Stability of coherent dipole oscillations with space charge

Oliver Boine-Frankenheim, Oleksandr Chorniy (PhD work)
and Th. Weiland (TU Darmstadt)

Contents:

The new SIS double rf system and expected longitudinal impedances

Elliptic bunch distribution with space charge and beam loading

- -Loss of Landau damping

Gaussian bunch distribution with space charge

- -Nonlinear space charge

Dispersion relation and stability scans

BTF measurements in SIS:

- - 'low intensity'
- - 'high intensity'

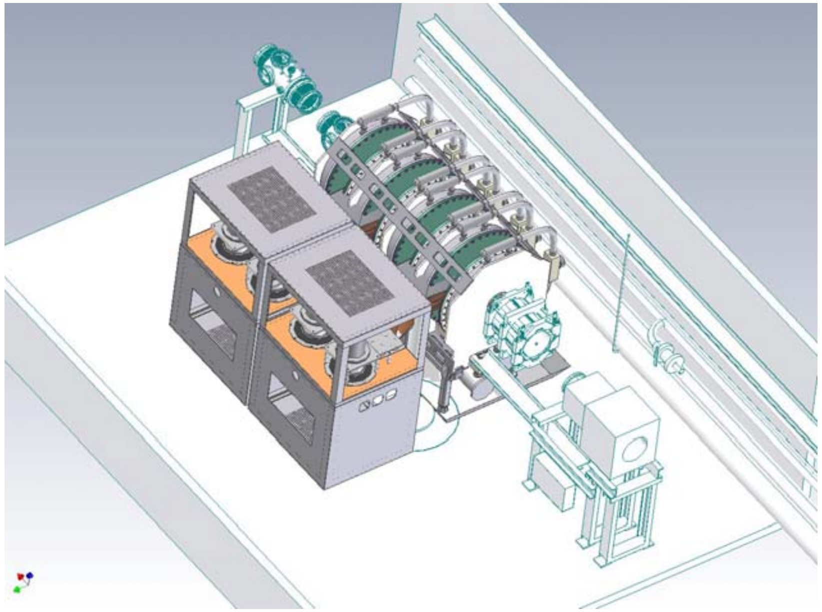
Conclusions

The new SIS double rf system
Fast acceleration of U^{28+} ions

	V_0 [kV]	f [MHz]	harmonic
MA	40	0.43-2.8	2
Ferrite	16	0.86-4.2	4

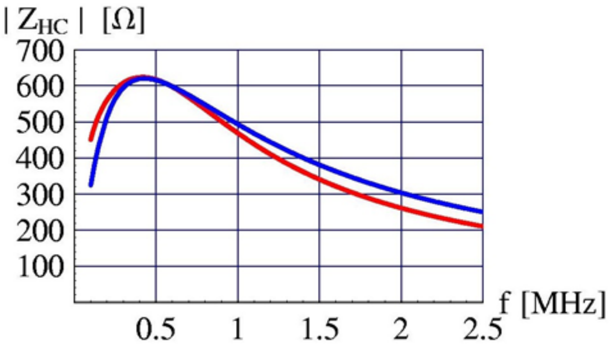
- ◊ Existing 32 kV, h=4 system provides insufficient acceptance for fast (4 Hz, 10 T/s) acceleration of intense U^{28+} bunches.
- ◊ The new double rf system should provide a larger bucket area and flattened bunches to increase the space charge limit.
- ◊ No possibilty to blow-up the long. emittance.
- ◊ Beam loading compensation and feedback requirements with space charge are presently main R&D issues.

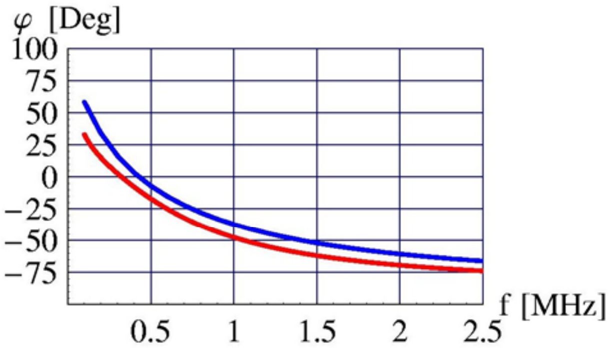
Four-gap magnetic alloy cavity
(40 kV, 0.43-2.8 MHz, 2.5 m)



P. Hülsmann, GSI

Broadband MA cavity impedance
and other longitudinal impedance contributions





$$Z_{bl}(\omega) = \frac{R_c}{1 + iQ_c\left(\omega/\omega_r - \omega_r/\omega\right)}$$

P. Hülsmann, private communication.

Beam loading: double harmonic RF system

	R_c [Ω]	Q	f_{res}
MA	1900	0.4	420 kHz
Ferrite	3000	10	$4f_0$

Other impedances of relevance in SIS:

1) Space charge impedance (2 kΩ, 11.4 MeV/u)

$$\frac{Z_{\parallel}^{sc}}{n} = i\frac{Z_0 g}{2\beta\gamma^2}\frac{1}{1+\left(n/n_c\right)^2}$$

2) Narrow band impedances (high-Q)

=> effective impedances

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Elliptic bunch distribution
matched bunch with space charge and beam loading

Rf voltage function (double rf):

$$V_{rf}(\phi) = \sin\phi - \sin\phi_s - \alpha\left(\sin\left[\phi_{s2} + 2(\phi - \phi_s)\right] - \sin\phi_{s2}\right)$$

