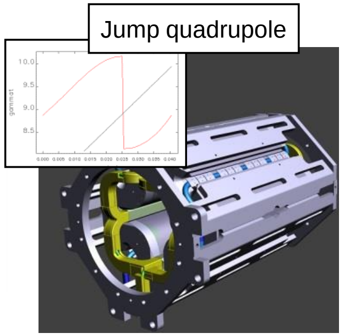
- SIS100 high γ_t scheme
  - Q_h=21.8 and lattice distortion to yield γ_t=45
  - Achieved by splitting F quads in two families
  - Challenges:
    - Control of irregular optics
    - Large chromatic tune spread $\Delta Q_n = \pm0.25$
    - Non-linear α-buckets due to small $\eta_0 = 5\cdot10^{-4}$





- SIS100 γ_t jump scheme
  - Q_h=10.4 to yield γ_t=9 and large dispersion
  - Integration of 12 jump quads (6 π-doublets)
  - Challenges:
    - Control of optics during jump
    - Small momentum acceptance $\delta \leq 5\cdot10^{-3}$





4. Minimum „effective“ initial beam loss

SIS18

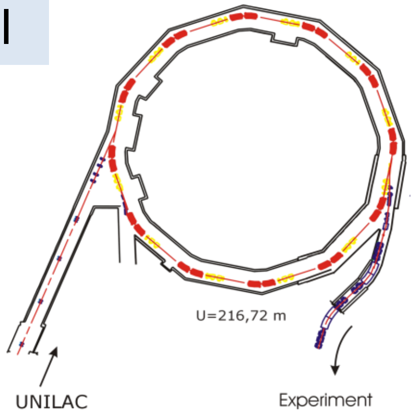
Halo Collimation in Transfer Channel

Collimation of transverse phase space and imaging optics upstream injection

1. Image plane
(Injection channel)

Imaging optical system

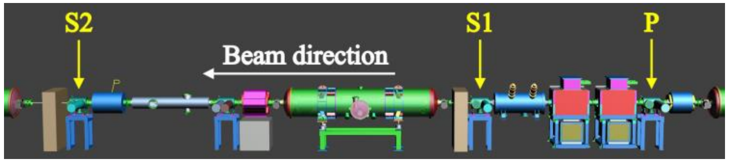
Object plane
(three stage collimation)

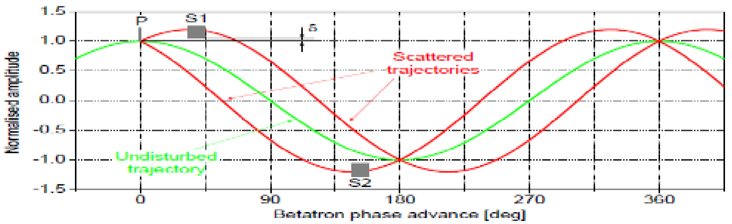


2. Image plane
(Backside injection septum)

SIS100

Halo Collimation System in SIS100 Straight





Major concern:
Beam loss of bunched beam with large tune spread over 1 s storage time at injection (resonance trapping).

Special requirements on field quality
Field quality
Reproducibility of manufacturing errors (random errors)
Resonance correction

Summary

- The Generation of High Intensity Heavy Ion Beams beyond the presently achieved level requires Lower Charge States
- Low Charge State Operation requires a dedicated Machine Layout with several Technical Implications
- GSI/FAIR has developed the understanding for Low Charge State Synchrotrons and developed a dedicated Machine Layout and dedicated Technologies
- A dedicated Heavy Ion Synchrotron does not easily match the requirements for Proton Operation and vice versa