SIMULATIONS OF BEAM DYNAMICS AND BEAM LIFETIME FOR THE PROTOTYPE EDM STORAGE RING

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DPG Spring Meeting

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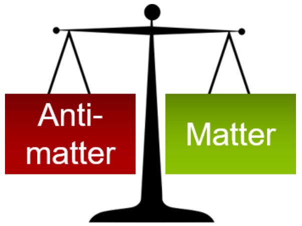
OUTLINE

1) Introduction
2) EDM Measurement using Storage Ring
3) Prototype EDM Storage Ring
4) Simulation Results
5) Conclusion

INTRODUCTION

Big Bang



Equal amount of matter & antimatter

Today

[1]

Matter

Baryon Asymmetry

⇩

$$= \frac{N_B - N_{\bar{B}}}{N_\gamma}$$

Observed value * $\approx \mathbf{10^{-10}}$

Expected value $\approx \mathbf{10^{-18}}$

Early Universe

Preference of matter

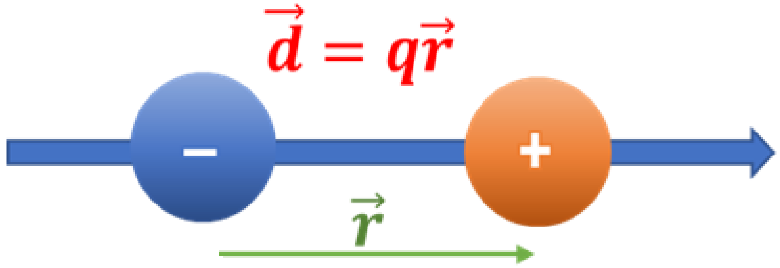
Sakharov criteria (1967): [2]

- Baryon number violation
- No thermic equilibrium
- $\mathcal{C}$, $\mathcal{CP}$ **violation**

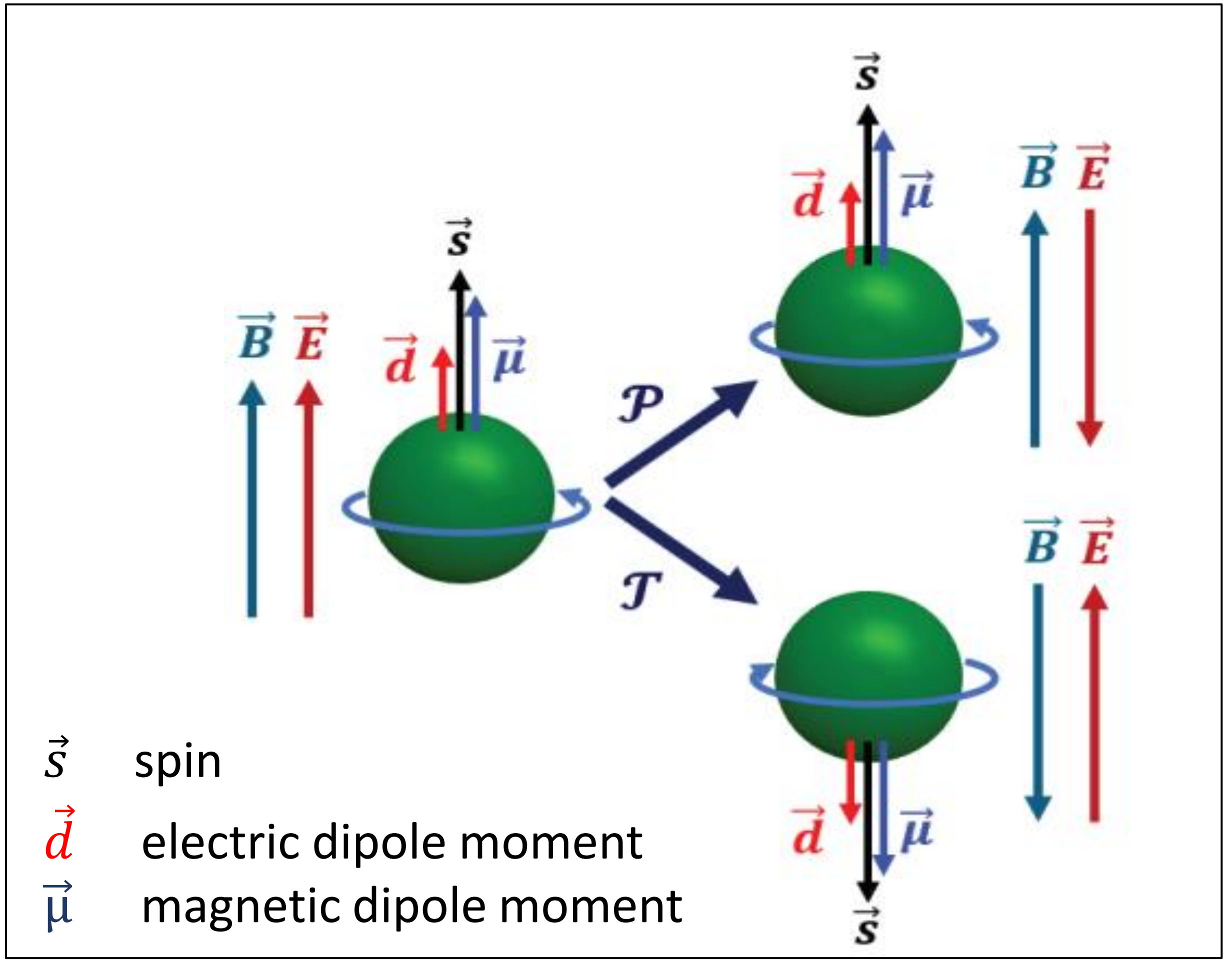
Search for $\mathcal{CP}$ violation beyond the Standard Model

* Cosmological Models

Electric Dipole Moment (EDM)



