PS2 review

Negative Momentum Compaction lattice options for PS2

Y. Papaphilippou

May 29th, 2008

Contributors

- J. Barranco, W. Bartmann, M. Benedikt, C. Carli (CERN), D. Trbojevic (BNL)

Acknowledgements

- G. Arduini, R. deMaria, R. Garoby, B. Goddard, S. Hancock, J. Jowett, E. Metral, D. Möhl (CERN), Y. Senichev (FZ Jülich)

Outline

- Negative (Flexible) Momentum Compaction modules
  - Design principle
    - Example: J-PARC main ring
  - NMC rings
    - With dispersion suppressor
    - Resonant
    - Hybrid
  - Tunability and optics' parameter space scan
  - Chromaticity correction
  - Dynamic aperture
- Comparison and perspectives

Negative Momentum Compaction modules

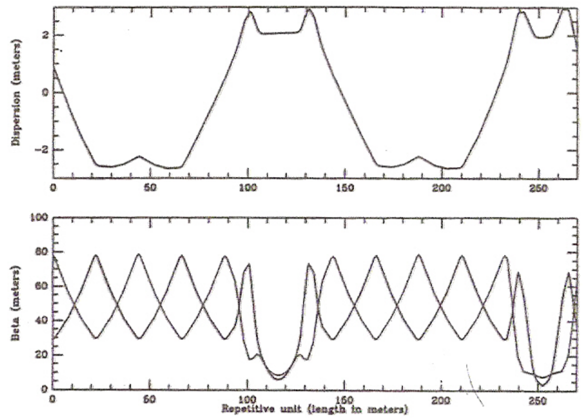
- Avoid transition crossing (beam instabilities and losses)
- Aim at negative momentum compaction

$$a_c = \frac{1}{C}\oint \frac{D(s)}{\rho}ds < 0$$

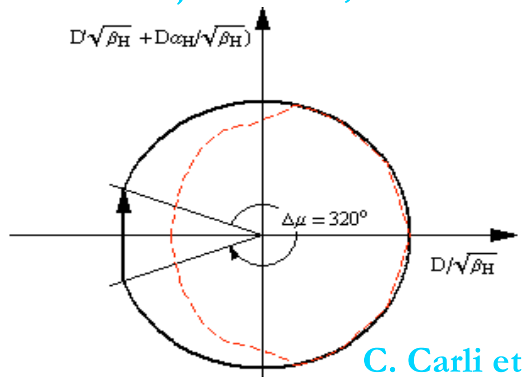
- Modulate dispersion using cells with different bending power
- Normalized coordinates

$$\chi = \frac{D_x}{\sqrt{\beta_x}} \quad \text{and} \quad \xi = D_x'\sqrt{\beta_x} + \frac{\alpha_x D_x}{\sqrt{\beta_x}}$$

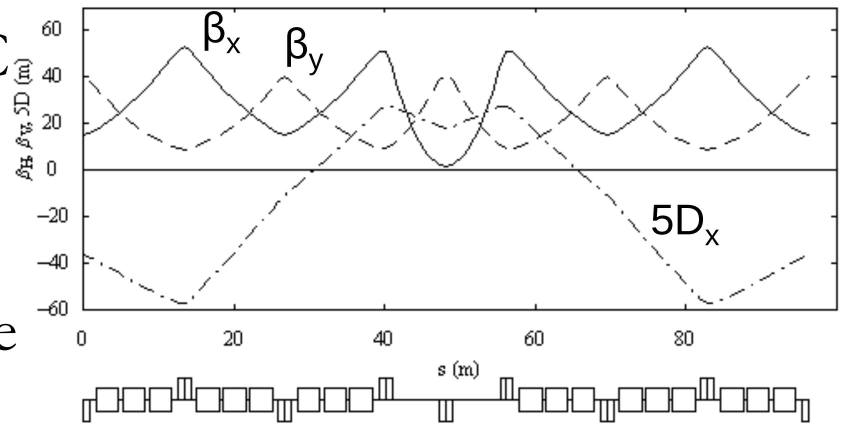
- Dispersion vector (χ, ξ) is invariant outside bends, i.e. vary it with bends in areas of negative dispersion to get NMC
- Similar approach used for J-PARC high energy ring lattices
- **Main difficulty for PS2**: extremely low γ_t **≈10i** (high dispersion) in limited space



D. Trbojevic et. all, EPAC 90.

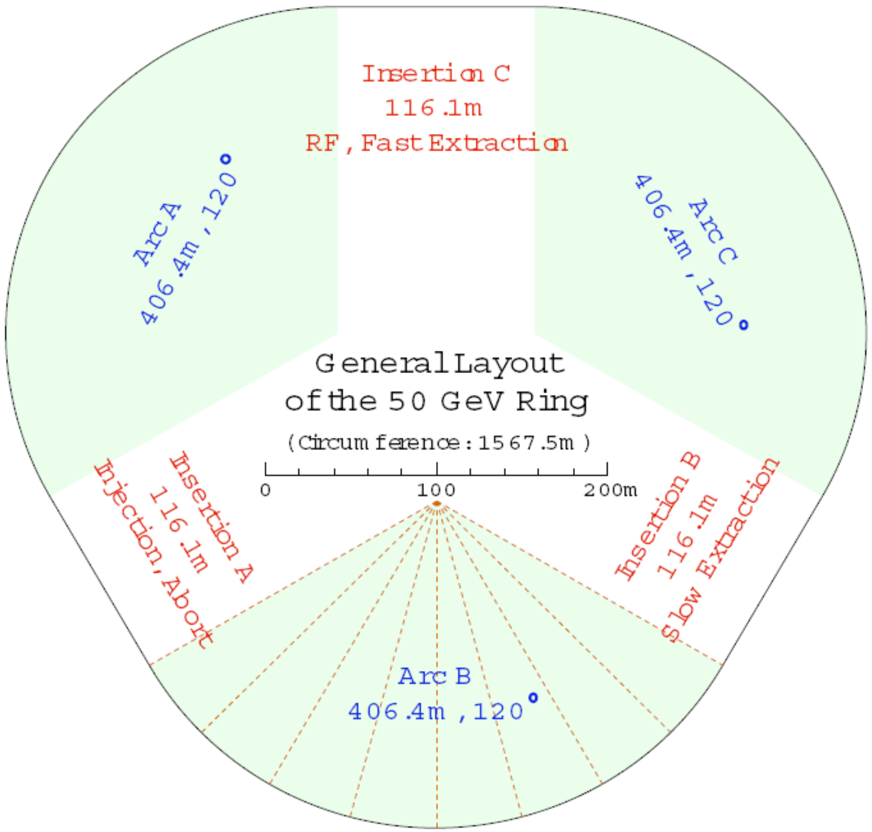


C. Carli et al. PAC07



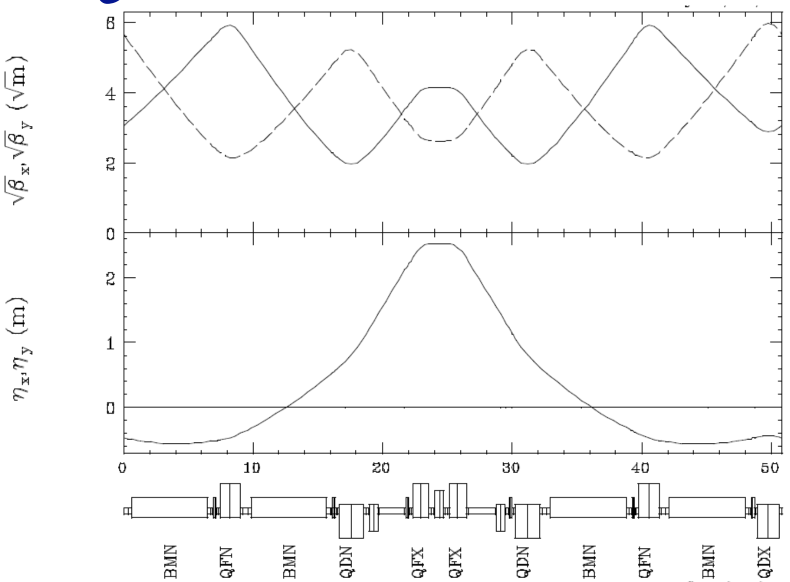
J-Parc Main Ring

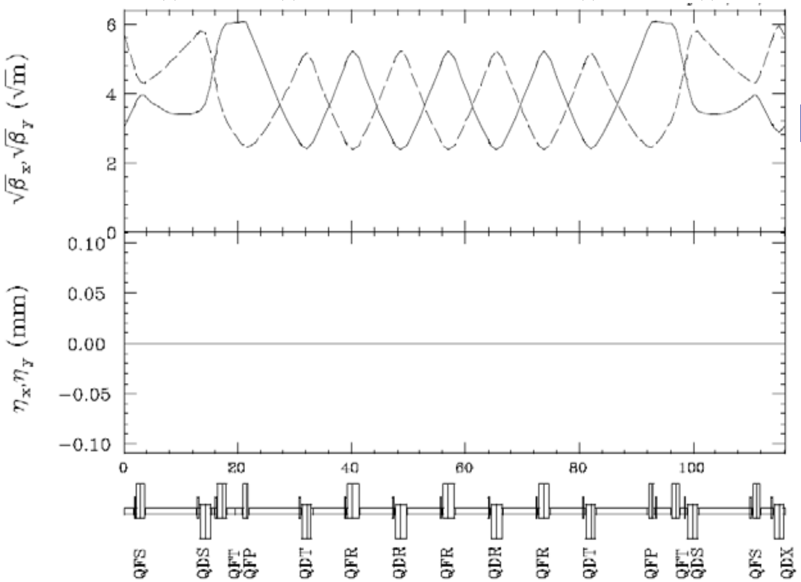
- **1567.5m** long ring with triangular shape with three **406.4m** long arcs and **116.1m** long straight sections
- Optics design criteria
  - 3 super-periods (arc + long straight for injection/collimation, extraction and RF)
  - Reasonable tuning range for tunes, chromaticity and aim at negative momentum compaction factor (imaginary γ_t)



Parameter	J-PARC	PS2
Circumference [m]	1567.5	1346.4
Injection energy [GeV]	3	4
Extraction energy [GeV]	50	50
Particles/pulse [10^{13}]	33	3.2 - 13
Repetition rate [Hz]	0.3	0.21 - 0.42

