



# Storage ring for hadronic EDM measurements

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# What I'm going to talk about

- ▶ What is an EDM ?
- ▶ JEDI Collaboration (Jülich Electric Dipole moment Investigations)
- ▶ How do we measure EDM on a storage ring
- ▶ My PhD work:
  - ▶ Analytical calculations of electric fields
  - ▶ Trajectories of particles
  - ▶ Spin transfer functions in the fringe field
- ▶ What's next?

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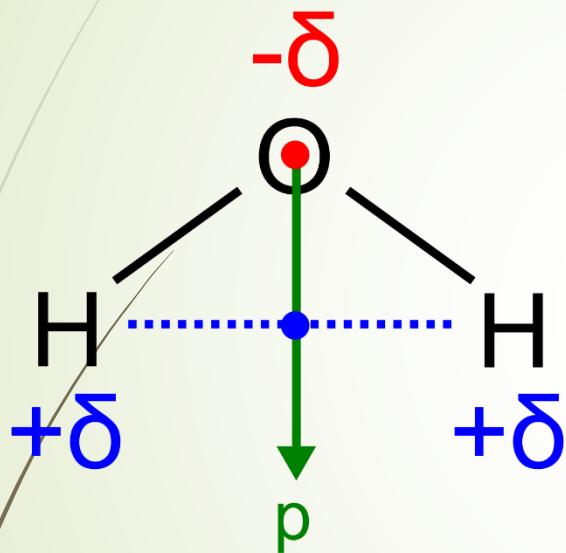
EDM



EDM

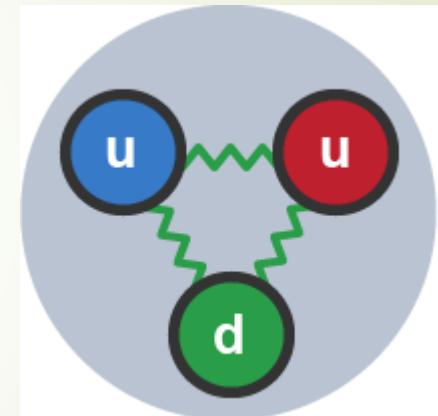
EDM : Electronic dance music

# EDM : The electric dipole moment



- Barycentre -
- Barycentre +

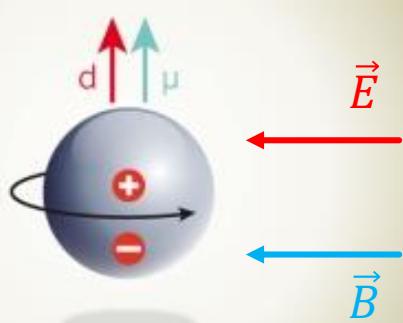
Water molecule  
C.m ou Debye



Proton  
e.cm

# The electric dipole moment - 2

- EDM : Electric moment intrinsic to a particle, aligned with the spin.

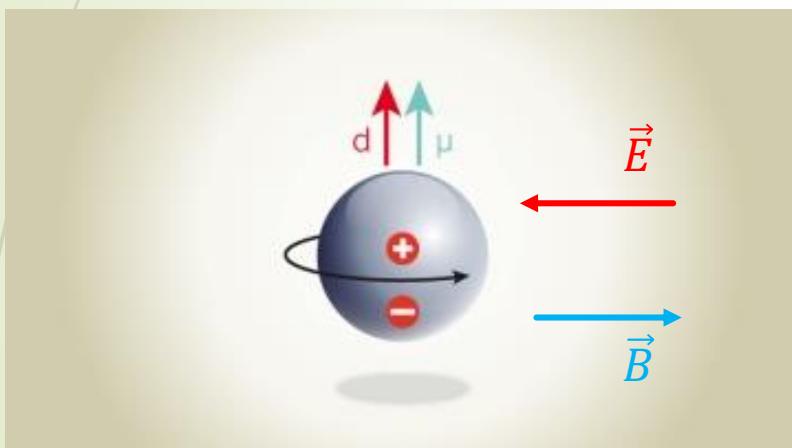


$$\frac{d\vec{S}^*}{dt^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*$$

\* : at rest

# The electric dipole moment - 2

- EDM : Electric moment intrinsic to a particle, aligned with the spin.



