Heavy Ion Synchrotrons
Beam Dynamics Issues and Dynamic Vacuum Effects

Peter Spiller
ICFA-HB 2014, East Lansing
November 2014
High Charge State Heavy Ions in Synchrotrons

<table>
<thead>
<tr>
<th>Facility</th>
<th>Operator</th>
<th>Charge</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS</td>
<td>BNL</td>
<td>$5 \times 10^9$</td>
<td>Au$^{77+}$</td>
</tr>
<tr>
<td>PS</td>
<td>CERN</td>
<td>$1 \times 10^9$</td>
<td>Pb$^{53+}$</td>
</tr>
<tr>
<td>Nuclotron</td>
<td>JINR</td>
<td>$1.5 \times 10^7$</td>
<td>Xe$^{44+}$</td>
</tr>
<tr>
<td>SIS18</td>
<td>GSI</td>
<td>$4 \times 10^9$</td>
<td>U$^{73+}$</td>
</tr>
<tr>
<td>CSRm</td>
<td>IMP</td>
<td>$1 \times 10^9$</td>
<td>U$^{72+}$</td>
</tr>
<tr>
<td>SPS</td>
<td>CERN</td>
<td>$4 \times 10^9$</td>
<td>Pb$^{82+}$</td>
</tr>
<tr>
<td>LHC</td>
<td>CERN</td>
<td>$4 \times 10^{10}$</td>
<td>Pb$^{82+}$</td>
</tr>
<tr>
<td>RHIC</td>
<td>BNL</td>
<td>$1.7 \times 10^{11}$</td>
<td>Au$^{79+}$</td>
</tr>
</tbody>
</table>

JPARC has just organized 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?
New: Cooled pbar Beams (15 GeV)
Intense Cooled Radioactive Beams
Parallel Operation

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Beam Intensity</td>
<td>x 100-1000</td>
</tr>
<tr>
<td>Secondary Beam Intensity</td>
<td>x 10 000</td>
</tr>
<tr>
<td>Heavy Ion Beam Energy</td>
<td>x 30</td>
</tr>
</tbody>
</table>

Goal in 2015

GSI GmbH

FAIR
GmbH
Primary Beams – Secondary Beams

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

**Primary Beams**
- $^{40}\text{Ar}^{18+}$: $2 \times 10^{12}$/s @ 1 – 2 AGeV
- $^{238}\text{U}^{28+}$: $5 \times 10^{11}$/s @ 1 – 2 AGeV
- $^{40}\text{Ar}^{18+}$: $2 \times 10^{10}$/s @ 1 – 45 AGeV
- $^{238}\text{U}^{28+}$: $1 \times 10^{10}$/s @ 1 – 35 AGeV
- Protons: $2 - 5 \times 10^{13}$/s @ 30 GeV

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

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

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GSI Helmholtzzentrum für Schwerionenforschung GmbH
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.
RIB generation and pre-cooling
Target matching and fast bunch rotation in the CR

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**Collector Ring (CR)**
- Circumference: 212 m
- Rigidity: 13 Tm

**CR ring properties:**
- RIB:
  - Energy: 740 MeV/u
  - Momentum Acceptance: ±1.5%
  - Transverse Acceptance: 200x10^{-6} m
  - Cooling Down Time: 1.5 s
- pbar:
  - Energy: 3.0 GeV
  - Momentum Acceptance: ±3.0%
  - Transverse Acceptance: 240x10^{-6} m
  - Cooling Down Time: 10 s

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**RF voltage in the CR:**
- Voltage: 200 kV (1.5 MHz)
- Duration: 0.1 ms

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**Short SIS 100 bunches:**
- Target matching
- RIB/pbar pre-cooling
- dp/p = ± 0.1%
- 60 ns

---

**From SIS 100**

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**After bunch rotation and debunching in CR**
- ±2.5%
- ±0.75%
- ±0.5%
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
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 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 Bi⁴⁺ to 50 MeV/u
3 MJ Bi⁺-ions for Ignition of an Indirectly Driven Target

**DORA (Doppelring Anlage)**
(study group for future accelerators at GSI 2000)
Linac for U⁴⁺ to 50 MeV/u
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.
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 dedicated 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.
<table>
<thead>
<tr>
<th>Isotope</th>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}_{4+}U$</td>
<td>Max. Beam Intensity, (2.2 keV/u)</td>
<td>20 emA</td>
</tr>
<tr>
<td></td>
<td>$I_{\text{max}}$@beam power, (1.4 MeV/u)</td>
<td>18 emA@1500 kW</td>
</tr>
<tr>
<td></td>
<td>Transv. Emittance (LEBT) (90%, total)</td>
<td>120 $\pi$-mm-mrad</td>
</tr>
<tr>
<td></td>
<td>Macropulse Length</td>
<td>$\leq 150$ µs</td>
</tr>
<tr>
<td></td>
<td>Beam loading (IH2)</td>
<td>710 kW (18 emA)</td>
</tr>
<tr>
<td>$^{28}_{2+}U$</td>
<td>Max. Beam Current, (1.4 MeV/u)</td>
<td>15.0 emA</td>
</tr>
<tr>
<td></td>
<td>Max. Beam Intensity, 11.4 MeV/u, $I_{\text{max}}$@beam power</td>
<td>15.0 emA@1453 kW</td>
</tr>
<tr>
<td></td>
<td>Transfer to the SIS18</td>
<td>$3.3 \cdot 10^{11}$</td>
</tr>
<tr>
<td></td>
<td>Ions/100µs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transv. Emittance (11.4 MeV/u) (90%, tot.)</td>
<td>7.0 $\pi$-mm-mrad</td>
</tr>
<tr>
<td></td>
<td>Pulse spread, $\Delta p/p$</td>
<td>0.001</td>
</tr>
</tbody>
</table>
# Low Charge State Heavy Ion Injectors

