8^{th} *International Conference on Nuclear Physics in Storage Rings*

STORI'11

"Synchrotron Oscillation Effects on Observation of an RF-solenoid Spin Resonance for a Polarized Deuteron Beam at COSY"

Greta Guidoboni

University of Ferrara and INFN Ferrara

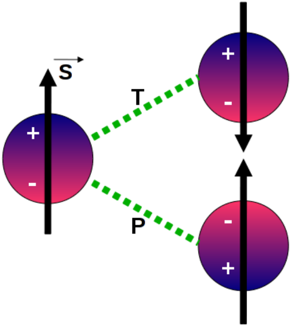
Italy

Laboratori Nazionali di Frascati

October 11, 2011

Why it is important to study the Electric Dipole Moment

- EDM is a permanent charge separation within the particle volume.
- EDM must lie along the spin axis
- EDM violates both P and T



Under CPT theorem

CP VIOLATION → Baryon Asymmetry

- Standard Model is not enough to explain the BA
- SM predicts a non vanishing EDM but unobservably small

$$|d_e|_{SM} < 10^{-38} e \cdot cm$$
$$|d_n|_{SM} < 10^{-32} e \cdot cm$$

- Models beyond SM predict values within the sensitivity of current or planned experiments

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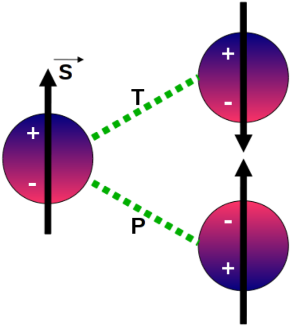

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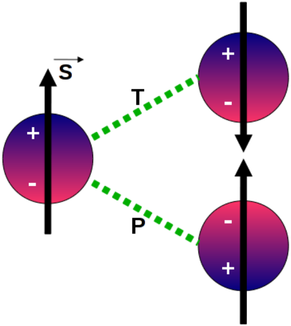

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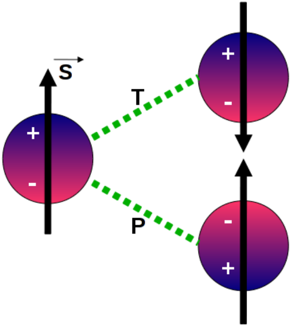

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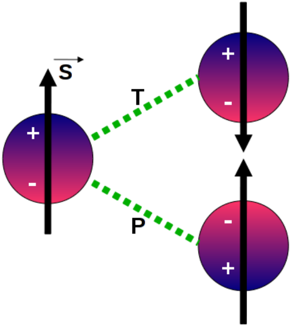

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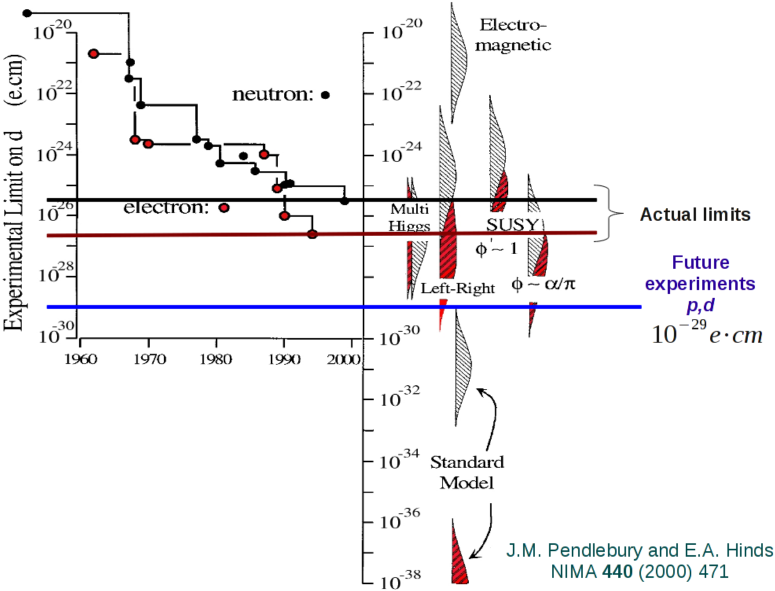
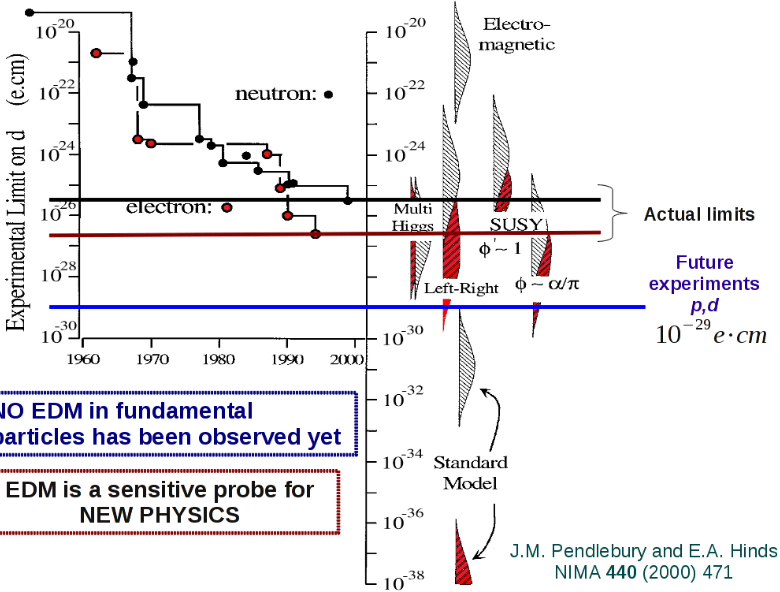


