Cautious Prototype EDM Plan

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3 Abstract

- Uncertainties concerning vacuum requirements and beam lifetime in all-electric storage rings suggest the need for a prototype proton storage ring capable of providing the data needed for a plausible feasibility study for an eventual, full-scale, proton EDM storage ring.
- A 7.5 MeV, all-electric, (cryogenic) proton storage ring is proposed. Its primary purpose would be to serve as a prototype for an eventual 233 MeV, all-electric frozen spin proton storage ring for measuring the electric dipole moment (EDM) of the proton.
- By commissioning the ring also with polarized 15 MeV electrons, the ring's secondary (but immediate) purpose would be to perform a frozen spin measurement of the electron EDM. (Depending on electron polarimetry not yet proven to be practical) the earliest elementary particle physics result the ring could achieve would be a measurement of the electron EDM, possibly lowering the already impressively low upper limit.

4 Abstract (continued)

- The two most serious uncertainties concerning the eventual proton EDM measurement concern the (current dependent) stored beam lifetime and the eventually achievable systematic error in the proton EDM measurement.
- Measurements using the proposed prototype ring would provide the information needed to resolve the first of these uncertainties. The proposed ring would also provide empirical experience needed to assess the systematic EDM error an eventual full-scale proton EDM ring could provide.
- The facility would also serve as a test bed for investigating stochastic cooling, vacuum system refinement, self-magnetometry, Touschek particle loss, IBS, and other critical issues any EDM storage ring will face.
- This is a natural sequel to a chain of previous facilities: the Brookhaven AGS-Analogue Ring, the Aarhus ELISA ring, and (especially) the Heidelberg CSR (cryogenic storage ring), all of which serve as partial prototypes for the eventual proton EDM ring.

5 The Brookhaven "AGS-Analogue" electrostatic ring

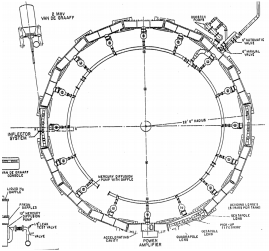

Figure 1: The 10 MeV "AGS-Analogue" elctrostatic ring has been the only relativistic all-electric ring. It was built in 1954, for U.S.$600,000. It could (almost) have been used to store 15 MeV frozen spin electrons. It was the first alternating gradient ring, the first to produce a "FODO neck-tie diagram", and the first to demonstrate passage through transition (which was its *raison d'être*).

- AGS Analogue, 1952
  conception, design, constructiom, complete physics program, decommission: 5 years
- EDM ring
  conception, design: 8 years and counting
- What gave AGS Analogue the advantage?
- Hint: computers only became available about 1955

6 Brookhaven Electron AGS Analogue

- The first EDM prototype was the 1954 Brookhaven Electron AGS Analogue, 1953-1957, described by Plotkin, and analysed in considerable detail in my book.
- Unlike the following "prototypes" this ring had the advantage (because it used 10 MeV electrons) of being fully relativistic.
- The full success of this project assured that the Courant-Snyder formalism describing magnetic rings is largely applicable to electric rings, in spite of the kinematic effects of changing electric potential in an electric ring.
- Beam capture into RF buckets was achieved, as was successful acceleration through transition. Transverse phase space structure was shown to conform closely to analytic theory.
- This was, however an accelerator, rather than a storage ring. Beam survival was measured in milliseconds.

7 Prototypes for an all-electric EDM storage ring

- Though none have been intended for this purpose, there have been three significant prototypes for an all-electric, electric dipole moment (EDM) storage ring. they are all plotted on more or less the same scale in Figure 2.
- ELISA and CSR are previously-constructed (non-relativistic) proton (and other ion) storage rings. Parameters for an 2012 BNL-proposed proton EDM ring are also included.
- A somewhat lower energy ring (satisfactory for reduced-precision proton EDM measurement) that would more or less match the existing COSY footprint is discussed in a later section.

