Simulations Of Beam Losses For The Prototype Electric Dipole Moment Storage Ring

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Workshop on PSTP-22 Mainz

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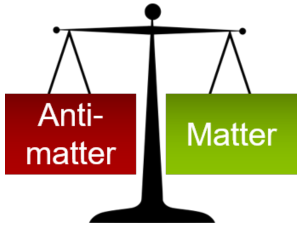
OUTLINE

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

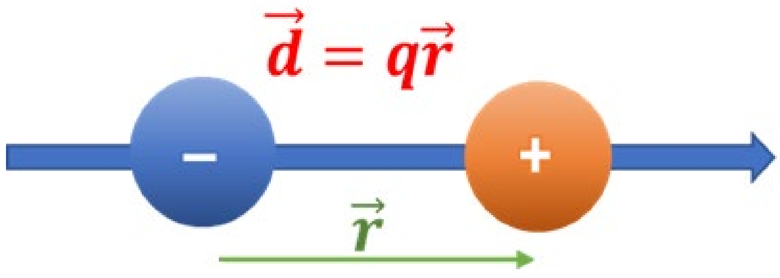
Sakharov criteria (1967): [2]

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

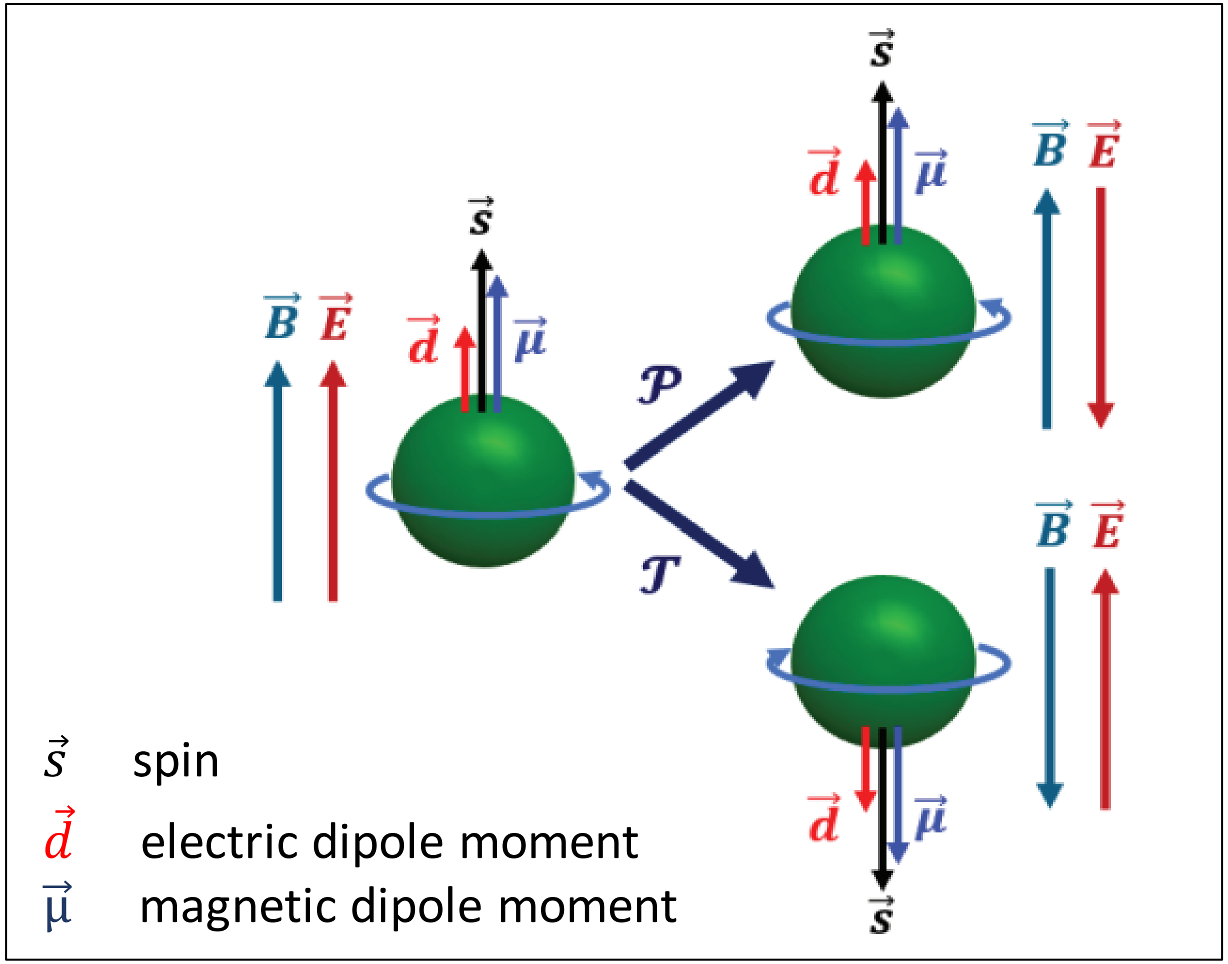
Search for $\mathcal{CP}$ violation beyond the Standard Model

* 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

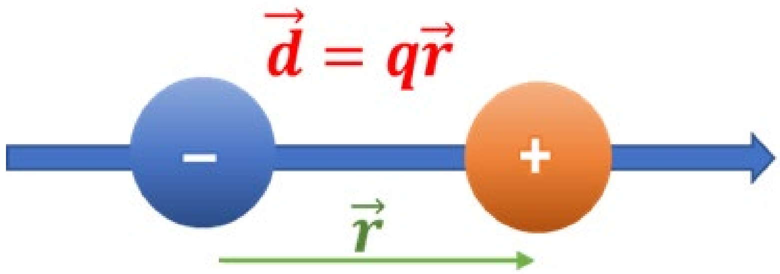


$$H = H_M + H_E = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

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

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

Electric Dipole Moment (EDM)



