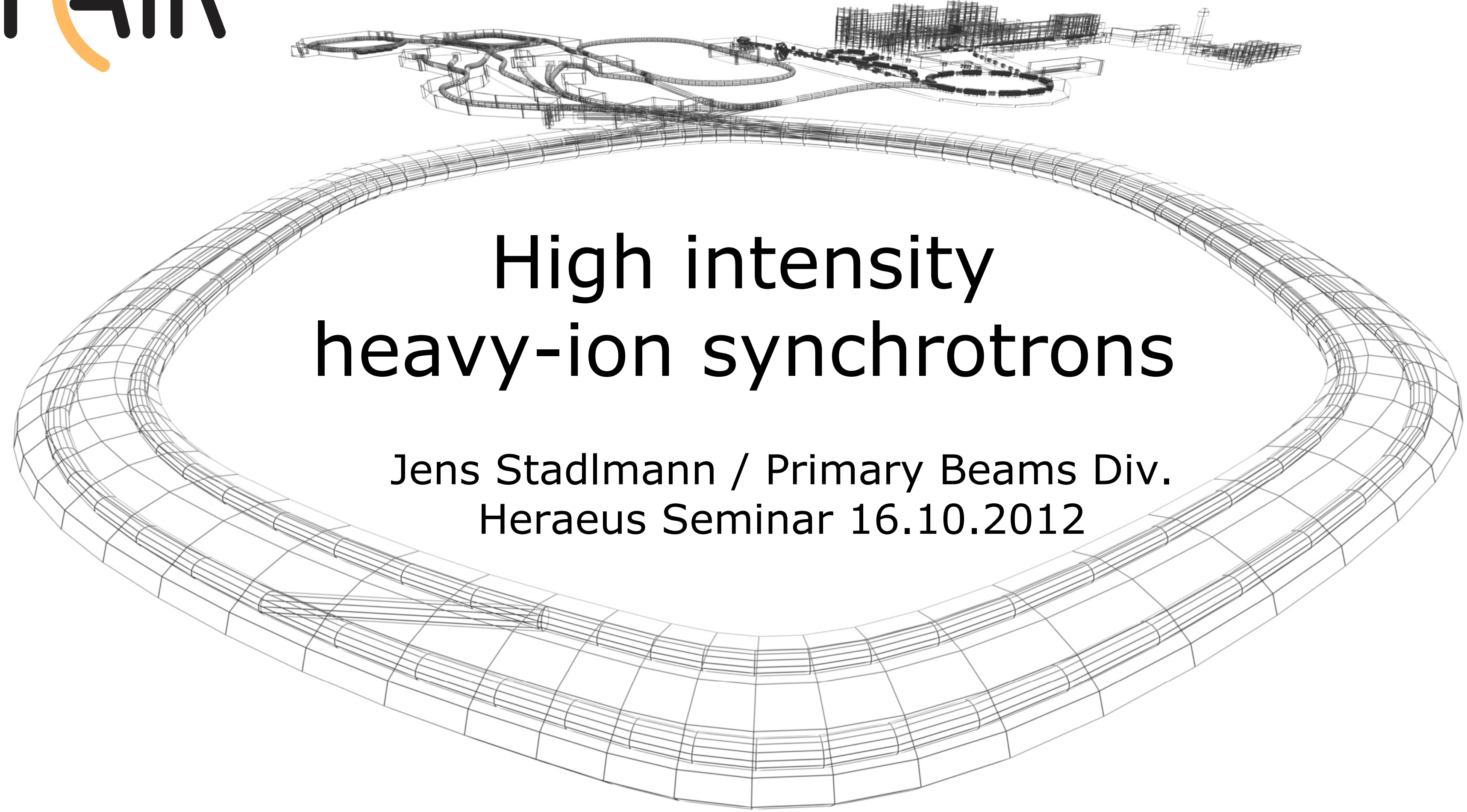


High intensity heavy-ion synchrotrons

Jens Stadlmann / Primary Beams Div.

Heraeus Seminar 16.10.2012

Contents

- Overview and some historic machines.
- Basic principle of synchrotrons,
  - Layout,
  - principle of acceleration -> RF,
  - transverse motion,
  - tune and tune-shift.
- Going to highest intensities with heavy ions,
  - Major obstacle: vacuum control.
- Conclusion.

Some synchrotron-history

- Proposal of a pulsed magnet ring by Oliphant 1943.
- Discovery of phase stability by Veksler 1944 and McMillan 1945.
- Electron synchrotron demonstration by Goward and Barnes 1946 at Woolwich Aresanl, UK.
- Two month later General Electric Laboratory's 70 MeV electron machine at Schenectady, USA, by Elder, Gurewitsch, Langmuir and Pollock.

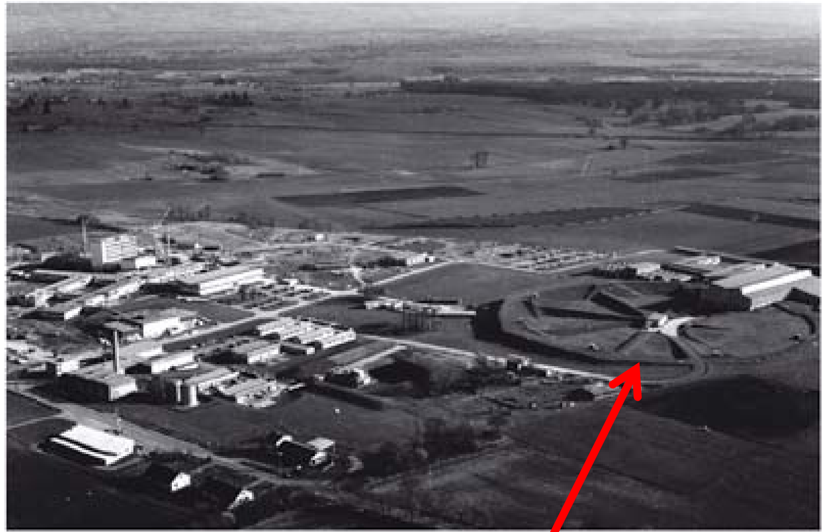
The first proton machine were build in the early 50s. Alternate gradient focussing and colliders followed.

(All dates taken from E.J.N. Wilson, "Fifty Years of Synchrotrons)

„Living history": PS and AGS

PS @ CERN

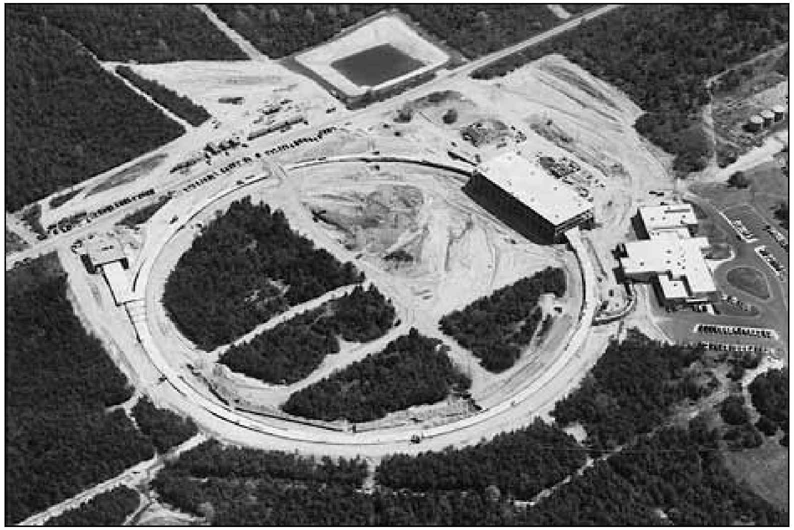
28 GeV p, late 1959



CERN 1959, PS to the right

AGS @ Brookhaven

33 GeV p, Summer 1960



Alternating Gradient Synchrotron under construction, c. 1957.

Both machines are still operational today!

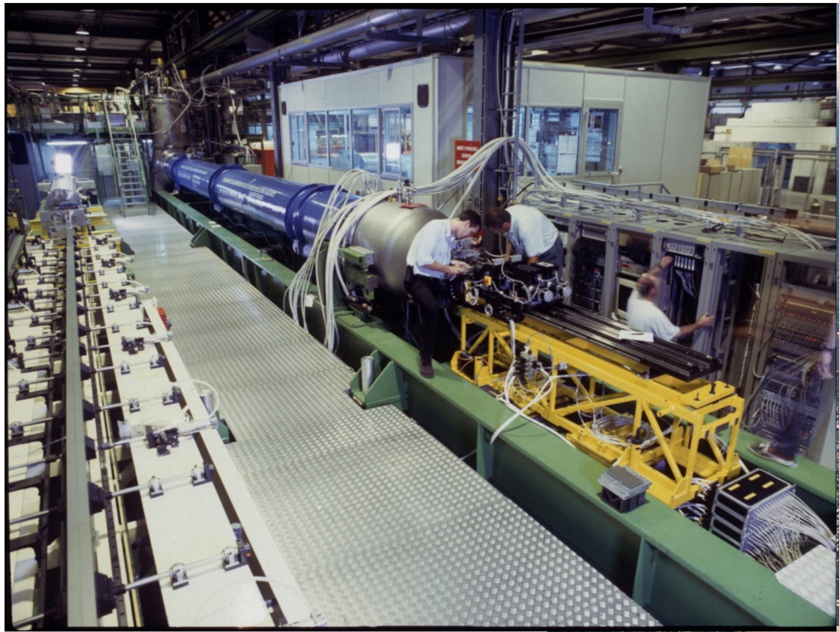
They accelerate ions and protons. They feed beams into SPS/LHC (PS) and RHIC (AGS) and are documenting the success story of synchrotron accelerators.

Collider I: Brookhaven Nat'l Labs, Long Island, USA

RHIC: Relativistic Heavy Ion Collider

AGS: Alternating Gradient Synchrotron

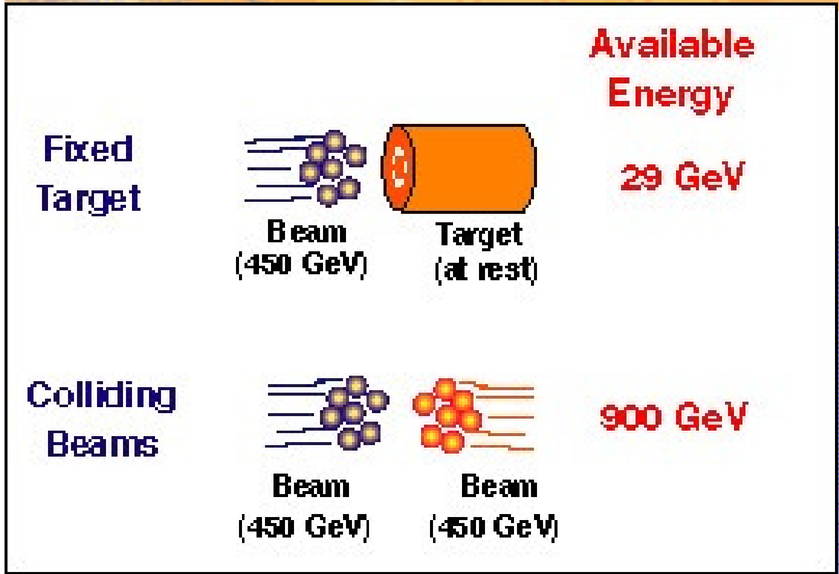
Collider II; CERN Large Hadron Collider (LHC)



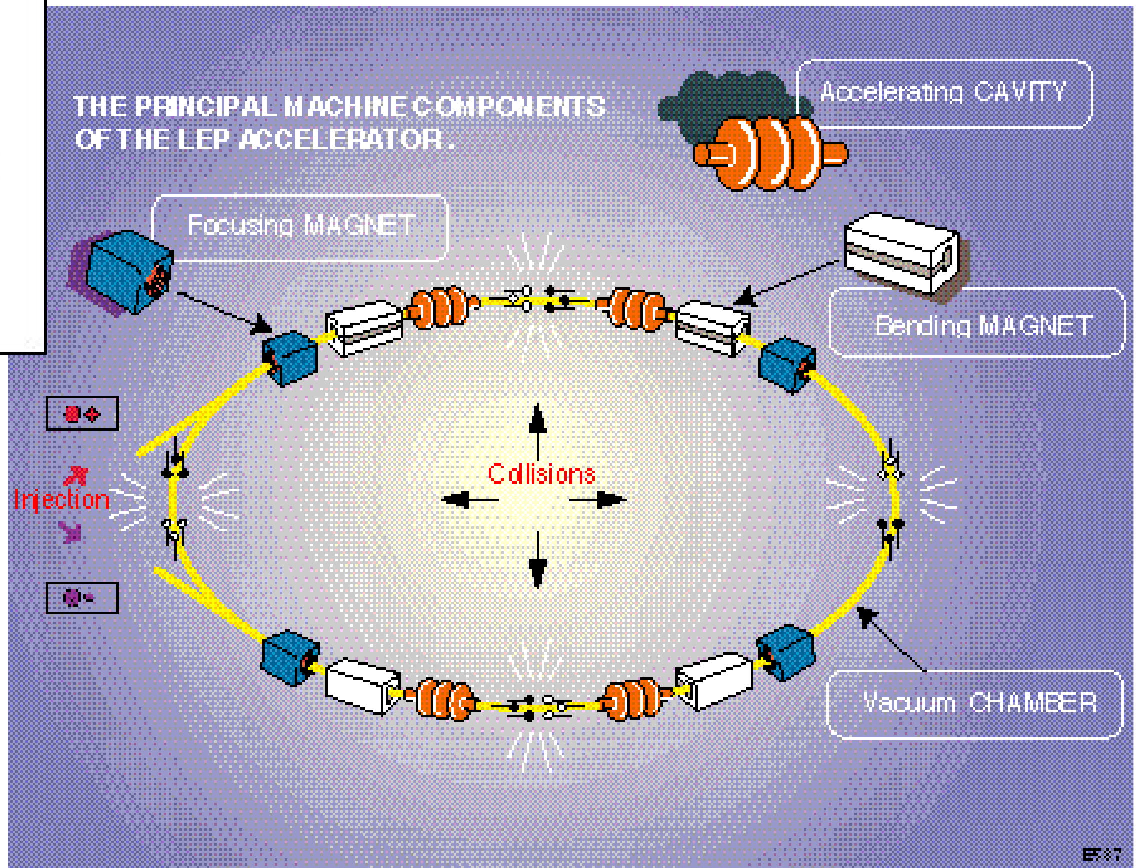
Protons and heavy ions (Pb)
Energy: now 3.5 TeV
(up to 7 TeV later)
Protons in the ring: 3E14
Current: 0.5 A
Beam energy: 3 MJ
Magnetic dipole field: 8 T

