Electron and muon g-2 experiments: present and future

Kent Wootton

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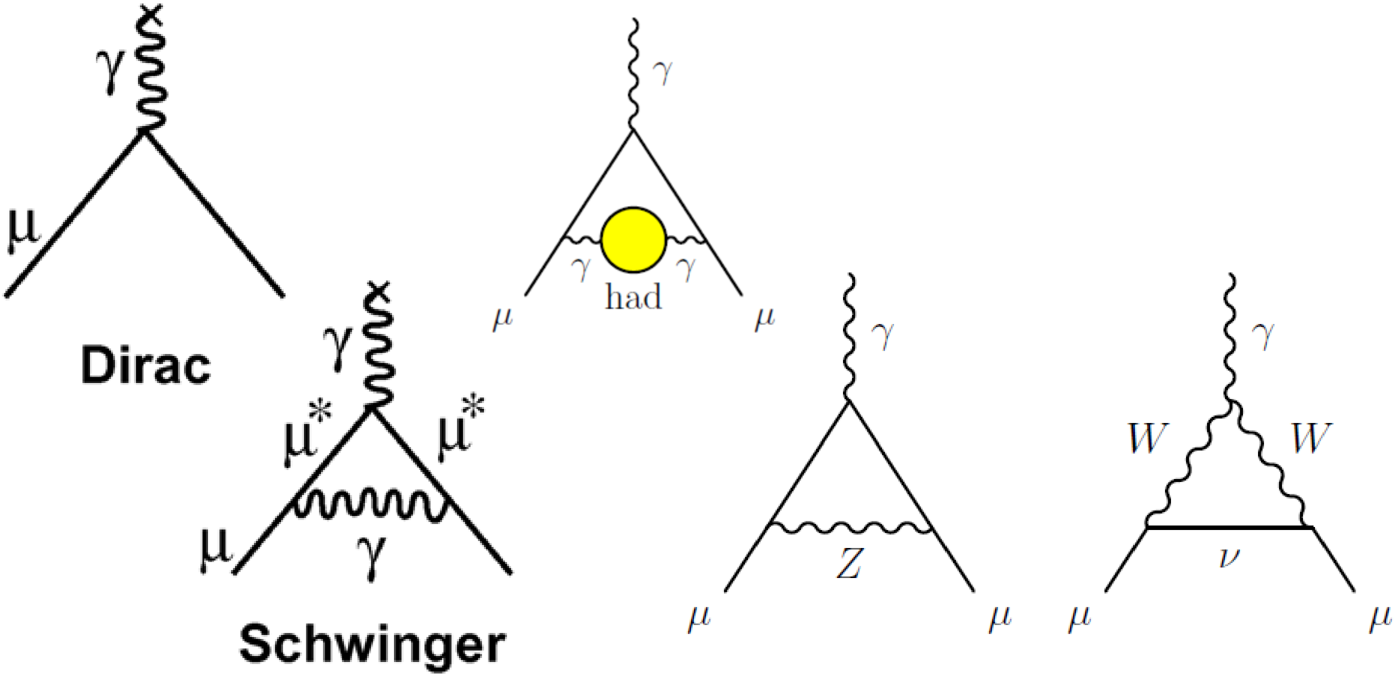
Outline

- Polarised beams in storage ring accelerators
  - Physics motivation
  - Quantities measured
- Resonant depolarisation experiments with electrons
  - Apparatus and detector choices
  - Physics results
- Fermilab muon g-2 experiment (E989)
  - Proposed calorimeter for GeV decay electrons
  - Coherent betatron oscillations
- Future electron experiments
  - Circular Unruh effect

POLARISED BEAMS IN STORAGE RINGS

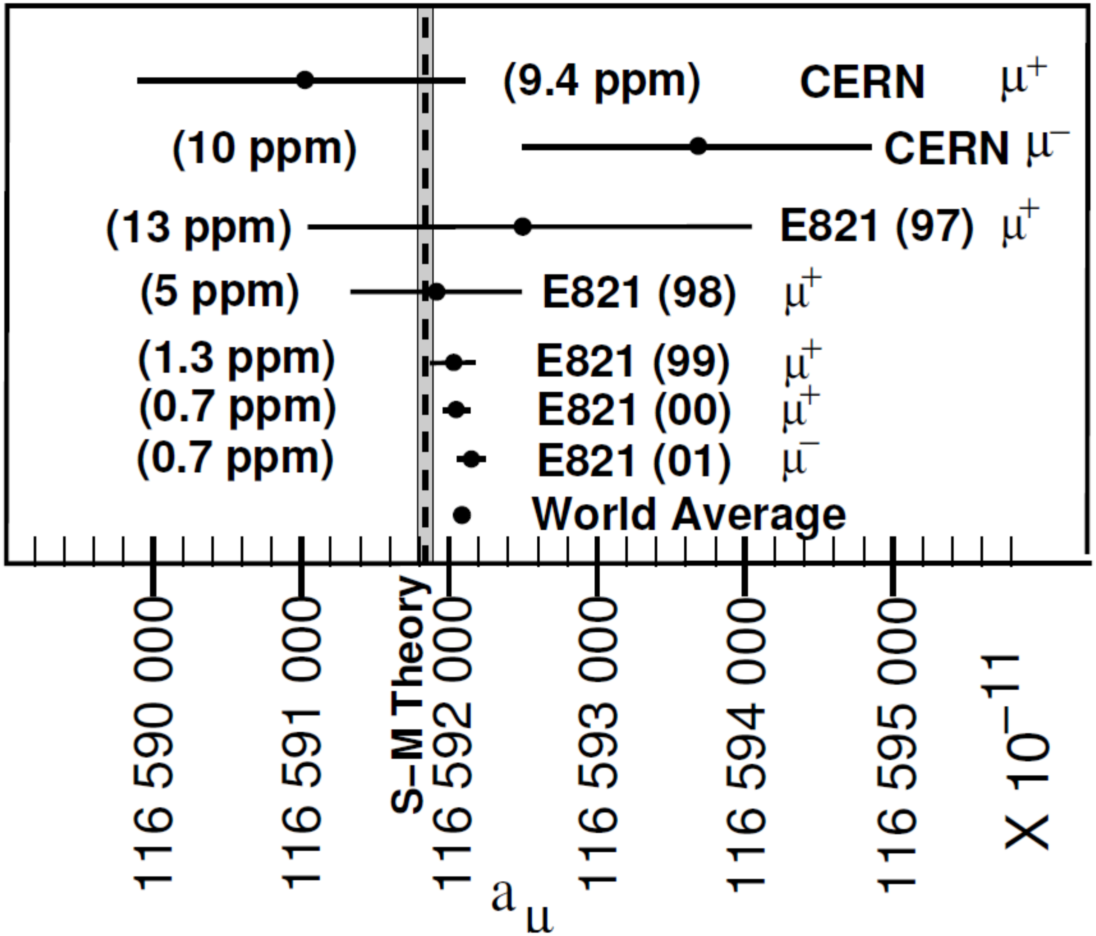
Magnetic moment

$$g_\mu = 2.002\,331\,841\,78(108)(66)$$



Miller, et al. (2007) Rep. Prog. Physics 70, 795.
Beringer, et al. (2012) Phys. Rev. D 86, 010001.

Physics motivation



Fermilab E989 Conceptual Design Report (2013)

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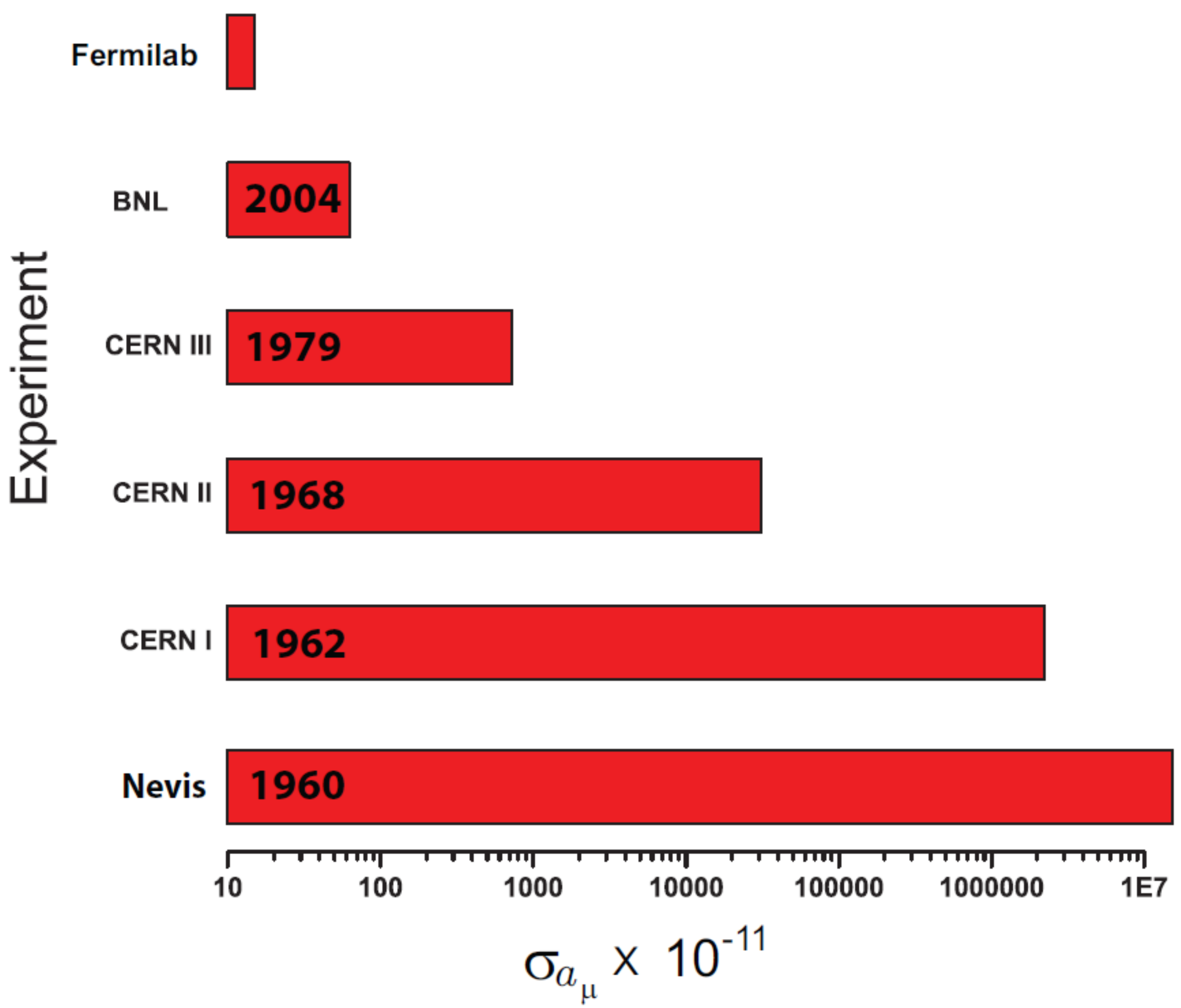
Fermilab muon g-2 experiment (E989)



What is measured in g-2 experiments?

- Thomas – BMT equation

$$\vec{\Omega}_{BMT} = -\frac{q_e}{\gamma m_e c}\left[(1+a\gamma)\vec{B}_{\perp} + (1+a)\vec{B}_{\parallel} - \left(a\gamma + \frac{\gamma}{\gamma+1}\right)\vec{\beta}\times\vec{E}\right]$$

- Describes rate of spin precession
- For a storage ring without transverse electric fields

$$\vec{\Omega}_{BMT} \times \vec{S} \equiv f_{spin} = -\frac{q_e\left|\vec{B}_{\perp}\right|}{\gamma m_e c}\left[(1+a\gamma)\right]$$

