

Record-high Resolution Experiments on Comparison of Spin Precession Frequencies of Electron Bunches Using the Resonant Depolarization Technique in the Storage Ring

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Introduction

- The work is devoted to preparation of the experiment for CPT theorem test
- CPT theorem predicts that the **g-factor, mass, charge, absolute value of magnetic moment, life time** etc. of particle and anti-particle are equal
- Today it is completely unclear, how and in what a violation of CPT symmetry could appear
- In our experiments using the resonant depolarization technique (RD) at the storage ring, the spin precession frequencies of e^+ and e^- depending on a **combination** of constants **$(g-2)/2$** and **e/mc** can be simultaneously measured and compared

CPT Test World Accuracy

$$e^+ \leftrightarrow e^-$$

$$(q_{e^+} - q_{e^-})/e < 4 \times 10^{-8}$$

$$(m_{e^+} - m_{e^-})/m_{average} < 8 \times 10^{-9}$$

$$(\mu'_{e^+} - \mu'_{e^-})/\mu'_{average} < 3.5 \times 10^{-9}$$

$$(\mu'_{e^+} - \mu'_{e^-})/\mu'_{average} < 1.0 \times 10^{-8}$$

VEPP-2M, 1987


Comparison of the polarization extents of e^+ and e^- after adiabatic crossing the spin resonance. Treated as AMM comparison assuming $q_{e^+} = q_{e^-}$.

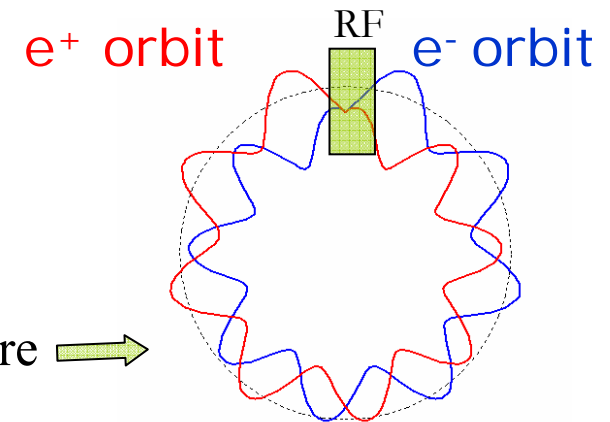
Van Dyck, et al. 1987
Electrons/Positrons in the Penning trap.
Comparison of purely the factors (g-2) for e^+ and e^- :
 $\delta(g-2)/2 \sim 4 \cdot 10^{-12}$

Both methods are different from that we apply

CPT Symmetry Test at the Storage Ring

- Spin precession frequency $\Omega = \nu\Omega_0 = q'\langle H \rangle$,
 $q' = [(g - 2) / 2] \cdot [e / mc]$, $\nu = \gamma \cdot [(g - 2) / 2]$
- Revolution frequency $\Omega_0 = ec \left\langle \frac{H}{E} \right\rangle$ is the same

for e^+ and e^- , but the orbits are not coincident like in Figure 



- If CPT is true then $\langle H \rangle_+ = \langle H \rangle_-$ in a machine with the mirror symmetry, so $\Omega_+ = \Omega_-$
- If $e^+ \neq e^-$, $m_+ \neq m_-$, then $\Omega_0^+ = \Omega_0^- \rightarrow e^+$ and e^- orbits differ from those of the mirror symmetry type and thus $\langle H \rangle_+ \neq \langle H \rangle_-$
- Beside, generally $q'_+ \neq q'_-$ (anomalous parts of gyromagnetic ratio)
- Ideal storage ring with the mirror symmetry but without electrical fields :

$$\Delta\Omega = \Omega_+ - \Omega_- = q'_+ \langle H \rangle_+ - q'_- \langle H \rangle_- \neq 0 \text{ due to violation of CPT Symmetry}$$

CPT Symmetry Test at the Storage Ring (cont.)

The possibility for such an experiment depends on an answer to question:

What an accuracy of the mirror symmetry of storage ring can one provide to exclude the influence of systematic errors on $\langle H \rangle_{\pm}$?

By indirection, the achieved accuracy in VEPP-2M experiment (10^{-8}) proves that a fine precision mirror symmetry of the storage ring can be realized.

Objectives

- It is of interest to measure difference $|\Omega_+ - \Omega_-|$ with an accuracy of the order of 10^{-9} . This will be a next step as compared even with Van Dyck (non-relativistic, not all constants included).
- At the first stage of our experiments, we compare the spin precession frequencies of **two electron bunches**, simultaneously circulating in the VEPP-4M storage ring, with the aim to reach a minimal statistic error and to investigate some systematic errors.

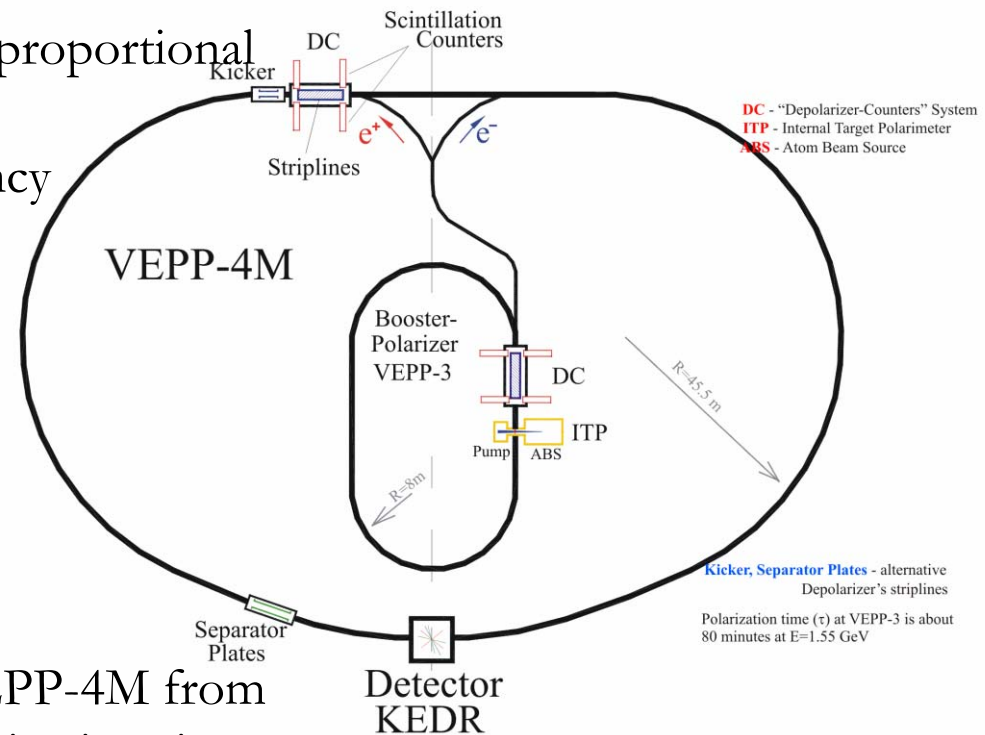
RD technique at VEPP-4M

(RD was proposed and applied for the first time in BINP, 1975)

