EDM 2018

Mike 24th January 2018

2017

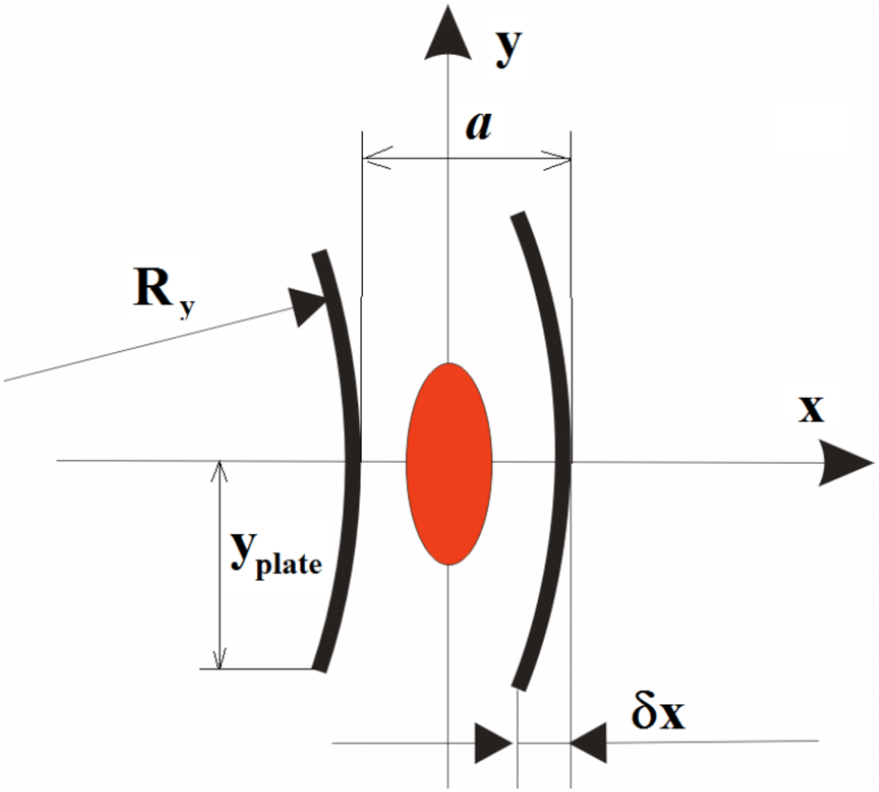
- 2011 BNL proposal
- Considerable effort by community
  - Components (shielding, deflectors…)
  - Instrumentation (SQUIDs, Polarimetry…)
  - Lattice
  - Simulations
  - Systematics
  - NB Lebedev's evaluation
- CERN
  - Sketch possible implementation
  - Components
  - Examine systematics

Working assumption: it's tough but doable

Questions on basics

- Systematics
  - In particular radial B-field – see Christian
- Simulations
  - Consistent handling of KE changes in electric field?
- Focusing strength
  - Weak
    - “required mechanical accuracies of bending plates manufacturing, assembly and installation look too tight”
  - Strong (AG)
    - Reduced sensitivity to effect of Br on CW/CCW splitting
    - Strong focusing rules out 10^{-29} e.cm (?)
  - Back to weak?

Requirements to Manufacturing and Installation of Bending Plates



- The plate bending radius in the vertical plane is $R_y = R_0 / m$ = 201 m
  - For vertical displacement y_{plate}=10 cm it yields δx of 25 μm
    - Looks impossible to manufacture and install with required accuracy
- Non-parallel plates (non-concentric plate surfaces) create skew-quad field with gradient $G_s = \theta E_0 / a$, where θ is the angle between plates
  - Requirement to have this skew gradient much smaller than the gradient of vertical focusing field, $\theta E_0 / a \ll m E_0 / R_0$, yields: $\theta \ll 1.5\cdot 10^{-4}$
    - with margin of 100 (skew quads are still required) one obtains very tight requirement: $\theta < 1.5\cdot 10^{-6}$
- Looks like that the required mechanical and installation accuracies are too tight => Soft-focusing -> Normal strong-focusing machine!!!

