High Energy
High Intensity
Hadron Beams

APD
Accelerator Physics and synchrotron Design

generation and stability of intense long flat bunches

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with help from

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BEAM'2007, CERN

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the issues

- LPA upgrade scenario requires ~5x10^{11} protons per bunch, 50 ns spacing, flat longitudinal profile
- questions:
  - **how & where can such intense bunches be generated?**
  - **how & where can they be made flat?**
  - **do they remain stable and do they preserve their longitudinally flat shape?**

generation of 5x10^{11} p/bunch at 50 ns*

- SPL & PS2 are being designed for 4x10^{11} p/bunch at 25 ns spacing
- → getting 4x10^{11} p/bunch at 50 ns is easy
- 5.0-5.5x10^{11} (with margin) may be reached by one of the following methods:

  - raising SPL energy by 17% ***[length? gradient?]***
  - bunch merging at PS2 extraction ***[losses? PS2 rf!]***
  - slip stacking in SPS ***[losses? SPS rf!]***
  - slip stacking in LHC ***[losses? LHC rf!]***

***thanks to S. Hancock for helpful discussions**

stability of intense bunches

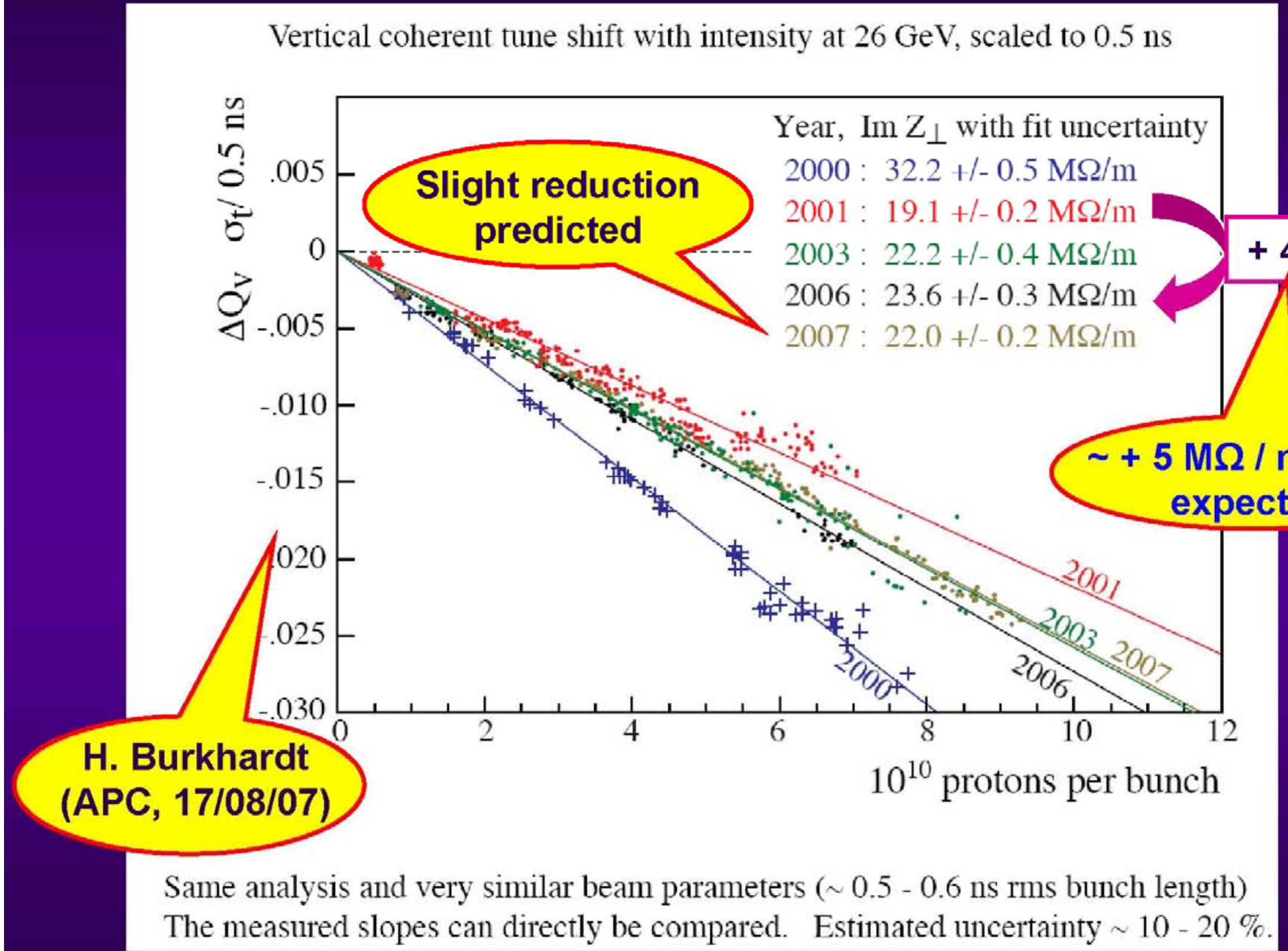
limits from SPS impedance:

- TMCI
- longitudinal coupled bunch instability

electron-cloud: not expected to be a problem at 50-ns bunch spacing

SPS transverse impedance

Elias Metral, SPS upgrade meeting 21.08.2007



Z_y~23 MOhm/m

SPS TMCI instability

first ever observation of TMCI instability with proton beam

E. Metral, EPAC2002:

$$N_{b.thr} = \frac{8\pi Q_y |\eta| \varepsilon_{||}}{e^2 c} \frac{f_r}{|Z_y^{BB}|} \left(1 + \frac{f_{\xi,y}}{f_r}\right)$$

H. Burkhardt, G. Arduini, E. Benedetto, E. Metral, G. Rumolo, EPAC2004

threshold
$N_{b,thr} \sim 10^{11}$ at 26 GeV for $\varepsilon_{||} \sim 0.2$ eVs

tripling emittance → factor 3
raising injection energy to 50 GeV
→ larger $|\eta|$ → factor ~2.5
raising Qy' to ~10 → factor 2

threshold can be shifted way above 5×10^{11} protons per bunch

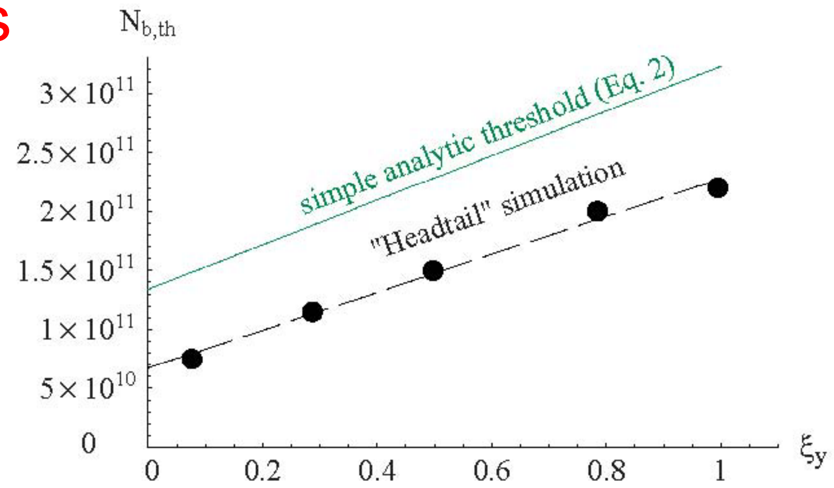
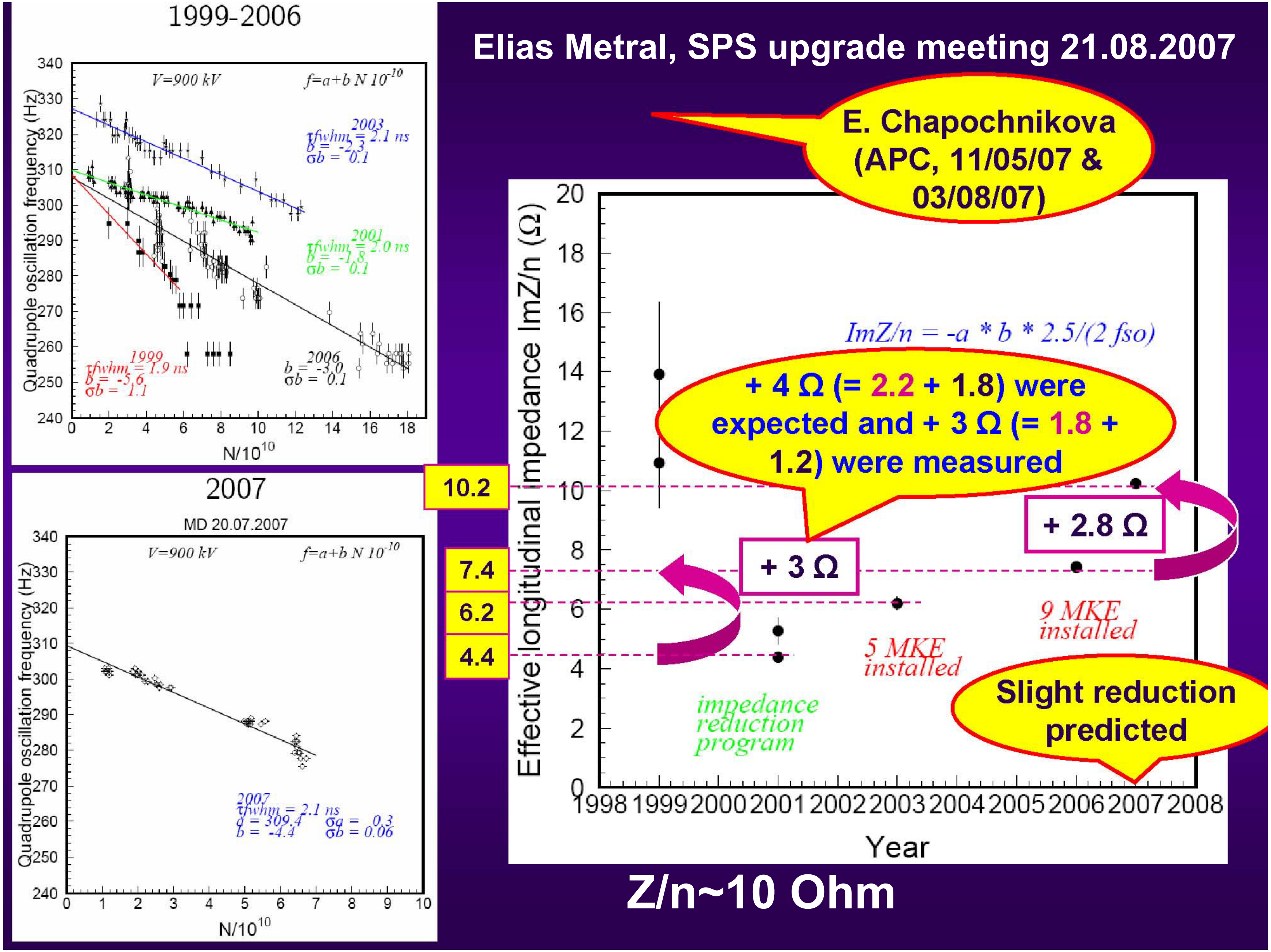


Figure 5: Instability threshold intensity as function of the vertical chromaticity.

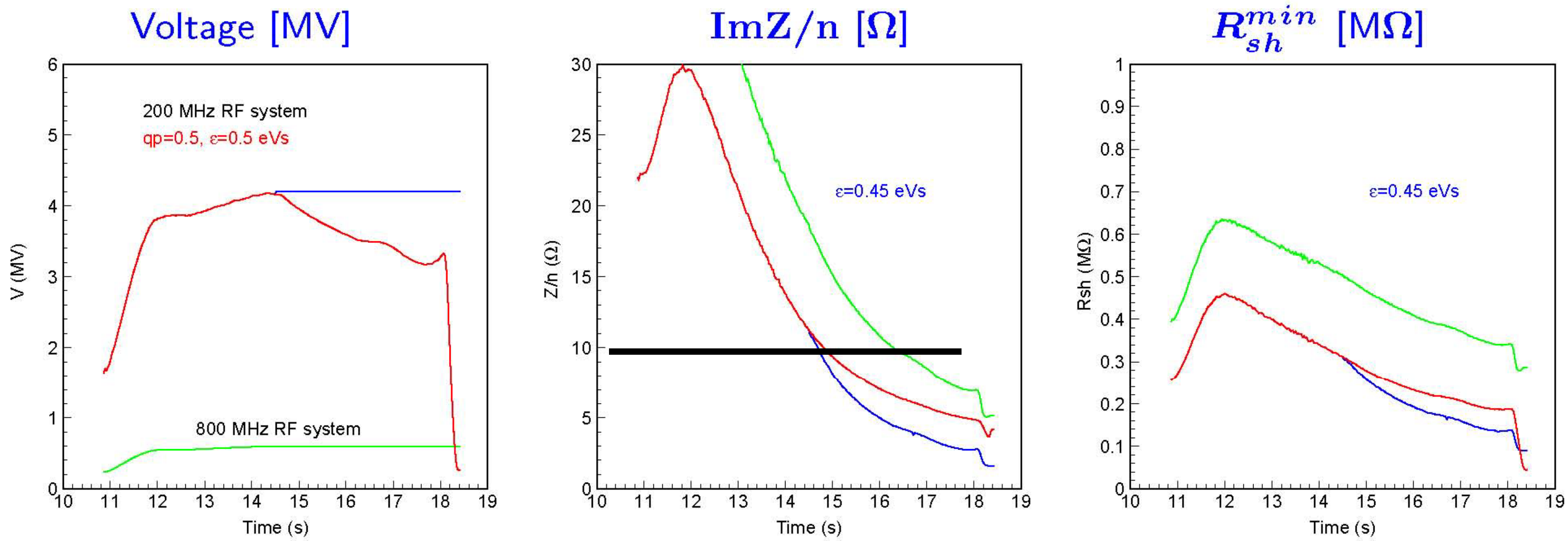
Note: TMCI threshold goes to ~0 for double harmonic rf (Y. Chin, CERN SL/93-03 (AP)