J.M. Pendlebury and E.A. Hinds
NIMA **440** (2000) 471



NO EDM in fundamental particles has been observed yet

EDM is a sensitive probe for NEW PHYSICS

J.M. Pendlebury and E.A. Hinds
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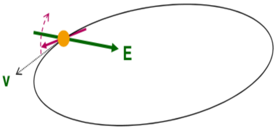
How to measure EDM for charged particles?

1. $\frac{d\vec{s}}{dt} = \vec{d} x \vec{E}$ **EDM signal=spin precession**

   charge particle would be lost in $\vec{E}$!

2. **Storage ring** is the **solution for charge particles!**

   $\rightarrow$ Injection with **spin aligned along the velocity** and radial $\vec{E}$ field



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3. Keep spin aligned with velocity.

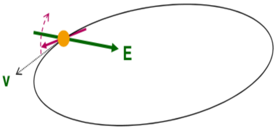
   $\rightarrow$**Frozen spin technique**

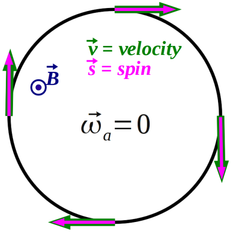
$$\vec{\omega_a} = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left\{ a\vec{B} + \left[a - \left(\frac{m}{p}\right)^2 \right] \frac{\vec{\beta} x \vec{E}}{c} \right\} = 0$$

ω_s Spin precession in the horizontal plane

ω_c Particle angular frequency

$a = \frac{g-2}{2}$ anomalus moment





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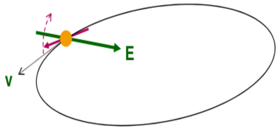

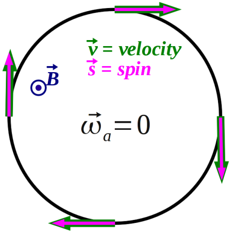

Different solutions for proton and deuteron

How to measure EDM for charged particles in a storage ring?

Frozen spin techinque

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Proton solution

- a=1.79
- **magic momentum**
  $p = \frac{m}{\sqrt{a}} = 0.7 GeV/c$
  $$\Rightarrow \quad \left[a - \left(\frac{m}{p}\right)^2 \right] = 0$$
- **pure electric ring**
  $$\vec{B} = 0$$

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- **pure electric ring**

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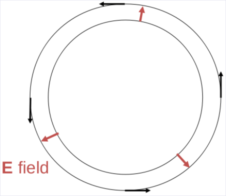
Deuteron solution

- a=-0.14 $\Rightarrow \nexists$ magic momentum
- $\vec{B}$ with outward $\vec{E}$

$$E = \frac{aBc\beta\gamma^2}{1 + a\beta^2\gamma^2}$$

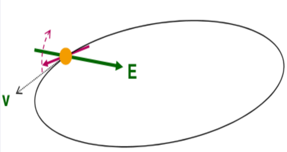


How to measure EDM for charged particles in a storage ring?

Spin Coherence time?