- **EDM**: a permanent separation of positive and negative charge (vector along spin direction)
- Fundamental property of particles (like mass, charge, magnetic moment)
- Existence of EDM only possible if violation of time reversal and parity symmetry



$$H = H_M + H_E = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

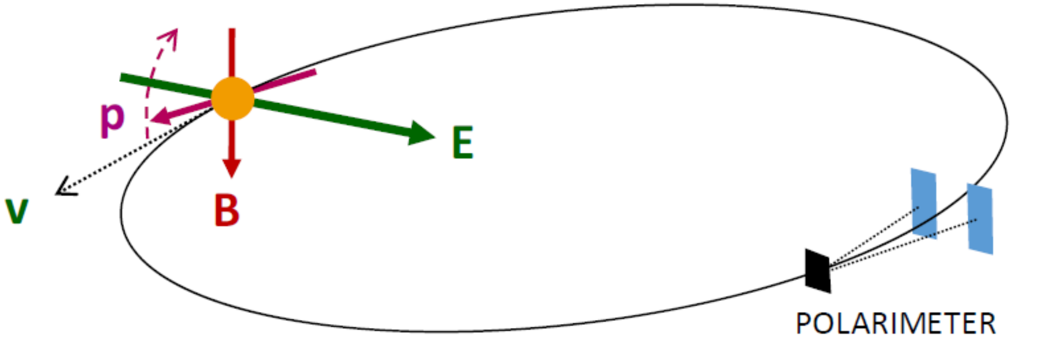
$$P : H = -\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}$$

$$T : H = -\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}$$

EDM MEASUREMENT USING STORAGE RING

Basic Principle

1) Inject longitudinally polarized beam in storage ring
2) Radial electric field interacting with EDM (**torque**)
3) Observe vertical polarization with time



[3]

Spin motion: **Thomas-BMT-Equation**

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{S} = (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \times \vec{S}$$

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

If G > 0 → pure electric ring
If G < 0 → combination of E-B

Frozen Spin $\vec{B} = 0$ ⇒ $\left(G - \frac{1}{\gamma^2 - 1}\right) \equiv 0!$ ⟶ Magic momentum

Stage 1

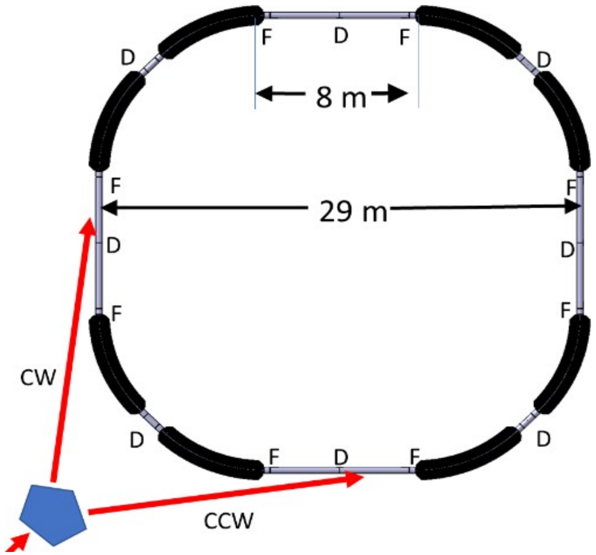
Precursor experiment at COSY at FZ Jülich

- Magnetic storage ring
- Deuterons with p= 970 MeV/c

Advancement towards final storage ring will
- Decrease the systematic errors
- Increase EDM measurement`s precision

Stage 2

Prototype proton storage ring

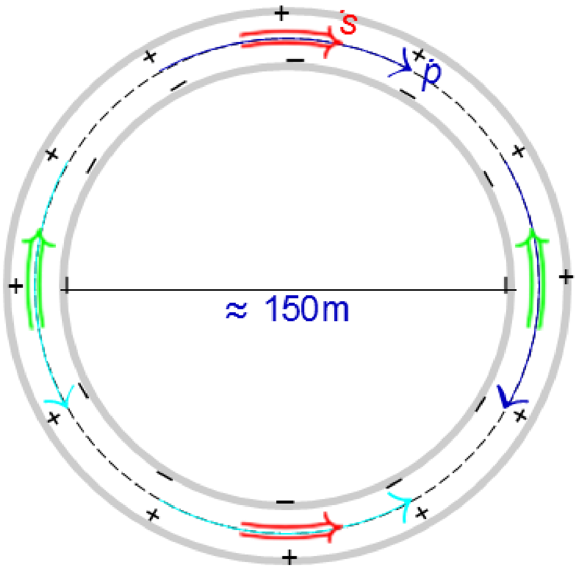


- Electric magnetic storage ring
- Simultaneous CW and CCW beams
- Operates at 30 MeV and 45 MeV

Stage 3

[4]

Final storage ring



- Pure Electrostatic storage ring
- Proton Magic momentum (701MeV/c)

Stage 1

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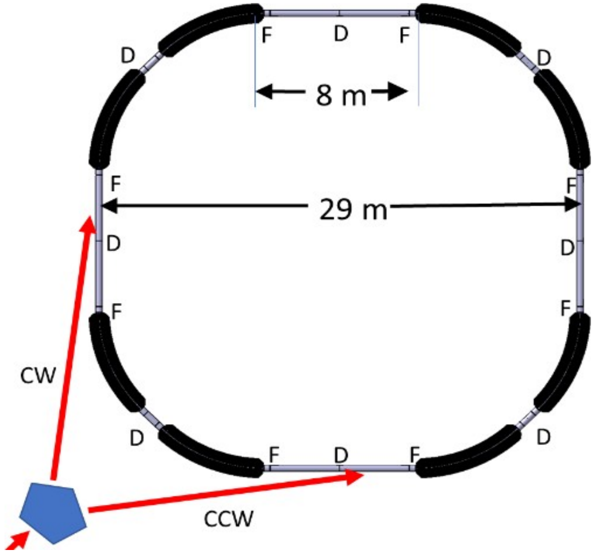

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[4]

