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

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Saad Siddique & Prof. Dr. Andreas Lehrach

Member of the Helmholtz Association

III. Physikalisches Institut B

RWTH AACHEN UNIVERSITY

JEDI

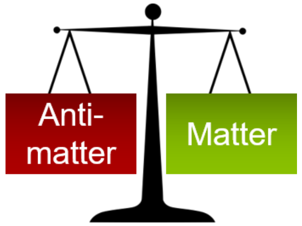
JÜLICH Forschungszentrum

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

Early Universe

Preference of matter

Sakharov criteria (1967): [2]

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

Today

[1]

Matter

Baryon Asymmetry

⇩

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

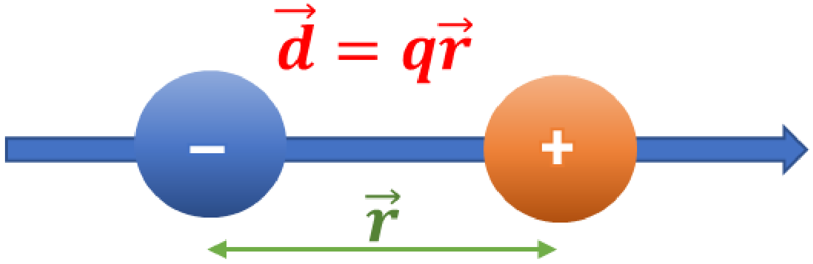
Observed value * $\approx \mathbf{10^{-10}}$

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

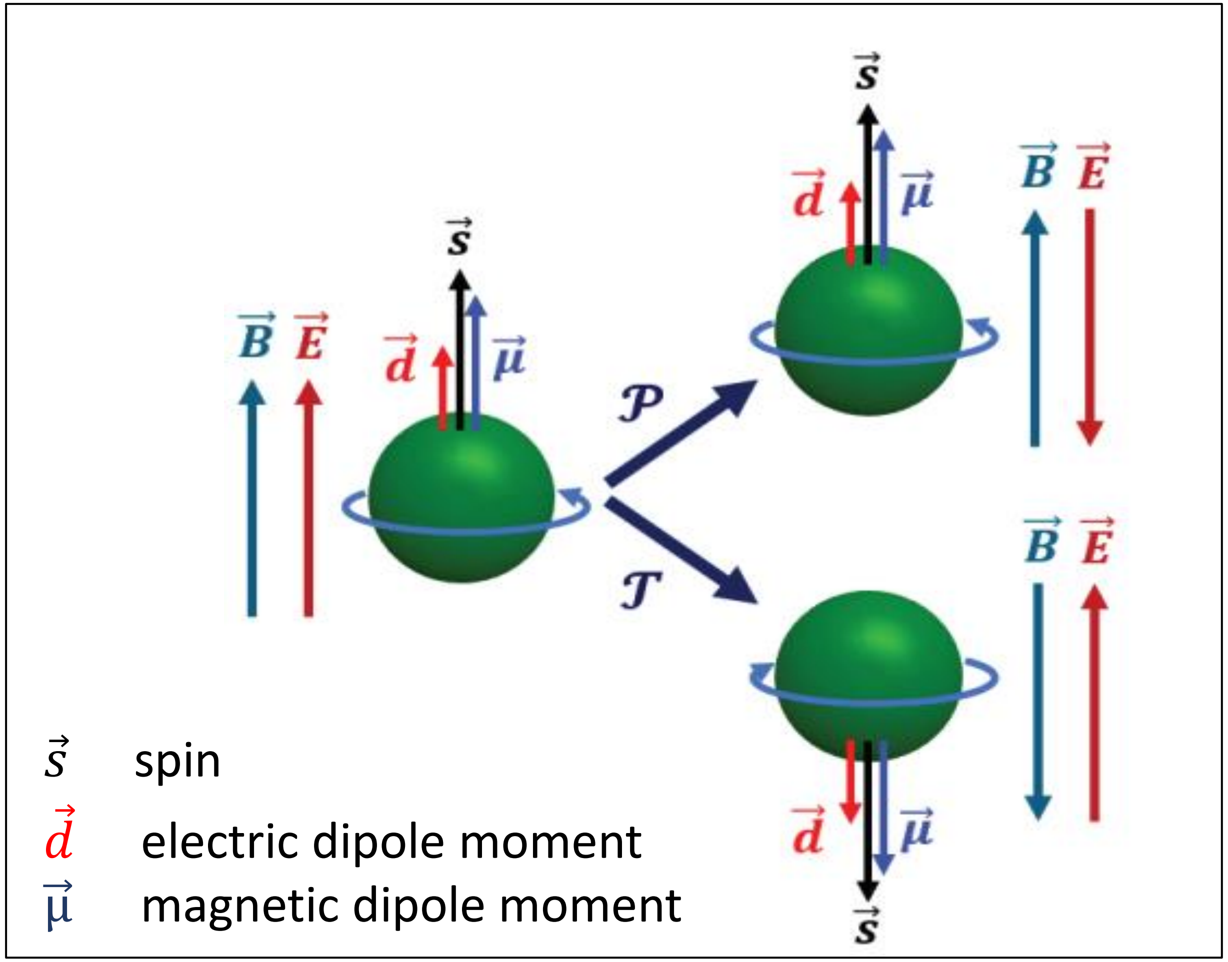
Search for $\mathcal{CP}$ violation beyond the Standard Model

* 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



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

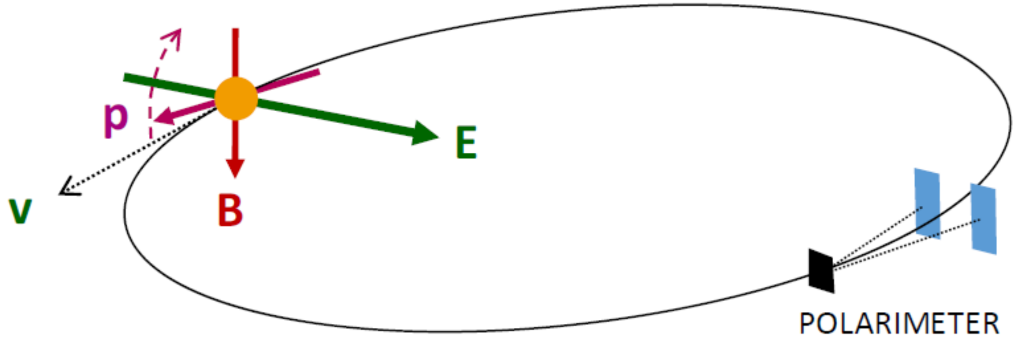
$$P : H = -\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}$$

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

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

EDM MEASUREMENT USING STORAGE RING [4]

Stage 1

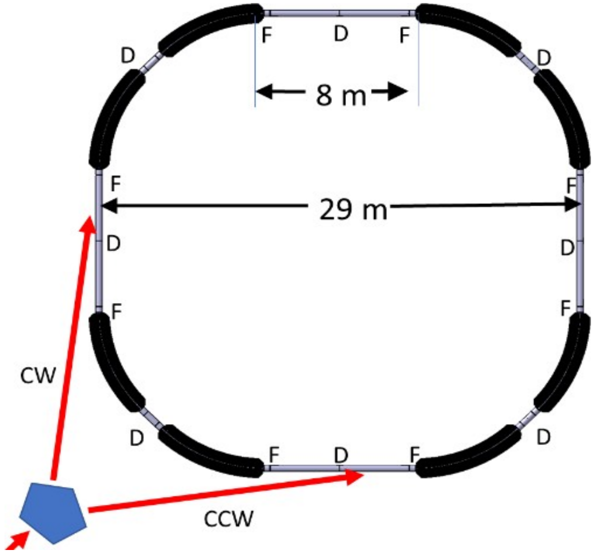
Precursor experiment at COSY at FZ Jülich

- 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

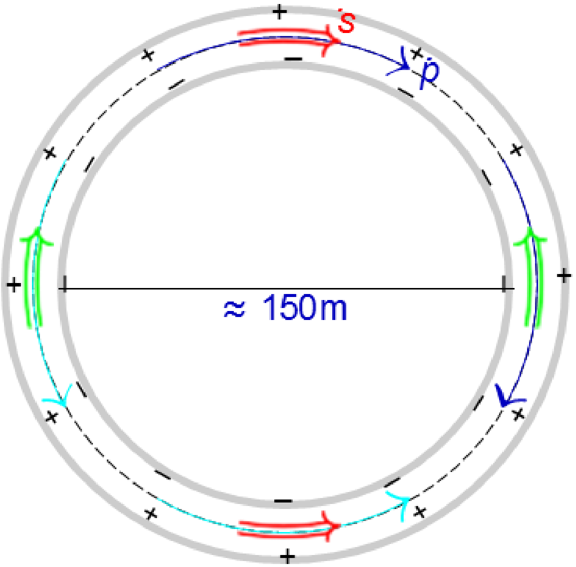
Prototype proton storage ring



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

Stage 3

Final storage ring



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

PROTOTYPE EDM STORAGE RING [5]