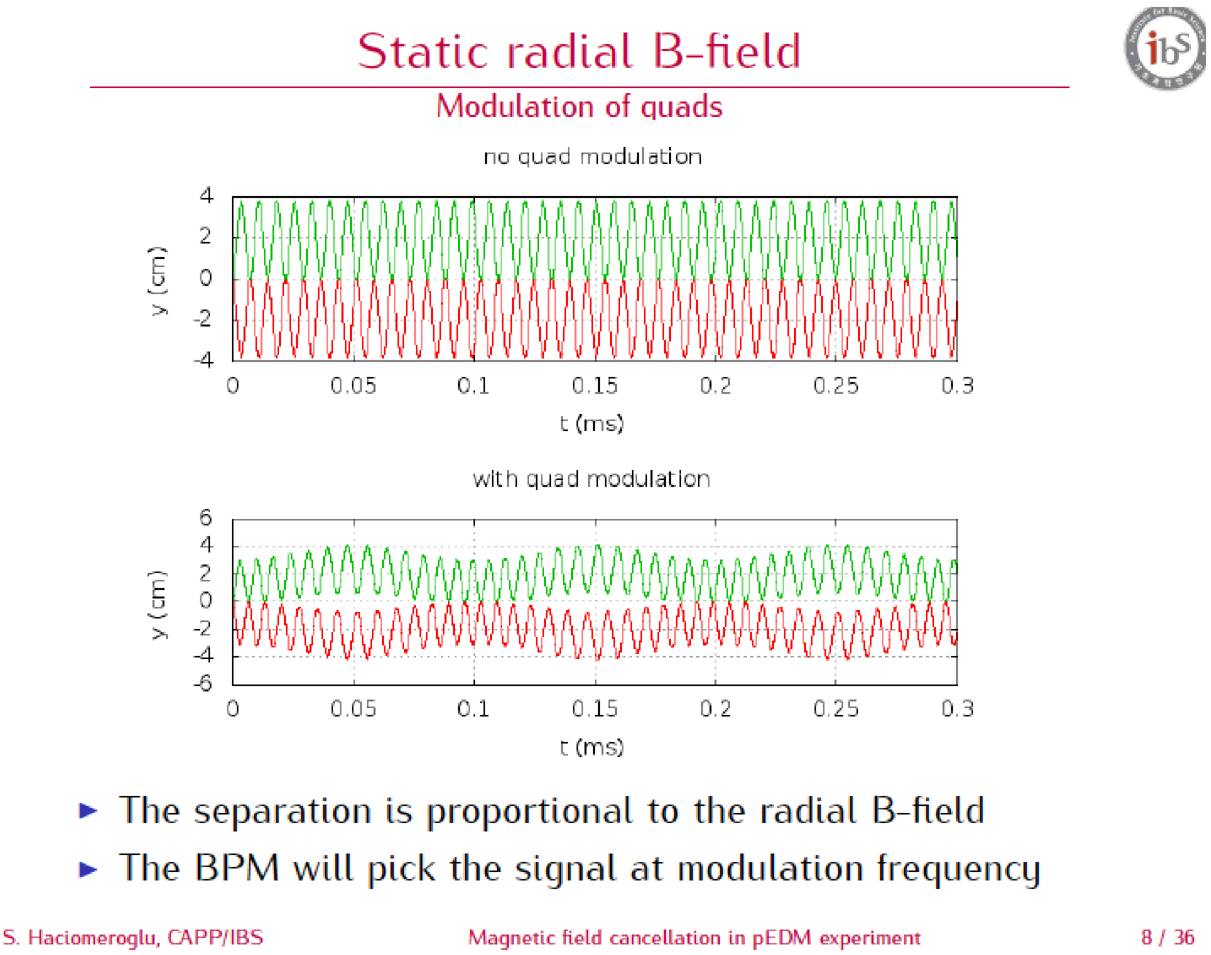
Conclusions

- Overall concept of proton EDM electrostatic machine is not limited by the considered beam-physics issues
- Judged on pure acceleration physics grounds the strong focusing ring looks better than the soft focusing ring
  - Larger momentum acceptance and particle number
  - Suppressed IBS rates

	Soft focusing	Strong focusing
Circumference, m	263	300
Qx/Qy	1.229/0.456	2.32/0.31
Particle per bunch	$1.5 \cdot 10^8$	$7 \cdot 10^8$
Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$	0.0046/0.0066	0.0146/0.0265
Rms emittances, x/y, norm, μm	0.56/1.52	0.31/2.16
Rms momentum spread	$1.1 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$
IBS growth times, x/y/s, s	300/(-1400)/250	7500
RF voltage	13	10.3
Synchrotron tune	0.02	0.006

- Analysis of spin decoherence for both rings is required to see their potential for EDM
    - In particular, the sensitivity of spin decoherence to sextupoles
- Small vertical tune requires exceptionally high mechanical accuracies of bending plates manufacturing
    - Corrections are required for any ring
    - At minimum a standard set: dipole correctors, trim quads, skew-quads and sextupoles.
    - Note that all soft-focusing machines which were built had much larger ratio of the gap to radius
        - It greatly alleviates problems
- 2 feedback systems are required to cancel the vertical magnetic field and keep the spin aligned along velocity
- It is not feasible how the average radial magnetic field can be suppressed below 1 nG
    - It is already unprecedented level of magnetic field suppression for such large vacuum chamber
    - Looks like we are above the desired value by about 4 order of magnitude

Can you get down to order 10 aT?