Total voltage function:

$$V(\phi,t) = V_{rf}(\phi,t) + V_{sc}(\phi,t) + V_{bl}(\phi,t)$$

space charge factor: $\Sigma = \frac{1}{V_0 / V_{s0} - 1}$

Potential function: $Y(\phi,t) = -\int_{\phi_s}^{\phi} V(\phi')d\phi'$

'Hamiltonian': $H = \frac{\dot{\phi}^2}{2} - \omega_s^2 Y(\phi)$

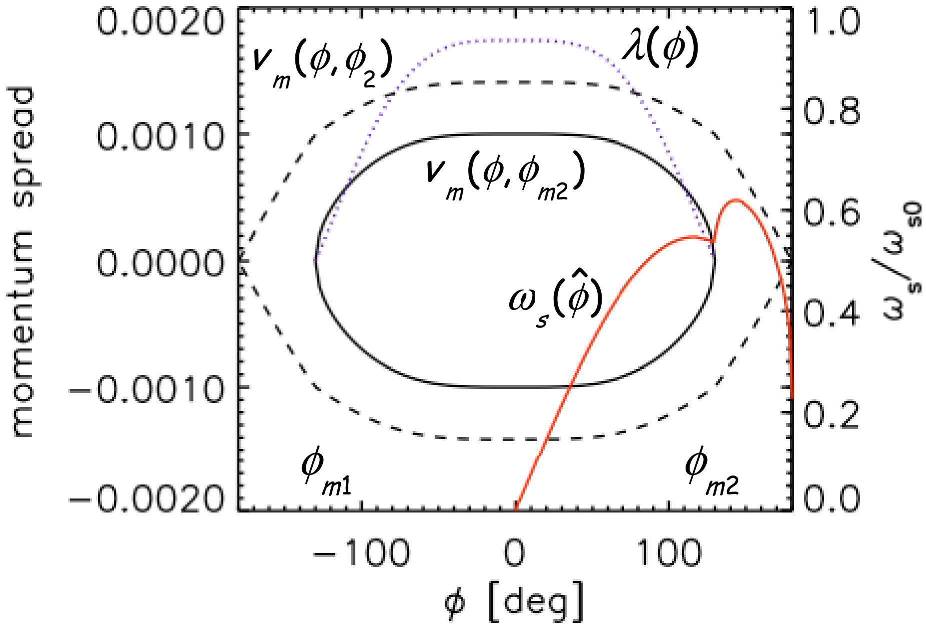
'Hofmann-Pedersen' distribution:

$$g(H) = C\sqrt{H_m - H} \qquad H_m = \frac{v_m^2}{2} = -\omega_{s0}^2 Y(\phi_{m2})$$

velocity function:

$$v_m^2(\phi,\phi_{m2}) = 2\omega_{s0}^2\left(Y(\phi) - Y(\phi_{m2})\right)$$

Example (no beam loading): $V_{rf}(\phi) = \left(\sin\phi - \frac{1}{2}\sin 2\phi\right)$

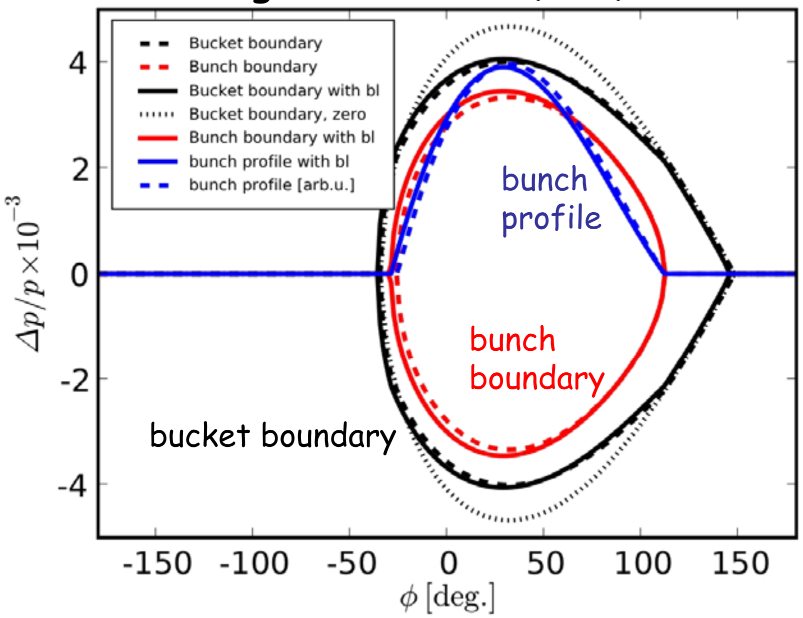


QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

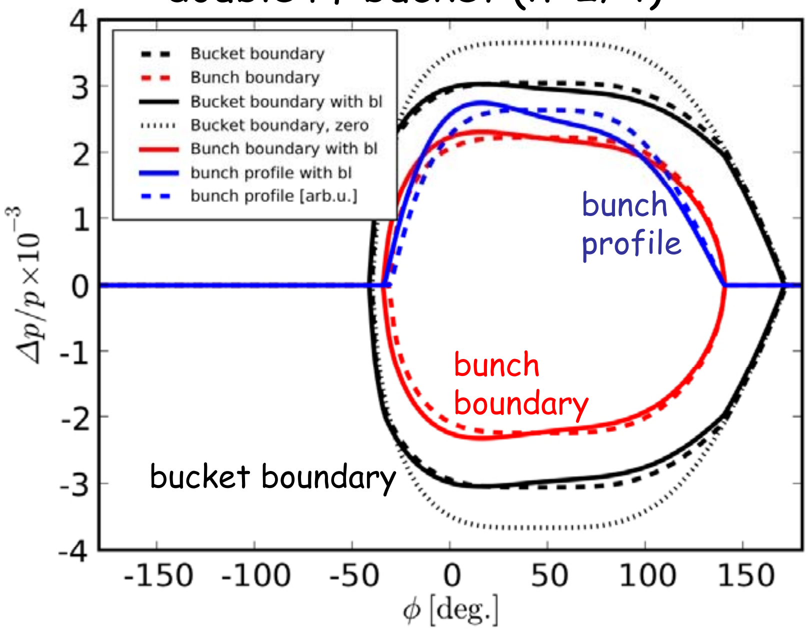
Expected bucket and bunch areas in SIS 18

including space charge and beam-loading

single rf bucket (h=2)



double rf bucket (h=2/4)