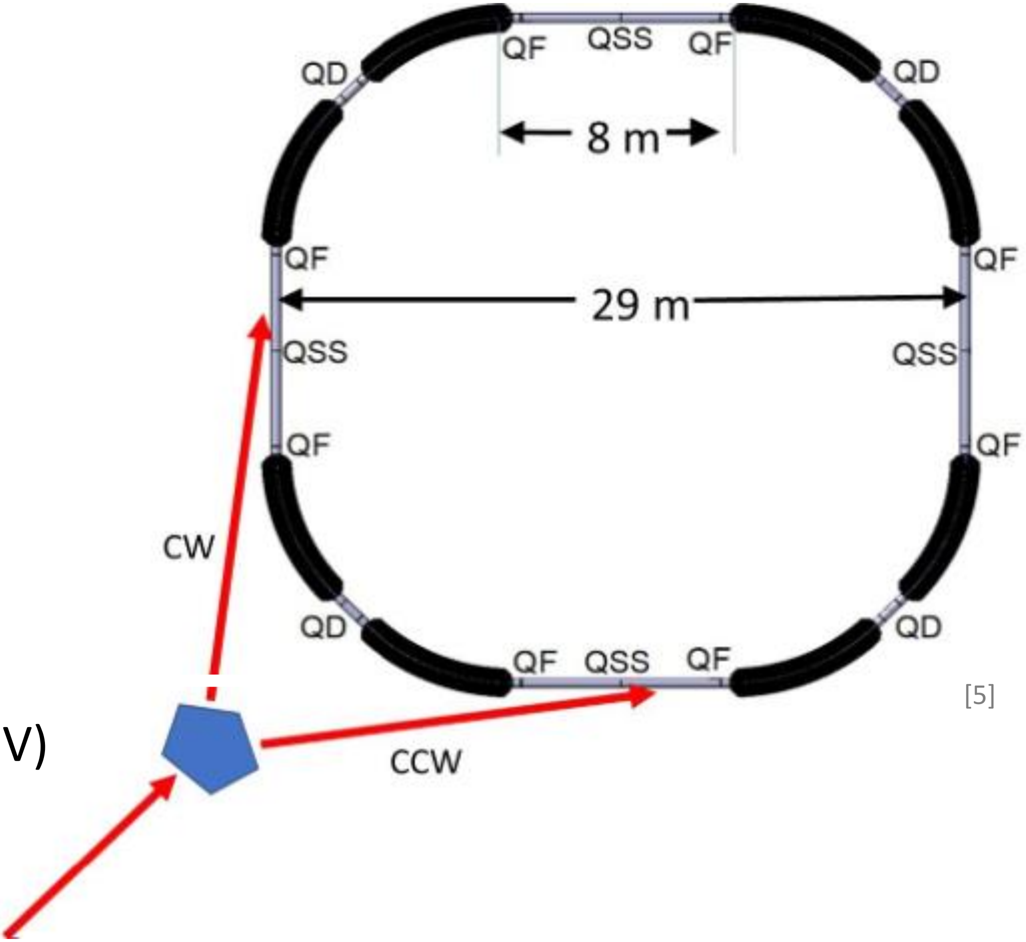
Goals:

- Frozen spin capability
- Storage of high intensity CW and CCW beams simultaneously
- 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 ≈ 100 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)



[5]

SIMULATION RESULTS

- Lattice Optics
- Estimations of Beam Losses

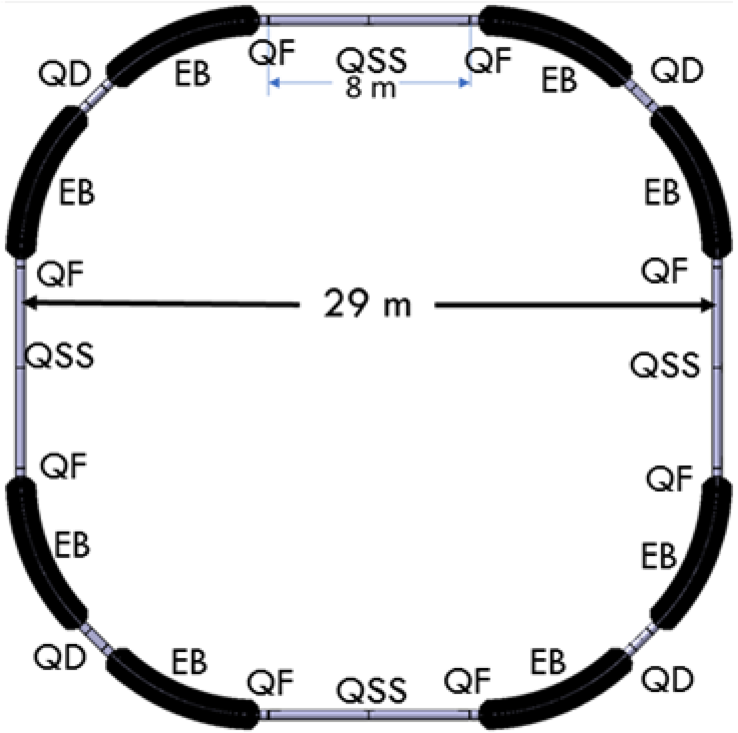
LATTICES

- **MADX** (Methodical Accelerator Design) [6]
- 1st Stage of PTR is studied (*i.e T=30 MeV of protons*)

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

- Four different lattices studied
  1. Strong focusing
  2. Medium focusing
  3. Weak focusing
  4. Weaker focusing

[5]