Static radial B-field

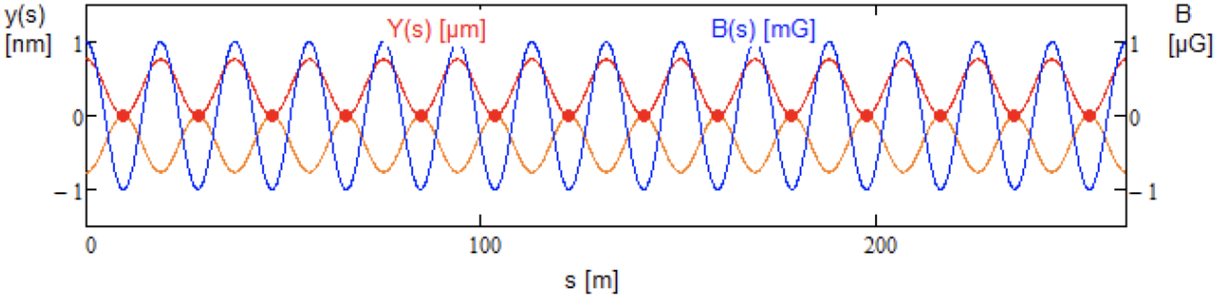
Modulation of quads

- The separation is proportional to the radial B-field
- The BPM will pick the signal at modulation frequency

S. Haciomeroglu, CAPP/IBS Magnetic field cancellation in pEDM experiment 8 / 36

See Christian… it's not obvious

- In principle, no magnetic shielding will be required with continuous BPM measurement around the ring.
- The finite number of detectors limits the magnetic field modes to which the system is sensitive by the Nyquist sampling theorem.
- The critical parameter is the detected average radial B-field and that can be wrong only when the mode is equal to the number of the BPM locations around the ring as well as its integer multiples.



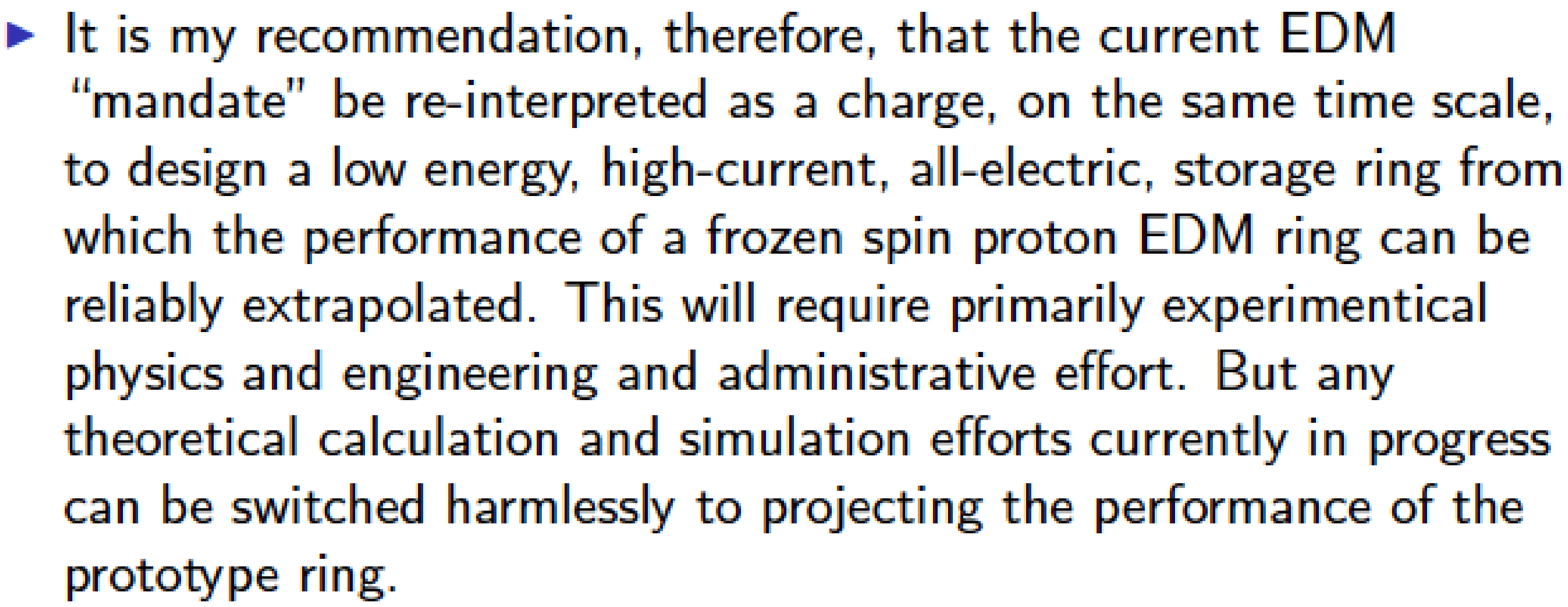
Are 10 SQUID-based BPM stations around the ring adequate?

