Observation of Collective Effects
during Positron and Electron Operation at PETRA III.

Three-Way Meeting, Aug. 1-2, 2013
Argonne National Laboratory.

Rainer Wanzenberg
DESY
Aug. 1, 2013
Outline

> Introduction
  - PETRA III (History, Parameter)
  - Emittance Diagnostics

> Operation with e+
  - Electron Cloud Effects

> Operation with e-
  - Ion Effects
  - Single Bunch Effects (TMCI)

> Test Runs at Low Energy (3 GeV) and Low Emittance
  - Intra Beam Scattering / Emittance Growth
PETRA - History

The PETRA ring was built in 1976 as an electron – positron collider and was operated from 1978 to 1986 in this collider mode.

From 1988 to 2007 PETRA II was used as a preaccelerator for the HERA lepton hadron collider ring.

2007 – 2008: The PETRA ring was converted into a synchrotron light facility.

**e+ operation (2009 – 2012)**

2009 commissioning with beam
2010 “friendly users”,
**first indication of electron cloud effects**,  
40 x 4 = 160 / 60 x 4 = 240 Bunches
2011 regular user operation
60 x 4 = 240 / 240 x 1 Bunches (32 ns)
2012 regular user operation
240 x 1 / 320 x 1 Bunches

**e- operation (started Jan 2013)**

2013 regular user operation
480 and 960 bunches (design)
PETRA III - Overview

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PETRA III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy / GeV</td>
<td>6</td>
</tr>
<tr>
<td>Circumference /m</td>
<td>2304</td>
</tr>
<tr>
<td>Total current / mA</td>
<td>100</td>
</tr>
<tr>
<td>Emittance (horz. / vert.) /nm</td>
<td>1 / 0.01</td>
</tr>
</tbody>
</table>

Wigglers

Arc: FODO Lattice

Experimental Hall

Damping wigglers
10 wigglers

Insertion Devices
1 x 10 m 8+1 DBA
3 x 5 m cells
10 x 2 m

RF section
12 cavities

Injection

FB cavities
8 cavities

Undulators
PETRA III Emittance Diagnostics

Diagnostic Beam Line (Exp. Hall)

Interferometric beam size measurements (North)

Reference:
PETRA III
G. Kube, DIPAC’07, EPAC’08
ATF - KEK
H.Hanyo et al., Proc. of PAC99 (1999), 2143

60 x 4 bunches, 100 mA
Vert. Emittance
~ 5 pm rad
(March 8, 2012)
### PETRA III – Parameters, Filling patterns

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>PETRA III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy / GeV</td>
<td>6</td>
</tr>
<tr>
<td>Circumference /m</td>
<td>2304</td>
</tr>
<tr>
<td>RF Frequency / MHz</td>
<td>500</td>
</tr>
<tr>
<td>RF harmonic number</td>
<td>3840</td>
</tr>
<tr>
<td>RF Voltage / MV</td>
<td>20</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$1.22 \times 10^{-3}$</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.049</td>
</tr>
<tr>
<td>Total current / mA</td>
<td>100</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>960</td>
</tr>
<tr>
<td>Bunch population / $10^{10}$</td>
<td>40</td>
</tr>
<tr>
<td>Bunch separation / ns</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Emittance (horz. / vert.) /nm</td>
<td>1 / 0.01</td>
</tr>
<tr>
<td>Bunch length / mm</td>
<td>12</td>
</tr>
<tr>
<td>Damping time H/V/L / ms</td>
<td>16 / 16 / 8</td>
</tr>
</tbody>
</table>

#### Filling scheme

- **40 x 1**
  - 192 ns
  - Bunch positions (8 ns spacing)
- **60 x 1**
  - 128 ns
- **60 x 4**
  - 80 ns
- **240 x 1**
  - 32 ns
- **320 x 1**
  - 24 ns
- **480 x 1**
  - 16 ns
- **960 x 1**
  - 8 ns

**achieved:**
- **e⁺**
  - 80 mA: 40 bunches; 100 mA: 60, 240, 320 bunches
- **e⁻**
  - 100 mA: 40, 60, 480, 960 bunches
Electron clouds

Broad band resonator model + coasting beam model *)
threshold density:

$$\rho_{e,th} = \frac{2\gamma c \omega_e \sigma_z}{K Q \sqrt{3} r_e \beta L}$$

$$Q \sim 5 < K$$

$L =$ circumference of the ring

<table>
<thead>
<tr>
<th>$K$</th>
<th>$\sim \omega_e \sigma_z / c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETRA III:</td>
<td>$\sim 1.4 \times 10^{12} \text{ m}^{-3}$</td>
</tr>
</tbody>
</table>