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

TRANSFER MATRIX FOR ELECTROSTATIC DEFLECTOR

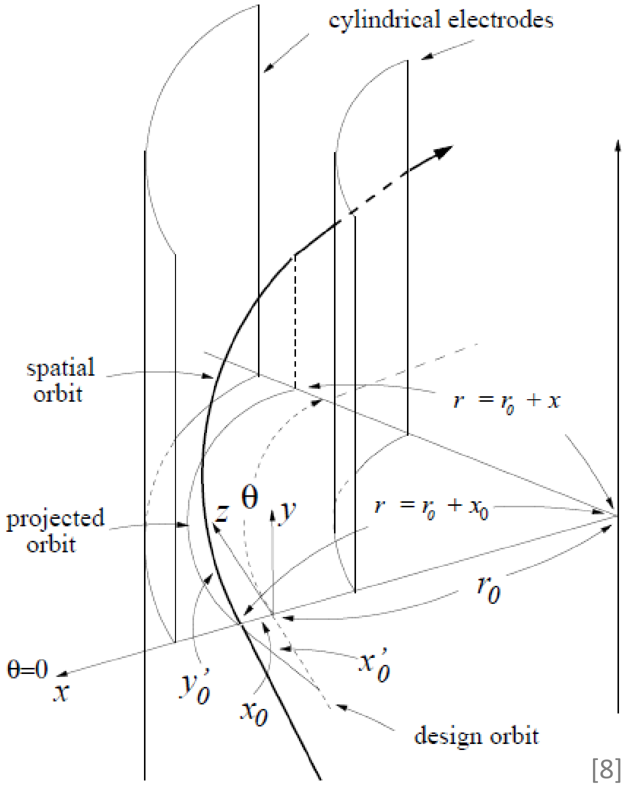
For pure electrostatic deflectors

- 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

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

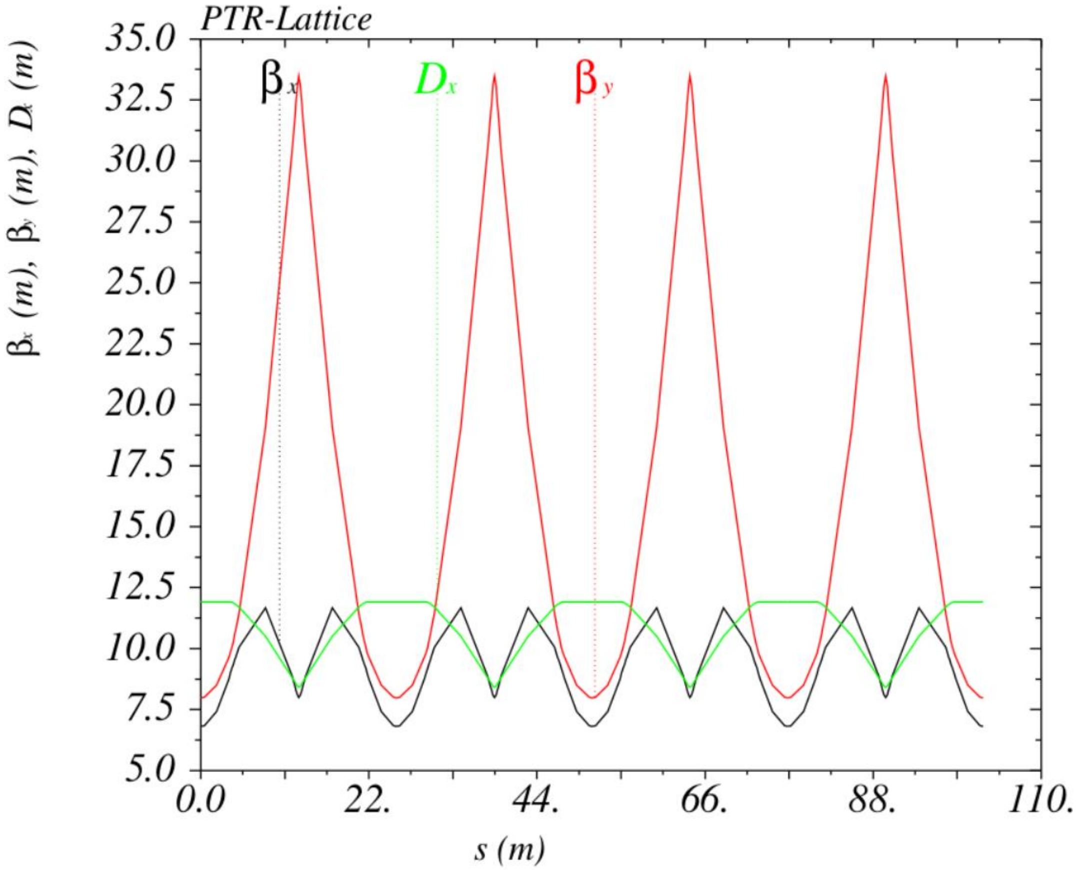


[8]

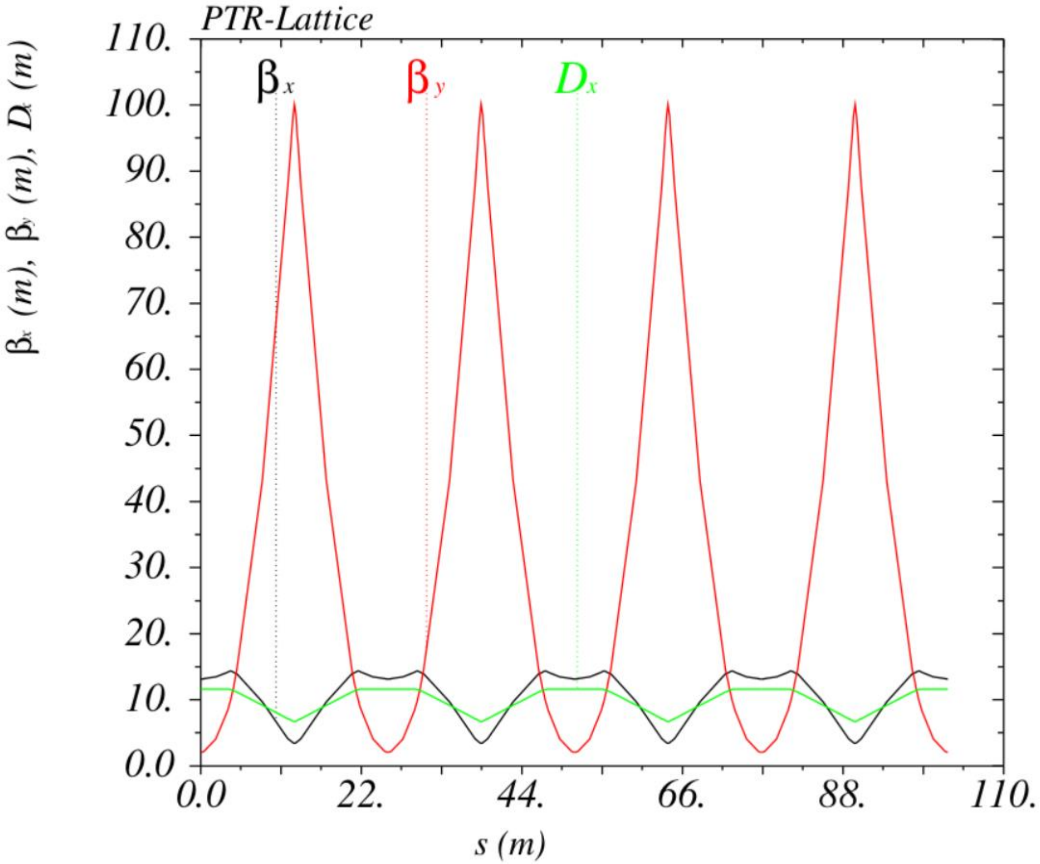
SIMULATION RESULTS

Four different lattices

1. *Strong focusing* strength with $\beta_{y-max} = 33\ m$



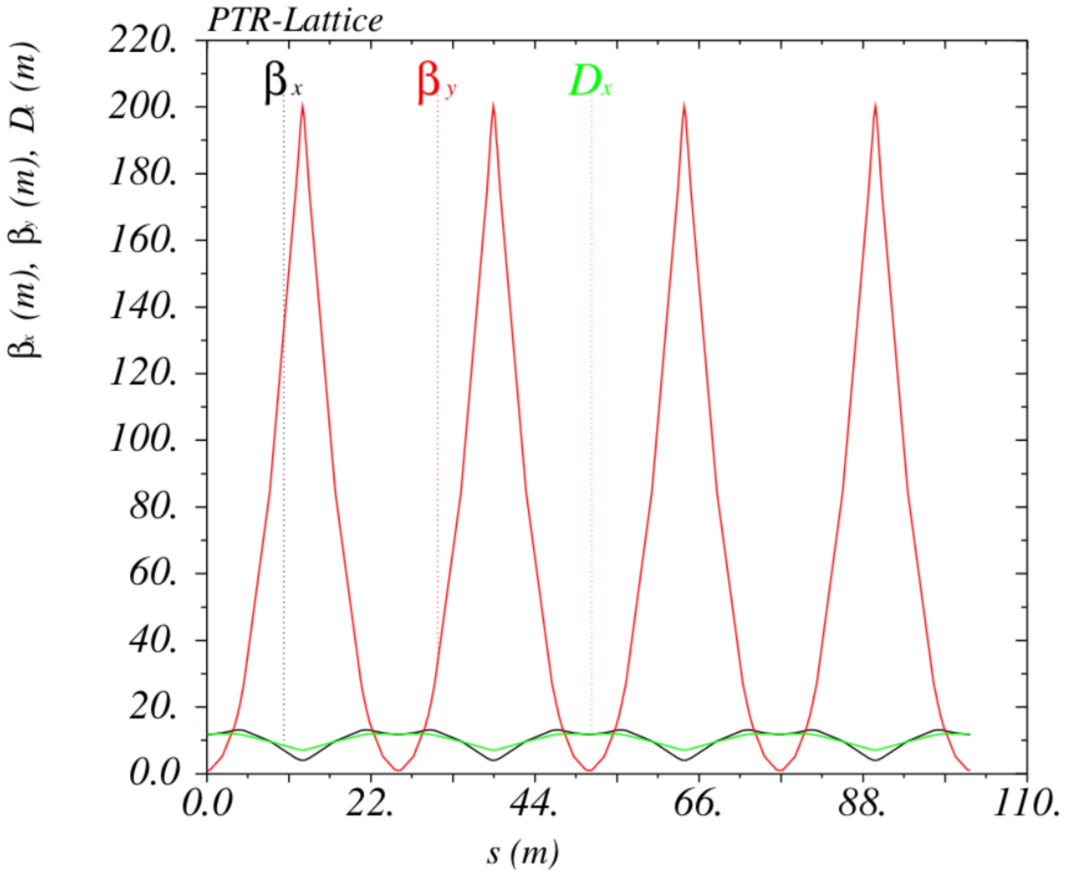
2. *Medium focusing* strength with $\beta_{y-max} = 100\ m$