Val Lebedev from Fermilab actually went through the whole experimental method a few years earlier. He asked all the correct questions and has written presentations, etc., on how to improve the ring design. In one point he had a typo, in a relationship showing the sensitivity to radial B-field higher modes around the ring. When we have 10 SQUID-based BPM stations around the ring, it is possible (unlikely, but possible) that there is an N=10 radial B-field, Fourier component around the azimuth, causing the counter-rotating beams to also oscillate in a similar manner, even though the total radial B-field integrated around the ring is zero! The correct one is

$$\frac{B_{r,N}}{B_{r,0}} = \left(\frac{N^2 - Q_y^2}{Q_y^2}\right)^2 \approx \left(\frac{N}{Q_y}\right)^4, \qquad (3)$$

which for N=10, and a vertical tune of Q_y=0.1, we gain eight orders of magnitude, i.e., the field would have to be higher than 1nT to cause a confusion. More stations might be needed if a higher vertical tune is used to keep the highest B-field component in the ring from going lower.

Cautious prototype



- It is my recommendation, therefore, that the current EDM “mandate” be re-interpreted as a charge, on the same time scale, to design a low energy, high-current, all-electric, storage ring from which the performance of a frozen spin proton EDM ring can be reliably extrapolated. This will require primarily experimentical physics and engineering and administrative effort. But any theoretical calculation and simulation efforts currently in progress can be switched harmlessly to projecting the performance of the prototype ring.

Richard Talman

Ambitious Prototype

- Reduced energy EDM ring on COSY footprint
- Spin tunes in superimposed electric and magnetic fields
- IRON-FREE strip-line magnetic field
- Frozen spin operation with weak vertical magnetic field
- Proton EDM measurement in ring matched to COSY footprint
- Low energy p-helium and p-carbon polarimetry candidates
- Electron EDM measurement in ring matched to COSY footprint

