Small Project Final Report, July, 2015

DOE Office of Nuclear Physics (NP)
Facilities and Project Management Division

<u>Proposal Name:</u> Simulation and Optimization of the Spin Coherence Time for the Proton EDM Measurement. OSP Number: 62355/A001

<u>Report Date:</u> July 15, 2015

<u>Principal Investigator:</u> Richard Talman, Professor of Physics, emeritus, Cornell

<u>Work-scope Highlights:</u>

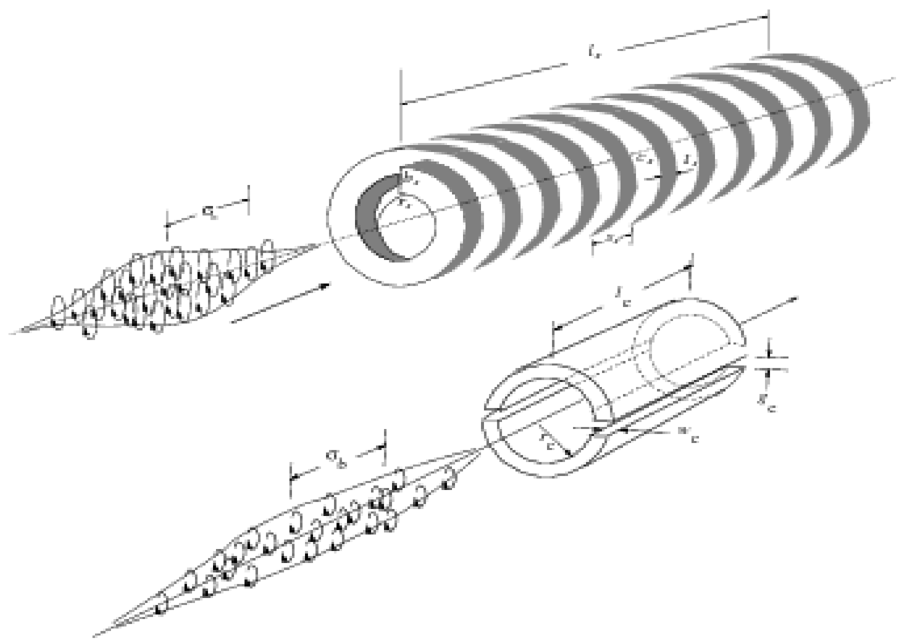
This is the ninth (and final) quarterly report under the 2013 grant (and the sixteenth of the continuing project). This quarter has been devoted to developing and preliminary testing of a novel "resonant polarimeter" to be used for measuring the polarization of beams in storage rings. This will be the main topic covered in this quarterly report.

The ETEAPOT computer code produced under the grant has been documented in one paper and its practical application has been described in another. Both of these papers have been accepted for publication in Physical Review, and are currently at the final proofreading stage, for their simultaneous publication. A 90 page "white paper" on design issues for a circular Higgs factory, arXiv:1504.01627vi [physics.acc-ph] 29 Mar 2015, " Scaling Behavior of Circular Colliders Dominated by Synchrotron Radiation" has also been accepted for publication in the World Scientific Journal, IJMPA.

The recent P5 High Energy Particle Physics Panel has endorsed the importance of measuring the EDM of the proton (and other elementary particles). This matches well with our state of development of UAL/ETEAPOT, whose purpose is modeling the all-electric storage rings needed for measuring the proton EDM (or, alternatively, the electron EDM).

Electron and proton EDM's can be measured in "frozen spin" (with the beam polarization always parallel to the orbit, for example) storage rings. For electrons the "magic" kinetic energy at which the beam can be frozen is 14.5 MeV. For protons the magic kinetic energy is 230 MeV. The currently measured upper limit for the electron EDM is much smaller than the proton EDM upper limit, which is very poorly known. Nevertheless, because the storage ring will be an order of magnitude cheaper, a sensible plan is to first build an all-electric electron storage ring as a prototype. Such an electron ring was successfully built at Brookhaven, in 1954, as a prototype for their AGS ring. This leaves little uncertainty concerning the cost and performance of such a ring. (This is documented in one of the Physical Review papers mentioned above.)