<table>
<thead>
<tr>
<th>Linac</th>
<th>Institute</th>
<th>Source type</th>
<th>Ion species</th>
<th>Injection energy [MeV/u]</th>
<th>Injection Current [pmA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNILAC &gt;SIS</td>
<td>GSI</td>
<td>MEVVA/Varis, Chordis,</td>
<td>U$^{28+}$</td>
<td>11.4</td>
<td>0.5 (design) 0.18 (achieved)</td>
</tr>
<tr>
<td>&gt;AGS Booster</td>
<td>BNL</td>
<td>EBIS</td>
<td>Au$^{31+}$</td>
<td>1</td>
<td>0.05 (design) 0.025 (achieved)</td>
</tr>
<tr>
<td>Linac 3 &gt;LEIR</td>
<td>CERN</td>
<td>ECR</td>
<td>Pb$^{27+}$</td>
<td>25</td>
<td>0.007</td>
</tr>
<tr>
<td>HIAF Sc linac &gt; ABR35 (proposed)</td>
<td>IMP</td>
<td>SECR</td>
<td>U$^{34+}$</td>
<td>25</td>
<td>0.025-0.05</td>
</tr>
<tr>
<td>Sc linac &gt; ABR35 (proposed)</td>
<td>JPARC</td>
<td>SECR</td>
<td>Au$^{32+}$</td>
<td>13</td>
<td>0.01 – 0.03</td>
</tr>
</tbody>
</table>
New intensity record in UNILAC:
7 emA of U$^{28+}$ beam current reached by means of pulsed, high pressure gas (100 bar) stripper
FAIR intensity goals can only be reached by lowering the charge states. Incoherent tune shift limits the maximum intensity in SIS18.

\[-dQ \propto Z^2/A \quad \rightarrow \quad \text{Poststripper charge states will be used}\]

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

No stripping loss (charge spectrum) in the transfer channel $(N_{\text{uranium}} \times 7)$!
About one order of magnitude enhanced space charge limit by lower charge state.
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.](image)
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.
### Existing and planned heavy ion synchrotrons operated with intermediate charge states

<table>
<thead>
<tr>
<th>Existing</th>
<th>Institute</th>
<th>Number of ions / cycle</th>
<th>Ion species</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS Booster</td>
<td>BNL</td>
<td>$5 \times 10^9$</td>
<td>$\text{Au}^{32+}$</td>
</tr>
<tr>
<td>LEIR</td>
<td>CERN</td>
<td>$1 \times 10^9$</td>
<td>$\text{Pb}^{54+}$ (quite high q)</td>
</tr>
<tr>
<td>SIS18</td>
<td>GSI/FAIR</td>
<td>$4 \times 10^{10}$ (reached) - $1.5 \times 10^{11}$</td>
<td>$\text{U}^{28+}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Under Construction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS100</td>
<td>FAIR</td>
</tr>
<tr>
<td>NICA Booster</td>
<td>JINR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proposed</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HIAF</td>
<td>IMP</td>
</tr>
<tr>
<td>RCS</td>
<td>JPARC</td>
</tr>
</tbody>
</table>
New Intermediate Charge State
Heavy Ion Proposal HIAF / IMP
New Intermediate Charge State
Heavy Ion Proposal JPARC
# Beam Parameters SIS100

<table>
<thead>
<tr>
<th>SIS100</th>
<th>Protons</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of injections</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Number of ions per cycle</td>
<td>$2.5 \times 10^{13}$ ppp</td>
<td>$5 \times 10^{11}$</td>
</tr>
<tr>
<td>Maximum Energy</td>
<td>29 GeV</td>
<td>2.7 GeV/u</td>
</tr>
<tr>
<td>Ramp rate</td>
<td>4 T/s</td>
<td>4 T/s</td>
</tr>
<tr>
<td>Beam pulse length after compression</td>
<td>50 ns</td>
<td>90 - 30 ns</td>
</tr>
<tr>
<td>Extraction mode</td>
<td>Fast and slow</td>
<td>Fast and slow</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>0.7 Hz</td>
<td>0.7 Hz</td>
</tr>
</tbody>
</table>