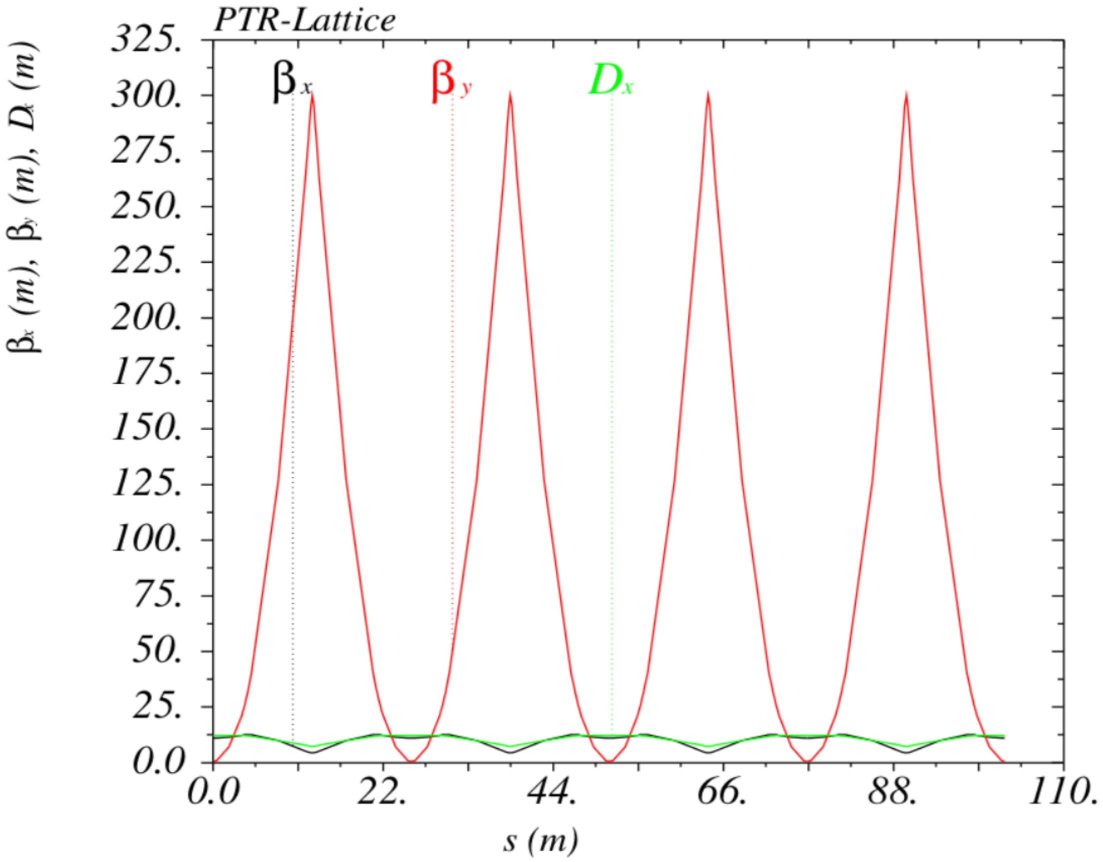
SIMULATION RESULTS

Four different lattices

3. *Weak focusing* strength with $\beta_{y-max} = 200\ m$



4. *Weaker focusing* strength with $\beta_{y-max} = 300\ m$



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 with all effects

i. With residual gas
ii. With target

Calculations for four lattices are performed in each case

ESTIMATION OF BEAM LOSSES

1. Hadronic interaction

i. With residual gas
ii. With target

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

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

i. With residual gas

- Gases are $H_2 : N_2$ with 80:20
- $\sigma_{tot} = 204 \text{ mb}$
- *Nitrogen equivalent pressure* $P_{eq} = 2.8 \times 10^{-11}\ Torr$
- $n_{rg} = 1.9 \times 10^6\ particles$
- f_0 =1.138 MHz

ii. With Target

- *Hydrogen pellet target with thickness* $n_t = 4.0 \times 10^{15}\ atoms\ /cm^2$
- $\sigma_{tot} = 85\ mb$

$$\tau^{-1} = 2.99 \times 10^{-15}\ s^{-1} < \tau^{-1} = 3.86 \times 10^{-7}\ s^{-1}$$

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

ESTIMATION OF BEAM LOSSES

Lattice type	$\langle\beta_\perp\rangle$ (m)	θ_{min} (mrad)
Strong	12.206	0.905
Medium	21.560	0.681
Weak	36.312	0.525
Weaker	51.535	0.441

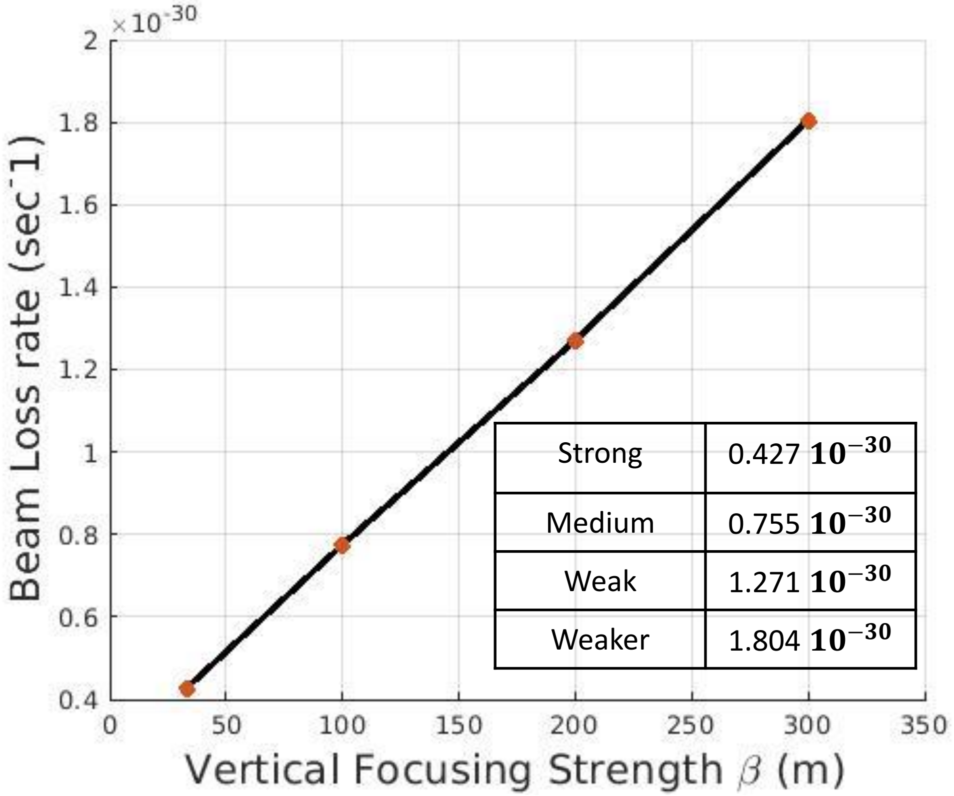
2. Coulomb Scattering

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

Where : $\sigma_{tot} \propto \frac{1}{\gamma\beta\,\theta}$ and $\theta = \sqrt{\frac{A}{\beta_\perp}}$

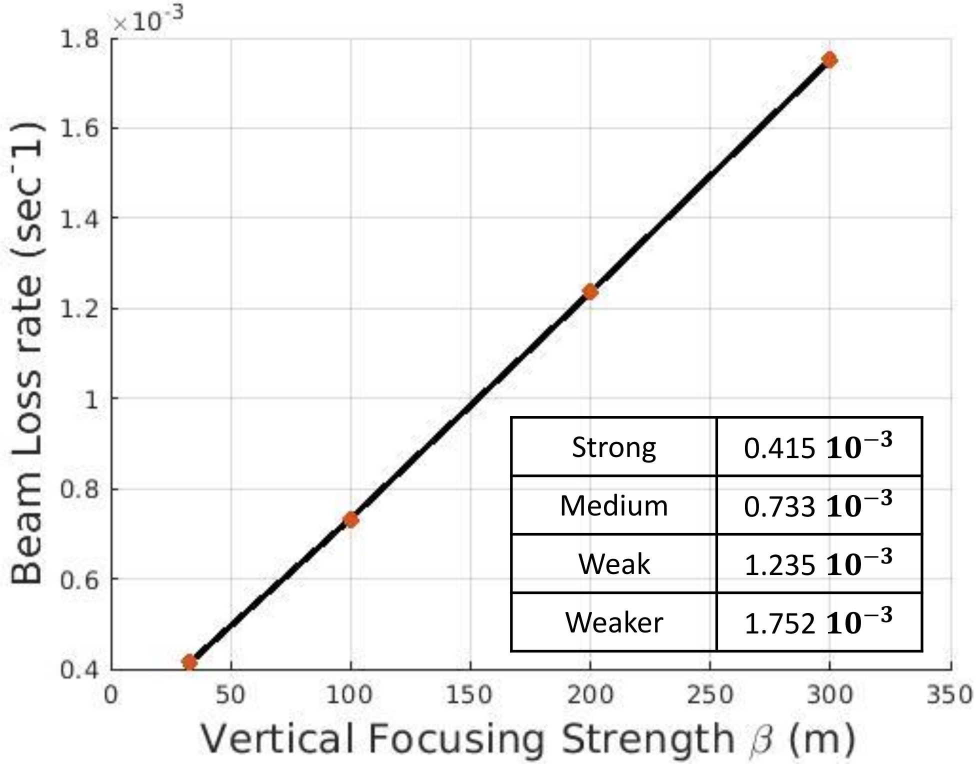
A=Transverse acceptance=10 mm mrad
$\beta_\perp$ = Transverse betatron amplitude

i. With residual gas:



Strong	0.427 10^{-30}
Medium	0.755 10^{-30}
Weak	1.271 10^{-30}
Weaker	1.804 10^{-30}

ii. With Target



Strong	0.415 10^{-3}
Medium	0.733 10^{-3}
Weak	1.235 10^{-3}
Weaker	1.752 10^{-3}

ESTIMATION OF BEAM LOSSES

3. Energy Loss Straggling

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

P=*relative beam loss probability per turn*

Probability depends on maximum energy loss and longitudinal acceptance

Maximum energy loss $\epsilon_{max} = 66.32\ keV$ ⟹ longitudinal momentum deviation $\delta_{max} = 1.12 \times 10^{-3}$

Geometrical longitudinal acceptance $\delta_{acc} = \dfrac{chamber\ radius}{Max.\ dispersion} = \dfrac{30\ mm}{D_{max}}$

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

$\delta_{max} < \delta_{acc}$ ⟹ No beam loss with T=30 MeV theoretically

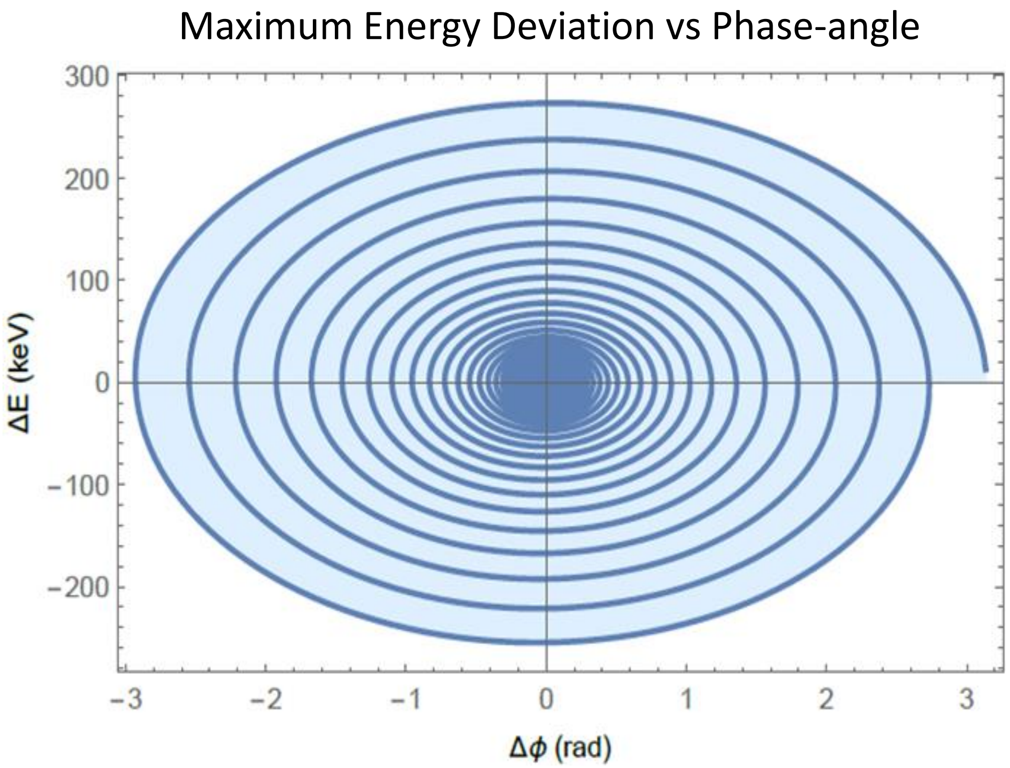
ESTIMATION OF BEAM LOSSES

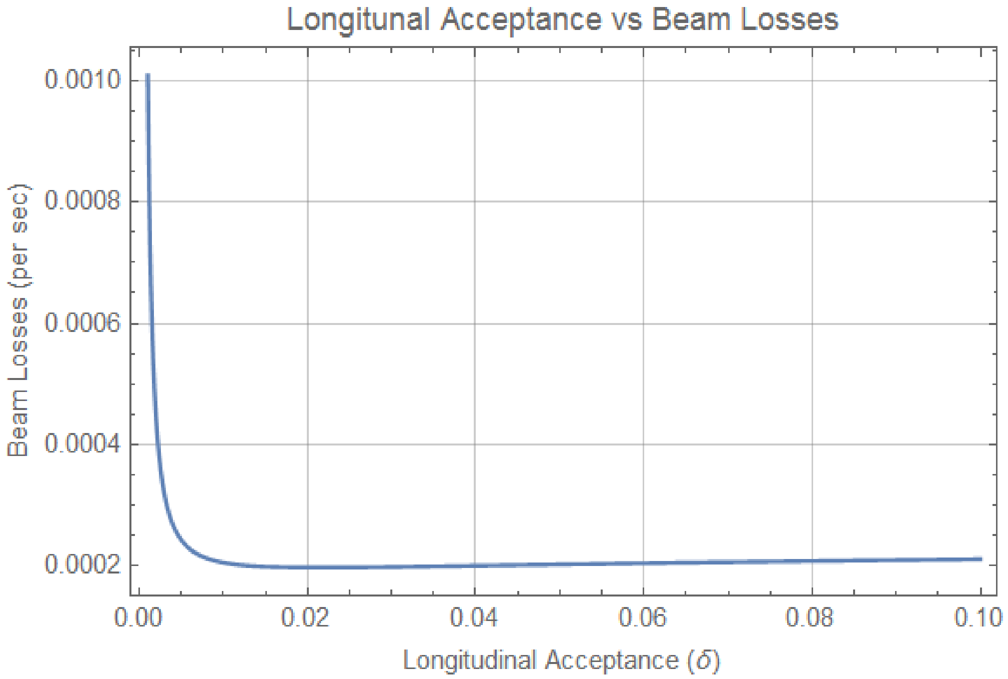
$$\Delta E_{max} = \pm\sqrt{\frac{2\,\beta^2 e\,U\,E}{\pi q\,(\alpha_c - 1/_{\gamma^2})}}$$