SPS longitudinal impedance



longitudinal coupled bunch instability

Threshold impedances at nominal LHC intensity



- With 800 MHz off instability at injection is observed at $\sim 1.3 \times 10^{11}$/bunch (higher than nominal) and at 2×10^{10}/bunch on the flat top
- With 800 MHz on instability only on the flat top up to nominal (1.2×10^{11})
  $\Rightarrow$ controlled emittance blow-up (threshold $\propto \varepsilon^2$)

E.Shaposhnikova,"Studies of Beam Behavior in Double RF System," APC 6.6.2007

how to make “flat” or “hollow” bunches?

modification of distribution or *change of potential in the LHC itself* or *in the injector complex*

several techniques are available:

- **2nd harmonic debuncher in linac** [J.-P. Delahaye et al 1980]
- **empty bucket deposition in debunched beam** [J.-P.Delahaye et al 1980 , A. Blas et al 2000]
- **higher harmonic cavity** [J.-P.Delahaye et al 1980]
- **blow up by modulation near f_s + VHF near harmonic** [R. Garoby, S. Hancock, 1994]
- **recombination with empty bucket w double harmonic rf** [C. Carli, M. Chanel 2001]
- **redistribution of phase space using double harmonic rf** [C. Carli, M. Chanel 2001]
- **RF phase jump** [RHIC]
- **band-limited noise** [E. Shaposhnikova]

flattening by 2nd harmonic linac debuncher

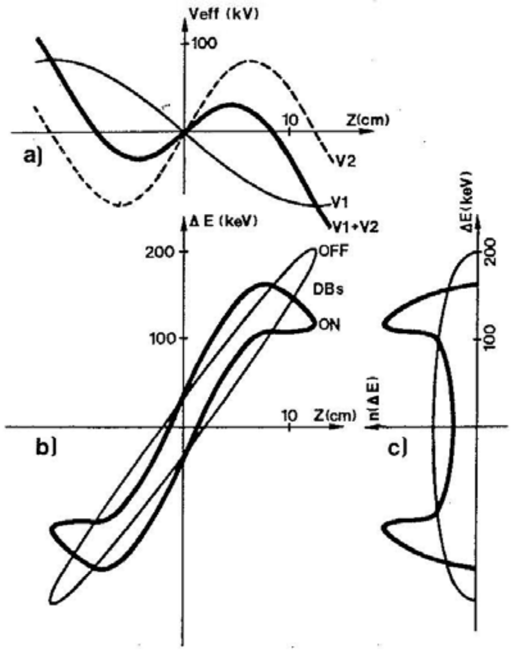
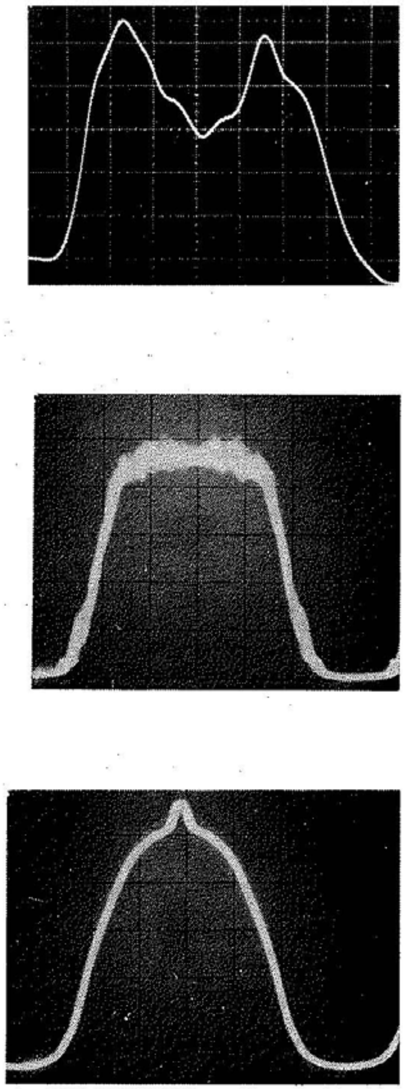


Fig. 4 - a) Effective debuncher voltage of fundamental (V1) and second harmonic (V2) debunchers, b) corresponding linac bunch shapes without (OFF) and with debunchers (ON), c) resulting energy distribution.



a) Energy distribution in PSB measured by the beam transfer function[11]; 62 keV/Div.

b) Bunch shape 5 ms after trapping; 50 ns/Div.

c) Bunch shape 500 ms after trapping; 50 ns/Div.

Fig. 5 - Tailored linac energy distribution and bunches at 50 MeV (N ∿ 5 × 10^{11} p).

J.-P. Delahaye et al, "Shaping of Proton Distribution for Raising the Space Charge of the CERN PS Booster", 11th HEACC, Geneva, 1980

flattening by empty bucket deposition

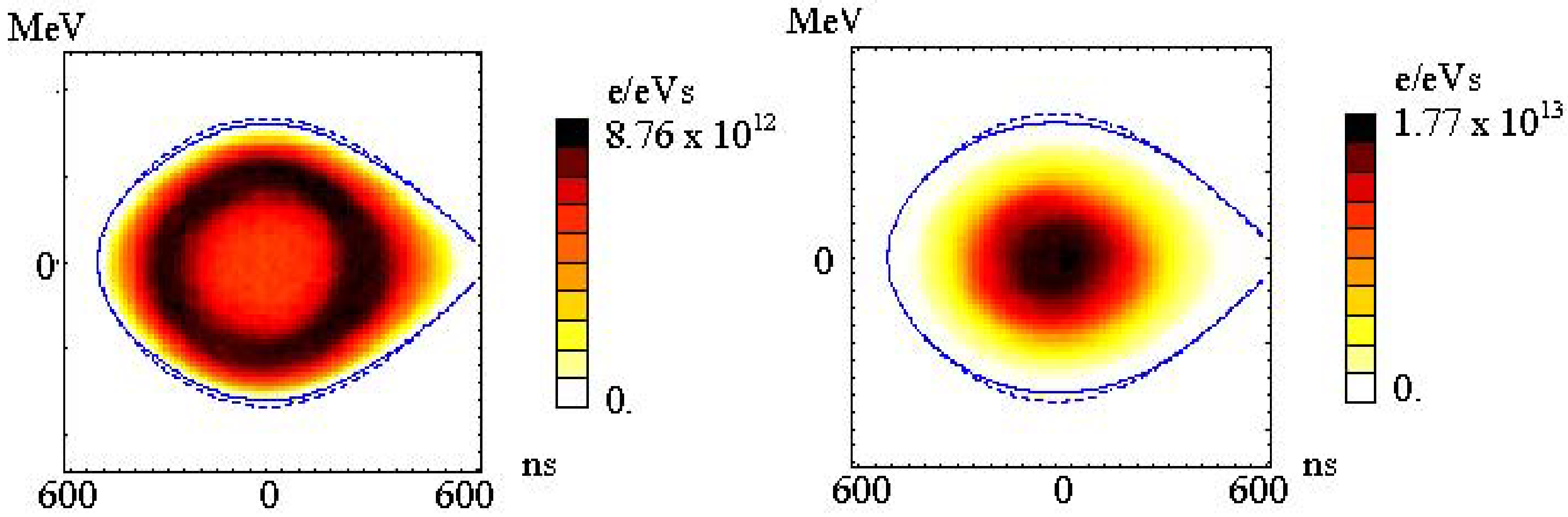


Figure 5: To the left, a flat bunch of 7.4×10^{12} protons and, to the right, a normal bunch of the same intensity. Note the different density scales.

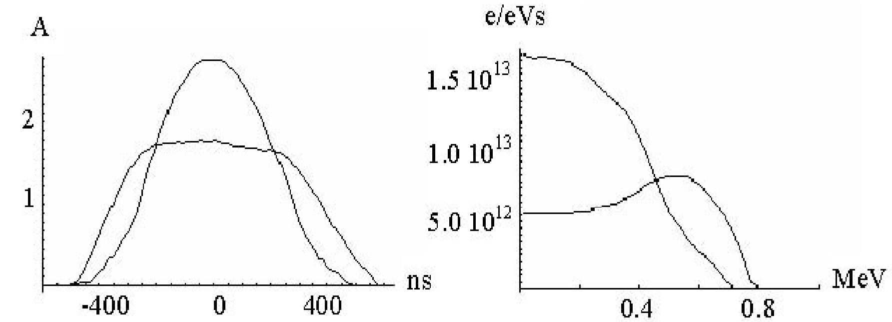


Figure 6: To the left, the measured bunch profiles of the two distributions of Figure 5. The bunching factor is improved from 0.32 to 0.49. To the right, the corresponding 2D density profiles.

A.Blas, S. Hancock, M. Lindroos, S. Koscielniak, "Hollow Bunch Distributions at High Intensity in the PS Booster", EPAC 2000, Vienna

flattening by 2nd harmonic ring cavity

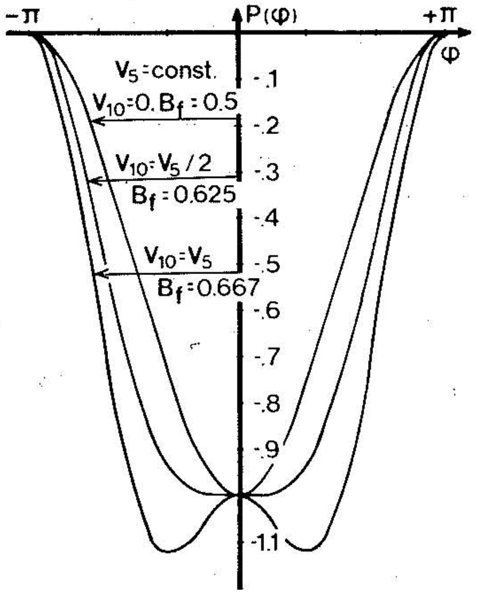


Fig. 6 – RF potential well and bunching factors B_f.[14)]

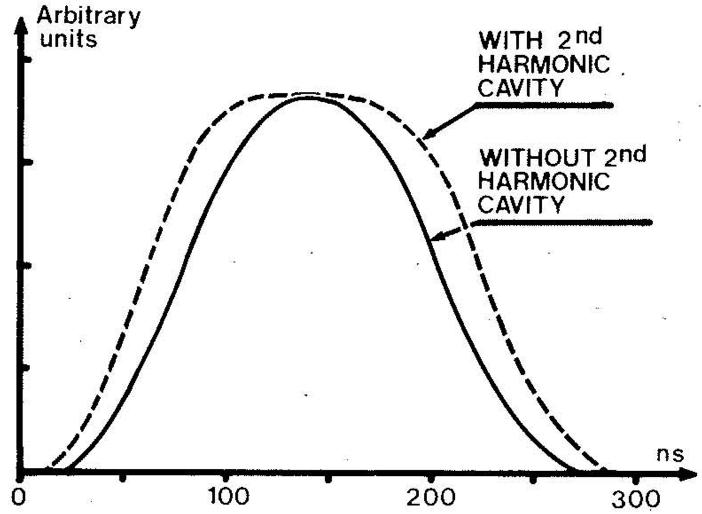


Fig. 7 – Observed bunch shapes

Table 4 – Typical intensities per pulse accelerated in ring 3 (in units of 10^{12} p).

