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Minimizing the Fluctuation of Resonance Driving Terms for Analyzing and Optimizing the Storage Ring Dynamic Aperture

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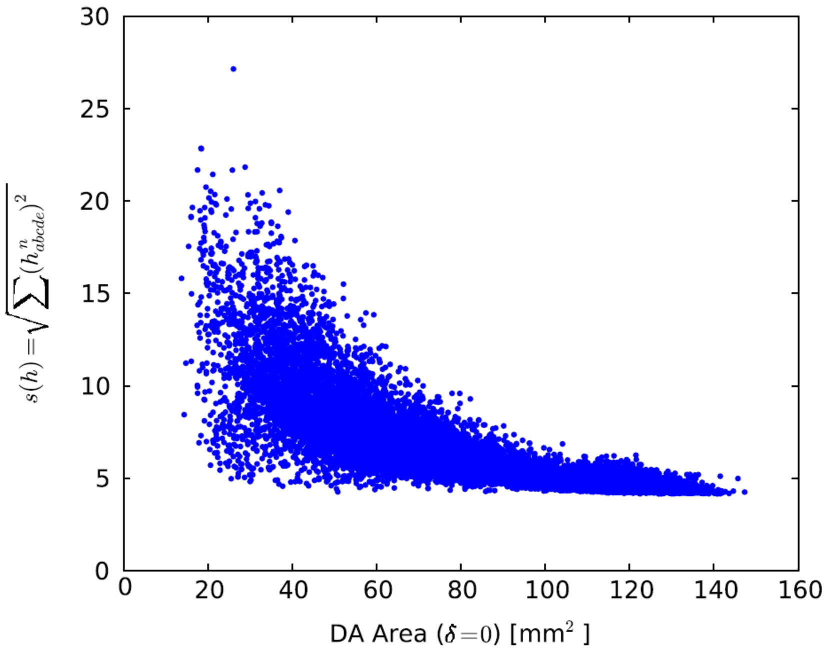
Outline

- ❑ Introduction
- ❑ Analyzing DA based on minimizing RDT fluctuations
  - ➢ Correlation between RDT fluctuations and DA
  - ➢ Physics behind minimizing RDT fluctuations
  - ➢ Low- and high-frequency RDT fluctuations
- ❑ Optimizing DA based on minimizing RDT fluctuations
- ❑ Conclusion

Dynamic aperture optimization

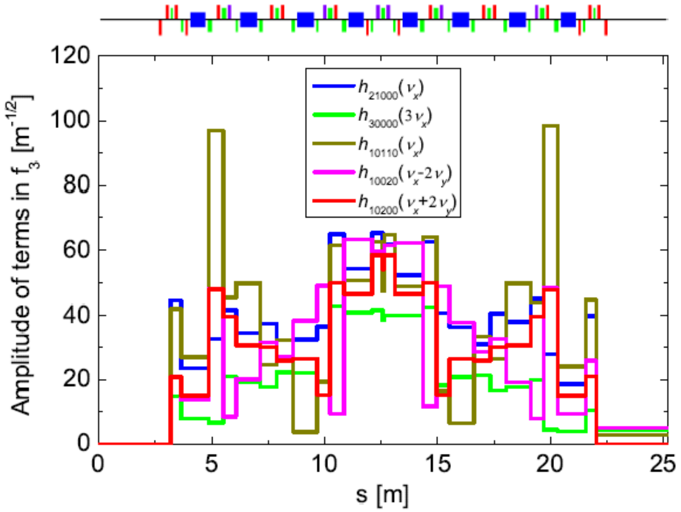
- Two widely-used approaches for dynamic aperture (DA) optimization
  - ① Minimization of resonance driving terms (RDTs)
  - ② Tracking based direct optimization with evolutionary algorithms
- The 1st analytical approach:
  - Small RDTs is a necessary but not sufficient condition for large DA (see the figure);
  - Fast optimization, physical analysis.
- The 2nd numerical approach:
  - In principle, the largest DA can be found;
  - Very time-consuming, basically no physics.
- For better DA optimization:
  - Powerful analytical approach (to be further developed) + powerful numerical approach.



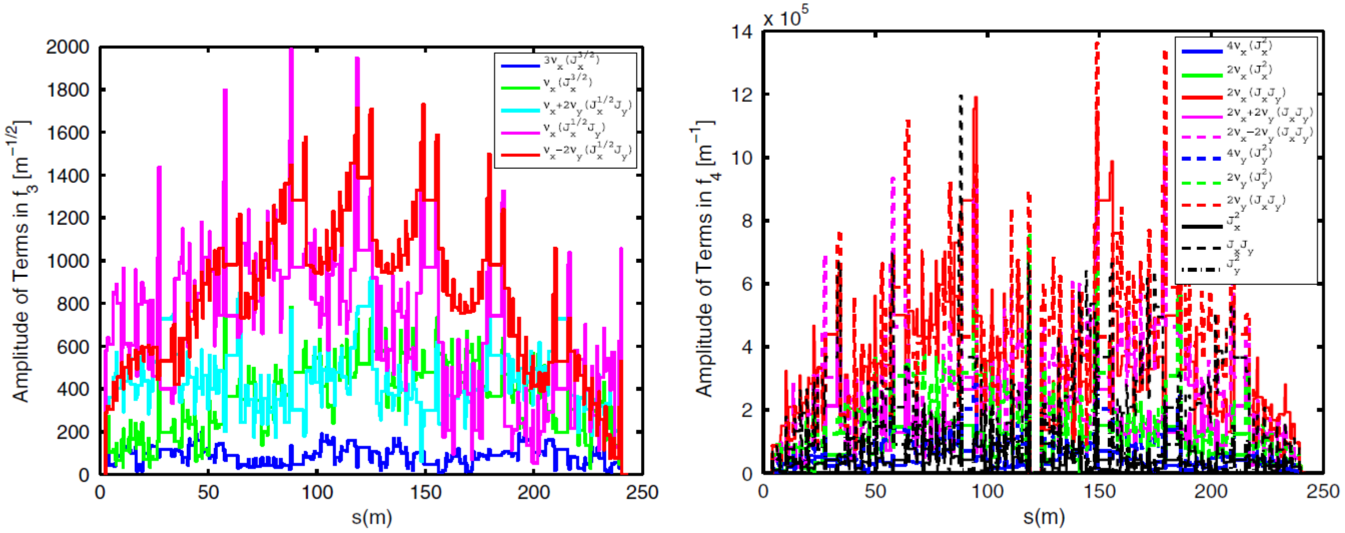
Correlation between DA area and RDTs.
L. Yang, et al., PRAB, 14, 054001 (2011).

Control of the variation / fluctuation of RDTs

- Nonlinear dynamics cancellation
  - The nonlinear cancellation within a lattice cell (left figure) is more effective than the cancellation over some cells (right figure) in enlarging the DA.
  - The variation / fluctuation of RDTs in the former is smaller than that in the latter, which inspires us that reducing the RDT fluctuations could be very beneficial for enlarging the DA.



The variation of 3rd-order RDTs along a lattice cell.



The variation of 3rd- and 4th-order RDTs along 8 lattice cells.
Y. Cai, et al., PRST-AB, 15, 054002 (2012).

