Damping Ring Alternative Design Options

FCCee Pre-Injector: CHART Collaboration Meeting
20th and 21st of April, 2023

LNF, Frascati, Italy

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Thanks to: P. Raimondi, P. Craievich, K. Oide, T. Raubenheimer, F. Zimmermann, A. Santis
for their useful discussions

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- Reasons to look for an alternative design for the DR
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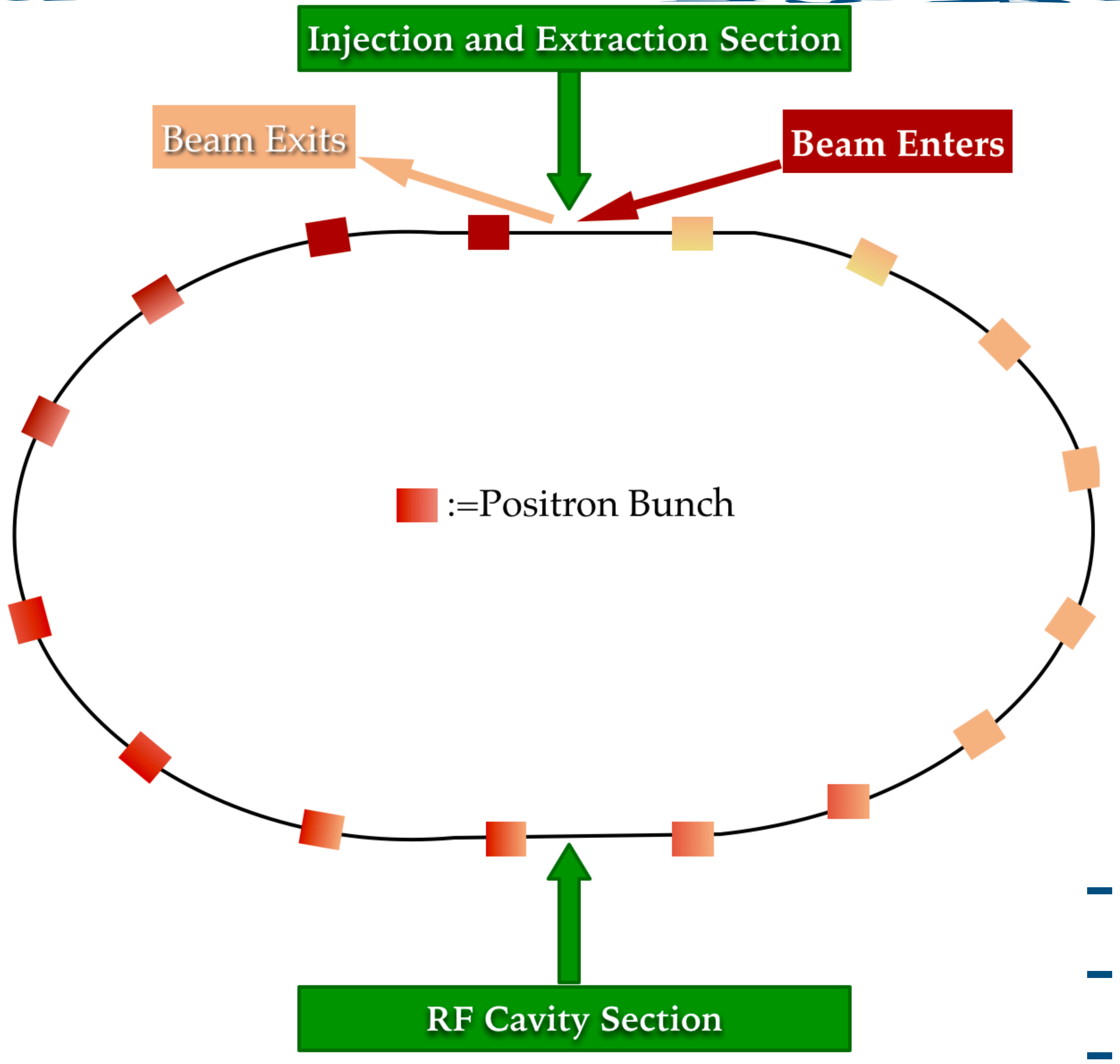
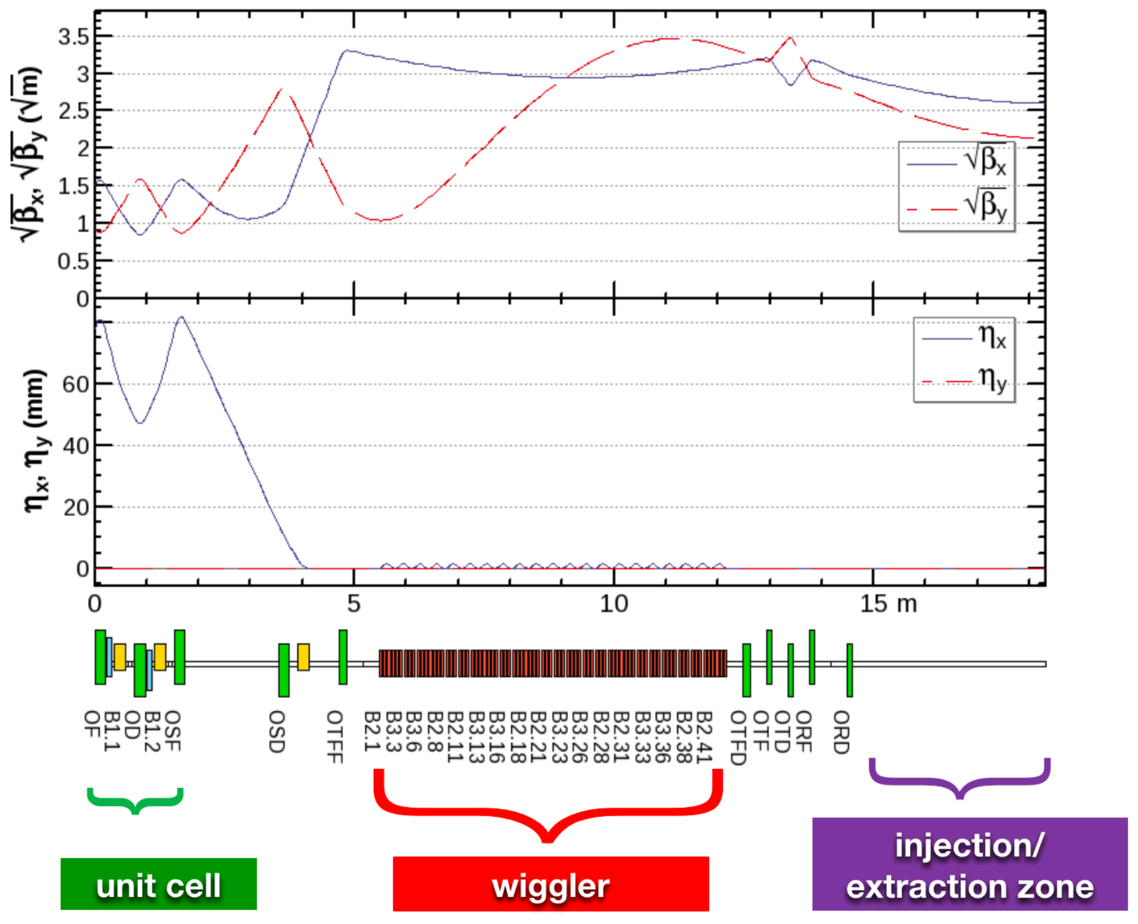
  - DBA and TBA,
  - Reversed bend FODO,
  - Combined function magnet.
- Comparison of different evaluated options
- Higher energy DR
- Summary and next steps



Parameters	Value
Circumference	242 m
Energy	1.54 GeV
Bunch intensity	2.1E10
Number of trains x bunches in a train	8 x 2 bunches
Transverse Damping Time	10.5 ms
Store time for a train	40 ms
Energy loss per turn	0.225 MeV
SR Power loss	15.7 kW



- **FODO** lattice
- Racetrack layout (each arc has 57 units)
- Dipoles: 21cm, 0.66 T, 1.552 degree
- **Phase advance** in the arc is **69.5⁰/66⁰** (h/v)
- 2+2 wigglers in straight sections (each 6.64 m)
- Total wiggler length is 26.56 m - 1.8T magnetic field

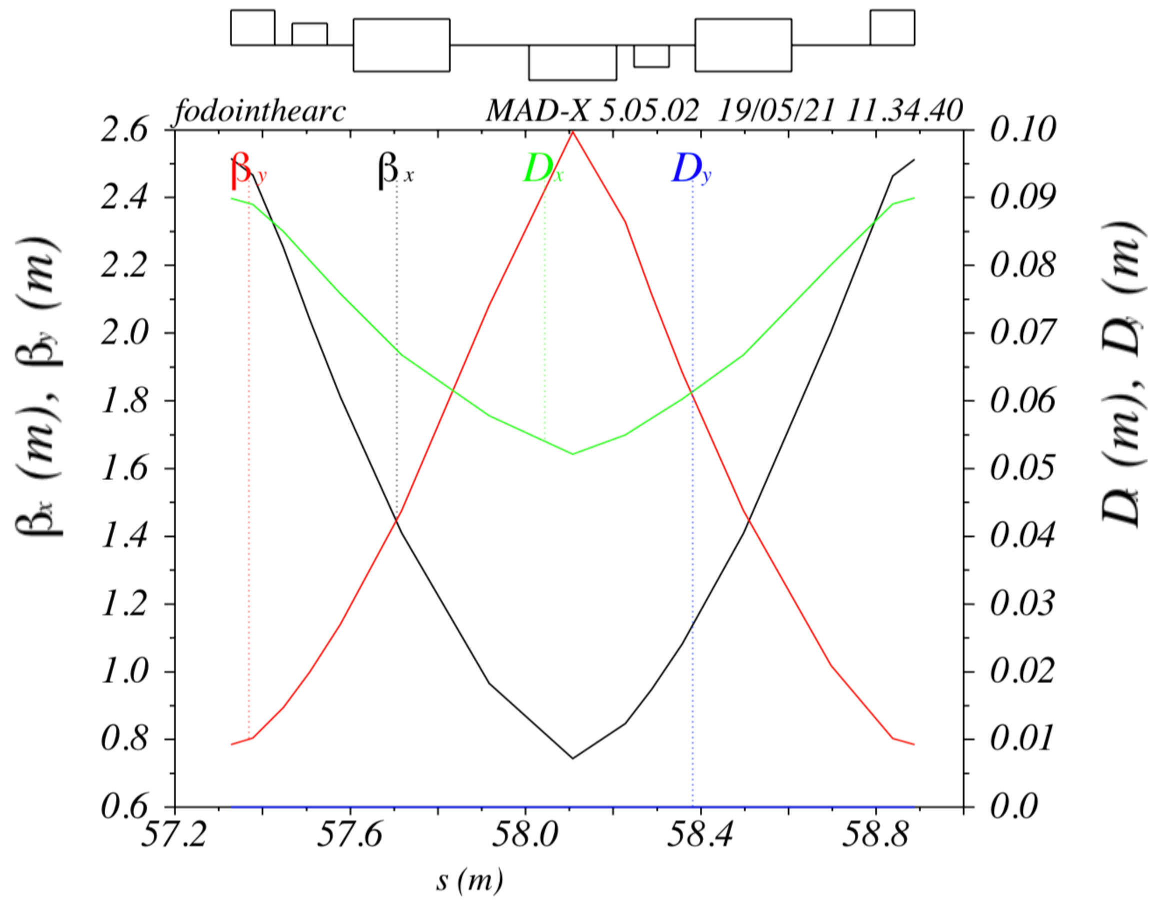
- 2 RF (1+1) in the straight section (U_o=0.225 MeV, V_{rf}=4 MV, 400 MHz, 5 MV/m RF).
- Energy acceptance is large: around **+/-7%**
- Eq. **emittance** including wiggler magnet is 0.96 nm.rad (without IBS) (it growths to **2 nm.rad** with IBS)

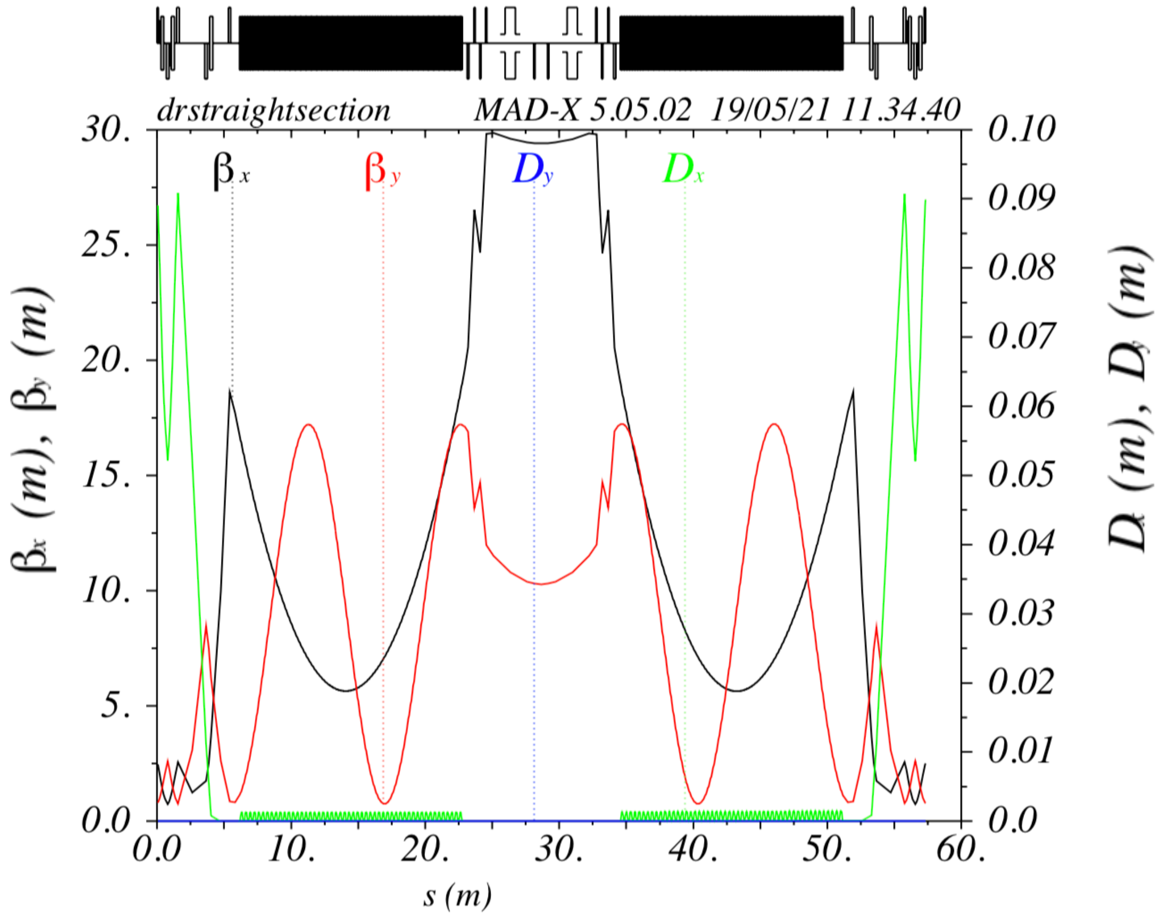
S. Ogur, K. Oide et. al.

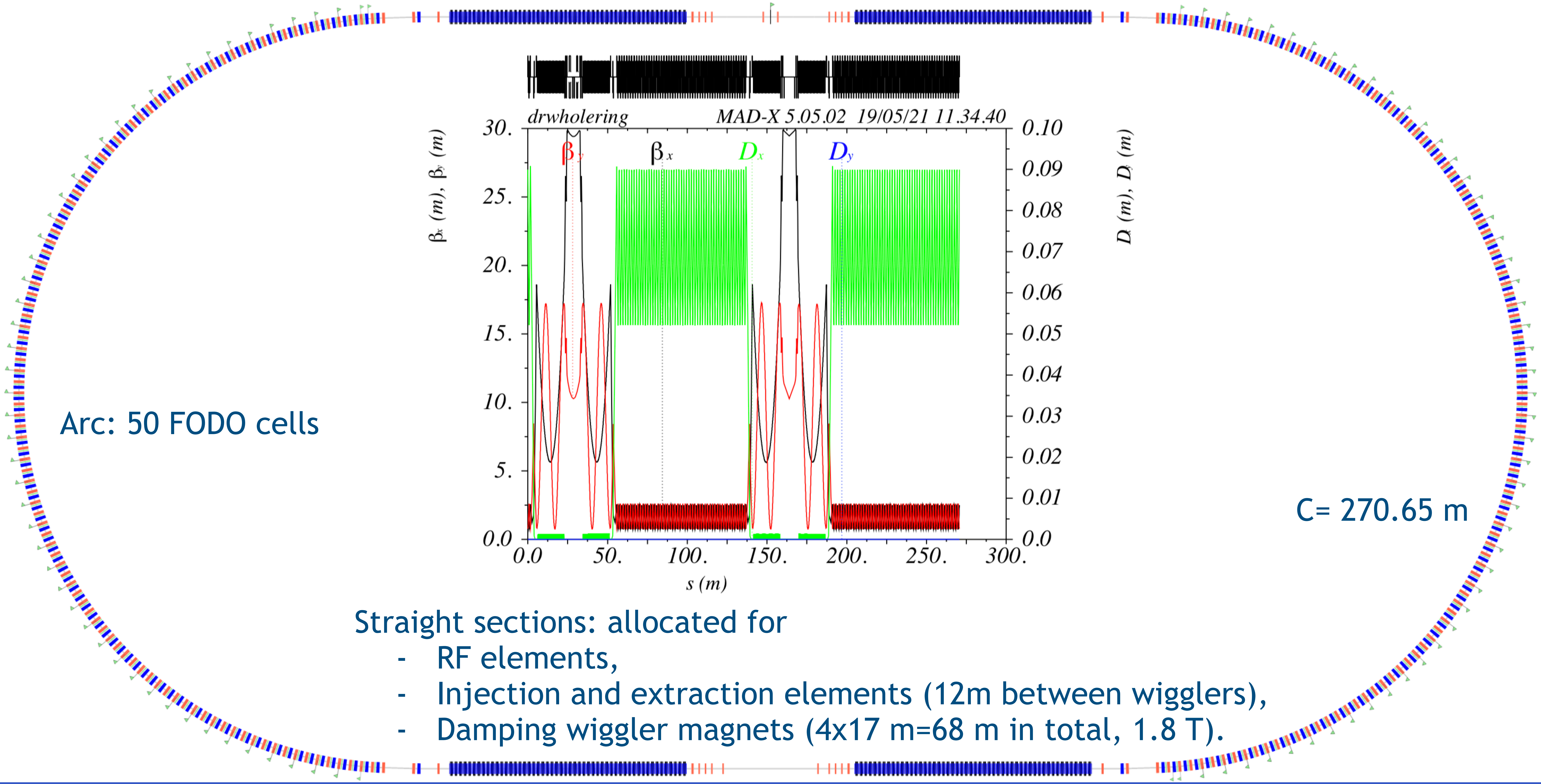
Review of “after CDR” version of the DR

- The design is modified to comply with the changing requirements (damping time mainly) after CDR.

C. Milardi, O. Blanco, A. De Santis







Arc: 50 FODO cells

C= 270.65 m

Straight sections: allocated for

- RF elements,
- Injection and extraction elements (12m between wigglers),
- Damping wiggler magnets (4x17 m=68 m in total, 1.8 T).

Review of “after CDR” version of the DR

- The design is modified to comply with the changing requirements (damping time mainly).

A lot of elements and very long damping wiggler magnet were used

Parameters	CDR	After CDR
Bending magnet quantity	**232**	**212**
Dipole magnet length [m]	0.21	0.21
Bending angle [degree]	1.55	1.69
Dipole magnetic field [T]	0.66	0.72
Filling factor	0.2	0.15
Damping wiggler magnet [m/T]	26.5 m / 1.8 T	**68 m / 1.8 T**
Robinson wiggler magnet [m / T]	-	-
Circumference [m]	242 m	270 m
Emittance [nm.rad] (inlc. IBS)	2 nm.rad	2.76 nm.rad
Damping time	**10.5 ms**	5.9 ms
Energy loss per turn	0.255 MeV	0.47 MeV

Lots of elements were used and the design is not providing required parameters, anymore.

