PAL-EUV Beam Dynamics study

Jaehyun Kim

Pohang Accelerator Laboratory, POSTECH

POHANG ACCELERATOR LABORATORY

Outline

❖ PAL-EUV booster

- Current design
- Alternative design (preliminary)
- Comparison

❖ PAL-EUV storage ring

- Current design
- Alternative design (preliminary)
- Comparison

❖ Summary

Motivation

- PAL-EUV is a compact size accelerator complex consists of gun, 20 MeV linac, 22.2 m booster and 36.0 m – 400 MeV storage ring
- Although it has compact size, its nonlinear property is as strong as a typical 4GSR machine (e.g. small dynamic aperture, small momentum aperture)
- This study investigates dynamic property of current PAL-EUV design and explores alternative designs providing better nonlinearity and robustness
- Design of compact size and low energy storage ring is somewhat delicate due to

  - Long damping time (damping time $\propto \frac{1}{E^3}$)

  - Short Touschek lifetime (Touschek lifetime $\propto E^3$)

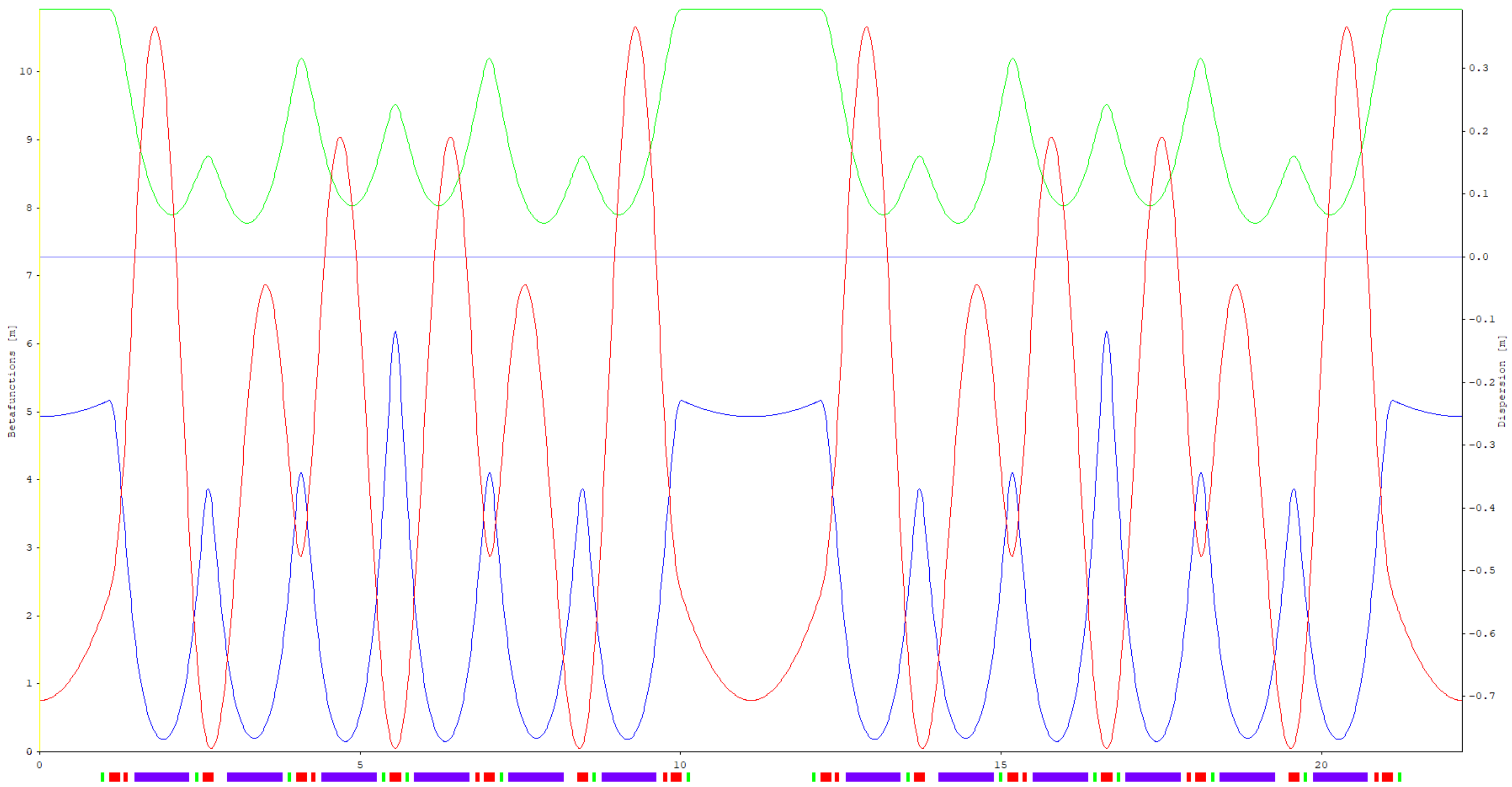
  - Strong dipole edge-focusing effect

  - Dense arrangement of magnets and possible strong cross-talk

❖**PAL-EUV booster**

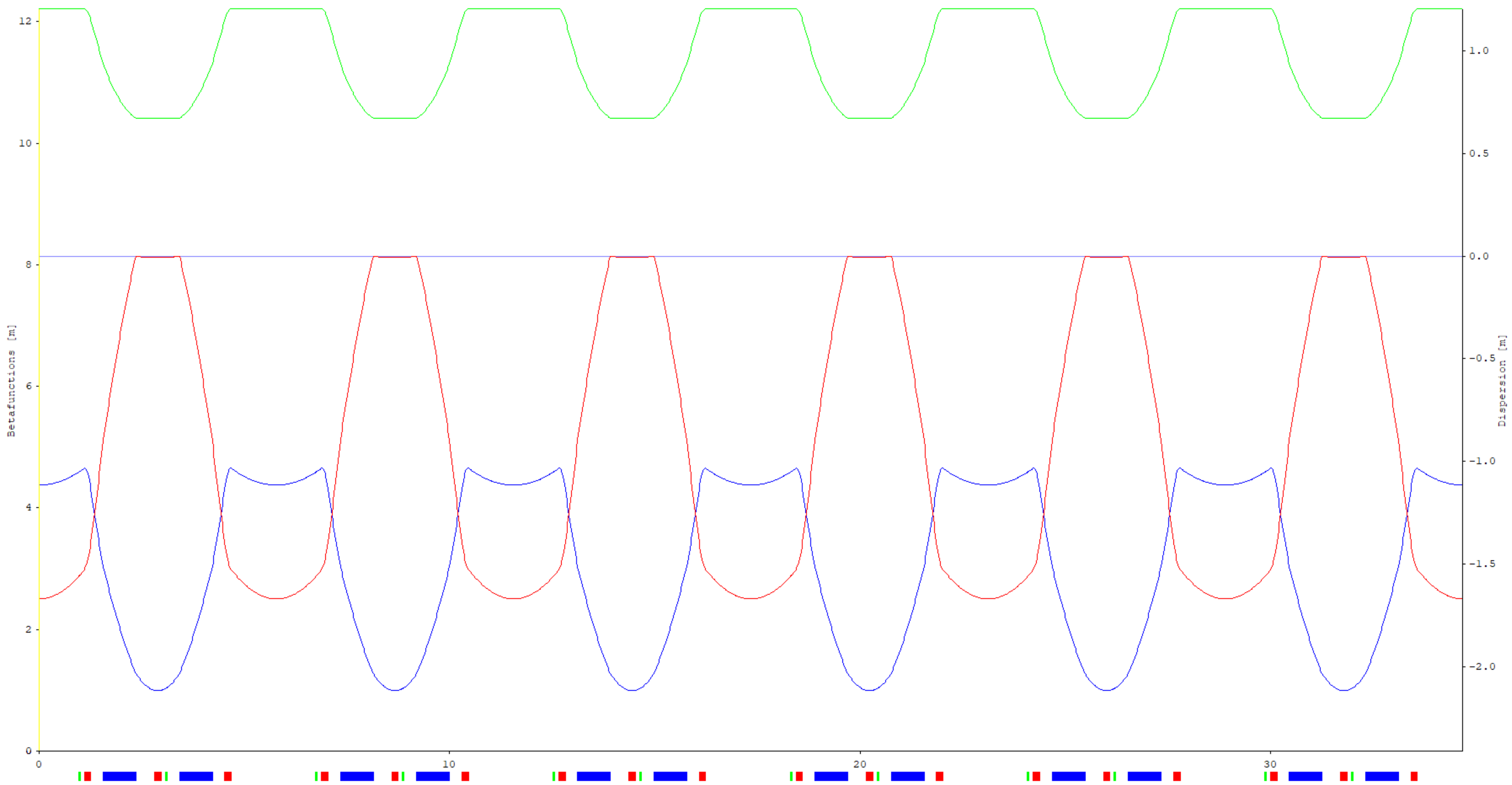
- **Current design**
- **Alternative design (preliminary)**
- **Comparison**

PAL-EUV booster (current design)



Parameters	Value
Energy (MeV)	**20 - 400**
Circumference (m)	**22.20**
Equilibrium emittance (nm) @400 MeV	**1.75**
Tunes (H,V)	**4.84 / 3.66**
Natural chromaticity (H,V)	**-11.2/ -15.7**
Chromaticity (corrected) (H,V)	**1, 1**
Hor. Damping partition	**2.0459**
Momentum compaction	$\mathbf{2.798 \times 10^{-2}}$
Energy spread (σ_δ) @ 20 MeV / 400 MeV	$\mathbf{0.019 \times 10^{-3}}$ / $\mathbf{0.389 \times 10^{-3}}$
Energy loss per turn (keV) @20 MeV / 400 MeV	**0.0 / 1.4**
Main RF voltage (keV)	**70**
Damping time (H/V/Z) (ms) @ 20 MeV / 400 MeV	**166066 / 339759 / 356113** **20.76 / 42.47 / 44.51**