J-PARC Main Ring lattice

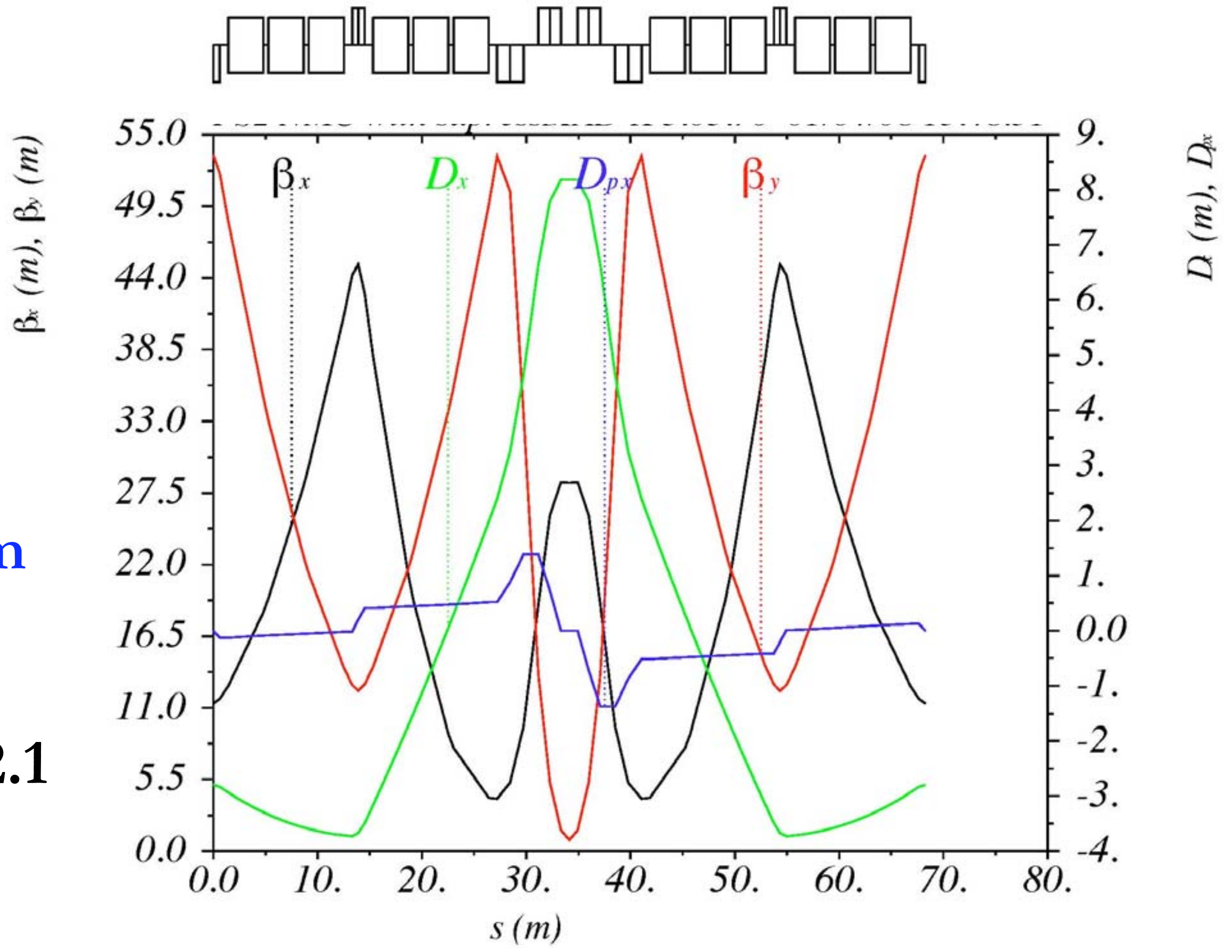




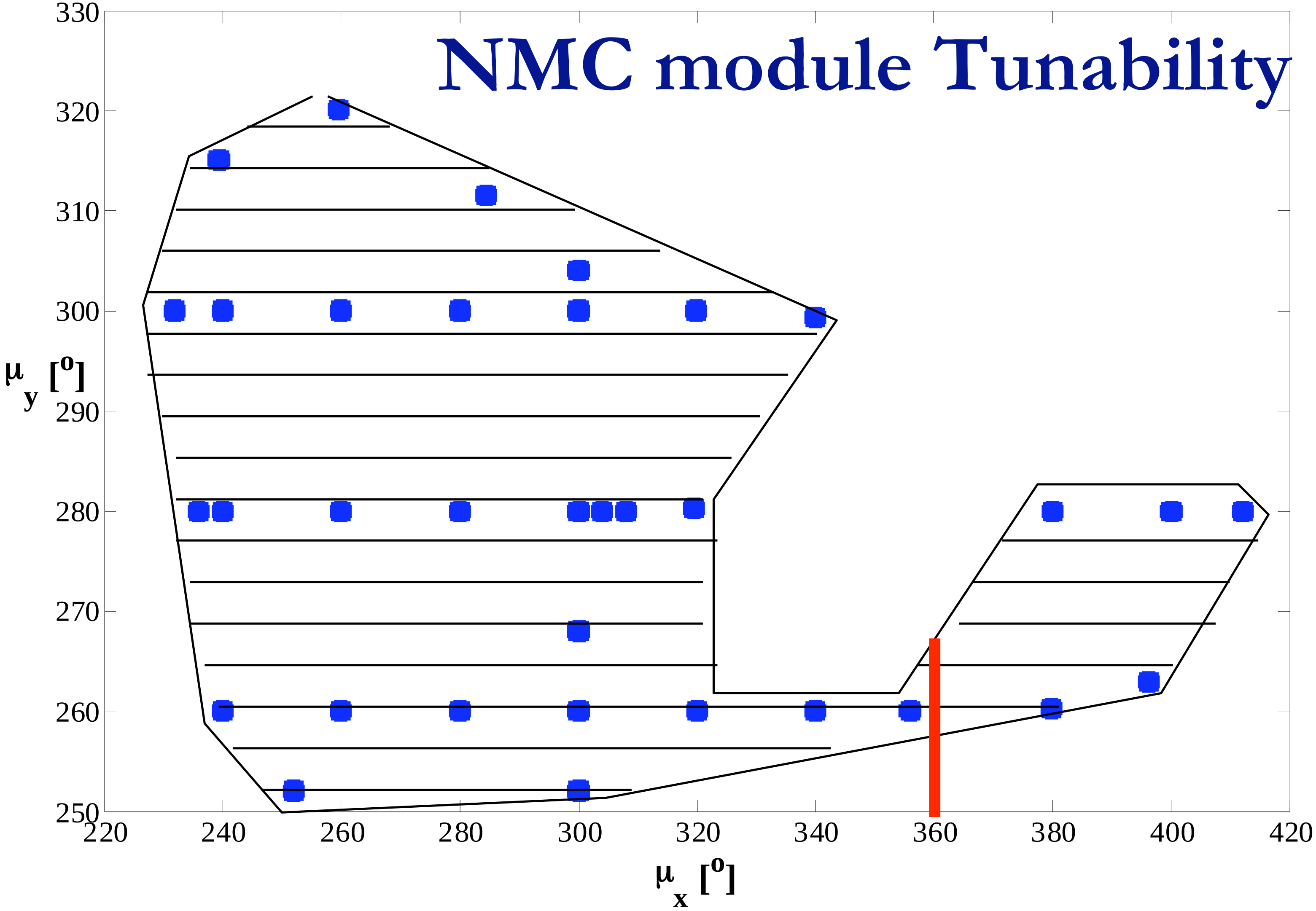
- Arc with eight **50m**-modules
  - **32** dipoles (5.85m), 4 families of **57** quadrupoles (1.26-1.86m)
  - Module of 3 DOFO cells with central half-cells without bend, with γ_t of **31.6i**
  - Reasonable β and η maxima (35m, 3m)
  - Horizontal and vertical phase advance of $3\pi/2$, giving a total of 12π (zero dispersion)
  - Vertical phase advance tunable down to 200^o
- Long straight with 3 central DOFOs and doublet matching in either side
  - 7 families of **15** quadrupoles (0.9-1.76m)
  - FODO cells used for adjusting phase advance (collimation) long half-cell for injection, beam dump and fast extraction, short half-cellfor slow extraction (electrostatic septum)

The “short” NMC module

- 1 DOFO cell with 3 + 3 bends and a low-beta doublet
- γ_t of **8.1i**
- Phase advances of **306°** and **288°** per module
- Four families of quads, with max. strength of **$0.1m^{-2}$**
- Max. beta of **44** and **53m**
- Min. dispersion of **-4m** and maximum of **8m**
- Chromaticities of **-1.3,-2.1**
- Total length of **68.25m**
- Magnet-to-magnet drift space requirements satisfied

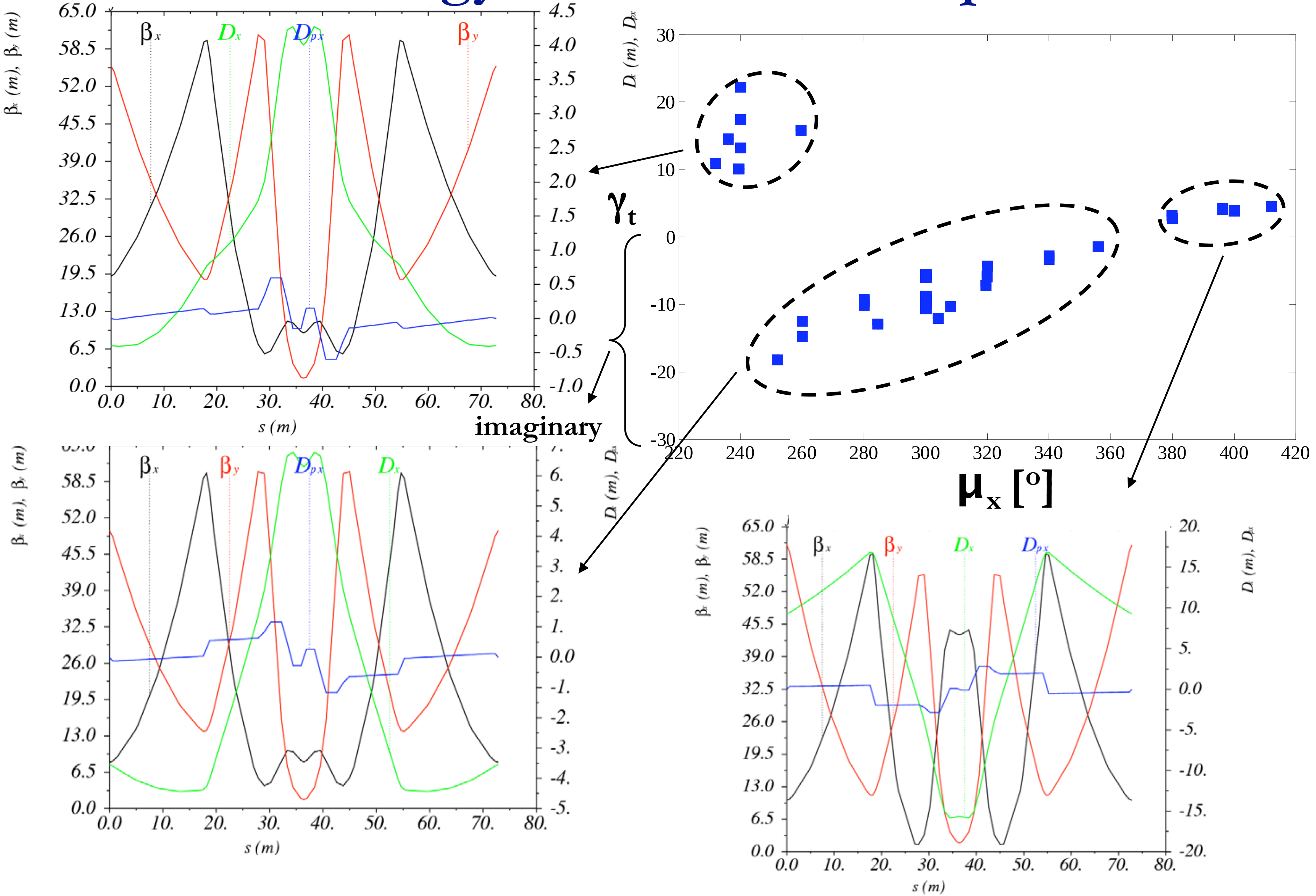


NMC module Tunability

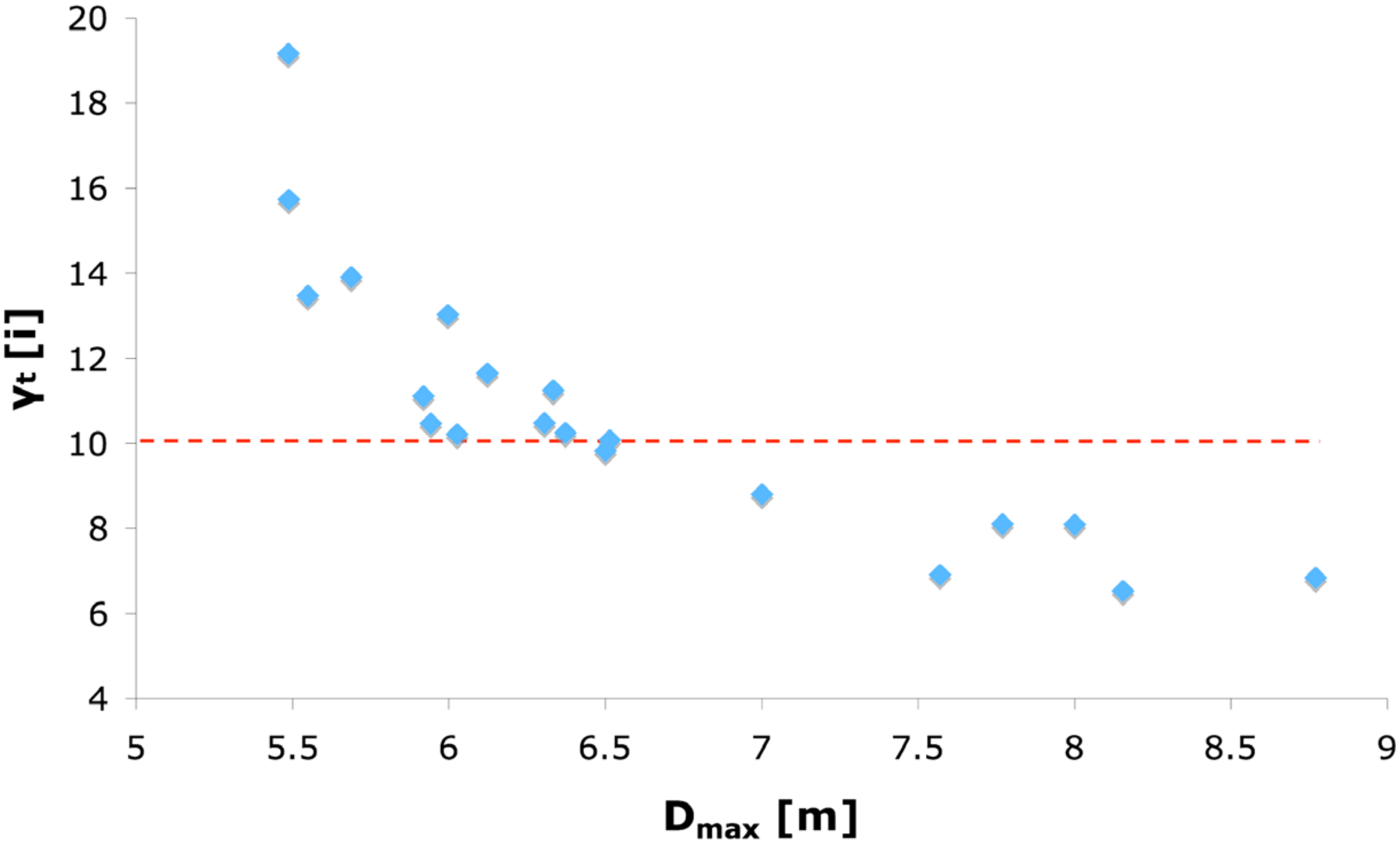


- Phase advance tunable between **240o** and **420o** in the horizontal and between **250o** and **320o** in the vertical plane

