OUTCOME OF THE EuCARD-2 SLOW EXTRACTION WORKSHOPS

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Motivation for slow extraction workshops

With beginning of 2016, several activities and events to generate discussion on requirements of experiments of GSI and FAIR among experimenters and accelerator physicists:

- Two GSI internal HIC4FAIR follow-up workshops with focus on many topics. Spill quality in reality and required by detectors of experimenters was one topic among others.
- First slow extraction workshop. Idea:
  - benefit from worldwide expertise.
  - comparison, in particular, of spill quality with other facilities.
- Second slow extraction workshop at CERN in November 2017 to follow up work on slow extraction issues.
- First workshop: 27 talks, 5 from medical facilities
- Second workshop: 35 talks, 3 from medical facilities.

Main topics

- Most talks on beam loss reduction and spill quality improvement.
- Beam loss reduction more important for machines with high beam energy and intensity. Examples:
  - Dynamic bump and Hardt Condition to adapt dynamically separatrix to ES septum, e.g.
    talk M. Tomizawa (J-PARC) on Main Ring, Slow Extraction Workshop 2016.
    talk L. Stoehl (CERN) on CERN-SPS, Slow Extraction Workshop 2017.
  - Massless septum to avoid particle loss at ES septum, e.g.
    talk K. Brunner (CERN) on CERN-SPS, Slow Extraction Workshop 2017.
- Medical accelerators: rather moderate energies and intensities. Hence topic less critical. Instead spill quality is essential.

Spill quality

Spill structure: important topic for medical synchrotrons.

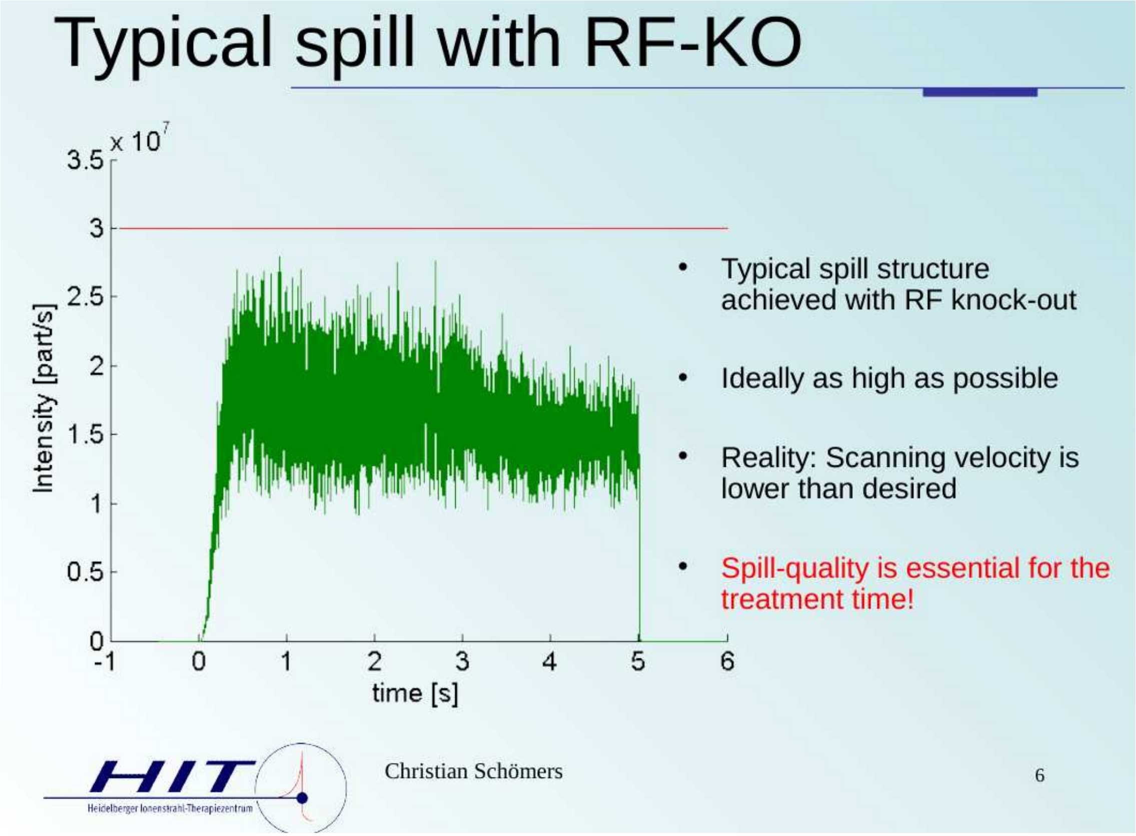

Figure: C. Schömers, slow extraction workshop 2016.

- Spill structures create intensity peaks.
- Lower average intensity.
- Longer irradiation time.
- More exhausting for patient and lower efficiency of device.

Spill quality

- Distinguish spill structures according to duration:

  1. "macro" structure $t_{struct} \sim 1$ s ... 10 ms:
     Important for all synchrotrons, reduction in medical facilities by spill regulation systems, i.e. basically feed back systems.
  2. "micro" structure $t_{struct} \sim 10$ ms ... 1 μs:
     - Important for all synchrotrons.
     - Field ripple in magnets arising from power supply ripple assumed to be major source.
     - Several techniques for reduction.
  3. "nano" structure $t_{struct} < 1\ \mu$s:
     - Not critical for medical accelerators.
     - Important for detectors of many particle experiments. Was a topic of experimenters talks during and motivation for first workshop in 2016, see talk of J. Pietraszko on "The HADES/CBM physics case requirements".

