Comagnetometry Measurement of Electric and Magnetic Dipole Moments

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Need for **prototype ring** to **demonstrate EDM measurement capability**

Co-magnetometer EDM measurement strategies

Site-independent, scale invariant, **lattice design**

Specialize to PTR in Juelich, Germany, COSY beam hall

PRESENT DAY doubly frozen **polarized p and d EDM meaurement capability**

FUTURE doubly-magic, **p-3He** , and **p-e+ EDM difference** measurements with **BSM precision**

References

Extra figures

Various PTR operational MODES

3 Why PTR is needed

- Responsible planning for an eventual "**Holy Grail"** all-electric EDM storage ring with simultaneously counter-circulating $\mathcal{E} = 232.8\,\text{MeV}$ frozen spin proton beams **requires the construction of a prototype ring**
- To maintain flexibility the PTR lattice design has been left "scale-invariant" and site independent
- For numerical examples: $\mathcal{C}$=117 m, 1/4 scale relative to "Holy Grail" ring,
- Except for PTR construction itself, this needs only present day technology and apparatus available in the COSY facility.

- "In-plane" and "out-of-plane" refer to the horizontal ring beam plane.
- Exploit "**in-plane symmetry** to detect **BSM time-reversal violation** in the form of "**out-of-plane" precession of beam polarizations**.
- Use **simultaneously counter-circulating beams** on "identical" orbits to **cancel systematic EDM measurement errors.**
- **Self-magnetometry**: cancels the dominant systematic error source $\langle B_r \rangle$ by canceling out-of-plane (vertical) orbit separations.
- Both beams spins are frozen, with at least one (and preferably both) "globally", **spin tune** $Q_s = 0$ so that the **EDM signal accumulates monotonically**.
- **Stabilize all fields by phase locking both revolution frequencies and both beam polarizations, using their own MDMs as "magnetometric gyroscopes"**.

5 **Summarize** EDM measurement strategy

- **Use threefold phase locking:**
  1. Primary beam 1, CW, **globally frozen**
  2. Secondary beam 2, CCW, globally or locally (Q_s = rational fraction) frozen
  3. Synchronous bunch capture with different beam 1 and beam 2 harmonic numbers in a common RF cavity
- **This accurately matches beam 1 and beam 2 orbits.**
- **This allows conditions to be reset**, including magnetic or electric field reversal, **without the need for unachievably high precision direct electric and magnetic field measurement**.

6 Perspective view of one PTR quadrant

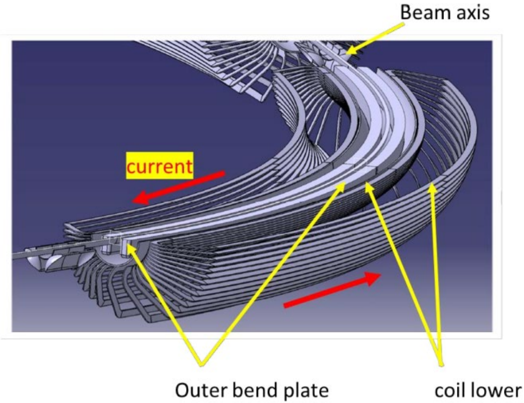
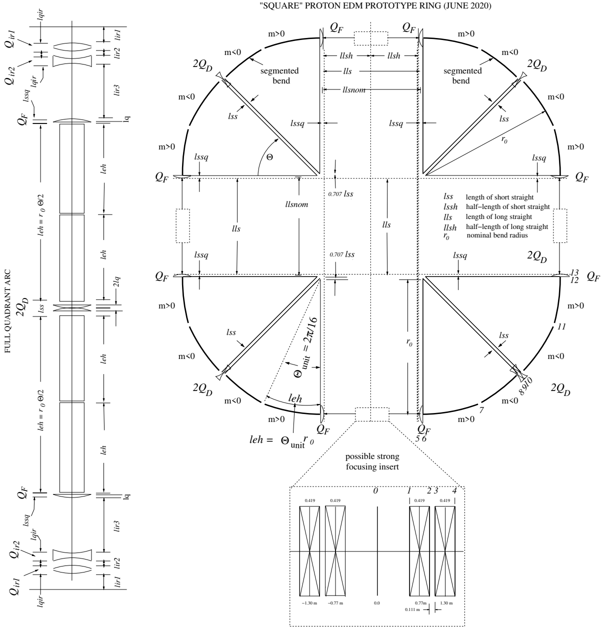


Figure 1 : Perspective mock-up of one quarter of PTR. Helmut Soltner design: partially-canceling nested coil, $\cos\theta$-dipoles coils. with “short-circuited” coil ends to cancel magnetic end-fields, surround the beam tube containing cylindrical electrodes.