Correlation between RDT fluctuations and DA

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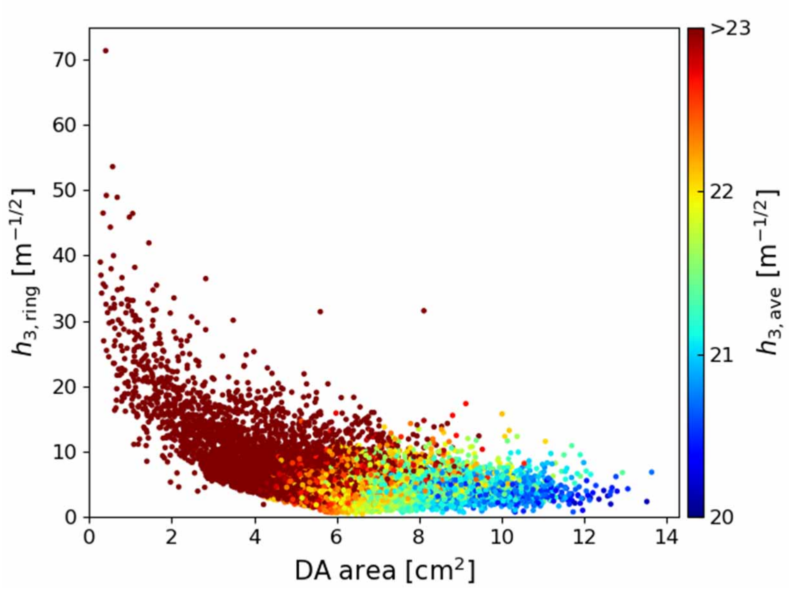
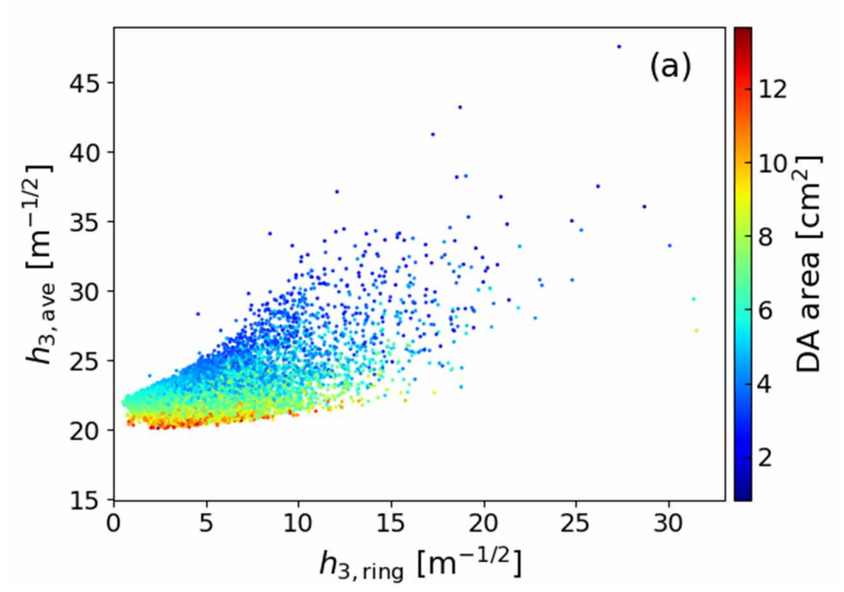
- The 1st lattice example:
  - Double-bend achromat lattice of SSRF
  - 8 families of sextupoles, 10000 nonlinear solutions
- The RDT fluctuations are quantitatively represented by the average RDTs.
- Minimizing RDT fluctuations is more effective than minimizing the commonly used one-turn RDTs in enlarging the DA.





Correlation between DA area, 3rd-order one-turn RDTs ($h_{3,\ ring}$) and 3rd-order RDT fluctuations ($h_{3,\ ave}$) .

Correlation between RDT fluctuations and DA

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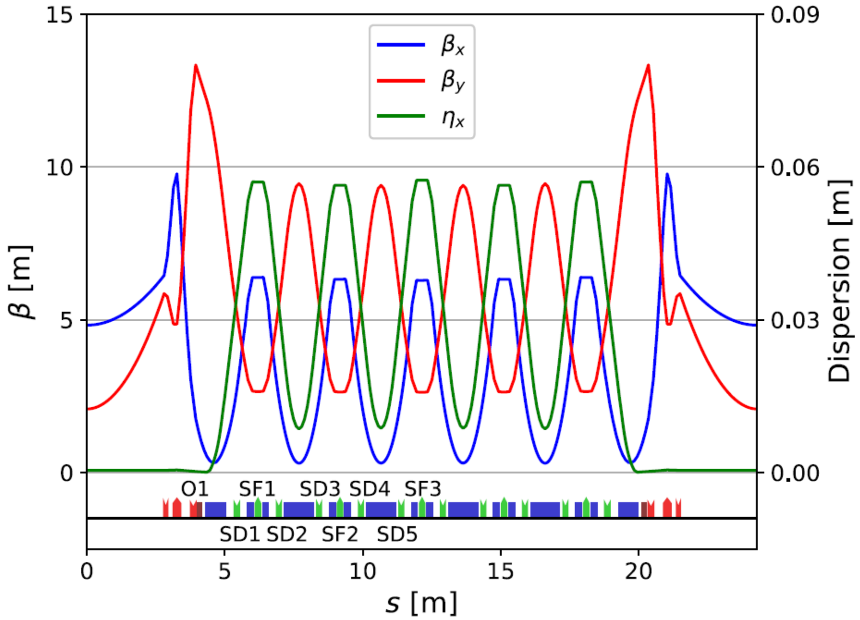
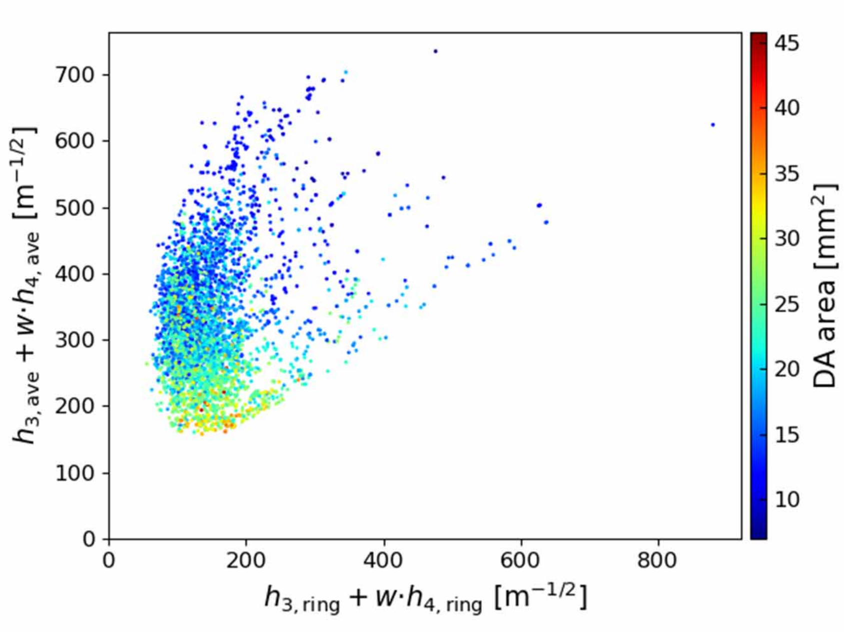
- The 2[st] lattice example:
  - Six-bend achromat lattice
  - 8 sextupole families + 1 octupole family
- Both 3[rd]- and 4[th]-order RDTs are considered.
- Minimizing RDT fluctuations is also more effective.



Six-bend achromat lattice.



Correlation between DA area, one-turn RDTs and RDT fluctuations.

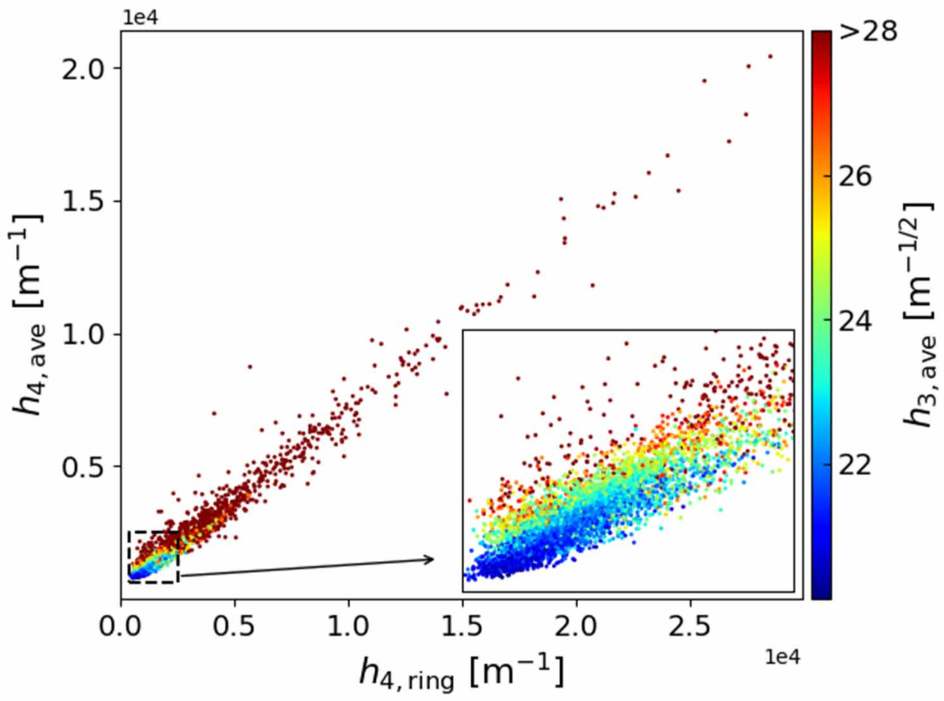
Correlation between low- and higher-order RDTs

- Lattice example: SSRF lattice

- As we know, for the commonly used one-turn RDTs, if the 3rd-order one-turn RDTs are smaller, the 4th-order one-turn RDTs can be larger.

