Simulations of Slow Extraction in SIS-18

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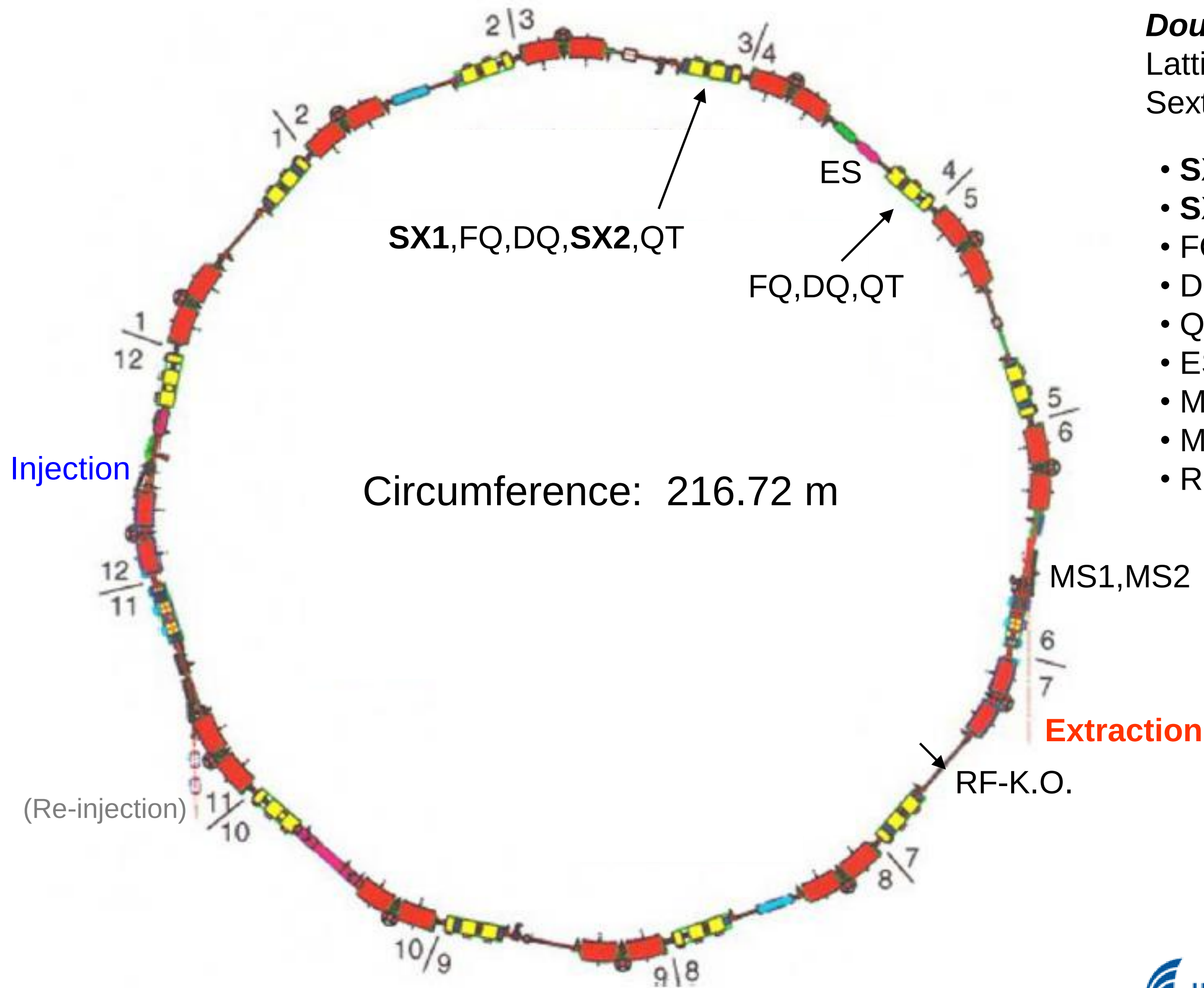
Overview

- Theory pertaining to slow RF KO extraction as employed in the existing SIS.
- Simulation results of RF KO schemes: Dual FM and BPSK.
- Simulation of Knock-Out in the presence of ripple in the current through the dipole series circuit and transverse white noise beam excitation.
- Various measurements.
- Summary.

SIS-18 at a Glance

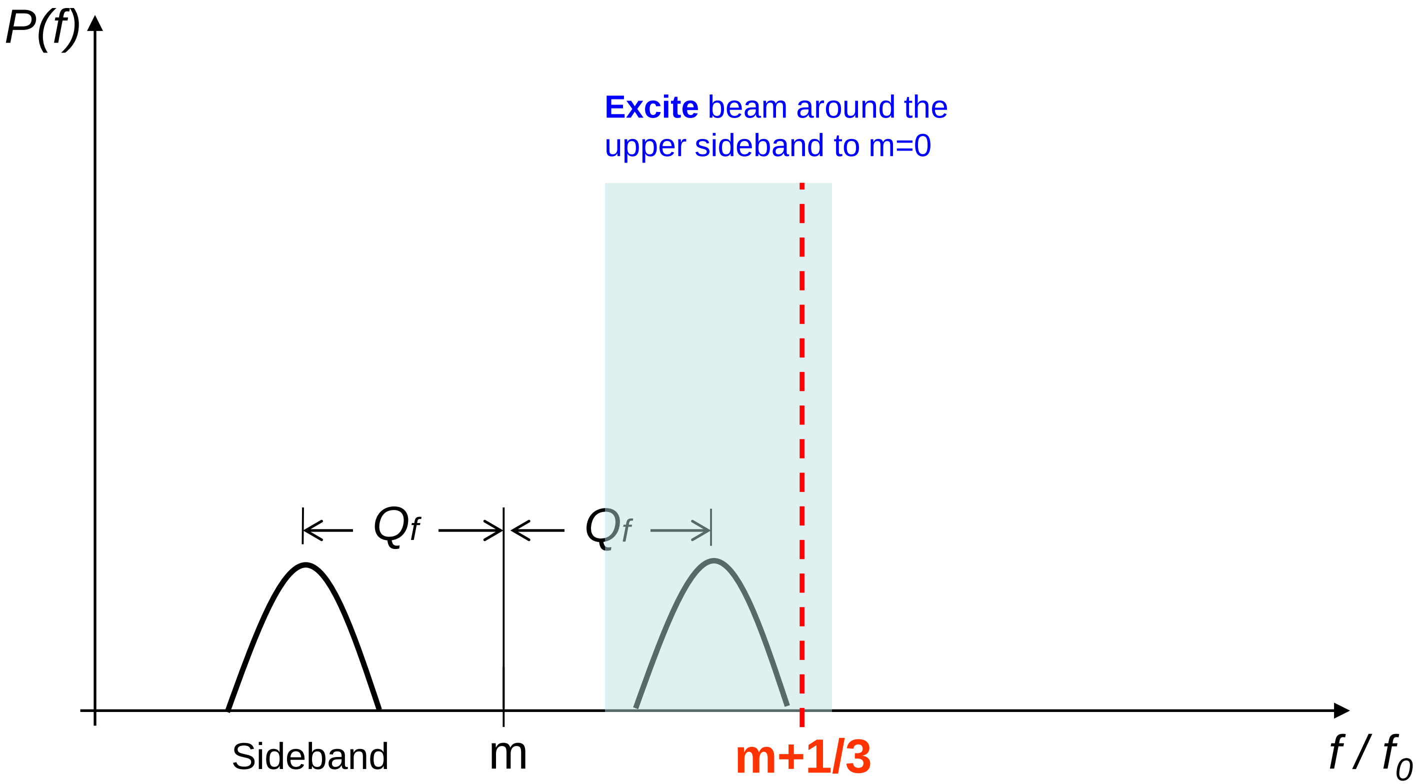


Doublet lattice
Latticle *periodicity*: 12
Sextupoles (SX) in odd periods

- **SX1** = Res. + Hor. Chro.
- **SX2** = Ver. Chro.
- FQ = Horizontal Focusing Quad.
- DQ = Horizontal Defoc. Quad.
- QT = Triplet Quad.
- ES = Electrostatic Extr. Sept.
- MS1 = First Extr. Mag. Sept.
- MS2 = Second Extr Mag. Sept.
- RF-K.O. = RF Knock-Out Exciter