Consideration for a new DR Layout

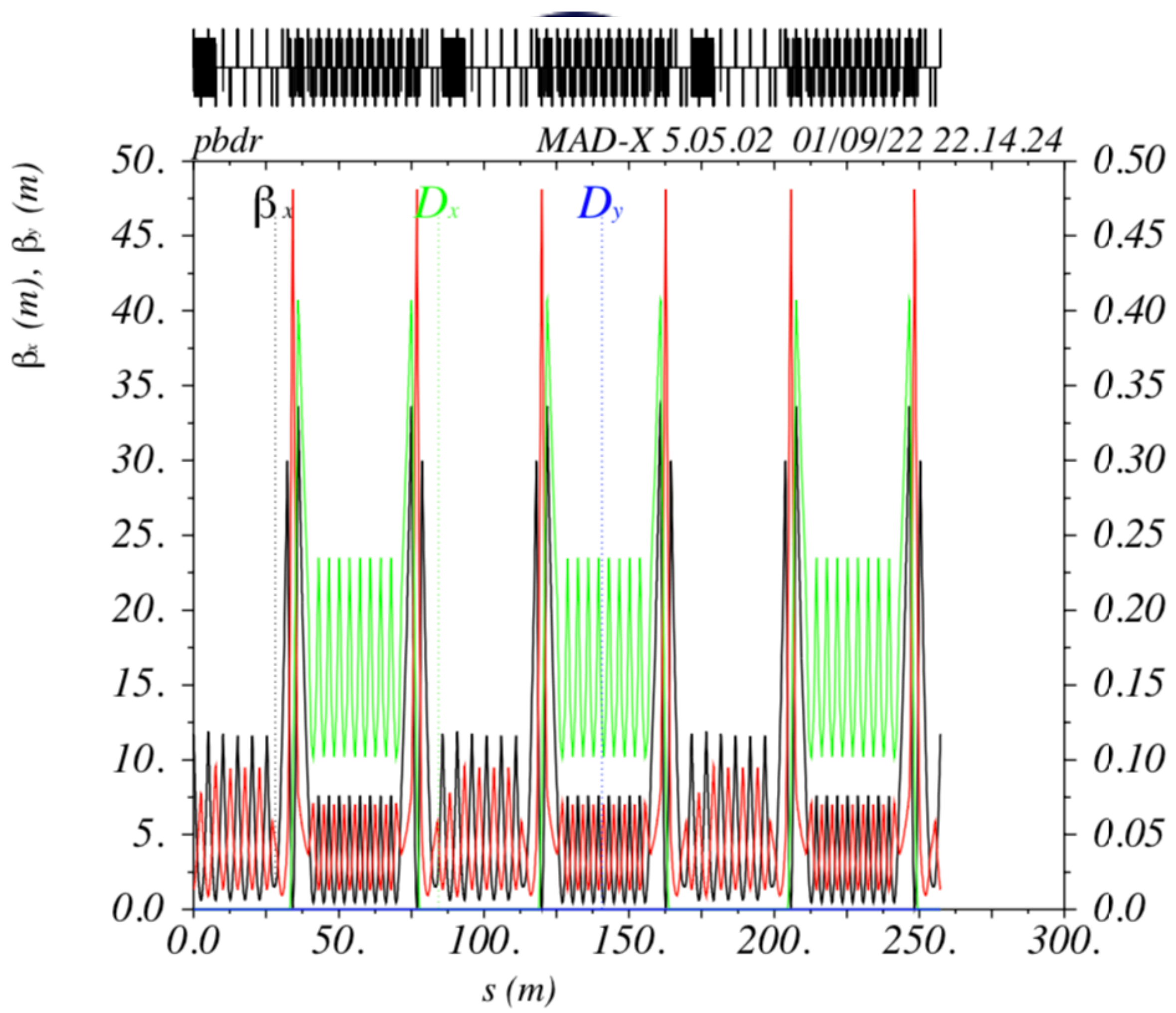
Reasons to revise the DR design:

- **A large number of elements** were used in the DR (**232 dipole magnets** were used: which determines high number of components such as: quadrupoles, sextupoles, octupoles, steering magnets, and beam diagnostics high realization costs, complicate installation and alignment procedures.)
- **Magnetic field** (there is no obstacle to make it higher: 0.66 T dipole magnet field)
- **Long damping wiggler** (revised design after CDR included 68 m, CDR version had 26.56 m)
- Straight sections: 2 straight sections were allocated (3 SS might be better in terms of NLD and for insertion devices)
- **Not optimum phase advance** were chosen for the beam emittance damping
- CDR version is not providing the required parameters (not anymore).

New approach:

- Higher magnetic field which makes damping time shorter **(positive)**
- Less magnets **(positive)** which make larger emittance **(negative)**
- Optimum phase advance for the FODO lattice **(positive and negative)**
- Three straight sections **(positive)**
- Robinson wiggler may be used (introduced options with and without RW in the following slides).

Layout shown in the previous meeting



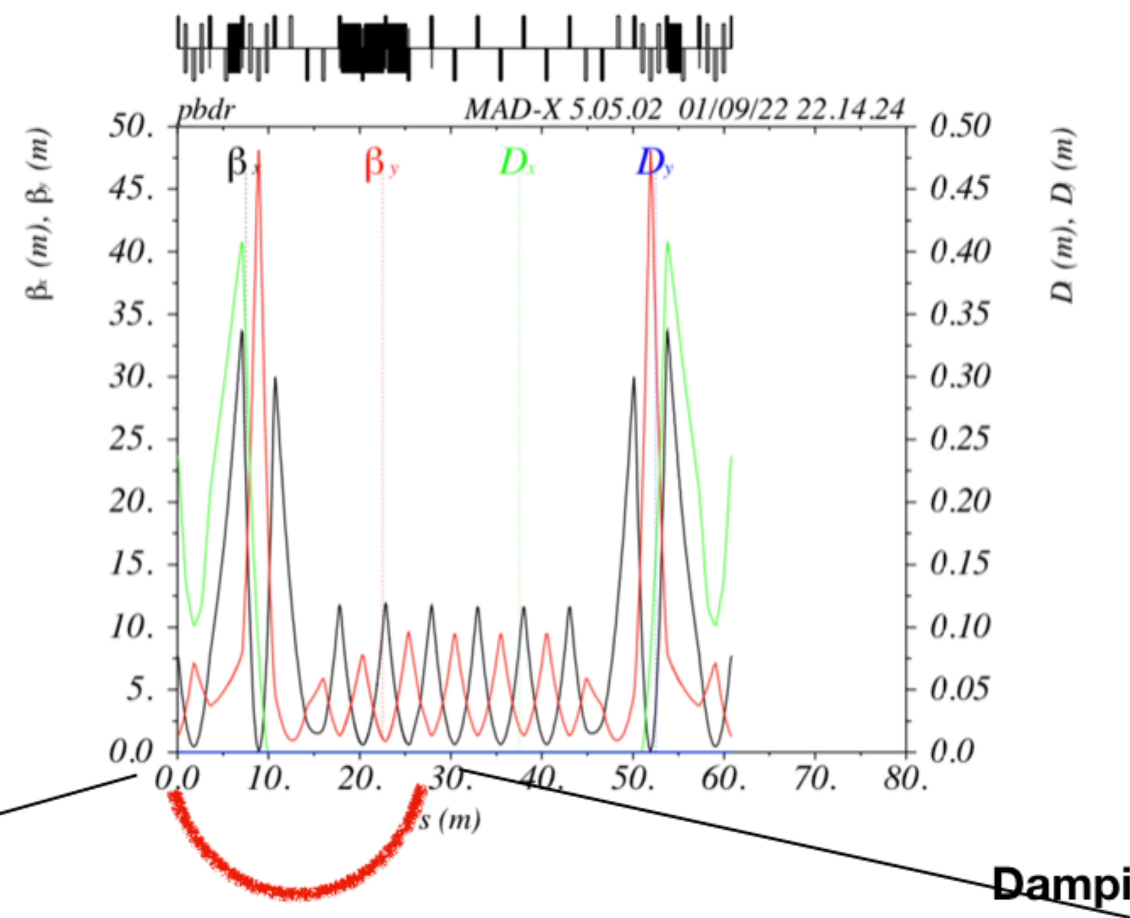
- The design of the DR composes of 3 arcs and 3 straight sections.
- Arcs consist of 11 FODO cells and each of the straight sections have 4 FODO cell (without dipole magnets)

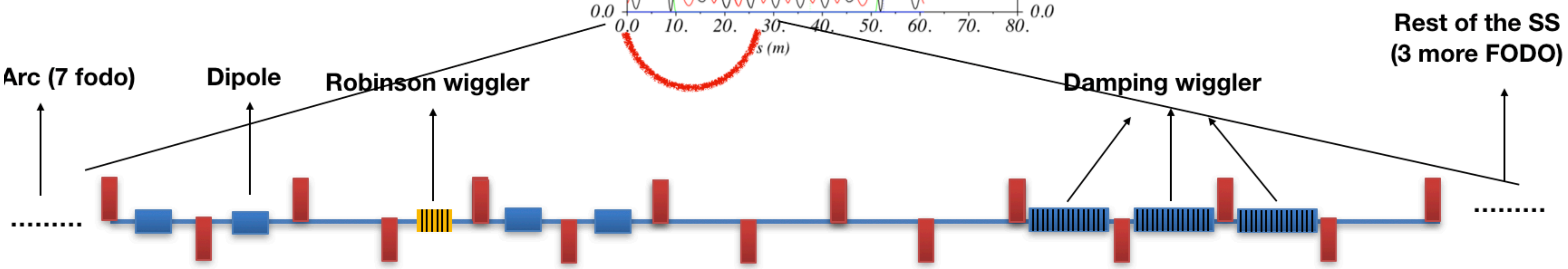
Straight Section (SS) area with 5 cell;

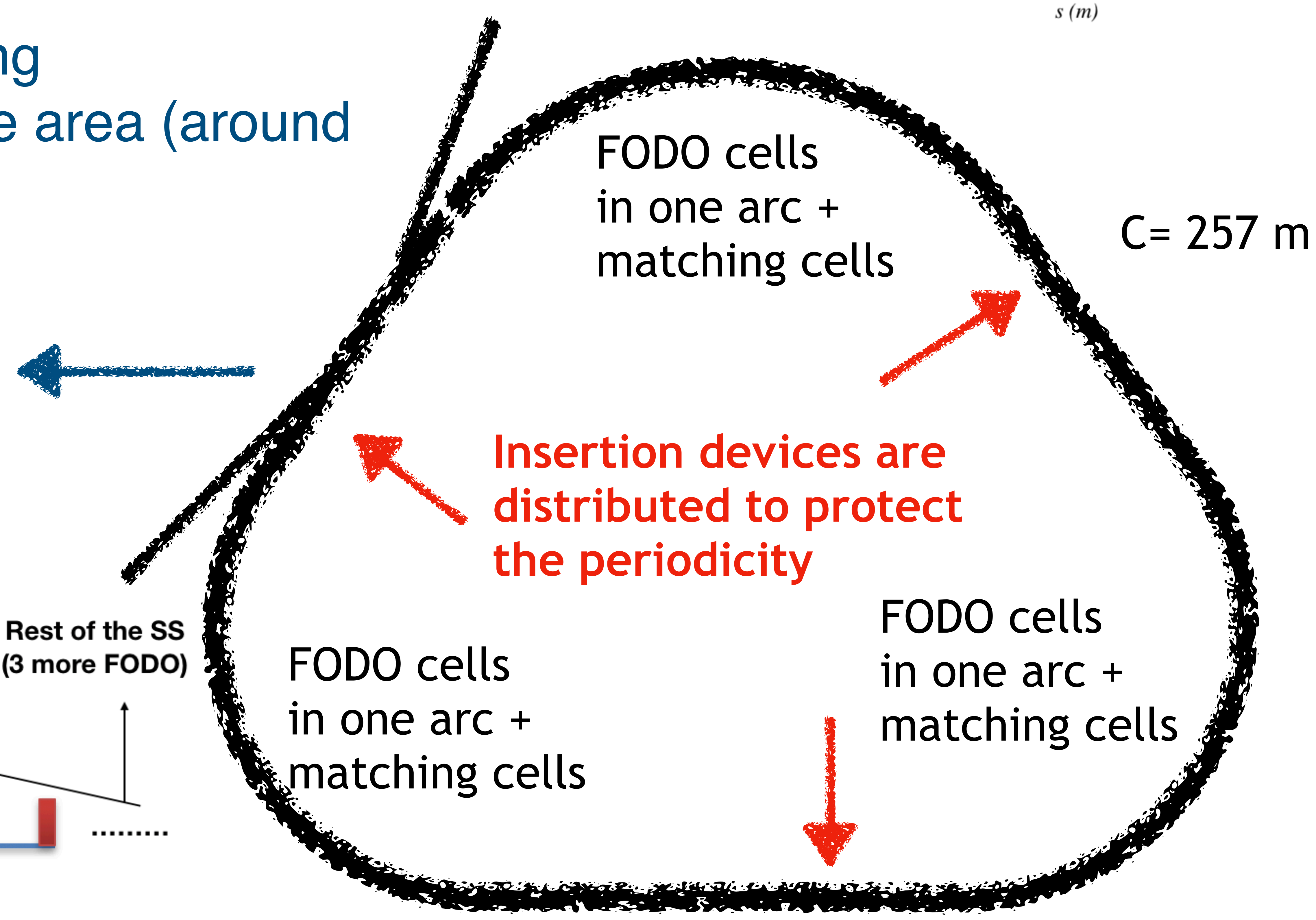
- 3 damping wiggler are allocated (each of them is around 2 m).

Straight Section (SS) area + matching area as also showing

- the Robinson wiggler which is allocated to the dispersive area (around 1.3 m).







Summary and next steps of the previous meetings

Parameters	CDR	After CDR	Option - 0
Bending magnet quantity	232	212	**72***
Dipole magnet length [m]	0.21	0.21	**0.28**
Bending angle [degree]	1.55	1.55	**5**
Dipole magnetic field [T]	0.66	0.66	**1.8**
Filling factor	0.2	0.19	**0.07**
Damping wiggler magnet	26.5 m / 1.8 T	68 m / 1.8 T	**18 m / 2 T**
Robinson wiggler magnet	-	-	**3.8 m / 1.1 T**
Circumference	242 m	240 m	**257.31 m**
Emittance	2 nm.rad	2.76 nm.rad	**4.89 nm.rad**
Damping time	10.5 ms	5.9 ms	**6 ms**
Energy loss per turn	0.255 MeV	0.47 MeV	**0.253 MeV**

Reminder: when we provided this option, the requirements were different.

Feedback from the meeting in December:

- The layout with three SS and having higher dipole magnetic field
- However, the magnetic field of the dipole magnets should not be higher than 1.5 T,
- New requirement for emittance should be met.

In this regard, we have **continued to revise the new layout** with the following "new" required parameter changes:

- **Emittance** should be reduced to **2 nm.rad**.

- In addition, based on internal discussions, we have also evaluated different options.

Clarification/updating of the required parameters

- Before we start to proceed on the existing design or to provide alternative designs, a good definition of the required parameters should be determined clearly. Some of the parameters are crucial to be able to provide a design.
- Based on many discussions, the following table summarizes the requirement parameters that we agreed on for the DR design:

Required Parameters	
Energy [GeV]	1.54
Circumference [m]	~250 m
Stored time [ms]	40
Damping time (hor.) [ms]	**~7.5**
Extraction geo. emittance (hor.) [nm.rad]	**~2**
Number of bunches	16
Energy spread @ extraction [%] (rms.)	-
Injection type	on axis
Number of straight sections	3
Injected Parameters	
Injected emittance (h) (e^-/e^+) [nm.rad/μm.rad]	5.5/1.29
Injected emittance (v) (e^-/e^+) [nm.rad/μm.rad]	6/1.22
Injected momentum spread [%] (e^-/e^+) (rms.)	0.2/5
Injected bunch length (e^-/e^+) (mm)	1/3.4

Investigated options

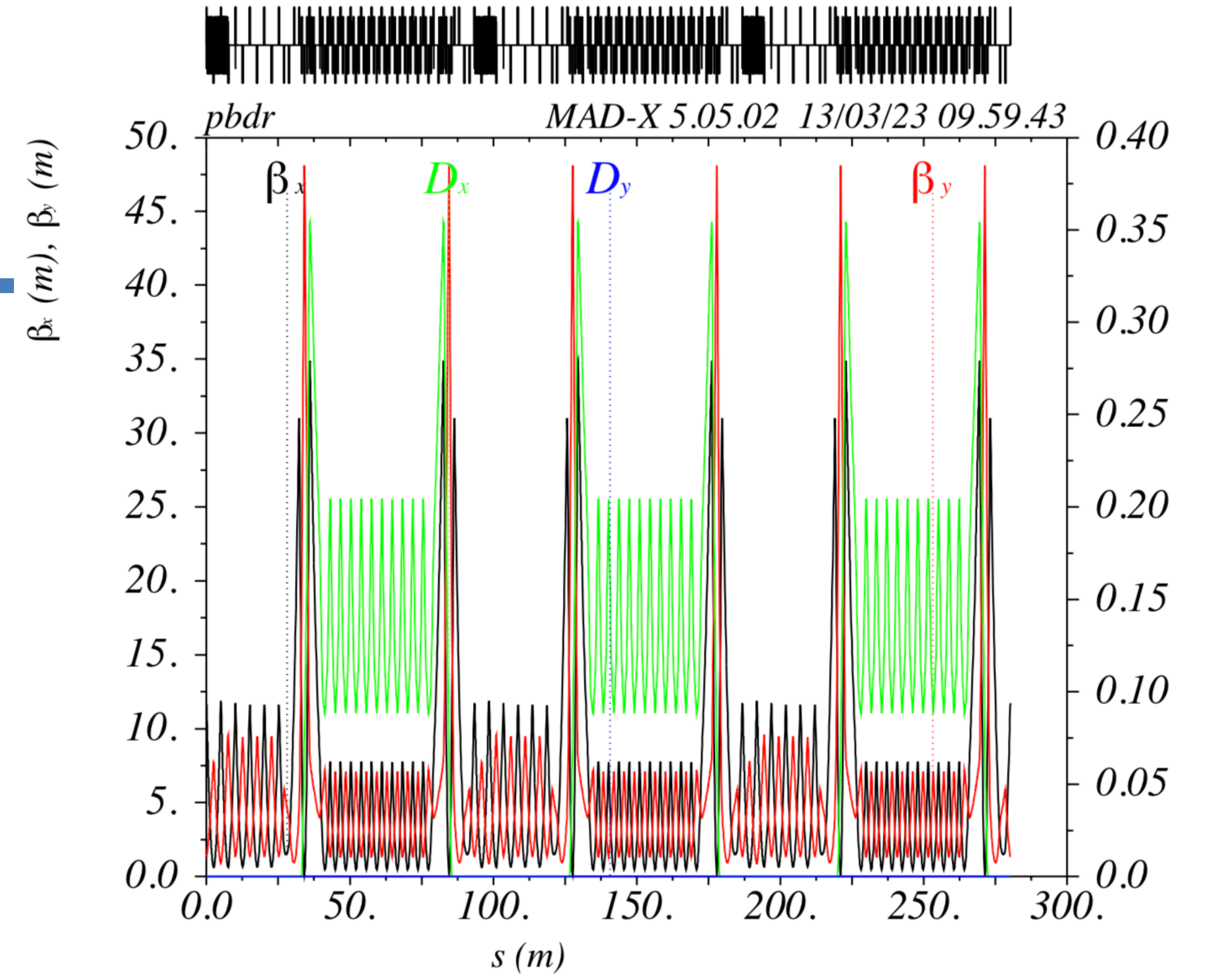
We have continued with our new approach to investigate several **options** to reach out the new requirements with an optimum design:

- Using **damping wiggler and Robinson wiggler** magnets **(Option 1)**,
- Option without Robinson wiggler magnet (SC DW) **(Option 2)**,
- Checked the **reversed bend** magnet **(Option 3)**,
- Checked **DBA (Option 4)**,
- Checked **TBA (Option 5)**,
- **FODO** + (relatively long) damping wiggler **without SC DW or RW (Option 6)**
- Recently, we started to check combined function magnet; it is still progressing **(Option 7)**.

We have also done **preliminary study for higher energies** based on the discussion in Orsay during injector workshop **(Option 8)**.