- Reducing 3rd-order RDT fluctuations can help reduce both 4th-order RDT fluctuations and 4th-order one-turn RDTs.

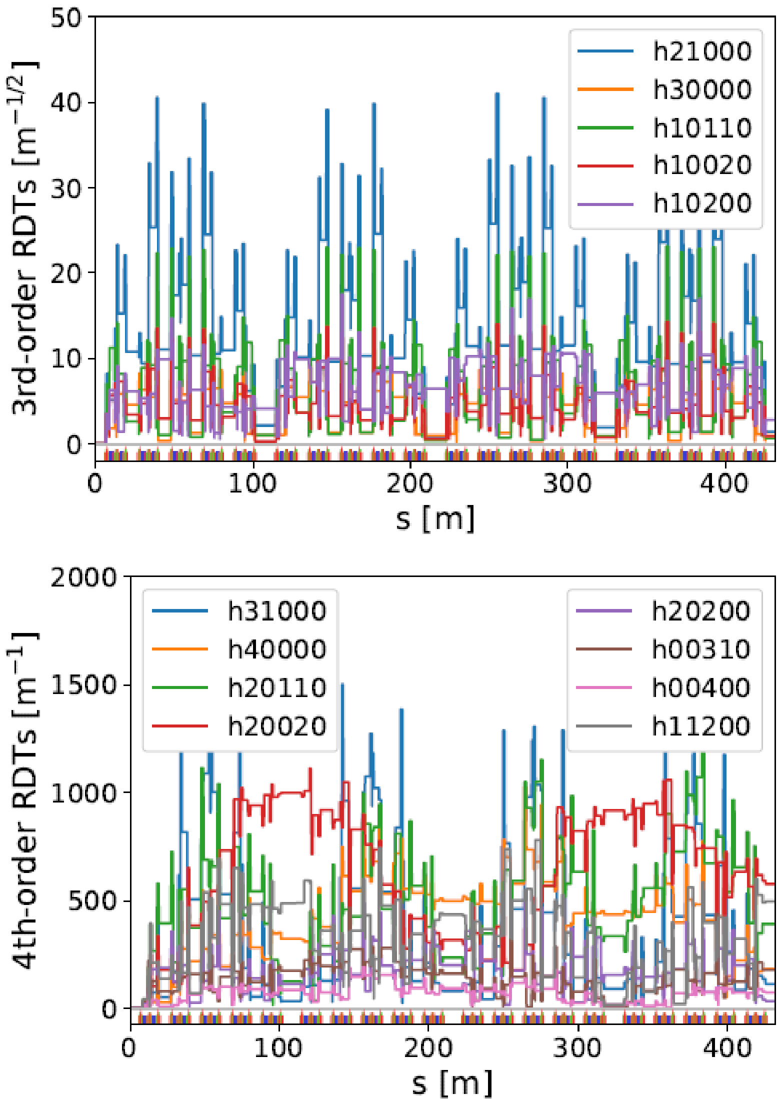
- How about 5th-order RDTs if 3rd-order RDT fluctuations are reduced?
  - Demonstrated using frequency map analysis.



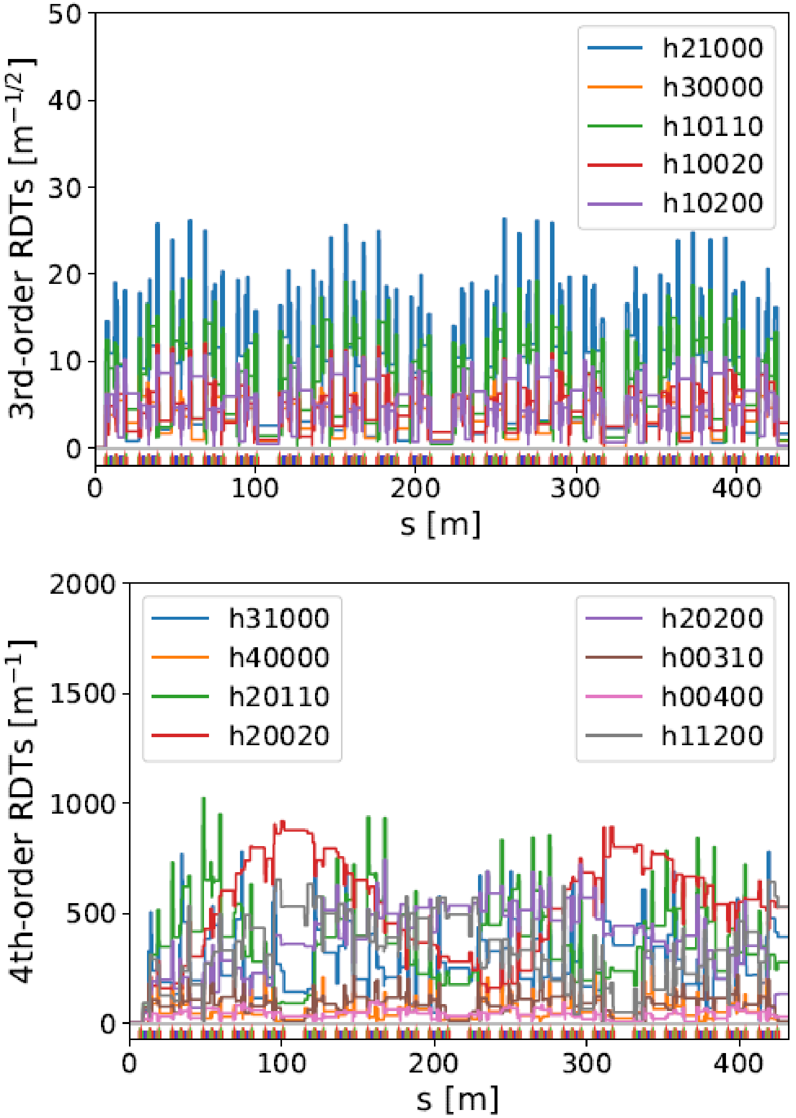
Correlation between low- and higher-order RDTs.