Transition energy versus horizontal phase advance

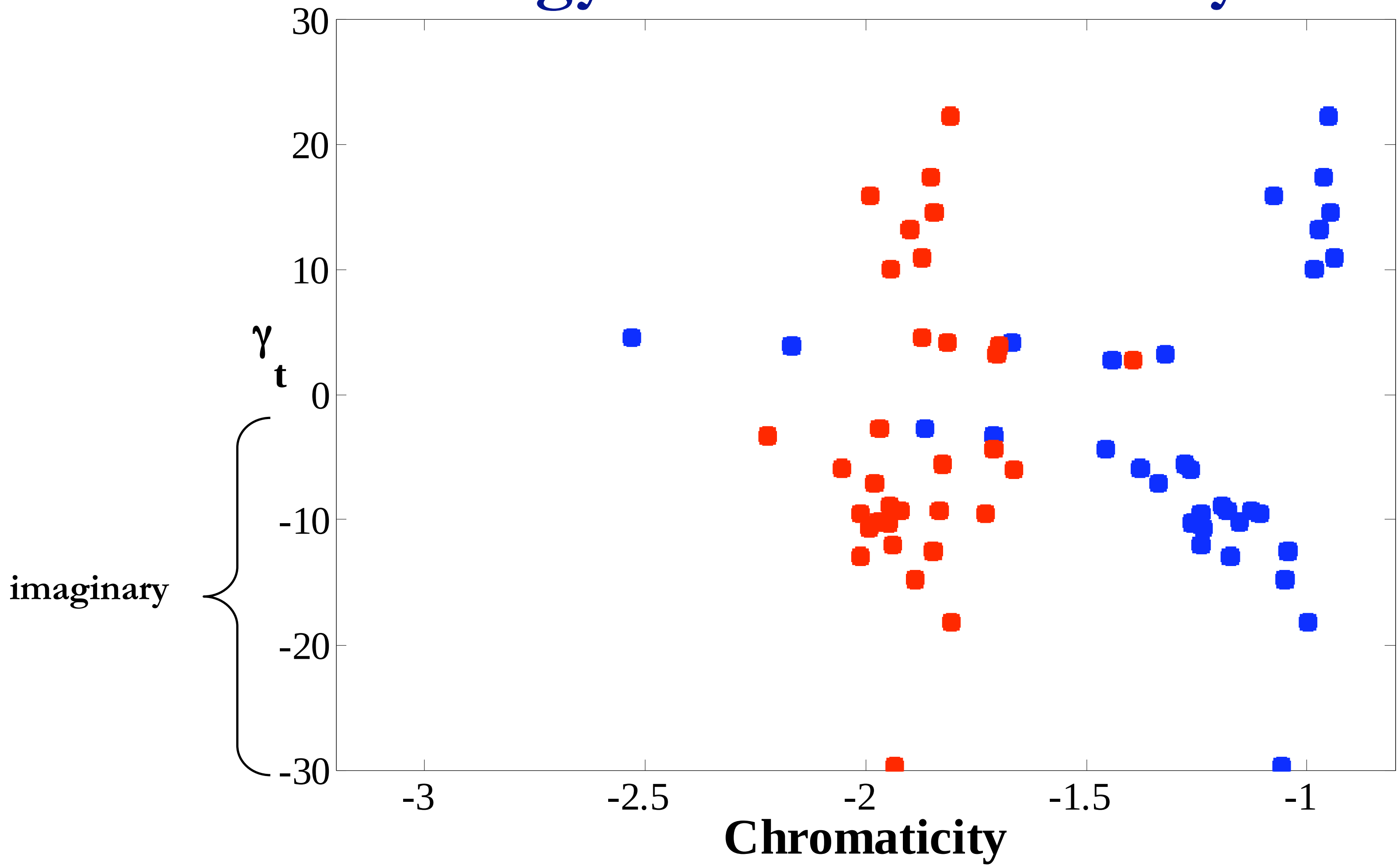


Dispersion versus transition energy



- Almost linear dependence of momentum compaction with dispersion max values
- Higher dispersion variation for γ_t closer to 0
- Smaller dispersion variation for higher γ_t

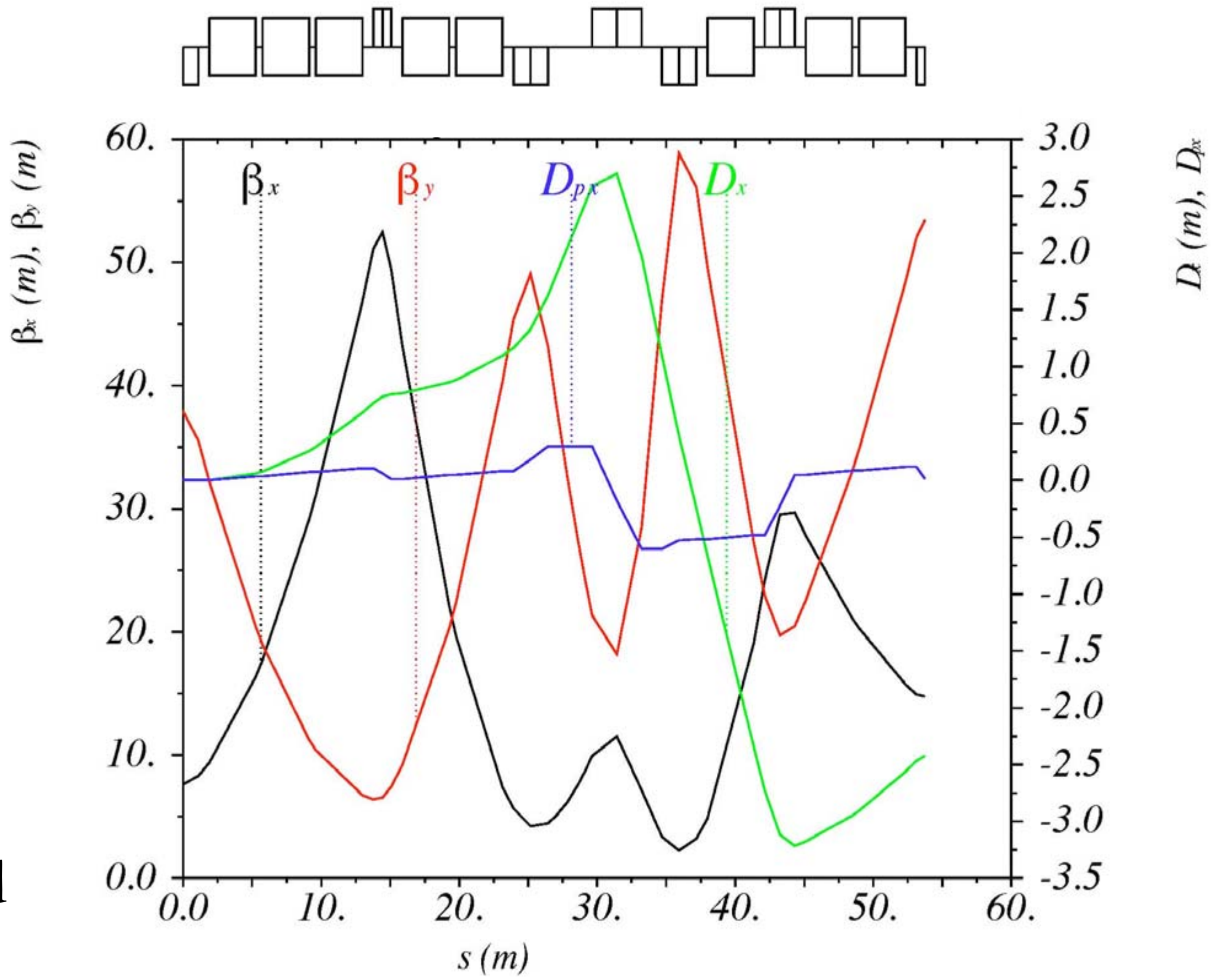
Transition energy versus chromaticity



- Higher in absolute horizontal chromaticities for smaller transition energies
- Vertical chromaticities between -1.8 and -2 (depending on vertical phase advance)
- Main challenge: design of dispersion suppressor and matching to straights

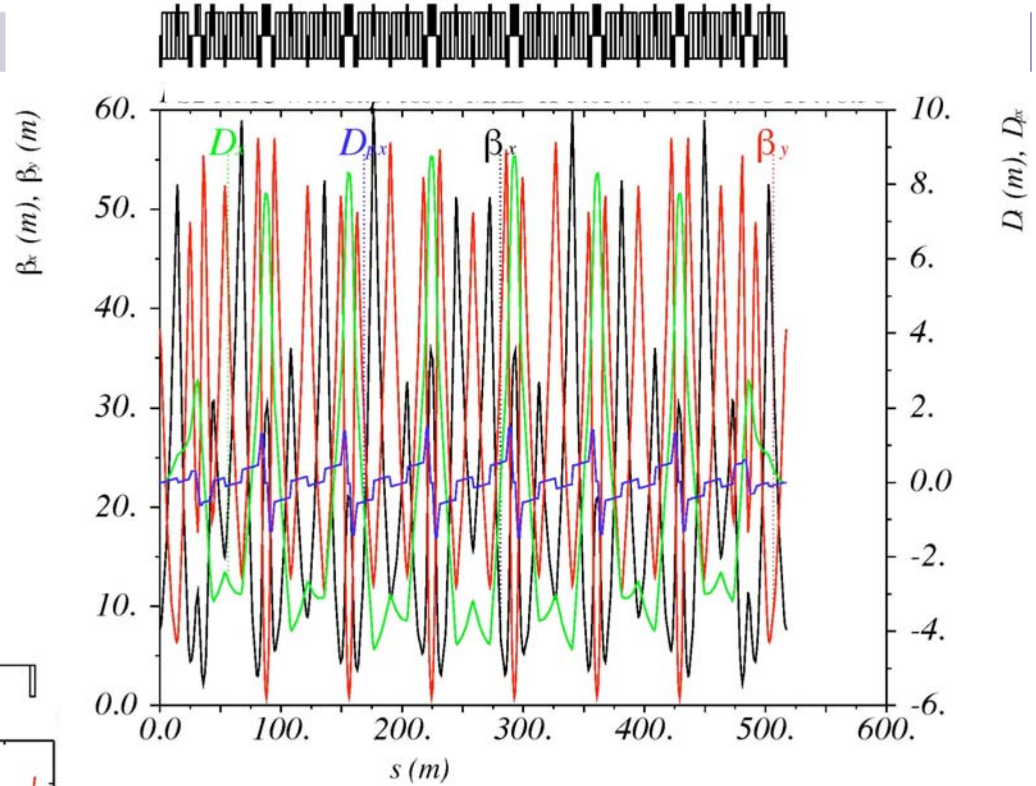
Dispersion suppressor and matching cell

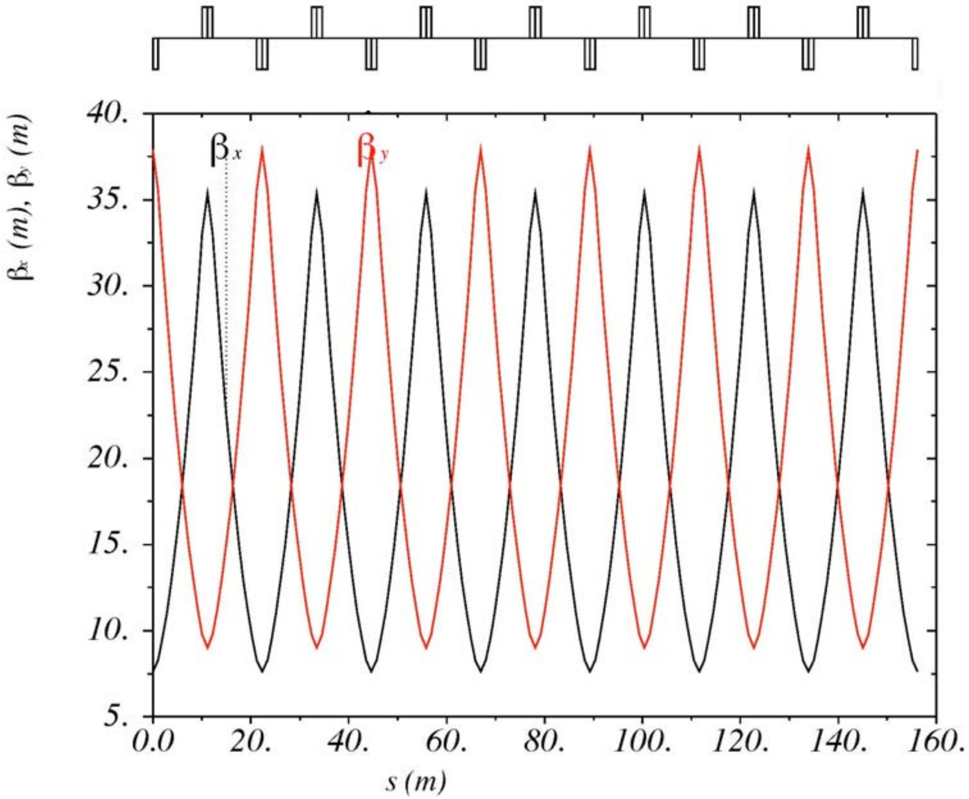
- Similar half module as for the NMC with **3+2** dipoles for suppressing dispersion and matching cell with **1+2** dipoles
- Using **5** families of quads with strengths within the imposed limits (sharing two half quads with the straight section and arc module)
- Maximum beta of **53** and **60m**
- Total length of **53.75m**