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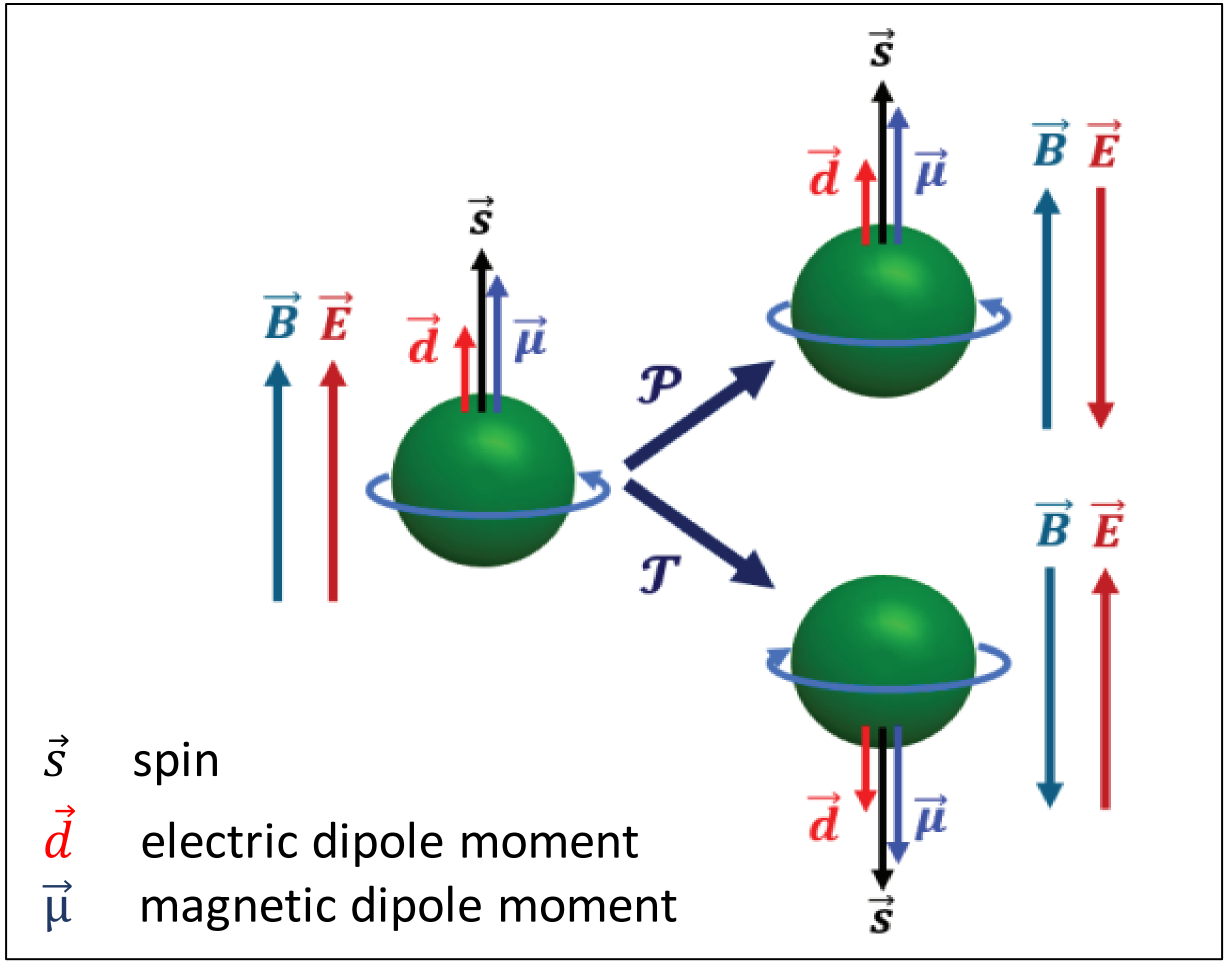

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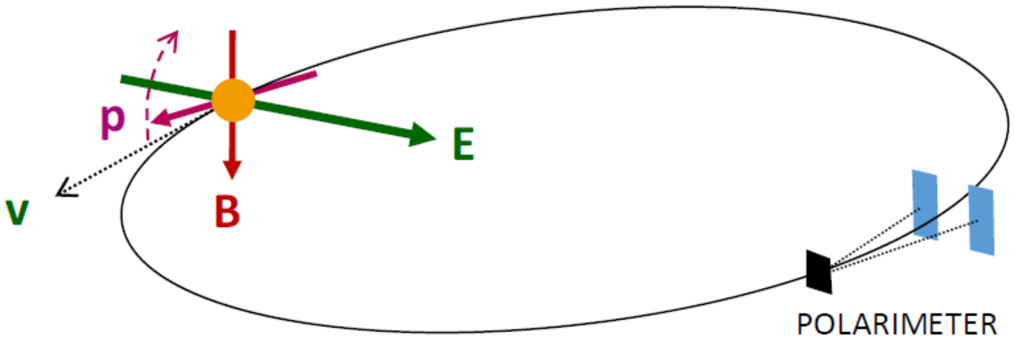
EDM MEASUREMENT USING STORAGE RING

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**

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

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

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

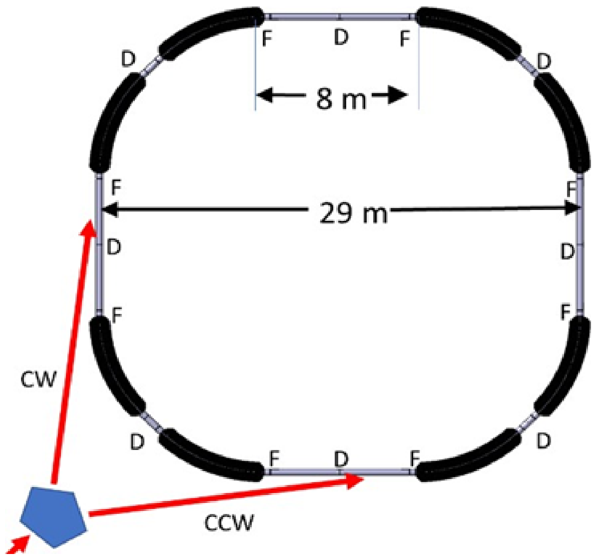
Precursor experiment at COSY FZ Jülich

- 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

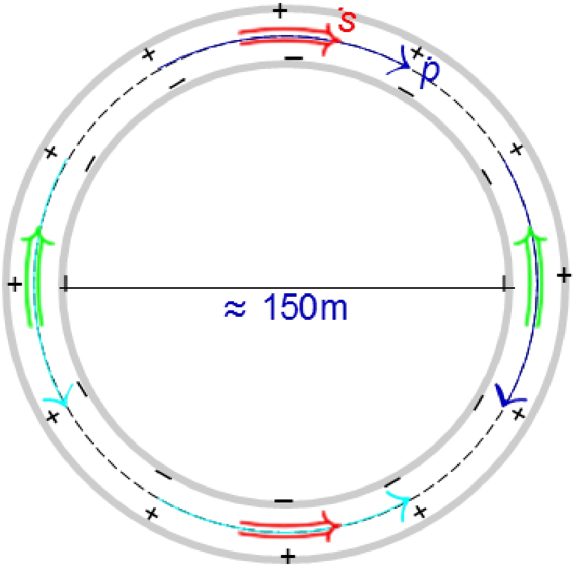


- Electric magnetic storage ring
- Simultaneous CW and CCW beams
- Operates at 30 MeV and 45 MeV

Stage 3

[4]

Final storage ring



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

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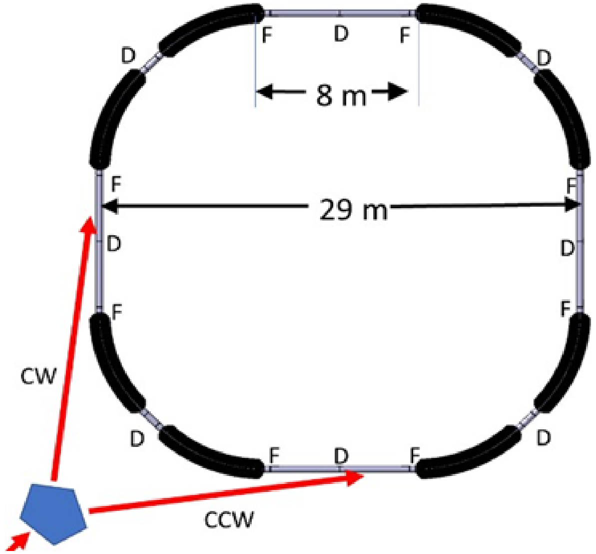

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[4]