Correlation between low- and higher-order RDTs

1st nonlinear solution: larger RDT fluctuations



2nd nonlinear solution: smaller RDT fluctuations



Correlation between low- and higher-order RDTs

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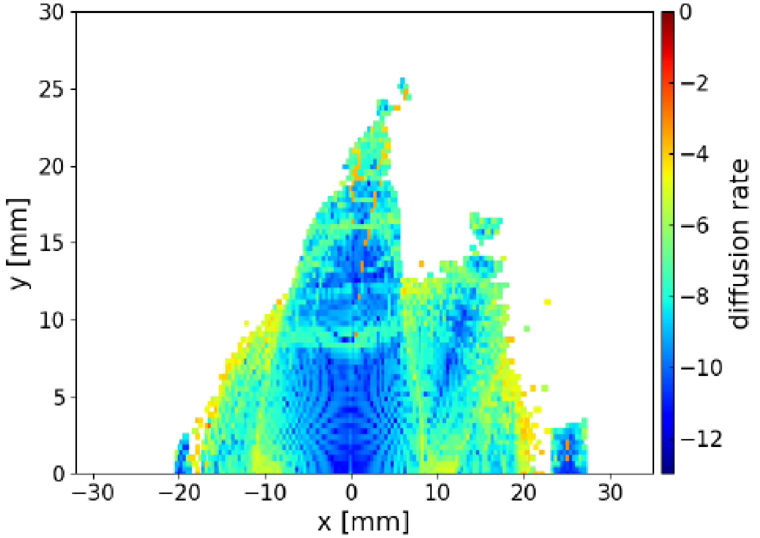
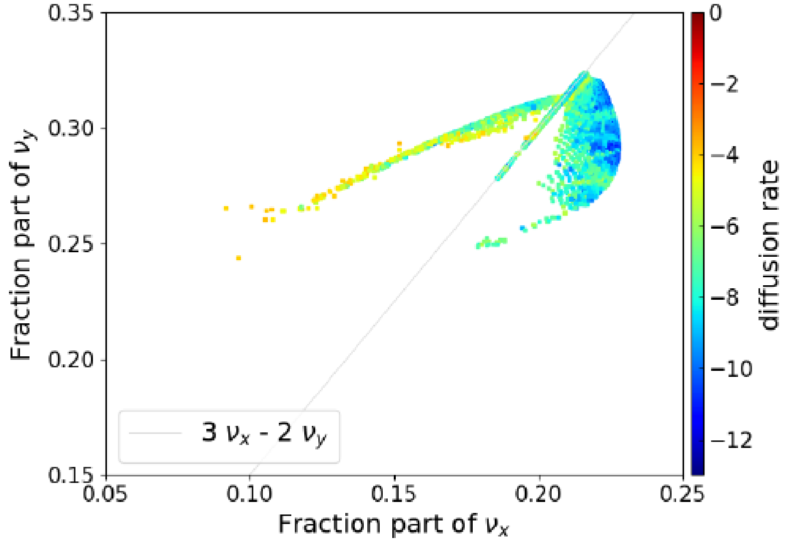
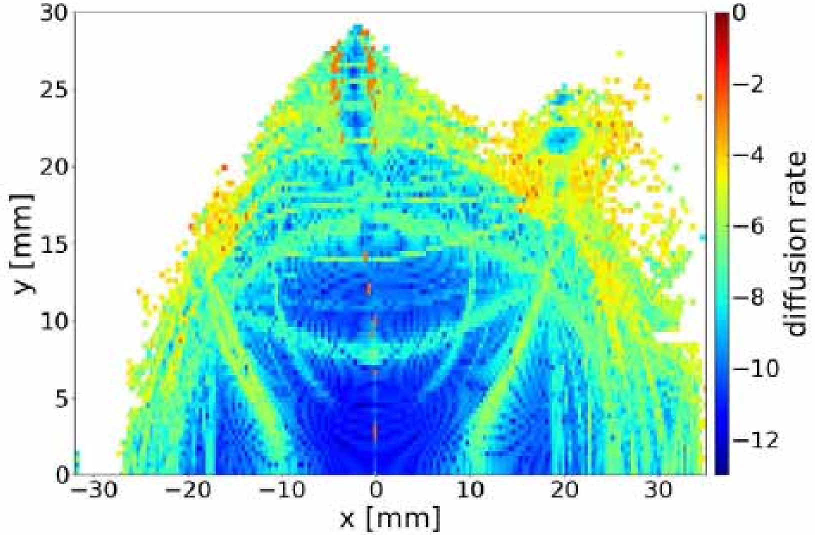
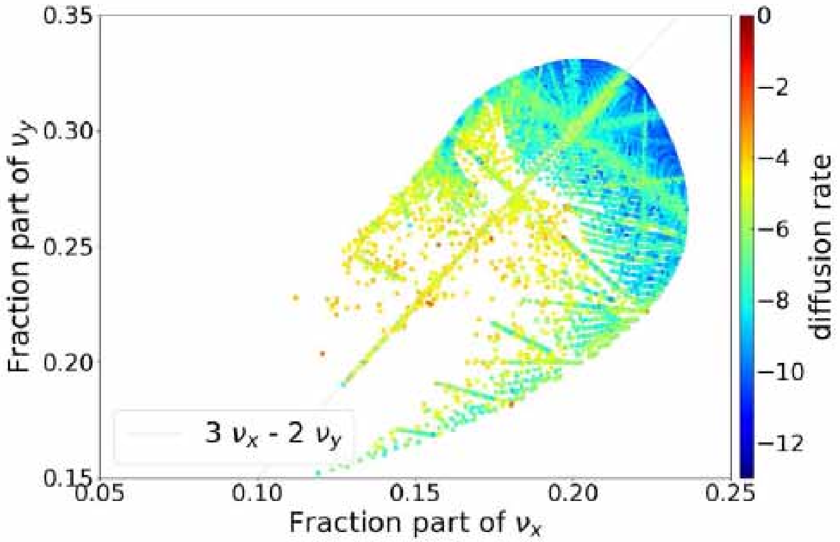
1st nonlinear solution: larger RDT fluctuations





2nd nonlinear solution: smaller RDT fluctuations





Physics behind minimizing RDT fluctuations

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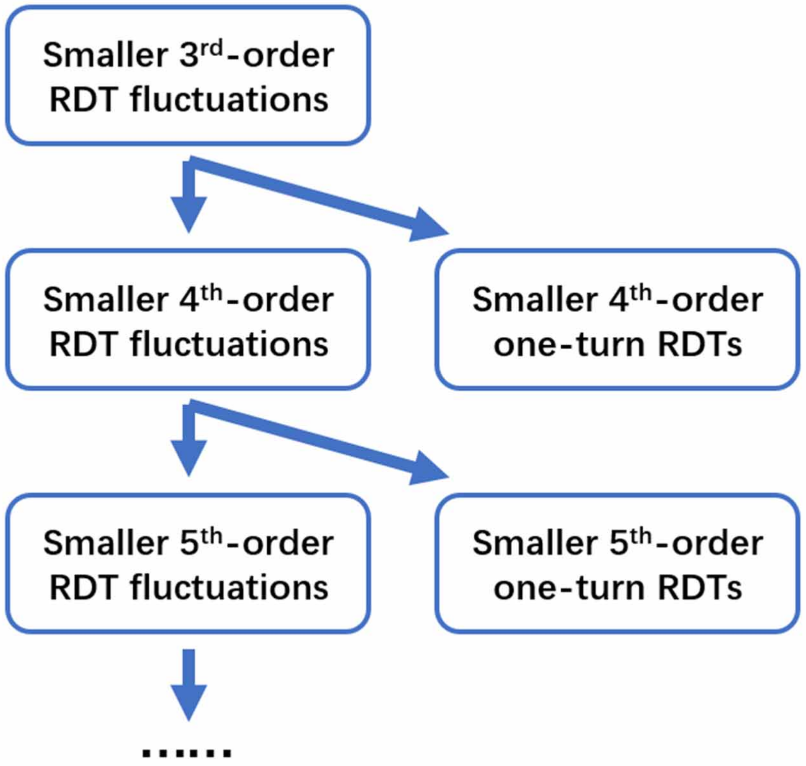
- Reducing low-order RDT fluctuations can help reduce higher-order and even higher-order RDTs.

- Based on minimizing RDT fluctuations, it would not be necessary to calculate higher-order RDTs in DA optimization.
  - For RDTs higher than 4th-order, they are not only more computationally complicated but also more numerous.

