# Update related to DR studies of FCCee Injector Complex

*FCCee Injector Design Meeting-19*

*29th of August, 2024*

*Remote Meeting*

**Ozgur ETISKEN (Kirikkale University)**

Thanks to C. Milardi, A. De Santis, S. Spampinati (LNF-INFN)

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# Outline

- Reminder for discussed versions before
- Feedback from FCC Week 2024
- Reminder related to DR parameter requirements
- Latest modification of DR Current design study of the damping ring @ 2.86 GeV
- Phase advance scanning for several parameters for optimization
- Incoming beam at injection section of DR
- Preliminary dynamic aperture calculation for bare lattice
- Discussion and next steps

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# Investigated options for the DR for old layout

- We have worked on alternative options for damping ring of FCCee injector and received feedback in the injector meetings. The options include;

  - Using **damping wiggler and Robinson wiggler** magnets, (RW was not people's favorite option)
  - Option without Robinson wiggler magnet (SC DW), (SC magnet is not preferable due to operational and cost reason)
  - Checked the **reversed bend** magnet (good for damping time but not efficient for emittance without insertion devices),
  - Checked **DBA (good for emitttance but not for damping time)**,
  - Checked **TBA (same result with DBA)**,
  - **FODO** + (relatively long) damping wiggler **without SC DW or RW**
  - Combined function magnet (DQ)**,**
  - **Higher energy options (2.42 GeV, 2.86 GeV, 3.0 GeV)**
- For details, here is the link of the presentations:

  - https://indico.cern.ch/event/1078111/
  - https://indico.cern.ch/event/1107304/
  - https://indico.ijclab.in2p3.fr/event/8920/timetable/?layout=room#20221125.detailed
  - https://agenda.infn.it/event/34369/timetable/#20230421.detailed
  - https://indico.cern.ch/event/1204896/
  - https://indico.cern.ch/event/1291141/
  - https://accelconf.web.cern.ch/ipac2023/pdf/MOPL175.pdf
  - https://indico.cern.ch/event/1402911/
  - https://indico.cern.ch/event/1298458/contributions/5977874/attachments/2875516/5035656/240611_fccweek_dr_light.pdf

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# Feedback from mid-term review

## Feedback from Mid-term review

Main Recommendation: optimize the Injector, especially the linac design and subsequently adjust Technical Infrastructure cost for length and power density

- Mitigation of the potential risk due to the common linac operating at 400 Hz
  - Reducing the gradients and thus the dissipated rf power – thermo-mechanical simulations to evaluate the cooling system for the rf structures and prototype phase for klystrons, HV modulators and RF structures → common linac at 400 Hz
  - Use a DR at higher energy to avoid to accelerate electron and positron bunches in the common linac during positron production → common linac at 200 Hz
- Overall reduction of the repetition rate
  - considering the option of using four bunches in the injector to reduce the repetition rate from 200/400 Hz to 100/200Hz.
    - with DR at higher energy repetition rate 100 Hz!

# Feedback from mid-term review

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Main Recommendation: optimize the Injector, especially the linac design and subsequently adjust Technical Infrastructure cost for length and power density

- Mitigation of the potential risk due to the c
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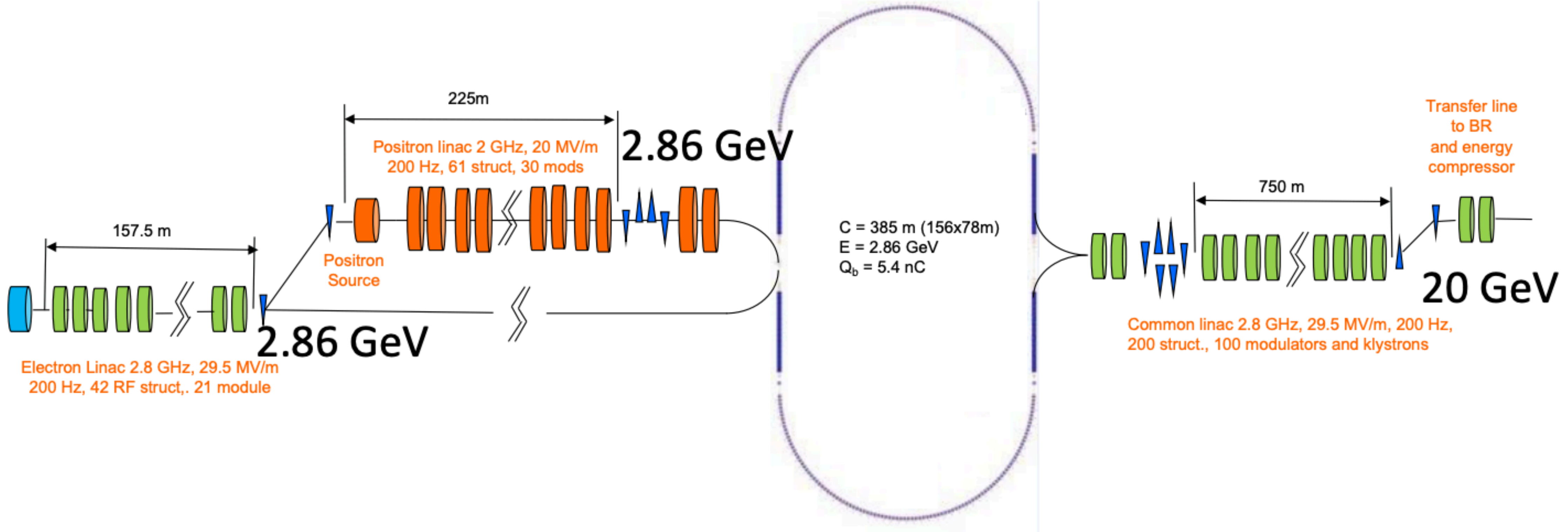
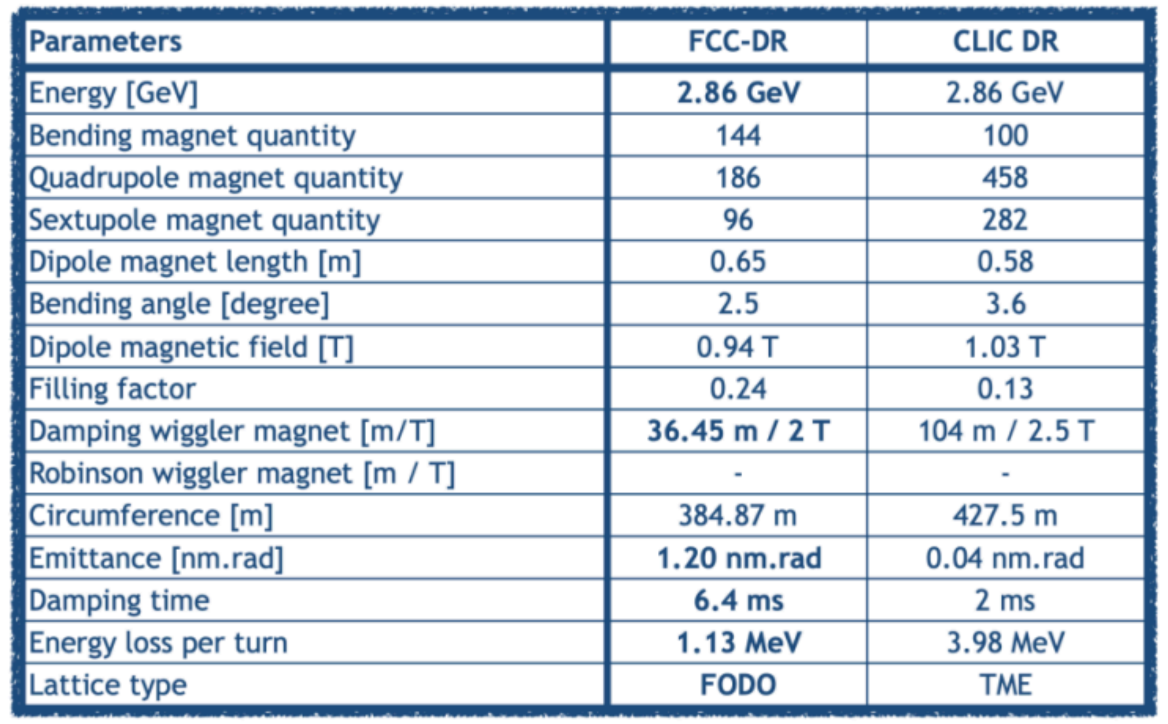
    - with DR at higher energy repetition ra

## Injector layout with DR at higher energy





| Parameters | FCC-DR | CLIC DR |
|---|---|---|
| Energy [GeV] | **2.86 GeV** | 2.86 GeV |
| Bending magnet quantity | 144 | 100 |
| Quadrupole magnet quantity | 186 | 458 |
| Sextupole magnet quantity | 96 | 282 |
| Dipole magnet length [m] | 0.65 | 0.58 |
| Bending angle [degree] | 2.5 | 3.6 |
| Dipole magnetic field [T] | 0.94 T | 1.03 T |
| Filling factor | 0.24 | 0.13 |
| Damping wiggler magnet [m/T] | **36.45 m / 2 T** | 104 m / 2.5 T |
| Robinson wiggler magnet [m / T] | - | - |
| Circumference [m] | 384.87 m | 427.5 m |
| Emittance [nm.rad] | **1.20 nm.rad** | 0.04 nm.rad |
| Damping time | **6.4 ms** | 2 ms |
| Energy loss per turn | **1.13 MeV** | 3.98 MeV |
| Lattice type | **FODO** | TME |

- The present positron yield would allow positrons to be generated at a lower electron beam energy. Preliminary study showed no more stringent specifications for the target (see Iryna's slides), compatibility with present target study
- Common linac: Rep rate 200 Hz instead of 400 Hz, dedicated linac for electron and positron before the DR.
- Overall, the cost of the hardware remains approximately the same, the costs of the CE and TI to be evaluated
- DR: there are two possible starting points: one by Ozgur and second from CLIC Pre-DR
  - I will organize a meeting with Catia's working group, Yannis and Hannes
- I agreed with Michael to prepare a proposal to be discussed in the next FCC week with SAC.

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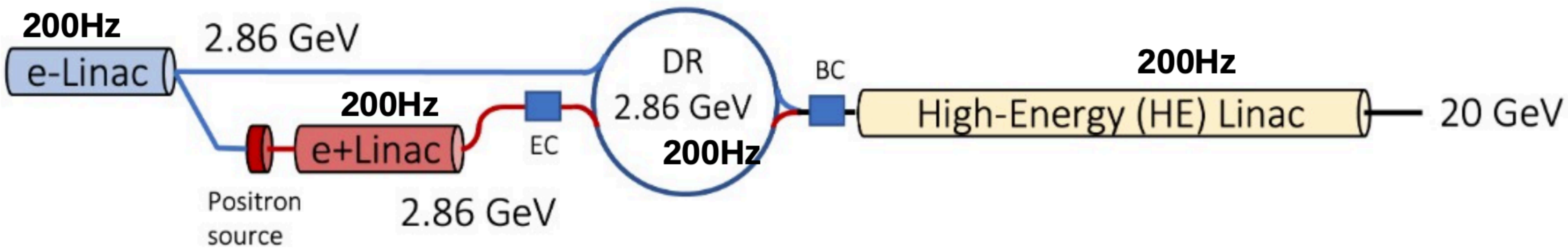
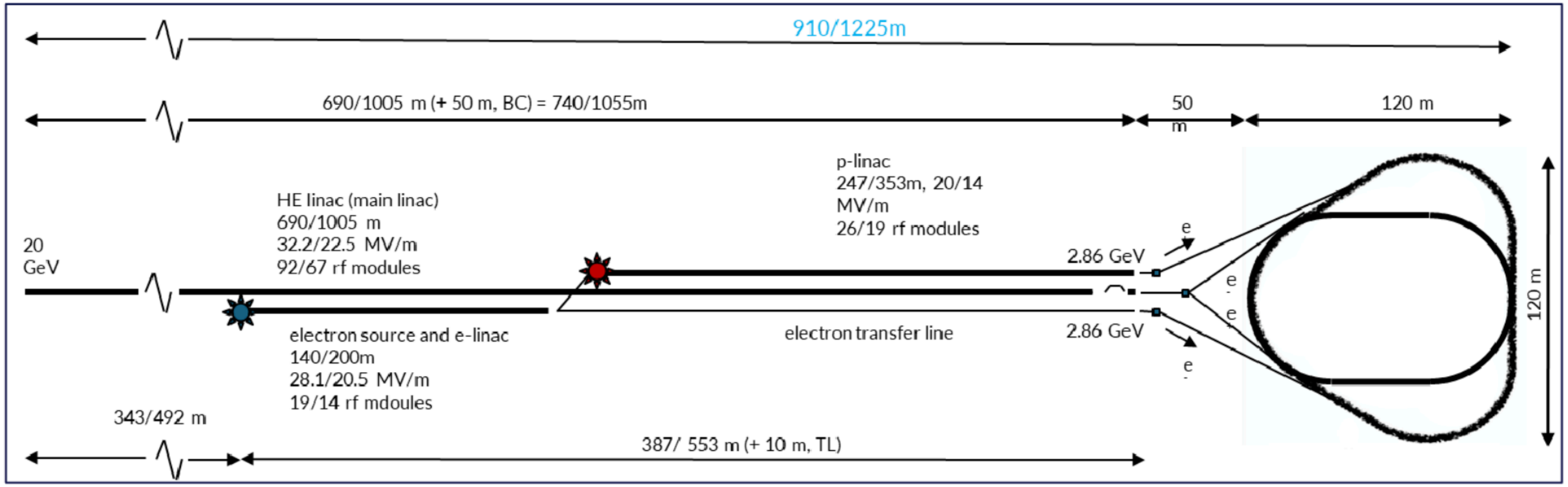
# Feedback from FCC Week 2024

- Based on also from mid-term review, **high energy DR at 2.86 GeV must be the only option** to be detailed and improved in the following months,
- CLIC-PDR is another option which needs considerable revisions since it does not provide beam requirements as it is.
- The baseline injector complex is the following:



Sketched layout becomes

P. Craievich / M. Benedikt



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# Design parameter requirements

- Before we start going into details, a good definition of the required parameters should be determined clearly.

- Based on many discussions, the following table summarizes the requirement parameters that we agreed on for the DR design:

| **Required Parameters (are changing)** | |
|---|---|
| Energy [GeV] | 2.86 |
| Circumference [m] | ~380 |
| Stored time [ms] | 40 |
| Longest damping time (hor.) [ms] | ~7.5 |
| Extraction geo. emittance (hor./vert.) [nm.rad] | ~1.8/0.18 |
| Number of bunches | 20 (4x5) |
| Energy spread @ extraction [%] (rms.) | - |
| Injection type | on axis |
| Number of straight sections | 3 |
| Dynamic aperture | +/- 3σ |
| Energy acceptance | +/- 2 % |

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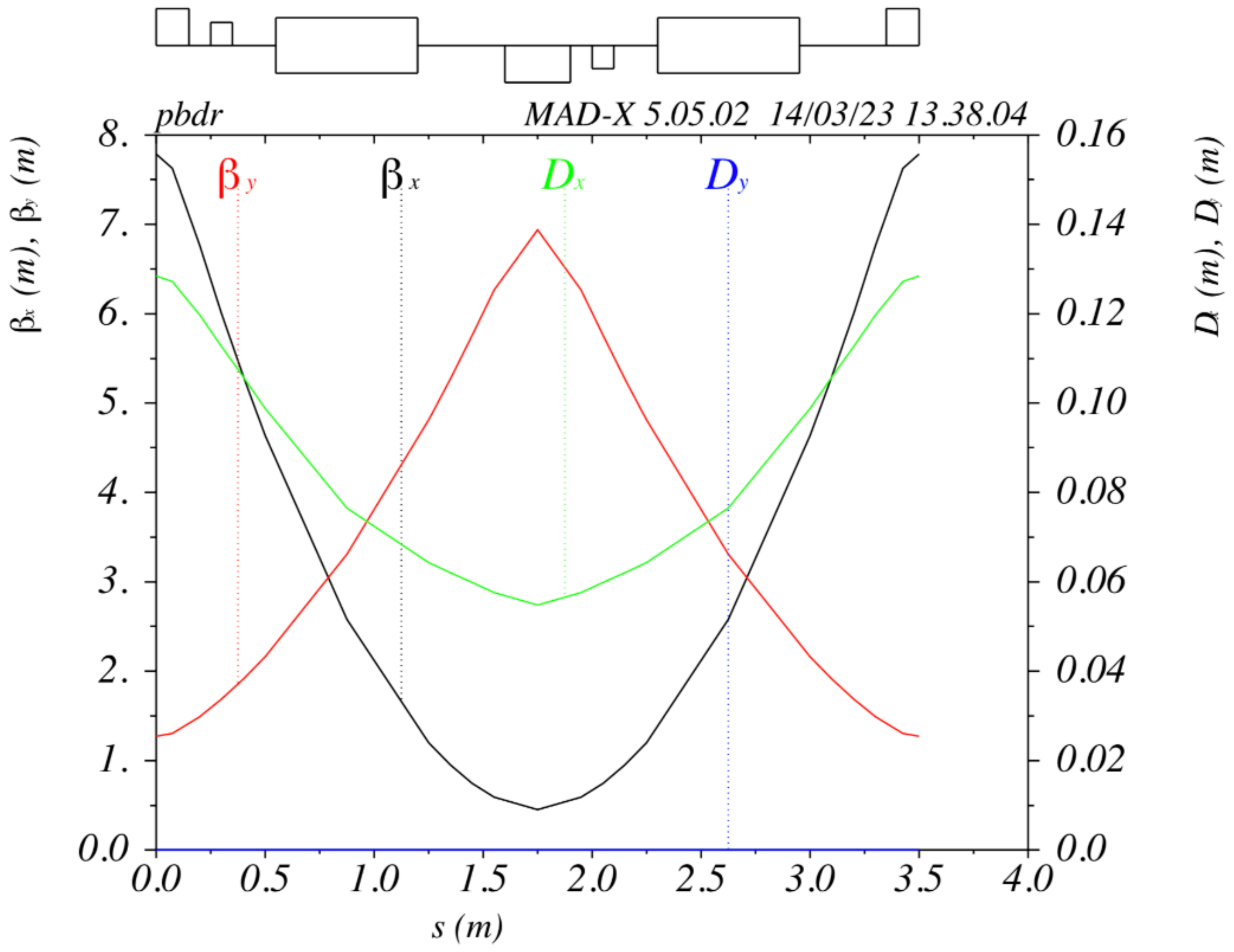
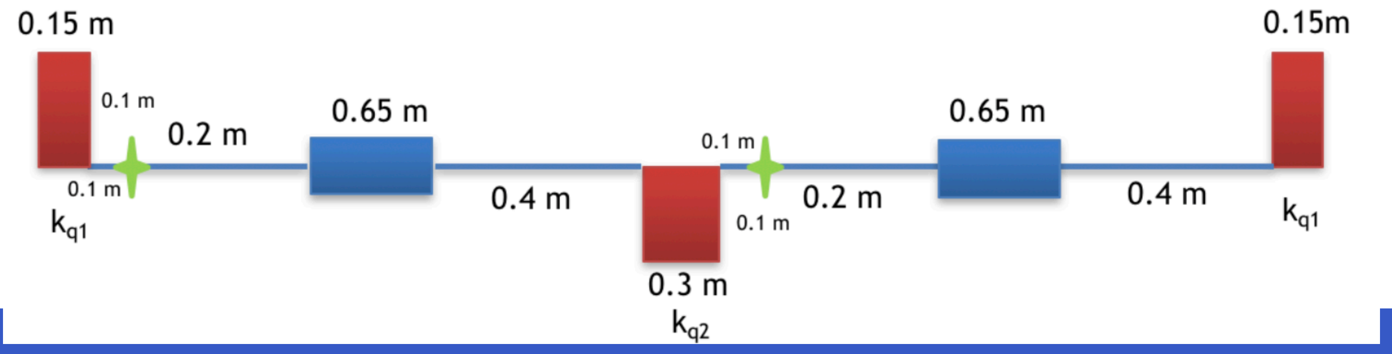
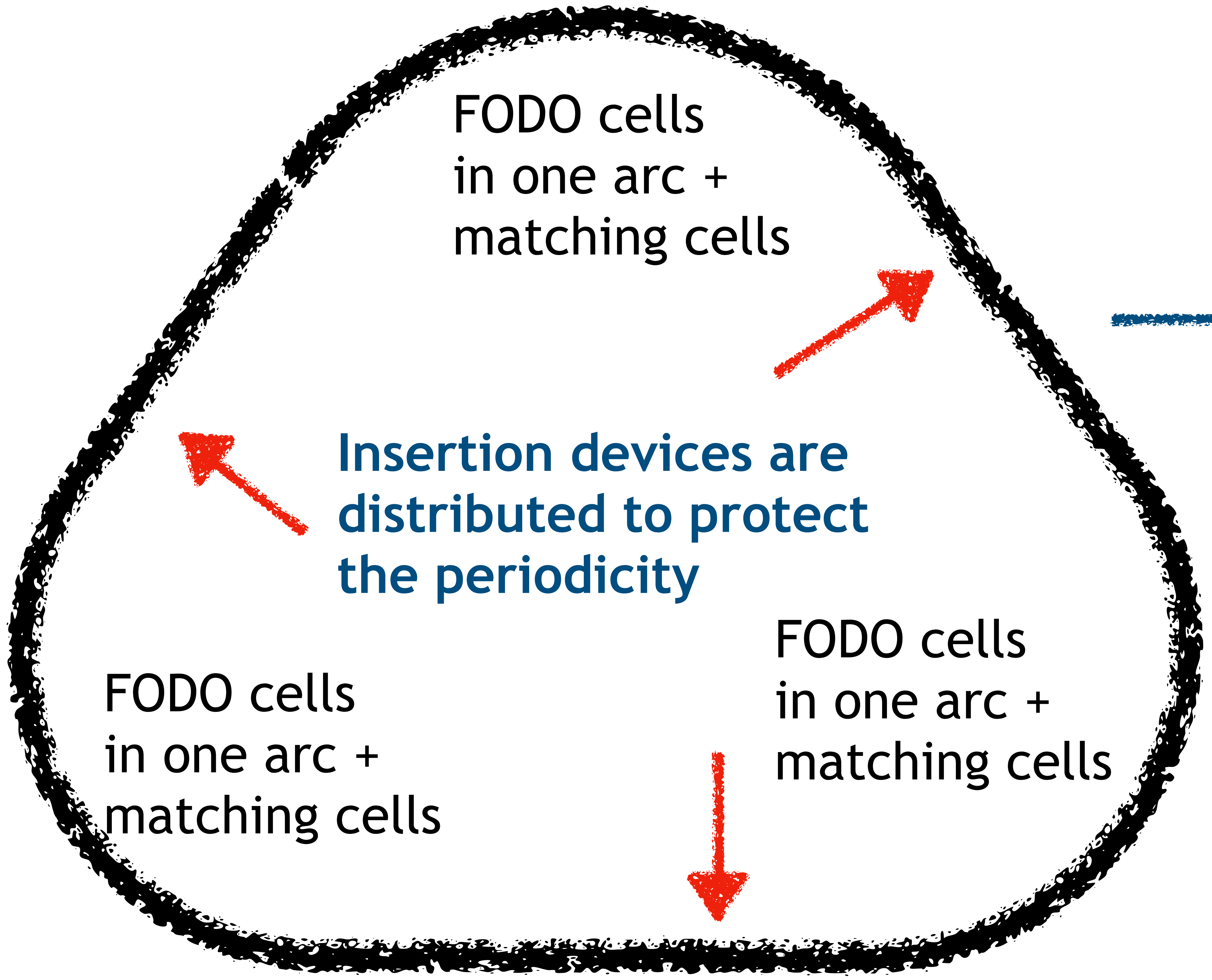
# Design study for the damping ring @ 2.86 GeV