parameter	symbol	unit	ELISA	CSR	pEDM -PROTO	pEDM-BNL
circumference	C	m	7.62	35	40	500
bend radius	r_p	m		1	3	40
electric field	E	MV/m			5	10
electrode gap	g	cm	4	6	3	3
gap voltage	V_g	KV	± 4	± 18	± 75	± 150
kinetic energy	K	MeV	0.025	0.3	7.5	233
proton velocity	v_p	m/s	2.2e6	7.5e6	3.77e7	1.8e8
revolution period	T_1	μs	3.5(p)	4.68(p)		2.78
momentum spread	$\Delta p/p$		$\pm$3e-3			$\pm$3e-3
RF voltage		KV	0.05			6.0
RF frequency	V_{rf}	KHz	10-500			
vacuum		torr	1e-11	1e-14	1e-14	1e-11
number of particles	N		1e7	1e7 (4e10 goal)		2e11
residual gas lifetime		s	20	2000		10,000 (req'd)
$\beta_{\max}$	spher.	m	12			
$\beta_{\max}$	cylind.	m	3.8			

8 Electrostatic EDM Prototype Storage Rings

Electrostatic accelerators that can be considered to be prototypes for the EDM storage ring are shown in the figure.

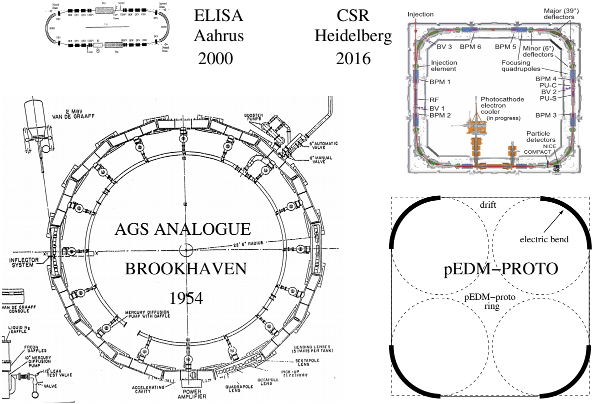

Figure 2: Layouts (all to more-or-less the same scale) of storage rings that can be viewed as prototypes for an eventual, all-electric, proton EDM storage ring, including, as well, a probably-undersized (because required equipment for injection, polarimetry, RF, etc is not included) cartoon of the proposed pEDM-PROTO ring.

9 ELISA storage ring

The second "prototype" was the ELISA storage ring shown in the figure. Properties of this ring are documented by S.P. Møller, in a series of papers listed in the bibliography.

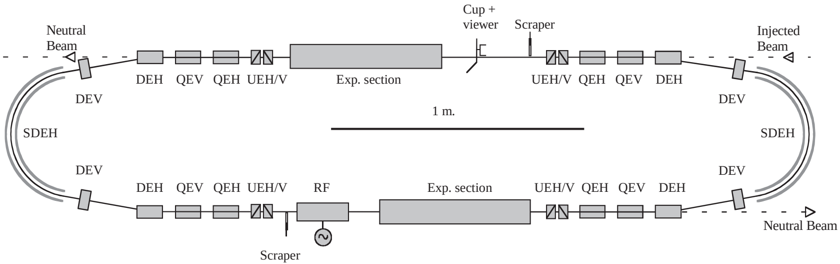

Figure 3: Layout of the ELISA low energy proton and ion storage ring, copied from Møller[2]

10 ELISA (continued)

- Designed for atomic physics, the ring has many components that are not relevant to our treatment of the ring as a prototype for high energy electrostatic storage.
- Still, though never intended as such, the ELISA ring can be viewed as a prototype for an all-electric proton EDM ring. Viewed in this way, ELISA provided serious warning concerning electrostatic storage rings.
- For a range of stored beam currents, beam survival in ELISA is plotted as a function of time, in Figure 4. As proton EDM prototype, the extremely short beam lifetimes cannot be regarded as promising.
- Furthermore the explanations for the lifetime limitations given in the reports mentioned above are not particularly persuasive. The experimenters eventually adopted "nonlinear effects" as the explanation for the curiously short beam survival time.
- For its intended atomic physics applications this limitation was apparently not debilitating, so the explanation for the lifetime behaviour was not pursued in depth.