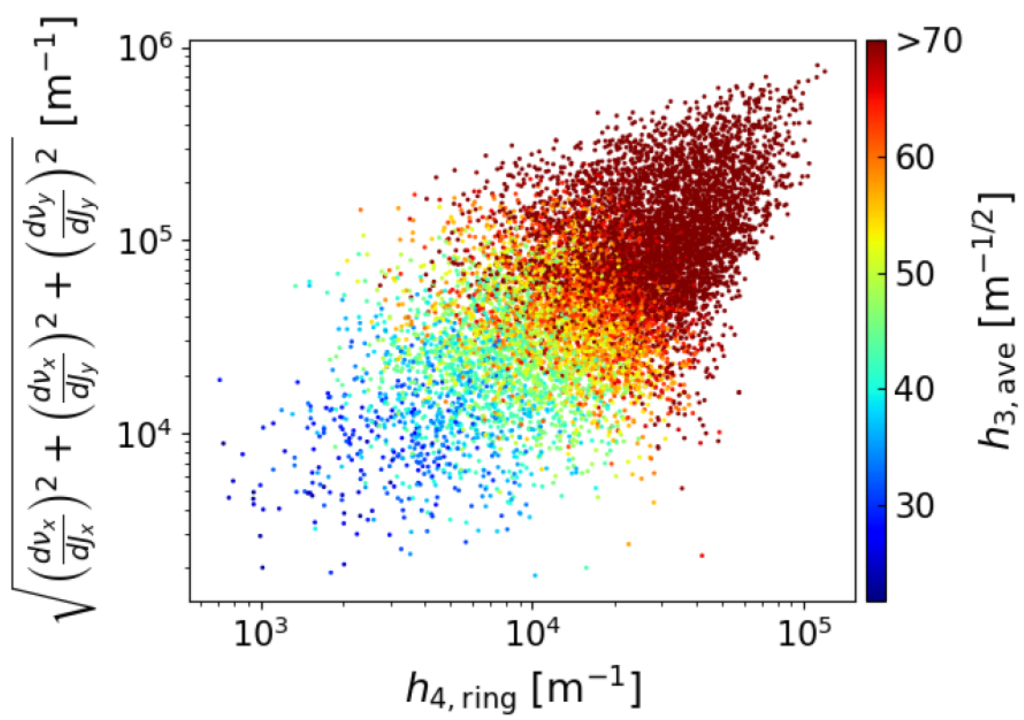


Schematic of the correlation between low- and higher-order RDTs.

Physics behind minimizing RDT fluctuations

- To have a larger DA, both RDTs and amplitude dependent tune shift (ADTS) terms need to be controlled.

- Reducing 3rd-order RDT fluctuations can also help control ADTS terms (see the figure).
    - Also taking the SSRF lattice as an example



Correlation between 3rd-order RDT fluctuations, 4th-order one-turn RDTs and ADTS terms.

Low- and high-frequency RDT fluctuation

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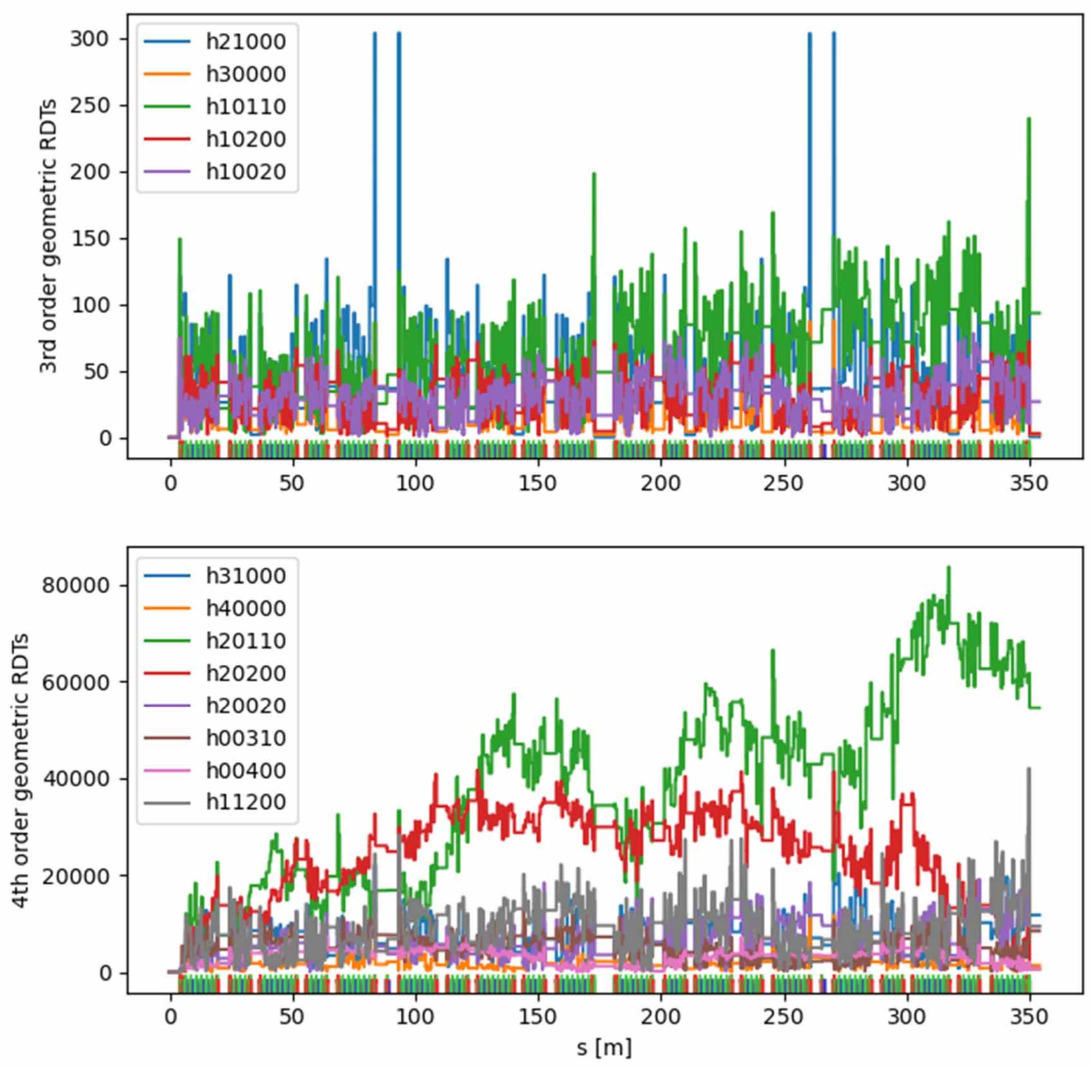
- RDT fluctuations are like waves, which can be considered to have low- and high-frequency RDT fluctuations.
- The low-frequency RDT fluctuations are related to the nonlinear cancellation over some lattice cells.
- The high-frequency RDT fluctuations are related to the nonlinear cancellation within a lattice cell.



3rd- and 4th-order RDT fluctuations of the SOLEIL II lattice.

Dynamics issues in the SOLEIL II CDR lattice

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- The SOLEIL II CDR lattice was designed and studied for different cases:
  - betatron tunes of (54.2, 18.2) & (53.2, 17.2)
  - low and high H-beta @ injection straight section

- Issue 1: When (54.2, 18.2) is reduced to (53.2, 17.2), the DA becomes smaller.
  - The storage ring has 2 super-periods, there is a rough –I transformation between 2 super-periods for the tunes (53.2, 17.2);
  - Smaller tunes are also beneficial for improving nonlinear dynamics.

- Issue 2: When the H-beta @ injection straight is increased to ~20 m, the DA is not increased.