- There were discussions for 2.42 GeV, 2.86 GeV and 3.30 GeV,
- We have presented a DR design for 2.86 GeV,
- 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 18 FODO cells and each of the straight sections have 6 FODO cells (with damping wiggler magnets)



**Arc**





FODO cells
in one arc +
matching cells

**Insertion devices are distributed to protect the periodicity**

FODO cells
in one arc +
matching cells

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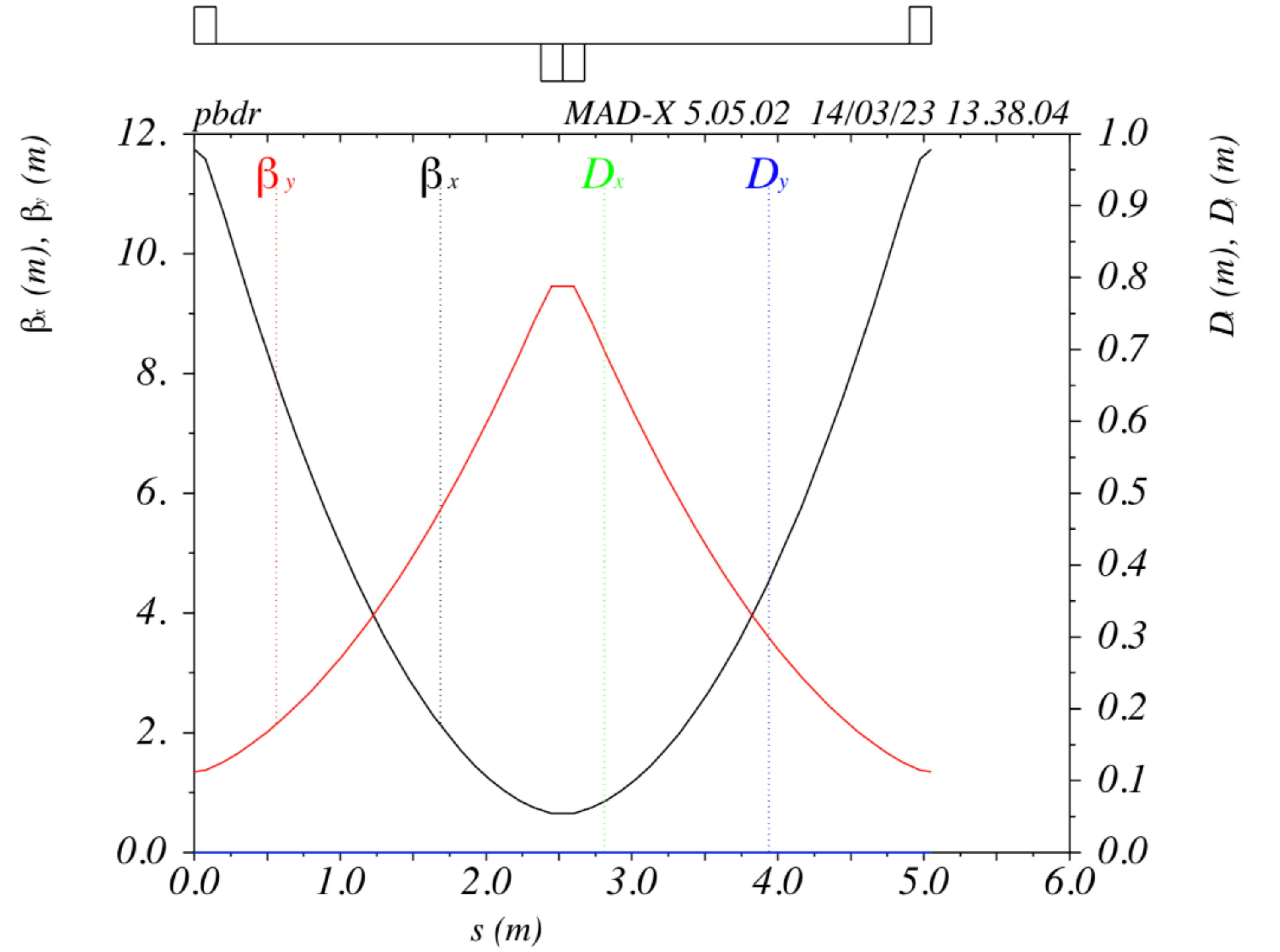
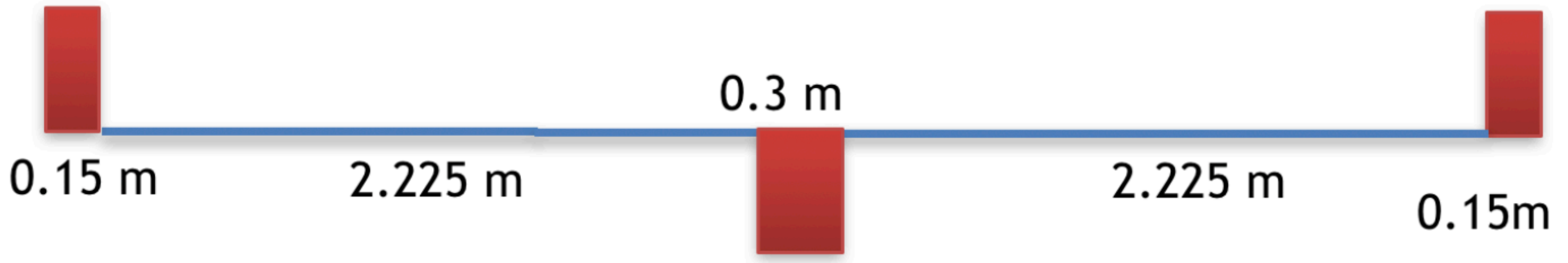
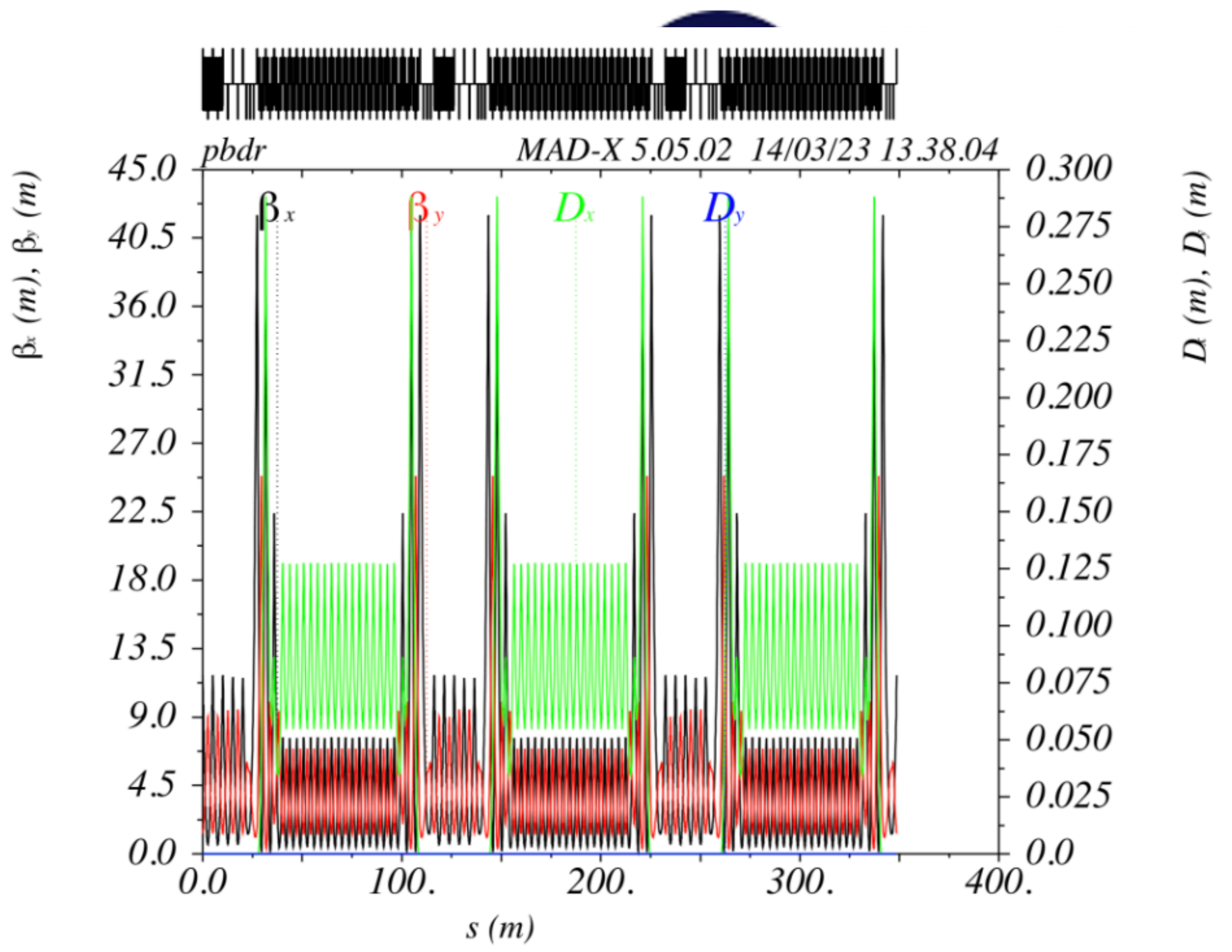


**SS**

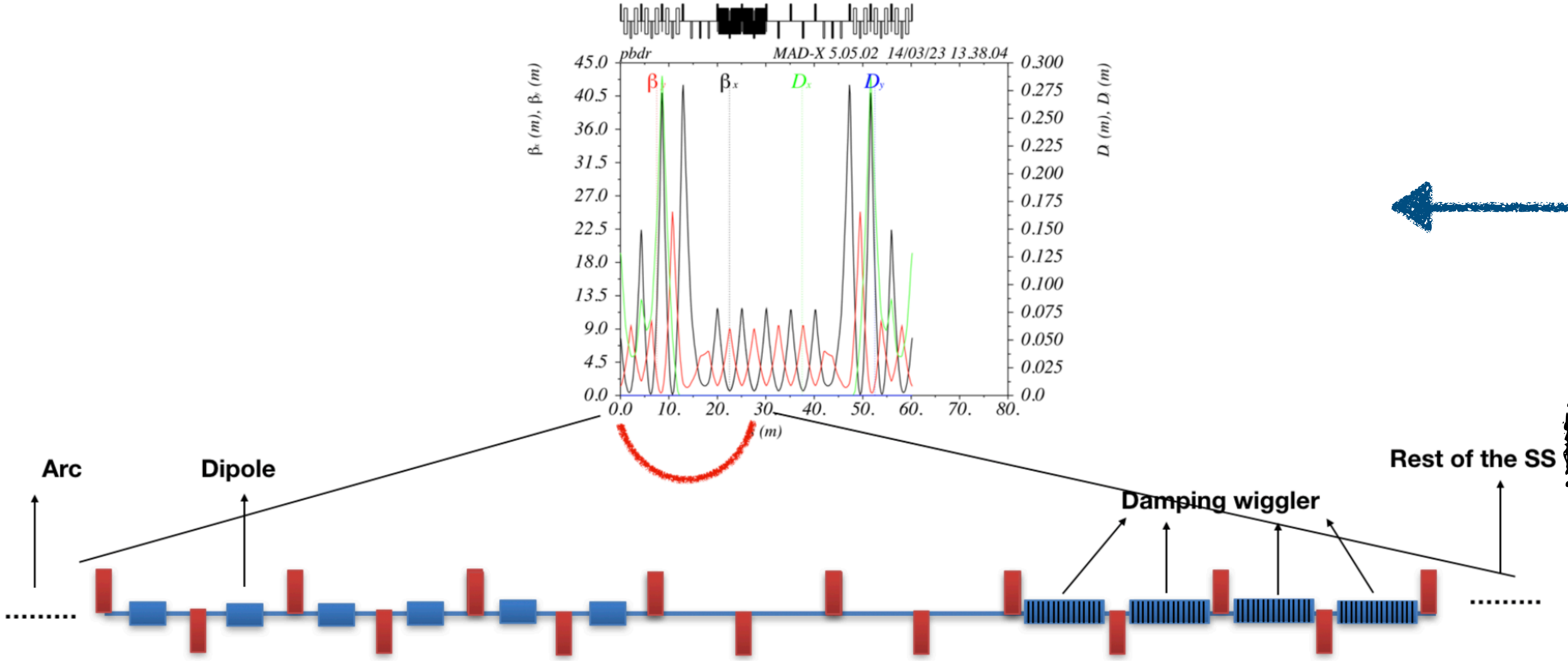


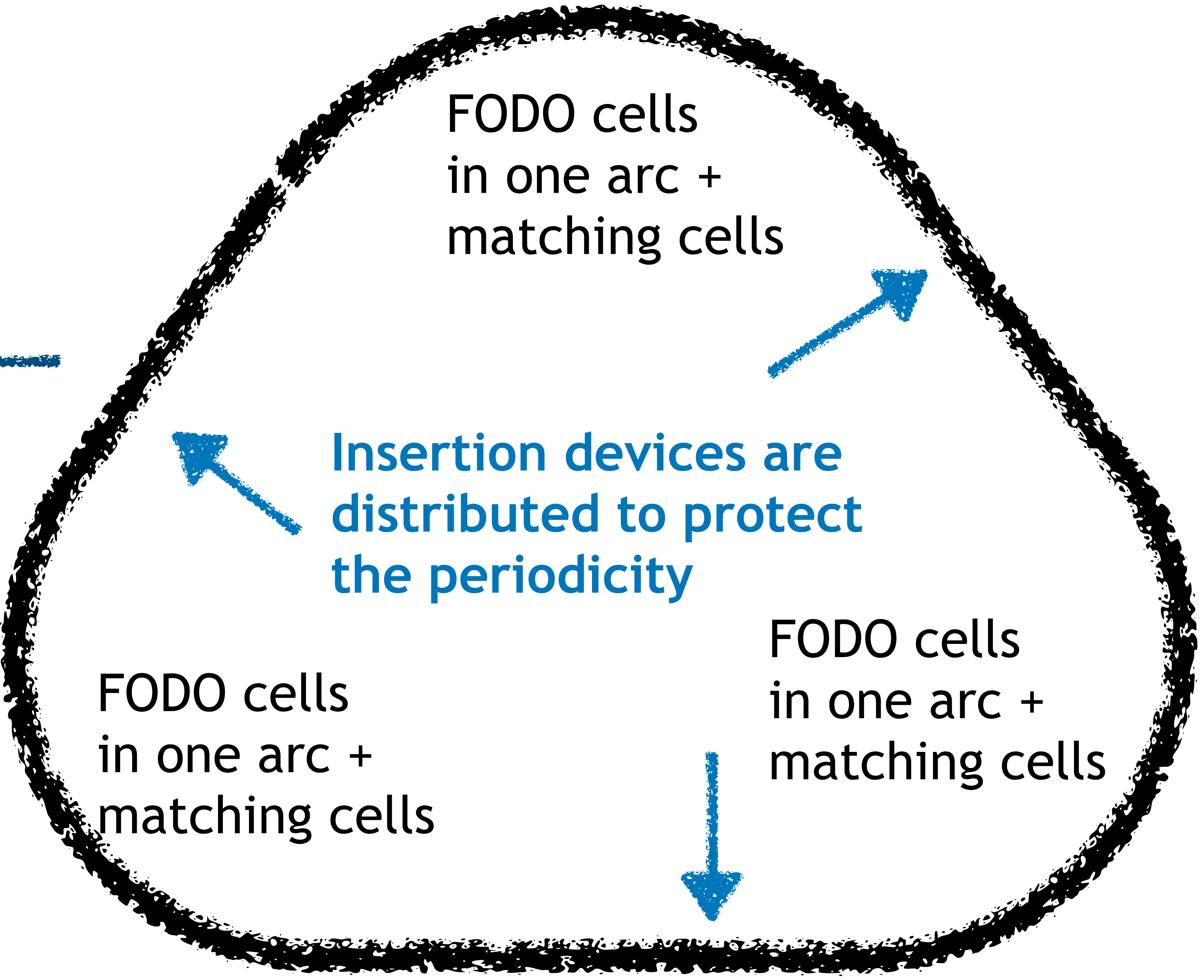
# Design study for the damping ring @ 2.