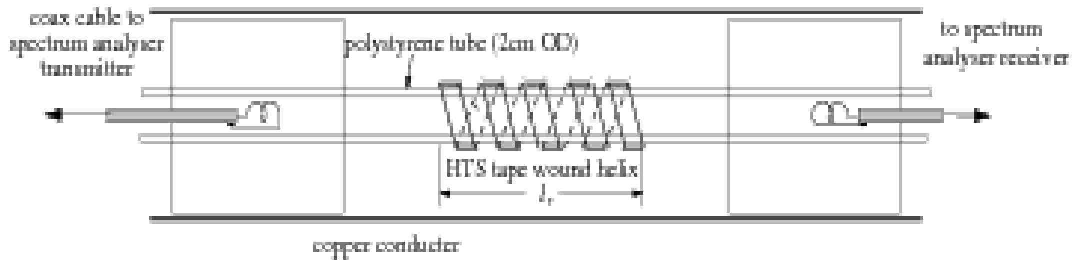
An important requirement for storage ring EDM measurement is the polarimetry needed to measure and control the beam polarization. For protons the polarization can be measured using the left-right (or up-down) asymmetry in scattering from carbon. This is "active" or "destructive" in the sense that the scattered protons are lost. Nevertheless it has been shown at the COSY ring in Juelich, Germany, because the analysing power is high, that this form of polarimetry is promising for the proton EDM mesurement. Electron beam polarization can also be measured actively by similar scattering or, alternatively, by laser scattering. But, in both cases, the analysing power is small---only a few percent. More effective polarimetry would greatly enhance the ability to measure, first, the electron EDM and, later, the proton EDM.



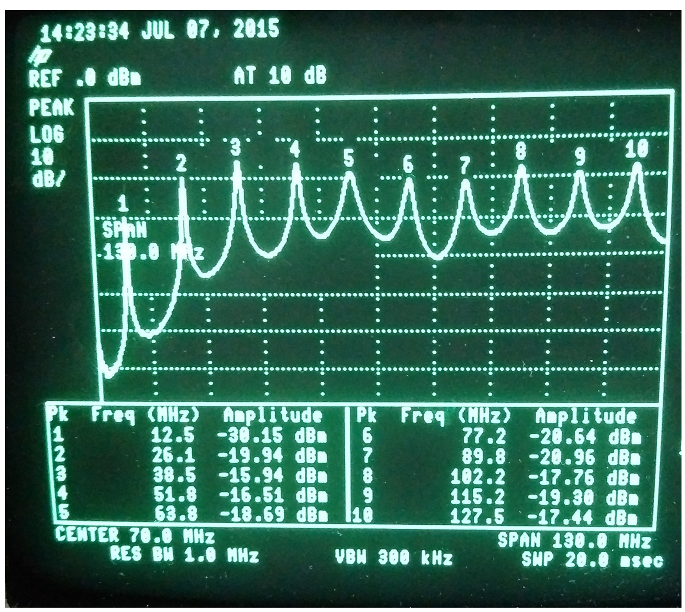
In a paper for the recent Cornell Workshop on High Current Electron beams, I have proposed to measure beam polarization by "resonant polarimetry". The figure shows a longitudinally polarized beam approaching a solenoid resonator (above) or a split-cylinder resonator (below). In nuclear magnetic resonance (NMR) the fields in a resonator "ring up" the nuclear spins. Here the spins ring up the resonator. A signal is produced in the solenoid by the magnetization of the passing beam. The solenoid, acting as a high-Q resonator, rings up to a measurably large amplitude. This polarimeter would be passive (no beam loss) with 100 percent analysing power.

After theoretical calculation of the excitation measurement (described in the paper just mentioned) the next step is to analyse the resonator circuitry. A set-up for doing this is shown in the next figure. The tracking generator of a spectrum analyser is weakly magnetically coupled at one (input) end of the solenoid and the spectrum analyser receiver is similarly coupled at the output end of the solenoid.

Such a configuration was setup with a 44 turn copper coil of length 27.9 cm, diameter 7.62 cm. Such a solenoid acts as a slow wave transmission line. (It is essential for the beam speed to differ from the transmission line phase velocity in order for energy to be transmitted from the beam to the resonator.) Such a transmssion line, open at both ends, has a fundamental resonance when the solenoid length is equal to 1/2 the guide wavelength. The solenoid is also resonant for all integer harmonics of the fundamental. The total number of observable harmonics should be equal to the the solenoid length divided by the wave guide half-wavelength.



The spectrum analyser display for this setup (though with room temperature copper rather than superconductor) is shown in the next figure. By showing 10 harmonics of the fundamental frequency of 12.5 MHz, this figure confirms the expected harmonic spectrum, and empirically establishes the resonator parameters. This is just a test, however, using an available, but unduly large diameter, solenoid coil having more turns than will be appropriate for the eventual polarimeter.



