Tune & Chromaticity measurements at GSI
What did we learn?

Rahul Singh

Gesellschaft für Schwerionenforschnung GSI

Workshop on 'Extracting information from Electro-Magnetic Monitors in Hadron Accelerators'

Geneva

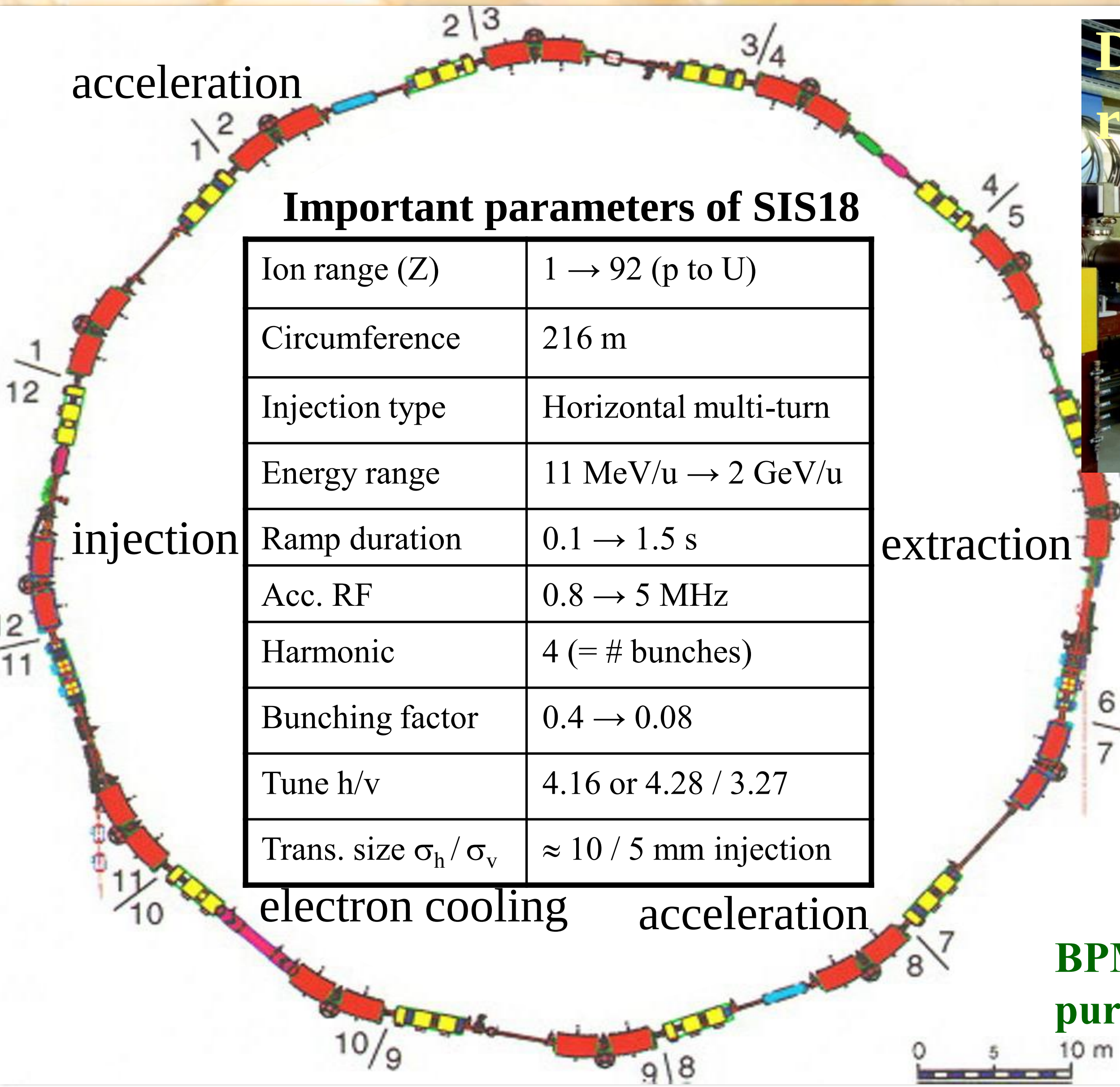
May 14th, 2018

This project has received funding from the European Union's Horizon 2020 research and Innovation program under Grand Agreement No. 730871

Outline

- Hardware details: BPM system(s) and tune measurement
- Low intensity tune spectra : Bunched beam transverse Schottky
- Head-tail modes : Head-tail mode excitation
- High intensity effects: Direct space charge and Impedances
- Measurements and interpretation: Tune spectra for high intensity beams
- Chromaticity measurement: Head-tail phase shift

GSI Heavy Ion Synchrotron SIS18 (Bρ=18Tm): Overview



Important parameters of SIS18

Ion range (Z)	1 → 92 (p to U)
Circumference	216 m
Injection type	Horizontal multi-turn
Energy range	11 MeV/u → 2 GeV/u
Ramp duration	0.1 → 1.5 s
Acc. RF	0.8 → 5 MHz
Harmonic	4 (= # bunches)
Bunching factor	0.4 → 0.08
Tune h/v	4.16 or 4.28 / 3.27
Trans. size σ_h / σ_v	≈ 10 / 5 mm injection

Upcoming FAIR:

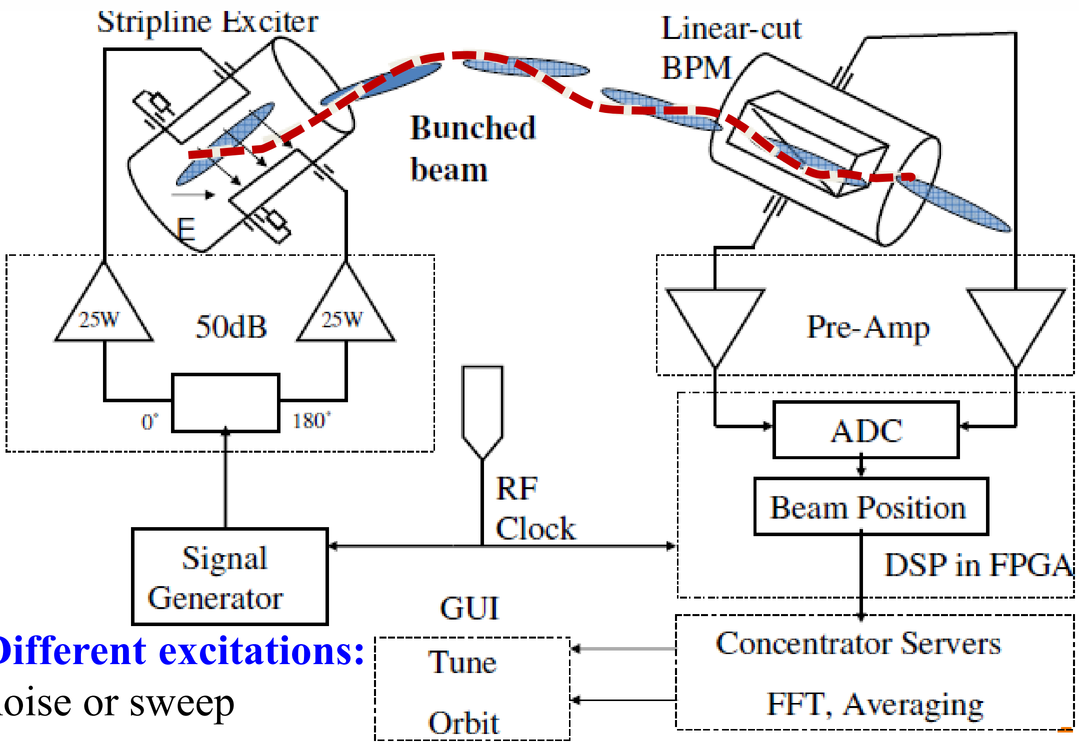
- SIS18 used as booster
- high intensities up to ‘space charge limit’
- precise control of beam parameter for emittance conservation & low losses

BPMs: 12 regular + 5 for special purpose stripline exciter

Tune , Orbit & POsition System TOPOS → Oversampling

General functionality:

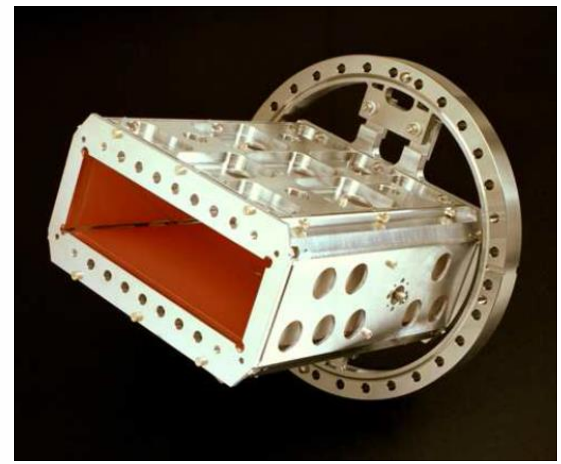
- The beam is excited by band-limited noise or sweep
- Broadband amplification & oversampling of bunches
- Position value for each bunch
- Fourier transformation gives the non-integer tune Q^f
- Mainly spectrum in baseband i.e. $Q^f < 1/2$



Different excitations:
noise or sweep

Linear cut BPM:

Size: 200 x 70 mm², length 260 mm
Position sensitivity:
$S_x = 0.44$ %/mm, $S_y = 1.6$ %/mm



Digital Electronics (LIBERA from I-Tech):

- ADC with 125 MSa/s
- ~9 effective bits
- FPGA: position evaluation etc.

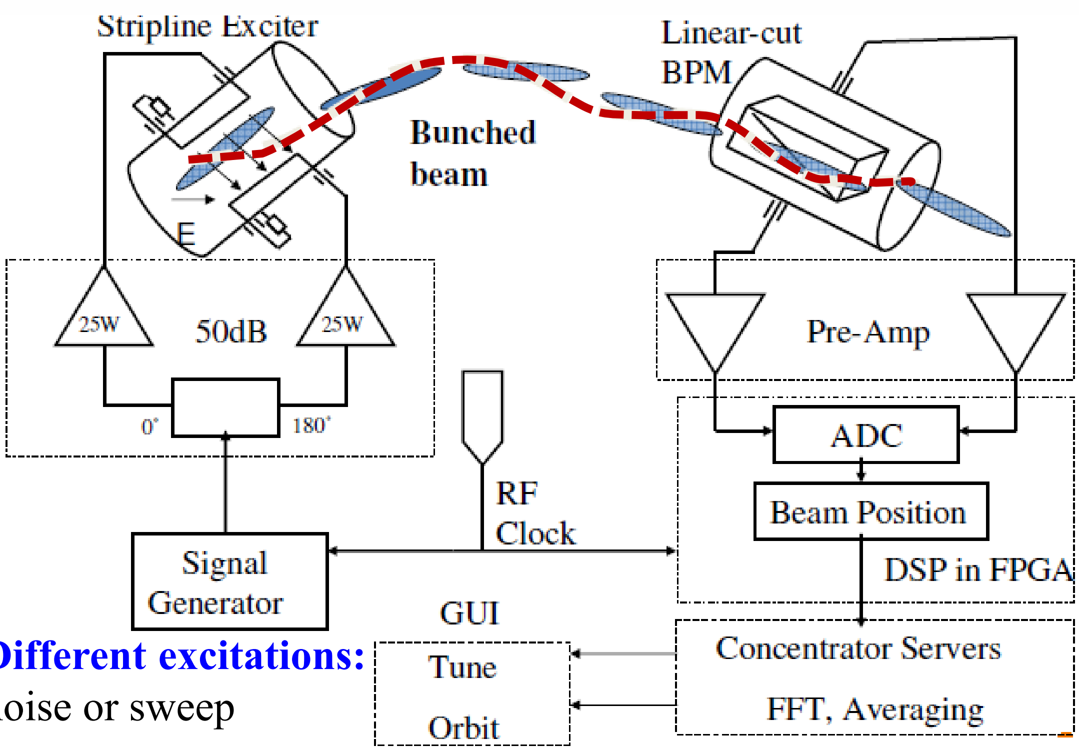
Remark: For FAIR-SIS100 12 eff. bits ADC

R. Singh (GSI) et al., Proc. HB'10, U. Springer et al., Proc. DIPAC'09

Tune , Orbit & POsition System TOPOS → Oversampling

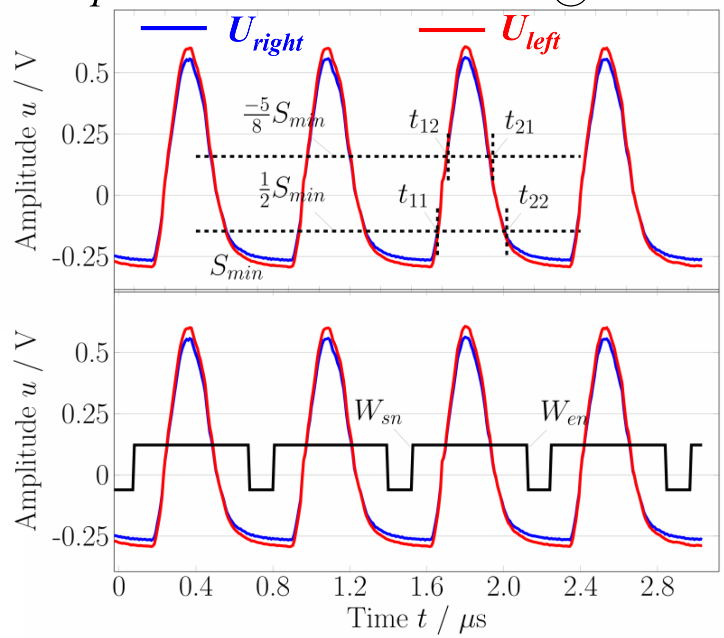
General functionality:

- The beam is excited by band-limited noise or sweep
- Broadband amplification & oversampling of bunches
- Position value for each bunch
- Fourier transformation gives the non-integer tune Q^f
- Mainly spectrum in baseband i.e. $Q^f < 1/2$



Different excitations:
noise or sweep

Example: One turn = 4 bunches @ 35 MeV/u



Steps for digital processing:

- Baseline restoration
- Integration of bunches
  ⇒ position for each bunch
- **Tune**: FFT on position of **same** bunch turn-by-turn i.e.1 of 4 per turn
- From **raw data**: bunching factor, ω_{synch} & head-tail bunch shape

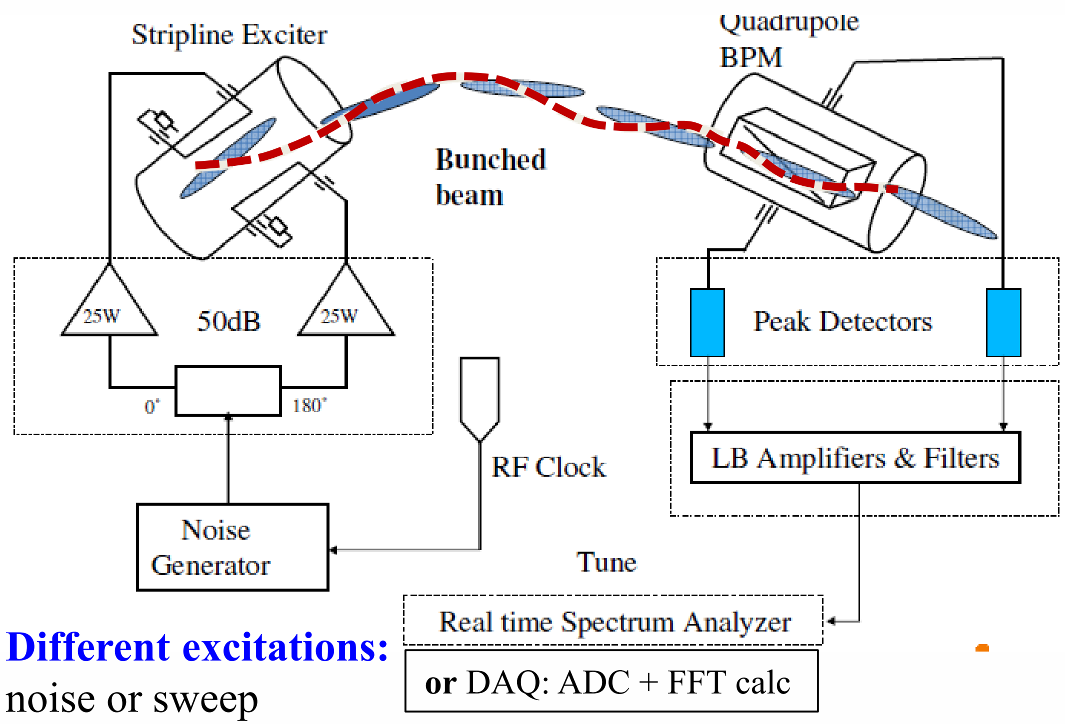
R. Singh (GSI) et al., Proc. HB'10, U. Springer et al., Proc. DIPAC'09