Straight Section (SS) area with 6 cell;

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





FODO cells
in one arc +
matching cells

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# Design study for the damping ring @ 2.86 GeV

| Parameters | CDR | Option - 1 | Option - 2 | Option-3 | Option-4 | CLIC-PDR |
|---|---|---|---|---|---|---|
| Energy [GeV] | 1.54 | 1.54 | 1.54 | **2.86** | 2.86 | 2.86 |
| Lattice type | FODO | FODO | FODO with DQ | FODO | FODO with DQ | TME |
| Layout | Racetrack | 3 arcs and 3 SS | Racetrack | 3 arcs and 3 SS | 3 arcs and 3 SS | Racetrack |
| Bending magnet quantity | 232 | 78 | 30 DQ / 12 D | 144 | 63 DQ / 18 D | 38 |
| Dipole magnet length [m] | 0.21 | 0.4 | 0.55 / 0.4 | 0.65 | 0.55 / 0.4 | 1.31 |
| Bending angle [degree] | 1.55 | 4.61 | 10 / 5 | 2.5 | 6 / 3 | 9.47 |
| Dipole magnetic field [T] | 0.66 | 1.03 | 1.62 / 0.81 | 0.94 | 1.51 / 0.75 | 1.2 |
| Quadrupole quantity | | | | 186 | 162 | 196 |
| Sextupole quantity | | | | 96 | 126 | 110 |
| Filling factor | 0.2 | 0.15 | 0.11 | 0.24 | 0.12 | 0.4 (incl. W) |
| Damping wiggler magnet | 26.5 m / 1.8 T | 36.45 m / 2 T | - / - | 36.45 m / 2 T | - / - | 108 m/1.9 T |
| Robinson wiggler magnet | - / - | - / - | - / - | - / - | - / - | -/- |
| Circumference | 242 m | 248.19 m | 181.74 m | 384.87 m | 326.61 m | 389.15 m |
| Emittance | 2 nm.rad | 2.1 nm.rad | 2.07 nm.rad | **1.20 nm.rad** | 0.85 nm.rad | 9.6 nm.rad |
| Damping time | 10.5 ms | 8.1 s | 8.5 s | **6.4 ms** | 4.6 ms | 2.68 ms |
| Energy loss per turn | 0.255 MeV | 0.31 MeV | 0.14 MeV | 1.13 MeV | 0.9 MeV | 2.75 MeV |

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|---|---|---|---|---|---|---|
| Energy [GeV] | 1.54 | 1.54 | 1.54 | **2.86** | 2.86 | 2.86 |
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| Layout | Racetrack | 3 arcs and 3 SS | Racetrack | 3 arcs and 3 SS | 3 arcs and 3 SS | Racetrack |
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| Bending angle [degree] | 1.55 | 4.61 | 10 / 5 | 2.5 | 6 / 3 | 9.47 |
| Dipole magnetic field [T] | 0.66 | 1.03 | 1.62 / 0.81 | 0.94 | 1.51 / 0.75 | 1.2 |
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| Damping wiggler magnet | 26.5 m / 1.8 T | 36.45 m / 2 T | - / - | 36.45 m / 2 T | - / - | 108 m/1.9 T |
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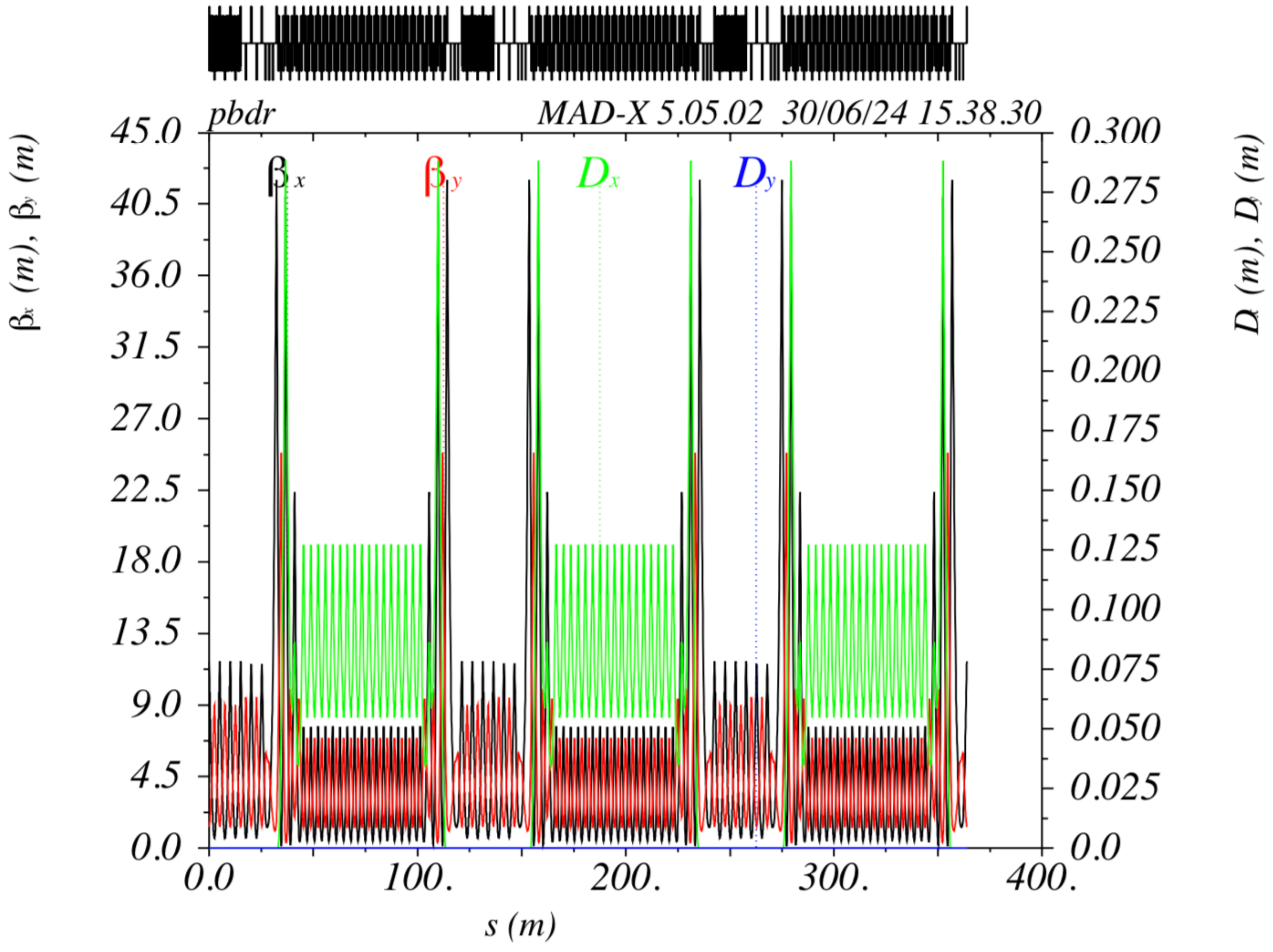
| Emittance | 2 nm.rad | 2.1 nm.rad | 2.07 nm.rad | **1.20 nm.rad** | 0.85 | |
| Damping time | 10.5 ms | 8.1 s | 8.5 s | **6.4 ms** | 4.6 ms | 2.68 ms |
| Energy loss per turn | 0.255 MeV | 0.31 MeV | 0.14 MeV | 1.13 MeV | 0.9 MeV | 2.75 MeV |

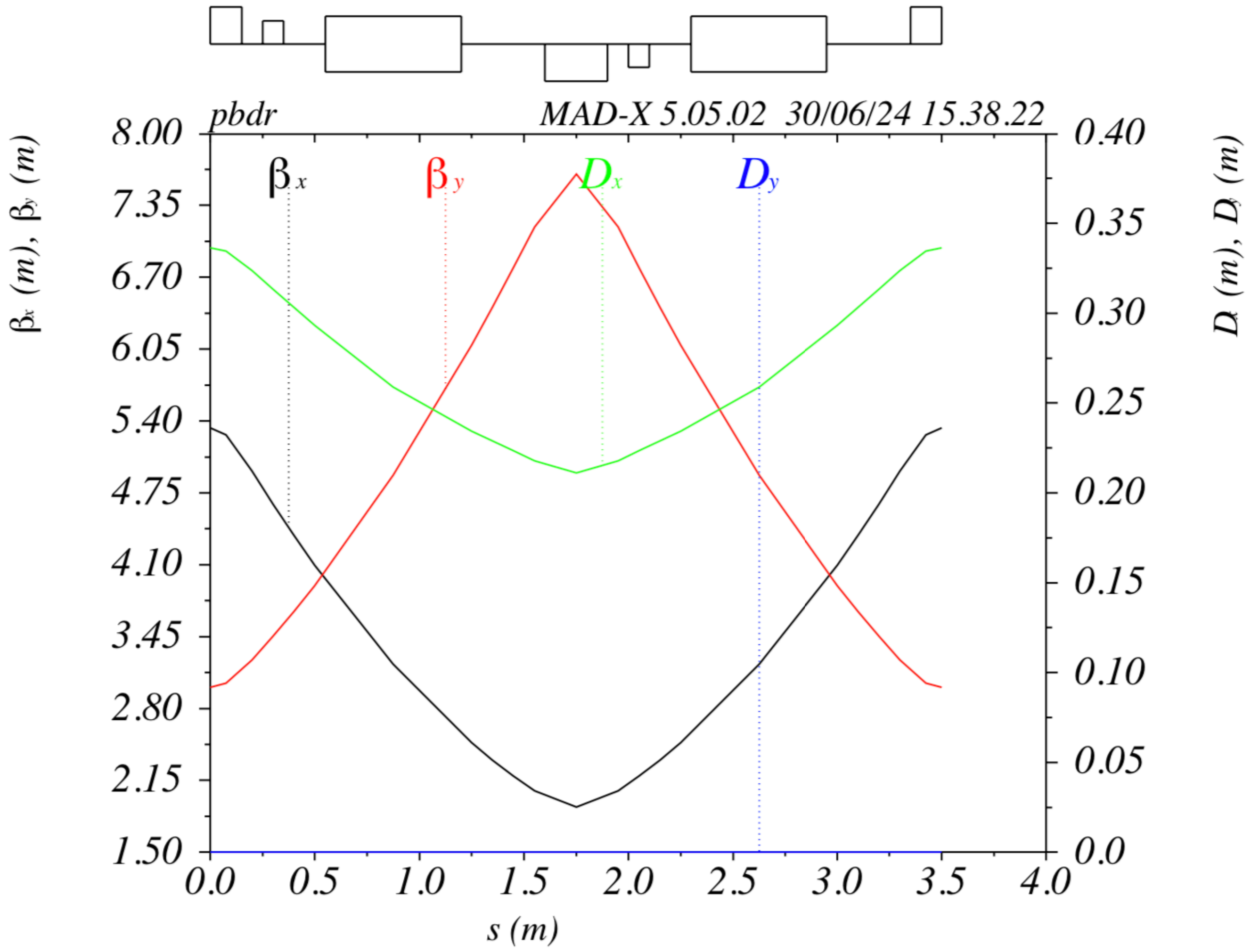
This can be relaxed up to 1.8 nm.rad:

- reducing number of dipoles (good for having shorter ring),
- or relaxing quadrupole strengths (good for DA)

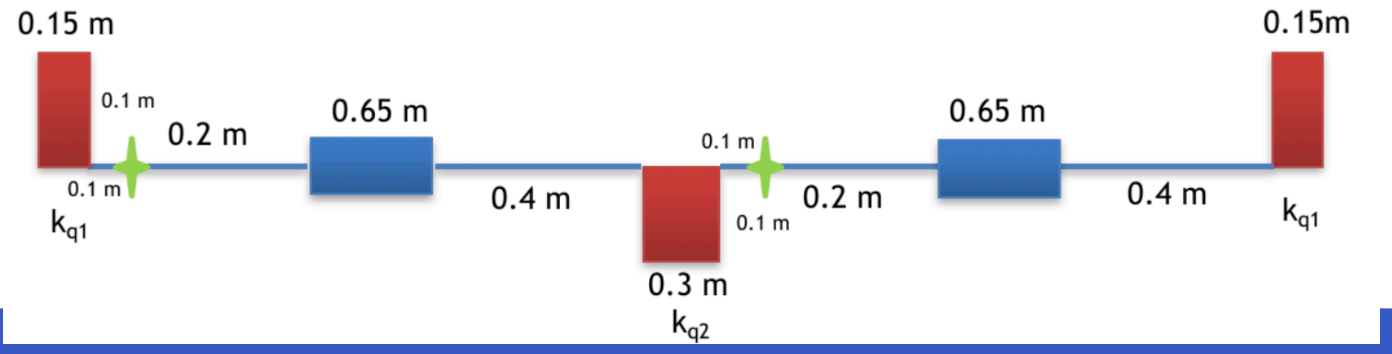
# Design study for the damping ring @

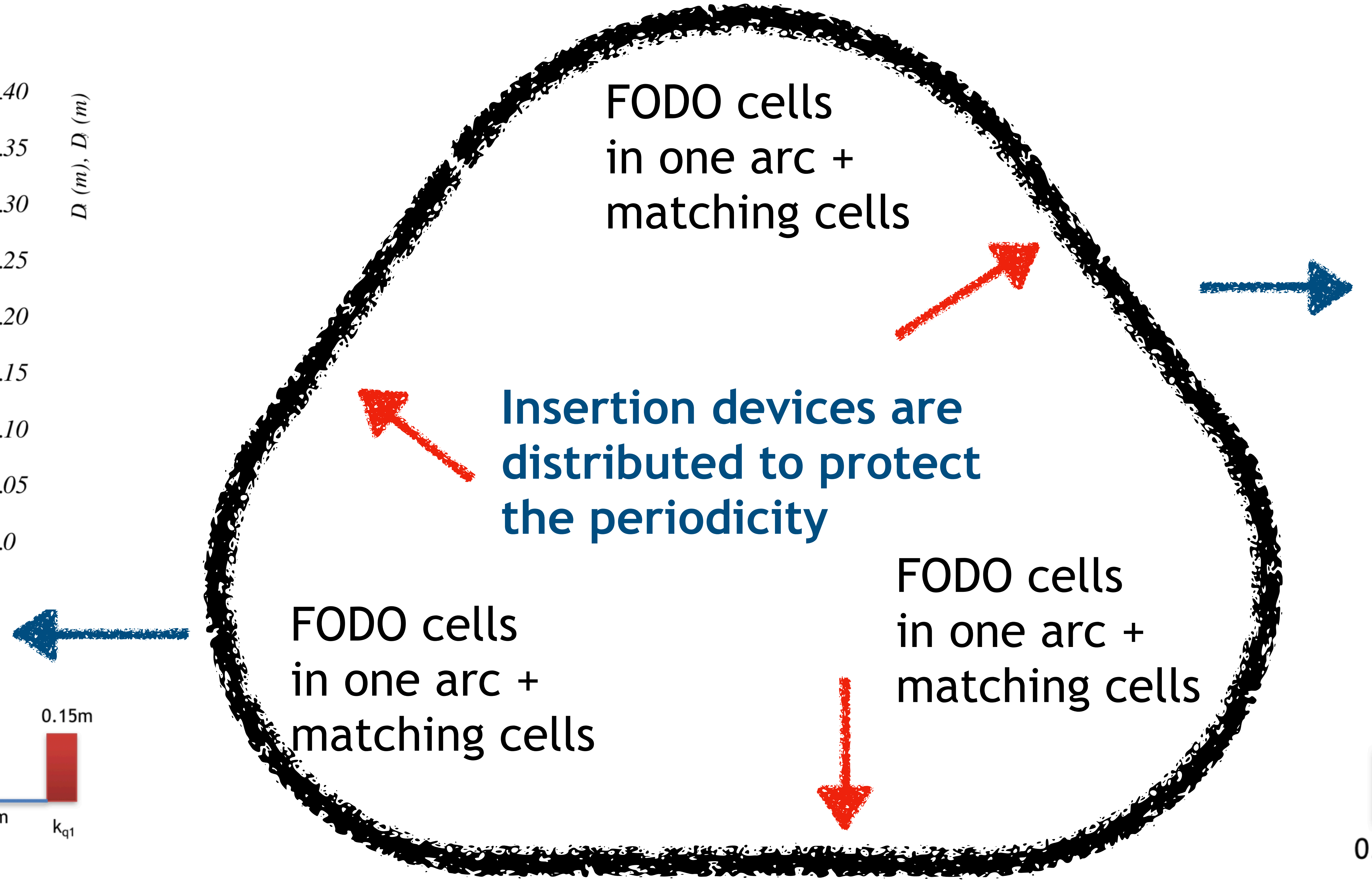
**132 dipole magnets, 135 degree phase advance, 1.7 nmrad emittance, 5.9 ms, 363 m**