RF Knock-Out Extraction

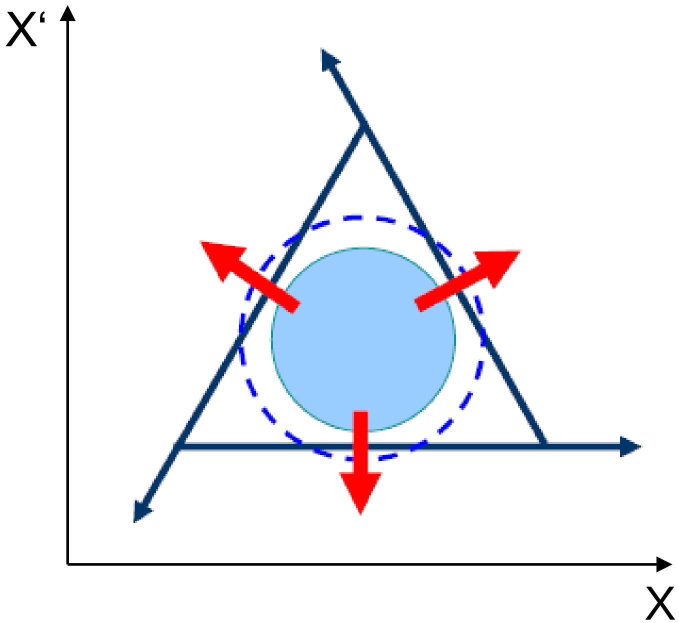
Transverse *Schottky* Spectrum:



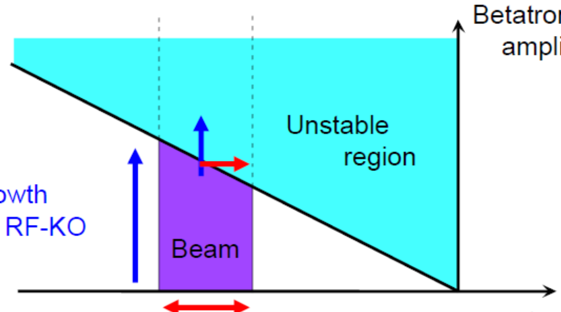
(Beam revolution frequency f_0)

RF Knock-Out Extraction

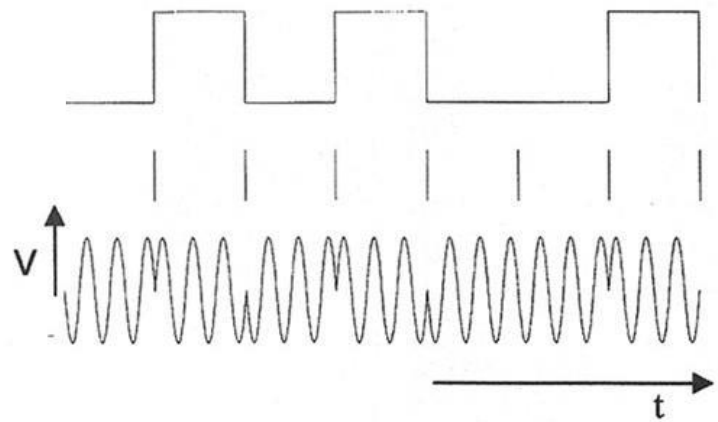
Diffusion by ***transverse RF-field***



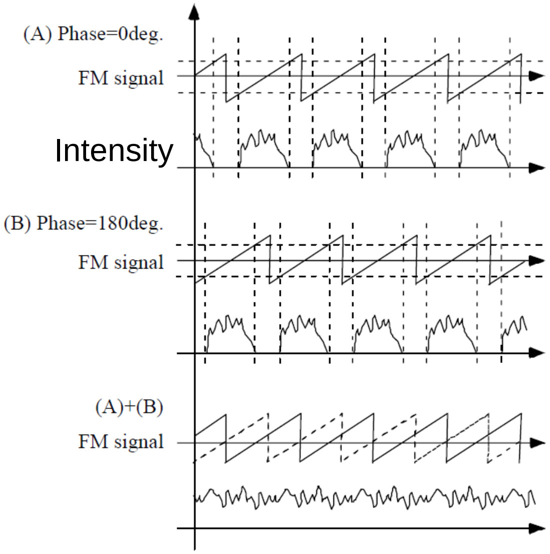
Longitudinal motion contributes to extraction through horizontal chromaticity.



BPSK (GSI, Darmstadt)



Dual FM (HIMAC, Chiba)



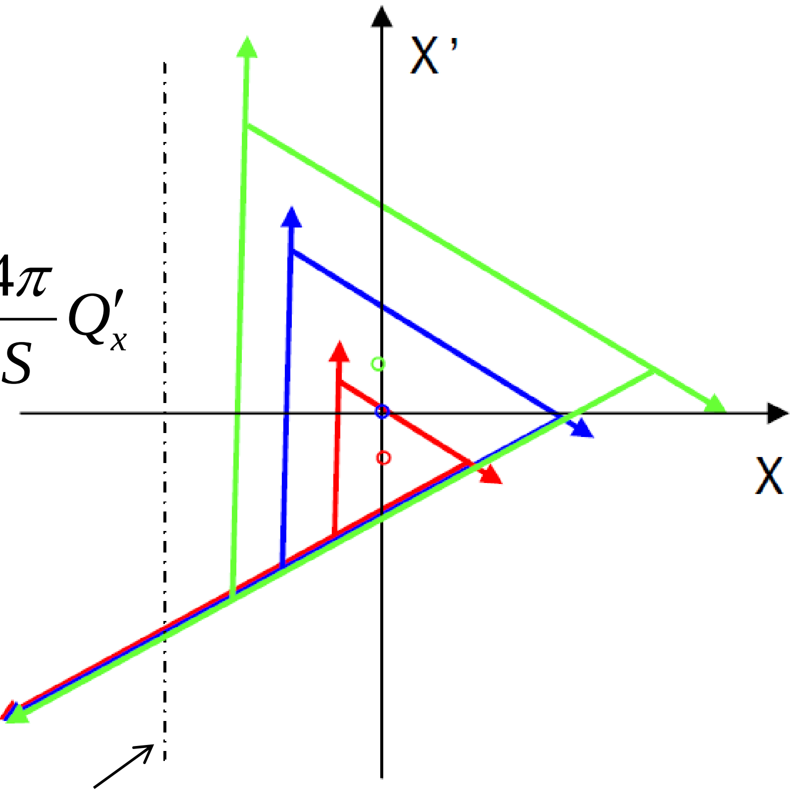
Separate Function method is yet another improvement.