Base-band Tune system BBQ→ analog Peak Detection

The beam is excited to betatron oscillation by band-limited noise or chirp:

- The beam position is determined by analog manner via peak detector measured
- Filtering of base-band component deliver the non-integer tune Q^f

System designed by M. Gasior (CERN)



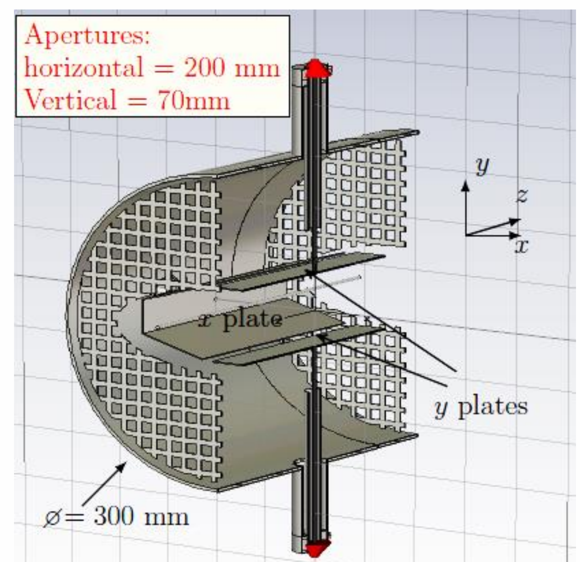
Different excitations:
noise or sweep

'Quadrupolar' BPM:

Size: 200 x 70 mm^2, length 210 mm

Position sensitivity:

S_x = 1.4 %/mm, S_y = 2.1 %/mm



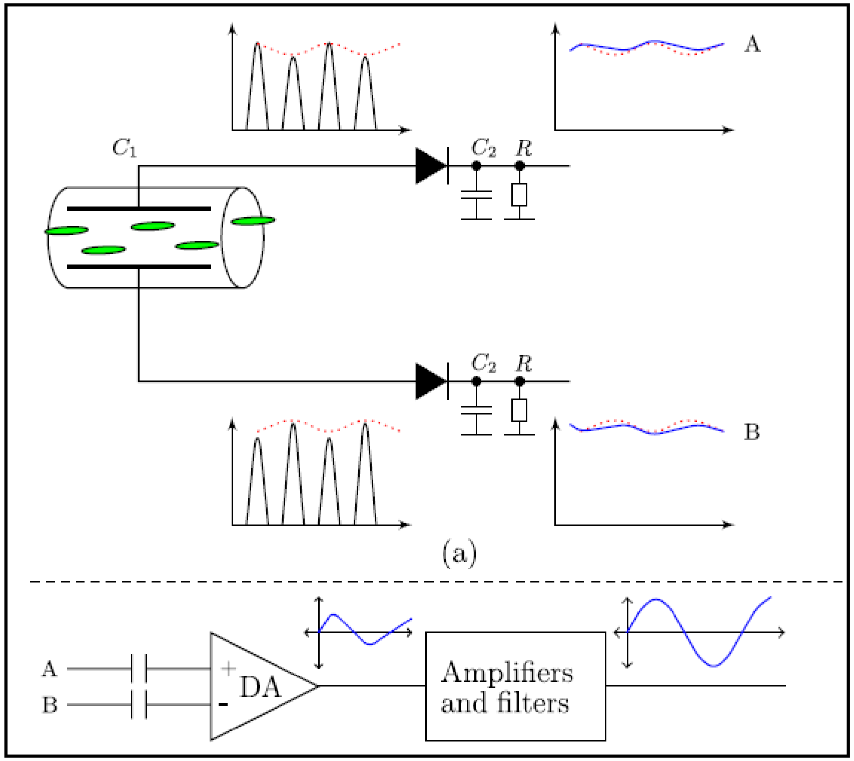
BBQ design: M. Gasior BIW'12; GSI measurements; R. Singh (GSI) et al., Proc. HB'12 and DIPAC'13

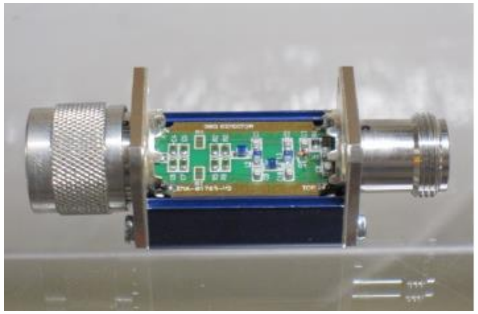
Base-band Tune system BBQ→ analog Peak Detection

The beam is excited to betatron oscillation by band-limited noise or chirp:

- The beam position is followed using peak detectors i.e. time constants as parameters
- Filtering of base-band component deliver the non-integer tune Q^f

System designed by M. Gasior (CERN)





Steps of analog processing:

- Peak detection
- Amplification of the difference
- Filtering
- Feeding to spectrum analyzer or DAQ

⇒ weighted folding of spectrum to baseband

BBQ design: M. Gasior BIW'12; GSI measurements; R. Singh (GSI) et al., Proc. HB'12 and DIPAC'13

Comparison BBQ versus TOPOS

BBQ:

- Peak detection using analog circuit i.e. no further treatment possible
- High dynamic range
- Result: tune with higher sensitivity

⇒ 'Easy-to-use' device

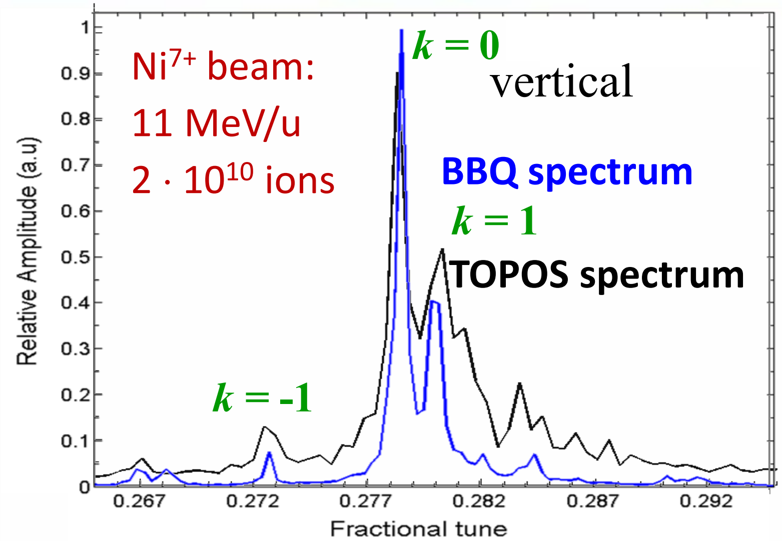
TOPOS:

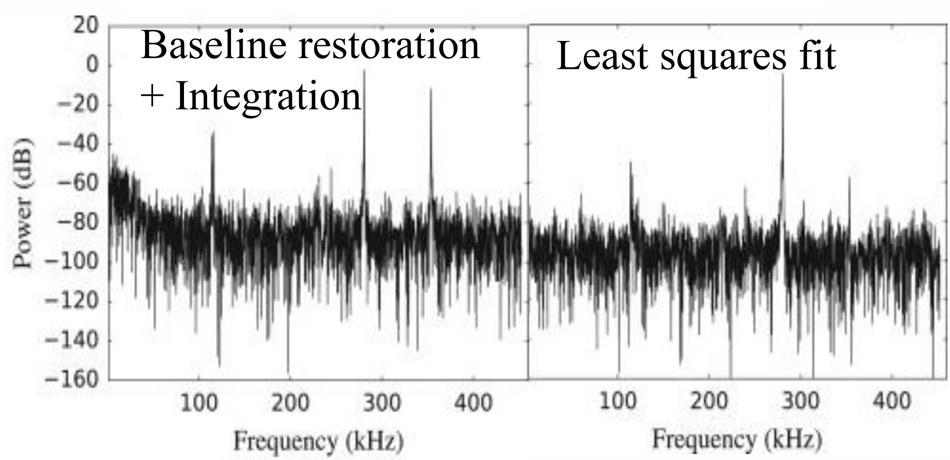
- Oversampled digitization of the BPM signals
- Full time domain information
- Versatile data processing possible e.g. picking 1 of 4 bunches, filtering ...
- Results: Position, tune, longitudinal profile synchrotron frequency ω_s

⇒ versatile due to full information stored

Remark: Improved position algorithm based on least squares fit brings the sensitivity close to BBQ at SIS-18

A. Reiter and R. Singh, NIM-A, 2018 10.1016/j.nima.2018.02.046





5 x higher signal-to-background + higher resolution + better common mode suppression

Tune Determination at SIS18: Online Display in Control Room

Online display for tune measurement during acceleration

Excitation with
band-limited noise

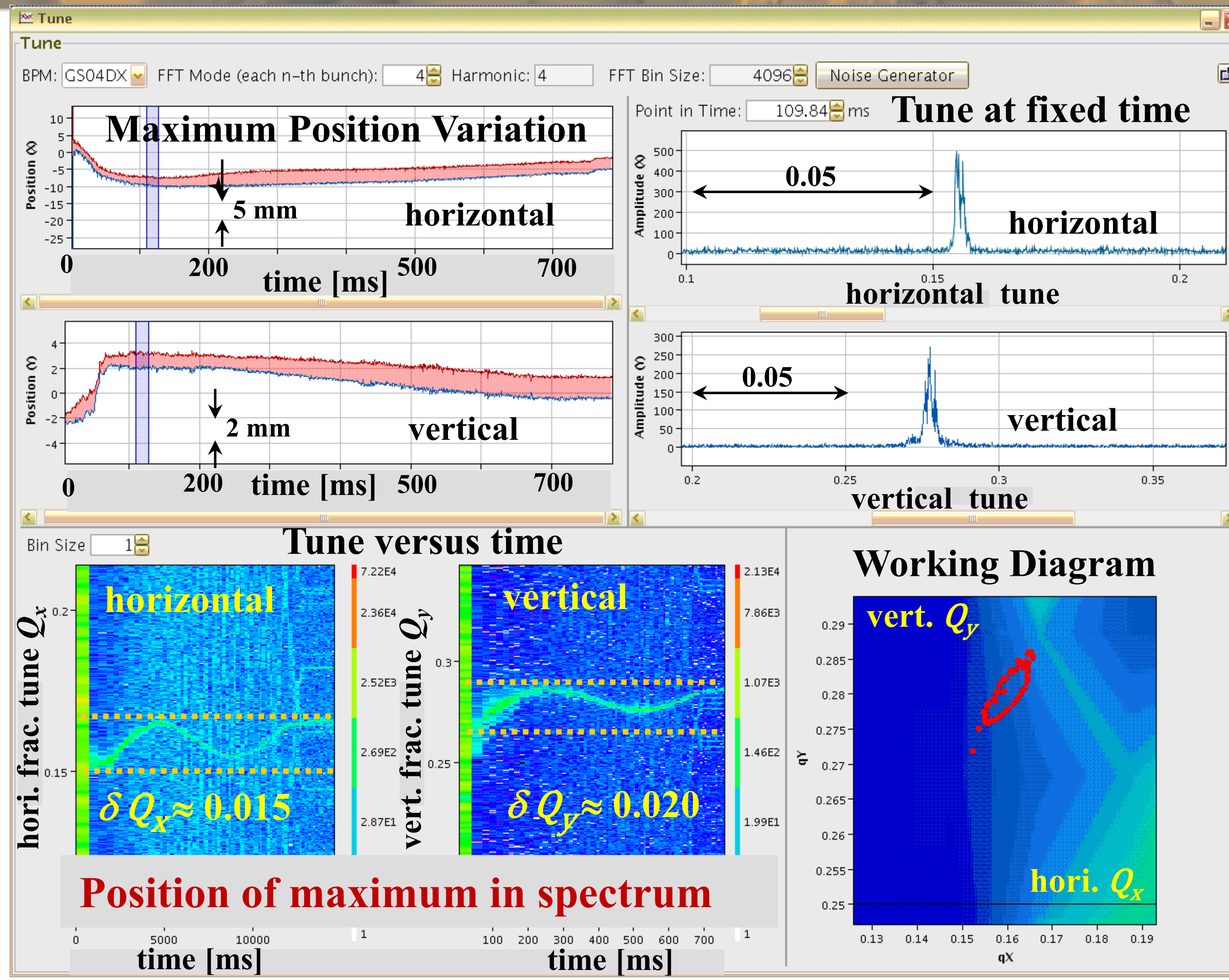
Time resolution:
4096 turns ≈ 20 – 4.5 ms

Variation during ramp:
triplett to duplett focusing

Result:

- Online display for user
- Sufficient signal strength with moderate excitation
- Minor emittance growth

Beam parameter:
10^{10} Ar^{18+} , 11 → 300 MeV/u
within 0.7 s
→ **tune variation by imperfect focusing ramp**



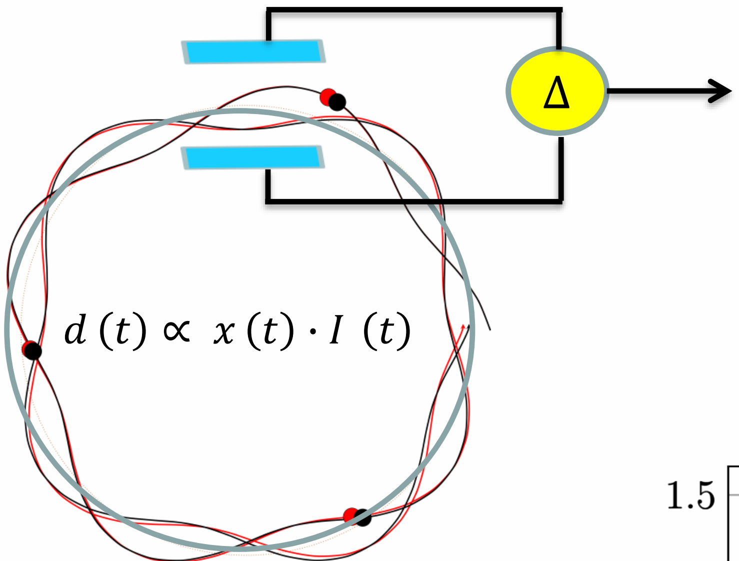
P. Kowina et al., Proc. BIW'10; R. Haseitl et al., Proc. DIPAC'11, G. Jansa et al., Proc. ICALEPCS'09