**Arc**





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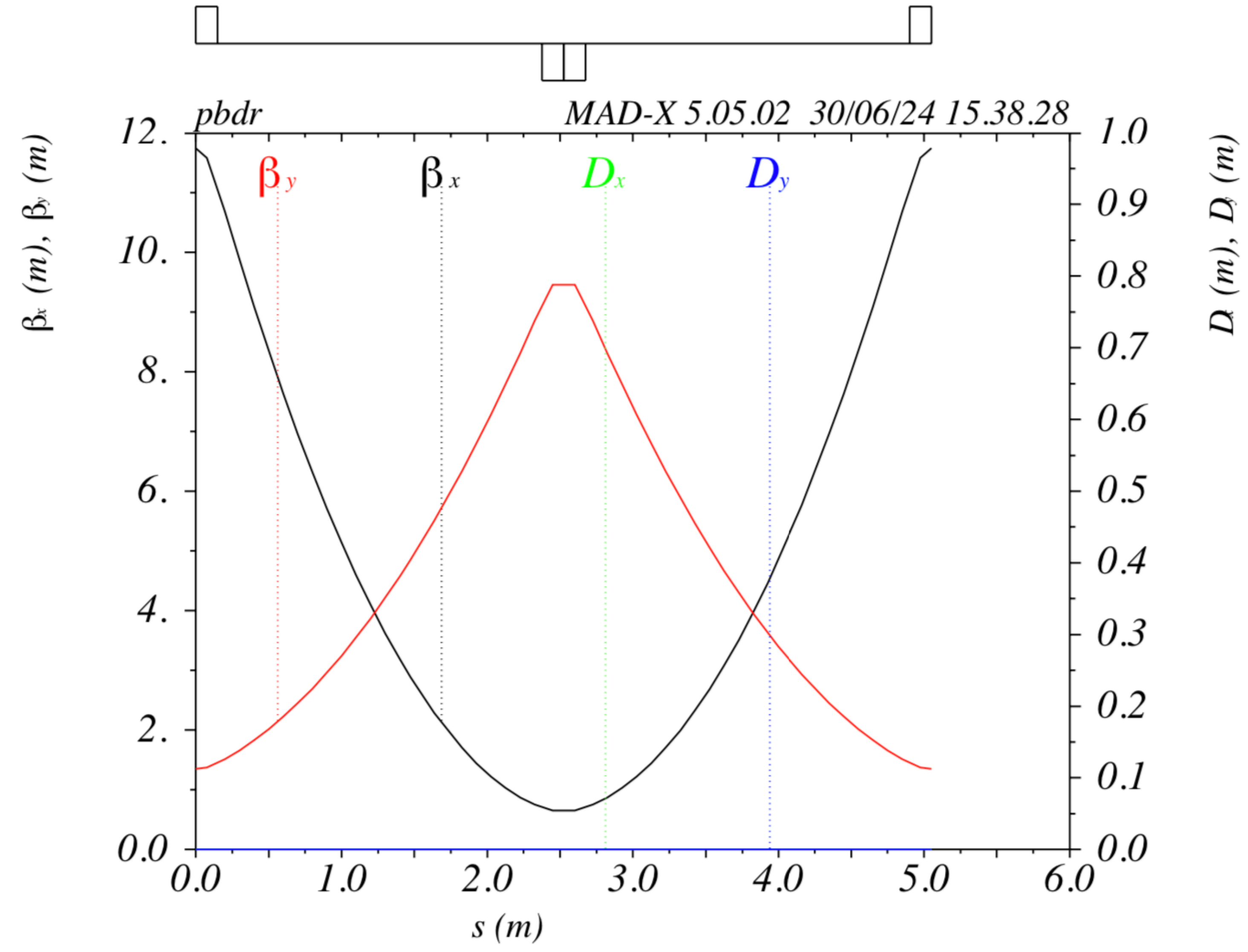
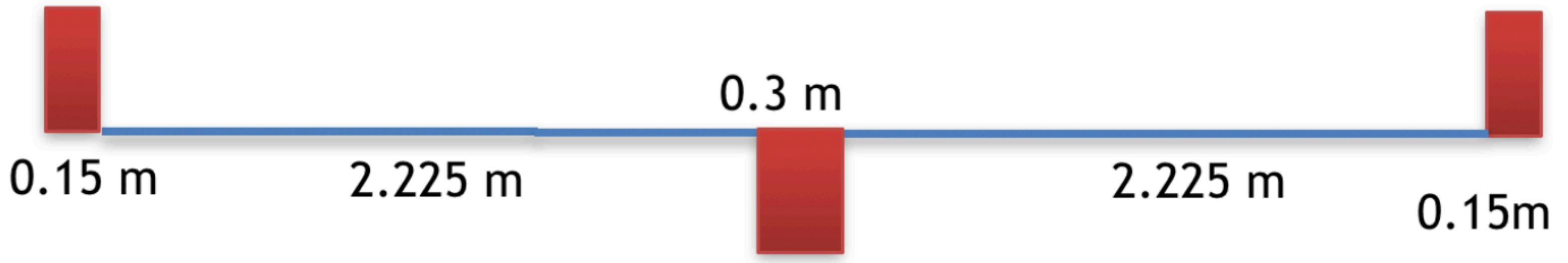
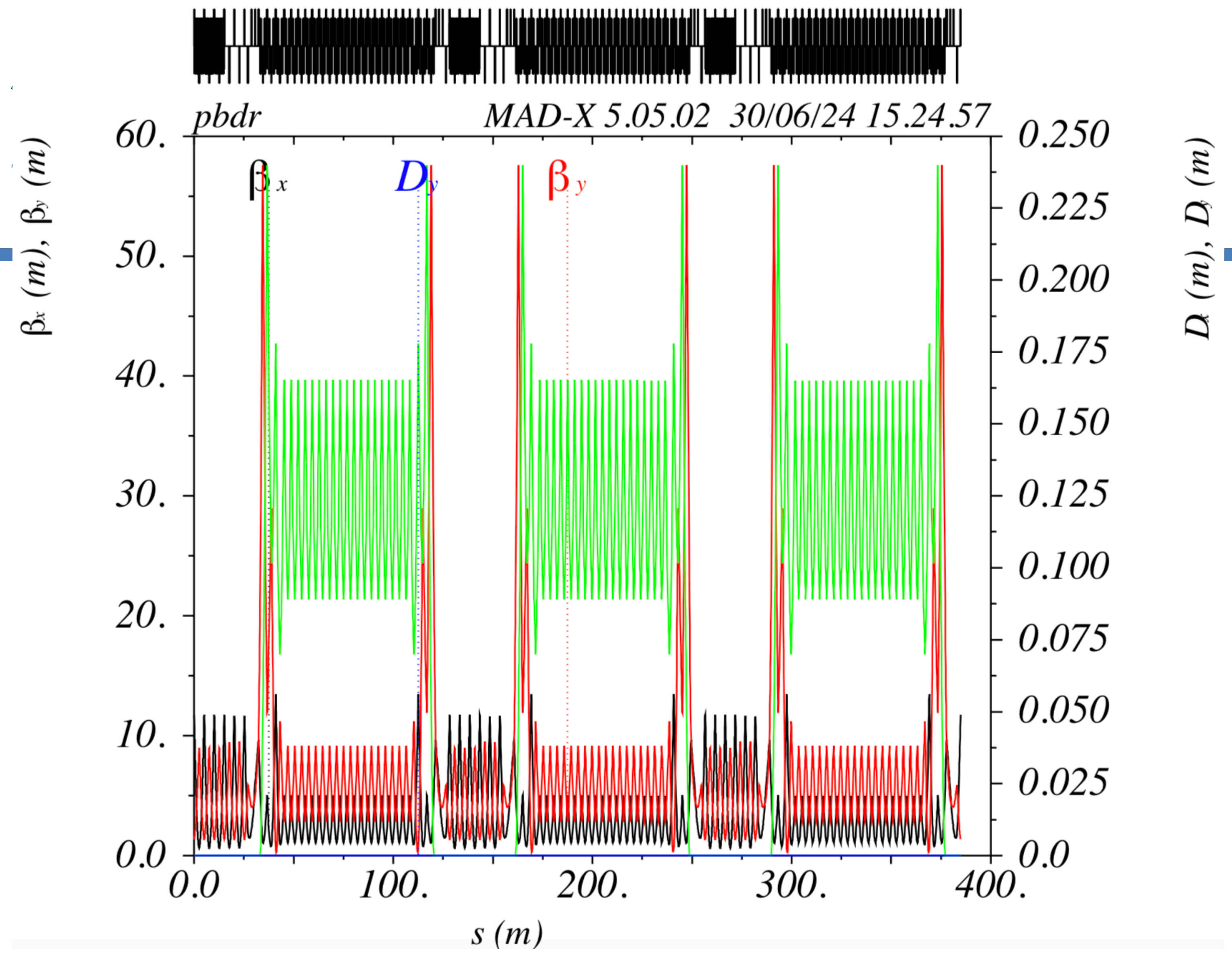


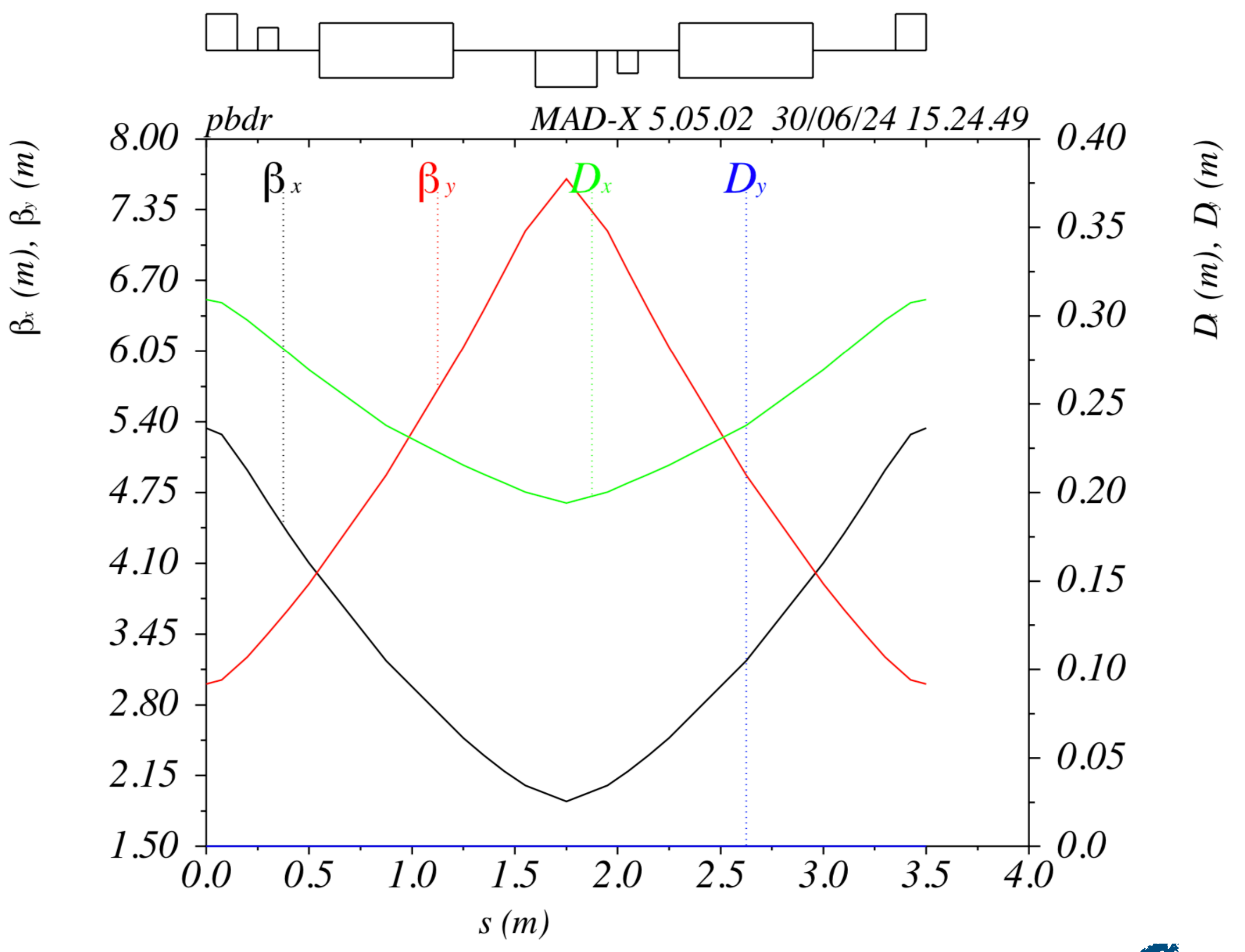
**SS**



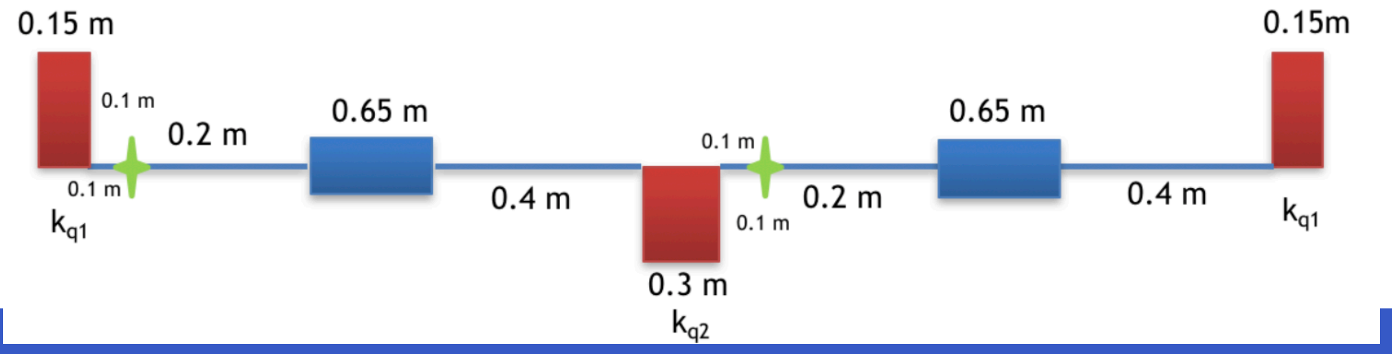
# Design study for the damping ring @

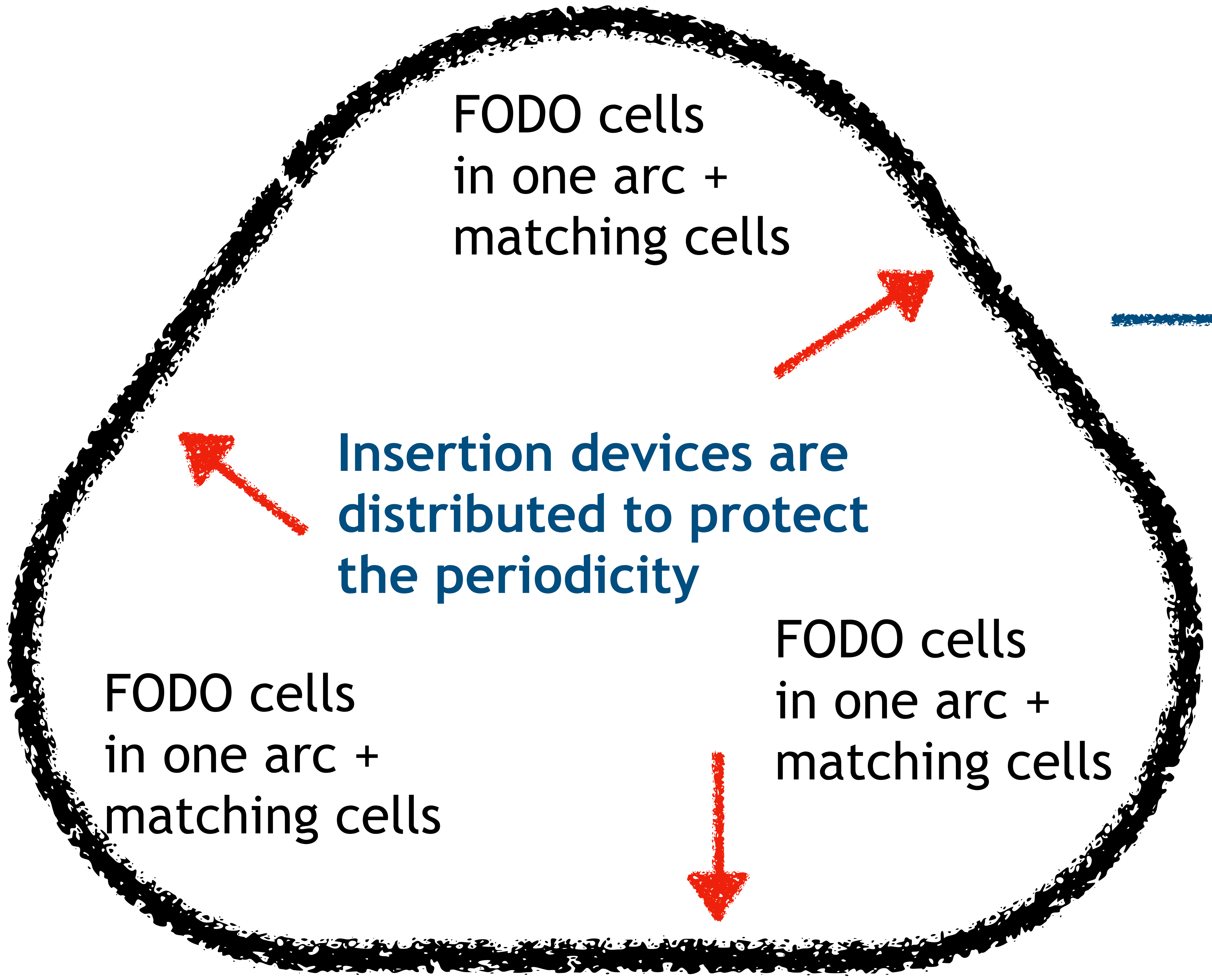


**144 dipole magnets, 97 degree phase advance, 1.8 nmrad emittance, 6.4 ms, 384 m**



**Arc**





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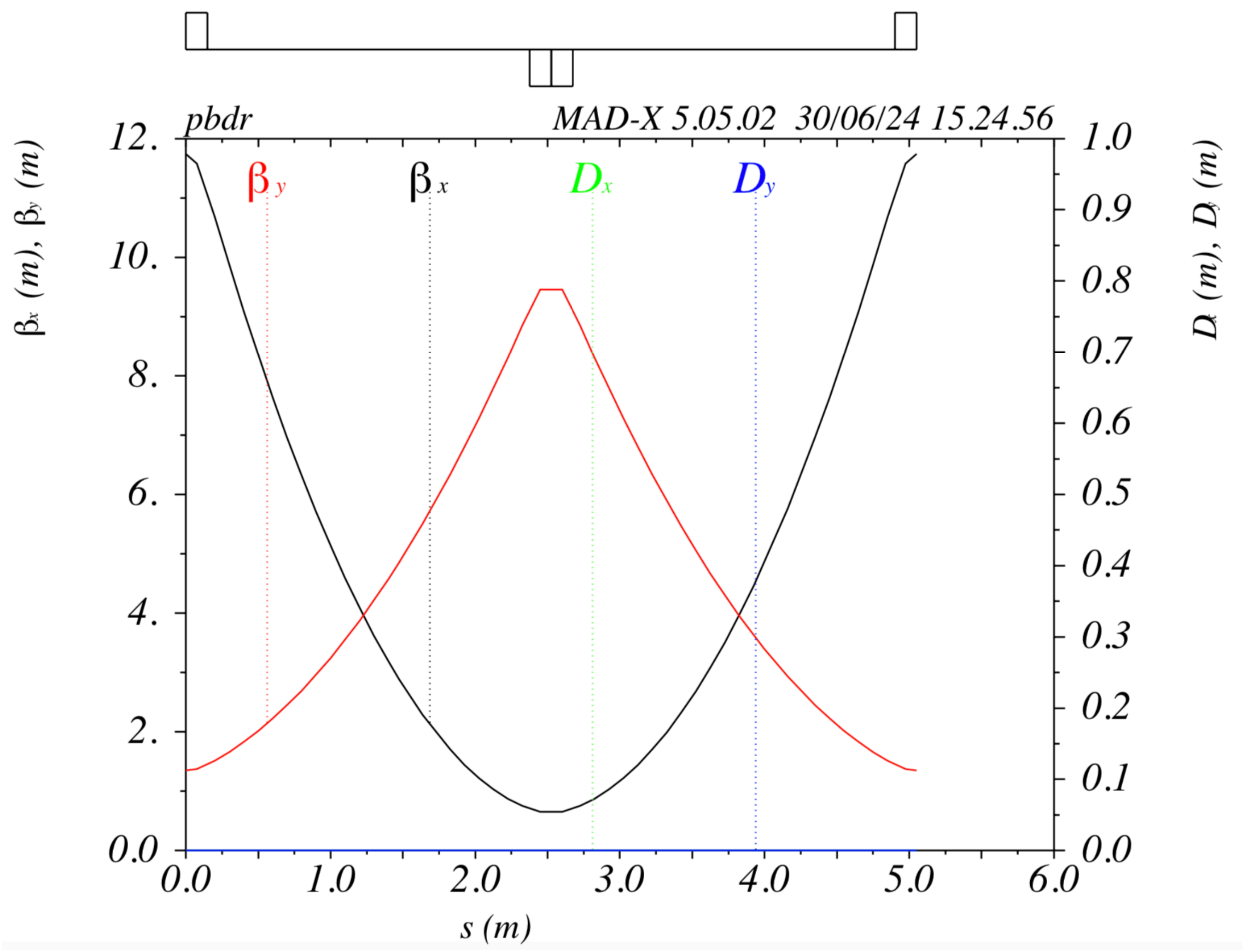
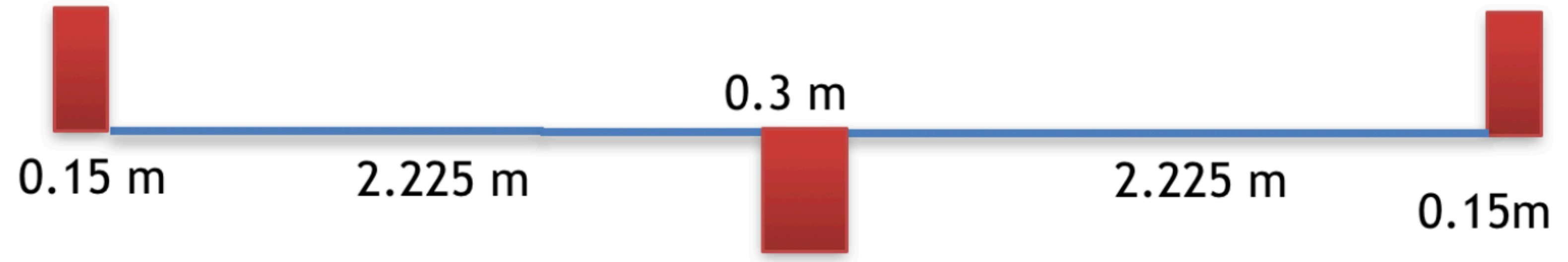