11 ELISA (continued)

- To treat ELISA as a proton EDM prototype, it seems to me, demands a more persuasive understanding of the curiously non-exponential beam decay observed in ELISA.
- The superimposed tangents shown in the figure were drawn at $t = 0$ to the decay curves of Figure 4 and the resulting decay rates are plotted as a function of beam current in Figure 5.
- For low beam current the observed decay rate is 0.05/s. By itself, this was neither surprising nor alarming. It is consistent with their anticipated decay rate due to residual molecules in their vacuum system, based on their measured vacuum pressure. Extrapolated to the much stiffer frozen spin proton energy, achievement of beam lifetime sufficient for EDM measurement can be confidently predicted for the eventual proton EDM ring.
- *It is the rapid increase in decay rate with increasing beam current observed at ELISA that is alaming*.

12 ELISA (continued)

- A likely explanation for the suprisingly short ELISA beam decay time, it seems to me, is that some beam-dependent process exists, which leads to vacuum system degradation, proportional to beam current.
- No such effect is mentioned in their reports on ELISA performance. Possible current-dependent beam loss due to intrabeam scattering (IBS) is mentioned in the ELISA reports, but not considered by the authors to be strong enough to account for the high current behaviour.
- To the contrary, BETACOOL simulations reported by Papash[6] ascribe the high current beam loss to IBS.
- The quite high dispersion, relative to gap width, also increases the likelihood of loss of off-momentum particles. And the RF voltage, 0.05 KV, (strikingly low, for example, compared to the ± 4 KV, electrode voltages) suggests the possibility of Touschek effect particle loss out of stable RF buckets.

13 ELISA (continued)

- The ELISA authors emphasize the superior performance with cylindrical, as contrasted to spherical electrode shape. But, as read from their beta function plots, their maximum beta function values are $\beta_{x,max}$(cylindrical)=3.8 m and $\beta_{x,max}$(spherical)=12 m. Since the dominant beam loss from residual gas scattering presumeably appears at this point it is not surprising that the cylindrical choice yields longer beam lifetime.
- The larger value of $\beta_{x,max}$(spherical) results from the incidental focus near the ends of the electric bend elements. This focus happens to be sharper in the spherical case, which accounts for the larger nearby beta function.
- But this is fortuitous lattice design choice, and should not be read as incriminating the spherical electrode shape. (In fact, a ring with purely spherical electrodes is one of the few "integrable" lattices for which sinusoidal oscillations are valid to arbitrarily great amplitudes; i.e. there is no dynamic aperture limit.)

14 ELISA (continued)

- The inferior lifetime with spherical electrodes has to be blamed on the far larger value of $\beta_{x,max}$(spherical) in the spherical case, and not on the particular electrode shape.
- Because of the small gap width g needed to produce high electric field, the radial aperture of any all-electric proton EDM storage ring will always be uncomfortably small. Like ELISA, limited radial acceptance will make any such electric storage ring hypersensitive to vacuum pressure degradation of any kind.
- This is the consideration mentioned in the abstract, that strongly advocates the construction of a low energy prototype like the pEDM-PROTO ring proposed in this report.

15 ELISA beam lifetime

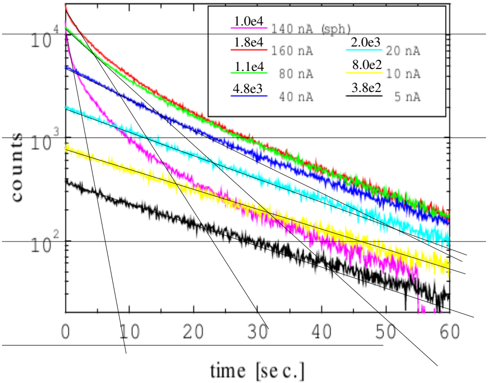

Figure 4: Stored ELISA beam current $I(t)$ (expressed as "counts" $C(t)$) surviving after time t, plotted vs t. The purpose for the straight lines superimposed on this graph (as preparation for the present report), was to determine the initial beam decay rate as a function of beam current. The results are plotted in Figure 5.