- Minimal detectable precession $\theta \approx 10^{-6} rad$

(vertical polarization measurement
$\rightarrow$ see next slides)



- Assuming $d \approx 10^{-29} e \cdot cm$ and $E = 17MV/m$

$$\left.\begin{array}{l} \theta_{EDM}(t) = \frac{2dE}{\hbar} t = 5 \left(\frac{10^{-9} rad}{s} \right) t \\ 1 \quad turn \approx 10^{-6} s \end{array}\right\} \Rightarrow \theta_{EDM} \approx \frac{10^{-15} rad}{turn}$$

- 10^9 turns needed to detect θ_{EDM}
- spin coherence time $t > 1000s$
- $10^{-29} e \cdot cm$ precision $\rightarrow$ 1 year of data taking.

Beam polarization studies at COSY!

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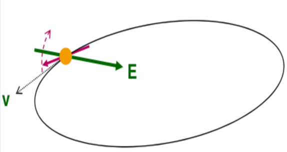

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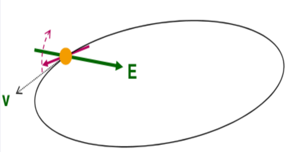

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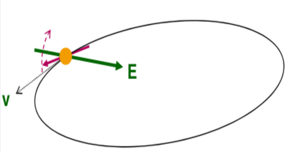

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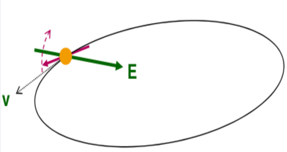

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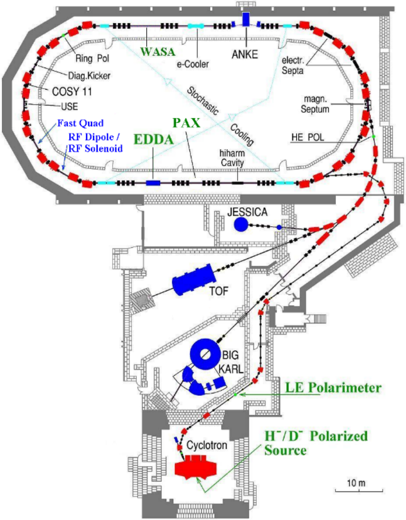
Experimental setup at COSY

COSY RING: COoler SYnchrotron



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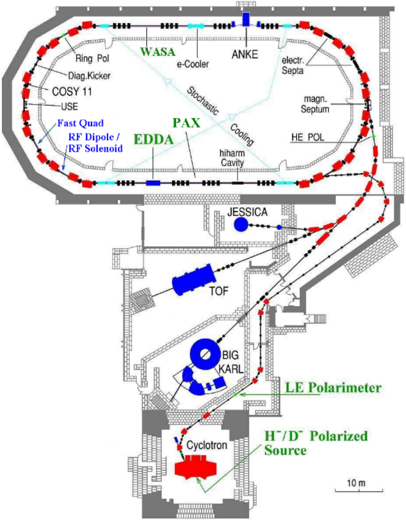
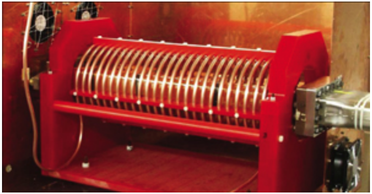


RF Solenoid: spin flipper



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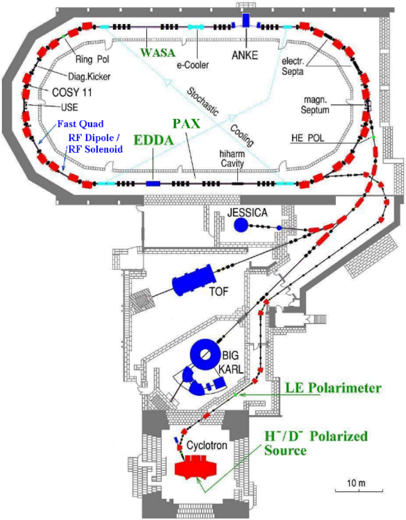

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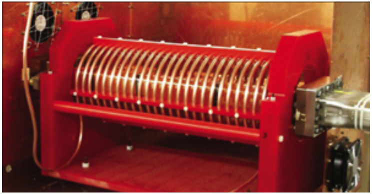
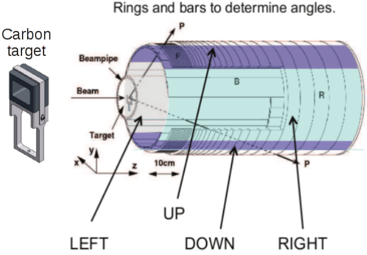
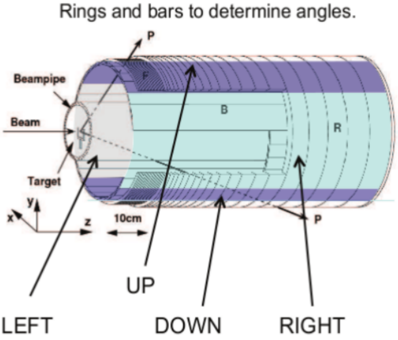