- Compare with the cyclotron frequency

$$f_{cyc} = -\frac{q_e\left|\vec{B}_{\perp}\right|}{\gamma m_e c}$$

- Measurement of frequencies

Arnaudon 1995 Z. Phys. C. 66, 45

RESONANT DEPOLARISATION EXPERIMENTS WITH ELECTRONS

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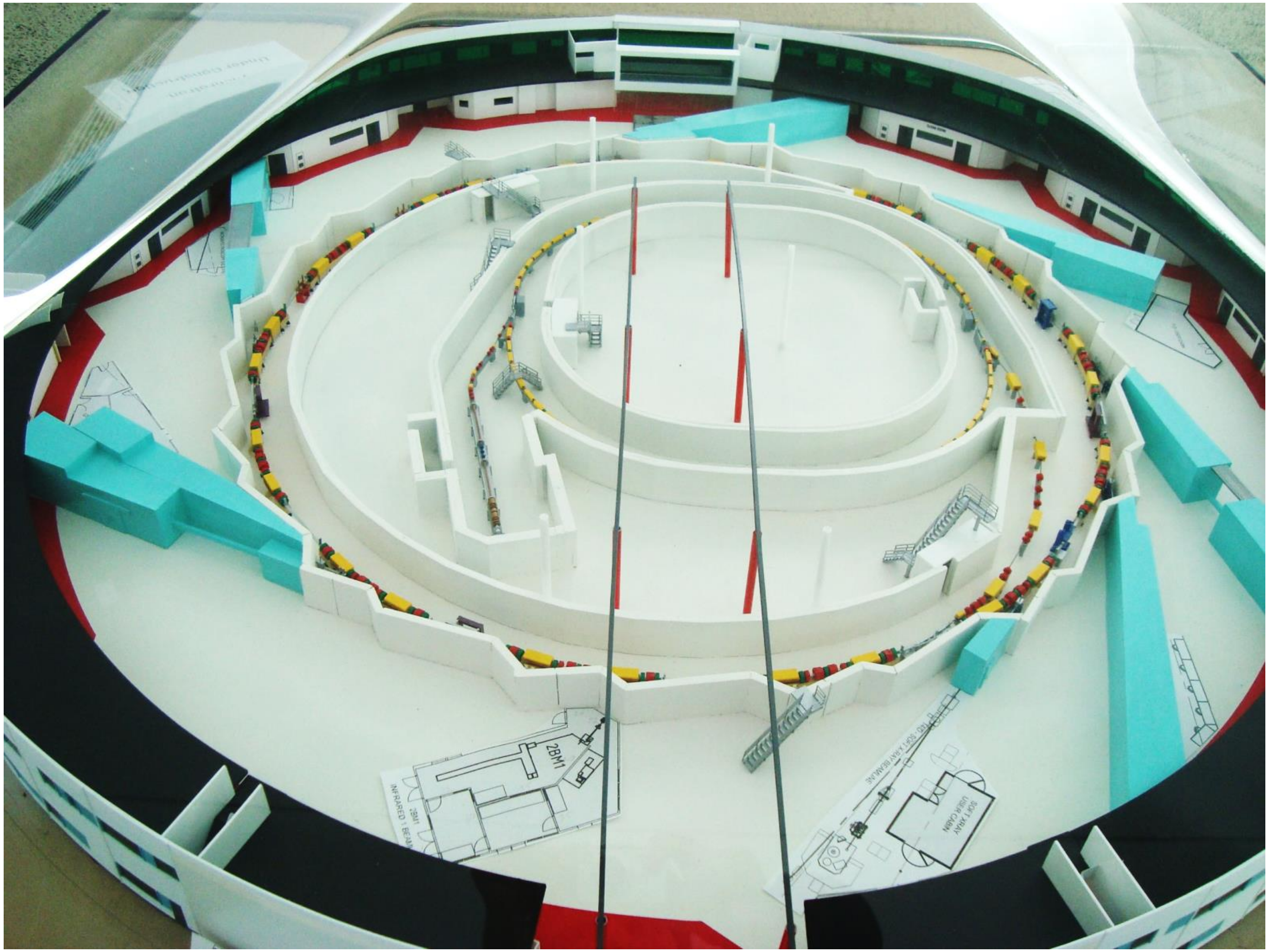
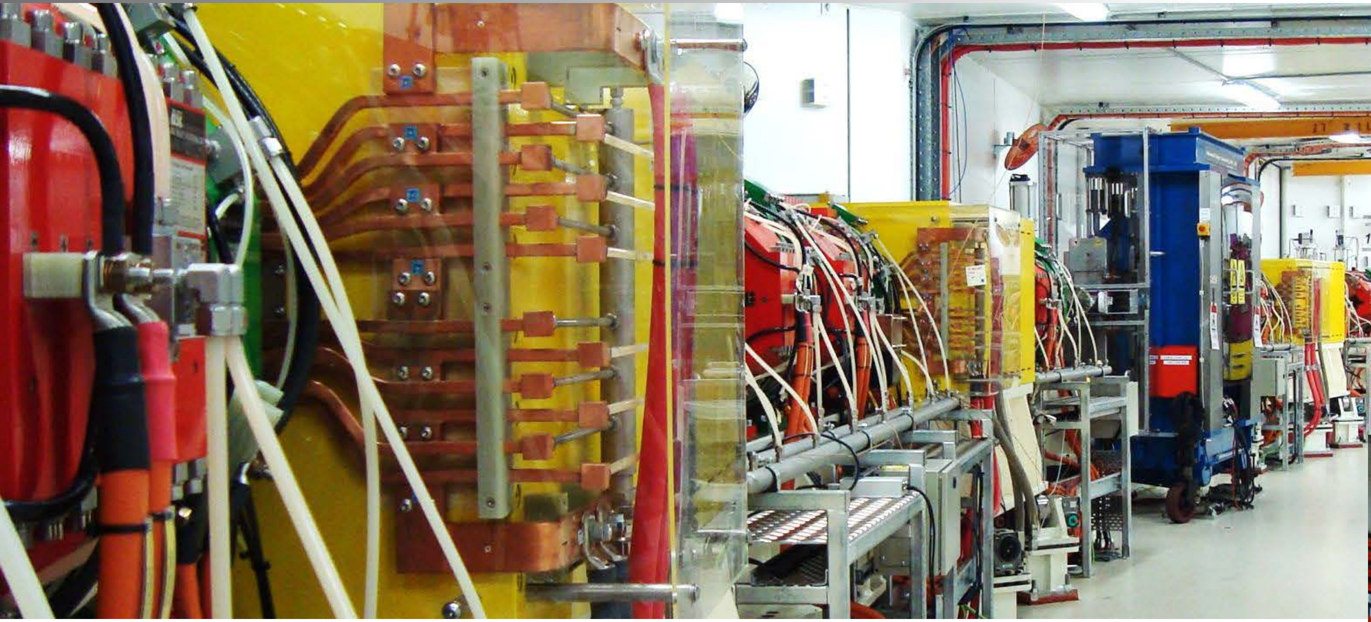


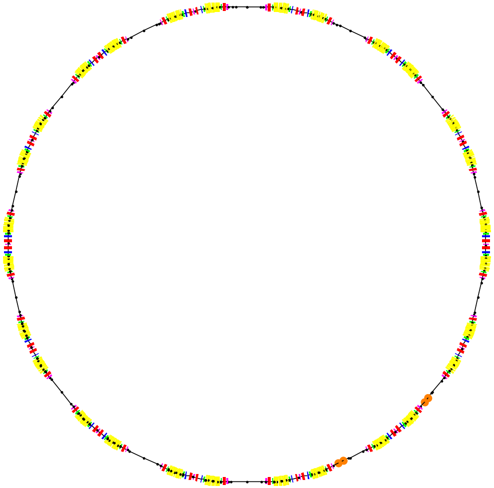
Storage ring

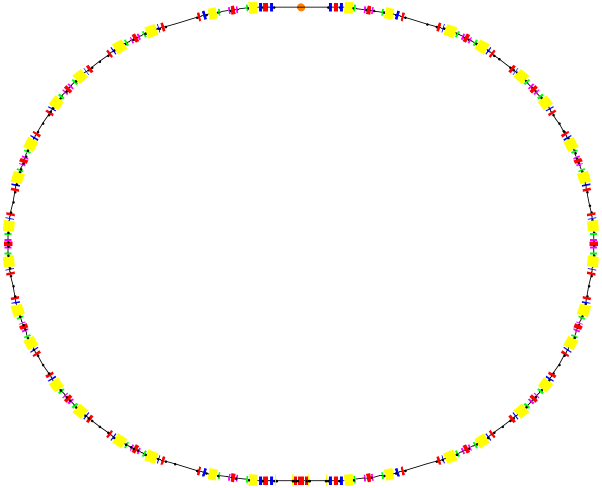


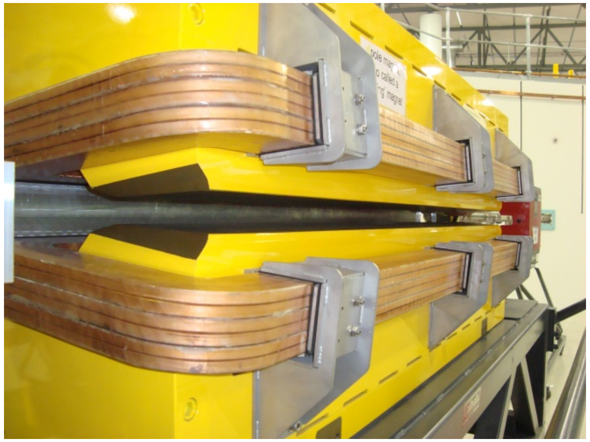
- 3 GeV electron ring
- Periodicity 14, Double Bend Achromat
- 216.0 m circumference
- RF 500 MHz, 3.0 MV
  - 4 × CW klystron

Storage ring light sources

- 3 GeV
- DBA cell
  - Gradient dipoles
- Like many other low horizontal emittance rings

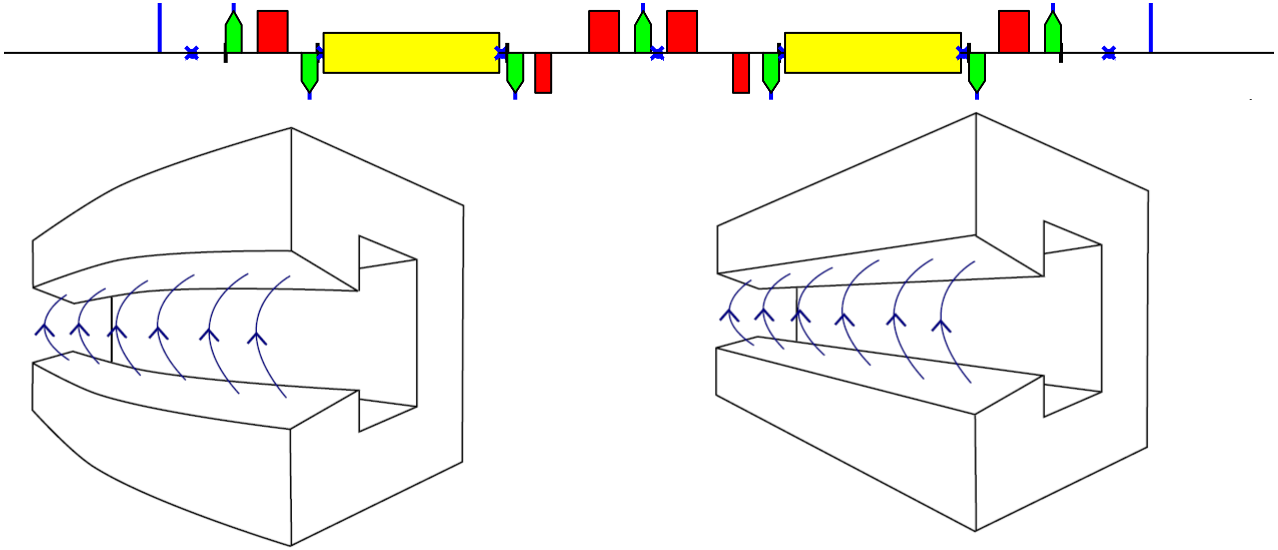






Motivation – electron rings

- Lower horizontal emittance by incorporating defocussing gradient into bending magnet
  - DBA, TBA, MBA, TME lattices heading in this direction
  - Can eliminate quadrupoles from lattice

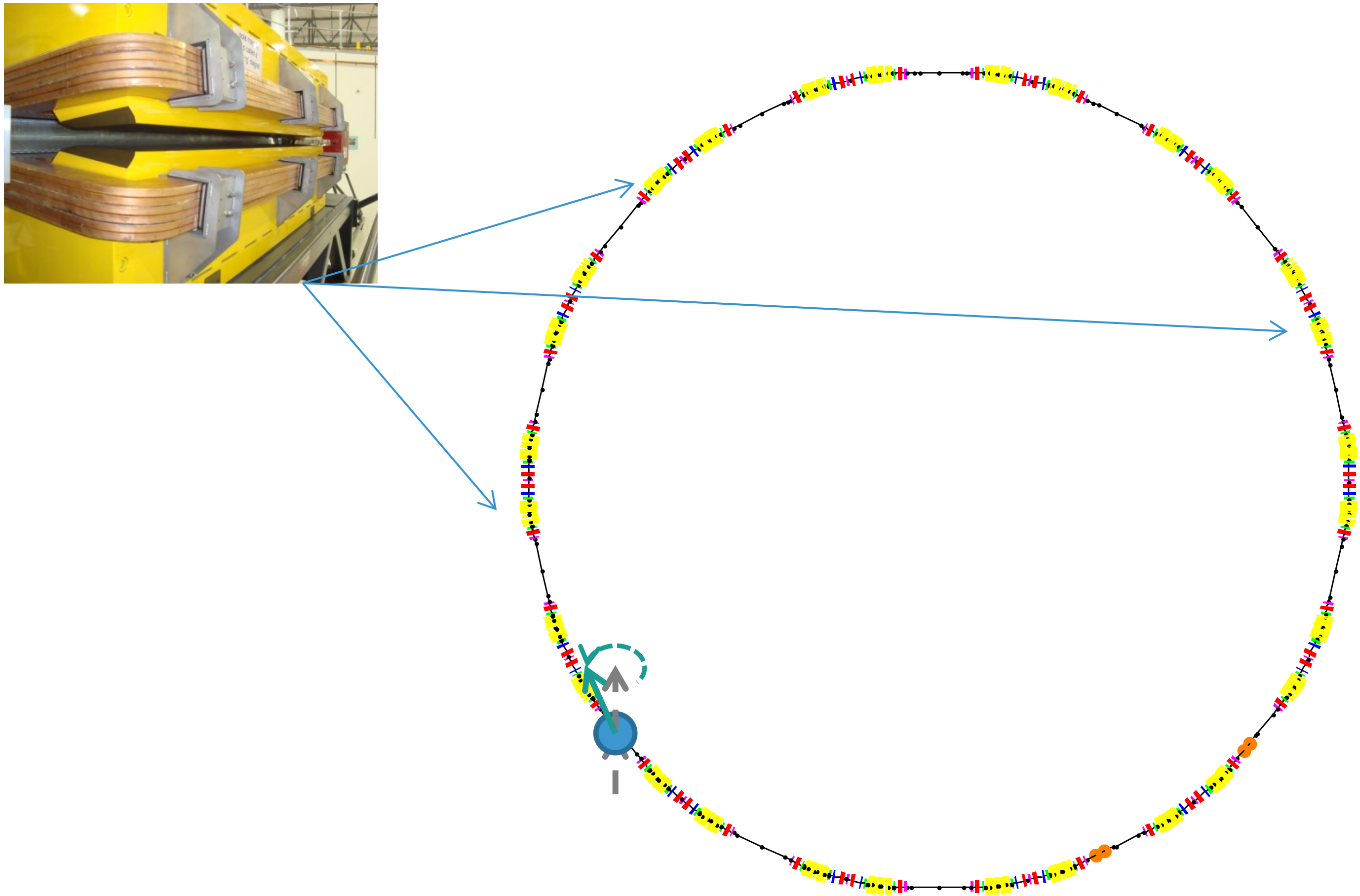


- Build a straight, rectangular magnet with defocussing gradient
  - What equation describes the particle motion?