Option 1: DR with DW and RW

- The design of the DR composes of 3 arcs and 3 straight sections.
- Arcs consist of 11 FODO cells and each of the straight sections have 5 FODO cells

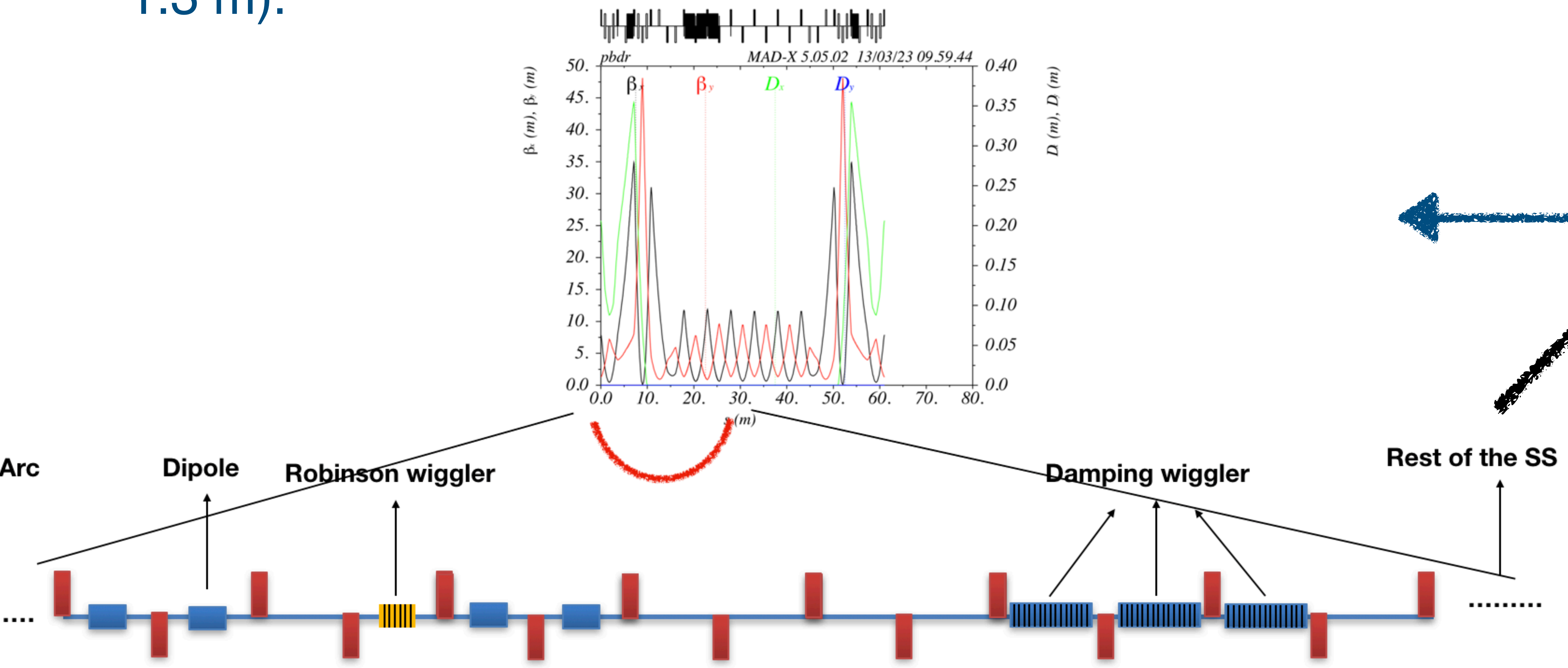


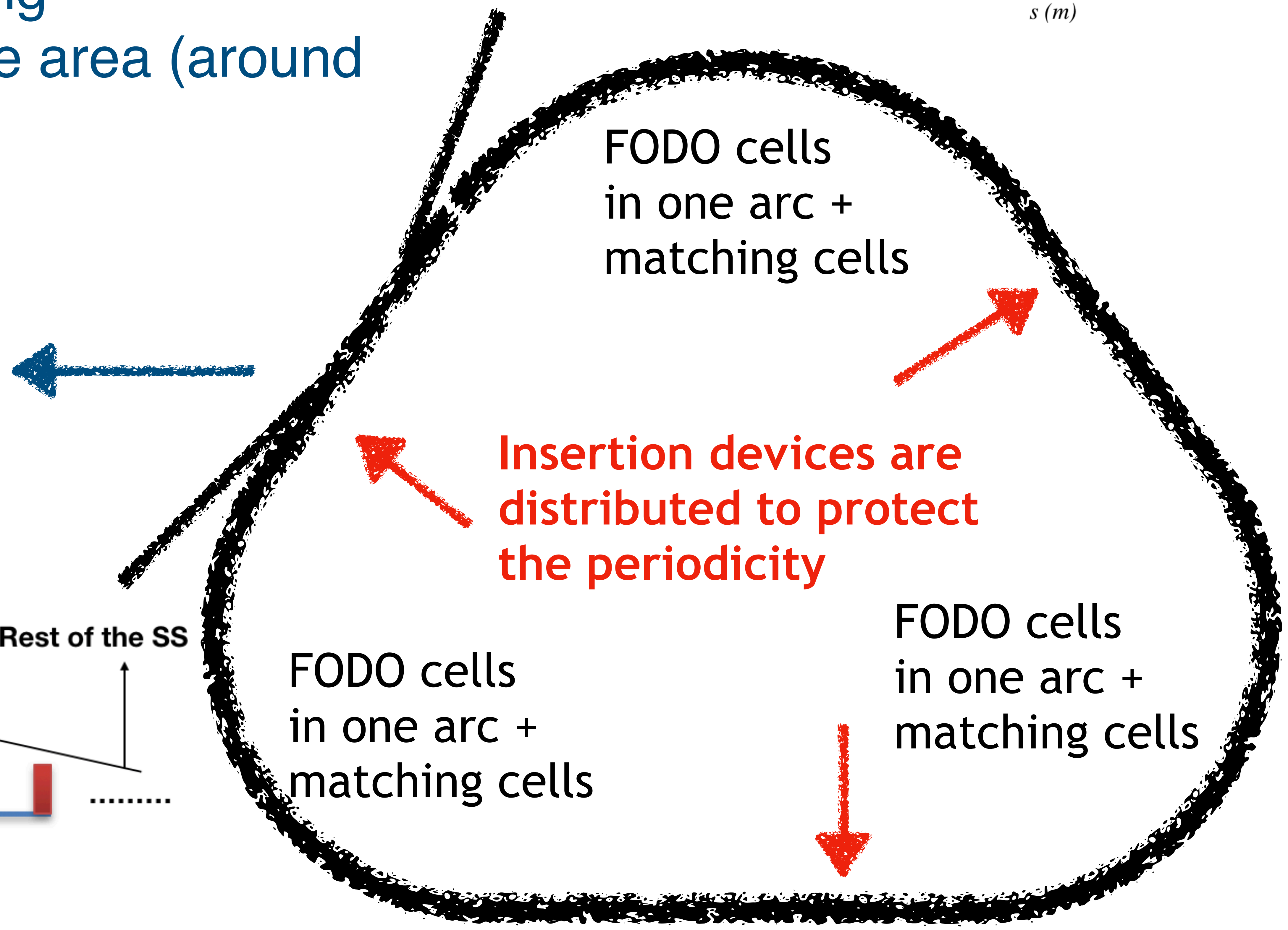
Straight Section (SS) area with 5 cell;

- 3 damping wiggler are allocated (each of them is around 2 m).

Straight Section (SS) area + matching area as also showing

- the Robinson wiggler which is allocated to the dispersive area (around 1.3 m).





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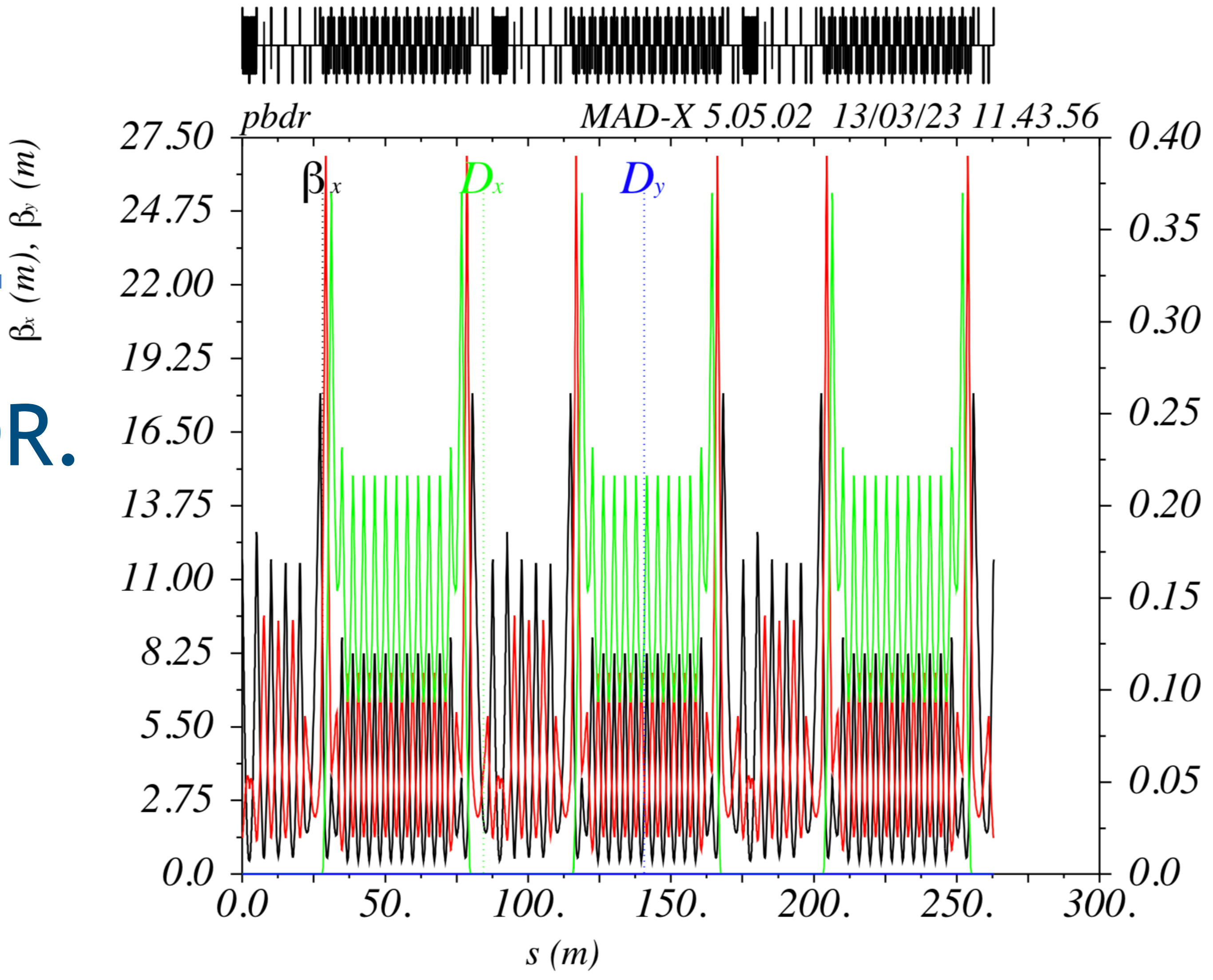
Option 1: DR with DW and RW

Parameters	CDR	After CDR	New (option - 0)	New (option - 1)
Bending magnet quantity	232	212	72	84
Dipole magnet length [m]	0.21	0.21	0.28	0.3
Bending angle [degree]	1.55	1.55	5	4.28
Dipole magnetic field [T]	0.66	0.66	1.8	1.27
Filling factor	0.2	0.19	0.07	0.09
Damping wiggler magnet	26.5 m / 1.8 T	68 m / 1.8 T	18 m / 2 T	18 m / 1.8 T
Robinson wiggler magnet	-	-	3.8 m / 1.1 T	3.8 m / 1.8 T
Circumference	242 m	240 m	257.31 m	280.23 m
Emittance	2 nm.rad	2.76 nm.rad	4.89 nm.rad	2.12 nm.rad
Damping time	10.5 ms	5.9 ms	6 ms	5.7 ms
Energy loss per turn	0.255 MeV	0.47 MeV	0.253 MeV	0.23 MeV

It provides all the required parameters; however,
We continued our study to find an option without Robinson wiggler

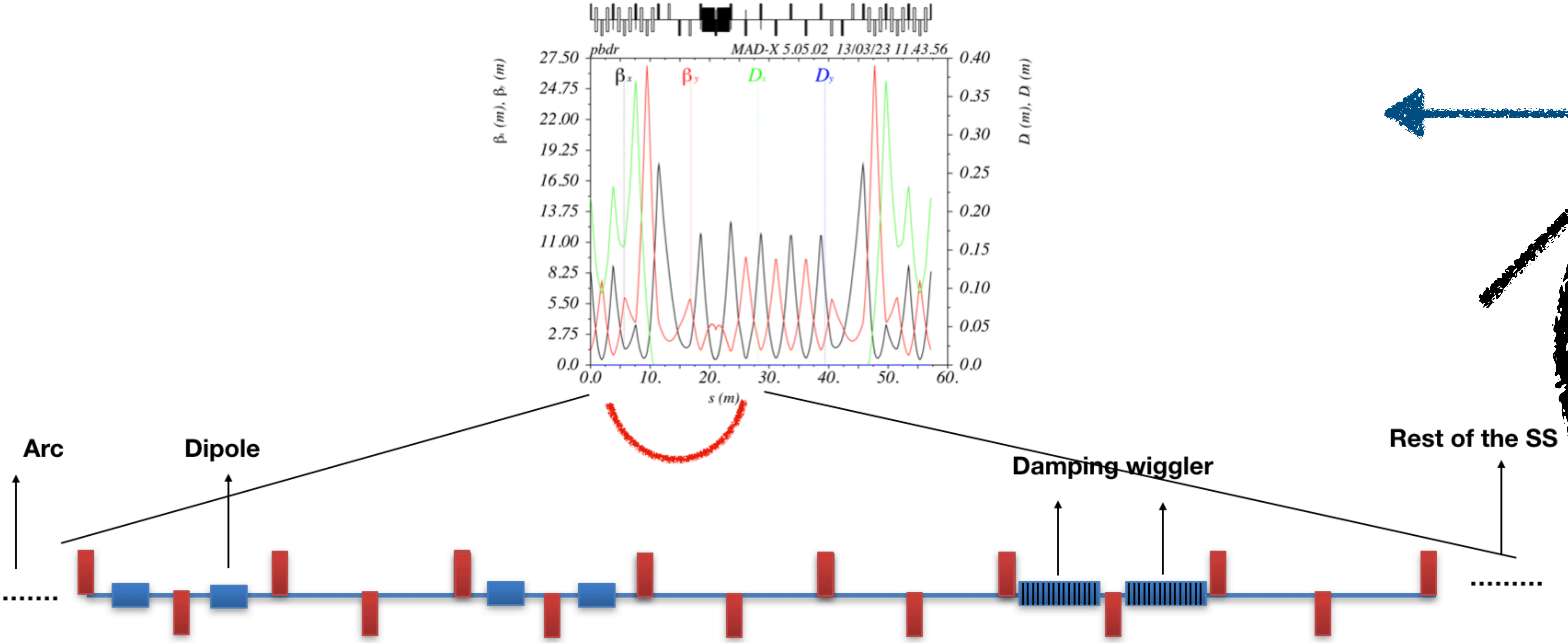
Option 2 -DR with SC DW (Without RW)

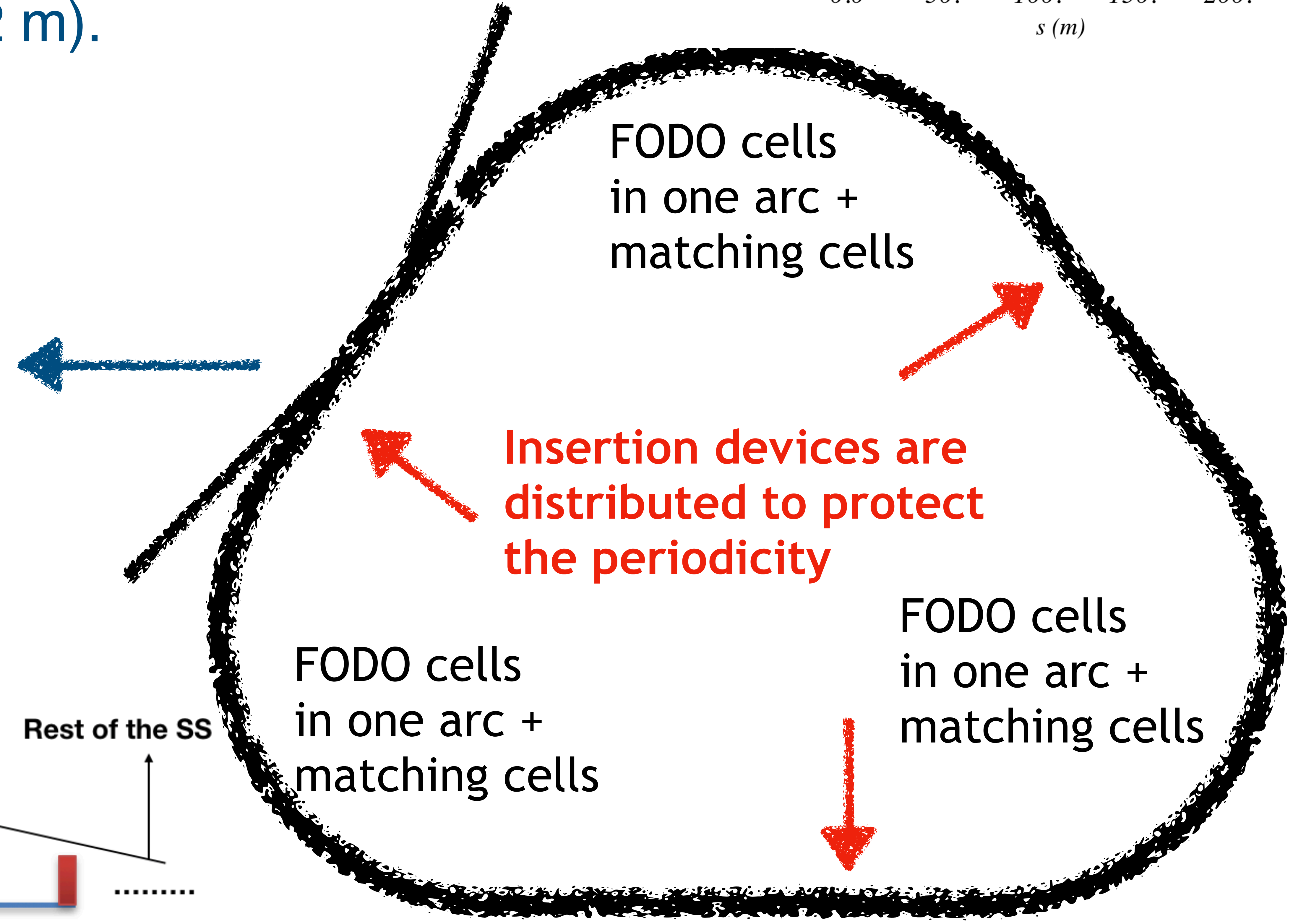


- Based on analytical and numerical calculations, a new layout are provided for the DR.
- The design of the DR composes of 3 arcs and 3 straight sections.
- Arcs consist of 11 FODO cells and each of the straight sections have 5 FODO cells

Straight Section (SS) area with 5 cell;

- 2 damping wiggler are allocated (each of them is around 2 m).





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Option 2 -DR with SC DW (Without RW)

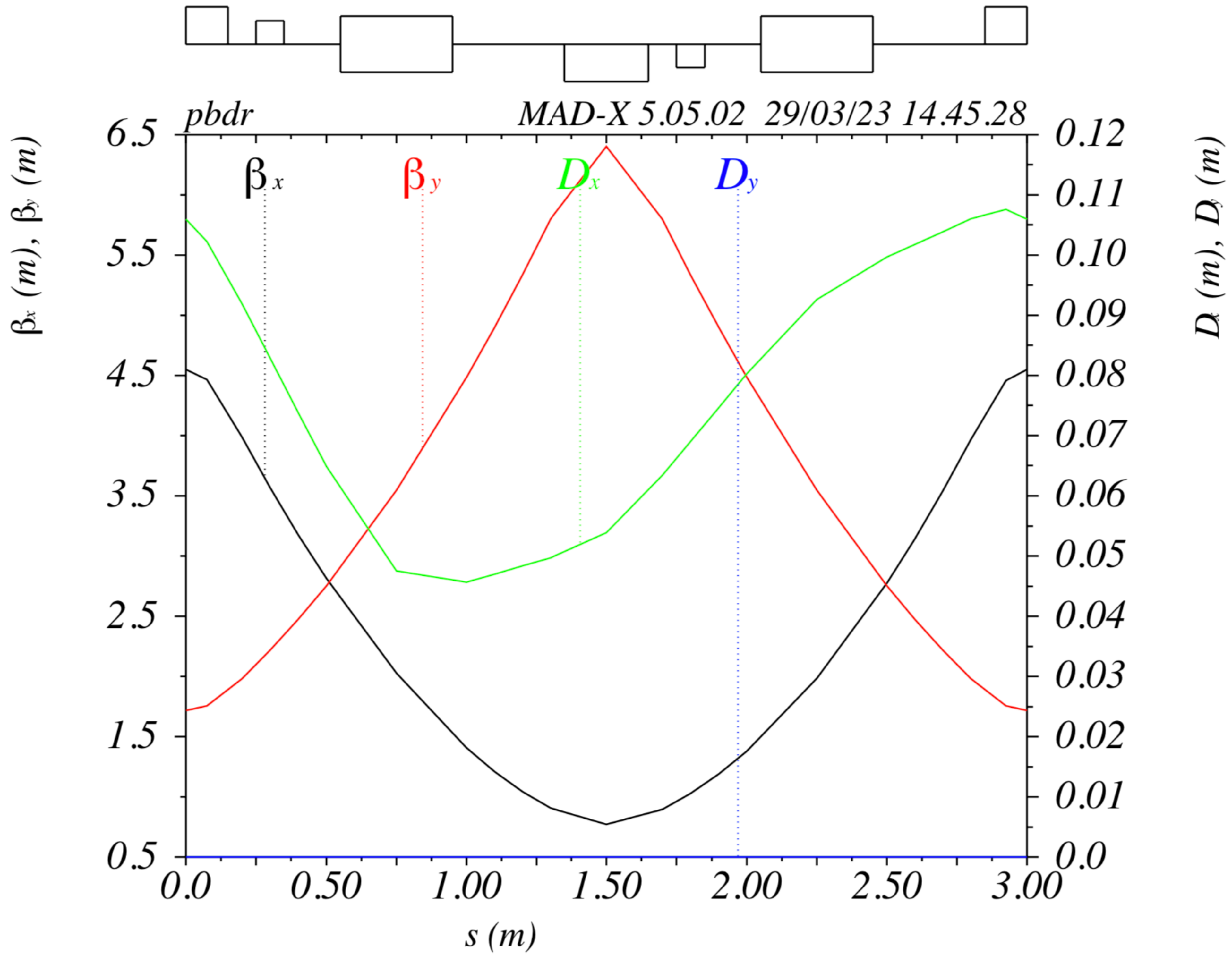
Parameters	CDR	After CDR	New (option - 0)	New (option - 1)	New (option - 2)
Bending magnet quantity	232	212	**72**	84	84
Dipole magnet length [m]	0.21	0.21	**0.28**	0.3	0.4
Bending angle [degree]	1.55	1.55	**5**	4.28	4.28
Dipole magnetic field [T]	0.66	0.66	**1.8**	1.27	1.27
Filling factor	0.2	0.19	**0.07**	0.09	0.12
Damping wiggler magnet	26.5 m / 1.8 T	**68 m / 1.8 T**	**18 m / 2 T**	18 m / 1.8 T	**12 m / 4 .4 T**
Robinson wiggler magnet	-	-	**3.8 m / 1.1 T**	3.8 m / 1.8 T	-
Circumference	242 m	240 m	**257.31 m**	280.23 m	262.92 m
Emittance	2 nm.rad	2.76 nm.rad	**4.89 nm.rad**	**2.12 nm.rad**	**2.06 nm.rad**
Damping time	**10.5 ms**	5.9 ms	**6 ms**	**5.7 ms**	**6.1 ms**
Energy loss per turn	0.255 MeV	0.47 MeV	**0.253 MeV**	0.23 MeV	0.439 MeV

It provides all the required parameters; however,
We continued our study to find an option without superconducting magnet

We have continued to investigate if we can find another solution without SC wiggler and RW.