5 Reduced energy EDM prototype ring

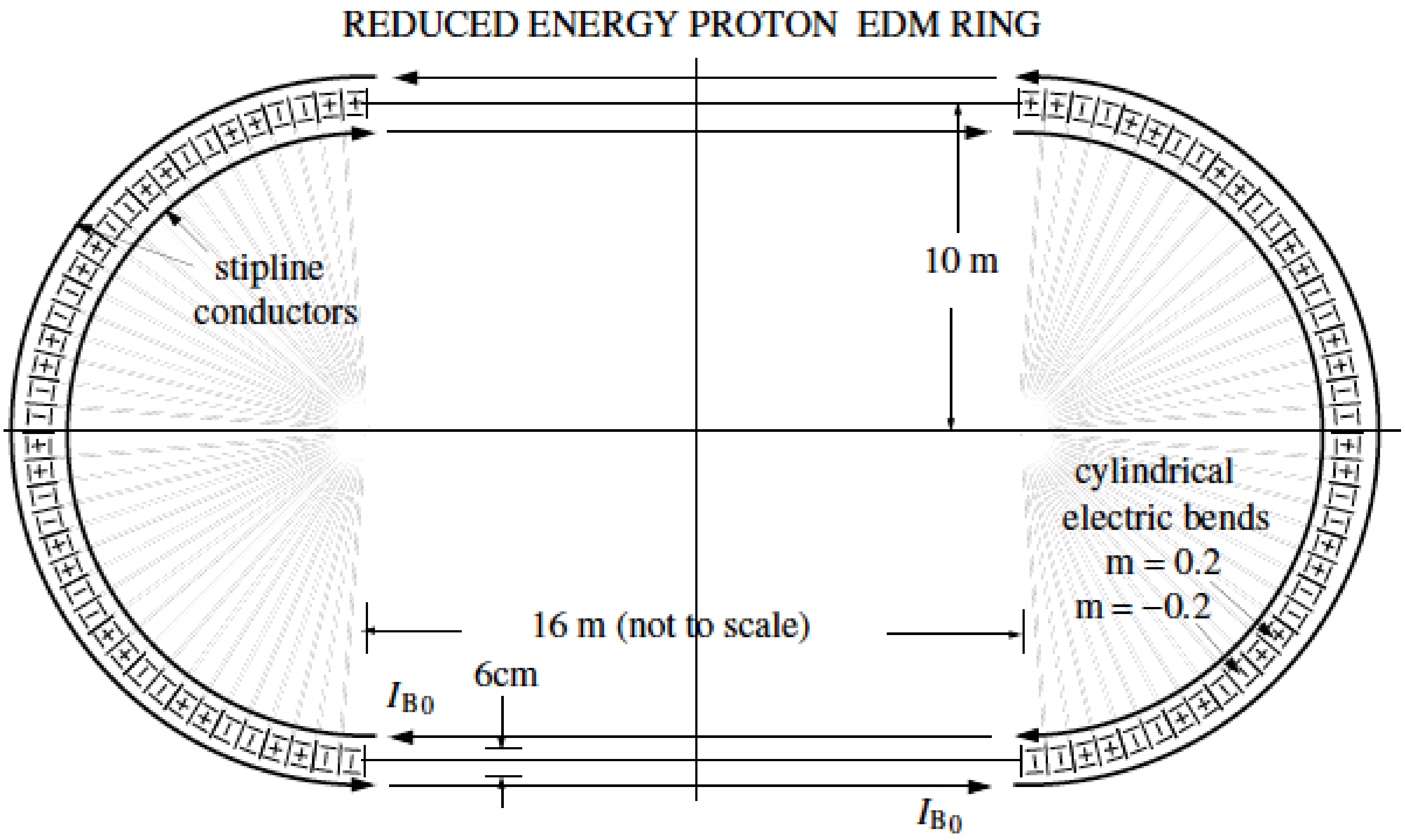


Figure 1: (Reduced energy and circumference) proton EDM prototype ring. Superimposed magnetic field (0.00865 T) is required because the proton 45 MeV kinetic energy is less than the 233 MeV magic energy required to freeze the spins in an all-electric ring.

7 Proton parameter table

Table 1: Parameters for maximum bend radius prototype on COSY footprint. The values in this, and subsequent tables are only crude, because the short drift lengths are being neglected. Since transverse dynamics is purely geometrical, kinematic quantities such as speed and energy, and even particle type, do not enter,

parameter	symbol	unit	value
arcs			2
cells/arc	$N_{\rm cell}$		20
bend radius	r_0	m	16
short drift length	L_D	m	1.2
accumulated drift length		m	83.2
circumference	$\mathcal{C}$	m	184
field index	m		± 0.2
horizontal beta (max)	β_x	m	57
vertical beta	β_y	m	1050
(outside) dispersion	D_x^O	m	9.7
horizontal tune	Q_x		1.81
vertical tune	Q_y		0.028
protons per bunch	N_p		1.0×10^8
horz. emittance	ϵ_x	μm	?
vert. emittance	ϵ_y	μm	?
(outside) mom. spread	$\Delta p^O/p_0$		$\pm 2 \times 10^{-4}$
(inside) mom. spread	$\Delta p^I/p_0$		$\pm 2 \times 10^{-5}$

Prototype

- If we continue… a prototype of some sort would appear inevitable
- To test:
  - Shielding, b-field compensation
  - Components
  - Instrumentation
  - Measurement techniques
  - Systematics

Option – axion search

- The method uses a combination of B and E-fields to produce a resonance between the $g - 2$ precession frequency and the background axion field oscillation to greatly enhance the sensitivity to it.