For Strong Lattice

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

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





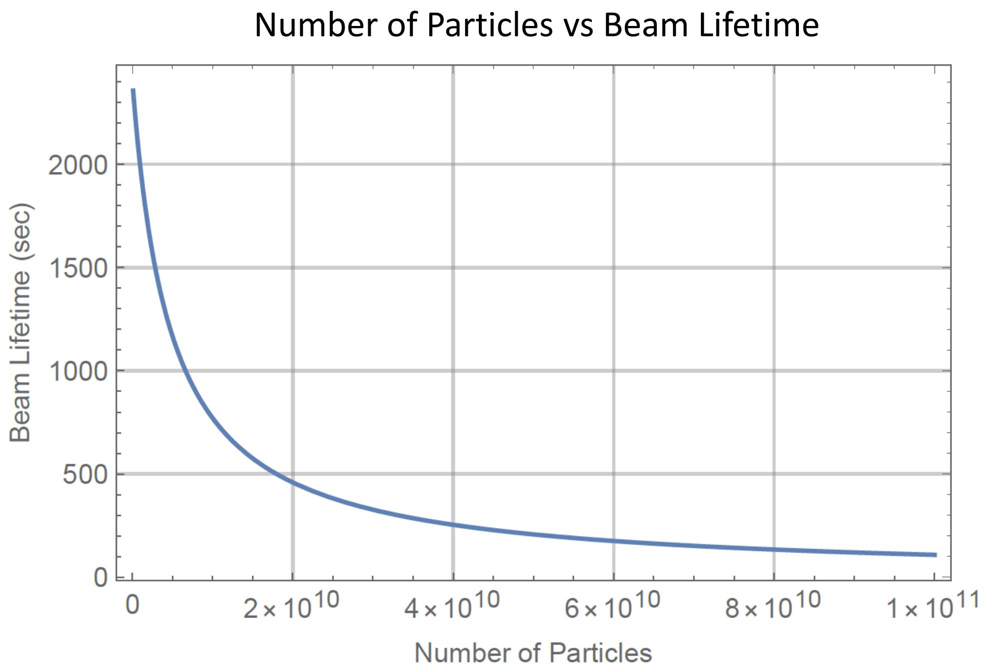
ESTIMATION OF BEAM LOSSES

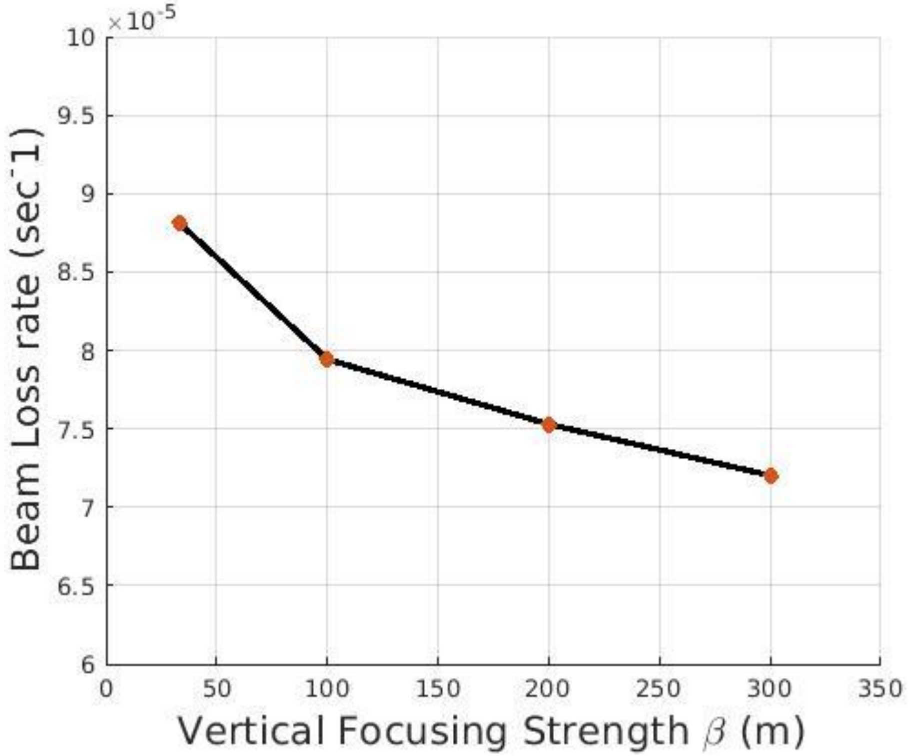
4. **IntraBeam Scattering (IBS)**

- Longitudinal acceptance
- Phase-space density

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

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





Lattice type	$1/\tau_{loss}$ $(10^{-5} s^{-1})$
Strong	8.814
Medium	7.942
Weak	7.529
Weaker	7.202

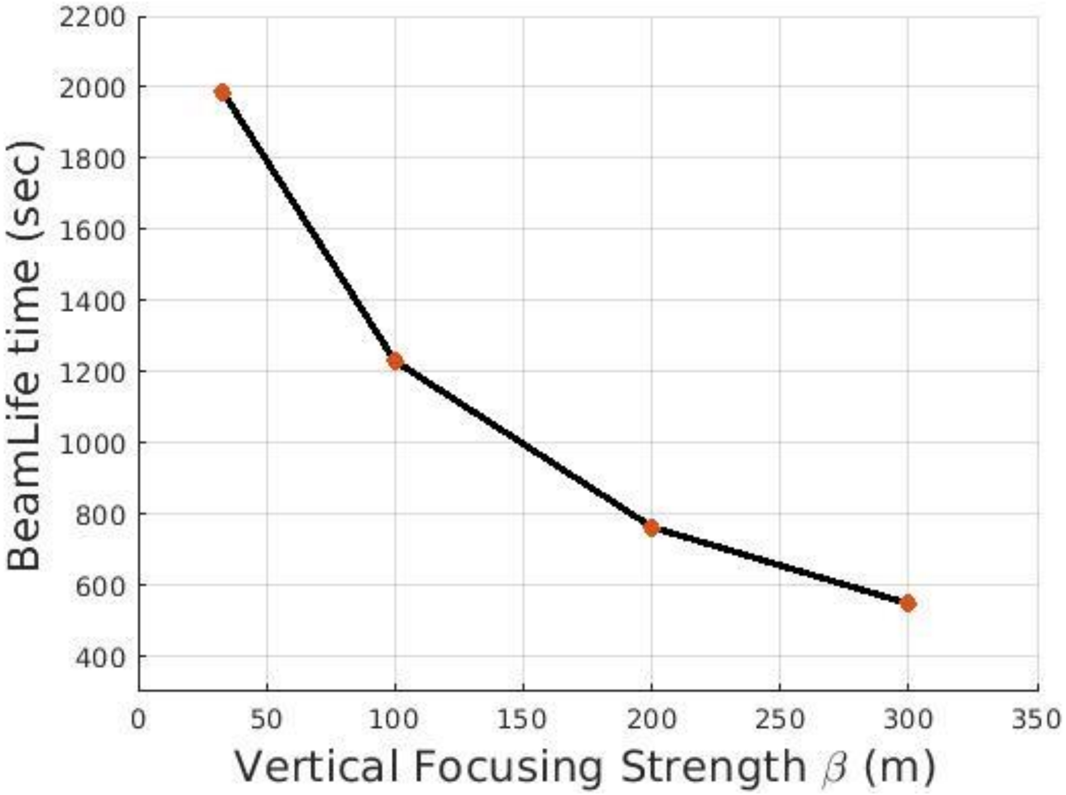
ϵ = emittance of beam
β =average beta function
Lc= coulomb logarithm
N=10^9 *particles*
$\gamma\beta$*= beam momentum*

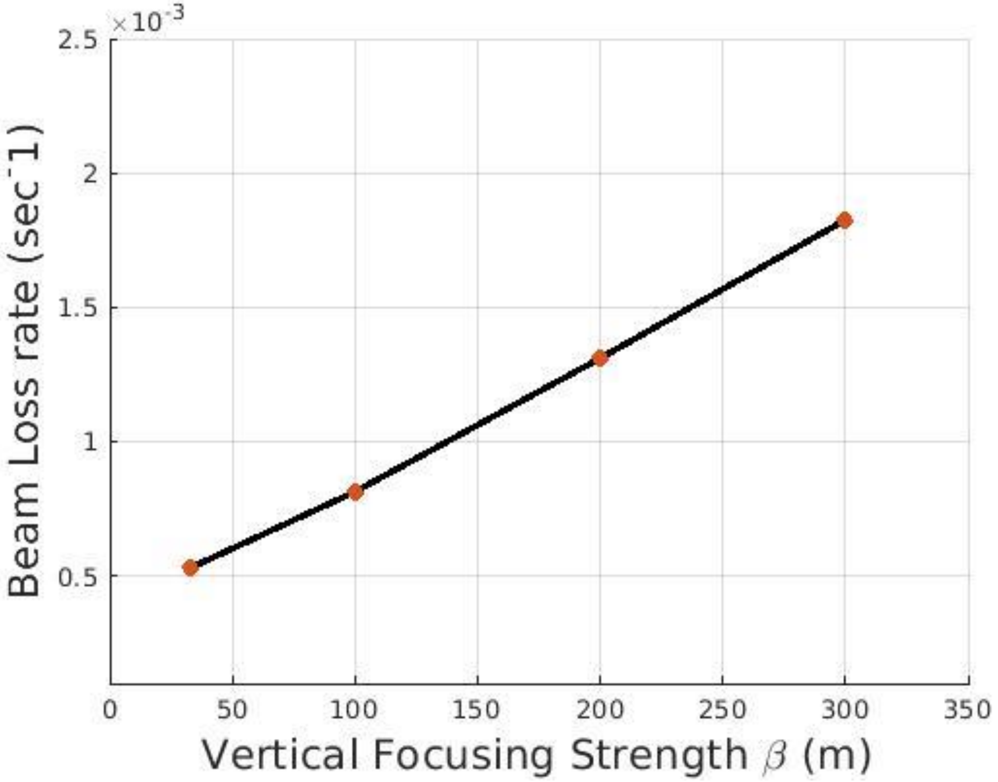
ESTIMATION OF BEAM LOSSES

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	$1/\tau_{loss}\ (10^{-3}s^{-1})$	$\tau_{total}\ (s)$
Strong	0.530	1986
Medium	0.813	1230
Weak	1.310	763
Weaker	1.825	547





CONCLUSION

Summary:

- Preliminary design of prototype EDM ring
- Optics simulations by using MADX with electrostatic transfer matrix
- Four lattices with different focusing strengths studied
- Beam losses calculated for all lattices which shows
  - Strong focusing with $\beta_{y-max} < 100\ m$ is preferable
  - Beam lifetime ≈ 1985 sec

- Further investigations to eliminate systematic effects .
- Conceptual studies of PTR design is under consideration.