Option 3: reversed bend magnet

- Reversed bend magnet FODO cell: one of the bends in the ordinary FODO is reversed in its bend direction while preserving the bend radius.

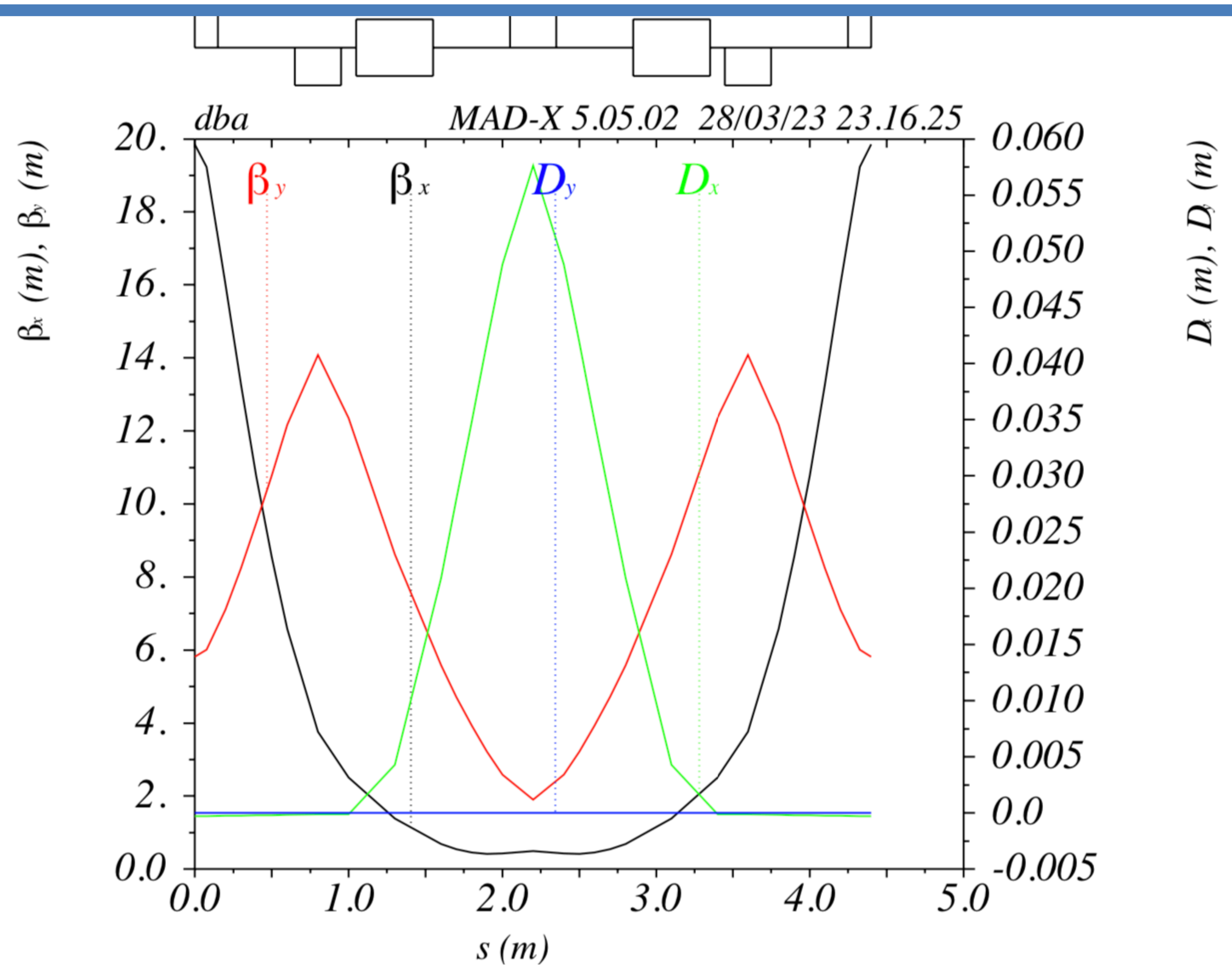


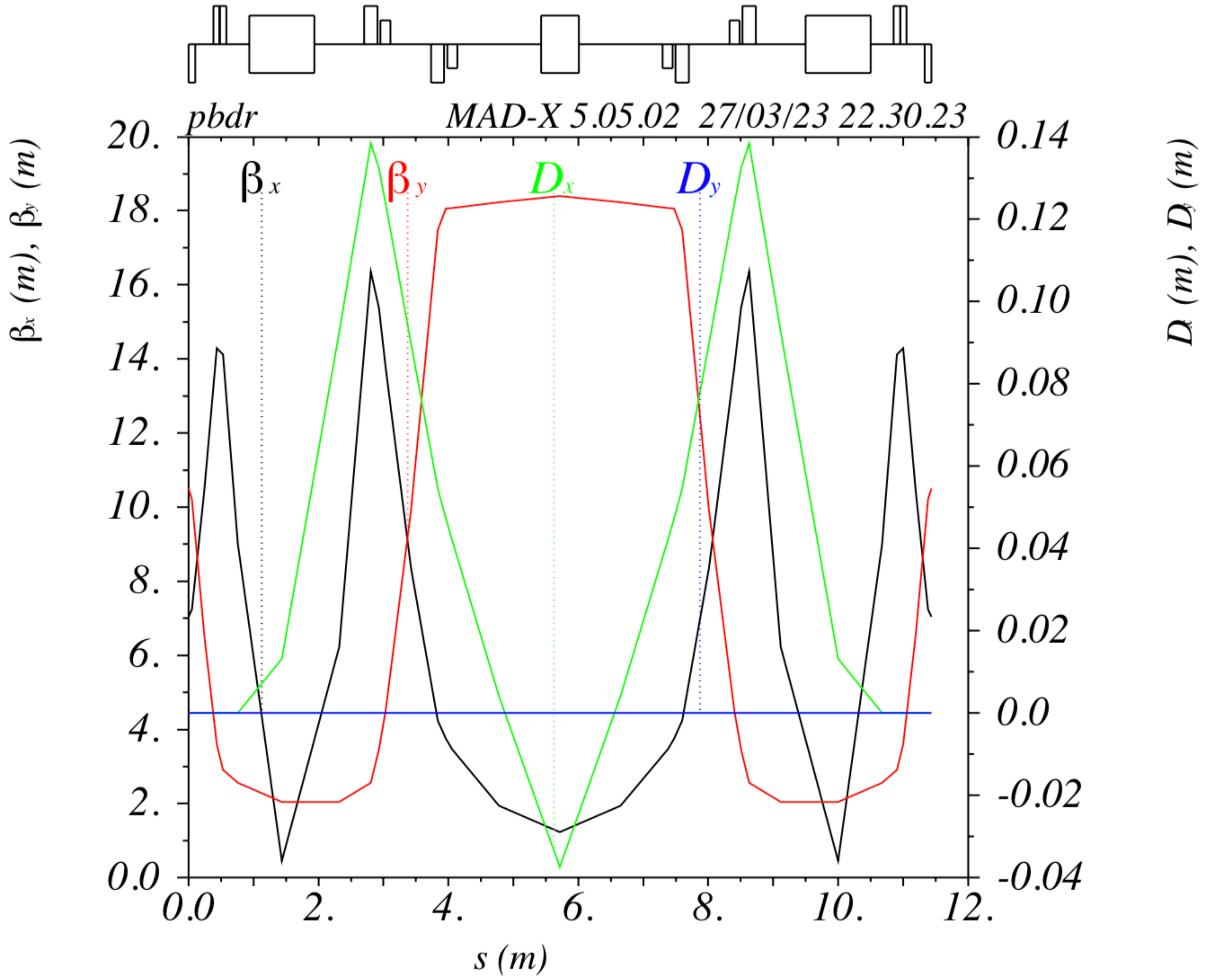
Theta1 / Theta 2	10 / 0	10 / -1	10 / -2	10 / -3	10 / -4	10 / -5	10 / -6	10 / -7	10 / -8	10 / -9
r	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Emittance (nm.rad)	12.7	10.99	9.73	9.08	9.07	9.65	10.74	12.28	14.19	16.45
Damping time (ms)	7.06	6.95	6.70	6.35	5.92	5.46	4.99	4.53	4.09	3.69
Energy loss/turn (MeV)	0.0048	0.0048	0.0050	0.0052	0.0055	0.0060	0.0065	0.0071	0.0079	0.0087
Energy spread (%)	0.077	0.076	0.076	0.075	0.074	0.074	0.074	0.074	0.075	0.076

Theta1 - Theta 2	5 / 5	4.5 / 4.5	4 / 4	3.5 / 3.5	3 / 3	2.5 / 2.5
r	0	0	0	0	0	0
Emittance (nm.rad)	7.10	5.16	3.16	2.41	1.51	0.87
Damping time (ms)	13.93	17.12	21.59	28.10	38.14	54.78
Energy loss/turn (MeV)	0.0024	0.0019	0.0015	0.0011	0.0008	0.0006
Energy spread (%)	54	52	49	45	42	38

So, after a quick check, we understood that the reverse bend lattice could be used to reduce the damping time well, but it is not very correct for the emittance. As a result, if we use reverse bend, we need to use insertion devices like we did for FODO.

Option 4 and 5: DBA and TBA



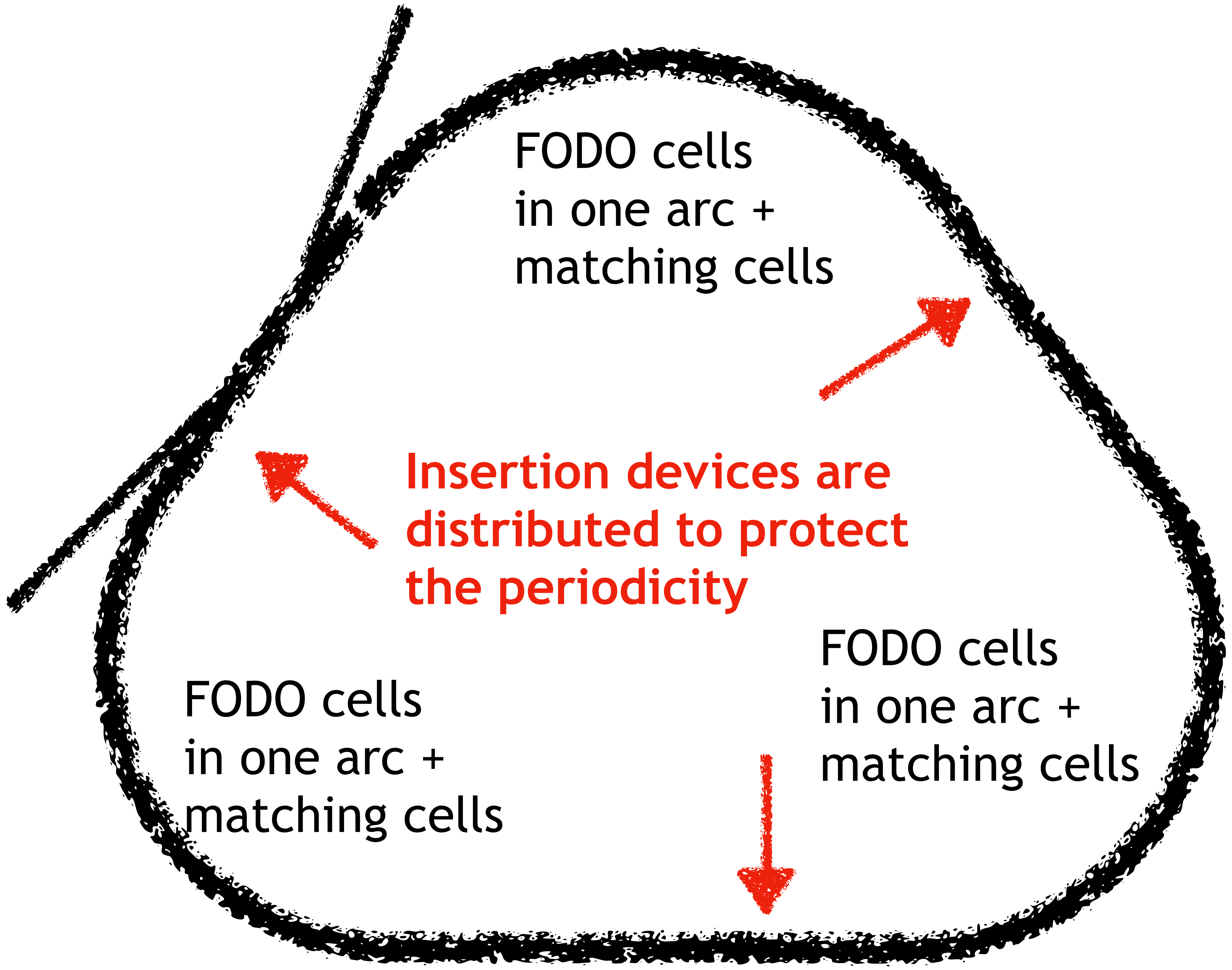


Parameters	FCC-DR
Energy [GeV]	1.54 GeV
Lattice type	DBA
Lattice length [m]	4.4
Bending angle [degree]	4
Emittance [nm.rad]	1.25 nm.rad
Damping time [ms]	29.2
Energy loss per turn	1.54 MeV
Energy spread [%]	0.04

Parameters	FCC-DR
Energy [GeV]	1.54 GeV
Lattice type	TBA
Lattice length [m]	11.4
Bending angle [degree]	6
Emittance [nm.rad]	1.63
Damping time [ms]	36.19
Energy loss per turn [MeV]	3.2
Energy spread [%]	0.05

Option 6: FODO again

- Based on analytical and numerical calculations, a new layout are provided for the DR.
- The design of the DR composes of 3 arcs and 3 straight sections.
- Arcs consist of 9 FODO cells and each of the straight sections have 5 FODO cells



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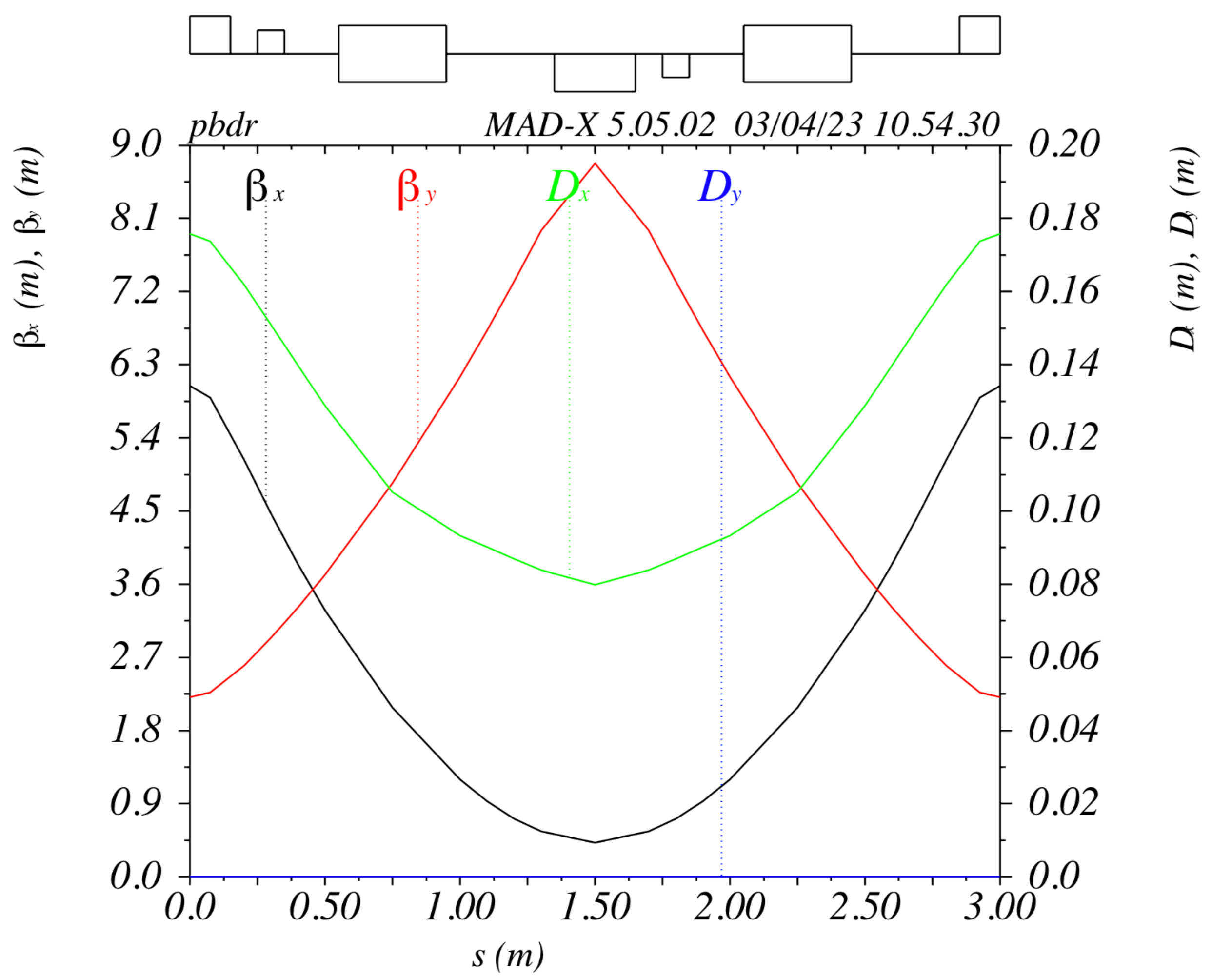
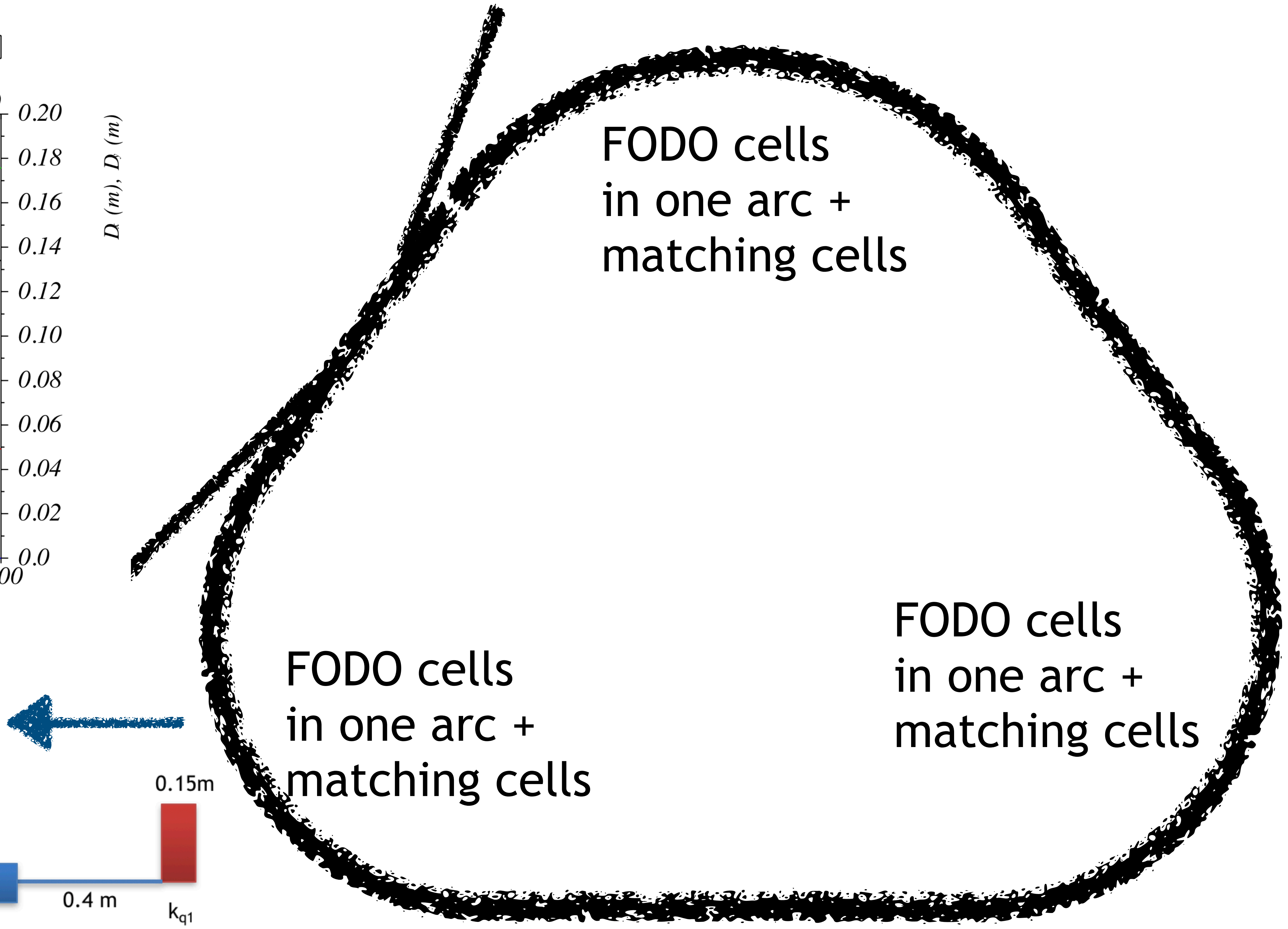
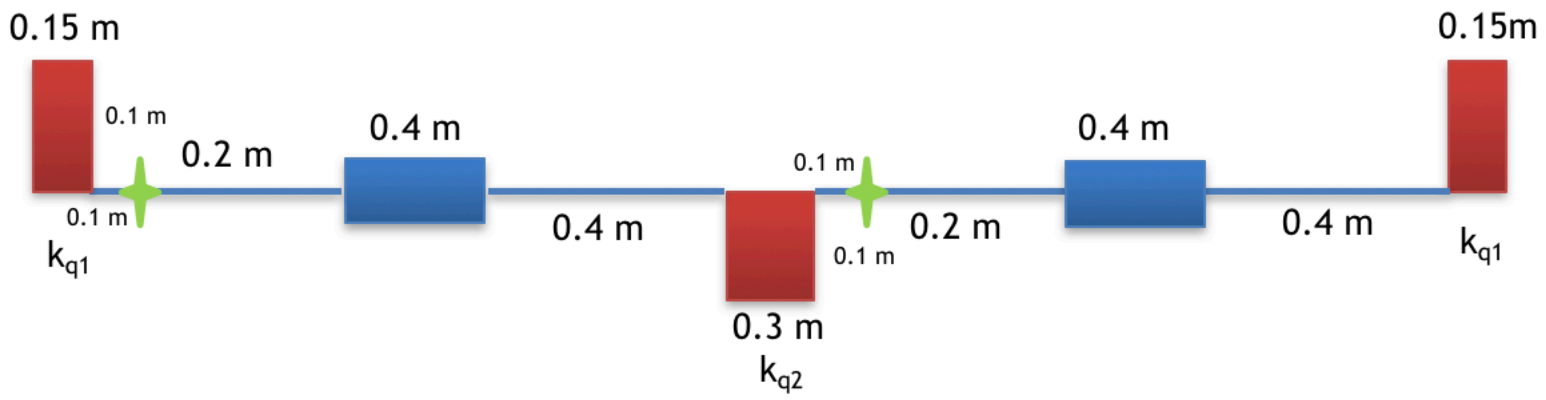