7 "Belt and Suspnders", Modifiable focusing



Scale-invariant, site independent lattice design

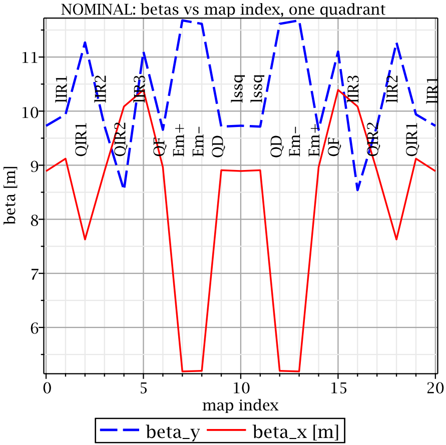


Figure 2 : Beta functions for one quadrant of the PTR-NOMINAL lattice. Note that the horizontal axis is element-index (not longitudinal coordinate *s*.) Element names are listed across the top. Solid (red) is horizontal, dashed line (blue) is vertical.

9 PTR + bunch accumulator BA

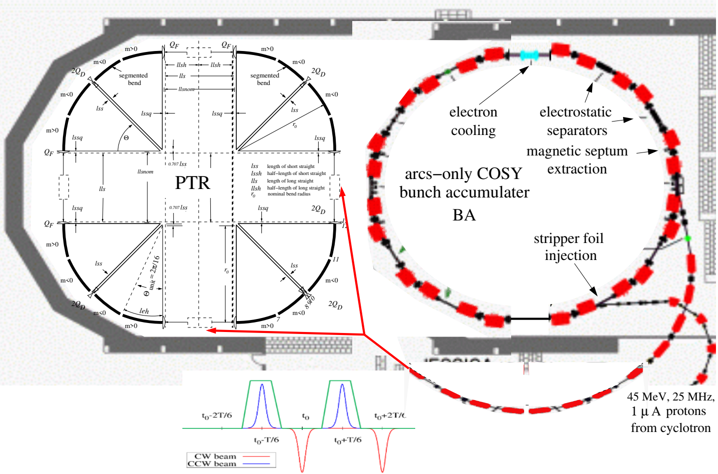


Figure 3 : If implemented in the COSY Hall, the bunch accumulator, BA, would be arcs-only COSY, rebuilt with existing electron cooling, stripper-foil injection and electrostatic-magnetic extraction.

PTR (**weak focusing FODO**) nominal parameters

Table 1 : PTR and COSY-arcs bunch accumulater (BA) parameters.

file name	variable name	unit	BA COSY-arcs-only	PTR rounded-square
circumference	`circum`	m	117.200	117.200
bend radius	`r0`	m		11.0
E fld., 30 MeV prot.	E	MV/m		5.370
long strt. length	`lls`	m		11.38
avail. strt. sec. len.	4×`lls`	m		45.5
electrodes/quadrant				4
bend/electrode	`Thetah`	r		$2\pi/16$
electrode length	`Leh`	m		4.32
PTR stored p's no BA				0.6×10^{7}
COSY-arcs BA			0.6×10^{11}	0.6×10^{11}
min/max horz. beta	$beta_x$	m		5.2/10.4
min/max vert. beta	$beta_y$	m		8.5/11.7
horizontal tune	Q_x			2.665
vertical tune	Q_y			1.775

11 **PRESENT DAY** doubly frozen proton and deuteron beam pairings

bm 1	m1 GeV	G1	q	β_1	K1 MeV	E0* MV/m	cB0* cT/1e3	m2 GeV	G2	q	$-\beta_2/\beta_1$ $*\dagger$	KE2 MeV	Qs2	bm 2
	$r_0* =$ 11.0 m			Qs1=0		**PRESENT**	**DAY**				PTR			
p	0.9383	1.7928	1	0.31304	49.7	6.26	8.11	0.9383	1.79	1	41/57	24.7	-2/1	p
p	0.9383	1.7928	1	0.29175	42.7	5.33	7.76	1.8756	-0.57	1	53/100	22.8	-9/8	d
d	1.8756	-0.5713	1	0.18000	31.1	-7.73	74.12	1.8756	-0.57	1	83/172	7.12	-25/31	d
d	1.8756	-0.5713	1	0.17760	30.3	-7.52	73.11	0.9383	1.79	1	35/67	4.06	43/127	p