$\Sigma \approx 0.4$: ca. 30 % of the rf voltage requirement is due to space charge

Beam loading: affects the bunch form in the double rf bucket.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Synchrotron frequency

Loss of Landau damping

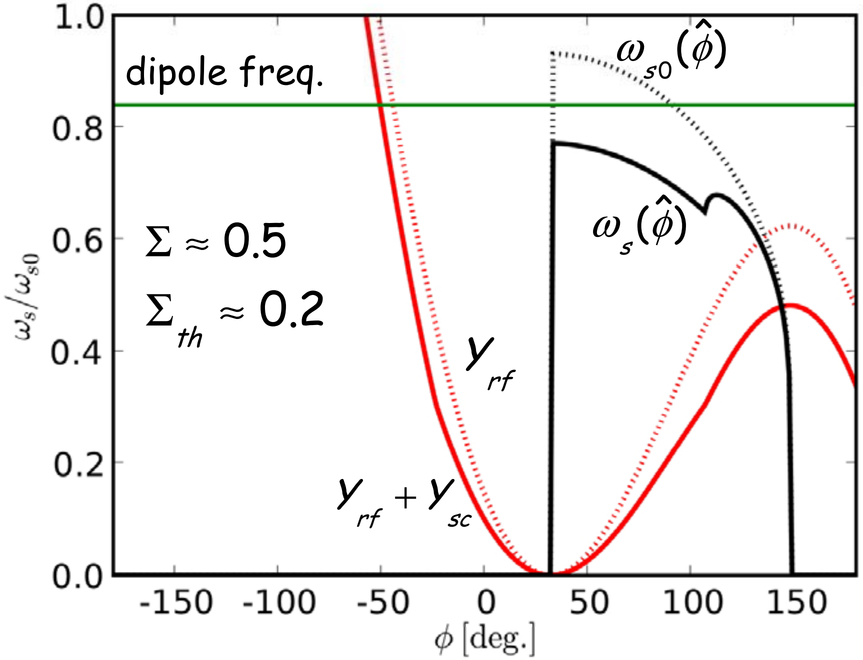
Synchrotron period: $T_s(\hat{\phi}) = \frac{2\pi}{\omega_s(\hat{\phi})} = 2\frac{R}{h}\int_{\hat{\phi}_1}^{\hat{\phi}_2} \frac{d\phi}{v_m(\phi,\hat{\phi}_2)}$

Coherent dipole frequency: $\Omega_c^2 \approx \omega_{s0}^2 \frac{1}{u_m}\int_{\phi_{m1}}^{\phi_{m2}} V_{rf}^2 \, d\phi$

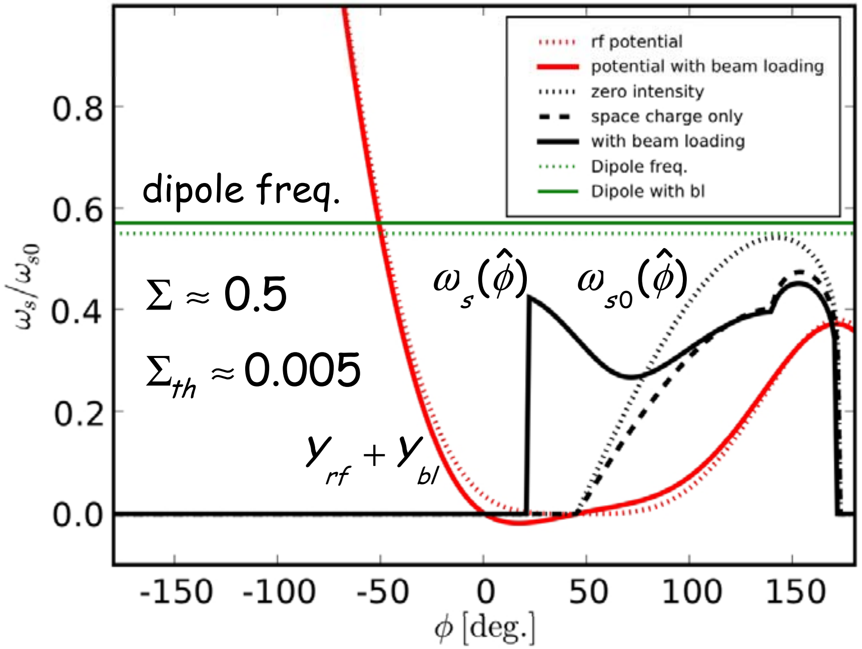
Space charge induced 'Loss of Landau damping':

$$\Omega_c \geq \omega_{max}(\Sigma) \quad \Rightarrow \quad \Sigma_{th}$$

single rf bucket (with space charge)



double rf bucket (+ beam loading)