PAL-EUV booster alternative design (preliminary)



Parameters	Value
Energy (MeV)	**20 - 400**
Circumference (m)	**34.680**
Equilibrium emittance (nm) @400 MeV	**30.96**
Tunes (H,V)	**2.42, 1.38**
Natural chromaticity (H,V)	**-2.1, -1.8**
Chromaticity (corrected) (H,V)	**1, 1**
Hor. Damping partition	**1.648**
Momentum compaction	**0.1408**
Energy spread (σ_δ) @ 20 MeV / 400 MeV	$\mathbf{0.014 \times 10^{-3}}$ / $\mathbf{0.285 \times 10^{-3}}$
Energy loss per turn (keV) @20 MeV / 400 MeV	**0.0 / 1.5**
Main RF voltage (keV)	**70**
Damping time (H/V/Z) (ms) @ 20 MeV / 400 MeV	**450494 / 499538 / 264147** **56.31 / 62.44 / 33.02**

Comparison on lattice parameters and magnets

Lattice parameters

Parameters	Current design	Alternative design
Energy (MeV)	**20 - 400**	**20 - 400**
Circumference (m)	**22.20**	**34.680**
Equilibrium emittance (nm) @400 MeV	**1.75**	**30.96**
Tunes (H,V)	**4.84 / 3.66**	**2.42, 1.38**
Natural chromaticity (H,V)	**-11.2/ -15.7**	**-2.1, -1.8**
Chromaticity (corrected) (H,V)	**1, 1**	**1, 1**
Hor. Damping partition	**2.0459**	**1.648**
Momentum compaction	2.798×10^{-2}	**0.1408**
Energy spread (σ_δ) @ 20 MeV / 400 MeV	0.019×10^{-3} / 0.389×10^{-3}	0.014×10^{-3} / 0.285×10^{-3}
Energy loss per turn (keV) @20 MeV / 400 MeV	**0.0 / 1.4**	**0.0 / 1.5**
Main RF voltage (keV)	**70**	**70**
Damping time (H/V/Z) (ms) @ 20 MeV / 400 MeV	**166066 / 339759 / 356113** **20.76 / 42.47 / 44.51**	**450494 / 499538 / 264147** **56.31 / 62.44 / 33.02**

Magnet specifications

-Normalized strengths are in MAD unit

Current design

Type	EA	Length	Max. strength
Bend (combined function of bend-quad-sext)	**12**	**0.85 m**	**B0 = 0.822 [T]** **K1 = -3.448** $[1/m^{-2}]$ **K2 = -21.576** $[1/m^{-3}]$
16 cm quad	**14**	**0.16 m**	**K1 = 20.30** $[1/m^{-2}]$
6 cm quad	**8**	**0.06 m**	**K1 = 4.52** $[1/m^{-2}]$
Sext	**16**	**0.04 m**	**K2 = 1116.4** $[1/m^{-3}]$