Table 1: ELISA decay data.

current nA	counts[0]	counts[t]	t s	electrode shape
160	1.8e4	1.0e2	22.5	cylindrical
80	1.1e4	1.0e2	36	"
40	4.8e3	1.0e2	54.5	"
20	2.0e3	1.0e2	56	"
10	8.0e2	1.0e2	46	"
5	3.8e2	1.0e2	28	"
140	1.0e4	1.0e2	6.5	spherical

17 ELISA beam lifetime (continued)

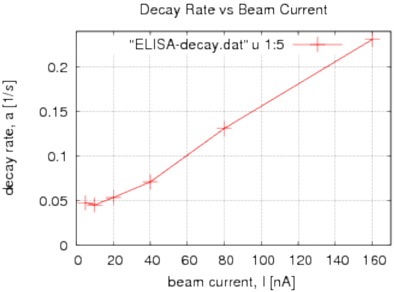

Figure 5: For beam current monitor counts $C(t)$, modeled as $C(t) = C(0)\, e^{-a(I)t}$, the initial decay rate $a(I)$ is plotted as a function of stored current I. Procedure for obtaining this data is explained in the caption to FIgure 4. For small beam currents the decay rate is roughly what is expected from scattering from residual vacuum chamber particles. *It is the rapid increase in decay rate with increasing beam current that needs to be understood, and rectified, before an optimistic feasibility study for an eventual proton storage ring EDM measurement can be produced.*

18 Heidelberg Cryogenic Storage Ring CSR

The third, most recent, and far more promising, prototype has been the CSR (Cryogenic Storage Ring), built recently in Heidelberg, and described by R. von Hahn et al.[7]. Very detailed, though preliminary, designs and cost estimates are given in reference [8]. Beam survival is plotted in Figure 6.

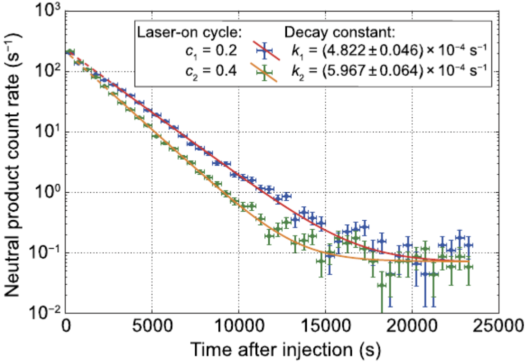

Figure 6: Beam survival plot for the Heidelberg CSR ring. This beam survival is at quite low beam current. Estimated parameters are given in the table shown previously..

19 CSR (continued)

- The extremely long beam lifetime (amply long enough for comfortable EDM measurement) can be ascribed to the cryogenic ring design. But, because the CSR proton beam current has so far been quite low, comparable with the low beam current data at ELISA, the possibility of current-dependent beam loss mechanisms. as observed at ELISA, has not yet been addressed at the CSR ring.
- A cartoon design for my proposed pEDM-PROTO ring is included in Figure 2. At a preliminary conceptual level, the ring will resemble the CSR ring, especially in the respect of cryogenic beam line elements and vacuum system. The most important difference will be the twenty-five times higher proton energy, which will require much longer electrodes, with much higher electric fields. Neither of these factors is likely to increase the cost very much, and the complexity and costs can be expected to be quite similar to CSR.

20 Electron spin tunes in electric and magnetic rings

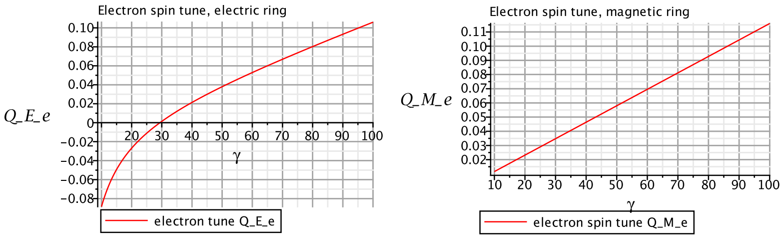

Figure 7: The “magic” value is $\gamma_e \approx 30$, but this can be changed by a large factor by superimposing magnetic field on the electric bending field.