Circumference: 27 km

Special synchrotrons: Collider

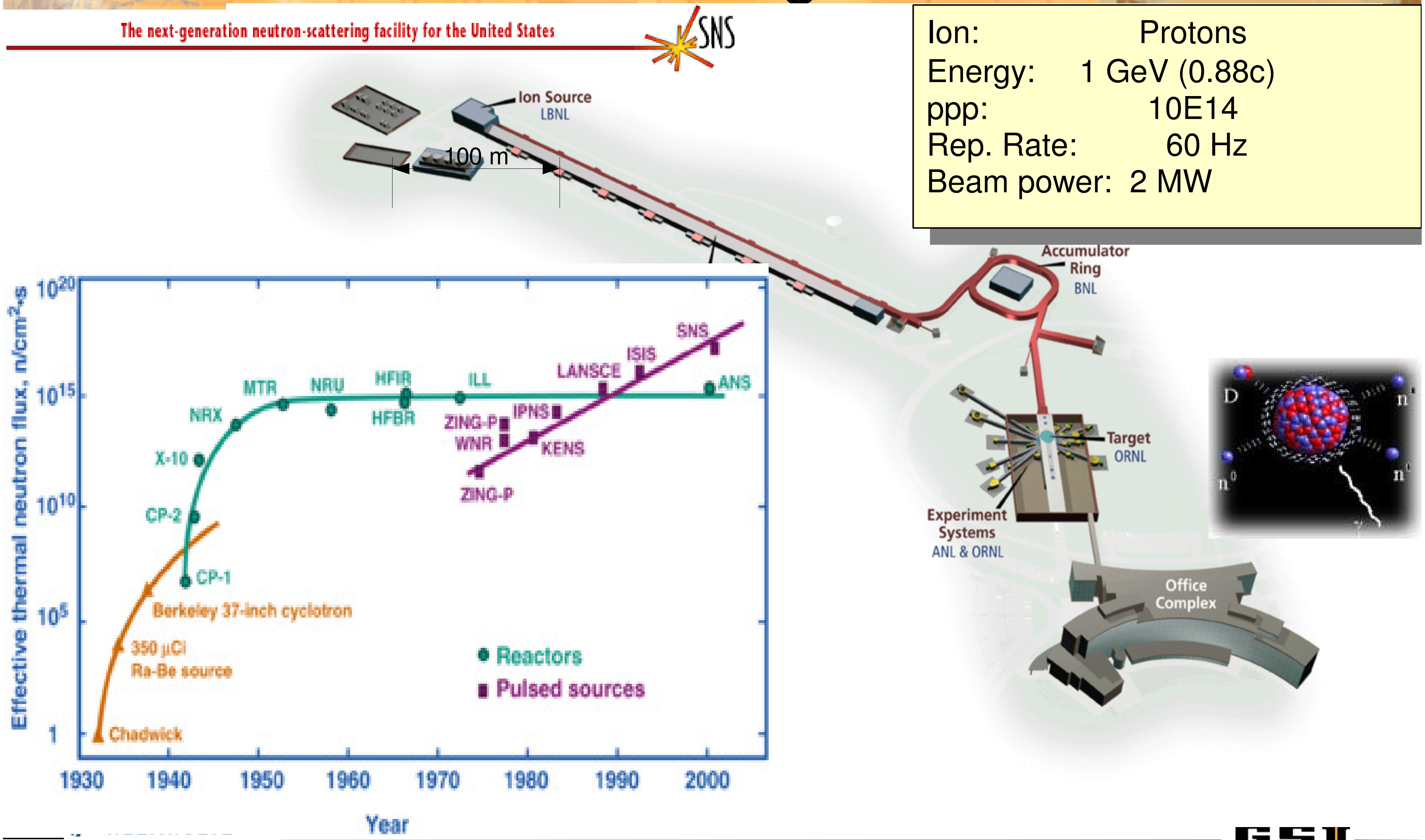


If the incoming beam is simply slammed into a stationary target, much of the energy is taken up by the target's recoil.

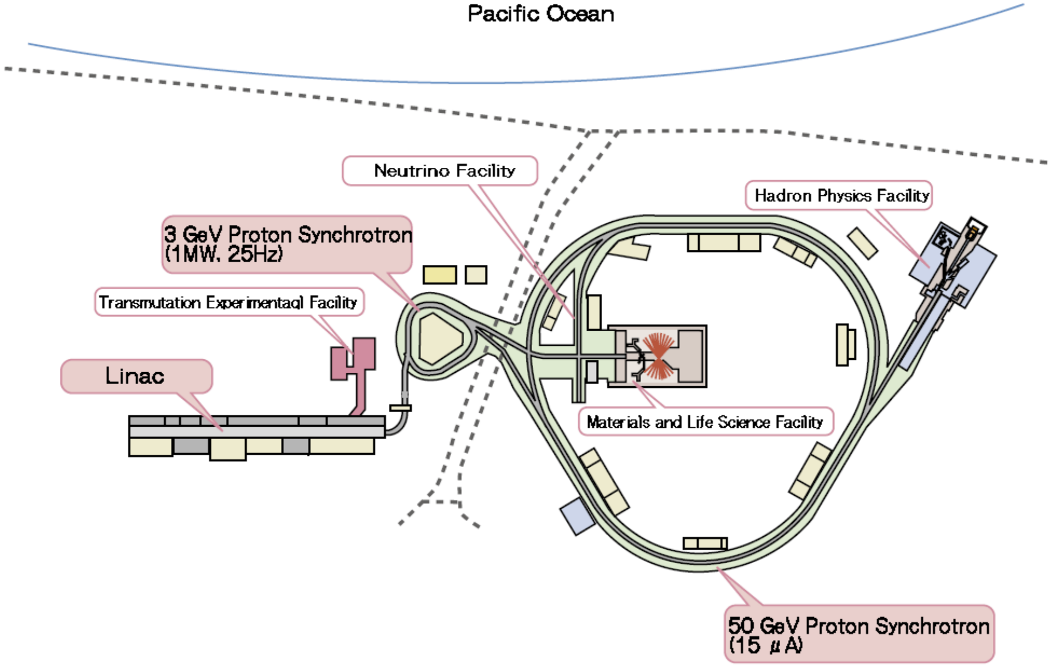


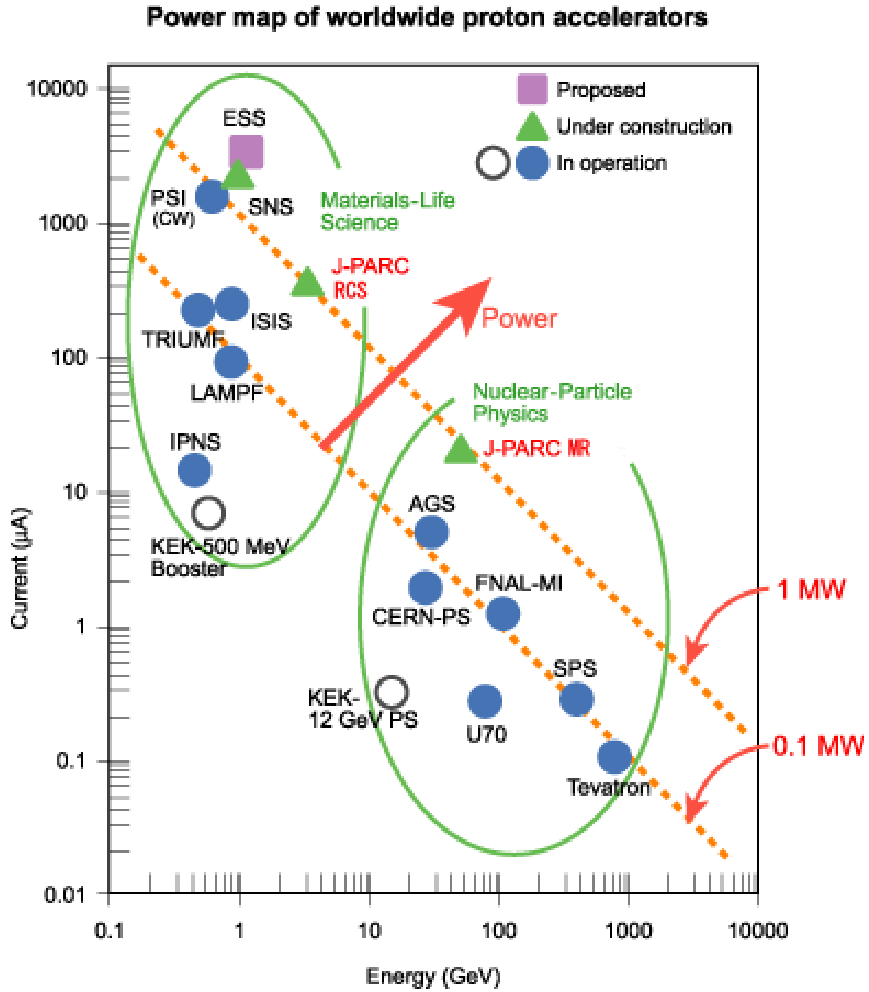
Intensity I: Neutron Spallation Source, SNS in Oakridge, USA

Ion: Protons
Energy: 1 GeV (0.88c)
ppp: 10E14
Rep. Rate: 60 Hz
Beam power: 2 MW



Intensity II: J-PARC, Japan

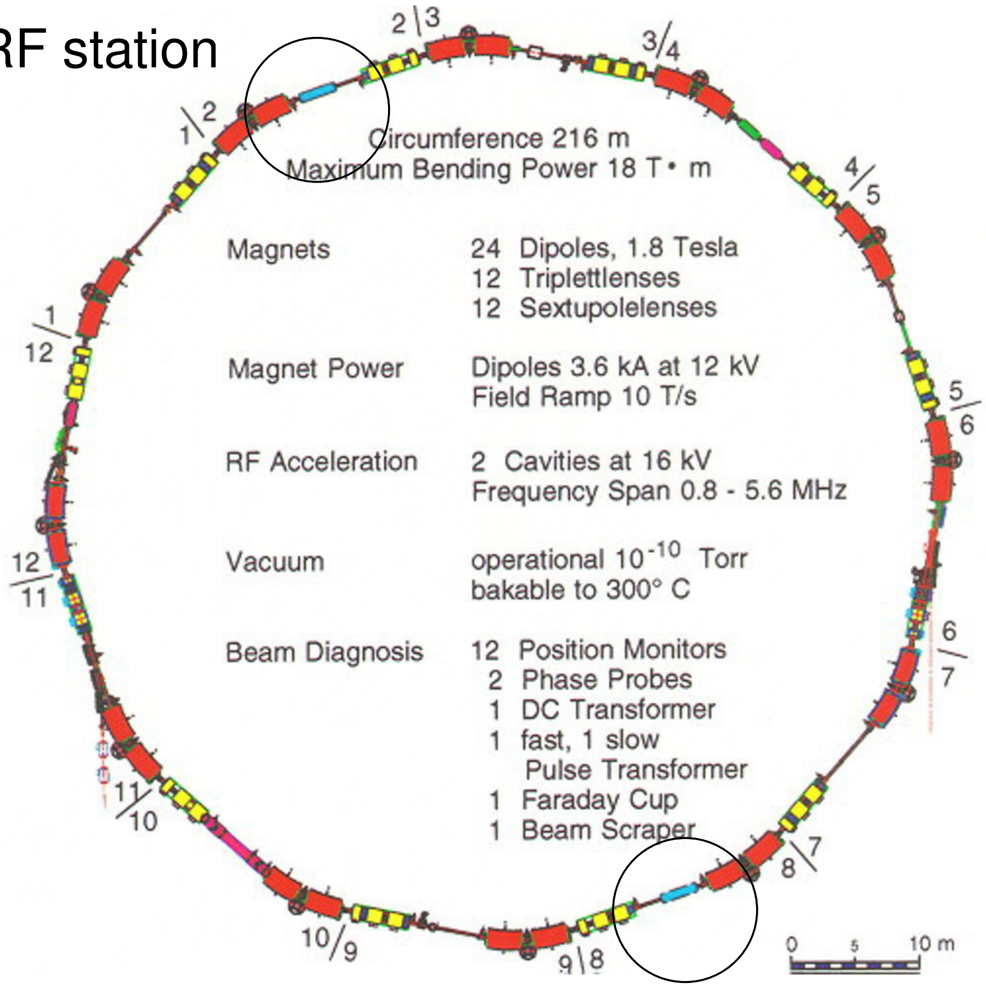




J-PARC was heavily affected by the earthquake in March 2011 !
Damage has been repaired and the facility is working again.

Working principle I: "Schwer Ionen Synchrotron": SIS

RF station



SIS: Bρ=18 Tm

RF station ω_{RF}

Revolution frequency:

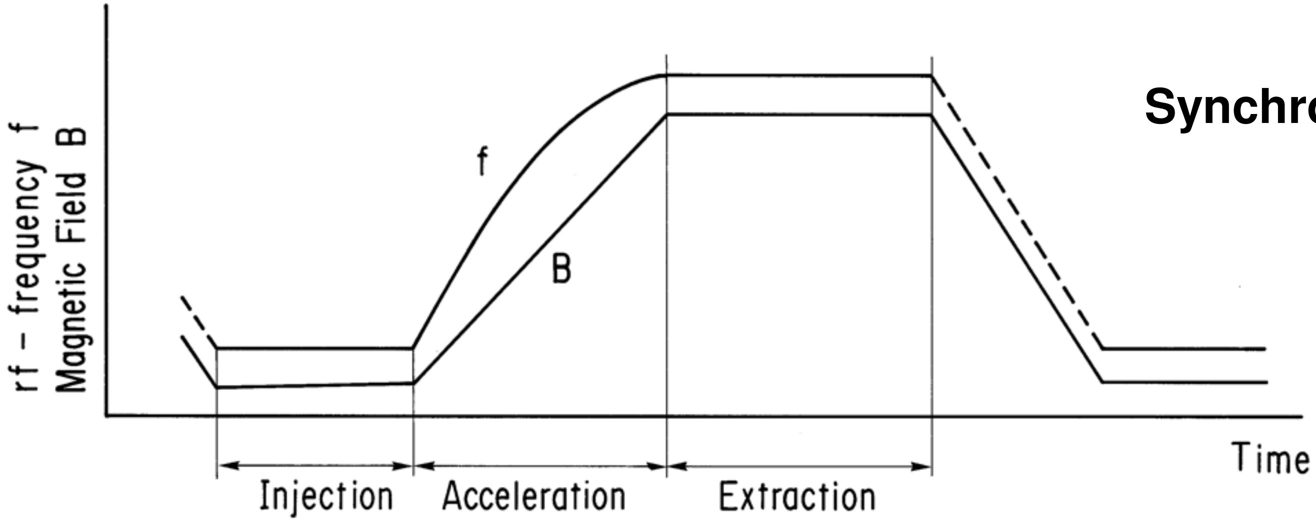
$$\omega_0 = \frac{qB_0}{\gamma m} = \frac{v_s}{R}$$

Design momentum:

$$p_s = \gamma m v_s = qB_0 R_0$$

- Constant orbit radius
- Variable magnetic fields
- ‚Synchronous': $h\omega_0 = \omega_{RF}$
- Pulsed beams

Working principle of a synchrotron II



Synchrotron cycle

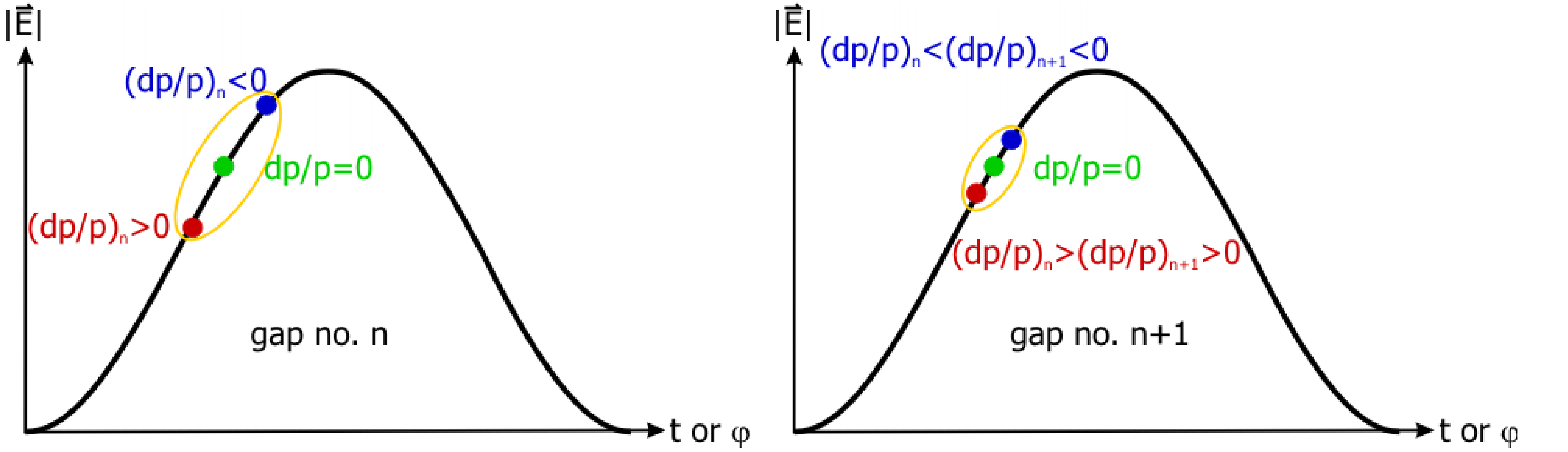
Repetition rate $(T_{rep})^{-1}$:
(time needed for one complete cycle)$^{-1}$

Total beam energy: $W_{tot} = NW_{kin}$

Beam power: $P_{beam} = \frac{W_{tot}}{T_{rep}}$

Types of synchrotrons (a bit arbitrary):
- slow cycling synchrotron: < 1 Hz
- fast cycling synchrotron: 1-10 Hz
- Rapid Cycling Synchrotron (RCS): > 10 Hz

RF: Phase Stability and Longitudinal Focusing



- dp/p=0: no change
- dp/p<0: more accelerated
- dp/p>0: less accelerated

Result:
phase focusing,
and oscillation around (dp/p=0)
so called synchrotron oscillations

RF special I: Dual harmonic rf buckets

Dual rf systems are employed e.g. in:
CERN PSB, ISIS, J-PARC RCS, GSI SIS-18..