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

O. Boine-Frankenheim, T. Shukla, PRST-AB 2005

Loss of Landau damping

Bunch in a single rf bucket with linear space charge

Pedersen, Sacherer, 1977

Zur Anzeige wird der QuickTime™
Dekompressor „TIFF (Unkomprimiert)“
benötigt.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Gaussian bunch distribution
with nonlinear space charge

Elliptic dist.: more convenient
Gaussian dist.: more realistic for heavy ions

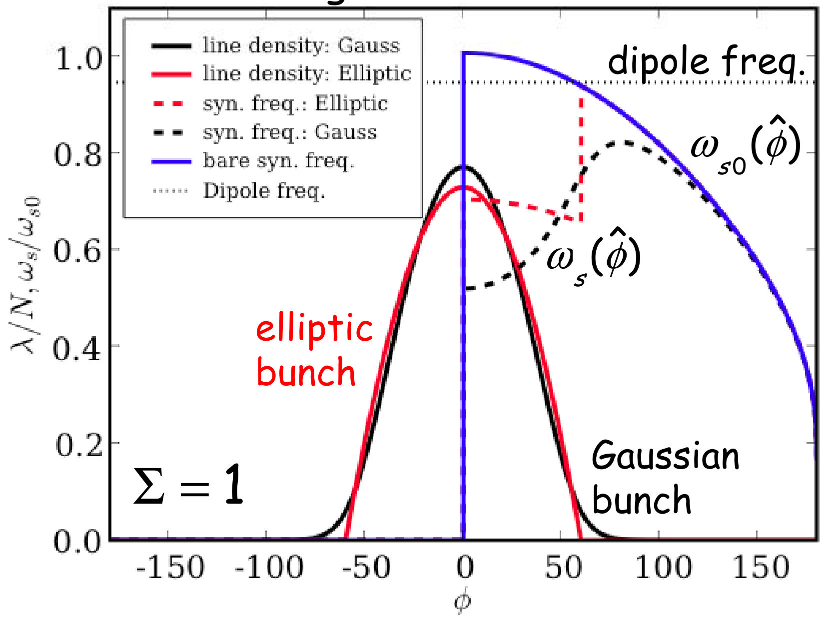
- o Role of nonlinear space charge ?
- o Loss of Landau damping ?
- o Stability of coherent (dipole) modes ?

Gaussian bunch profile $$\lambda(\phi) = \lambda_m \exp\left(\frac{\omega_{s0}^2 Y(\phi)}{2H_{rms}} \right)$$

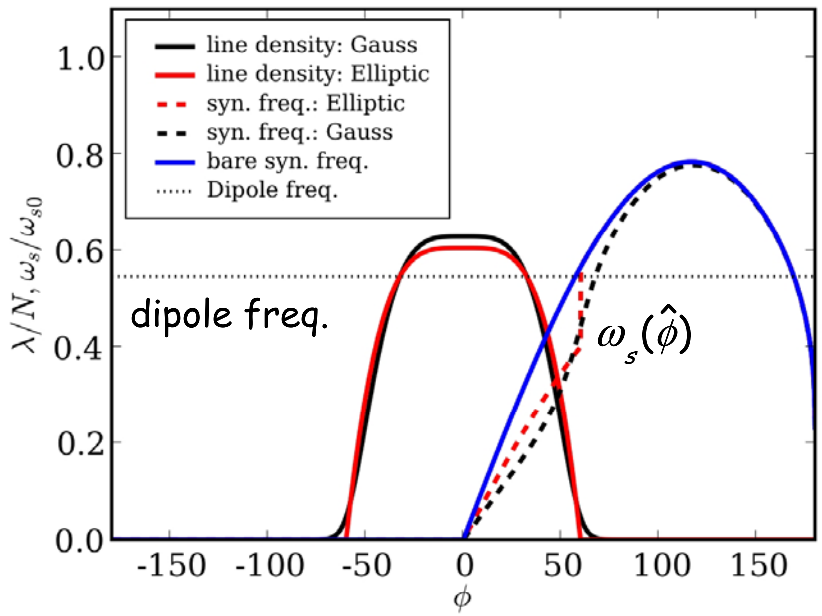
$$\omega_s(\hat{\phi}) \approx \omega_{s0} - \omega_{s0}\frac{\hat{\phi}^2}{16} - \Delta\omega_s\left(1 - G(\hat{\phi})\right)$$

(nonl. rf) (nonl. space charge)

single rf bucket



double rf bucket



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Bunch Stability
with nonlinear space charge

Coherent (dipole) frequency shift:

$$\Delta\Omega_c = \frac{i\omega_{s0}}{2}\left(Z^R_{eff} + iZ^I_{eff}\right)$$

Effective dipole impedance: $$Z_{eff} \propto \frac{\sum_n |\lambda'_n| \frac{Z(n\omega_0 \pm \Omega_c)}{n}}{\sum_n |\lambda'_n|}$$

Dispersion relation (Moehl, CERN 1997):

$$1 = -\pi \int_0^{\pi} [\Delta\Omega - \Delta\omega_s(\hat\phi)] \frac{2\omega_{s0} f'(\hat\phi)\hat\phi^2 d\hat\phi}{\Omega^2 - \omega_s^2(\hat\phi) + i\gamma\omega_{s0}}$$