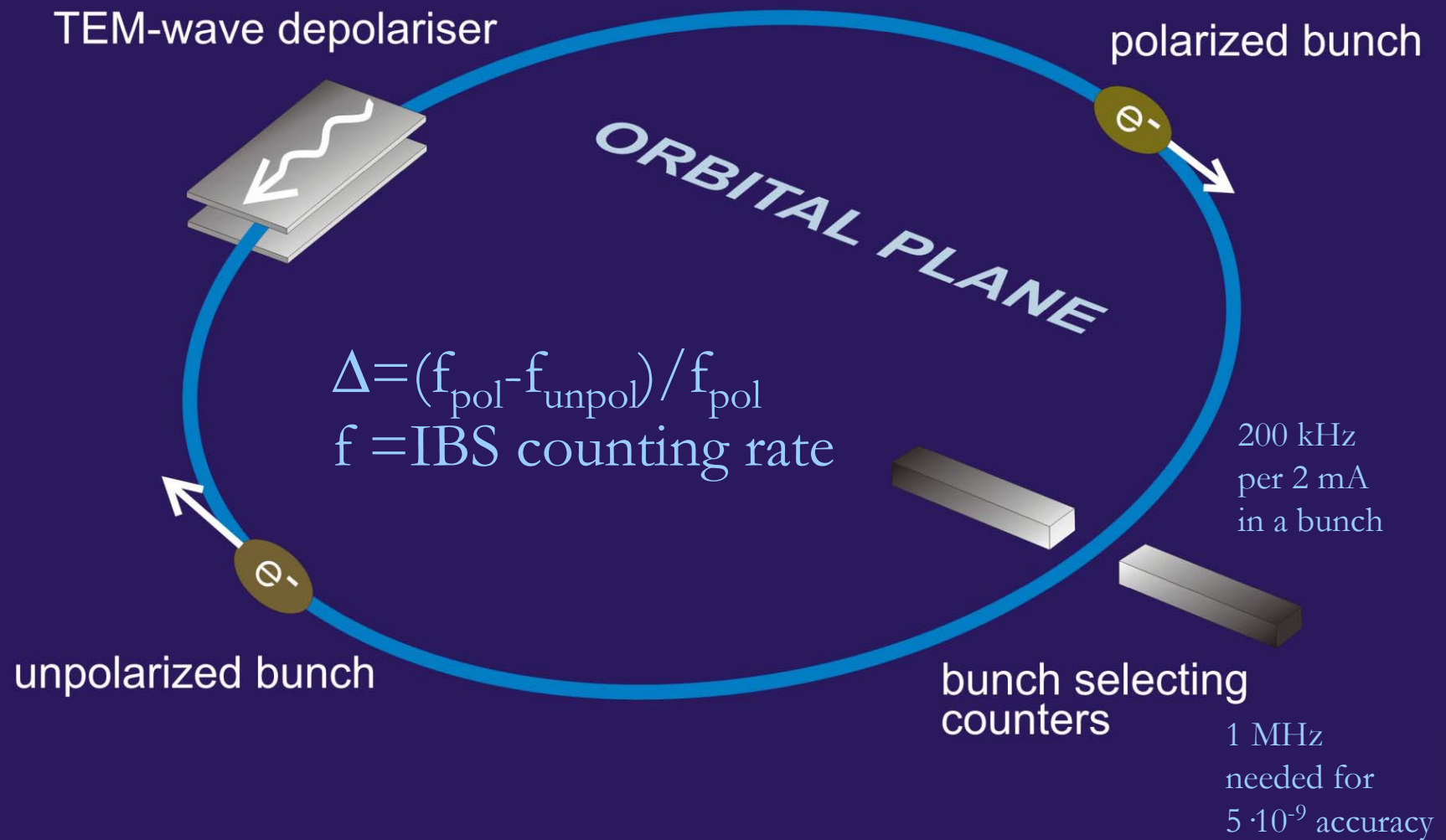
- Average spin frequency in a beam is proportional to an average beam energy
- Spin freq. is measured by the frequency of the TEM-wave-based depolarizer being scanned at the moment of the beam polarization destruction:

$$\Omega_s \pm \Omega_d = k \Omega_0$$

- Depolarization is determined by the jump in counting rate of intra-beam-scattering (Touschek) particles
- Polarized beams are injected into VEPP-4M from a booster-polarizer VEPP-3 (the polarization time is about 1 hour at E=1.85 GeV)



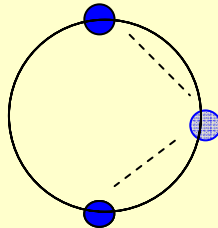
TWO BUNCH TECHNIQUE



Multi-bunch techniques

2+1

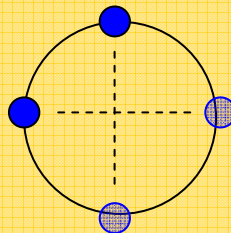
1 polarized e^- bunch +
1 polarized e^- bunch
+
1 unpolarized e^- bunch



- All three bunch currents are equal
- Normalization by third (unpolarized) bunch

2+2 (Two Pairs of like signs)

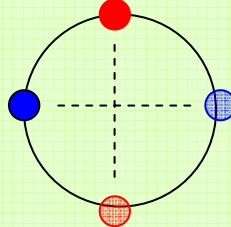
1 polarized e^- bunch+
1 unpolarized e^- bunch
+
1 polarized e^- bunch+
1 unpolarized e^- bunch



- Currents are equal within each pair
- Normalization by the unpolarized bunch in each pair
- Study of the dependence of spin tune on the bunch current

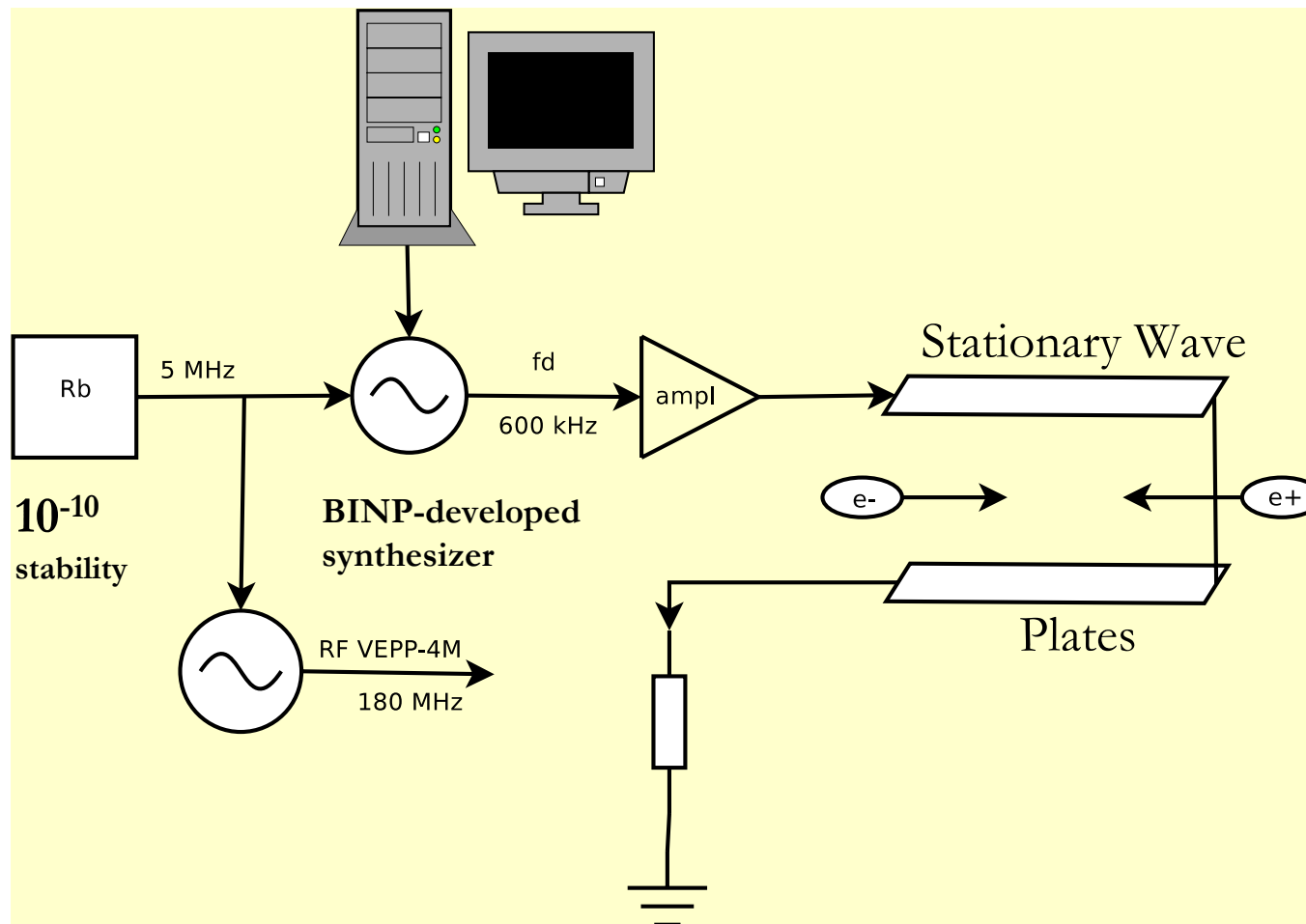
2x2 (Two Pairs of opposite signs)