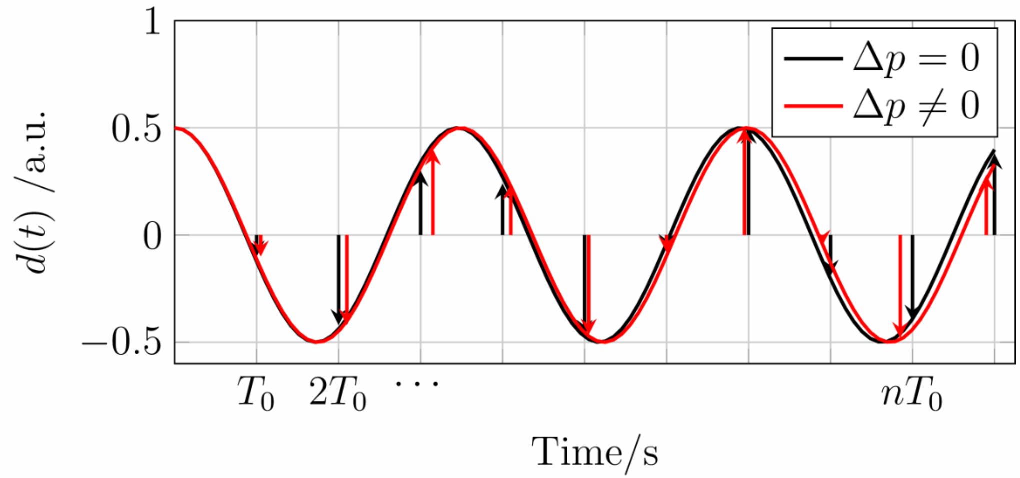
Outline

- Hardware details: BPM system(s) and tune measurement
- Low intensity tune spectra : Bunched beam transverse Schottky
- Head-tail modes : Head-tail mode excitation
- High intensity effects: Direct space charge and Impedances
- Measurements and interpretation: Tune spectra for high intensity beams
- Chromaticity measurement: Head-tail phase shift

Basic of Tune Spectrum: Non-interacting Particle Model

Dipole moment ***d(t)*** comprises betatron = amplitude ***x(t)*** & synchrotron = phase ***I(t)*** modulation



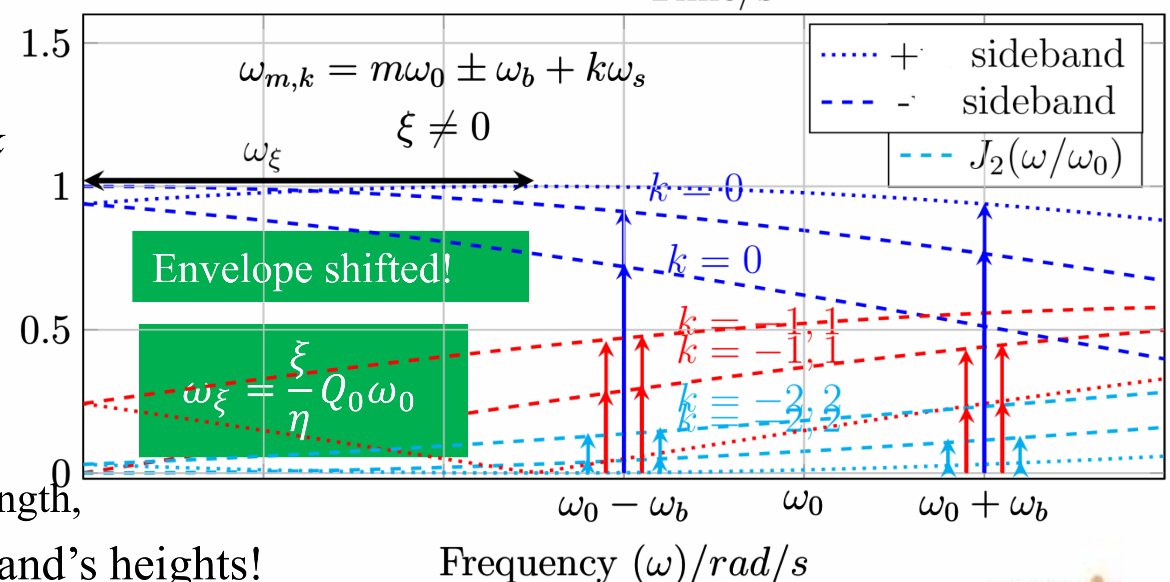


- Frequency of harmonics ***m*** **&** mode ***k***

$$\omega_{m,k}^{\pm} = m\omega_0 \pm \omega_b \pm \omega_k$$

- Sideband amplitude given by Bessel-function J_k of order ***k***

$$\text{Amplitude} \quad r_{m,k}^{\pm} \propto J_k\left[\left(\omega_{m,k}^{\pm} - \omega_{\xi}\right)\frac{a}{\omega_0}\right]$$



ω_b betatron freq. ω_0 rev. freq. ***a*** bunch length,

Finite chromaticity ξ modifies sideband's heights!

Time Domain Mode Structure: Non-interacting Particle Model

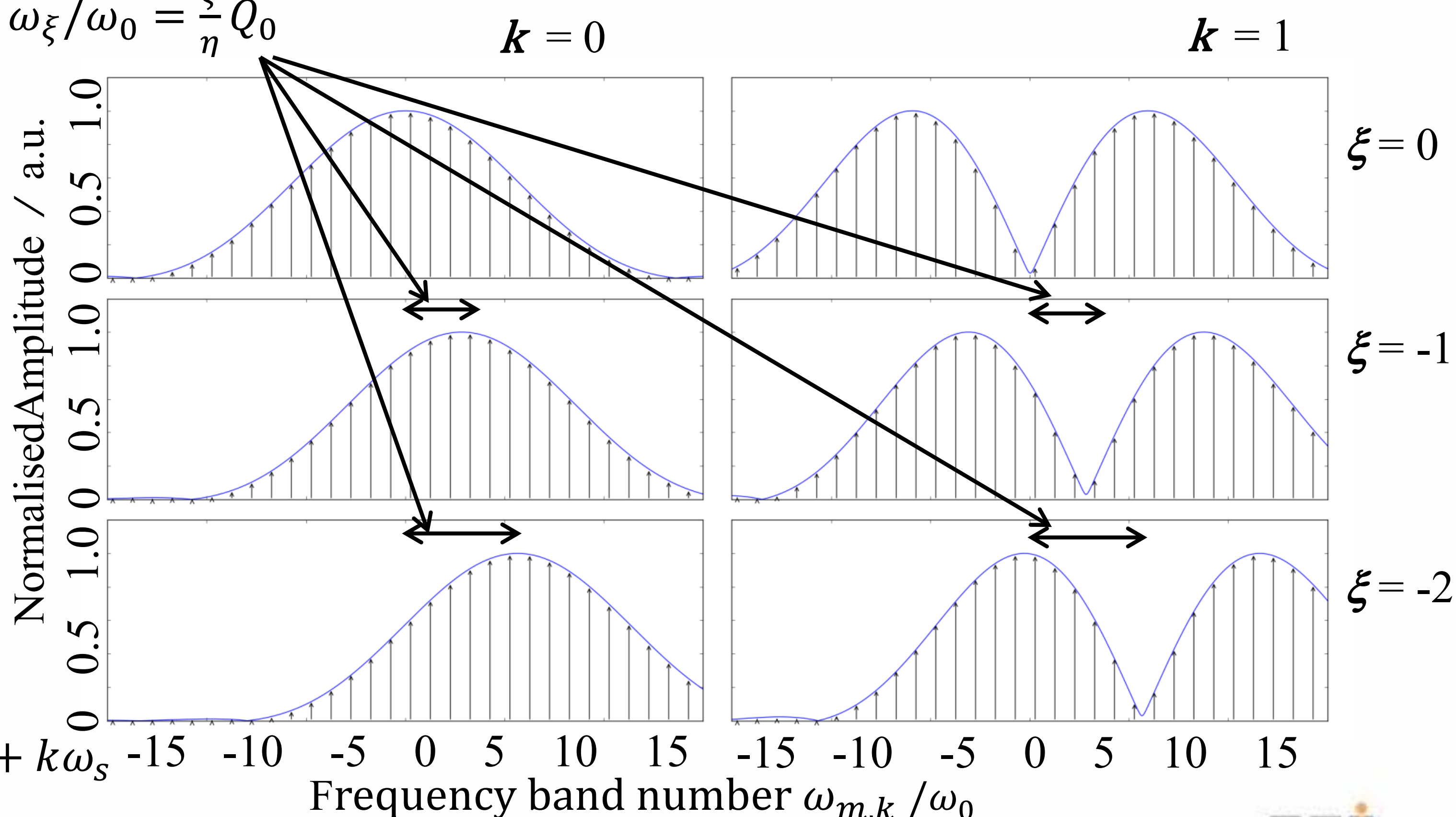
Bessel's function as envelope represent unrealistic "hollow bunches". F. Sacherer (in 1978) found sinusoidal Eigen-functions good approximations for parabolic bunches

$$\bar{x}_k(\tau) = \cos(\pi(k+1)\tau/\tau_b) \cdot e^{-i\omega_\xi \tau}$$

F. Sacherer: Transverse bunched beam instabilities : Theory

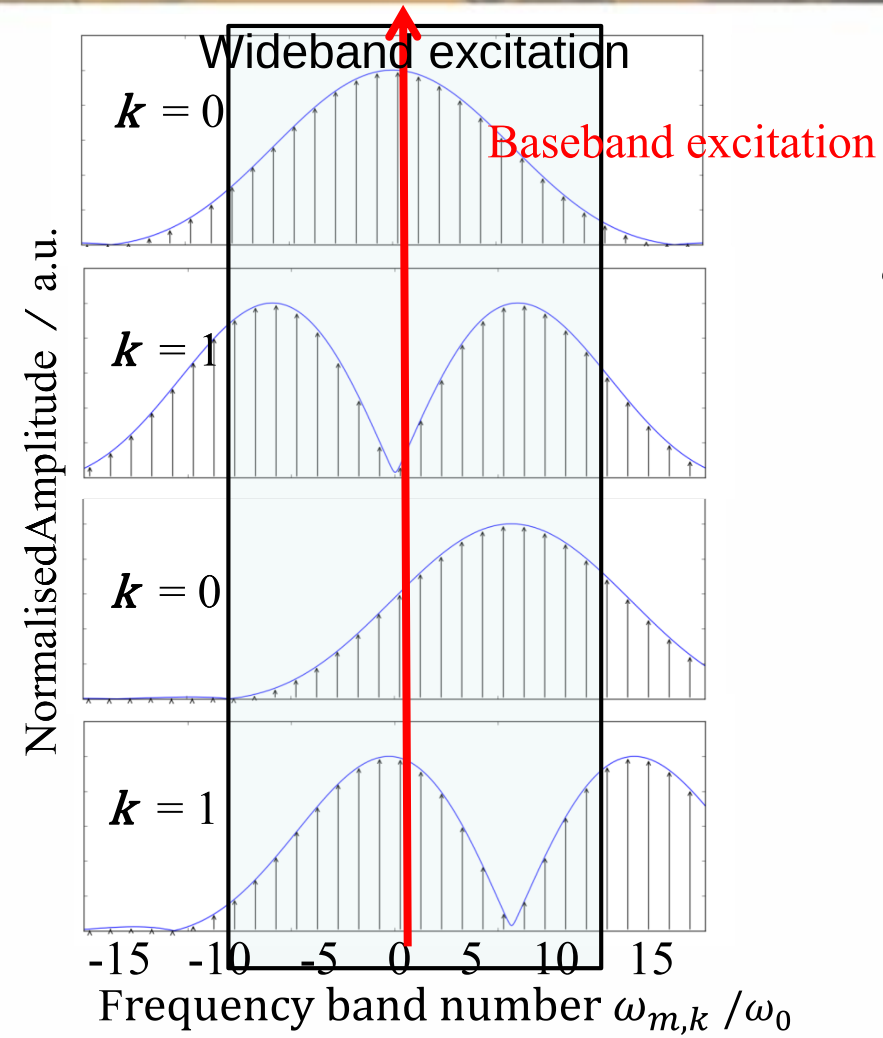
Chromatic tune $\omega_\xi/\omega_0 = \frac{\xi}{\eta} Q_0$

SIS18 injection:
Q_0 = 3.27, η = -0.92



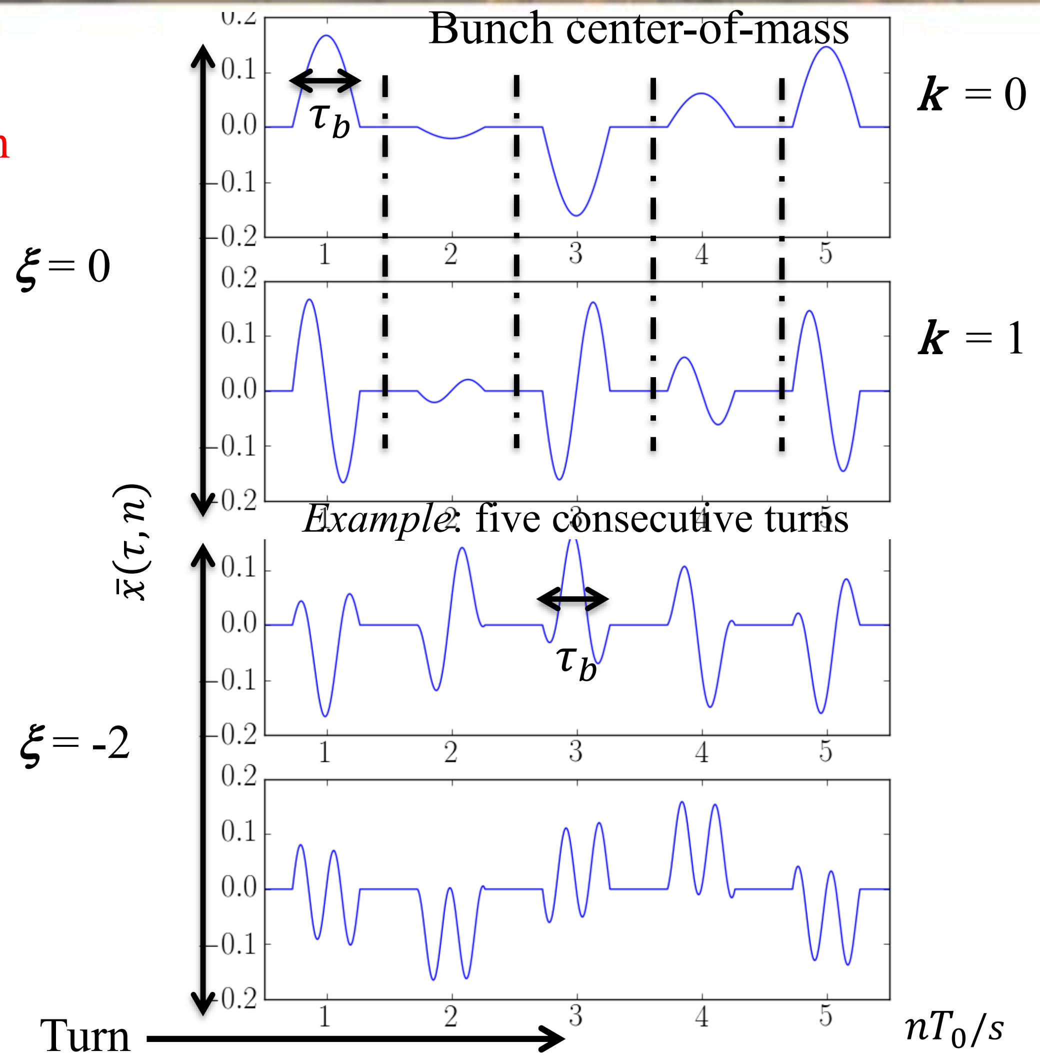
$$\omega_{m,k} = m\omega_0 + \omega_b + k\omega_s$$