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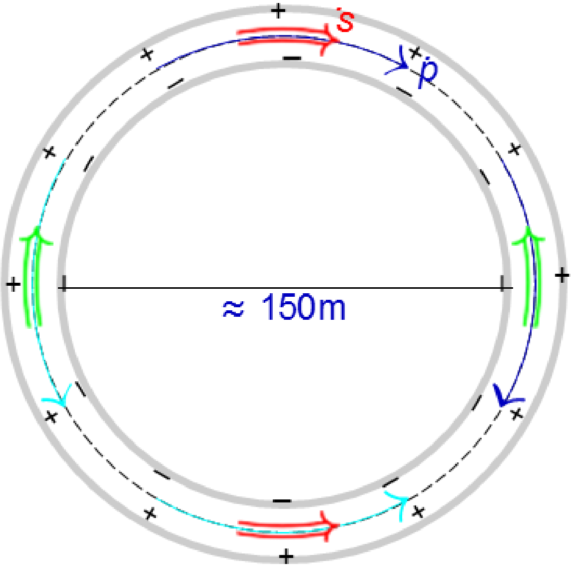

- Pure Electrostatic storage ring
- Proton Magic momentum (701MeV/c)

PROTOTYPE EDM STORAGE RING [5]

Goals:

- Frozen spin capability
- Storage of high intensity CW and CCW beams simultaneously **Beam life time > 1000 s**
- 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

PROTOTYPE EDM STORAGE RING [5]

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my TASK

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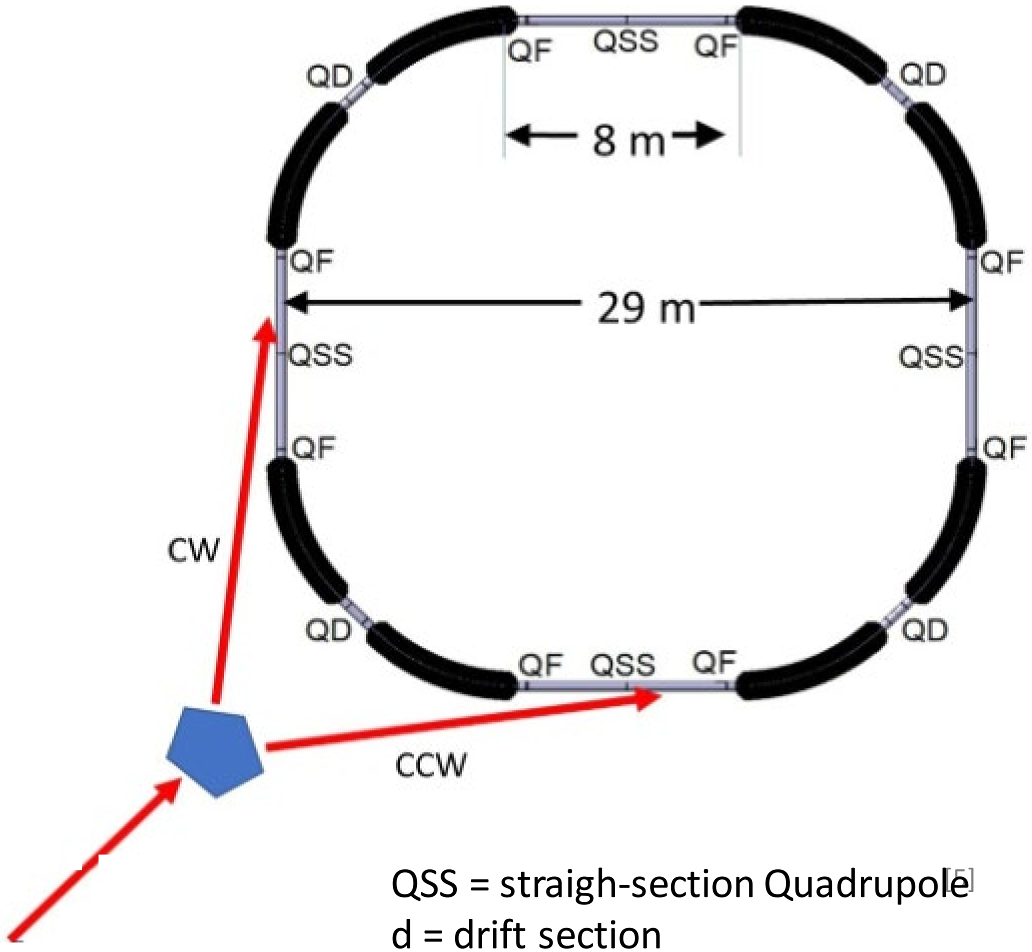
RING DESIGN AND PARAMETERS [5]

Basic layout

- Fourfold symmetric squared ring
- Circumference ≈ 123 m
- 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)



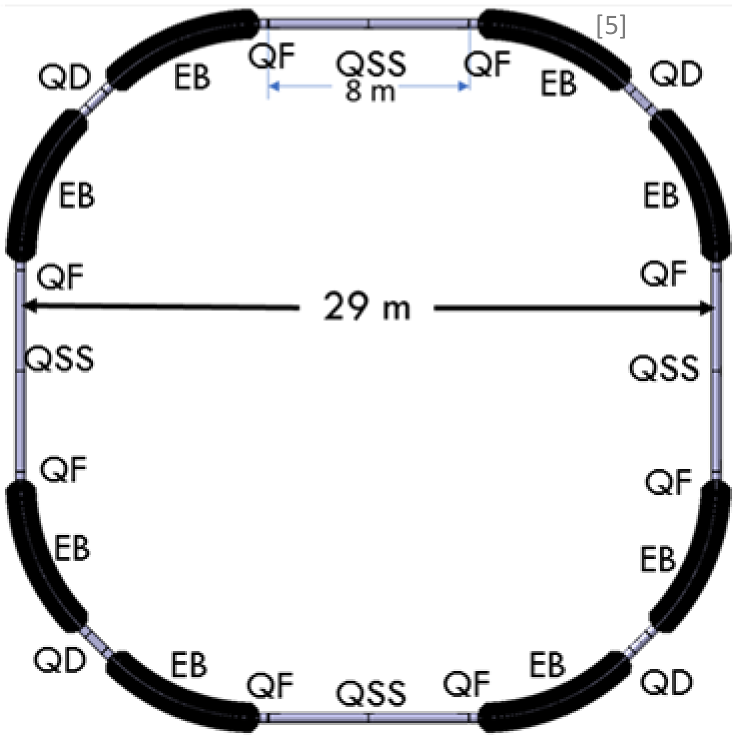
QSS = straigh-section Quadrupole [5]
d = drift section
QF = focusing quadrupole
QD = defocusing quadrupole
EB = electrostatic bending

SIMULATION RESULTS

- Lattice Optics
- Estimations of Beam Losses

LATTICE OPTICS :

- **MADX** (Methodical Accelerator Design)[6]



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

Lattice type	β_{y-max} (m)	Q_x	Q_y
Strong	33	1.754	1.227
Medium	100	1.835	1.748
Weak	200	1.796	1.881
Weaker	300	1.770	1.923

Lattice Flexibility :

