SLOW EXTRACTION, THEORETICAL ASPECTS

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Aim of the talk: Presentation of some aspects of slow extraction from SIS-100.

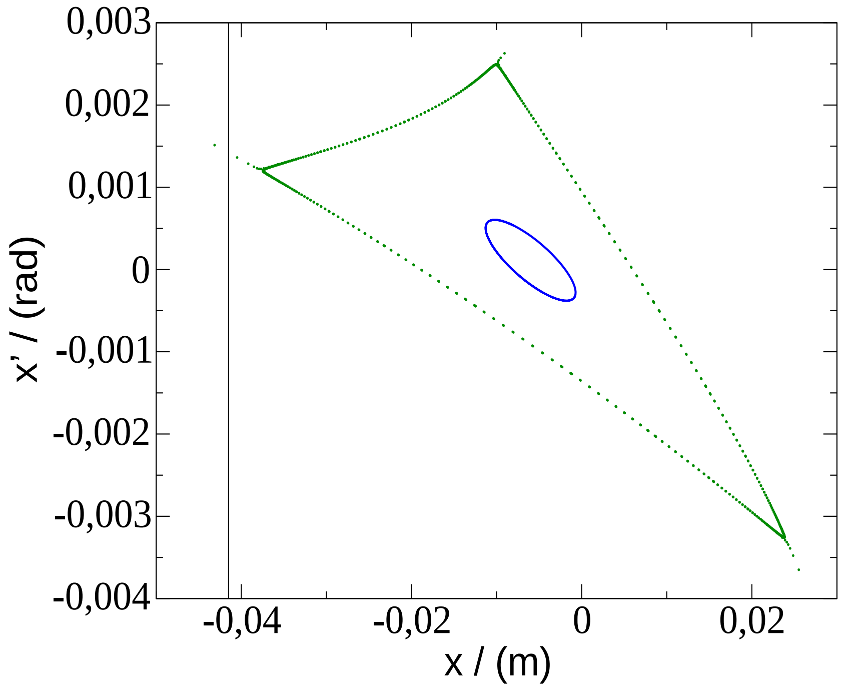
Major issues of theoretical modelling

1. Beam loss:
   - Concerns machine protection against irradiation and, hence, possibility of operation.
   - Causes: Magnets' field imperfections and high current effects.
2. Spill structure:
   - Concerns suitability of beam for users.
   - Ideal: constant spill without structure.

→ Both have to be minimised.

Slow extraction methods at GSI and FAIR

- Slow extraction:
  - excitation of third integer resonance with sextupole magnets leading to triangular horizontal phase space area.
  - beam size slowly exceeds triangle and particles successively leave beam.
- In GSI / FAIR two methods (planned to be) in use:
  - quadrupole driven extraction
    $\rightarrow$ at present in SIS-18
  - RF Knock-Out extraction
    $\rightarrow$ foreseen in SIS-100