Arc and long straight section

- Arc composed of six NMC modules and two dispersion suppressors with matching cells
- Total length of **517m**

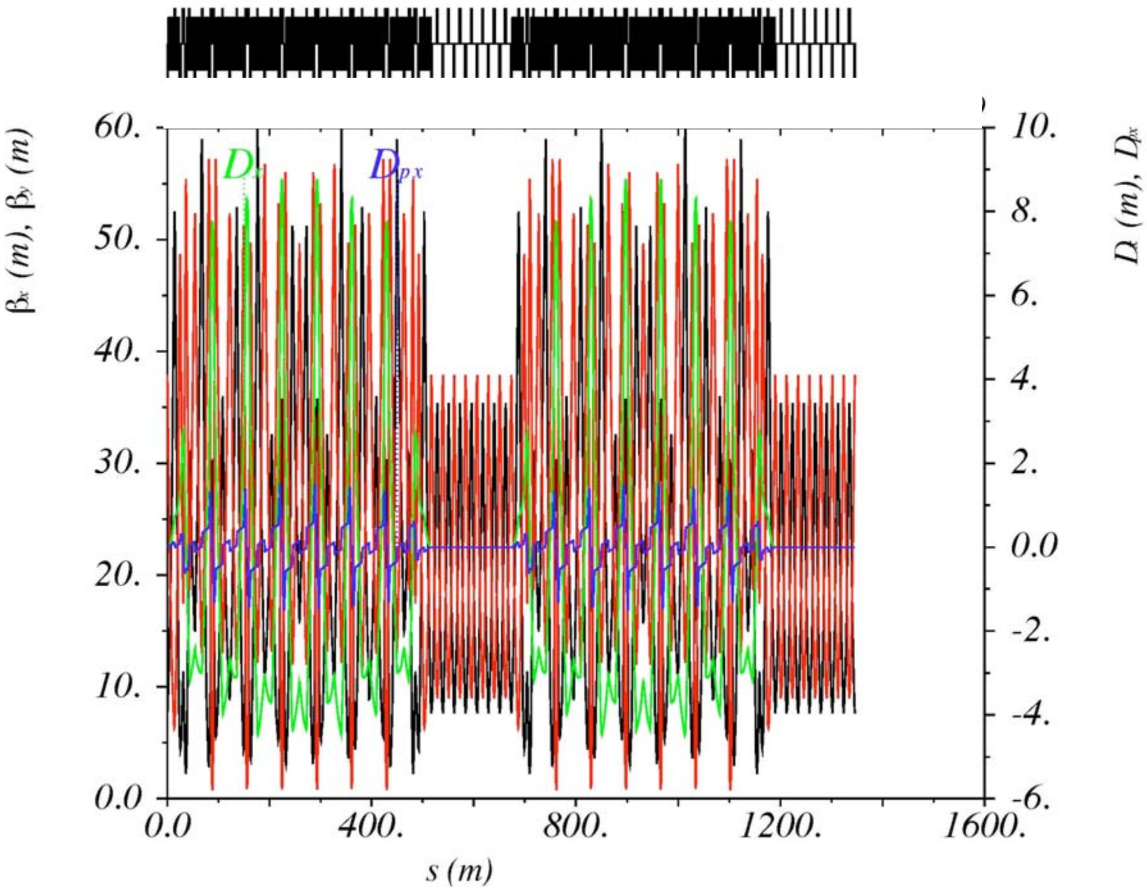




- Straight section with 7 FODO cells with horizontal phase advance of **85.25°** and vertical of **74°**
- Straight section drift of **9m**
- Only two families of quadrupoles are used
- Extra two families can be added for internal phase adjustments
- Total length of **156.2m**

The NMC with dispersion suppressor ring I

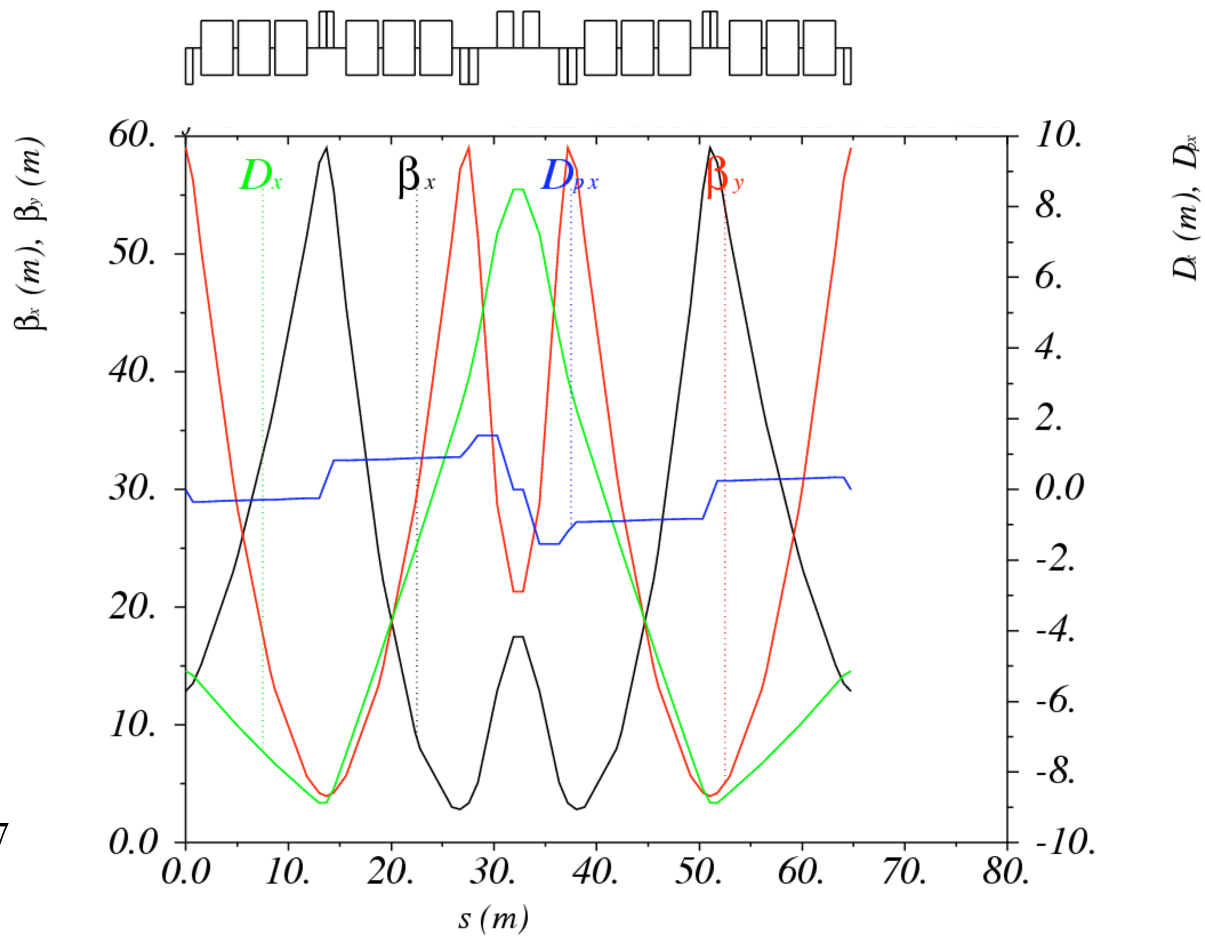
- γ_t of **10.9i**
- Tunes of **16.75 and 14.2**
- **176** dipoles**, 3.4m** long (**1.8T** field)
- **134** quadrupoles in **11(+ 2)** families of 6 types (lengths and apertures), with max. strength of **0.1m^{-2}**
- Max. beta of **60m** in horizontal and **57m** in the vertical plane
- Dispersion min. of **-4m** and max. of **8.8m**
- Chromaticities of **-24** and **-32**
- Total length of **1346.4m**



The resonant NMC module

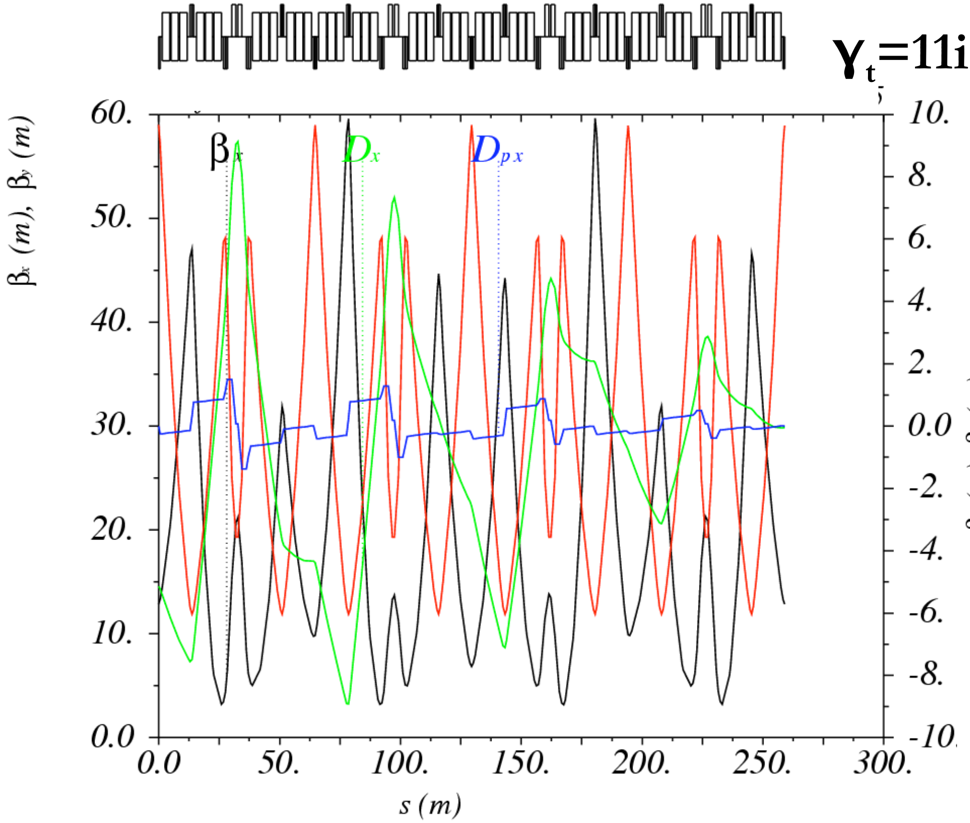
e.g. Y. Senichev BEAM'07

- 1 symmetric FODO cell with 3 + 3 bends and a low-beta doublet
  - Phase advances of 315º,270º per module
    - **8 x** 315º->7 x 2π
    - **8 x** 270º->6 x 2π
  - γ_t of **5.7i!!!**
  - **Four** families of quads, with max. strength of $0.1m^{-2}$
  - Max. beta of around **59m** in both planes
  - Min. and max. dispersion of **-8.5m** and **8.9m**
  - Chromaticities of -1.5,-1.7
  - Length of **1.2m** between QF and D
  - Total length of **64.8m**