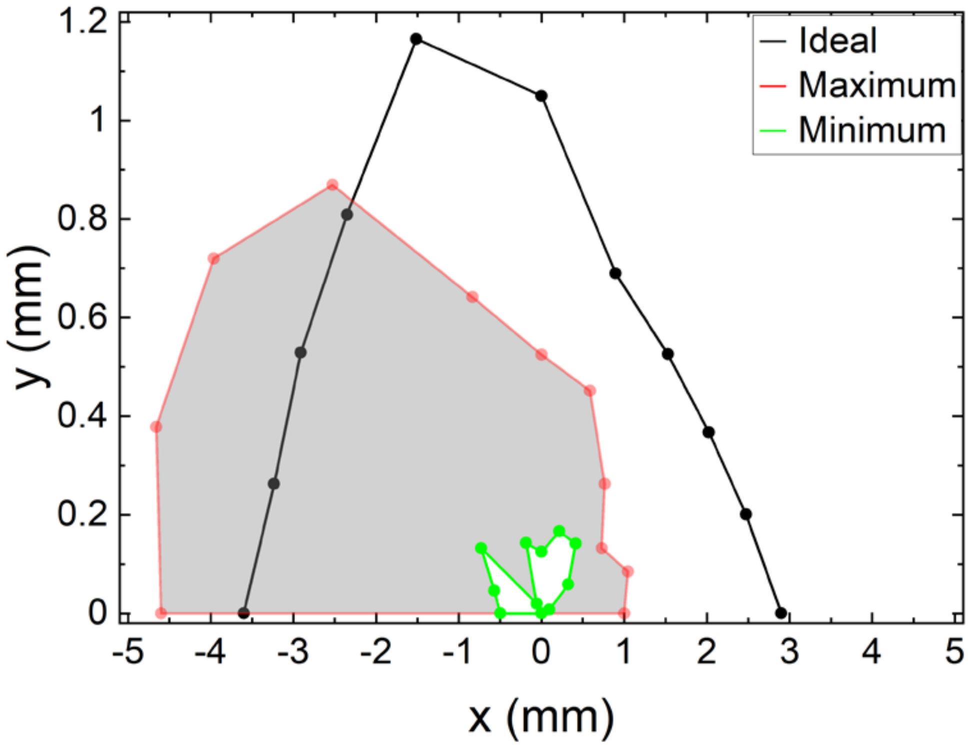
Alternative design

Type	EA	Length	Max. strength
Bend (combined function of bend-quad)	**12**	**0.80 m**	**B0 = 0.874 [T]** **K1 = -0.260** $[1/m^{-2}]$
16 cm quad*	**18**	**0.16 m**	**K1 = 3.70** $[1/m^{-2}]$
Sext*	**12**	**0.04 m**	**K2 = -36.9** $[1/m^{-3}]$

*reusable

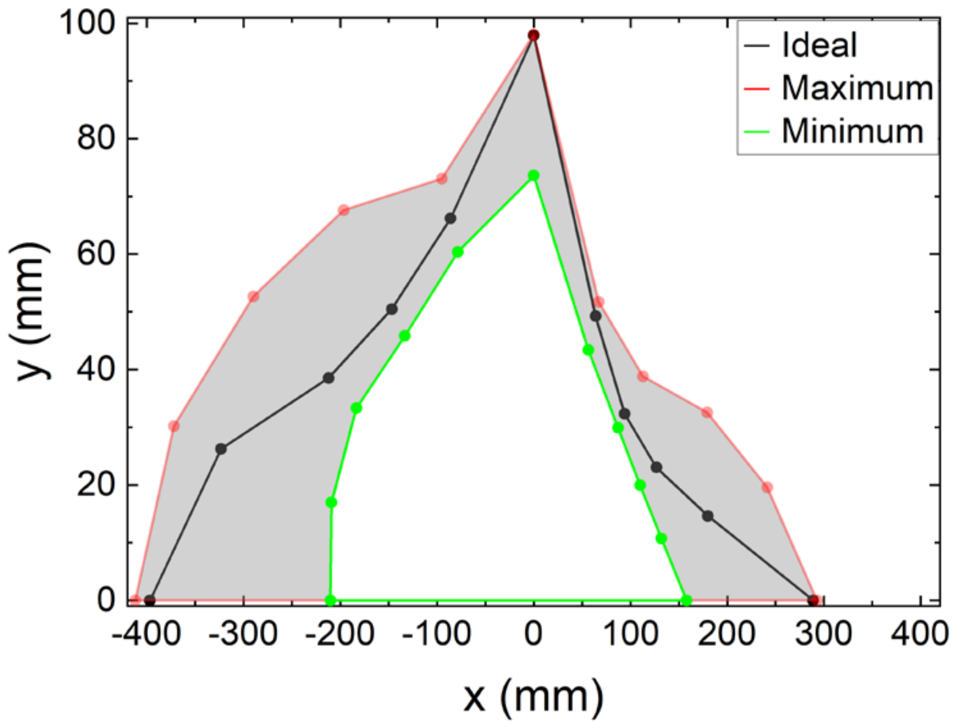
Comparison on dynamic aperture

Current design



Random errors on magnet misalignment
(rms value, 2-sigma cut used):
30 um in H/V , 250 um in L

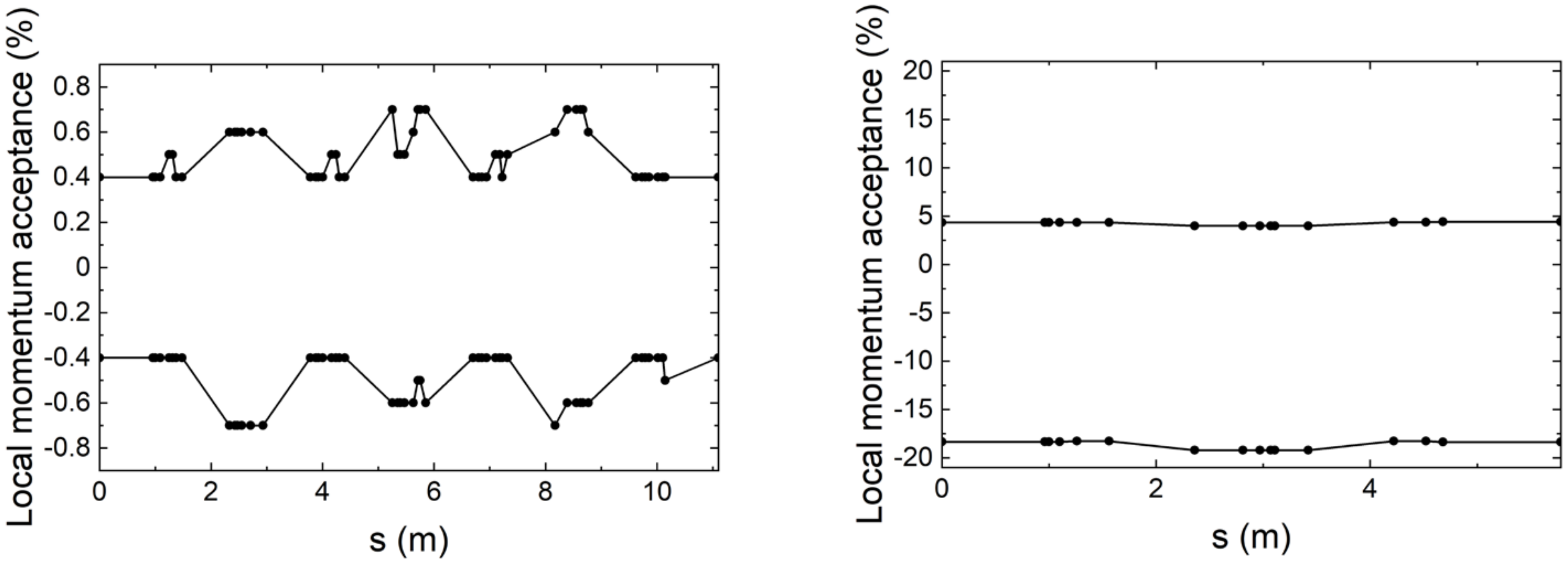
Alternative design



Random errors on magnet misalignment
(rms value, 2-sigma cut used):
300 um in H/V , **2500 um** in L