Advantages:

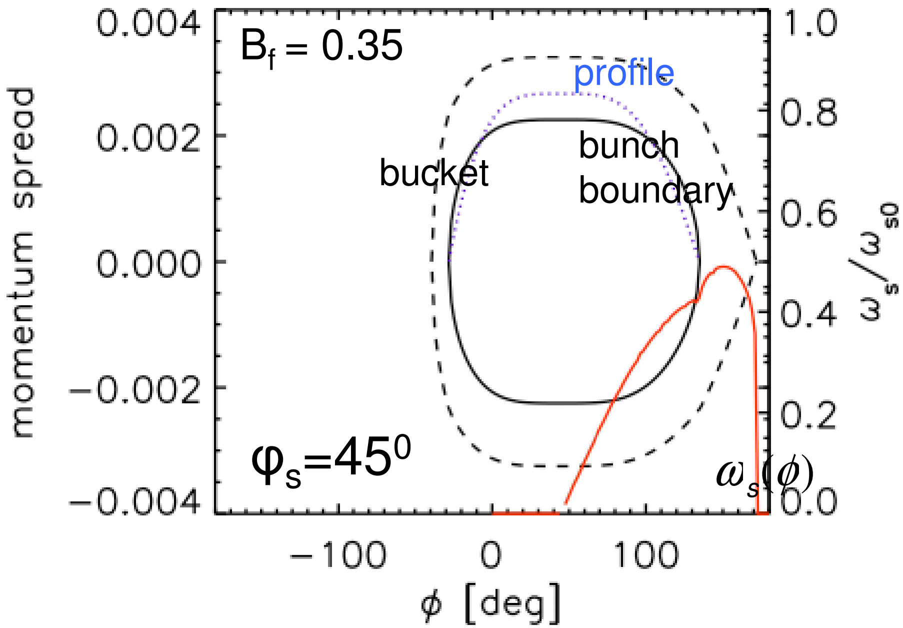
- **flattened bunches** (lower peak current)
- larger bucket area

Complication:

- control of the phase difference
- 'fully nonlinear synchrotron oscillations'

Example case SIS-18:
V_0=40/16 kV, h=2/4 (f_{min}=430/860 kHz)

SIS-18: Dual rf bucket with flattened bunch profile



-> dedicated RF talk by H. Klingbeil

RF special II: Fast bunch compression

For applications e.g. in nuclear physics a single, short bunch is extracted to the production target.

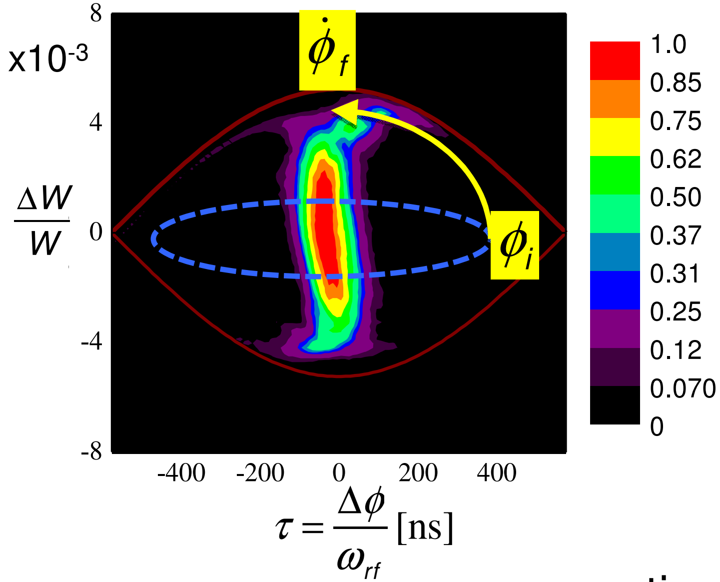
Bunch rotation:
Sudden switch-on of an additional rf voltage causes the bunch to rotate in the bucket.

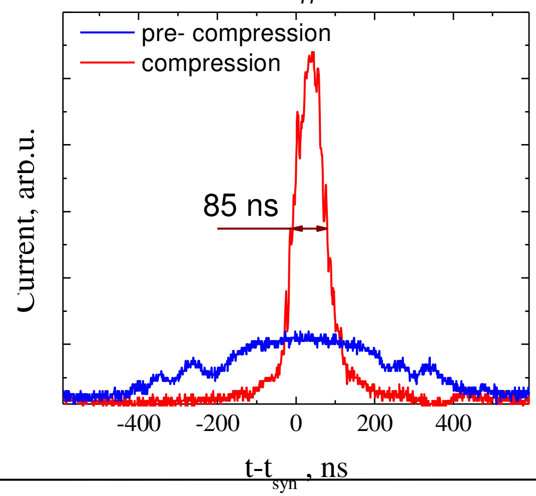
The compression takes only a quarter of a synchrotron period.

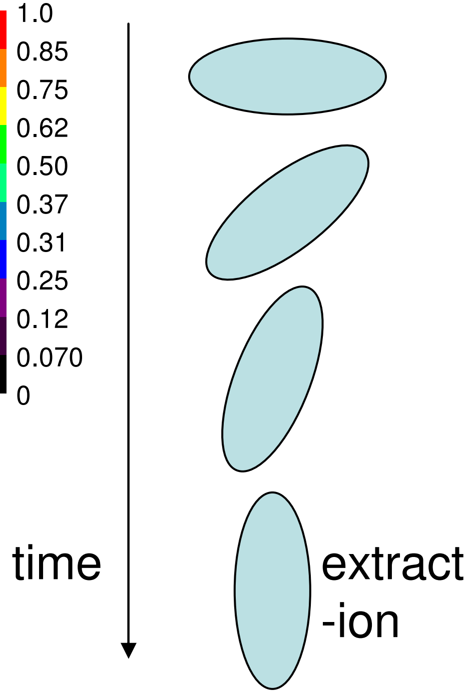
$$T_{rot} = \frac{T_s}{4} < 1\,\text{ms}$$

-> (broadband) rf cavity with fast rise time needed !

Bunch rotation in SIS-18

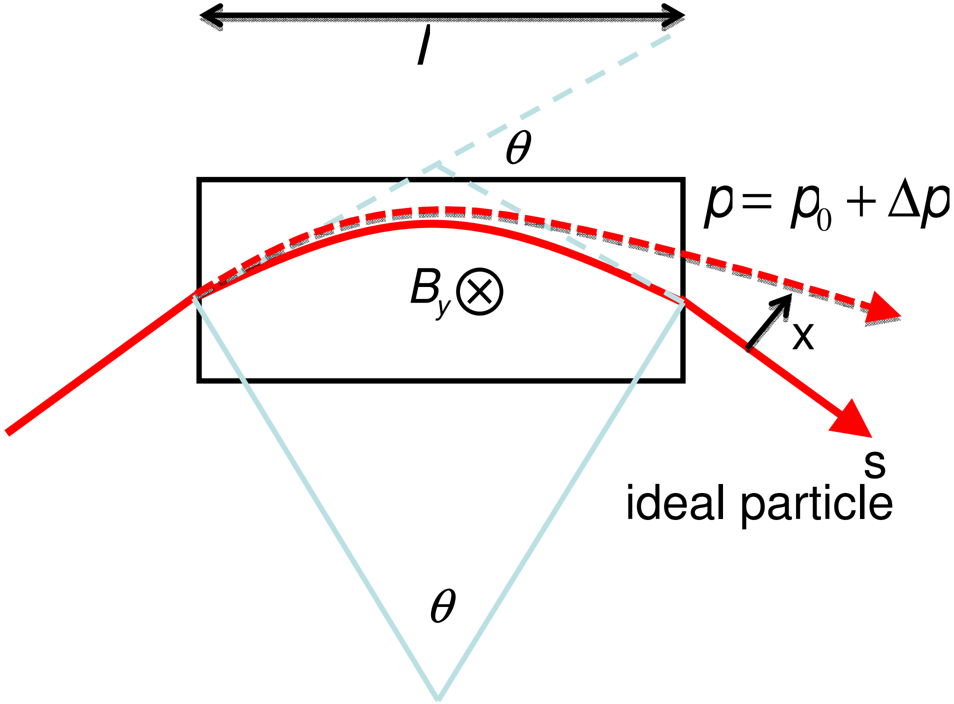






Final bunch length depends on the initial momentum spread !

Transverse motion in dipole magnets



$$\theta = \frac{q}{p_0}\int_{s_1}^{s_2} B_y ds \approx \frac{l}{R_0}$$

Horizontal particle offset: x

Divergence: $x' = \dfrac{dx}{ds}$

Path length: $s = \beta_0 ct$

$$\Delta\theta = \theta\frac{\Delta p}{p} \quad \Rightarrow \quad x'' = \frac{1}{R}\frac{\Delta p}{p_0}$$

$$x'' + \frac{1}{R^2}x = \frac{1}{R}\frac{\Delta p}{p_0}$$

'weak' focusing — inhomogeneous part

Rapid/fast ramping dipole magnets
Examples

Large apertures

SIS-18 dipoles: 20 cm x 8 cm

J-PARC RCS: 25 cm x 19 cm

Ramping rates (Bdot):

SIS-18 dipoles: 10 T/s

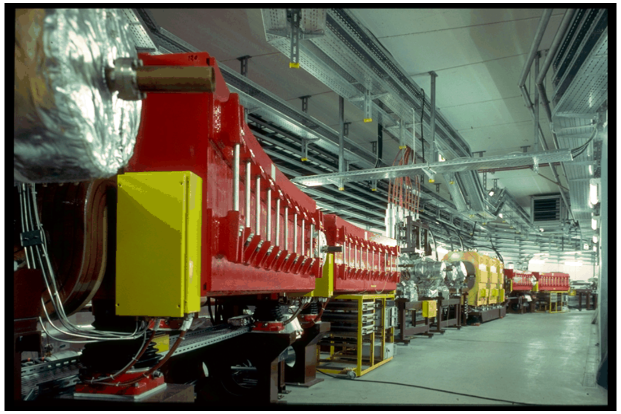
J-PARC RCS dipoles: 40 T/s

Max. B-Field

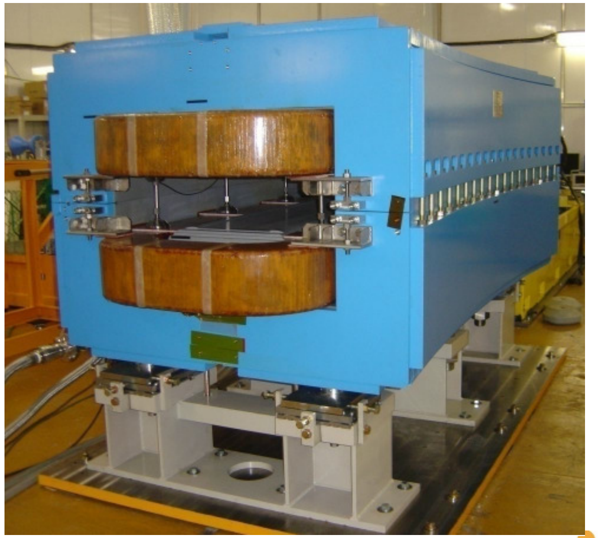
SIS-18: 1.8 T

J-PARC RCS: 1.1 T

Fast ramping (3 Hz) SIS-18 dipoles

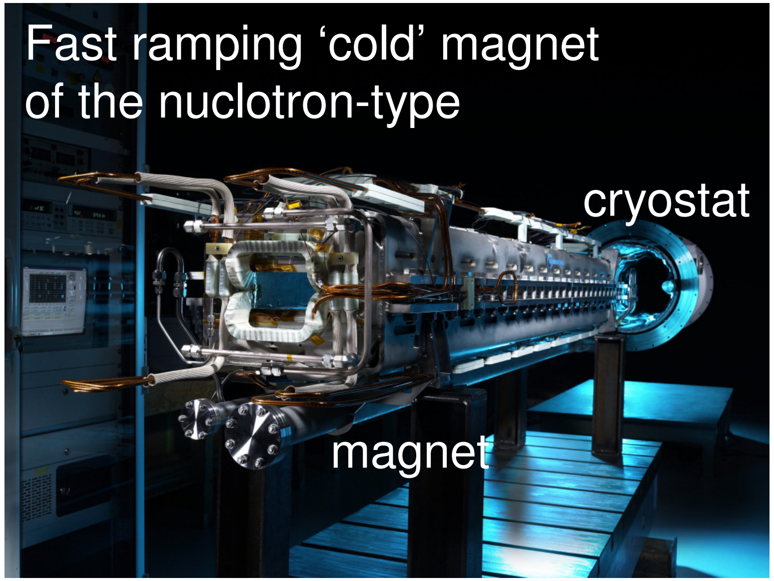


J-PARC RCS (25 Hz) dipole

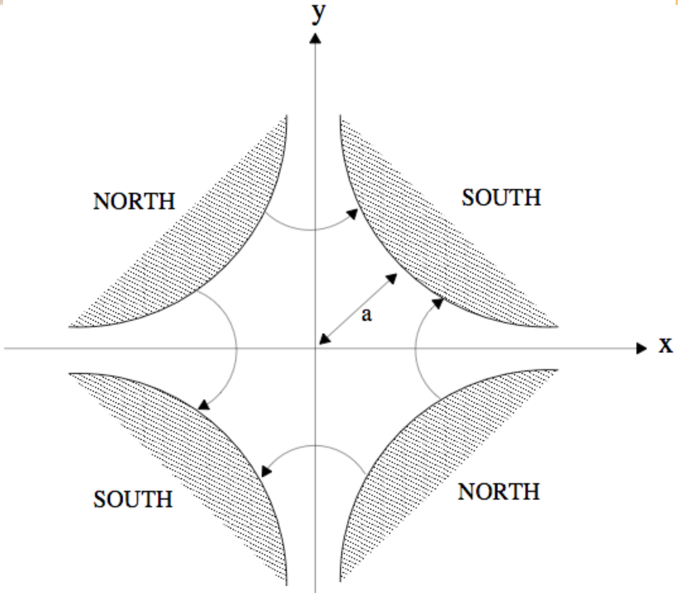


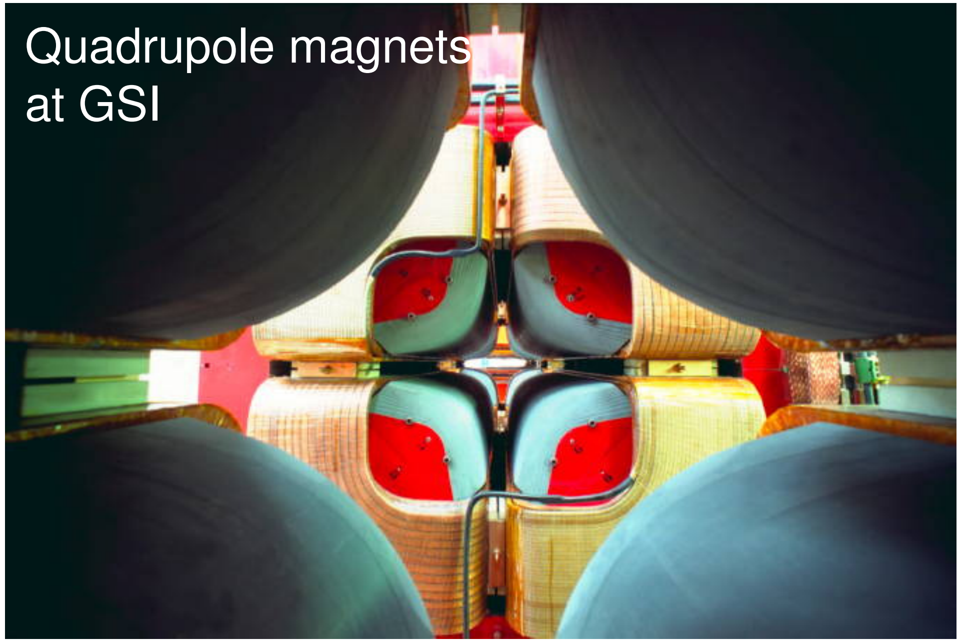
SIS-100 superferric dipole:

13 cm x 6 cm
Bdot = 4 T/s
B_{max}= 1.9 T
pipe at 20 K
(as cryo-
pump)



Quadrupole magnets and beam focusing





Magnetic field:

$$B_y = B_0 \frac{x}{a}, \quad B_x = B_0 \frac{y}{a}$$

Focusing gradient:

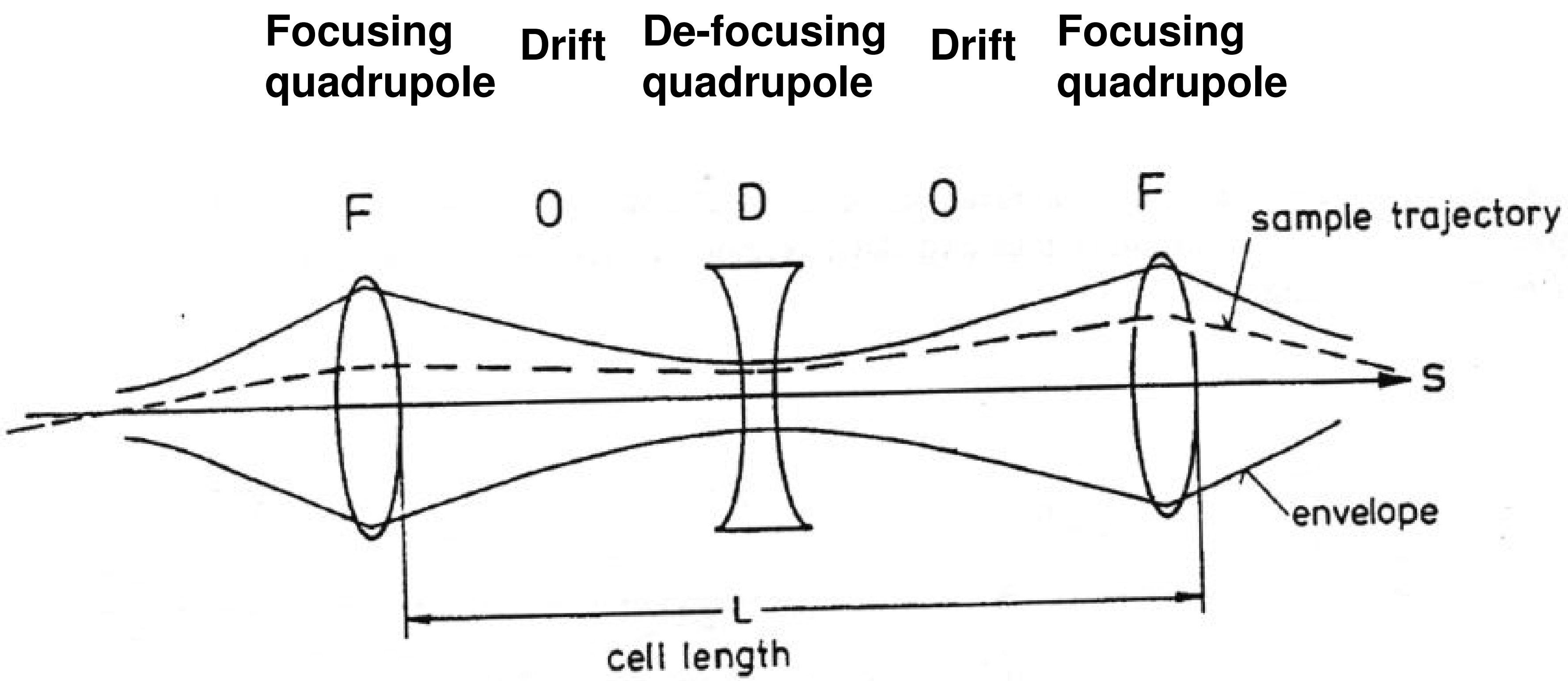
$$\kappa = \frac{q}{p_0} \frac{\partial B_x}{\partial y} = \frac{q}{p_0} \frac{\partial B_y}{\partial x}$$

Equations of motion:

$$x'' + \kappa(s) x = 0$$ (horizontal)

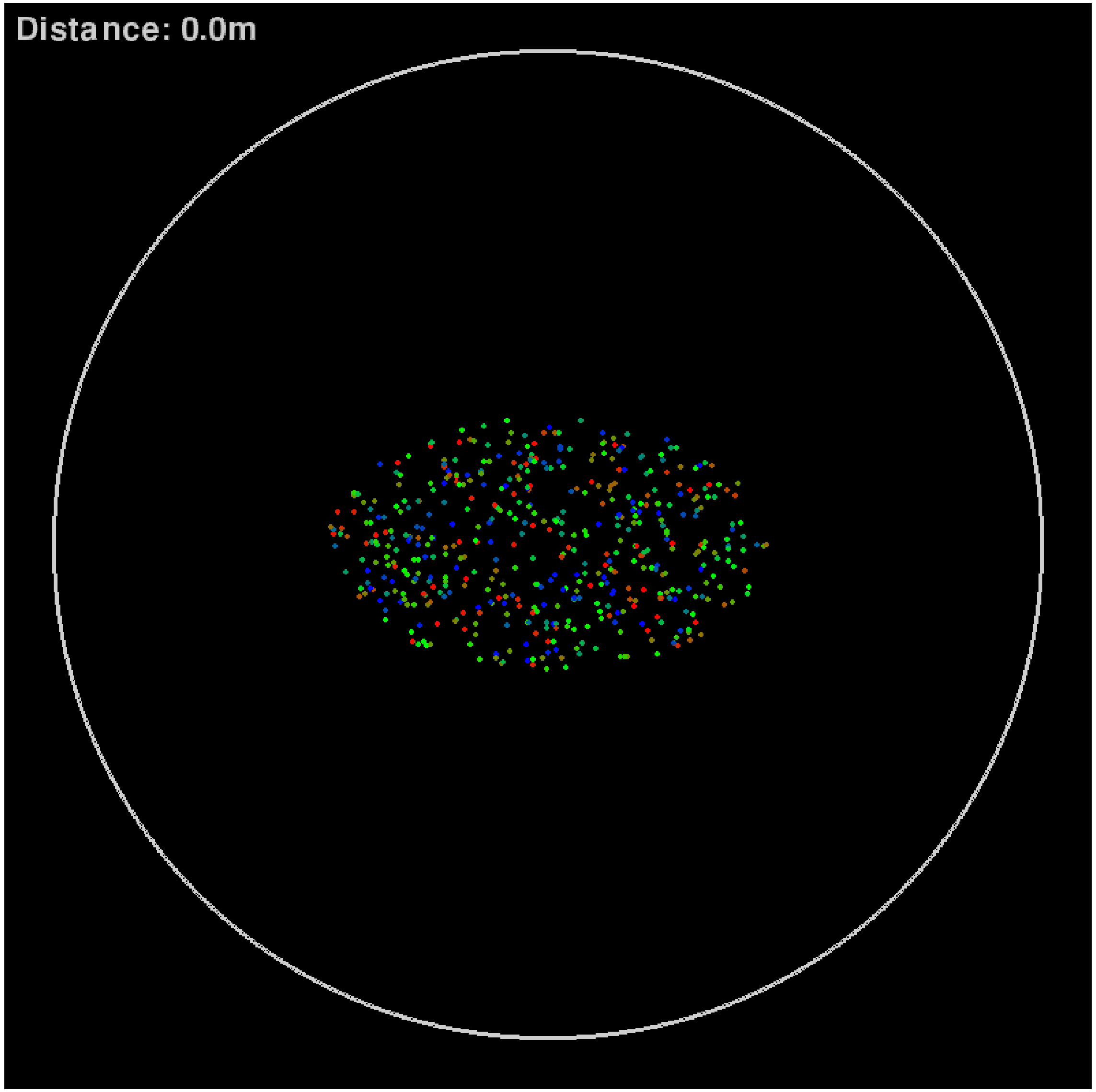
$$y'' - \kappa(s) x = 0$$ (vertical)

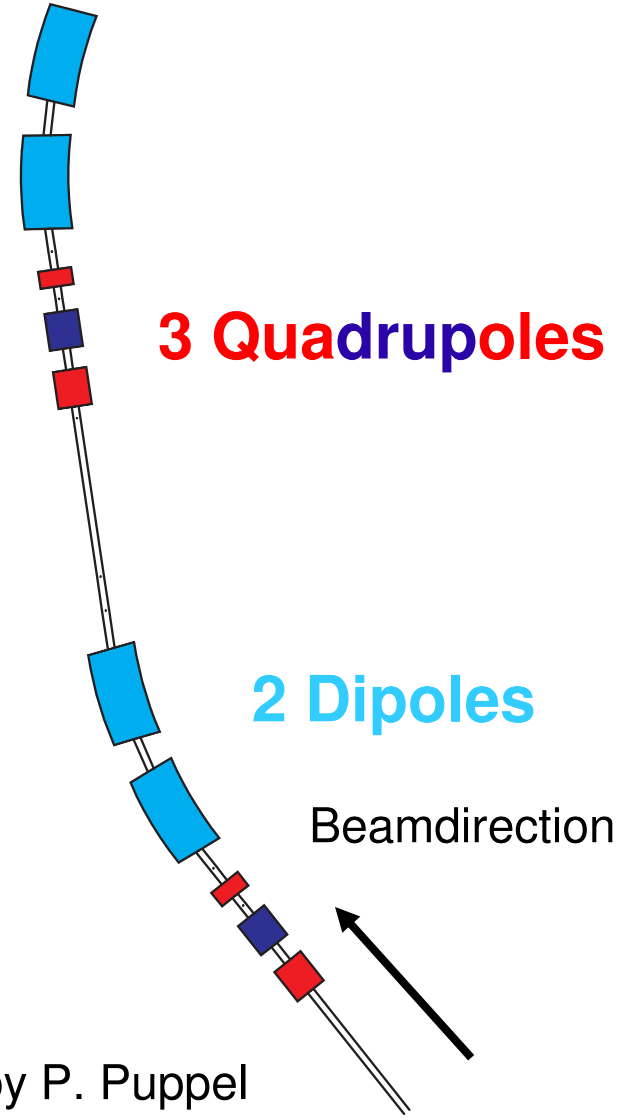
Alternating Gradient Focusing



Sequence of focusing and de-focusing lenses acts as effective focusing lens

Particles on the run, have a look

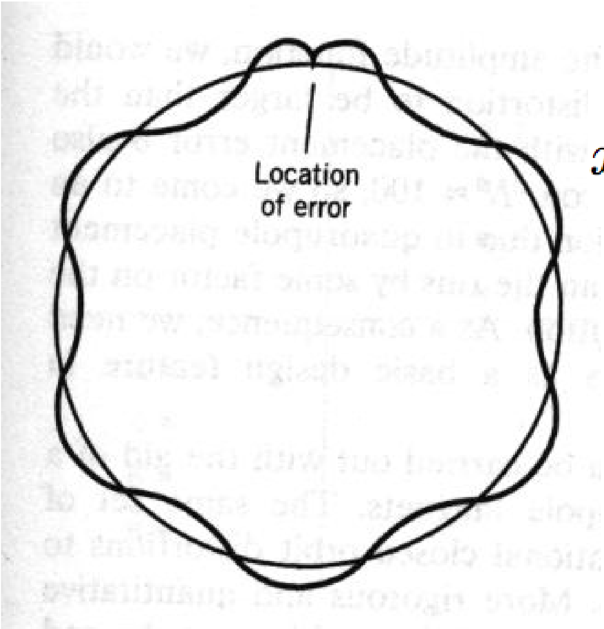




by P. Puppel

Errors: The ions stray from the ideal path

$$\begin{pmatrix} x_0 \\ x_0' \end{pmatrix} = (I - M)^{-1} \begin{pmatrix} 0 \\ \theta \end{pmatrix} = \frac{\theta}{2 \sin \pi Q} \begin{pmatrix} \hat{\beta}_0 \cos \pi Q \\ \sin \pi Q - \hat{\alpha}_0 \cos \pi Q \end{pmatrix}$$



Betatron oscillation:

$$x(s) = \frac{\theta \beta_0^{1/2} \beta(s)^{1/2}}{2 \sin \pi Q} \cos(\psi(s) - \pi Q)$$

The errors of the dipoles are additive

$$\theta = \sum_j \theta_j = \sum_j \frac{l_j}{R} \frac{\Delta B_j}{B} \approx \frac{\Delta B}{B} \approx 10^{-4} \text{ rad}$$

resulting amplitude (GSI's SIS18):