Issue 1: tunes of (54.2, 18.2) & (53.2, 17.2)

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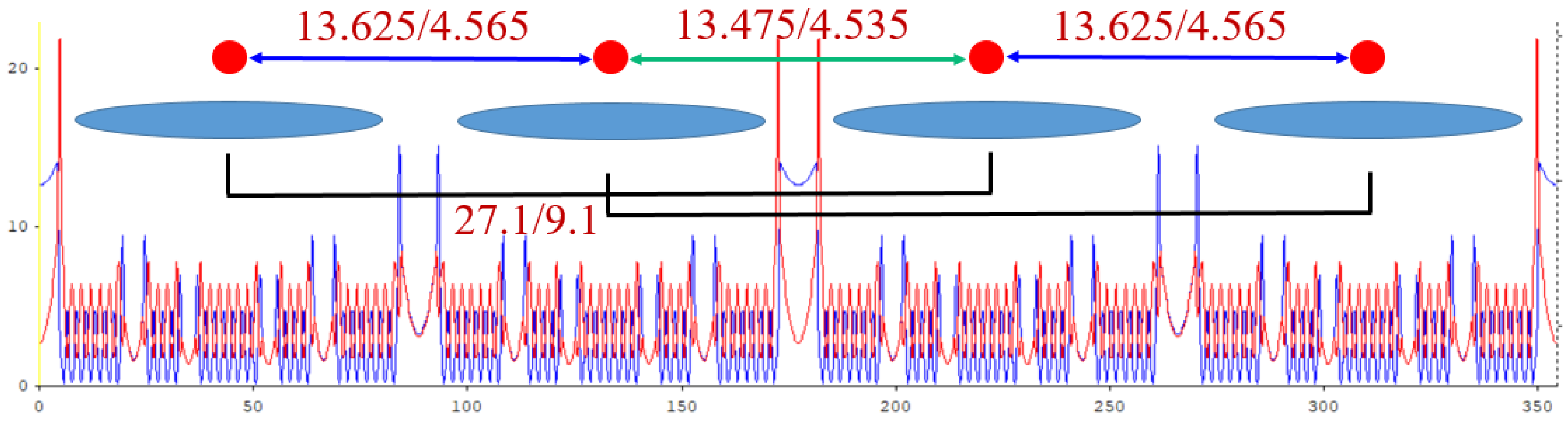
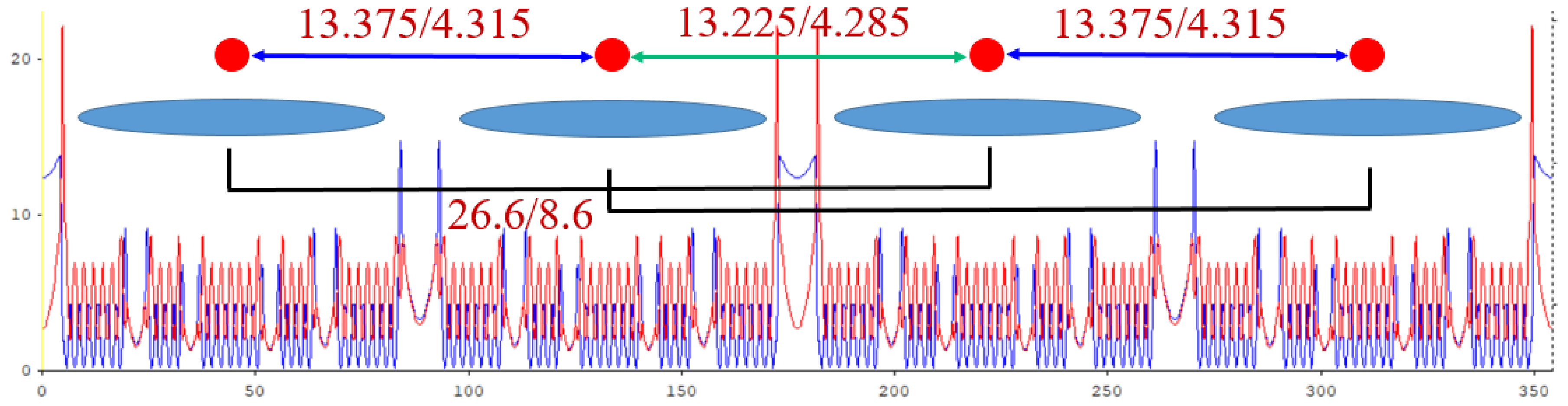
- The ring lattice can basically be seen as consisting of mainly 4 identical parts.
- These parts can be further modelled as “macro-particles” located at the middle positions.
- A macro-particle represents all nonlinear magnets of a part.

Tunes: **54.2/18.2**



Tunes: **53.2/17.2**



Issue 1: tunes of (54.2, 18.2) & (53.2, 17.2)

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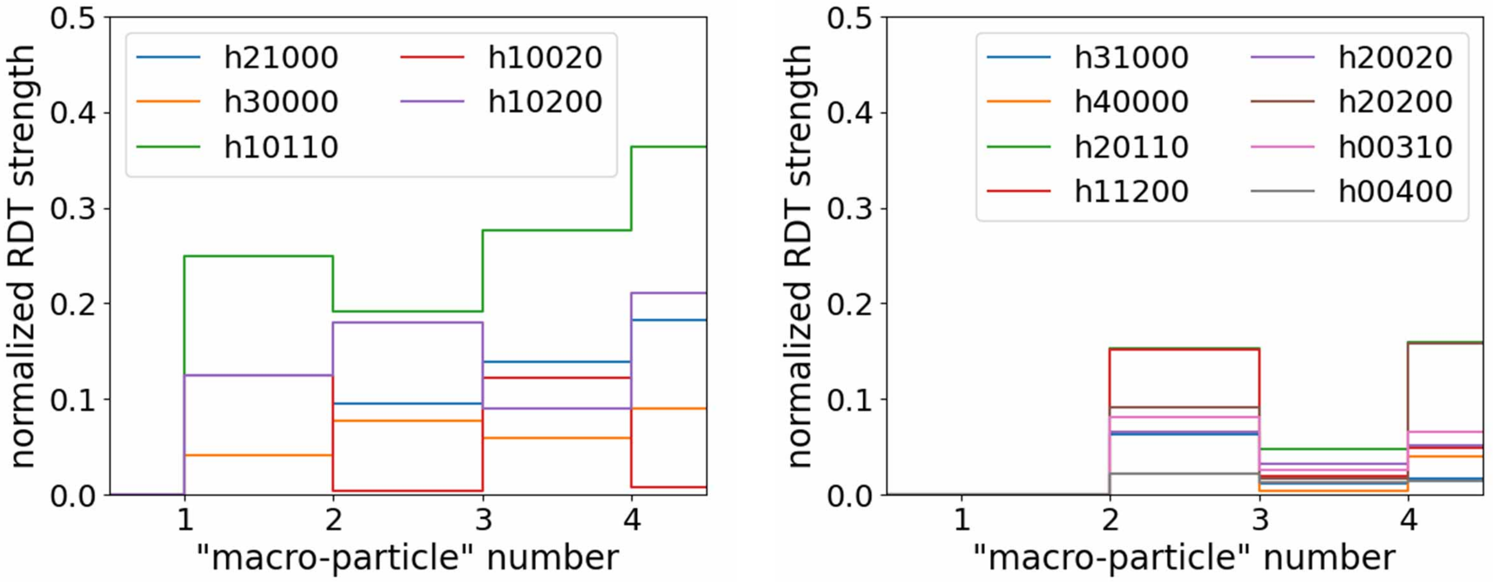
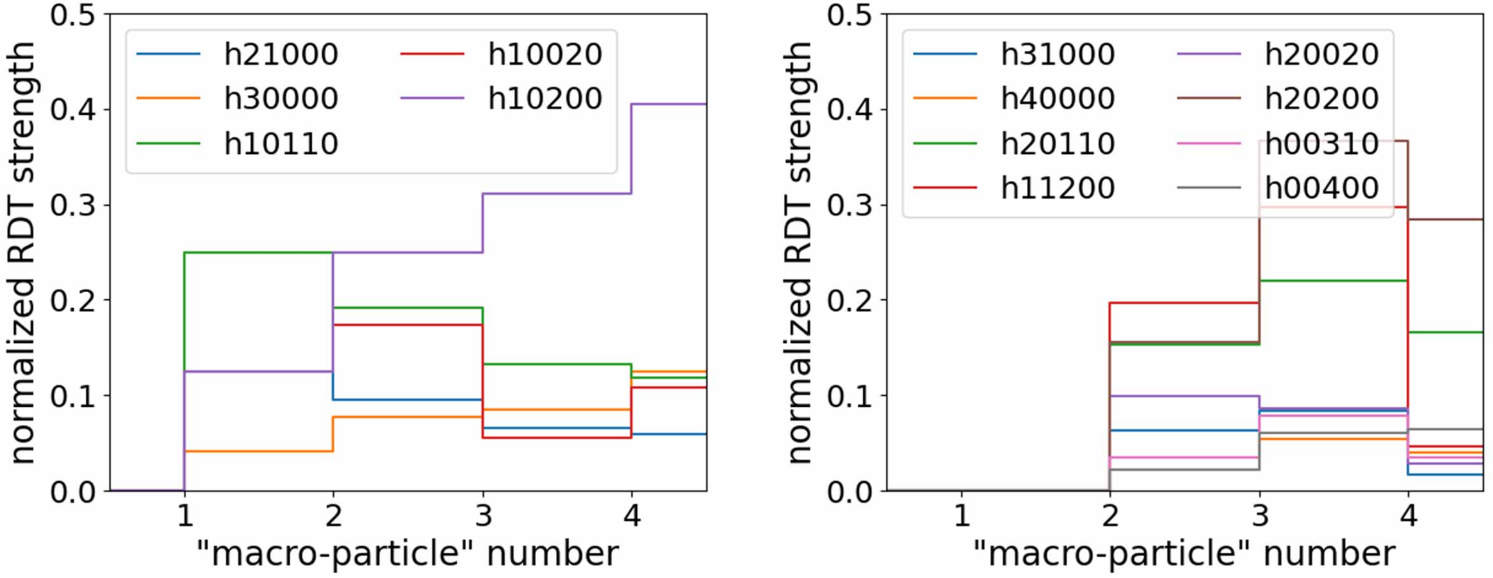
- To calculate RDTs, each macro-particle is treated as a thin sextupole, and the values of sextupole strength and beta functions at the positions of macro-particles are all set to 1.