Arc cell



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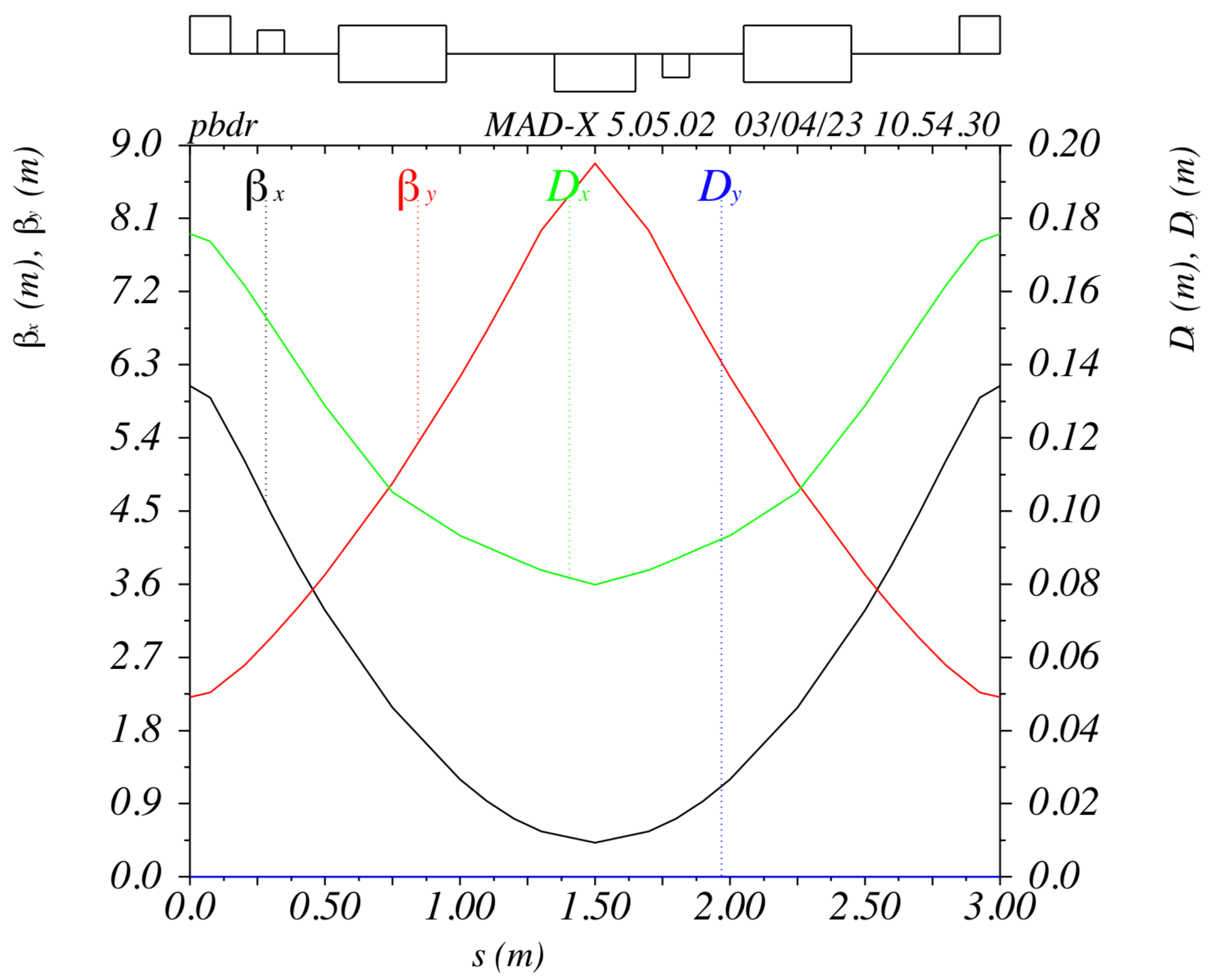
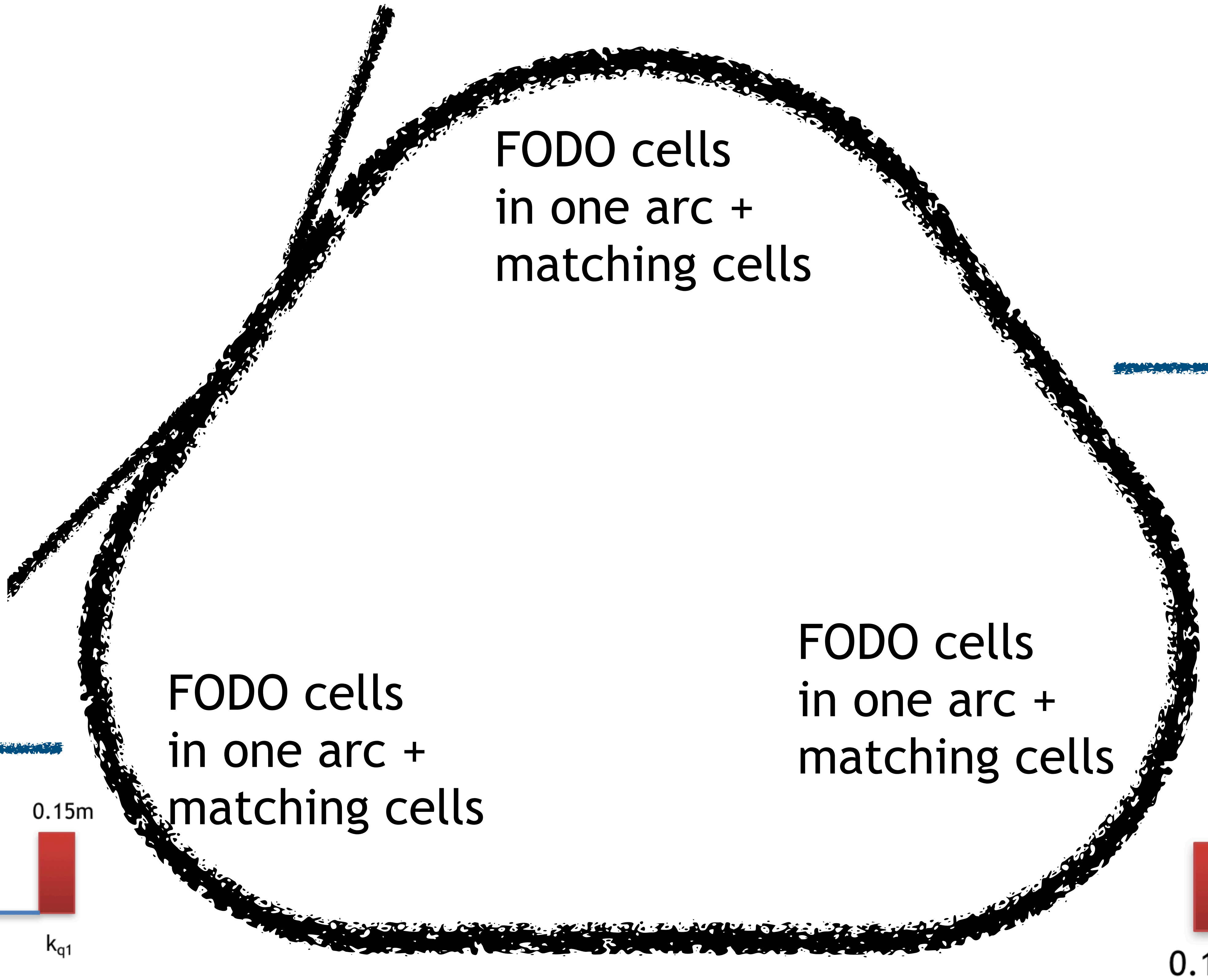
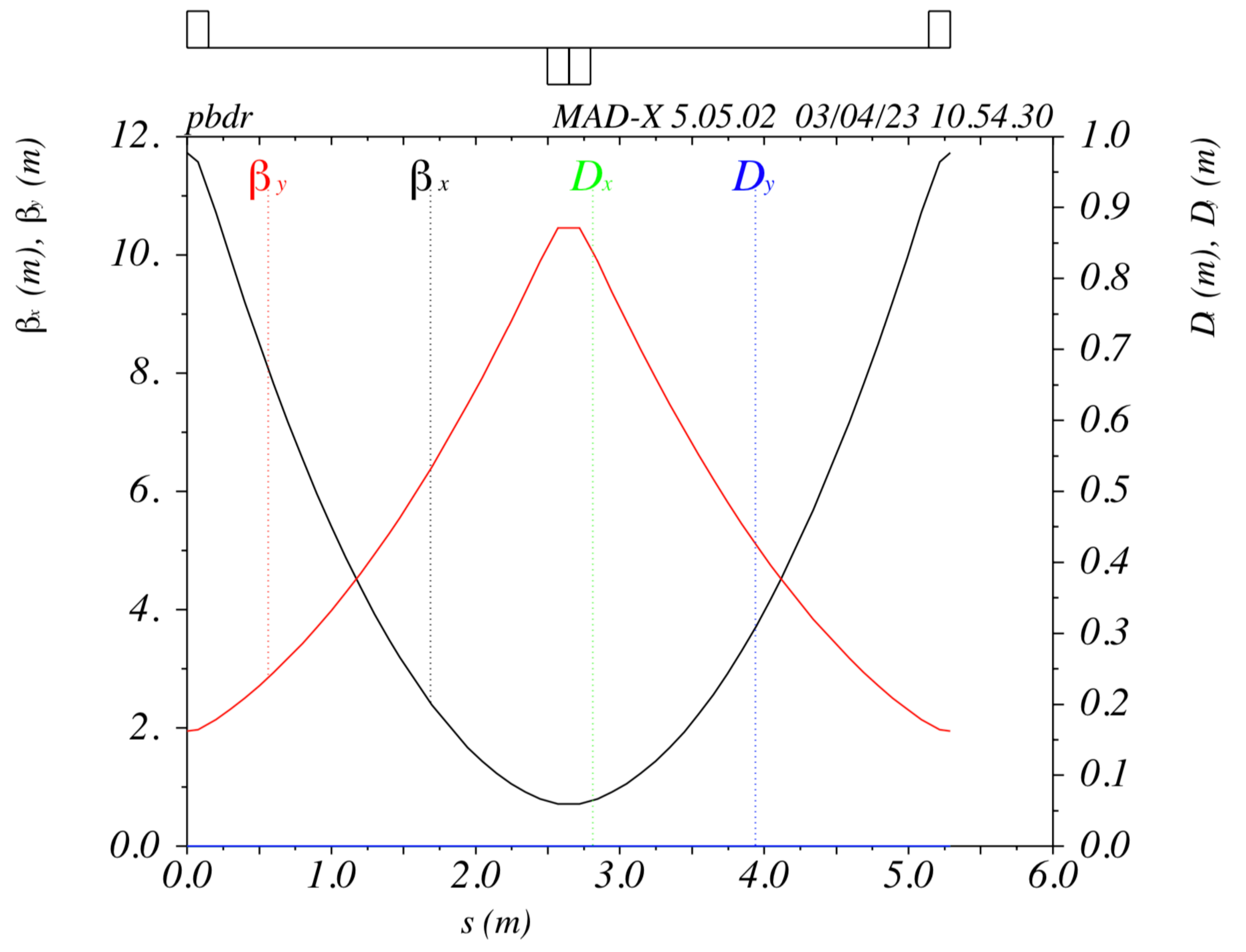
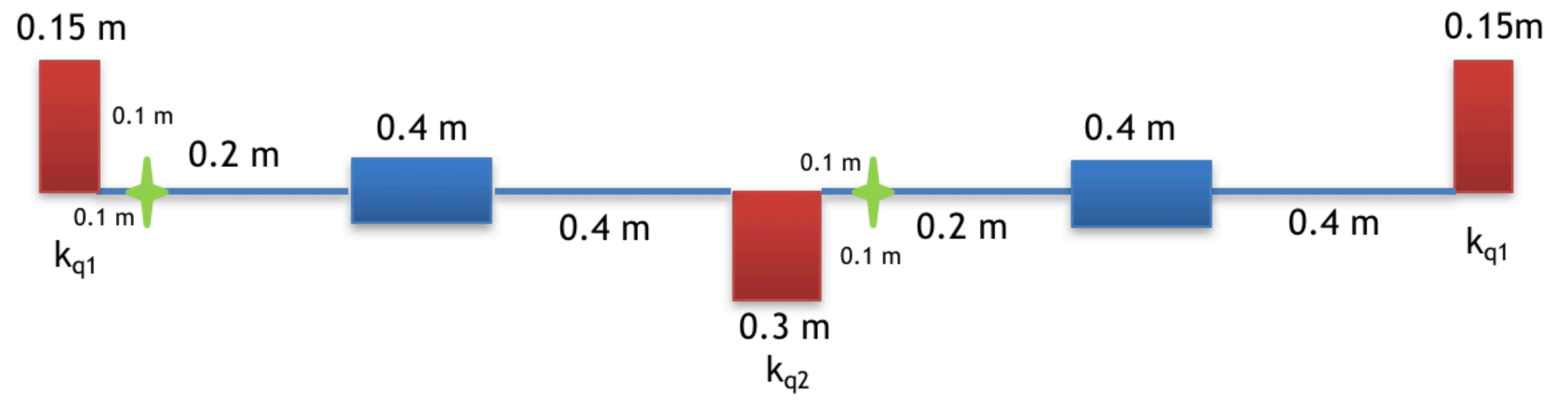
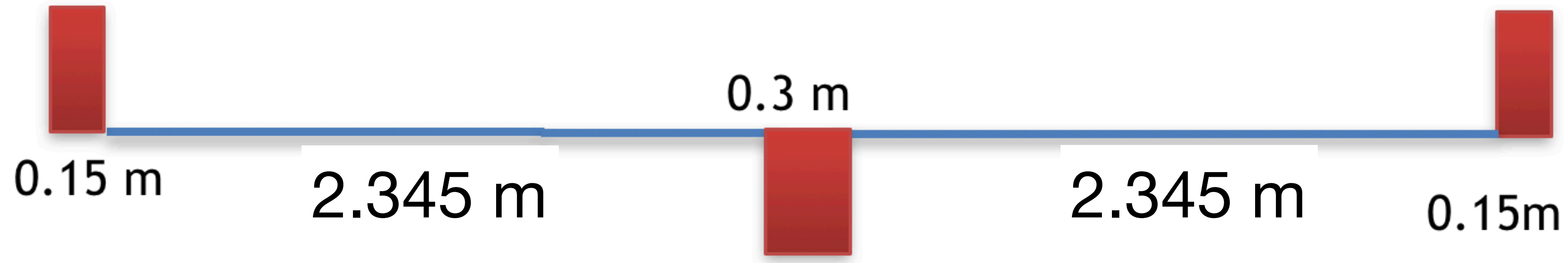






