PETRA 2 x 21 GeV

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Abstract

The beam energy of the e^+e^- storage ring PETRA is presently being upgraded from its design value of 2x19 GeV to 2x22.5 GeV by additional rf-power and more accelerating cavities. Energies of 2x21.7 GeV have been reached so far. The newly installed 320 cavity cells significantly decreased thresholds for single beam instabilities and increased the strength of satellite resonances. This paper describes the countermeasures which have been taken such as optics modifications, the operation of the higher harmonic rf-system, correction of spurious dispersion, manipulation of damping partition and their effects on the beams. An up-date of the PETRA performance at high energies is presented.

Introduction

PETRA was designed to reach its maximum luminosity between 15 GeV and 16 GeV beam energy. The most frequently used energy during 3 years was 2x17.5 GeV with luminosities up to $2\cdot10^{31}cm^{-2}s^{-1}$. 2x18.3 GeV were reached with reduced luminosity /1/.

To continue the physics research program to higher energies the number of rf-transmitters and the number of rf-cavities were doubled. This new installation is now nearly completed. At present the maximum energy with a luminosity $\geq 1\cdot10^{30}cm^{-2}s^{-1}$ is 2x21.7 GeV.

The disadvantage of having so many cavities installed in the storage ring is the smaller threshold for instabilities and the increased strength of synchro-betatron resonances. To overcome these problems the following measures were taken:

a) use of an optics with high momentum compaction at injection energy (7 GeV) for increasing the bunch length
b) shift of the rf-frequency at injection so as to reduce the longitudinal damping and enhance the momentum spread of the beam and the bunch length
c) use of a higher harmonic rf-system for bunch lengthening and satellite suppression
d) during energy ramping change to an optics with low momentum compaction to reach the highest energy with given rf-voltage
e) at the high operating energy use of an optics with small horizontal emittance to make the horizontal beam size small
f) application of a careful orbit and dispersion correction to get the small vertical beam size needed for good specific luminosity and satellite compensation.

The result at 2x21.5 GeV are currents of 4x2.7 mA and luminosities up to $6\cdot10^{30}cm^{-2}s^{-1}$.

Upgraded rf-system

The maximum design energy of PETRA was 2x19 GeV. This energy was reached in 1980 with an rf-power P_{rf} = 4x900 kW into 300 cavity cells with a total shunt impedance R_s = 960 MΩ. The peak voltage was $U_{rf} = \sqrt{2R_sP_{rf}}$ = 83 MV.

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The klystron output is about 20 % larger than P_{rf} to make up for reflections and losses in the waveguide system.

Since spring of this year we use 8x800 kW rf-power, limited by the maximum power dissipation per cavity, and 524 cavity cells with R_s = 1750 MΩ. The peak voltage is now U_{rf} = 150 MV.

The new cells are combined into 7 cell structures instead of the old 5 cell structures /2/. The beam hole diameter was changed from 120 mm to 80 mm to get an additional increase in shunt impedance per cell. But this measure increased the HOML-impedance by a factor of two, and strengthened the driving terms for synchro-betatron resonances.

A further step in adding more cavities is planed for August of this year: With the addition of another 148 cavity cells the peak voltage should be increased to 180 MV.

The frequency of the accelerating structure is 500 MHz. A second harmonic rf-system at 1000 MHz has been built for bunch lengthening /3/. It consists of one transmitter with 600 kW power output and 152 cavity cells with 185 M Ω shunt impedance. The peak voltage of the 1 GHz system is 13 MV.

Both rf-systems occupy all the space available in the long straight sections of PETRA. Further increase of the peak voltage is only possible by using superconducting techniques /4/.

The maximum energy achieved with 150 MV + 13 MV rf-voltage was 2x22.0 GeV. During high energy physics runs in June and July 83 the energy region between 2x20.0 GeV and 2x21.6 GeV was scanned in 15 MeV steps with integrated luminosities per experiment up to 200 nb^{-1} per day.

