Lattice Design for a Proton EDM Prototype Storage Ring (PTR)

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2 Outline

- Responsible planning for a "nominal all-electric EDM storage ring" with counter-circulating $\mathcal{E} = 232.8\,\mathrm{MeV}$ frozen spin proton beams requires the construction of a prototype ring (PTR)
- The final PTR size will depend on relationships among circumference $\mathcal{C}$, proton energy $\mathcal{E}$ and bending electric field E
- To maintain flexibility the lattice design has been left "scale-invariant" and site independent
- For numerical examples: $\mathcal{C}$=117 m, 1/4 scale relative to "nominal all-electric"
- This paper presents numerous PTR lattice configurations

4 Perspective view of one PTR quadrant

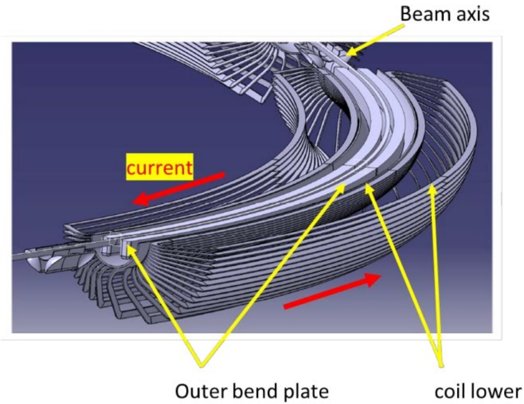
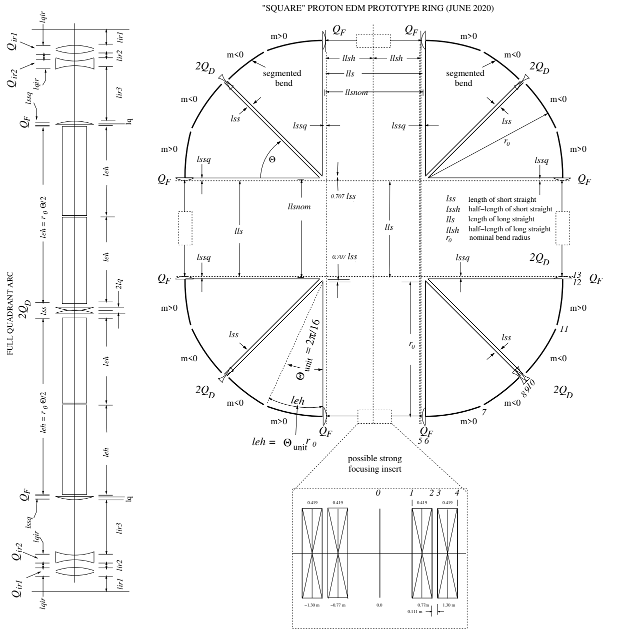


Figure 1 : Perspective mock-up of one quarter of PTR. (Partially-canceling nested coil, Helmut Soltner design for field quality and to minimize stray flux) “reflected” $\cos\theta$-dipoles coils surround the beam tube in which the electrodes are accommodated. “Short-circuited” coil ends cancel undesirable end-fields.