Spill quality

Examples for techniques developed to reduce micro spill structures:

- Improved magnet power supply configuration to lower magnetic field ripple, e.g.
  talk K. Brown (BNL) on AGS, Slow Extraction Workshop 2016.
- Empty bucket channelling, e.g.
  talk K. Brown (BNL) on AGS, Slow Extraction Workshop 2016.
- Stochastic extraction, i.e. resonant longitudinal rf noise excitation of the beam, e.g. talk H. Stockhorst (FZ Jülich), Slow Extraction Workshop 2016.
- Extraction of bunched beams, e.g.
  talk P. Forck (GSI), Slow Extraction Workshop 2016.
  talk P. Schmid (GSI), Slow Extraction Workshop 2017.
- Betatron core e.g.
  talk M. Pullia (CNAO) on MedAustron and CNAO, Slow Extraction Workshop 2016.
- Air coil quadrupole to counteract spill ripple of beam due to magnetic field ripple, e.g.
  talk M. Pullia (CNAO) on MedAustron and CNAO, Slow Extraction Workshop 2016.
  talk C. Krantz (MIT), Slow Extraction Workshop 2017.

Active scanning methods

- All medical facilities with participants at Slow Extraction Workshops (CNAO, HIMAC, HIT/MIT, MedAustron) with synchrotron as main device.
- Use active scanning method to deposit energy precisely in tumour, as mentioned in many talks:
  - Procedure based on precise placing of energy deposition defined by Bragg peak in any part of human body.
  - Requires very precise energy setting of device in wide energy range which is provided by synchrotrons
    $\rightarrow$ major advantage of synchrotrons.

Comparison of measured spills

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Using the data provided in the indico web site of "The Slow Extraction Workshop" the following table is constructed.

Institution Name 1	PPBrms/ PPBave 1 ms bin 2	Particles per 1 ms bin 3	PPBrms/ PPBave Original bin 4	Particles per original bin 5	Spill duration (sec) 6	Total particles Per Spill 7	Original Bin (ms) 8	Efficiency 9	Beam type, Remarks 10
CERN, M. Fraser	0.157	1.0e10	0.158	4.0e9	4.0	4.0e13	0.4	98%	proton, unbunched
MIT, C. Krantz	0.166	34000	0.250	1700	8.0	2.72e8	0.05		ion (C12+), bunched KO
BNL, K. Brown	0.188	3.17e10	0.208	1.27e9	2.4	7.6e13	0.04	98 %	proton, empty 93 MHz bucket at 5 kV
HIT, C. Schoemers	0.210	30000	0.305	1500	5.0	1.4e8	0.05	C: 65%, P: 60%	ion (C12+), bunched KO
FJZ, H. Stockhorst	0.279	3700	0.279	3700	3.5	1.3e7	1.0	98%	proton, unbunched stochastic
IHEP, S. Ivanov	0.329	(1.5-7.5)e8	0.448	6.0e7 – 3.0e8	1.35	(2-10)e12	0.04	90 – 94%	proton, unbunched stochastic
GSI, P. Forck	0.334	900	0.575	18	1.55	1.4e6	0.02		ion, bunched KO
MedAustron, A.Wastl	0.541	3.6e6	0.901	72000	5.0	1.8e10	0.02	80 %	proton, unbunched with betatron core
BNL, K. Brown	0.565	3.88e10	0.870	1.55e9	1.6	6.2e13	0.04	98 %	proton, no empty bucket filtering, random noise, no power supply harmonics
J-PARC, M. Tomizawa	0.637	2.3e10	0.911	2.3e8	2.1	4.774e13	0.01	99.5 %	proton, unbunched
GSI, P. Forck	0.642	550	0.806	11	2.0	1.1e6	0.02		ion, bunched resonant
GSI, P. Forck	0.726	1000	1.40	20	2.1	2.1e6	0.02		ion, unbunched resonant
FZJ, H. Stockhorst	1.11	1400	1.11	1400	3.0	4.3e6	1.0	98%	proton, resonant extr.

Result of Slow Extraction Workshop 2016: Spill comparison.

Spills characterised by:

$$\frac{\text{PPBrms}}{\text{PPBav}} \equiv \frac{\Delta N_{bin,rms}}{N_{bin,av}}$$

13 spills in table. Wide range of bin duration: $t_{bin} \in [0.01, 1.0]$ ms

→ Average of short bins in longest bin duration $t_{bin} = 1.0$ ms to make spills comparable.

Comparison of measured spills

- $\mathrm{PPBrms/PPBav}$ varies in range $0.16, \ldots, 1.1$.
- Three spills from medical facilities:

facility	$\mathrm{PPBrms/PPBav}$ 1 ms/orig. bin	orig. bin duration ms	measurement details
MIT	$0.17/0.25$	0.05	C^{12+} ions bunched, rf-ko extr.
HIT	$0.21/0.30$	0.05	C^{12+} ions bunched, rf-ko extr.
MedAustron	$0.54/0.90$	0.02	protons unbunched, betatron core

  – Keep in mind uncertainty of results, e.g. due to unknown particle detectors.

  – rf-ko extraction gives better spills than betatron core.
  Possibly because extraction of bunched beams gives spill improvement, see spills 11 and 12 in table: GSI resonant extraction of bunched and unbunched ion beams.

- Unfortunately, no spill from HIMAC and CNAO $\rightarrow$ further example for rf-ko extraction using different ko signal (HIMAC) and betatron core (CNAO).

More information on the web pages of both slow extraction workshops:

- Darmstadt 2016:

  `https://indico.gsi.de/event/4496/timetable/#all.detailed`

- CERN 2017:

  `https://indico.cern.ch/event/639766/timetable/#all.detailed`

Thank you for your attention