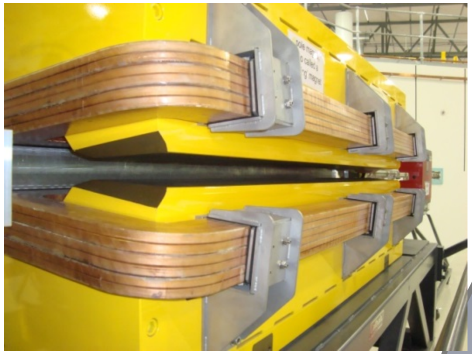
Electron spin resonant depolarisation

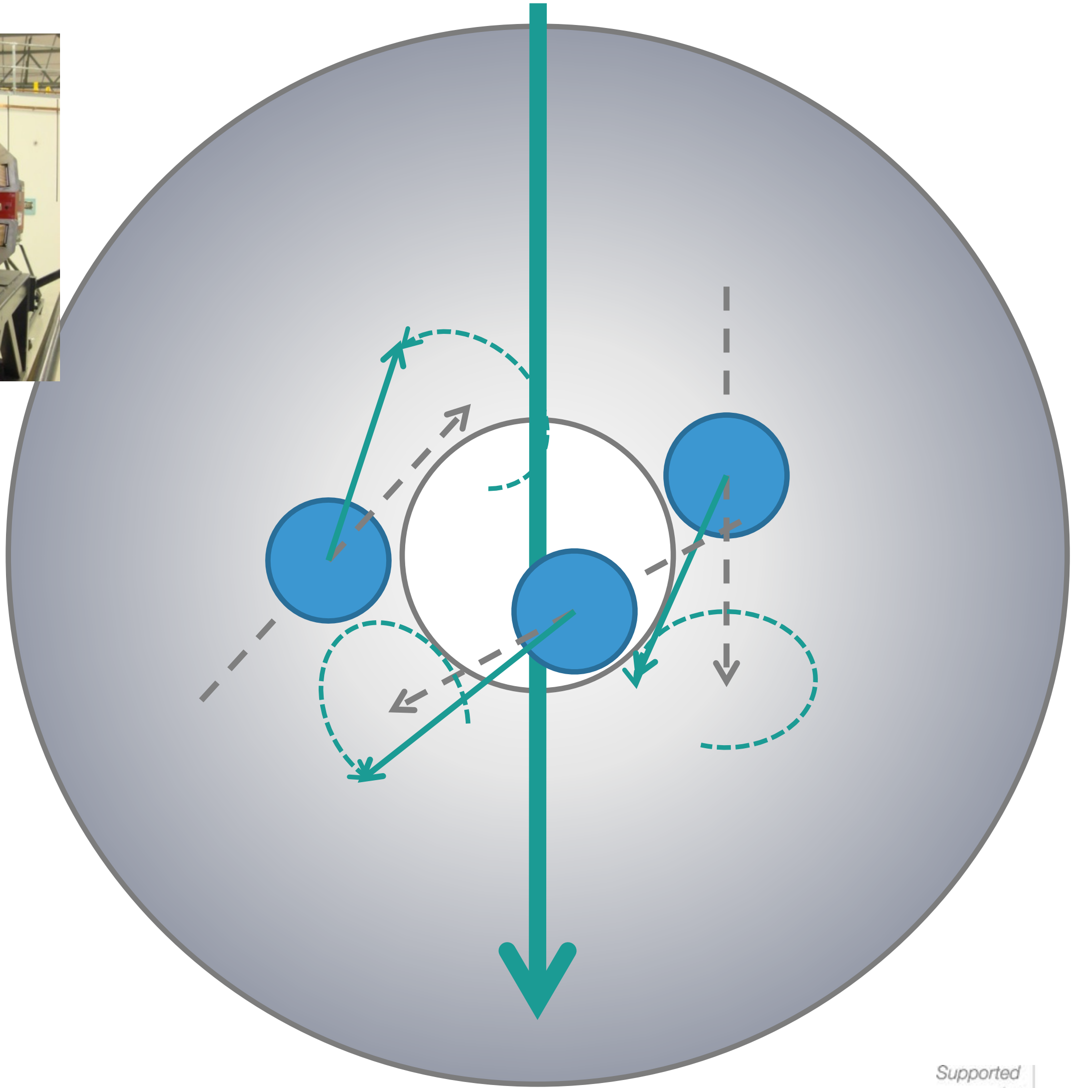
- Precision measurement of beam energy and momentum compaction
  - Tells us about value of dispersion function where there is bending
- Require:
  - Spin-polarised electron beam
  - Spin precession
  - Method of depolarising the beam
  - Method of monitoring beam polarisation
- These measurements will be compared to simulations of the trajectory through the bending magnet

Resonant spin depolarisation

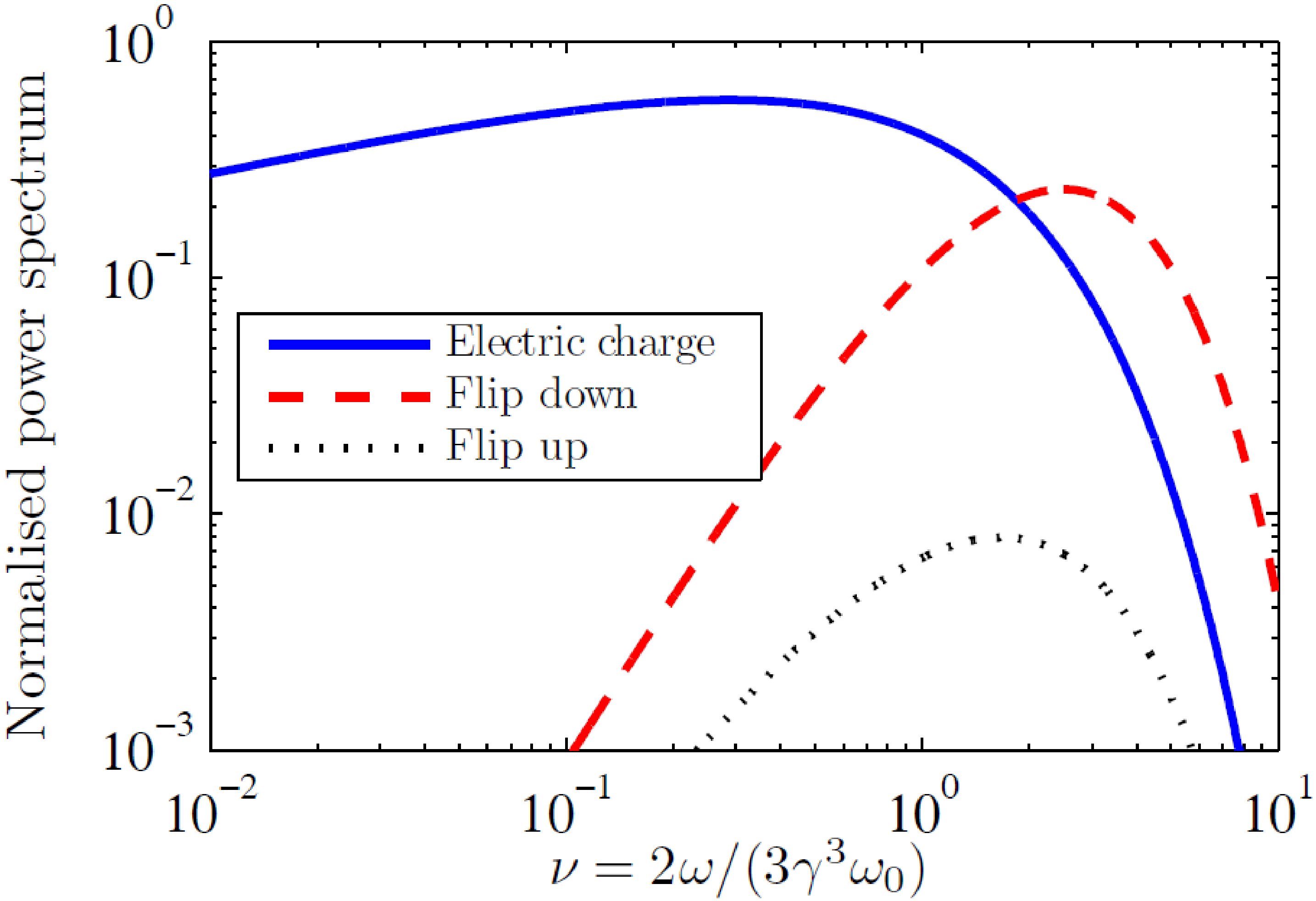


Sokolov-Ternov Effect





Sokolov-Ternov Effect



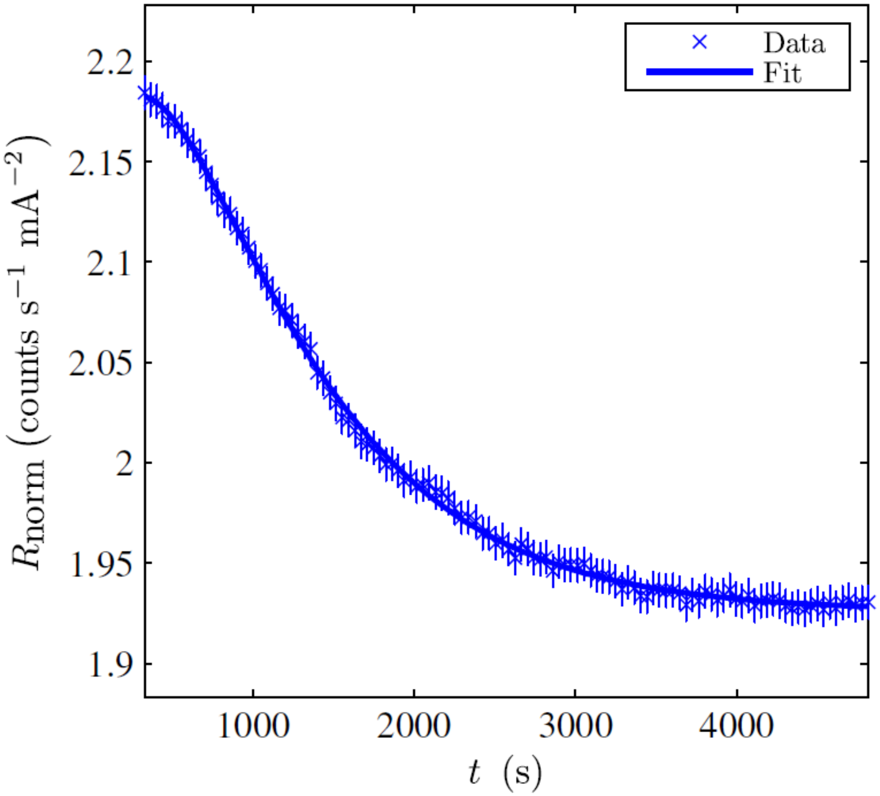
Polarised beam

We get it for free!
Sokolov-Ternov effect

$$\tau_{ST} = \frac{8}{5\sqrt{3}} \frac{m_e \rho^2 R}{\hbar \gamma^5 r_e}$$

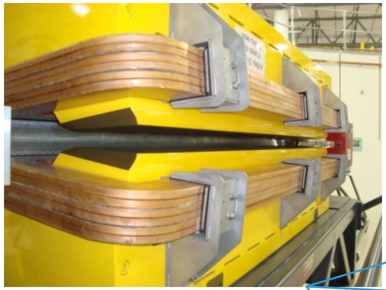
Sokolov & Ternov 1964 Sov. Phys. Dokl. 8, 1203-5.

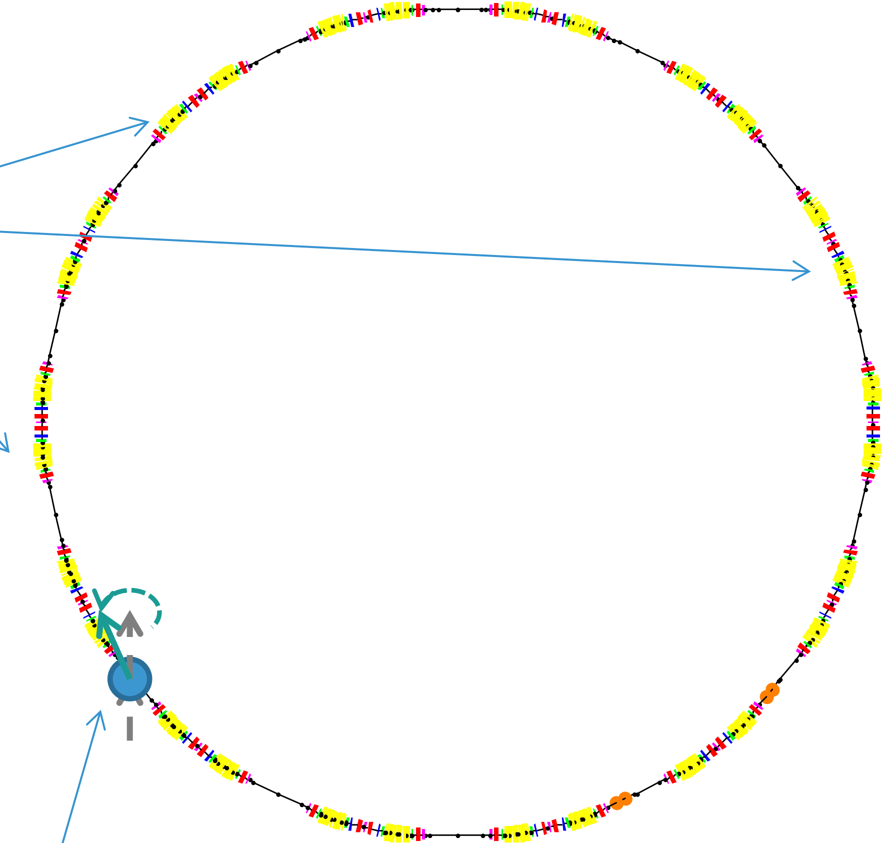
Ring		Measured	Model
AS	τ	806(21)	807
SPEAR3	τ	840(12)	1003