Axion search

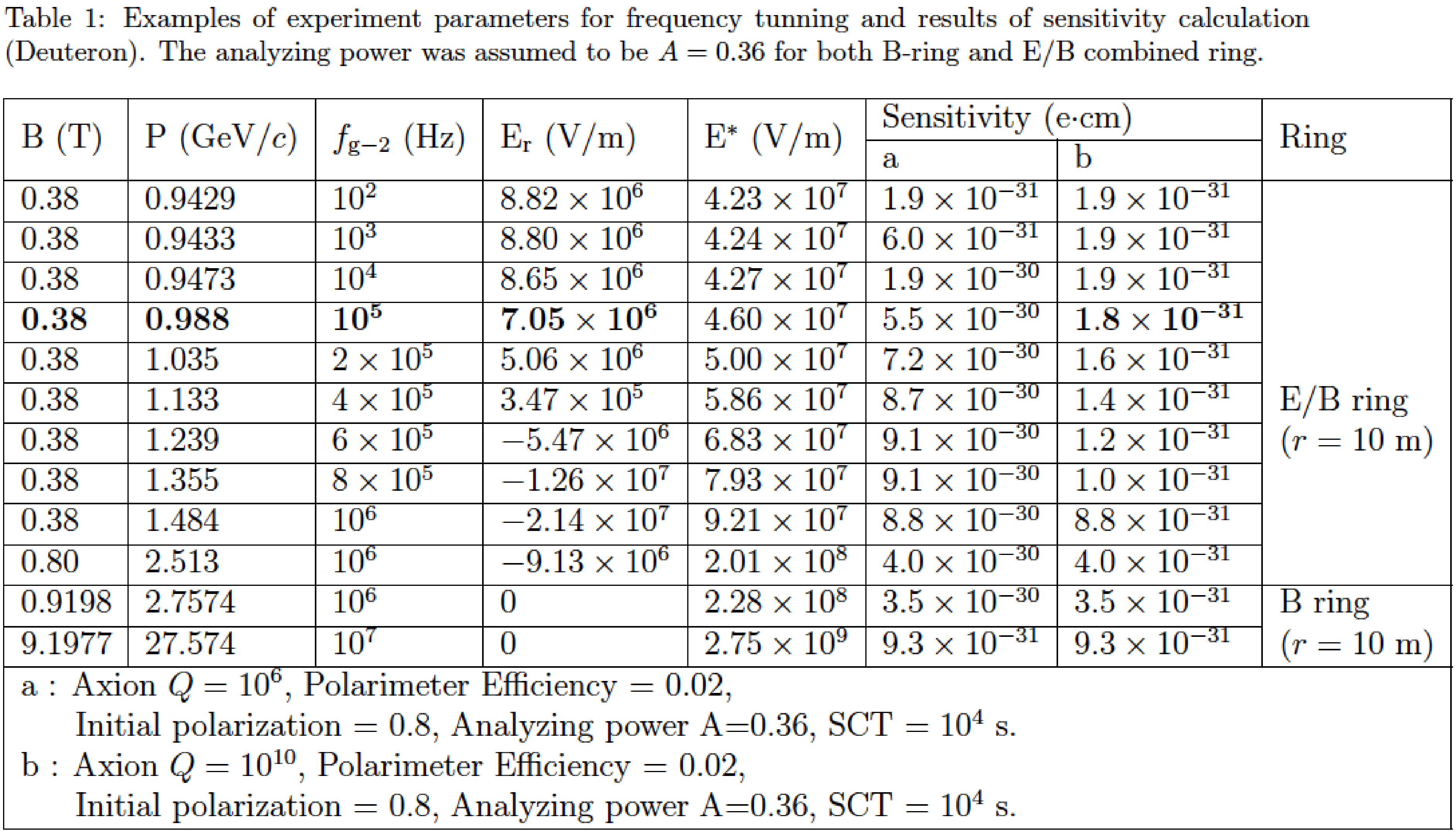


Table 1: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Deuteron). The analyzing power was assumed to be $A = 0.36$ for both B-ring and E/B combined ring.

B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm)		Ring
					a	b	
0.38	0.9429	10^2	8.82×10^6	4.23×10^7	1.9×10^{-31}	1.9×10^{-31}	E/B ring ($r = 10$ m)
0.38	0.9433	10^3	8.80×10^6	4.24×10^7	6.0×10^{-31}	1.9×10^{-31}	
0.38	0.9473	10^4	8.65×10^6	4.27×10^7	1.9×10^{-30}	1.9×10^{-31}	
0.38	**0.988**	$\mathbf{10^5}$	$\mathbf{7.05 \times 10^6}$	4.60×10^7	5.5×10^{-30}	$\mathbf{1.8 \times 10^{-31}}$	
0.38	1.035	2×10^5	5.06×10^6	5.00×10^7	7.2×10^{-30}	1.6×10^{-31}	
0.38	1.133	4×10^5	3.47×10^5	5.86×10^7	8.7×10^{-30}	1.4×10^{-31}	
0.38	1.239	6×10^5	-5.47×10^6	6.83×10^7	9.1×10^{-30}	1.2×10^{-31}	
0.38	1.355	8×10^5	-1.26×10^7	7.93×10^7	9.1×10^{-30}	1.0×10^{-31}	
0.38	1.484	10^6	-2.14×10^7	9.21×10^7	8.8×10^{-30}	8.8×10^{-31}	
0.80	2.513	10^6	-9.13×10^6	2.01×10^8	4.0×10^{-30}	4.0×10^{-31}	
0.9198	2.7574	10^6	0	2.28×10^8	3.5×10^{-30}	3.5×10^{-31}	B ring ($r = 10$ m)
9.1977	27.574	10^7	0	2.75×10^9	9.3×10^{-31}	9.3×10^{-31}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