Dipole Vacuum chamber **), SEY = 2.7 as received

Electron cloud build-up simulations
ECLOUD code (CERN) ***)

Electron cloud (pattern 60 x 4)

Al, 80 mm x 40 mm

*) K. Ohmi: Electron Cloud Effect in Damping Rings of Linear Colliders, "ECLOUD'04"

**) D.R. Grosso et al: Secondary Electron Yield of Al Samples from the Dipole chamber of PETRA III, IPAC'11

***) G. Rumolo, F. Zimmermann, CERN-SL-Note-2002-016

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Vertical emittance blow up (640 bunches, 2010)

640 bunches, 8 ns bunch spacing + gap
639 x 8 ns = 5112 ns, gap 2568 ns, total current 65 mA

Measured Emittance on May 11, 2010
Horz. 1.38 nm
Vert. 128 pm
(Average, all bunches)
Operation with e+ in 2012 / Understanding of eclouds

Conditioning (integrated beam current)
133 Ah → 577 Ah → 980 Ah → 1050 Ah → 1520 Ah

Dedicated Scubbing Runs: March 3-4 and 10-11, 2012

User runs with 240 (32 ns) and 320 (24 ns) bunches.

Understanding of the Ecloud effects at PETRA III:

1) Investigation of the surface chemical state of the Al alloy
   (CNR, LNF-INFN, R. Cimino, R. Larciprete et al. Phys Rev. STAB 16, 051003 (2013) )
   After scrubbing SEY 1.5 … 1.8, but scrubbing is not permanent, Al has a chemical propensity towards oxygen, the Al surface binds O atoms and the SEY is increased, no significant build-up of a graphitic layer

2) Simulation of ecloud build-up for different filling patterns
   (workshop ECLoud’12)
   Comparing the central e- density for different filling patterns (60x4 vs. 80x4) indicates that a SEY of ~ 2.0 is consistent with the observations based on the estimates for the instability threshold.

Open issues:
   Strong fluctuations of the simulated Central density
   Primary photoelectron density is not well known

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Operation with Electrons in 2013, Ion effects

**Filling schemes without a clearing gap**

<table>
<thead>
<tr>
<th>Filling scheme</th>
<th>Bunch positions (8 ns spacing)</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>25</th>
<th>27</th>
<th>29</th>
<th>31 ... 960</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 x 1</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>192 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 x 1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>128 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>960 x 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 ns</td>
<td></td>
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<tr>
<td>480 x 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16 ns</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>320 x 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240 x 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>192 x 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160 x 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>72 ns</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**critical ion mass (classical ion trapping)**

\[
A > A_c = N_b \frac{L_b r_p}{2 \sigma_y (\sigma_x + \sigma_y)}
\]

<table>
<thead>
<tr>
<th>(N_b) : (A_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>960: 1 240: 16 120: 66</td>
</tr>
<tr>
<td>480: 4 192: 26</td>
</tr>
<tr>
<td>320: 9 160: 37</td>
</tr>
</tbody>
</table>

**User runs, total current 100 mA**

Ions:
- \(A = 2 \quad H_2\)
- \(A = 16 \quad CH_4\)
- \(A = 18 \quad H_2O\)
- \(A = 28 \quad CO, N_2\)
- \(A = 32 \quad O_2\)
- \(A = 44 \quad CO_2\)

**Vertical emittance growth, Threshold current \sim 60 mA**
Vertical Emittance Growth, e- Operation

Jan 15, 2013 240 bunches, 100 mA

Jan 15, 2013 480 bunches, 100 mA

Jan 17, 2013 960 bunches, 100 mA

Threshold current ~ 60 mA

Lower sideband

Vertical tune
PETRA III: Vacuum

**Without beam** ~ $6 \times 10^{-10}$ mb

- 28.03.2012
- Pressure (Ion Pumps) 12:48:40.008
- 0 mA

**With beam, 100 mA, 240 bunches**
- arc ~ $3 \times 10^{-9}$ mb
- ring ~ $1.4 \times 10^{-8}$ mb

**undulators**  **wiggler sections**  **undulators**

- 29.03.2012
- Pressure (Ion Pumps) 00:23:28.000

Dynamic pressure rise versus Integrated current

\[
\lambda_{ion} = d_{gas} \sigma_{ion} N_0 = 2 \text{ Mbarn} \quad d_{gas} N_0
\]

= 230 ions/cm,  \( p = 1 \times 10^{-9} \text{ mb} \)

1 turn, 960 Bunches, \( N = 5 \times 10^9 \text{ e-} / \text{bunch} \)

Ion effects: 220 bunches (32 ns spacing) + gap

Single bunch intensity versus bunch position

Jan 17, 2013, 220 Bunche, 100 mA, vertical emittance

Fast Ion Instability?

