# Perspectives for Storage Ring EDM Searches

October 2, 2012 | Andreas Lehrach

on behalf of the JEDI collaboration
(Jülich Electric Dipole Moment Investigations)

# Outline

## Introduction

## EDM Measurements in Storage Rings

- COSY as EDM Injector
- Dedicated Storage Rings
- First Direct Measurement at COSY

## Simulation Programs

- Computational Needs
- Performance and Benchmarking

## Summary/Outlook

# Limits for Electric Dipole Moments

**EDM searches - only upper limits up to now (in *e*·cm):**

| Particle/Atom | Current EDM Limit | Future Goal |
|---|---|---|
| Neutron | $< 3 \times 10^{-26}$ | $\sim 10^{-28}$ |
| $^{199}$Hg | $< 3.1 \times 10^{-29}$ | $\sim 10^{-29}$ |
| $^{129}$Xe | $< 6 \times 10^{-27}$ | $\sim 10^{-30} - 10^{-33}$ |
| Proton | $< 7.9 \times 10^{-25}$ | $\sim 10^{-29}$ |
| Deuteron | ? | $\sim 10^{-29}$ |

Huge efforts underway to improve limits / find EDMs

CP can have different sources

It is important to measure neutron **and proton and deuteron**, and light nuclei EDMs in order to disentangle various sources of CP violation

# Thomas-BMT Equation

Equation for spin motion of relativistic particles in storage rings
for $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$.

The spin precession relative to the momentum direction is given by:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = \frac{e\hbar}{mc} \left\{ G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \left( \vec{v} \times \vec{E} \right) + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right\}.$$

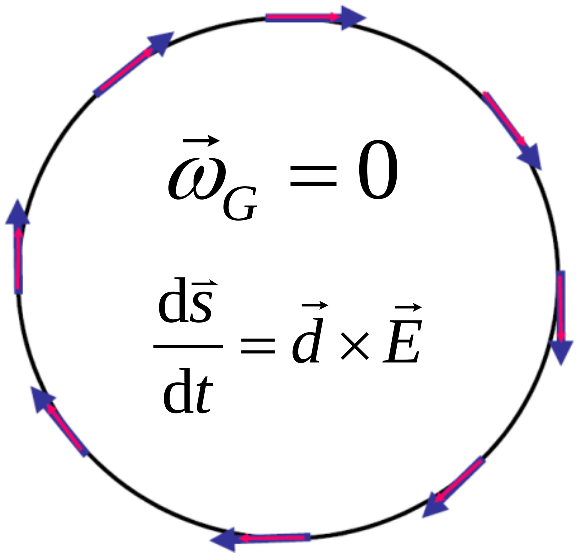
Magnetic Moment

Electric Dipole Moment

$$G = \frac{g-2}{2}, \vec{\mu} = 2(G+1) \frac{e\hbar}{2mc} \vec{S}, \text{and } \vec{d} = \eta \frac{e\hbar}{2mc} \vec{S}.$$

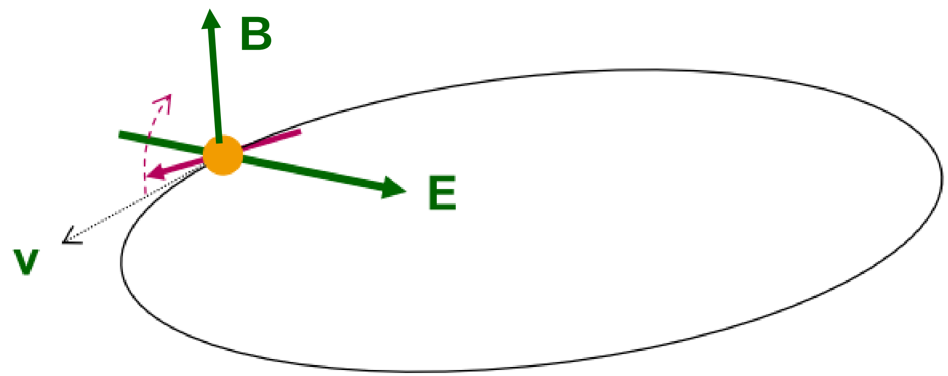
# Search for Electric Dipole Moments

NEW approach: EDM search in time development of spin in a storage ring:



$$\vec{\omega}_G = 0$$

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{d} \times \vec{E}$$




“Freeze“ horizontal spin precession; watch for development of a vertical component !

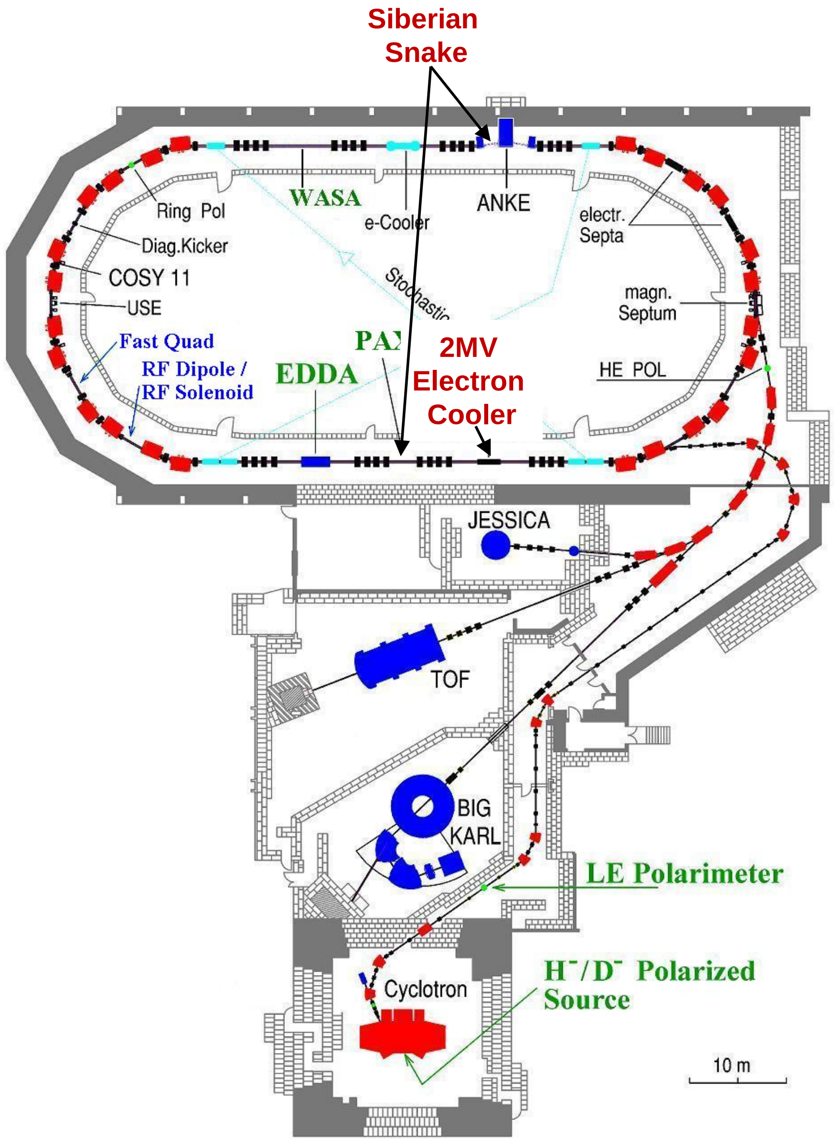
**A *magic* storage ring for protons (electrostatic), deuterons, …**