**SS**



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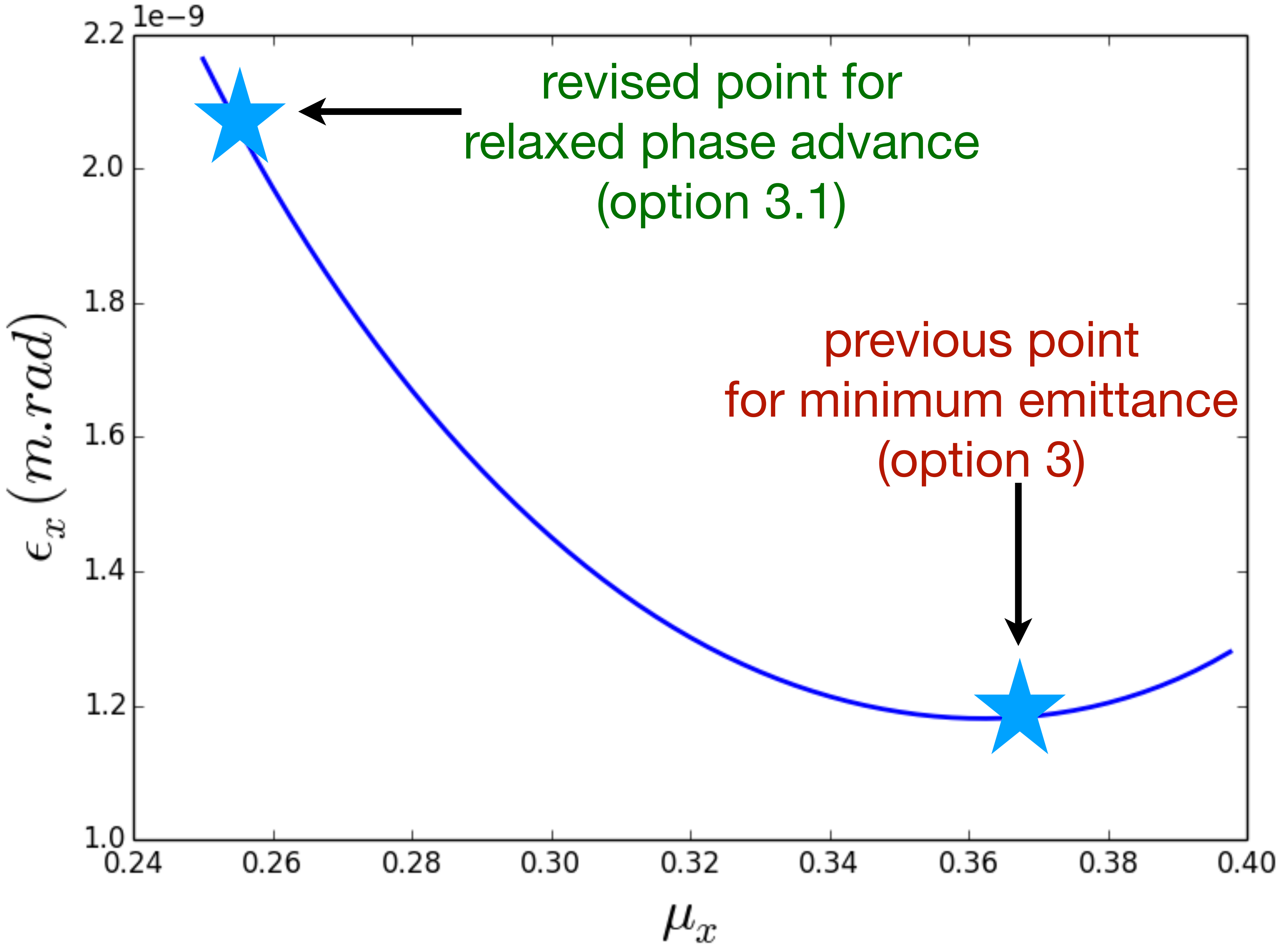
# Emittance vs Horizontal Phase Advance

- h/v **emittance** is mainly determined **by the dipoles in the arcs** of the ring.
- A numerical parametrization of the equilibrium horizontal emittance with the horizontal advance of the arc FODO cell was performed.



# Design study for the damping ring @ 2.86 GeV

| **Parameters** | CDR | Option - 1 | Option - 2 | Option-3 | Option-3.1 | Option-4 | CLIC-PDR |
|---|---|---|---|---|---|---|---|
| Energy [GeV] | 1.54 | 1.54 | 1.54 | 2.86 | **2.86** | 2.86 | 2.86 |
| Lattice type | FODO | FODO | FODO with DQ | FODO | FODO | FODO with DQ | TME |
| Layout | Racetrack | 3 arcs and 3 SS | Racetrack | 3 arcs and 3 SS | 3 arcs and 3 SS | 3 arcs and 3 SS | Racetrack |
| Bending magnet quantity | 232 | 78 | 30 DQ / 12 D | 144 | 144 | 63 DQ / 18 D | 38 |
| Dipole magnet length [m] | 0.21 | 0.4 | 0.55 / 0.4 | 0.65 | 0.65 | 0.55 / 0.4 | 1.31 |
| Bending angle [degree] | 1.55 | 4.61 | 10 / 5 | 2.5 | 2.5 | 6 / 3 | 9.47 |
| Dipole magnetic field [T] | 0.66 | 1.03 | 1.62 / 0.81 | 0.94 | 0.94 | 1.51 / 0.75 | 1.2 |
| Quadrupole quantity | | | | 186 | 186 | 162 | 196 |
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| Damping wiggler magnet | 26.5 m / 1.8 T | 36.45 m / 2 T | - / - | 36.45 m / 2 T | 36.45 m / 2 T | - / - | 108 m/1.9 T |
| Robinson wiggler magnet | - / - | - / - | - / - | - / - | - / - | - / - | -/- |
| Circumference | 242 m | 248.19 m | 181.74 m | 384.87 m | 384.87 m | 326.61 m | 389.15 m |
| Emittance | 2 nm.rad | 2.1 nm.rad | 2.07 nm.rad | 1.20 nm.rad | **1.76 nm.rad** | 0.85 nm.rad | 9.6 nm.rad |
| Damping time | 10.5 ms | 8.1 s | 8.5 s | 6.4 ms | **6.4 ms** | 4.6 ms | 2.68 ms |
| Energy loss per turn | 0.255 MeV | 0.31 MeV | 0.14 MeV | 1.13 MeV | 1.13 MeV | 0.9 MeV | 2.75 MeV |

# Incoming beam

- The incoming beam should be accepted by the DR:
  - The **dynamic aperture** (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects,
  - The value of the **maximum momentum deviation**, for which a particle may have and **still** undergo **stable synchrotron oscillation**, is called the **momentum acceptance** of the accelerator.
  - The required acceptance around the ring should be also checked for mechanical acceptance.

| **Injected beam parameters** | |
|---|---|
| Energy [GeV] | 2.86 |
| Horizontal emittance [nm.rad] (geo.) | 1615 |
| Vertical emittance [nm.rad] (geo.) | 1615 |
| Energy spread | +/- 2 % |

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# Incom

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  - The value of the **maximum momentum devi stable synchrotron oscillation**, is called the r
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| Injected beam parameters | |
|---|---|
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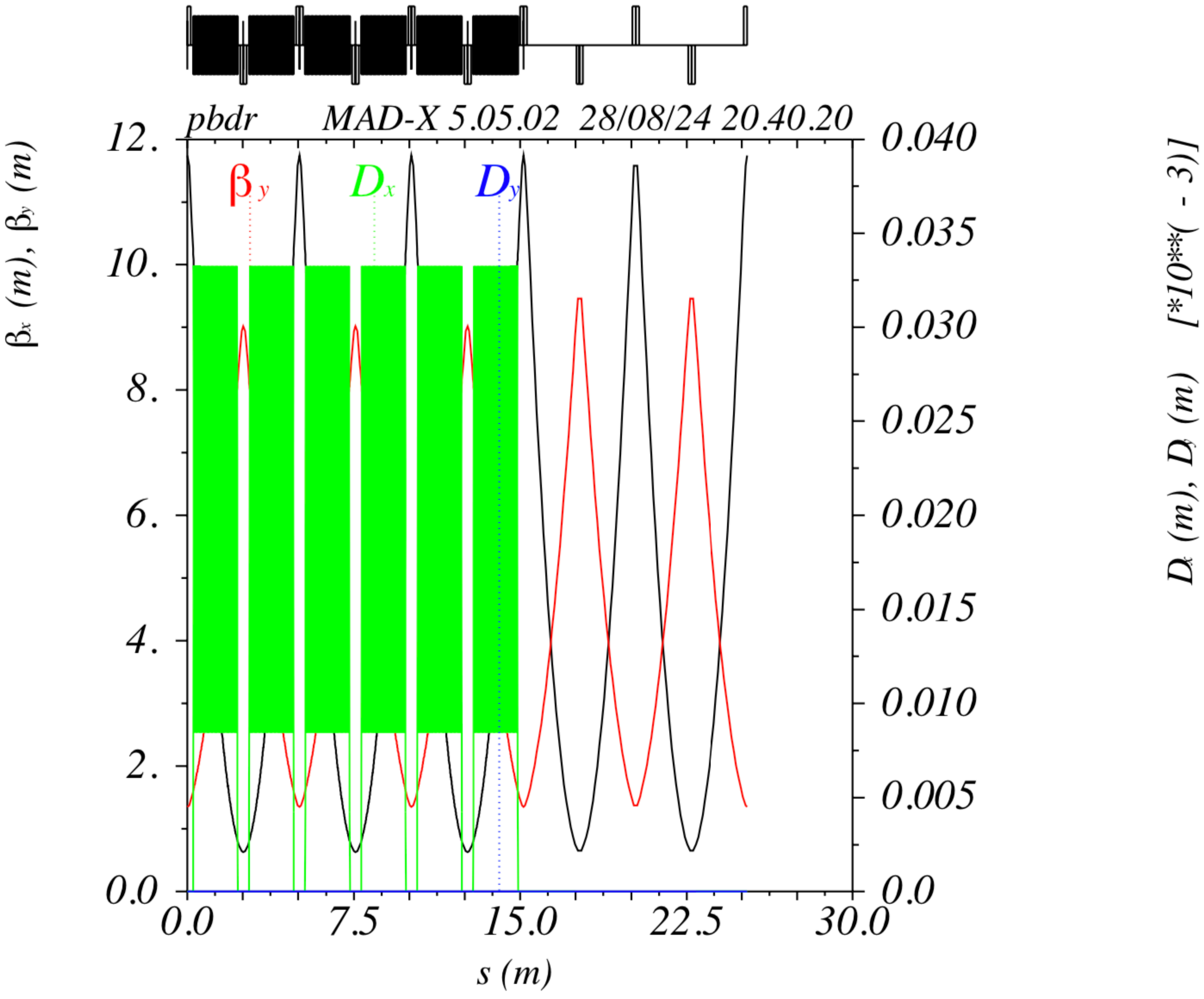
| Vertical emittance [nm.rad] (geo.) | 1615 |
| Energy spread | +/- 2 % |

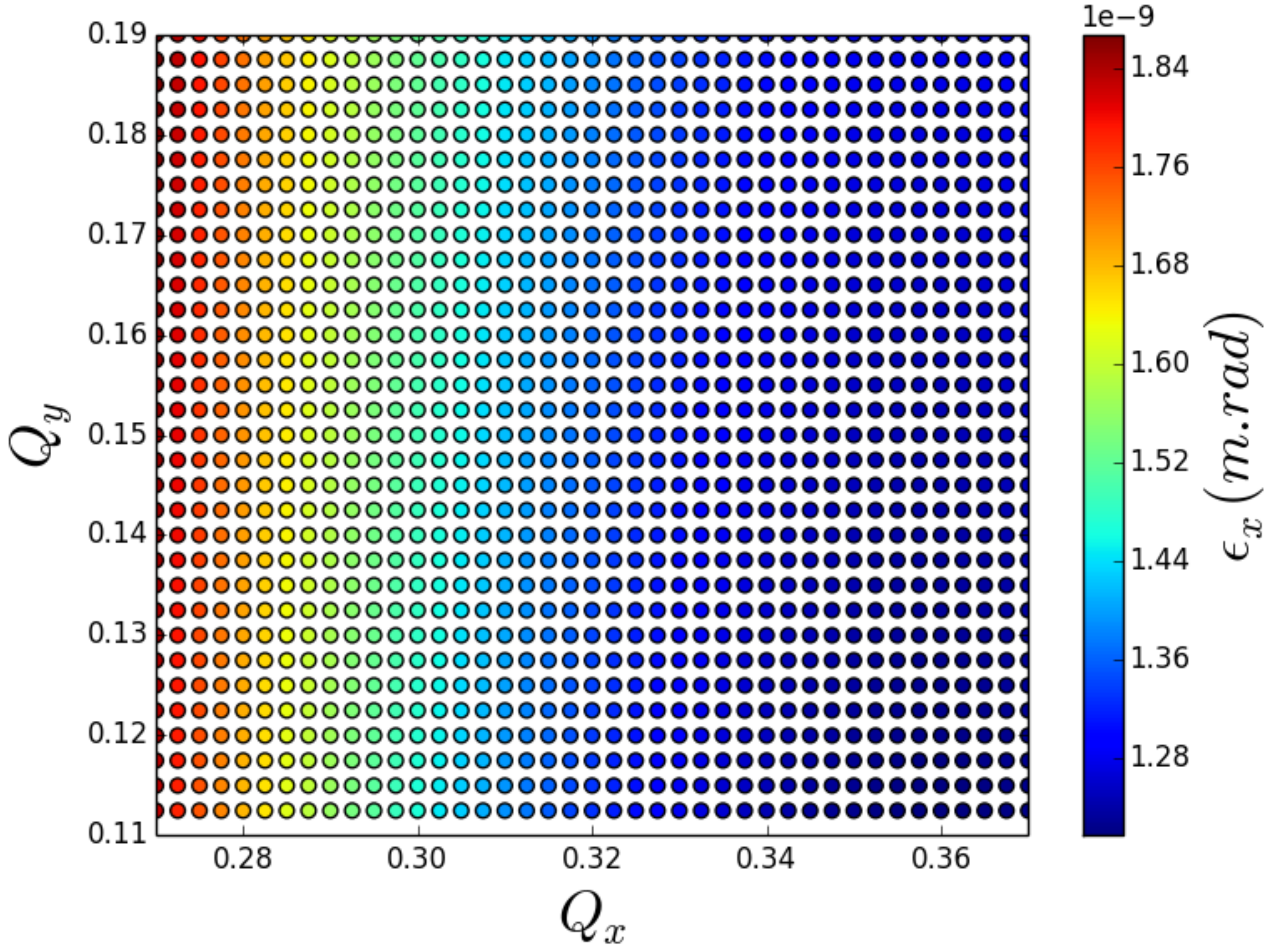


**$\sigma_y$= 1.88 mm at $\beta_y$=2.2 m in dispersion free section**

**$\sigma_x$= 3.50 mm at $\beta_y$=7.6 m in dispersion free section**

# Phase advance scanning

- h/v **emittance** is mainly determined **by the dipoles in the arcs** of the ring.
- A numerical parametrization of the equilibrium horizontal emittance with the horizontal and vertical phase advances of the arc FODO cell was performed.



- The minimum emittance can be achieved for a **horizontal phase advance** of ~ 0.383 which was our previous point. However, we choose around ~**0.27** in horizontal plane.

- Minimal dependence on the vertical phase advance. We choose lower vertical phase advance ~0.11.