RF voltage	Injection (50 MeV)	After capture	At 200 MeV
Fundamental (V_5) only	9.6	6.3	5.9
2nd-harmonic (V_{10}) added ($V_{10} = 0.5\ V_5$)	9.8	7.8	7.2

J.-P. Delahaye et al, "Shaping of Proton Distribution for Raising the Space Charge of the CERN PS Booster", 11th HEACC, Geneva, 1980

blow up by modulation near f_s + VHF

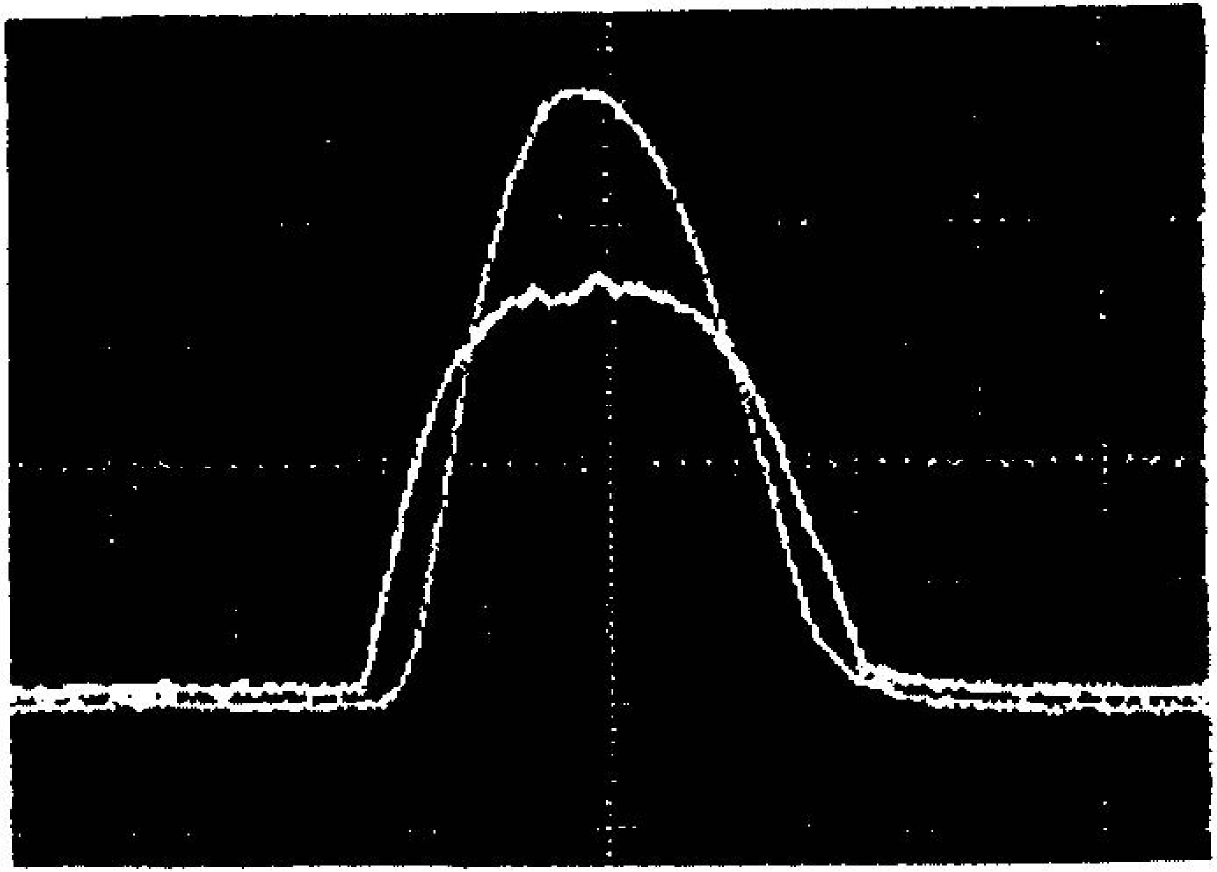


Figure 2. Bunch profile before and after blow-up.

R. Garoby, S. Hancock, "New Techniques for Tailoring Longitudinal Density in a Proton Synchrotron", EPAC 94, London

recombination with empty bucket

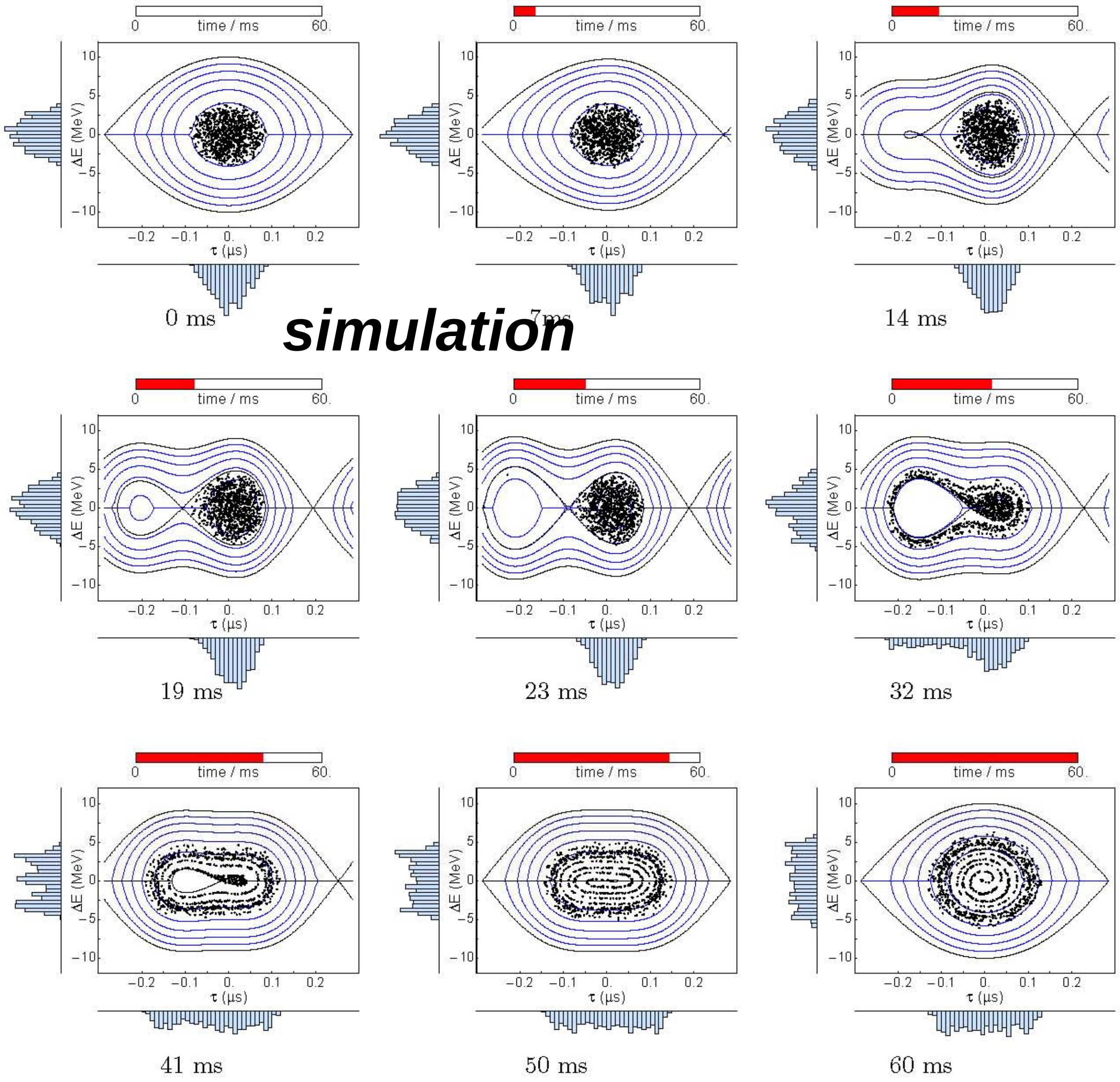
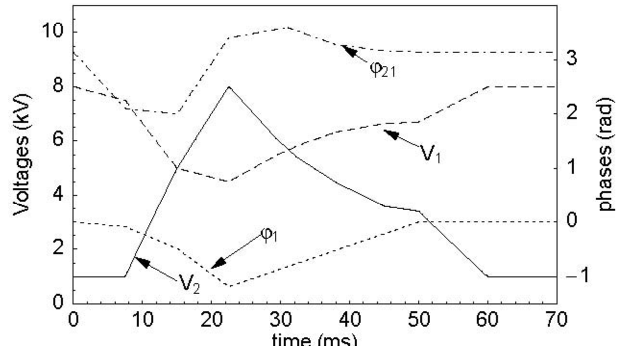


Figure 4: *Blow-up by recombination of a bunch with an empty bucket with improved adiabaticity at small amplitudes. Simulated phase space portraits at different times during the process, with RF parameters versus time plotted in Figure 3.*

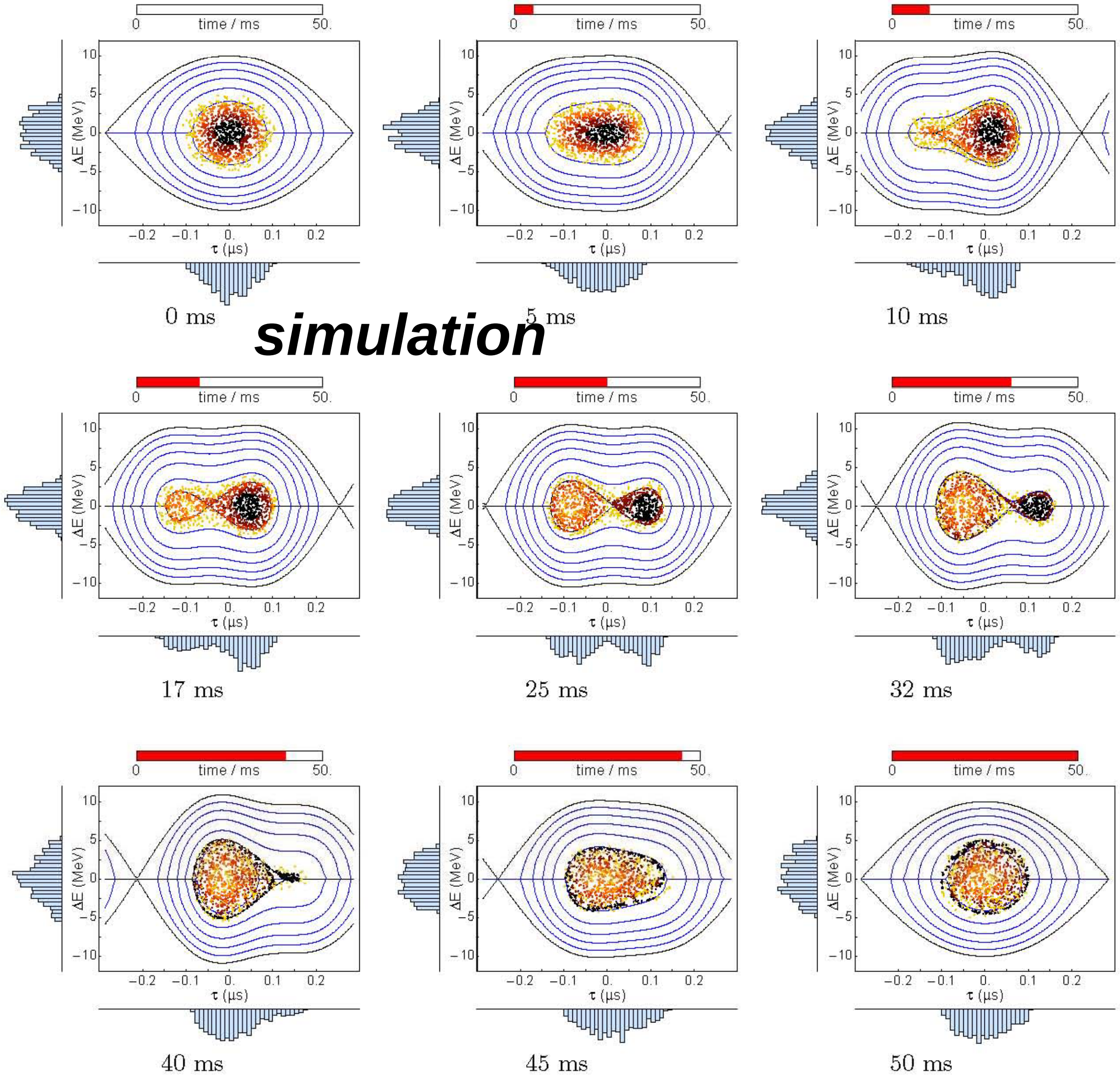


rf voltages and phases

empty phase space is inserted close to center

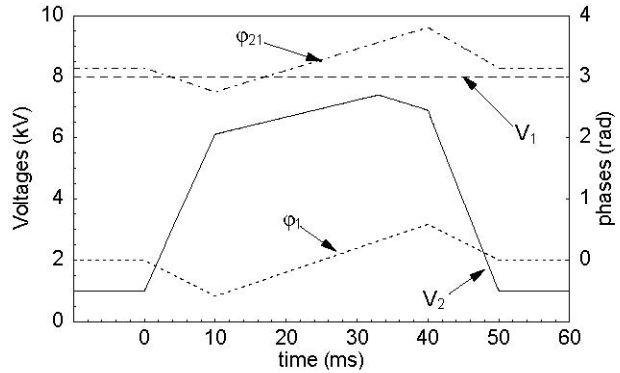
C. Carli, "Creation of Hollow Bunches using a Double Harmonic RF System", CERN/PS 2001-073 (AE); C. Carli and M. Chanel, HB2002 proceedings, AIP CP642

redistribution of phase-space surfaces



simulation

Figure 6: *Redistribution of phase space surfaces to create hollow bunches. Simulated phase space portraits at different times during the process, with RF parameters versus time plotted in Figure 5.*



rf voltages and phases

high density region and periphery are exchanged

C. Carli, "Creation of Hollow Bunches using a Double Harmonic RF System", CERN/PS 2001-073 (AE); C. Carli and M. Chanel, HB2002 proceedings, AIP CP642