5 "Belt and Suspnders", Modifiable focusing



6 How PTR relates, in detail, to the full-scale EDM ring

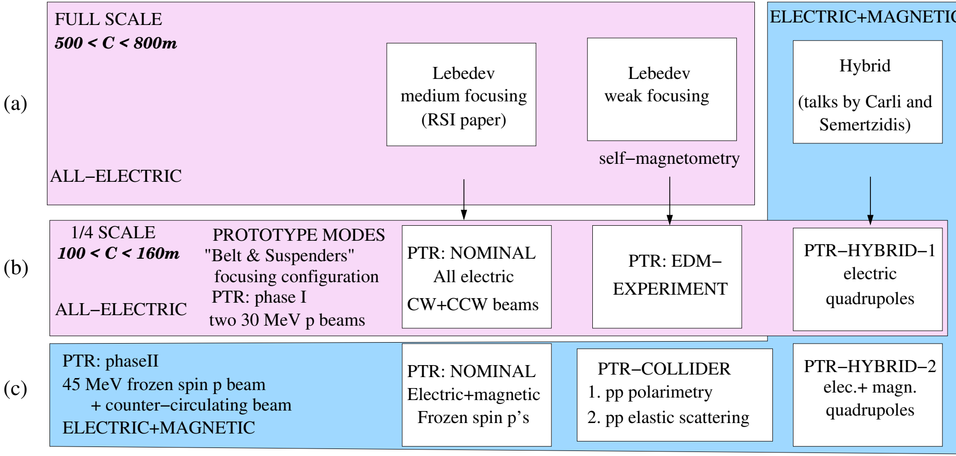


Figure 2 : Chart showing how PTR relates to full scale 232.8 MeV proton EDM ring. Background shading is purple for all-electric, blue for electric + magnetic. (a) Full scale ring designs, (b) 1/4 scale PTR operational "MODES" for Phase I prototype studies, (c) MODES for Phase II and III prototype studies.

PTR + bunch accumulator BA

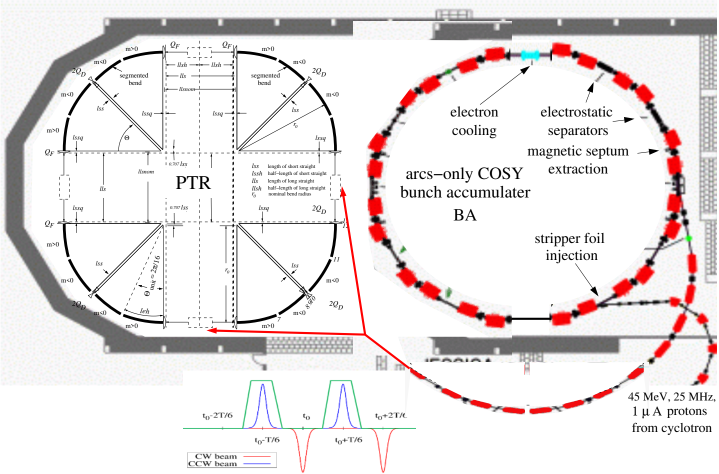


Figure 3 : If implemented in the COSY Hall, the bunch accumulator, BA, would be arcs-only COSY, rebuilt with existing electron cooling, stripper-foil injection and electrostatic-magnetic extraction.

PTR nominal parameters. (Quads at straight centers turned off.)

Table 1 : PTR and COSY-arcs bunch accumulater (BA) parameters. ** For increased free drift length, the bend radius has been decreased from 13.50 m to 9.70 m since the CYR.

file name	variable name	unit	BA COSY-arcs	PTR rounded-square
circumference	`circum`	m	117.200	117.200
bend radius	`r0`	m		13.50**
E fld., 30 MeV prot.	E	MV/m		4.37
long strt. length	`lls`	m		7.75
avail. strt. sec. len.	4×`lls`	m		32.6**
electrodes/quadrant			4	4
bend/electrode	`Thetah`	r		$2\pi/16$
electrode length	`Leh`	m		5.30
PTR stored p's no BA	`particles`			0.6×10^7
COSY-arcs BA	`particles`		0.6×10^{11}	0.6×10^{11}
min/max horz. beta	$beta_x$	m		4.0/32.0
min/max vert. beta	$beta_y$	m		19.0/29.3
horizontal tune	Q_x			1.69
vertical tune	Q_y			0.79

9 Stripper foil injection explanation

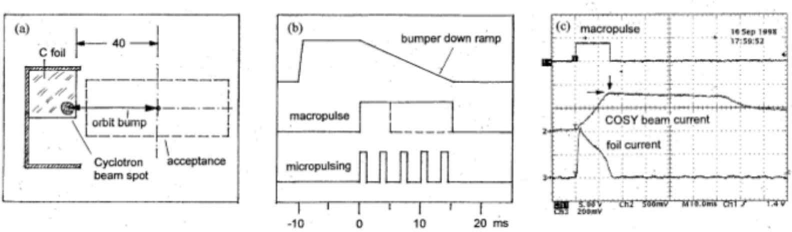


FIG. 3. Principle of the stripping injection at COSY. H^- or D^- delivered by the cyclotron injector change their charge state in a 20 μg/cm^2 carbon foil. Before injection the COSY orbit is bumped to the edge of the stripper foil (a). During the injection time, defined by the macropulse length, the 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 4 : Explanation of COSY stripper foil injection. Copied (along with original figure number) from H.J. Stein, et al.