Excitation of Head-tail Modes



Choose any/many frequency bands to excite

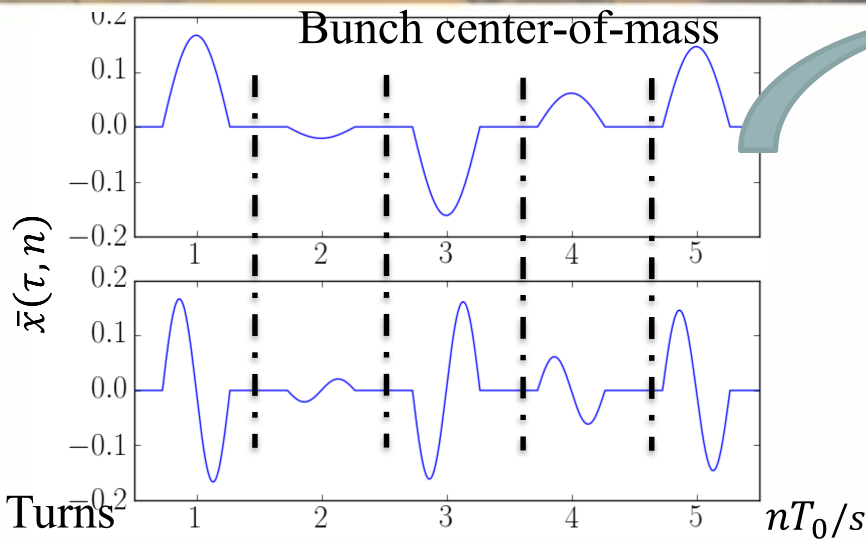
$$\omega_{m,k} = m\omega_0 + \omega_b + k\omega_s$$

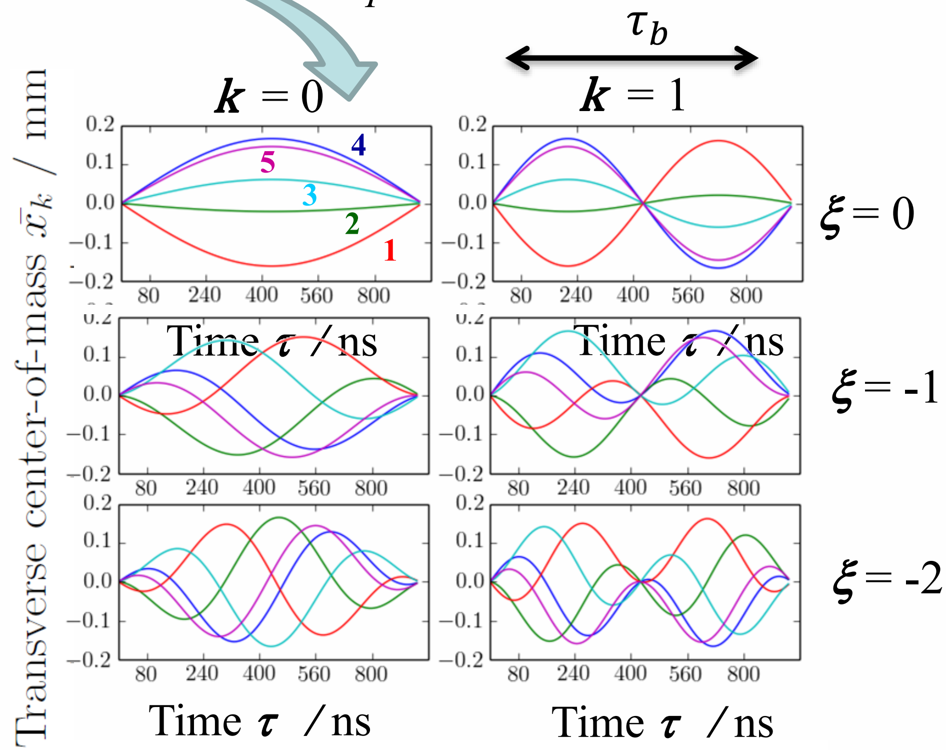


Head-tail mode oscillations:

$$\bar{x}_k(\tau, n) = Re(\bar{x}_k(\tau) \cdot e^{-i(\omega_b + k\omega_s)T_0 n})$$

Time Domain Mode Structure: Non-interacting Particle Model





$$\bar{x}_k(\tau, t) = \bar{x}_k(\tau) \cdot \cos[(\omega_b + k\omega_s)t + \omega_\xi \tau]$$

Non -zero chromaticity ⇔ intra-bunch movement

Phase shift depending on the separation $\Delta\tau$

For $k = 0$, $\Delta\varphi = \omega_\xi \Delta\tau = \frac{\xi}{\eta} Q_0 \omega_0 \Delta\tau$

$$\xi = \frac{\Delta\varphi\, \eta}{Q_0 \omega_0 \Delta\tau}$$

SIS18 injection:
$Q_0 = 3.27$, $\eta = -0.92$

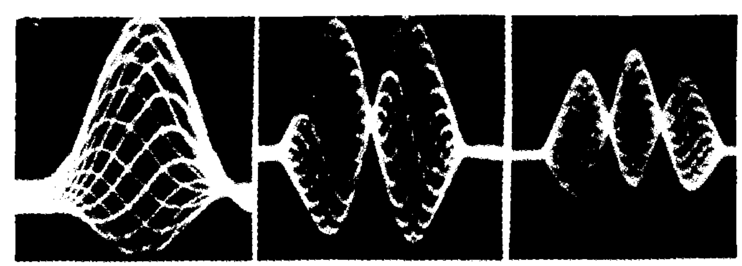
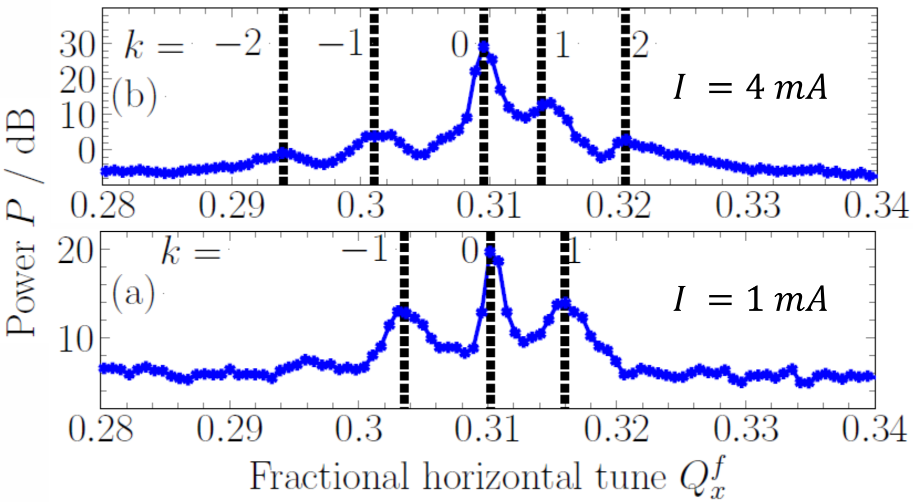


Fig. 2 Head-tail modes observed in the CERN Booster[6].
F. Sacherer: Transverse bunched beam instabilities : Theory

Tune Spectra at SIS18: Modification with intensity

Higher current: The „global" peak moves to the left. The symmetry of the spectrum is broken.



Low current: Tune spectra has symmetric sidebands due to synchrotron motion.

Relevant GSI SIS18 parameters

Parameter	Typical Value
Circumference	216 m
Beam current	$10^7 - 10^{13}$ charges
Injection energy	11.4 MeV/u ($\beta = 0.15$)
Betatron tune Q_x & Q_y	4.31 or 4.17 & 3.28
Synchrotron tune Q_s	0.007 (~ 1.4 kHz)
Trans. size σ_x & σ_y	6…10 & 3…5 mm

Most measurement and tests at prolonged injection flat-top with highest ΔQ performed.

General questions: Not high enough for instability

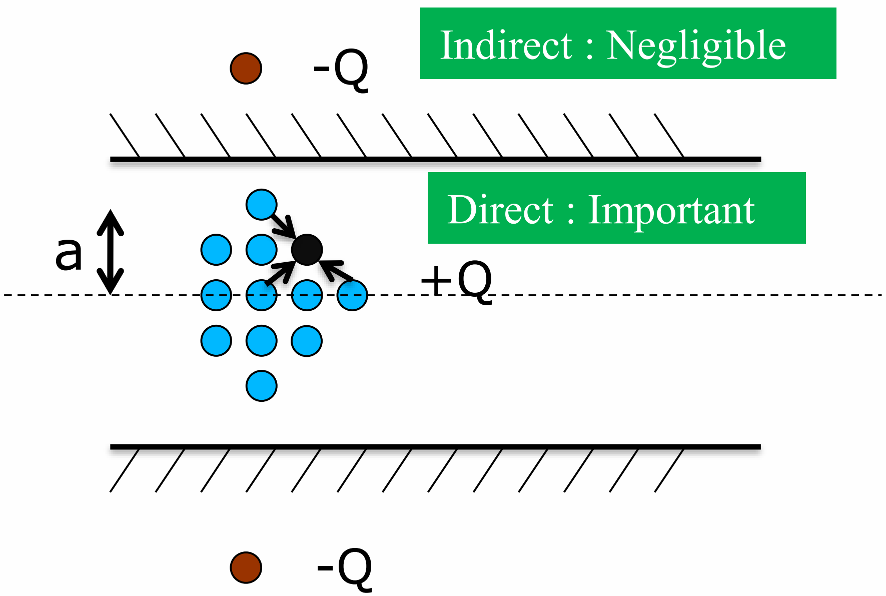
- Why is the tune spectrum modified at increasing beam current ?
- Very practical: Which peak is the coherently shifted tune ?
- What can we learn from this modification for further beam parameters ?

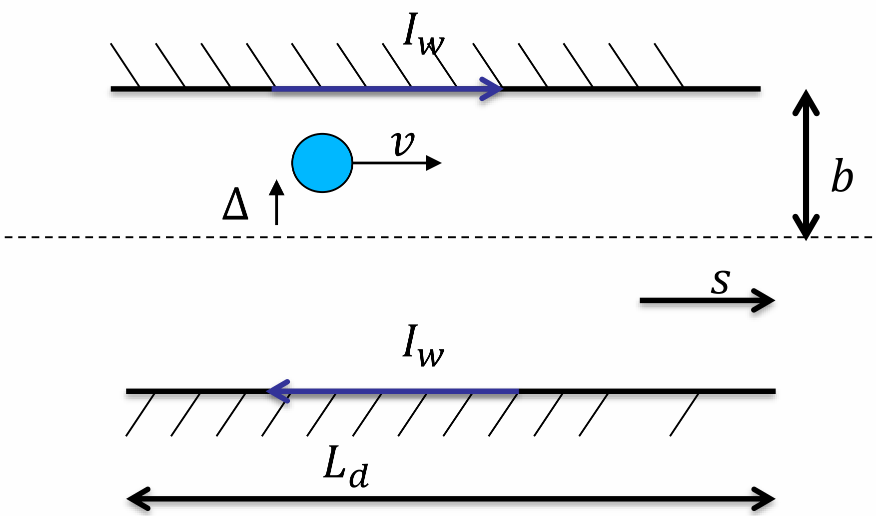
Outline

- Hardware details: BPM system(s) and tune measurement
- Low intensity tune spectra : Bunched beam transverse Schottky
- Head-tail modes : Head-tail mode excitation
- High intensity effects: Direct space charge and Impedances
- Measurements and interpretation: Tune spectra for high intensity beams
- Chromaticity measurement: Head-tail phase shift

Space charge and impedances for transverse motion

Model assumptions: round constant beam & pipe radius, constant or KV distribution,





Interaction of individual particles with each other and the boundaries → Incoherent effect

Non-linear force with strong dependence on beam distribution → Will lead to a negative tune spread

Interaction of center-of-mass motion with boundaries → Coherent effect

$$Z_{\perp}(\omega) = -j\frac{\int_0^{L_d}(E(s,\omega) + v \times B(s,\omega))_{\perp} ds}{\beta I \Delta}$$

Formulas: coherent Tune Shift and incoh. Tune Spread

Model assumptions: round constant beam & and perfectly conducting pipe radius, KV distribution, constant synchrotron tune ...

Transverse impedance $Z_\perp = i\,\dfrac{Z_0}{2\pi(\beta_0\gamma_0 b)^2}$

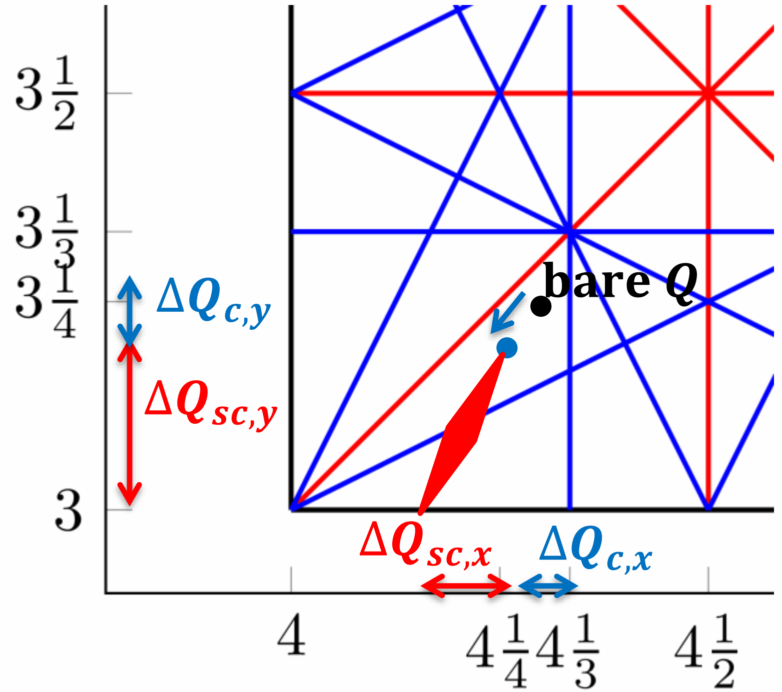
Coherent tune shift $\Delta \boldsymbol{Q}_c = i\,\dfrac{qI_pR^2Z_\perp}{2Q_0\beta_0W_0}$

Incoh. tune spread $\Delta \boldsymbol{Q}_{sc} = \dfrac{qI_pR}{4\pi\epsilon_0 c W_0 \beta_0{}^3\gamma_0{}^2\varepsilon}$

Relation $\Delta Q_c = \Delta Q_{sc} \cdot \left(\dfrac{a}{b}\right)^2$ ← beam radius ← pipe radius

Space charge parameter $q_{sc} = \dfrac{|\Delta Q_{sc}|}{Q_s}$

$\boldsymbol{q}_{sc}$ includes effect of longitudinal oscillations



b pipe radius, ***R*** synchrotron radius, $Z_0 = \sqrt{\mu_0/\epsilon_0}$
q ion charge, $\boldsymbol{I_p}$ peak current, $\boldsymbol{Q_0}$ bare tune
$\boldsymbol{W_0}$ total energy, $\boldsymbol{\beta_0}$ velocity, $\boldsymbol{\gamma_0}$ Lorentz factor
a beam radius, $\boldsymbol{\varepsilon}$ transverse emittance

Analytical Model: Space Charge Modification of Tune Spectra

Assumption of analytical description of head-tail modes by M. Blaskiewicz (1998):

- Transverse phase space: KV-distribution
- Longitudinal 'airbag' phase space: phase → constant momentum only two velocities $\mathbf{v}_s = \pm \mathbf{v}_{s0}$

  ⇒ synchrotron tune: $Q_s = \pi \mathrm{v}_{s0} / (R\,\omega_0\, a)$

Low intensity: spacing of sidebands: $\Delta Q_k = kQ_s$

High intensity: spacing of sidebands:

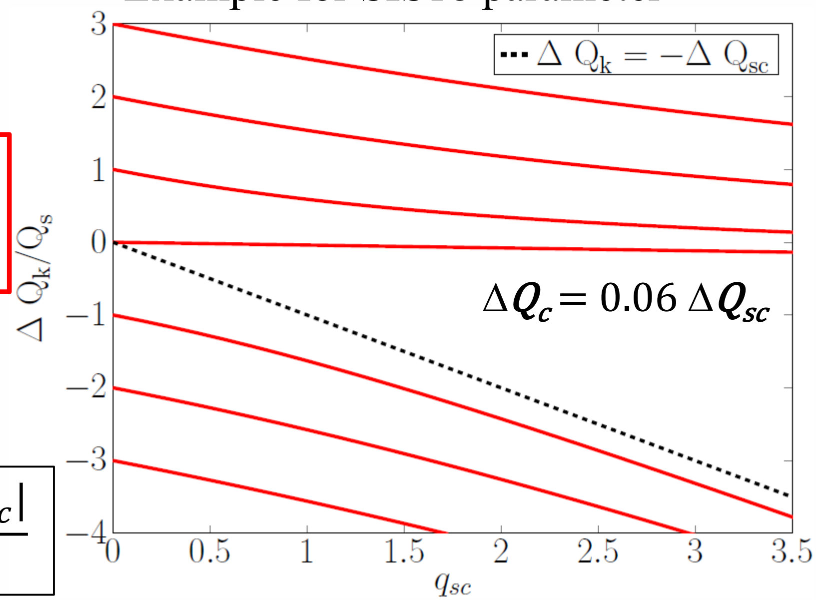
$$\Delta Q_{\pm k} = -\frac{\Delta Q_{sc} + \Delta Q_c}{2} \pm \sqrt{\frac{(\Delta Q_{sc} - \Delta Q_c)^2}{4} + (kQ_s)^2}$$

ΔQ_c **coherent tune shift**

ΔQ_{sc} **incoherent tune spread**

Example for SIS18 parameter

$$q_{sc} = \frac{|\Delta Q_{sc}|}{Q_s}$$



Findings:

- $\boldsymbol{k} = 0$ it is $\Delta Q_0 = -\Delta Q_c$ i.e. value of shifted bare tune
- $\boldsymbol{k} > 0$, head-tail modes come closer as $q_{sc} = \Delta Q_{sc}/Q_s$ increases
- $\boldsymbol{k} < 0$ almost constant slope (but larger Landau damping ⇔ broader and lower spectral lines)

M. Blaskiewisz: *Fast head-tail instabilities with space charge,* Phys. Rev. Acc.. Beams 1, 044201, (1998)

A. Burov, *Head-tail modes for strong space charge*, Phys. Rev . Acc. Beams 12, 044202, (2009)

O. Boine-Frankenheim et .al., *Transverse Schottky noise spectrum for bunches with space charge*, Phys. Rev .Acc.. Beams 12, 114201, (2009)

Measurements: Overview of Beam Parameters

Parameter	Symbols	Value	Value	
Beam	$^{A}\text{Ion}^{q+}$	$^{238}U^{73+}$	$^{14}N^{7+}$	
Energy	W_{kin}	11.4 MeV/u	11.56 MeV/u	Longitudinal Schottky
No. of particles	N_p	$(1\ \dots 12)\cdot 10^8$	$(1\ \dots 15)\cdot 10^9$	Current Transformer
Emittance	ε_x & $\varepsilon_y(2\sigma)$	45 & 22 mm-mrad	33 & 12 mm-mrad	Profile Monitor
Tune	Q_{x0} & Q_{y0}	4.31 & 3.27	4.16 & 3.27	TOPOS or BBQ
Bunching factor	B_f	0.4	0.37	TOPOS
Synchrotron tune	Q_{s0} & $Q_{s,meas}$	0.007 & 0.0065	0.006 & 0.0057	TOPOS
Chromaticity	ξ_x & ξ_y	-0.94 & -1.85 set	-1.7 & -2.1 meas.	TOPOS

Measurement of **all** relevant beam parameters to calculate $\boldsymbol{q_{sc}}$ for horizontal and vertical direction, respectively:

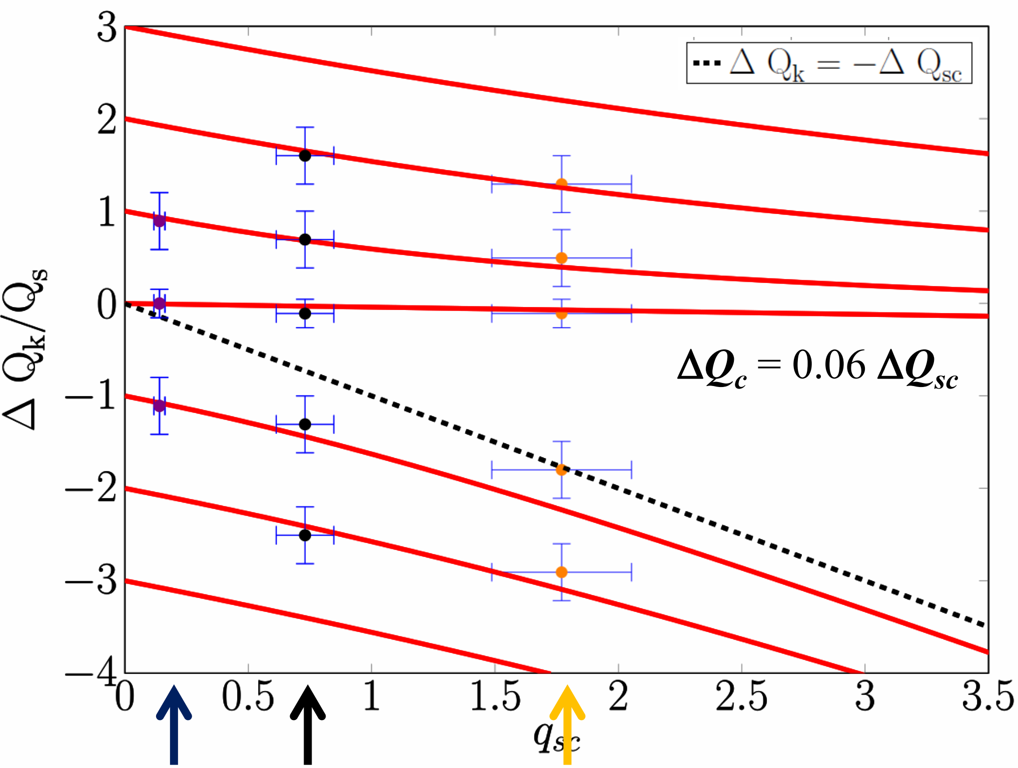
$$q_{sc,x} = \frac{|\Delta Q_{sc}|}{Q_{s,meas}} = \frac{1}{2\varepsilon_0}\cdot\frac{q^2 N_p / B_f}{Q_{s,meas} W_0\, \beta_0{}^2\, \gamma_0{}^2\, \varepsilon_{eff,x}}$$

Presented tune spectra are measured by BBQ or TOPOS

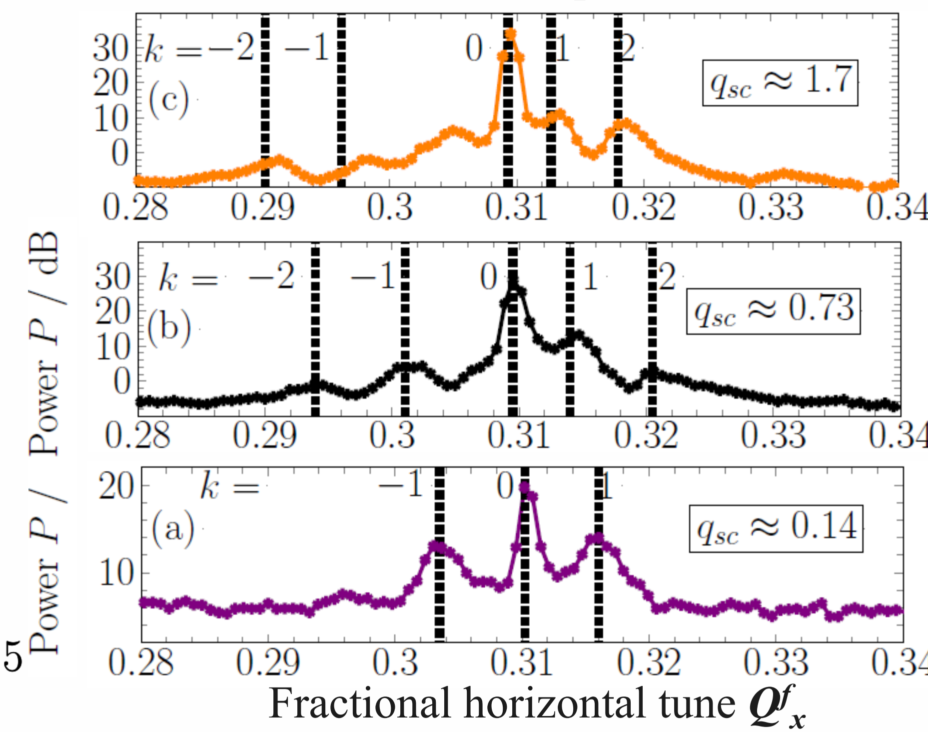
effective emittance $\varepsilon_{eff,x} = 1/2\,(\varepsilon_x + \sqrt{\varepsilon_x \varepsilon_y\, Q_{x0}/Q_{y0}})$

Measurements: Moderate Space Charge Parameter

Beam: U^{73+}, 11.4 MeV/u, (1 ... 12) · 10^8 ions, $Q_s = 0.007 \Leftrightarrow f_s = \frac{Q_s \omega_0}{2\pi} = 1.4$ kHz



Measured spectra



Red lines: predicted lines using **measured** beam parameters:

$$\Delta Q_{\pm k} = -\frac{\Delta Q_{sc} + \Delta Q_c}{2} \pm \sqrt{\frac{(\Delta Q_{sc} - \Delta Q_c)^2}{4} + (k Q_{s,meas})^2} \qquad q_{sc} = \frac{|\Delta Q_{sc}|}{Q_{s,meas}}$$

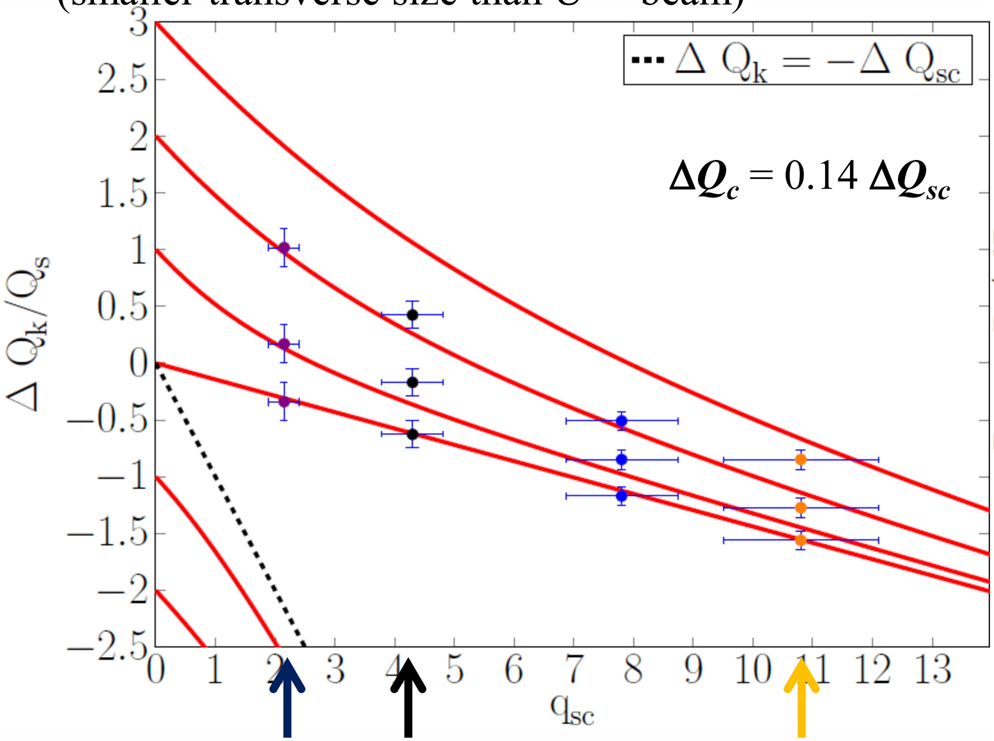
R. Singh et al., *Interpretation of transverse tune spectrum in a heavy-ion synchrotron*, Phys. Rev. Acc. Beams 13, 034201 (2013)

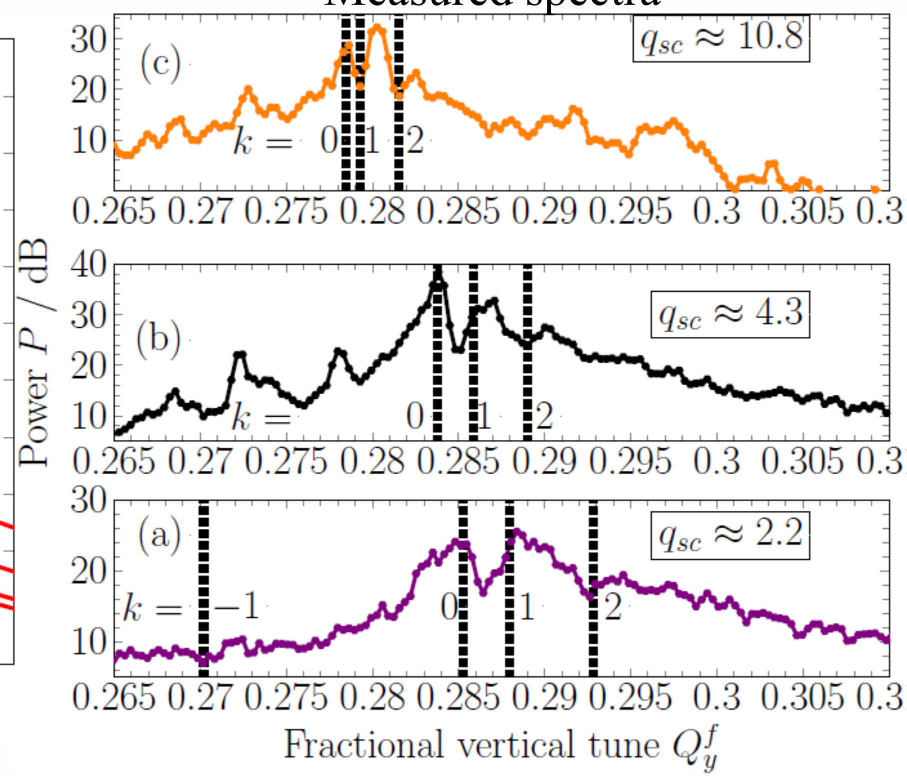
Measurements: Strong Space Charge Parameter

Beam: N^{7+}, 11.56 MeV/u, $(3 \ldots 15) \cdot 10^{9}$ ion, $Q_s = 0.006 \Leftrightarrow f_s = \frac{Q_s \omega_0}{2\pi} = 1.2$ kHz

(smaller transverse size than U^{73+} beam)