Arc cell

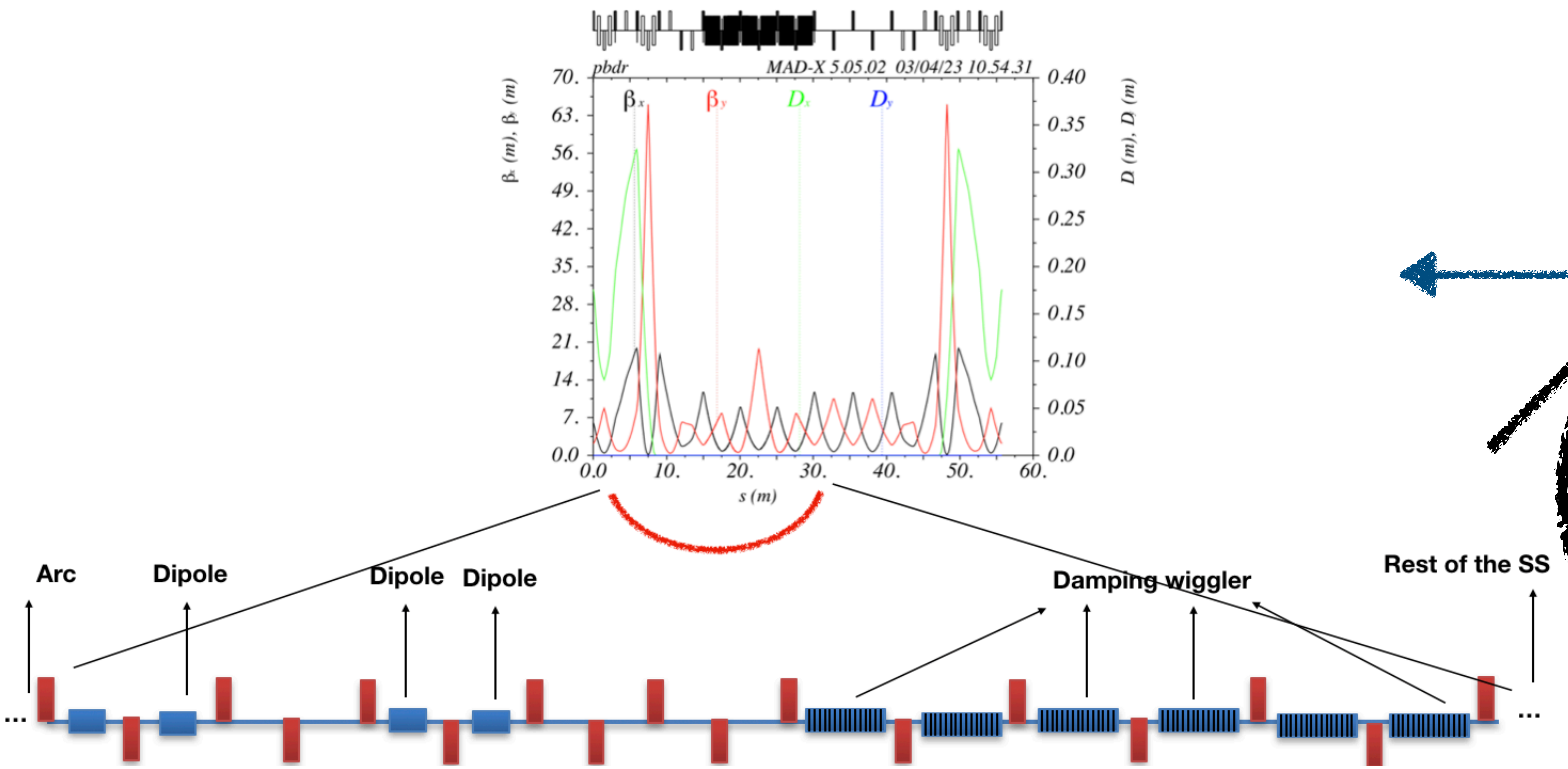


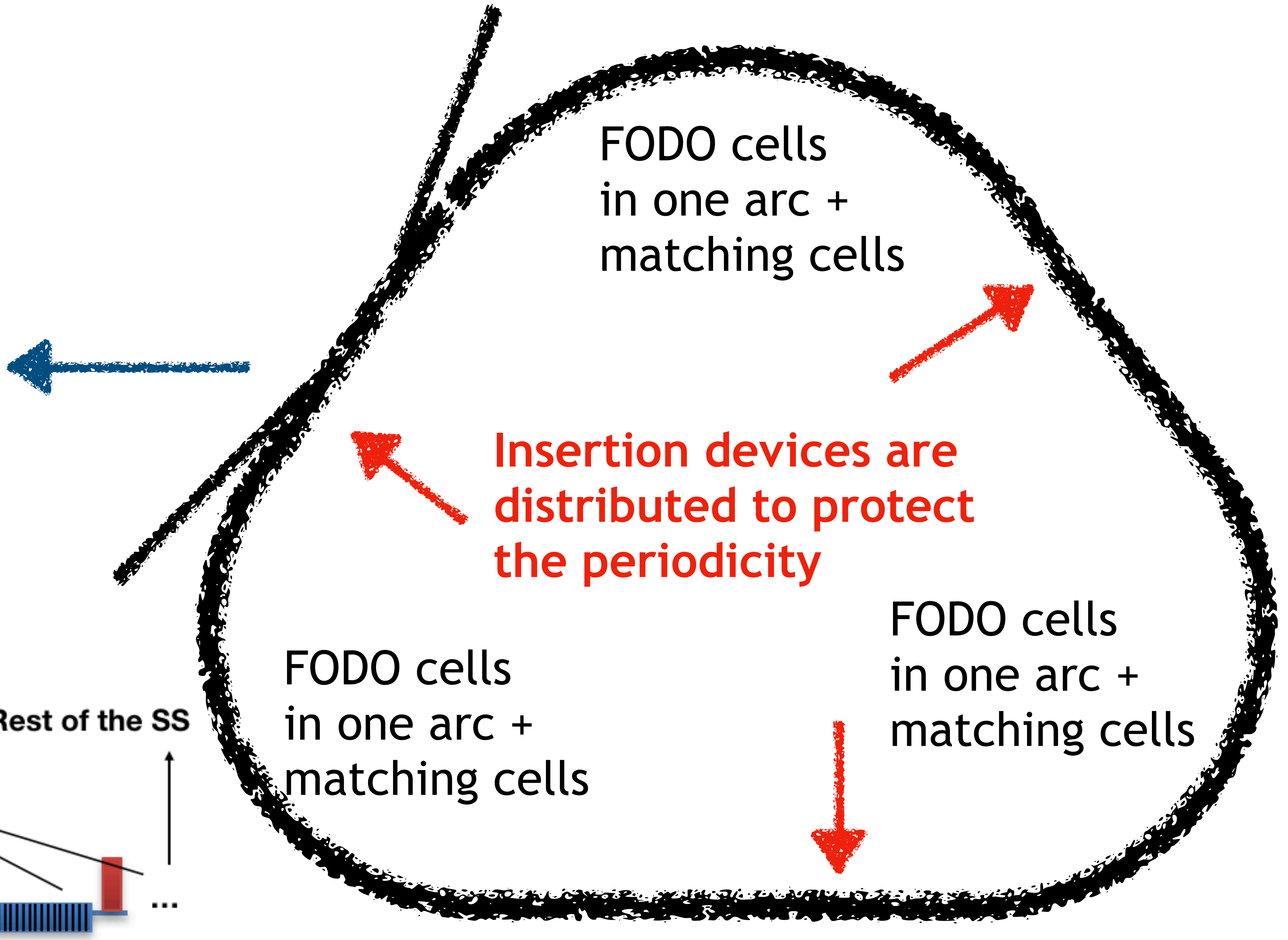


Option 6: FODO again

Straight Section (SS) area with 5 cell;
- **3 cells include damping wiggler (each of them is around 2 m).**

Straight Section (SS) area + matching area as also showing

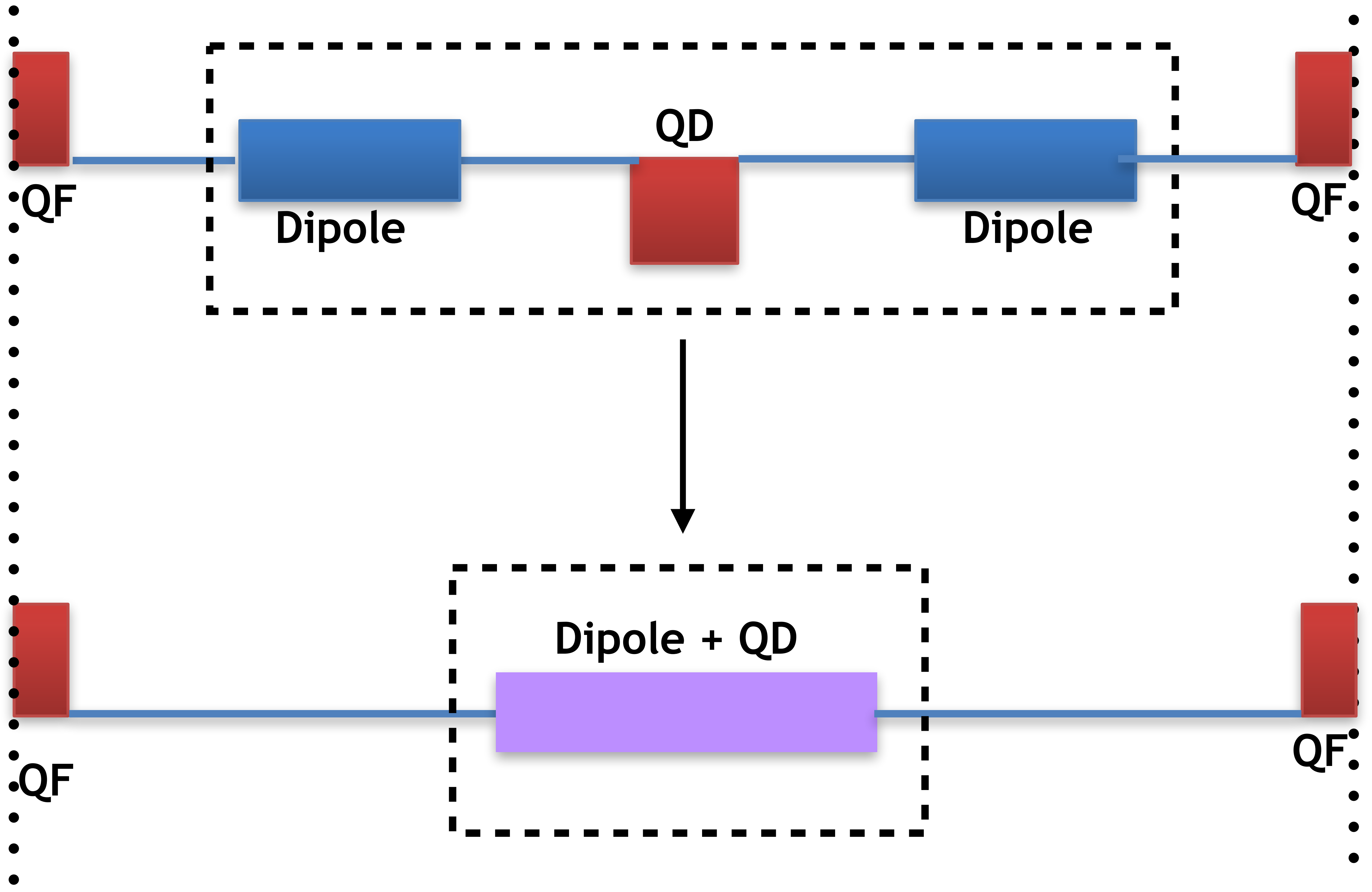


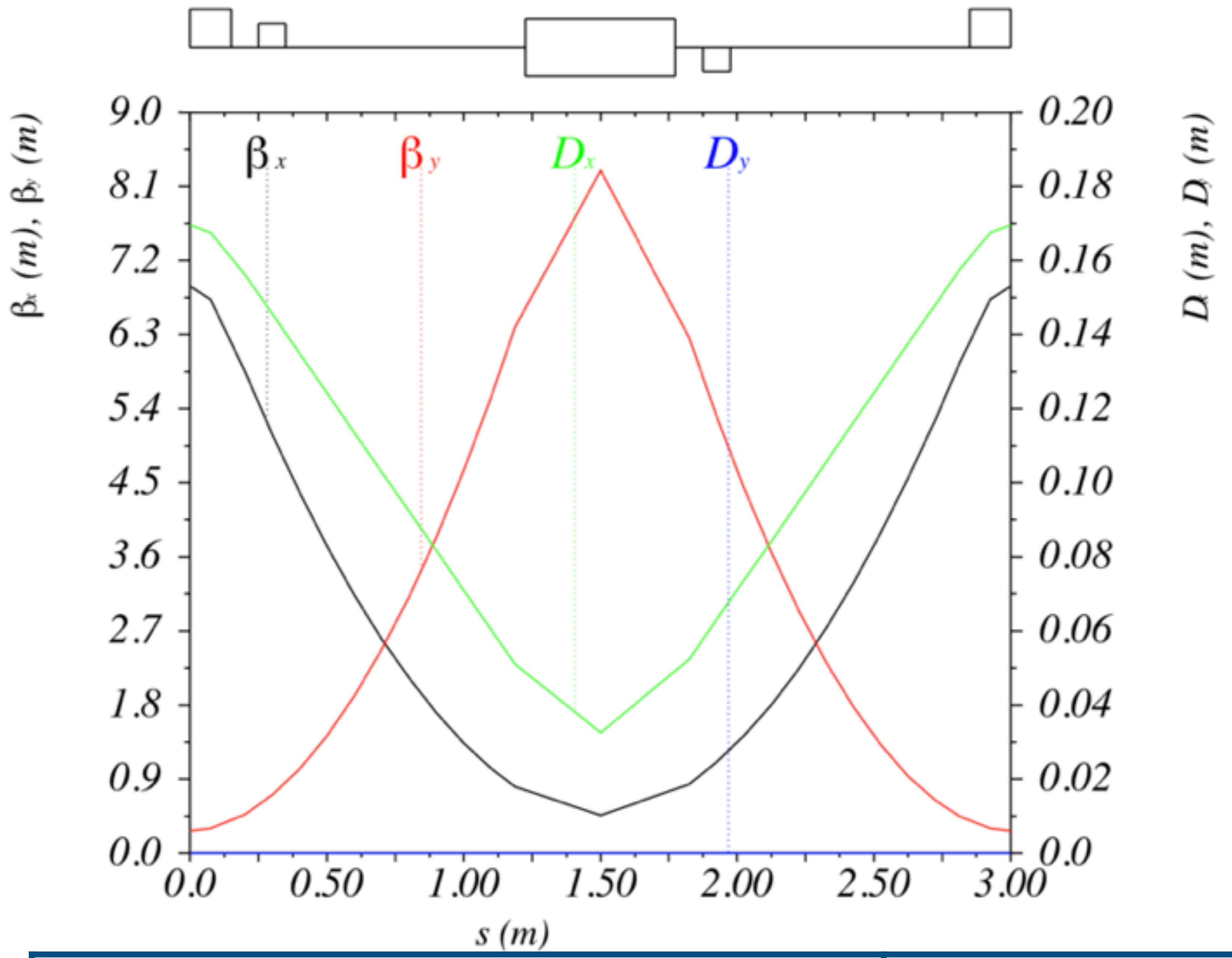


Mid - Summary

Parameters	CDR	After CDR	Option - 0	Option - 1	Option - 2	Option - 6
Bending magnet quantity	232	212	72	84	84	78
Dipole magnet length [m]	0.21	0.21	0.28	0.3	0.4	0.4
Bending angle [degree]	1.55	1.55	5	4.28	4.28	4.61
Dipole magnetic field [T]	0.66	0.66	1.8	1.27	1.27	1.03
Filling factor	0.2	0.19	0.07	0.09	0.12	0.15
Damping wiggler magnet	26.5 m / 1.8 T	68 m / 1.8 T	18 m / 2 T	18 m / 1.8 T	12 m / 4 .4 T	36.45 m / 2 T
Robinson wiggler magnet	-	-	3.8 m / 1.1 T	3.8 m / 1.8 T	-	-
Circumference	242 m	240 m	257.31 m	280.23 m	262.92 m	248.19 m
Emittance	2 nm.rad	2.76 nm.rad	4.89 nm.rad	**2.12 nm.rad**	2.06 nm.rad	**2.1 nm.rad**
Damping time	10.5 ms	5.9 ms	6 ms	**5.7 ms**	6.1 ms	**8.1 s**
Energy loss per turn	0.255 MeV	0.47 MeV	0.253 MeV	0.23 MeV	0.439 MeV	0.31 MeV

Option 7: Combined function magnet





- After our first check, it seems that it become possible to reach to the required parameters with less magnets with this option. But, we have not checked the full ring yet.

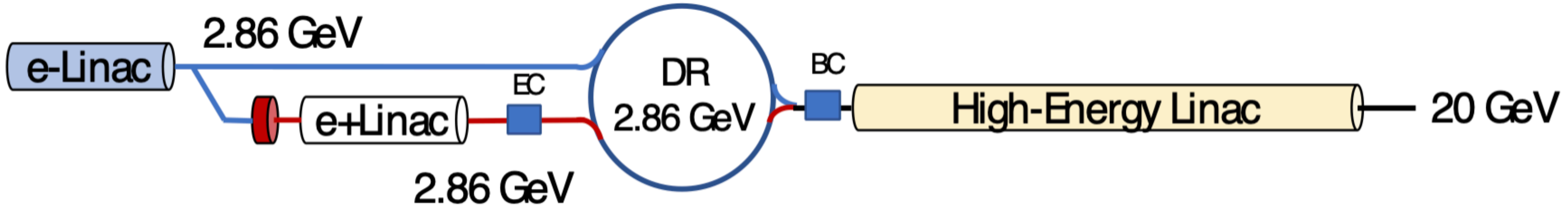
Parameters	FCC-DR
Energy [GeV]	1.54 GeV
Lattice type	CF
Lattice length [m]	3
Bending angle [degree]	9
Emittance [nm.rad]	1.93
Damping time [ms]	4.6
Energy loss per turn [MeV]	3.7
Energy spread [%]	0.09
Damping partition (D)	-0.75
Magnetic field of the dipole magnets [T]	1.5

Higher energy damping ring discussion

PAUL SCHERRER INSTITUT PSI

Injector layout with DR at higher energy

FUTURE CIRCULAR COLLIDER

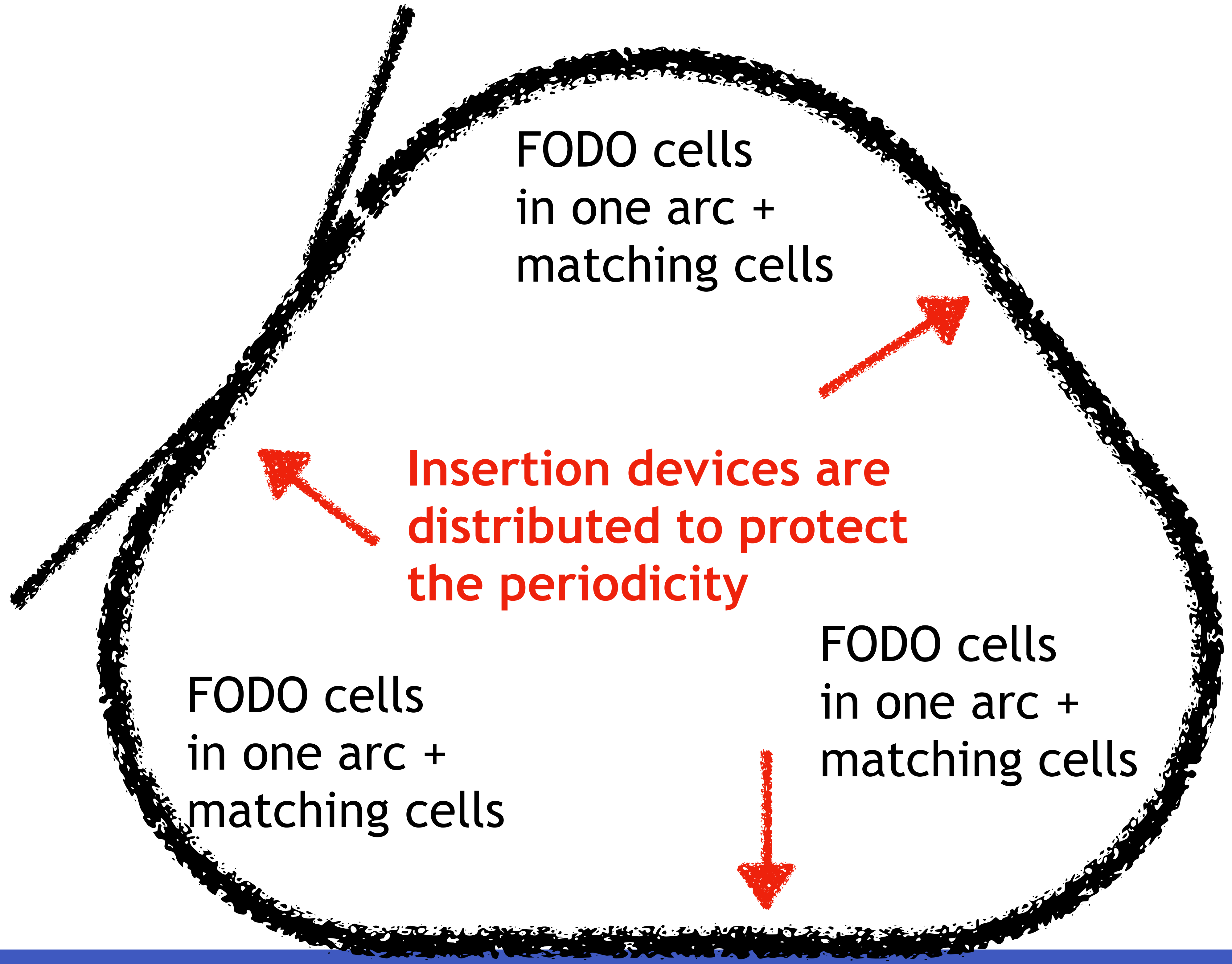


- The high positron yield would allow positrons to be generated at a lower electron beam energy 2.42, 2.86 or 3.30 GeV
- The large increasing of the yield (comparison to KEK) is largely due to larger aperture of the RF cavities and larger magnetic field provided by the AMD. Basically we “simply” increased the acceptance of the injector/linac system and moved the problem downstream to the damping ring
- Increasing the energy of the damping (lower geometrical emittance) ring and reducing the energy of the drive beam (lower yield at the linac) creates a better balanced system
- Rep rate up to 400 Hz with 2-bunch for RF pulse (as rep rate in common linac) → linac cycle 12.5 s for 2x5000 rf pulses
- Dedicated linac for electron and positron up to 2.42, 2.86, or 3.30 GeV.
- No return arc for positron/electron beams → it is easier to preserve emittance (no trivial issue)
- DR for both electrons and positrons. In principle a higher charge with higher emittance from the photo-injector is possible because can be dumped in DR
- Easier operation of the common linac, seconds instead of milliseconds between e+ and e- operations
- Drawback: DR at higher energy?
  - SLS-2: 2.7 GeV, circumference 288 m, magnetic peak field 1.3 T, angle 3.5 deg

Based on this slide of Paolo, we have also investigated higher energy damping ring.