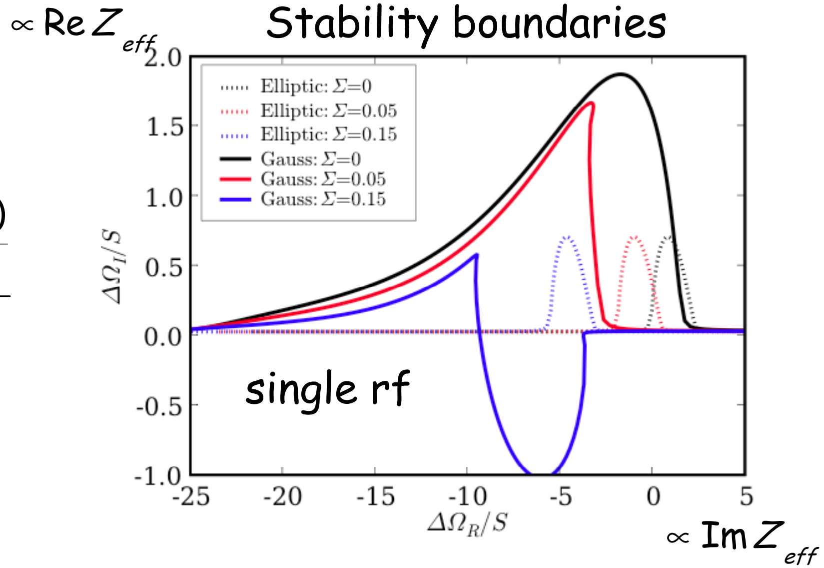
For an elliptic bunch distribution (const. $\Delta\omega_s$):

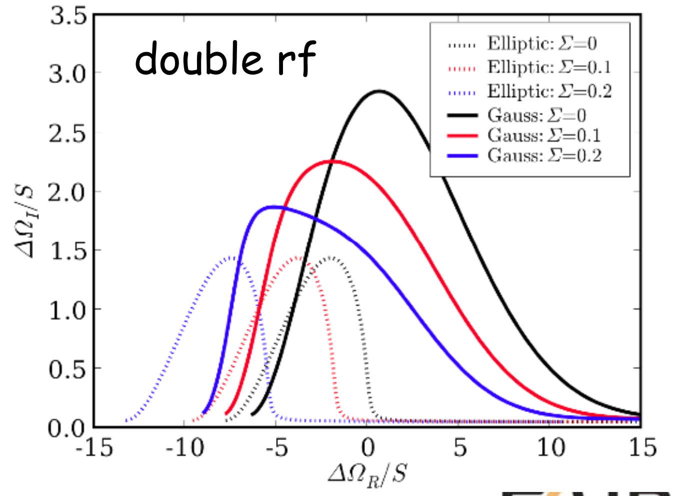
$$1 = -\pi(\Delta\Omega - \Delta\omega_s)\int_0^{\pi} \frac{f'(\hat\phi)\hat\phi^2 d\hat\phi}{\Omega - \omega_s + i\gamma}$$

K.Y. Ng, FNAL report (2005)