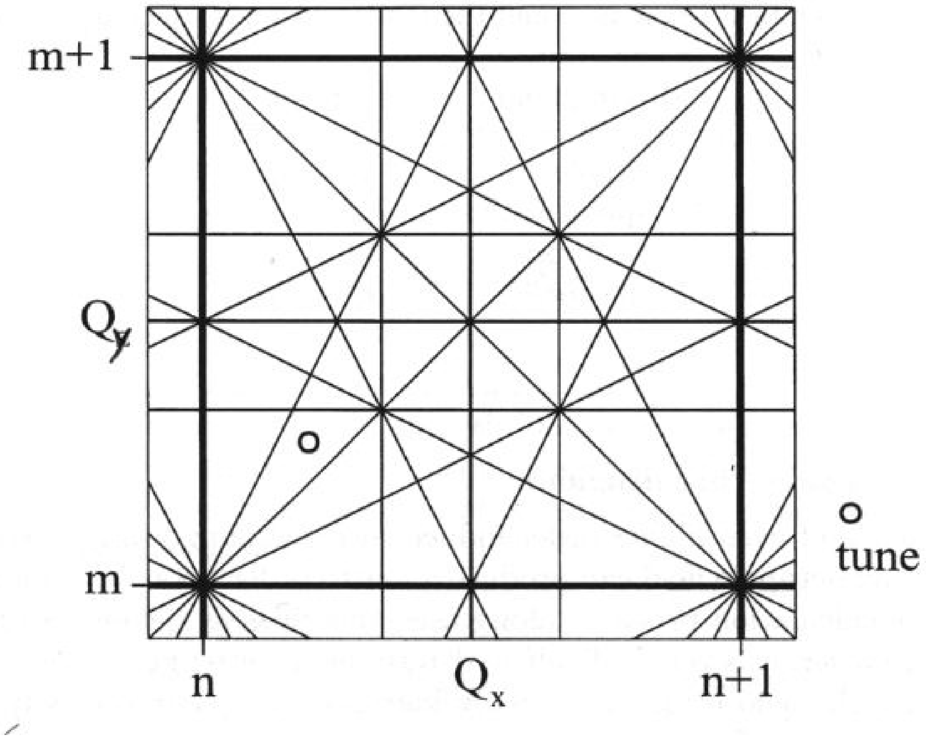
$$|\hat{x}| \approx \frac{(10^{-4} \text{ rad})(30 \text{ m})}{2 \sin \pi 4.2} \approx 1 \text{ cm}$$

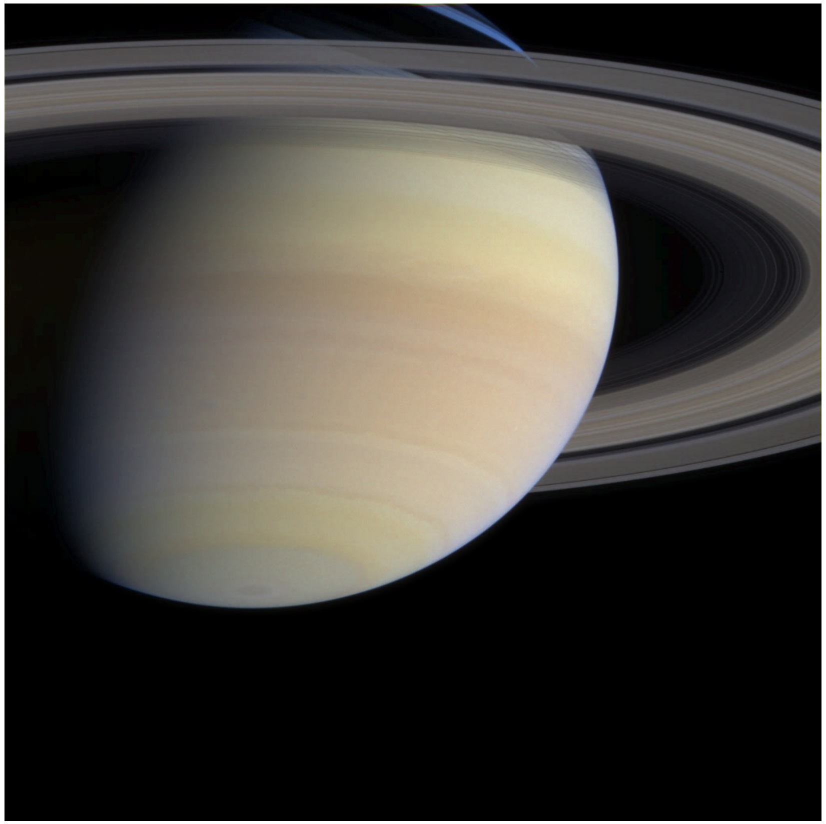
Number of betatron oscillations per turn is the "tune" (Q).

Tune and resonances

$$nQ_x + mQ_y = p$$

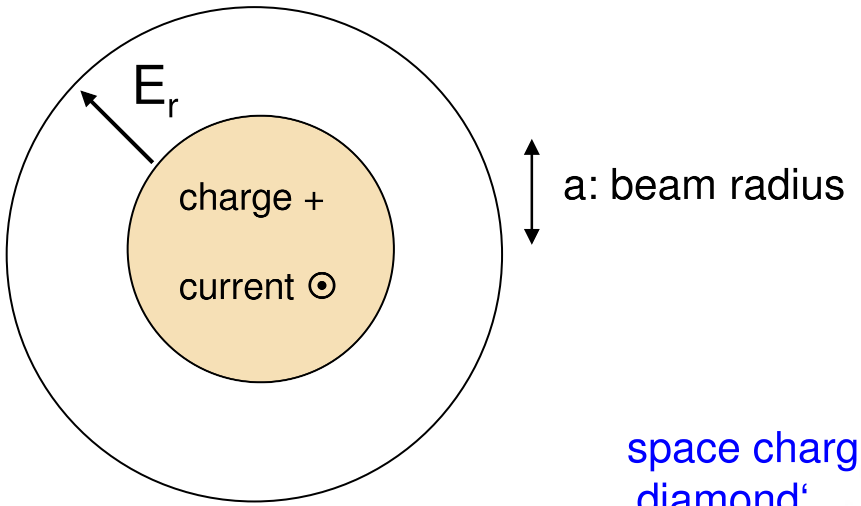
Order of resonance:
|n+m|

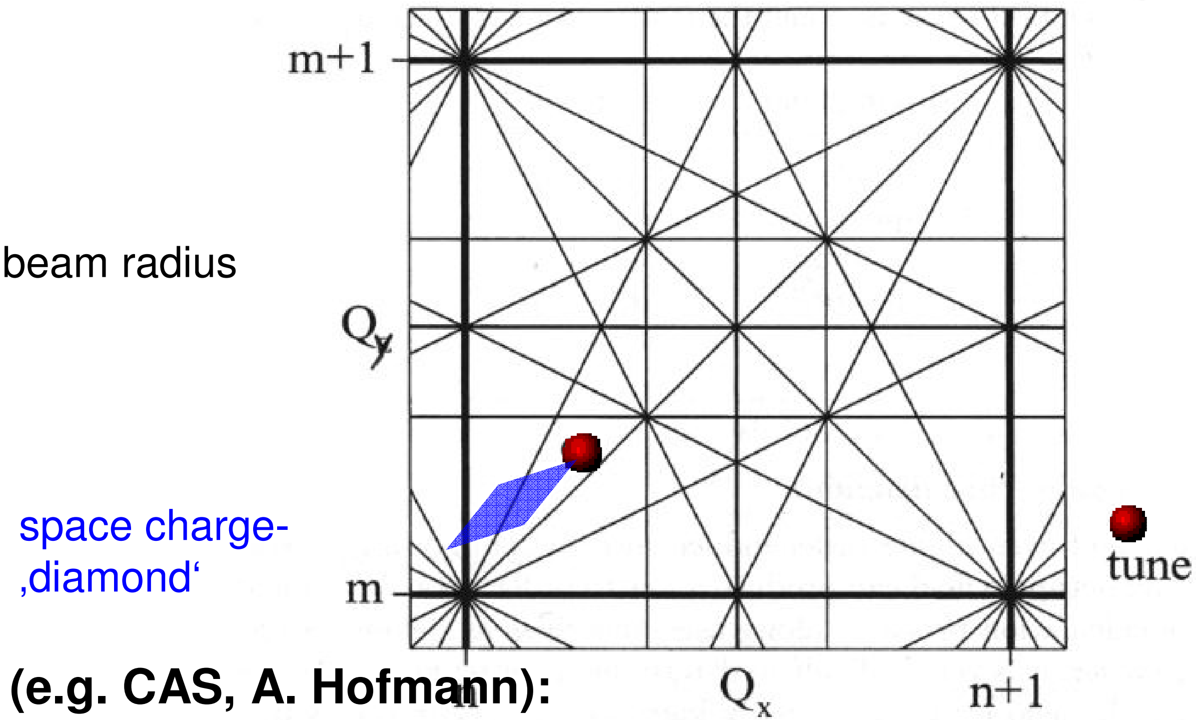




Space charge tune shift

Beam in vacuum tube





Space charge tune spread (e.g. CAS, A. Hofmann):

$$\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{g_f}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{2}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$$

‘Space charge limit’ $|\Delta Q_y| \lesssim 0.5$ (text books)

g_f: Transverse profile (Gauss: 2, homogenous: 1)
B_f < 1: bunching factor
$\varepsilon_{x,y}$: transverse emittances
N: number of particles in the ring
q: particle charge
m: particle mass

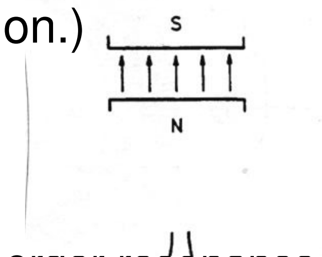
(Slow) extraction

Slow extraction examples: GSI SIS-18 and SIS-100, J-PARC MR, BNL AGS

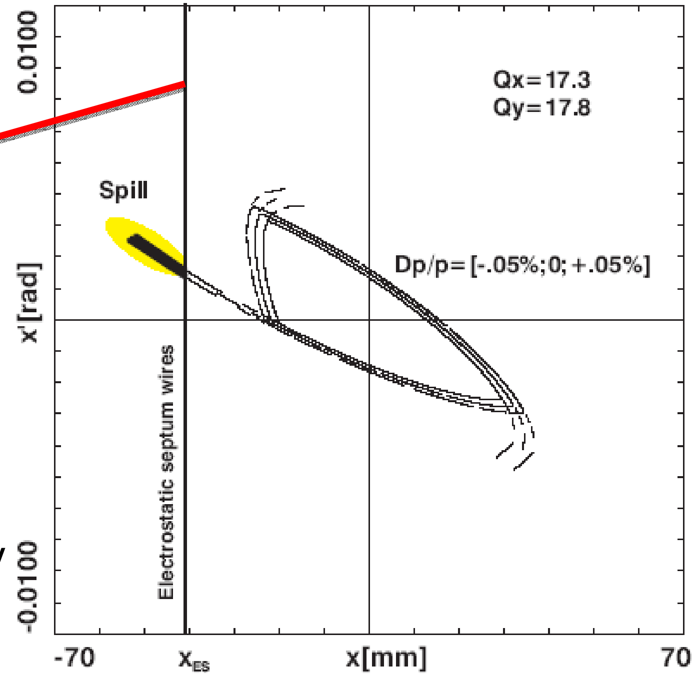
Fast extraction: in one turn using a kicker (e.g. after bunch compression.)

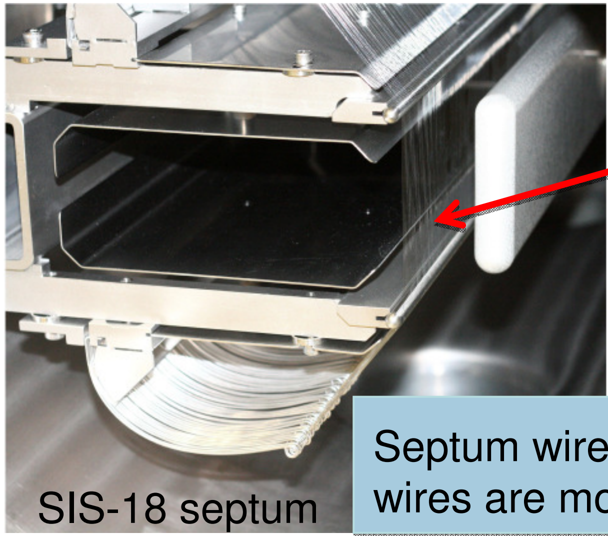
Slow extraction: over many turns (up to seconds !).
The horizontal tune is moved close to a third order resonance excited by sextupole magnets.
The particles on the resonance are extracted using electrostatic and magnetic septa.

Sextupole:



Separatrix (third order resonance)



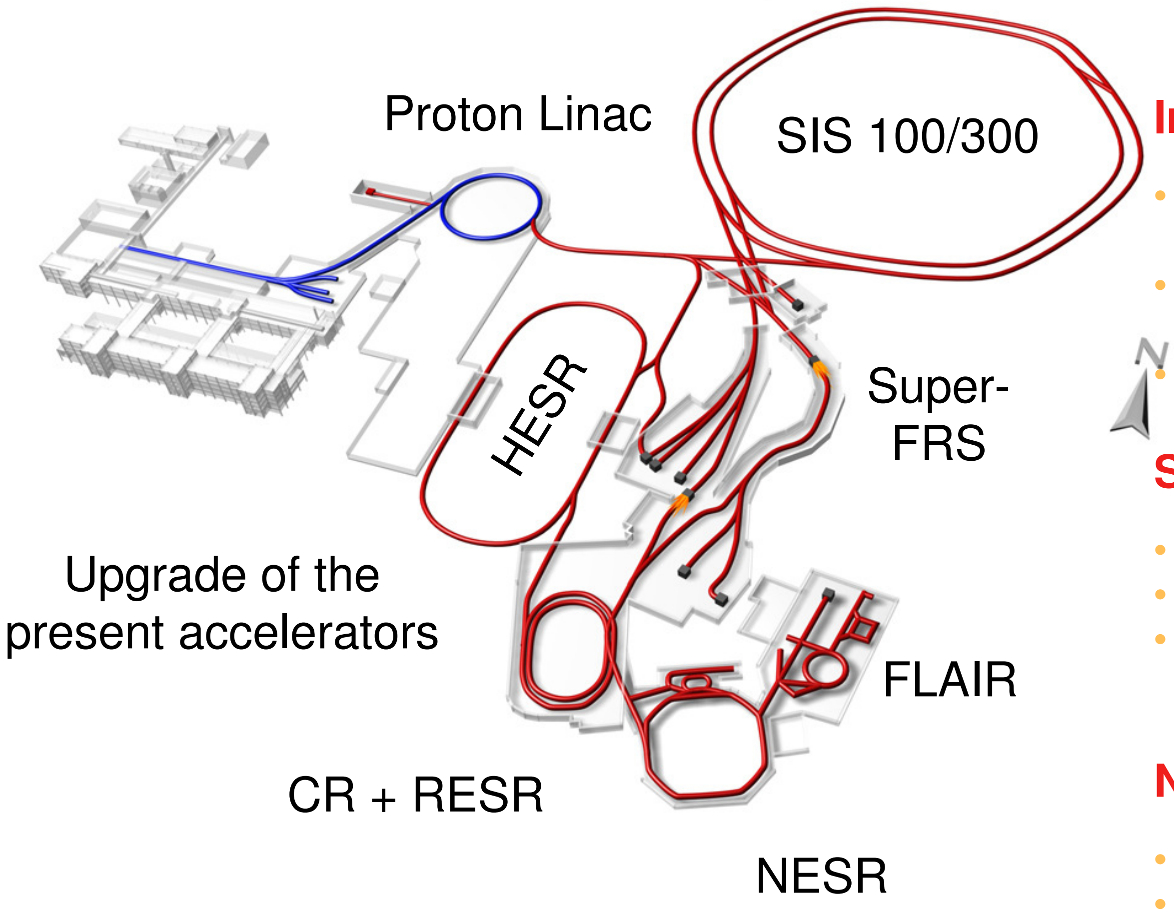


SIS-18 septum

Septum should be as thin as possible to avoid losses !