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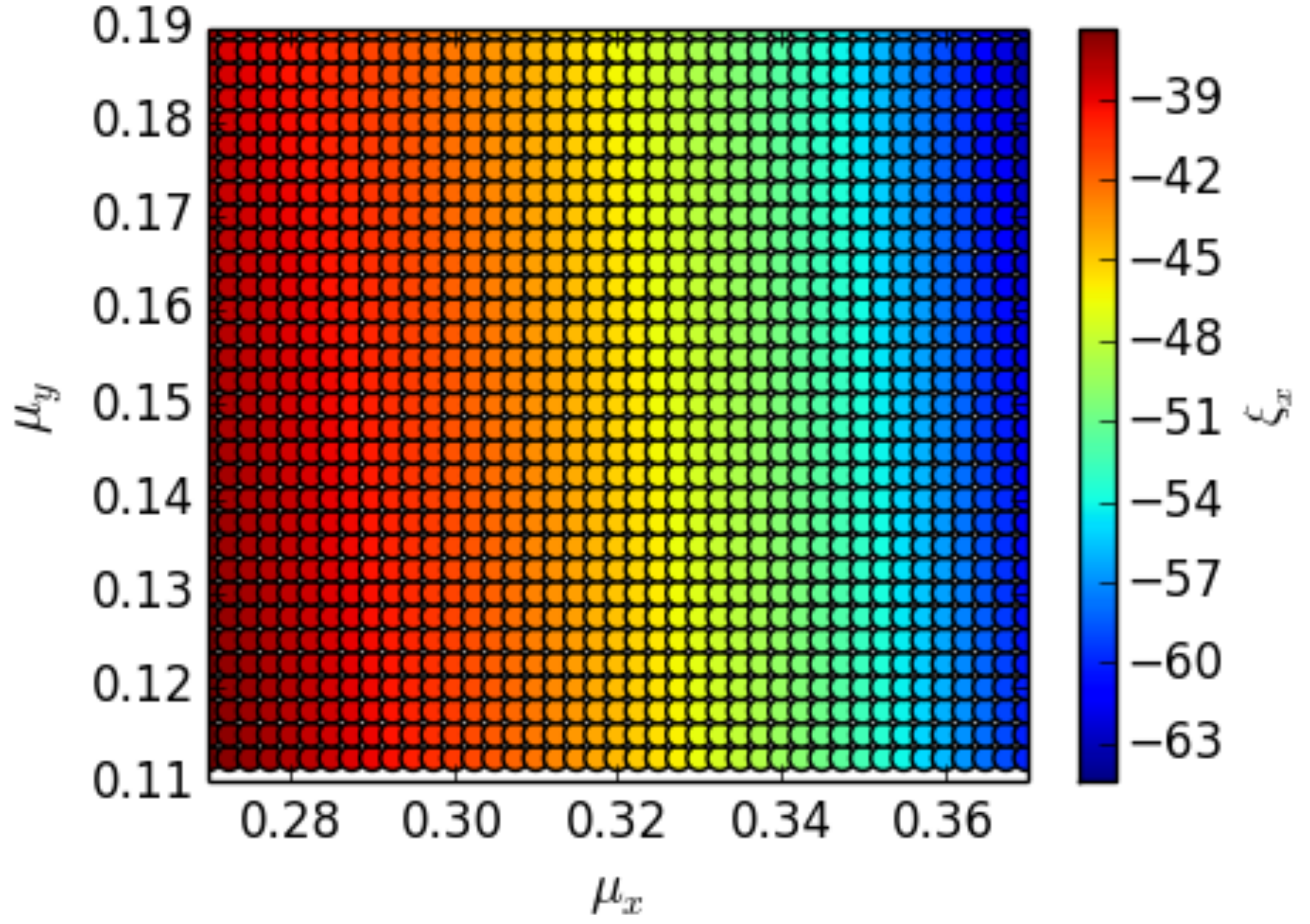
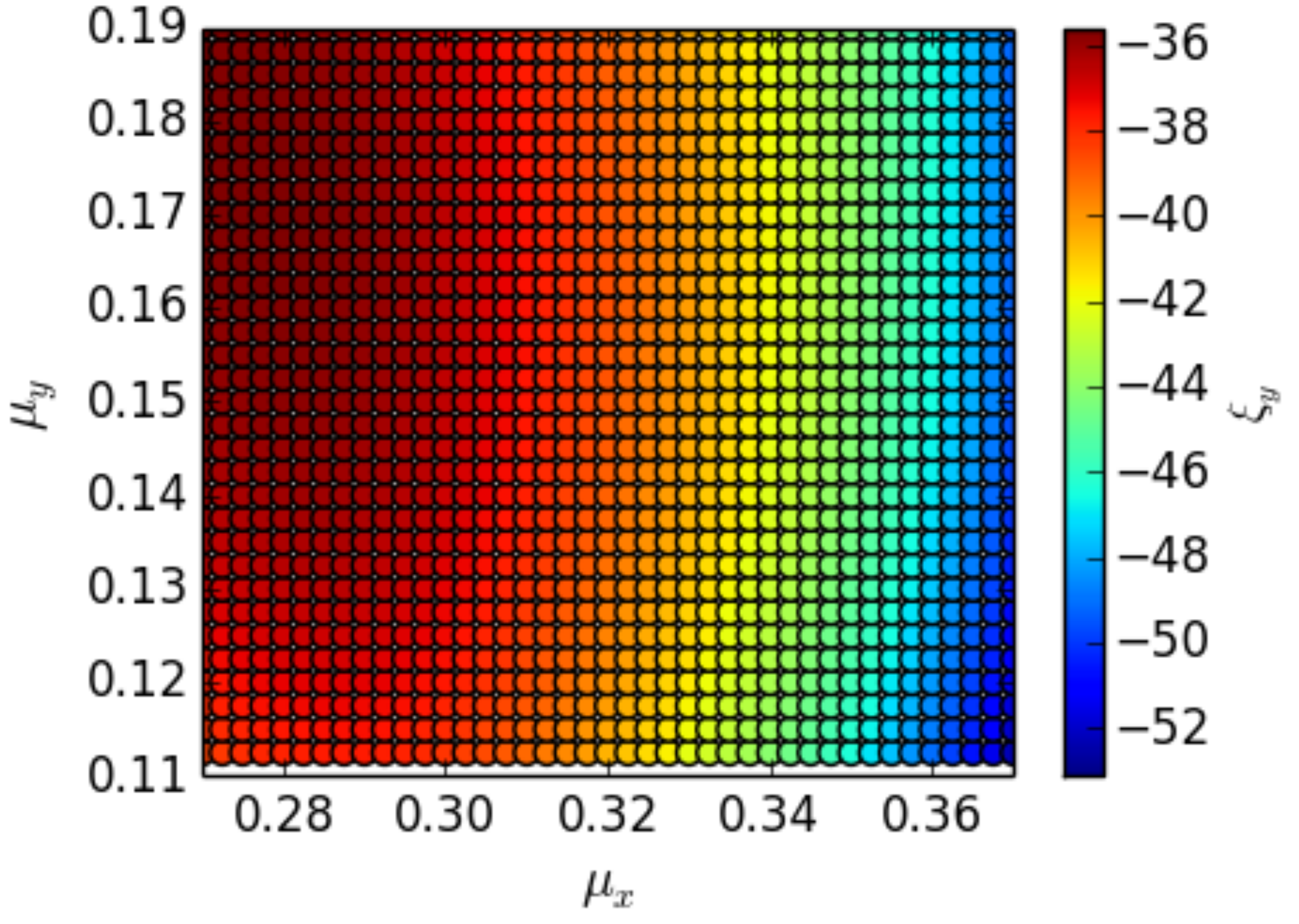
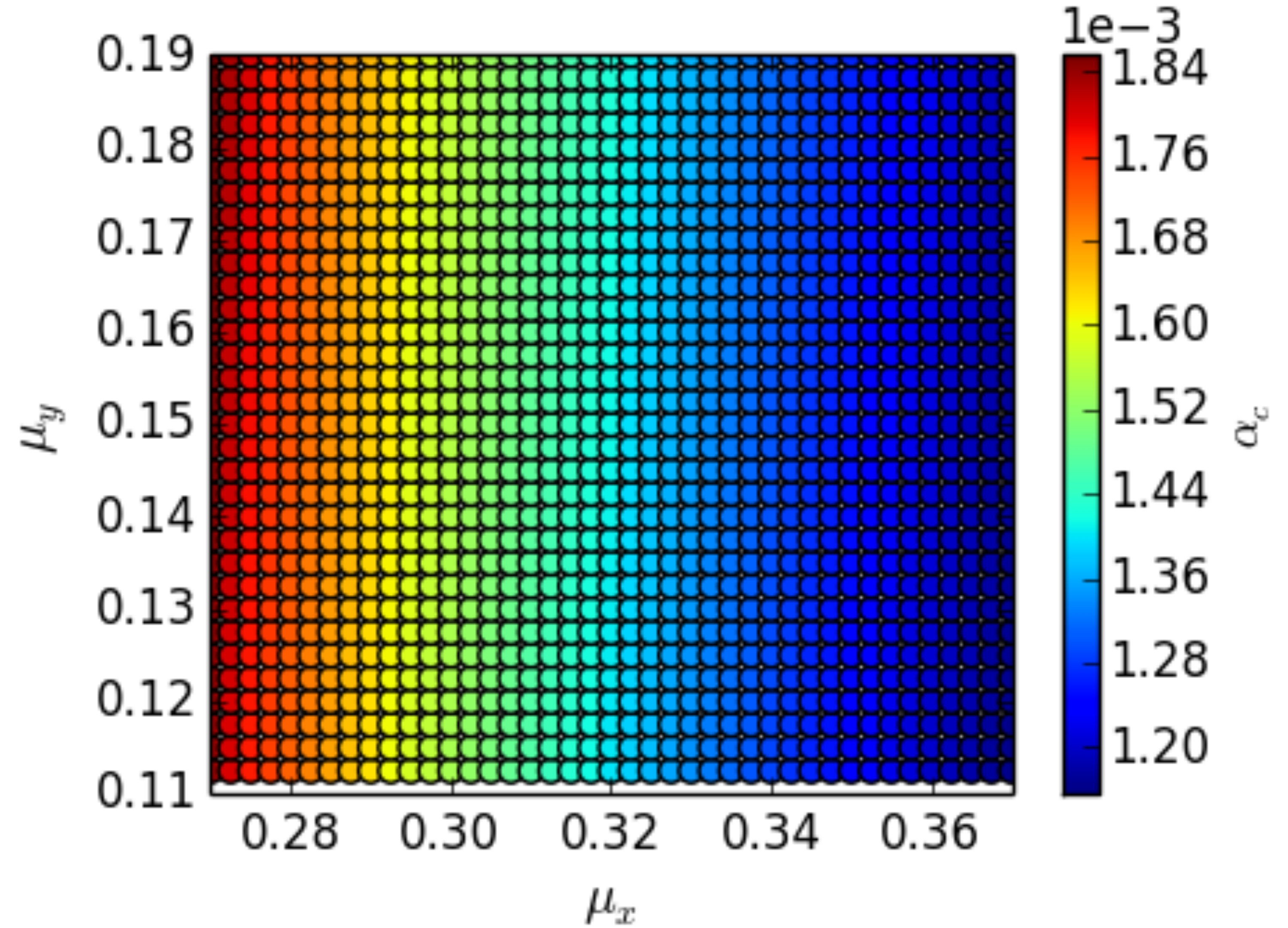
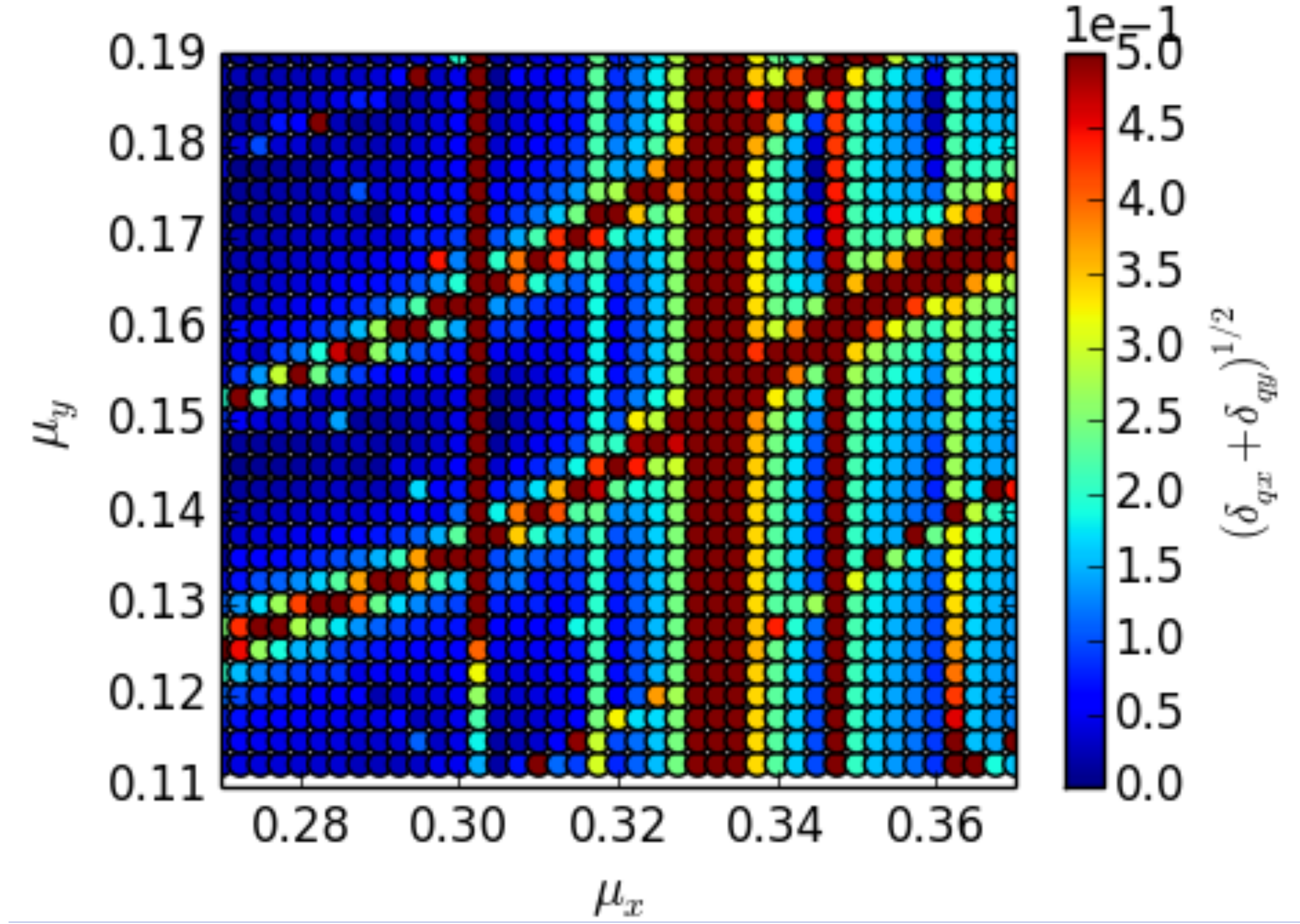
# Phase advance scanning

h/v **emittance** is mainly determined **by arcs** in the ring. Thus, FODO **phase advance** in the arc is scanned to observe the behavior of some important parameters like **emittance**, **chromaticity**, **tune shift with amplitude**, **momentum compaction factor** etc.









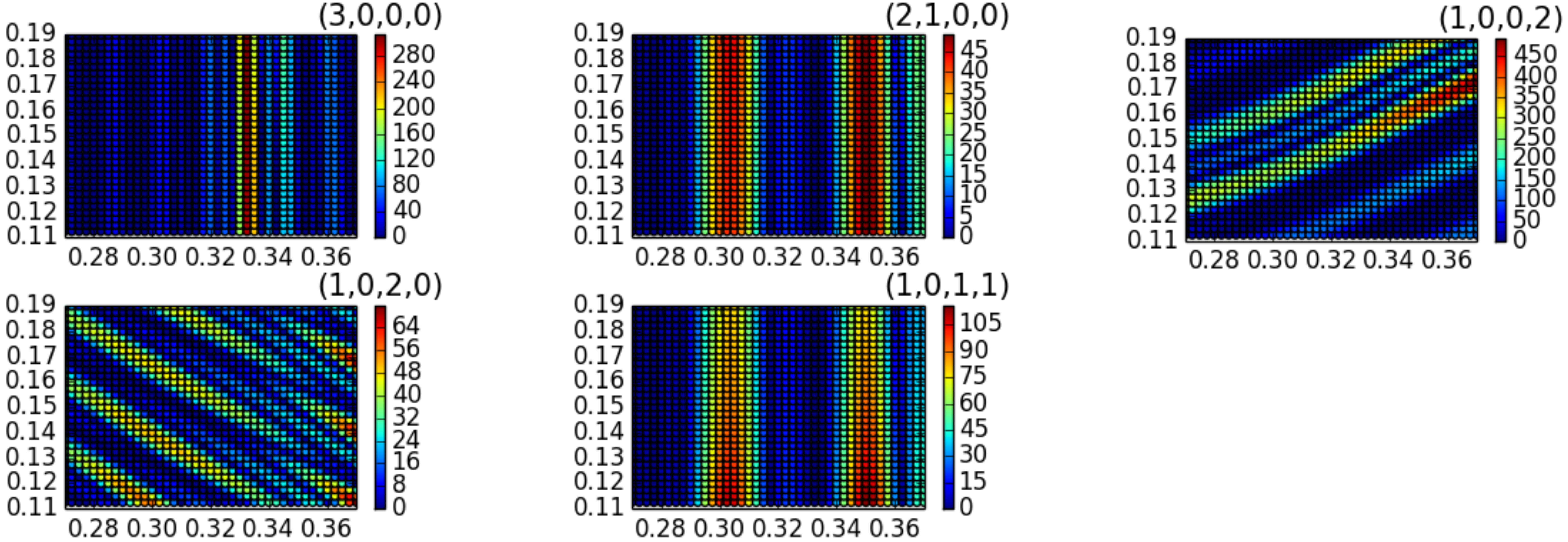
- h/v **chromaticity** seems around **-40/-35 at the specified area.**

- **Momentum compaction factor** seems around **1.8*10$^{-3}$**.

- Tune shift with amplitude seems low at the specified phase advances. We choose lower horizontal/vertical (~0.27/0.11) phase advance.

# Phase advance scanning

- The MAD-PTC has been used for the calculation of resonance driving terms, taking into account fringe fields.
- The resonance driving terms calculation have been performed for the ring for different phase advances of the FODO cell.
- Figures below shows the dependence of the third order resonance driving terms on the horizontal and vertical phase advances of the FODO cell.
- Blue means to small resonance excitation, while red indicates maximum excitation.



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# Phase advance scanning

- The MAD-PTC has been used for the calculation of resonance driving terms, taking into account fringe fields.
- The resonance driving terms calculation have been performed for the ring for different phase advances of the FODO cell.
- Figures below shows the dependence of the fourth order resonance driving terms on the horizontal and vertical phase advances of the FODO cell.
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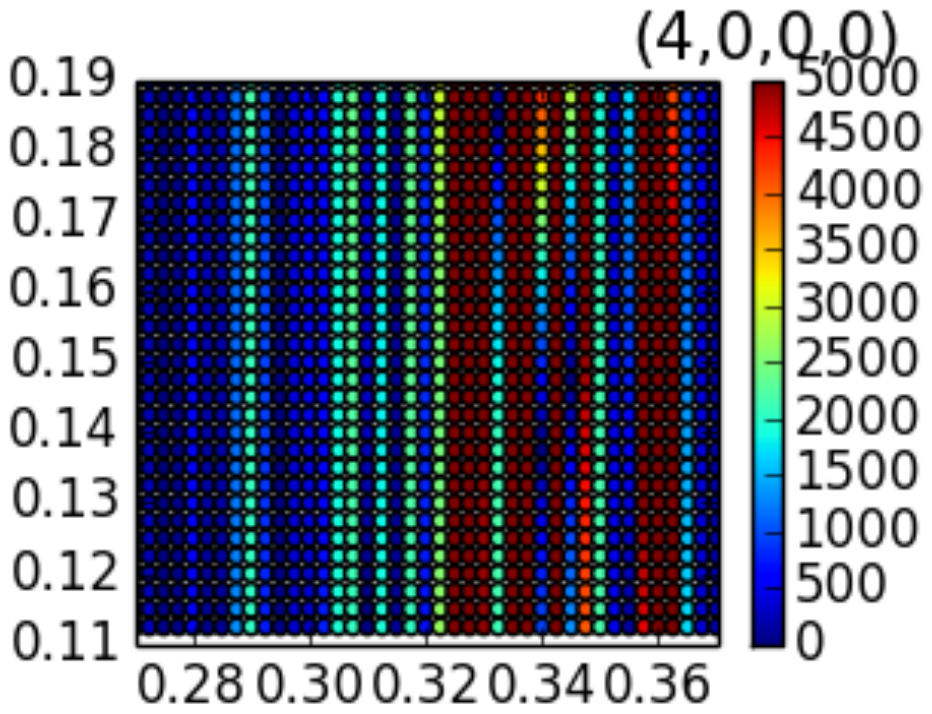