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THANK YOU

BACK-UP SLIDES

$$EB = \begin{bmatrix} \cos\xi\theta & \frac{R_0}{\xi}\sin\xi\theta & 0 & 0 & 0 & \frac{2-\beta^2}{\xi^2}R_0(1-\cos(\xi\theta)) \\ -\frac{\xi}{R_0}\sin\xi\theta & \cos\xi\theta & 0 & 0 & 0 & \frac{2-\beta^2}{\xi}\sin\xi\theta \\ 0 & 0 & \cos\eta\theta & \frac{R_0}{\eta}\sin\eta\theta & 0 & 0 \\ 0 & 0 & -\frac{\eta}{R_0}\sin\eta\theta & \cos\eta\theta & 0 & 0 \\ -\frac{2-\beta^2}{\xi}\sin\xi\theta & -\frac{2-\beta^2}{\xi^2}R_0 1-\cos\xi\theta & 0 & 0 & 1 & R_0\theta[\frac{1}{\gamma^2}-(\frac{2-\beta^2}{\xi})^2(1-\frac{\sin\xi\theta}{\xi\theta})] \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

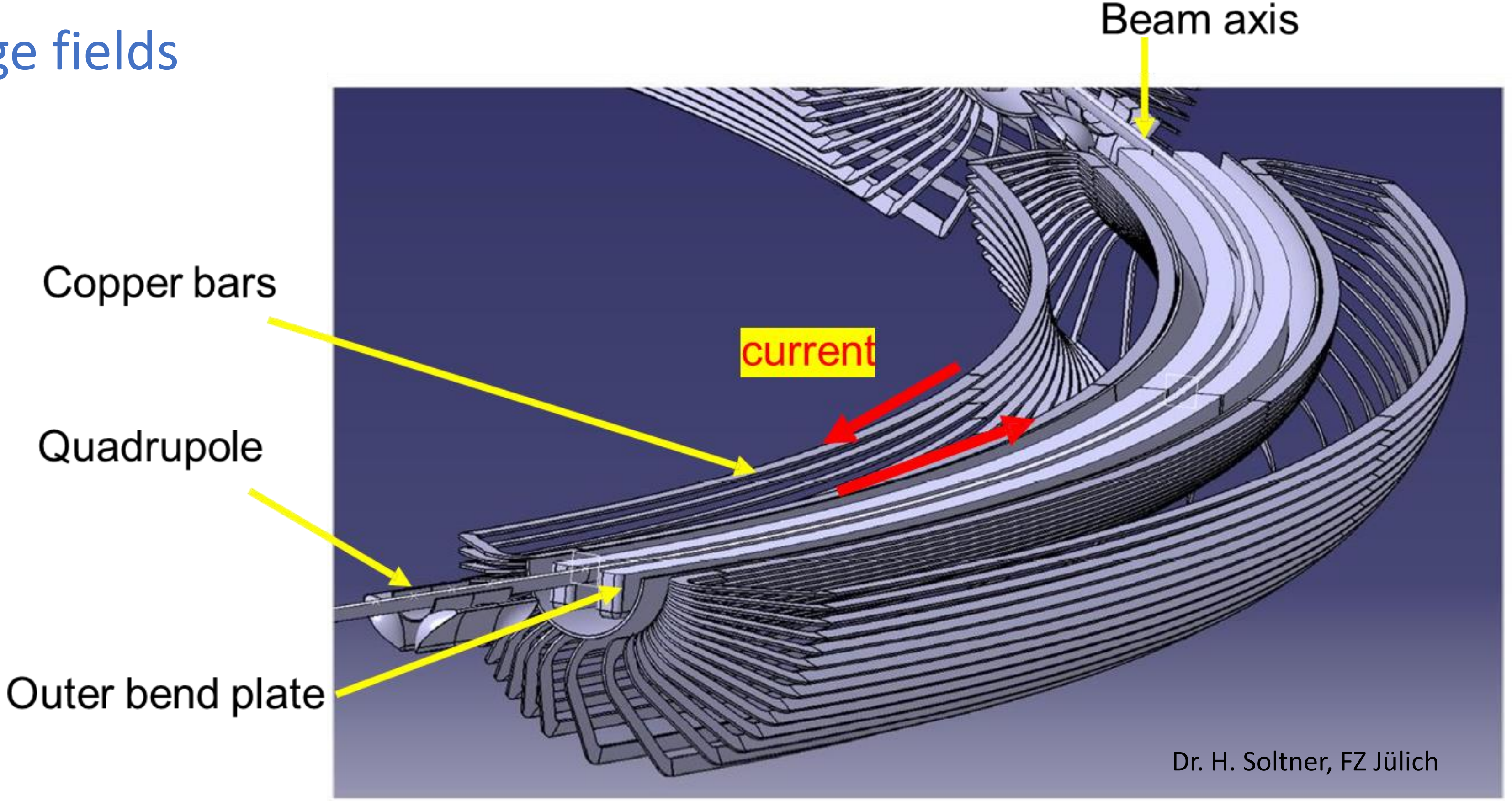
Kinematic Parameters

Parameter	**Frozen spin**	**Pure electric**	**Unit**
$E_{Kinetic}$	45	30	MeV
β	0.299	0.247	
Pc	294.057	239.158	MeV/c
Bρ	0.981	0.798	Tm
Eρ	87.941	59.071	MV
ϒ	1.048	1.032	
Emittance	1.0	1.0	mm mrad
Acceptance	10	10	mm mrad

ELECTRIC MAGNETIC BENDING

- Iron free shielding for reversel of $\vec{B}$
- Special design to avoid fringe fields

Electric		
No.of bends	8	
Length $_{\text{effective}}$	6.959	m
Horizontal $_{\text{gap b/w plates}}$	60	mm
Potential $_{\text{b/w Plates}}$	200	KV
Electric field	6.667	MV/m
$\theta_{\text{Bendig angle}}$	45	degree
Magnetic		
Magnetic field	0.04	T
Current density	5	Amm^{-2}
No. of windings	60	per element