- turn = 4096, rf on, sr on, no physical aperture used
- Correction (i.e., orbit correction, LOCO) is not applied for each seed
- 100 error seeds
- The new design rarely reduces for the error which means it is much robust for the error.
- **For original lattice, only 3 error seeds have a stable dynamic aperture, for new lattice, all 100 error seeds have it.**

Comparison on momentum aperture



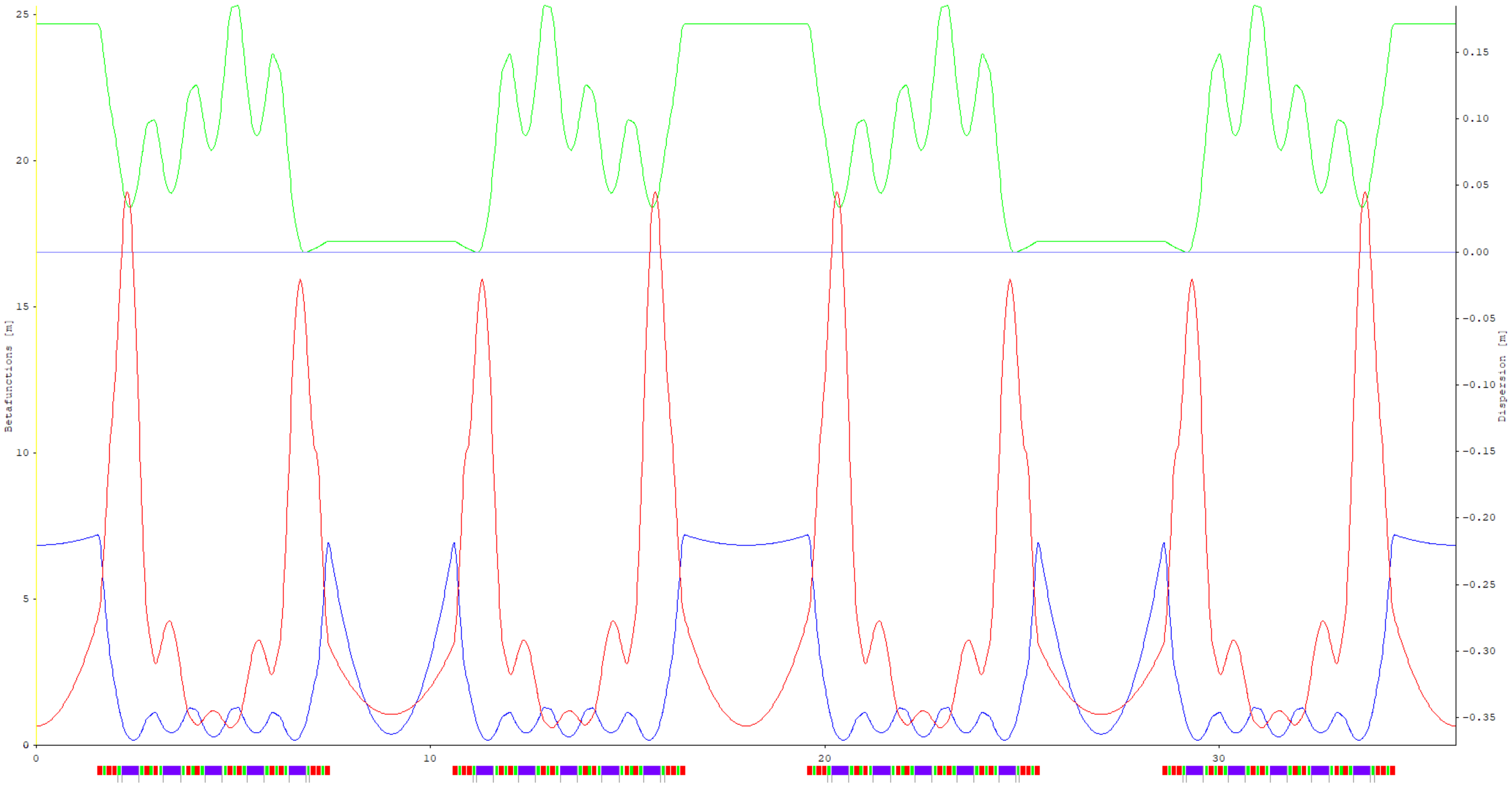
Ideal lattice	Touschek Lifetime [h]
Original	0.11
New	20916.56

- Turn = 8192, rf on, sr on, no physical aperture used
- Charge = 10 pC, Rf voltage = 70 KeV, rf frequency ~ 500 MHz, coupling = 10%, IBS effect not considered.
- **Ideal local momentum acceptance is much bigger for new design than that of original design.**
- **Large local momentum acceptance results in long Touschek lifetime for the new design case.**

❖PAL-EUV storage ring

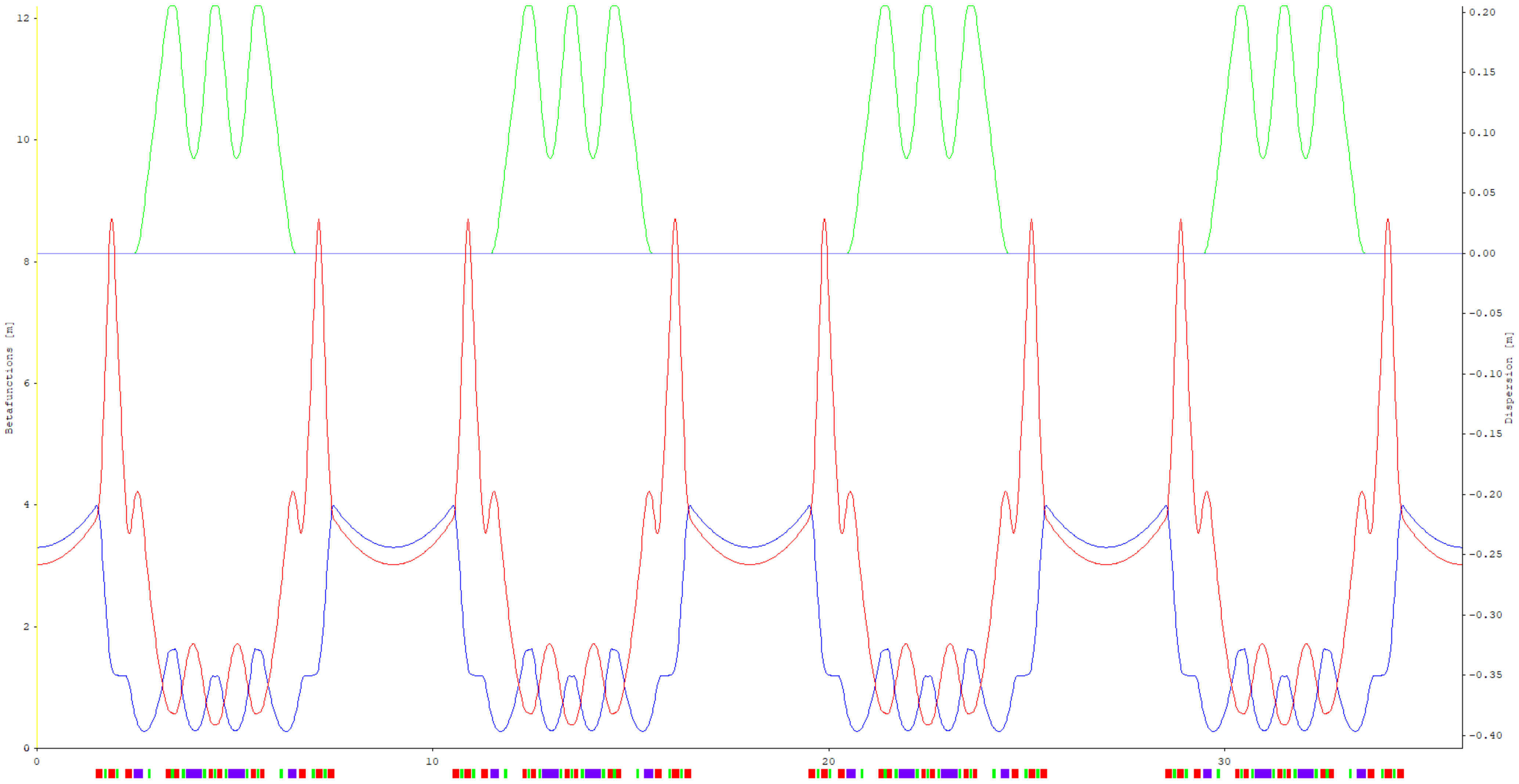
- Current design
- Alternative design (preliminary)
- Comparison