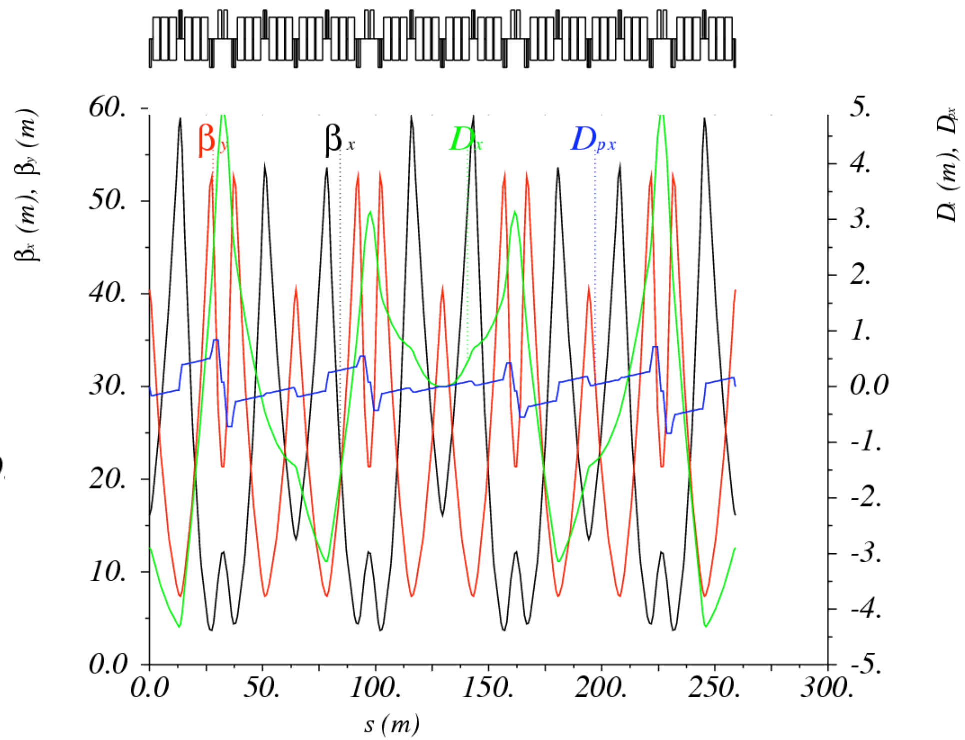


Suppressing dispersion

γ_t=11i

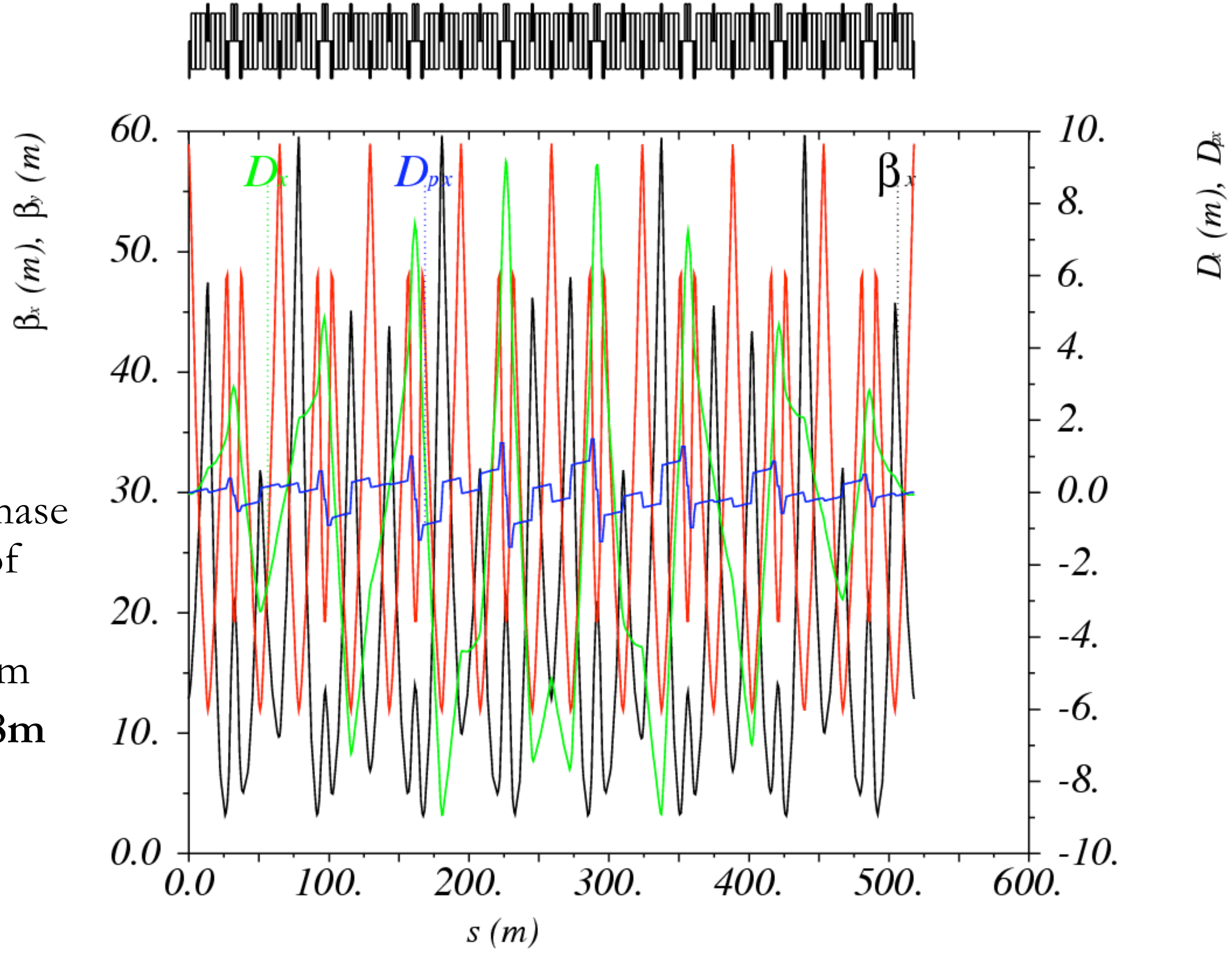


γ_t=17i



- Dispersion is suppressed by fixing horizontal phase advance to multiple of 2π
- Solution with **odd** number of 2π multiples preferable for getting **lower imaginary γ_t**

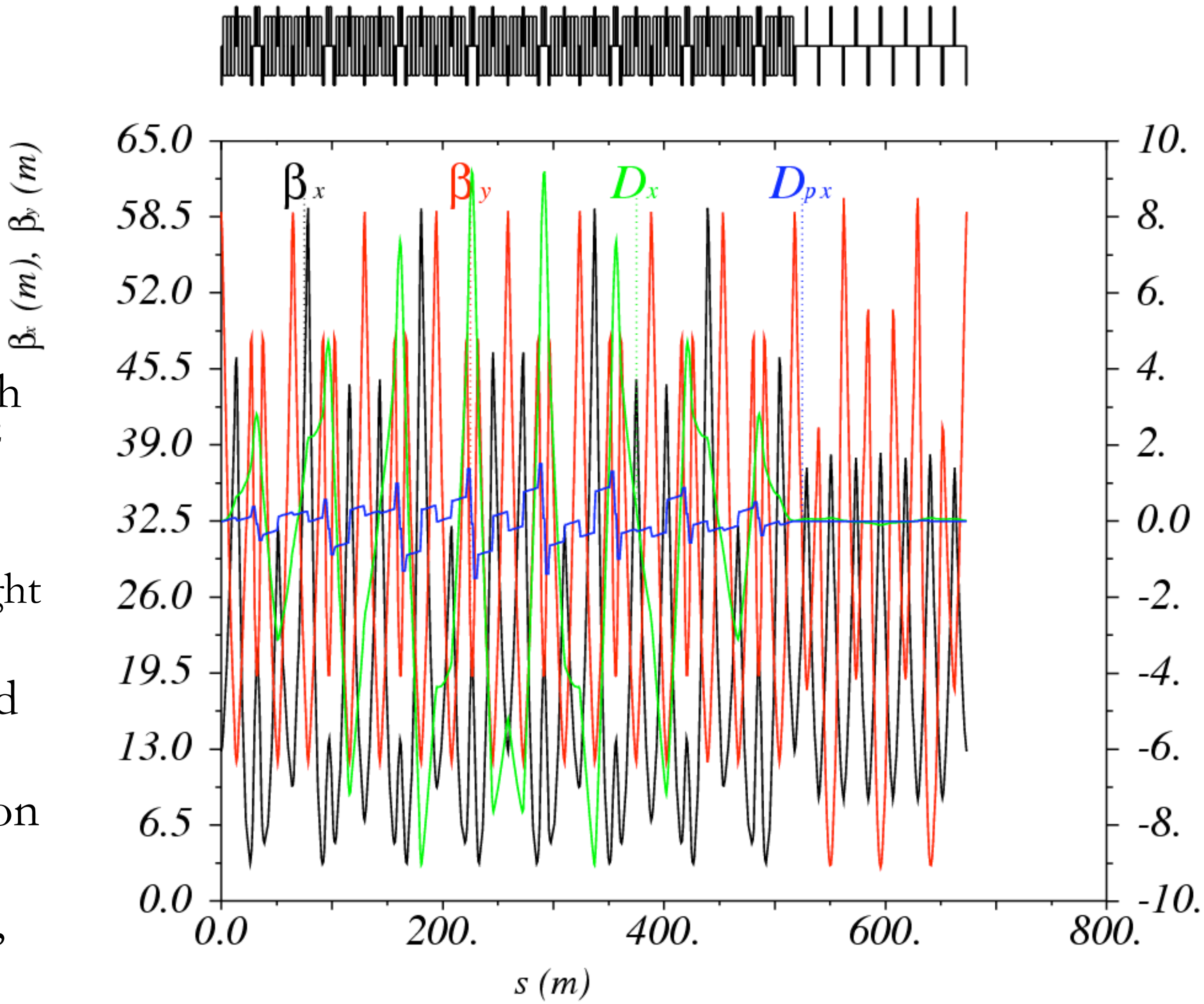
The "resonant" NMC arc



- 8 NMC modules
- Total horizontal phase advance multiple of 2π
- Maximum β of 59m
- Total length of **518m**

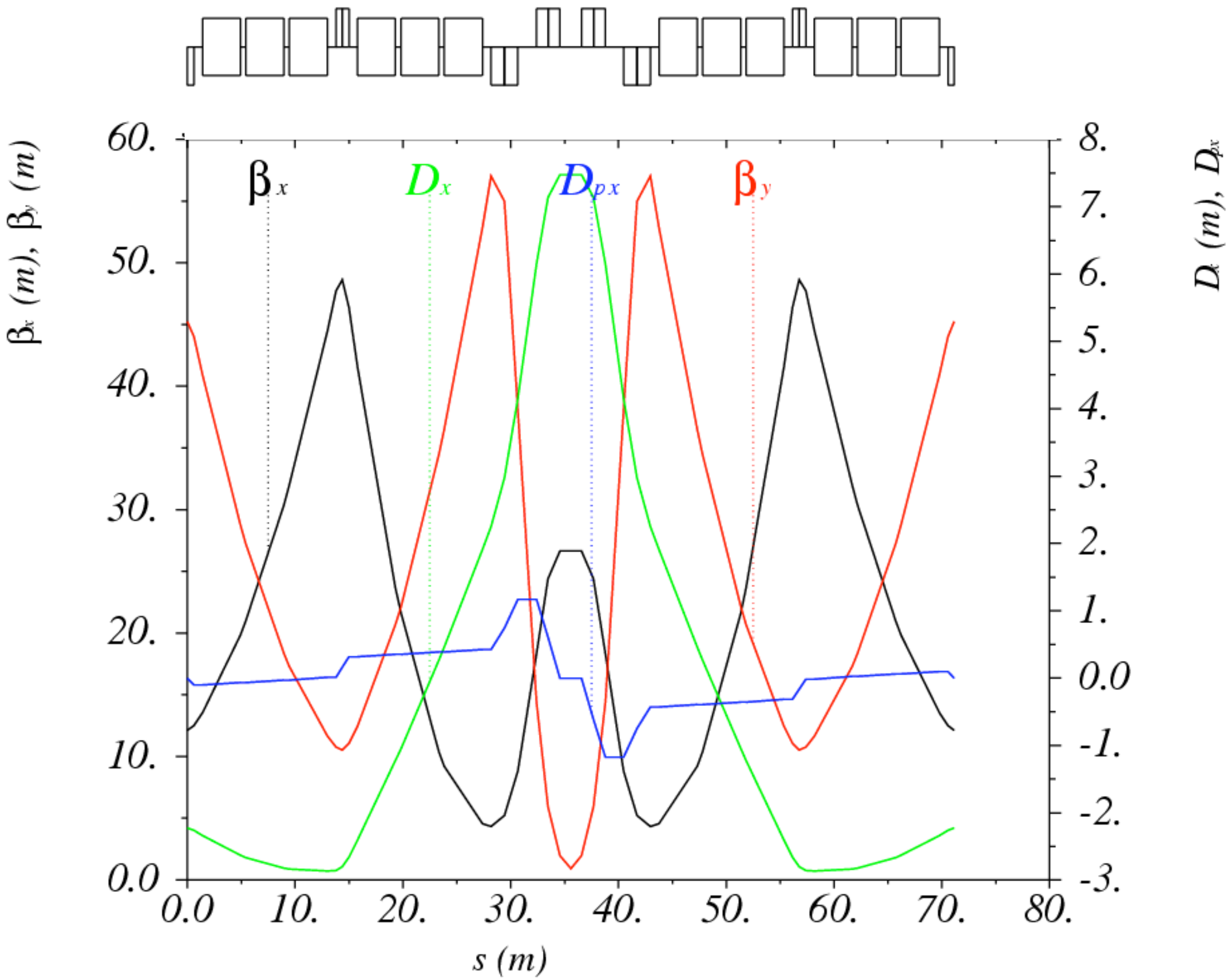
The "resonant" NMC ring II

- Adding a straight section with 7 FODO cells, using 2 matching quadrupoles
  - Straight drift of **9.4m**
  - Tunes of (16.8,9.8)
  - γ_t of **10.7i**
  - 8 families of quads, with max. strength of 0.1m^{-2}
    - Extra families for phase advance flexibility in the straight
  - Max beta of around **60.5m** in horizontal and vertical plane
  - Min. and max. dispersion of **-8.5m** and **8.9m**
  - Chromaticities of -21.7, -19.8
  - Total length of **1346.4m**