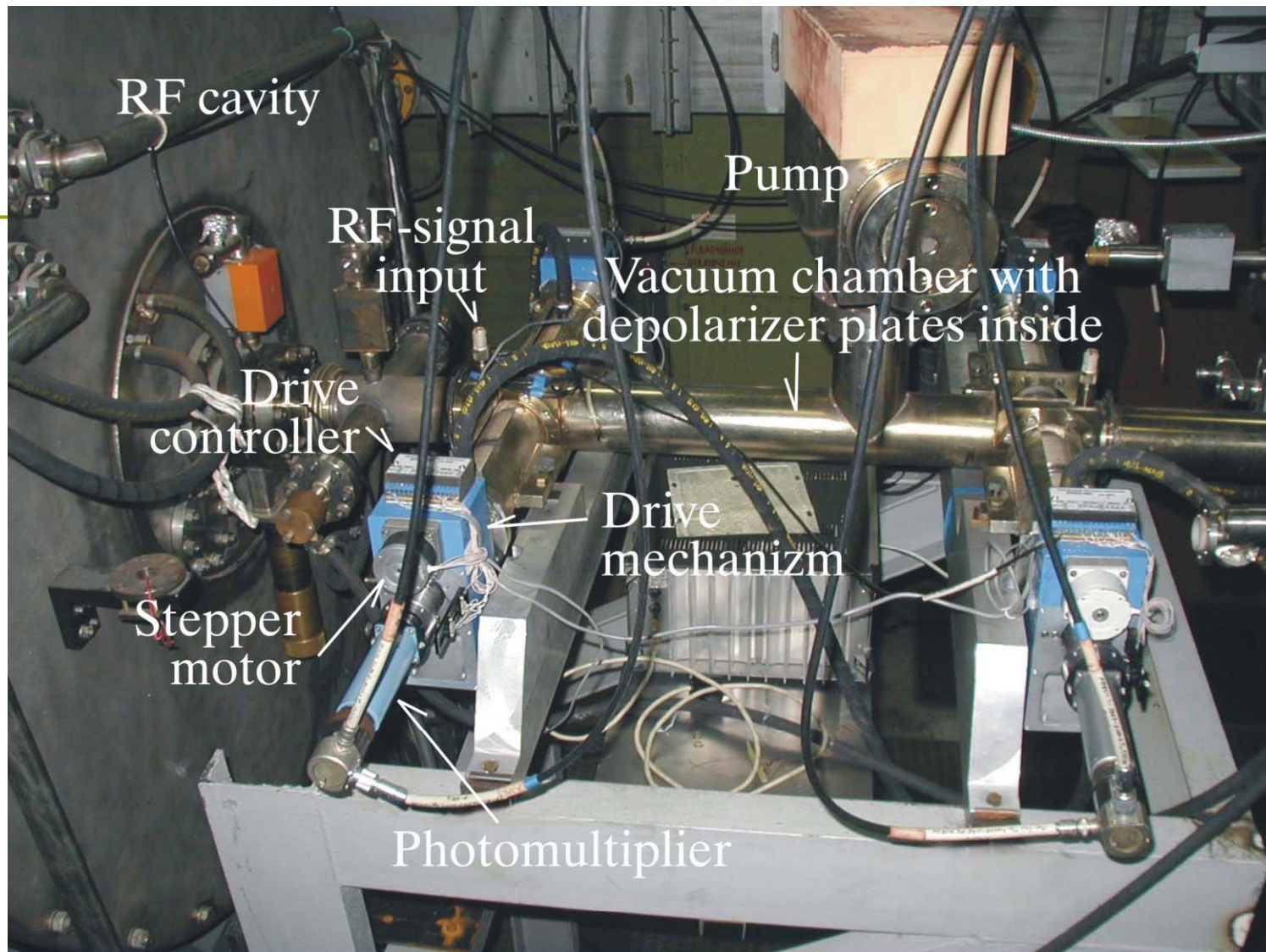
1 polarized e^- bunch+
1 unpolarized e^- bunch +
1 polarized e^+ bunch+
1 unpolarized e^+ bunch



Comparison of e^- and e^+ spin frequencies

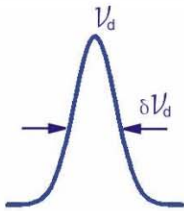

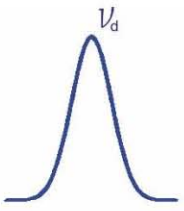
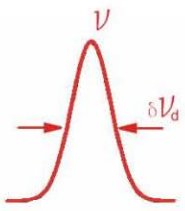
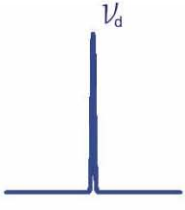
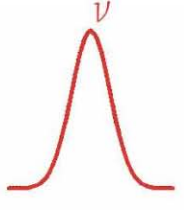
Control of the depolarizer