Fig. 1 shows as an example for the results the measured R-values ($R = \sigma_{hadron}/\sigma_{\mu\mu}$) up to 43 GeV. The total integrated luminosity collected at PETRA since 1979 was 115 pb^{-1} per experiment.

This luminosity is reached with rather small currents: Two bunches in each direction with 2.5 mA per bunch or $4\times1.2\cdot10^{11}$ stored particles. Table 1 gives a summary of the relevant parameters.

Table 1:

Energy	E = 2x21.5 GeV
Bunch current	$I_b = 2.5$ mA $\hat{=} 1.2\cdot10^{11} e_o f_o$
Total number of bunches	$m = 4$
Amplitude function at IP	$\beta^*_x = 1.2$ m
	$\beta^*_z = 0.08$ m
Emittance at 21.5 GeV	$\varepsilon_x = 21\cdot10^{-8}\pi$ radm
	$\varepsilon_z = 0.008\cdot\varepsilon_x$
Luminosity	$L = 5\cdot10^{30}cm^{-2}s^{-1}$
ν-shift	$\Delta\nu_x = 0.006$
	$\Delta\nu_z = 0.017$

7 61 7 120

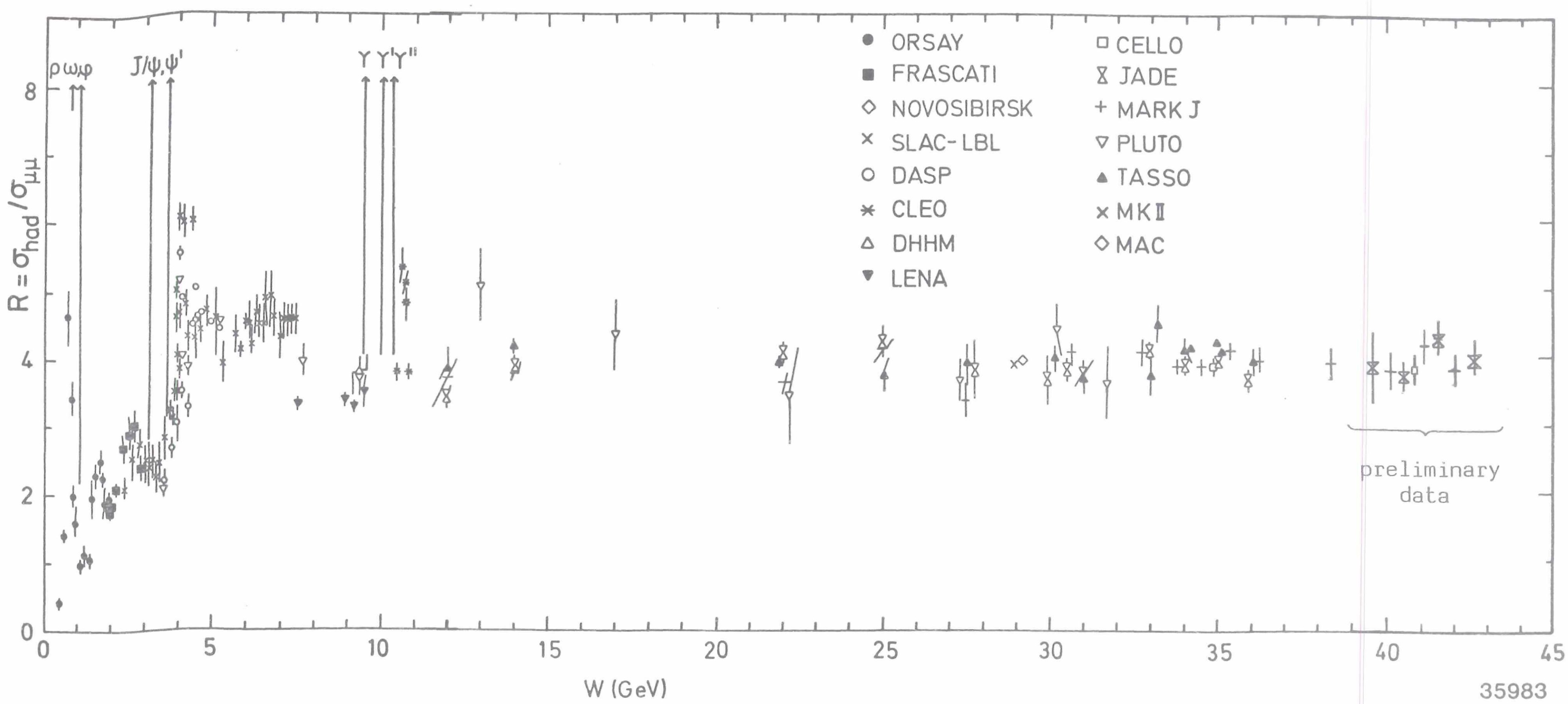

Fig. 1: Ratio of hadron to muon production cross-section showing the energy range of physics experimentation with PETRA

Optics Modification

4x4 additional quadrupoles in the 4 rf-sections were added to allow smaller ß-values in the cavities in order to fight single bunch instabilities. The mini-beta quadrupoles were replaced by longer ones to overcome saturation effects. Beta values of $\beta_z^* = 8$ cm and $\beta_x^* = 120$ cm are normally used up to the highest energy.

Injection at 7 GeV and luminosity operation at 21 GeV require substantially different optics and a continuous transfer between them during energy ramping. Due to the large number of independent PETRA quadrupole circuits (22 instead of 19 so far), rather extreme features could be realized /5/:

- Injection optics with large momentum compaction ($\alpha = 4.6 \cdot 10^{-3}$) for long bunch length
- small ß-values in the rf-section ($\beta_x = 9$ m; $\beta_z = 18$ m) for reducing instabilities
- large ß-values at the IP ($\beta_x^* = 2.4$m; $\beta_z^* = 1.3$m) for maximum acceptance
- luminosity optics with small momentum compaction ($\alpha = 2.4 \cdot 10^{-3}$) for maximum energy
- periodic dispersion in the arcs for low emittance ($\varepsilon_x/E^2 = 4.6 \cdot 10^{10}$radm GeV^{-2})
- low ß-values at the IP ($\beta_x^* = 1.2$ m; $\beta_z^* = .08$ m)