Measured spectra





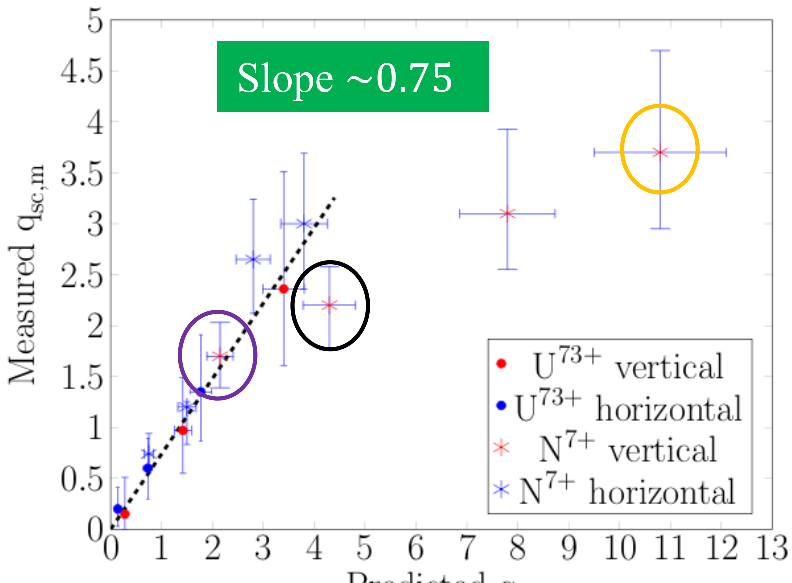
Predicted spectra : red lines

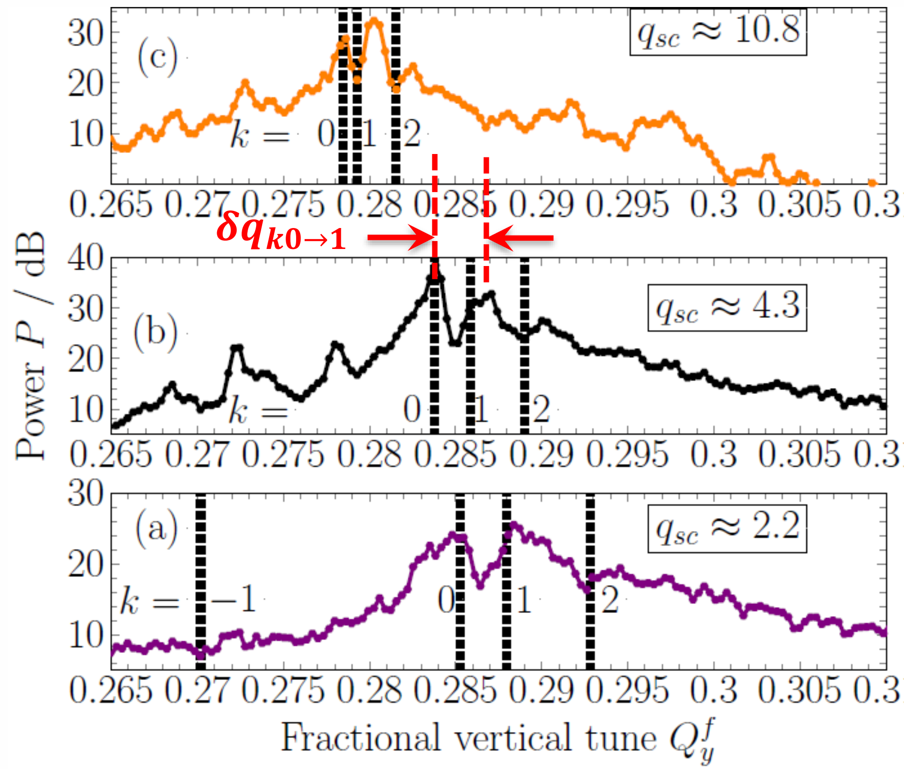
$$\Delta Q_{\pm k} = -\frac{\Delta Q_{sc} + \Delta Q_c}{2} \pm \sqrt{\frac{(\Delta Q_{sc} - \Delta Q_c)^2}{4} + (k Q_{s,meas})^2} \qquad q_{sc} = \frac{|\Delta Q_{sc}|}{Q_{s,meas}}$$

R. Singh et al., *Interpretation of transverse tune spectrum in a heavy-ion synchrotron*, Phys. Rev. Acc. Beams 13, 034201 (2013)

Comparison of Predicted and Measured Space Charge Parameter

The values q_{sc} from the depicted measurements with U^{73+} and N^{7+}





Measurement of all parameters:

- **Predicted** $q_{sc,x} = \frac{1}{2\varepsilon_0} \cdot \frac{q^2 N_p / B_f}{Q_{s,meas} W_0 \beta_0^2 \gamma_0^2 \varepsilon_{eff,x}}$
- **Measured** q_{sc} based on the distance between lines of modes $k =$ 0 and 1 : $\delta q_{k\,0\to\,1}$

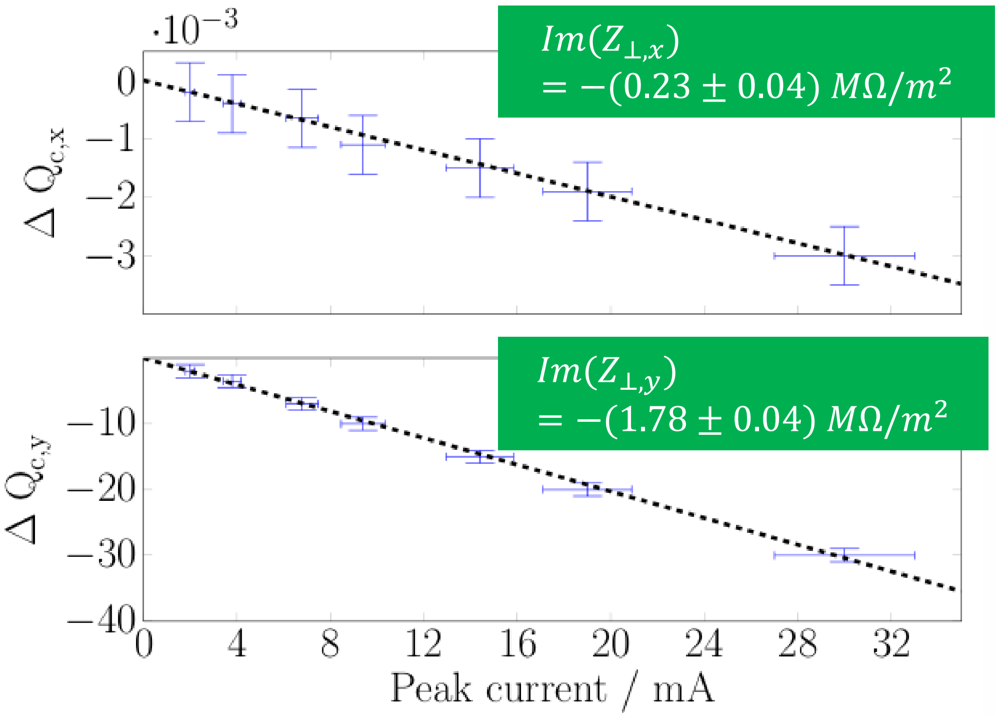
Findings:
- General trend well reproduced i.e. reason for modified tune spectra was found
- Significant deviation for higher values of q_{sc} (as expected from analytic model)

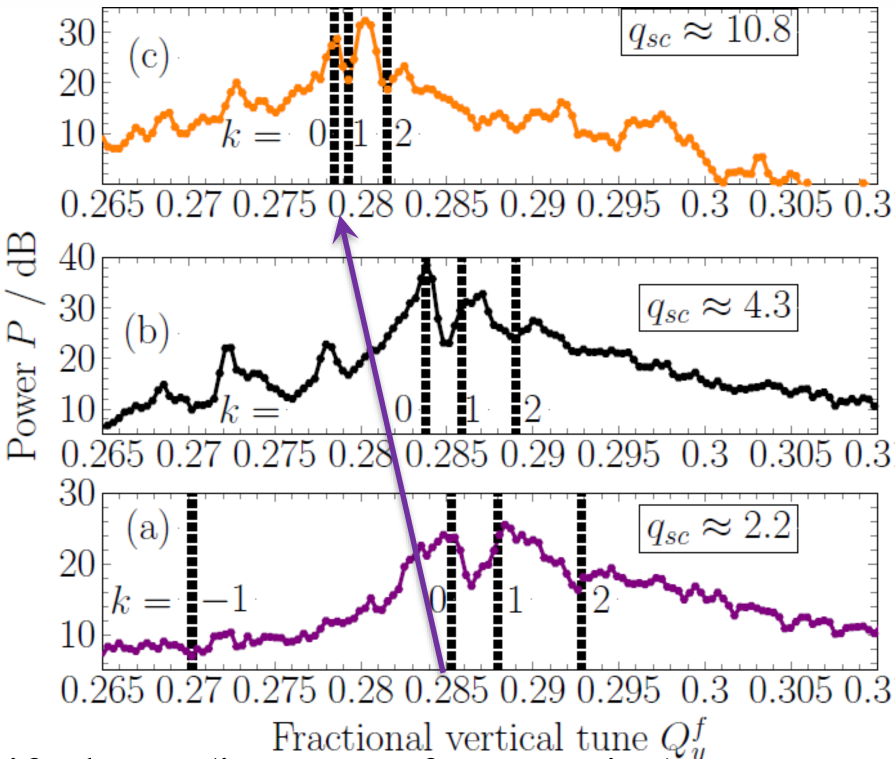
→ Does a better model with high prediction power exists ?
Can such model be applied to SIS18 parameter providing a plots of tune spectra ?

R. Singh et al., *Interpretation of transverse tune spectrum in a heavy-ion synchrotron*, Phys. Rev. ST Acc. Beams 13, 034201 (2013)

Measurements: Determination of coherent Tune Shift ΔQ_c

The coherent tune shift ΔQ_c from the depicted N^{7+} spectra and further spectra with Ar^{18+}





For $\boldsymbol{k} = 0$: $\Delta \boldsymbol{Q}_c = \Delta \boldsymbol{Q}_{k=0}$ i.e. value of coherently shifted tune (important for operating)

Results:

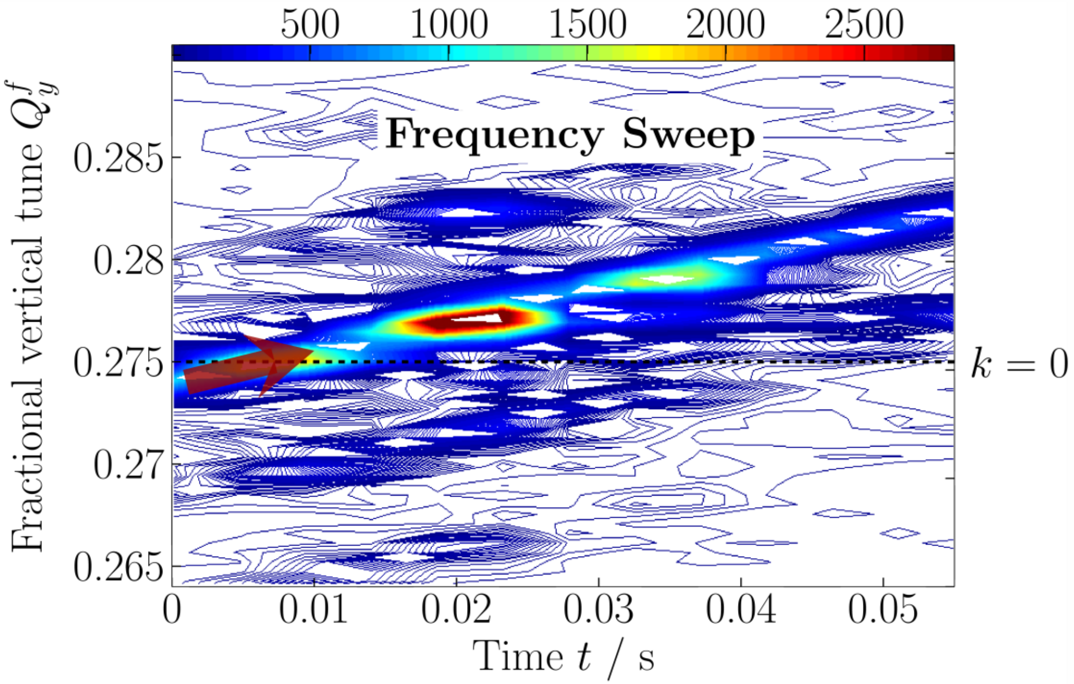
- Expected linear scaling coherent tune shifts versus peak beam current I_p
- For value of slope the resistive, effective impedance $\boldsymbol{Z}_\perp$ can be determined
  $\Rightarrow$ estimation of effective beam pipe radius $b_x \sim 115 \pm 5.5$ mm & $b_y = 35 \pm 1$ mm

R. Singh et al., *Interpretation of transverse tune spectrum in a heavy-ion synchrotron*, Phys. Rev. Acc. Beams 13, 034201 (2013)

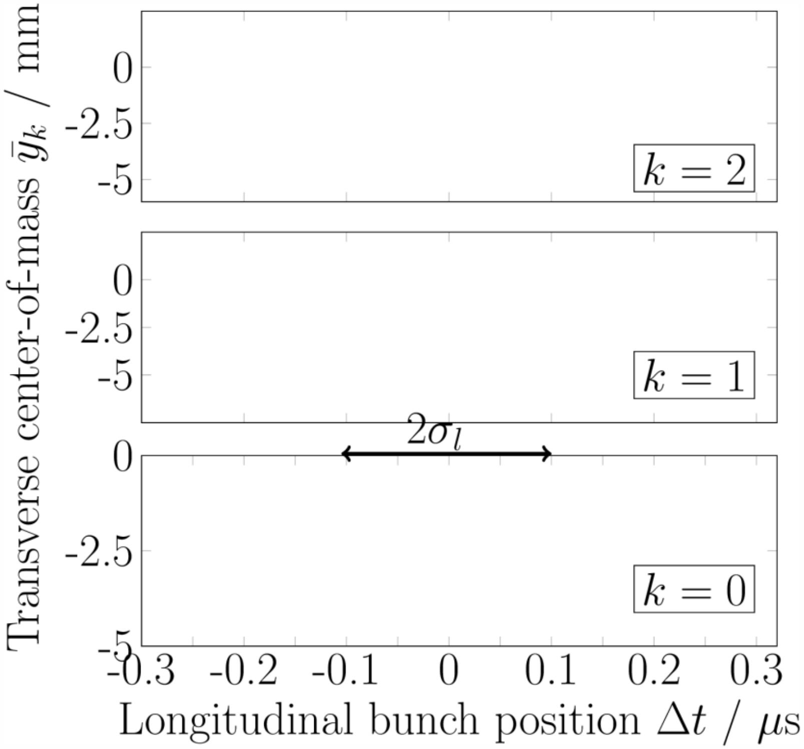
Time Domain Identification of Head-tail Modes

Frequency sweep allows the observation of bunch center oscillations i.e. head-tail modes
Beam parameter: $15 \cdot 10^9$ N^{7+} at 11.5 MeV/u, $Q_y = 3.75$, $\xi = -2.1$

Tune spectrogram during sweep:



11 consecutive turn-by-turn center-of-mass recordings:



Results:

- Sweep excitation allows excitation of individual head-tail modes
- The mode-structure verifies the spectra interpretation

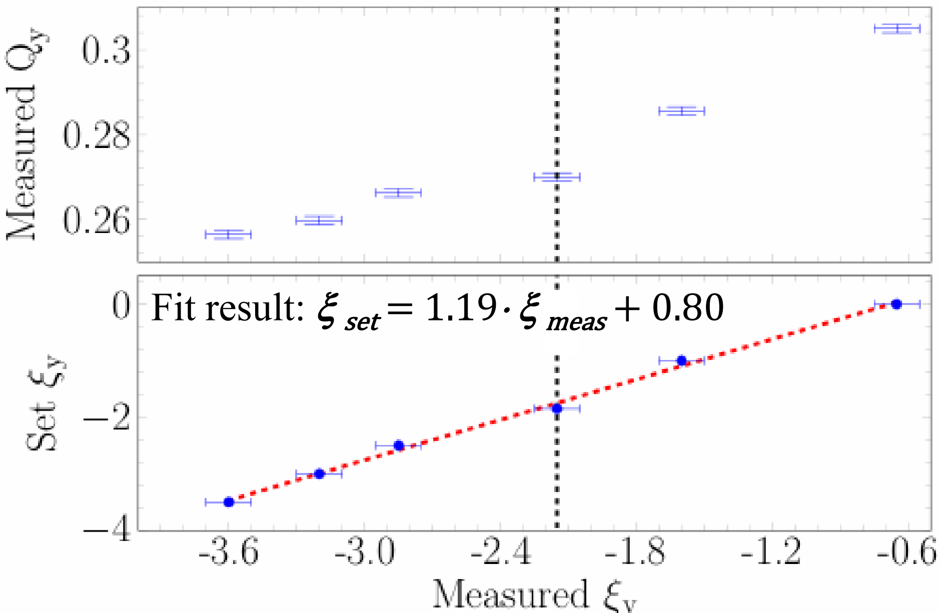
Remark: Eigen-functions for high intensities could be determined