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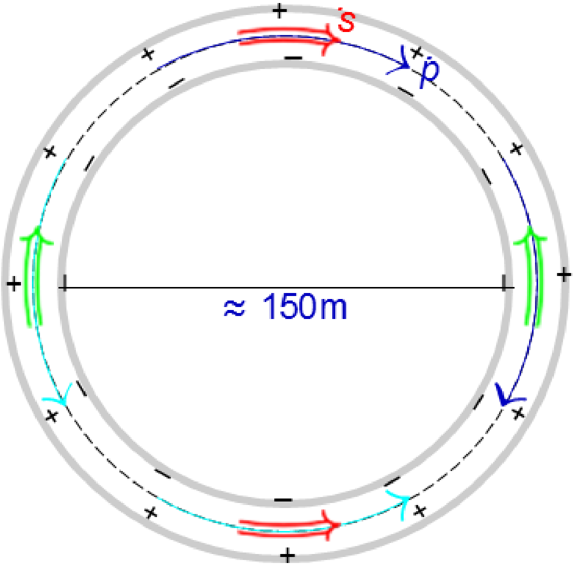

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PROTOTYPE EDM STORAGE RING [5]

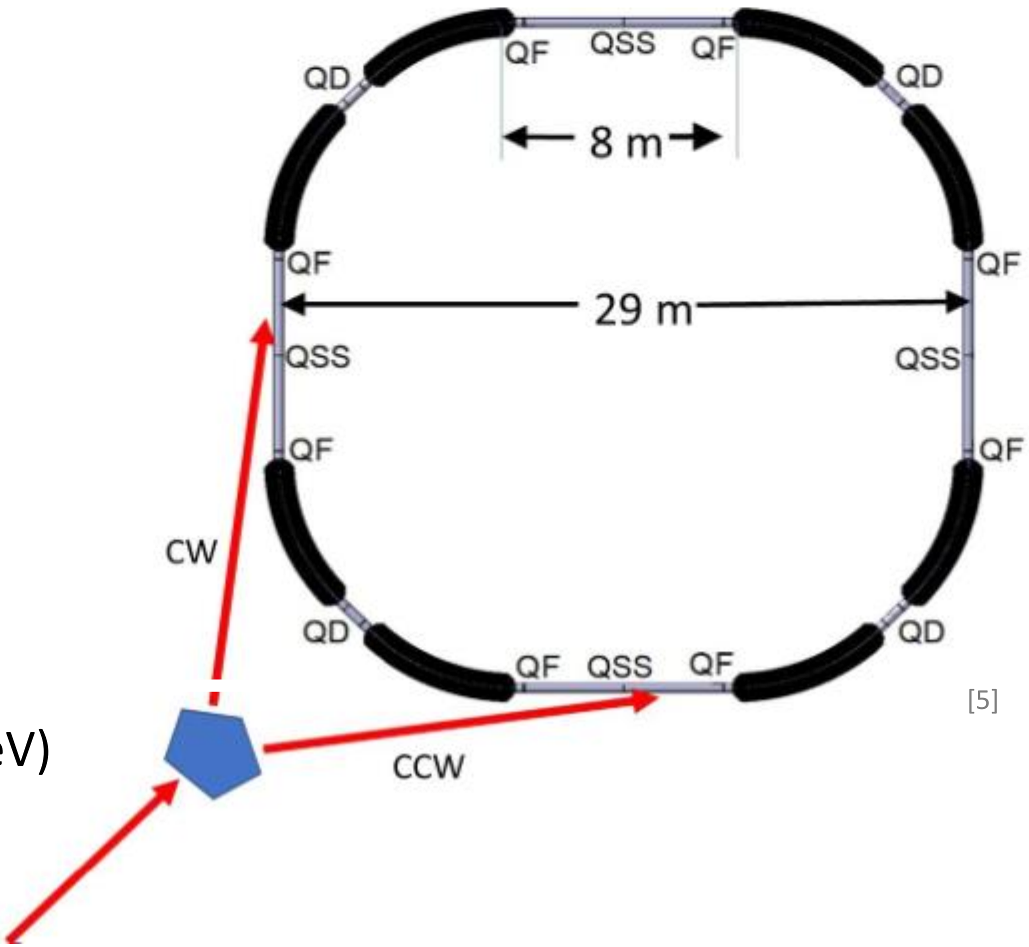
Goals:

- Frozen spin capability
- Storage of high intensity CW and CCW beams simultaneously $\tau > 1000\ sec$
- Beam injection with multiple polarization states
- Develop and benchmark simulation tools
- Develop key technologies beam cooling, deflector, beam position monitors, magnetic shielding….
- Perform EDM measurement

RING DESIGN AND PARAMETERS [5]

Basic layout

- Fourfold symmetric squared ring
- Circumference ≈ 123 m
- Each straight section is 8m long
- Three families of quadrupoles will be used
  - i. Focusing QF
  - ii. Defocusing QD
  - iii. Straight section QSS
- Ring will be operated in two modes
  - i. With all electric bendings (at T=30 MeV)
  - ii. With electric and magnetic bendings (at T=45 MeV)



SIMULATION RESULTS

- Lattice Optics
- Estimations of Beam Losses

LATTICES

[6]

- **MADX** (Methodical Accelerator Design)