Tunes:
54.2/18.2



- The tune (53.2, 17.2) has larger low-frequency RDT fluctuations and thus smaller DA.

Tunes:
53.2/17.2

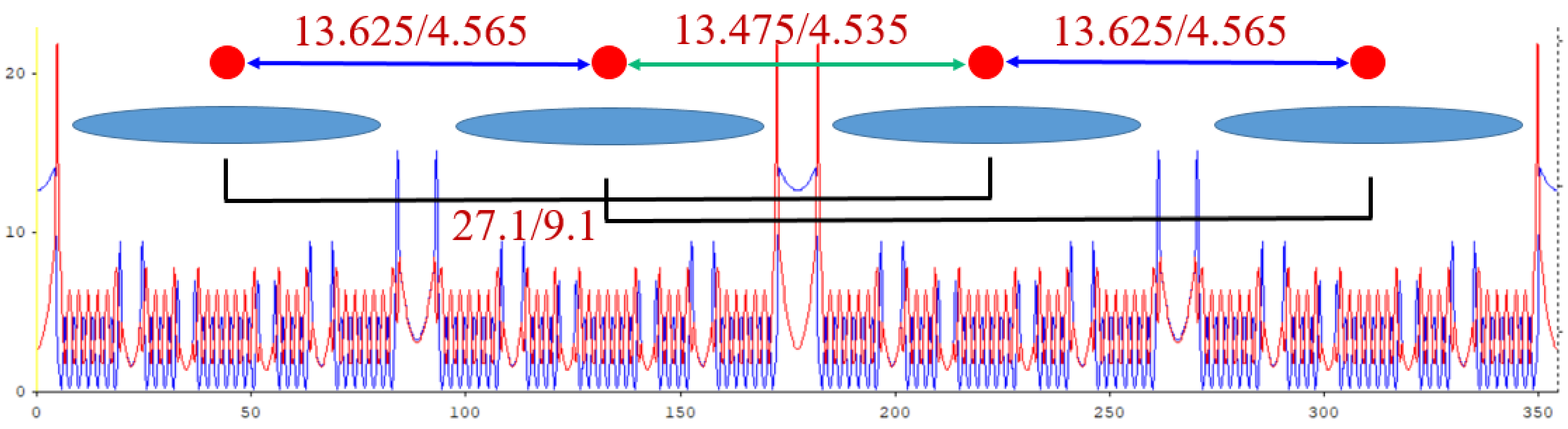


Issue 2: low & high H-beta @ injection straight

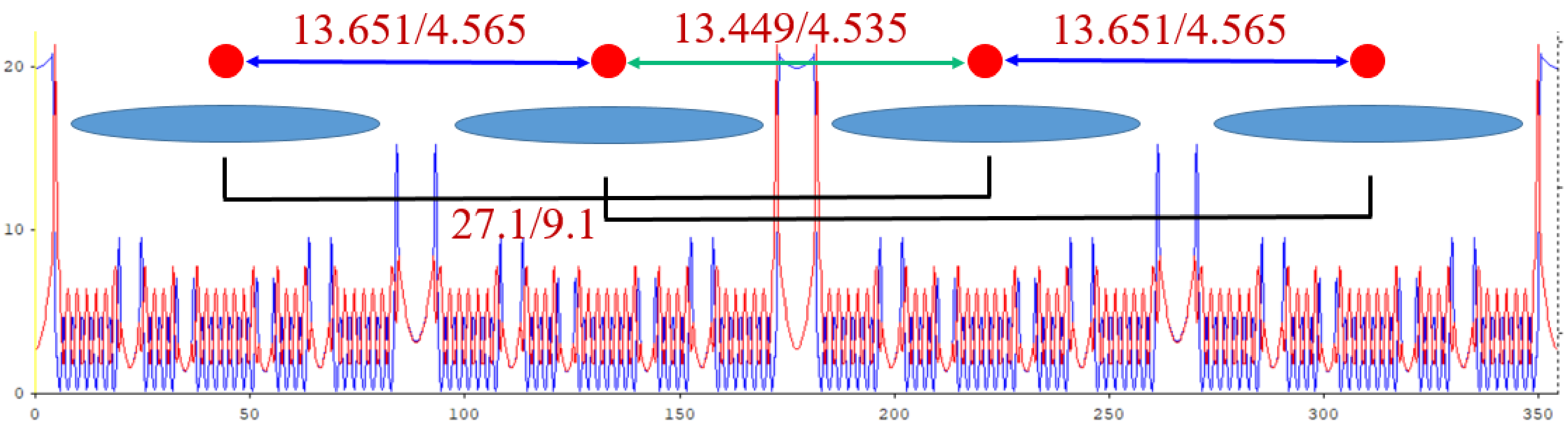
- The two cases have the same betatron tune of (54.2, 18.2).

- The same simplified model is used for calculating low-frequency RDT fluctuations.