After Noda, Furukawa

Hardt Condition

* Shifts in the separatrix positions due to chromaticity (Q‘) and dispersion (D, D‘) can result in alignment of the extraction arms leading to the septum.
* Optimum extraction efficiency obtained this way.
* Separatrices plotted below are for 3 particle momenta.

$$D_n \cos(\alpha_0 - \Delta\mu) + D_n' \sin(\alpha_0 - \Delta\mu) = -\frac{4\pi}{S} Q_x'$$



(W. Hardt, CERN)

Chromaticity Correction in SIS-18

Sextupoles change the chromaticity:

$$Q'_x - Q'_{x,nat} = -\frac{1}{4\pi}\int_0^C K_{sexts}(s)\beta_x(s)D_x(s)ds$$

$$Q'_y - Q'_{y,nat} = +\frac{1}{4\pi}\int_0^C K_{sexts}(s)\beta_y(s)D_x(s)ds$$

Optical functions $\beta(s)$ and $D(s)$ are same at each sextupole. Therefore;

$$K_{2,1C} = \frac{4\pi}{L_{eff,1C}N}\frac{\beta_{x,3C}\left(Q'_y - Q'_{y,nat}\right) + \beta_{y,3C}\left(Q'_x - Q'_{x,nat}\right)}{D_{x,1C}\left(\beta_{x,1C}\beta_{y,3C} - \beta_{y,1C}\beta_{x,3C}\right)}$$

$$K_{2,3C} = \frac{4\pi\left(Q'_x - Q'_{x,nat}\right) + ND_{x,1C}\beta_{x,1C}K_{2,1C}L_{eff,1C}}{L_{eff,3C}ND_{x,3C}\beta_{x,3C}}$$

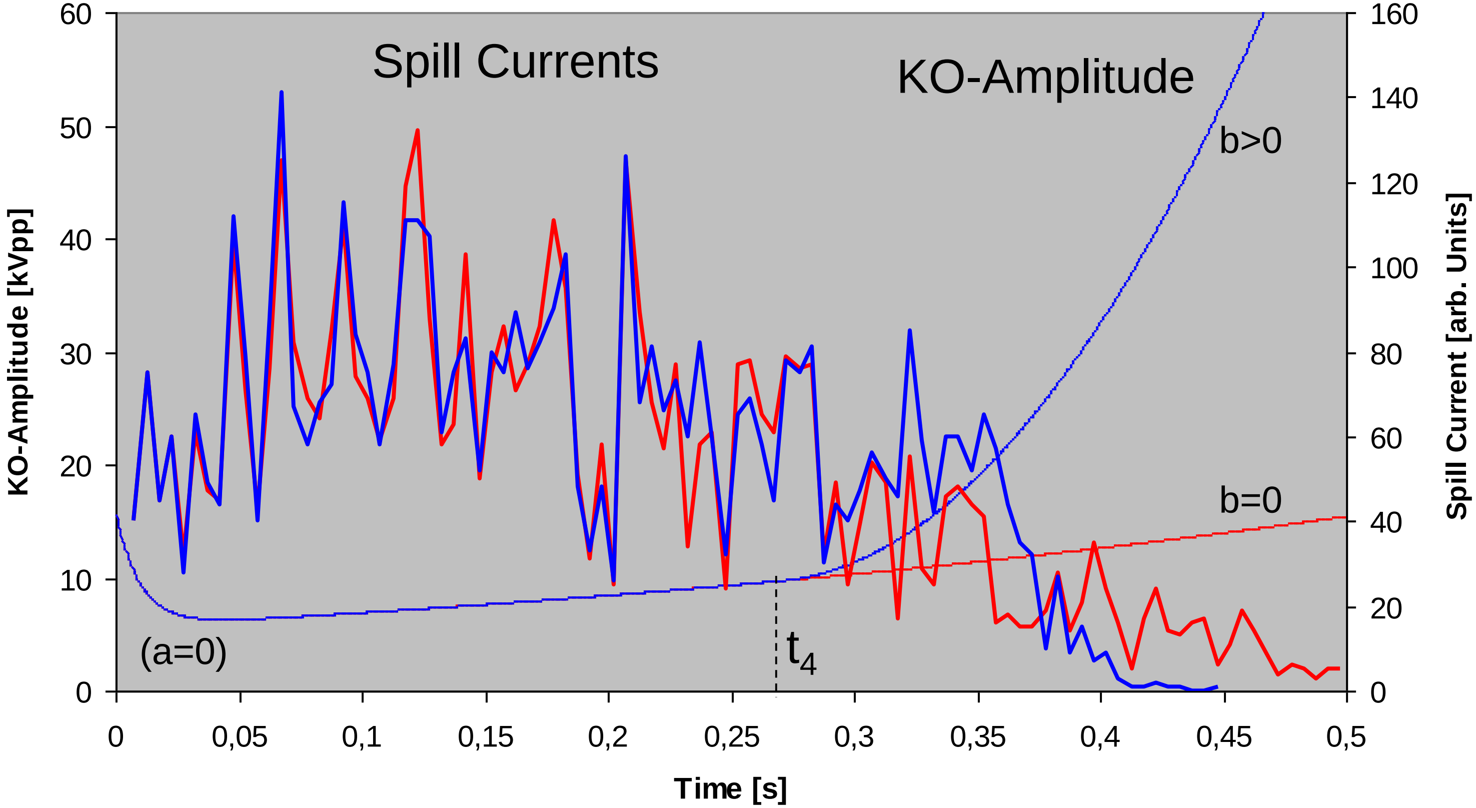
Natural chromaticity: Q'_{nat}

Adjusted chromaticity: $Q' = \frac{dQ}{d\delta}, \quad \delta = \frac{\delta p}{p_0}$

N = number of *1C*-Sextupoles = number of *3C*-Sextupoles

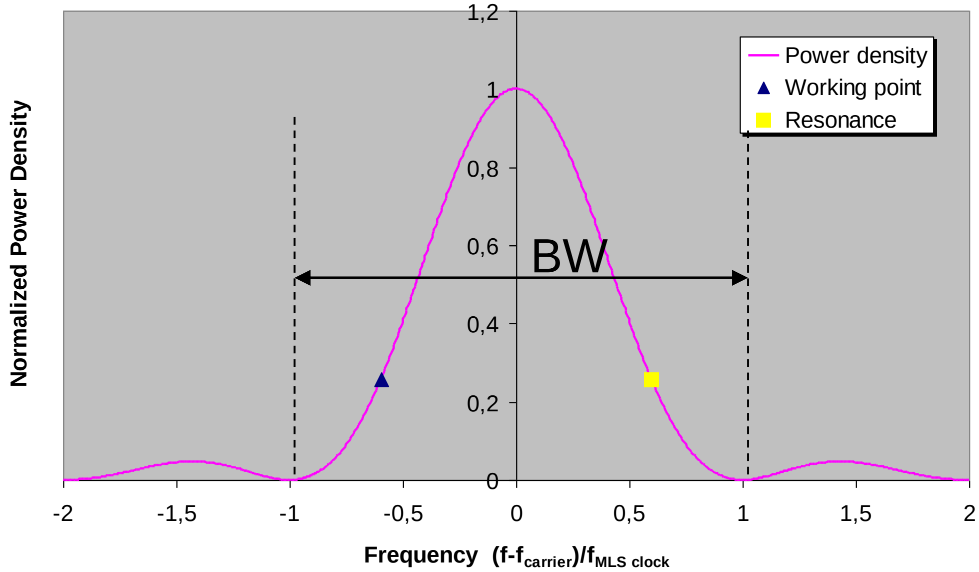
Beam Intensity Control

SIS-100 $^{238}U^{28+}$ 100Tm:

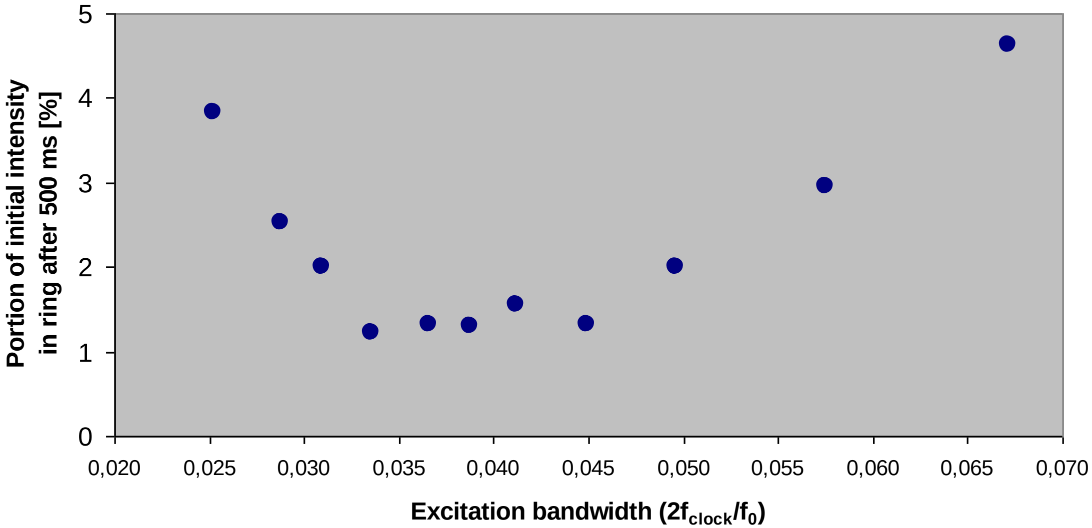


$$t_3 < t_4 : \quad V_{KO} = \left(U_1 - \frac{U_2}{e} \right) e^{-\frac{t}{\tau_1}} + \frac{U_2}{e} e^{\frac{t}{\tau_2}} + at^2 H(t_3 - t) + bt^2 H(t - t_4)$$

Optimising the RF Knock-Out Bandwidth



$$G(f) = AT_S \left[\frac{Sin(\pi(f - f_C)T_S)}{\pi(f - f_C)T_S} \right]^2$$



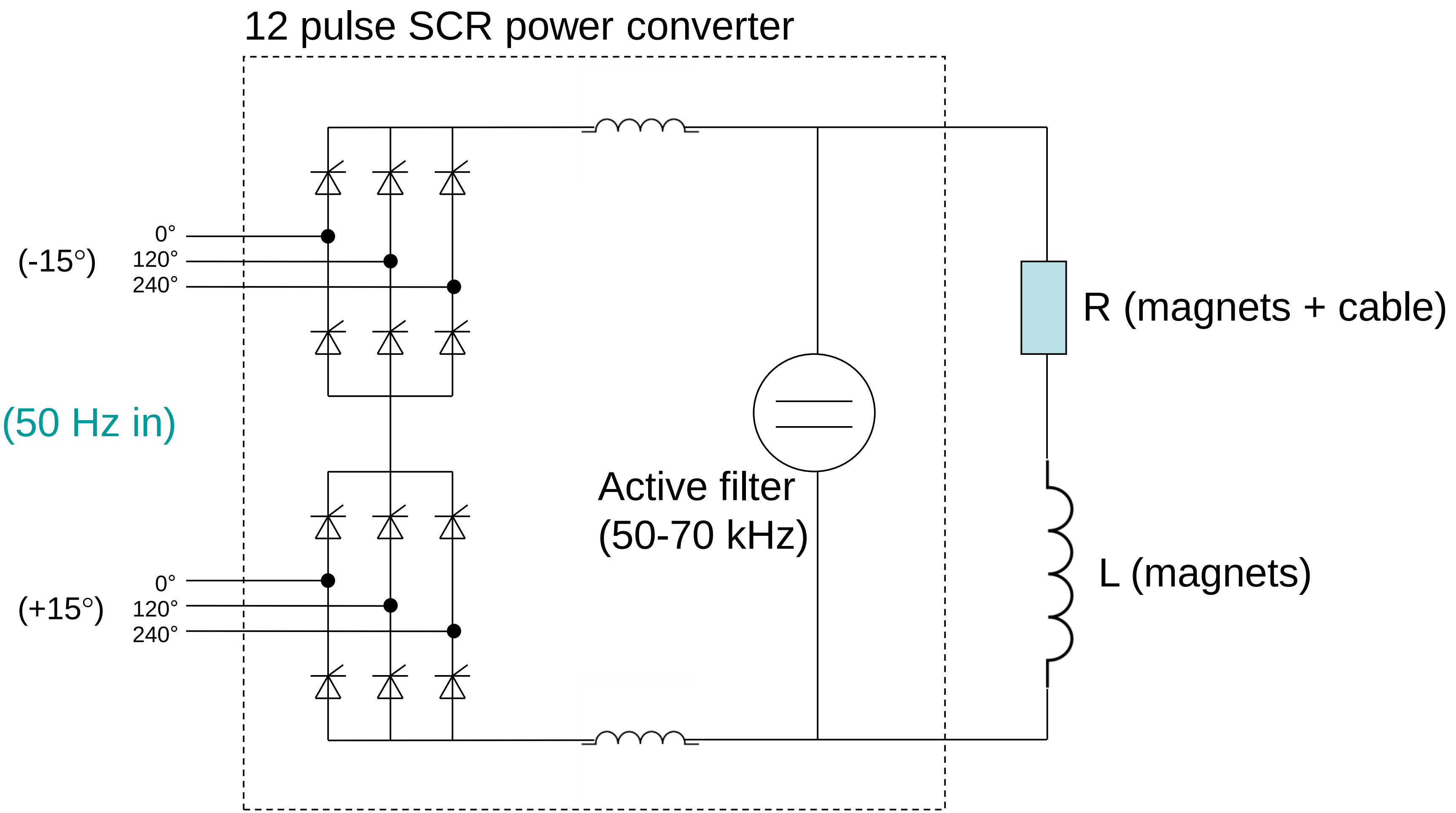
SIS-100:

$^{238}U^{28+}$

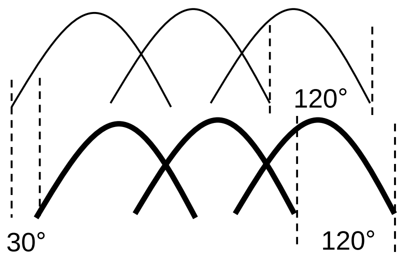
Bρ=100Tm

HELMHOLTZ GEMEINSCHAFT GSI FAIR

SIS-18 Quadrupoles - Power Converters



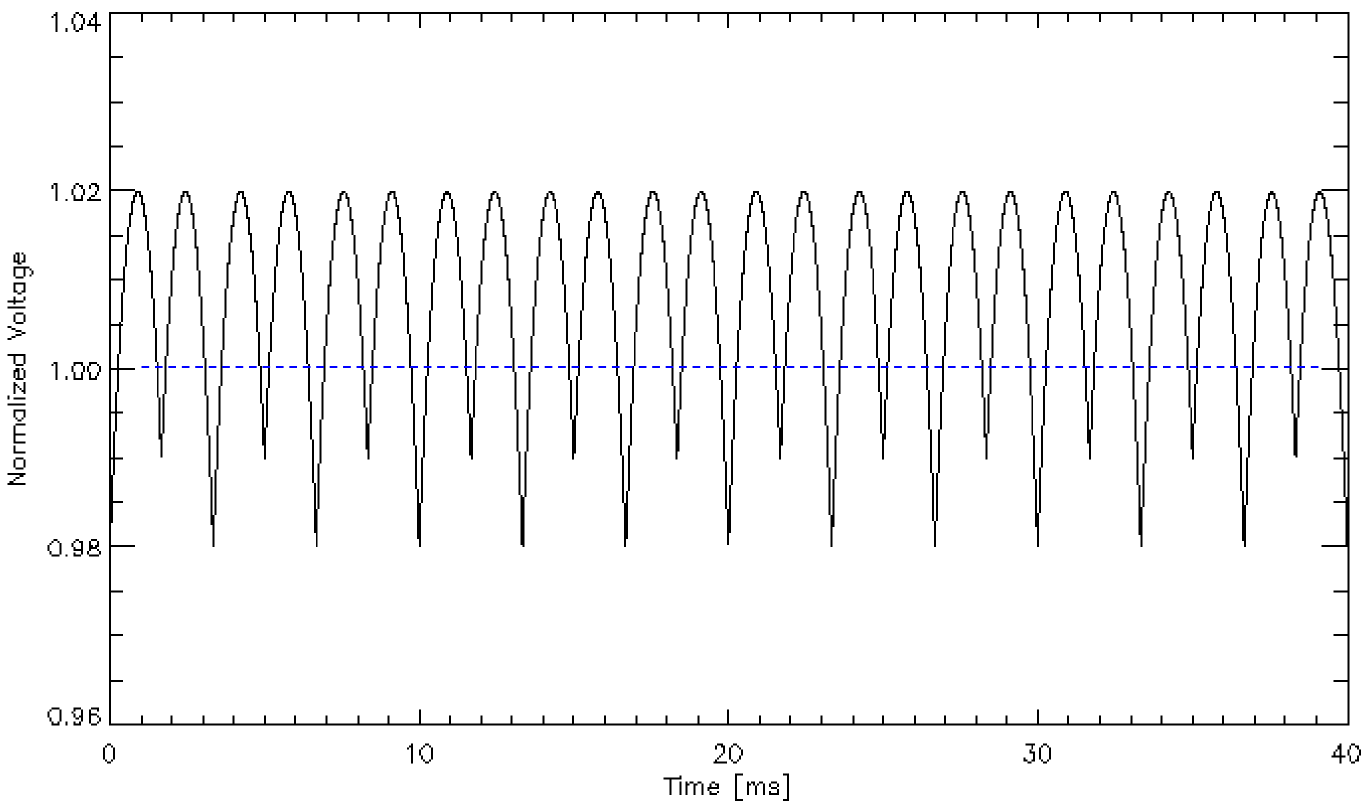
SIS-18 Quadrupoles - Power Converters



12-pulse SCR supply.
Grid 50 Hz, 3-phase.
Main component 600 Hz.
Smaller 300 Hz also present.

$$\frac{\Delta U}{U_0} \approx \pm 2\%$$

Active filtering → $\Delta U/U_0 < 2\%$



SIS-100 Quadrupoles - Power Converter

600 Hz also in SIS-100 quadrupole power converters:

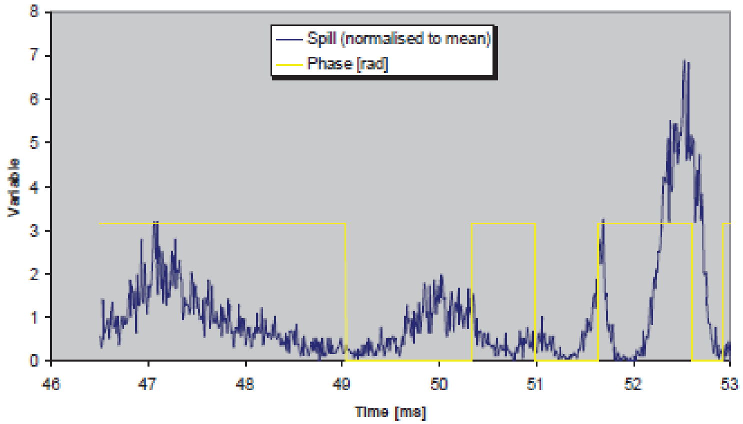
- 12 pulse line commutated converter (SCR.)
- Switching Mode (SM) structure: Hard switching.
- Supplies current to the main quadrupoles.
- All main quadrupoles but 2 are superconducting.
- U_{max} = 640 V at 100 Tm
- $\Delta U/U_{max} = \pm 1\%$
- Strongest ripple at f = 600 Hz
- L = 29 mH (series load)
- R from connecting cable only.
- $Z \approx 2\pi f L$
- $\Delta I = \Delta U/Z$ = 59 mA
- I_{max} = 7.8 kA (100 Tm)
- $\Delta I/I = \pm 7.5 \times 10^{-6}$
- Closed-loop control has N=18-bit ADC for current measurement.
- 2^N-1 levels from zero to I_{max} (Unipolar current, Bipolar voltage.)
- Therefore, minimum possible accuracy is 30 mA

During flattop: Magnets are not ramped!

300 Hz component: $\Delta U/U_{max} = \pm 0.5\%$ would yield same ΔI

SIS-18 Simulation - Spill under 2 forms of KO

a) BPSK: $U_{eff} = 1.3$ kV



b) Dual FM: $U_{eff} = 4.5$ kV

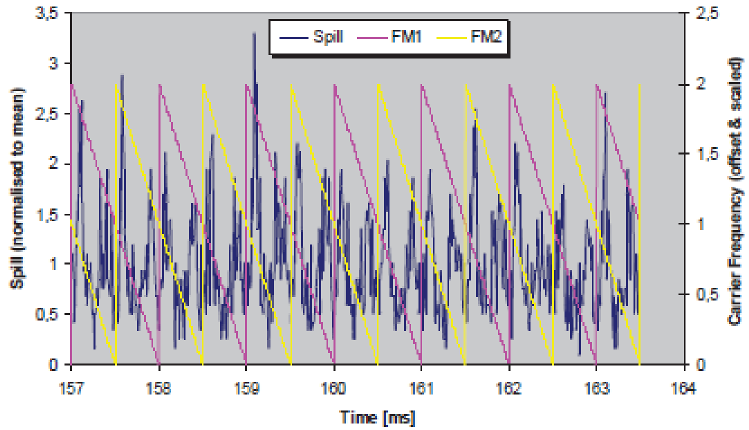
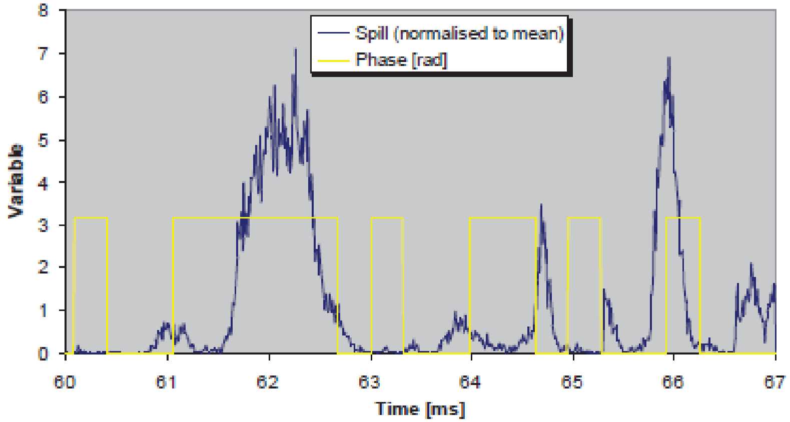


Figure 1: (Colour) Spill with a) BPSK and b) Dual FM. Horizontal chromaticity Q_h'=-6.94 (=$\Delta\nu/\delta$), unadjusted from natural value. Bin size 10 µs (ca. 10 turns), $^{12}C^{6+}$, 6.35 Tm.