One cell = QSS-d-QF-d-EB-d-QD-d-EB-d-QF-d-QSS

Betatron tunes

$0.2 \leq Q_x \leq 2.5$

$0.1 \leq Q_y \leq 2.5$

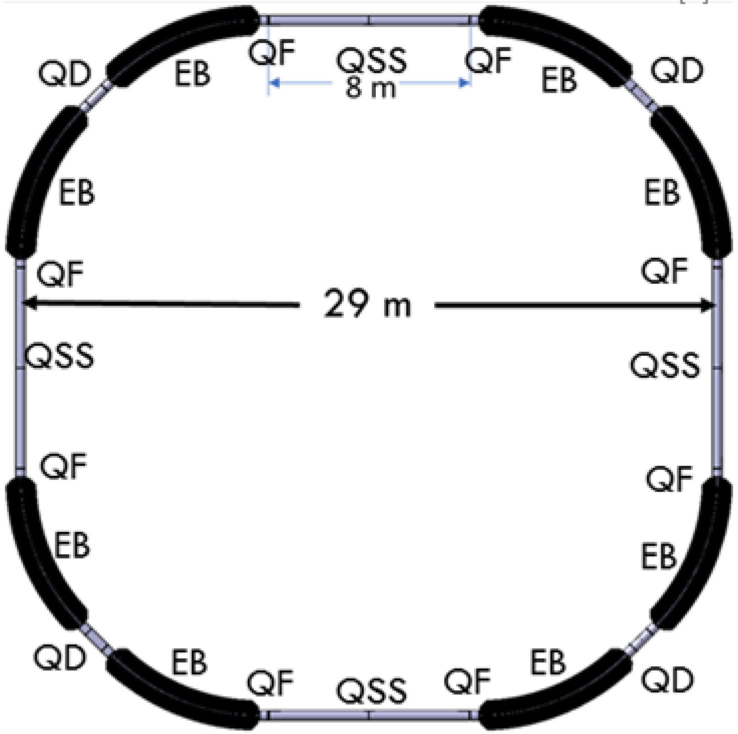
Betatron functions

$\beta_x \leq 20\ m$

$\beta_y \leq 400\ m$

- **Four different lattices studied**
  1. Strong Lattice with $\beta_{y-max} = 33\ m$
  2. Medium Lattice with $\beta_{y-max} = 100\ m$
  3. Weak Lattice with $\beta_{y-max} = 200\ m$
  4. Weaker Lattice with $\beta_{y-max} = 300\ m$

[5]



QSS = straigh-section Quadrupole
d = drift section
QF = focusing quadrupole
QD = defocusing quadrupole
EB = electrostatic bending

ESTIMATION OF BEAM LOSSES [9,10,11,12]

Four main effects of beam losses

1. Hadronic Interactions
2. Coulomb Scattering
3. Energy Loss Straggling
4. Intra Beam Scattering

Two different scenarios

I. With Residual gas
II. With Residual Gas + Target

i. Residual gas

- Gases are H_2 : N_2 with 80:20
- $\sigma_{tot} = 204$ mb
- *Nitrogen equivalent pressure* $P_{eq} = 2.8 \times 10^{-11}\ Torr$
- $n_{rg} = 5.30 \times 10^5\ atoms/cm^3$
- f_0 =0.596MHz

ii. Target

- *Carbon target with thickness*

$n_t \sim 2 \times 10^{12}\ atoms\ /cm^2$

Calculations for four lattices are performed in each case

1. Hadronic interaction

$$\tau^{-1} = n\sigma_{tot} f_0$$

$\tau_{loss} = beam\ loss\ rate$
$n = target\ thickness\ or\ rest\ gas\ density$
$\sigma_{tot} = total\ cross\ section$
$f_0 = revolution\ frequency$

i. Residual gas

ii. Target

$$\tau^{-1} = 3.51 \times 10^{-9}\ s^{-1} \quad < \quad \tau^{-1} = 2.14 \times 10^{-6}\ s^{-1}$$

As there is no dependency on optical functions this effect remains the same for all lattices

2. Coulomb Scattering

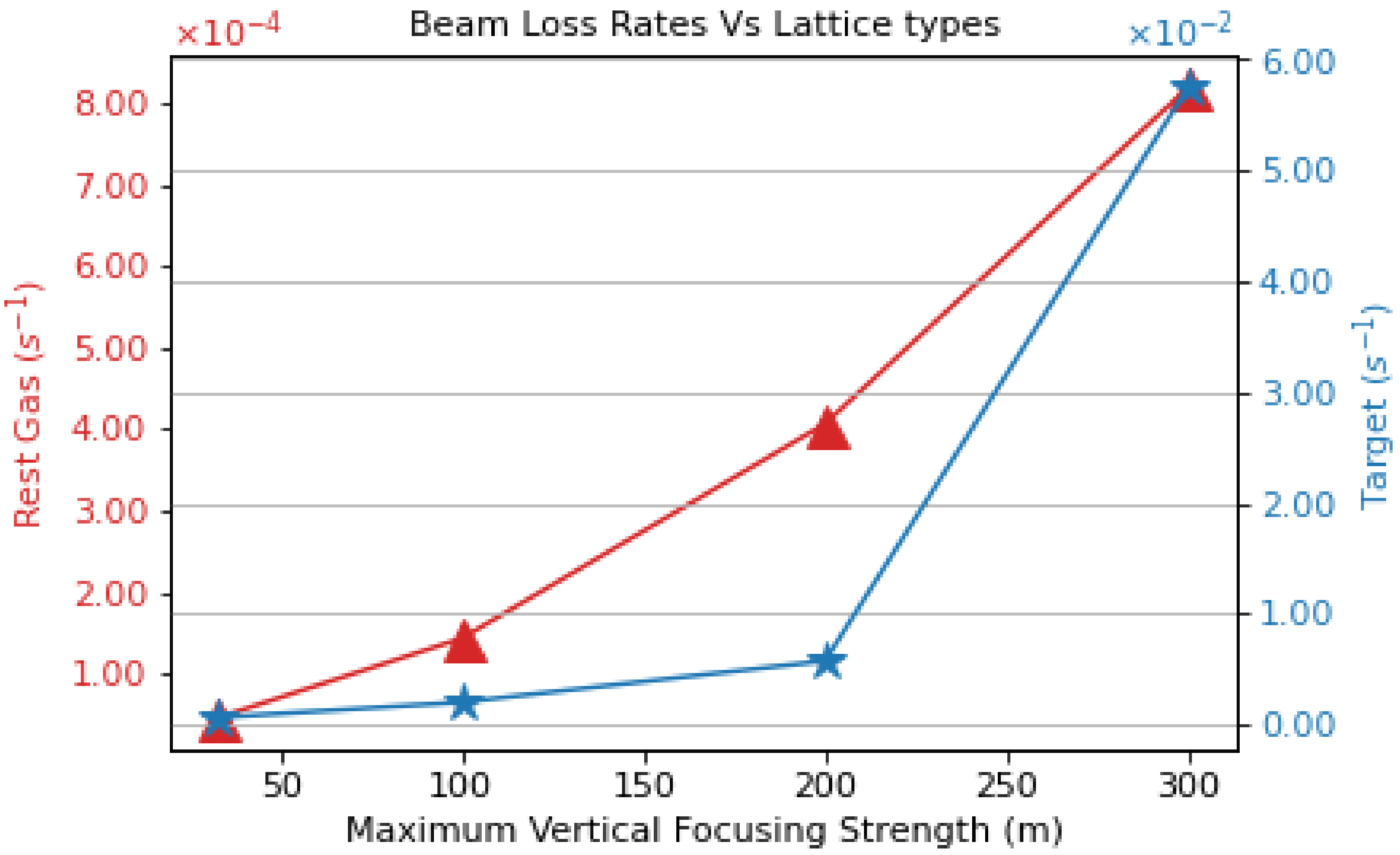
$$\tau^{-1} = n\sigma_{tot} f_0$$

Where : $\sigma_{tot} \propto \frac{1}{\gamma\beta\,\theta}$

and

$$\theta = \sqrt{\frac{A}{\beta_\perp}}$$

A=Transverse acceptance > 10 mm mrad
$\beta_\perp$ = Transverse betatron amplitude