redistribution of phase-space surfaces

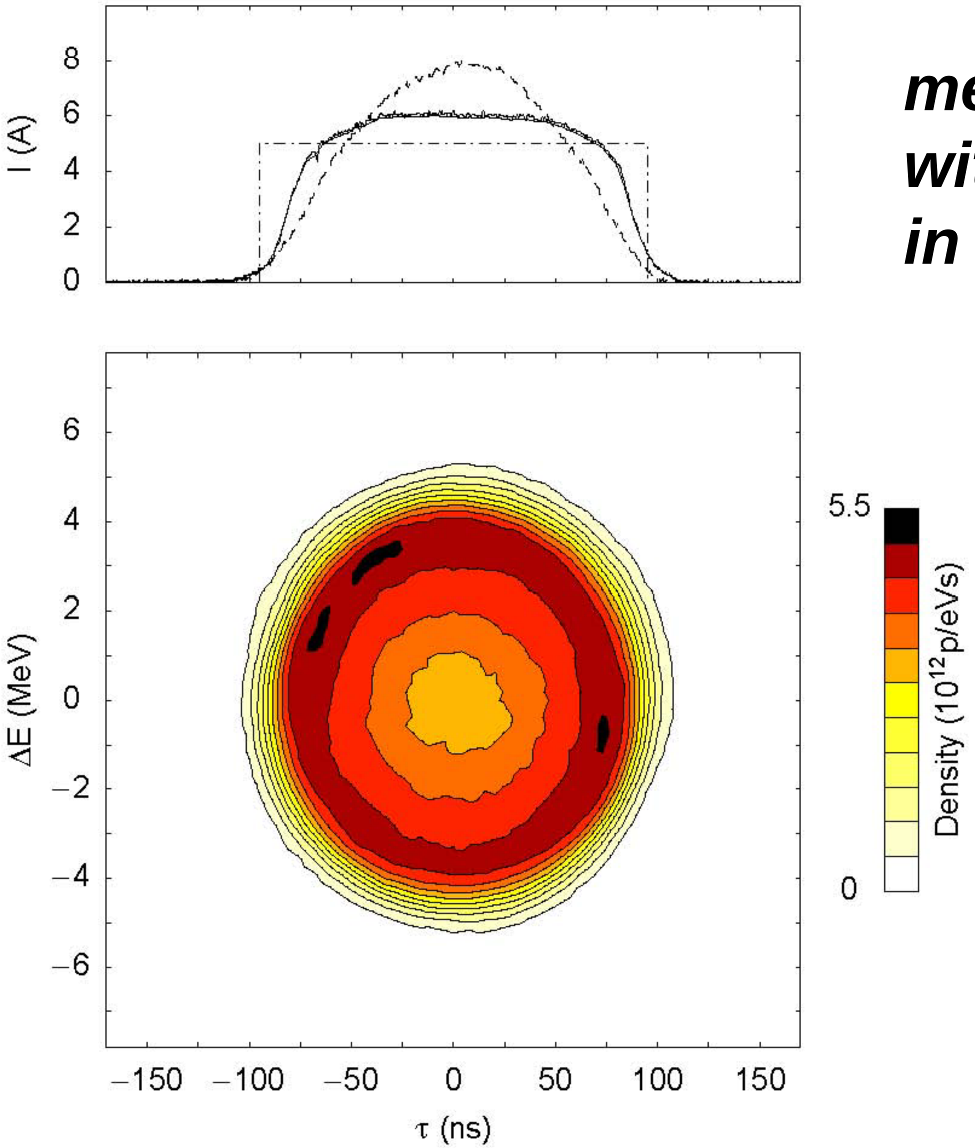


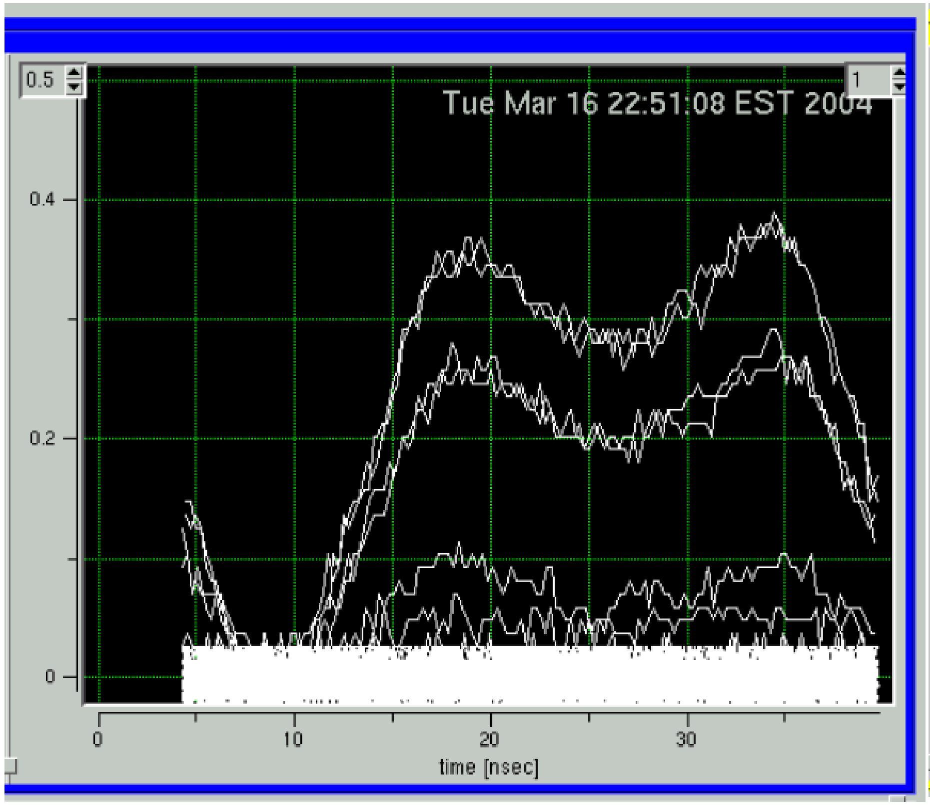
FIGURE 3. Tomographic reconstruction of the phase after redistribution of phase space surfaces.

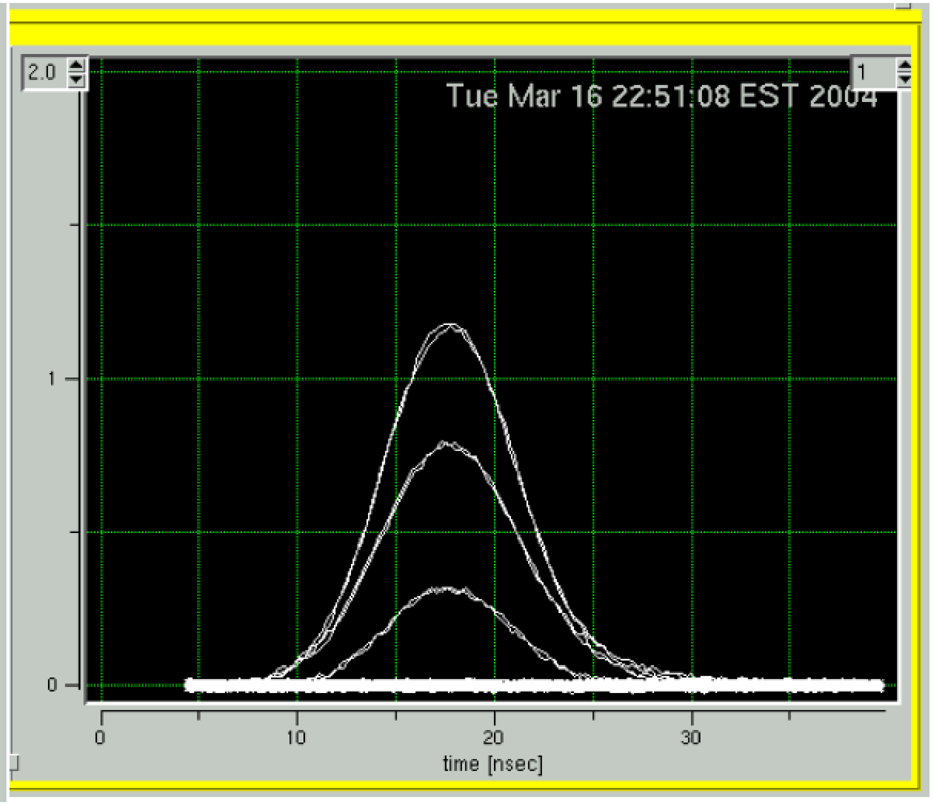
measurement with 6x10^12 p/bunch in the PS Booster

C. Carli, "Creation of Hollow Bunches using a Double Harmonic RF System", CERN/PS 2001-073 (AE); C. Carli and M. Chanel, HB2002 proceedings, AIP CP642

flattening by rf phase jump

- gold beam, store at 100 GeV/u with h=360 RF system; no collision
- no Landau cavity, no dampers, no kickers
- hollow beam in blue ring (created by RF phase jump), normal beam in yellow ring





Jie Wei (BNL & IHEP), “IBS theories, codes, and benchmarking”, IBS’07

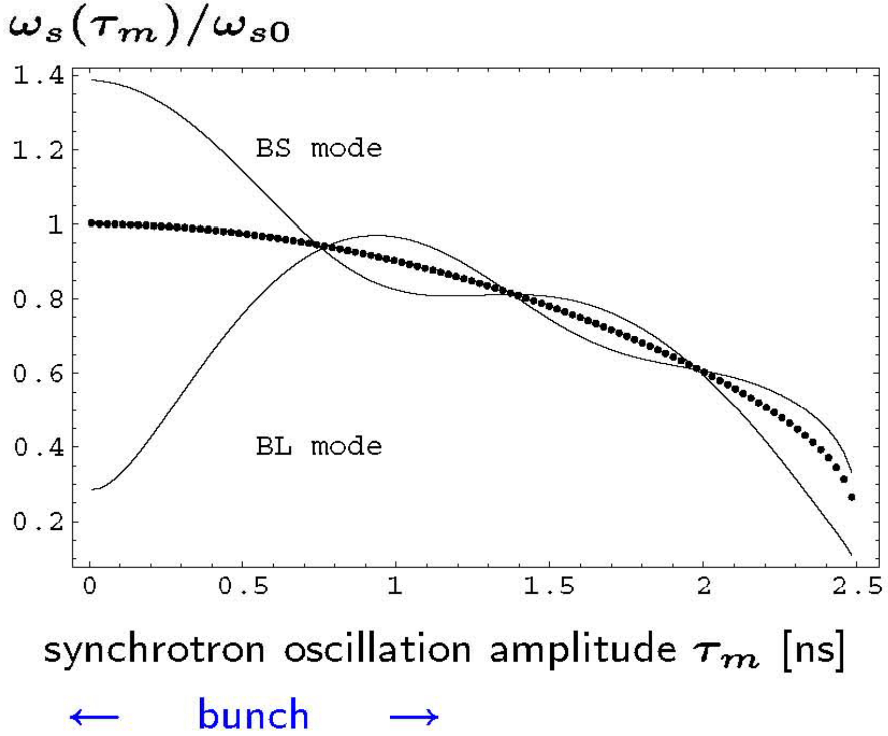
are “flat” or “hollow” bunches stable?

- Landau damping for double rf system
- Landau damping for flat bunch
- stability of hollow bunches with rf & phase loop
- effect of IBS

loss of Landau damping with double rf system

Bunch shortening (BS) or bunch lengthening (BL) mode?

→ **flat bunches**



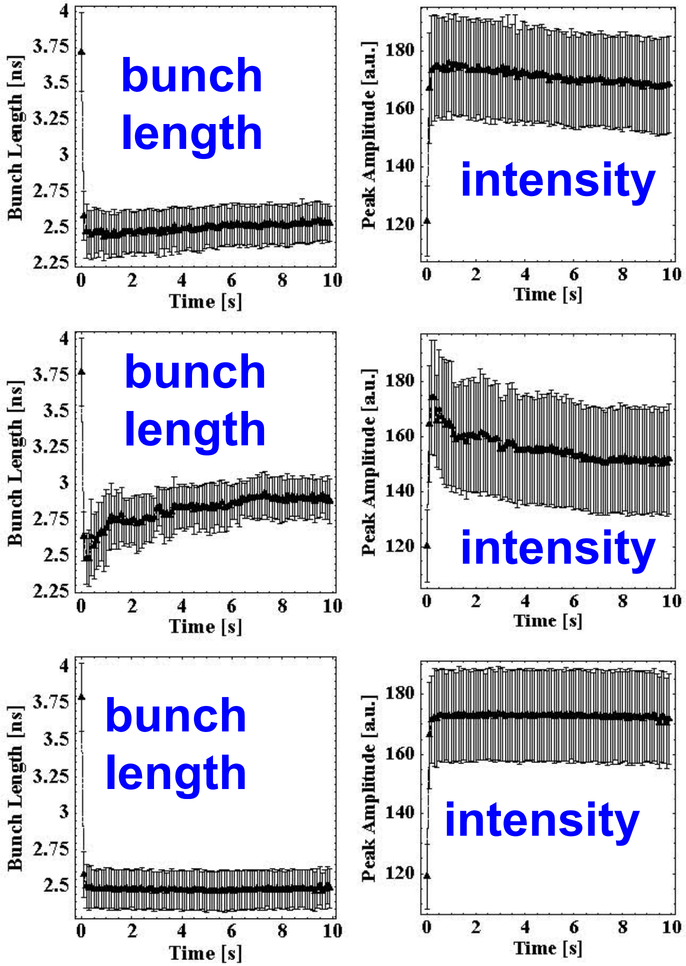
$V_2/V_1 = 0.23$, $h_2/h_1 = 4$, $\phi_{s0} = \pi$

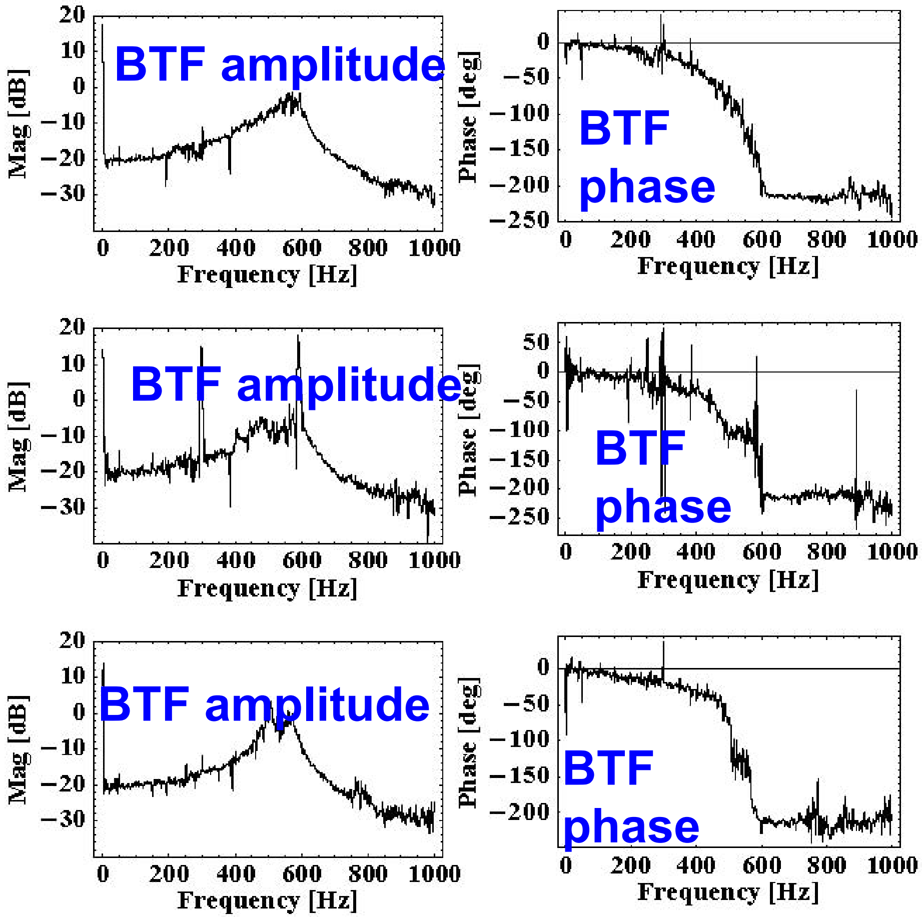
- No self-stabilisation in BL mode for increasing emittance above ε_{cr}
- Region with $\omega_s'(J) = 0$ in BS mode is further away
- Large coherent signal was observed in measurements only in BL mode (→ studies planned for 2006)

loss of Landau damping!