a) BPSK: $U_{eff} = 1.1$ kV



b) Dual FM: $U_{eff} = 5.3$ kV

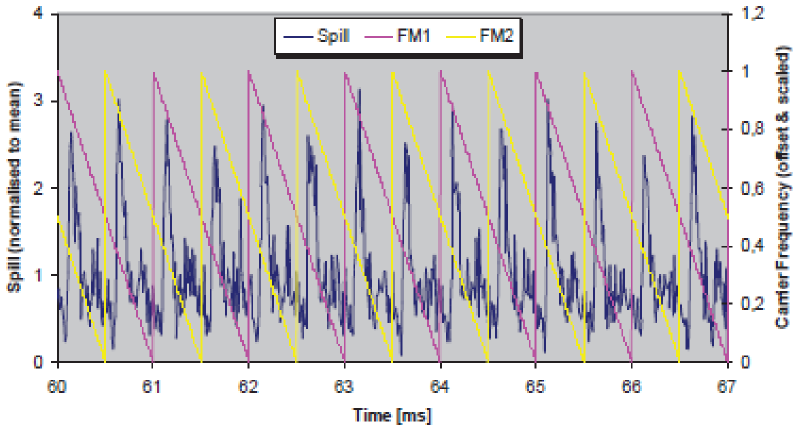
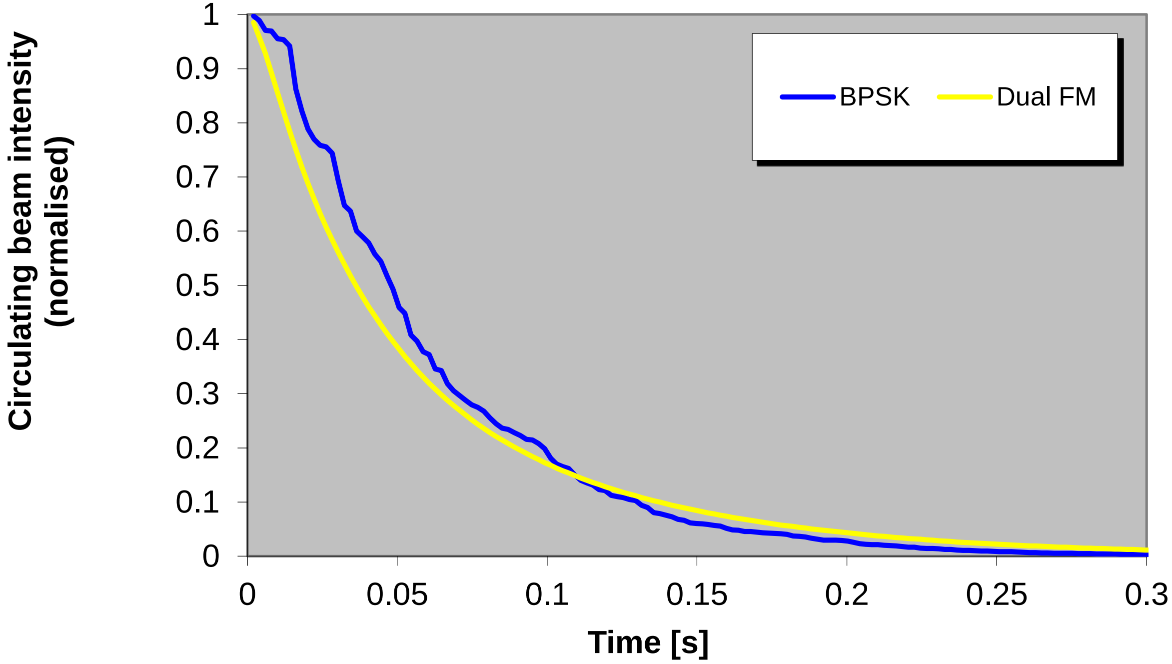


Figure 3: (Colour) Spill with a) BPSK and b) Dual FM. Low chromaticity Q_h'=-0.29 for the Hardt condition. Bin-size 10µs (ca. 10 turns). Beam ions: $^{12}C^{6+}$, rigidity 6.35 Tm.

SIS-18 Simulation – Circulating beam intensity

Beam intensity reduction with time in SIS with Hardt condition. BPSK (U_{eff}=1.1kV) and DFM (U_{eff}=5.3kV):



SIS-18 Simulation - Spill under 2 forms of KO

Nominal operation

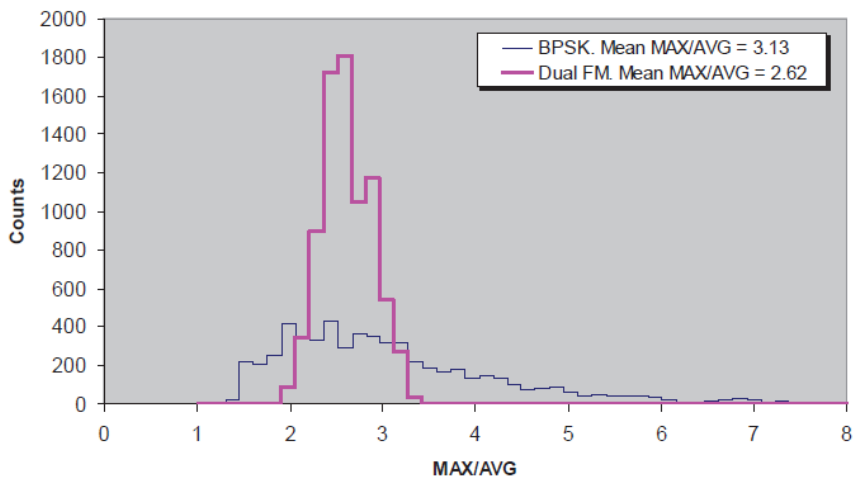


Figure 2: (Colour) Roughness parameter distribution. Beam/machine parameters same as Fig. 1. Histograms formed with ‘sliding’ window 1ms (100 spill-bins) in size.

Hardt condition

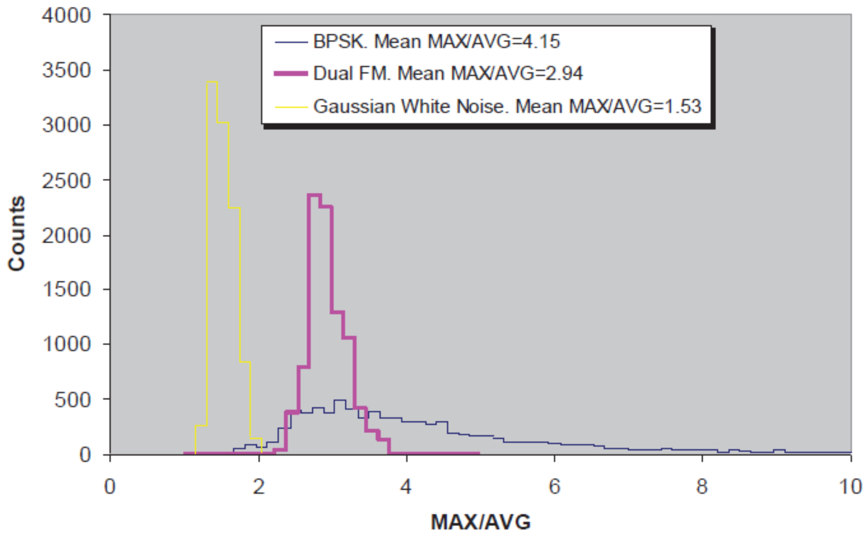
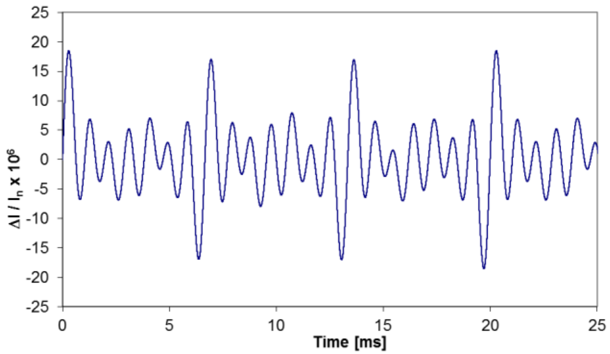
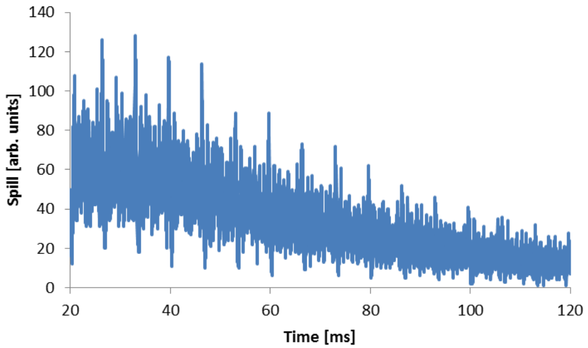


Figure 4: (Colour) Roughness parameter distributions. Beam/machine parameters same as Fig. 3. Histograms formed with ‘sliding’ window 1ms (100 spill-bins) in size.