3. Energy Loss Straggling

$\tau^{-1} = f_0 \mathrm{P}$

P=*relative beam loss probability per turn*

Probability depends on maximum energy loss (ϵ_{max})and longitudinal acceptance (δ_{max})

$$\epsilon_{max} = 66.32\ keV$$

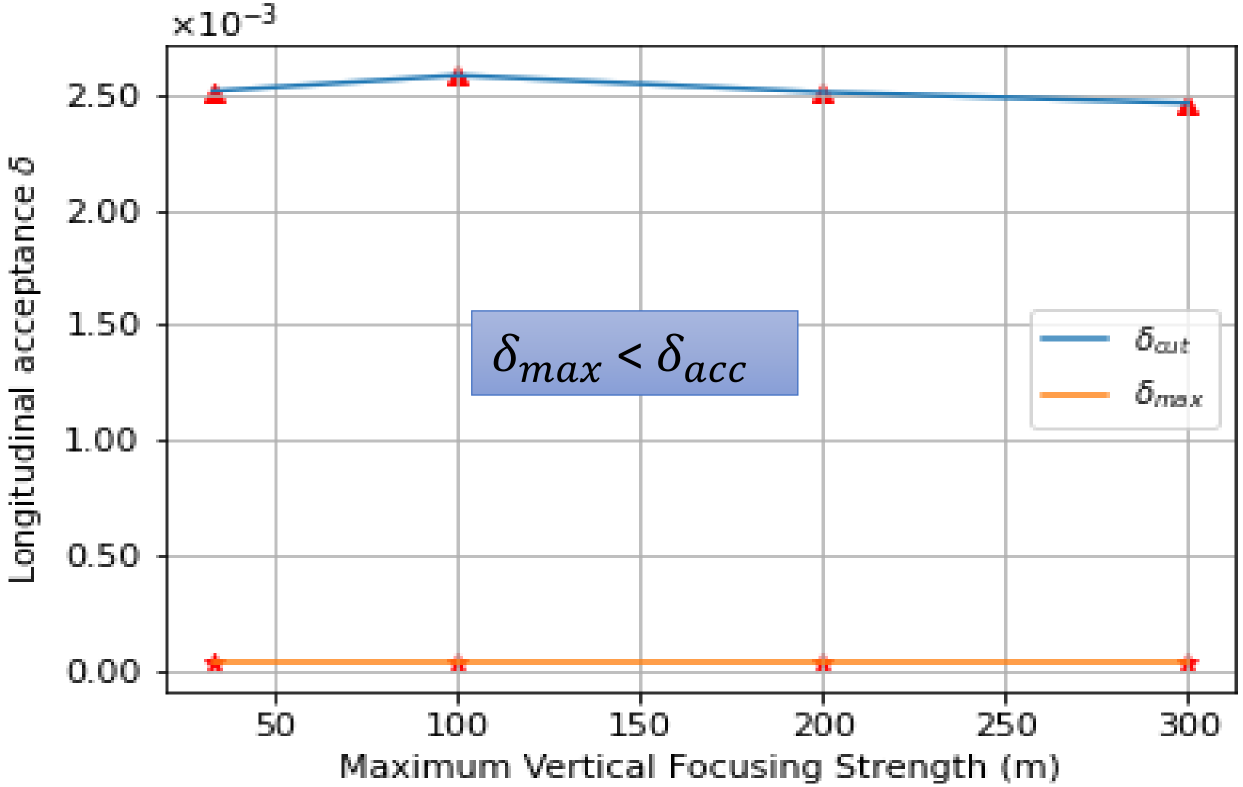
⇩

$$\delta_{max} = 3.35 \times\ 10^{-5}$$

Geometrical longitudinal acceptance

$$\delta_{acc} = \frac{chamber\ radius}{Max.\ dispersion} = \frac{30\ mm}{D_{max}}$$