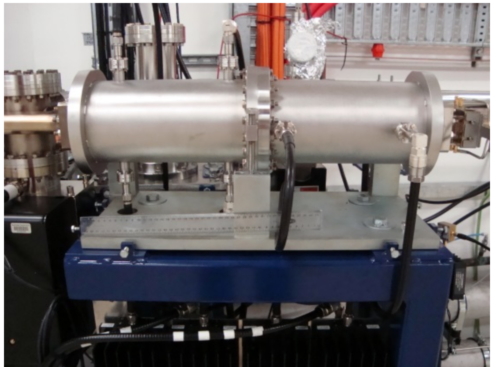


Wootton et al. (2013) Phys. Rev. ST – Accel. Beams. 16, 074001

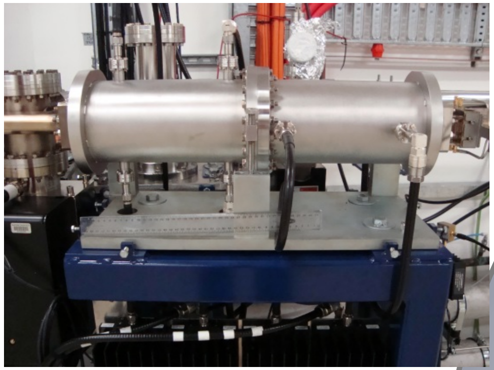
Resonant spin depolarisation

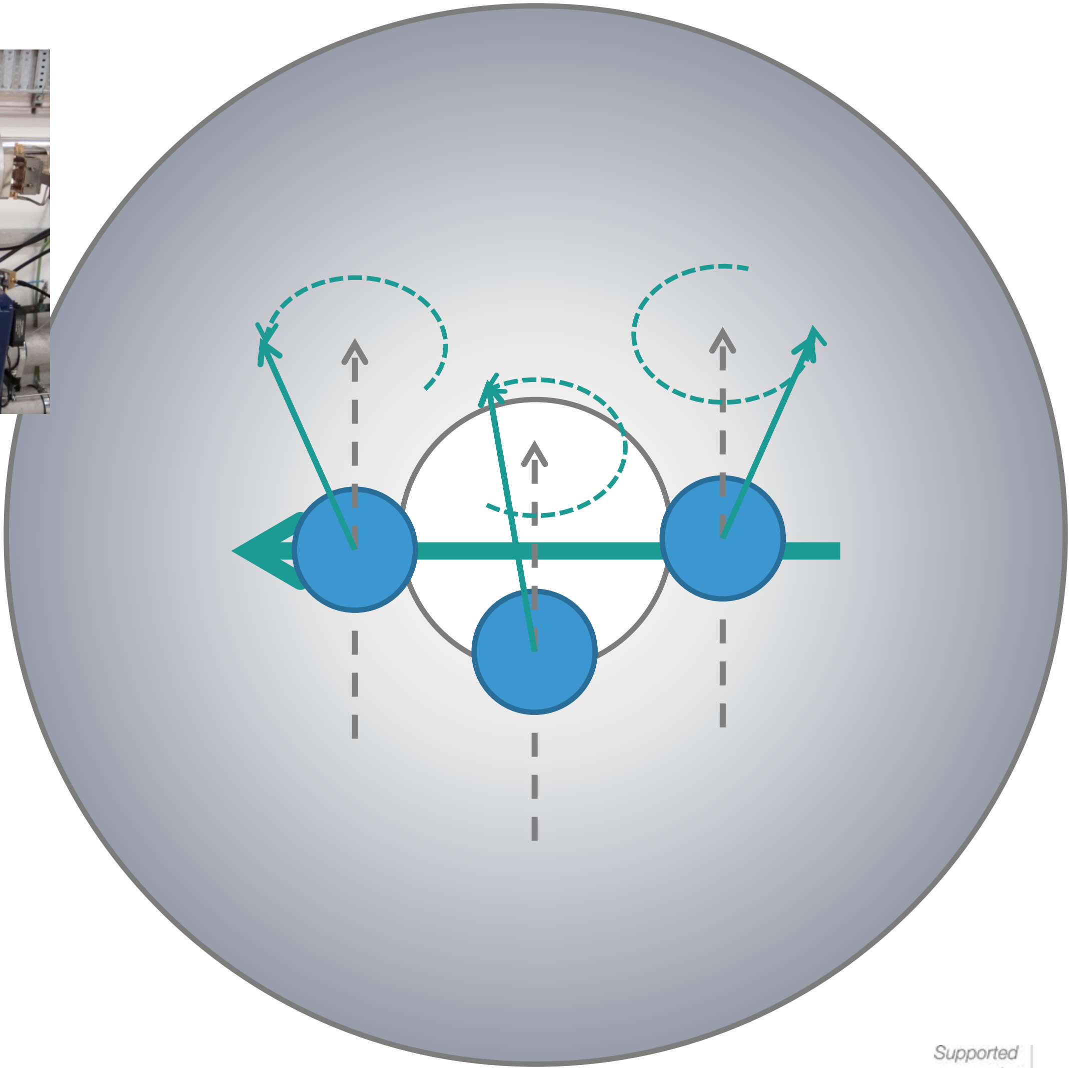




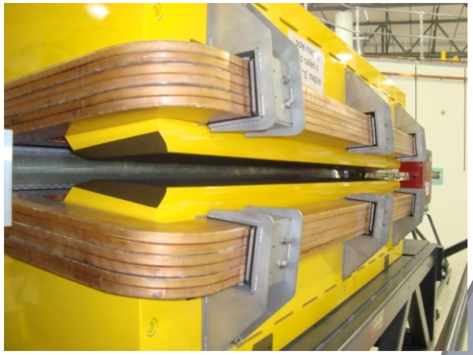


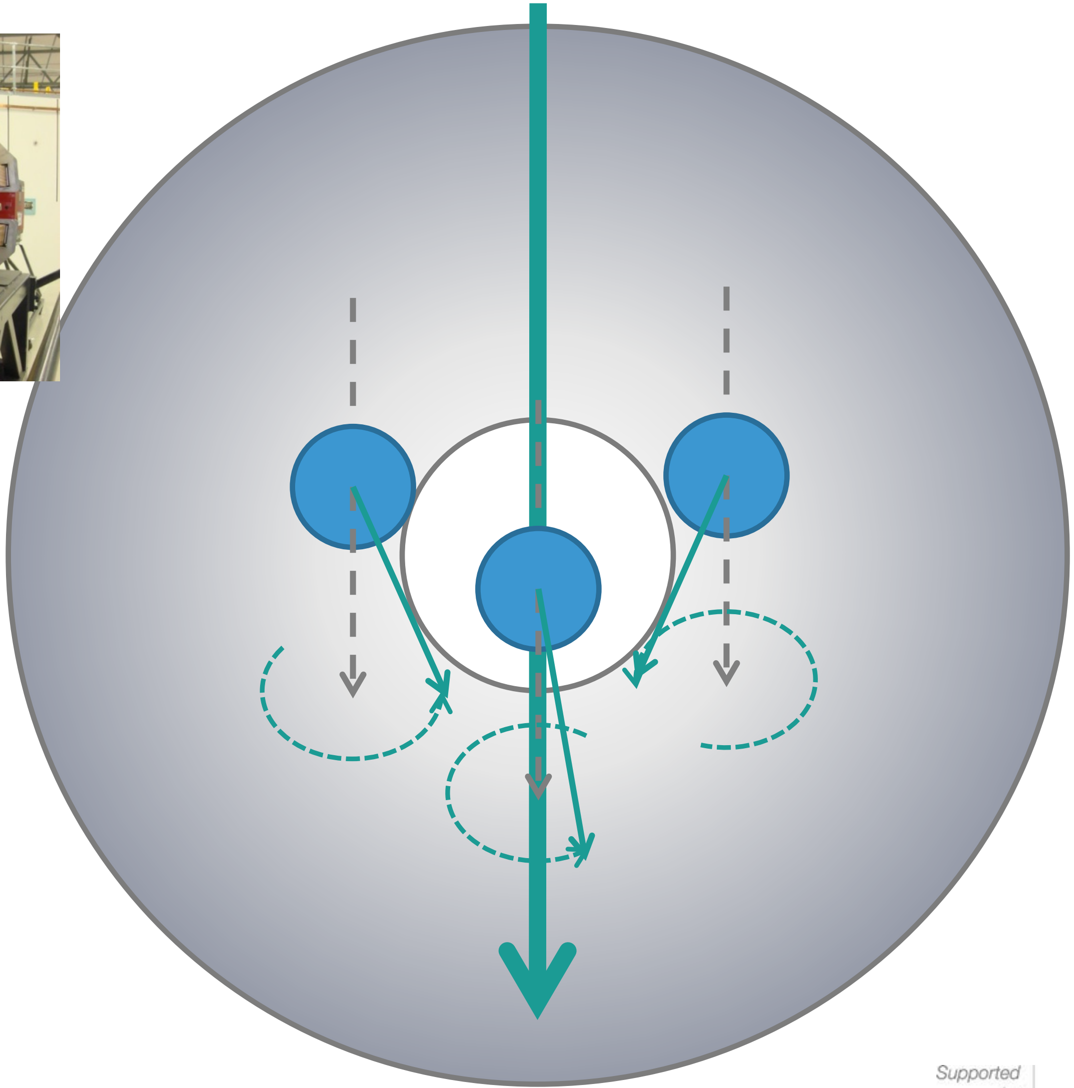
Resonant spin depolarisation



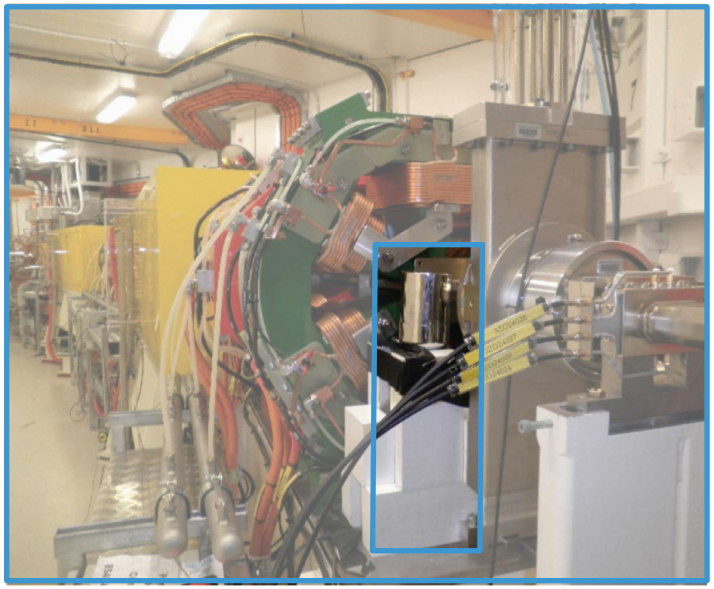


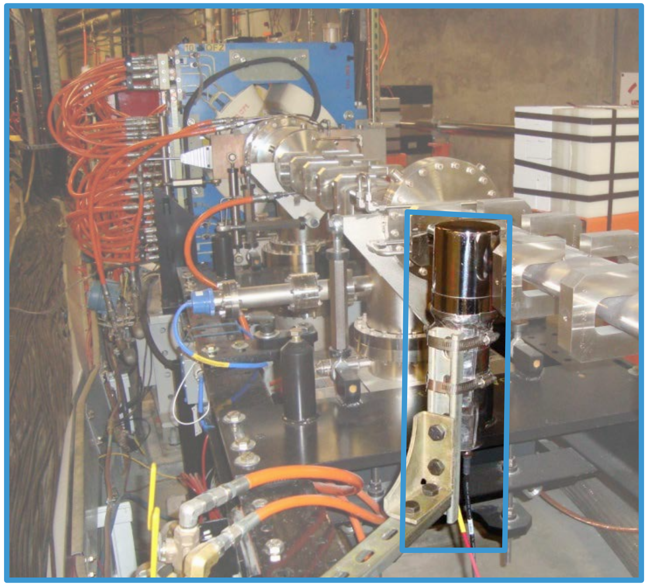
Sokolov-Ternov Effect

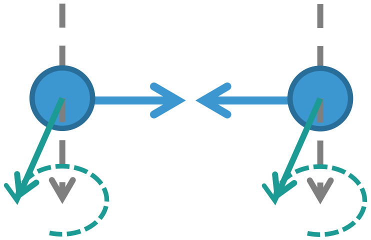


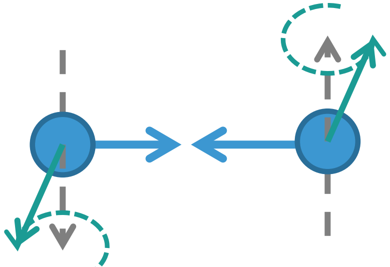


Polarisation monitor







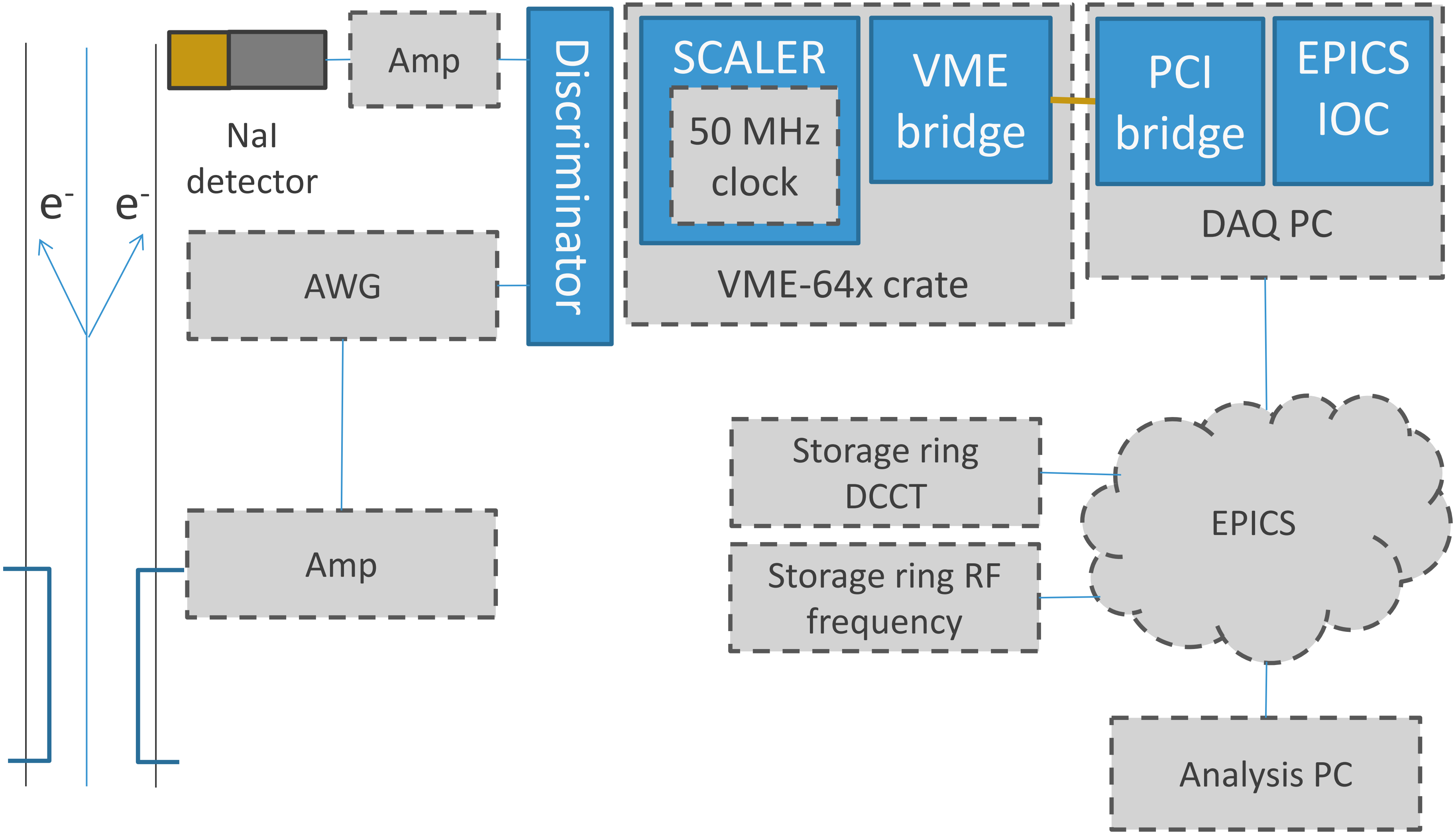


- Loss rate from Touschek scattering strongly dependent upon polarisation

Bernardini et al., 1963 Phys. Rev. Lett. 10, 407.

Serednyakov 1976, Sov Phys JETP 71, 2025.