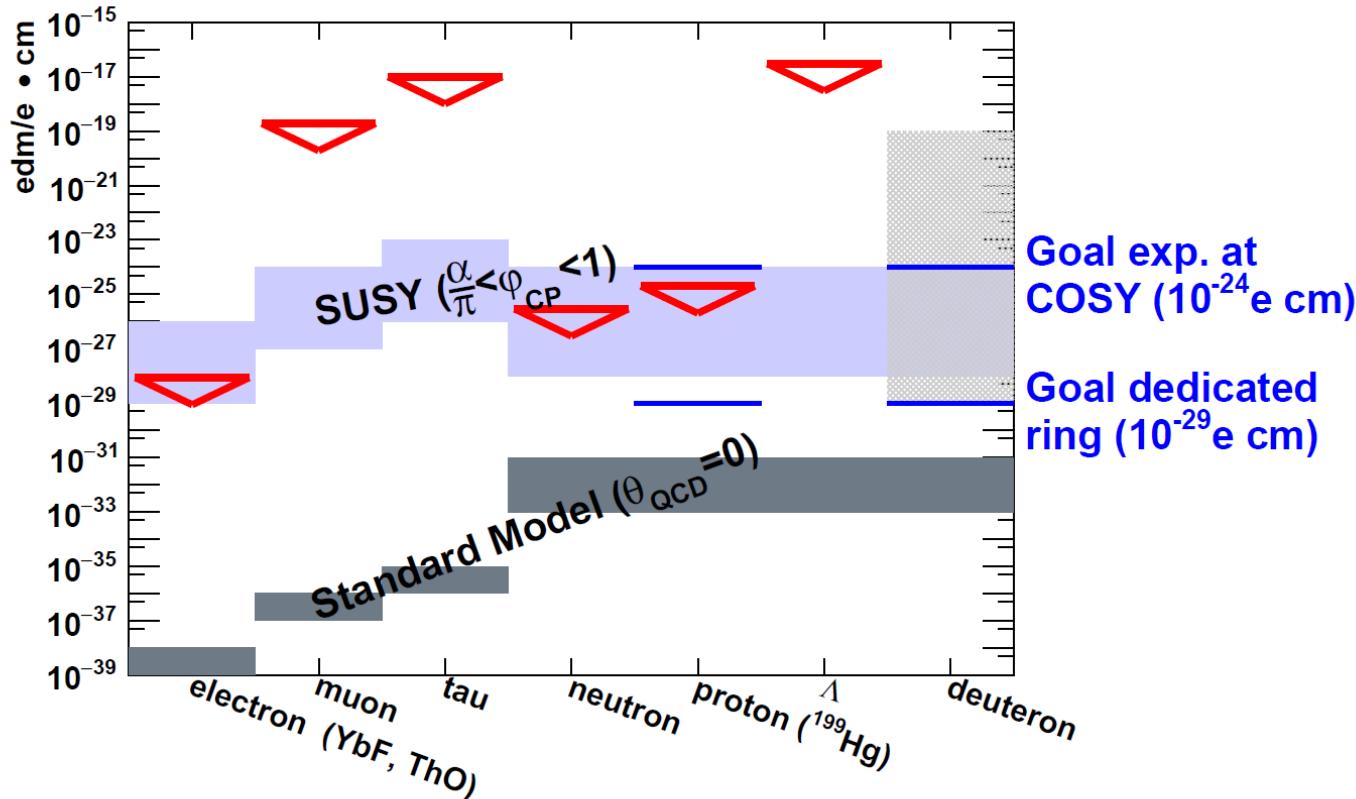
$$\frac{d\vec{S}^*}{dt^*} = \vec{d} \times \vec{E}^* - \vec{\mu} \times \vec{B}^*$$

\* : at rest

- Potential source of T/CP violation-> Matter/antimatter asymmetry
- Allow us to constrain certain theories (SUSY, MS extensions ...)

# Actual limits on EDM

## EDM: Current Upper Limits

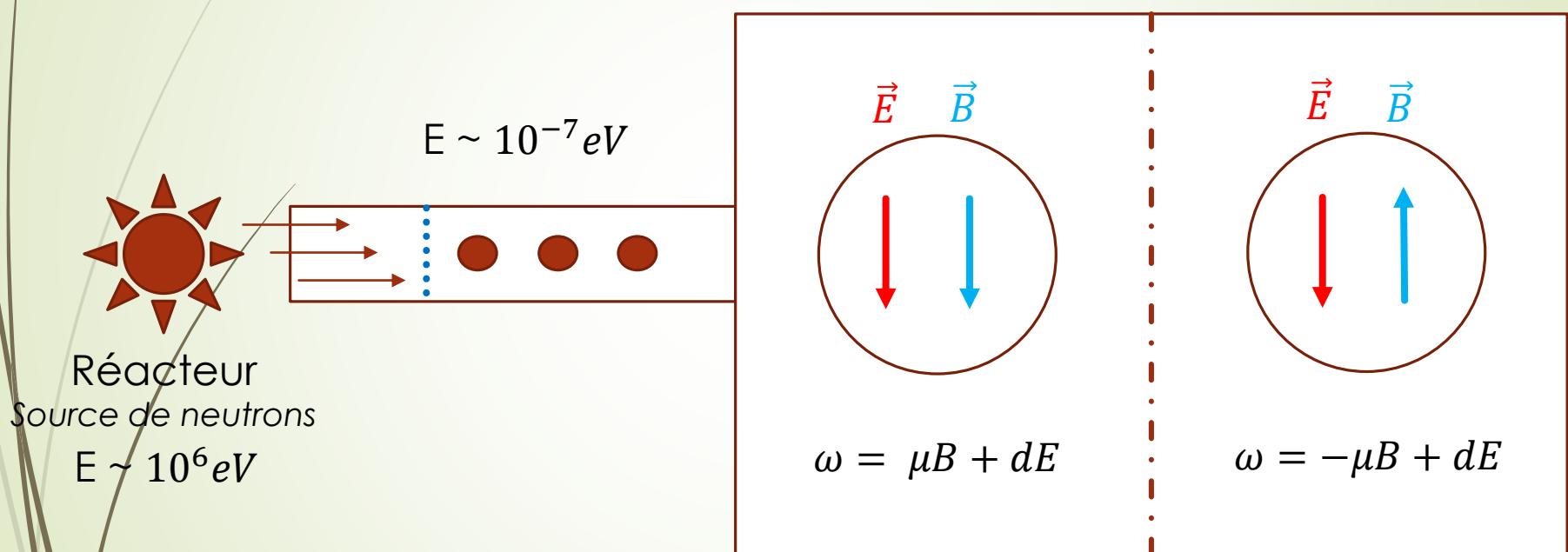


FZ Jülich: EDMs of **charged** hadrons:  $p$ ,  $d$ ,  $^3\text{He}$

# Actual limits on EDM



# Neutron EDM



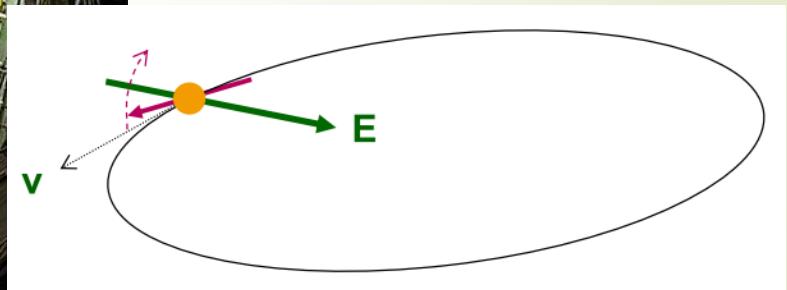
$$\Delta\omega \propto d < 2,9 \cdot 10^{-26} e \cdot cm$$