EDDA detector: continuous polarimeter



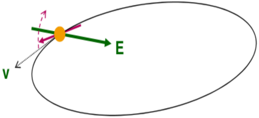
EDDA detector

Carbon target



EDM signal from the asymmetry

$$\epsilon_{EDM} = \frac{L-R}{L+R} = \frac{3}{2} p_V A_y$$



- beam moves toward thick target$\rightarrow$ continuous extraction
- EDDA scintillators stop elastic deuterons from the target
- elastic scattering $\rightarrow$ spin sensitive process (large cross section for d-C)

EDDA detector

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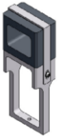

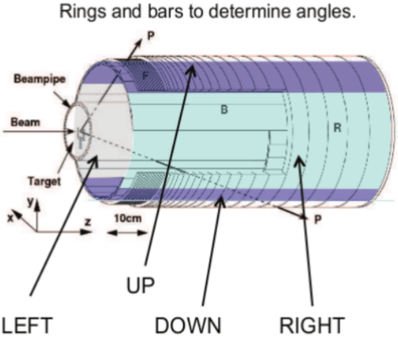

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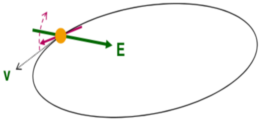

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Polarization measurements at COSY

Original aim

Study of **momentum spread** $\frac{\Delta p}{p}$ and **emittance** effects on the spin coherence time of a deuteron beam.

But...

Synchrotron oscillation effects dominated our measurments!
The rest of this talk is about synchrotron oscillations.

Experimental conditions

- **RF-solenoid spin resonance**.
- **Continuous record** of **vertical polarization** (EDDA detector).

Deuteron beam momentum	$p = 0.97 GeV/c$
Relativistic factor	$\gamma = 1.12583$
Cyclotron frequency	$f_{cyc} = 750602.5 \pm 0.5 Hz$
Bunched beam (h=1) **cooled** and **uncooled**	

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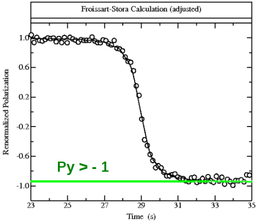
Froissart-Stora frequency scan

Identification of the spin resonance frequency.

- $f_{res} = f_{cyc}(1 - G\gamma) > f_{cyc}$
- Δf =400Hz, linear ramping in 40s

Uncooled



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Fixed frequency measurements

Study of the spin resonance and solenoid strength effect.

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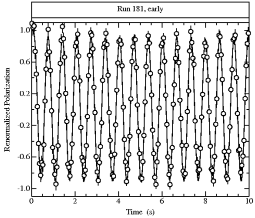

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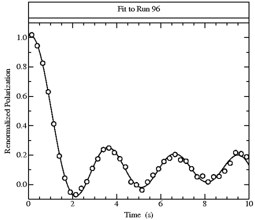

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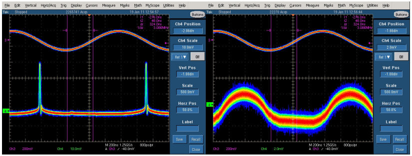
Study of the spin resonance and solenoid strength effect.

Cooled and Uncooled bunch shape



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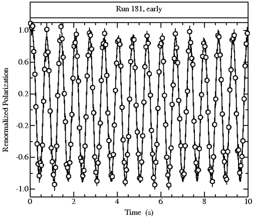

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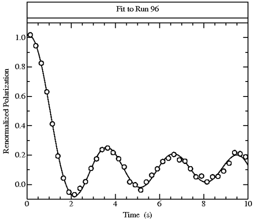

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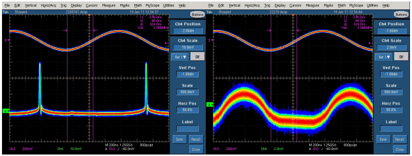
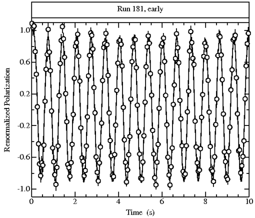
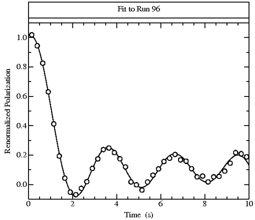