Apparatus


Amp
NaI detector
Discriminator
SCALER
50 MHz clock
VME bridge
PCI bridge
EPICS IOC
DAQ PC
VME-64x crate
e-
e-
AWG
Amp
Storage ring DCCT
Storage ring RF frequency
EPICS
Analysis PC

Thomas – BMT equation

- Describes adiabatic spin evolution

$$\vec{\Omega}_{BMT} = -\frac{q_e}{\gamma m_e c}\left[(1 + a\gamma)\vec{B}_\perp + (1 + a)\vec{B}_\parallel - \left(a\gamma + \frac{\gamma}{\gamma+1}\right)\vec{\beta} \times \vec{E}\right]$$

- For a storage ring light source, simplify to

$$\vec{\Omega}_{BMT} \times \vec{S} \equiv f_{spin} = -\frac{q_e\left|\vec{B}_\perp\right|}{\gamma m_e c}[(1 + a\gamma)]$$

- By comparison with the cyclotron frequency

$$f_{cyc} = -\frac{q_e\left|\vec{B}_\perp\right|}{\gamma m_e c}$$

$$\therefore \nu_{spin} = a\gamma$$

$$a = 0.001\,159\,652\,180\,76(27)$$

ν_{spin} *is a frequency*

Arnaudon 1995 Z. Phys. C. 66, 45

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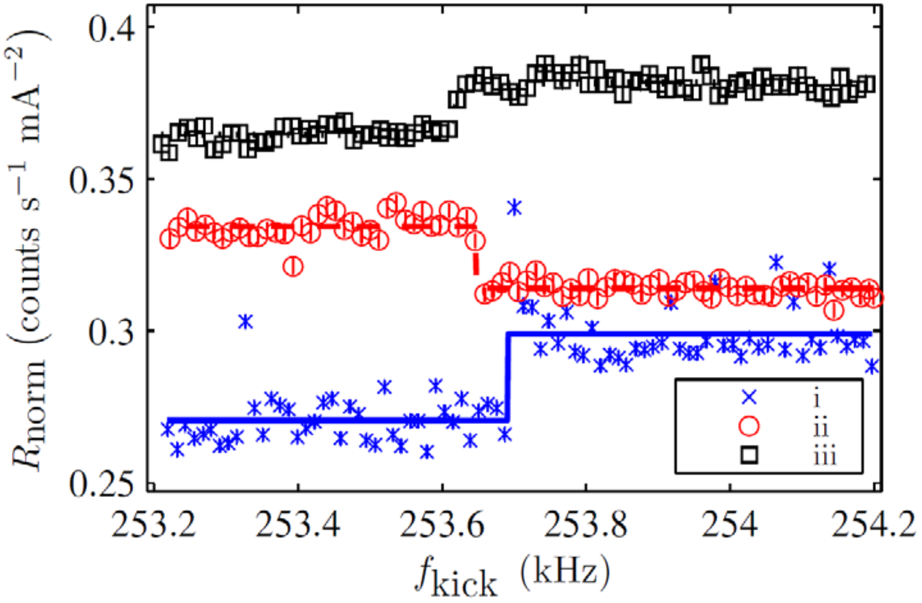
Beam energy measurement

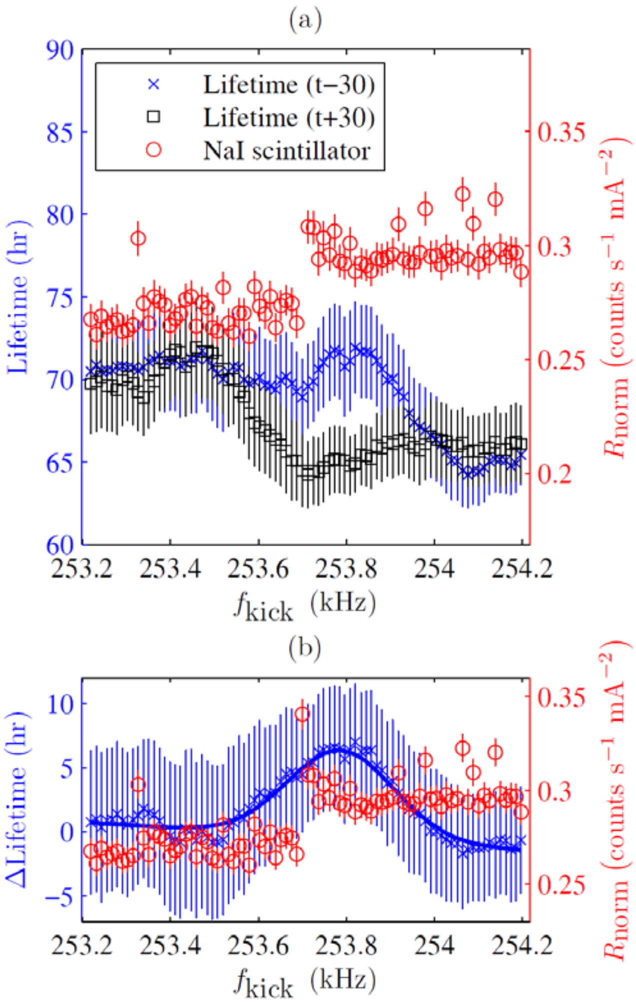
- 0.25362(2) MHz
- 2.997251(7) GeV

Ring		Measured
AS	E	3.013408(8)
SPEAR3	E	2.997251(7)

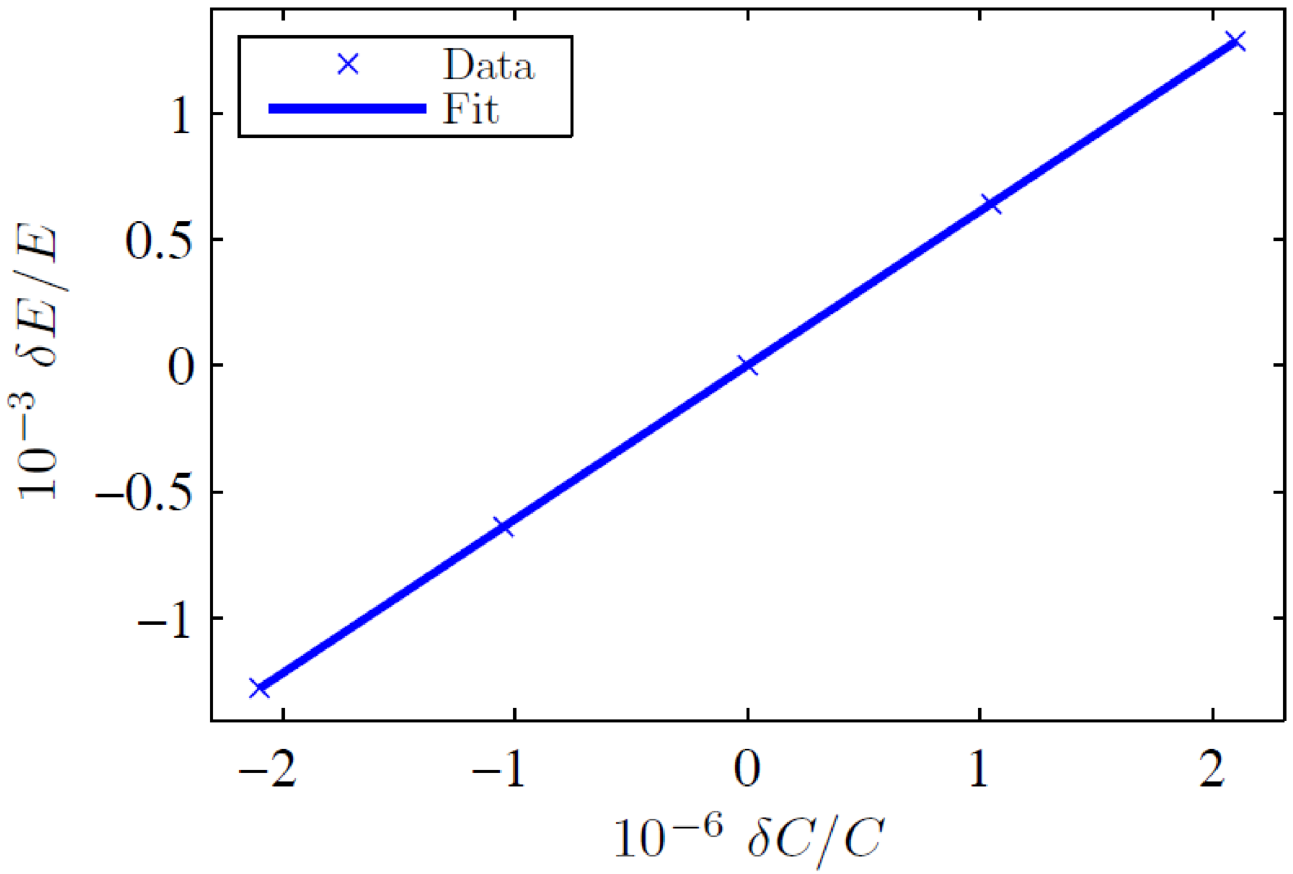


Wootton et al. (2013) Phys. Rev. ST – Accel. Beams. 16, 074001

Beam Energy Measurement – Detector Choice



Momentum compaction factor



Wootton et al. (2013) Phys. Rev. ST – Accel. Beams. 16, 074001

Measured MCF

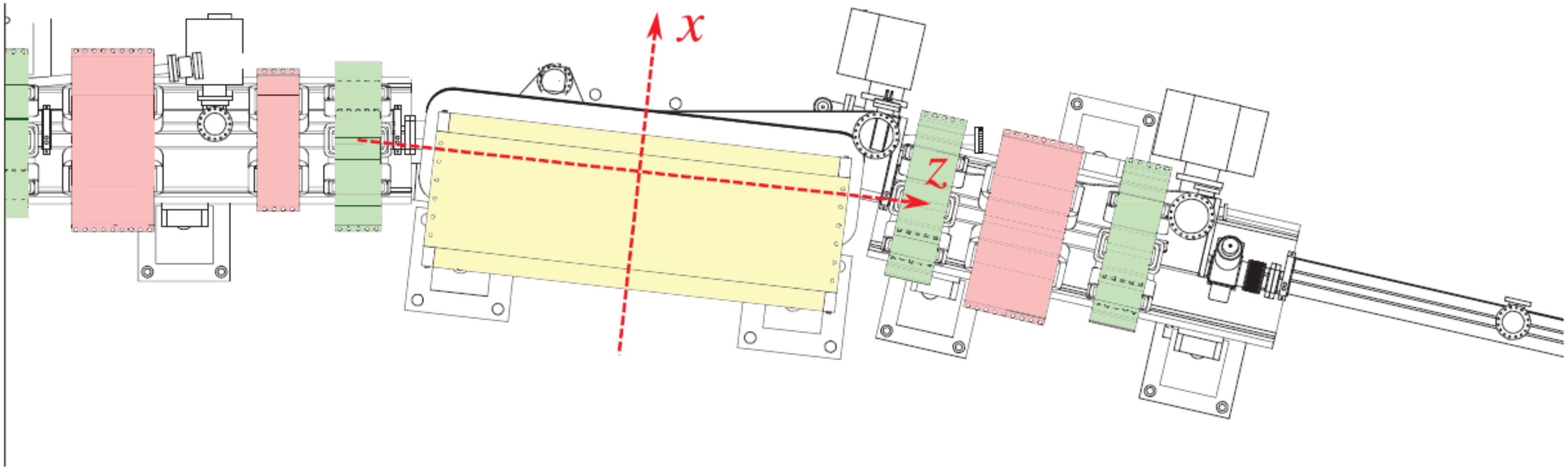
- Measured the momentum compaction factor
  - What does that tell us?

$$\alpha_c = \frac{1}{C}\oint_0^C \frac{\eta_x(s)}{\rho(s)}\,ds$$

- Tells us about value of dispersion function where there is bending
- Bending radius
  - How do we model the bending magnet?

Coordinate system for following equations

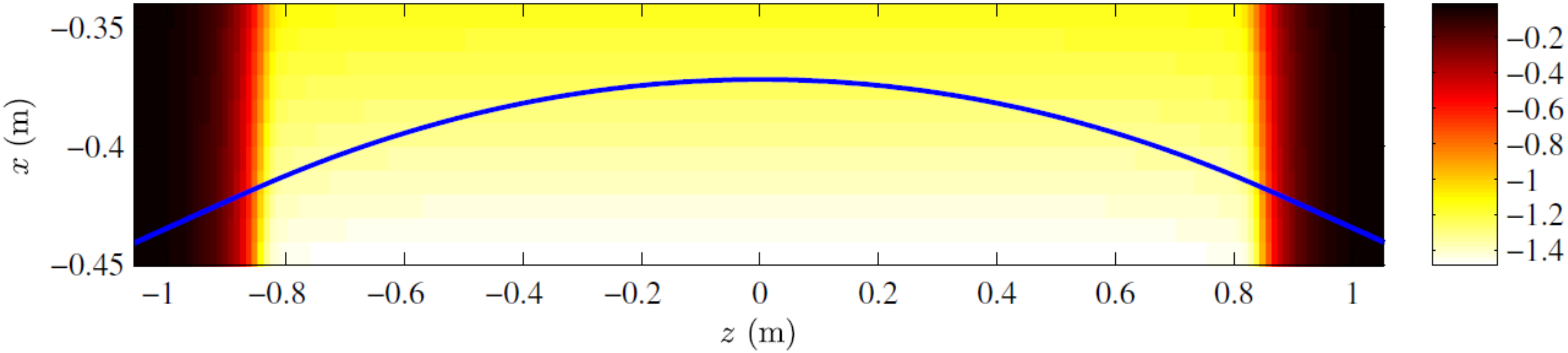
- We are trying to evaluate the trajectory, so we cannot use the normal curvilinear coordinates
- Define rectangular coordinate system along main bending magnet axis



Wootton et al. (2013) Phys. Rev. ST – Accel. Beams. 16, 074001

Numerical evaluation of trajectory

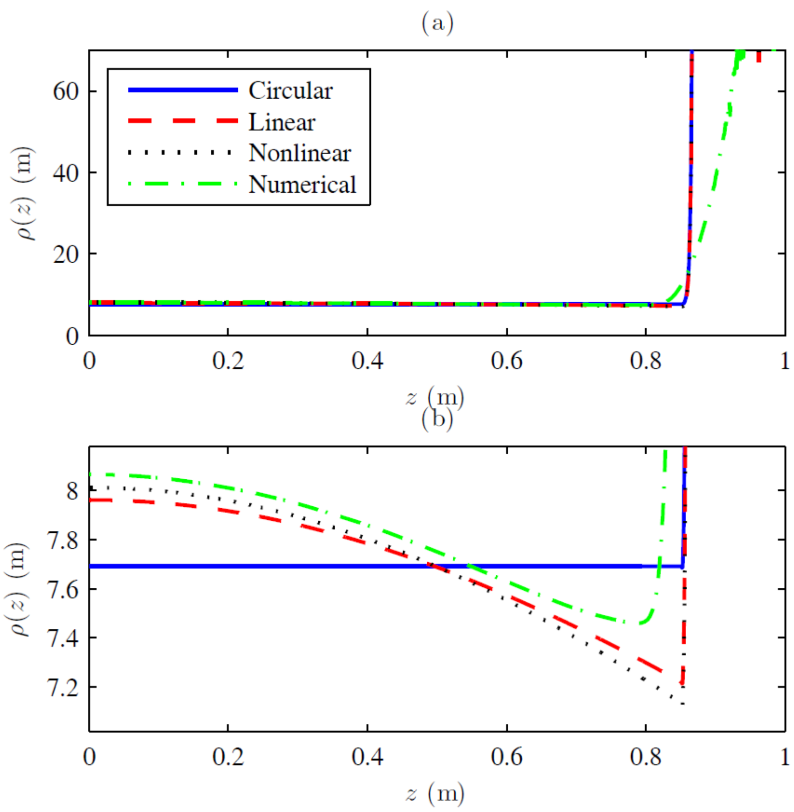
- Analytical models of trajectory
  - Circular
  - Linear hyperbolic cosine
  - Nonlinear hyperbolic cosine