Septum wires: Ø 0.025 mm (W-Re alloy
wires are mounted under tension

FAIR - Facility for Antiproton and Ion Research



Improvements

- Primary intensities: factor 100 – 1000
- Secondary radiocative beams: up to factor 10 000
- Ion energy: factor 34

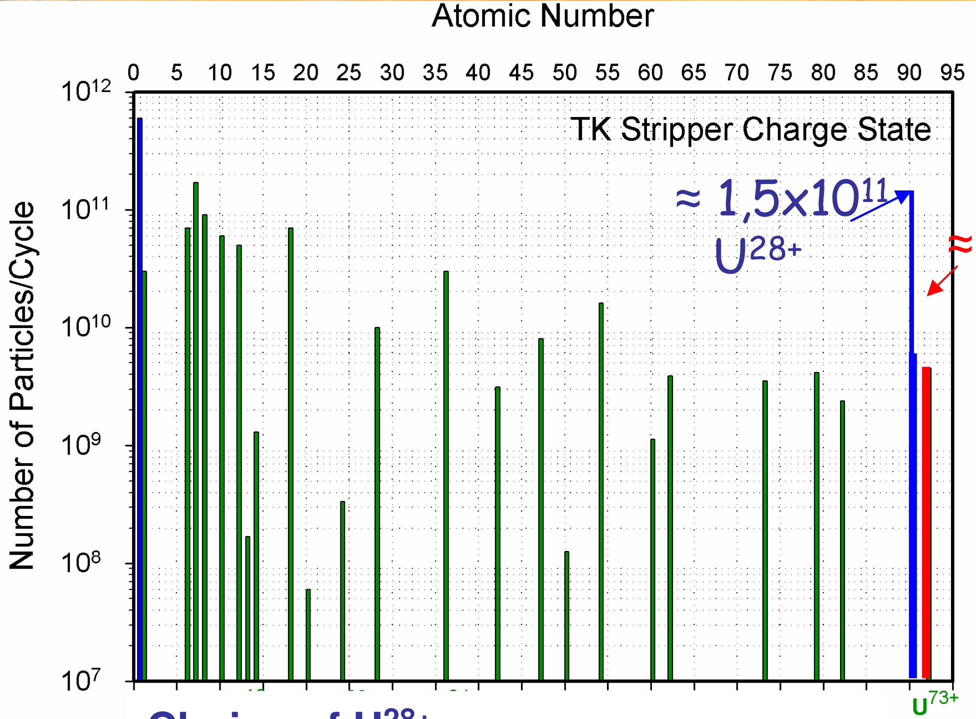
Special properties

- Intense cooled radioactive ion beams,
- cooled anti-proton beams up to 15 GeV,
- Internal high luminosity targets in storage rings.

New technology

- Fast ramped superconducting magnets
- Electron cooling for high intensity and high-energy beams.
- Fast stochastic cooling

SIS 18 as Injector for SIS 100



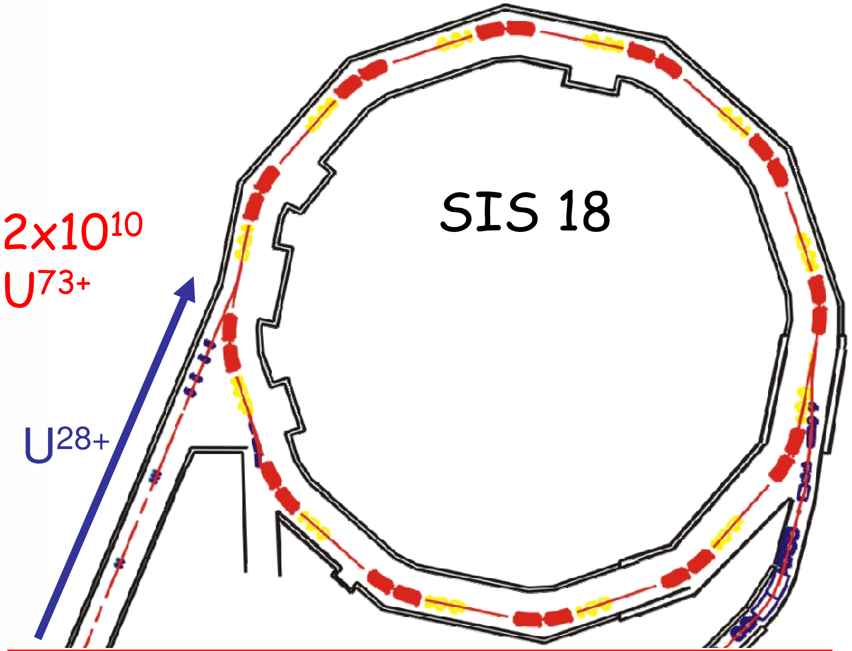
Choice of U^{28+}

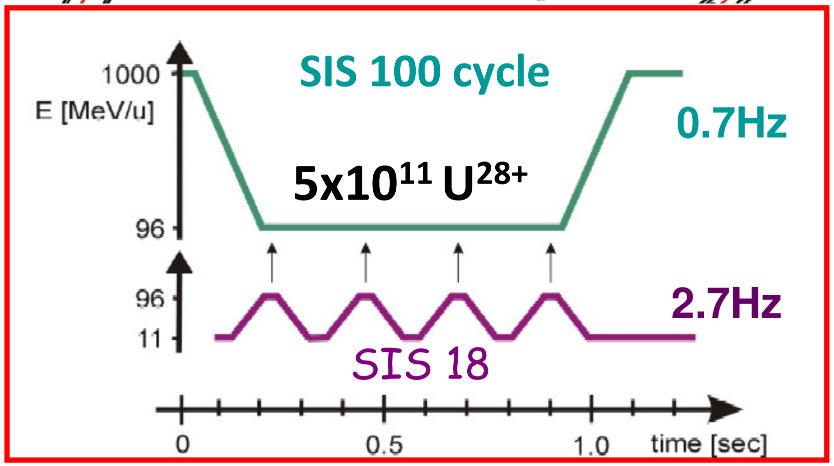
+ Lower space charge

  → higher intensity N_{max}~A/Q^2

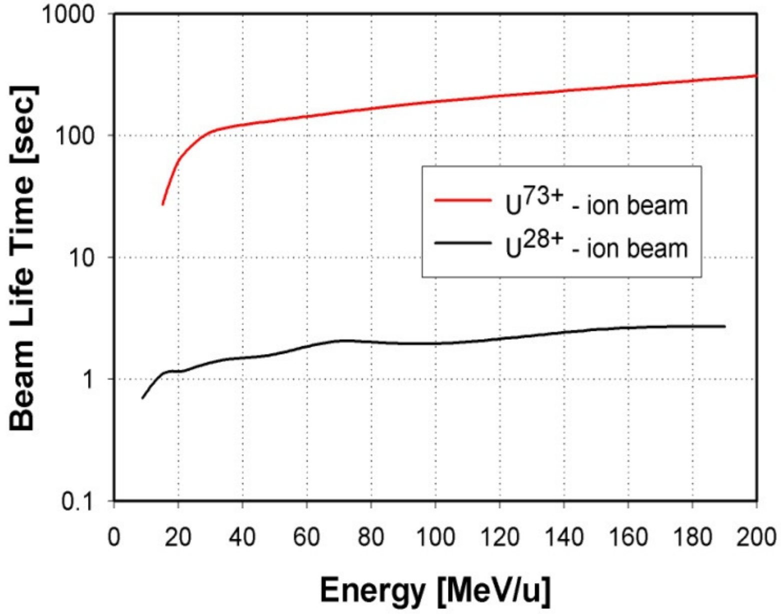
+ No stripping losses

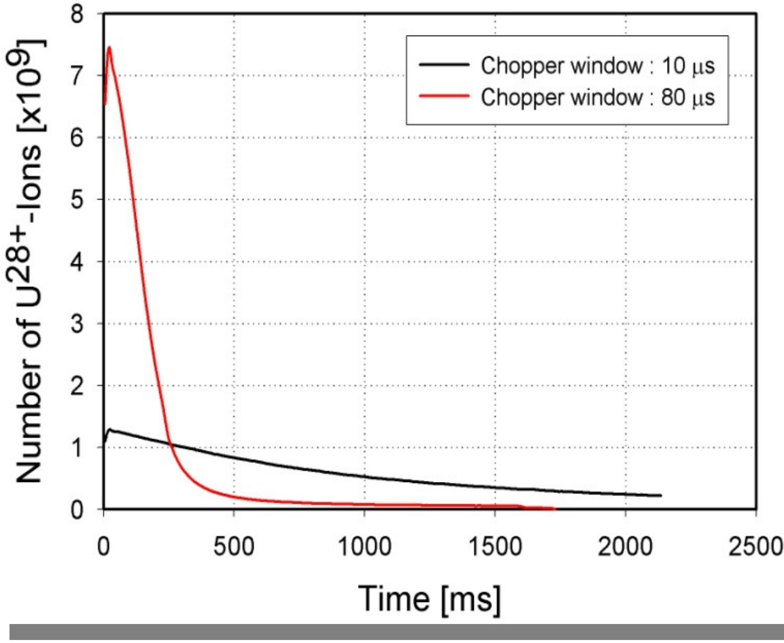
- Lower beam lifetime





Life Time and Beam Loss:
XHV is the key to heavy ion acceleration





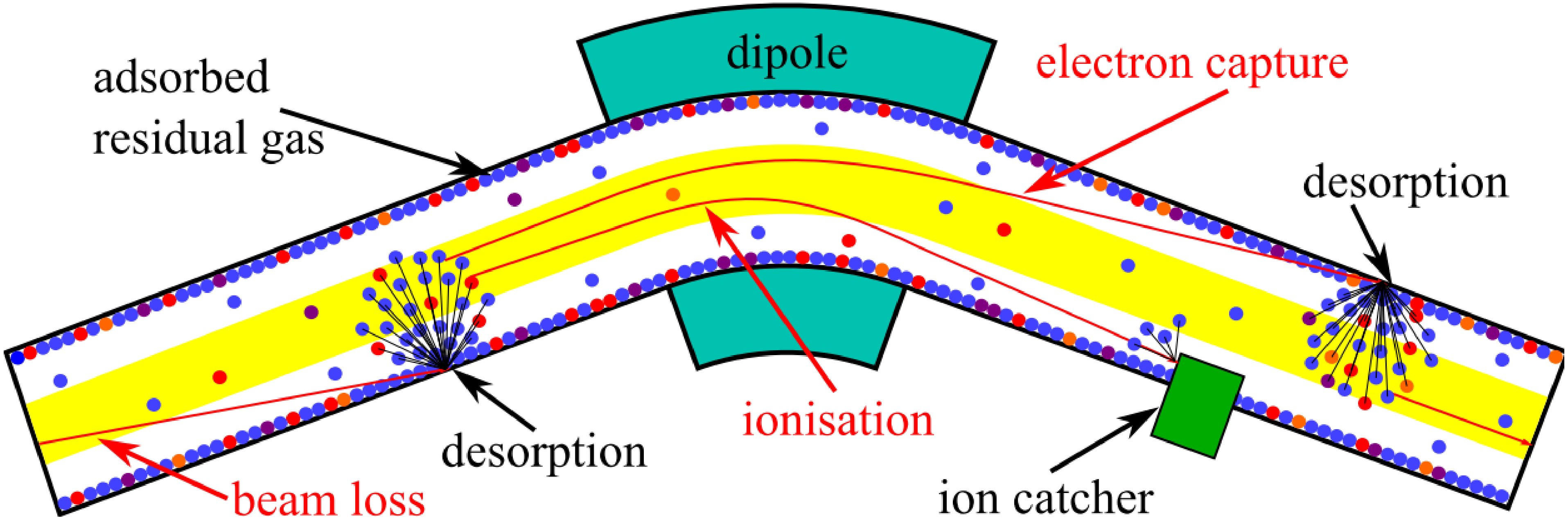
- Life time of U^{28+} is significantly lower than of U^{73+}

- Life time of U^{28+} depends strongly on the residual gas pressure and composition

- Ion induced gas desorption ($\eta \approx$ 10 000) increases the local pressure

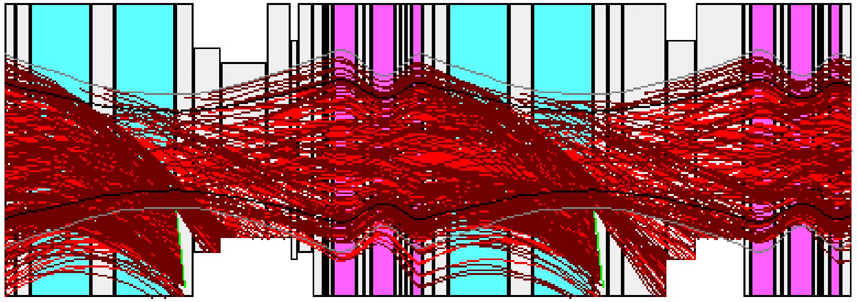
- Beam loss increases over propotional with intensity -> Dynamic vacuum

What happened? - Dynamic vacuum!

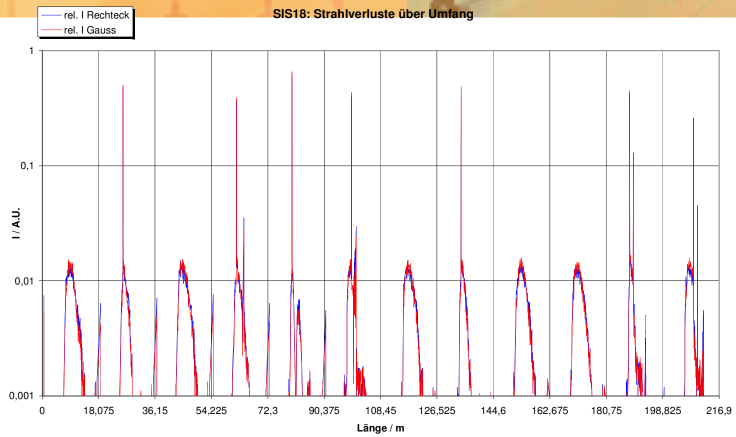


No cure by good initial vacuum or pumping power alone!

