A Prototype Storage Ring for the Precision Frontier

Paolo Lenisa

University of Ferrara and INFN (Italy)

744. Heraeus Seminar, March 29th, 2021

Introduction

- The experimental activity of the JEDI Collaboration at the COSY storage rings in the past years, has culminated in fundamental achievements:
  - Spin-coherence time > 1000 s
  - Spin-tune measurement with unprecedented precision $\Delta\nu_s/\nu_s \leq 10^{-10}$
  - Implementation of spin-feedback system

- The beam-time will provide the first upper limit for the deuteron EDM and the first direct measurement of the EDM of a charged hadron in a storage ring
  - Milestone for the field and experimental validation of the method

- COSY will stop running in 2024

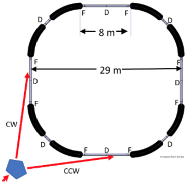
- The JEDI and CPEDM collaborations agreed upon the strategy for the next steps

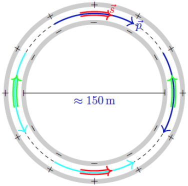
Strategy: staged approach

Staged approach

On the basis of the preparedness of the required technological developments

Stage 1	Stage 2	Stage 3
precursor experiment at COSY (FZ Jülich)	prototype ring	dedicated storage ring





Stage 1
- magnetic storage ring

now

Stage 2
- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3
- magic momentum

(701 MeV/c)

10 years

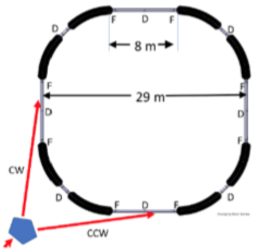
$\sigma_{EDM}/(e \cdot \mathrm{cm})$

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

Stage 2: prototype EDM storage ring

100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- Frozen spin including additional vertical magnetic fields



Challenges

- All electric & E-B combined deflection
- Test of hybrid lattice?
- Storage time
- CW-CCW operation
  - Orbit control
  - Control of orbit difference
- Polarimetry
- Spin-coherence time
- Magnetic moment effects
- Stochastic cooling

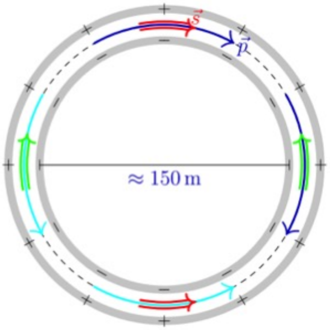
Objectives of PTR

- Study open issues.
- First direct proton EDM measurement.

Stage 3: precision EDM ring

500 m circumference (with E = 8 MV/m)

- All-electric deflection
- Magic momentum for protons (p = 701 MeV/c)



Challenges

- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($>$ 1000 s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual (intentional) B_r field

"Holy Grail" of storage rings (largest electrostatic ever conceived)

Dissemination

Grants and evaluations

ERC Advanced Grant srEDM (Hans Ströher, Proposal No. 694340)

Helmholtz Evaluation Report, Topic 2, Cosmic Matter in Lab., 01/2020

- Goals in Program Oriented Funding IV period
  - Initiation of the proton Electric Dipole Moment (EDM) project at COSY-ring to open an opportunity to explore physics beyond the standard model.
- Work program:
  - Use COSY, the world's only storage ring for polarized proton and deuterium beams at the IKP facility at FZJ. This will explore the scientific potential for proton/deuteron EDM experiments in the COSY-ring.
  - Perform within PoF IV an Axion search via oscillating EDMs at COSY, which may open the way to new concepts that may extend the reach in precision down to $1 \times 10^{-29} e \cdot cm$.

Deliberation Document 2020 Update European Strategy for Particle Physics:

- ... the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported.

Expressions of Interest

JENAS - Expression of Interest (June 2020)

- Rings for the Search of Charged-Particle Electric Dipole Moments (EDM)
  C. Carli, P. Lenisa, J. Pretz (for the JEDI- and CPEDM collaborations)

Snowmass process (Aug. 2020)

- Storage Rings for the Search of Charged-Particle Electric Dipole Moments C. Carli, P. Lenisa, J. Pretz, F. Rathmann, and H. Ströher
- Opportunities for Fundamental Physics using Small-scale Storage Ring Experiments
  N. N. Nikolaev, F. Rathmann, R. Talman, H. Ströher, et al.
- **The proton storage ring experiment**
  Storage ring EDM collaboration