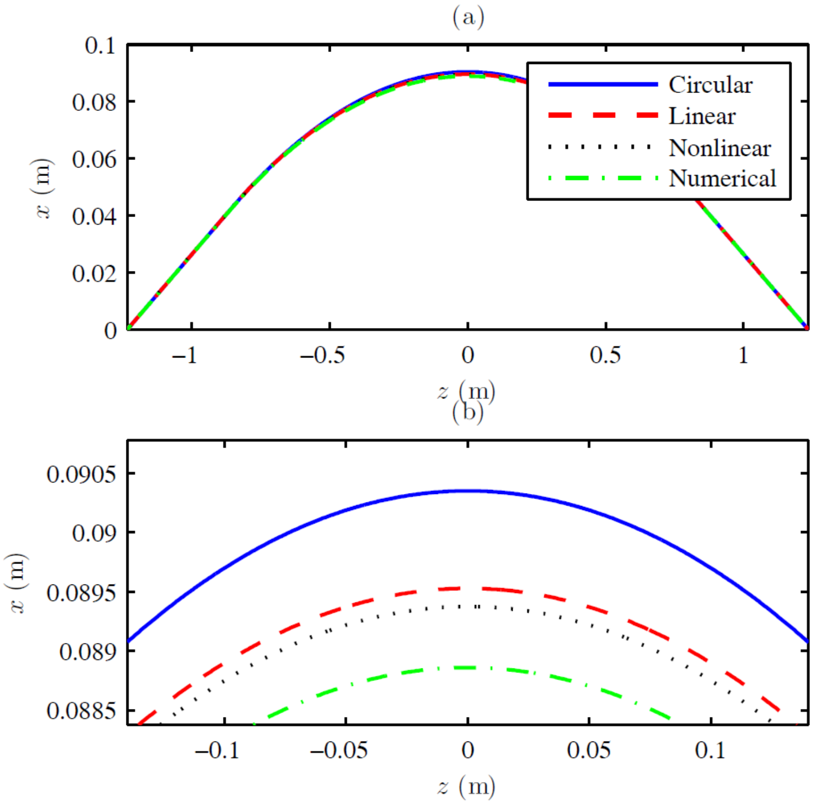


- Magnetic field measured on horizontal mid-plane with Hall probe (2D – map)
- Fourth-order Runge-Kutta integration of trajectory
  - Constraints on total deflection angle, equal position at entrance and exit

Yoon 2004 NIMA, 9, 523

Comparison of models



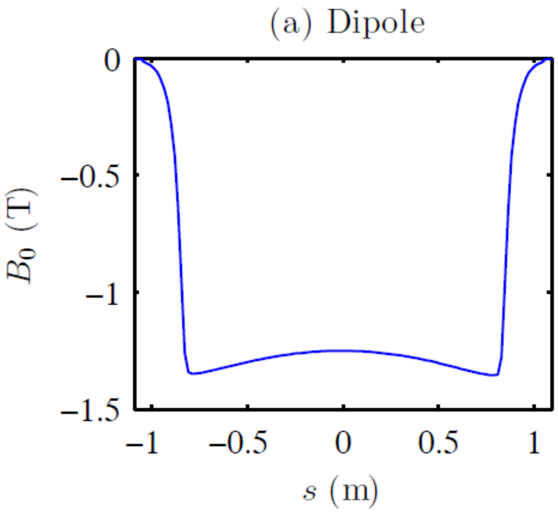


Wootton et al. (2013) Phys. Rev. ST – Accel. Beams. 16, 074001

Momentum compaction factor

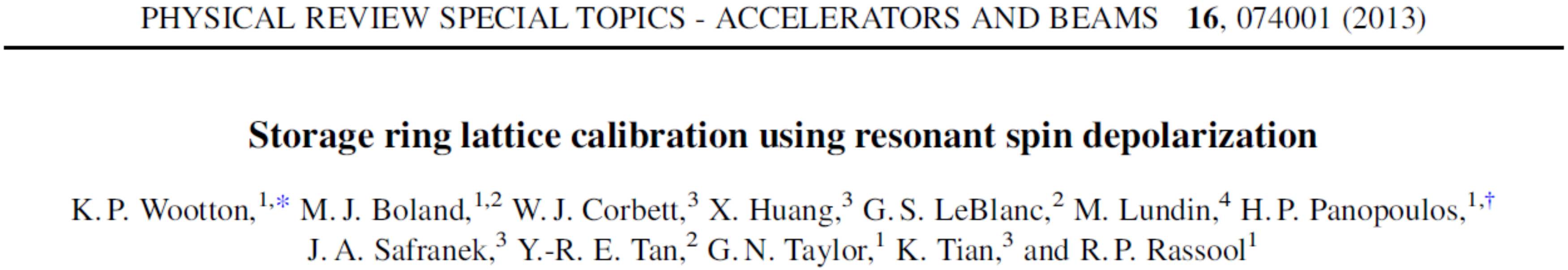
Approach	**AS**	**SPEAR3**
Linear hyperbolic cosine	0.00205	0.00162
Numerical	0.00211	0.00165
Measured	0.00211(5)	0.00164(1)

- Within uncertainty, measured agrees with numerical integration and disagrees with linear hyperbolic cosine.
- A better model for the trajectory than usual hyperbolic cosine
- Accuracy in model comes from correct distribution of the dipole field



Summary

- Rectangular magnet with defocussing gradient
  - Circular, linear hyp. cosine, nonlinear hyp. cosine, numerical trajectories
- Simulation of momentum compaction factor
- Within uncertainty, measured momentum compaction factor agrees with numerical integration and disagrees with linear hyperbolic cosine trajectory
- Model accuracy comes from correct distribution of the dipole field



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 074001 (2013)

Storage ring lattice calibration using resonant spin depolarization

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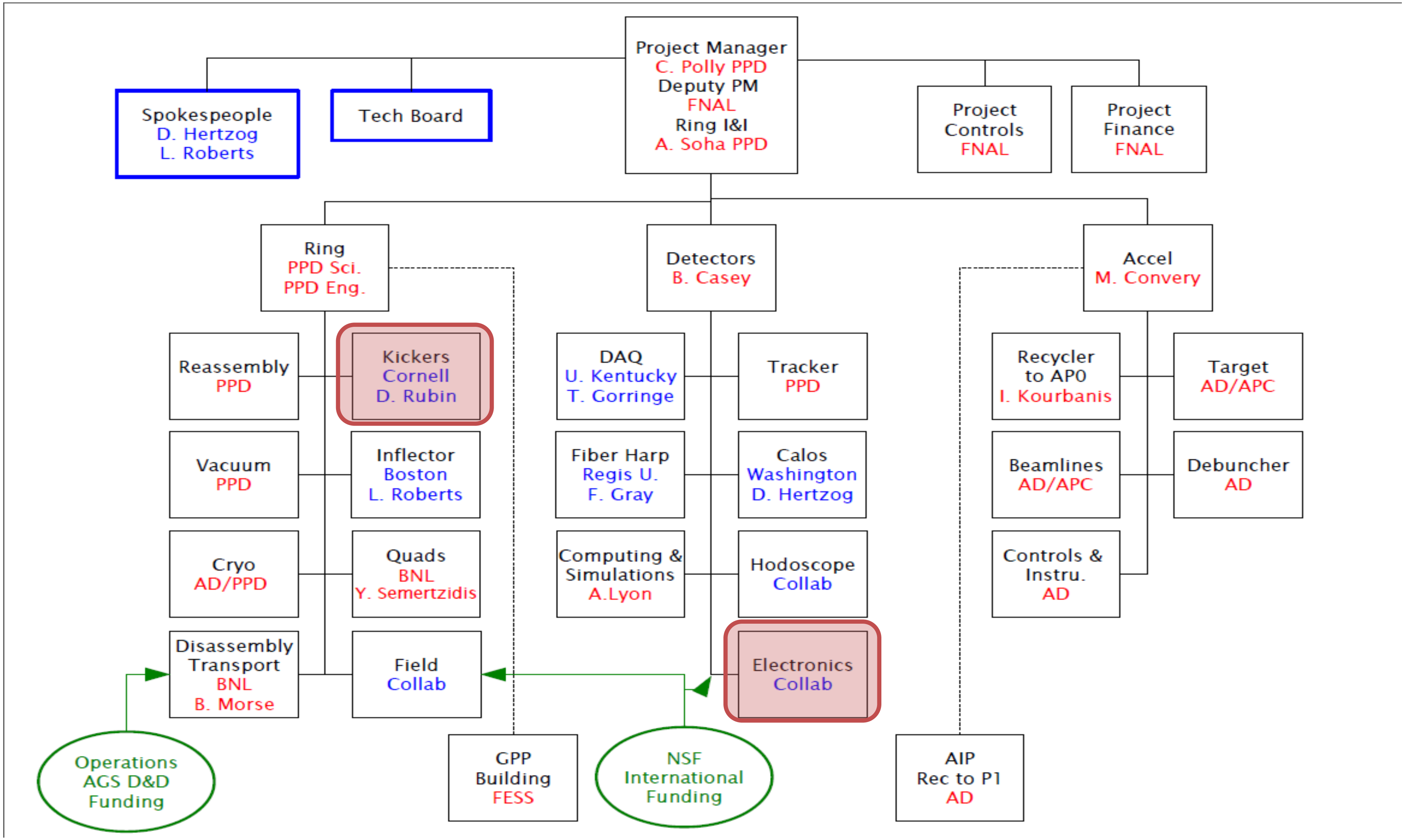
FERMILAB MUON G-2 EXPERIMENT (E989)

Fermilab muon g-2 collaboration



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Deputy PM
FNAL
Ring I&I
A. Soha PPD

Spokespeople
D. Hertzog
L. Roberts

Tech Board

Project
Controls
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Finance
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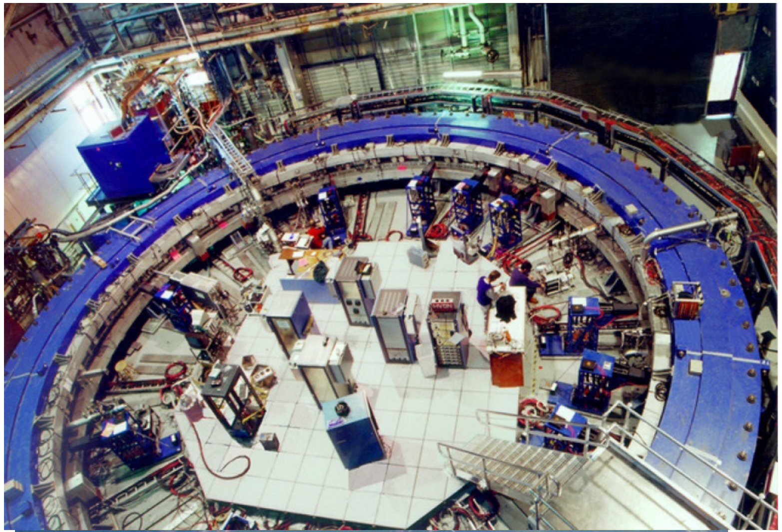
Rec to P1
AD

Supported by Australian Government State Government Victoria

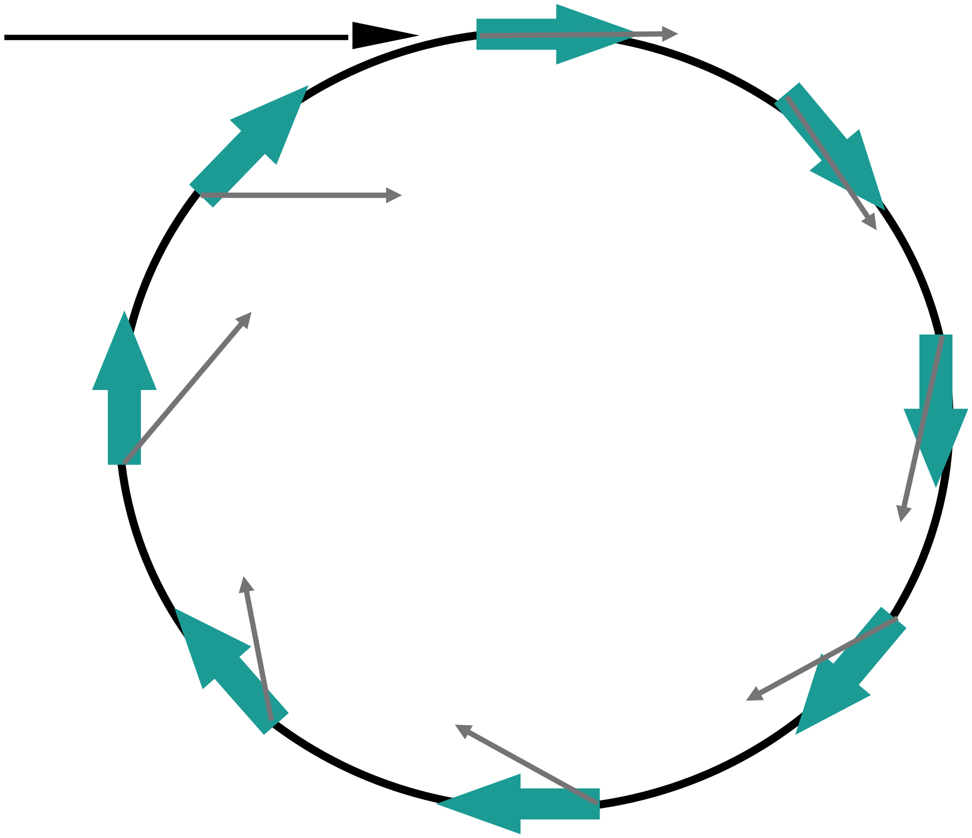
Muon g-2 accelerators

- Tertiary muon beam
- Proton beam
  - $p = 8.9\ \mathrm{GeV/c}$
  - 2×10^{20} protons on target per year
- Pion beam
  - $p = 3.11\ \mathrm{GeV/c}$
  - $\gamma\tau = 570\ \mathrm{ns}$
- Muon beam
  - $p = 3.094\ \mathrm{GeV/c}$
  - $\gamma\tau = 64\ \mu\mathrm{s}$



Muon storage ring

- Injected muon beam longitudinal polarisation
- Orbital angular momentum precesses at the revolution (cyclotron) frequency
- Spin precession advances ahead of orbital angular momentum
  - Thomas precession