![Graph](image-url)
## SIS18 FAIR Booster Mode

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>FAIR Booster</th>
<th>Today</th>
<th>FAIR Booster</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference Ion</strong></td>
<td>U²³⁺</td>
<td>U²⁸⁺</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td><strong>Maximum Energy</strong></td>
<td>1 GeV/u</td>
<td>0.2 GeV/u</td>
<td>4 GeV</td>
<td>4 GeV</td>
</tr>
<tr>
<td><strong>Maximum Intensity/Cycle</strong></td>
<td>4x10⁹</td>
<td>1.5x10¹¹</td>
<td>5x10¹⁰</td>
<td>2.5x10¹²</td>
</tr>
<tr>
<td><strong>Repetition Rate</strong></td>
<td>0.3 - 1 Hz</td>
<td>2.7 Hz</td>
<td>0.3 – 1 Hz</td>
<td>2.7 Hz</td>
</tr>
</tbody>
</table>

![Graph showing energy and time for SIS100 and SIS12]
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
Dynamic Vacuum: Main Issue of the FAIR Booster Operation

- Life time of $\text{U}^{28+}$ is significantly lower than of $\text{U}^{73+}$
- Life time of $\text{U}^{28+}$ 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 significantly 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: $2 \times 10^{11}$
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.
Machine Cycles
and Integral Cross Section

SIS100 cycles

NICA booster cycle

LEIR cycle

$\sigma_{\text{int}}$ depends on the specific machine cycle

$\sim \int \sigma(E(t)) \, dt$
### Strength of Charge Exchange and Dynamic Vacuum

Charge exchange loss and dynamic vacuum scale with: $[N \times \sigma_{\text{int}}] \times f_{\text{rep}}$

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Institut</th>
<th>Ion species</th>
<th>Total integ. cross section</th>
<th>Number of ions</th>
<th>$N \times \sigma_{\text{int}}$</th>
<th>Rep. rate [Hz]</th>
<th>$N \times \sigma \times f_{\text{rep}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS Booster</td>
<td>BNL</td>
<td>Au$^{31+}$</td>
<td>$4.5 \times 10^{-21}$</td>
<td>$5 \times 10^9$</td>
<td>$2.2 \times 10^{-11}$</td>
<td>5</td>
<td>$1.1 \times 10^{-10}$</td>
</tr>
<tr>
<td>LEIR</td>
<td>CERN</td>
<td>Pb$^{54+}$</td>
<td>$5.5 \times 10^{-20}$</td>
<td>$1 \times 10^9$</td>
<td>$5.5 \times 10^{-11}$</td>
<td>0.25</td>
<td>$1.4 \times 10^{-11}$</td>
</tr>
<tr>
<td>NICA Booster</td>
<td>JINR</td>
<td>Au$^{32+}$</td>
<td>$4.9 \times 10^{-21}$</td>
<td>$4 \times 10^9$</td>
<td>$1.9 \times 10^{-11}$</td>
<td>0.25</td>
<td>$4.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>SIS18</td>
<td>GSI</td>
<td>U$^{28+}$</td>
<td>$8.7 \times 10^{-22}$</td>
<td>$1.5 \times 10^{11}$</td>
<td>$1.3 \times 10^{-10}$</td>
<td>3</td>
<td>$3.9 \times 10^{-10}$</td>
</tr>
<tr>
<td>SIS100</td>
<td>FAIR</td>
<td>U$^{28+}$</td>
<td>$1.8 \times 10^{-21}$</td>
<td>$6 \times 10^{11}$</td>
<td>$1.1 \times 10^{-9}$</td>
<td>0.5</td>
<td>$5.5 \times 10^{-10}$</td>
</tr>
<tr>
<td>Bring</td>
<td>HIAF</td>
<td>U$^{34+}$</td>
<td>$2.5 \times 10^{-21}$</td>
<td>$5 \times 10^{11}$</td>
<td>$1.25 \times 10^{-9}$</td>
<td>0.09</td>
<td>$1.1 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
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.

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 control/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)

![Cryopant dominated by AC loss](image)

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

**SIS100**

Charge separator lattice provides 100% catching efficiency

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

Cryogenic ion-catchers with low desorption yield surfaces and cryo-pumping chamber
Lattice for Low Charge State Heavy Ions

 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.

 Peaked distribution of ionization beam loss in SIS100.
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 high $\gamma_t$ scheme
  - $Q_h=21.8$ and lattice distortion to yield $\gamma_t=45$
  - Achieved by splitting F quads in two families
  - Challenges:
    - Control of irregular optics
    - Large chromatic tune spread $\Delta Q_n = \pm 0.25$
    - Non-linear $\alpha$-buckets due to small $\eta_0 = 5 \cdot 10^{-4}$

- SIS100 $\gamma_t$ jump scheme
  - $Q_h=10.4$ to yield $\gamma_t=9$ and large dispersion
  - Integration of 12 jump quads (6 $\pi$-doublets)
  - Challenges:
    - Control of optics during jump
    - Small momentum acceptance $\delta \leq 5 \cdot 10^{-3}$

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