E. Shaposhnikova, "Studies of Beam Behavior in a Double RF System," APC 6. 6. 2007; E. Shaposhnikova et al, "Beam Transfer Functions and Beam Stabilisation in a Double RF System," PAC2005 Knoxville; Also E.S., CERN SL/94-19 (F), 1994

loss of Landau damping with double rf system





single RF

BL mode; strong coherent response at $\omega_s'(J)=0$!

BS mode

Figure 1: The average (24 bunches) bunch length (left) and peak amplitude (right) on the SPS flat bottom at 26 GeV/c with the 800 MHz RF system off (top) and 800 MHz in BL (middle) and in BS (bottom) mode. Average bunch intensity $\bar{N}_b = 1.25 \times 10^{11}$, $V_1 = 3$ MV, $V_2 = 0.7$ MV.

Figure 2: BTF amplitude (left) and phase (right) measured on the 26 GeV/c flat bottom in the SPS for single (top) and double RF system in BL (middle) and BS (bottom) operation modes (as in Fig. 1), $\omega_{s0}/(2\pi) = 313$ Hz.

E. Shaposhnikova, "Studies of Beam Behavior in a Double RF System," APC 6. 6. 2007; E. Shaposhnikova et al, "Beam Transfer Functions and Beam Stabilisation in a Double RF System," PAC2005 Knoxville; Also E.S., CERN SL/94-19 (F), 1994

bunch shape evolution with double rf system

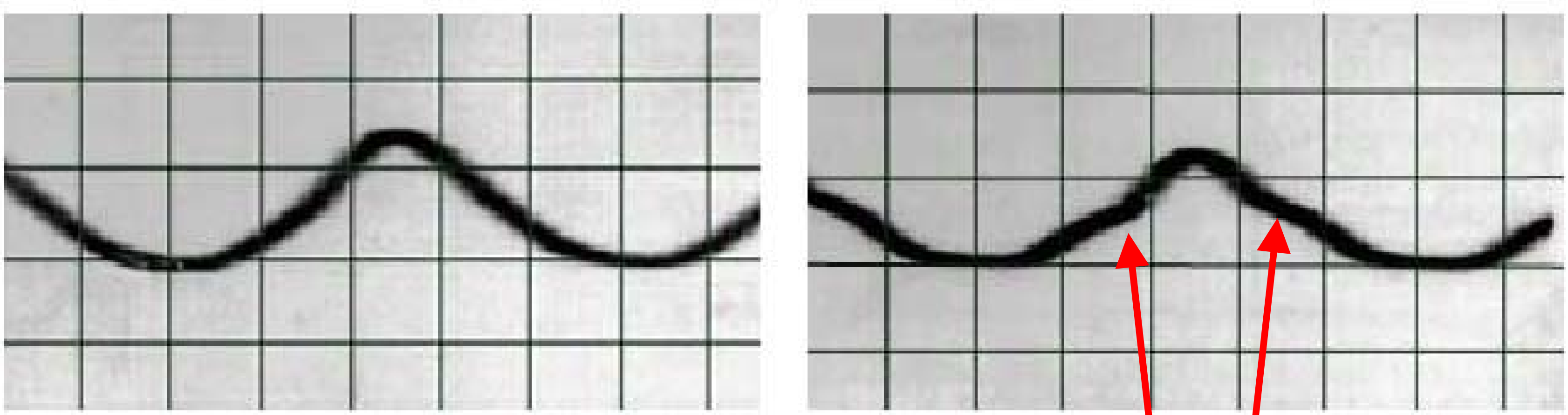


Figure 6: Bunch profiles at the beginning (left) and the end (right) of the 10 min coast at 120 GeV/c in BL mode from Fig. 5. Horizontal scale 1 ns/div.

creation of shoulders in regions where $dF_0/dJ=0$

E. Shaposhnikova, “Studies of Beam Behavior in a Double RF System,” APC 6. 6. 2007; E. Shaposhnikova et al, “Beam Transfer Functions and Beam Stabilisation in a Double RF System,” PAC2005 Knoxville; Also E.S., CERN SL/94-19 (F), 1994

HEADTAIL simulations for double rf system

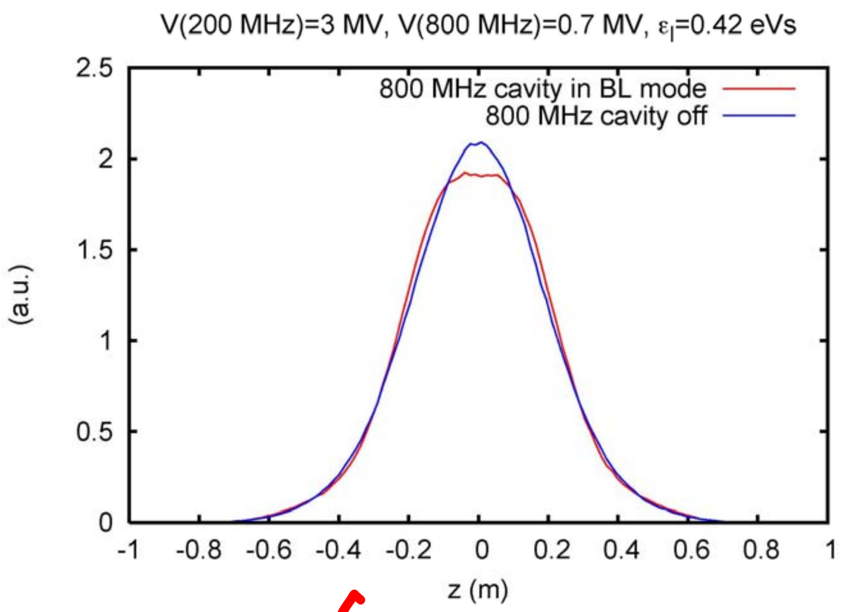
recent addition to HEADTAIL code (G. Rumolo):

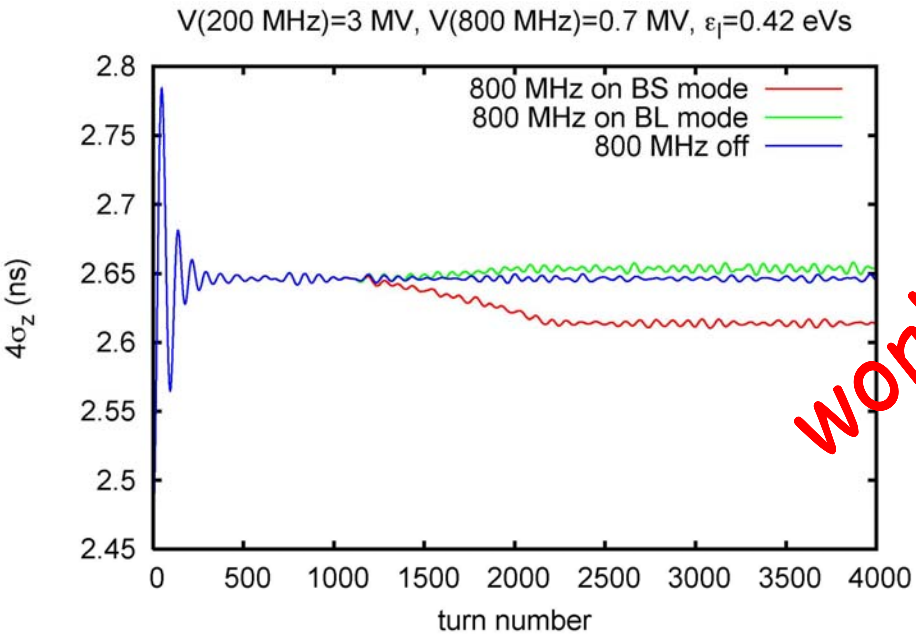
higher order harmonic cavity

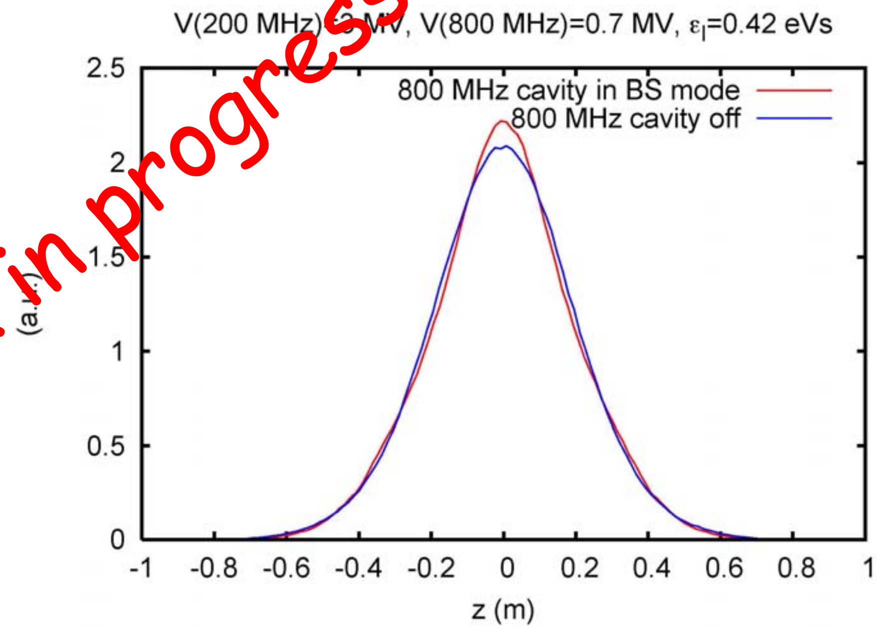
- can be switched on and ramped;

tested for current SPS parameters (200 and 800 MHz):

bunch shape in Bunch Shortening and Bunch Lengthening mode







work in progress

flat bunch distributions

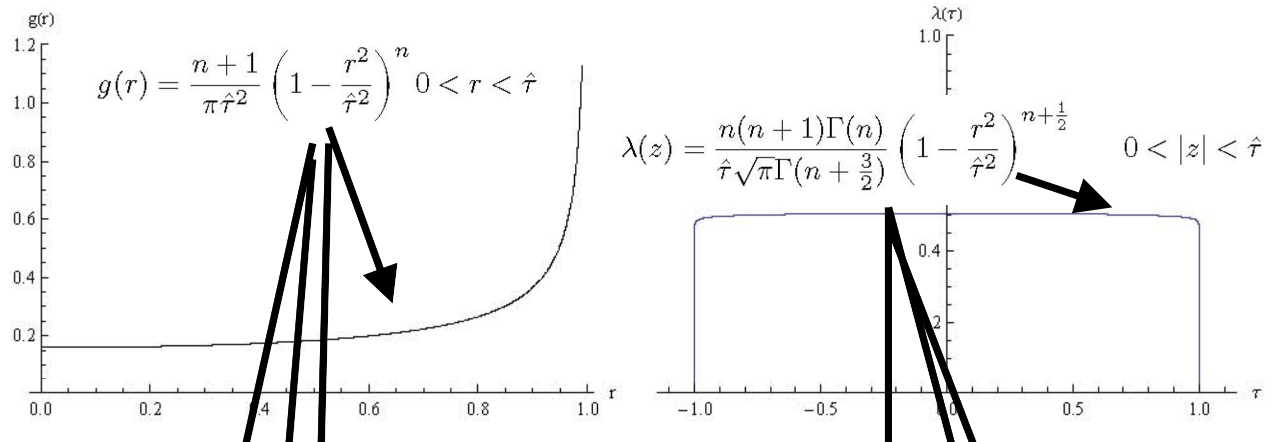


Fig. 4: Parabolic-like distribution in (20) for $n = -\frac{1}{2}$ and its projection $\lambda(z)$ onto the time axis.

flat distribution as limiting case of Ruggiero-Berg class of parabolic distributions, *n*=-1/2