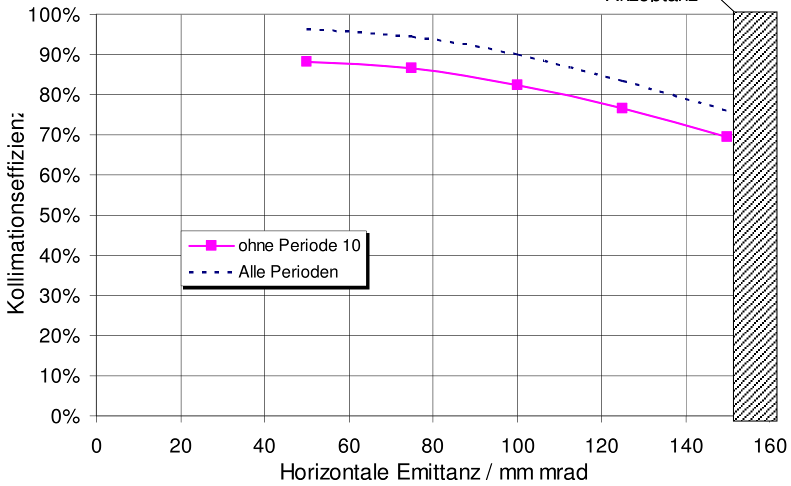
Charge exchange loss catcher System



Ionization beam loss in section 11,12



Beam loss distribution U^{29+}

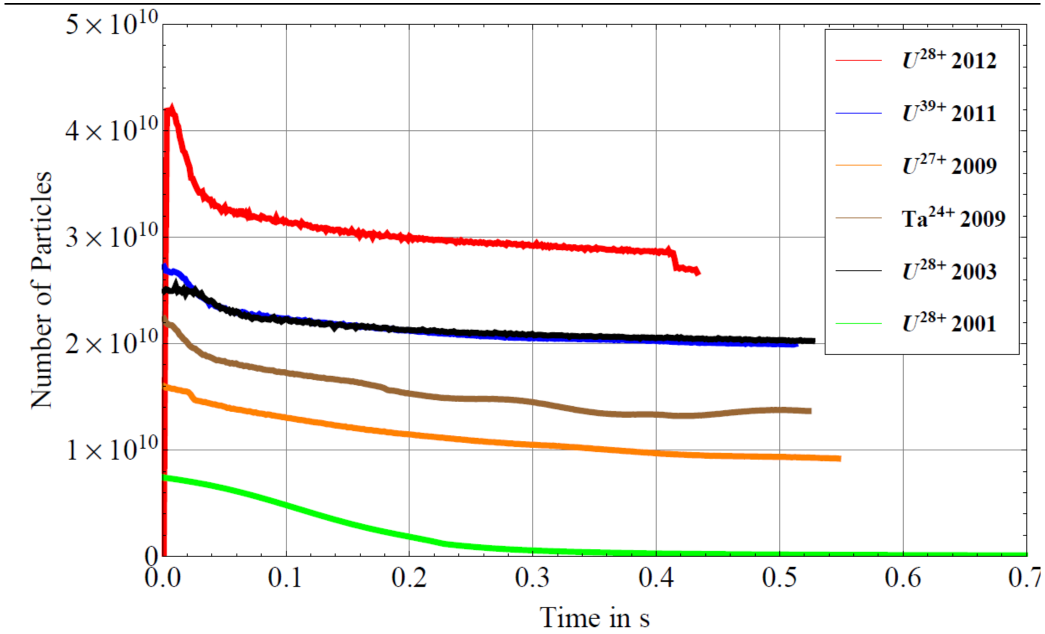


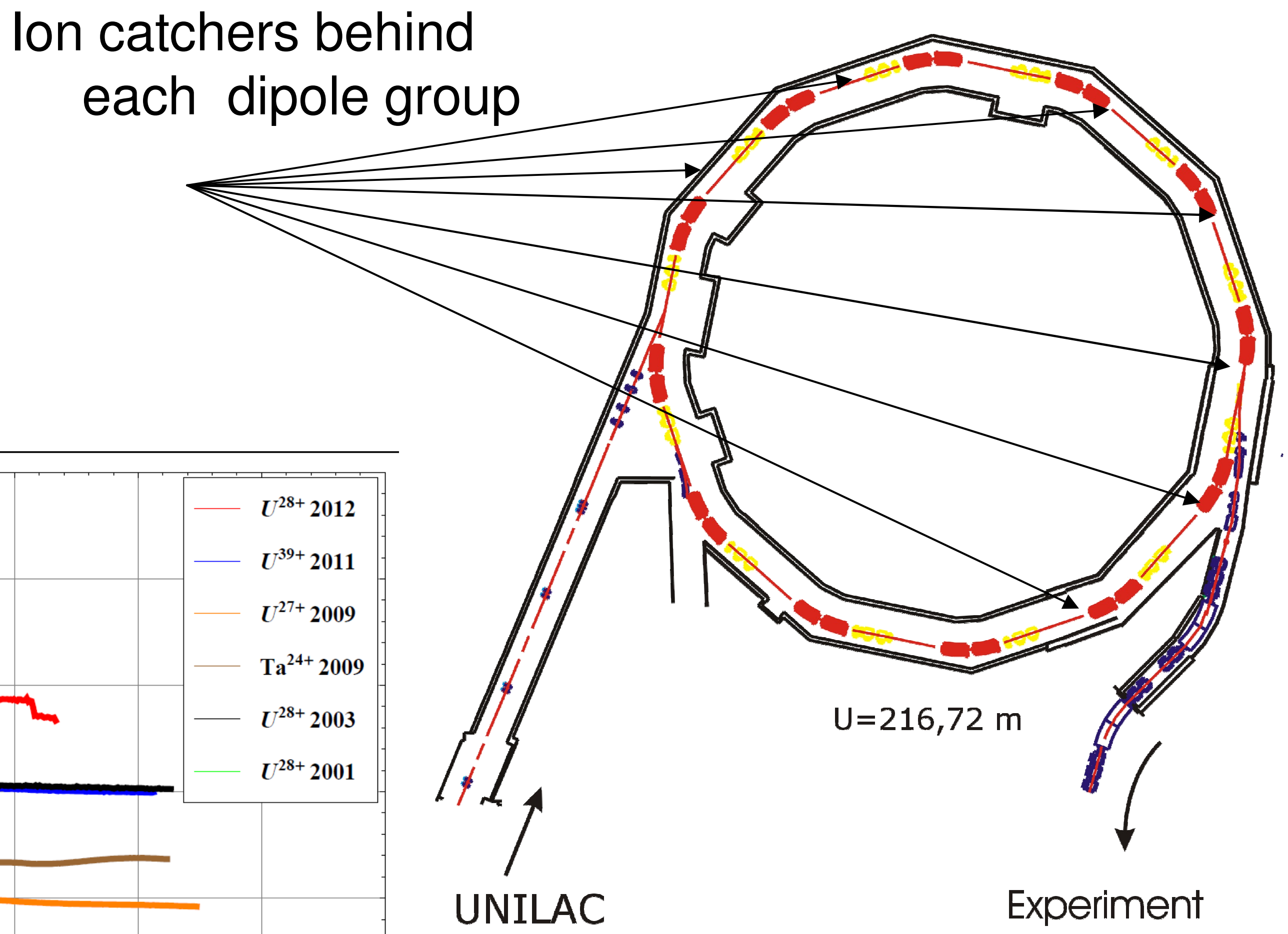
Scraper efficiency U^{29+}

- **Developed for heaviest ions**
  (highest ionization cross sections)
- **Triplet/ doublet structure is suitable but:**
  bending power of dipoles to high
  > Limited collimation efficiency
  depending on emittance (70 %)

Results of the combined upgrade measures.

- Injection upgrade,
- power system upgrade I (faster ramping),
- vacuum system upgrade (e.g. NEG coating)
- Ion catchers for dynamic vacuum control.

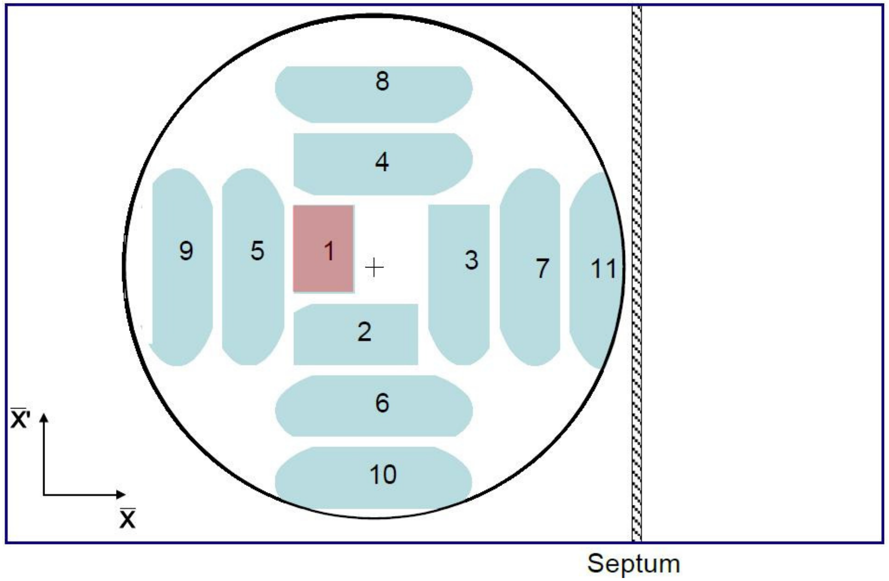


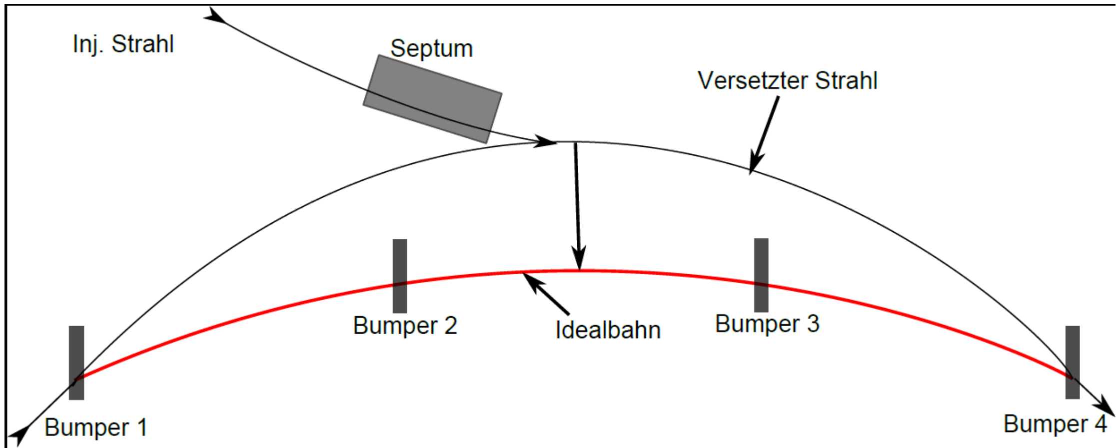


Upgrade not complete!

Multiturninjection I

Multiturninjection is the injection of a long pulse from a linac into a synchrotron. Simultaneously to the linac pulse the trajectory of the injected beam is moved by fast bumper magnets to fill the large acceptance of the synchrotron with the comparable smaller linac beam.



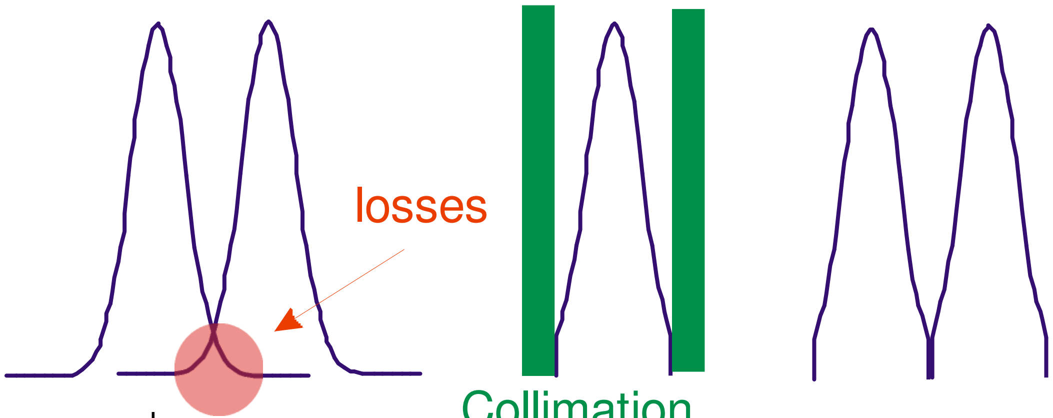


• Beam losses during this process lead to gas desorption and may cause dynamic vacuum effects.

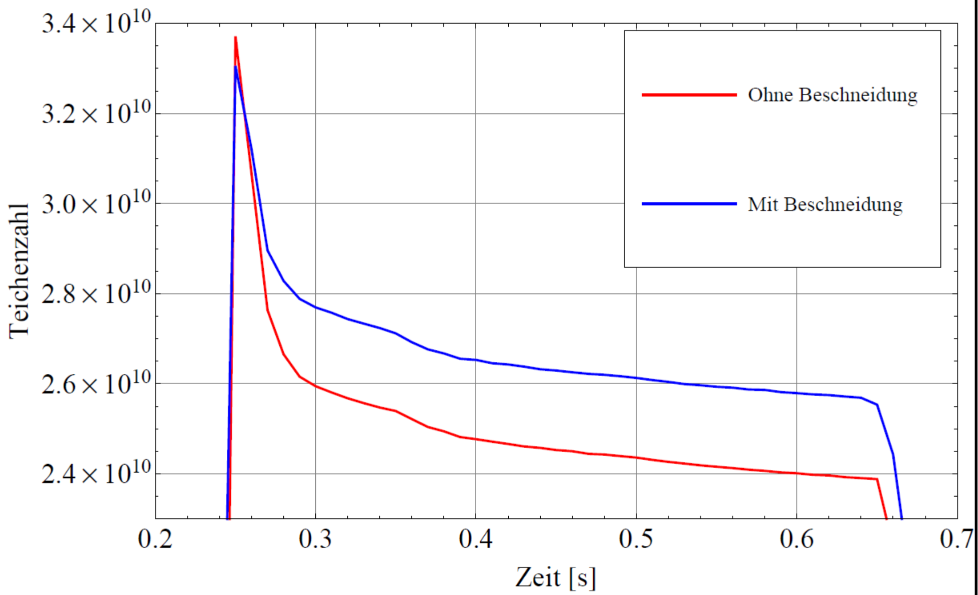
(by Y. el-Hayek)

Multiturninjection II: Transfer of losses into the injection channel

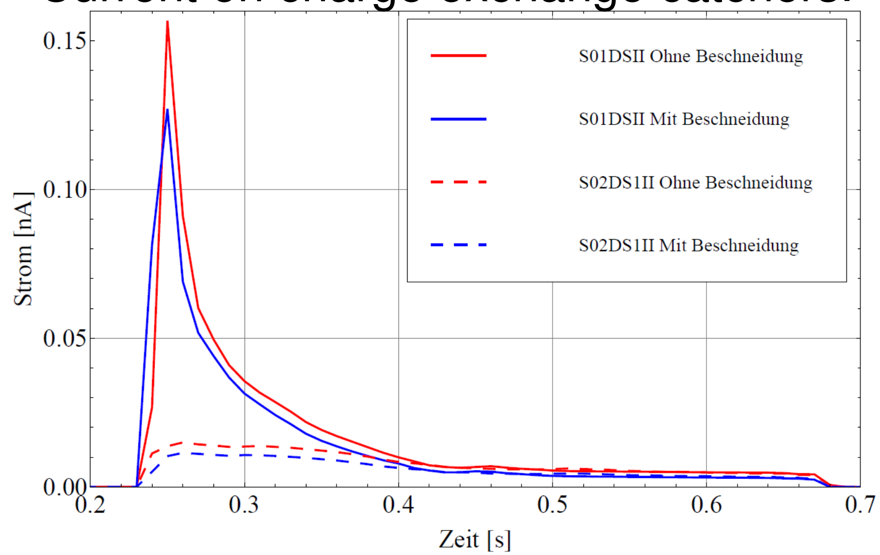
Experiments at the synchrotron SIS18 to transfer the beam losses from the synchrotron into the injection channel to avoid gas desoprtion.



Intensity plot



Current on charge exchange catchers.