Option-8: Design study for 2.86 GeV option

- There were discussions for 2.42 GeV, 2.86 GeV and 3.30 GeV,
- We have provided a preliminary design for 2.86 GeV,
- We have also made a quick comparison, since it is the same energy of CLIC damping ring.
- Based on analytical and numerical calculations, a layout are provided for the 2.86 GeV option.
- The design of the DR composes of 3 arcs and 3 straight sections.
- Arcs consist of 16 FODO cells and each of the straight sections have 5 FODO cells



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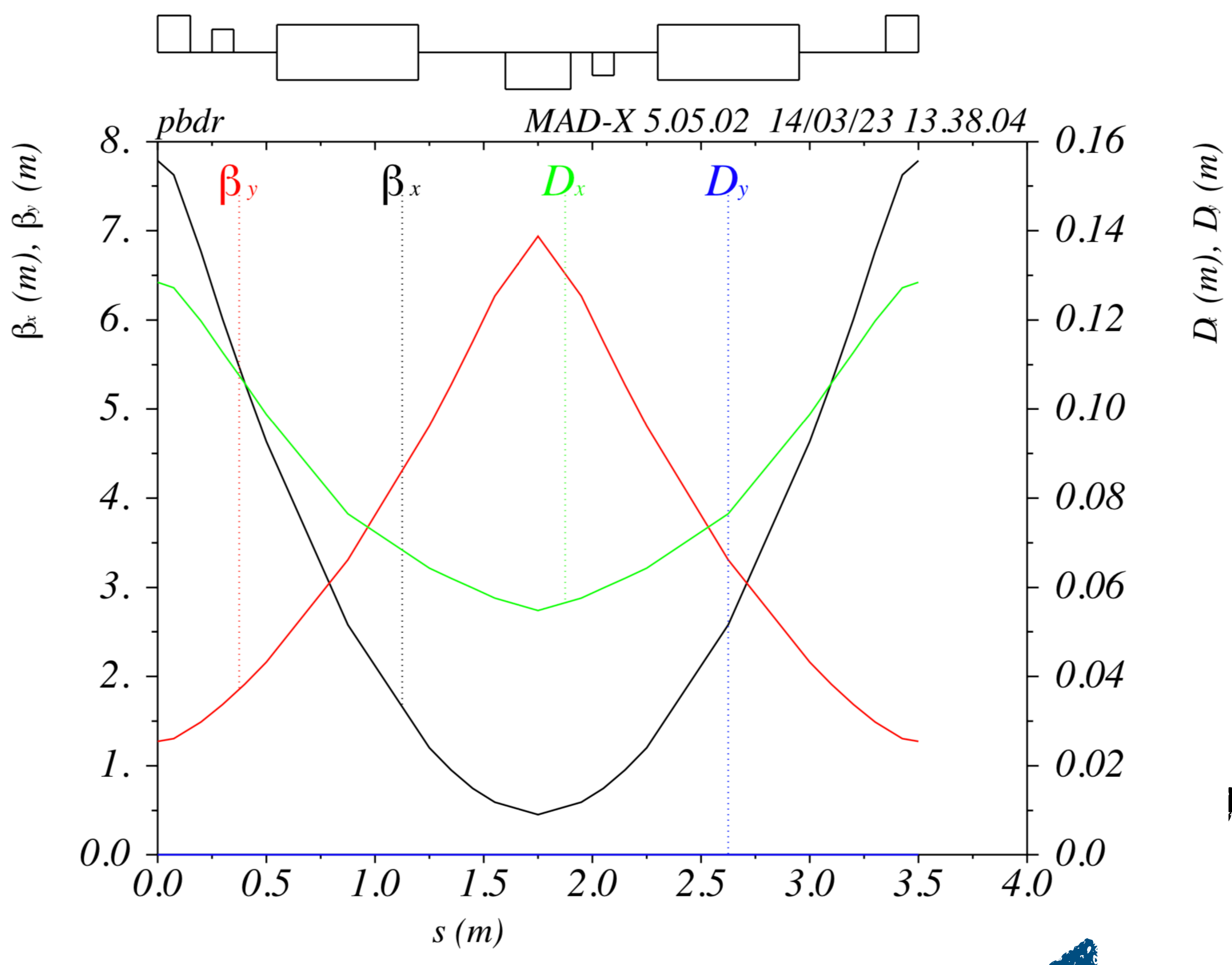
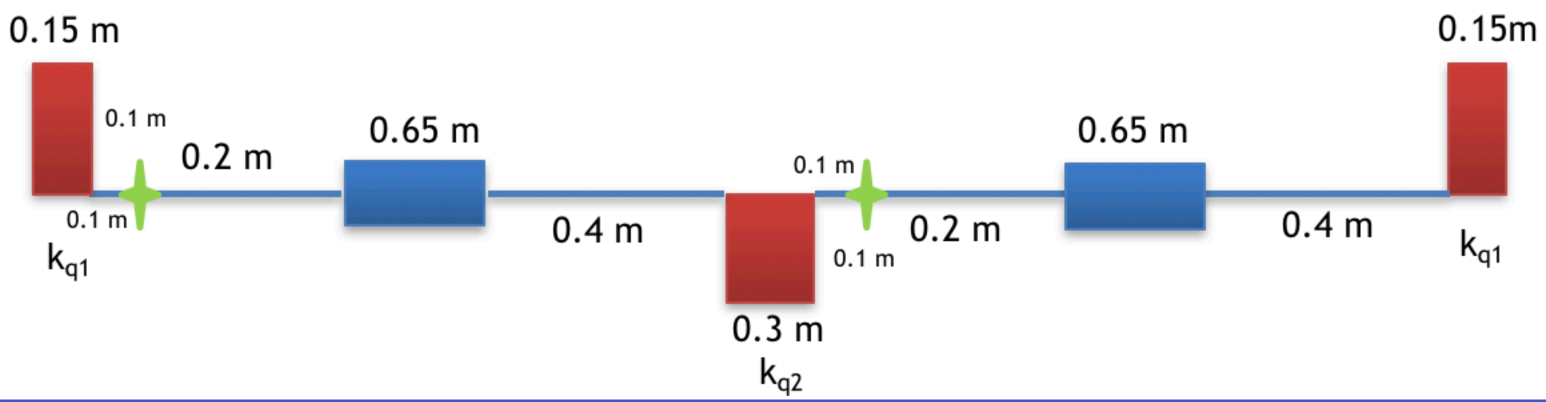
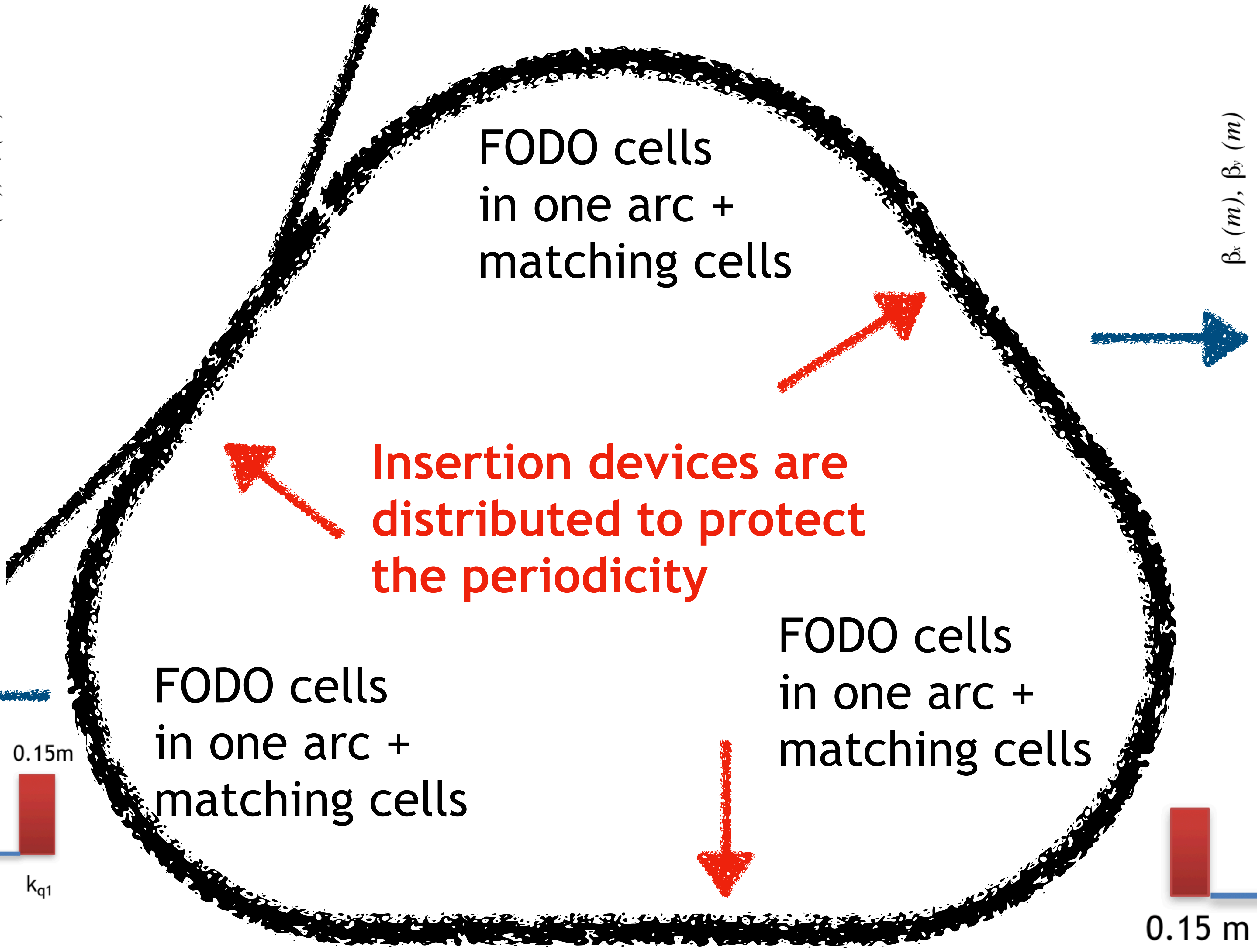
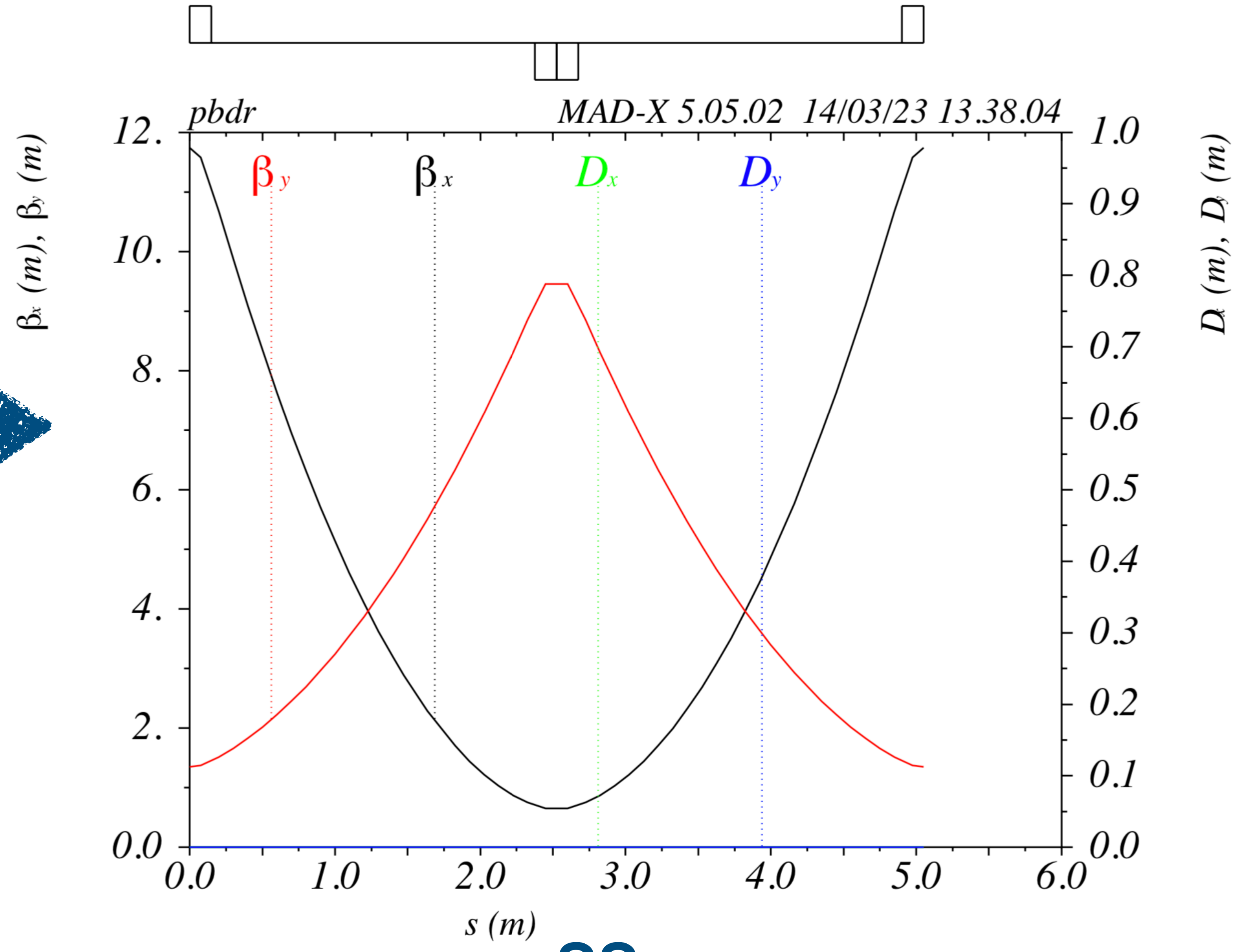