PAL-EUV SR parameters



Parameters	Value
Energy (MeV)	**400**
Circumference (m)	**36.0**
Emittance (nm)	**1.18**
Tunes (H,V)	**7.15, 3.14**
Natural chromaticity (H,V)	**-10.7, -16.9**
Chromaticity (corrected) (H,V)	**1 , 1**
Hor. Damping partition	**1.86**
Momentum compaction	$\mathbf{1.036 \times 10^{-2}}$
Energy spread (σ_δ)	$\mathbf{0.389 \times 10^{-3}}$
Energy loss per turn (keV)	**1.7**
Damping time (H/V/Z) (ms)	**31.14 / 58.07 / 51.15**
Beam current (mA)	**140**

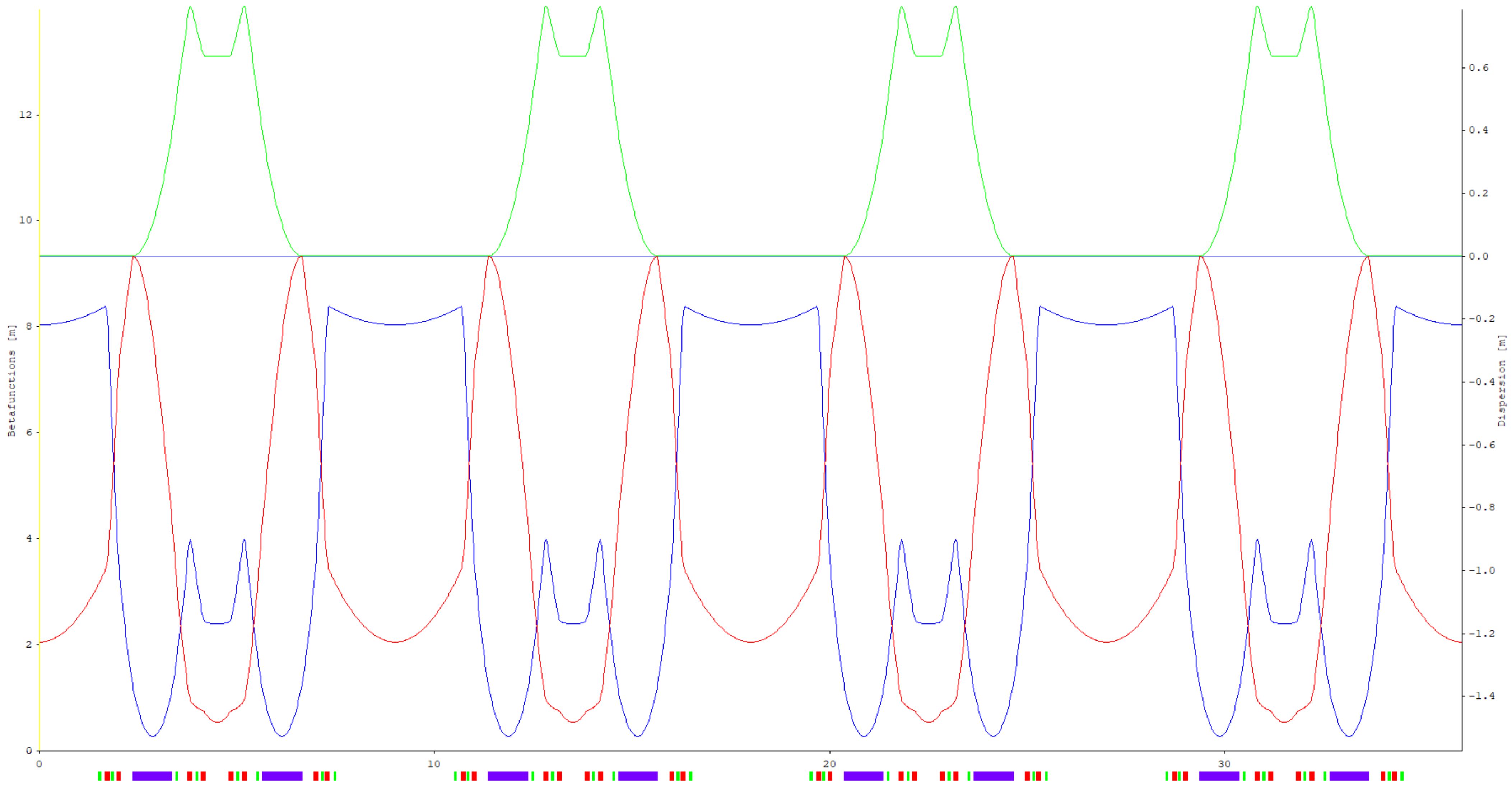
PAL-EUV SR alternative design-1 (preliminary)



4-bend achromat

Parameters	Value
Energy (MeV)	**400**
Circumference (m)	**36.0**
Emittance (nm)	**3.51**
Tunes (H,V)	**6.22 / 3.34**
Natural chromaticity (H,V)	**-7.2, -8.4**
Chromaticity (corrected) (H,V)	**1, 1**
Hor. Damping partition	**1.696**
Momentum compaction	$\mathbf{1.1 \times 10^{-2}}$
Energy spread (σ_δ)	$\mathbf{0.467 \times 10^{-3}}$
Energy loss per turn (keV)	**3.0**
Damping time (H/V/Z) (ms)	**20.40 / 32.41 / 22.97**