Technical Design Report

Technical Design Report

Present status: CERN Yellow Report

F. Abusaif et al.: *Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study*: https://arxiv.org/abs/1912.07881.

Next step: Technical Design Report

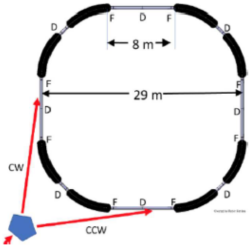
- PTR Lattice design
- Beam transfer and injection system
- Electrostatic deflectors
- Magnetic bends
- Multipole elements
- Ring vacuum system
- Stochastic cooling
- RF Cavity
- Spin manipulation tools
- Polarimeter
- Beam diagnostics

- support needed

PTR lattice design (protons)

Beam parameters and layout defined in CYR

- p at 30 MeV all-electric CW-CCW beams operation
- p at 30 to 45 MeV frozen spin, with additional vertical B field
- relates to full scale 232.8 MeV proton EDM ring



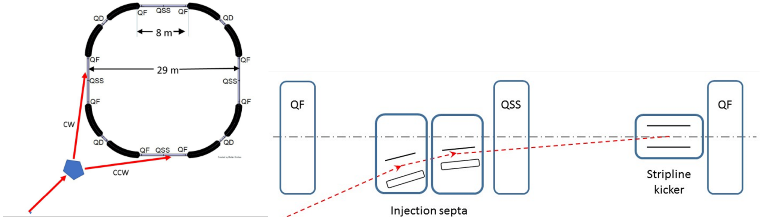
	E only	E & B frozen spin		unit
Bending radius	8.86	8.86		m
Kinetic energy	30	30	45	MeV
$\beta = v/c$	0.247	0.247	0.299	
γ (kinetic)	1.032	1.032	1.048	
Momentum	239	239	294	MeV/c
Electric field E	6.67	4.56	7.00	MV/m
Magnetic field B		0.0285	0.0327	T
rms $\epsilon_x = \epsilon_y$	1	1		π mm mrad
Transv. acc. $a_x = a_y$	> 10	> 10		π mm mrad

→ talk by R. Talman

- support needed

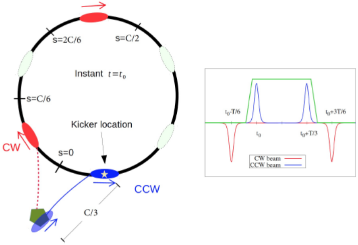
Beam transfer and injection

- Injection concept by M. Atanasov, B. Balhan, J. Borburgh, L. Jorat



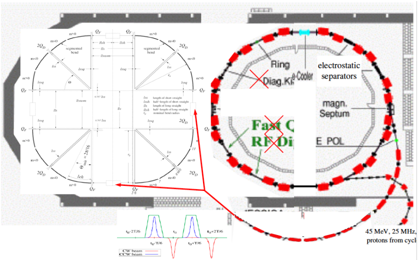
→ talk by J. Borburgh

- Test at COSY: spin manipulation after injection feasible



→ talk by J. Slim

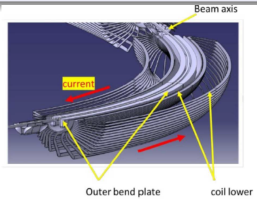
Bunch-accumulator?



file name	variable name	unit	COSY-arcs BA	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
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

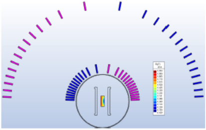
Electrostatic deflectors & magnetic bends

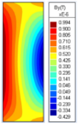
- Concept for electrostatic deflector available
- Next step: build prototype with RWTH Aachen
- Studies of straight E/B deflector to improve voltage holding capability at Jülich



		units
Electric		
electric field	7.00	MV/m
gap between plates	60	mm
plate height (straight part)	151.5	mm
plate length	6.959	m
total bending length	55.673	m
total straight length	44.800	m
bend angle per unit	(45°)	m

- Concept for magnetic add-on to deflector available.
- Magnetic system ($\cos\theta$) outside the vacuum tube.
- System included in prototype developm. with RWTH-Aachen



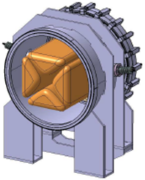


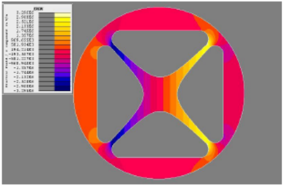
Magnetic		
magnetic field	0.0327	T
current density	5.000	A/mm^2
windings/element	60	

$\rightarrow$ talk by H. Soltner

Multipole elements

- Design of electrostatic elements by J. Burbough (CERN)
- Electrostatic quadrupoles
  - aperture diameter 80mm, applied $\pm$ 20 kV.
  - Simulated design with vacuum chamber of 400mm diameter.