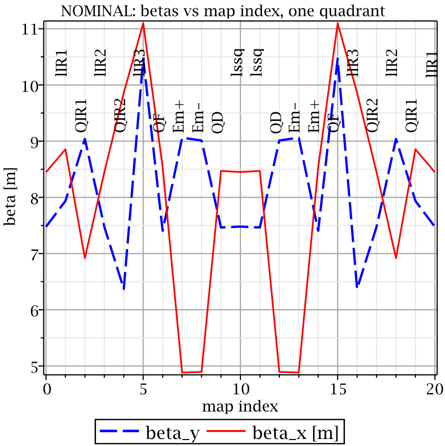


Figure 5 : Beta functions for one quadrant of the PTR-NOMINAL lattice. Note that the horizontal axis is element-index (not longitudinal coordinate *s*.) Element names are listed across the top. Solid (red) is horizontal, dashed line (blue) is vertical.

11 NOMINAL MODE optics

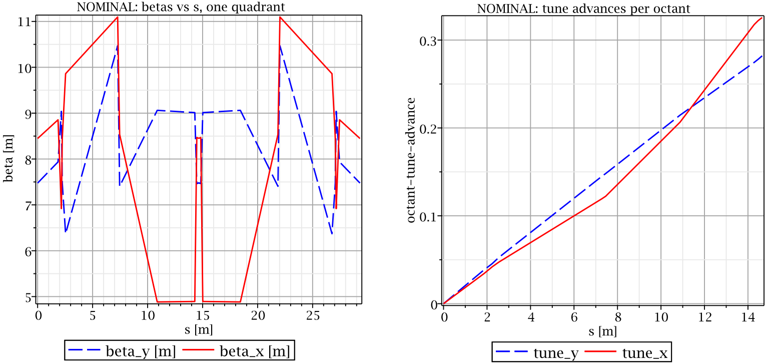


Figure 6 : **Left:** Same as previous figure, one quadrant PTR: NOMINAL beta functions, but plotted aginst longitudinal coordinate *s*. **Right:** Tune advances for one octant.

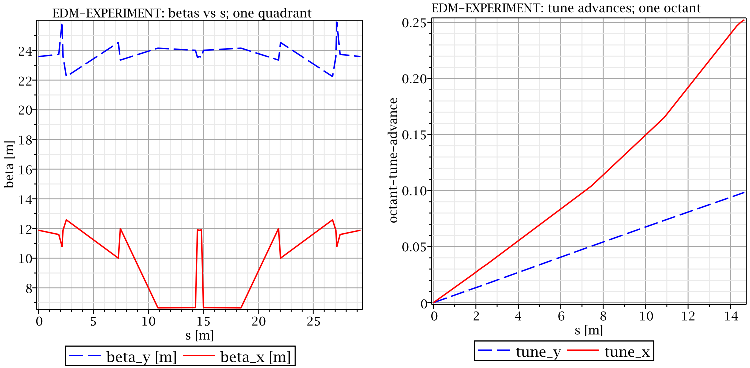


Figure 7 : Cancelation of $\langle B_r \rangle$ depends on sensitive "self-magnetometry" (precision proportional to $1/Q_y$) which requires small Q_y, requiring $\beta_y(s)$ to be large for all s.

13 COLLIDER/BM-BM-POLARIMETER MODE (Phase III ?)

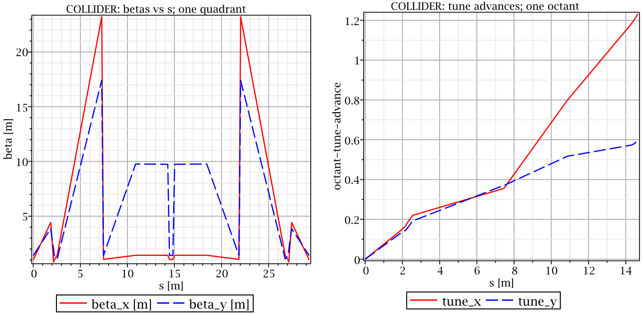


Figure 8 : **Left:** Beta functions for a "COLLIDER/BEAM-BEAM POLARIMETER" mode of PTR operation. **Right:** Corresponding tune accumulations for one octant. The special feature of this mode is the minimized beta function values at the mirror symmetry, intersection points (IP).