# The JEDI collaboration

JEDI : (Jülich Electric Dipole moment Investigations)

<http://collaborations.fz-juelich.de/ikp/jedi/>

- ▶ Measurement of electric dipole moment of proton/deuteron/helion...
  - ▶ Aimed limit :  $10^{-29} \text{ e.cm}$
  - ▶ Actual limit :  $10^{-26} \text{ e.cm}$



Proof of principle:

$$\sim 10^{-24} \text{ e.cm}$$

CoSy : Cooler Synchrotron

In the particle referencial :

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$$\frac{d\vec{S}^*}{dt^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*$$

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In the laboratory referencial:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

Thomas-BMT

$$\vec{\Omega} = -\frac{e}{m} \left\{ G \vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) (\vec{\beta} \times \vec{E}) + \frac{\eta}{2} (\vec{E} + \vec{v} \times \vec{B}) \right\}$$

$$G = \frac{g - 2}{2},$$

$$d = \eta e \hbar / 4mc$$

Magnetic Moment

EDM

But : Cancel magnetic part (horizontal precession )  
 + maximised electric part (vertical precession)

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In the laboratory referencial:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

Thomas-BMT

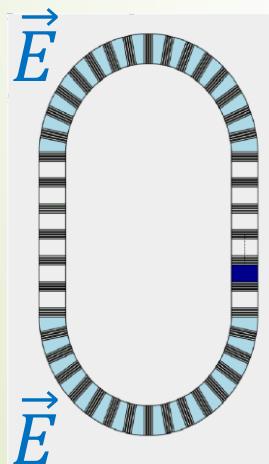
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$$G = \frac{g - 2}{2},$$

$$d = \eta e \hbar / 4mc$$

Magnetic Moment

EDM



Energy	~270 MeV
Radius	40 m
E field	12MV/m



# $10^{-29}$ e.cm ?

► A LOT OF STATISTICS:

- $2 \cdot 10^{10}$  particles / beam
- $2 \cdot 10^8$  turns / second
- $10^7$  seconds run / year



$10^{25}$  particles/year

► But also systematic errors:

- Fake EDM signal :  $B = 10^{-17} T \rightarrow$  Contra-rotativ beams
- Trajectory measurements at  $10^{-9}$  m
- Electrical fringe fields → ???

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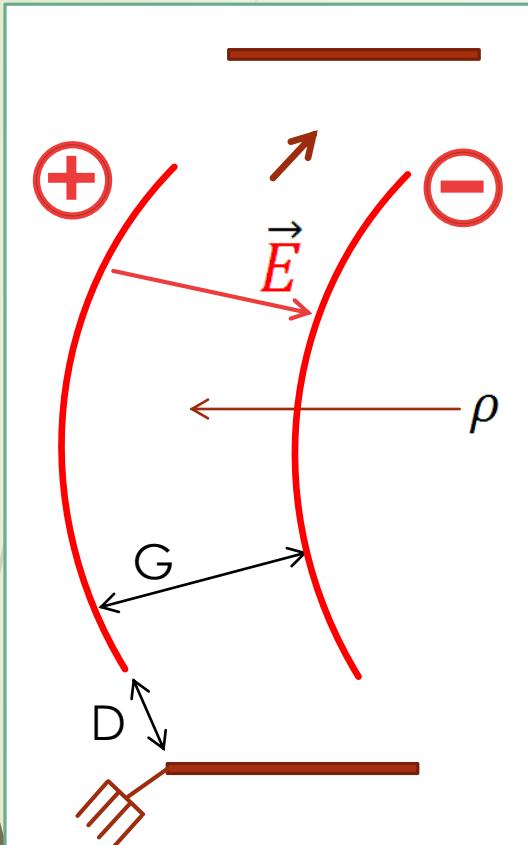


$10^{25}$  particles/year

► But also systematic errors:

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# Effect of the electrostatic deflectors on spin dynamics



$$\rho = 40m$$

$$G = 40mm$$

$$E = 12MV/m$$

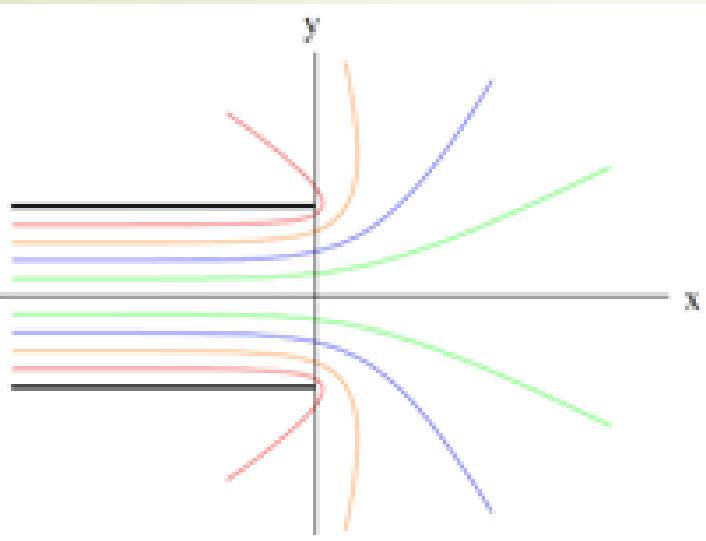
Program :

- Analytical models(field, trajectory, spin)
- Implementing in a code (BMAD)
- Optimisation of reference scenarios

Question : Do fringe fields have a significative effect on spin dynamics ?  
If yes, can we correct them?