Stable phase space area and beam

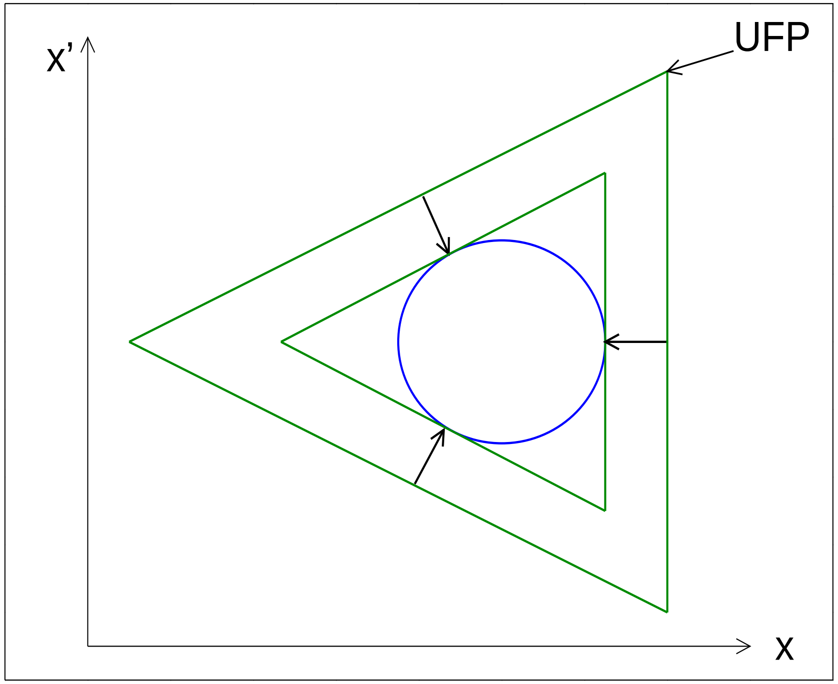
$E = 2.7\ \mathrm{GeV/u}$

Quadrupole driven extraction

- Shift machine tune to resonance tune, $Q_x \to Q_{x,res}$, with fast quadrupole magnet.
- Corners are Unstable Fixed Points (UFP) with

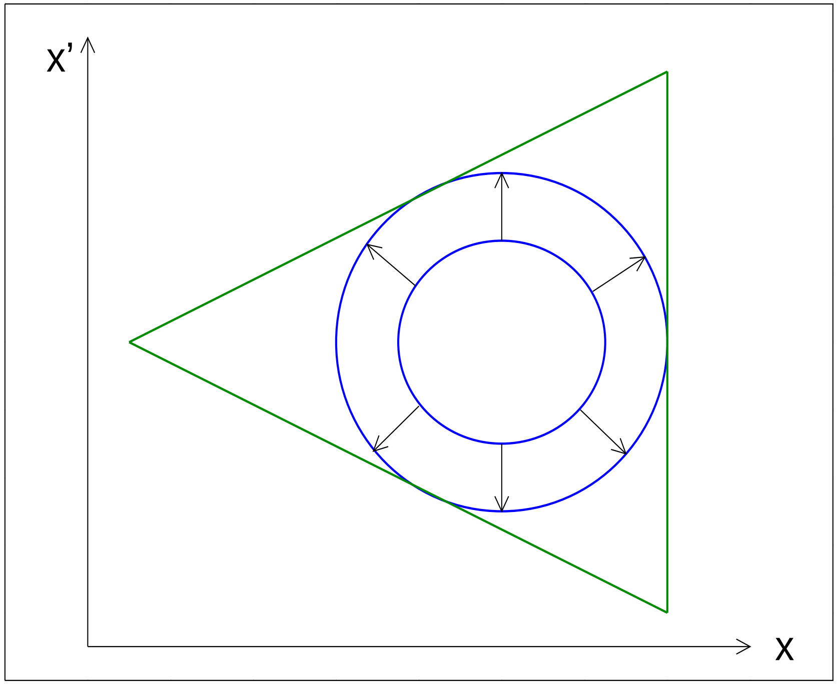
$$|\vec{x}_{UFP}| \propto |Q_x - Q_{x,res}|$$

- Stable phase space area shrinks below beam width.
- Particles become successively unstable.
- Advantage: Simple procedure.
- Disadvantage: Optics changes during extraction.



RF Knock-out extraction

- Excite beam using horizontal RF signal.
- Slow increase of horizontal beam size beyond the stable phase area.
- Particle become successively unstable and can be extracted.
- Disadvantage: need for a n RF Knock-out Exciter: RF device with power $\sim 1\ \mathrm{kW}$, where frequency and voltage amplitude can be very precisely set.
- Advantage: static optics.