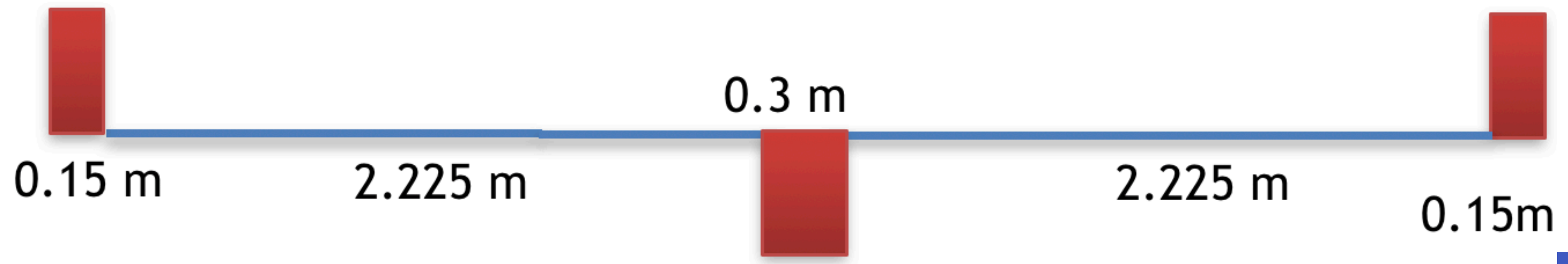
Arc



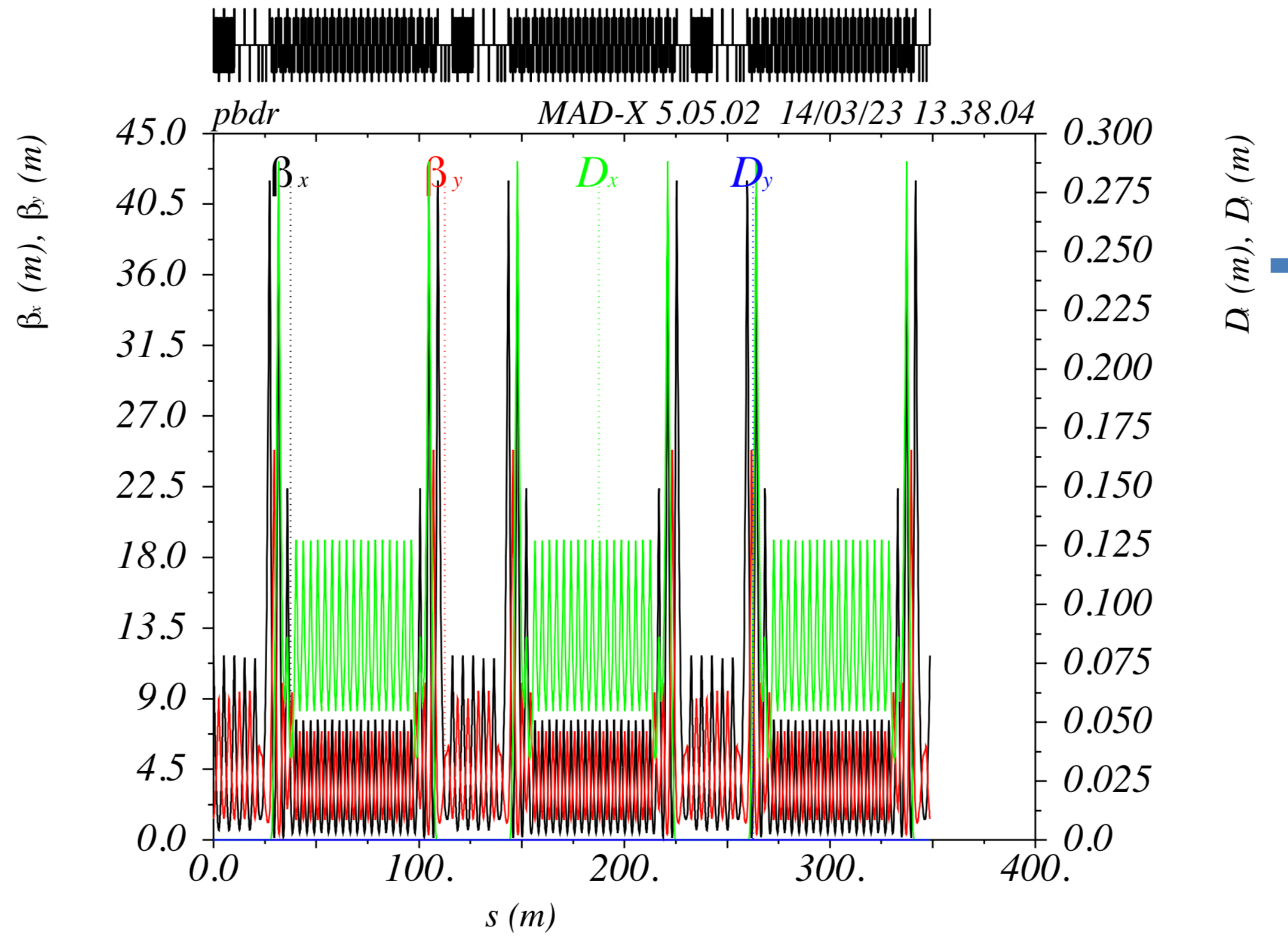




SS

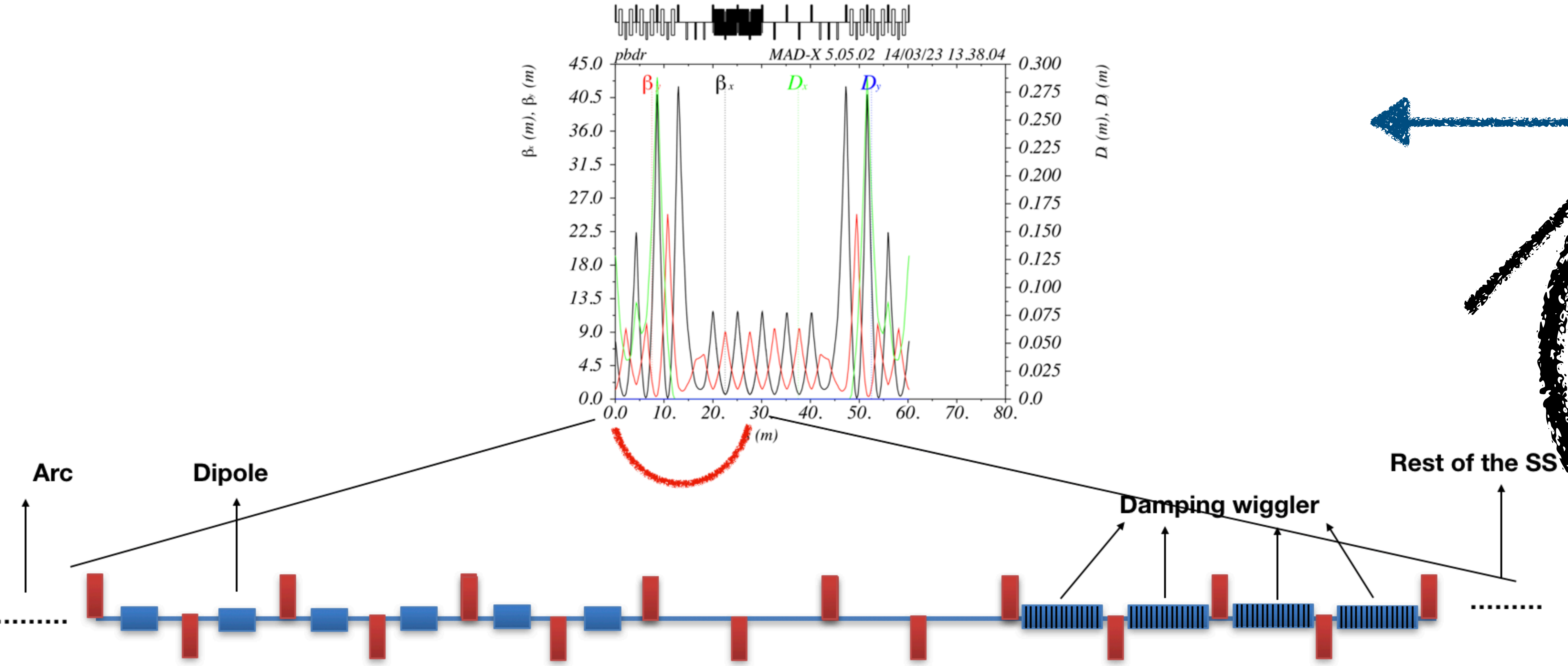


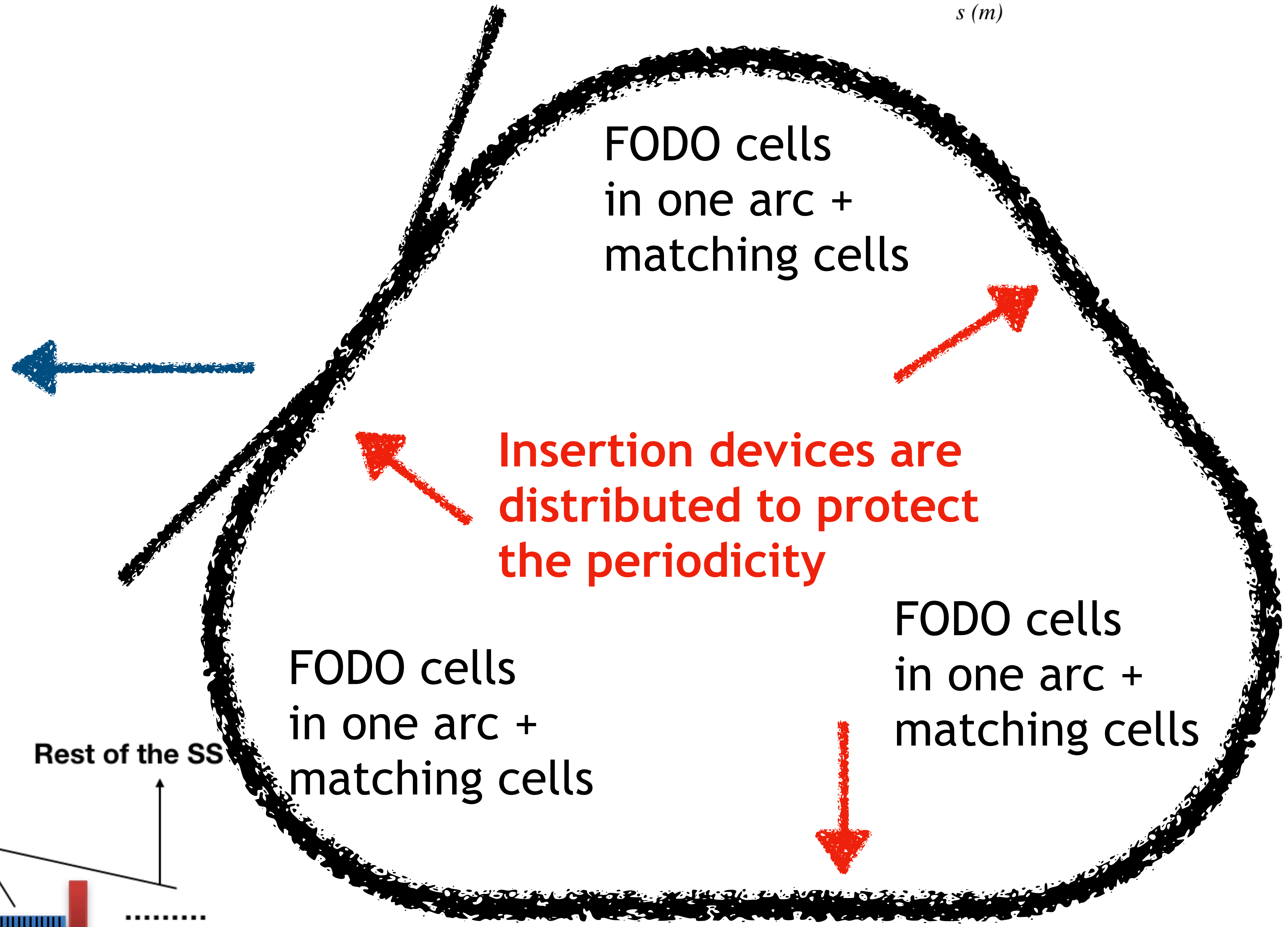
Option-8: Design study for 2.86 GeV



Straight Section (SS) area with 5 cell;

- **4 damping wiggler are allocated (each of them is around 2 m).**





A reminder: CLIC Main Damping Ring (2.86 GeV)

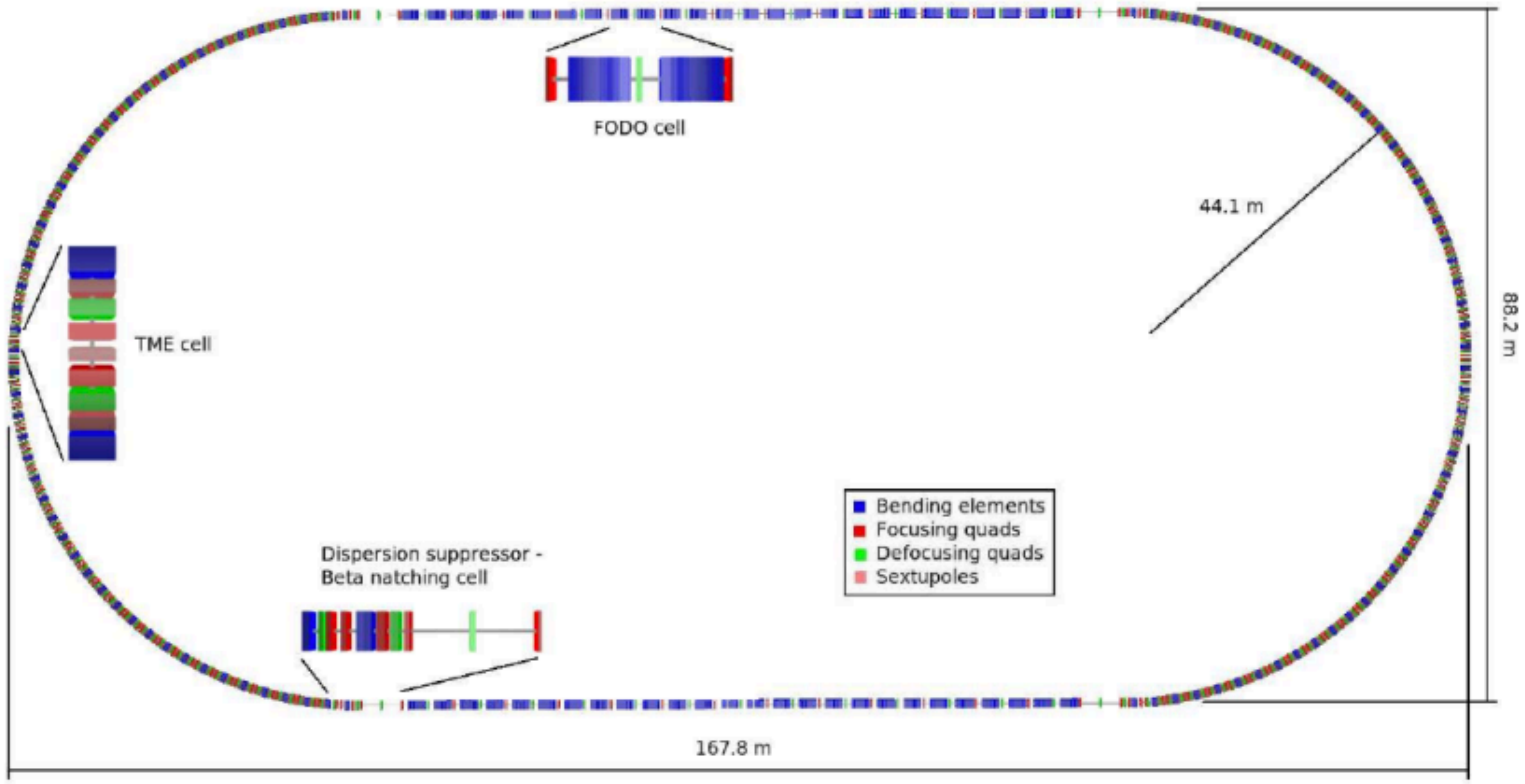


Table 7.3: List of magnetic parameters for the CLIC DRs.

Type	Location	Length [m]	Number	Families	Pole tip field [T]	Full aperture H/V [mm]
Dipoles	Arc DS-BM	0.58	96 4	1	0.97	80/20
Quadrupoles	Arc	0.20	376	2	1.0	20/20
	LSS	0.20	28+26	2		
	DS-BM	0.20	24	12		
	DS-BM	0.31	4	2		
Sextupoles	Arc	0.15	188+94	2	0.5	20/20
Wigglers	LSS	2.00	52	1	2.5	80/13

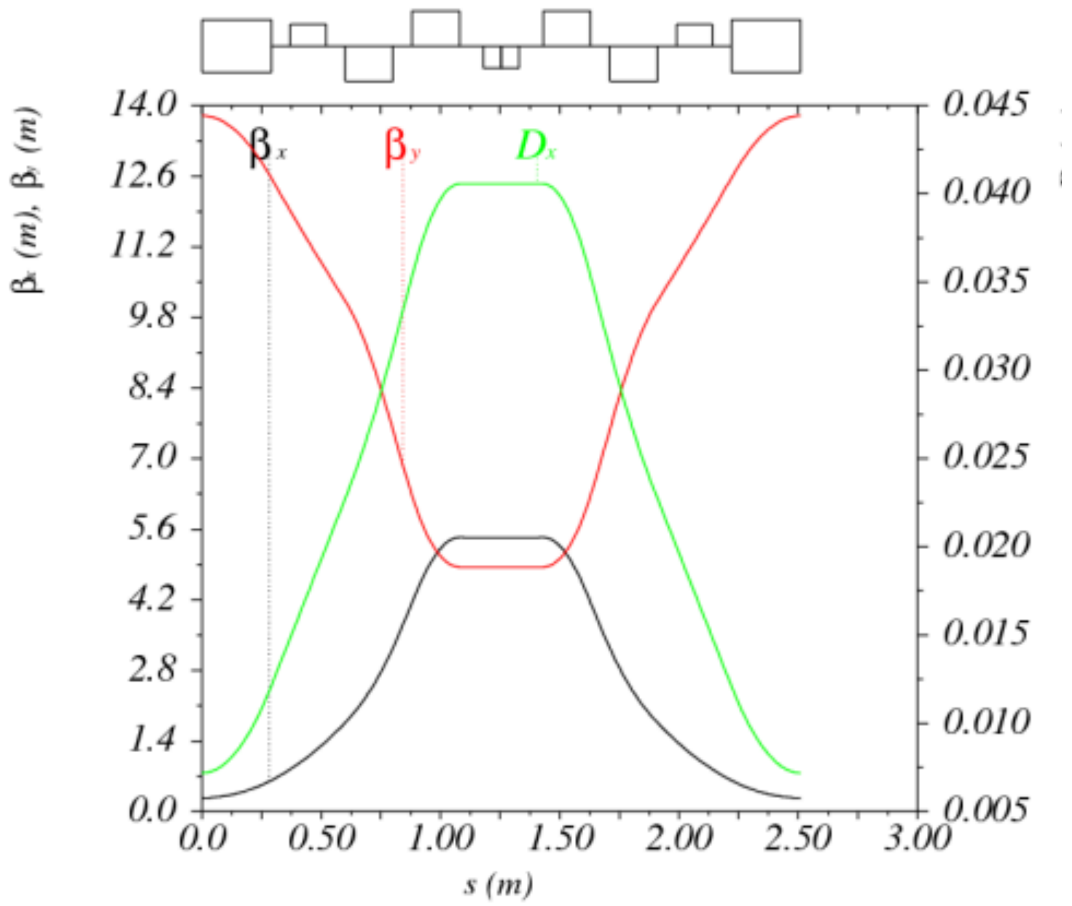
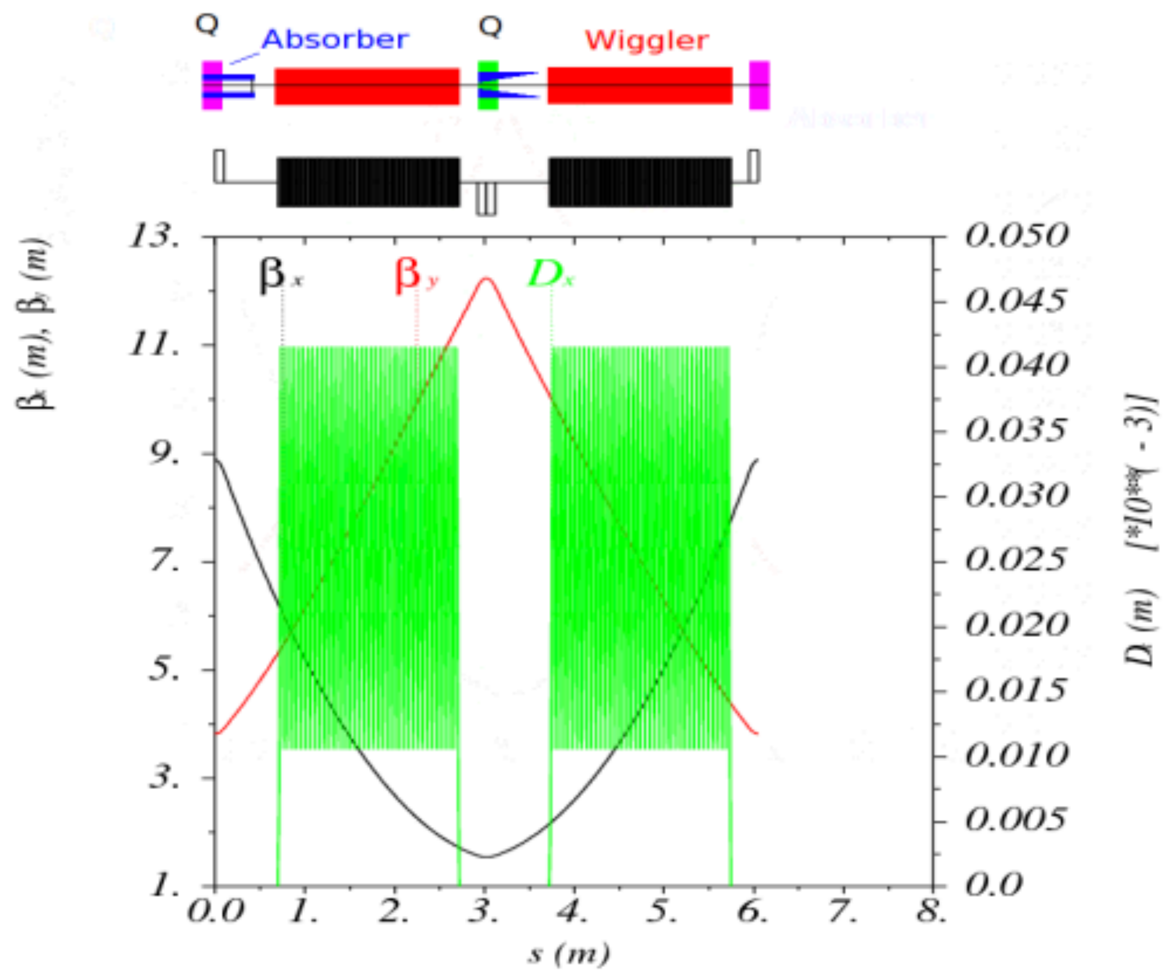


Figure 7.11: Optical functions of the arc TME cell.



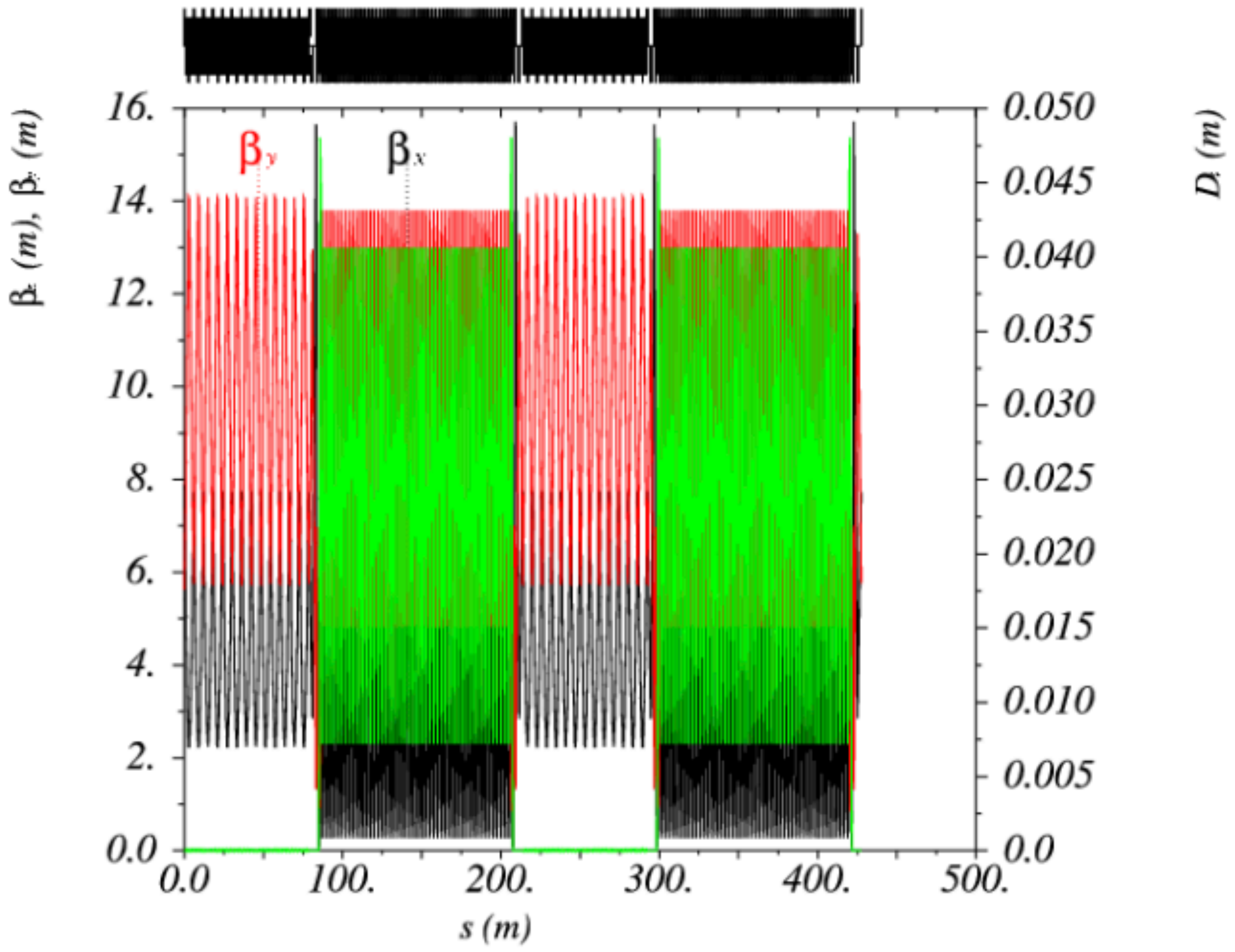


Figure 7.24: The optics functions of the CLIC DR.

Option 7: A Comparison with CLIC DR

- We have also made a quick comparison, since it is the same energy of CLIC damping ring.

Parameters	FCC-DR	CLIC DR
Energy [GeV]	2.86 GeV	2.86 GeV
Bending magnet quantity	132	100
Quadrupole magnet quantity	186	458
Sextupole magnet quantity	96	282
Dipole magnet length [m]	0.65	0.58
Bending angle [degree]	2.72	3.6
Dipole magnetic field [T]	0.94 T	1.03 T
Filling factor	0.24	0.13
Damping wiggler magnet [m/T]	24.3 m / 2 T	104 m / 2.5 T
Robinson wiggler magnet [m / T]	-	-
Circumference [m]	348.72 m	427.5 m
Emittance [nm.rad]	2.15 nm.rad	0.04 nm.rad
Damping time	7.1 ms	2 ms
Energy loss per turn	0.92 MeV	3.98 MeV
Lattice type	FODO	TME

Summary and next steps

- We have been evaluating different options including different type of cell and magnet
- We will still be checking the combined function option in the following days
- One of the options will be determined and the nonlinear beam dynamics study will be started
- We are planning to show only one option with DA calculations in the FCC Week
- We have also checked the higher energy option, it may be worked in detail in future if this becomes the case

Thank you!