- PTR quadrupoles max. pole tip potential 30 kV (margin for conditioning)
  - 3D design available;
  - sextupole, octupole and higher harmonics reasonable

$\rightarrow$ talk by J. Borburgh

- support needed

Vacuum system

- Ring vacuum given by minimum required beam lifetime of about 1000 s.
  - N_2 pressure $< 10^{-12}$ mbar; H_2 pressure $< 5 \times 10^{-11}$ mbar.
- Stochastic cooling rate better than 5×10^{-3} mm mrad/s.
- Non-vibrational system that avoids generation of magnetic fields
  - Cryogenic or NEG pumping?
- Mechanical alignment of elements inside vacuum pipe of 400 mm diameter
  - active compensation of oscillations/ground motion
- Shielding (passive versus active)

- support needed

Stochastic cooling

- Control proton beam emittance during measurements: 30 MeV to 45 MeV.
- Cooling should compensate emittance growth of 5×10^{-3} mm mrad/s.
  - Interplay between stochastic cooling and evolution of horizontally polarized ensemble of particles unknown.
  - Studies of emittance growth and spin coherence time at PTR.
- Aim: provide basic design of stochastic cooling system for PTR.

RF-cavity

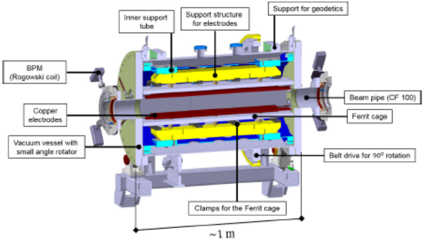
- Azimuthal magnetic fields lead to spin rotations of the magnetic moment.
- Even for perfectly aligned cavity, individual particles experience horizontal magnetic fields and spin rotations into vertical and horizontal directions.
- Effect on EDM measurement suppressed
- Design of RF cavity required that minimizes unwanted spin rotations.

- support needed

Spin-manipulation

Longitudinal RF-solenoid

- Vertical polarisation of stored beam rotated into horizontal plane.
  - Typical ramp-up times from vertical to horizontal polarisation: 200 ms.
  - Optimize design for PTR.



RF-Wien filter

- Applies transv. magnetic fields to spin, exerting minimal Lorentz force on beam:
  - optimize design for PTR
  - two of them needed for CW-CCW operations

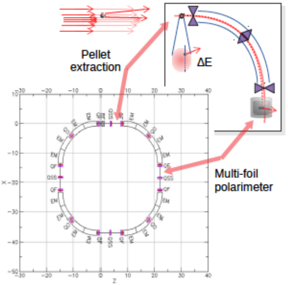
Polarimetry

Noise extraction

- dC (pC) scattering works with polarization errors $\delta p/p = 10^{-6}$

Sample polarimeter

- Polarization profile determination at low energies:



- C multifoil polarimeter based on Si-detectors with pellet extraction (J. Gooding, Univ. of Liverpool).
- Ballistic Si pellet target for homogeneous beam sampling.
- E_{loss} of 100 keV in 50 μm pellet $\rightarrow$ track displaced by 2.5 cm behind 45^o bend.

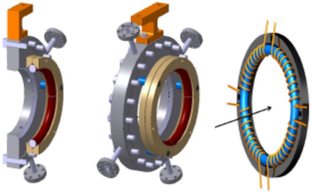
$\rightarrow$ talk by J. Gooding

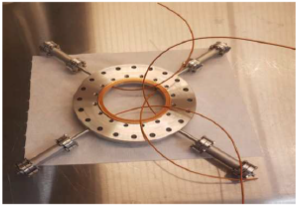
Beam diagnostics

Beam position monitor

- Development of prototype BPM based on segmented toroidal coil: Rogowski coil
- advantages over conventional split-cylinder BPMs
  - short insertion length: many BPMs can be installed
  - inexpensive
  - high sensitivity to position of bunched beams

$\rightarrow$ talk by F. Abusaif





Other diagnostics needed:

- Beam profile monitor, non-destructive for emittance measurement
- BCT, also to adjust CW/CCW beam currents

Simulations

- Beam and spin-tracking simulations to scrutinise and validate concepts and ideas
- Code bench-marking on existing COSY data
- Working group established (additional help welcome)

