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THE EXPERIMENTAL STUDY OF A HIGHER HARMONIC rf SYSTEM IN PETRA

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Summary

At the natural bunchlength the single bunch currents in PETRA are limited by satellite resonances and a new vertical instability[1], which causes a vertical blow-up of a particle bunch if the single bunch current reaches the threshold value of that instability. The "PETRA instability" was explained in terms of head-tail mode coupling[2] and according to this model the vertical blow-up was cured by bunchlengthening changing the longitudinal damping partition. The disadvantage of this kind of bunchlengthening is the increase of energy spread leading to a reduction of quantum life time during energy ramping. The satellite resonances are avoided by a careful steering of the longitudinal and transverse tunes. A more effective method of bunch lengthening is the use of a higher harmonic rf system. Such a system was installed in PETRA. With the higher harmonic rf system the threshold current of the vertical "PETRA instability" could be increased from 3 mA (natural bunchlength) to 15 mA (with higher harmonic rf system). Besides bunchlengthening the higher harmonic system leads to a considerable reduction of satellite effects in the range of normal PETRA tunes.

Basic considerations

The dynamics of a double rf system is described in great detail in ref. 3. Following this analysis we present the determination of the relevant parameters for PETRA.

The higher harmonic rf system of PETRA was installed in the west of the ring, where 8 seven-cell 1 GHz cavities provided a peak voltage of 5 MV on the second harmonic with respect to the fundamental 500 rf system. The available rf power input was about 200 kW.

Figure 1 shows the voltage of the fundamental rf system $\mathcal{U}_{500}$ as a function of the phase angle φ of the passing bunch; $\mathcal{U}_T$ is the "particle voltage" defined by the synchrotron radiation loss and the higher order mode losses; φ_s denotes the equilibrium phase angle.

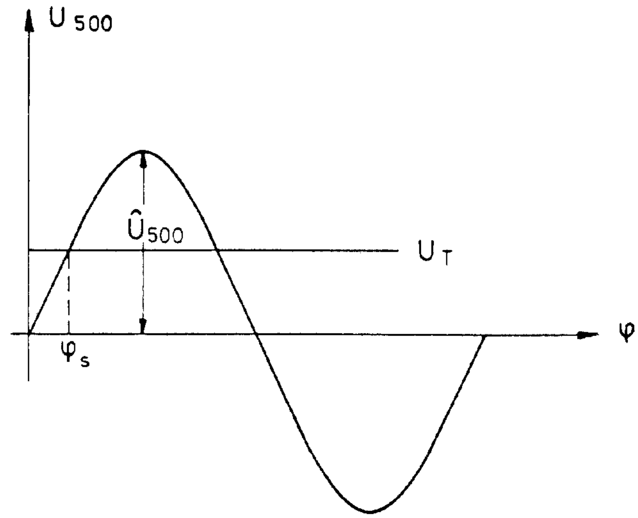

Fig. 1

phase focussing by the fundamental rf system

The synchrotron motion governed by the fundamental rf system is described by a differential equation for : φ

$$\ddot{\varphi} + \frac{\hat{\mathcal{U}}_{500}\,\alpha\,\omega_0^2\,h}{2\pi\,E/e}\left[\sin\varphi - \frac{\mathcal{U}_T}{\hat{\mathcal{U}}_{500}}\right] = 0 \qquad (1)$$

where we defined

$\hat{\mathcal{U}}_{500} \hat{=}$ peak voltage of the 500-MHz system
$\alpha \hat{=}$ momentum compaction factor
$\omega_0 \hat{=}$ circular revolution frequency
$h \hat{=}$ harmonic number
$E \hat{=}$ equilibrium particle energy

The small-amplitude synchrotron frequency of (1) is

$$\Omega_s^2 = \frac{\hat{\mathcal{U}}_{500}\,\alpha\,\omega_0^2\,h}{2\pi\,E/e}\cos\varphi_s \qquad (2)$$

The Hamilton function of equ. (1) reads:

$$H = \frac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

with

$$V(\varphi) = \frac{\hat{\mathcal{U}}_{500}\,\alpha\,\omega_0^2\,h}{2\pi\,E/e}\left[-\cos\varphi - v\varphi\right] \qquad (3a)$$

and

$$v = \mathcal{U}_T/\hat{\mathcal{U}}_{500} \qquad (3b)$$

It is convenient to introduce

$$\eta^2 = \dot{\varphi}^2 \Big/ \frac{\hat{\mathcal{U}}_{500}\,\alpha\,\omega_0^2\,h}{2\pi\,E/e}\,, \quad \mathcal{H} = H \Big/ \frac{\hat{\mathcal{U}}_{500}\,\alpha\,\omega_0^2\,h}{2\pi\,E/e} \qquad (4)$$

so that we can write

$$\mathcal{H} = \frac{1}{2}\eta^2 + \mathcal{U}(\varphi) \qquad (5a)$$

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with the "potential"

$$\mathcal{U}(\varphi) = -\cos\varphi - v\varphi \qquad (5b)$$

and the "force"

$$F(\varphi) = \sin\varphi - v \qquad (5c)$$

The maximum value of $\mathcal{H}$ is defined by the maximum value of the energy spread, i.e. by the maximum value of η, which we call $\hat{\eta}$