Simulations of the fast ion instability indicate an emittance growth for 960 bunches. (G. Xia et al., Ion Effect Issues in PETRA III, PAC 2009, Vancouver)

The instability should be less prominent for fewer bunches - contrary to the observations.

emittance growth (25 pm), but ok at full current
Ionen effects: Couple Bunch Motion

March 7, 2013: 240 Bunche, 100 mA
Multi bunch spectrum: Coupled bunch motion
6.17 MHz
9.26 MHz = 71 f₀
11.48 mHz

15.6 MHz = 240 f₀ / 2, frequency

Qualitative Understanding:

Two stream instability, coupled ion and beam motion

k = mode number

Ions  ~  exp(i Ω t)
Beam  ~  exp(i (k θ - Ω t))

Complex solution of the dispersion relation

Mode k is instable with growth rate:

\[
\frac{1}{\tau} = \text{Im}[\Omega]
\]

Single Bunch Instabilities (TMCI)

Tune spectrum, e+ operation
June 20, 2012  10 Bunche  26 mA
lower sideband

Single bunch
design current  2.5 mA

achieved: 1 bunch  with 5 mA
( Feb. 18, 2011 )
but with emittance growth
(56 pm rad)

**e+ operation**

operation with 40 bunches
40 x 2 mA = 80 mA
requires a large vertical chromaticity
(5 ... 7 units) to avoid
vertical emittance growths
or beam instabilities

**e- operation**

operation with 40 bunches
40 x 2.5 mA = 100 mA
requires a moderate vertical
chromaticity (1... 2 units) to avoids
vertical emittance growth

Additional incoherent tune spread
due to trapped ions ???
or single bunch ecloud effects
for e+ ???
Tuneshift  e+ and e-

**e+ Oct 17, 2012**  Chromaticity horz.+1 / vert. +2  **e- Jan 17, 2013**

- **Tuneshift are similar but**
- e+ instable at 1.7 mA with a chromaticity of +2

\[
\frac{\Delta f_x}{\Delta I} = -0.216 \text{ kHz/mA}
\]

\[
\frac{\Delta f_y}{\Delta I} = -1.32 \text{ kHz/mA}
\]

\[
\frac{\Delta f_y}{\Delta I} = -1.342 \text{ kHz/mA}
\]

\[
\frac{\Delta Q}{\Delta I} = 0.01 / \text{mA}
\]

- **f_0 = 130 kHz**
- **1.7 mA**

(Instability)

- **2.5 mA**

(not instable)
July 16, 2013
PETRA III, 3 GeV,
horz. Emittance 160 pm rad
I = 5 mA in 480 bunches,
N = 5 x 10^8 / Bunch

July 2013
Several test runs at low energy

FODO arcs: 72 deg lattice
wiggler section matched,
predicted emittance:
3 GeV: 160 pm rad

Intrabeam scattering:

\[ A \sim \frac{N_0}{\gamma^4 \epsilon_x \epsilon_y \sigma_s \sigma_p} \]

\[ \frac{1}{\tau_x} = \left\langle A \left[ f(1/a, b/a, q/a) + \frac{D_x^2 \sigma_h^2}{\sigma_x^2 \sigma_p^2 f(a, b, q)} \right] \right\rangle \]
Intra Beam Scattering / Emittance Growth

Measurements:
IBS: 160 pm rad → ~ 350 pm rad

work in progress:
modelling of the IBS
Conclusion

Collective effects determine the possible operation (filling pattern) of PETRA III:

- **Operation with e+**
  - User Runs with 40, 60, 240 and 320 bunches (Electron Cloud Effects)

- **Operation with e-**
  - User Runs with 40, 60, 480 and 960 bunches (Ion Effects)

- **Testruns with Low Energy (3 GeV) and Low Emittance**
  - $\epsilon x = 160 \text{ pm rad}$ only for low current 10 mA/960 (Intra Beam Scattering)

Challenges for the PETRA III Extension Project:

- **New Vacuum System** (more prominent ion effects for ~ 1 year)
  - Limitations for the operation mode with 480 or 960 bunches?

- **New Small Gap Chambers** (Wakefields and TMCI)
  - Vert. tuneshift: 1.3 kHz $\rightarrow$ 1.6 – 2.0 kHz ???
  - Limitations for the operation mode with 40 bunches
Thank you for your attention!

Acknowledgment:

Thanks go to my colleagues from DESY:

J. Keil, A. Kling, G. Kube, G.K. Sahoo