Cooled



Uncooled



Development of a "No Lattice Model" to reproduce data

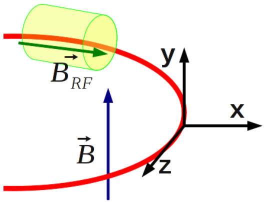
No Lattice Model: *basic idea*

- No particle tracking.
- Circular ring with a constant $\vec{B}$ and an RF-solenoid.
- Effects on spin orientation
  $\rightarrow$ **2 rotation matrices.**

$$\begin{array}{ccc} \hat{x} & \hat{y} & \hat{z} \end{array}$$

$$\begin{bmatrix} cos(\omega_r) & 0 & -sin(\omega_r) \\ 0 & 1 & 0 \\ sin(\omega_r) & 0 & cos(\omega_r) \end{bmatrix}$$

$$\begin{bmatrix} cos(\omega_s) & -sin(\omega_s) & 0 \\ sin(\omega_s) & cos(\omega_s) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Spin precession per turn

$$\omega_r = 2\pi\nu_s f_{cyc}$$

with $\nu_s = G\gamma$ spin tune

Solenoid kick

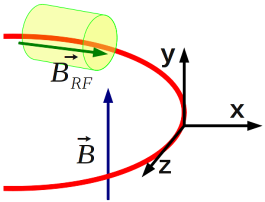
$$\omega_s = 2\pi\epsilon cos(2\pi f_{res} t + \phi_s),$$

with ϵ =solenoid strength

$t = \dfrac{n}{f_{cyc}}$, n = turn number

Valid for a particle on the central orbit and at f_{cyc}

No Lattice Model: *basic idea*



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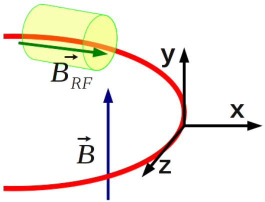

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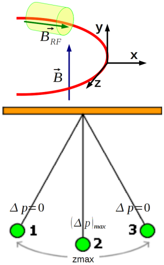
No Lattice Model: *synchrotron oscillations*



Synchrotron oscillations

- **Sinusoidal oscillations** along the beam (z) about the center of the bunch.

$$z(t) = zmax \cdot sin(2\pi f_{sync} t + \phi_{sync})$$

- z oscillation $\xrightarrow{reflects}$ $\frac{\Delta p}{p}$ oscillation.

Effects

$\frac{\Delta p}{p} \rightarrow \frac{\Delta \gamma}{\gamma}$ **spin tune** $\nu_s = G\gamma$

$$\omega_r = 2\pi(\nu_s + \Delta\nu_s) f_{cyc}$$

$\frac{\Delta p}{p} \rightarrow \frac{\Delta t}{t}$ **transit time** throught RF-solenoid

$$\omega_s = 2\pi\epsilon cos(2\pi f_{res}(t - t_p) + \phi_s)$$

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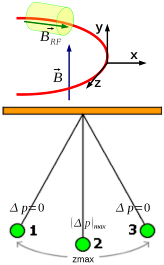

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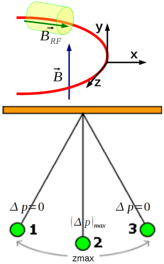

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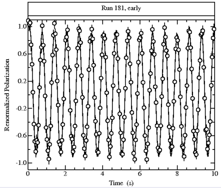
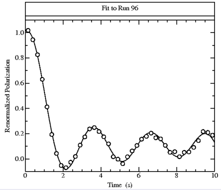
No Lattice Model: *amplitude distribution*

Cooled



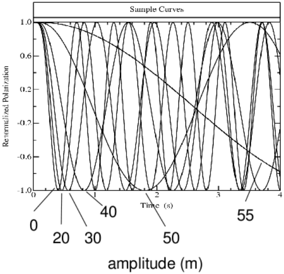
particles oscillate together

Uncooled



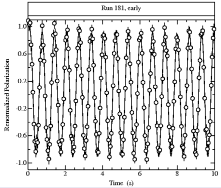
particles get out of phase

Vertical polarization P_y vs *zmax*



No Lattice Model: *amplitude distribution*

Cooled



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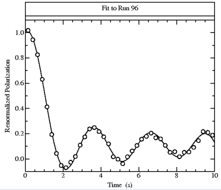