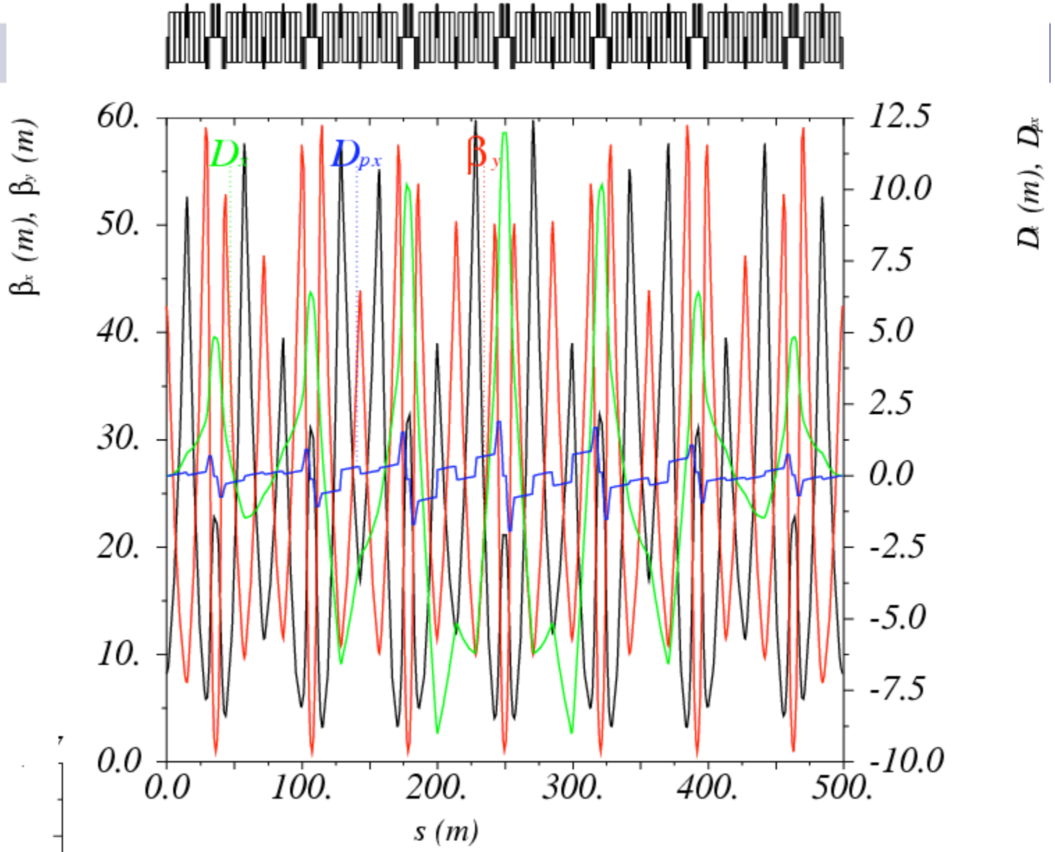
Yet…another NMC arc module

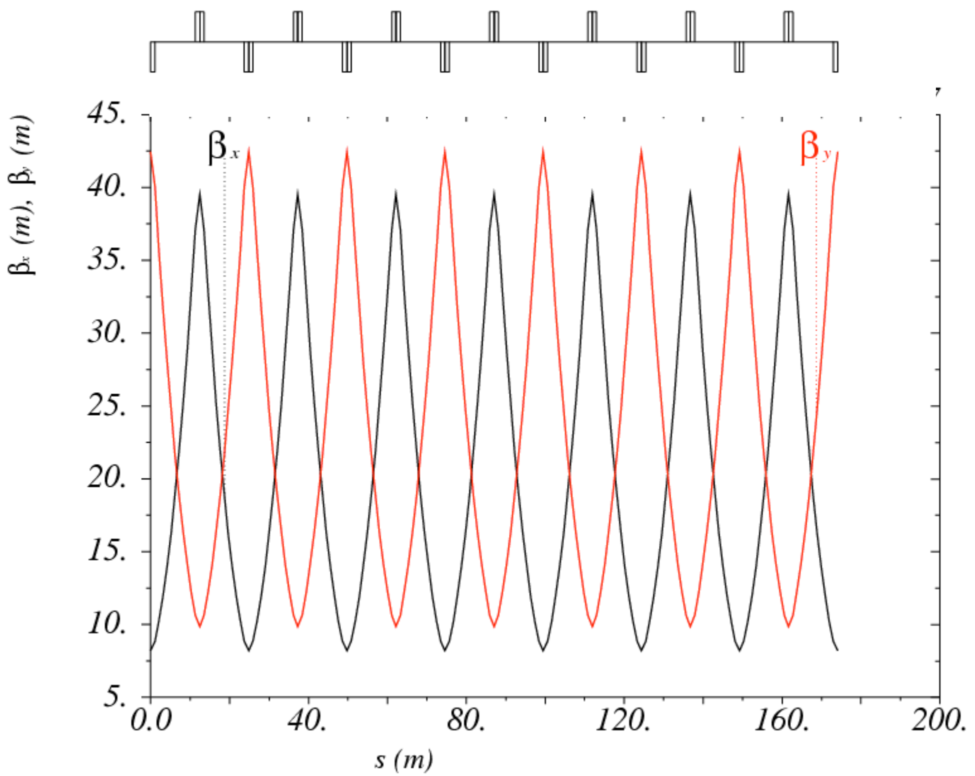
- 1 symmetric FODO cell with 3 + 3 bends and a low-beta doublet
  - Phase advances of 294°,310° per module
  - γ_t of **10.2i**
  - **4** families of quads, with max. strength of 0.1m^{-2}
  - Max. beta of **49m** and **57m**
  - Min. dispersion of -2.9m and maximum of **7.5m**



Arc and straight section

- Dispersion suppression with 2 extra quad families in the last arc modules
- Last arc quad. shared between arc and straight

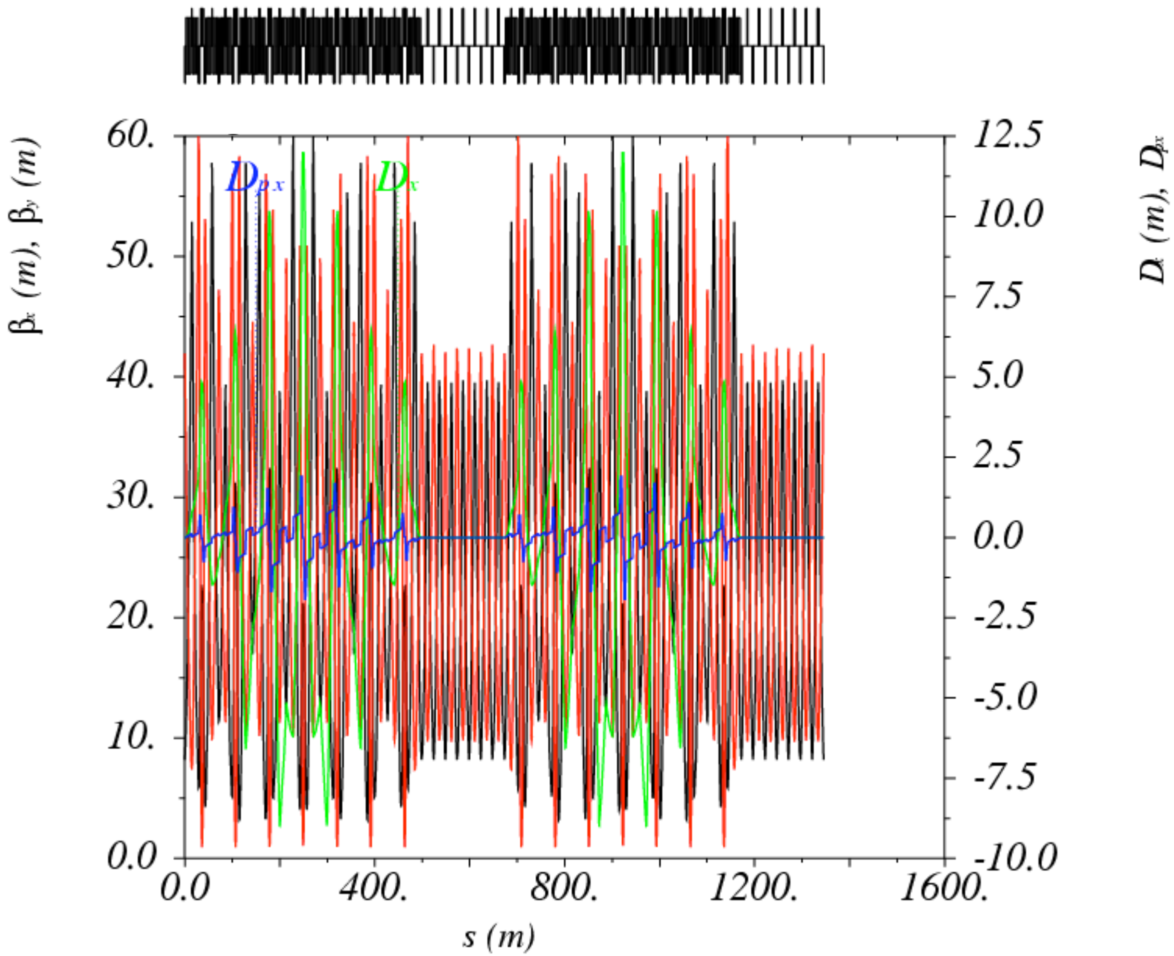




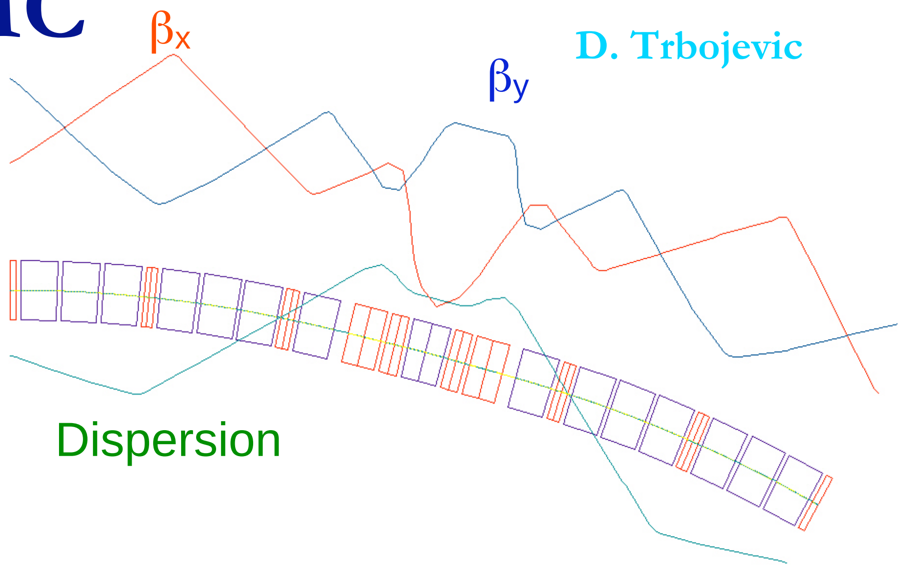
- Straight section with horizontal phase advance of **87.5°**
- Straight section drift of **10.2m**
- Only two families of quadrupoles are used
- Extra two families can be added for extra internal phase adjustments
- Perfectly matched to the arc

The "hybrid" NMC ring III

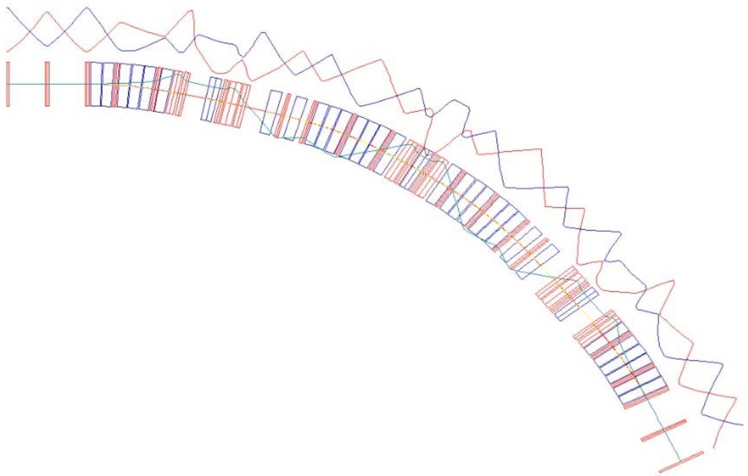
- Three types of 8 (+2) quadrupole families (max. strength of 0.1m^{-2}) for a length of **1346.4m**
- γ_t of **11i**
- Tunes matched to **(14.8,15.2)**
- Max. β's of around **60m** both planes
- Dispersion of **-9m** and maximum of **12m**
- Tunability between **14** and **16** in both planes but penalty on the beta function maxima
- Chromaticities of -21.5, -32.2