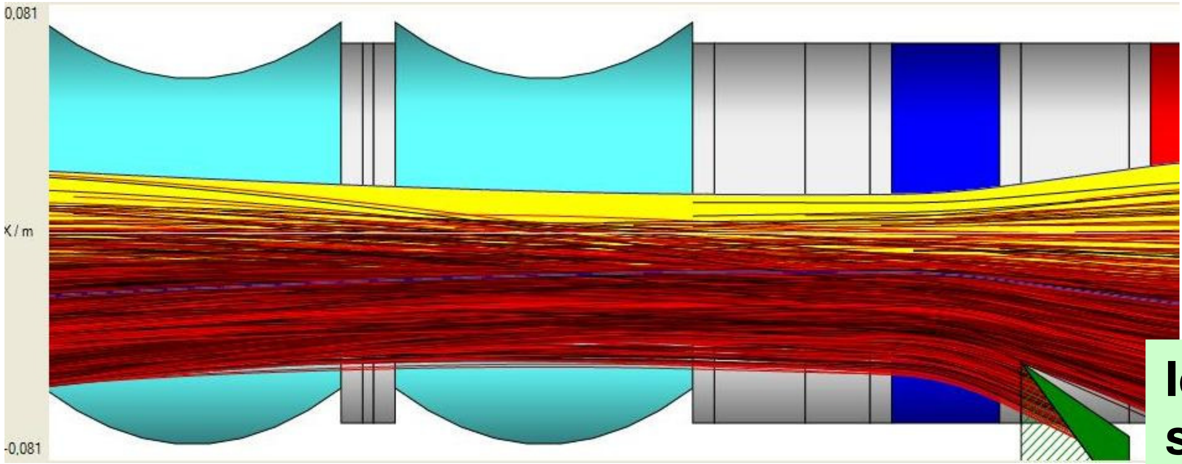
(by Y. el-Hayek)

SIS 100 Design: Special charge separator lattice for intermediate charge state operation

SIS 100 lattice optimized for minimum dynamic vacuum beam loss

Charge Separator Doublet Lattice with collimators

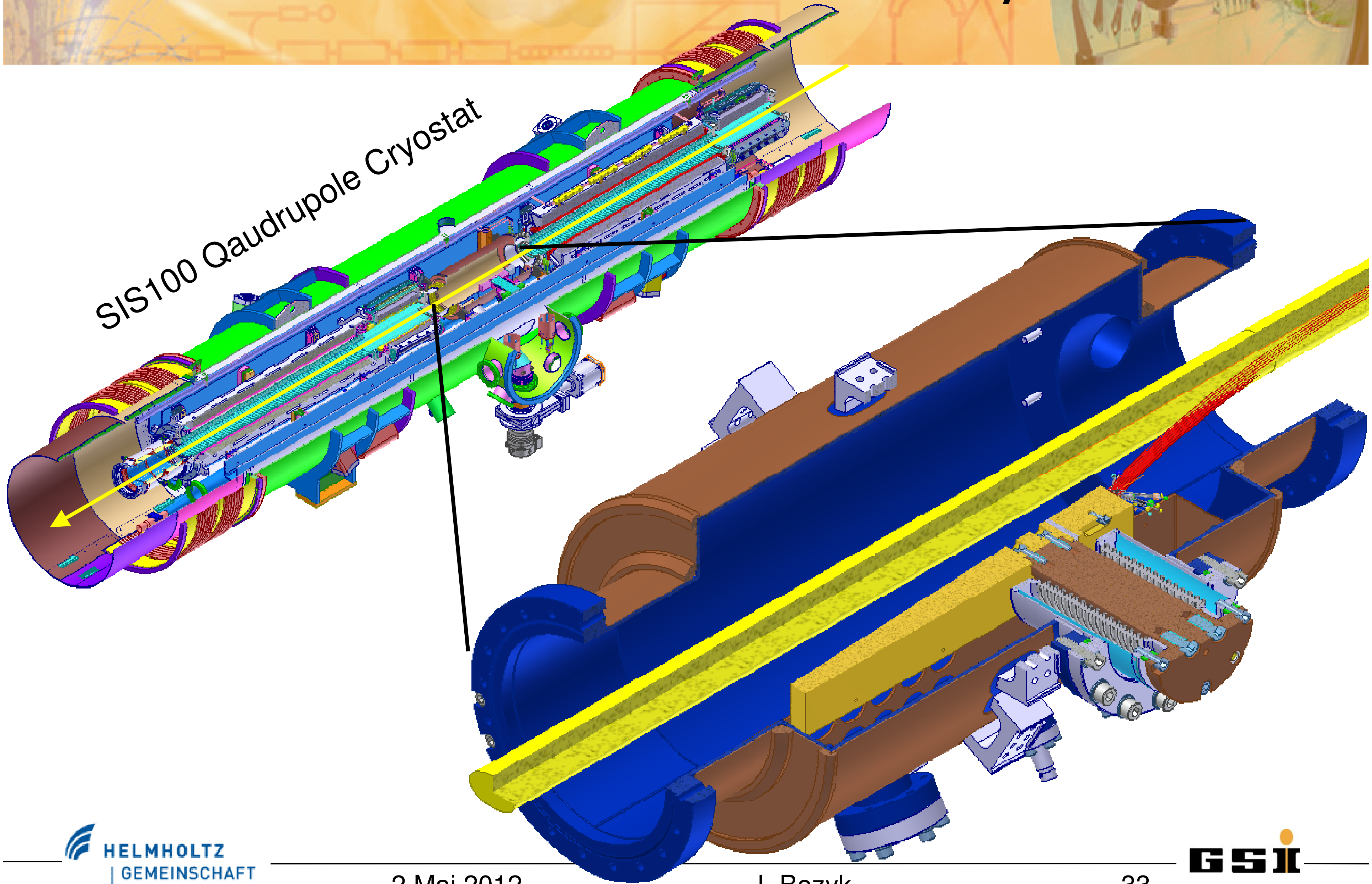
optimized for catching efficiency close to 100% for U^{29+}



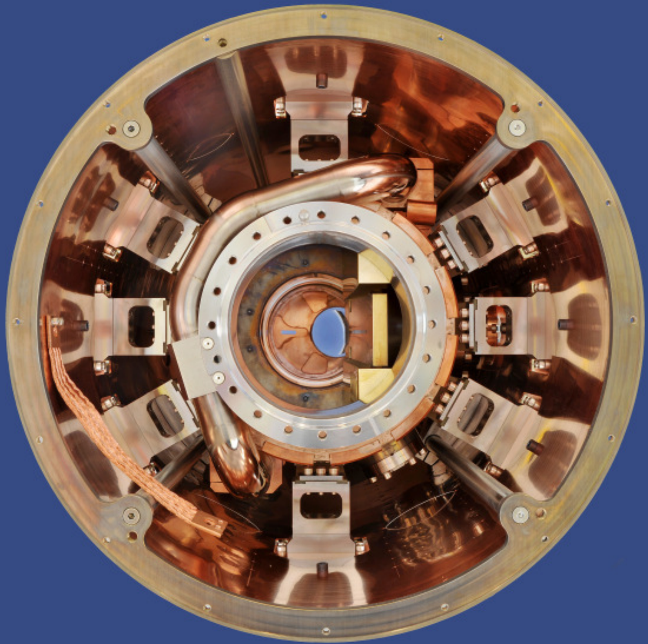
Ion catcher (at 50 K) in secondary chamber with enhanced pumping, confines most of desorbed gases

Minimum additional load for the UHV and the cryogenic system.

Ion catcher in the cold arcs: Cryo-Catcher



Cryo-Catcher prototype

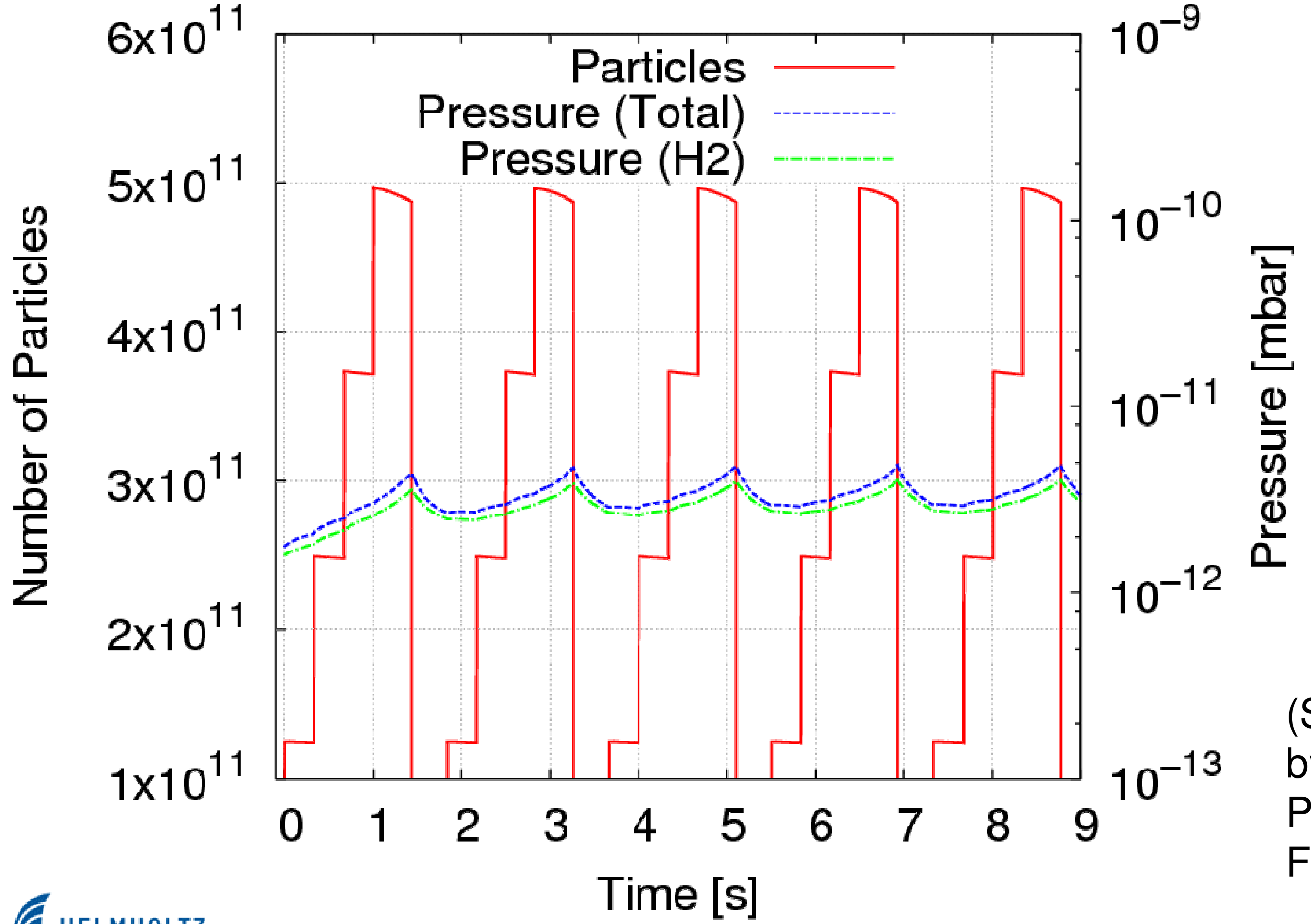


Prototype constructed and tested with beam from SIS18.

Funded by EU ColMat done by L. Bozyk et. al.

HELMHOLTZ GEMEINSCHAFT

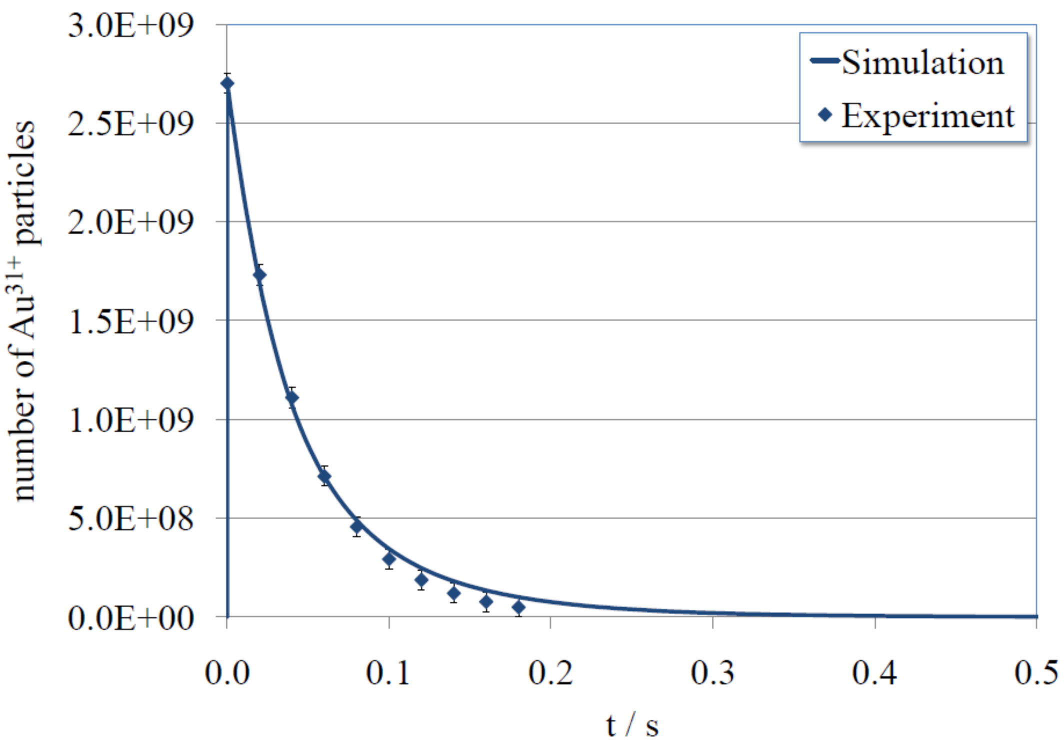
SIS100 cycle simulation



(Strahlsim code by C. Omet, P. Puppel and F. Chill)

Dynamic vacuum is a fundamental barrier for reaching higher ion intensities.

- LEAR @ CERN was suffering from DV effects and added collimators.
- Simulations with StrahlSim where confirmed by experiments at AGS @ BNL.
- StrahlSim calculations are us to design and upgrade the F/ accelerators.
- In one case the beam measurements from machine experiments could via StrahlSim be used to predict a vacuum leak.



Measuremet by C. Omet, P. Spiller and W. Fischer AGS, BNL, Au^{31+}

-> Dedicated talk by E. Mahner

Summary

- Synchrotrons: typically the ‘working horse’ in an accelerator chain.
- Average beam power up to 1 MW with RCSs (J-Parc, SNS)
- In fast ramping synchrotrons: Large peak power per cycle due to bunch compression.
- Intensity limitations in proton/ion synchrotrons:
  - At injection energy: Space charge tune spread and ring resonances (‘hard limit’).
  - At all energies: Coherent beam instabilities (not covered in this lecture)
  - At top energy: Beam loss induced activation of accelerator components
  - electron clouds (not covered in this lecture)
- Additional intensity limitations in heavy-ion synchrotrons:
  - Current from the ion source.
  - Efficiency of the multi-turn injection.
  - Charge changing processes with residual gas molecules.

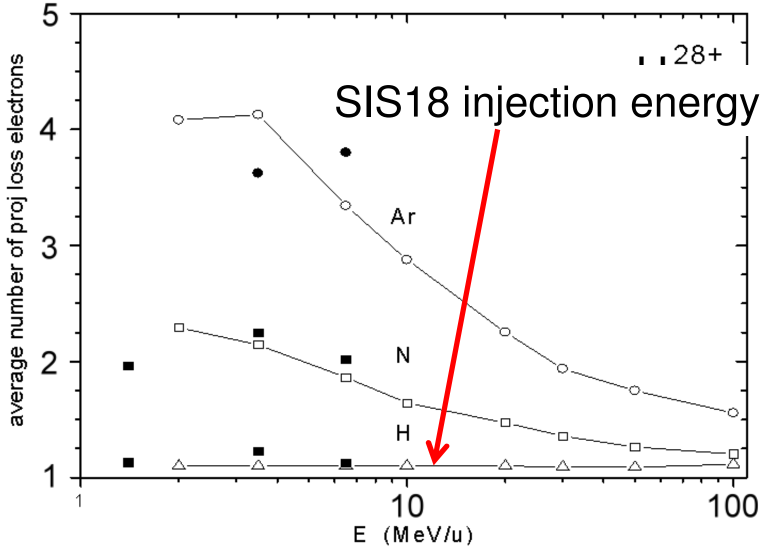
Thank you for your attention!

and to all the dedicated colleagues who let me steal their slides.

Cross Sections and Multiple Ionisation

- Life time measurements in SIS18
- Cross section measurements in ESR with internal gas target
- Lower cross sections for lighter ions
- Improved, relativistic atomics physics models and cross sections e.g. Shevelkov

R. Olsen et.al., HIF04



Multiple ionization reduces the scraper efficiency