| particle | p (GeV/c) | E (MV/m) | B (T) |
|---:|---:|---:|---:|
| **proton** | **0.701** | **16.789** | **0.000** |
| **deuteron** | **1.000** | **-3.983** | **0.160** |
| **$^3$He** | **1.285** | **17.158** | **-0.051** |

One machine with r ~ 30 m

Systematic error due to vertical electric fields and horizontal magnetic fields

# Cooler Synchrotron COSY




Ions: (pol. & unpol.) p and d

Momentum: 300/600 to 3700 MeV/c for p/d, respectively

Circumference of the ring: 184 m

Electron Cooling at injection

Stochastic Cooling above 1.5 GeV/c

Injection into EDM ring:

Longitudinal polarized, pre-cooled beam single bunch or bunch into bucket injection

# COSY Beam Parameter

- Beam intensity (polarized beams):

  $10^{10}$ protons or deuterons

- Beam polarization (1 GeV/c):

  0.8 of maximum possible value

- Transverse emittances:

  15-30 π mmm mrad (geom., 3σ uncooled at injection)

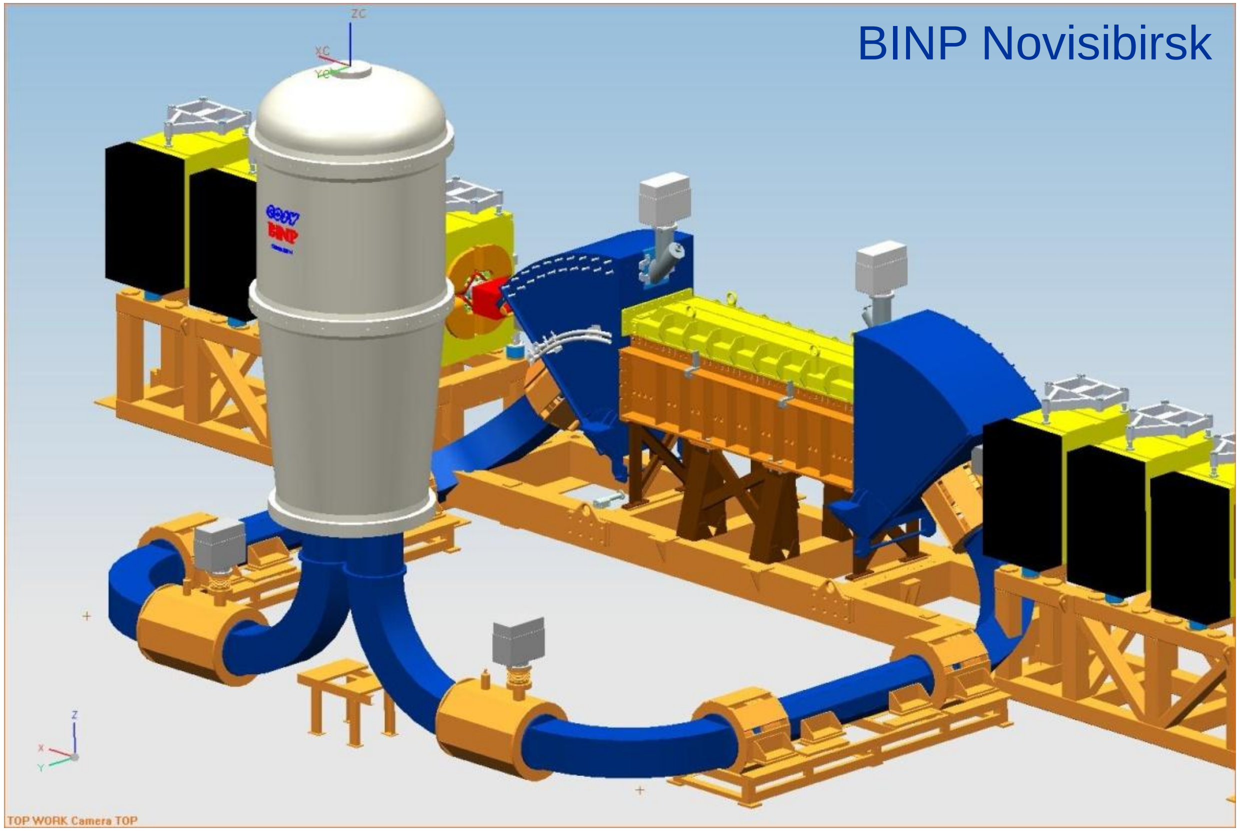
  below 3 π mm mrad (geom., 3σ cooled at injection)

- Momentum spread:

  $(\Delta p/p)_{rms}$ $< 10^{-3}$ (uncooled)

  $\ll 10^{-4}$ (cooled)