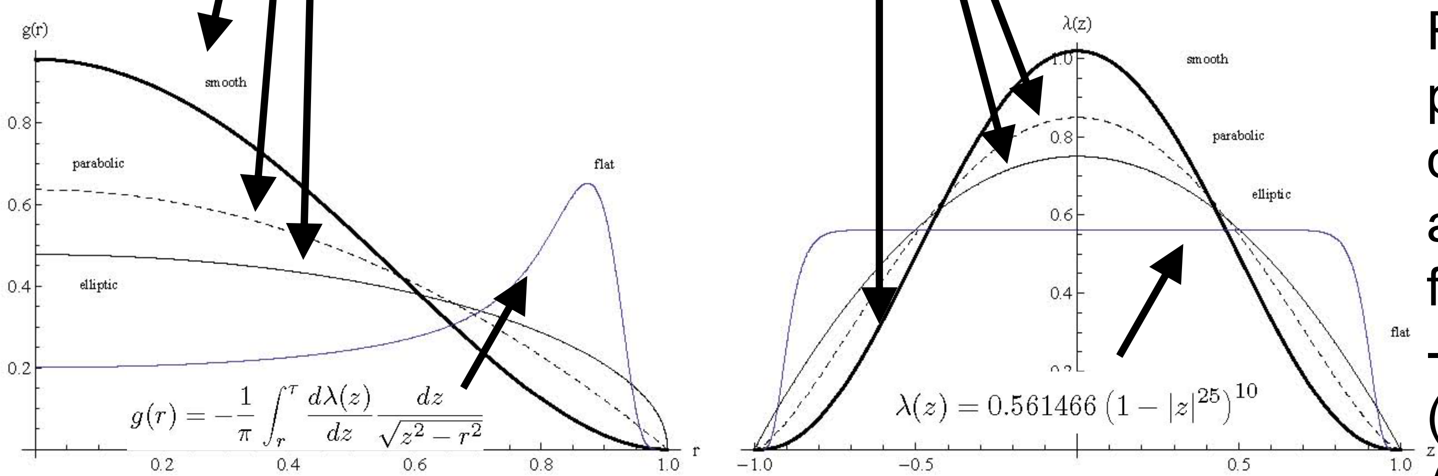


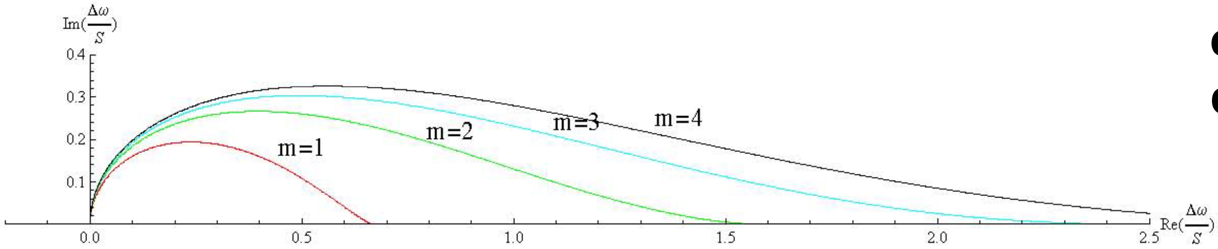
Fig. 6: Different distributions of phase space amplitude and their projections plotted together.

examples of Ruggiero-Berg parabolic-like distributions, and another flat distribution - a la Furman (including its Abel transform)

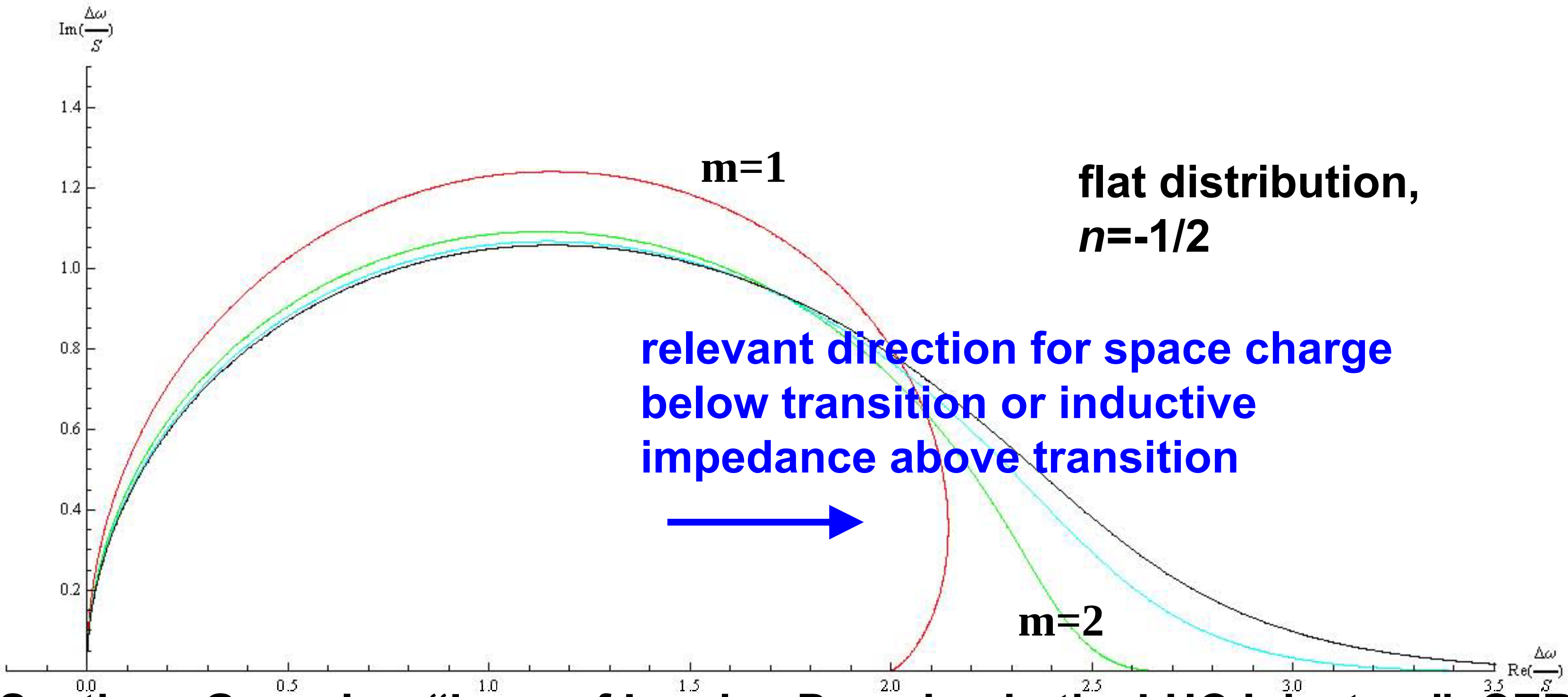
I. Santiago Gonzalez, “Loss of Landau Damping in the LHC Injectors”, CERN AB Note to be published; see also F. Sacherer, IEEE Tr. NS 20,3,825 (1973), E. Metral, CERN-AB 2004-002 (ABP), K.Y.Ng, FERMILAB-FN-0762-AD (2005)

Landau damping for flat bunches

stability diagrams from Sacherer dispersion relation



elliptical distribution, *n*=1/2



flat distribution, *n*=-1/2

I. Santiago Gonzalez, "Loss of Landau Damping in the LHC Injectors", CERN AB Note to be published; see also F. Sacherer, IEEE Tr. NS 20,3,825 (1973), E. Metral, CERN-AB 2004-002 (ABP), K.Y.Ng, FERMILAB-FN-0762-AD (2005)

Landau damping for flat bunches

coherent tune shift stability thresholds

distribution	n	$\Delta\omega_1/S$ (dipole)	$\Delta\omega_2/S$ (quadrupole)	$\Delta\omega_3/S$ (sextupole)	$\Delta\omega_4/S$ (octupole)
smooth	2	0.33	1	1.8	2.67
parabolic	1	0.5	0.33	2.25	3.2
elliptic	½	0.67	1.6	2.57	3.56
flat	-1/2	2	2.67	3.6	4.57
Furman flat	N/A	1.58	2.13	2.90	3.71

flat bunches are more stable!

I. Santiago Gonzalez, "Loss of Landau Damping in the LHC Injectors", CERN AB Note to be published

unstable hollow bunches with rf & phase loop

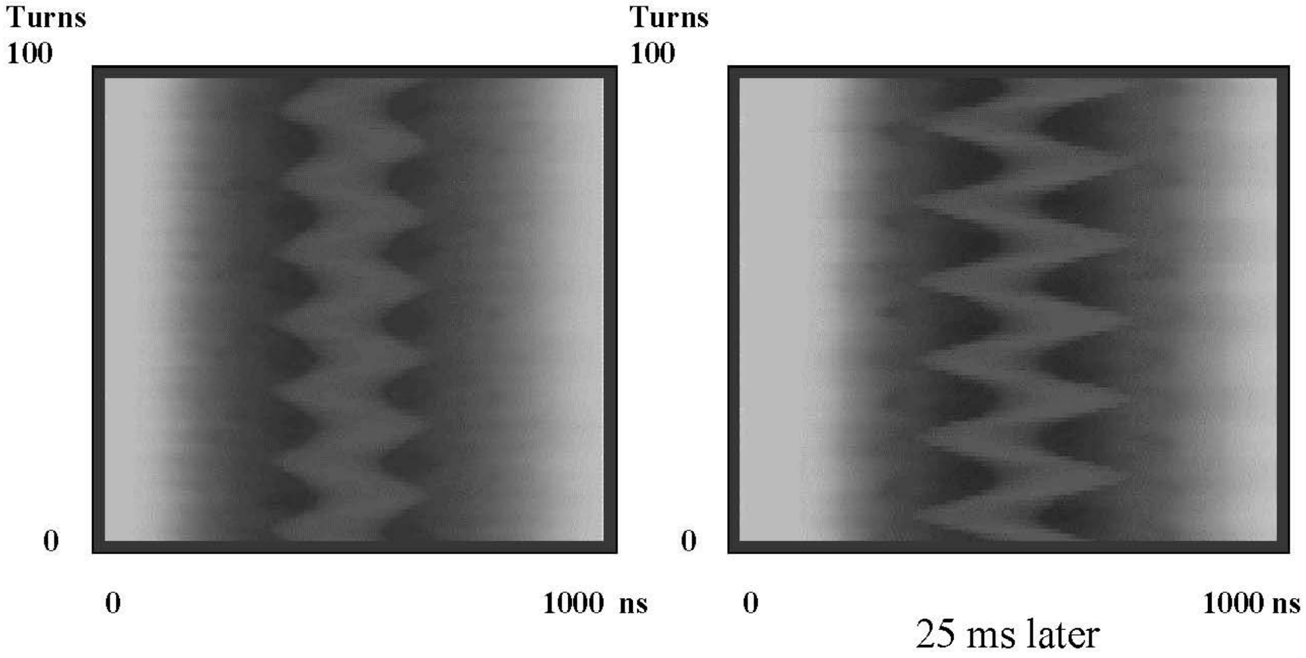
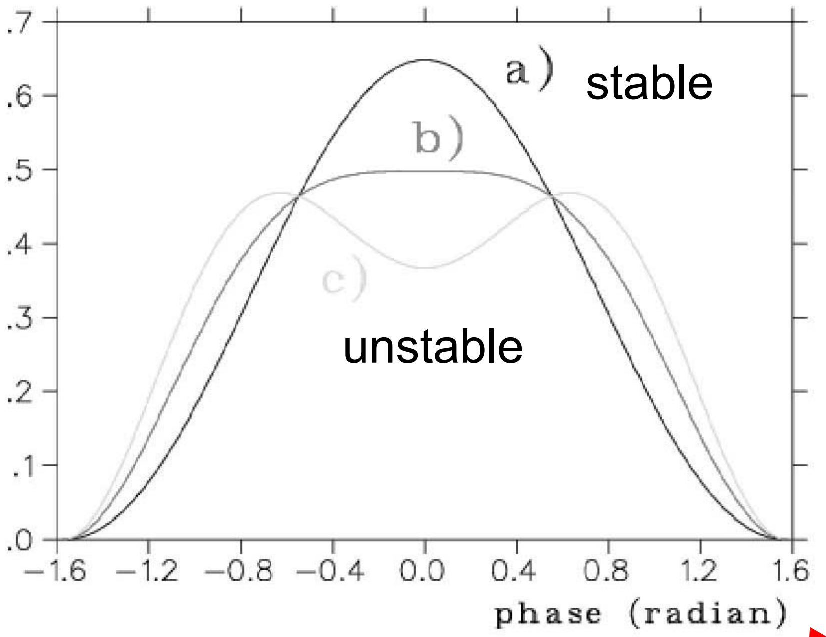


Figure 3: Development of an instability as the low-density central portion of a bunch is anti-damped. The plots consist of bunch profiles taken 25 turns apart plotted on the y-axis. On the x-axis, the intensity on a much shorter time scale along the bunch is represented as a grey-scale.