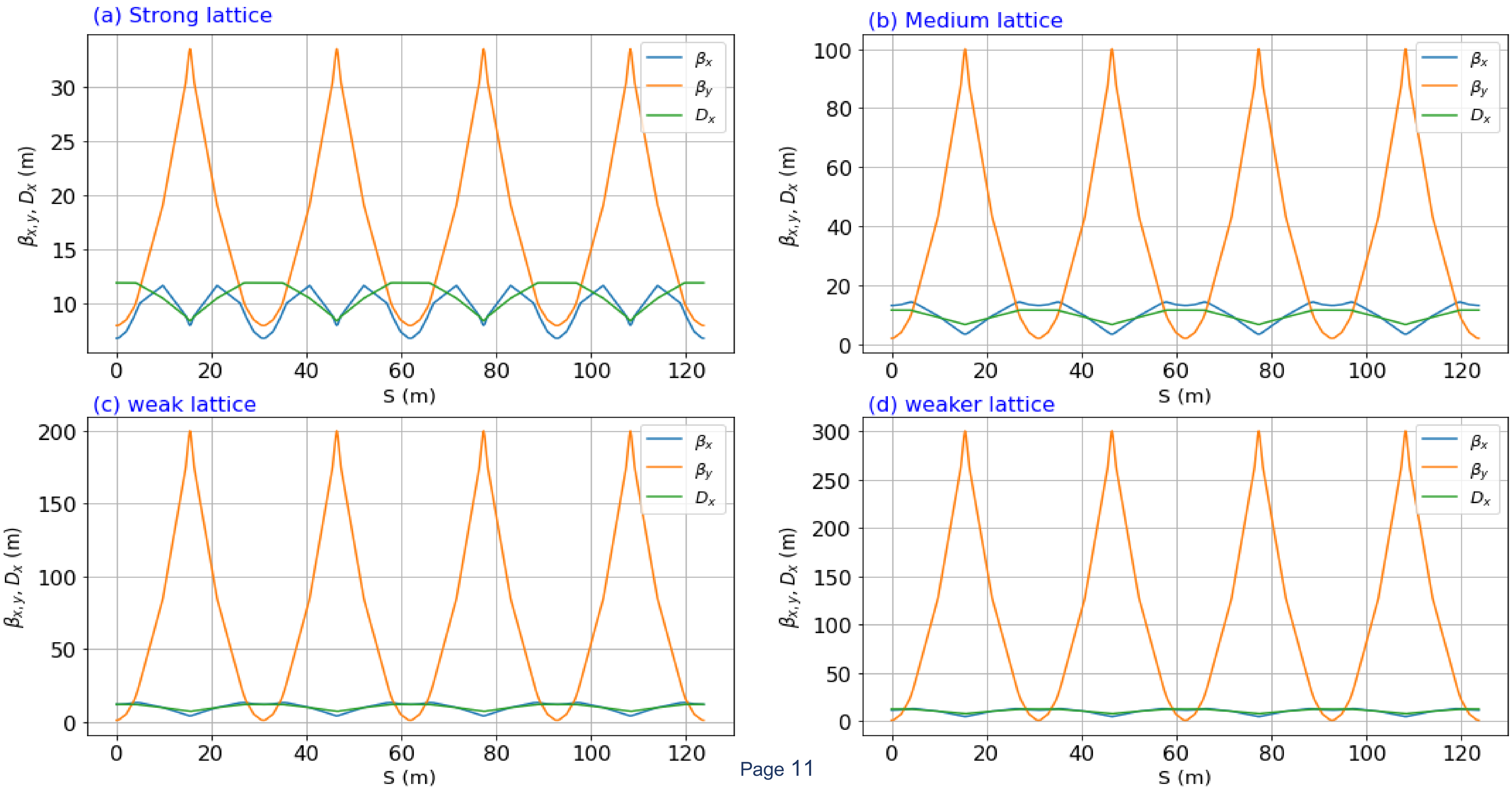
Betatron tunes

$$0.2 \leq Q_x \leq 2.5$$
$$0.1 \leq Q_y \leq 2.5$$

Betatron functions

$$\beta_x \leq 20\ m$$
$$\beta_y \leq 400\ m$$

LATTICE GENERATION:



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* $P_{eq} = 3.7 \times 10^{-11}\ mbar$
- $n_{rg} = 5.30 \times 10^5\ atoms/cm^3$
- 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

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

τ_{loss} = beam loss rate
n = target thickness or rest gas density
σ_{tot} = total cross section
f_0 = revolution frequency