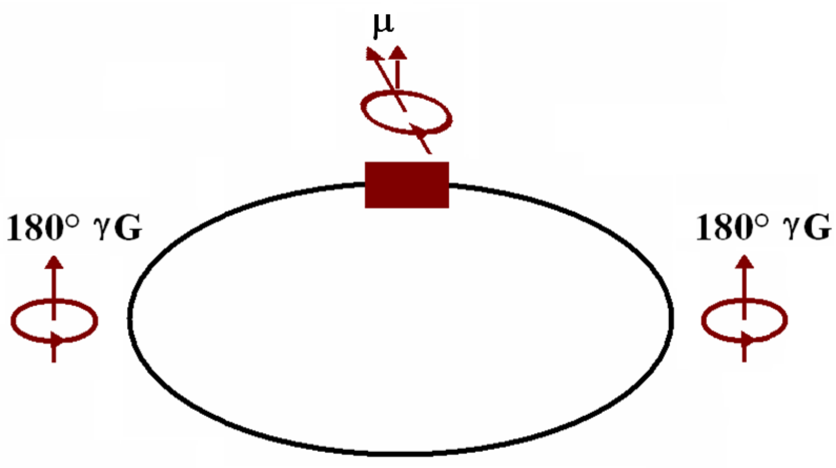
# New 2 MV Electron Cooler at COSY

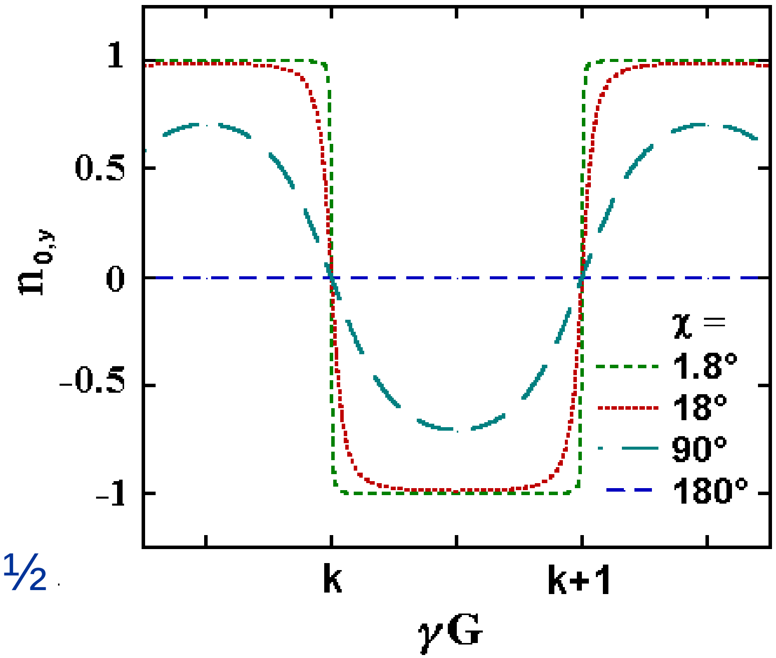



- Energy Range: 0.025 ... 2 MeV
- High Voltage Stability: $< 10^{-4}$
- Electron Current: 0.1 ... 3 A
- Electron Beam Diameter: 10 ... 30 mm
- Cooling section length: 2.694 m
- Magnetic field (cooling section): 0.5 ... 2 kG

Installation at COSY in the winter shutdown 2012/13

# Siberian Snakes




Full Siberian Snake: $\mu$ = 180° → $\nu_{sp}$ = ½

Spin manipulation or snake fields:

longitudinal fields (solenoids) at lower energies

transverse fields (helical dipoles) at higher energies

Full Siberian snake for 1 GeV/c: 3.75 Tm (protons), 12.24 Tm (Deuterons)

Superconducting 4.7 Tm solenoid is ordered.

Overall length: 1 m

Ramping time 30 s

Installation at COSY in spring 2013

# Deuteron EDM Proposal

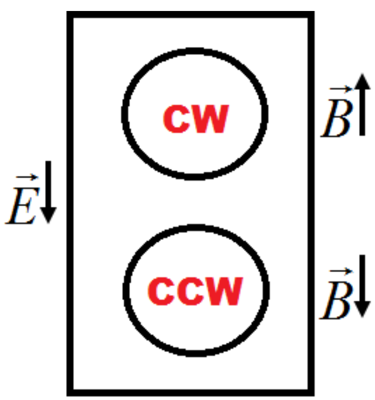
Deuteron momentum: $p$ = 1 GeV/c,

Ring parameter: $R_B$ = 8.4 m, $\langle R \rangle \sim$ 10 m, $C$ = 85m

Deflectors: $E_R$ = -12 MV/m (radial), $B_V$ = 0.48 T (vertical)

- 2004 BNL proposal: single ring
  CW and CCW consecutive beam injections
  Limiting error: time-dependent part of the
  average vertical electric field over the entire ring
  → sensitivity $\sim 10^{-27}\, e \cdot \mathrm{cm}$ for one year measurement


- 2008 BNL proposal: double ring
  CW and CCW simultaneously
  2-in-1 magnet design with common E-field plates
  → sensitivity $\sim 10^{-29}\, e \cdot \mathrm{cm}$ for one year measurement