The actual polarimeter resonant frequency is expected to be in the range 100 MHz < f_s < 1000 MHz. The following table shows the parameters for three test configurations and for three actual EDM storage ring applications. There are two major concerns about the practicality of this form of polarimetry. Even though the solenoid is largely insensitive to the direct Coulomb field of the passing charged beam bunch, this signal would overwhelm the magnetization signal, should both be at the same frequency. This makes it essential for the magnetization signal to be frequency-shifted away from the revolution frequency (or any harmonic of the revolution frequency). This can be accomplished by "rolling" the magnetization (i.e. slightly unfreezing it) at a frequency in the kiloHertz range. Such a rolling polarization can be produced artificially in a polarized linac beam, such as at J-LAB. It can also be produced in an EDM storage ring; examples are given in the table.

The other issue concerns the absolute level of the induced magnetization signal---being the result of the longitudinal Stern-Gerlach force, the signal is very weak. This requires the resonator Q-value to be very high, as shown in the table. For the polarimeter to

experiment			TEST	TEST	e-EDM	e-EDM	p-EDM	TEST
parameter beam conductor	symbol	unit	electron J-LAB linac HTS	electron J-LAB linac SC	electron ring HTS	electron ring SC	proton ring SC	proton COSY SC
ring freq.	f_0	MHz			10	10	1	9.804
magn. mom.	μ_p	eV/T	0.58e-4	0.58e-4	0.58e-4	0.58e-4	0.88e-7	0.88e-7
magic β	β_p		1.0	1.0	1.0	1.0	0.60	0.6
reson. freq.	f_r	MHz	190	190	190	190	114	114
reson. rad.	r_r	cm	0.5	0.5	2	2	2	2
reson. leng.	l_r	m	1.07	1.07	1.07	1.07	1.80	1.80
temperature	T	°K	77	1	77	1	1	4
phase vel./c	β_r		0.68	0.68	0.68	0.68	0.408	0.408
qual. factor	Q_r		1e6	1e8	1e6	1e8	1e8	1e6
resp. time	Q_r/f_r	s		0.53	0.0052	0.52	0.88	0.0088
beam current	I	A	0.001	0.001	0.02	0.02	0.002	0.001
bunches/ring	N_b				19	19	114	116
particles	N_e				1.2e10	1.2e10	1.2e10	6.4e9
part./bunch	N_e/N_b		3.3e7	3.3e7	0.63e9	0.63e9	1.1e8	5.5e7
mag. field	H_r	Henry	2.6e-7	2.6e-6	1.3e-6	1.3e-4	2.3e-6	1.15e-8
reson. curr.	I_r	A	2.2e-8	2.2e-6	2.2e-7	2.2e-5	0.50e-6	2.6e-9
mag. induc.	B_r	T	3.3e-13	3.3e-11	1.6e-12	1.6e-10	2.8e-12	1.4e-19
max energy	U_r	J	2.9e-23	2.9e-19	2.9e-21	2.9e-17	1.5e-20	3.8e-25
noise energy	$\overline{U_m}$	J	0.53e-21	0.69e-23	0.53e-21	0.69e-23	0.69e-23	2.8e-13
S/N(ampl.)	$\sqrt{U_r/\overline{U_m}}$		0.23	206	2.3	2055	45.8	0.117
S/N(ph-lock)	$(S/N)\sqrt{f_0}$	$s^{-1/2}$	3.2e3	2.8e6	3.2e4	2.8e7	4.9e5	1248

function satisfactorily it is essential for the signal to be large compared to the inevitable thermal noise level. Signal to noise ratios are given in the bottom two rows of the table. The second from bottom row gives the signal to noise ratio for a single pass measurement. In some of the cases this ratio is far too small to give a detectable single pass signal. The bottom row gives the signal to noise ratio that is achieved by phase-locking the detection for measurement times measured in seconds. The actual signal to noise ratio is obtained by multiplying the given factor by the square root of the measurement time in seconds. To achieve satisfactorily high Q-values it is essential for the resonator to be superconducting. Adequately high Q-values can be achieved with either high temperature superconducting (HTS) or conventional low temperature superconductors. Examples of both are given in the table.

Brief summary of activity issues, concerns, successes:

Numerous activities will be required to further the development of resonant polarimetry. Some next steps are listed here:

1. Negotiation has been begun with Erin Keehan, of SuperPower Inc., 450 Duane Ave., Schenectady, NY 12304 USA, concerning, as a *minimum*, the acquisition of the high temperature superconducting tape needed to make a prototype resonant solenoid. Or, alternatively, to obtain a price for SuperPower to produce the liquid nitrogen temperature set-up needed to perform the test. Most satisfactory would be a *maximum* involvement; a collaboration with SuperPower to measure the HTS Q value achievable at the 100 MHz frequency, and above, for which the performance of HTS is variable and poorly known at present.