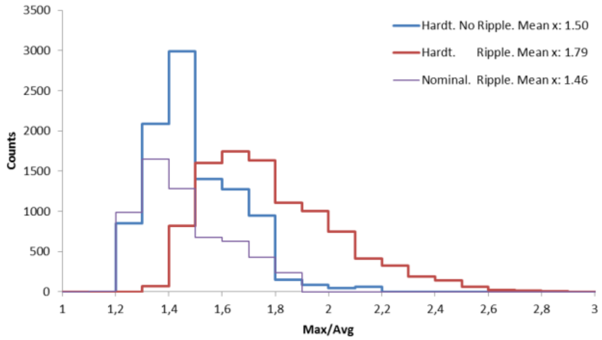
SIS-18 Simulation - Ripple in spill from dipoles



Ripple in dipoles: *partial* reconstruction from FFT of oscilloscope trace measurement of the current.

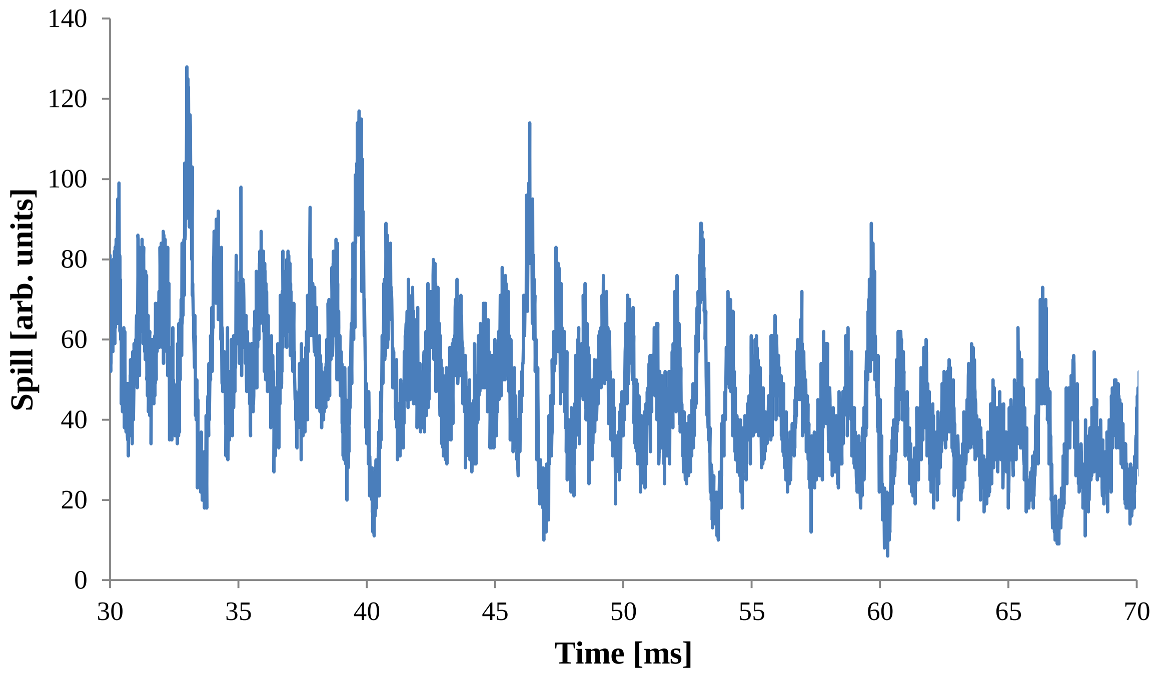


Spill from a DC circulating beam with Hardt condition.

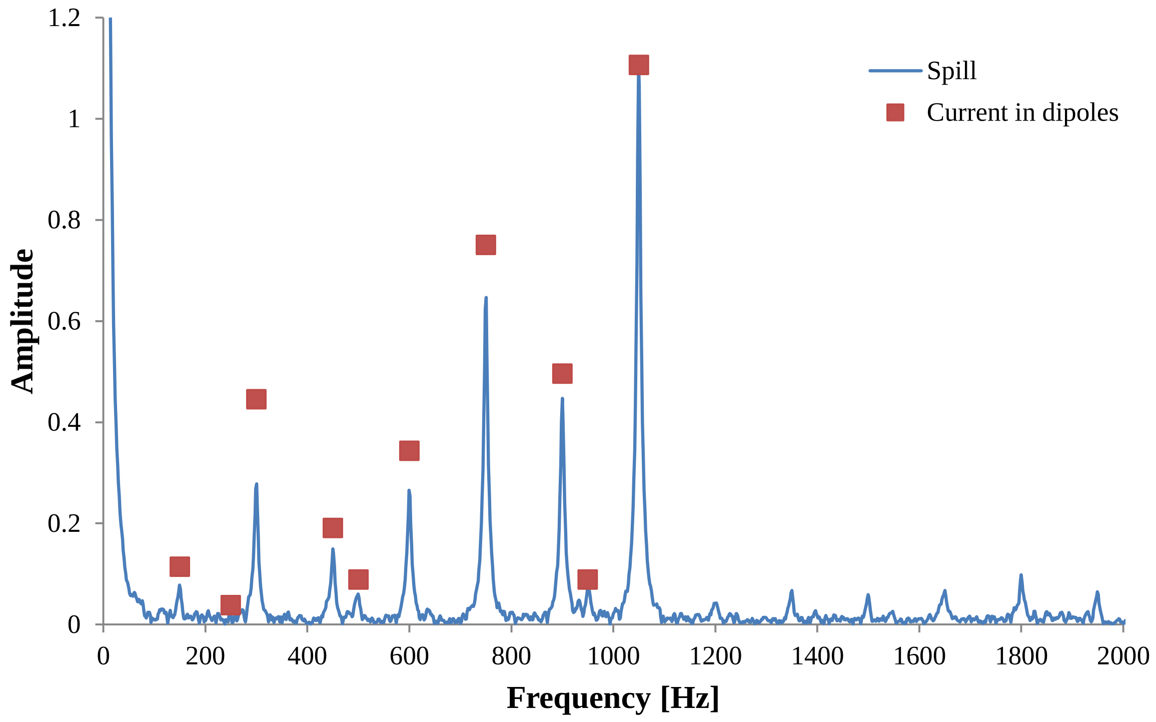


Distribution of spill smoothness parameter for 3 senarios.

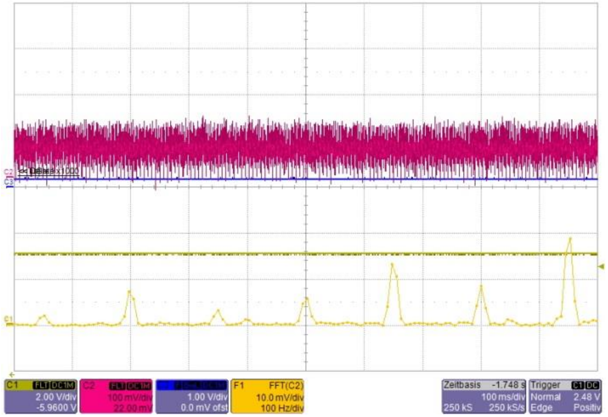
SIS-18 Simulation - Ripple in spill from dipoles