21 (Minimal) shared ring, proton and electron kinematics

- The proposed prototype ring has to be capable of storing either electrons or protons (though not at the same time).
- Its actual radius $R_{\rm proto}$ will be set by the 15 MeV electron energy needed for frozen spin electron operation, along with an appropriately-conservative choice of bending electric field, $E_{\rm proto}$ ($\stackrel{\rm e.g.}{=}$ 5 MV/m).
- To allow for diagnostic equipment, injection, RF cavities, etc. the mean radius $\overline{R}_{\rm proto}$ ($\stackrel{\rm e.g.}{=}$ 7.5m) will be larger than $R_{\rm proto}$ ($\stackrel{\rm e.g.}{=}$ 3.75 m).
- Because of the mass difference between m_e and m_p, the electron kinematics will be almost fully relativistic, while the proton kinematics will be almost purely non-relativistic. It is convenient to use (quite accurate) approximate kinematic equations matched to the separate cases.

(Minimal) shared ring (continued)

Let R ($\overset{\text{e.g.}}{=}$ 40 m) be the bend radius of an eventual, practical, 233 MeV proton EDM ring. Allowing for drifts (needed for miscellaneous ring equipment and to achieve below-transition operation, the mean radius will be $\overline{R}$ ($\overset{\text{e.g.}}{=}$ 80 m), corresponding to 500 m circumference.

The relativistically-exact formula for a circular orbit of radius r in electric field E is

$$eE = \frac{m\gamma v^2}{r}. \tag{1}$$

For electrons, in fully-relativistic approximation, this equation becomes

$$eE = \frac{m_e c^2 \gamma_e \beta_e^2}{r} \approx \frac{\mathcal{E}_e}{r}, \tag{2}$$

where $\mathcal{E}_e$ is the total energy.

For protons in the same electric field E and radius r, in non-relativistic approximation, the equation becomes

$$eE = \frac{m_p c^2 \gamma_p \beta_p^2}{r} \approx \frac{m_p c^2 \beta_p^2}{r}. \tag{3}$$

Dividing the outer versions of Eqs. (2) and (3) produces

$$\beta_p^2 \approx \frac{\mathcal{E}_e}{m_p c^2} \left(= \frac{15}{938} = 0.0160 \right), \tag{4}$$

where the electron magic, frozen spin, total energy of 15 MeV has been assumed. The proton kinetic energy is

$$K_p = \frac{1}{2}\, m_p c^2 \beta_p^2 = \frac{\mathcal{E}_e}{2} = 7.5\,\mathrm{MeV}. \tag{5}$$

In words, the proton kinetic energy is equal to half the electron total energy, for a relativistic electron and a non-relativistic proton to have the same radius of curvature in the same electric field.

Treating all electrons as free, even if they are bound in atoms, the Rutherford scattering cross section formula for kinetic energy E_K proton scattering at laboratory angle Θ, into laboratory solid angle $d\Omega$, is

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha\hbar c}{4E_K \sin^2(\Theta/2)}\right)^2 = \frac{1.29\times 10^{-31}\,\mathrm{MeV}^2\mathrm{m}^2}{E_K^2\,\sin^4(\Theta/2)}. \qquad (6)$$

The solid angle within the range $d\Theta$ is

$$d\Omega = 2\pi\sin\Theta d\Theta \approx 4\pi\sin(\Theta/2)d\Theta, \qquad (7)$$

where the second form is valid for all realistically small scattering angles. Then the scattering cross section can also be expressed as

$$\frac{d\sigma}{d\Theta} = \frac{1.62\times 10^{-30}\,\mathrm{MeV}^2\mathrm{m}^2}{E_K^2\,\sin^3(\Theta/2)}. \qquad (8)$$

Particle loss (continued)

- Expressed, as they are, in terms of kinetic energy, these formulas are valid for both relativistic and non-relativistic particles.
- These well known formulas have been reviewed in the current context, only because the angular acceptance of *any all-electric ring will be pinched by the requirement that the maximum electric field is more-or-less inversely proportional to* g*, the gap between electrodes.*
- This, plus the requirement of weak focusing, to improve spin coherence time, and reduce systematic error in the EDM measurement, can result in the angular acceptance $\Theta_{\rm max}$ being small enough to cause single-scattered protons to be lost.