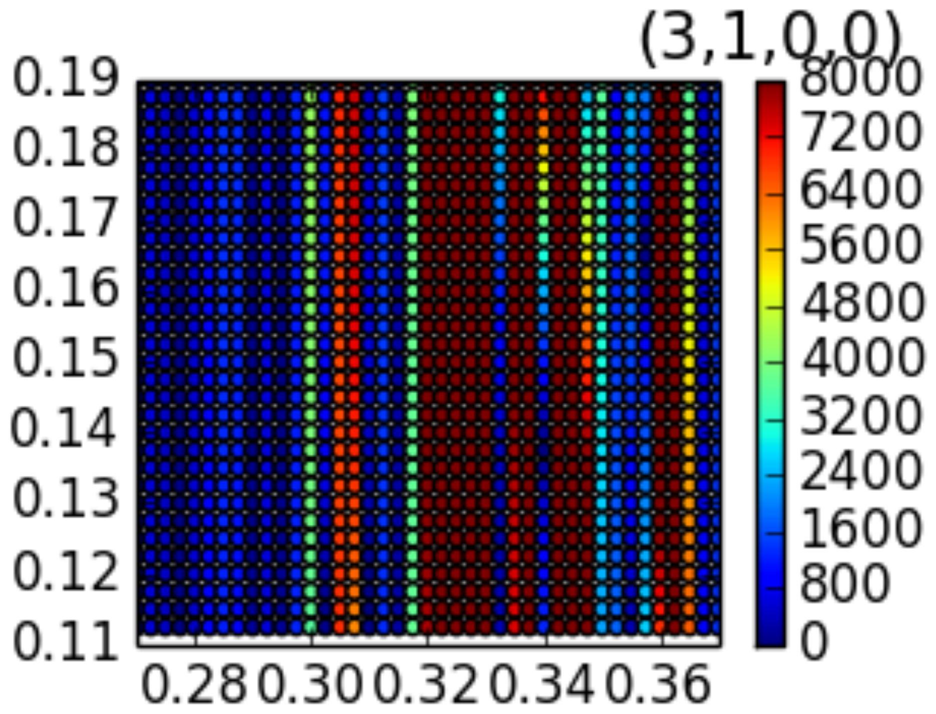

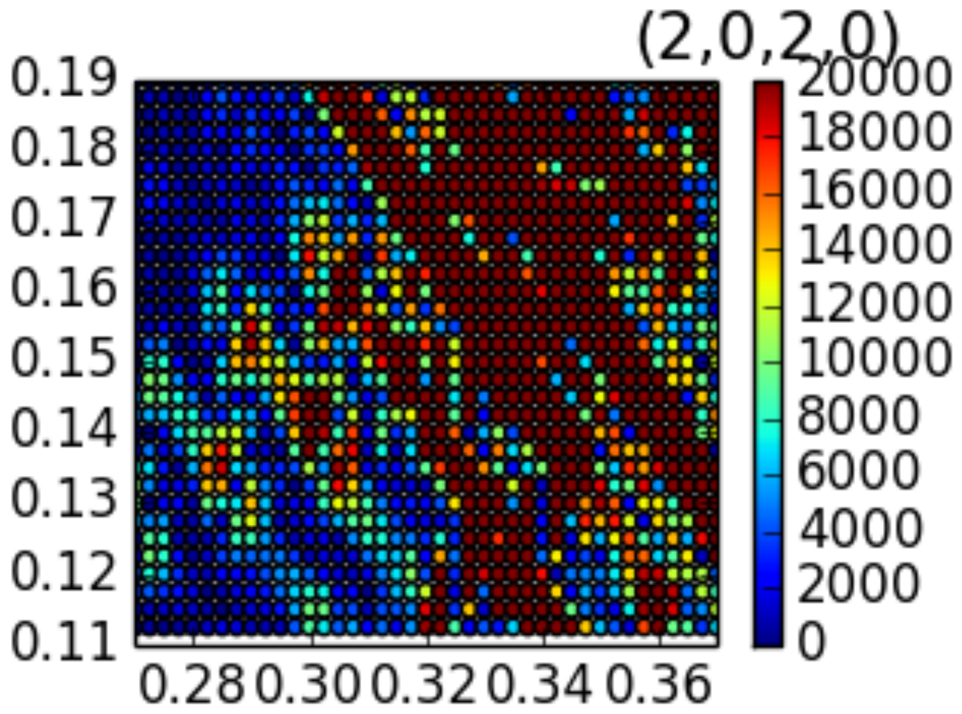

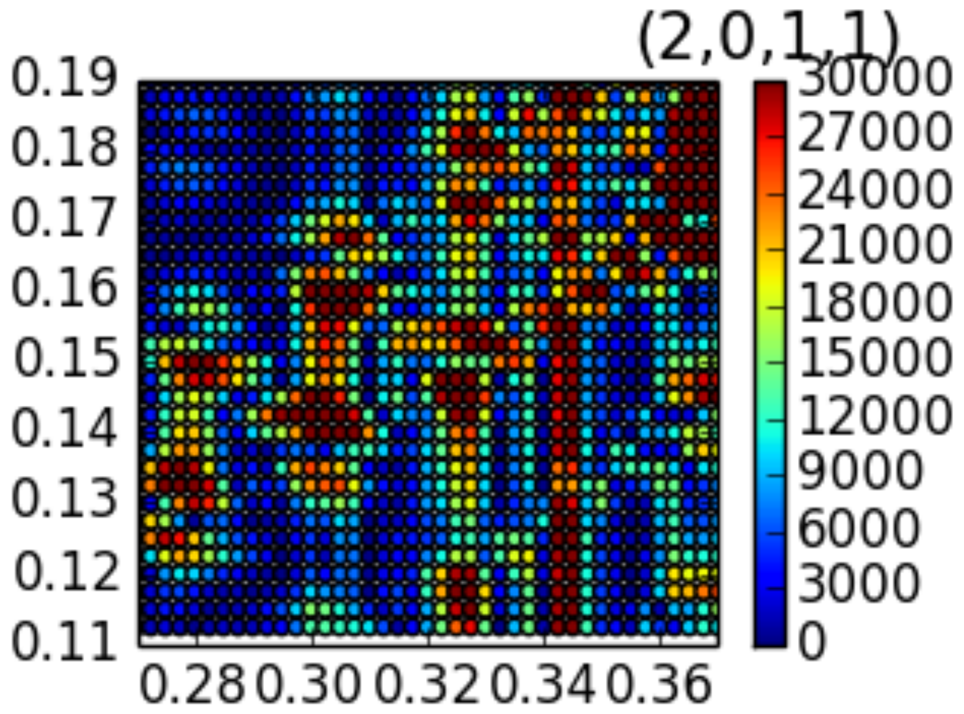

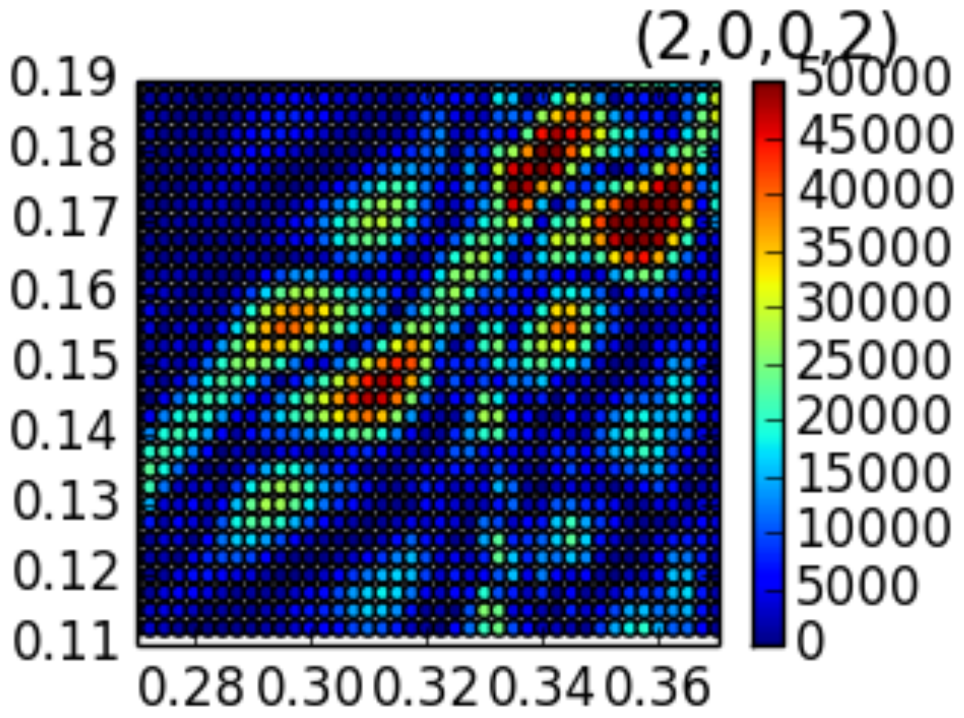

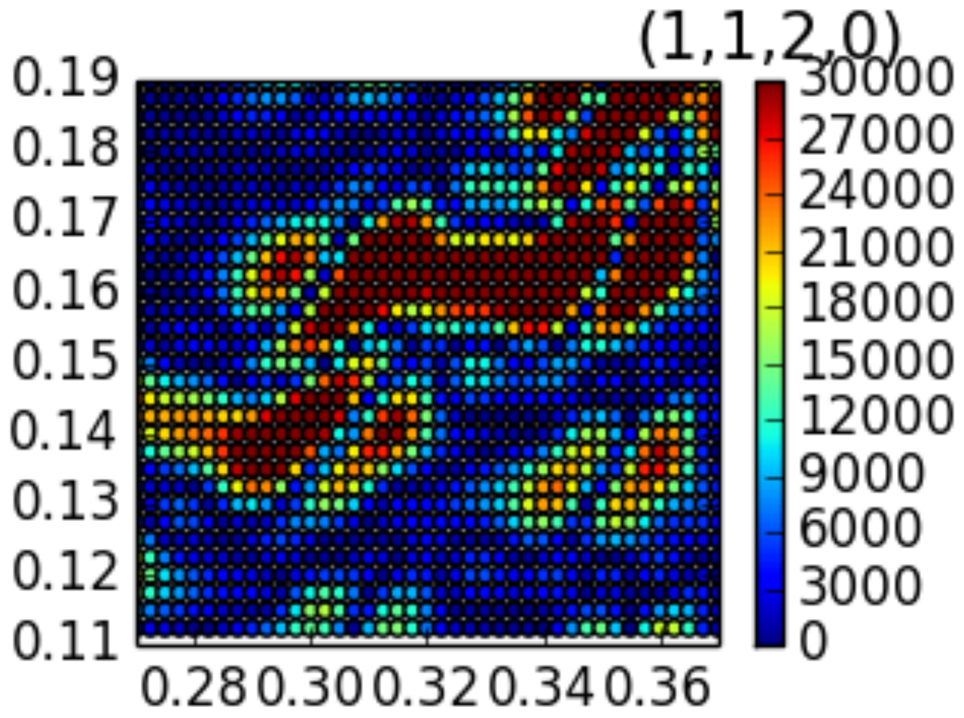

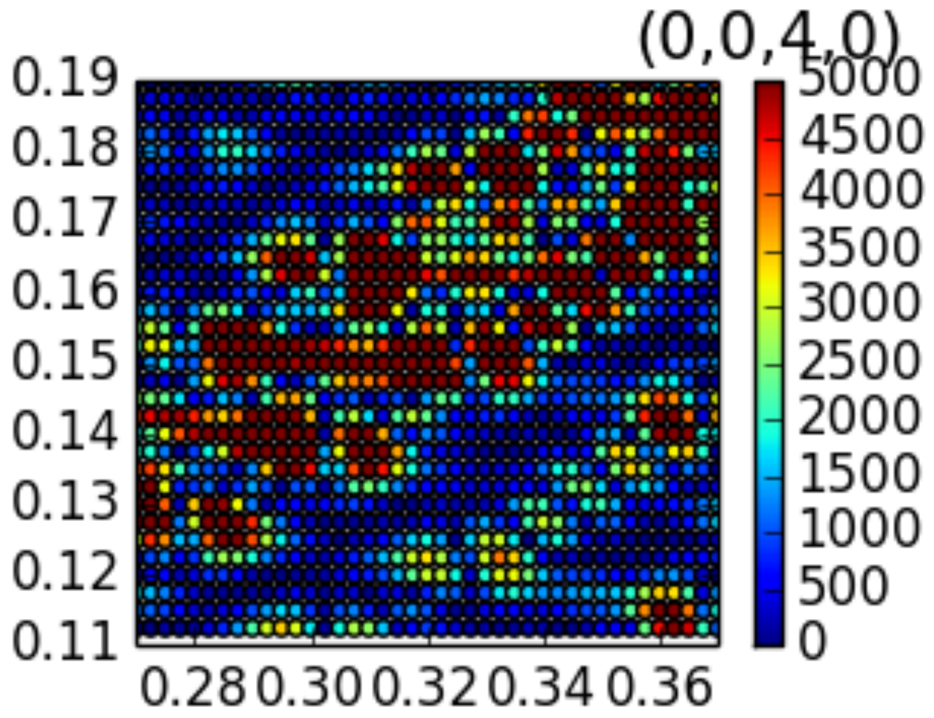

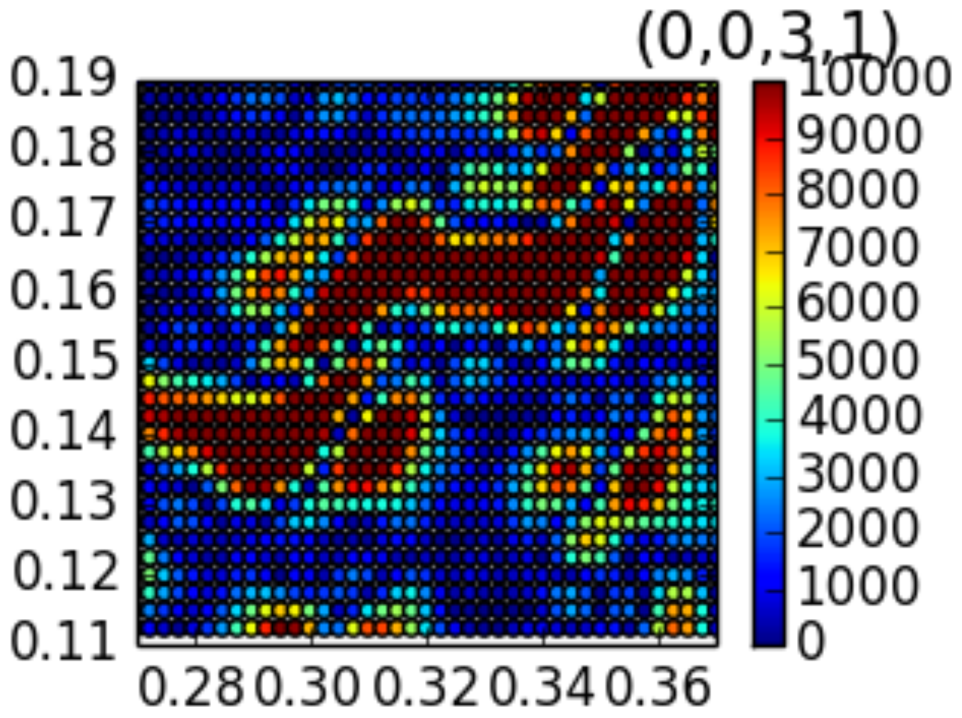

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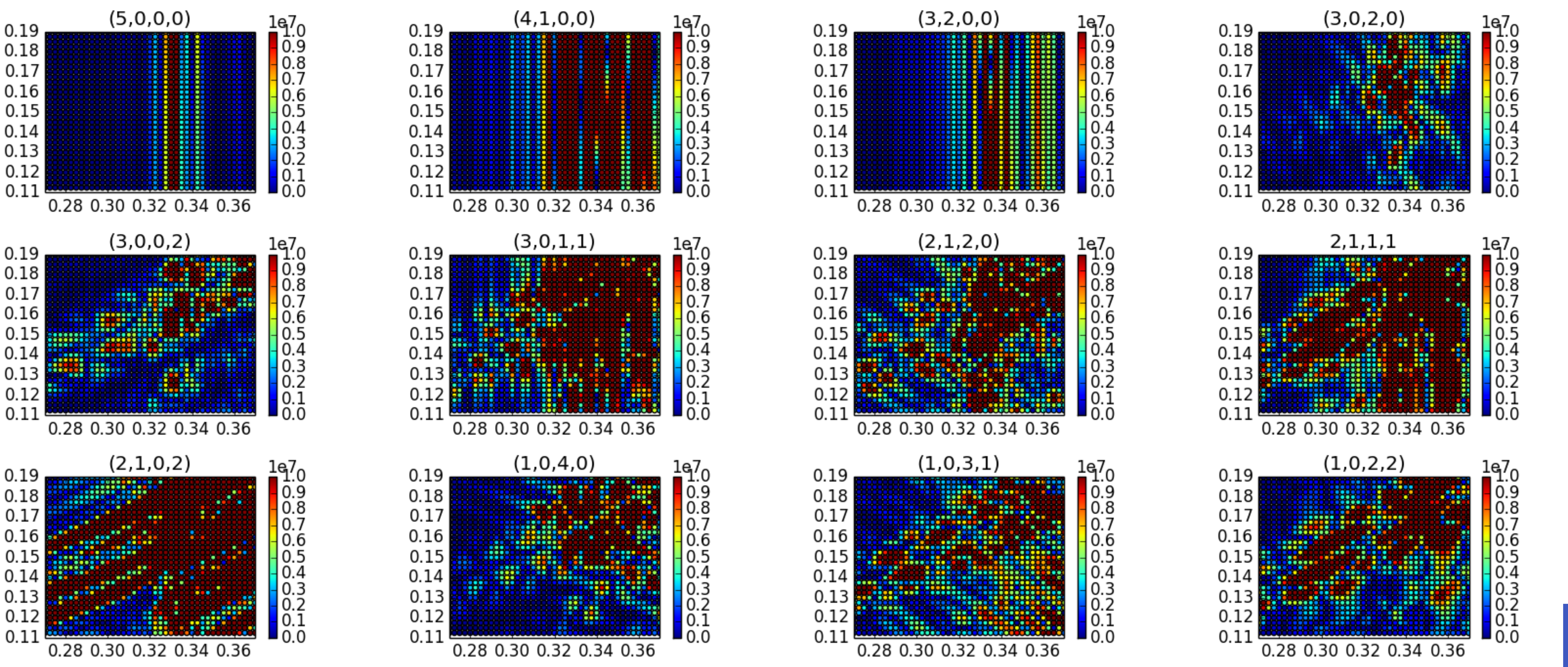
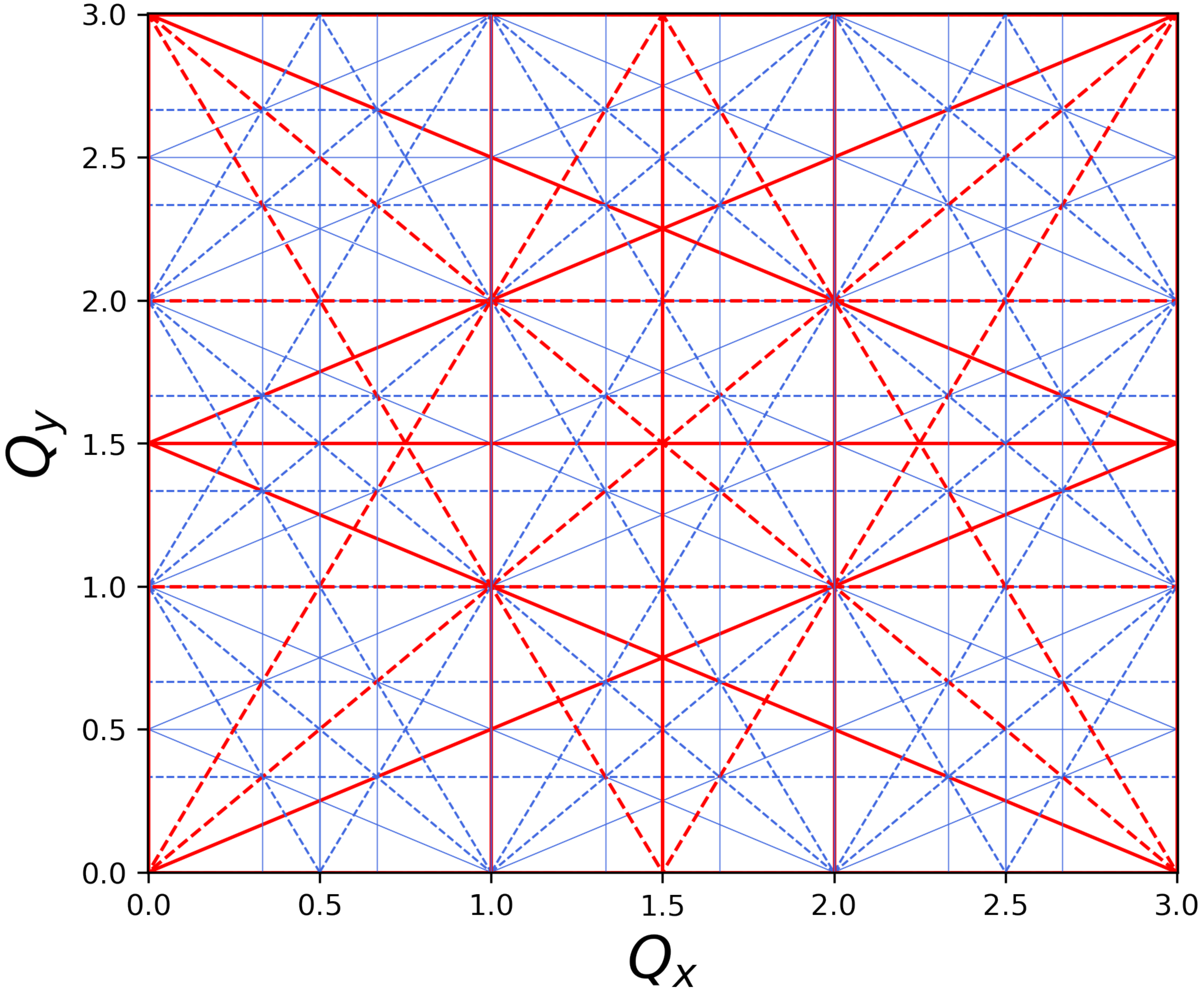
# Phase advance scanning

- The MAD-PTC has been used for the calculation of resonance driving terms, taking into account fringe fields.
- The resonance driving terms calculation have been performed for the ring for different phase advances of the FODO cell.
- Figures below shows the dependence of the fifth order resonance driving terms on the horizontal and vertical phase advances of the FODO cell.
- Blue means to small resonance excitation, while red indicates maximum excitation.



# Resonance diagram



**The resonance condition:**

$$n_xQ_x + n_yQ_y = r. \times P$$

- Tune working point on a resonance diagram up to 3th order
- Systematic **(red)**, non-systematic **(blue)**, normal **(solid)** and skew **(dashed)** resonances

Resonance diagram up to the 3rd order for a ring with a periodicity of 3 It is shown between 0-3 since it will repeat itself for every 4 integers due to the periodicity.