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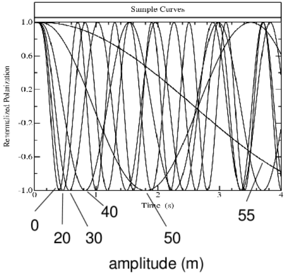
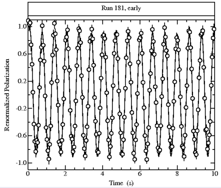


1) Larger amplitude
$\rightarrow$ Smaller RF-solenoid strength

No Lattice Model: *amplitude distribution*

Cooled



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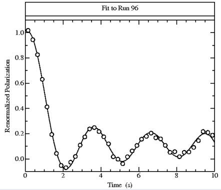
Uncooled



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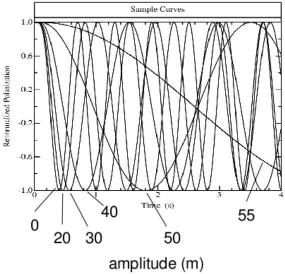

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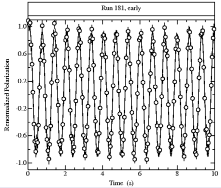
Data oscillation patterns

$$P_y = a_1 f(zmax_1) + \ldots + a_N f(zmax_N)$$

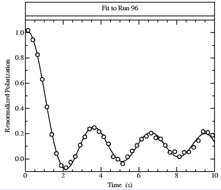
No Lattice Model: *amplitude distribution*

Cooled



particles oscillate together

Uncooled



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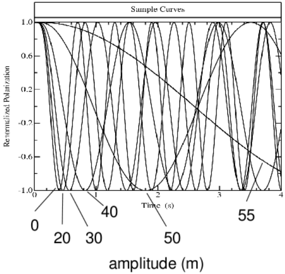
Vertical polarization P_y vs *zmax*



1) Larger amplitude
→ Smaller RF-solenoid strength

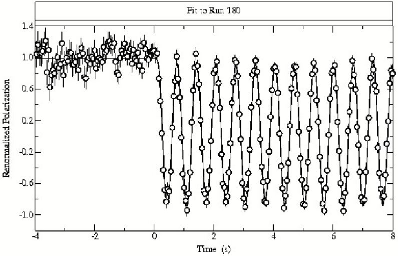
Data oscillation patterns

$$P_y = a_1 f(zmax_1) + \ldots + a_N f(zmax_N)$$

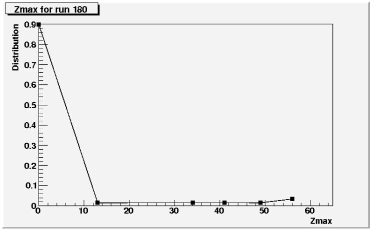
2)Choose amplitudes to reproduce data

Fixed Frequency data: *cooled beam*

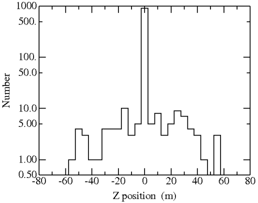
Oscillation patterns



Amplitude distribution



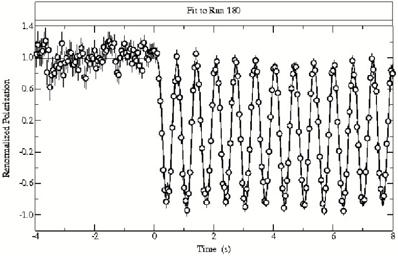
Beam bunch distribution



Distribution of 1000 particles

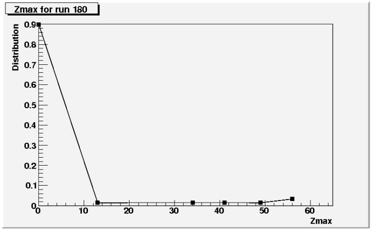
Fixed Frequency data: *cooled beam*

Oscillation patterns



Uncooled portion leads to initial 9% depolarization

Amplitude distribution



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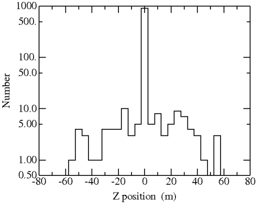
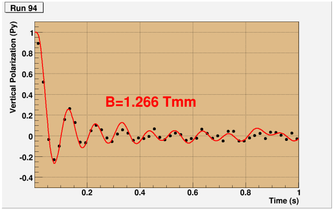