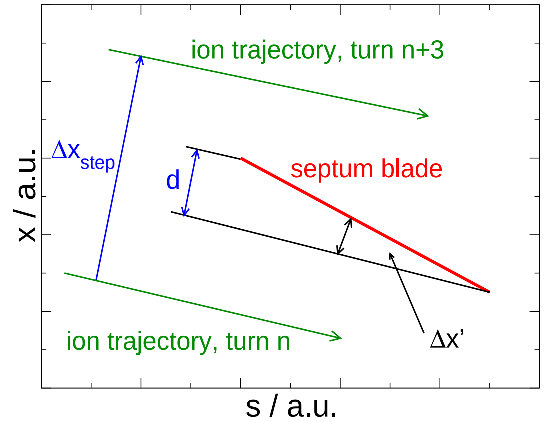
Beam loss estimate

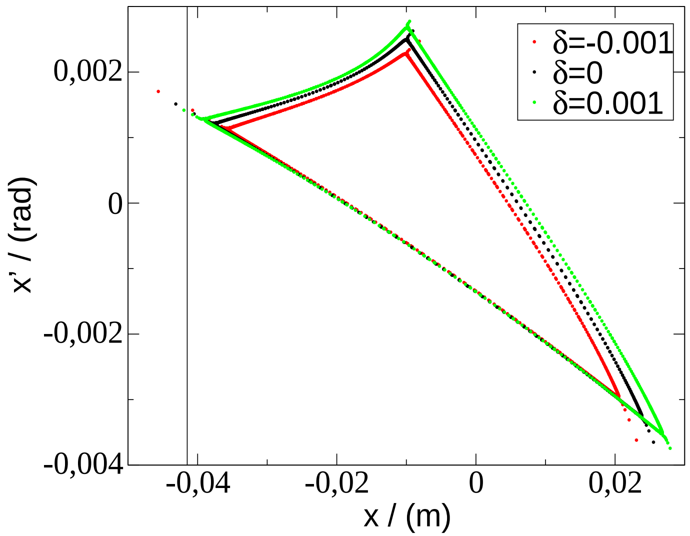
1st Step: Definition of lattice settings for the unperturbed machine (D. Ondreka)

Major criterion: Avoiding beam loss at Electro-Static Septum (ESS):

Optimisation of orientation of stable phase space area and spiral step to minimise cross section:

$$\sigma_{ESS} \propto |\Delta x'| = |x'_{sep} - x'|.$$





Momentum spread δ_p

$\rightarrow$ spread in x' of particles at ESS:

Dispersion D, D' $\rightarrow$ shift of stable phase space area

Chromaticity ξ_x $\rightarrow$ size of stable phase space area

Compensation with sextupoles (Hardt condition):

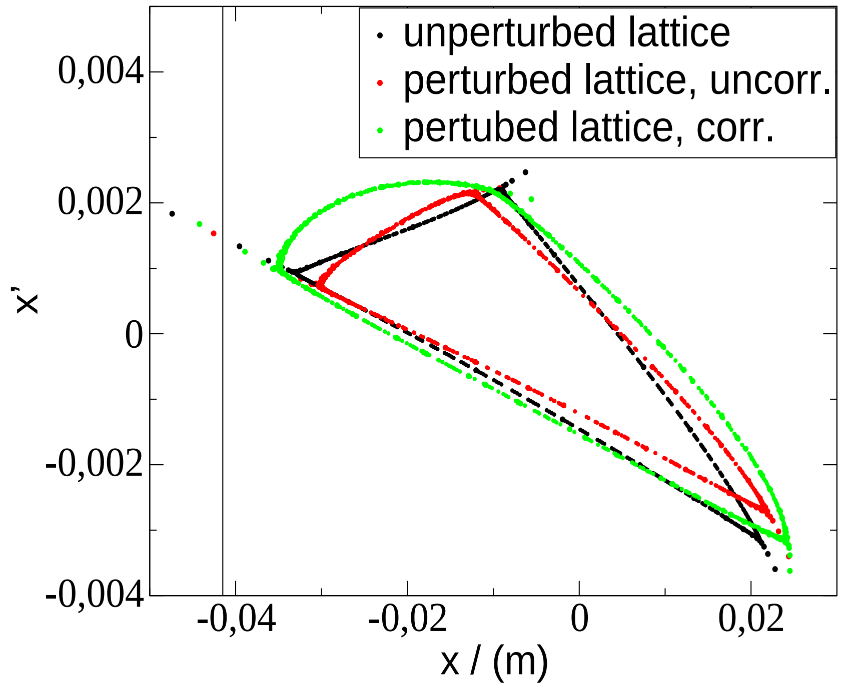
Set $\xi_x Q_x = -1$ and achieve no beam loss.

Beam loss estimate

2nd Step: Inclusion of Perturbations: SIS-100 $\rightarrow$ magnet field imperfections

Assume fields imperfections in dipoles and quadrupoles:

- Perturbations of closed orbit.
- Resonance excitation
  $\rightarrow$ deformation of stable phase space area.