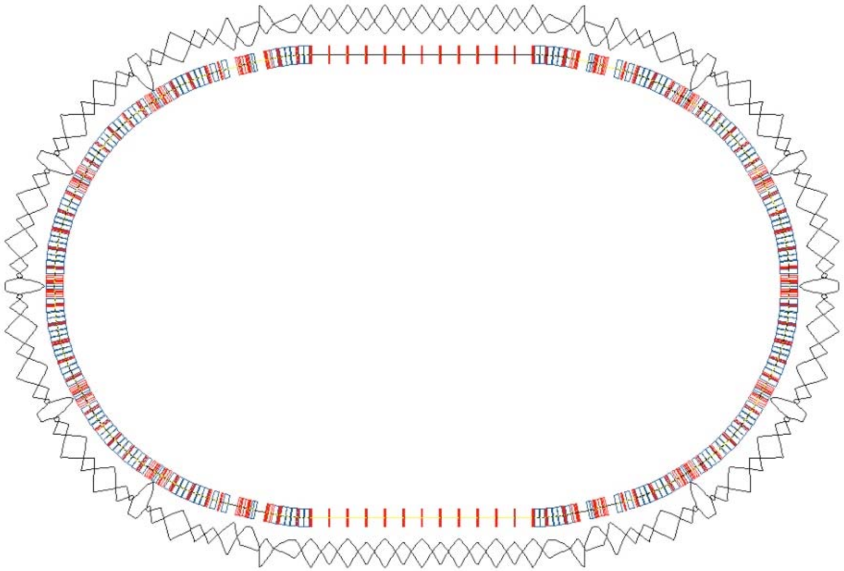


High filling factor NMC



- High filling factor module with additional dipoles in between the low beta doublets
- γ_t of **8.66i** for the module and **11.6i** for the ring
- Max. horizontal beta of **53m** and vertical of **46m**
- Min. dispersion of **–4.3** and maximum of **3.3 m**
- Maximum quadrupole gradient of **0.11m^{-2}**
- Total length of **75.9 m**
- Chromaticities of **-20.2** and **-17.4**

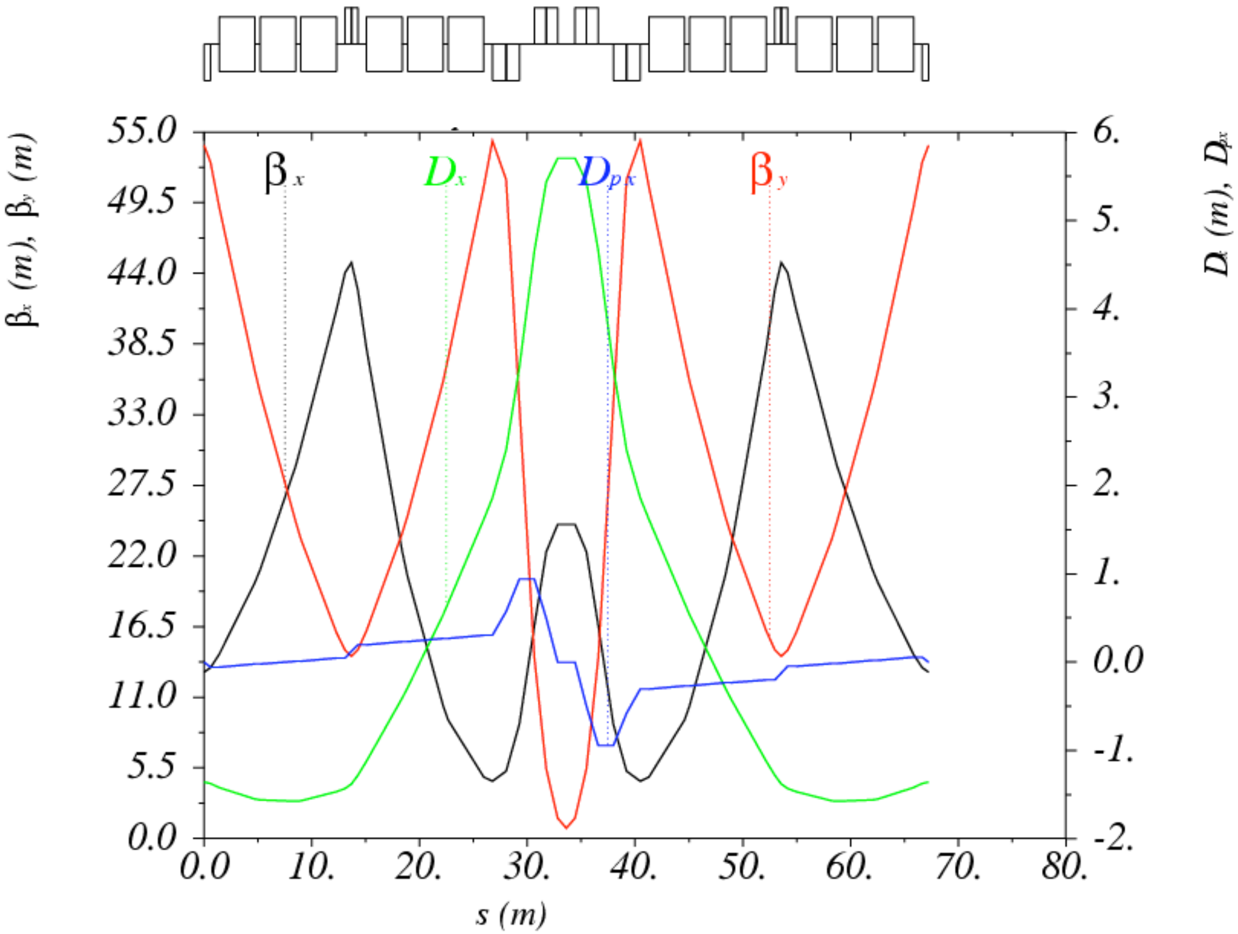




- Main disadvantage is the long arc: only **6** cells available for long straight sections

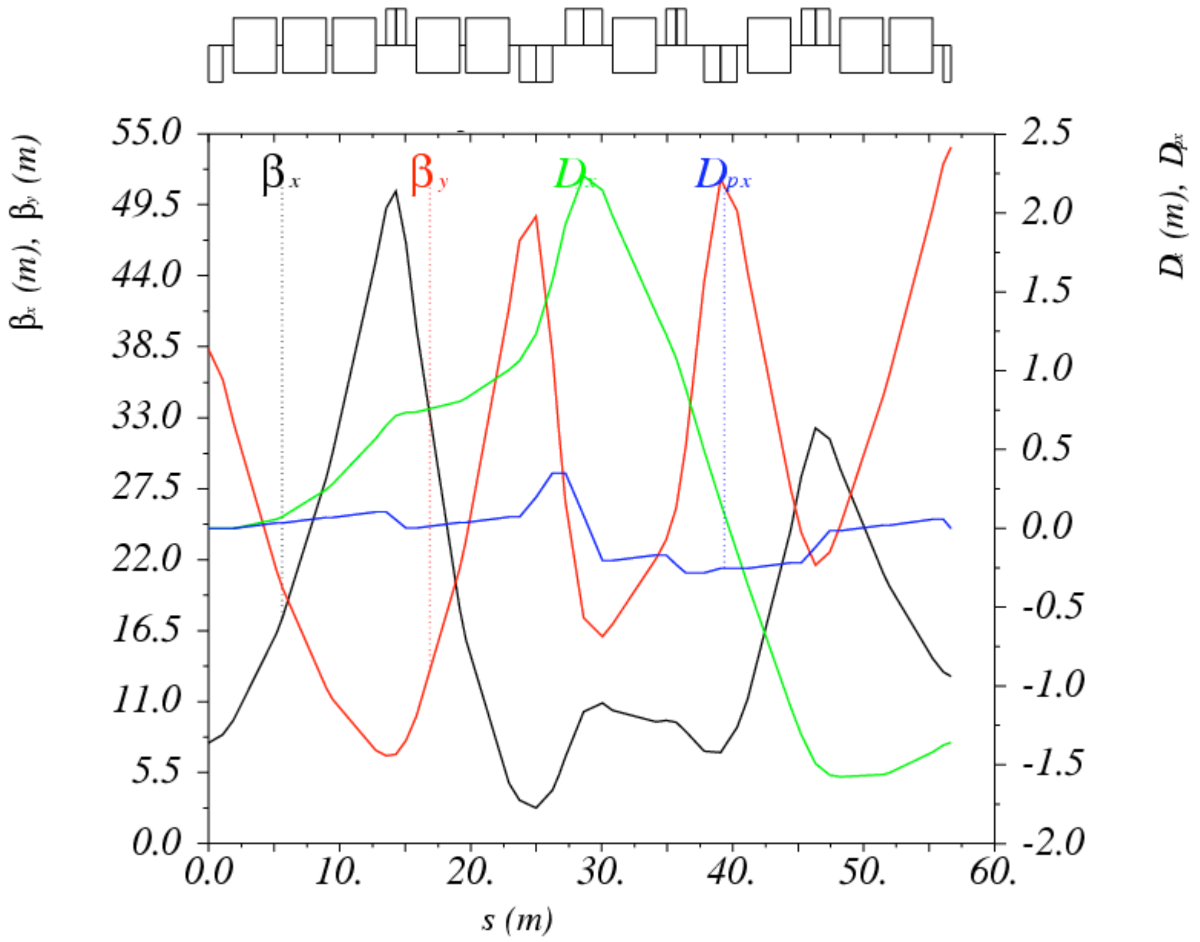
"Short" NMC module with high imaginary γ_t

- Raising the γ_t to **15.3i** by decreasing the phase advances per module to **280°** and **275°** (from **306°** and **288°**)
- Max. beta of **44** and **53m** (as before)
- Min. dispersion of **-1.5m** (from **-4m**) and max. of **5.7m** (from **8m)**
- Chromaticities of **-1.1** and **-2** from (**-1.3** and **-2.1)**
- Total length of **67.25m** (from 68.25)