Current Limitations

After the installation of additional 32 cavities with 7 cells each, the maximum currents in PETRA dropped from 4x7 mA to about 4x3 mA. Also the maximum single bunch current obtained by continuous injection into one bunch dropped from 20 mA to about 8 mA, i.e. by more than a factor of 2. The limitation in both cases, which was already given by synchro-betatron resonances /6/, is now stronger since the strength of these resonances is increased considerably. The single bunch turbulent vertical instability /7/ also became stronger; the threshold dropped from 3 mA to 1.8 mA and limits the single bunch current if the bunch length is not increased artificially by changing the damping partition and the momentum compaction factor.

Increasing the number of 5 cell cavities from 15 to 60 during the summer of 81 did not cause a significant growth of satellite strength. But the addition of 32 7-cell cavities to the 60 5-cell cavities clearly increased the satellite strength. Already the installation of 4 7-cell cavities in a straight section with 12 5-cell cavities increased the sensitivity of the satellite resonances on orbit position in this straight section by more than a factor of 2. It seems that the stronger sensitivity is mainly caused by the smaller inner diameter of the 7-cell cavities which is only 8 cm instead of 12 cm as in the 5-cell cavities.

The limiting satellite resonances are produced in the cavities by spurious dispersion /8/ and by transverse fields with a longitudinal gradient /9,10/. Both types of resonances can be compensated in a wide range by orbit bumps in the cavities and by orbit bumps in the mini beta quadrupoles where dispersions are generated that run around the whole ring. However, the beams must be injected at 7 GeV, and during the ramping to higher energies the compensation cannot be maintained due to the strong sensitivity on orbit position. Therefore, the best way to avoid the satellites as far as possible is to stay with the synchrotron and betatron frequencies exactly between the resonances. This is performed during energy ramping by an automatic control system which measures and corrects the betatron frequencies.