See http://www.bnl.gov/edm

# Jülich All-In-One Ring Lattice

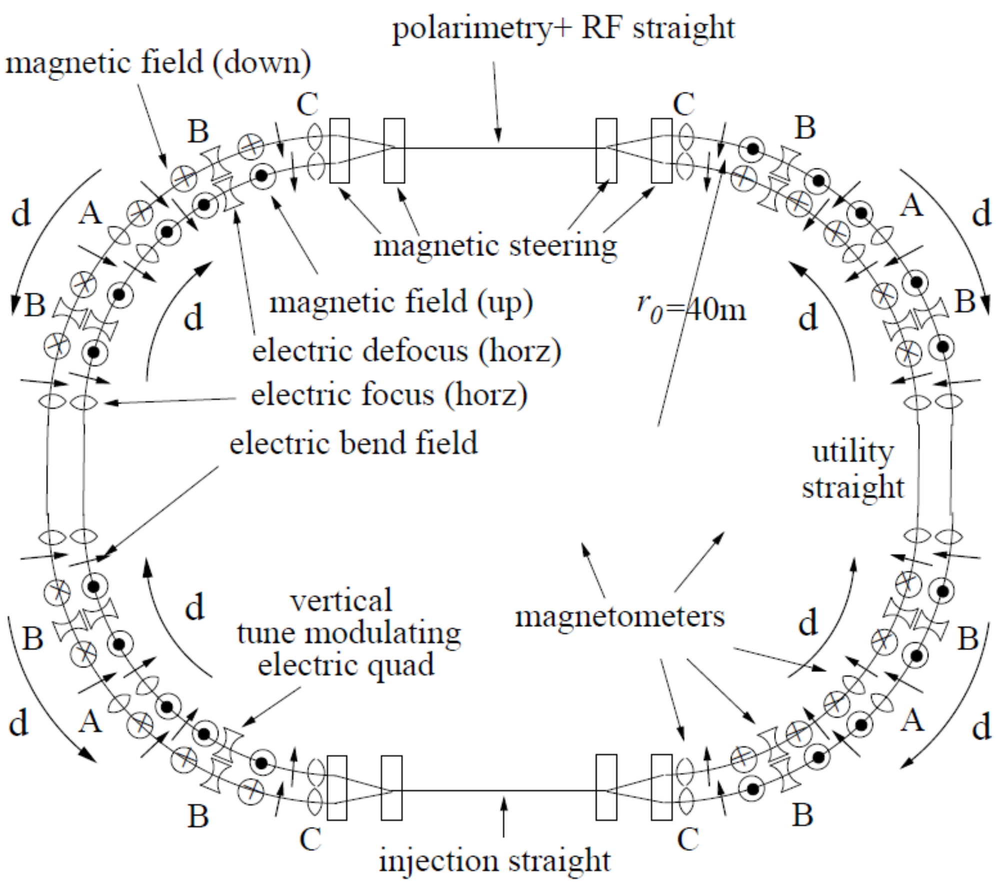



Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

All-In-One Storage Ring Lattice for Baryon EDM Measurements
February, 2012

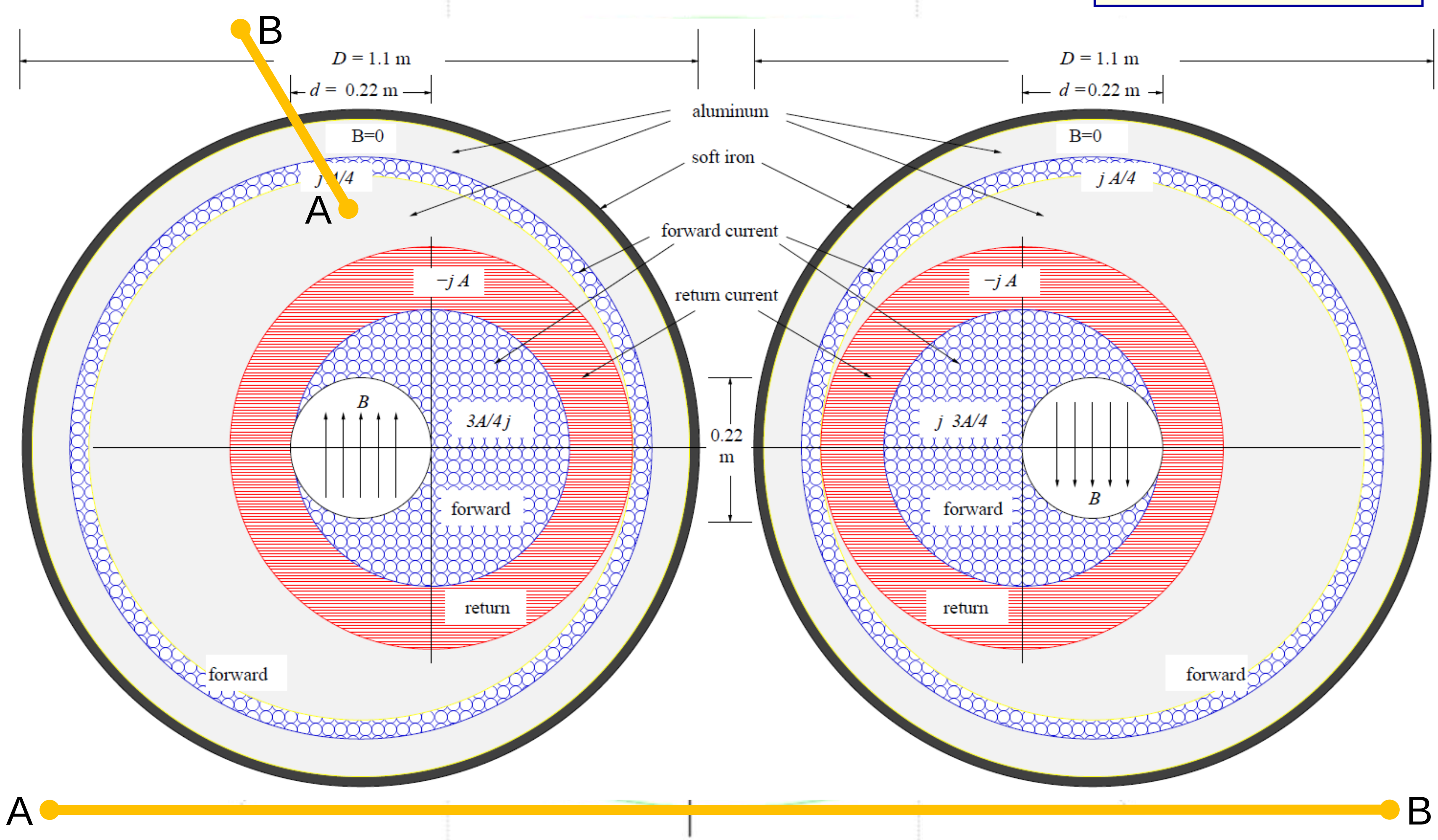
Richard Talman, Cornell University, Ithaca, N.Y.