- Quantities expressed as rational fractions are exact and phase locked to arbitrarily high accuracy,
- Except for PTR construction itself, these pairings use only **present day technology and apparatus**.
- Beam 1: is globally frozen in every case ; **Qs1=0/1**; So that the **beam 1 EDM signal accunulates monotonically**
- Except for r_0*, $*\dagger$, E0* and cB0* columns, all entries are **EXACT**, either **integers**, or (truncated) **physical constants** or **calculable,** kinematic quantities (truncated)
- "Closed orbit mismatches", from the $*\dagger$ column, are
  0.71927 = 41/57 - 0.0000282
  0.52997 = 53/100 - 0.0000299
  0.48261 = 83/172 + 0.0000518
  0.52235 = 35/67 - 0.0000380

12 **FUTURE p-h**, and **proton-e+ EDM difference** measurements with **BSM precision**

bm 1	m1 GeV	G1	q	β_1	K1 MeV	E0* MV/m	cB0* cT/1e3	m2 GeV	G2	q	$-\beta_2/\beta_1$ $*\dagger$	KE2 MeV	Qs2	bm 2
	$r_0* =$	50.0 m		Qs1=0		**FUTURE**		“	HOLY		GRAIL	“		
p	0.9383	1.7928	1	0.59840	233	8.39	-5e-4	0.9383	1.79	1	-1/1	233	0/1	p
	$r_0* =$	11.0 m				**FUTURE**					PTR			
p	0.9383	1.7928	1	0.27831	38.6	3.90	6.13	2.8084	-4.18	2	107/180	39.2	0/1	h
h	2.8084	-4.1842	2	0.16544	39.2	3.90	-6.13	0.9383	1.79	1	180/107	38.6	0/1	p
p	0.9383	1.7928	1	0.40238	86.6	11.6	8.77	0.0005	.0012	1	82/33	30.1	0/1	e+
e+	0.0005	0.0012	1	0.99986	30.1	11.6	-8.77	0.9383	1.79	1	33/82	86.7	0/1	p

- Quantities expressed as rational fractions are exact and can be phase locked to arbitrarily high accuracy,
- Rational fraction entries in the $*\dagger$ column of the tables are fixed by RF synchronism; the orbit circumference ratios are close, but not exact
  $0.59445 = 107/180 + 0.0000055$
  $1.68218 = 180/107 - 0.0000629$
  $2.48486 = 82/33 + 0.0000115$
  $0.40247 = 33/82 + 0.0000310$
- Precise magnetic field reversal is assured by three-fold phase locking.

References

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15 Extra Figures

16 PTR operational MODE parameters

Table 2 : PTR operational MODE parameters. EDM-EXPERIMENT entails reducing Q_y until β_y becomes unacceptably large. COLLIDER entails reducing intersection point beta functions $\beta_x = \beta_y^*$ until $\beta_x^{\max}$ becomes unacceptably large.

file name	variable name	unit	NOMINAL	EDM-EXPERIMENT	COLLIDER/ POLARIMETRY
bend radius	`r0`	m	11.0	11.0	11.0
E fld., 30 MeV prot.	E	MV/m	5.370	5.370	5.370
long straight length	`lls`	m	14.91	14.91	14.91
electrodes/quadrant			4	4	4
bend/electrode	`Thetah`	r	$2\pi/16$	$2\pi/16$	$2\pi/16$
electrode length	`Leh`	m	4.32	4.32	4.32
circumference	`circum`	m	117.220	117.220	117.220
min/max horz. beta	$beta_x^{\texttt{min/max}}$	m	5.2/10.4	9.0/15.5	$\beta_y^*/(24/\beta_y^*)$
min/max vert. beta	$beta_y^{\texttt{min/max}}$	m	8.5/11.7	$22/(\approx 20/Qy)$	$\beta_y^*/(17/\beta_y^*)$
horizontal tune	`Qx`		2.665	$1.5 < Q_x < 1.95$	~ 9.8
vertical tune	`Qy`		1.775	$0.7 > Qy > 0.05$	~ 4.8

17 NOMINAL MODE optics

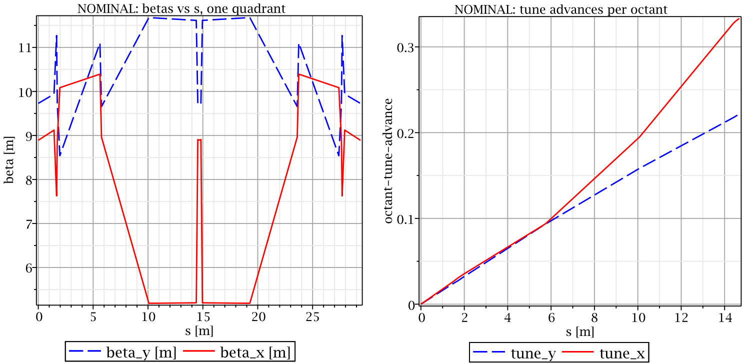

Figure 4 : **Left:** Same as previous figure, one quadrant PTR: NOMINAL beta functions, but plotted aginst longitudinal coordinate *s* assuming COSY beam hall installation. **Right:** Tune advances for one octant.