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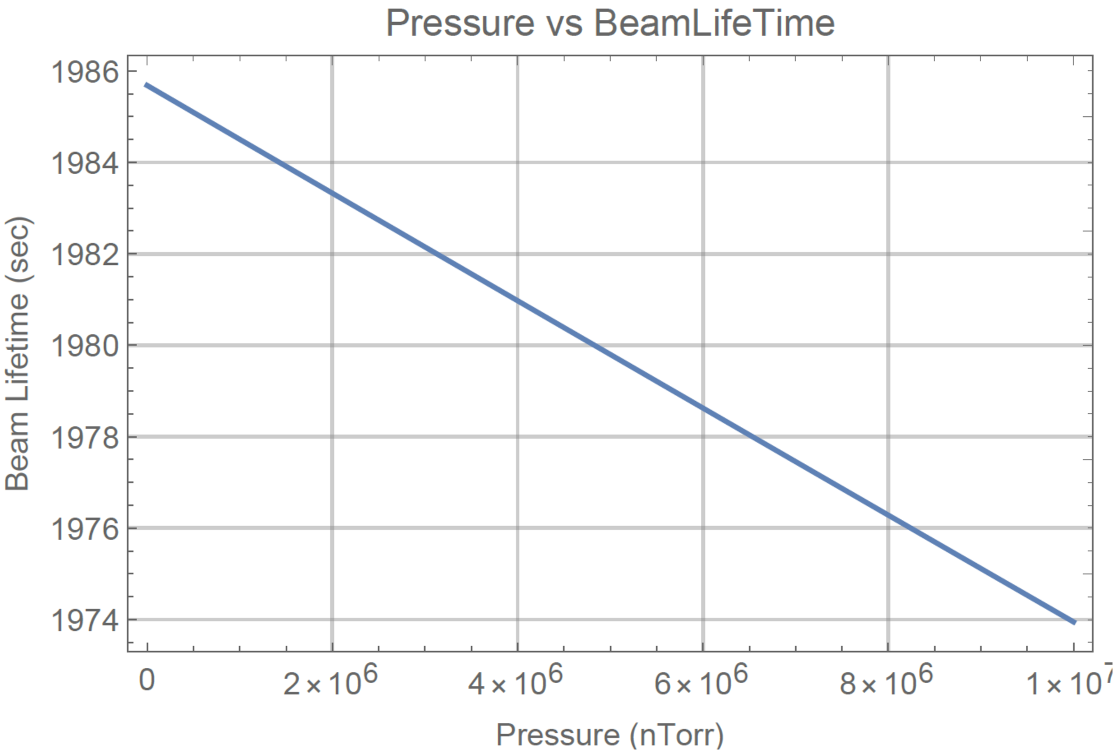
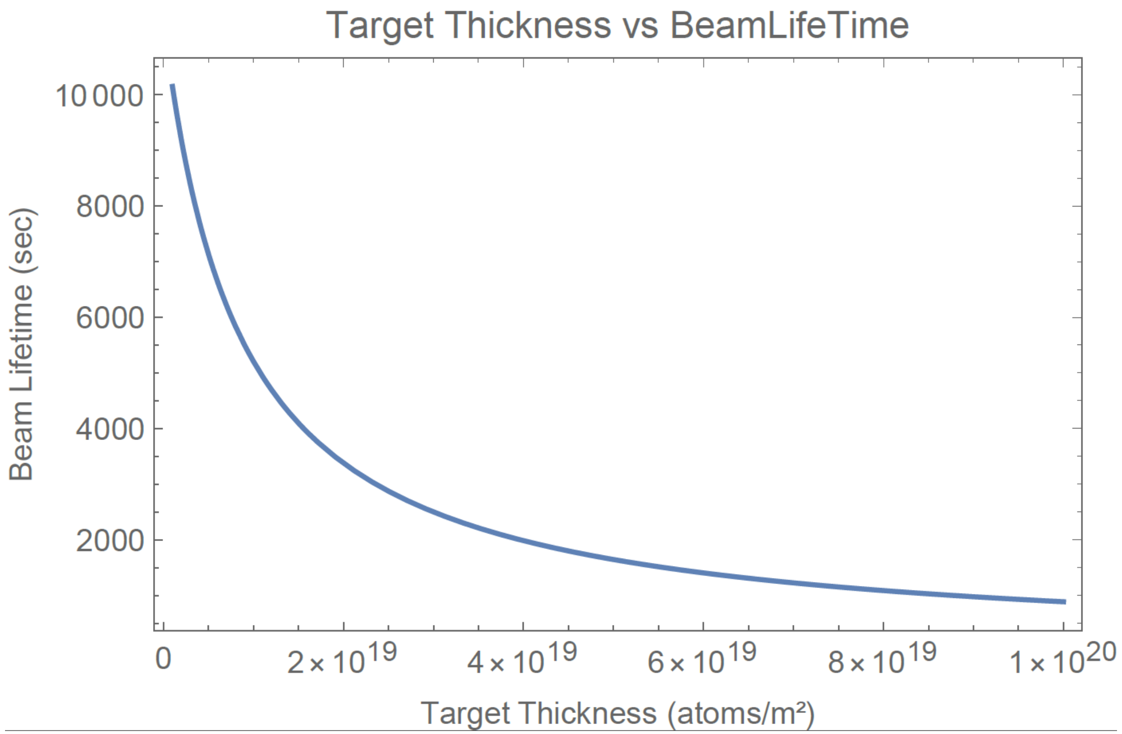
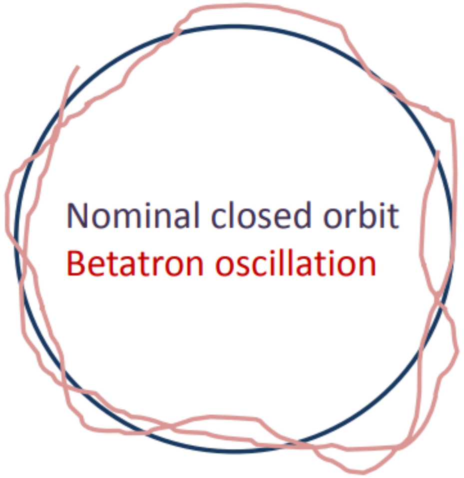
PLOTS

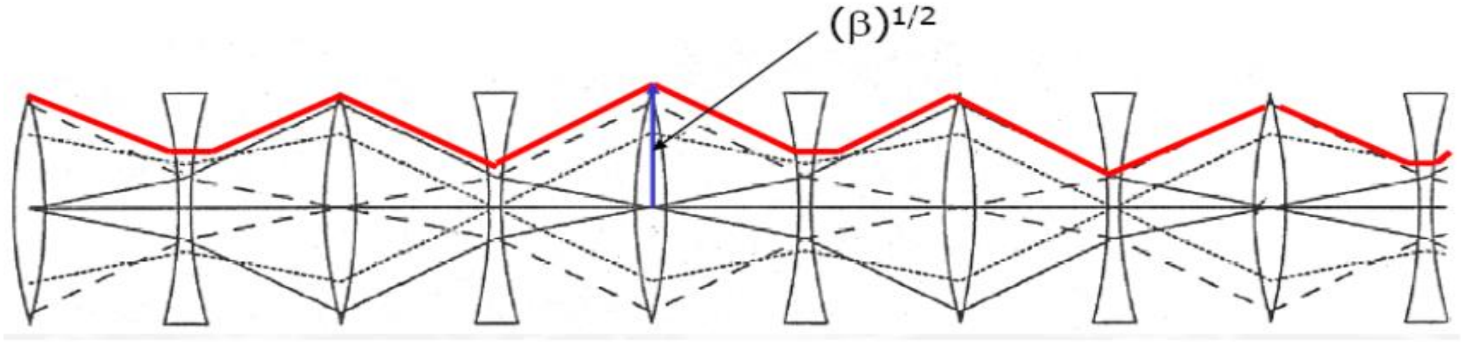

Pressure vs BeamLifeTime
Beam Lifetime (sec)
1986
1984
1982
1980
1978
1976
1974
0
2×10^6
4×10^6
6×10^6
8×10^6
1×10^7
Pressure (nTorr)


Target Thickness vs BeamLifeTime
Beam Lifetime (sec)
10 000
8000
6000
4000
2000
0
2×10^{19}
4×10^{19}
6×10^{19}
8×10^{19}
1×10^{20}
Target Thickness (atoms/m²)

BRIEF INTRODCTION TO ACCELERATOR PHYSICS

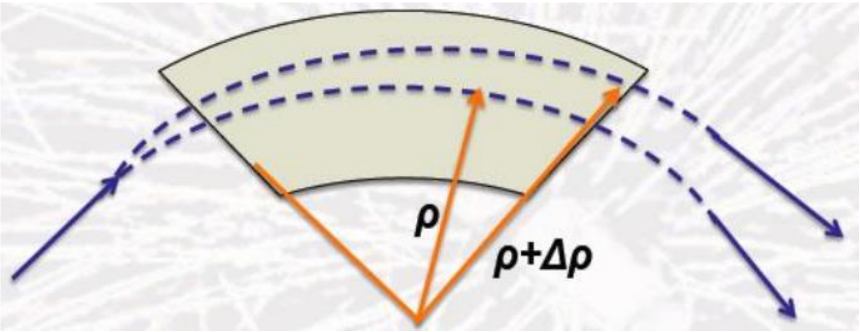


β_x, β_y are betatron functions



$$x(s) = \underbrace{\sqrt{\epsilon\, \beta_x(s)}}_{\text{Amplitude of an oscillation}} \cos(\varphi(s) + \varphi_0)$$

$\beta(s)$ represents the envelope of all particle trajectories at a given position s in a storage ring



- Off-momentum particles oscillate around a different closed orbit
- The displacement between the designed and displaced orbits is controlled by the dispersion function D(s)

TUNE VARIABILITY

Number of betatron oscillations per turn is known as betatron tune

- Betatron tunes can be varied over a large range

Betatron tunes

$$0.2 \le Q_x \le 2.5$$
$$0.1 \le Q_y \le 2.5$$

- Lattice can be adjusted from ultra-weak to moderate focusing

Betatron functions

$$\beta_x \le 20\ m$$
$$\beta_y \le 400\ m$$