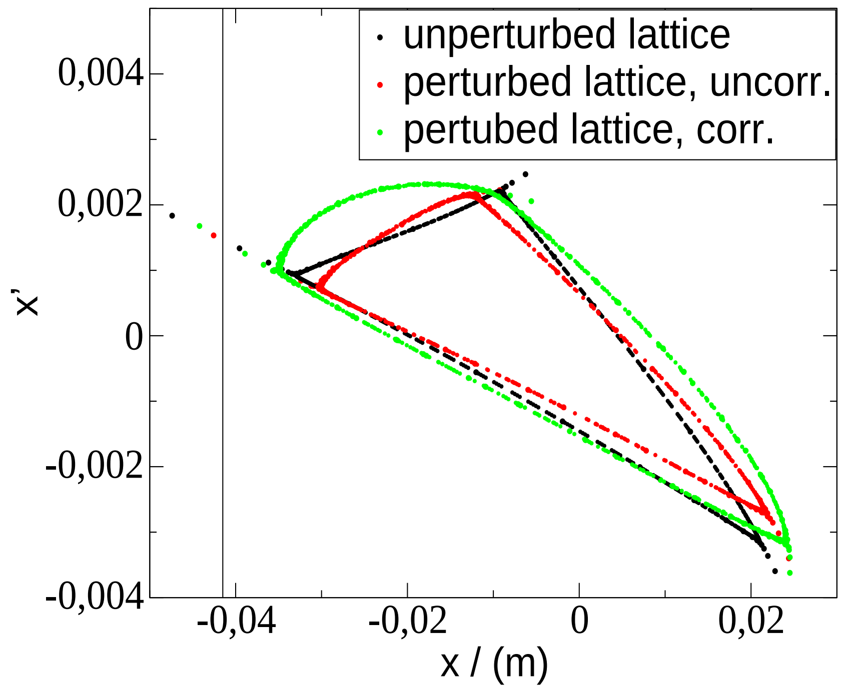
Particle loss estimated with multi-particle tracking:

- Correct inclusion of all physical apertures.
- With magnet errors large particle loss $\sim 10\ \%$ along whole ring because spiral step strongly increased.
- Can be reduced to a $\sim 1\ \%$ due to lattice corrections. Major ingredient: weaker resonance sextupoles.

Beam loss estimate

Remark:

Beam loss reduction based on very precise optimisation of the lattice settings and knowledge of lattice at computer. Hence, obtained beam loss relies on agreement of model with future real machine. Intrinsic uncertainties in



- lattice functions.
- phase space angle x' of particles at septum position.
- magnet imperfections with random contributions.

$\Downarrow$

1. Results show possibility of beam loss reduction in principle and knobs to be optimised.
2. Random magnet imperfections $\rightarrow$ only statistical statement, application of many error sets.

Intensity effects

Incoherent and coherent effects:

1. Incoherent effect:
   - Defocusing due to space charge of beam.
   - Effect important near beam centre → expect weak influence on slow extraction[1].
2. Coherent effects:
   - Based on dielectric effect: beam interaction with e.g. image charges in beam pipe or electron clouds[2].
   - Drives coherent beam oscillations, become unstable if threshold is exceeded and oscillation not damped.

     → beam position uncertain near ESS.

     → beam destruction.

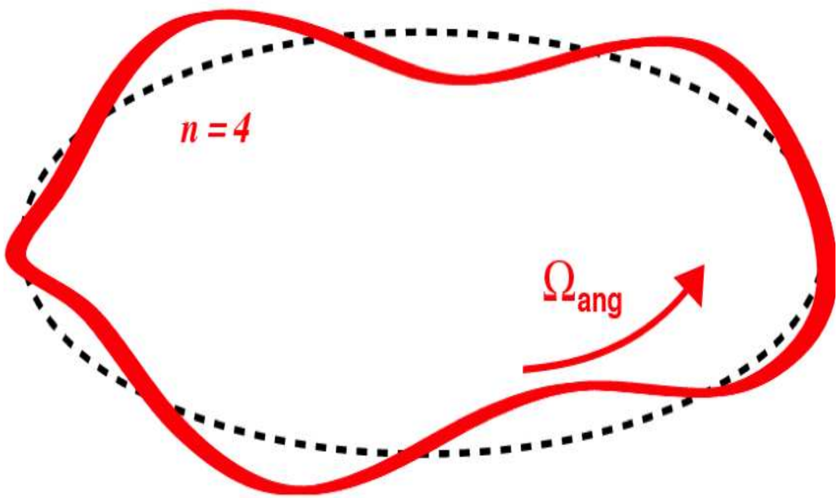


Figure: V. Kornilov.

[1] S. Sorge, Proc. of HB workshop 2010, Morschach, Switzerland.
[2] F. Petrov and O. Boine-Frankenheim, NIM-A 723 (2013).