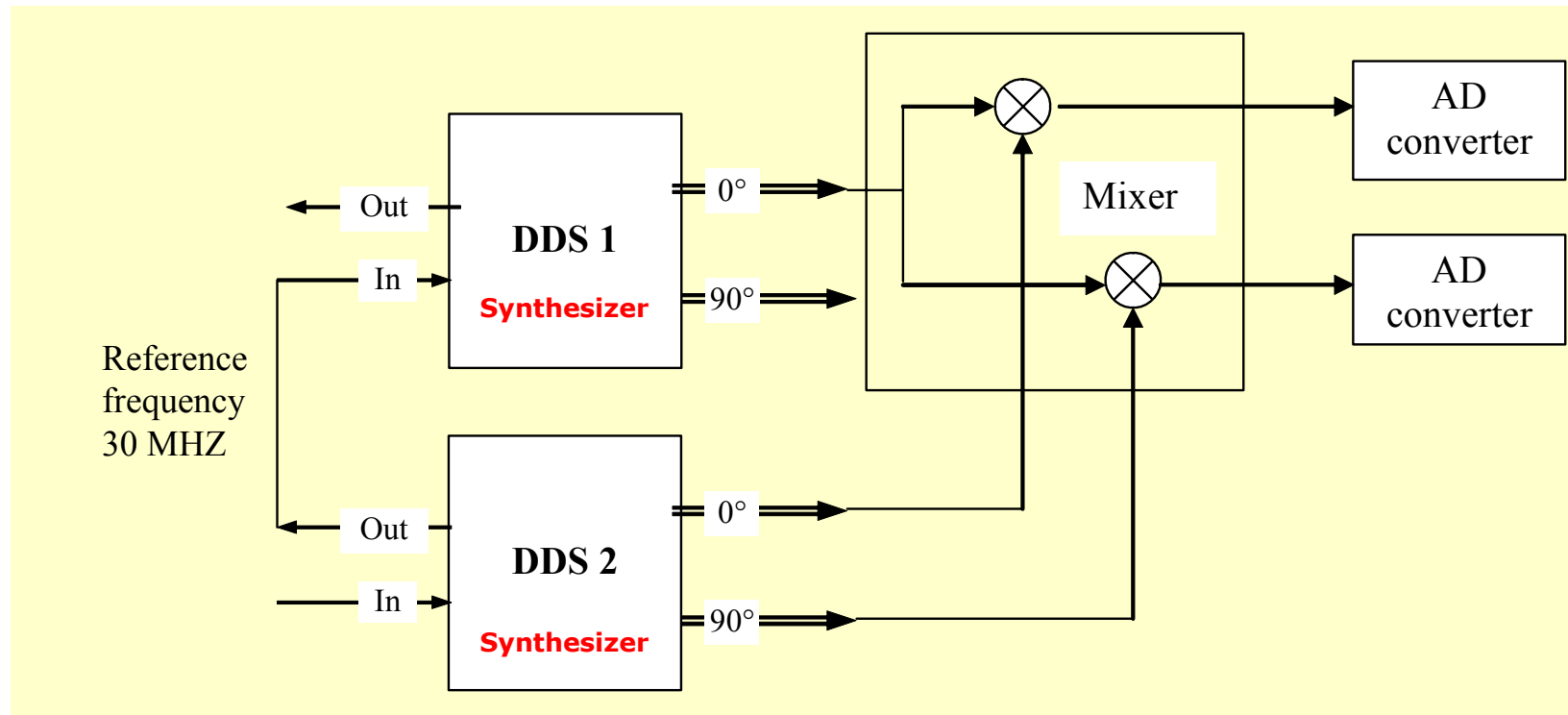
Intra-beam scattering-based polarimeter KARAKATITSA
at technical straight section of VEPP-4M

Types of scanning

case	depolarization rate	linewidth	
		depolarizator	spin
“club”	$\tau_d \sim \left(\frac{2\pi w ^2 f_0}{\delta v_d} \right)^{-1} \sim (10 \div 100) \text{ sec}$		
J/ψ 100 eV/sec $ w \sim 5 \cdot 10^{-7}$	$\tau_d \sim \left(\frac{2\pi w ^2 f_0}{\delta v_d} \right)^{-1} \sim \left(\frac{2\pi w ^2 f_0}{\delta v} \right)^{-1} \sim (1 \div 2) \text{ sec}$		
AMM (CPT) 5 eV/sec $ w \sim 3.4 \cdot 10^{-8}$	$\tau_d \sim \left(\frac{2\pi w ^2 f_0}{\delta v} \right)^{-1} \sim 400 \text{ sec}$ $\Lambda^{-1} \ll \tau_d$		

**Superfine
scan**

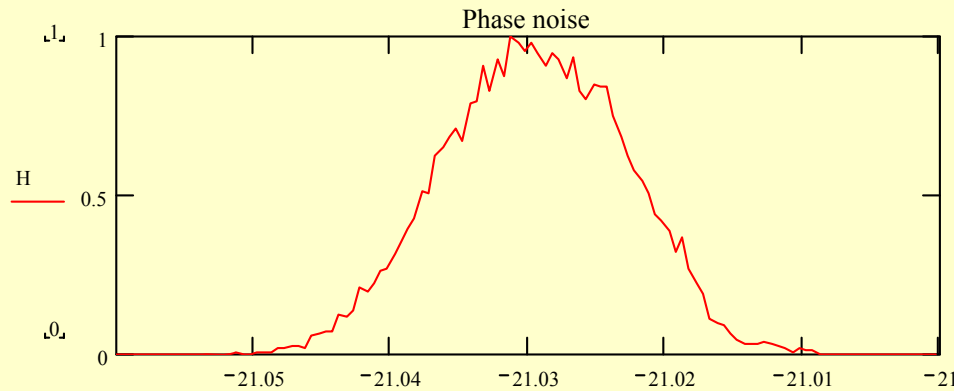
Measurement of the synthesizer noise (Bench-test scheme)



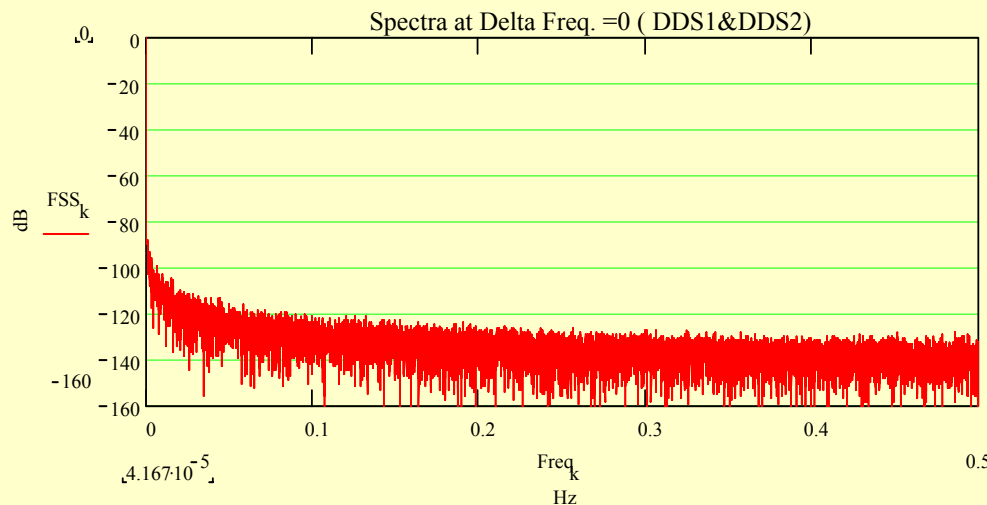
- Output frequency of the synthesizer = 1 MHz
- DDS2 is used as a common source of 30 MHz frequency
- Internal multiplier of each synthesizer raises the reference frequency from 30 to 180 MHz
- 20-bit Analog-to-Digital Converter integrates over 320 millisecond time interval

Synthesizer noise

(Results of bench-top measurements)