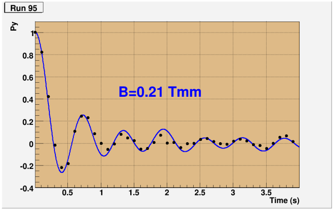
Distribution of 1000 particles

Fixed Frequency data: *uncooled beam*

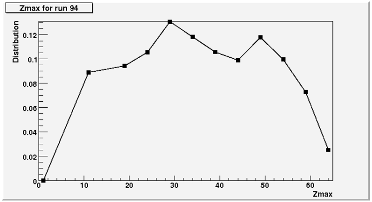
Oscillation patterns

Different solenoid strengths

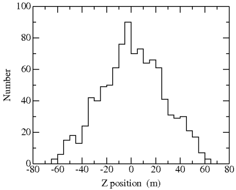




Amplitude distribution



Beam bunch distribution



Distribution of 1000 particles

Fixed Frequency data: *uncooled beam*

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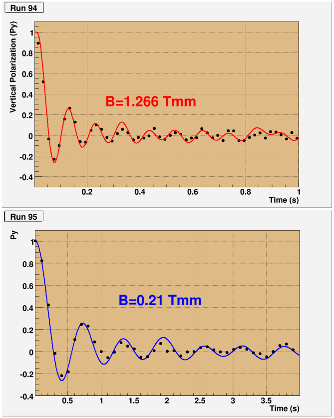

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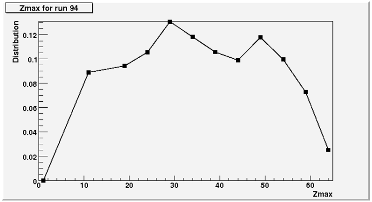

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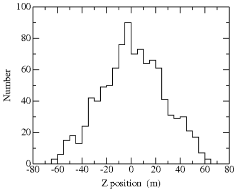
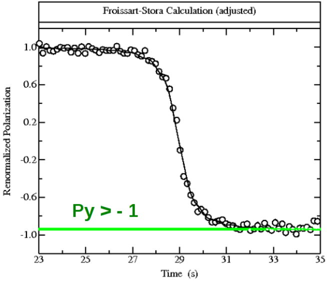


Distribution of 1000 particles

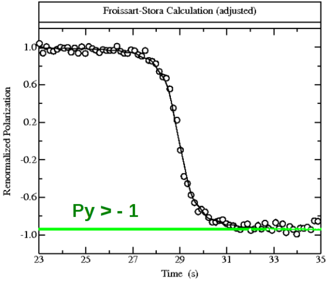
Bunch shape fits patterns

Froissart-Stora scan: *uncooled beam*



Not complete spin flip.

Froissart-Stora scan: *uncooled beam*



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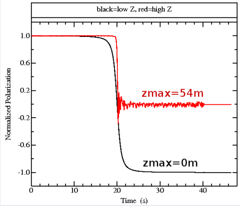
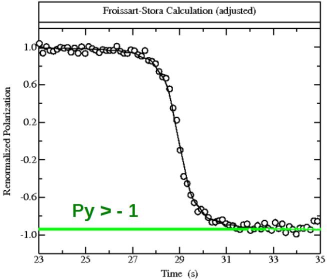
F-S for one particle



Froissart-Stora scan: *uncooled beam*



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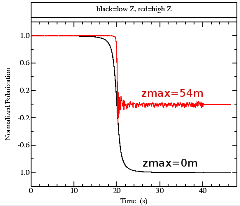
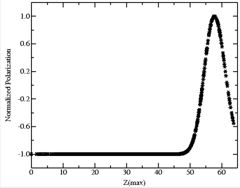
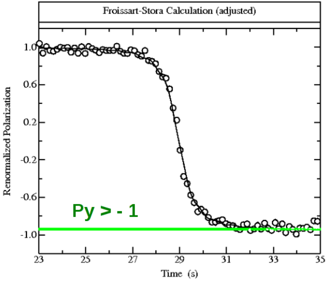


Final polarization vs Zmax



zmax≤48m→*complete spin flip*
zmax=58m→ *No spin flip*

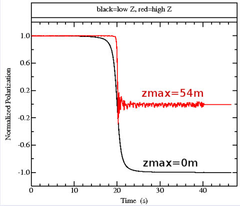
Froissart-Stora scan: *uncooled beam*



Not complete spin flip.

contribution from particles with $48 \leq zmax \leq 58$m

F-S for one particle



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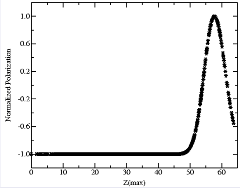

zmax$\leq$48m$\rightarrow$*complete spin flip*
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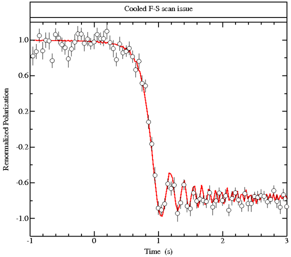
Froissart-Stora scan

COOLED beam

- complete flip for zmax$\leq$48m.
- data$\rightarrow$no complete spin
- data$\rightarrow$no fit with cooled beam distrib.
- data fit$\rightarrow$zmax$\simeq$51m.