Intensity effects

Beam instabilities, example

- Instabilities damped by Landau damping: spread in betatron frequencies due to momentum spread:

$$\Delta Q_{\xi,z} = |\eta(n - Q_{z,0}) + Q_{z,0}\xi_z| \; \delta_p, \quad z = x, y$$

with phase slip factor η, mode number n, chromaticity ξ_z, and momentum spread δ_p.

- SIS-100 conditions: Beam with $5 \cdot 10^{11}$ U^{28+} ions, $\delta_{p,rms} = 5.0 \cdot 10^{-4}$.
  - Most dangerous: horizontal resistive wall mode with $n = 18$ $(f = 170\ \mathrm{kHz})$.

    $\rightarrow$ unstable if $|\xi_x Q_x| < 1.5$ (V. Kornilov).

    $\rightarrow$ But, requirement to chromaticity correction from Hardt condition: $|\xi_x Q_x| = 1.0$.
  - Transverse feed-back system $\rightarrow$ additional noise.
  - If possible, slow extraction method with less chromaticity correction

    $\rightarrow$ subject of further beam dynamics studies.

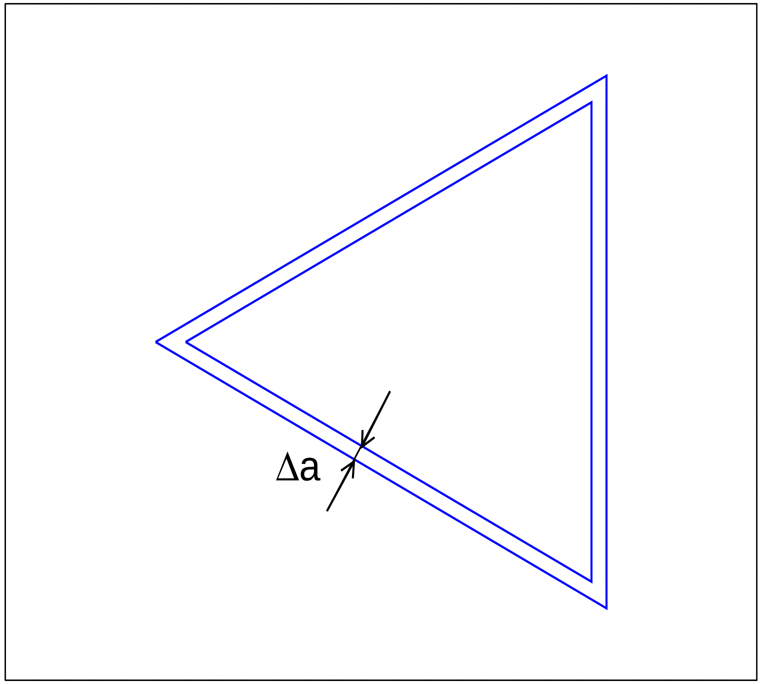
Micro spill structure

Spill structure:

- “Macro” spill structure: global spill with time structures ~ 1 sec:
  - Regulation of fast quadrupole or RF Knock-out voltage.
- Micro spill structure: time structure < 1 msec.
  - Status of studies concerning SIS-100 at the very beginning.
  - Two mechanisms important according to literature and studies for SIS-18:
    $\rightarrow$ Ripple in field of magnets.
    $\rightarrow$ Time structure of RF Knock-out signal used in SIS-18.

Micro spill structure, field ripple

- Origin: ripple in the power supplies of
  - Main magnets.
  - Fast quadrupole: quadrupole driven extraction.
- Consequence:
  - Machine tune oscillates by ΔQ_x.
  - Edge of stable phase space area oscillates by Δa.
  - Corners are unstable fixed points of betatron motion, i.e. slow betatron motion



- Accumulation of particles near fixed points which become suddenly unstable and leave beam in "micro-bunches" $\rightarrow$ time structure with frequency $\sim$ 1 kHz.
- Goal: Find way to push particles faster across edge of stable phase space area.