Gauss: double rf more stable with space charge

Stability boundaries

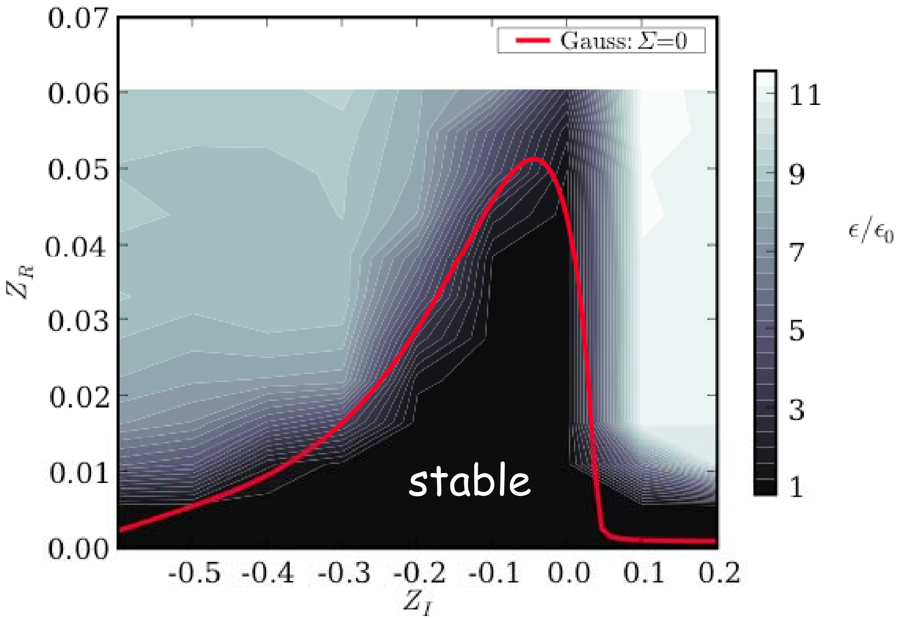


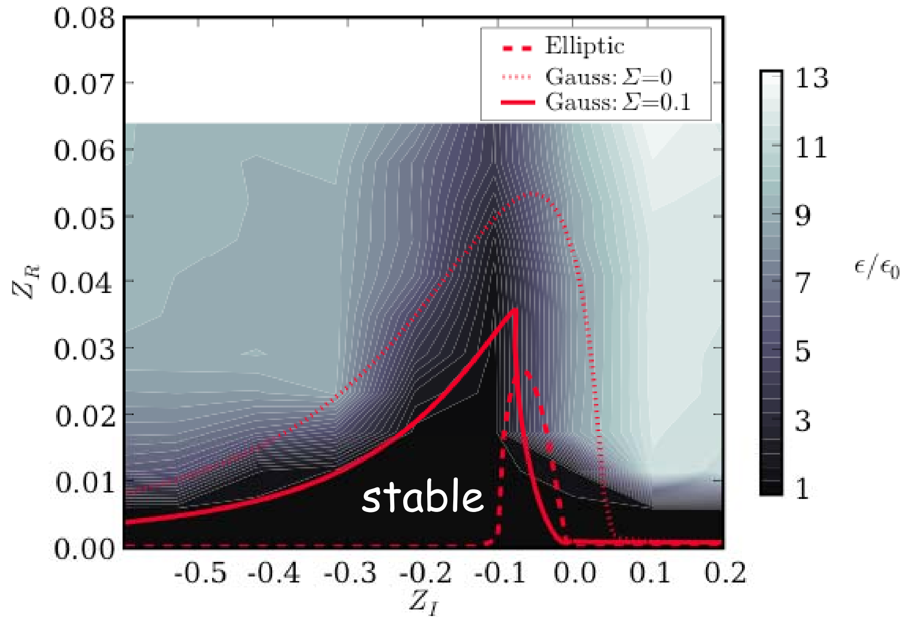


QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Bunch stability scans
single rf bucket

Stability scans:
- Longitudinal beam dynamics code 'LOBO'
- Initial matched Gaussian bunch
- Simulation runs with different effective impedances
- Plot the final bunch area as a function of the effective impedance.



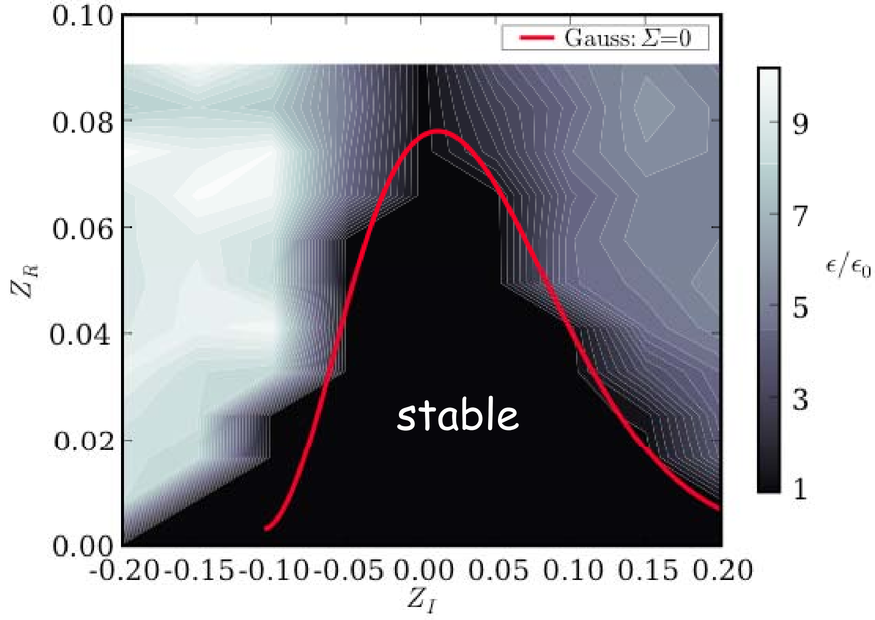


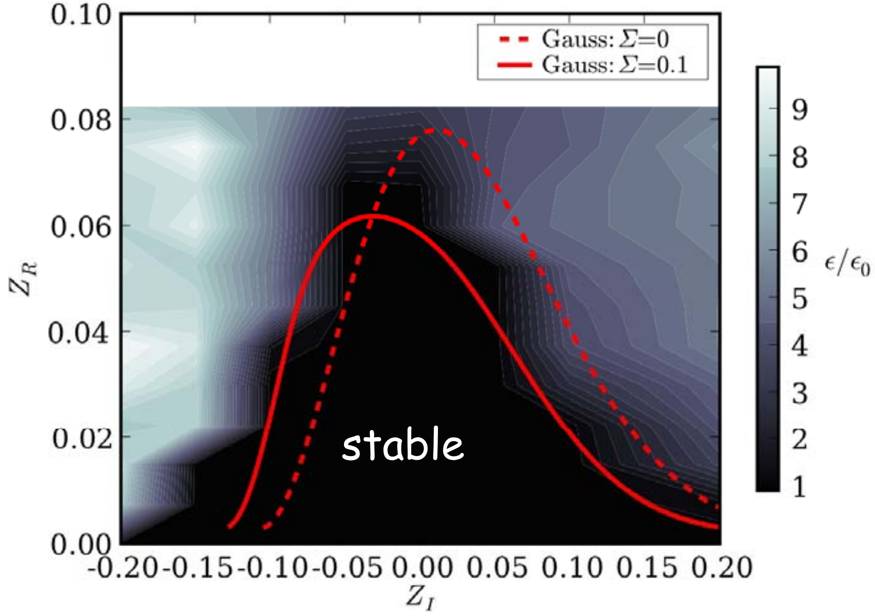
Above ∑≈1 no stable area can be observed !

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Bunch stability scans

double rf





Rather good agreement between the stability boundary from the dispersion relation and the simulations scans.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Longitudinal Bunched BTF

single rf bucket

- Simulation scans need a lot of computer resources.
- Beam Transfer Function (BTF) measurements are faster.

rf phase modulation: $V_{rf}(\phi) = V_0 \sin(\phi + \hat{\varepsilon}\sin(\Omega_m t))$

BTF: $r(\Omega_m) = \frac{\hat{\phi}}{\hat{\varepsilon}} = \frac{\text{bunch offset amplitude}}{\text{rf phase modulation}}$

Stability boundary: $r^{-1}(\Omega_m) = \Delta\Omega$

- With space charge the $(\text{BTF})^{-1}$ does not necessarily relate to the stability boundary.
- The BTF is only defined with Landau damping or external damping.