February 13, 2012

# Jülich All-In-One Ring Lattice

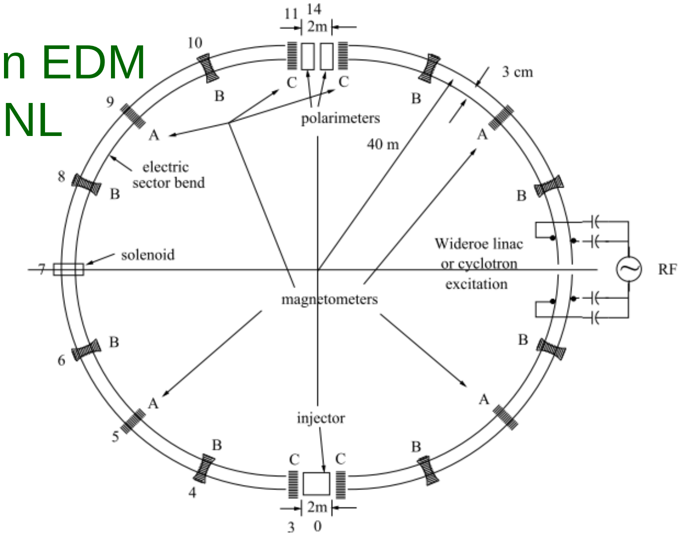
Iron-free, current-only, magnetic bending, eliminates hysteresis
→ achievable field of copper magnets of ~ 0.15 T.

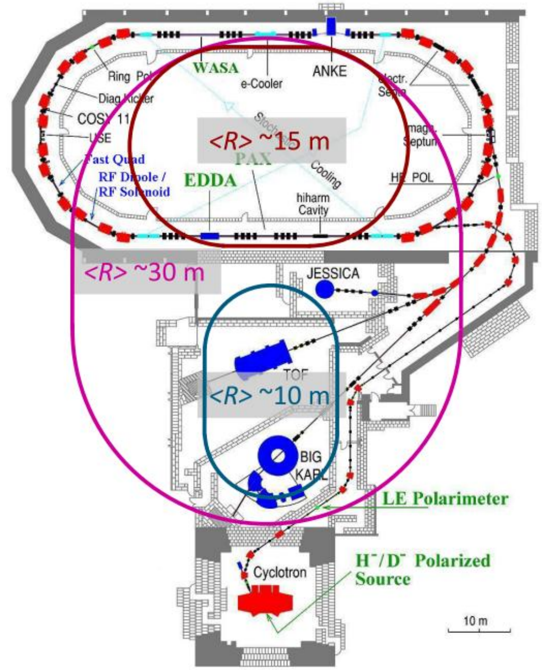
Talk by R. Gebel



# EDM Projects

Proton EDM
BNL



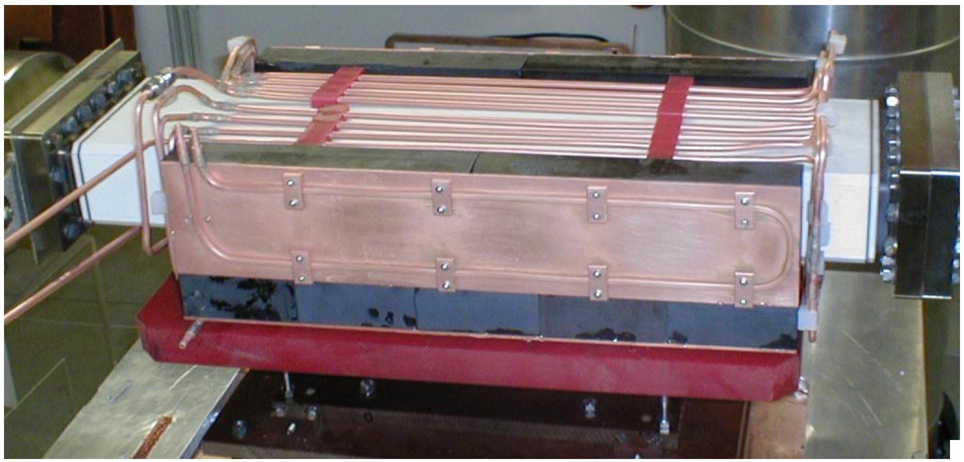

Light-Ion EDM
Jülich

| R&D Activity | Goal | Test |
|---|---|---|
| Internal Polarimeter | spin as a function of time<br>Systematic errors < 1 ppm | EDM at COSY |
| | Full-scale polarimeter | EDM at COSY |
| Spin Coherence Time | $>10^3$ s | EDM at COSY |
| Beam Position Monitor | resolution 10 nm,1 Hz BW<br>64 BPMs, $10^7$ s measurement time<br>→ 1 pm (stat.) relative position (CW-CCW) | BNL<br>RHIC IP |
| E/B-field Deflector | 17 MV/m 2 cm plate separation, 0.15-0.5T | Jülich |

# Spin Manipulation at COSY

RF-induced spin resonance: $$f_r = f_c(k \pm \gamma G)$$

horizontal RF-B Fields



## RF Dipole (dismantled)

- 8-turn water-cooled copper coil in a ferrite box
- Length 0.6 m
- Frequency range roughly 0.4 to 1.2 MHz
- Integrated field $\int B_{rms}\, dl$ ~ 0.54 T·mm