Luminosity

The maximum luminosity is now given by the maximum currents as limited by satellite resonances, and by the minimum beam size. The tune shifts due to the beam-beam interaction are small ($\Delta Q_x = 0.006$, $\Delta Q_z = 0.017$) and there is no blow-up of the beams as observed at lower energies /6/. The specific luminosity, i.e. the luminosity divided by the product of the bunch currents, is constant during a run:

$L_s = 4 \cdot 10^{29} cm^{-2} sec^{-1} mA^{-2}$.

The horizontal emittance is minimized by optimizing the dispersion distribution in the arcs of the machine; it is now 10 % smaller than in former optics. The beam height is given by coupling of betatron oscillations and by the spurious vertical dispersion /11/. The betatron coupling is produced by solenoid fields (1) and by vertical orbit displacements in the sextupoles (2). The polarities of the uncompensated solenoid fields of the 3 detectors are chosen such that they compensate each other partly. The remaining emittance coupling (1) is 1 %o. Typical vertical orbit displacements in the sextupoles are in the order of 0.5 mm and produce a coupling (2) of about 2 %o. These couplings can be reduced with 2 rotated quadrupoles which suppress the first harmonic of the coupling.

Spurious vertical dispersion is caused by vertical orbit displacements in quadrupoles where a vertical curvature of the orbit is produced (3), and by vertical orbit displacements in sextupoles where the horizontal dispersion is coupled into the vertical direction (4). The first effect (3) gives a vertical emittance of about 1 %o of the horizontal emittance, and the second effect (4) gives about 4 %o, assuming an rms-value of .5 mm for the displacements. The vertical dispersion is minimized by 4 orbit bumps in the mini beta quadrupoles at the 4 interaction regions; they mainly suppress the first harmonic of the dispersion. Local compensation of the dispersion would reduce the beam height further. This requires a precise measurement of the dispersion, a task which is being prepared now.

Calculating the beam height at the interaction point one has to take into account two additional contributions: a vertical dispersion (5) and a coupling of amplitude functions (6) at the interaction point. The expectation value of the first contribution (5) to the square of the beam height is 1/4 of the vertical emittance produced by vertical dispersion in the bending magnets (3+4). The expectation value of the second contribution is 1/2 of the vertical emittance produced by the coupling (1+2). Thus one obtains for $\sigma_z^2/(\beta_z \varepsilon_x)$ about 11 %o. Minimum values of 7 %o, calculated from luminosity measurements, were obtained after very careful minimization of the dispersion and of the coupling with orbit bumps and with skew quadrupoles, respectively.

Future Aspects

In order to reach higher currents at the injection energy and to keep them during energy ramping we will use the 2nd harmonic rf-system /3/. For energies between 7 and 13 GeV, the system is strong enough to compensate the voltage gradient of the accelerating voltage to zero at the bunch position. With this compensation, the current limit of the vertical single bunch instability has been found to go up by a factor of 2.5 and the satellite resonances have been found to vanish. It should thus be possible to ramp up much higher currents to 13 GeV, where the synchrotron frequency will be made to jump to larger values sufficient to give a good beam life time at 22 GeV. The jump is accomplished by switching the phase of four of the 500 MHz transmitters. The voltage gradient, then, is of course no longer compensated, but it is hoped that the beams can be stably brought up further due to the higher energy.

This scheme will be tested after the installation of additional 144 cavity cells during August 83, and the maximum energy of PETRA will be increased to 2x22.5 GeV.

Higher energies up to 2x30 GeV can be reached in PETRA by superconducting techniques. Two tests with superconducting rf-structures were made in PETRA. A single cell 500 MHz sc cavity /12/ and a 5 cell 500 MHz sc cavity /13/ were able to accelerate a stored beam, and they stayed superconducting during several weeks of normal machine operation without any deterioration. A 9-cell 1000 MHz sc cavity /4/ is scheduled to be tested in PETRA for February 84.

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