Weak space charge $\Sigma < \Sigma_{th}$

Σ=0: $r_0(\Omega_m) = -\pi \int_0^{\pi} \frac{f'(\hat{\phi})\hat{\phi}^2 d\hat{\phi}}{\Omega_m - \omega_s(\hat{\phi}) + i\gamma}$

Elliptic dist.: $r^{-1}(\Omega_m) = r_0^{-1}(\Omega_m) - \Delta\omega_s$

Gauss: $r(\Omega_m) = \frac{r_0(\Omega_m)}{1 - D(\Omega_m)}$

Strong space charge $\Sigma > \Sigma_{th}$

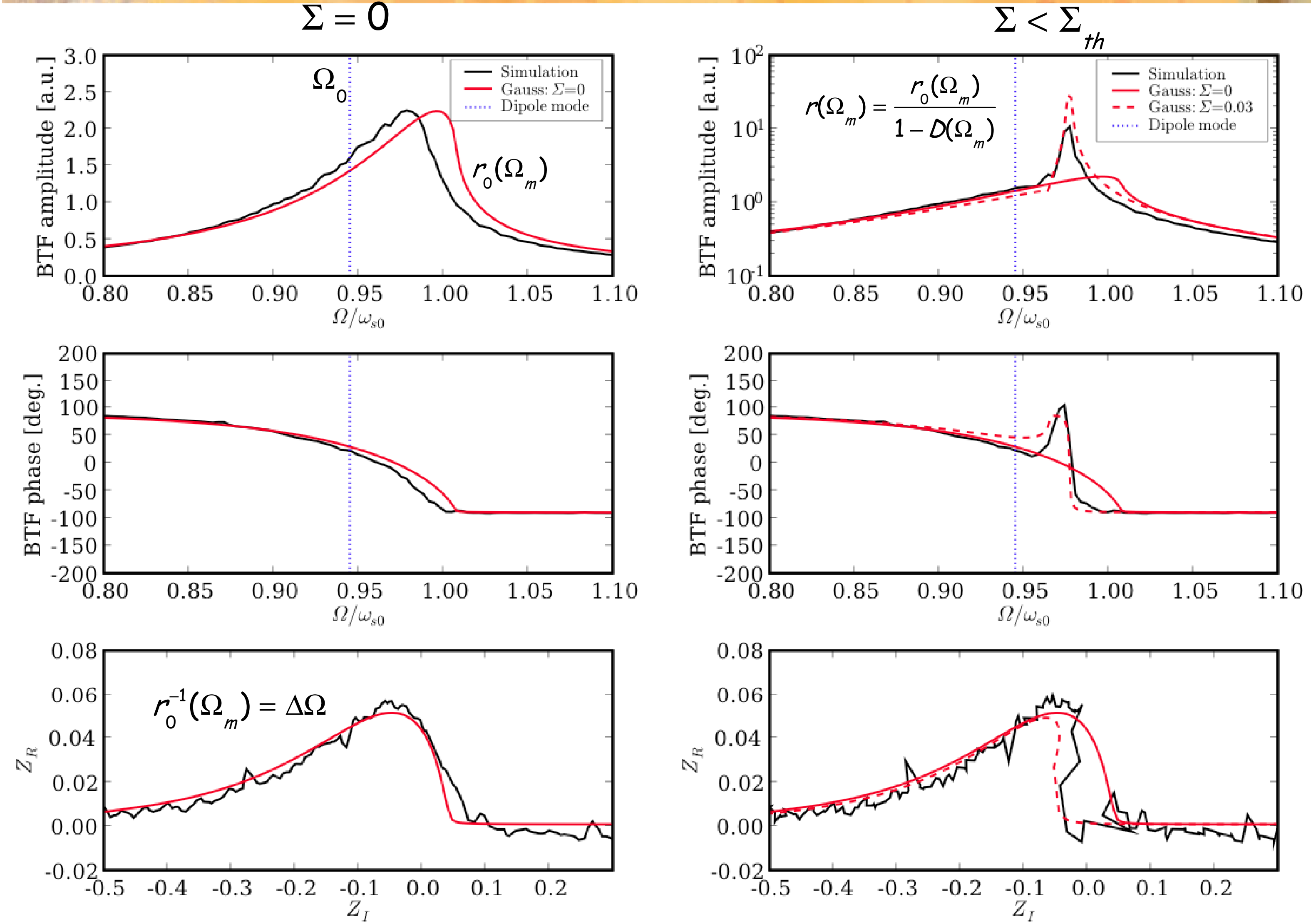
$$\ddot{\bar{\phi}} + 2\gamma\dot{\bar{\phi}} + \Omega_c^2\bar{\phi} = \hat{\varepsilon}\Omega_m^2 \sin(\Omega_m t)$$

('External' damping rate γ)

$$r(\Omega_m) = \frac{\Omega_m^2}{\Omega_c^2 - \Omega_m^2 + i2\gamma\Omega_m}$$

BTF Simulations

Computer Beam Transfer Function (CBTF)