14 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 IP beta functions $\beta_x = \beta_y^* \equiv \beta*$ until $\beta_x^{\max}$ becomes unacceptably large.

file name	variable name	unit	NOMINAL	EDM-EXPERIMENT	COLLIDER/POLARIMETER
bend radius	`r0`	m	8.70	8.70	8.70
E fld., 30 MeV prot.	E	MV/m	6.79	6.79	6.79
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	3.416	3.416	3.416
circumference	`circum`	m	117.220	117.220	117.220
min/max horz. beta	$beta_x^{\mathtt{min/max}}$	m	4.9/11.1	6.6/12.5	$\beta*/(24/\beta*)$
min/max vert. beta	$beta_y^{\mathtt{min/max}}$	m	6.4/10.4	$22/(\approx 20/Qy)$	$\beta*/(17/\beta*)$
horizontal tune	`Qx`		2.60	$1.5 < Q_x < 1.95$	~ 9.8
vertical tune	`Qy`		2.26	$0.7 > Qy > 0.05$	~ 4.8

15 Doubly-magic proton minus helion EDM parameters

Table 3 : Doubly-frozen-spin CW proton, CCW helion EDM difference parameters. See Fig. 9 for "self-magnetometry", sensitivity $\sim 1/Q_y$.

file name	variable name	unit	EDM-EXPERIMENT
bend radius	`r0`	m	8.70
long straight length	`lls`	m	14.91
circumference	`circum`	m	117.220
K.E. of proton	p	MeV	38.594301
E fld	E	MV/m	3.900
B fld	B	T	0.02043
CW proton spin tune	Q_s(p)		0
CCW 39.24 MeV He3 spin tune	Q_s(h)		0
min/max horz. beta	$beta_x^{\mathtt{min/max}}$	m	10/16
min/max vert. beta	$beta_y^{\mathtt{min/max}}$	m	110/130
horizontal tune	`Qx`		1.58
vertical tune	`Qy`		0.16

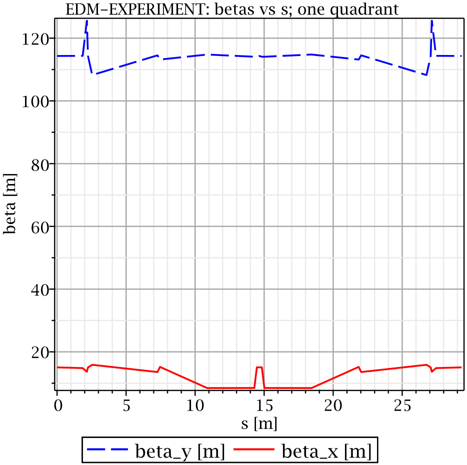


Figure 9 : Cancelation of $\langle B_r \rangle$ depends on sensitive "self-magnetometry" (precision proportional to $1/Q_y$). Here $Q_y = 0.16$.

17 References

- N. Hempelmann et al., *Phase-locking the spin precession in a storage ring,* P.R.L. 119, 119401, 2017
- D. Eversmann et al., *New method for a continuous determination of the spin tune in storage rings and implications for precision experiments,* Phys. Rev. Lett. **115** 094801, 2015
- F. Abusaif et al., *Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study,* https://arxiv.org/abs/1912.07881, 2019
- V. Anastassopoulos et al., *A storage ring experiment to detect a proton electric dipole moment,* Review of Scientific Instruments, 87, 115116, 2016
- S. Haciomeroglu and Y.K. Semertzidis, *A hybrid ring design in the storage-ring proton electric dipole moment experiment,* arXiv:1806.09319, 2018
- R. Talman, *A Doubly-Magic Storage Ring EDM Measurement Method,* arXiv:1812.05949, December, 2018
- H.J. Stein, et al., *Present Performance of Electron Cooling at COSY-JUELICH,* `www.researchgate.net/publication/48198877`, research article, January 2011