PAL-EUV SR alternative design-2 (preliminary)



Parameters	Value
Energy (MeV)	**400**
Circumference (m)	**36.0**
Emittance (nm)	**11.10**
Tunes (H,V)	**3.86 / 2.73**
Natural chromaticity (H,V)	**-7.7, -5.6**
Chromaticity (corrected) (H,V)	**1, 1**
Hor. Damping partition	**1.29**
Momentum compaction	2.294×10^{-2}
Energy spread (σ_δ)	0.314×10^{-3}
Energy loss per turn (keV)	**1.8**
Damping time (H/V/Z) (ms)	**47.76 / 54.02 / 28.90**

Double-bend achromat

Comparison on lattice parameters

Lattice parameters

Parameters	Current design (5BA)	Alternative design-1 (4BA)	Alternative design-2 (DBA)
Energy (MeV)	**400**	**400**	**400**
Circumference (m)	**36.0**	**36.0**	**36.0**
Emittance (nm)	**1.18**	**3.51**	**11.10**
Tunes (H,V)	**7.15, 3.14**	**6.22 / 3.34**	**3.86 / 2.73**
Natural chromaticity (H,V)	**-10.7, -16.9**	**-7.2, -8.4**	**-7.7, -5.6**
Chromaticity (corrected) (H,V)	**1 , 1**	**1, 1**	**1, 1**
Hor. Damping partition	**1.86**	**1.696**	**1.29**
Momentum compaction	$\mathbf{1.036 \times 10^{-2}}$	$\mathbf{1.1 \times 10^{-2}}$	$\mathbf{2.294 \times 10^{-2}}$
Energy spread (σ_δ)	$\mathbf{0.389 \times 10^{-3}}$	$\mathbf{0.467 \times 10^{-3}}$	$\mathbf{0.314 \times 10^{-3}}$
Energy loss per turn (keV)	**1.7**	**3.0**	**1.8**
Damping time (H/V/Z) (ms)	**31.14 / 58.07 / 51.15**	**20.40 / 32.41 / 22.97**	**47.76 / 54.02 / 28.90**

Comparison on magnets

Magnet specifications

-Normalized strengths are in MAD unit

Current design

Type	EA	Length	Max. strength
Bend (combined function of bend-quad)	20	0.43 m	B0 = 0.974 [T] K1 = -5.59 [$1/m^{-2}$]
10 cm quad	56	0.10 m	K1 = 23.74 [$1/m^{-2}$]
Sext	64	0.05 m	K2 = 1818.81 [$1/m^{-3}$]

Alternative design-1 (4BA)

Type	EA	Length	Max. strength
40 cm bend (combined function of bend-quad)	8	0.40 m	B0 = 1.747 [T] K1 = -7 [$1/m^{-2}$]
20 cm bend (combined function of bend-quad)	8	0.20 m	B0 = 1.747 [T] K1 = -6.39 [$1/m^{-2}$]
10 cm quad*	24	0.10 m	K1 = 23.68 [$1/m^{-2}$]
15 cm quad	24	0.15 m	K1 = 15.37 [$1/m^{-2}$]
Sext*	52	0.05 m	K2 = 1730.3 [$1/m^{-3}$]

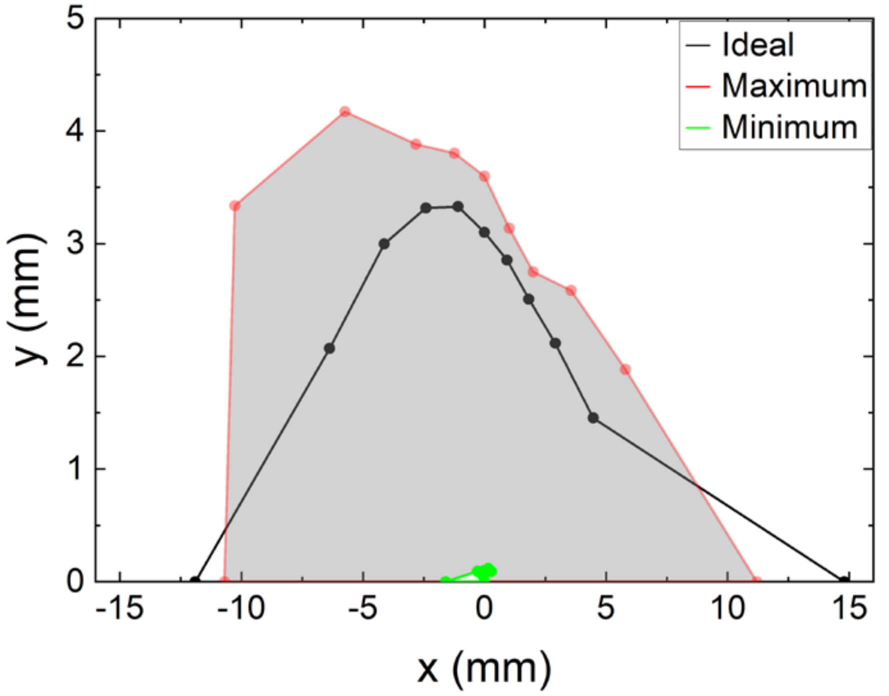
Alternative design-2 (DBA)

Type	EA	Length	Max. strength
Bend (combined function of bend-quad)	8	1.0 m	B0 = 1.047 [T] K1 = -0.7 [$1/m^{-2}$]
10 cm quad*	32	0.10 m	K1 = 18.20 [$1/m^{-2}$]
Sext*	32	0.05 m	K2 = 711.0 [$1/m^{-3}$]

*reusable

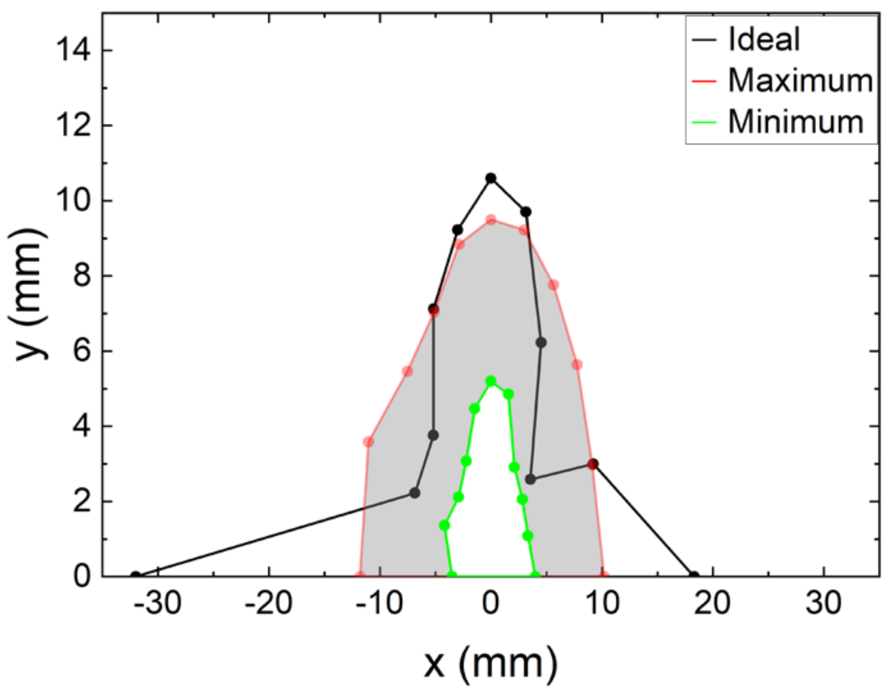
Comparison on dynamic aperture

Current design



Random errors on magnet misalignment
(rms value, 2-sigma cut used):
30 um in H/V , 250 um in L