# Fringe fields

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Additional components for the field:

- Fake EDM signal
- Modified trajectories
- Non linearities

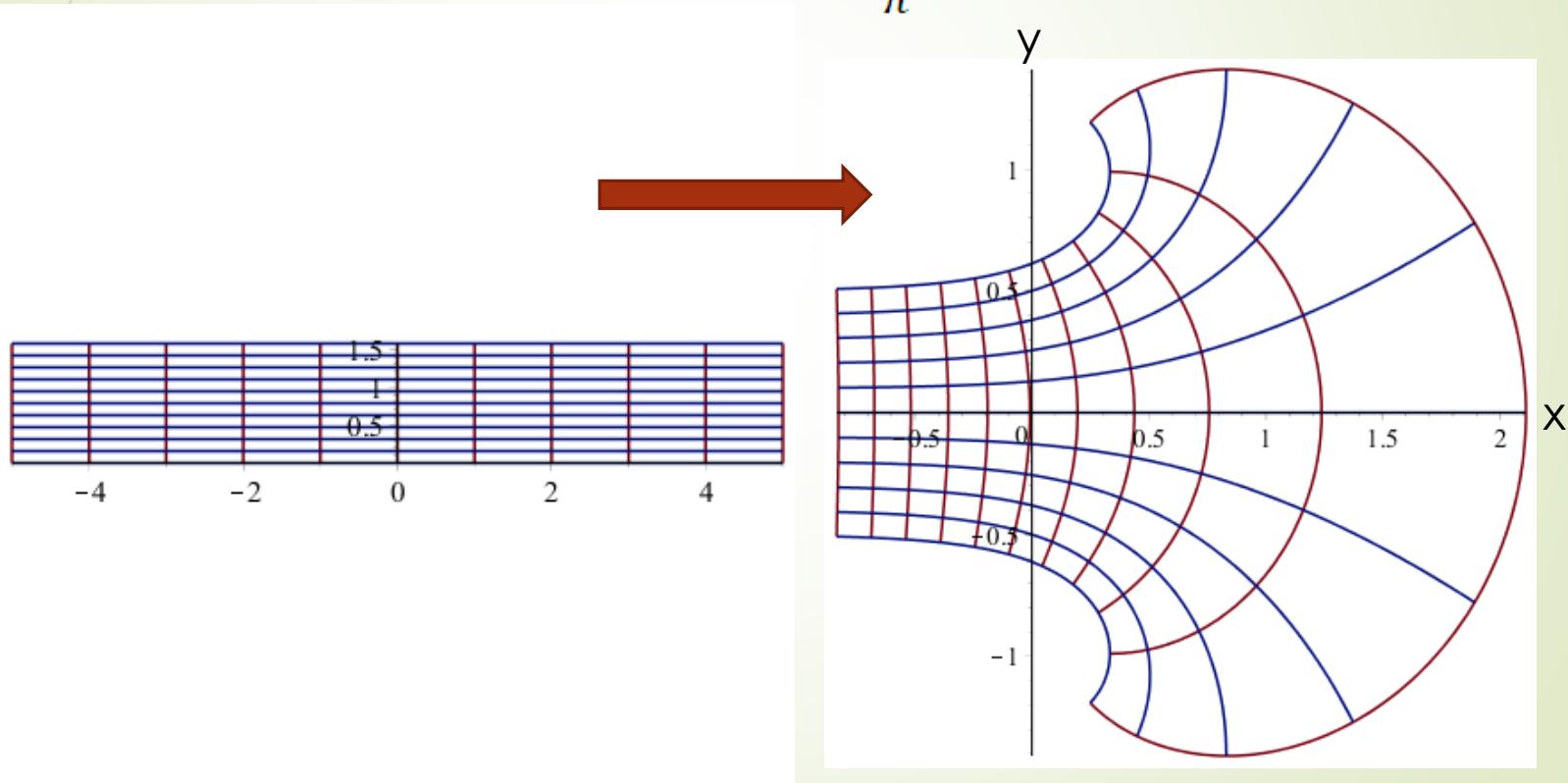
Rotations are non commutatives :

- Systematic errors

- ▶ No electrostatic rings, with this level of exigence
- ▶ Actual models are 1st order, with no fringe fields
- ▶ Need configurable and highly accurate models :
  - Analytical models needed