SIS-18 Simulation - Ripple in spill from dipoles

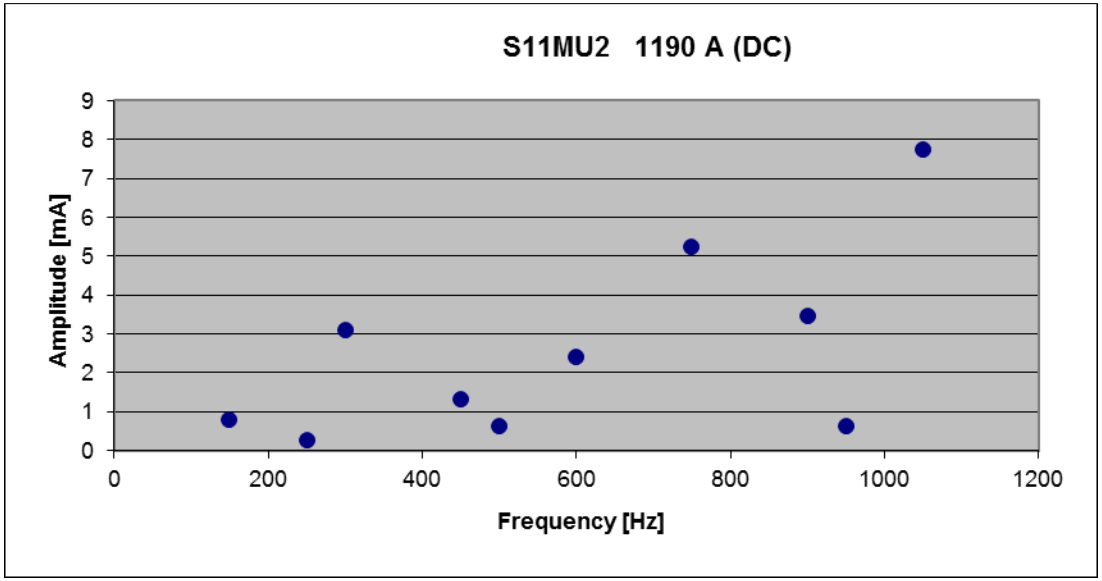


SIS-18 measurement - Ripple in dipoles' power converter



Frequency [Hz]	Amplitude ΔI [mA]
150	0.8
250	0.2667
300	3.111
450	1.3333
500	0.6222
600	2.4
750	5.2444
900	3.4667
950	0.6222
1050	7.7333

Max. $dI / I_n = 2.2E\text{-}5$



SIS-18 Power Converters – Ripple Measurements

Table 1: Summary of measurements taken on the flattop of three machine cycles.

Circuit	Rigidity Bρ [Tm]								
	6			10			18		
	I_n [A]	**Freq. [Hz]**	**ΔI [mA]**	**I_n [A]**	**Freq. [Hz]**	**ΔI [mA]**	**I_n [A]**	**Freq. [Hz]**	**ΔI [mA]**
S01QS1F	420	300	0.2	700	300	0.2	1270	300	0.2
		600	0.2		600	0.7		600	0.5
S12QS1F	420	300	0.2	700	300	0.2	1270	300	0.2
		600	0.1		600	0.5		600	0.2
S01QS2D	400	300	0.3	665	300	0.2	1203	300	0.2
		600	0.6		600	0.1		600	0.5
S12QS2D	400	300	0.4	665	300	0.4	1203	300	0.2
		600	1		600	0.8		600	0.4
S01QS3T	81	300	0.2	137	300	0.2	248	300	0.1
		600	0.1		600	0.3		600	0.5
S11MU2	1092	600	2	1820	600	4	3340	600	2
		1050	8		900	8		900	6

(Welker, Kirk 2010)

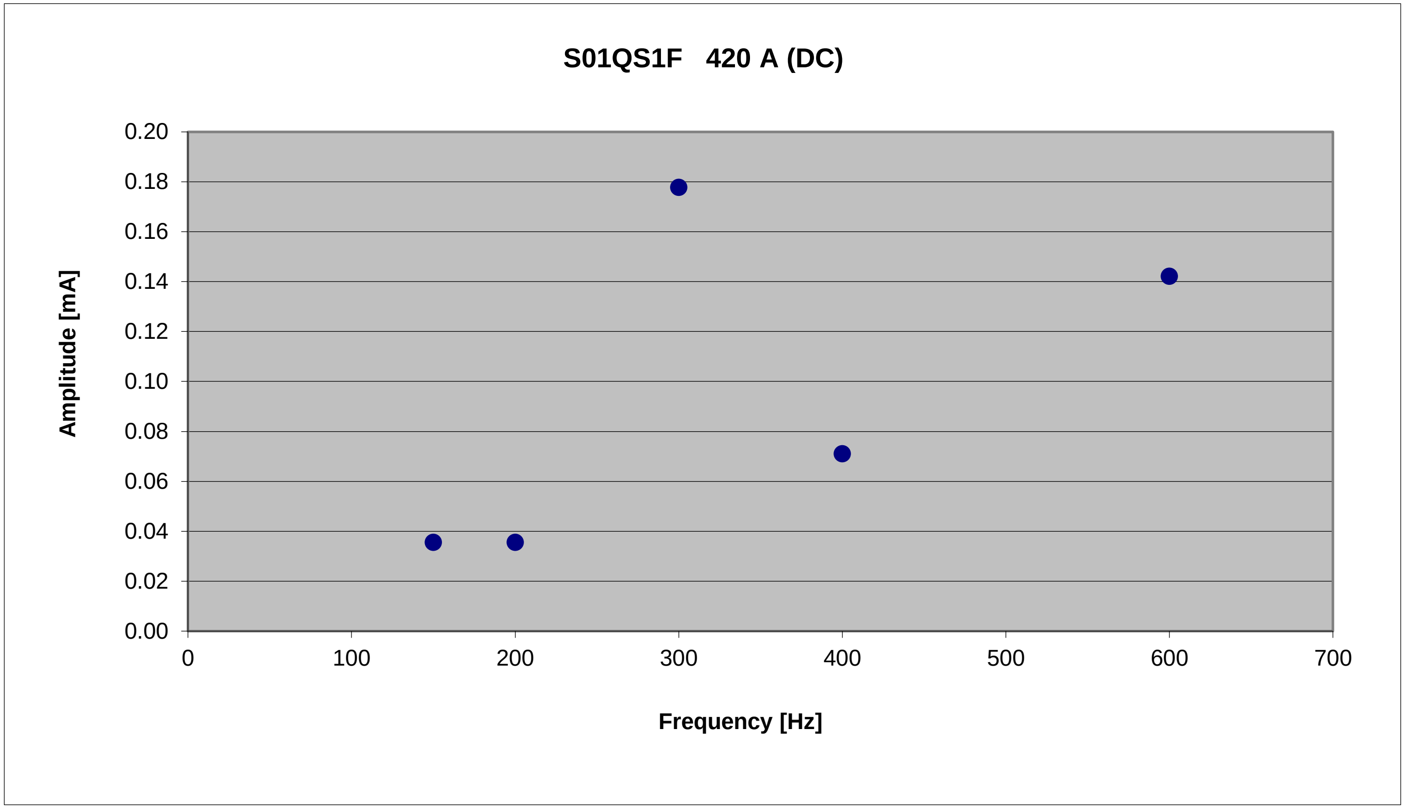
SIS-18 Power Converters – Ripple Measurements

Table 2: Summary of measurements taken at maximum current in the main quadrupoles.

Circuit	I_n [A]	ΔI at 300 Hz [mA]	ΔI at 600 Hz [mA]
S01QS1F	1764	0.5	0.8
S12QS1F	1760	0.2	0.4
S01QS2D	1750	0.2	0.4
S12QS2D	1750	0.2	0.4
S01QS3T[1] S01QS3T[2]	807 820	0.3 0.4	0.4 0.4

(Welker, Kirk 2010)

SIS-18 Power Converters – Ripple Measurements



Max. dI / I_n = 1.1E-6

(Welker, Kirk 2010)

Summary

- Simulations of RF Knock-Out from the present SIS synchrotron at GSI were carried out with a particle tracking code under a Hardt-condition and a nominal (commissioned) operating condition (non-Hardt). Effects of magnet ripple not included.
- Careful comparision of BPSK and Dual FM show improved spill quality in the spill microstructure when Dual FM was applied to the RF Knock-Out exciter.
- Dual FM would however require a larger maximum deflection angle of the ions by the Knock-Out exicter.
- This deflection cannot be acheived with the present specifications.
- Hardt condition with reasonably realistic ripple in the dipoles shows up in the spill microstructure, however not under nominal conditions.