i. Residual gas

ii. Target

$$\tau^{-1} = 3.51 \times 10^{-9}\ s^{-1}$$

<

$$\tau^{-1} = 2.14 \times 10^{-6}\ s^{-1}$$

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

2. Coulomb Scattering

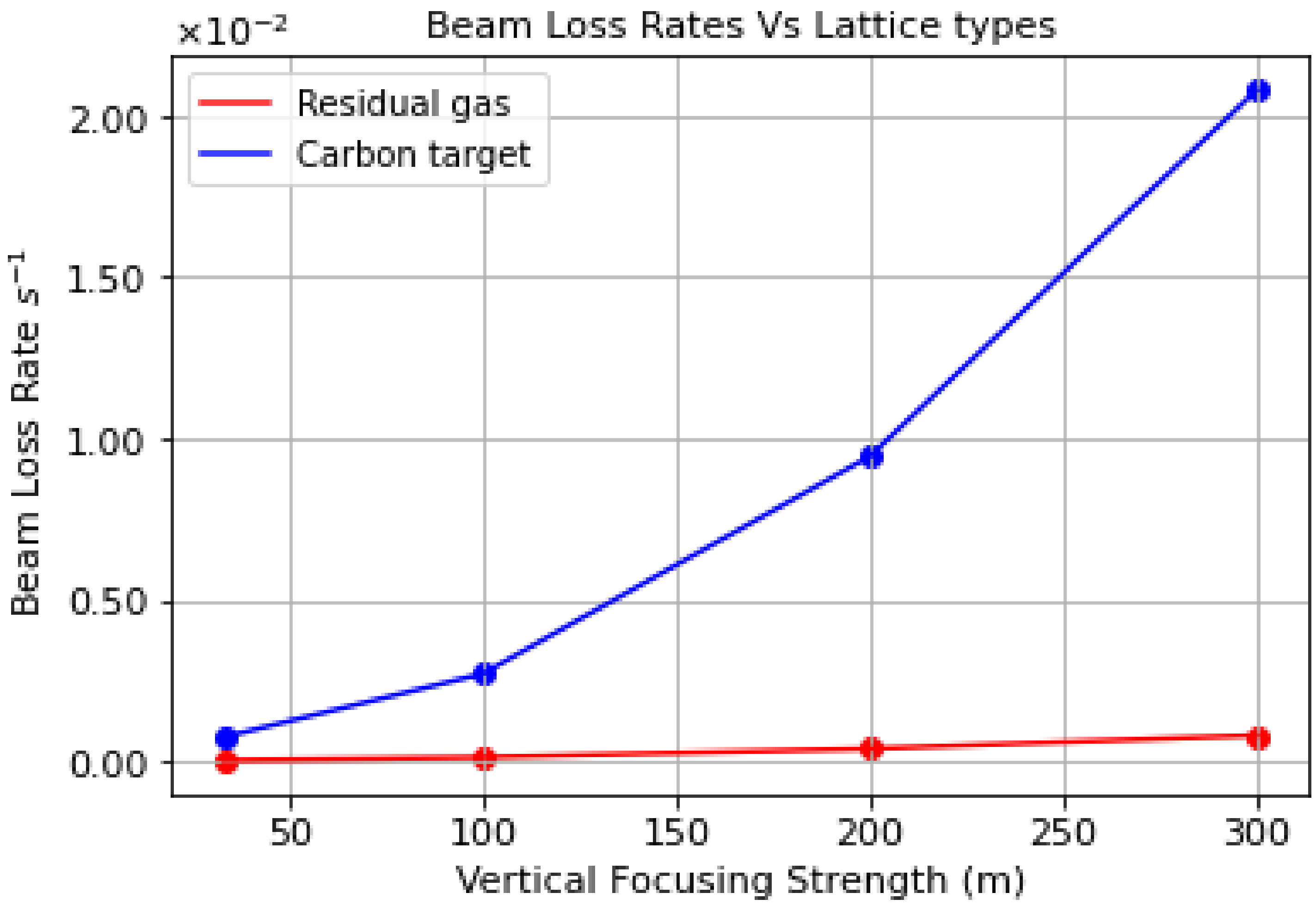
$$\tau^{-1} = n\sigma_{tot} f_0$$

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



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3. Energy Loss Straggling

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

P=*relative beam loss probability per turn*

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

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

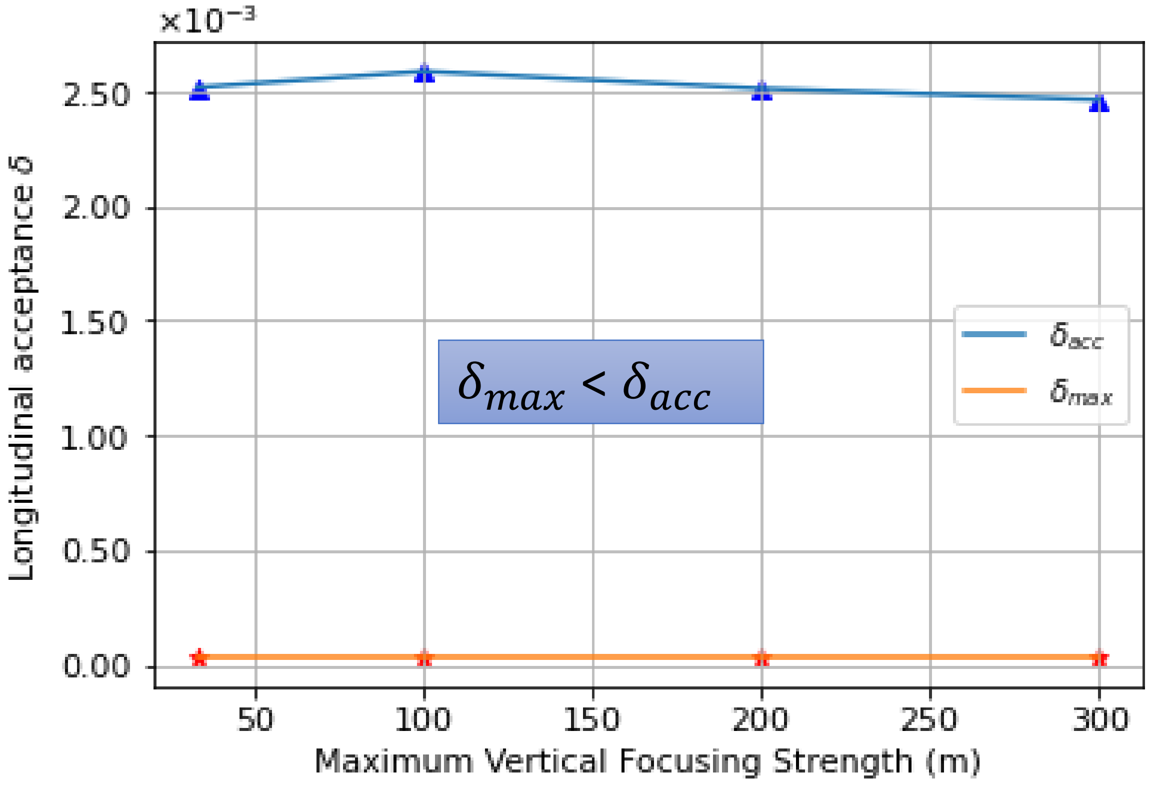
$$\Downarrow$$

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

Geometrical longitudinal acceptance

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

No beam loss with T=30 MeV theoretically



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

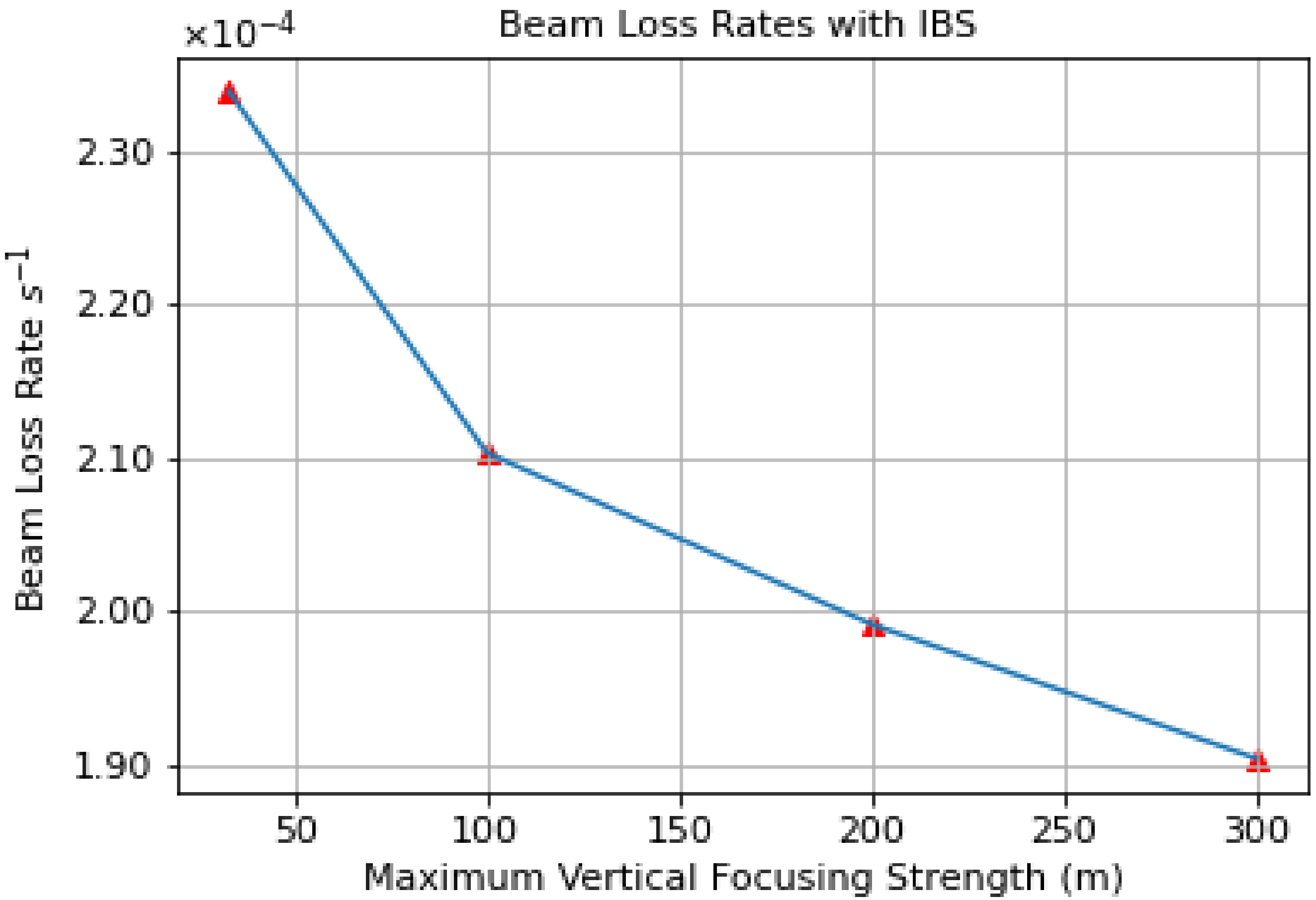
4. IntraBeam Scattering (IBS)