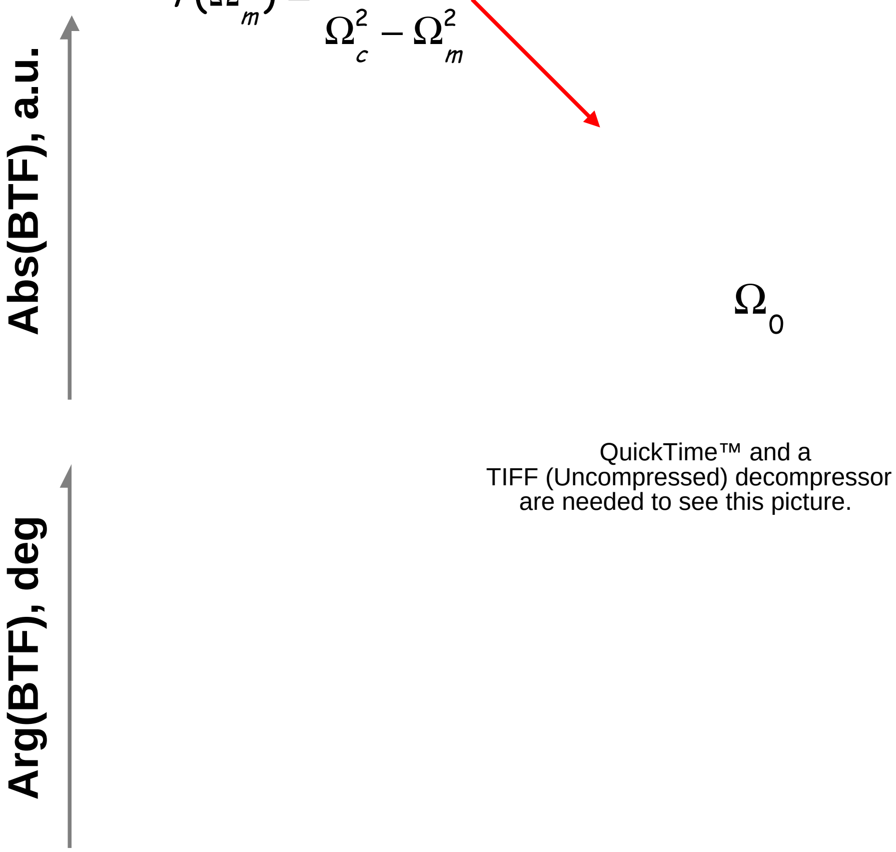


Longitudinal Bunched BTF Measurements

CERN PSB

'undamped oscillator'

$$r(\Omega_m) = \frac{\Omega_m^2}{\Omega_c^2 - \Omega_m^2}$$



longitudinal bunched BTF measurements with space charge were performed 1977 by F.Pederson and F.Sacherer.

Amplitude and phase response around the n=3 dipole sideband.

$$\Sigma < \Sigma_{th}$$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

BTF measurements in SIS

Low intensity

O. Chorniy

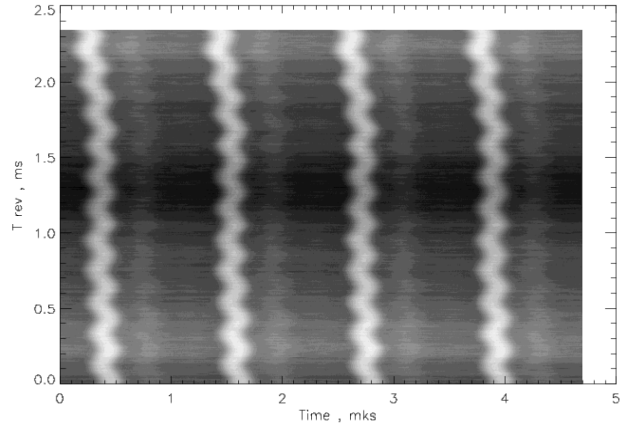
Ion: U^{73+}
Energy: 11.4 MeV/u
$N=1\text{-}6 \cdot 10^8$
Space charge: $\ll \Sigma_{th}$
rf. mod. ampl.: 0.1^0

Gaussian bunch profiles

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Rf phase modulation (sweep)

time



ring circumference

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

$r_0(\Omega_m)$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

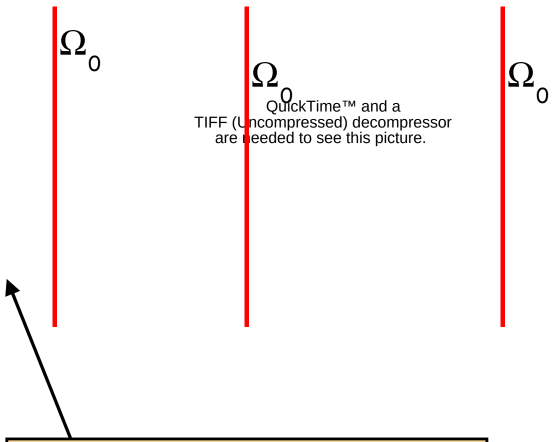
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

BTF measurements in SIS

with e-cooling

O. Chorniy

$\Sigma > \Sigma_{th}$



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

$$r(\Omega_m) = \frac{\Omega_m^2}{\Omega_c^2 - \Omega_m^2 + i2\gamma\Omega_m}$$

$$\Omega_c = \Omega_0 + \Delta\Omega_c$$

$$\Delta\Omega_c = \frac{i\omega_{s0}}{2}\left(Z_{eff}^R + iZ_{eff}^I\right)$$

Obtain the effective dipole impedance from the fit:

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Conclusions

Motivation

- new double rf system for SIS.
- stability of high intensity, high quality heavy ion bunches for FAIR.

Elliptic bunch distribution

- space charge and beam loading effects in different bucket forms
- loss of Landau damping for the dipole mode, especially in double rf buckets.

Gaussian bunches with nonlinear space charge

- loss of Landau damping in single rf buckets (not for double rf !)

Approximate dispersion relation and stability scans for the dipole mode.

- nonlinear space charge reduces the stability of the dipole mode in single rf buckets.

First results of BTF measurements in SIS (single rf buckets):

- weak space charge: Landau damping can be measured.
- strong space charge: bunch behaves like a driven oscillator, effective impedances.