The characteristic width of phase noise spectrum is 0.02 degrees

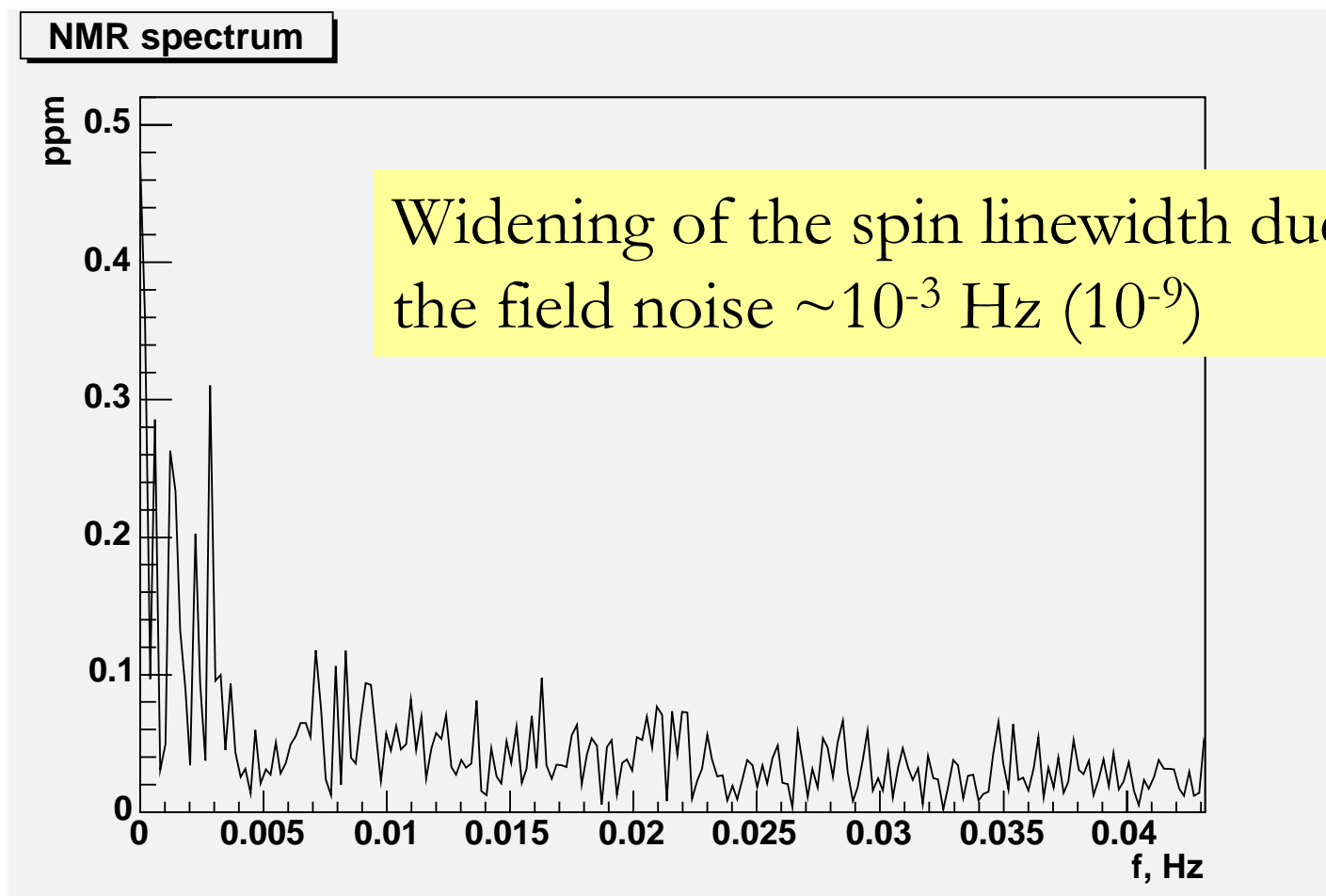


Spectral density of noise in a band of 10^{-4} Hz at 1 MHz
(at recalculation to 1Hz the spectrum will worsen by 40 dB)

Time of measurement of 12000 seconds corresponds to the frequency resolution (a band) of 10^{-4} Hz

Noise spectrum of the VEPP-4M field

(NMR probe in the reference magnet)



Linewidths

- Spin linewidth at VEPP-4M is determined by a quadratic nonlinearity of the guide field:

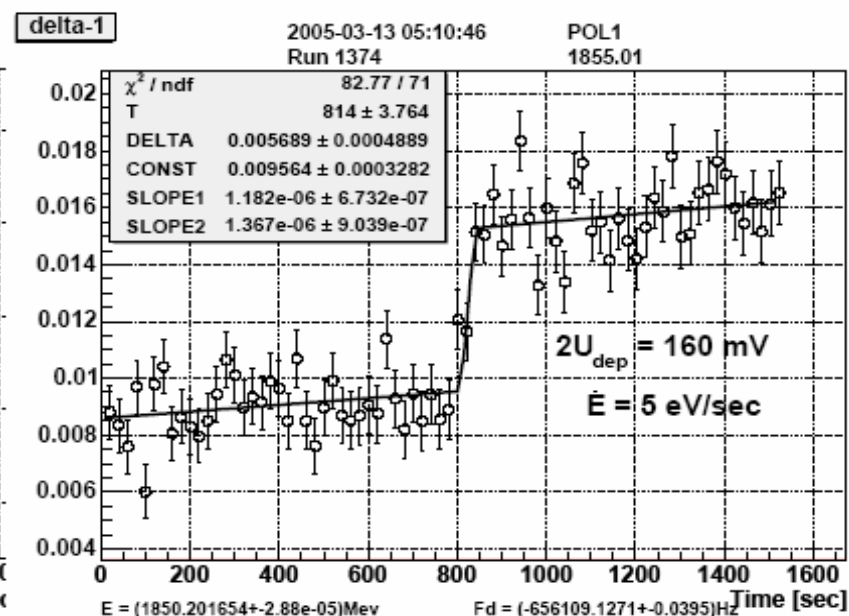
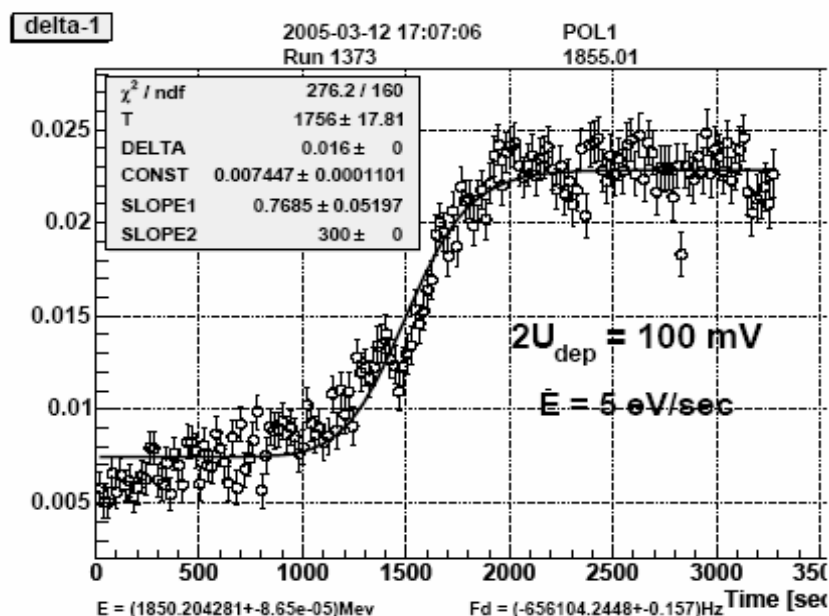
$$\sigma_\nu = \frac{\delta\nu}{\nu} \approx \langle H''(\sigma_x^2 + \eta_x^2 \varepsilon^2) \rangle \sim 5 \cdot 10^{-7} \text{ or } 1 \text{ keV or } 2 \text{ Hz}$$

- The intrinsic depolarizer linewidth as well as a widening of spin linewidth due to noise of the bending magnet field are negligible ($< 10^{-3} \text{ Hz}$)
- A “dynamic” widening of the depolarizer linewidth in the superfine scan with rate $\dot{f}_d \approx 10 \text{ mHz/s}$:

$$\delta f_d \sim \sqrt{\dot{f}_d} \sim 10^{-1} \text{ Hz or } 50 \text{ eV or } 2.5 \cdot 10^{-8} \text{ in resolution}$$

- Because of widening of spin and depolarizer linewidths we compare rather not spin frequencies but the related depolarization frequencies. This does not contradict our aims (the same conditions for bunches).