# Conformal mapping : electric field in a deflector

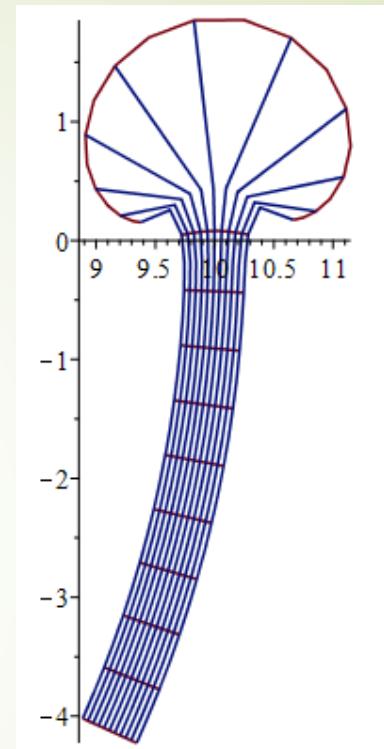
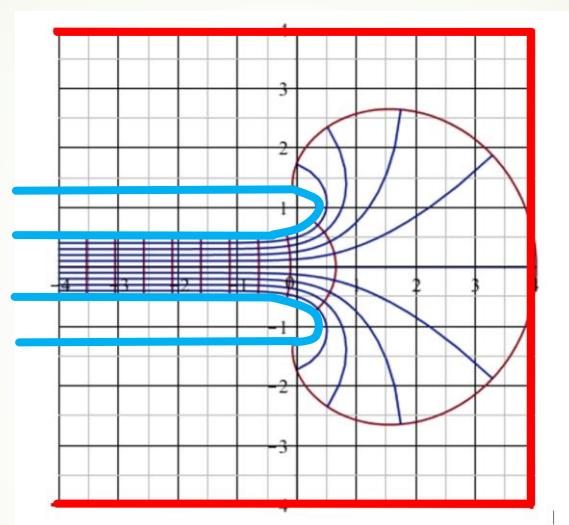
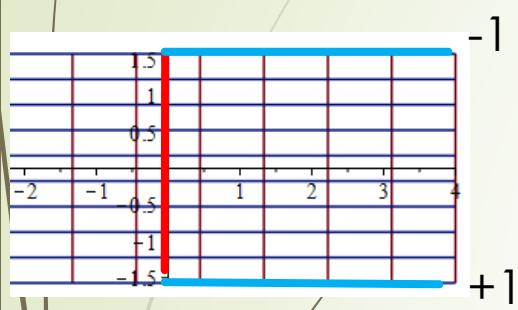
$$z \rightarrow Z_1 = 1 + z + e^z \rightarrow Z_2 = \frac{1}{\pi} (1.376 + Z_1 + e^{Z_1})$$



Infinite plane capacitor

More realist electrodes

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 $z \rightarrow G \rightarrow Z_1 \rightarrow Z_2$  $Z_2 \rightarrow Z_3$ 

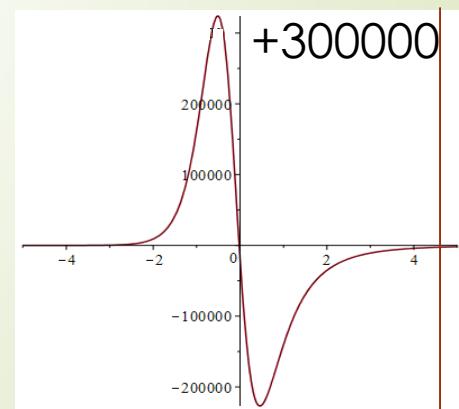
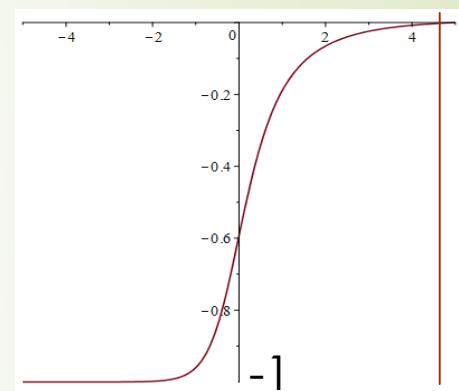
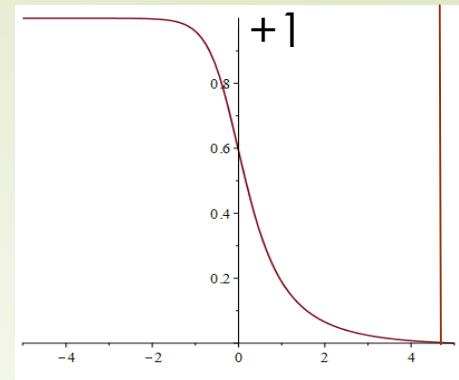
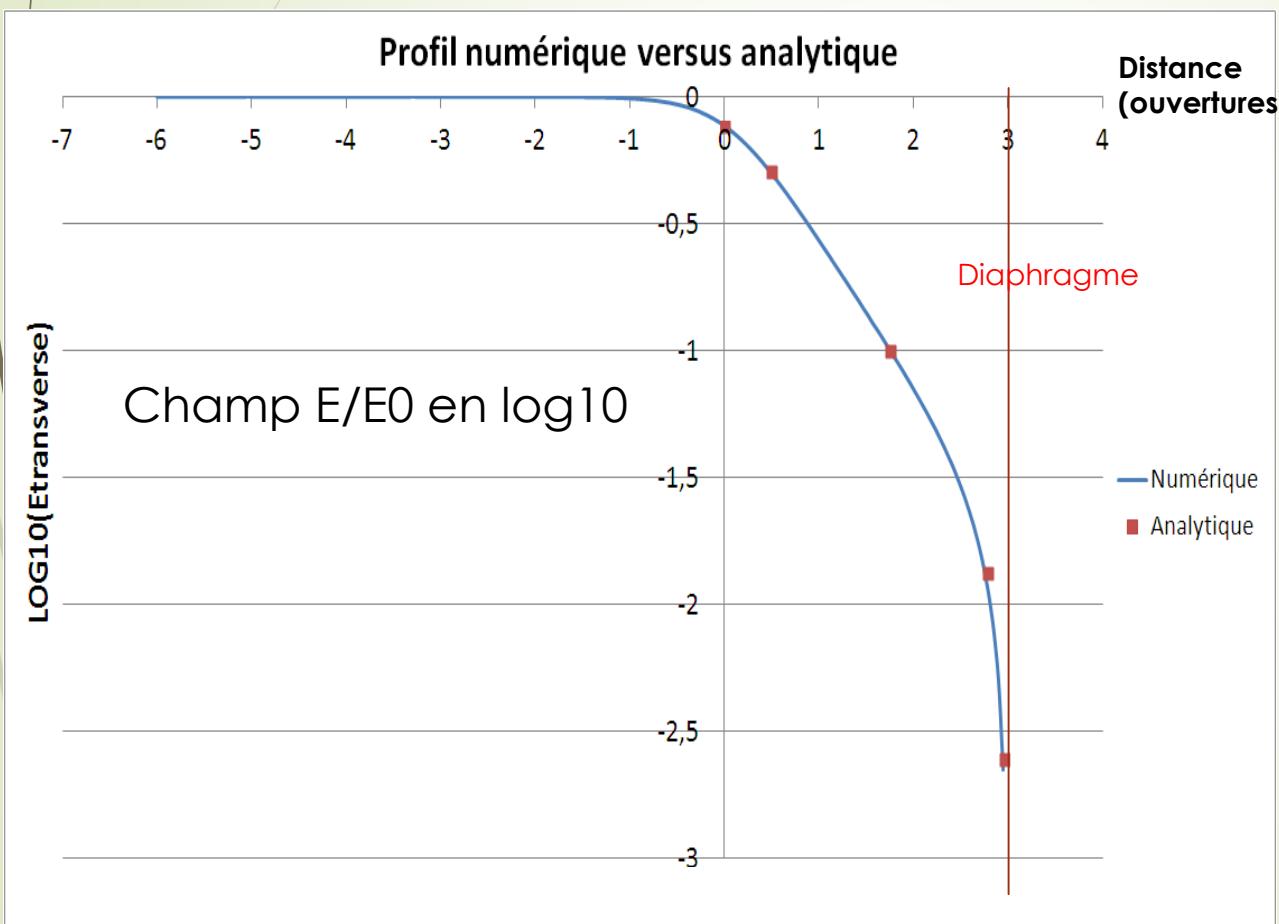
Pour illustration