No beam loss with T=30 MeV theoretically



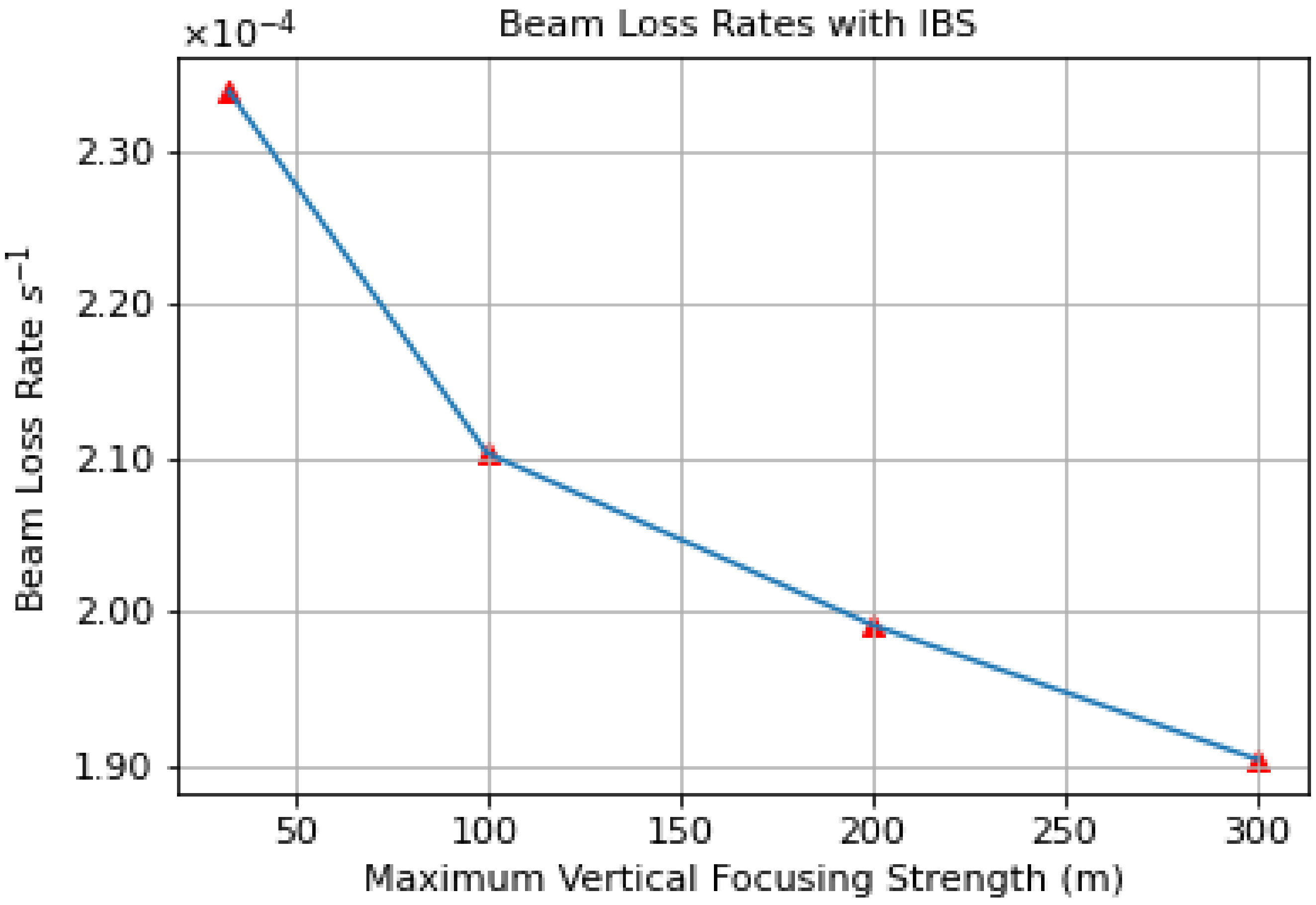
$\delta_{max} < \delta_{acc}$

4. IntraBeam Scattering (IBS)

$$\tau_{loss}^{-1} = \frac{D_{\parallel}^{IBS}}{L_c \delta_{acc}^2}$$

$$D_{\parallel}^{IBS} = longitudinal\ diffusion\ coefficient \sim \frac{N}{(\gamma\beta)\epsilon^{3/2}\sqrt{\beta}}$$

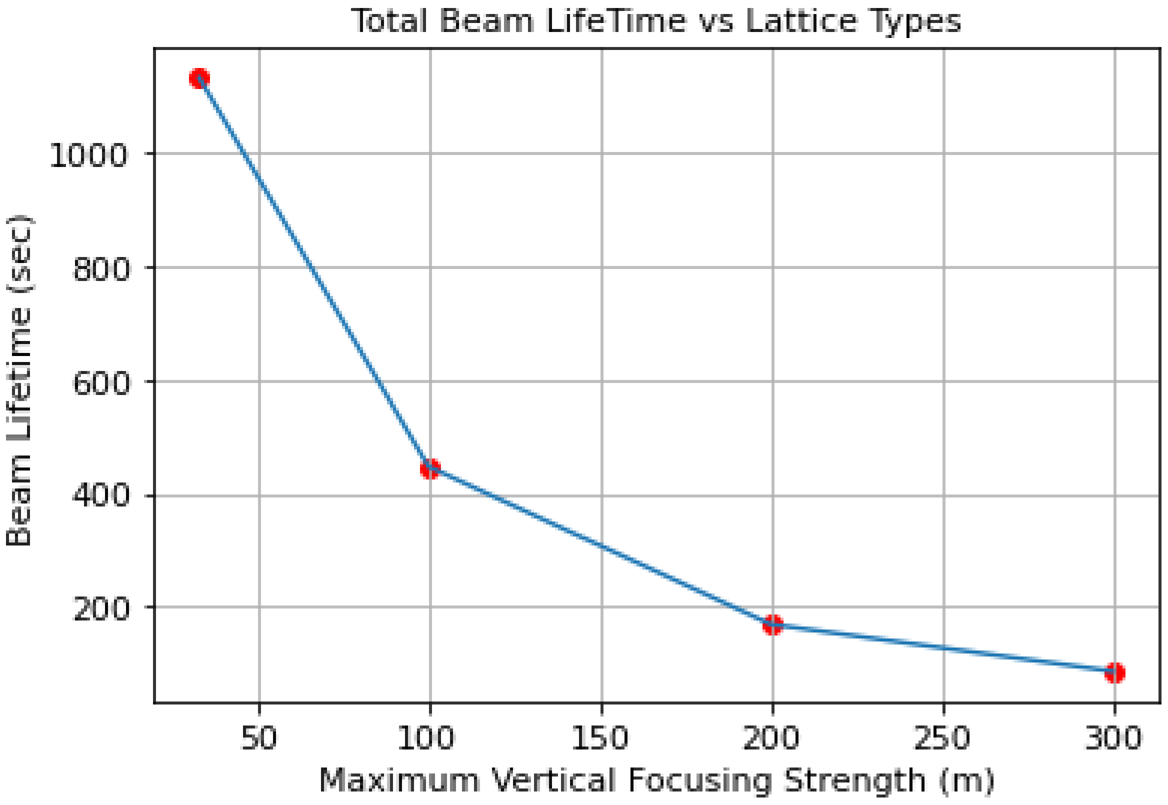
ϵ = *emittance of beam = 10 mm mrad*
β =*average beta function*
Lc= coulomb logarithm
N=10^9 *particles*
$\gamma\beta$= *beam momentum*



Total Beam loss rate

$$\left(\frac{1}{\tau}\right)_{Total} = \left(\frac{1}{\tau}\right)_{HI} + \left(\frac{1}{\tau}\right)_{CS} + \left(\frac{1}{\tau}\right)_{ES} + \left(\frac{1}{\tau}\right)_{IBS}$$

Lattice type	$1/\tau_{loss}$ $(10^{-4}s^{-1})$	τ_{total} (s)
Strong	8.82	1133
Medium	22.34	447
Weak	59.49	168
Weaker	117.79	85



Summary:

- Preliminary design of prototype EDM ring
- Most dominating effect is Single Coulomb Scatterings
- Lattice with $\beta_{y-max} \leq 100\ m$ is preferable for longer beam lifetime.