$\rightarrow$ talks by V. Poncza, A. Lehrach

Applications

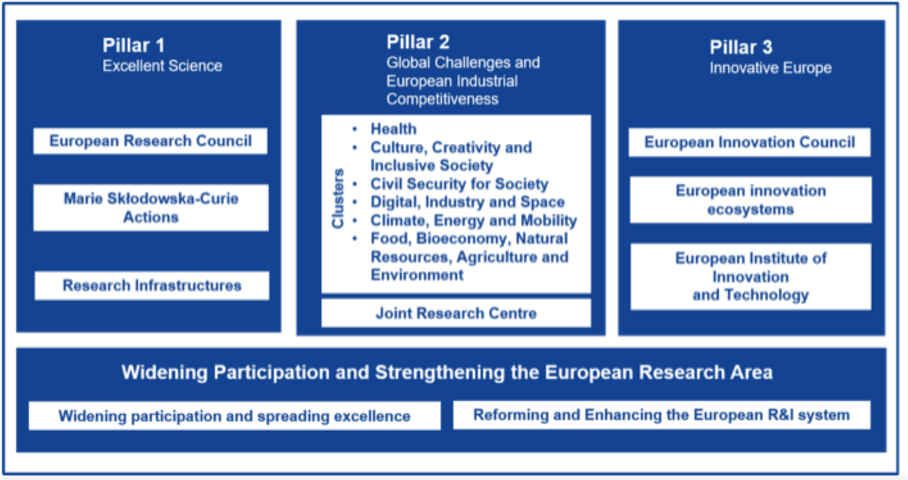
ERC-AdG: Pathfinder for a Charged-Particle EDM Storage Ring

Outcome in February 2021

- Evaluation
  - 4 reviewers - 3 marks each
  - 10 marks: excellent & exceptional
  - 2 marks: very good
- Panel comment
  - The project targets a prototype that would already push the current sensitivities but also is an important step towards the ultimate sensitivity. The proposed research addresses very important challenges. This project builds on a previous grant dedicated to study the EDM of deuterium. Unfortunately the results are not yet published. This fact adds uncertainty to the project, increasing the risk.

- A publication of the result of the precursor experiment is mandatory!

Design Study in Horizon Europe



Framework

Old program (HORIZON-2020): INFRADEV-01-2019-2020 - Design Studies

- 55 submittted applications
- 10 approved (2 in the accelerator sector)

New program (HORIZON-EUROPE): INFRADEV-01-01-2022 - Design Studies

- Foreseen deadline: 24.03.22 - Opening: winter 2021
- Duration: 3-4 years
  - Possible project development: 2023-2025/26
- Budget: total 3 M €
- Coordinator + N participants
  - Minimum 5 Institutions from 3 different countries
  - Endorsement letters from other Collaborators

1 - Excellence

Science case

- Search for static charged particle EDMs
  - EDMs $\rightarrow$ probes of CP-violating interactions
  - Matter-antimatter asymmetry
- Search for oscillating EDMs
  - Axion-gluon coupling
  - Dark matter search
- Potential sensitivity to gravitational effects

Objectives

- New class of (precision) storage rings (p: all-E; d, $^3\mathrm{He}$: comb. E/B);
- design demonstrator as:
  key performance enabler for the final precision storage ring;
- capable of providing a wealth of science already.

2 - Impact

Fundamental Science

- Physics beyond the SM-BAU, DM

Accelerator Science

- New class of precision storage rings
- All-electric ring (high field, field homogeneity and stability)
- E/B combined bending
- Storage time
- CW-CCW injection and operation
- Spin-coherence time in electric machine
- Optimum orbit control
- Systematic effects from magnetic moments
- Multi-bunch approach to co-magnetometry
- Stochastic cooling

Metrology

- Polarimetry (efficient, sampling, non-destructive)

3 - Implementation

3.1 - Work plan

- WP1 - Project coordination
- WP2 - Fundamental science
- WP3 - Accelerator science
- WP4 - Prototype ring layout
- WP5 - Ring Instrumentation
- WP6 - Expected performance - simulations
- WP7 - Parameter control and costing
- WP8 - Dissemination and outreach

- 3.2 Management structure, milestones and procedures
- 3.3 Consortiums as a whole
- 3.4 Resources to be committed

4 - Members of the Consortium

- 4.1 Participants (applicants)
- 4.2 Third parties involved in the project (including resources)
- 4.3 Annex to section 4: letters of support

More on strategy ...

Wednesday, 31 March

- 15:00 - 15:30 M. Lamont *"Next steps, where do we go from here?"*
- 15:30 - 16:30 Discussion

Thank you