2. (Highly preliminary) negotiation has begun with Fulvia Pilat and with Joseph Grames of J-LAB to pursue collaboration with J-LAB to develop resonant polarimetry with polarized electrons.

3. (Even more preliminary) negotiation has begun with Hans Stroeher, of the COSY lab in Juelich, Germany, to discuss the possibility of developing resonant polarimetry using the polarized proton beam in the COSY ring. This would be in the context of the ongoing program aiming for proton and deuteron EDM measurement at Juelich.

4. I am scheduled to give a paper "Resonant Polarimetry for Storage Ring EDM Measurement", at the "Polarimetry for Electron EDM" meeting in Mainz in September. I gave a similar talk at the Cornell workshop on "Intense Electron Beams" in June.

5. The possibility of measuring the electron EDM at Cornell Wilson Lab has been (very tentatively) discussed, including the possibility of collaboration with University of Liverpool (Themis Bowcock) and Korea Advanced Inst of Science and Technology (Yannis Semertzidis).

(Project as a Whole) Milestones, Completed:

1. Code ETEAPOT2 is now available at the "https://code.google.com/p/ual/" web address, as release 1220. This code can be used to simulate any electric lattice described in SXF format. Its capabilities include fast and exact tracking, where "exact" includes both orbit and spin. Spin evolution in dynamic lattices (bunched beams) is supported.
2. Two papers: "Symplectic orbit and spin tracking code for all-electric storage rings", and "Electric dipole moment planning with a resurrected BNL Alternating Gradient Synchrotron electron analog ring" are scheduled for publication in the next issue of PRST-AB.
3. Design and preliminary testing of resonant polarimetry has begun.

Future Milestones

The following topics represent future directions for EDM storage ring design and simulation. The code intensive developments are temporarily stalled for want of the funding needed to pay for computer programming. Natural next steps are listed next. At present none of these steps have been funded but, in one case, funding has been applied for.

1. All-electric lattices are sufficient for measuring the EDM of either the electron or the proton. The ETEAPOT code is satisfactory for modeling such rings, though its operational capabilities need to be generalized to include the modeling of realistic errors and error distributions.

2. Simulation apps for closed orbit smoothing, tune and chromaticity adjustment, decoupling, dynamic apertures, etc. in the presence of realistic errors need to be developed and applied for electric rings.

3. Measuring the EDM's of other particles (especially the deuteron, from which the neutron EDM can be inferred) require lattices having both electric and magnetic bending elements (without which the spins cannot be "frozen"). The ETEAPOT code needs to be generalized to model such rings. In particular, the exact solution of the Bargmann, Michel, and Telegdi, BMT equation for spin evolution in idealized magnetic bending elements (for which the orbits are helices) needs to be obtained and implemented in the code.

4. Detailed design the proposed *electron* and *proton* EDM storage rings need to be developed, in collaboration with the Brookhaven and Juelich EDM groups. An especially important aspect is the modeling of the required polarimetry. Furthermore, the polarimetry needs to be different for proton, deuteron and, especially electron EDM measurement. Resonant polarimetry is required for the electron measurement, and may be useful for the other cases. This requires substantial high frequency EM field calculations and RF circuit design.

5. In connection with both items (4) and many other accelerator design projects, there is a "tower of babel" problem, with different codes having different accelerator description languages. Mechanical conversion routines amongst ELEGANT, MADX, BMAD, UAL, etc. lattice descriptions are needed. Within UAL, working via an "arbitrary-lattice.xml" file, some of these conversions already exist, but need to be refined and the list expanded.

6. A BNL/Cornell/SMU collaboration, with respective PI's being Malitsky (the overall PI) from BNL, Talman, from Cornell, and Reynolds from Southern Methodist University, have submitted an application for two year funding in response to the DOE Invitation for Grant Applications ”Scientific Discovery through Advanced Computing (SciDAC): High Energy Physics, LAB 15-1210”. This represents a natural continuation (and large expansion) of the code development that has been proceeding under my current grant. Malitsky is to be responsible for the overall integration, I am to be responsible for the lattice design and ETEAPOT simulation effort, and Reynolds is to be responsible for integration of the SUNDIALS/ARKcode, parallel processing environment.

Budget: Submitted by Cornell University Administration
Summary of total expenditures: Submitted by Cornell University Administration
Summary of expenditures by fiscal year (FY): Submitted by Cornell University Administraton