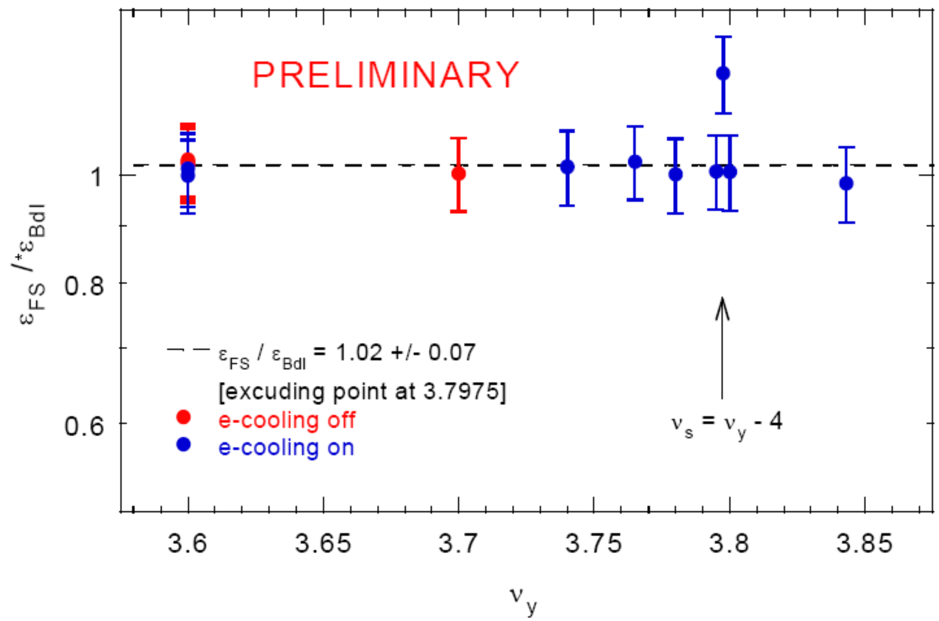
## RF Solenoid

- Water-cooled copper coil in a ferrite box,
- Length 0.6 m
- Frequency range roughly 0.6 to 1.2 MHz
- Integrated field $\int B_{rms}\, dl$ ~ 1 T·mm

# Resonance Strengh

RF Solenoid

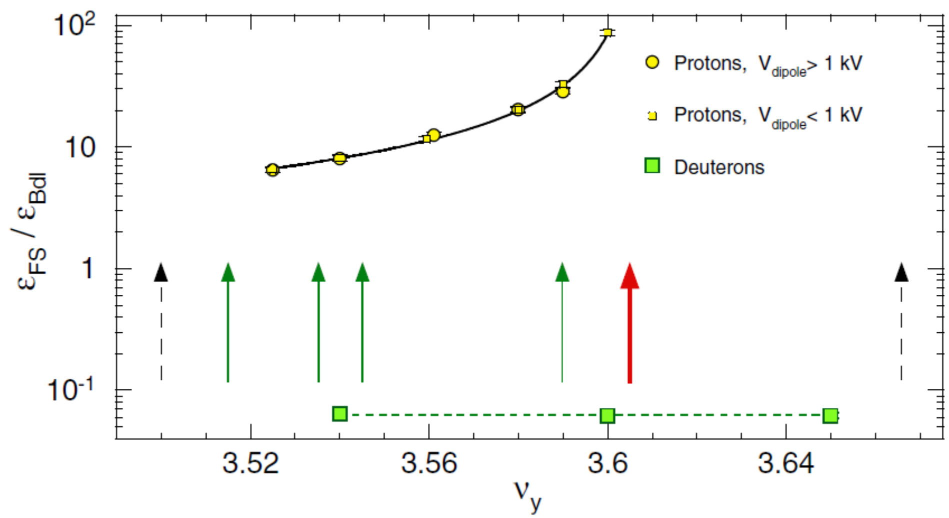
$$^{*}\mathcal{E}_{Bdl} = \frac{1}{\pi 2\sqrt{2}} \frac{e(1+G)}{p} \int B_{rms} dl,$$




RF Dipole

$$\mathcal{E}_{Bdl} = \frac{1}{\pi\sqrt{2}} \frac{e(1+G\gamma)}{p} \int B_{\rm rms} dl,$$

$$\mathcal{E}_{FS}/\mathcal{E}_{Bdl} = A + \frac{B}{|\nu_y - \nu_r|}.$$




**SPIN@COSY Collaboration**

Phys. Rev. ST Accel. Beams **9**, 051001 (2006)

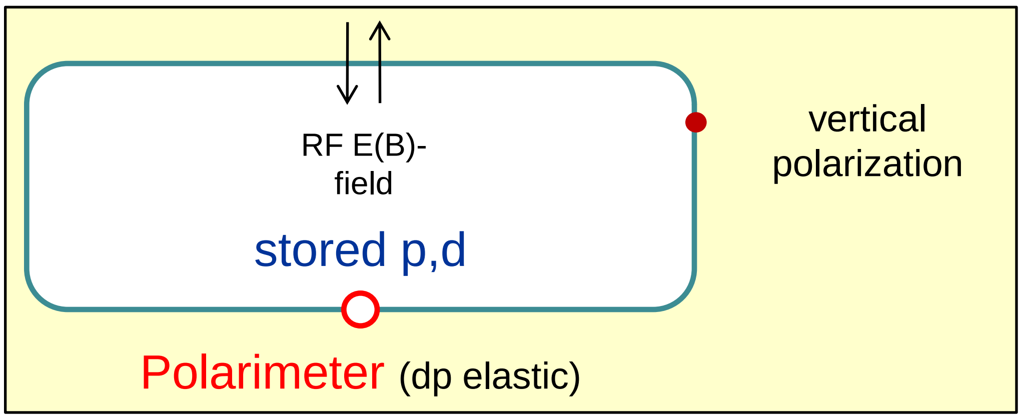
# Resonance Method with RF E/B Fields

## First direct measurement in COSY developed by the Jülich study group

RF-E/B spin flipper to observe a spin rotation by the EDM

Two possibilities:

1. $B^*=0 \Rightarrow B_Y = \beta\times E_R$ (~70 G for $E_R$=30 kV/cm) „Direct“ EDM effect
2. $E^*=0 \Rightarrow E_R = -\beta\times B_Y$ „Magic RF Wienfilter” No-Lorenz Force, „Indirect“ EDM effect




Tilt of the precession plane due to EDM

Observable:
Accumulation of spin rotations within spin coherence time

- EDM signal is **increased** during the cycle
- Statistical sensitivity for $d_d$ in the $10^{-23}$ to $10^{-24}$ $e\cdot$cm range possible
- Alignment and field stability of ring magnets
- Imperfection of RF E(B) spin flipper?