Alternative design-1 (4BA)

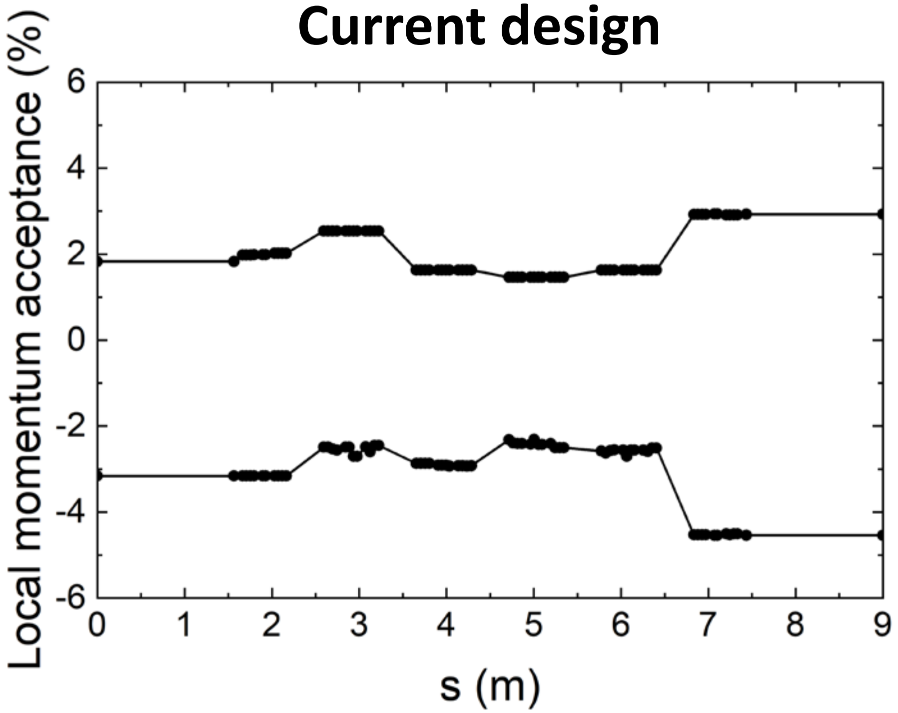


Random errors on magnet misalignment
(rms value, 2-sigma cut used):
30 um in H/V , 250 um in L

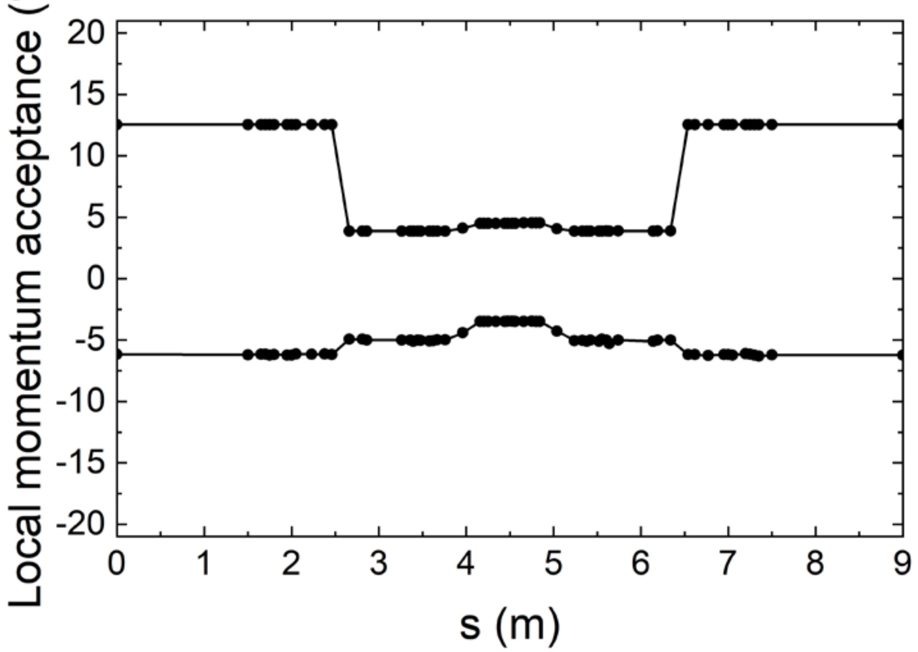
- ❖ rf on, sr on, no physical aperture used
- ❖ 100 error seeds, turn = 4096
- ❖ Correction (i.e., orbit correction, LOCO) is not applied for each seed
- ❖ The new design rarely reduces for the error which means it is much robust for the error.
- ❖ **For original lattice, only 24 error seeds have a stable dynamic aperture, for new lattice, all 100 error seeds have it.**

Comparison on momentum aperture

Current design



Alternative design-1 (4BA)



Ideal lattice	Touschek Lifetime [h]
Original	26.49
New	1122.01

- ❖ Turn = 1024, rf on, sr on, no physical aperture used
- ❖ Charge = 10 pC, Rf voltage = 70 KeV, rf frequency ~ 500 MHz, coupling = 10%, IBS effect not considered.
- ❖ **Ideal local momentum acceptance is much bigger for new design than that of original design.**
- ❖ **Large local momentum acceptance results in long Touschek lifetime for the new design case.**

Dipole edge-focusing and tune change

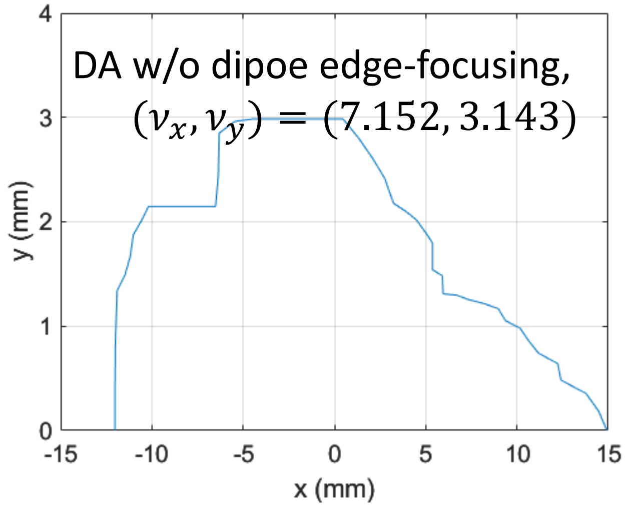
- Including dipole edge-focusing result in tune change in vertical plane
- For a sector bend magnet (pole-face rotation angle = 0), edge focusing at each pole-face is described by a matrix R