$$V(x, y) = \arctan \left[ \frac{\operatorname{sh}(\pi x) \cdot \sin(\pi y)}{1 + \operatorname{ch}(\pi x) \cdot \cos(\pi y)} \right]$$

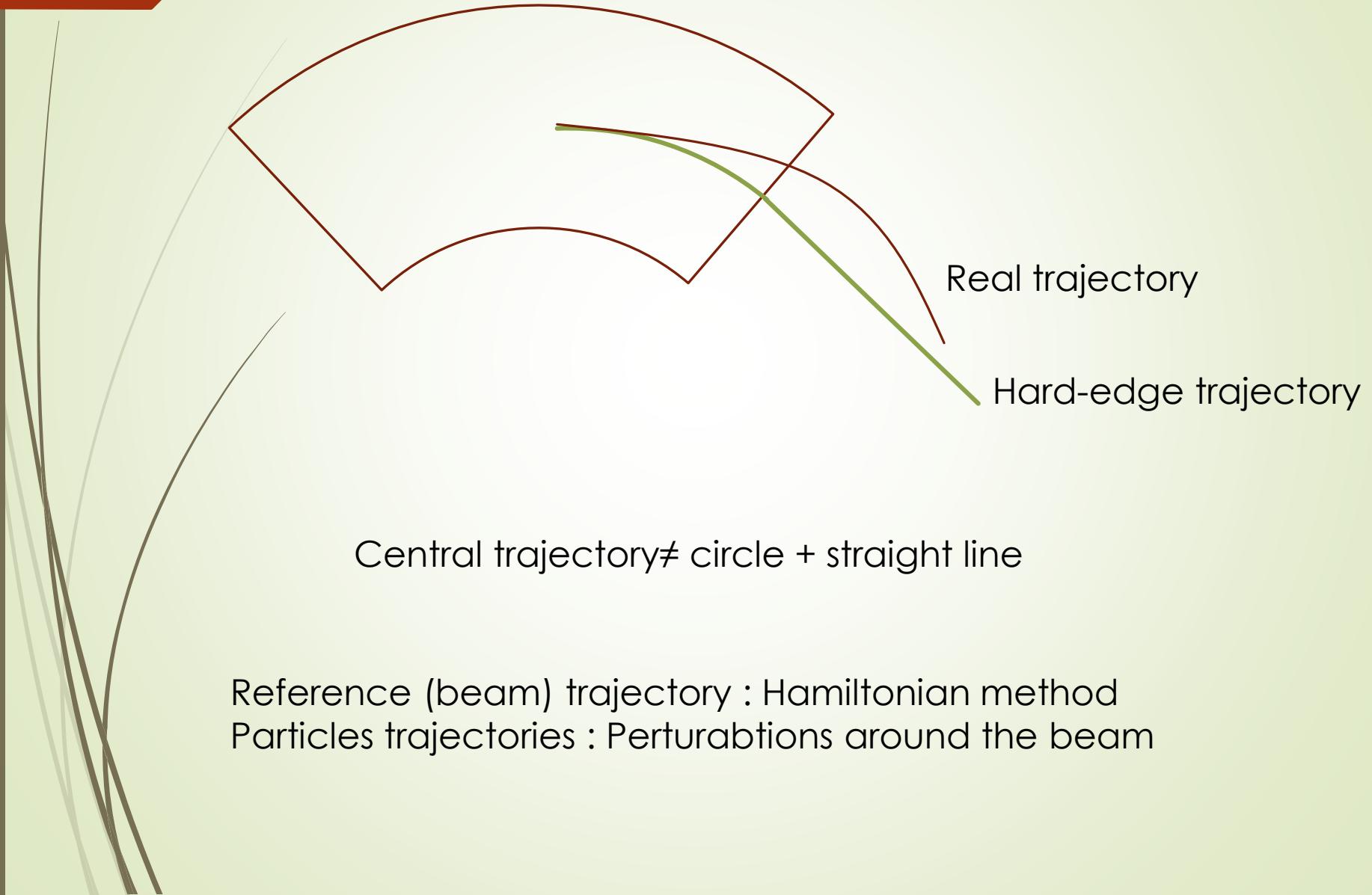
$$G(z) = 0.2 + \frac{\pi}{2} - \frac{5}{2} \cdot e^{\frac{2}{5}z} \cdot H_{\frac{1}{5} \frac{1}{5} \frac{6}{5}}(e^{2z}) \mapsto Z_1 = [1 + G(z) + e^{G(z)}]$$