**A. Blas,
S. Hancock,
M. Lindroos,
S. Koscielniak,
"Hollow Bunch Distributions at High Intensity in the PS Booster",
EPAC 2000,
Vienna**

unstable hollow bunches with rf & phase loop



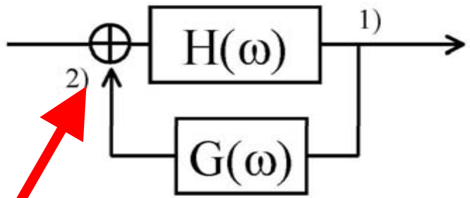
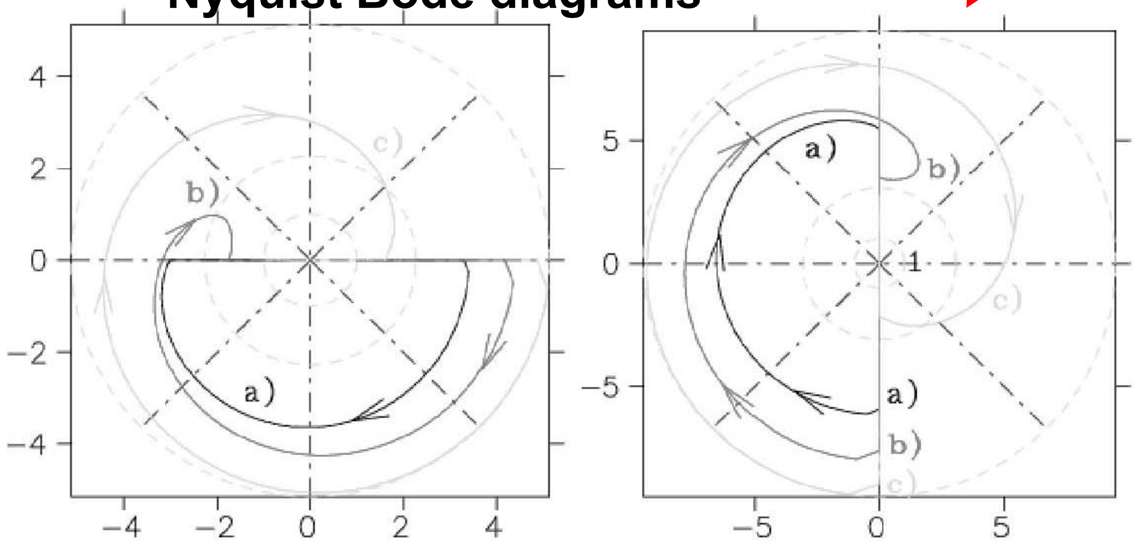


Figure 2: BTFs calculated for three different longitudinal particle distributions. The top plot shows the corresponding bunch shapes. The left-middle plot shows the BTFs at point 1) and the right-middle plot the BTFs at point 2).

Nyquist Bode diagrams



A.Blas, S. Hancock, M. Lindroos, S. Koscielniak, "Hollow Bunch Distributions at High Intensity in the PS Booster", EPAC 2000, Vienna

unstable hollow bunches with rf & phase loop

ordinary BTF: at dc phase -0 deg, and -180 deg at high frequency, passing through -90 deg between these two extremes

for hollow bunches: derivative of the distribution function positive for small amplitudes → additional -90 deg phase change from the residue term

for significantly hollow bunches: further -90 deg phase change (making a total of-360 deg) contributed by the principal value!

interpretation: **hollow bunch = sum of positive and (smaller) negative bunch**
BTF of a negative bunch is simply -1 times that of a positive bunch, and so has a phase response of +180 deg at low frequency and +0 at high frequency

the phase response of the sum can either lag or lead the excitation

→ **some hollow beams must become unstable when phase loop is closed; however, stability and growth rate depend on degree of hollowness.**

S. Koscielniak, "Transfer functions of hollow bunches", TRI-DN-99-25

unstable hollow bunches with rf & phase loop

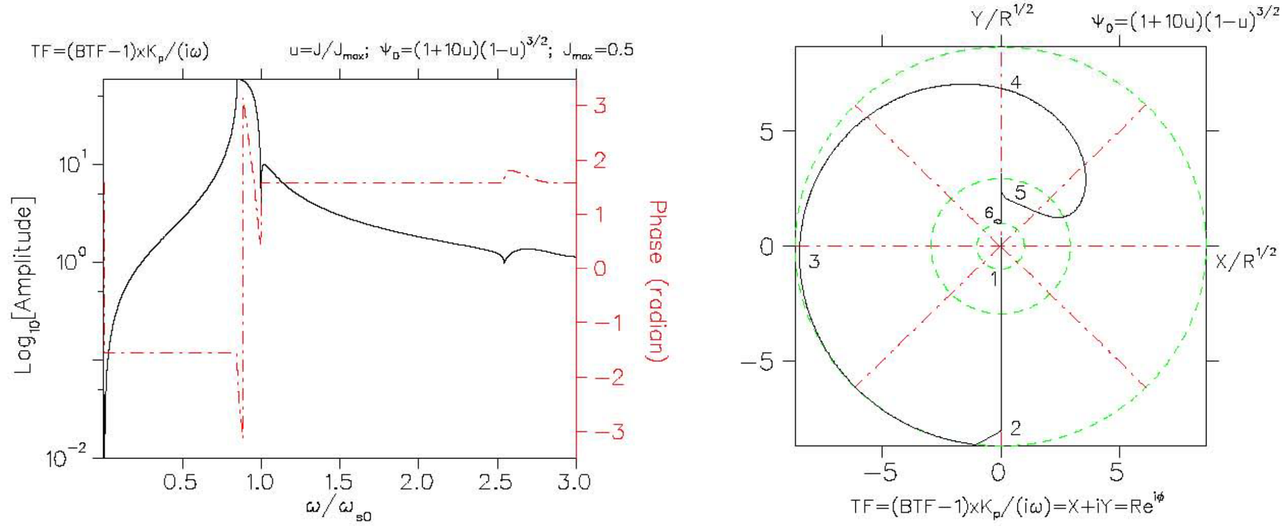


Figure 12: Amplitude/phase and polar plots of the transfer function with phase loop for $\Psi_0 \propto (0.1 + J)(\hat{J} - J)^{3/2}$. The gain $K_p = 3\Omega_s$ per radian.

slightly hollow bunch - stable

S. Koscielniak, “Transfer functions of hollow bunches”, TRI-DN-99-25

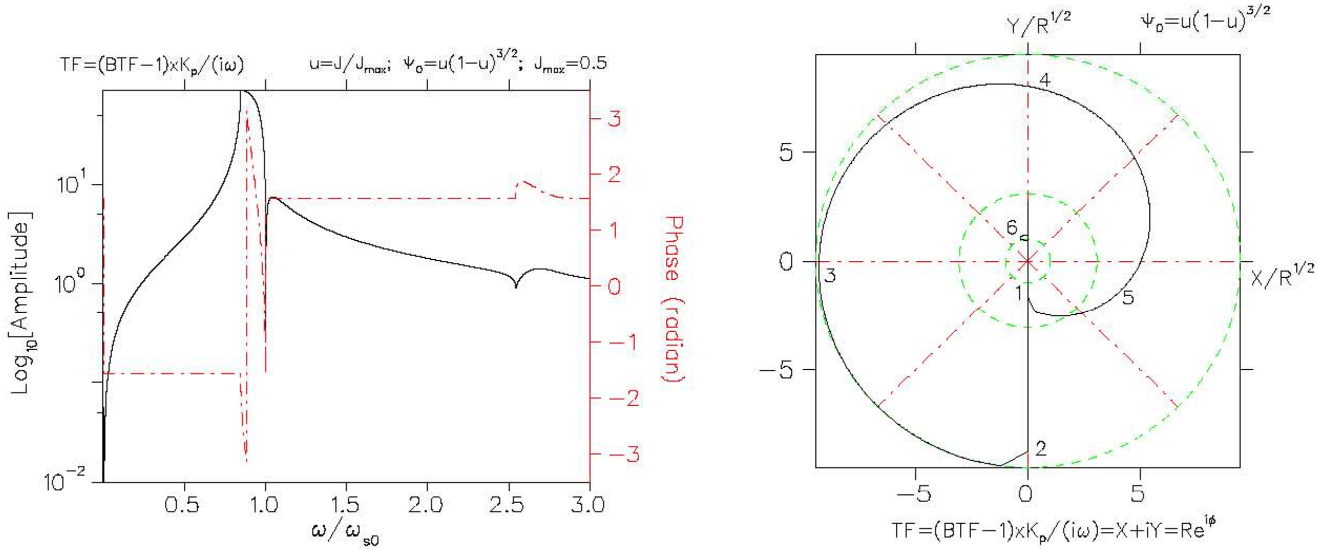


Figure 13: Amplitude/phase and polar plots of the transfer function with phase loop for $\Psi_0 \propto J(\hat{J} - J)^{3/2}$. The gain $K_p = 3\Omega_s$ per radian.

significantly hollow bunch - unstable

unstable hollow bunches with rf & phase loop

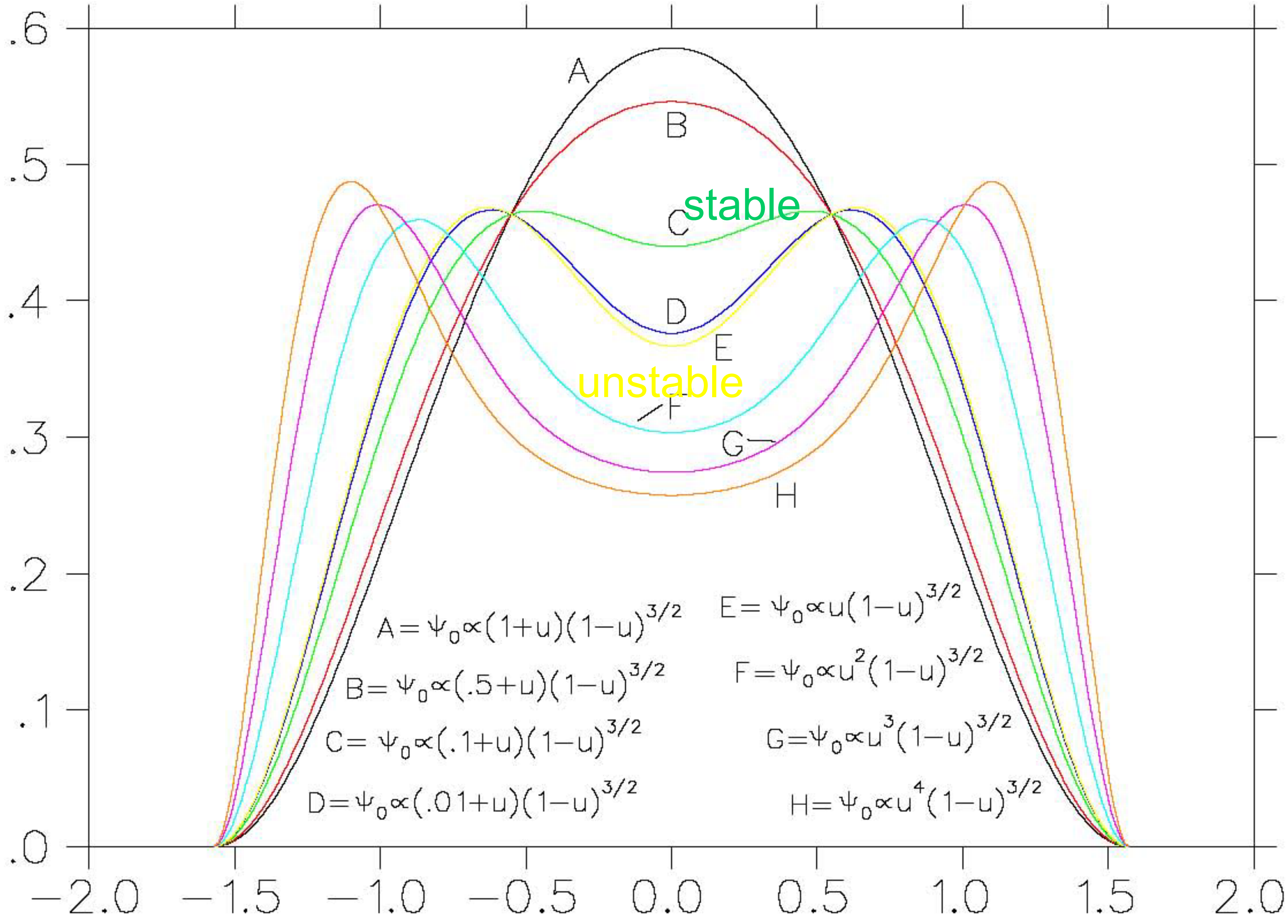


Figure 1: Bunch shapes arising from various phase space distribution functions Ψ_0.