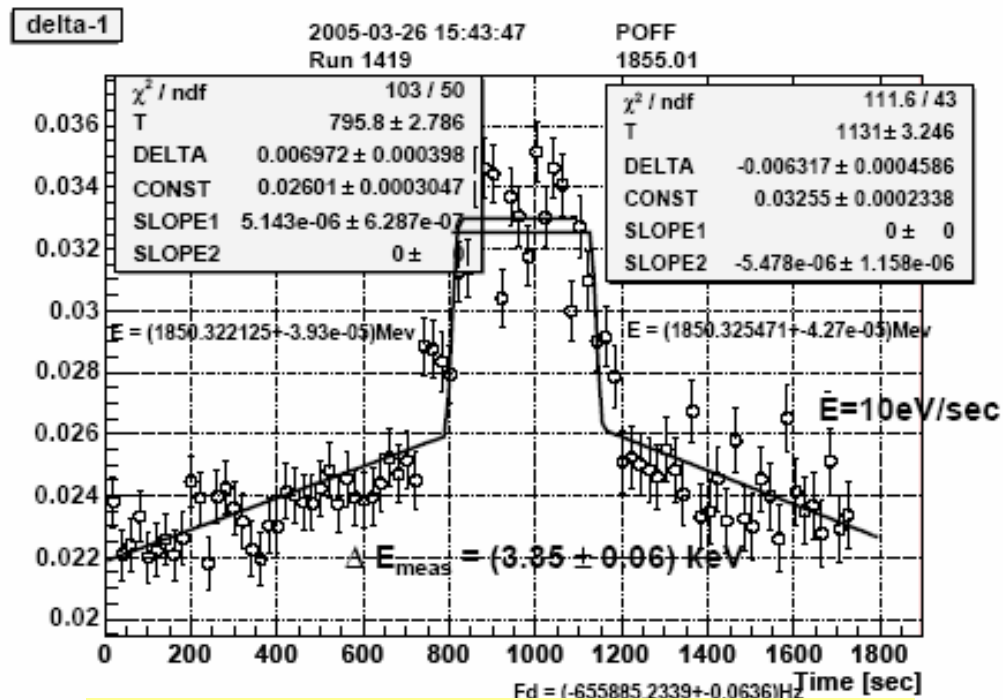
High resolution in the standard energy calibration (Two Bunch or “1+1” technique)



$$\frac{\sigma_{\Omega_s}}{\Omega_s} = 1.5 \times 10^{-8}$$

RF separation of two electron bunches

(both bunches are polarized; normalization by one of them)

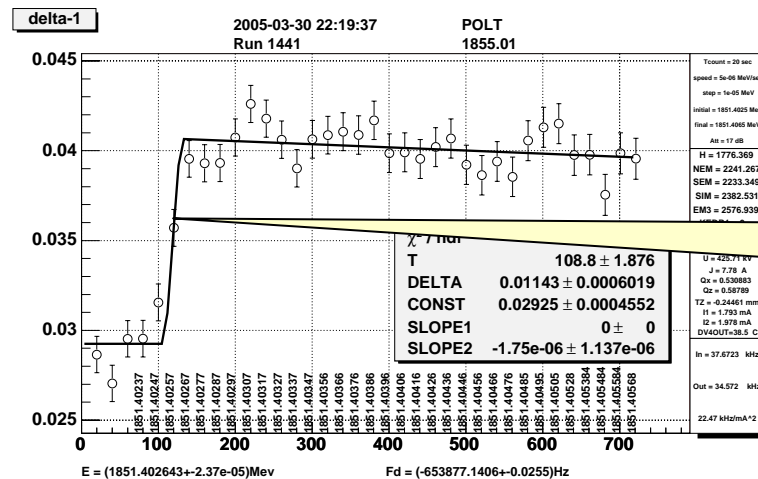


$\Delta E_{\text{meas}} = (3.35 \pm 0.06) \text{ keV}$
at the controlled separation
of 3 keV

- RF signal of rev. freq. on horiz. separ. plates.
- 180° phase difference
- Closed orbits are symm. separated
- Most fine result: (303 \pm 140) eV measured at the control of 360 eV

Simultaneous depolarizing of two polarized e- bunches with normalization by the third (unpolarized) bunch (2+1 technique)

Scan parameters:
 $2U_{dep}=230$ mV
 $\Delta E/\Delta t \approx 5$ eV/sec



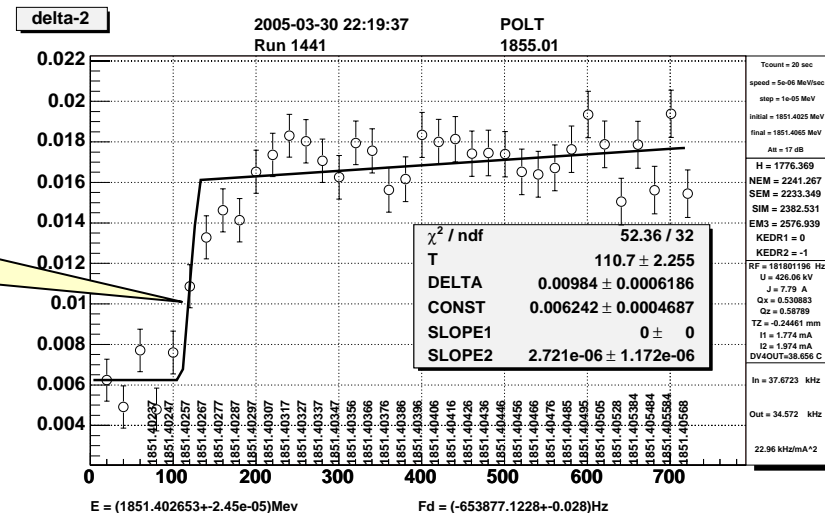
Bunch #1 / Bunch #3
 $E\#1=(1851.40264\pm 2.4e-05)$ MeV

Bunch #2 / Bunch #3
 $E\#2=(1851.40265\pm 2.4e-05)$ MeV

Summary:

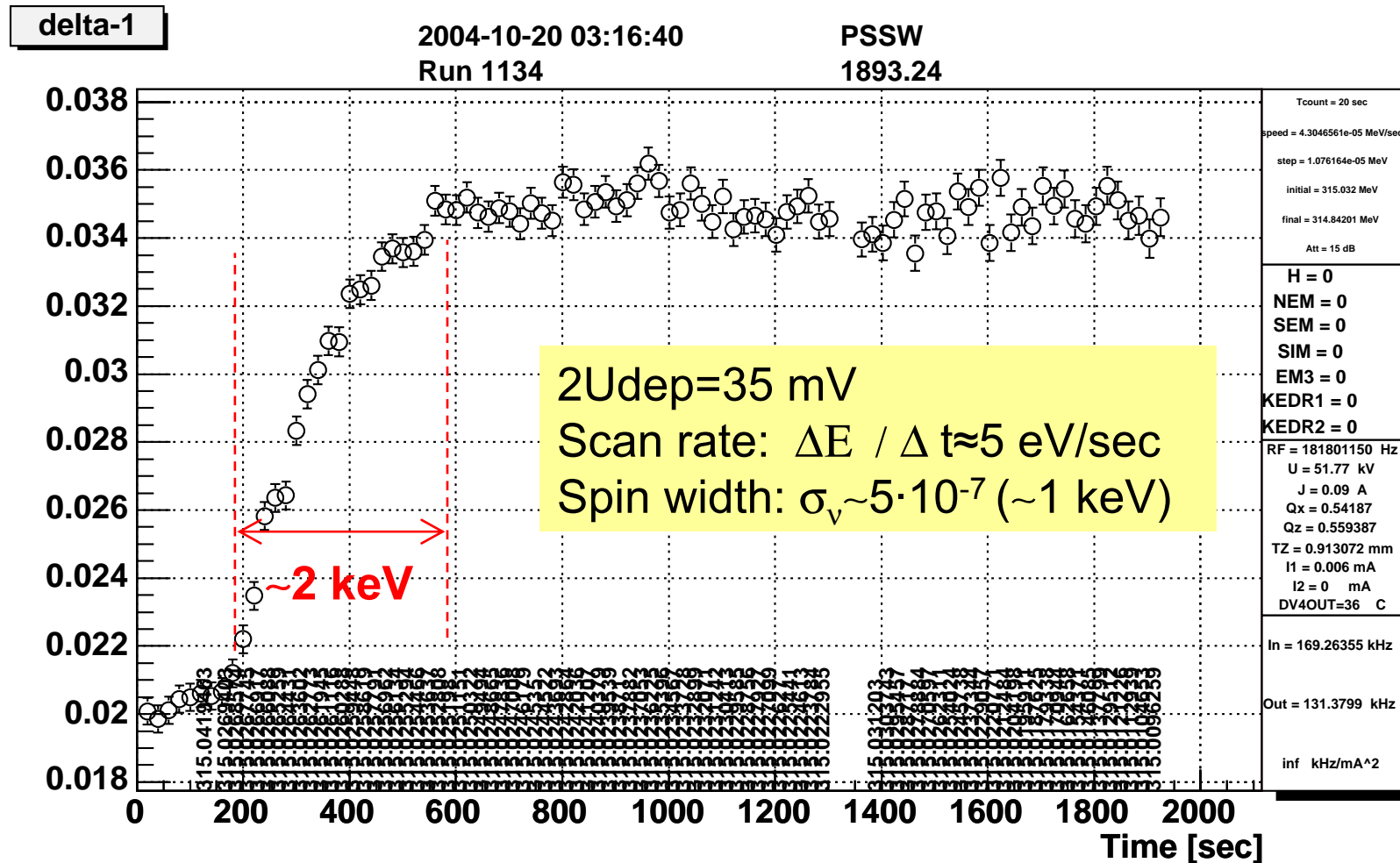
$E\#2 - E\#1=(10\pm 34)$ eV

Resolution: 2 e-08



“Long-drawn” jump in the high-resolution scan

The depolarizer's strength is relatively weak. The depolarization rate is defined by the diffusion of spin tunes in a beam and estimated through the spin linewidth.

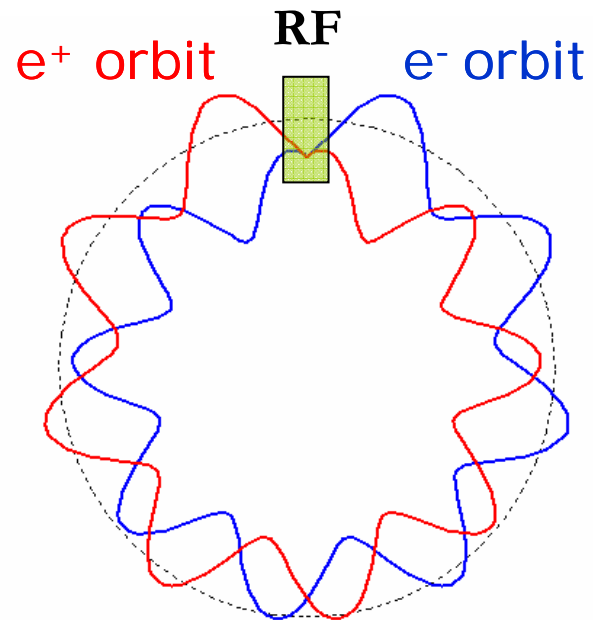


Systematic Errors:

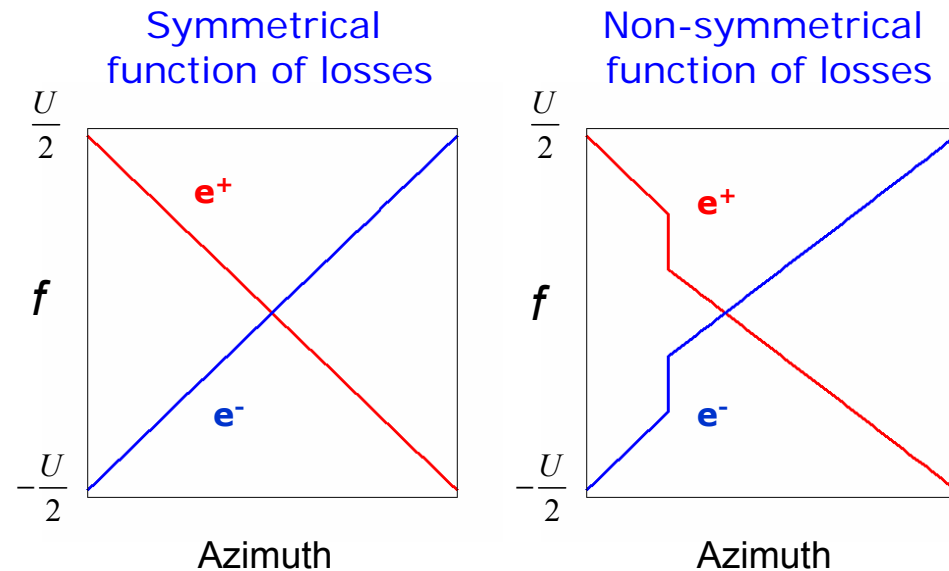
Energy/spin tune gap between electrons and positrons

- ▣ Asymmetry of the energy loss distribution over the ring
- ▣ RF cavity axis tilt
- ▣ Dependence on the bunch current
- ▣ Electrostatic fields (orbit separators, ion pumps, induced charging of the vacuum pipe surface...)
- ▣ Energy drift
- ▣ ...

Asymmetry of the energy loss distribution (SR+Coherent Losses)



“Sawtooth” effect in the orbits



$$E_{\pm}(\theta) \rightarrow E_{\pm}(0) \left[1 \mp \frac{U}{2} + f_{\pm}(\theta) \right]$$

Energy and Spin tune gap: $\frac{\langle E_+ \rangle - \langle E_- \rangle}{E_0} = 2 \cdot \left(\langle f \rangle - \frac{\langle K \eta_X f \rangle}{\langle K \eta_X \rangle} \right)$

In two cases:

- a) $K=const, \eta_X=const$
 - b) Mirror symmetry
- Gap=0

Asymmetry of the energy loss distribution (discussion)

- In two cases:

- a) $K=const$, $\eta_X=const$

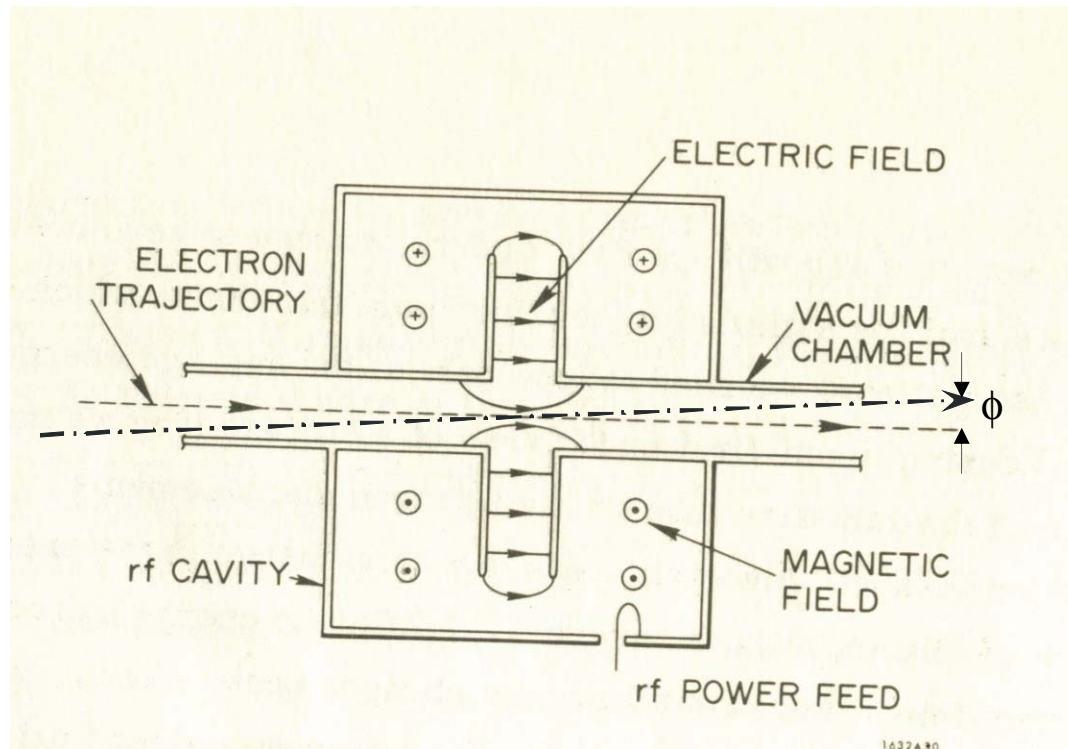
- and

- b) Mirror symmetry -

- the gap in energy/spin tune between e^+ and $e^- \equiv 0$.

- Generally, the effect of errors in the mirror symmetry $\ll U$ (loss per turn) $\propto E^3/\rho$, ρ is the orbit radius. For VEPP-4M ($\rho \approx 45$ m), the measure $U \approx 1.8 \cdot 10^{-5}$, $E=1.85$ GeV. Note, the close value of U was in AMM experiment at VEPP-2M, in which an accuracy of 10^{-8} was achieved

Tilting of RF Cavity axis about the beam axis



$$\left. \frac{\delta E}{E} \right|_{RF} \approx \left. \frac{\delta v}{v} \right|_{RF} \approx \pm \frac{\phi \eta_x}{\alpha \Pi} \cdot U$$

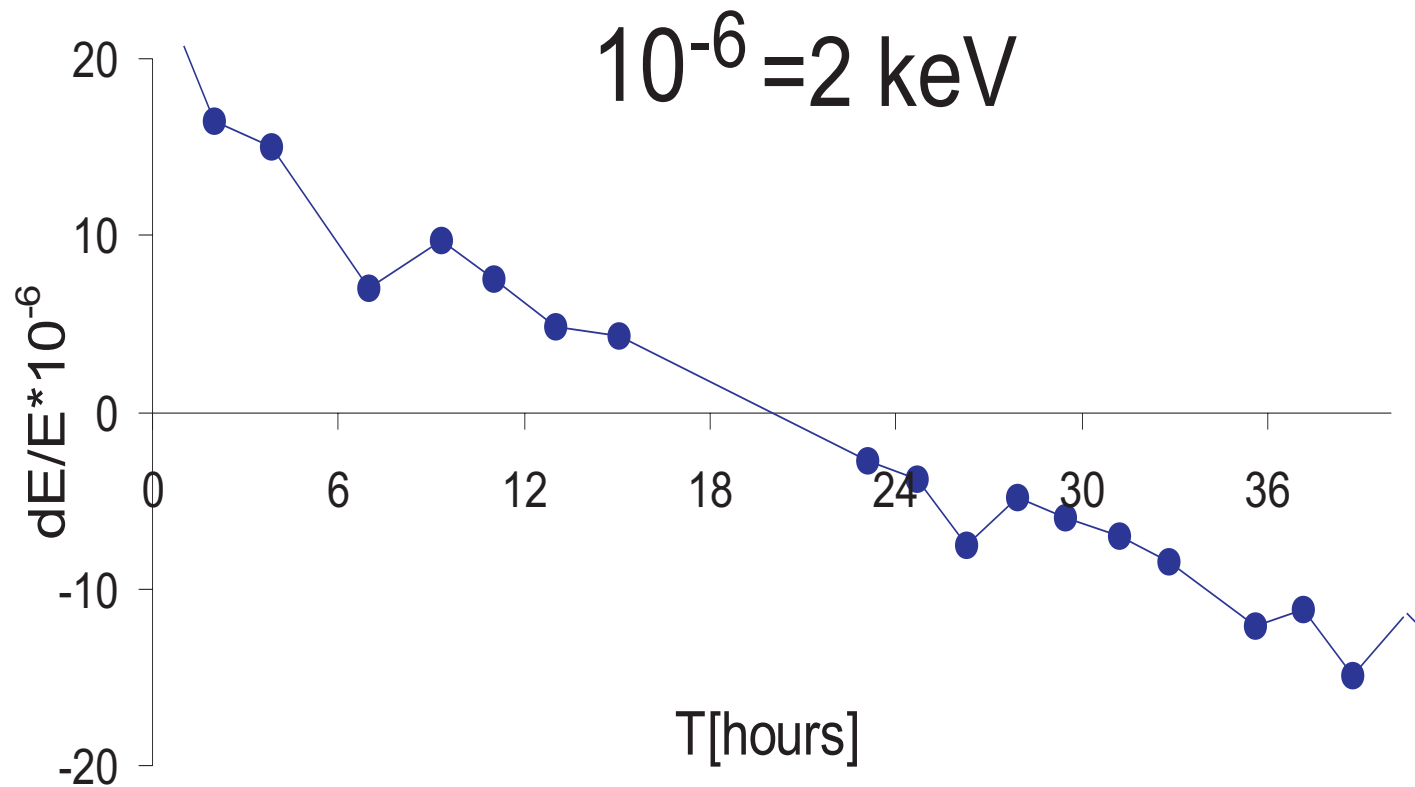
\pm electrons/positrons
 ϕ horizontal tilt angle
 η_x local dispersion func.
 U energy loss per turn
 α momentum compaction
 Π circumference
 $\eta_x \rightarrow 0$ needed!

$$\text{Energy and Spin Tune gap} \approx 2 \left. \frac{\delta E}{E} \right|_{RF}$$

Gap $\sim 5 \cdot 10^{-8}$ at $\phi \sim 0.01$,
 $\eta_x = 100$ cm, $U = 34$ keV,
 $E = 1.8$ GeV

LONG-TERM VEPP-4M ENERGY STABILITY

RD data on 26-28 Dec 2003



Drift of $\sim 1 \text{ keV/hour} = 0.3 \text{ eV/s} < \text{Scan rate} \sim 5 \text{ eV/s}$

Conclusions

- A record accuracy of $2 \cdot 10^{-8}$ achieved in comparison of depolarization frequency of two electron bunches.
- New RD techniques in multi-bunch regimes proposed and mastered
- Estimates of some sources of systematic errors affecting the experiment on comparison of electron and positron spin frequencies considered
- We plan to continue our experiment in the direction of decreasing statistic errors (mounting the additional counters To increase the rate up to 1 MHz) and studying systematic errors turning to measurements including positrons.