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

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

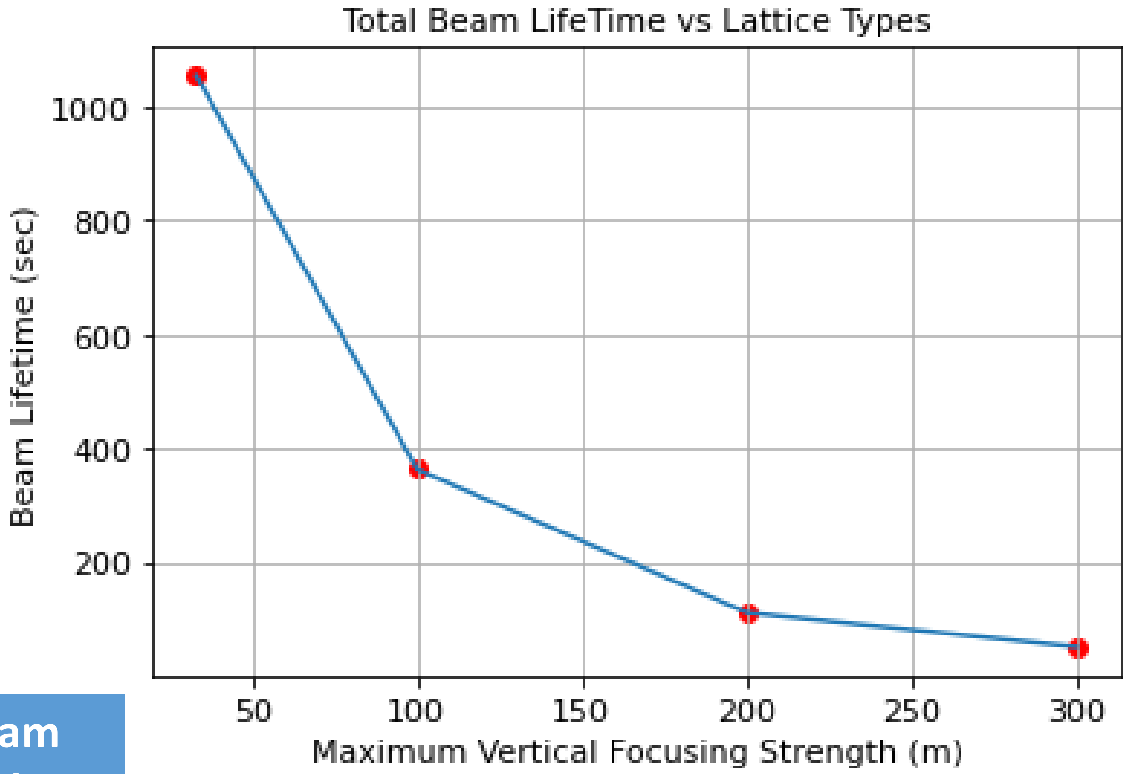
$D_{\parallel}^{IBS} = longitudinal\ diffusion\ coefficient$

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

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



With Analytical Formulas

Lattice Type (β_{y-max})	HI ($10^{-6}s^{-1}$)	SCS ($10^{-4}s^{-1}$)	IBS ($10^{-4}s^{-1}$)	Total loss rate ($10^{-4}s^{-1}$)	Beam Lifetime (s)
33m	2.17	7.65	2.34	9.47	1055
100m		27.3	2.10	27.5	363
200m		94.6	1.99	90.0	111
300m		208	1.90	195	51

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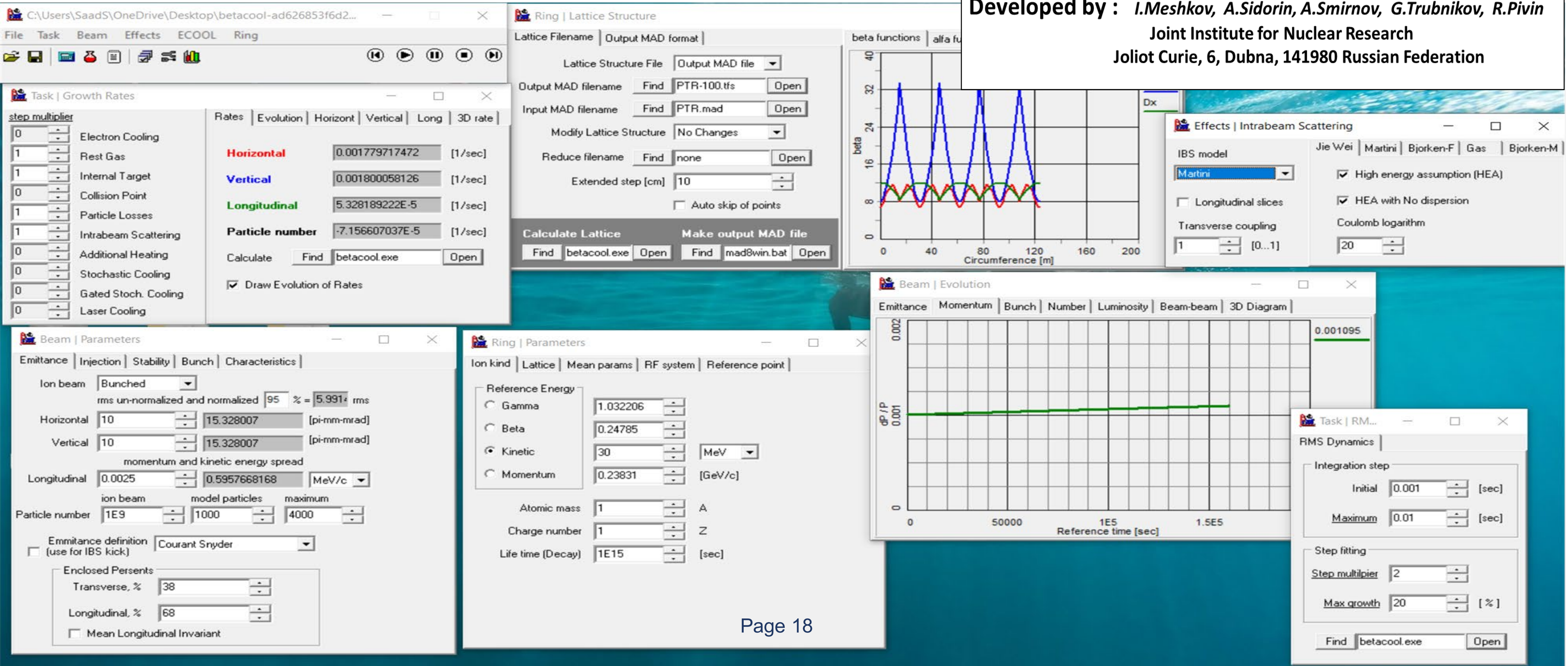
BETACOOL For Beam Dynamics:

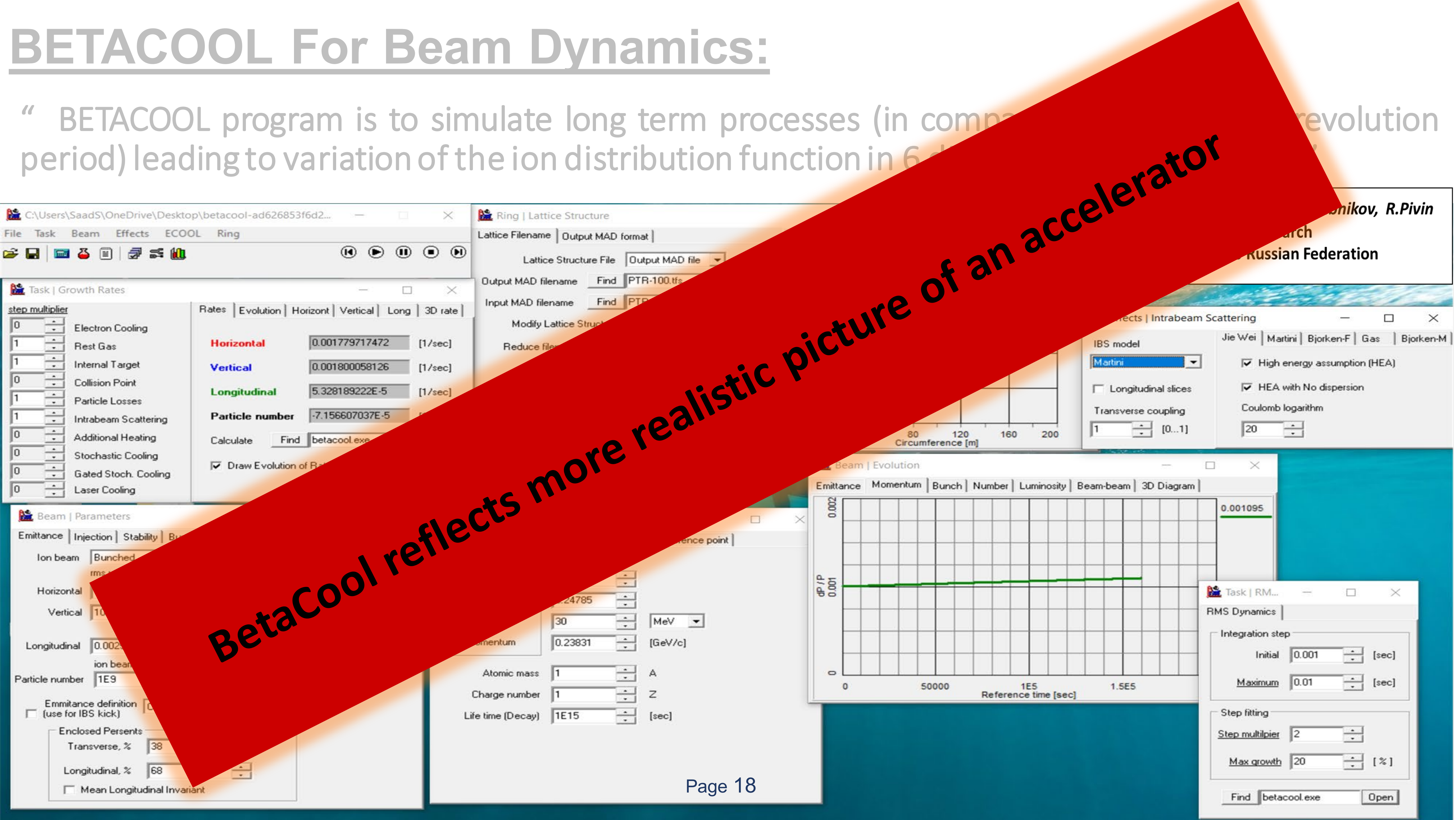
" BETACOOL program is to simulate long term processes (in comparison with the ion revolution period) leading to variation of the ion distribution function in 6 dimensional phase space."

Developed by : *I.Meshkov, A.Sidorin, A.Smirnov, G.Trubnikov, R.Pivin*
Joint Institute for Nuclear Research
Joliot Curie, 6, Dubna, 141980 Russian Federation



BETACOOL For Beam Dynamics:

“ BETACOOL program is to simulate long term processes (in comp... revolution period) leading to variation of the ion distribution function in 6 ...”



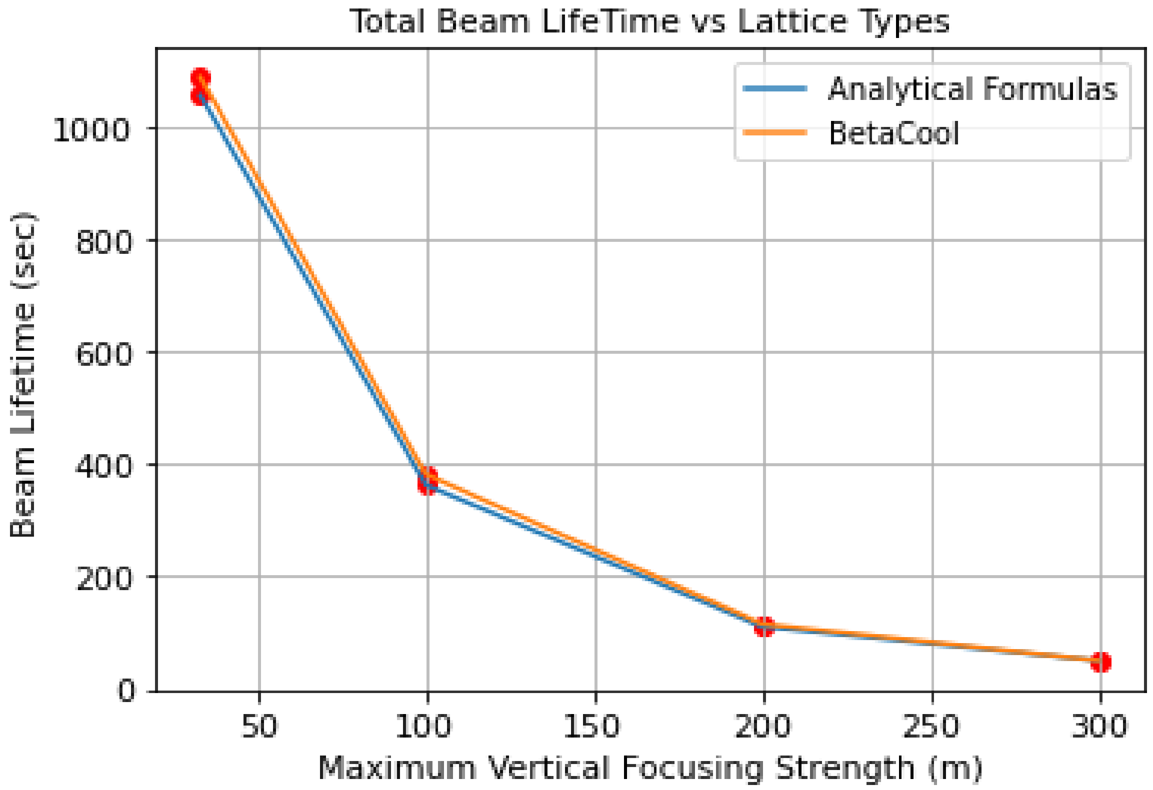
Comparison b/w Beam loss calculations

Analytical Formulas

Lattice Type (β_{y-max})	Total loss rate ($10^{-4}s^{-1}$)	Beam Lifetime (s)
33m	9.47	1055
100m	27.5	363
200m	90.0	111
300m	195	51