Froissart-Stora scan

COOLED beam

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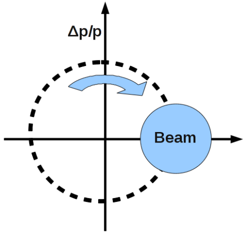
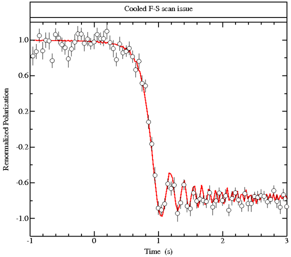
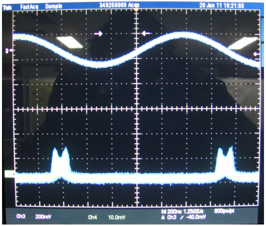
- data→no complete spin
- data→no fit with cooled beam distrib.
- data fit→zmax≃51m.

Double-peak effect

Cooled beam out of the central orbit.
Contribution to higher $\Delta p/p$ ($\rightarrow$ zmax).







Spin coherence time study for EDM experiment.

Development of a **No Lattice Model** (*synchrotron oscillations*) that well reproduces some of the experimental data:

Fixed frequecy scan

- importance of the amplitude distribution details.
- uncooled beam wiggles necessary to define the correct amplitude distribution.

Froissart-Stora scan

- modification of the solenoid flip efficiency (transit time through the RF-solenoid).
- RF-solenoid can no longer flip the spin for large amplitude.

CONCLUSION

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Studies of the Horizontal Spin Coherence Lifetime

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[1]*University of Ferrara and INFN, 44100 Ferrara, Italy*
[2]*High Energy Physics Institute, Tbilisi State University, 0218 Tbilisi, Georgia*
[3]*IKP, Forschungszentrum Jülich, 52425 Jülich, Germany*
[4]*Jagiellonian University, 31-007 Krakow, Poland*
[5]*Brookhaven National Laboratory, Upton, New York 11973 USA*
[6]*Institute for Theoretical and Experimental Physics, 117259 Moscow, Russia*
[7]*Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47408 USA*
[8]*Cornell University, Ithaca, New York 14850 USA*
[9]*Petersburg Nuclear Physics Institute, Gatchina 188350, Russia*
[10]*ZEL, Forschungszentrum Jülich, 52425 Jülich, Germany*

Collaboration

Studies of the Horizontal Spin Coherence Lifetime

P. Benati,[1] D. Chiladze,[2,3] J. Dietrich,[3] M. Gaisser,[3] R. Gebel,[3] G. Guidoboni,[1] V. Hejny,[3] A. Kacharava,[3] P. Kulessa,[4] A. Lehrach,[3] P. Lenisa,[1] B. Lorentz,[3] R. Maier,[3] D. Mchedlishvili,[2,3] W.M. Morse,[5] A. Pesce,[1] A. Polyanskiy,[3,6] D. Prasuhn,[3] F. Rathmann,[3] Y.K. Semertzidis,[5] E.J. Stephenson,[7] H. Stockhorst,[3] H. Ströher,[3] R. Talman,[8] Yu. Valdau,[3,9] Ch. Wiedeman,[3] and P. Wüstner[10]

[1]University of Ferrara and INFN, 44100 Ferrara, Italy
[2]High Energy Physics Institute, Tbilisi State University, 0218 Tbilisi, Georgia
[3]IKP, Forschungszentrum Jülich, 52425 Jülich, Germany
[4]Jagiellonian University, 31-007 Krakow, Poland
[5]Brookhaven National Laboratory, Upton, New York 11973 USA
[6]Institute for Theoretical and Experimental Physics, 117259 Moscow, Russia
[7]Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47408 USA
[8]Cornell University, Ithaca, New York 14850 USA
[9]Petersburg Nuclear Physics Institute, Gatchina 188350, Russia
[10]ZEL, Forschungszentrum Jülich, 52425 Jülich, Germany

Thanks for you attention!