$$\mapsto Z_2 = \frac{1}{\pi} \cdot [1.376 + Z_1 + e^{Z_1}] \mapsto Z_3 = \rho_0 \cdot e^{iG \cdot Z_3 / \rho_0}$$

# Electric field (3)



# Particle trajectories



# Spin Dynamics

Step by step tracking



Runge-Kutta etc...

Transfert matrix/function

$$\begin{bmatrix} \cos\left(\frac{\phi}{2}\right) - i \cdot u_{zm} \cdot \sin\left(\frac{\phi}{2}\right) & -(i \cdot u_{xm} + u_{ym}) \cdot \sin\left(\frac{\phi}{2}\right) \\ (-i \cdot u_{xm} + u_{ym}) \cdot \sin\left(\frac{\phi}{2}\right) & \cos\left(\frac{\phi}{2}\right) + i \cdot u_{zm} \cdot \sin\left(\frac{\phi}{2}\right) \end{bmatrix}$$

$$S_1 = M \cdot S_0$$

$$S_{turn} = M_1 \cdot M_2 \cdot M_3 \dots S_0$$

$$S_{Nturn} = M^N \cdot S_0$$

# Spin dynamics - 2

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$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{q}{mc^2} \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E}$$



Spinor formulation :

$$\begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}' = \frac{\textcolor{red}{F(s)}}{2} \begin{bmatrix} -i\bar{P}_y & \tilde{P}_s \\ -\tilde{P}_s & i\bar{P}_y \end{bmatrix} \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} = U \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

$$S' = U S$$

$$S = e^{\int U dt} \cdot S_0$$

Solution :

$$T = 1 + \int_0^L U ds + \int_0^L \left[ U \int_0^k U ds \right] dk$$

# Spin dynamics - 2

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$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

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Spinor formulation :

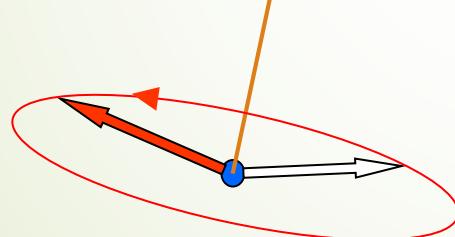
$$\begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}' = \frac{F(s)}{2} \begin{bmatrix} -i\bar{P}_y & \tilde{P}_s \\ -\tilde{P}_s & i\bar{P}_y \end{bmatrix} \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} = U \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

$$\begin{bmatrix} \cos\left(\frac{\phi}{2}\right) - i \cdot u_{zm} \cdot \sin\left(\frac{\phi}{2}\right) & -(i \cdot u_{xm} + u_{ym}) \cdot \sin\left(\frac{\phi}{2}\right) \\ (-i \cdot u_{xm} + u_{ym}) \cdot \sin\left(\frac{\phi}{2}\right) & \cos\left(\frac{\phi}{2}\right) + i \cdot u_{zm} \cdot \sin\left(\frac{\phi}{2}\right) \end{bmatrix}$$

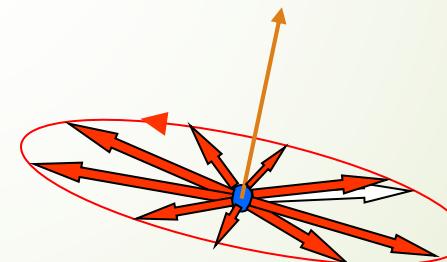
# Remaining work

- ▶ Spin dynamics in fringe field.
- ▶ Code all this stuffs
- ▶ Quantified systematic effet of the fringe field
- ▶ Evaluate spin coherence time of different scenarios.

Cohérence de spin



Les spins alignés à l'injection



Perte de la polarisation horizontale

T=1000 s

# Remaining work

- ▶ Spin dynamics in fringe field.
- ▶ Code all this stuffs
- ▶ Quantified systematic effet of the fringe field
- ▶ Evaluate spin coherence time of different scenarios.

Merci !



# Backup

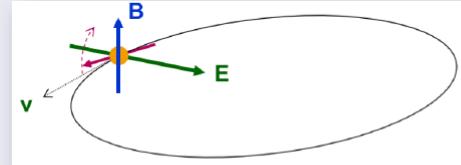


For any sign of  $G$ , in *combined* electric and magnetic machine:

- Generalized solution for magic momentum

$$E_r = \frac{GB_y c \beta \gamma^2}{1 - G\beta^2 \gamma^2}, \quad (11)$$

where  $E_r$  is radial, and  $B_y$  vertical field.