Talk by F. Rathmann

# RF E/B Spin Flipper

Two steps to develop a RF E/B Spin Flipper

1) Low-power device:
   E-Field : << 1 MV/m, B-Field ~ 7 Gauss

2) High-power device:
   E-Field : >> 1 MV/m, B-Field ~ 70 Gauss

Two resonance circuits with common master clock
Length ~1m
Frequency 0.3-1 MHz
In vacuum ~$10^{\wedge-9}$ mbar

or microwave structure (strip line)

# R&D Program JEDI

**(Jülich Electric Dipole Moment Investigations)**

1. Studies of the spin coherence time (SCT) with horizontal/vertical RF-B/E spin flipper
   - Different wave forms at different spin harmonics and beam energies
   - Goal is to get optimum setting of the RF-B field for maximum spin coherence time

2. Investigation of systematic effect with vertical/horizontal RF-B/E spin flipper
   - Alignment and field quality RF-B flipper
   - Opening angle of spin ensemble (beam cooling and heating)
   - Alignment of the ring magnets

3. Development and benchmark precision simulation programs for spin dynamics in storage ring
   - COSY-Infinity, integrating code, simple code

4. Polarimetry

5. Development of a high-power RF-E(B) spin flipper

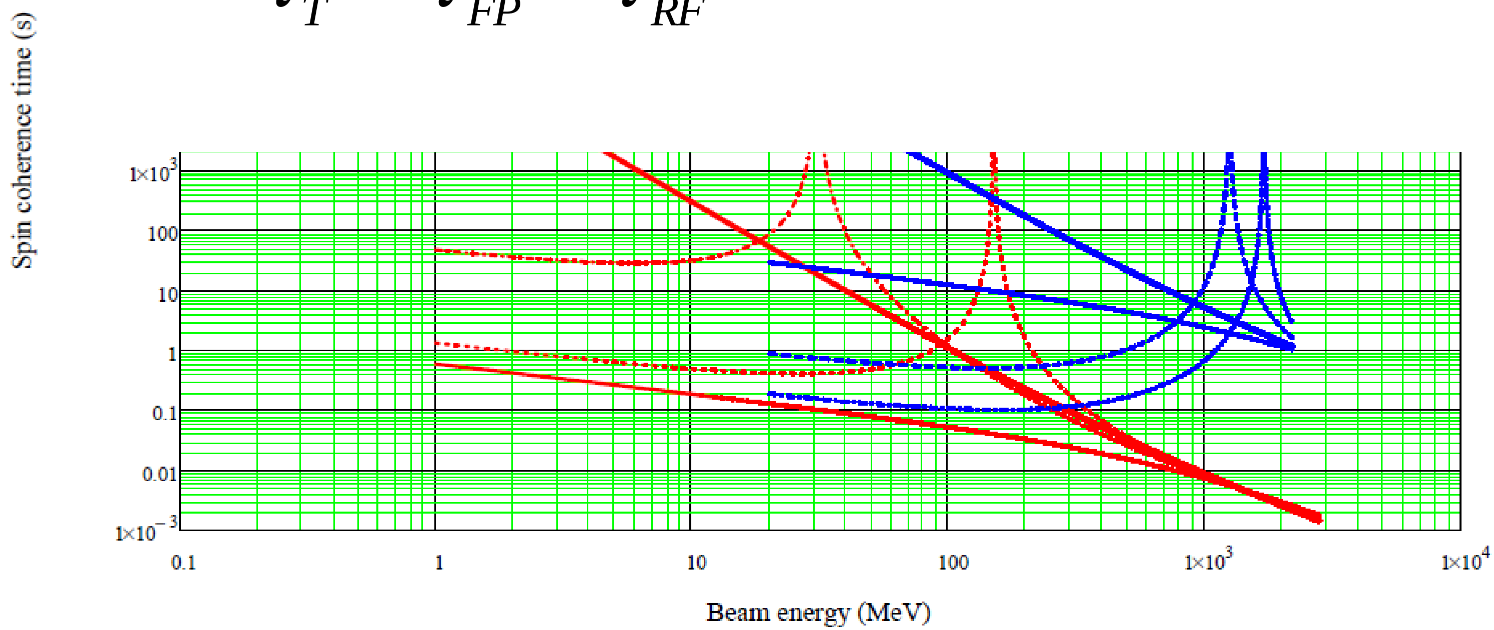
# Spin Coherence Time with RF Flipper

Exciting result of the Jülich Study Group

$$f_r = f_c(k \pm \gamma G)$$

Talk by K. Nikolaev and G. Guidoboni

$$\frac{1}{\tau_T} = \frac{1}{\tau_{FP}} + \frac{1}{\tau_{RF}} - A_{FP,RF} \cdot f(\tau_{FP}, \tau_{RF})$$




- Possibility to increase spin coherence time by 3 to 5 orders of magnitude in the ideal case

# COSY Upgrade

1. Improved closed-orbit control system for orbit correction in the micrometer range
   - → Increasing the stability of correction-dipole power supplies
   - → Increase number of correction dipoles and beam-position monitors (BPMs)
   - → Improve BPM accuracy, limited by electronic offset and amplifier linearity
   - → Systematic errors of the orbit measurement (e.g., temperature drift)

2. Alignment of Magnets and BPMs
   - → More precise alignment of the quadrupole and sextupole magnets
   - → BPMs have to be aligned with respect to the magnetic axis of these magnets

3. Beam oscillations
   - → Excited by vibrations of magnetic fields induced by the jitter of power supplies
   - → Coherent beam oscillation

4. Longitudinal and transverse wake fields
   - → Ring impedances

# Overall Schedule

Stepwise Approach of the JEDI Project

| Step | Aim / scientific goal | Device / Tools | Storage ring |
|---|---|---|---|
| 1 | Spin coherence time studies | Horizontal/vertical RF-B/E spin flipper | COSY |
| | Systematic error studies | Vertical/horizontal RF-B/E spin flipper | COSY |
| 2 | COSY upgrade | Orbit control, magnets, … | COSY |
| | First direct EDM measurement **at $10^{-24}$ e·cm** | High-power RF-E/B spin flipper | Modified COSY |
| 3 | Built a dedicated all-in-one ring for p, d, $^{3}$He | Common magnetic-electrostatic deflectors R&D funded by ARD (Accelerator Research and Development) of HGF | Dedicated ring |
| 4 | EDM measurement for p, d, $^{3}$He **at $10^{-29}$ e·cm** | | Dedicated ring |