Low H-beta @ injection straight

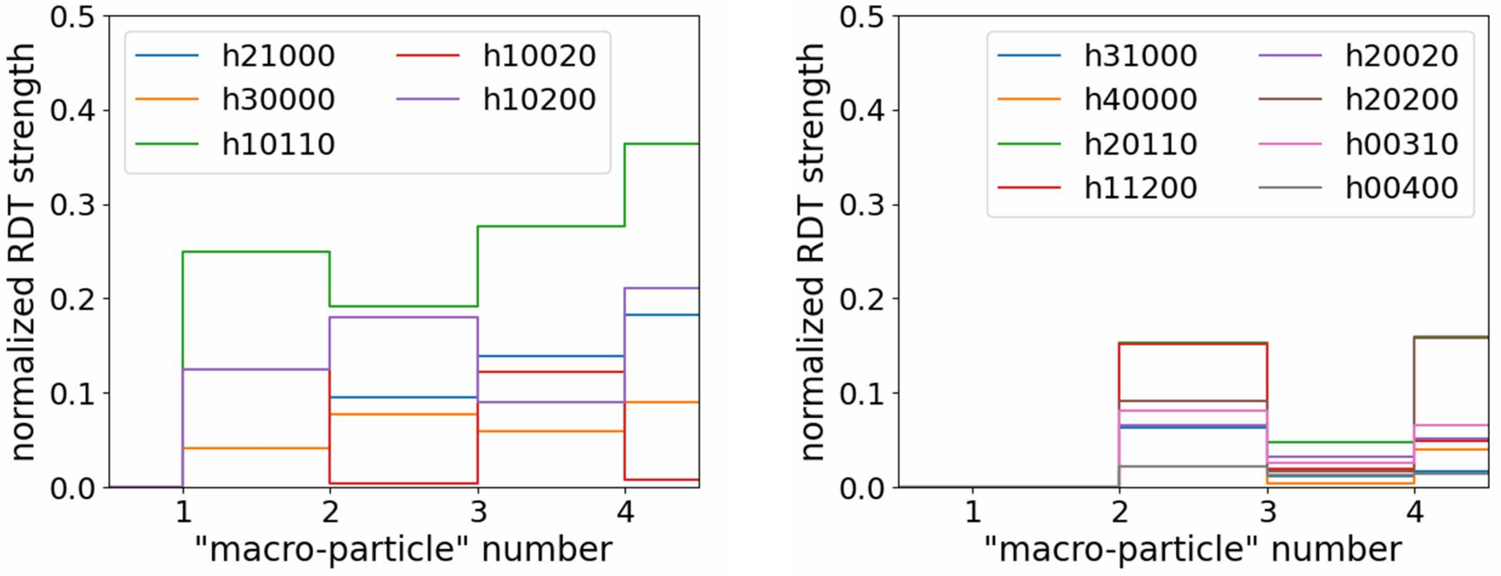


High H-beta @ injection straight



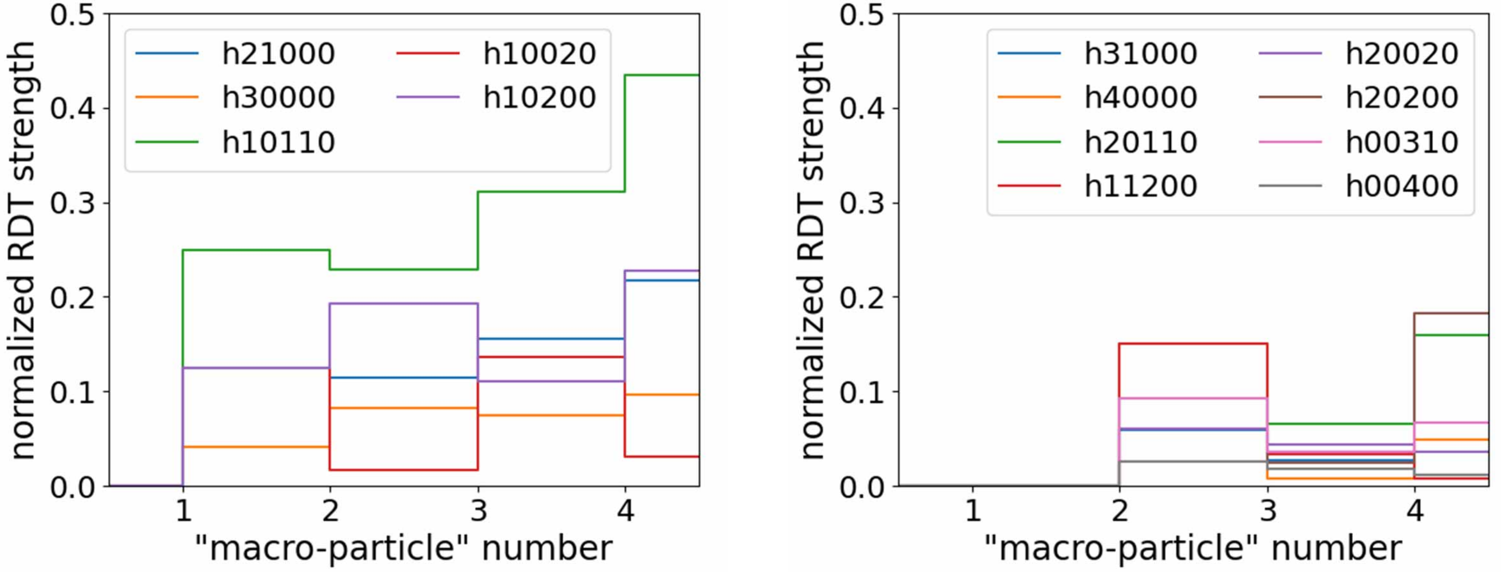
Issue 2: low & high H-beta @ injection straight

Low H-beta @ injection straight



- If the H-beta @ injection straight is increased, low-frequency RDT fluctuations will become larger.

High H-beta @ injection straight



Optimizing DA based on minimizing RDT fluctuations

- Lattice example:
  - SOLEIL II TDR lattice
  - tens of sextupole and octupole families

- The DA was preliminarily optimized based on numerically minimizing RDT fluctuations using genetic algorithms.

- The optimization was performed very fast as compared to the tracking-based numerical approach.

- Compared to the reference solution, the optimized solution has smaller RDT fluctuations and its horizontal DA is larger in the negative direction, where the beam is injected.

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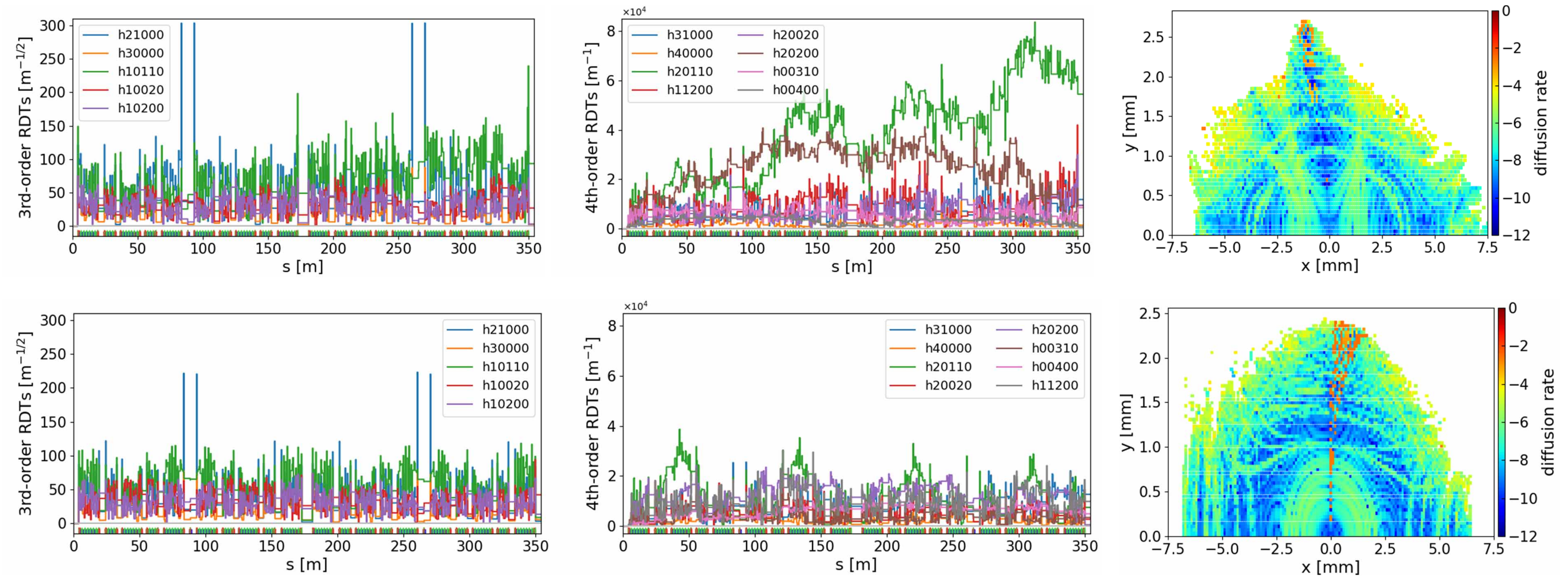
Optimizing DA based on minimizing RDT fluctuations

➢ Reference solution (top) & optimized solution (bottom)



➢ Based on minimizing RDT fluctuations, the nonlinear optimization, including both DA optimization and control of tune shifts with momentum, is ongoing.

Conclusion

- Minimizing the fluctuation of RDTs along the longitudinal position is much more effective than minimizing the commonly-used one-turn RDTs in enlarging the DA.

- Reducing low-order RDT fluctuations can also help reduce both higher-order RDT fluctuations and higher-order one-turn RDTs.

- Based on a simplified model, some nonlinear dynamics issues can be explained by using low-frequency RDT fluctuations.

- Based on minimizing RDT fluctuations using genetic algorithms, large DA solutions can be found very fast.

Thank you for your attention!