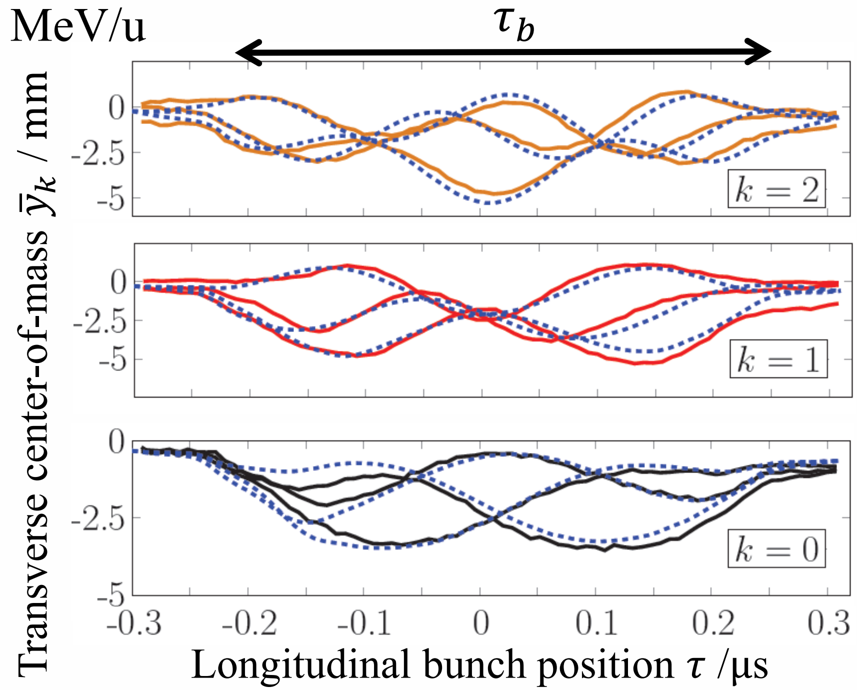
Determination of Chromaticity from Head-tail Oscillations

Fit of measured head-tail modes to the classical (i.e. without space charge) eigen-functions

$$\bar{y}_k(\tau,n) = \bar{y}_k(\tau)\cdot\cos\left[(\omega_b + k\omega_s)nT_0 + \omega_\xi\tau + \varphi_0\right] + y_{offset}$$

Beam parameter: low current $15\cdot10^9$ N^{7+} at 11.5 MeV/u





Results:

- Precise determination of chromaticity ξ
- SIS18: Deviation between set & actual value & coupling to tune due to uncorrected closed orbit

⇒ Reliable method but only for offline analysis

- Bold lines: measured bunch center
- Dotted lines: least squares fit with chromaticity ξ as fit parameter

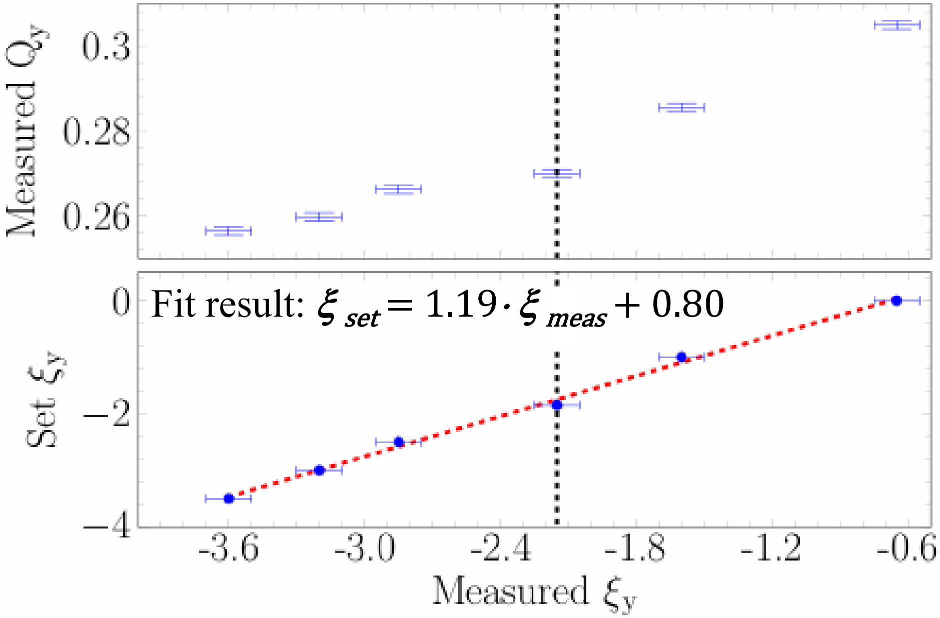
R. Singh et al., *Interpretation of transverse tune spectrum in a heavy-ion synchrotron*, Phys. Rev. Acc. Beams 13, 034201 (2013)

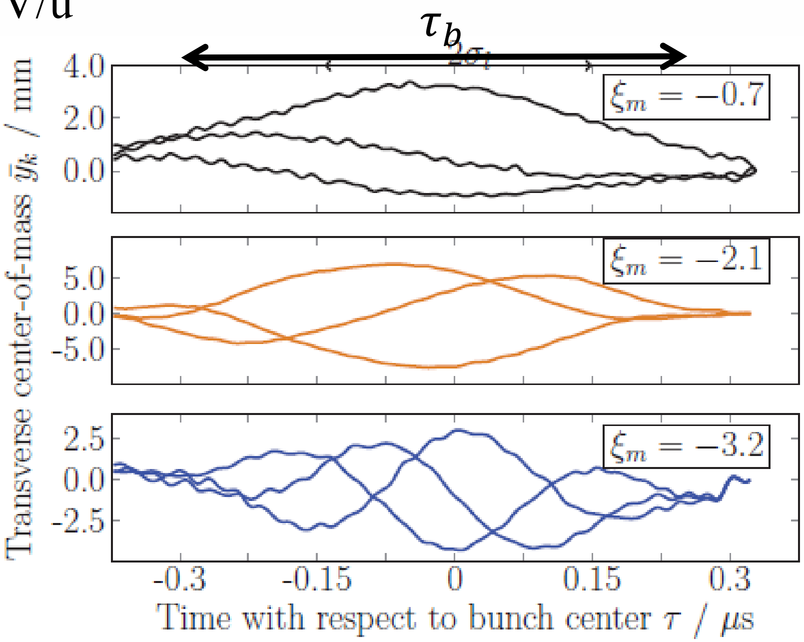
Determination of Chromaticity from Head-tail Oscillations

Fit of measured head-tail modes to the classical (i.e. without space charge) eigen-functions

$$\text{For } k = 0 \rightarrow \bar{y}_0(\tau, n) = \cos(\pi\tau/\tau_b) \cdot \cos[\omega_b n T_0 + \omega_\xi \tau + \varphi_0] + y_{offset}$$

Beam parameter: low current $15 \cdot 10^9$ N^{7+} at 11.5 MeV/u



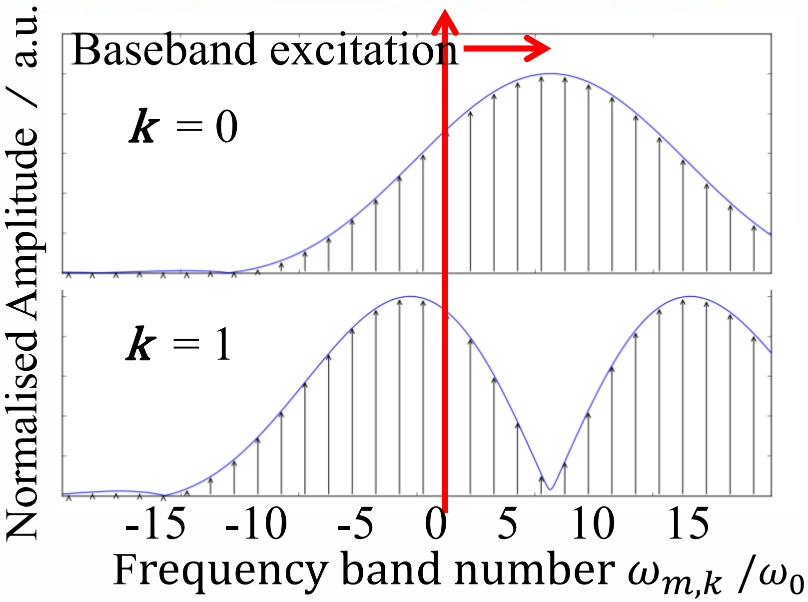


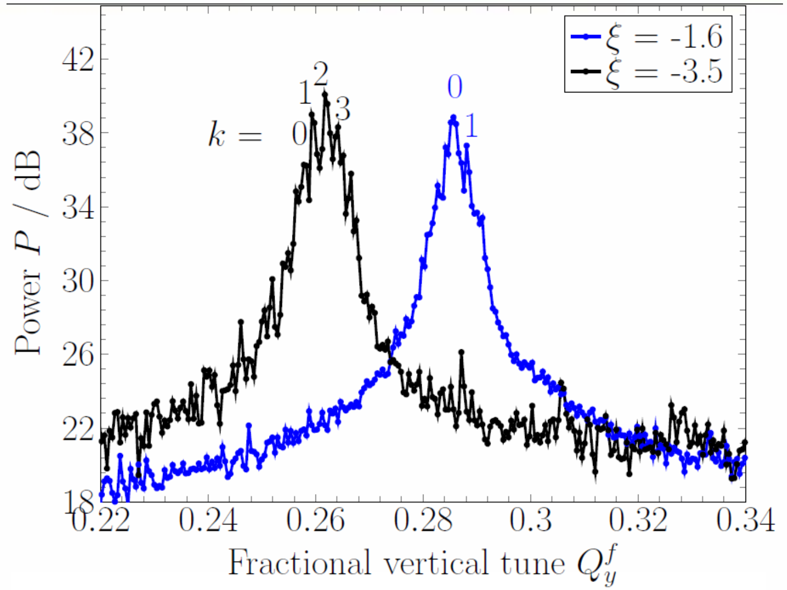
Results:

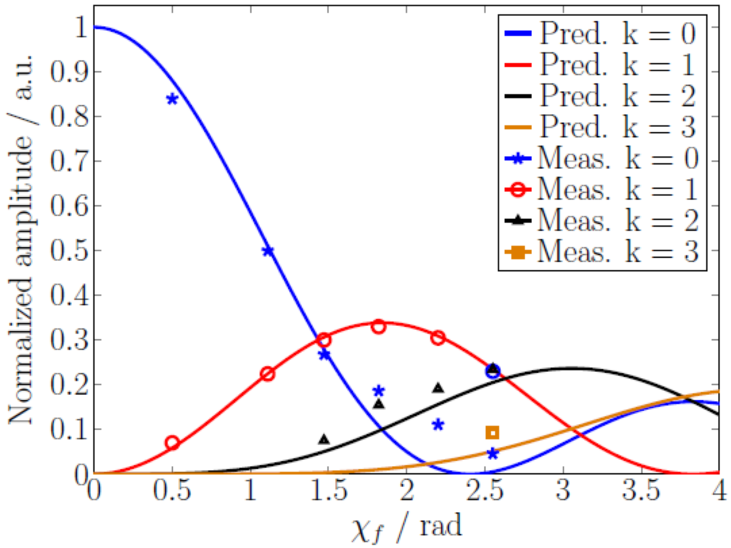
- SIS18: Deviation between set & actual value & coupling to tune due to uncorrected closed orbit
- Position measurement system not appropriate → a dedicated head tail monitor with hybrids better

- Beam losses at changed chromaticity
- The phase between two locations $\Delta\tau$ is a function of chromaticity as discussed earlier ($\omega_\xi \Delta\tau$)
- Phase shift constant between turns

Tune spectra vs Chromaticity







- Relative amplitudes of excited modes after a frequency sweep as a function of chromaticity
- Their excitability depends on the exact band/frequency of excitation
- To always have $k = 0$ mode as the dominant peak, excitation band should be close to ω_ξ

Tune Spectra at Higher Energies

During acceleration:

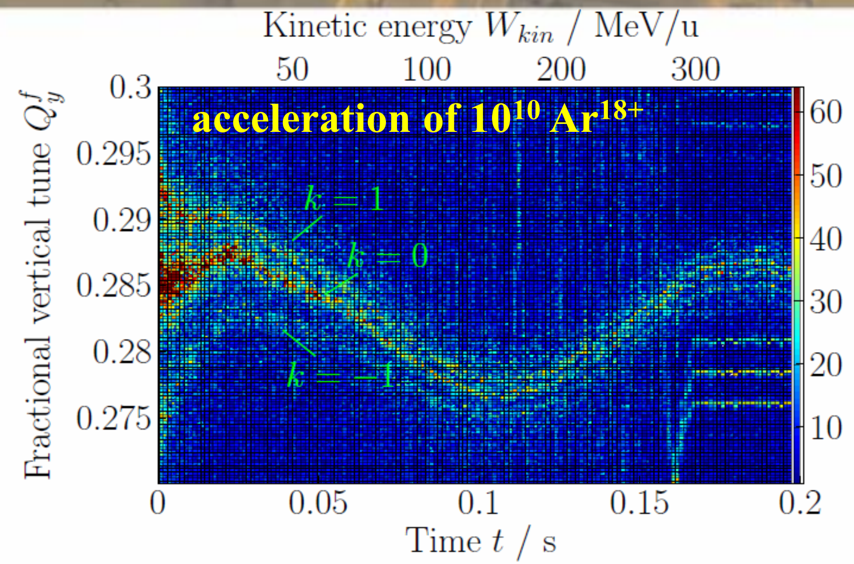
- transverse emittance decreases
- synchrotron tune Q_s decreases

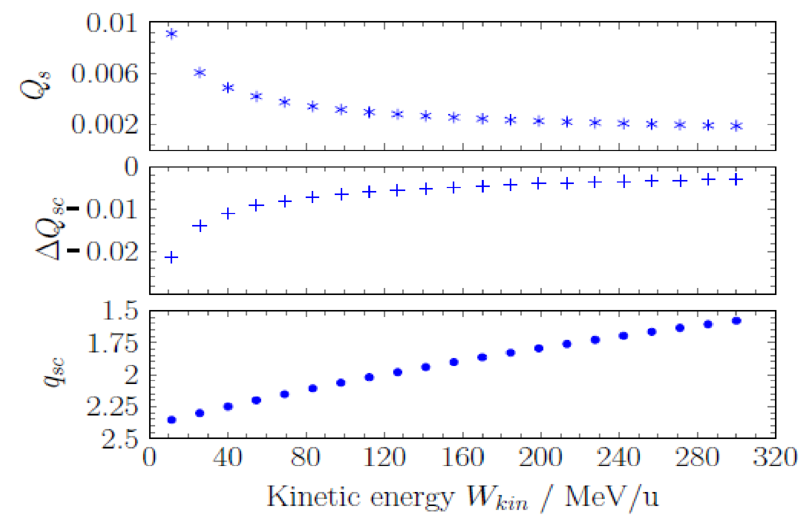
$\Rightarrow q_{sc} > 1$ i.e. relevant modification of spectrum

Typical values at other synchrotrons at injection:

Parameter	SIS18	SPS	RHIC	ANKA
I_{peak} / mA	10	1400	500	12
ε / mm·mrad	22	0.2	10	0.15
Lorentz fac. γ	1	27	4	100
Tune spr. ΔQ_{sc}	– 0.05	– 0.1	– 0.02	-10^{-4}
Synch. tune Q_s	0.007	0.015	0.0015	0.008
SC para. q_{sc}	**~ 7**	**~ 7**	**~ 13**	**~ 0**

Space charge modification of tune spectra is also relevant for other facilities !