With Betacool

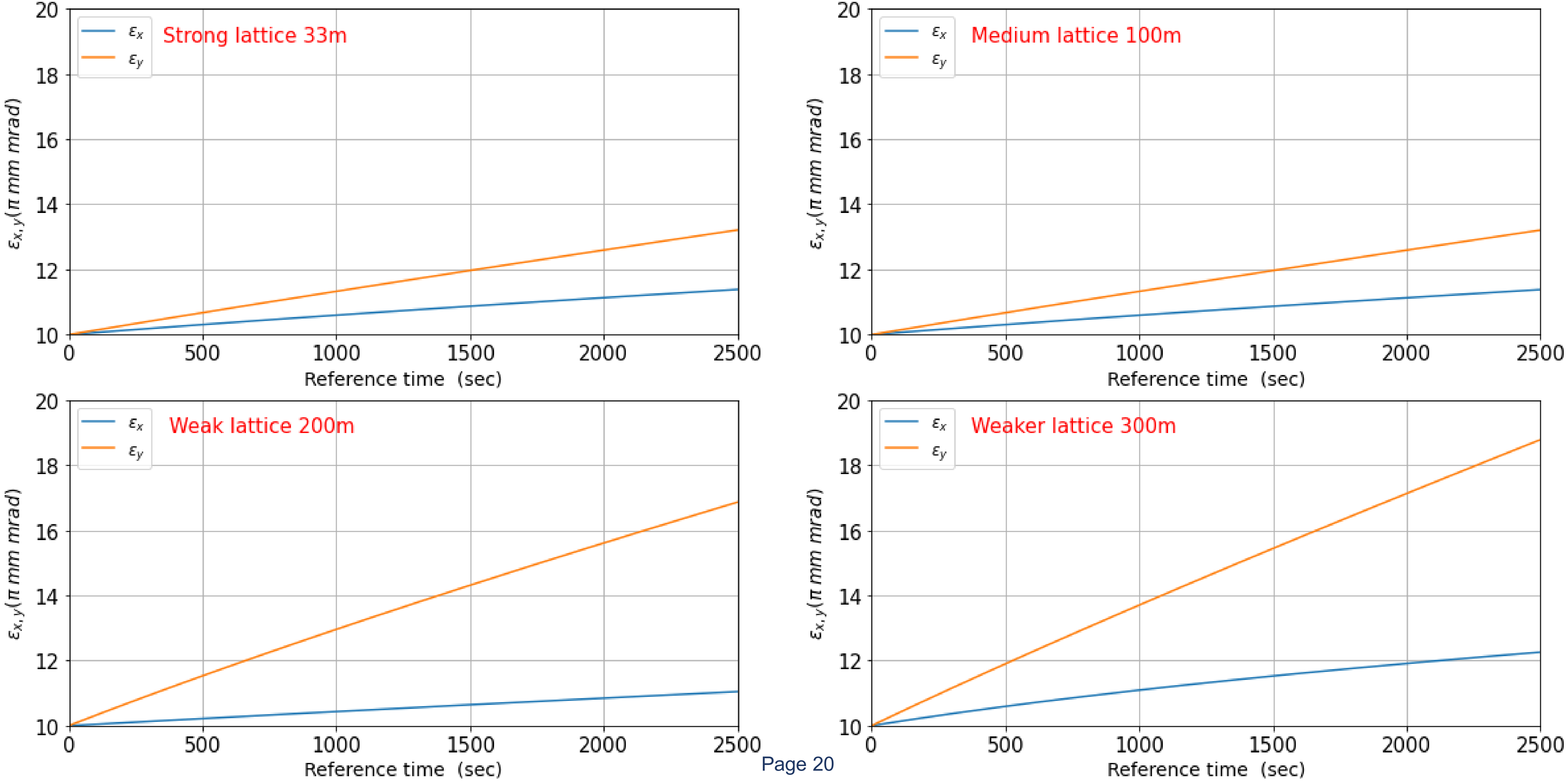
Lattice Type (β_{y-max})	Total loss rate ($10^{-4}s^{-1}$)	Beam Lifetime (s)
33m	9.197	1087
100m	2.62	382
200m	8.60	116
300m	1.94	51



Analytical formulas and BetaCool results showing an agreement.

HI (Hadronic Interactions), **SCS** (Single Coulomb Scatterings), **IBS** (Intera-Beam Scatterings) Martin Model

Emittance Growth starting with $\varepsilon_{x,y} = 10\pi\, mm\, mrad$ without target



Conclusion

Summary:

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

Outlook:

- These calculations will be performed with electromagnetic bendings.
- 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

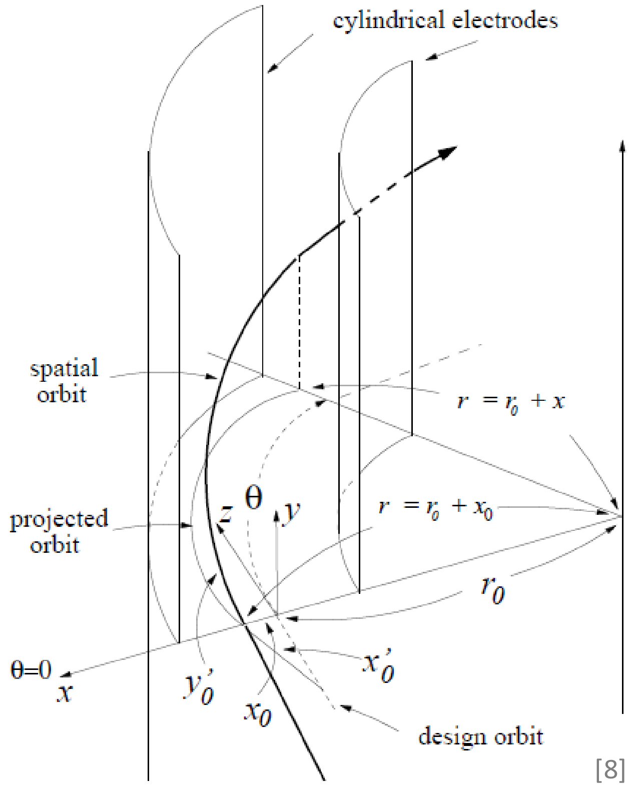
For pure electrostatic deflectors

- 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