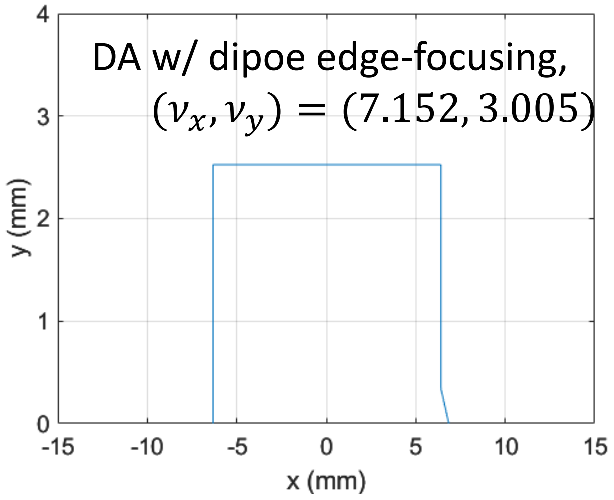
$$R = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{\tan(\psi)}{\rho} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

where $\psi = \kappa_1(\frac{g}{\rho})$

ρ = Bending radius of central trajectory
g = Total gap of magnet
κ_1 = An integral related to the extent of the fringing field of a bending magnet

-Current storage ring design has ρ = 1.3698 m, g = 0.024 m and κ_1= 0.5
-Including dipole edge-focusing changes tune from $(\nu_x, \nu_y) = (7.152, 3.143)$ to $(\nu_x, \nu_y) = (7.152, 3.005)$





Tune adjustment is required after including effect of dipole edge-focusing, in order to restore dynamic aperture

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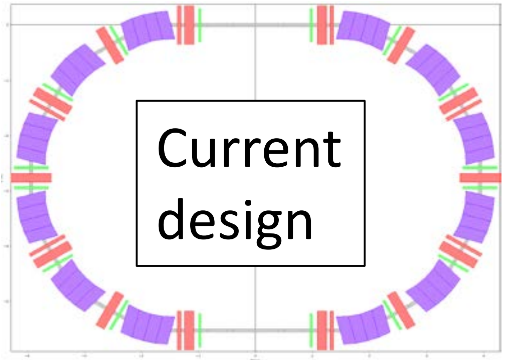
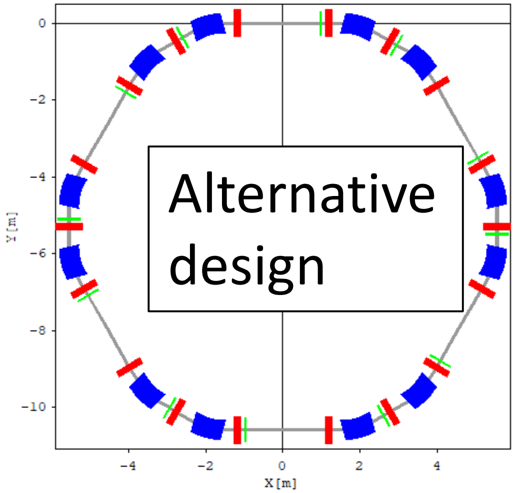
2D geometry

PAL-EUV booster

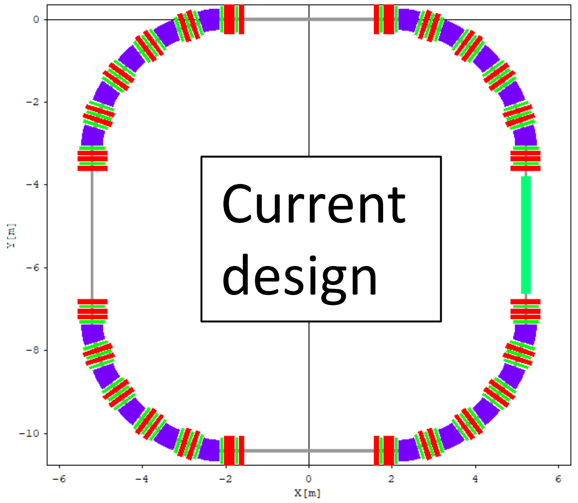


C = 22.2 m

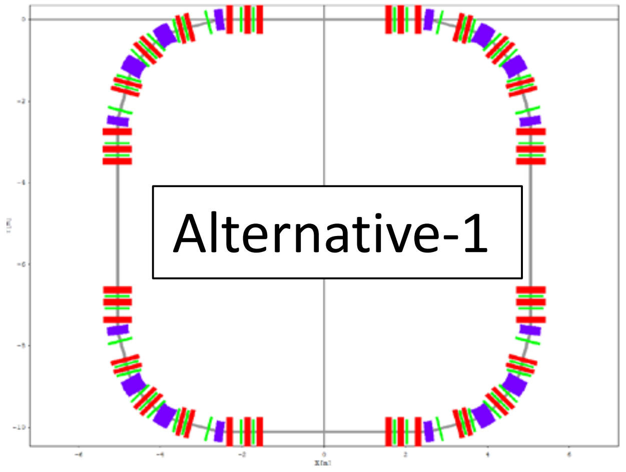


C = 34.68 m

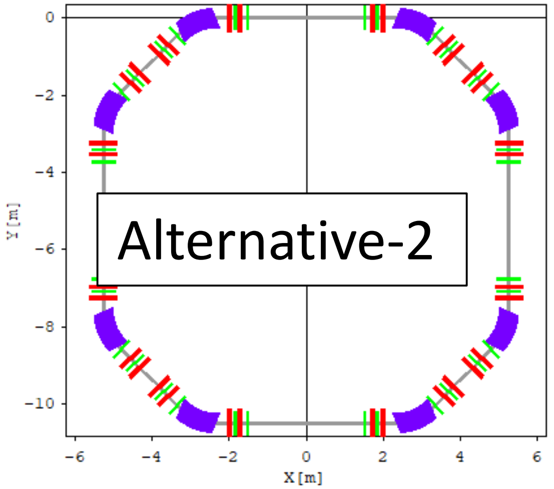
PAL-EUV storage ring



C = 36.0 m



C = 36.0 m



C = 36.0 m

Summary

- Beam Dynamics study on current PAL-EUV lattice design and alternative designs are performed
- Still working on finding an alternative design which keeps current lattice arrangement
- Presented alternative designs aim for relaxed nonlinear properties and robustness against alignment/roll/field errors
- Magnet reusability is also considered

- Alternative design on booster is much more robust against errors, but it doesn't fit current 22.2 m geometry
- Alternative design-1 on storage ring can provide similar dynamic aperture to that of current design but can provide much longer Touschek lifetime

Thank you for your attention