Axion search

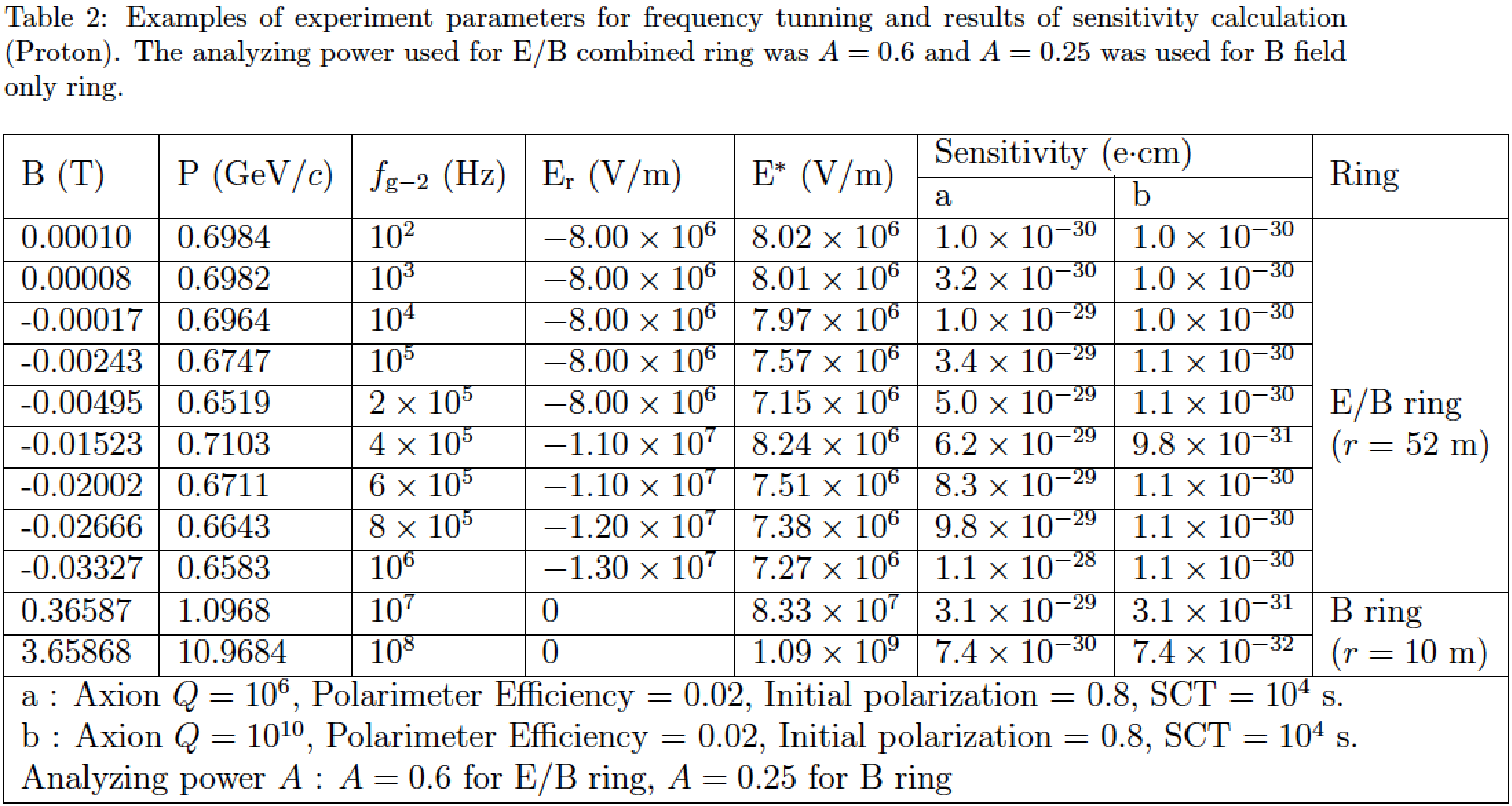


Table 2: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Proton). The analyzing power used for E/B combined ring was $A = 0.6$ and $A = 0.25$ was used for B field only ring.