- Some configurations for circular machine with fixed radius  $r = 25$  m:

particle	$G$	$p$ [MeV c $^{-1}$ ]	$T$ [MeV]	$E$ [MV m $^{-1}$ ]	$B$ [T]
proton	1.793	701	232.8	16.789	0.000
deuteron	-0.143	1000	249.9	-3.983	0.160
helion	-4.184	1285	280.0	17.158	-0.051

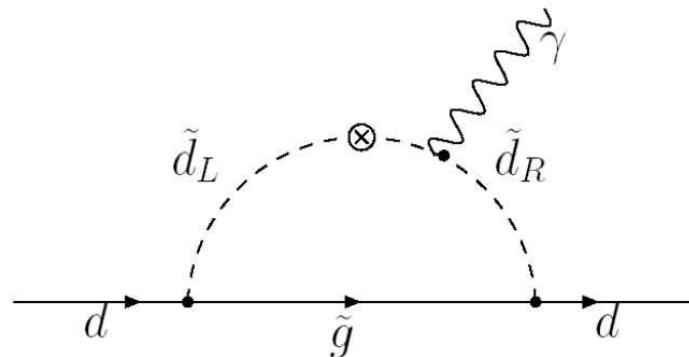
Offers possibility to determine

**EDMs of protons, deuterons, and helions in one and the same machine.**

# Supersymmetry / SUSY CP Problem

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- MSSM without corrections gives:  $\text{EDM} = 10^{-23-25} \text{ e.cm}$  **ALREADY RULED OUT!!**
- SUSY breaking introduces new CPv phases
- EDMs appear at 1-loop level



$$\kappa_i = \frac{m_i}{16\pi^2 M_{\text{SUSY}}^2} = 1.3 \times 10^{-25} \text{ cm} \times \frac{m_i}{1 \text{ MeV}} \left( \frac{1 \text{ TeV}}{M_{\text{SUSY}}} \right)^2,$$

- SUSY with extensions:  $\text{EDM} = 10^{-28} \text{ e.cm}$  **NEARLY WITHIN AIM OF cryoEDM!!**

# Statistical Sensitivity of an EDM Experiment

$$\sigma_{d\,p} \approx \frac{3\hbar}{PAE_R \sqrt{N_{Beam} f T_{Tot} \tau_{Spin}}}$$

$P = 0.8$

Beam polarization

$A = 0.6$

Analyzing power of polarimeter

$E_R = 17 \text{ MV/m}$

Radial electric field strength

$N_{Beam} = 2 \cdot 10^{10} \text{ p/fill}$

Total number of stored particles per fill

$f = 0.55\%$

Useful event rate fraction (polarimeter efficiency)

$T_{Tot} = 10^7 \text{ s}$

Total running time per year

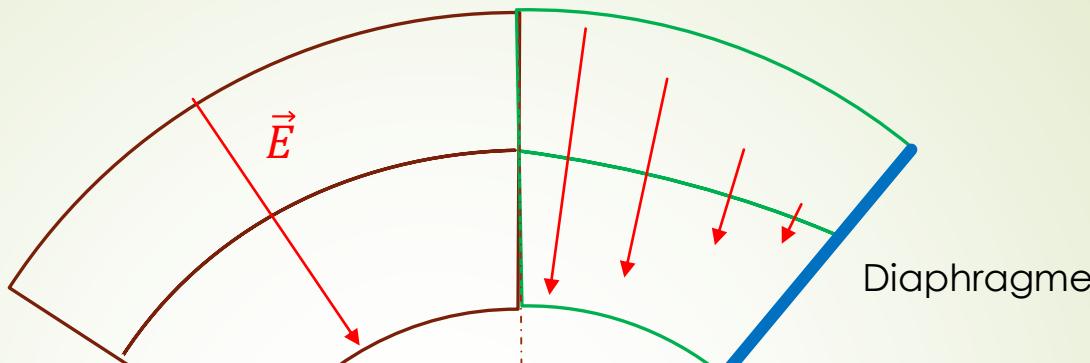
$\tau_{Spin} = 10^3 \text{ s}$

Polarization lifetime (**Spin Coherence Time**)

$$\sigma \approx 2.5 \cdot 10^{-29} \text{ e} \cdot \text{cm} \quad \text{for one year measurement}$$

Systematic error due to vertical electric fields and horizontal magnetic fields

# Trajectoire d'une particule dans le délecteur



Partie centrale :

- Méthode hamiltonienne
- Ordre 2 de perturbation

Champ de fuite:

- Méthodes de quadrature
- Polynômes orthogonaux spécifiques

$$\mathcal{H} = - \left( 1 + \frac{x}{\rho_0} \right) \cdot \sqrt{\frac{\gamma^2 - 1}{\gamma_0^2 \cdot \beta_0^2} - \left( \frac{p_x^2}{\rho_0^2} + \frac{p_y^2}{\rho_0^2} \right)}$$
$$= \mathcal{H}_{lin} + \tilde{\mathcal{H}}$$

Ordres de grandeur pour l'exemple de vérification :

$$\Delta\rho \sim 0,3 \text{ mm}$$

$$\Delta\theta \sim 4 \text{ mrad}$$

Résultats validés numériquement sur un exemple

# Dynamique de spin

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$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{q}{mc^2} \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E}$$

$$\frac{d\vec{S}}{ds} = \vec{\Omega}_s \times \vec{S}$$

$$\vec{\Omega}_s = \left( 1 + \frac{P_x^2 + P_y^2}{2} \frac{\beta_0 \gamma_0}{\beta \gamma} \right) \left( G - \frac{1}{\gamma^2 - 1} \right) \frac{\gamma_0^2 - 1}{\gamma \rho} \begin{pmatrix} 0 \\ \tilde{P}_s \\ \frac{\tilde{P}_s}{P_y} \end{pmatrix}$$

Forme de spineur plus adaptée :

$$\begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}' = \frac{F(s)}{2} \begin{bmatrix} -i\bar{P}_y & \tilde{P}_s \\ -\tilde{P}_s & i\bar{P}_y \end{bmatrix} \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} = U \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

Solution :

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