Outlook:

- Further investigations on beam and spin dynamics.
- Conceptual studies of PTR design is under consideration.

THANK YOU

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TRANSFER MATRIX FOR ELECTROSTATIC DEFLECTOR

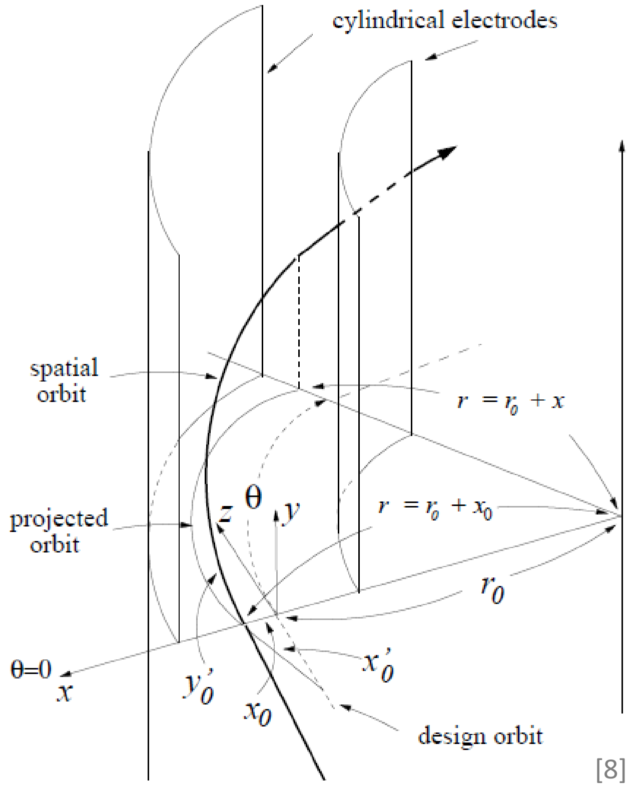
For pure electrostatic deflectors

- Transfer matrices derived from Hamiltonian (a brilliant work done by Rick Bartmaan) [7]
- For non-relativistic and the cylindrical electrodes

with $\xi=\sqrt{2}$ and $\eta=0$

ξ = horizontal focusing strength
η = vertical focusing strength

$$EB = \begin{bmatrix} 0.85418 & 3.30871 & 0 & 0 & 0 & 1.29205 \\ -0.0817166 & 0.85418 & 0 & 0 & 0 & 0.724056 \\ 0 & 0 & 1 & 3.47954 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -0.724056 & -1.29205 & 0 & 0 & 1 & 2.94856 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



[8]

ESTIMATION OF BEAM LOSSES

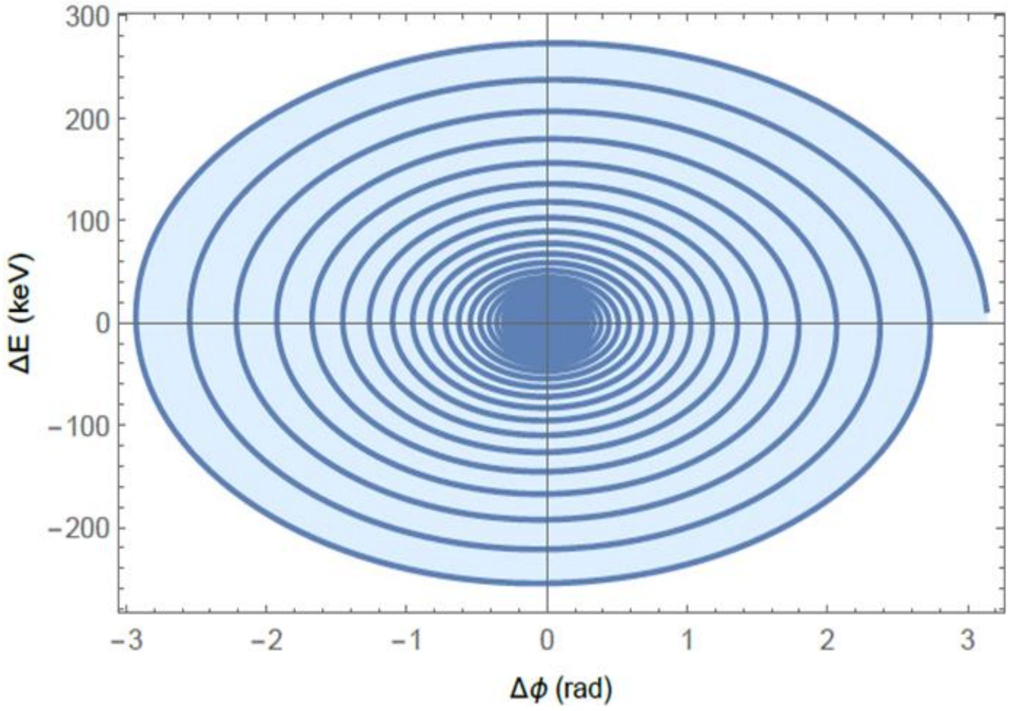
$$\Delta E_{max} = \pm \sqrt{\frac{2\,\beta^2 e\, U\, E}{\pi q\,(\alpha_c - {}^{1}/_{\gamma^2})}}$$