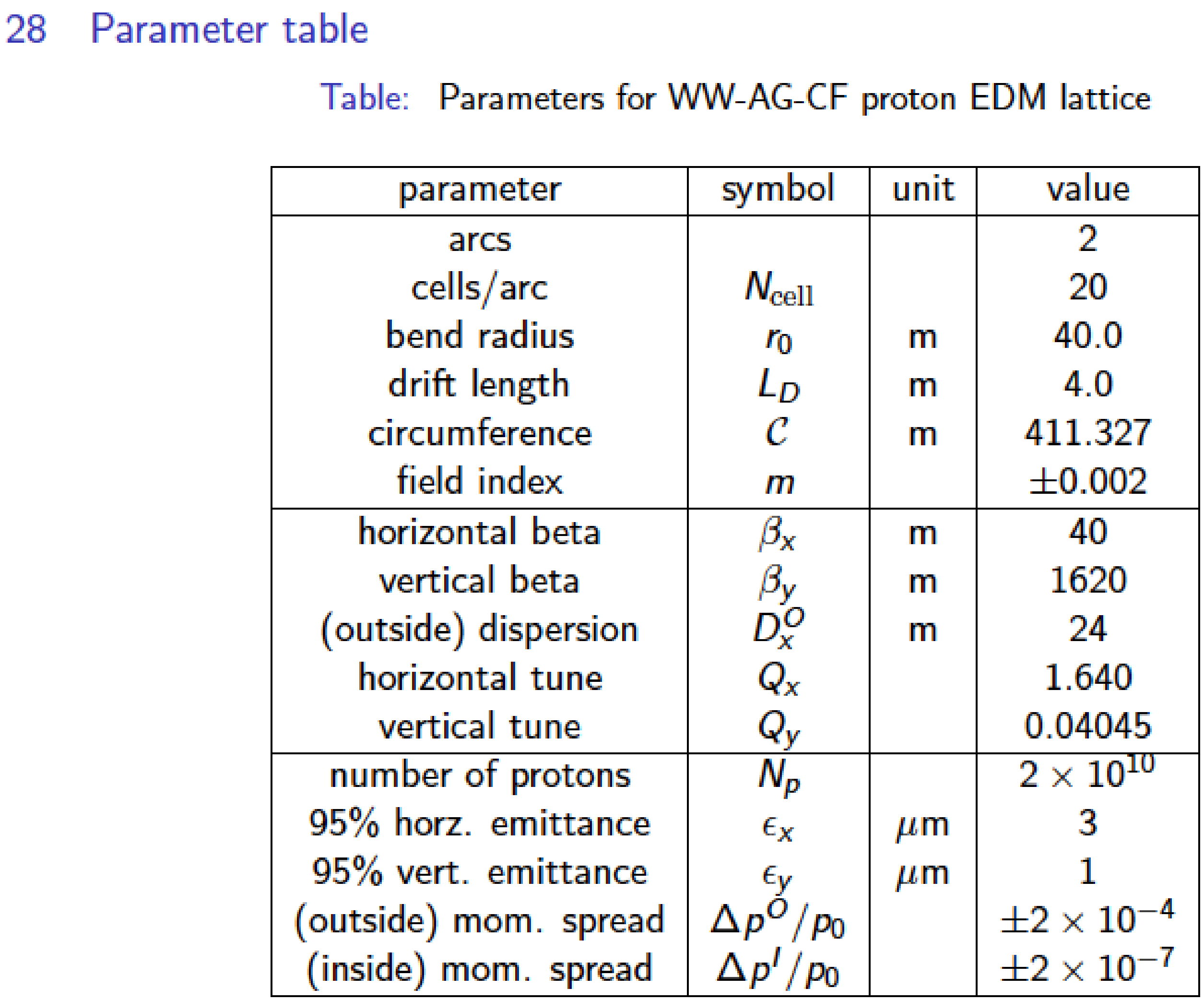
B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E* (V/m)	Sensitivity (e·cm)		Ring
					a	b	
0.00010	0.6984	10^2	-8.00×10^6	8.02×10^6	1.0×10^{-30}	1.0×10^{-30}	E/B ring ($r = 52$ m)
0.00008	0.6982	10^3	-8.00×10^6	8.01×10^6	3.2×10^{-30}	1.0×10^{-30}	
-0.00017	0.6964	10^4	-8.00×10^6	7.97×10^6	1.0×10^{-29}	1.0×10^{-30}	
-0.00243	0.6747	10^5	-8.00×10^6	7.57×10^6	3.4×10^{-29}	1.1×10^{-30}	
-0.00495	0.6519	2×10^5	-8.00×10^6	7.15×10^6	5.0×10^{-29}	1.1×10^{-30}	
-0.01523	0.7103	4×10^5	-1.10×10^7	8.24×10^6	6.2×10^{-29}	9.8×10^{-31}	
-0.02002	0.6711	6×10^5	-1.10×10^7	7.51×10^6	8.3×10^{-29}	1.1×10^{-30}	
-0.02666	0.6643	8×10^5	-1.20×10^7	7.38×10^6	9.8×10^{-29}	1.1×10^{-30}	
-0.03327	0.6583	10^6	-1.30×10^7	7.27×10^6	1.1×10^{-28}	1.1×10^{-30}	
0.36587	1.0968	10^7	0	8.33×10^7	3.1×10^{-29}	3.1×10^{-31}	B ring ($r = 10$ m)
3.65868	10.9684	10^8	0	1.09×10^9	7.4×10^{-30}	7.4×10^{-32}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.

b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.

Analyzing power A : $A = 0.6$ for E/B ring, $A = 0.25$ for B ring

Ultra-weak focusing



28 Parameter table

Table: Parameters for WW-AG-CF proton EDM lattice

parameter	symbol	unit	value
arcs			2
cells/arc	N_{cell}		20
bend radius	r_0	m	40.0
drift length	L_D	m	4.0
circumference	$\mathcal{C}$	m	411.327
field index	m		± 0.002
horizontal beta	β_x	m	40
vertical beta	β_y	m	1620
(outside) dispersion	D_x^O	m	24
horizontal tune	Q_x		1.640
vertical tune	Q_y		0.04045
number of protons	N_p		2×10^{10}
95% horz. emittance	ϵ_x	μm	3
95% vert. emittance	ϵ_y	μm	1
(outside) mom. spread	$\Delta p^O/p_0$		$\pm 2 \times 10^{-4}$
(inside) mom. spread	$\Delta p^I/p_0$		$\pm 2 \times 10^{-7}$

- Octupoles
- Rolling spin
- Resonant polarimetry

Conclusions

- Huge amount of work there in the EDM community
- However important questions still to be answered
  - Focusing etc.
  - Is the required level of accuracy achievable?
- Situation further muddied by options
  - Axion search, frequency domain, ultra-weak focusing etc.
- Prototype seems inevitable (if…)
  - Where to be decided
  - (CSR possibilities also being explored)

Next steps

- CP-EDM meeting 8-9 March
  - Should be interesting
- Thereafter re-scope for ESPP
  - At this stage imagine only a sketch of possible implementation at CERN/green field

Chapter	**Title**
	Executive summary
	Top level compilation
1	Introduction and motivation
2	Background and experience
3	Overview of pEDM experimental method
4	Ring design
5	Beam dynamics and control
6	Injection
7	Electric fields
8	Magnetic fields
9	Polarimetry
10	Instrumentation
11	RF, RF solenoids
12	Stochastic cooling
13	Measurement procedures
14	Systematics
15	Implementation
16	Prototype