S. Koscielniak, "Transfer functions of hollow bunches", TRI-DN-99-25

longitudinal emittance blow up

at various stages in the LHC accelerator chain (PSB, SPS, LHC) we blow up the longitudinal emittance to increase Landau damping and stabilize the beam

LHC: 0.6-1.0 eVs (450 GeV) → 2.5 eVs (7 TeV)

SPS: 0.35 eVs (26 GeV) → 0.6 eVs (450 GeV)

this longitudinal blow up could render useless any prior bunch shaping

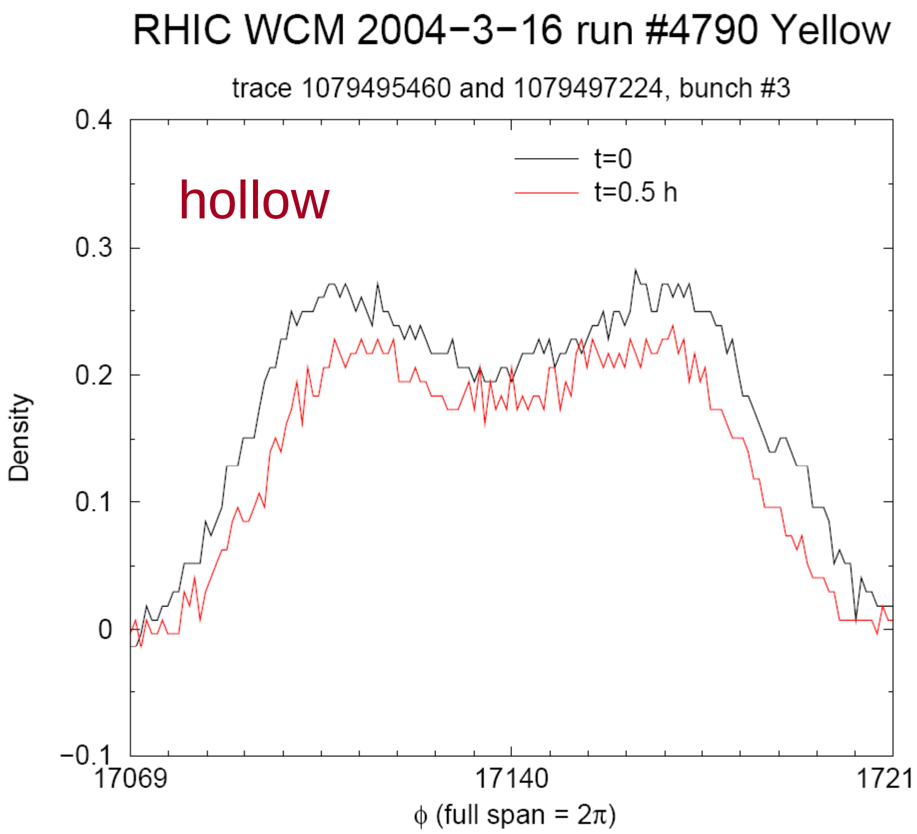
→ possibly the bunch flattening should be done in the LHC itself, at top energy

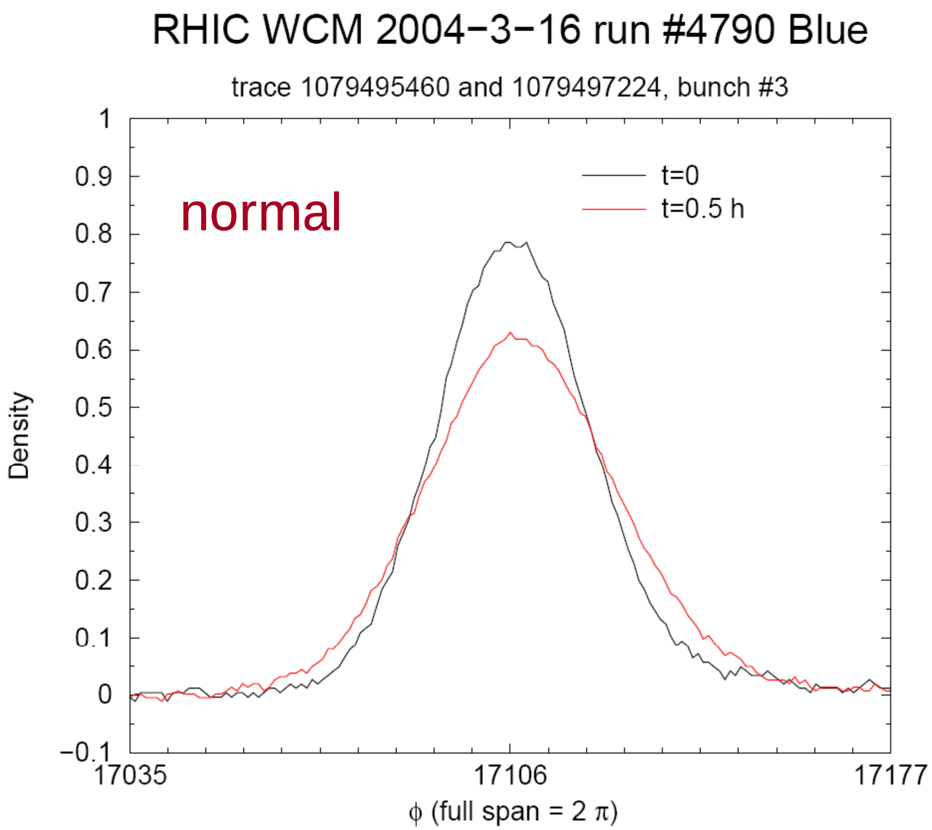
intrabeam scattering for flat or hollow bunches

- does IBS destroy the flat or hollow profile?
- RHIC experiments & simulations
  [courtesy Jie Wei]

beam profile evolution observed in RHIC

- normal beam: Gaussian-like shape, with increasing rms size
- hollow beam: reducing depth of the hole





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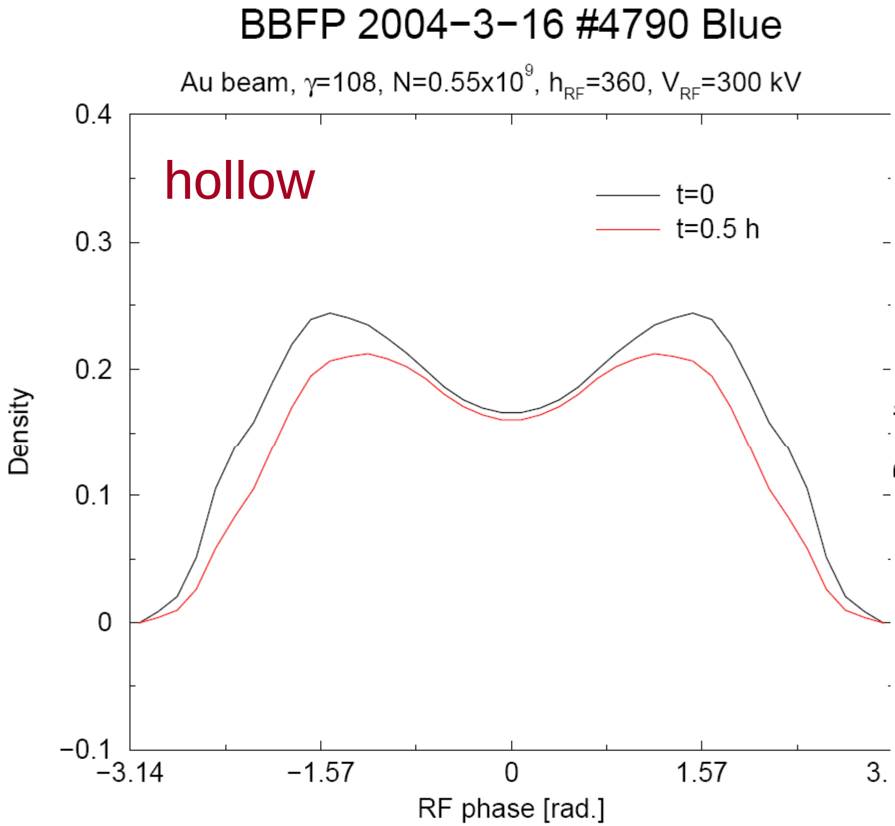
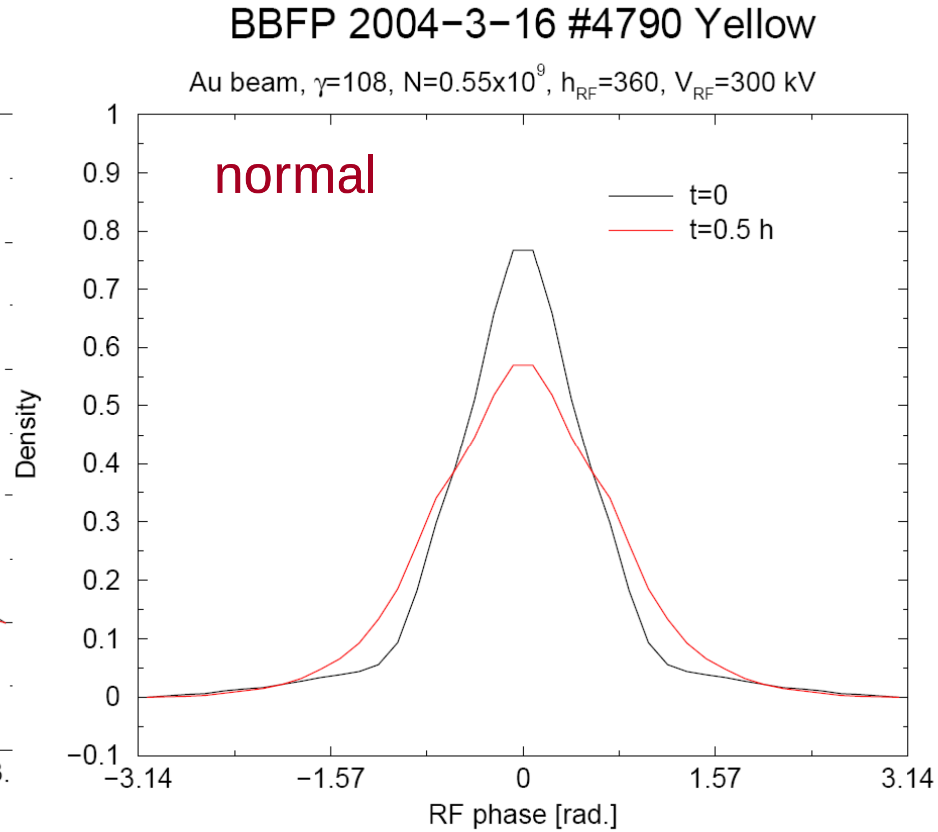
BBFP simulation of RHIC beam profiles

- good agreement obtained with code BBFP (Bunched-Beam Fokker-Planck solver) for both Gaussian and hollow beams
- code is available





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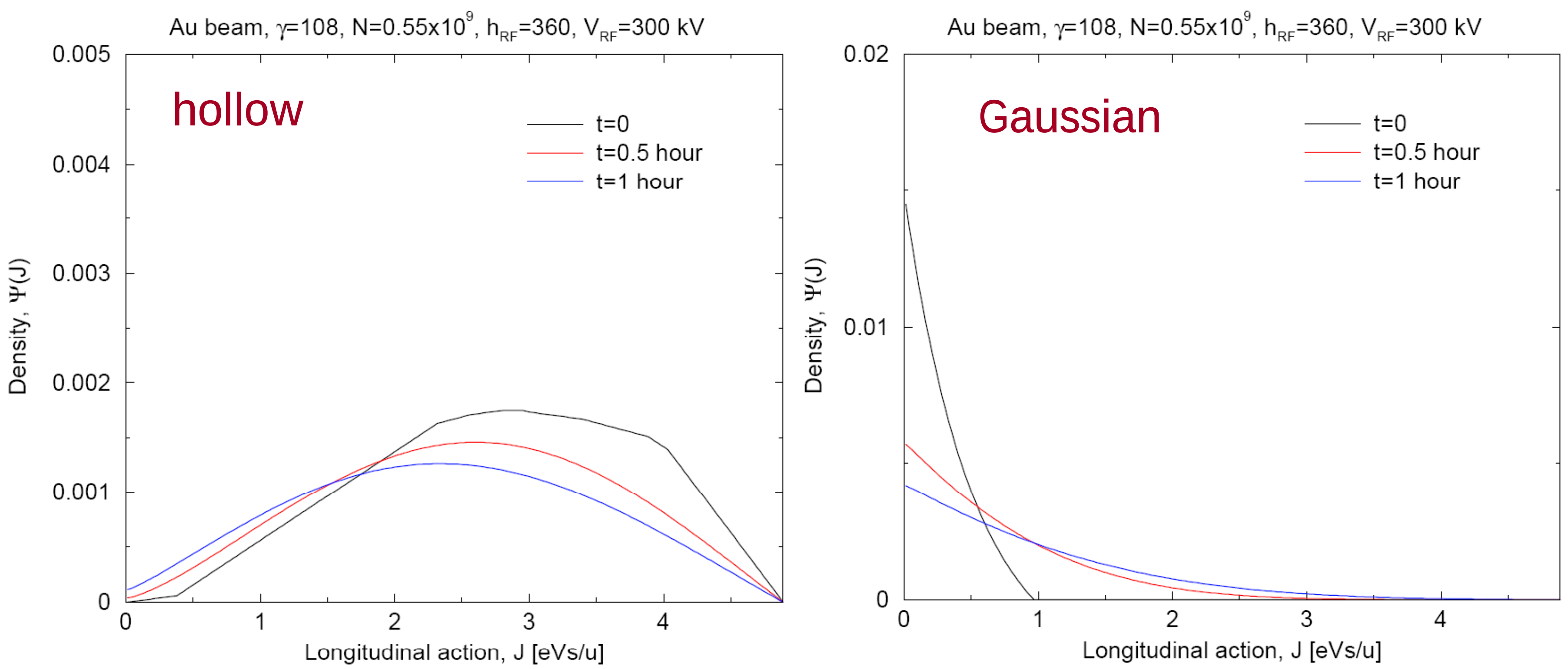
BBFP calculation in the action space

- density projection in longitudinal action
- results convertible to phase / momentum planes



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a few conclusions

- need concrete scheme for generating the 50-ns SLHC LPA beam
- several flattening techniques are available and could be applied in various CERN machines
- flat bunches in single-rf system are strongly Landau damped
- double rf system may lead to loss of Landau damping if the beam distribution occupies the region $\omega_s'(J)=0$; formation of shoulders
- significantly hollow bunches become unstable when rf phase loop is closed

next steps

- machine studies on beam stability and lifetime in double rf system (E. Shaposhnikova)
- machine studies on flat bunch stability and beam evolution in single rf system (E. Shaposhnikova)
- continued analytical studies of Landau damping
- simulations with HEADTAIL and BBFP codes
- development of detailed strategy to generate intense long flat 50-ns bunches in LHC (which machine, which method(s)?), implications for rf systems in one or several machines