26 Particle loss (continued)

- These formulas are simple and non-controversial which, one would think, enable easy extrapolation from low energy to high energy incident protons. In particular, the numerator E_K^2 factor promises rapidly improving beam lifetime with increasing proton energy.
- *Regrettably, the other factor determining particle loss, namely residual vacuum, is neither simple nor non-controversial.*
- Rutherford scattering cross sections fall dramatically with increasing angle Θ, but they never vanish. Somewhat surprisingly, the maximum laboratory scattering angle, $\Theta_{\mathrm{max}} = m_e/m_p = 0.0005\,\mathrm{r}$, is independent of E_K.

27 Particle loss (continued)

- The angular acceptance of most modern accelerators is sufficiently greater than m_e/m_p that no single p,e scatter can cause the proton to be extracted from the ring and lost[9] so the main effect of Rutherford scattering is emittance growth.
- All-electric rings will not have this luxury of angular aperture large compared to m_e/m_p. It will always be possible for a proton to be lost by scattering from a stray electron. Of course the electron will also be ejected, but there is the danger that a cascade of electrons may be produced as a result. This could lead to regenerative beam loss, possibly accounting for the ELISA behavior.
- *It is this uncertainty that makes it essential for the ELISA beam lifetime performance to be understood before serious design of a full-energy proton EDM ring can proceed responsibly.*

28 Particle loss (continued)

- The excellent beam lifetime observed with the Heidelberg CSR ring confirms that, by producing more-nearly perfect vacuum, the low beam current lifetime can be made almost arbitrarily large.
- *This consideration alone shows that any eventual proton EDM storage ring has to have cryogenically-cooled electrodes.*
- Though this CSR experience is valuable and encouraging, it is not really definitive. For one thing, the electric field sections are very short and represent only a quite small fraction of the CSR ring. More important, as I read their report, their experience so far is limited to proton beam currents too small for the anomalously short ELISA lifetime effct to have been encountered.
- Any mechanism, regenerative or otherwise, by which a high current proton beam causes vacuum degradation, can be lethal for the eventual proton EDM experiment. *Fortunately, since any such mechanism is unlikely to depend unpredictably on proton energy, it can be studied at quite low proton energy, with correspondingly less expensive apparatus.*
- It seems to me, therefore, that the only responsible next step toward assessing the feasibility of the storage ring EDM experiment is to build a prototype all-electric proton ring along the lines advocated in this report.

29 Conclusions and recommendations

- The storage ring EDM group has been invited to produce a report, due before the end of 2018, discussing the feasibility of storage ring measurement of proton and deuteron. Because the proton experiment is so much easier, the first phase of such a program, and therefore also of the feasibility study, can be expected to concentrate on the proton EDM measurement.
- Based on substantial theoretical and simulation studies and, especially, on experimental investigations at the COSY lab, Juelich, a substantial fraction of such a report can be based on current understanding. Surprisingly, some issues which were once terrifying, such as spin coherence time, polarimetry, and systematic errors, are already quite well understood. As a result, there is little doubt, once stable storage ring operation has been achieved, that the proton EDM can be measured with significantly better accuracy than the current neutron EDM upper limit.
- Meanwhile there are accelerator physics uncertainties concerning the mundane functioning of an all-electric EDM ring to store enough protons for long enough to perform the EDM measurement. There is no possibility whatsoever, for theoretical calculations and simulations performed over the next year (or longer) to change this situation. *The uncertainties can only be removed by experimentation.*

30 Conclusions and recommendations (continued)

- Once one accepts this conclusion one should also accept that activity should be be diverted immediately to planning for, and designing, an economical prototype facility specially designed to address accelerator physics uncertainties concerning the performance of high current electrostatic storage rings. This was the approach taken in 1953, when doubts about strong focusing arose at Brookhaven. It has been the approach taken, in many labs, for the ILC. It is a standard approach.
- 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.

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- Loss of protons by single scattering from residual gas is discussed in detail in a paper Frank Rathmann drew to my attention: C. Weidemann et al., *Toward polarized anti-protons: Machine development for spin-filtering experiments,* PRST-AB **18**, 0201, 2015