The higher harmonic rf system

The higher harmonic rf system can now be simply introduced by modifying the force F:

$$F(\varphi) = \sin\varphi - v - k\sin(n\varphi + \varphi_0) \qquad (6)$$

with the corresponding potential

$$\mathcal{U}(\varphi) = -\cos\varphi - v\varphi + \frac{k}{n}\cos(n\varphi+\varphi_0) \qquad (7)$$

Here n denotes the harmonic member with respect to the fundamental system.
For PETRA we have: n = 2.
The factor k is the ratio of the peak voltages of the two rf systems:

$$k = \hat{\mathcal{U}}_n / \hat{\mathcal{U}}_{500} \qquad (8)$$

peak voltage of the h.h. rf system.

The angle denotes the phase angle between the rf systems, which has to be properly adjusted.

Determination of parameters

The parameters are determined by the condition, that the bunchlength in the presence of the h.h. rf system becomes a maximum.
The conditions are:

i equilibrium $\quad : \mathcal{U}'(\varphi_s) = 0 \qquad (9a)$

ii compensation of the voltage gradient at the aquilibrium point $\quad : \mathcal{U}''(\varphi_s) = 0 \qquad (9b)$

iii symmetry of the distribution $\quad : \mathcal{U}'''(\varphi_s) = 0 \qquad (9c)$

The solution of the equations (9) leads to the following parameters

$$\sin\varphi_s = \frac{v}{1 - 1/n} \qquad (10a)$$

$$k^2 = \frac{1}{n^2}\cos^2\varphi_s + \frac{1}{n^4}\sin^2\varphi_s \qquad (10b)$$

$$\varphi_0 = \arctan\left(\frac{1}{n}\tan\varphi_s\right) - 2\varphi_s \qquad (10c)$$

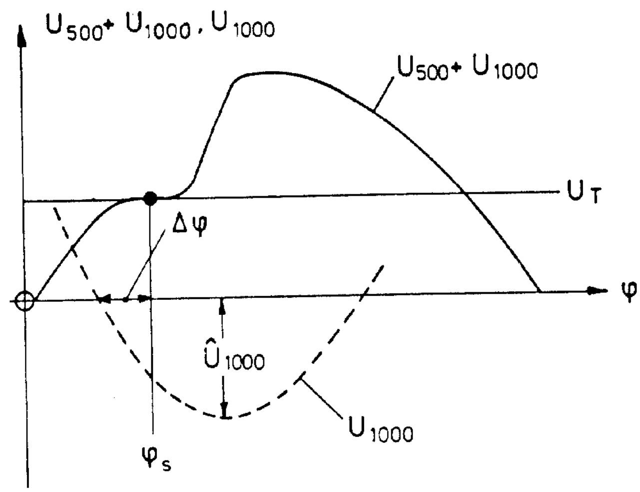
According to (10) we find for PETRA

$$\sin\varphi_s = \frac{4}{3}v \qquad (11a)$$

$$k = \sqrt{\frac{\cos^2\varphi_s}{4} + \frac{\sin^2\varphi_s}{16}} \approx \frac{1}{2}\cos\varphi_s \qquad (11b)$$

$$\varphi_0 = \arctan\left(\frac{1}{2}\tan\varphi_s\right) - 2\varphi_s \qquad (11c)$$

In order to keep the maximum bunchlength during current accumulation and energy ramping, the parameters have to be controlled accordng to (11 b) and (11 c).
Fig. 2 shows the superposition of the 500 MHz and the 1 GHz system



$$\Delta\varphi = 2\varphi_s + \varphi_0$$

Fig. 2
superposition of the 500 MHz voltage and the 1 GHz voltage

It turns out, that the conditions for gradient compensation and for symmetry lead to a φ_0, which differs from $-2\varphi_s$, so that the voltage $\mathcal{U}_{1000}$ does not pass through zero at the bunch center positon.
The deviation, however, is rather small at least at the injection energy, where the phase angle φ_s is small.
Fig. 3 shows the calculation of the potential for typical PETRA parameters at injection without (dashed line) and with the property adjusted h.h.r system (solid line)

PETRA Parameters:

E	=	7 GeV
$\hat{\mathcal{U}}_{500}$	=	10 MV
$\hat{\mathcal{U}}_{1000}$	=	5 MV
energy spread	=	$4.3\cdot 10^{-4}$
v	=	0.1
φ_s	=	7.6°
φ_0	=	−11.5°

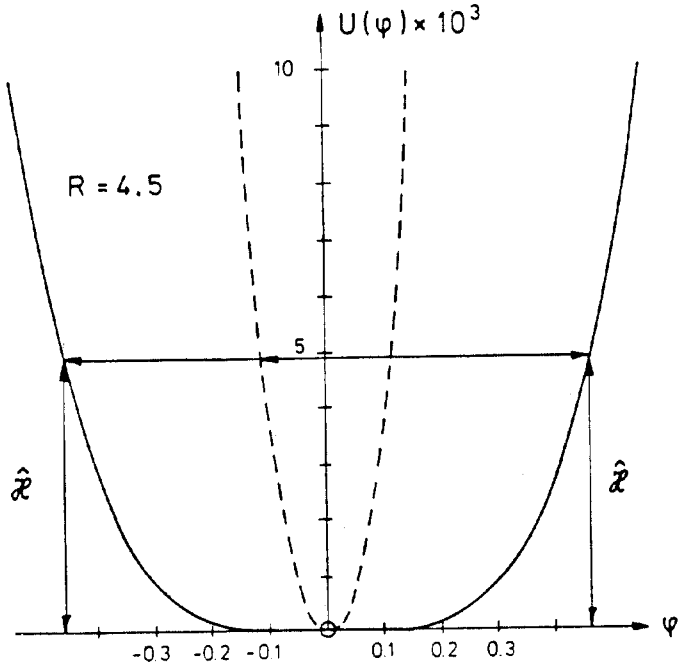


Fig. 3

potential $\mathcal{U}(\varphi)$ for typical PETRA parameters
The maximum bunch lengthening factor R turnes out to be 4.5.

The experimental observations

Operation and bunchlengthening

We started the observations at the injection energy of 7 GeV with the voltage parameters

$$\hat{\mathcal{U}}_{500} = 10\ \mathrm{MV},\ \hat{\mathcal{U}}_{1000} = 5\ \mathrm{MV}$$

for single bunch currents around 1 mA.

The synchrotron frequency was observed and minimized tuning the angle φ_0. This method served as a rough

adjustmet of φ_0. With help of the equipment used for the measurement of the PETRA bunchlength it was possible to display the longitudinal charge distribution of a single bunch.
A fine tuning of φ_0 allowed to produce symmetric charge distributions and a by a small readjustment of $\mathcal{U}_{1000}$ we arrived at the maximum bunchlength. The observed lengthening factor was in agreement with the value of fig. 3.

As expected from equ. 9 the phase adjustment is highly sensitive as regards symmetry and the maximum bunchlength.
Because of this sensitivity the long time stability of the rf system makes a control system necessary, which automatically provides the correct adjustment of .
In the meantime such a control system was developed by S. Pätzold 4.
The principle of this system is simple.
If there is a deviation from the correct φ_0 (equ. 11c), the longitudinal charge distribution becomes asymmetric. From this asymmetry a signal is derived controlling the phase of the higher harmonic system. The control system has been checked and it worked successfully leading to a completely stable bunch shape.

The vertical PETRA instability and satellite resonances

One of the most exciting questions was the influence of the 1 GHz system on the single bunch currents.

1. At the natural bunchlength the vertical "PETRA instability" limits the single bunch currents to 3 mA at 7 GeV .
2. Running into a horizontal or vertical satellite resonance can lead to a reduction of the stably stored single bunch current to 1 mA only.
3. With help of the optimally adjusted 1 GHz system at the injection energy at 7 GeV, the single bunch current was increased to 15 mA without any vertical or horizontal blow-up effects.
4. Even at these high single bunch currents no satellite effects were observed within a wide range of vertical and transverse PETRA tunes.

However, these conditions could only be reached by a continous optimization of the 1 GHz phase during injection, because at that time the φ_0 -control system was not yet available. Therefore an operation of the two rf systems with long time stability was not possible.
An attempt of energy ramping with high currents failed for the same reasons.
High-current experiments including the 1 GHz phase control will be performed as soon as possible.

Outlook

Since the quantum life time of the beam is determined by the voltage of the fundamental rf system, one has to increase the available 1 GHz peak voltage in order to keep the conditions (10) for maximum bunchlength at higher energies.
In the meantime the 1 Ghz system has been further developed: 8 seven-cell and 16 six-cell cavities provide an 1 GHz peak voltage of 15 MV at a power input of 600 kW. This then allows optimal bunch lengthening conditions up to an energy of about 13 GeV.

References:

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