R. Singh et al., PRST-AB 2013 and IBIC'13

Comparison to Theoretical Predictions

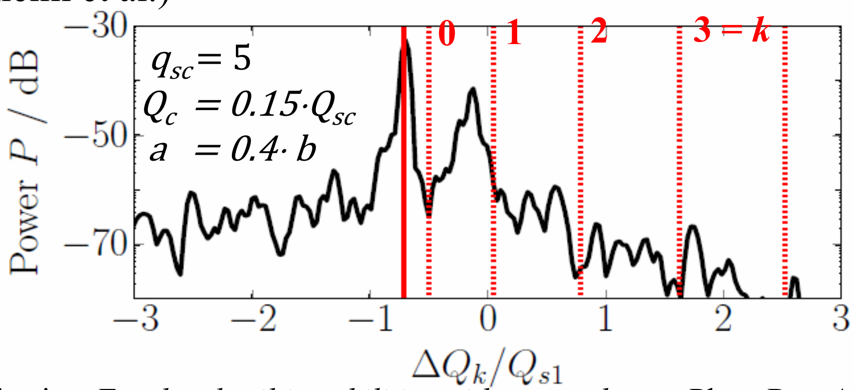
Theoretical investigations by other groups

as seen by a beam diagnostics person:

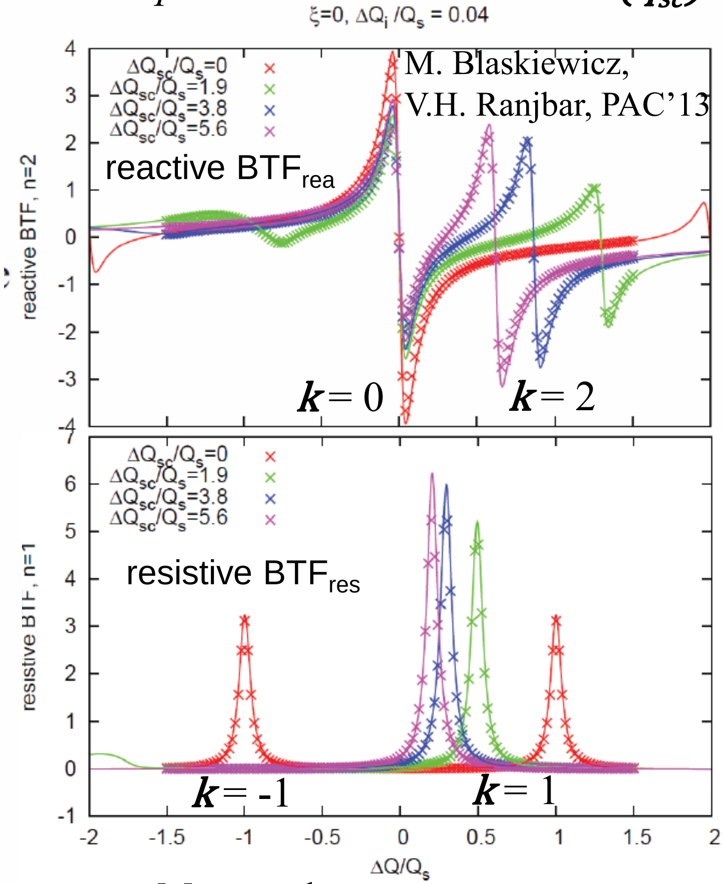
- Head-tail modes discussed for instabilities
- Eigen-frequencies predicted as a function of q_{sc}
- Landau damping stronger for negative modes
- Bunch length influences $Q_s(\sigma_{bunch}) \Rightarrow$ changes in spectrum
- Chromaticity influences the peak height and width
- **But:** Seldom plotted in terms of beam observables

  $\Rightarrow$ Prediction missing for height & width for SIS18

Example: PIC Schottky spectrum by code PATRIC (Boine-Frankenheim et al.)



Example: Plot of calculated $BTF(q_{sc})$



Measured tune spectrum:

$$P(\omega) = BTF^2_{rea}(\omega) + BTF^2_{res}(\omega)$$

M. Blaskiewisz: *Fast head-tail instabilities with space charge*, Phys. Rev. Acc. Beams 1, 044201, (1998)

A. Burov, *Head-tail modes for strong space charge*, Phys. Rev. Acc. Beams 12, 044202, (2009)

O. Boine-Frankenheim et .al., *Transverse Schottky noise spectrum for bunches with space charge*, Phys. Rev. Acc. Beams 12, 114201, (2009)

M. Blaskiewicz, V.H. Ranjbar *Transverse beam transfer functions via Vlasov equation,* Proc., PAC2013, Pasadena p. 1427 (2013).

Summary and Outlook

Experimental findings:

- System for **online** tune measurement realized, excitation with acceptable emittance growth
- Measurement of all beam parameters required for correct interpretation of tune spectrum
- Tune spectra: Eigen-frequencies significantly shifted for $q_{sc} \gtrsim 0.5$ by head-tail modes
- Coherently tune shift ΔQ_c measured by shift of $k = 0$ mode ⇒ **However**, $k = 0$ mode is **not** always the highest peak

  ⇒ spectrum must be interpreted e.g. by recording the mode structure of bunches !
- Estimation of tune spread ΔQ_{sc} available ⇒ usage for operation and MDs?
- Chromaticity measurement using head-tail phase shift

Lessons and outlook:

- Do not blame the hardware if the spectrum looks ugly
- Excite individual head-tail mode by harmonic excitation to measure chromaticity →Still to compare head tail chromaticity with rf modulation method
- Implications for tune feedback systems → Excite approximately at chromatic frequency to obtain $\boldsymbol{k = 0}$ mode as dominant peak

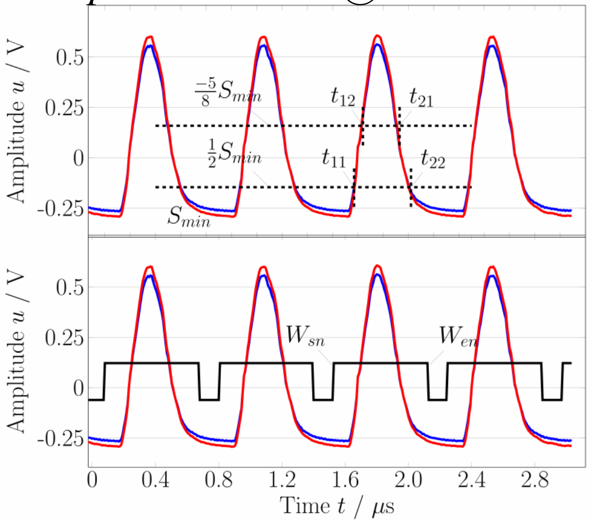
Thank you for your attention !

Extra slides

Position Determination: Integration versus least square Fit

Traditional: Integration

Example: One turn @ 35 MeV/u



1. Creation of window for one bunch of N samples
2. Determine baseline values $B_{l/r}$
3. Subtraction $U_{i,L/r} - B_{l/r}$ for $i = 1...N$
4. Integration of bunch signal

$$I_{l/r} = \sum_{i=1}^{N}\left(U_{i,l/r} - B_{l/r}\right)$$

5 .Position: $x = \frac{1}{S} \cdot \frac{I_l - I_r}{I_l + I_r}$

S is the position sensitivity

Novel: Ordinary least square fit algorithm:

1. Creation of window of a single bunch with N samples
2. Calculation of sum and difference for each sample:
   $\Sigma_i = U_{i,l} + U_{i,r}$ and $\Delta_i = U_{i,l} - U_{i,r}$ for $i = 1...N$
   'Plotting' Δ_i versus Σ_i
3. Assumption: From $x = \frac{1}{S} \cdot \frac{\Delta}{\Sigma} \Rightarrow \Delta_i = a \cdot \Sigma_i + b$
   with $a = x \cdot S$ and b as fit parameter
   $\Rightarrow$ Least square fit of Δ_i as a function of Σ_i
   General solution for fit parameter a :

$$a = \frac{\sum_{i=1}^{N}(\Sigma_i - \bar{\Sigma})(\Delta_i - \bar{\Delta})}{\sum_{i=1}^{N}(\Sigma_i - \bar{\Sigma})^2} = \frac{\mathrm{cov}(\Sigma,\Delta)}{\mathrm{var}(\Sigma)} \quad \& \quad b = \bar{\Delta} - a\bar{\Sigma}$$

   with average value $\bar{\Sigma} = \frac{1}{N}\sum_{i=1}^{N}\Sigma_i$ & $\bar{\Delta} = \frac{1}{N}\sum_{i=1}^{N}\Delta_i$

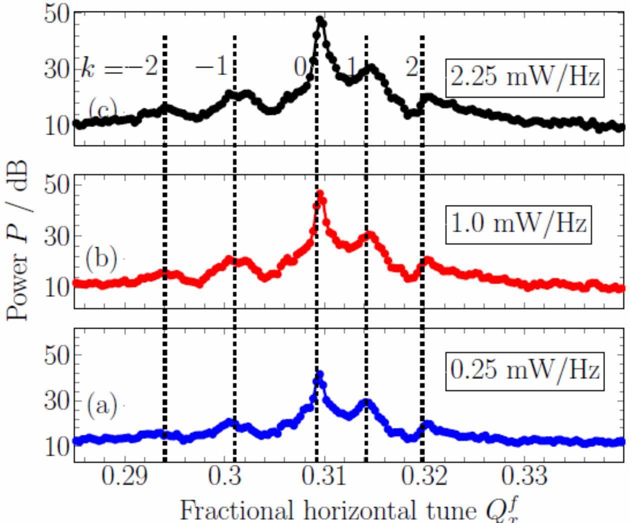
4. Position $x = a/S$ i.e. from fit value from diff-over-sum

Advantage:

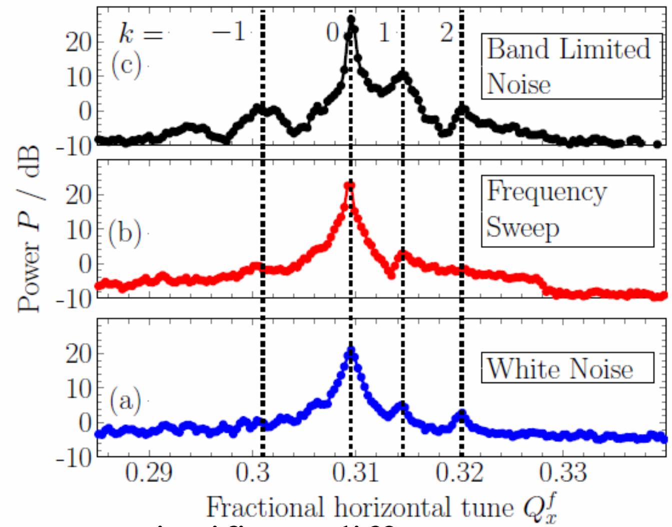
- No baseline reconstruction required
- Robust against offset etc. (here fit parameter b) i.e. high common and differential mode suppression
- Easy to implement
- For closed orbit: window over many bunches

Tune Spectra for different experimental Parameter

Variation of excitation power:



Variation of excitation type:



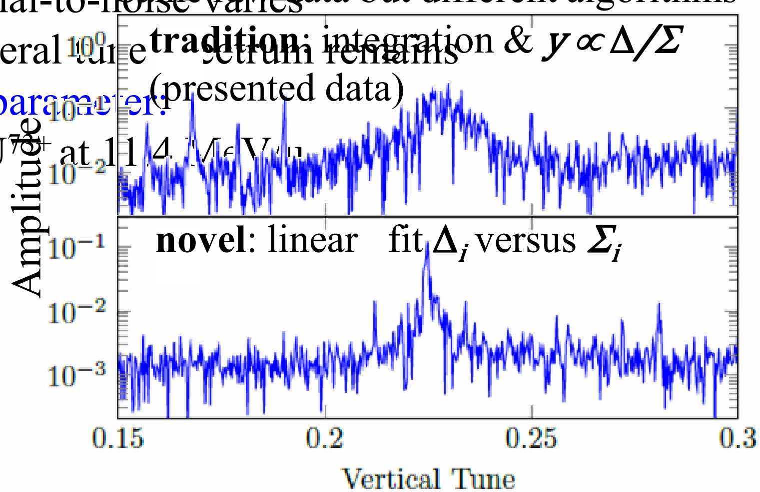
Result:

- signal-to-noise varies
- general tune spectrum remains

Beam parameter:

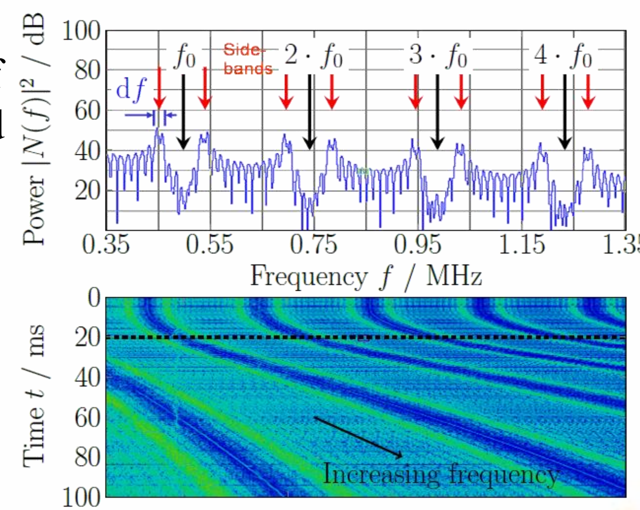
$5\cdot10^8$ U^{73+} at 11.4 MeV/u

Same raw data but different algorithms

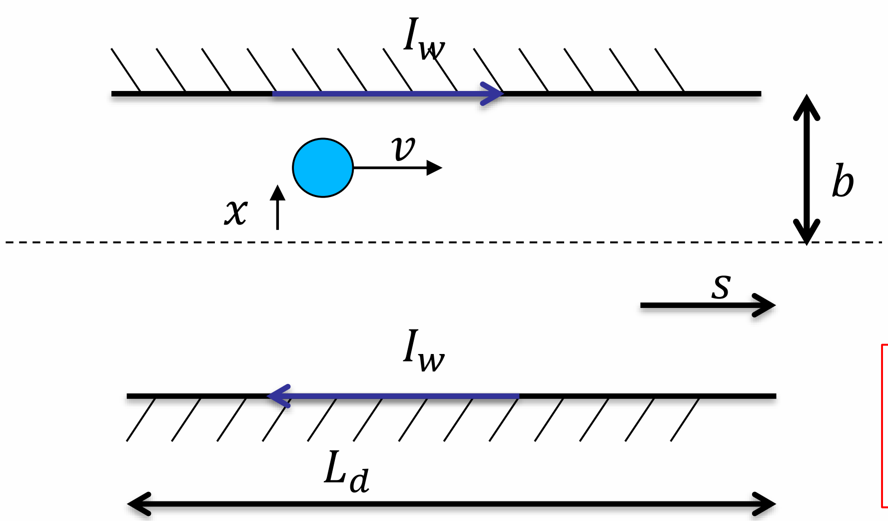


Result: No significant difference

Spectrum of band limited noise:



Transverse coupling impedances



- Effect of beam on itself through its environment
- $Im(Z_\perp)$ defines the frequency shift of the coherent modes. (Reactive)
- $Re(Z_\perp)$ defines the growth rate of these modes. (Resistive)

$$Z_\perp(\omega) = -j\frac{\int_0^{L_d}(E(s,\omega) + v \times B(s,\omega))_\perp ds}{\beta I x}$$

For a perfectly conducting beam pipe, it reduces to

Coherent tune shift

$$\Delta Q_c = -j\frac{qI_p R^2 Z_\perp}{2Q_0\beta_0 W_0} \propto \frac{\Delta Q_{sc} a^2}{b^2}$$

$$Z_\perp = -j\frac{Z_0}{2\pi{\beta_0}^2{\gamma_0}^2 b^2}$$

Characteristic impedance