Supported by

Thomas – BMT equation

- Describes adiabatic spin evolution

$$\vec{\Omega}_{BMT} = -\frac{q_\mu}{\gamma m_\mu c}\left[(1+a\gamma)\vec{B}_\perp + (1+a)\vec{B}_\parallel - \left(a\gamma + \frac{\gamma}{\gamma+1}\right)\vec{\beta}\times\vec{E}\right]$$

- For a storage ring with transverse electric fields

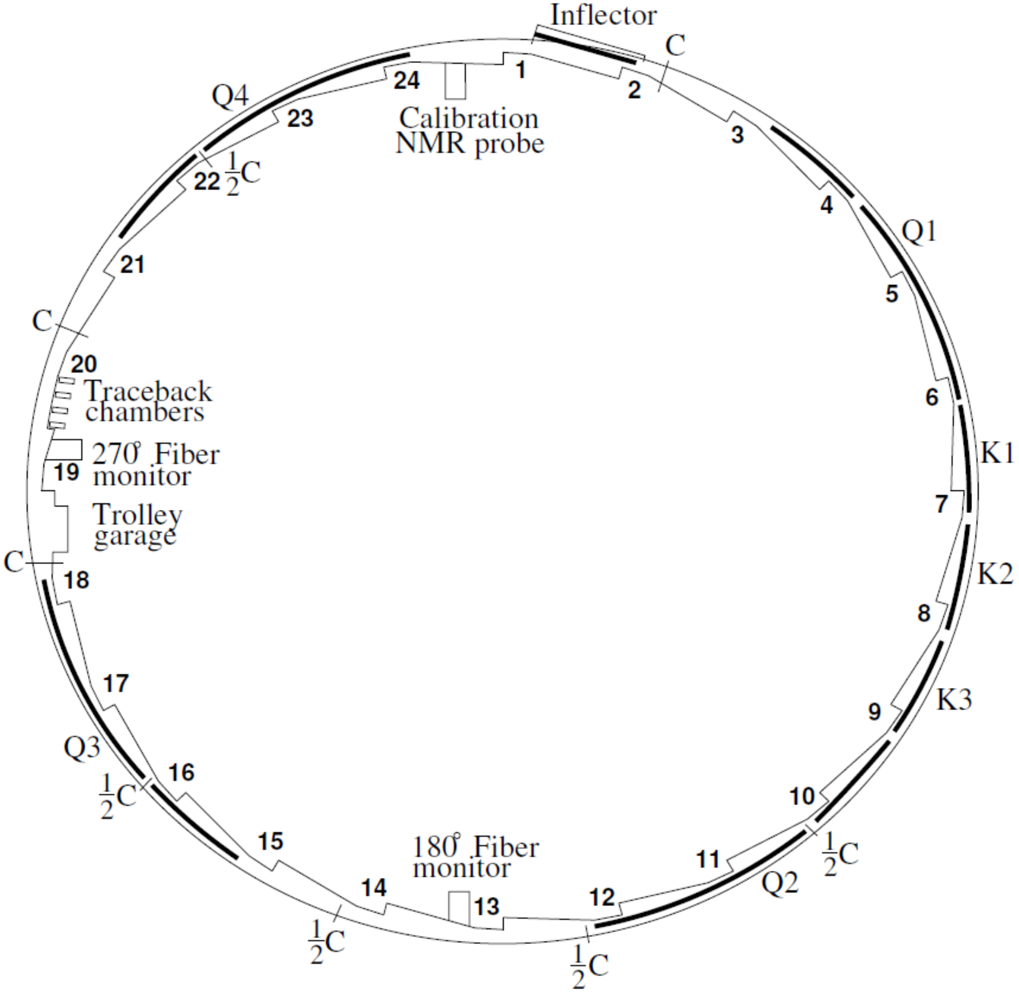
$$\vec{\Omega}_{BMT} \times \vec{S} \equiv f_{spin} = -\frac{q_\mu \left|\vec{B}_\perp\right|}{\gamma m_\mu c}\left[(1+a\gamma) - \left(a\gamma + \frac{\gamma}{\gamma+1}\right)\vec{\beta}\times\vec{E}\right]$$

- ‘Magic momentum’ Lorentz factor $\gamma = 29.3, \left(a\gamma + \frac{\gamma}{\gamma+1}\right) = 0$

Arnaudon 1995 Z. Phys. C. 66, 45

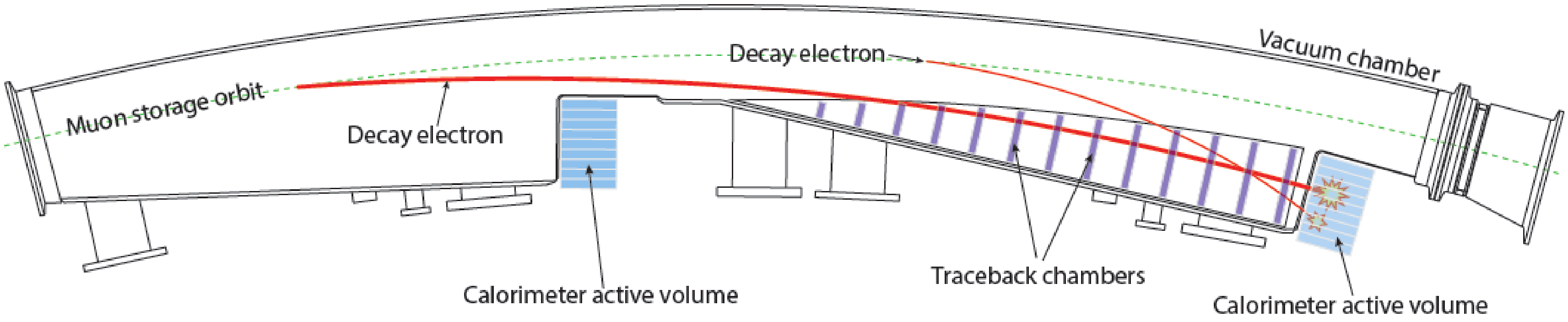
Muon storage ring

- Uniform bending field
  - Radius $\rho = 7.1\ \mathrm{m}$
  - Field $B = 1.45\ \mathrm{T}$
- Electrostatic quadrupoles
  - Vertical focussing
- Weak-focussing ring
  - Cyclotron $T_{\mathrm{cyc}} = 149\ \mathrm{ns}$
  - Betatron tune $Q_{\mathrm{x}} = 0.930$
  - $Q_{\mathrm{y}} = 0.370$
  - Spin tune $\mathrm{Q_{spin}} = 0.034$
- Decay electron detectors
  - Trackers
  - Calorimeters



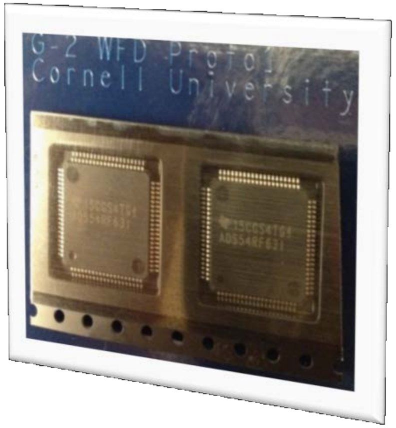
(The Muon (g-2) Collaboration), Phys. Rev. D, 73, 072003 (2006)

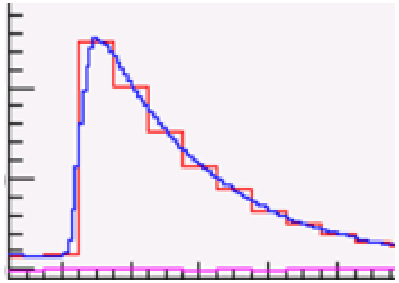
Decay electron detectors



Hertzog (The Muon (g-2) Collaboration) Fermilab PAC, 22 Jan 2014

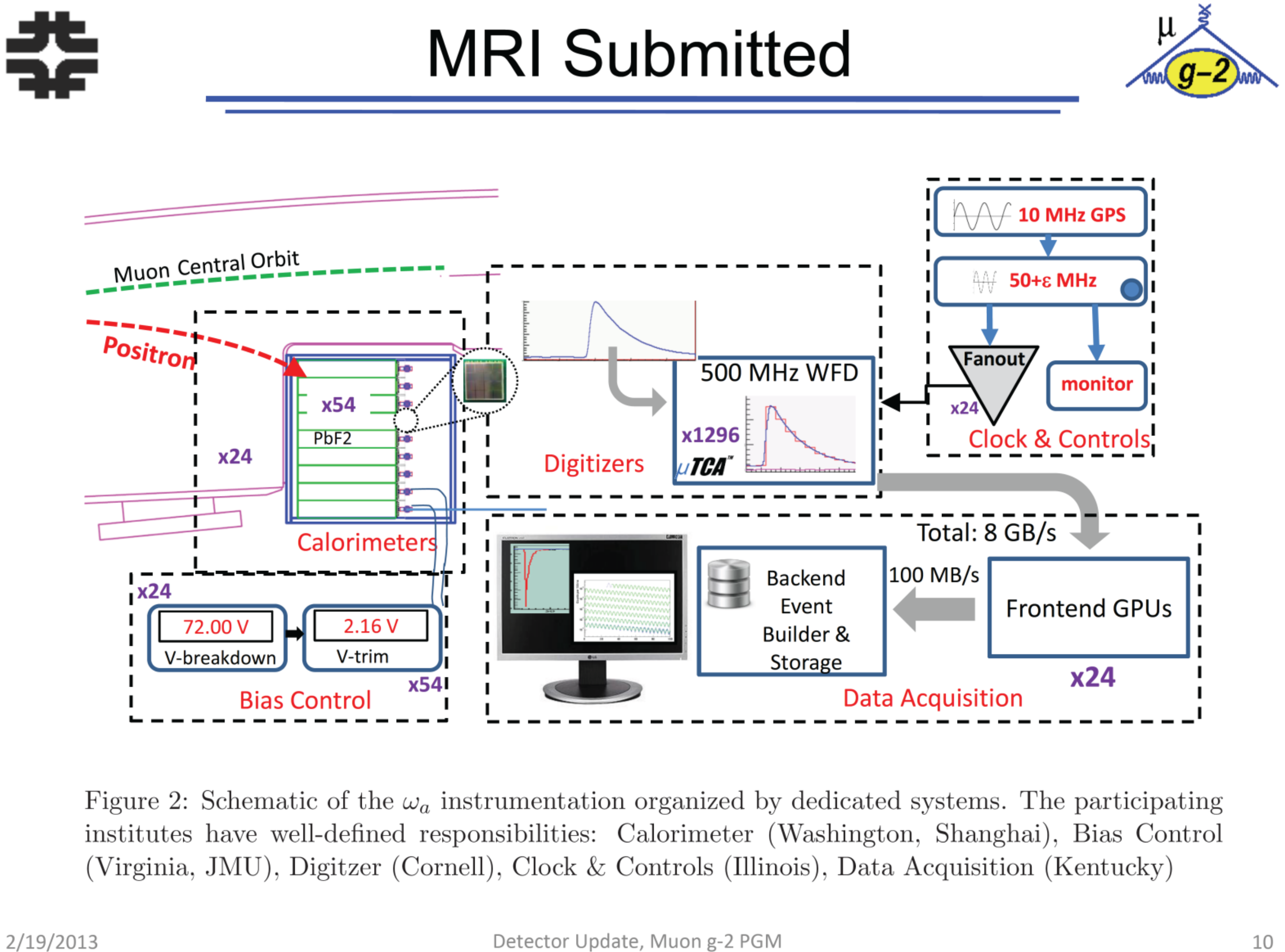
- Calorimeter
  - PbF$_2$ scintillator
  - Decay time $\approx 18\,\mathrm{ns}$
- ADC
  - Texas Instruments ADS54RF63
  - 12-bit ADC
  - 550 M samples per second





http://www.ti.com/product/ads54rf63

Decay electron detectors



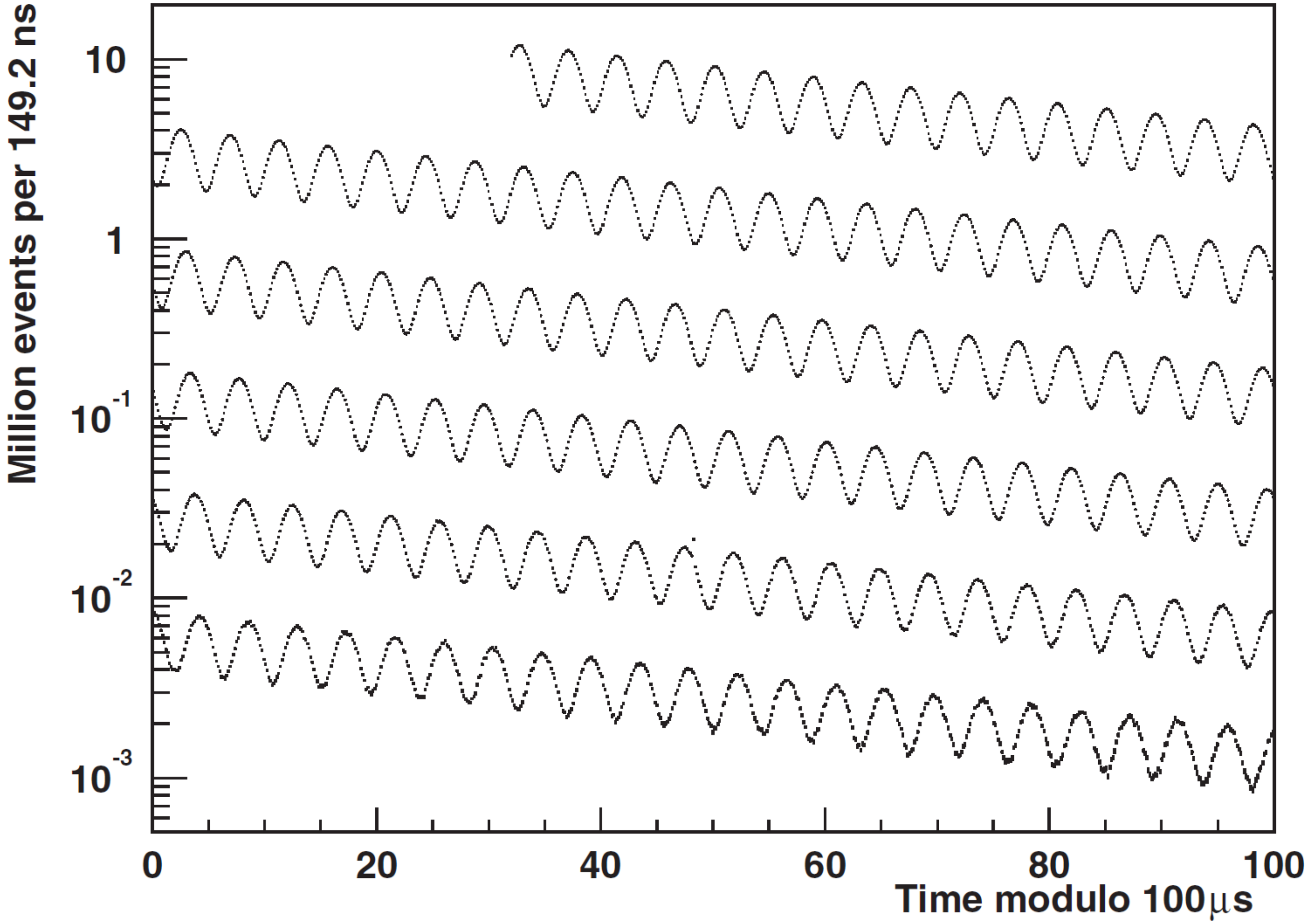
MRI Submitted

Figure 2: Schematic of the ω_a instrumentation organized by dedicated systems. The participating institutes have well-defined responsibilities: Calorimeter (Washington, Shanghai), Bias Control (Virginia, JMU), Digitzer (Cornell), Clock & Controls (Illinois), Data Acquisition (Kentucky)