Time scale Step 1-2: > five years
Step 3-4: > five years

# Computational Needs

- Particle revolutions: >>$10^6$ turns (1 seconds)
  → efficient simulation program
- Number of particle: $10^6$
  → MPI version on a supercomputer
- Precision:
  COSY measurement: $10^{-13}$–$10^{-12}$ radians per turn
  Dedicated ring: EDM rotation with by of $10^{-15}$ radians per turn → roughly $10^{-18}$ radians per element
  → double precision (64 Bit) provides16 significant decimal digits precision
- EDM spin kick is required
- RF E/B spin flipper element is needed

# Utilized Simulation Programs

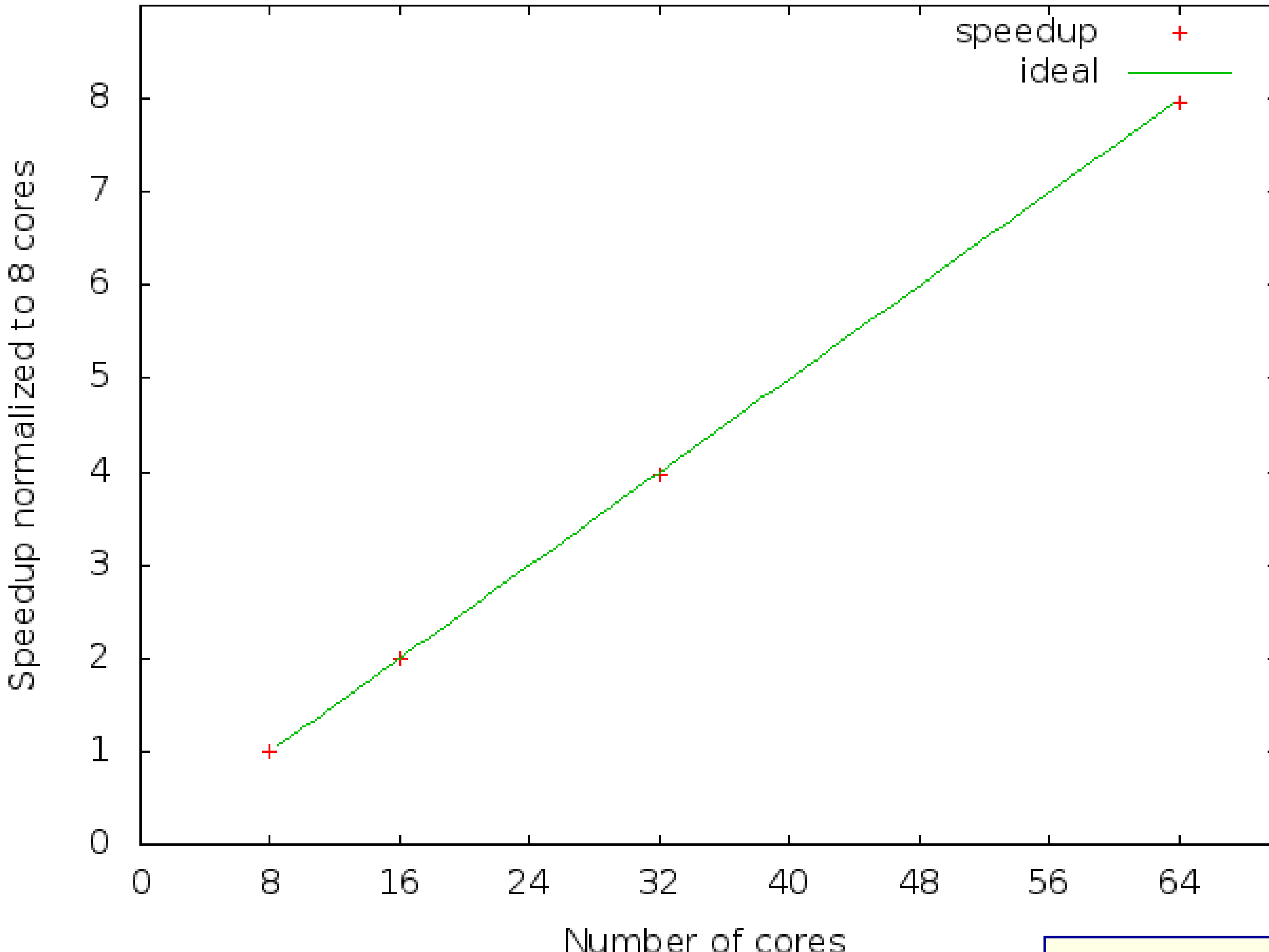
## COSY Infinity:

- based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle
- including higher-order nonlinearities, normal form analysis, and symplectic tracking
- the upgrade of COSY Infinity is supervised by M. Berz

- an MPI version of COSY Infinity is already running on the computer cluster at Michigan State University
- a project for the Jülich supercomputer is starting end of this year

Talk by M. Berz

# Code Performance

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Courtesy: D. Zyuzin (FZJ)

# Benchmarking

## Integrating program:

- differential equations of particle and spin motion in electric and magnetic fields are solved using Runge-Kutta integration
(integration step size 0.5 ps → maximum tracking 10 ms)

## Numerical integration:

- numerical integration of the Thomas-BMT differential equations for a spin motion with smoothly approximated parameters of orbital motion

Talk by Y. Senichev

## Rotation matrices:

- matrices for dipoles and RF Spin flipper including synchrotron oscillation

## Experiments:

- "analog computer" Cooler Synchotron COSY

# Conclusion / Outlook

EDM Measurement: Stepwise approach of the JEDI Project

- R&D work at COSY together with BNL
- Upgrade and first direct measurement at COSY
- Upgrade COSY as EDM injector
- Build a dedicated storage ring

Computational Needs

- Efficient simulation program on a super computer
- Benchmarking with other simulation programs and COSY experiments