Micro spill structure, field ripple

Additional remarks:

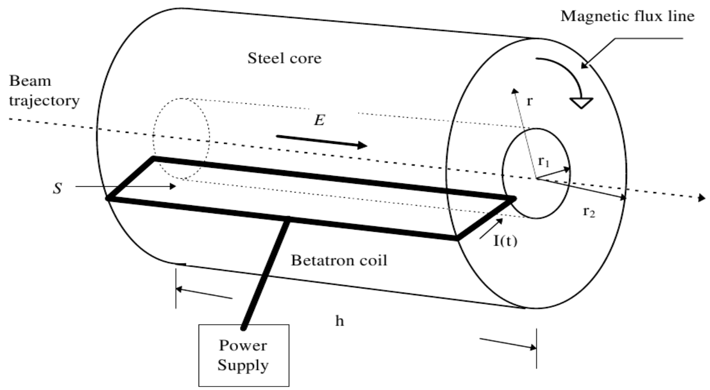
- Field ripple in main magnets: effect scales with total tune, because

$$\text{tune ripple } \Delta Q_x \propto Q_x$$

$$\Delta a \propto |Q_x + \Delta Q_x - Q_{x,res}|$$

$\rightarrow$ larger effect for larger total tune.

- Investigation of alternative scenarios:
  - acceleration driven extraction: betatron core[1,2].
  - stochastic excitation extraction[3].



Betatron core, $mass \approx 20$ tons

(Figure: L. Badano and S. Rossi[2])

[1]L. Badano *et al.* NIM-A 430 (1999), [2]L. Badano, S. Rossi, CERN/PS 97-19 (1997), [3]S. van der Meer, CERN/PS/AA 78-6 (1978)

Micro spill structure, RF Knock-out signal

SIS-18: Pseudo-random phase shift keying signal:

$$V(t) \propto \sin(2\pi f_C t + \phi)$$

- $f_C = (Q_{x,frac} + Q_{x,frac,res})/(2T_0)$ – carrier frequency
- $\phi = 0, \pi$ – pseudo-random phase according to pseudo-random sequence of bit states $0, 1$. Bit rate f_{bit} is adapted to required width of power spectrum.

$$f_{bit} \sim (10^3 ... 10^4)\ \mathrm{Hz}.$$

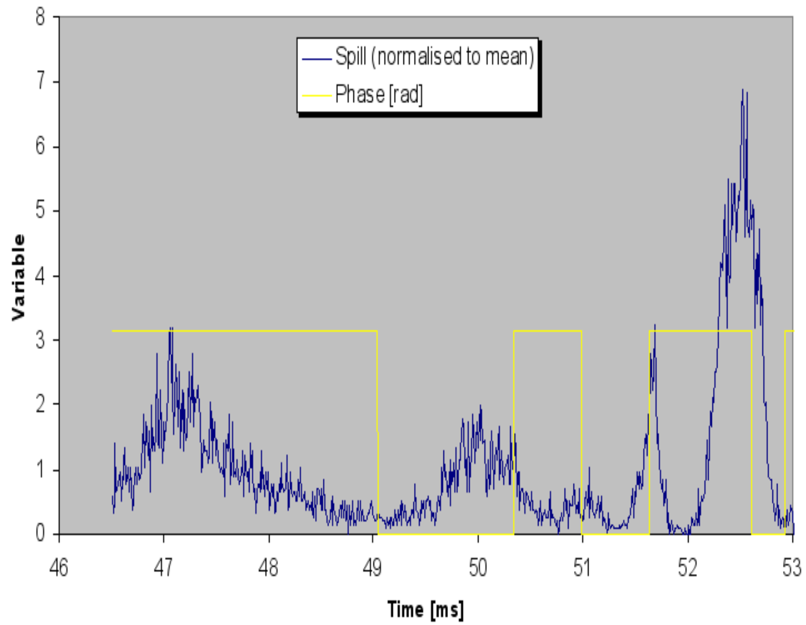


Figure: M. Kirk.

Correlation between extraction rate and bit status found in simulations (M. Kirk for SIS-18, S. Bracht for HIT synchrotron). Better behaviour with other noise types found.

$\rightarrow$ Investigation of other noise types also for SIS-100.

Summary

- Beam loss due to magnet imperfections on acceptable level.
- High current effects: ongoing work to identify constraints to settings and scenarios.
- Investigation of micro spill structure for SIS-100 slow extraction at beginning stage:
  - Evaluation of presently planned scenario (RF Knock-out extraction).
  - Check applicability of alternative techniques.
  - Many open questions.
  - Will be subject of workshop in June 2016.

Presented material represents work of whole PBBP department,

in particular G. Franchetti and V. Kornilov,

and from PBSP department

M. Kirk and D. Ondreka.