EDM-EXPERIMENT MODE

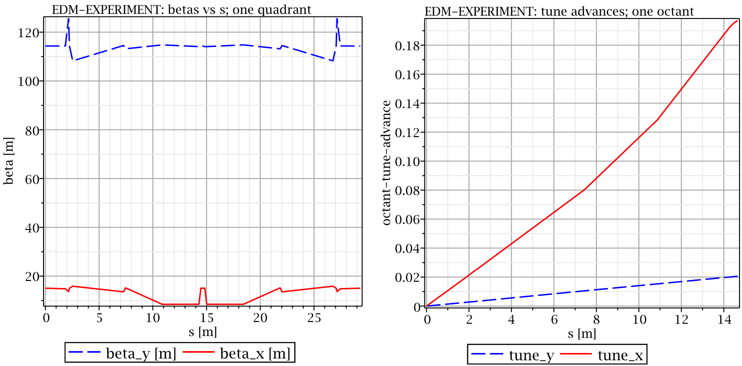

Figure 5 : Cancelation of $\langle B_r \rangle$ depends on sensitive "self-magnetometry" (precision proportional to $1/Q_y$) which requires small Q_y, and hence $\beta_y(s)$ large for all s.

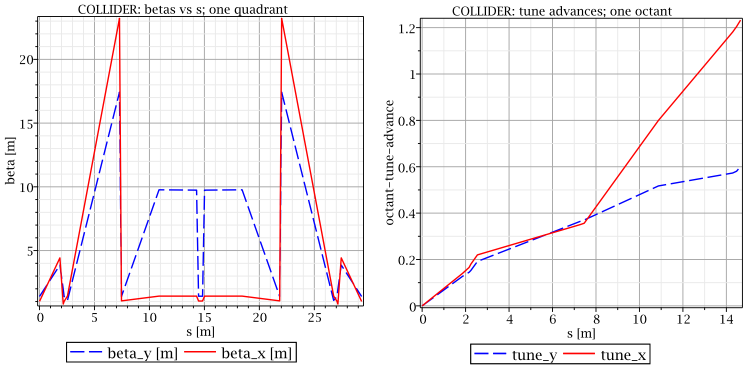

Figure 6 : Using “beta-squeeze” optics to reduce beta functions in both planes at the long straight section centers, countercirculating beams can be brought into a high luminosity collision configuration. This configuration can provide “beam-beam polarimetry” for EDM measurement consistency studies, or to measure *pp* and *dd* elastic scattering polarization dependence in the critical region below pion threshold, which is poorly understood at present.

20 Stripper foil injection explanation

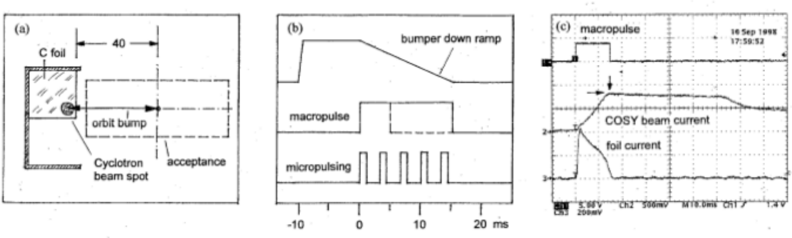

FIG. 3. Principle of the stripping injection at COSY. H^- or D^- delivered by the cyclotron injector change their charge state in a 20 $\mu g/cm^2$ carbon foil. Before injection the COSY orbit is bumped to the edge of the stripper foil (a). During the injection time, defined by the macropulse length, the orbit is moving back to its nominal position, coasting beam injection. Bumper ramp down time t_{ramp} and macropulse length t_{macro} are variable parameters (b). In (c) is shown an example for proton injection. With 6.7 μA current delivered by the cyclotron, the ring is filled in 15 ms with 8 mA circulating beam ($\approx 10^{11}$ protons at 45 MeV). Micropulsing by chopping the macropulse allows to reduce the intensity I_{cycl} of the incoming cyclotron beam.

Figure 7 : Explanation of COSY stripper foil injection. Copied (along with original figure number) from H.J. Stein, et al.