For Strong Lattice

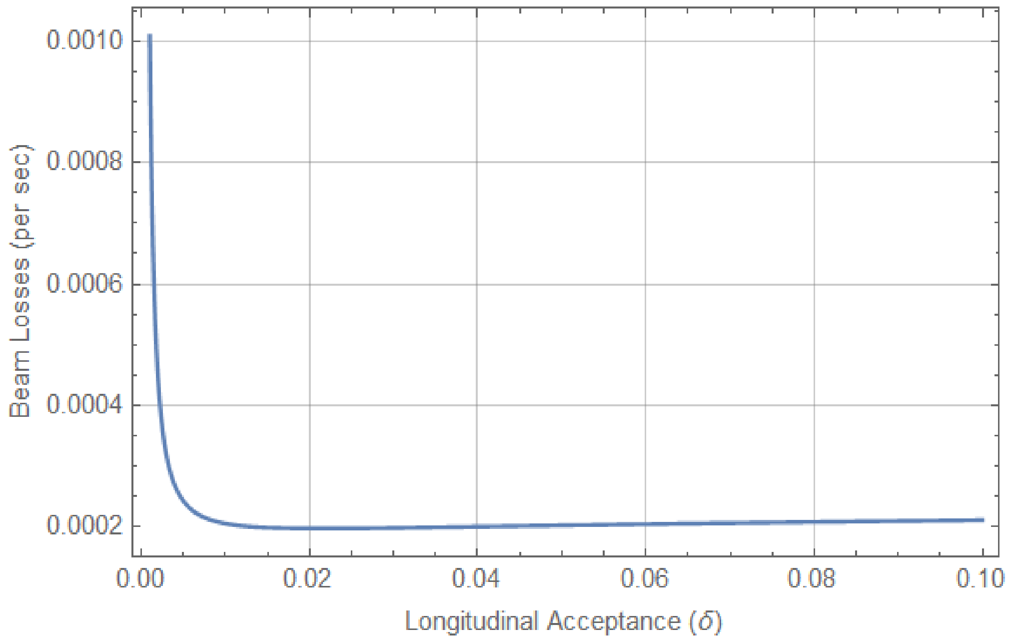
with $U = 4\,kV,\ \alpha_c = 0.554$

$\Delta E_{max} > \epsilon_{max}$

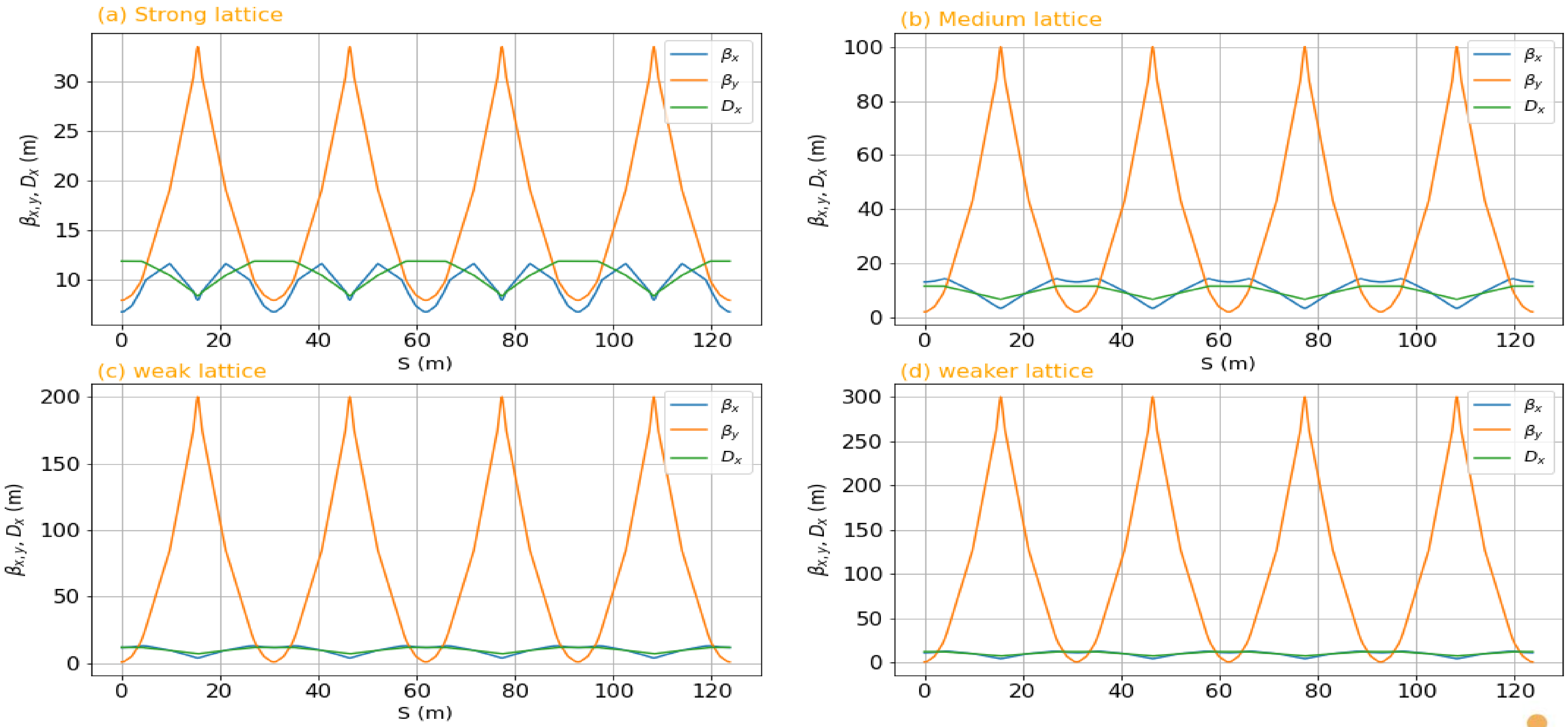
Maximum Energy Deviation vs Phase-angle



Longitunal Acceptance vs Beam Losses



PTR Lattices



Lattice type	δ_{acc} (10^{-3})
Strong	2.519
Medium	2.588
Weak	2.514
Weaker	2.466

Coulomb Scattering tables

With R.G

Lattice Type	BLR$(10^{-5} sec^{-1})$
Strong	4.57
Medium	14.30
Weak	40.66
Weaker	81.96

with carbon target

Lattice Type	BLR$(10^{-4} sec^{-1})$
Strong	6.46
Medium	20.22
Weak	57.48
Weaker	115.87