2/19/2013 Detector Update, Muon g-2 PGM 10

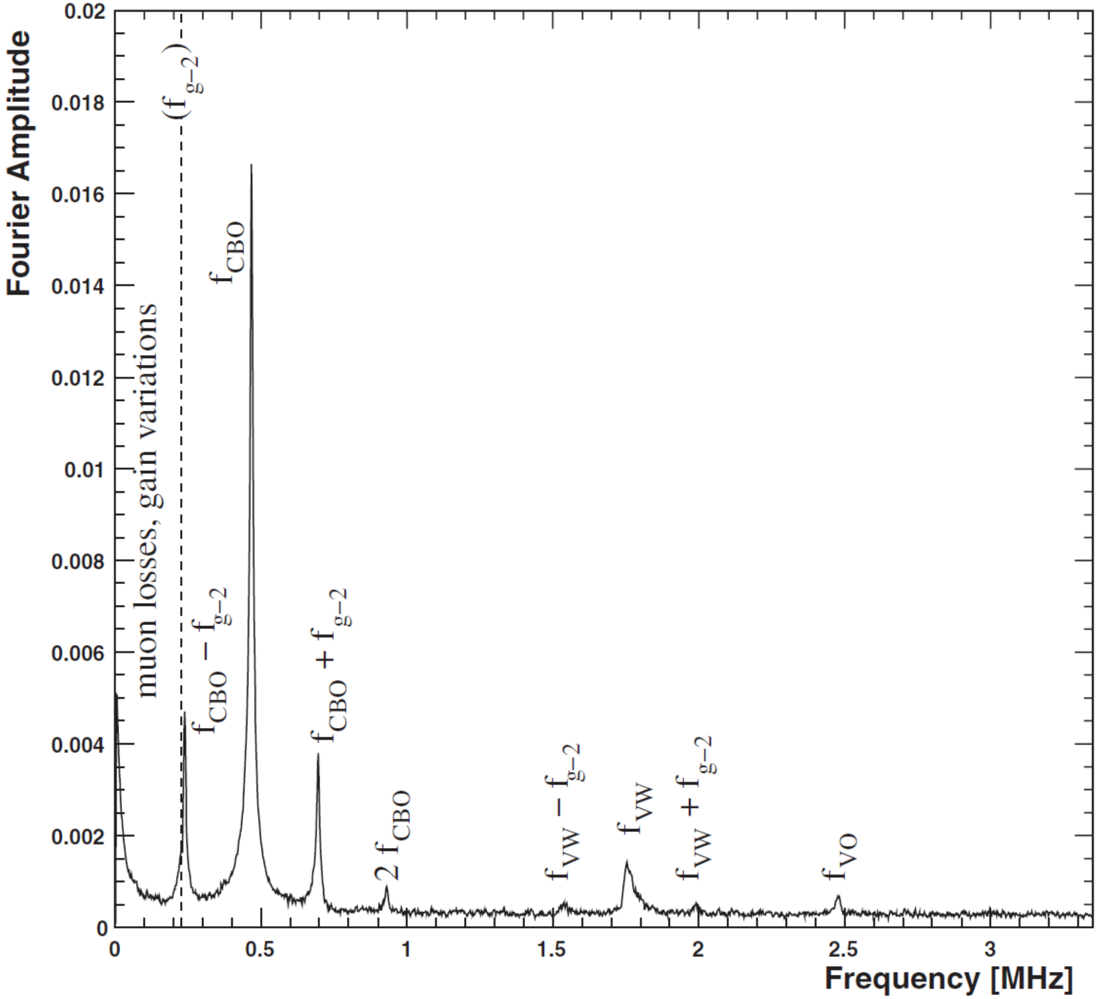
Hertzog (The Muon (g-2) Collaboration) Fermilab PAC, 22 Jan 2014

Decay electron detectors



(The Muon (g-2) Collaboration), Phys. Rev. D, 73, 072003 (2006)

Fourier transform – tune space



(The Muon (g-2) Collaboration), Phys. Rev. D, 73, 072003 (2006)

Summary

- Aim to measure muon anomalous magnetic moment to new precision
- Exploit magic momentum of 3.094 GeV
- Measure spin tune, cyclotron tune
  - Important to minimise systematic and statistical uncertainties
  - Avoid horizontal betatron tune

FUTURE ELECTRON BEAM G-2 EXPERIMENTS

Circular Unruh Effect

- Electromagnetic analogue of Hawking radiation
- Need accelerations possible approaching black holes
  - Of the order $a = 10^{20}\ \mathrm{m\ s^{-2}}$ $(E =\ 1400\ \mathrm{MV\ m^{-1}})$
  - Linacs $E \approx 10 - 100\ \mathrm{MV\ m^{-1}}$
- Circular accelerations

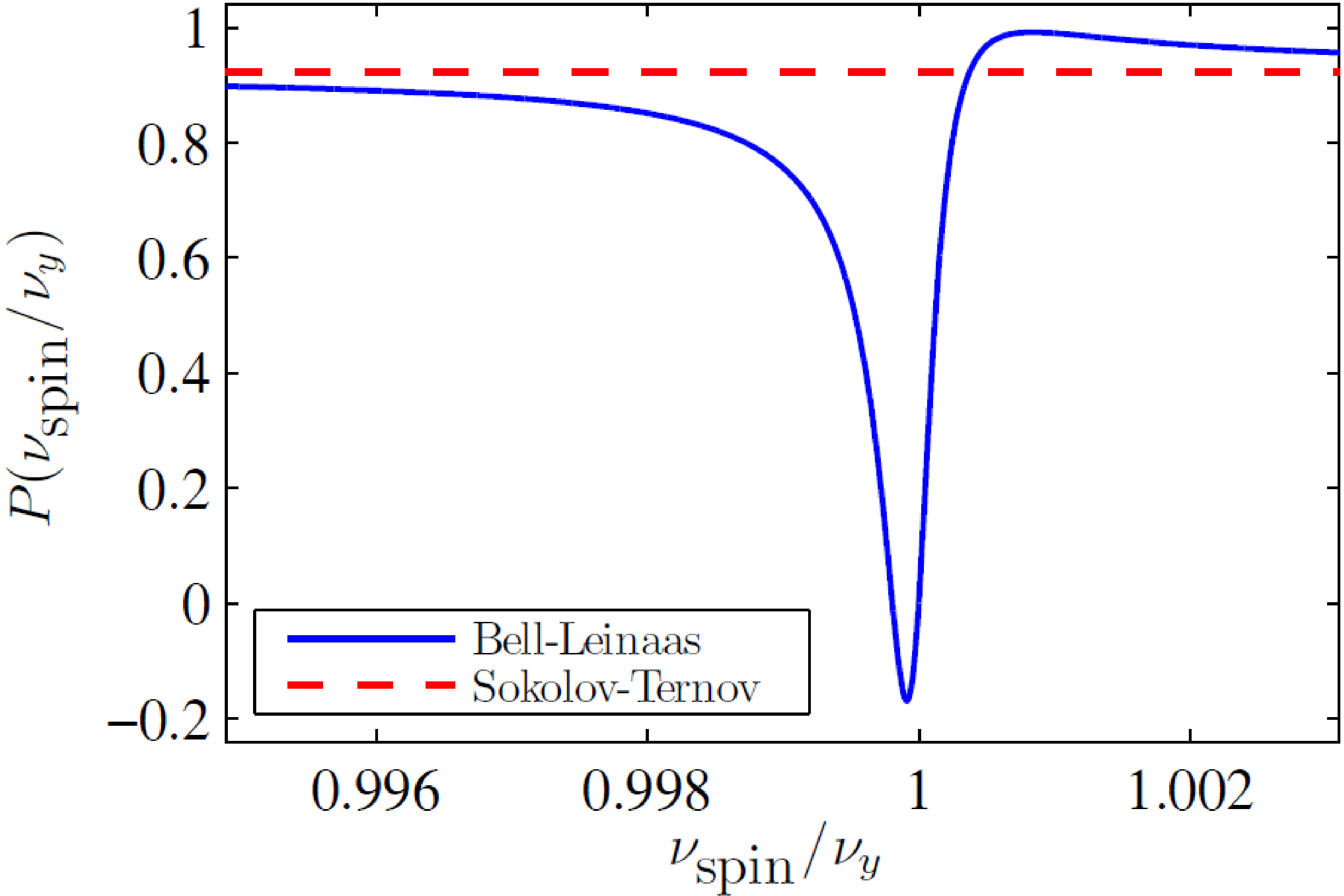
$$a = \frac{\gamma^2 c^2}{\rho}$$

- For $\gamma = 6000,\ \rho = 8\ \mathrm{m}$

$$a = 10^{23}\ \mathrm{m\ s^{-2}}$$

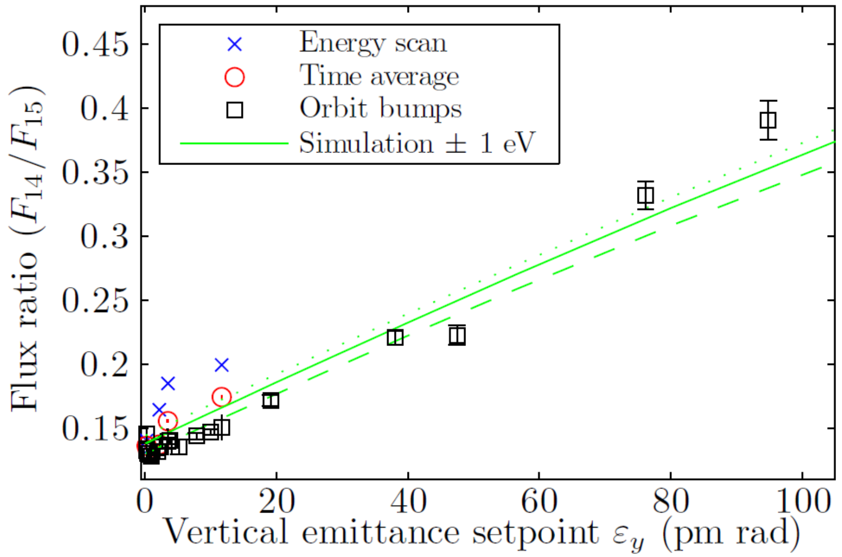
Bell and Leinaas (1983) Nucl. Phys. B 212, 131

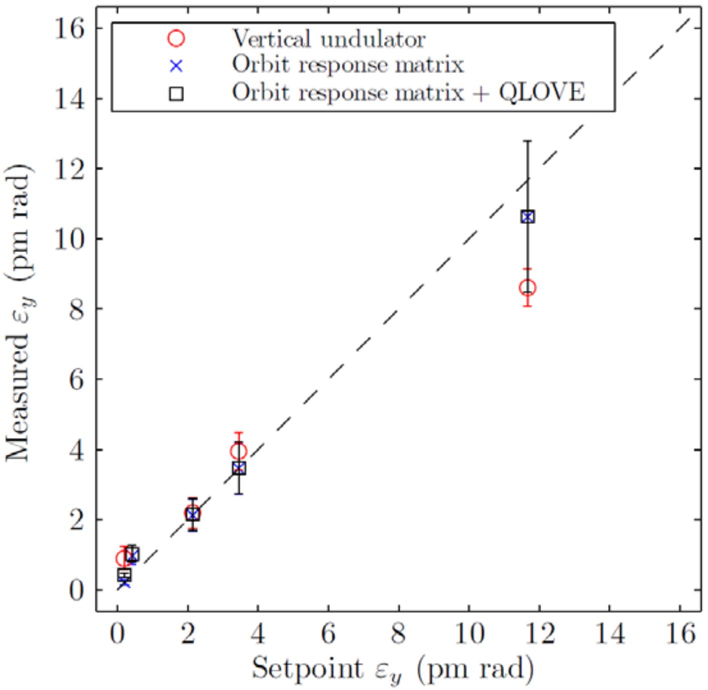
Bell-Leinaas Effect

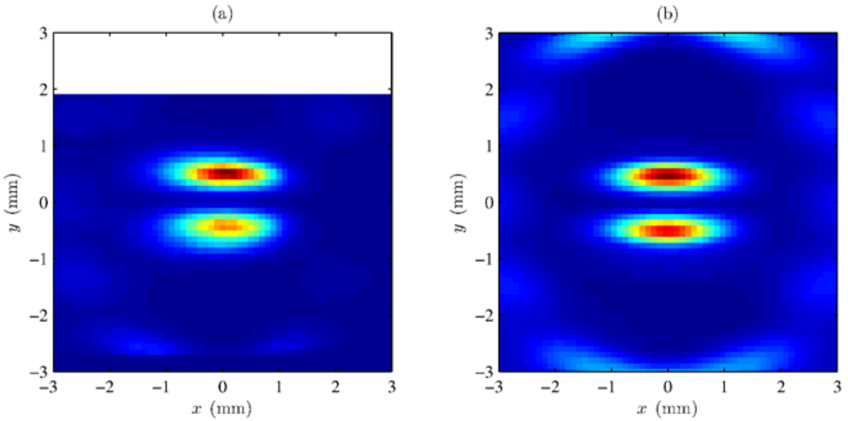


Bell and Leinaas (1983) Nucl. Phys. B 212, 131

Future electron beam g-2 experiments







K.P. Wootton, et al. (2012) Phys. Rev. Lett. 109, 194801.

Conclusions

- Spin is not a property often considered in accelerators
- Measure frequencies
- Determine either:
    - Properties of the accelerator (assume *a* known)
    - Properties of the beam (assume accelerator known)
- Electron experiments demonstrated calibration of unconventional bending magnet
- Fermilab muon g-2 experiment precision measurement
- Proposed experiment of circular Unruh effect using ultralow vertical emittance electron rings

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