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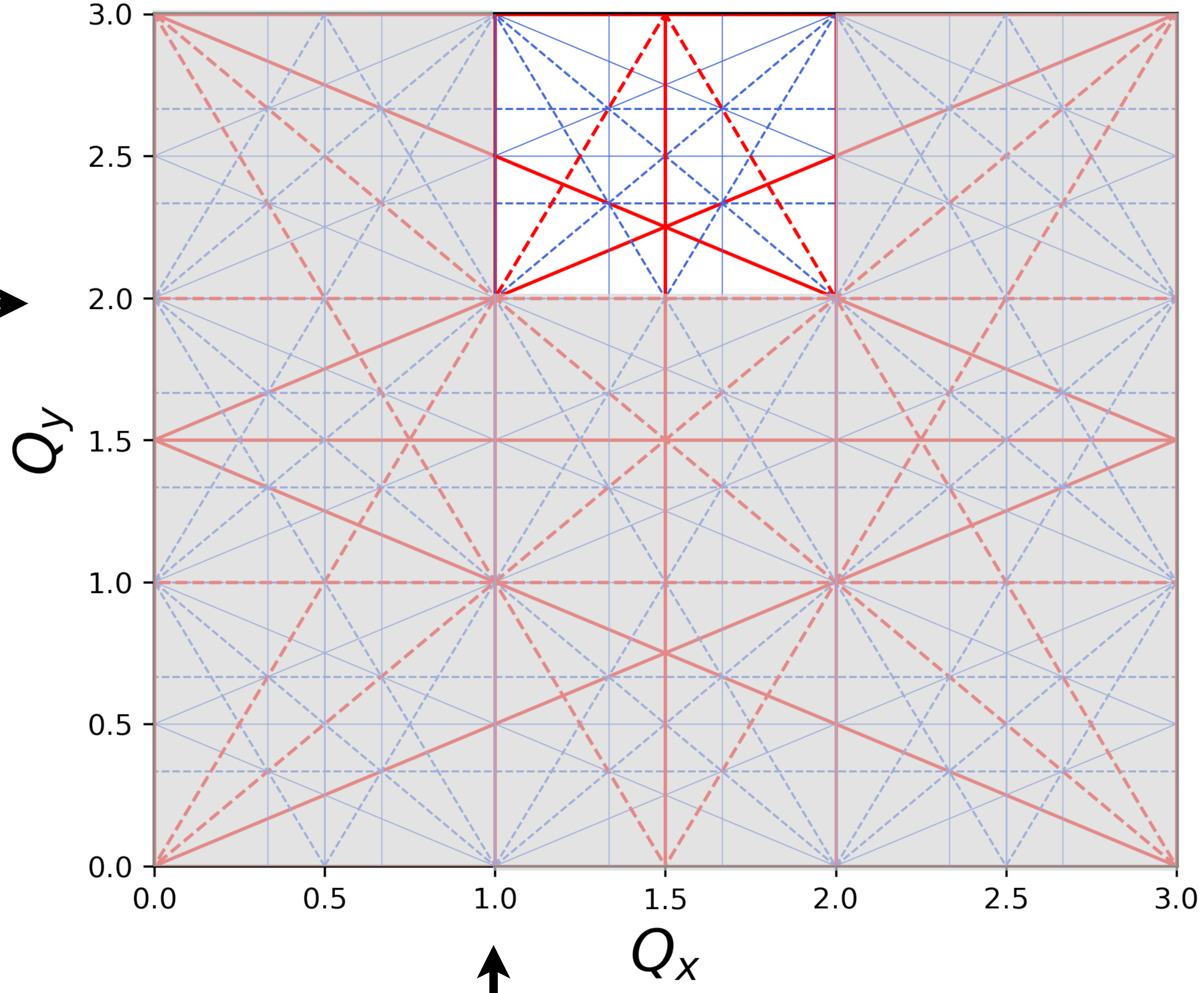
# Resonance diagram



**this corresponds to 0.11 $\mu_y$ ($Q_y$=14)**

**this corresponds to 0.27 $\mu_x$ ($Q_x$=28)**

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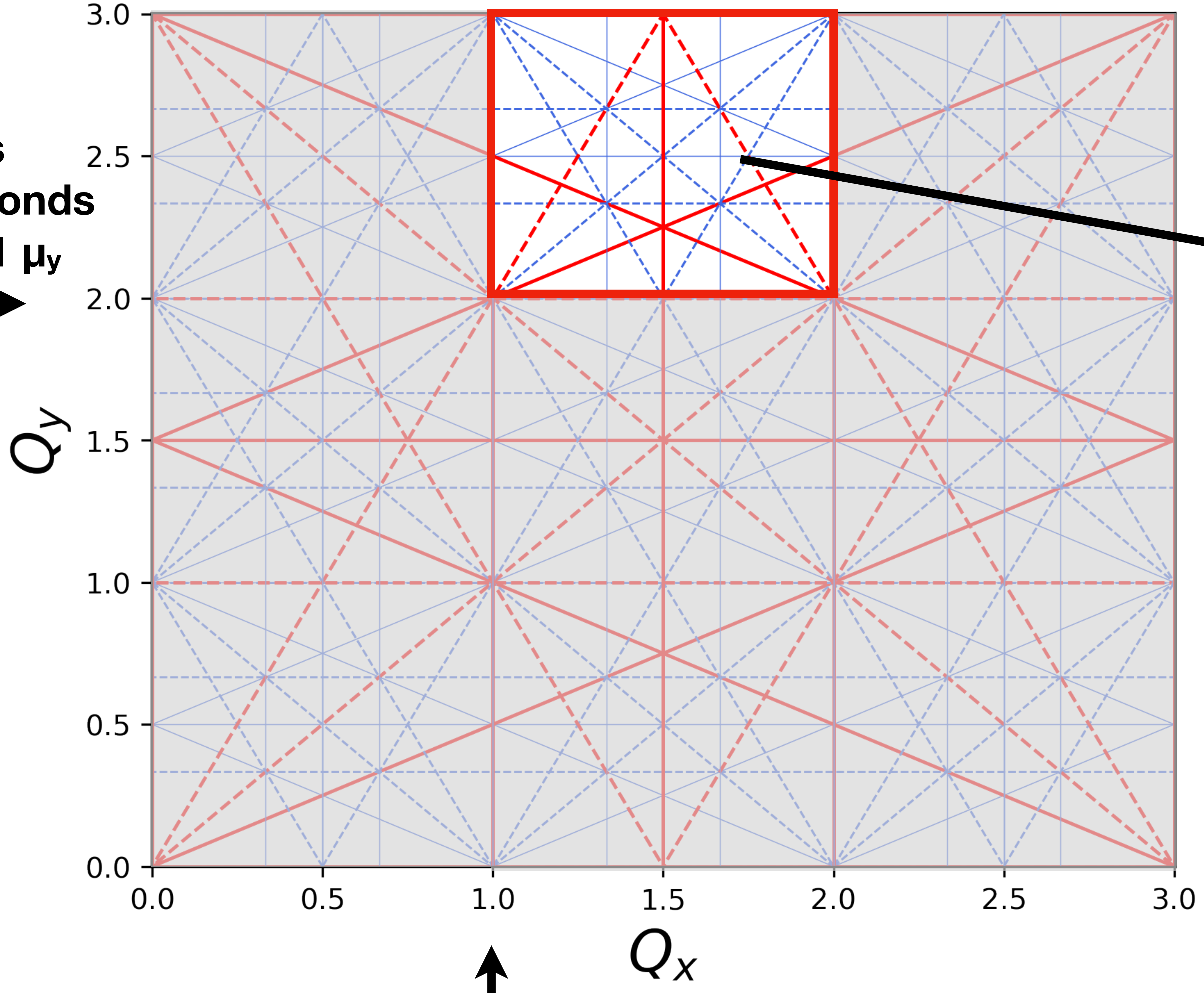
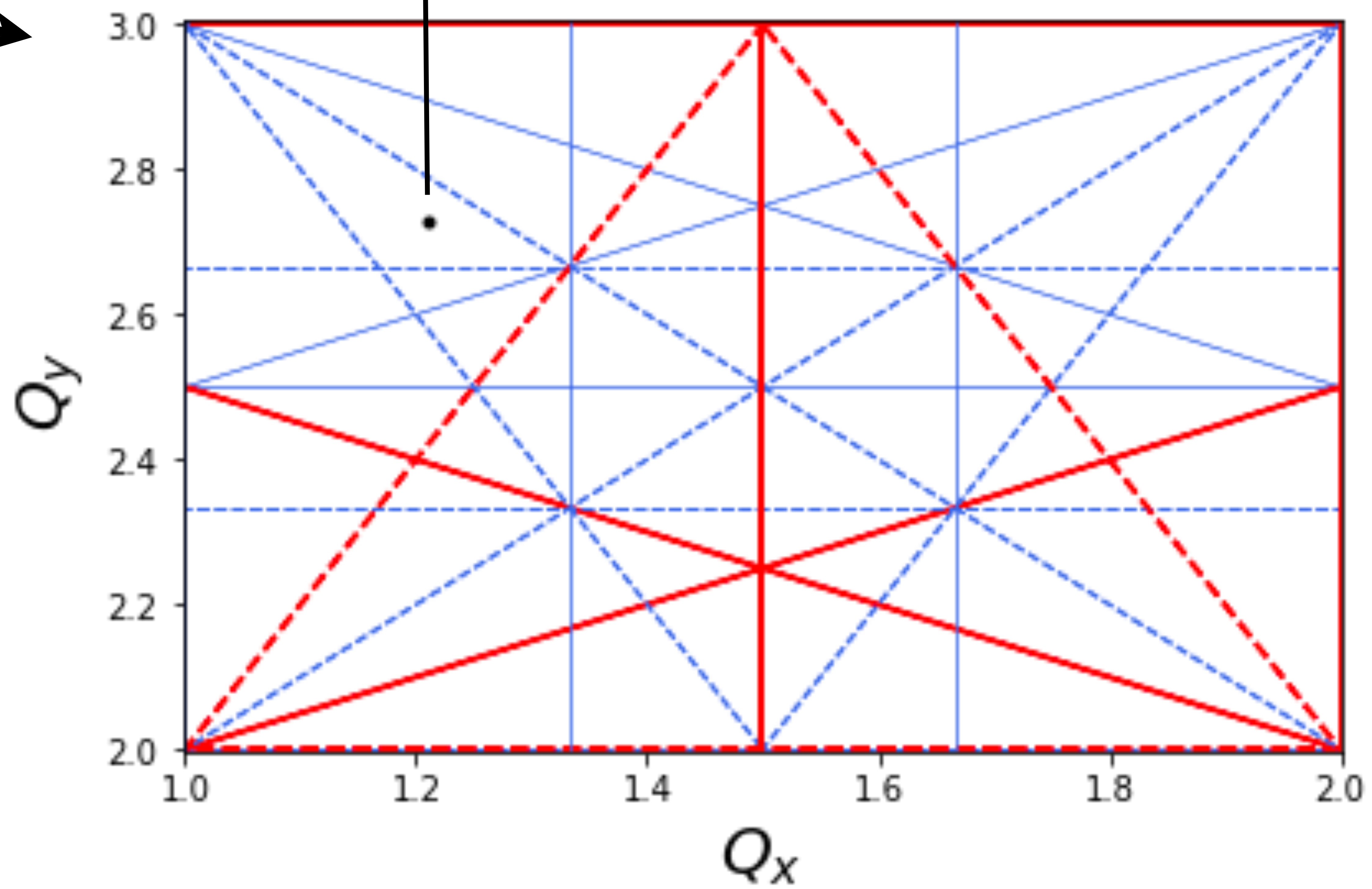
# Working point

**this corresponds to 0.11 $\mu_y$**



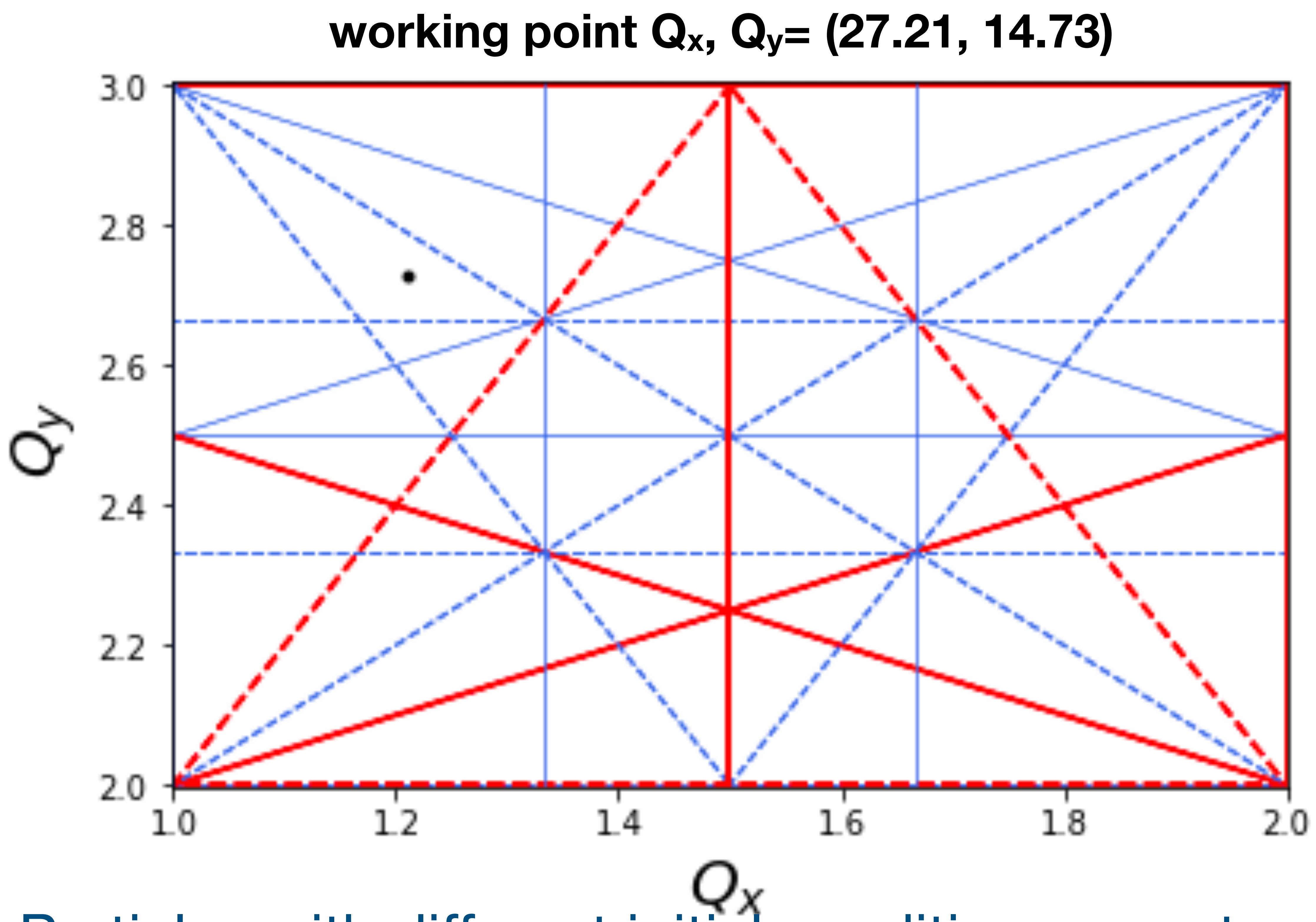
**this corresponds to 0.27 $\mu_x$**

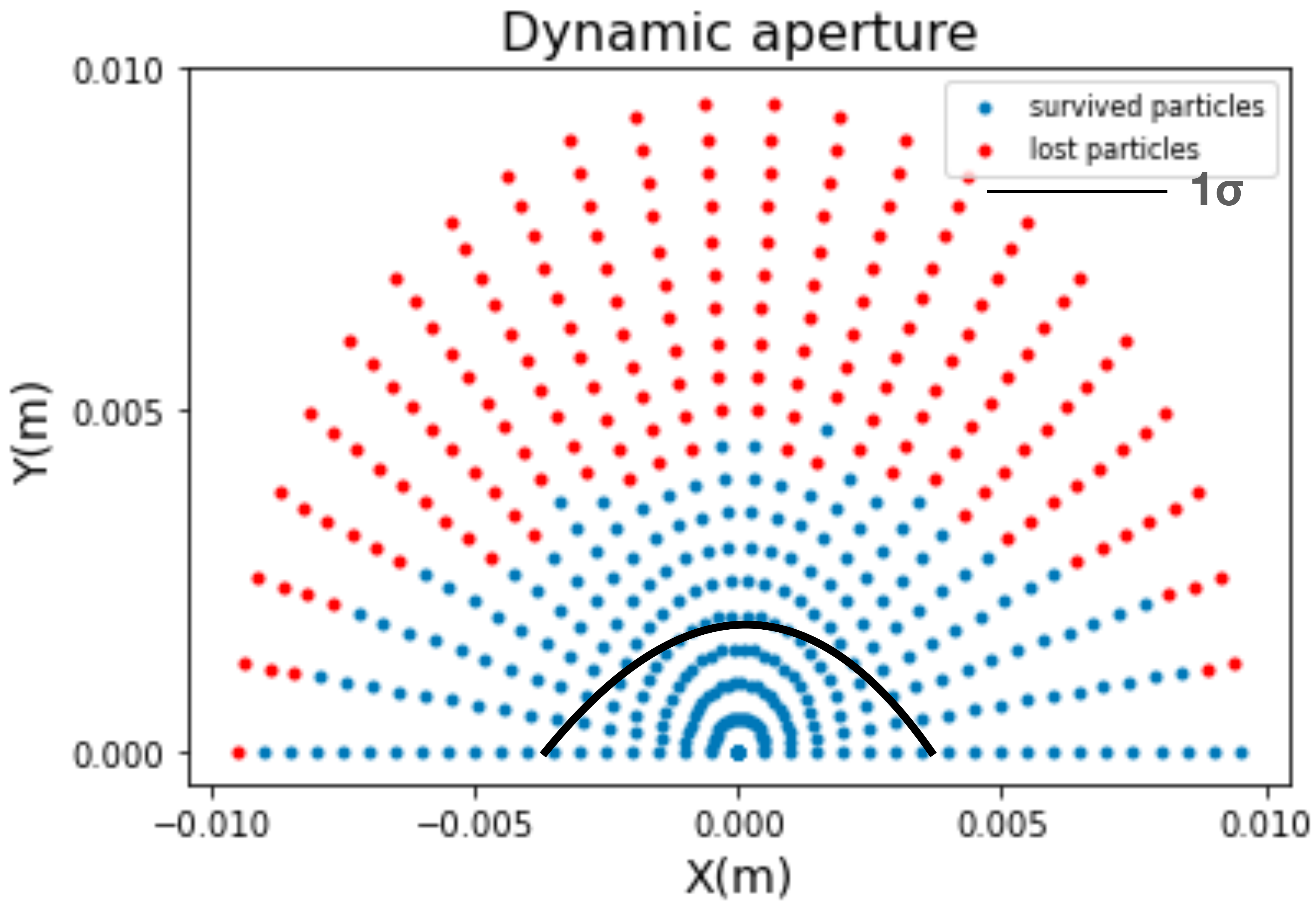
**working point $Q_x$, $Q_y$= (28.21, 14.73)**



# Dynamic aperture

- The **dynamic aperture** (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.





- Particles with different initial conditions were tracked for **1000 turns** (around 0.20 damping time).
- The DA of the DR for on energy machine is around **2.85σ** in horizontal plane and **2.65σ** in vertical plane.
- The results are for on-energy beam for now. Off-energy results are under study.

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# Summary and next steps

- Phase advance in horizontal plane has changed to relax the emittance up to 1.76 nm.rad,
- Detailed phase advance scanning has been performed for main parameters and rdt,
- Dynamic aperture calculation was performed and provided **2.85σ** in horizontal plane and **2.65σ** in vertical plane. Off-energy DA calculations are under study.
- DA studies will be going on in the following process.

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