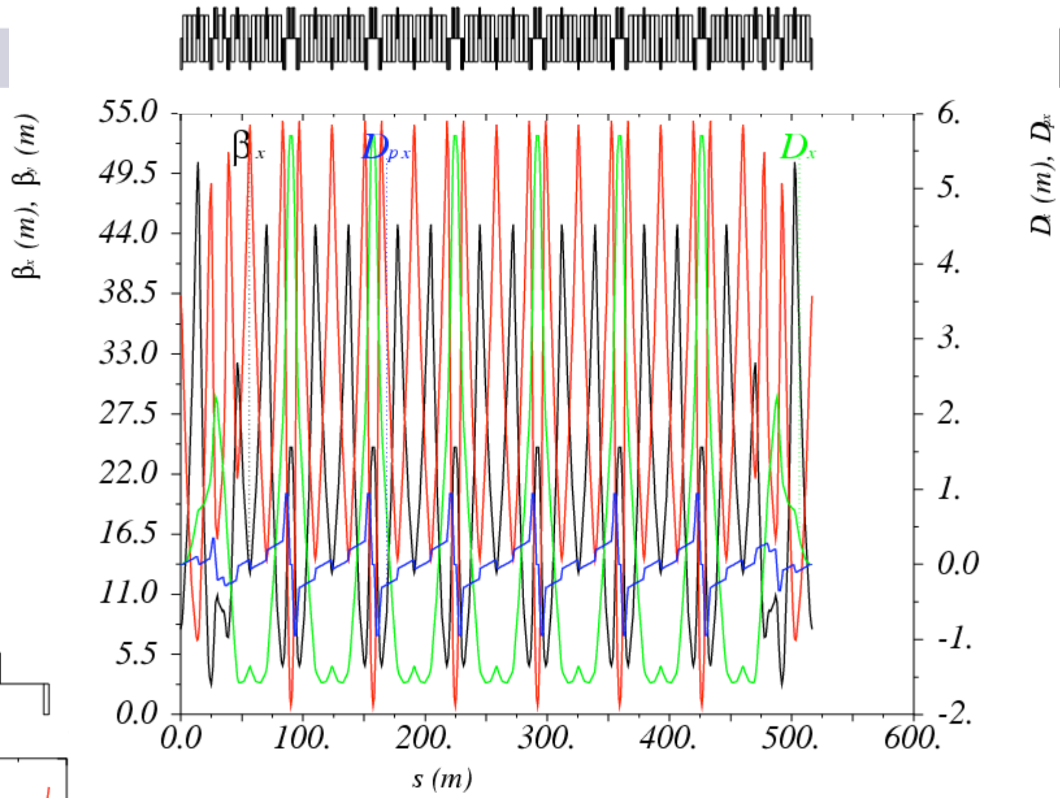
Dispersion suppressor and matching cell

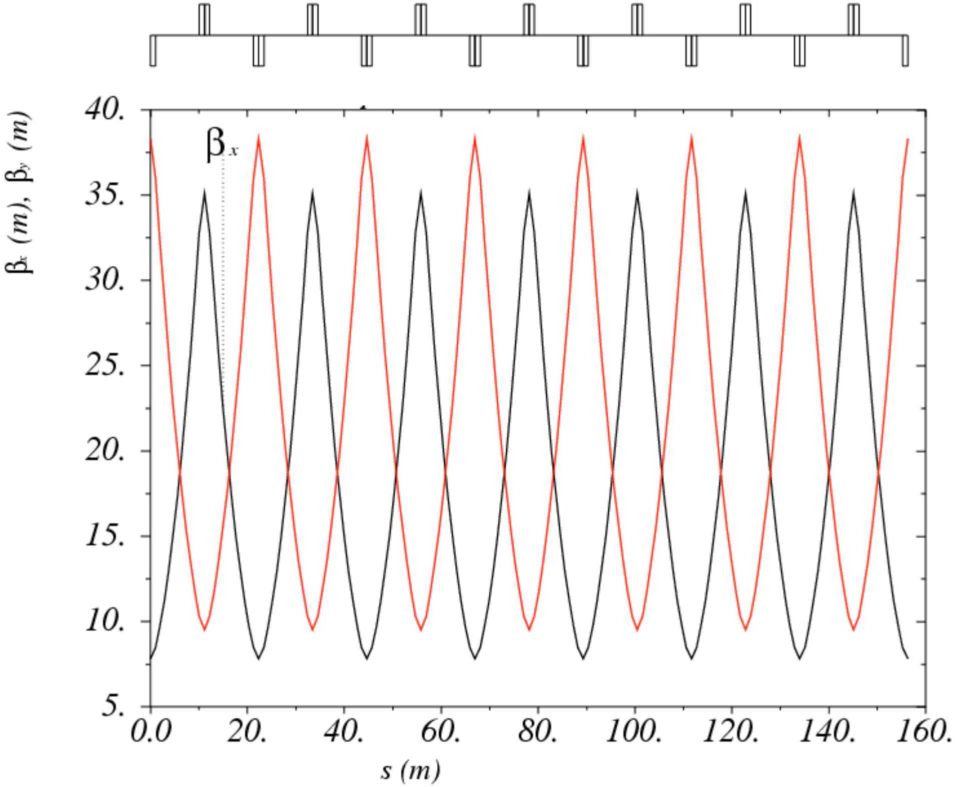
- Similar half module as for the NMC with **3+2** dipoles for suppressing dispersion and matching cell with **1+1+2** dipoles (from 1+2)
- Using **6** (instead of **5)** for better matching
- Maximum beta of **50** and **54m** (from 53 and 60m)
- Total length of 56.7m (from 53.8m)



Arc and long straight section

- Arc composed of six NMC modules and two dispersion suppressors with matching cells
- Total length of **517m** (as before)

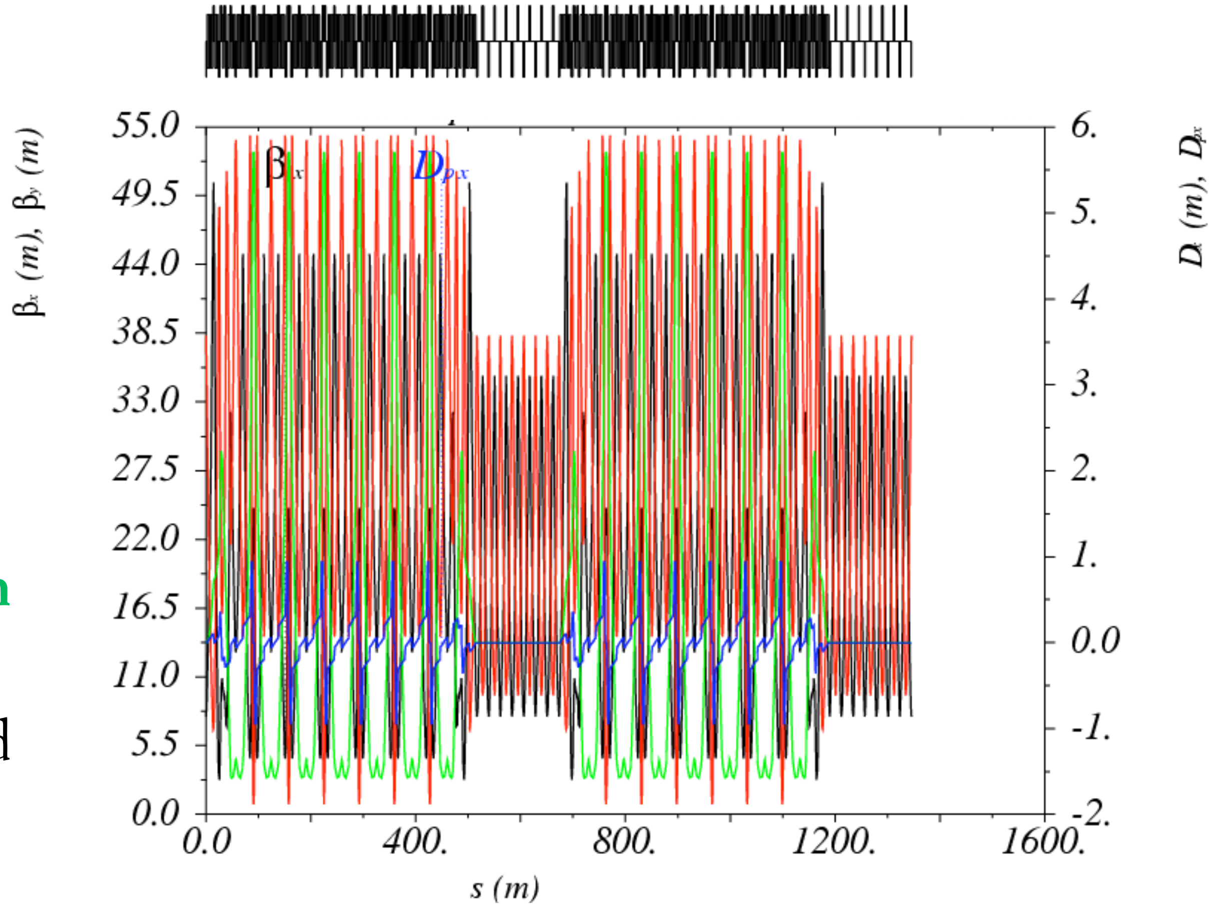




- Straight section with 7 FODO cells with horizontal phase advance of **84.35°** and vertical of **71.7°**
- Straight section drift of **9m** (as before)
- Total length of **156.3m**

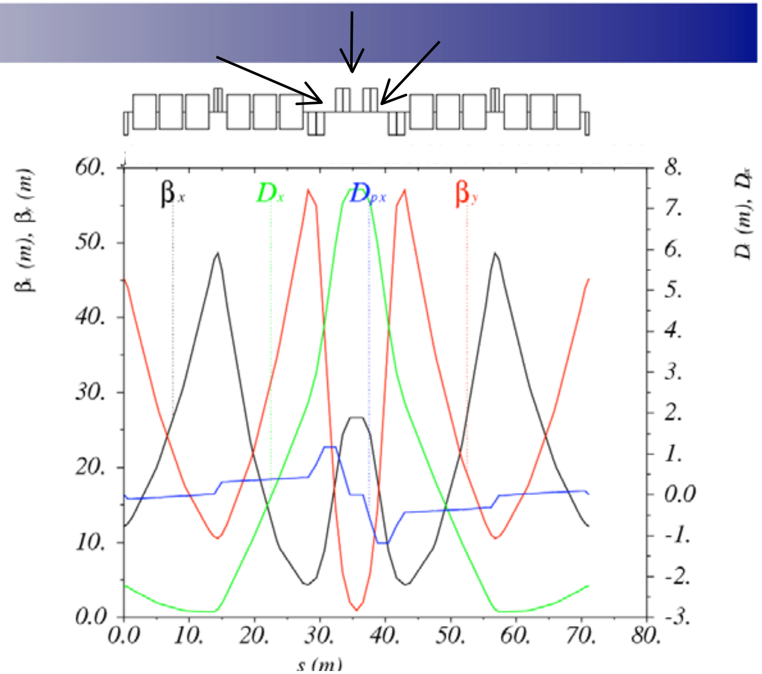
The NMC with dispersion suppressor ring Ib

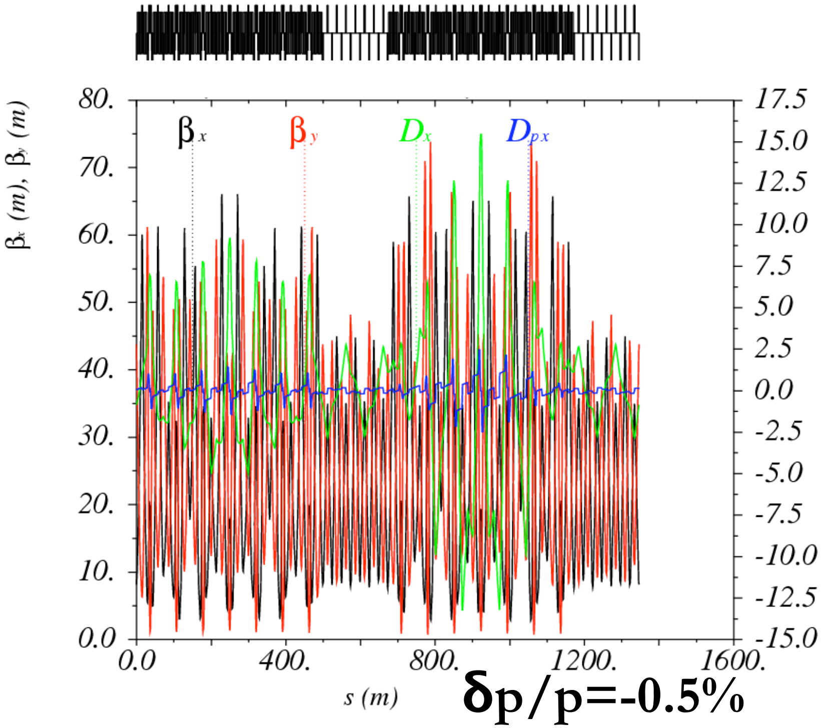
- γ_t of 19.8i
- Tunes of 15.75 and 13.75
- 180 dipoles, 3.3m long
- 134 quadrupoles in 12 (+ 2) families of 5 types with max. strength of $0.1m^{-2}$
- Max. beta of 51m in horizontal and 54m in the vertical plane
- Dispersion min. of -1.5m and max. of 5.7m
- Chromaticities of -21 and -31
- Total length of 1346.4m



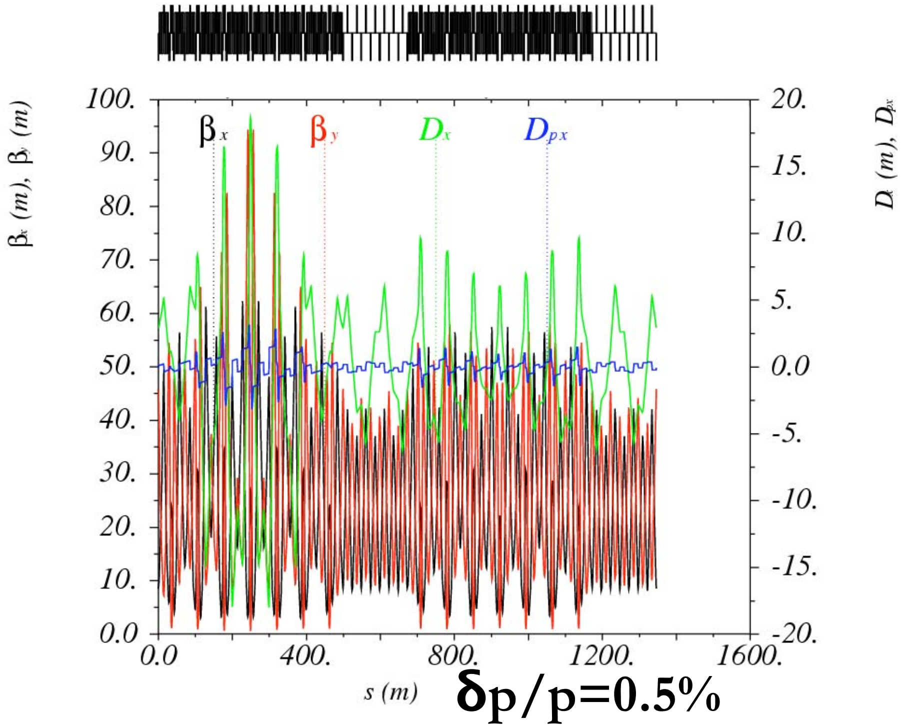
Chromaticity correction

- Same approach for all three lattice types
- Sextupoles of 0.4m long placed in the low beta doublet
- In principle 2 families needed for chromaticity correction
- Second-order chromaticity and off-momentum β-beating not corrected





δp/p=-0.5%

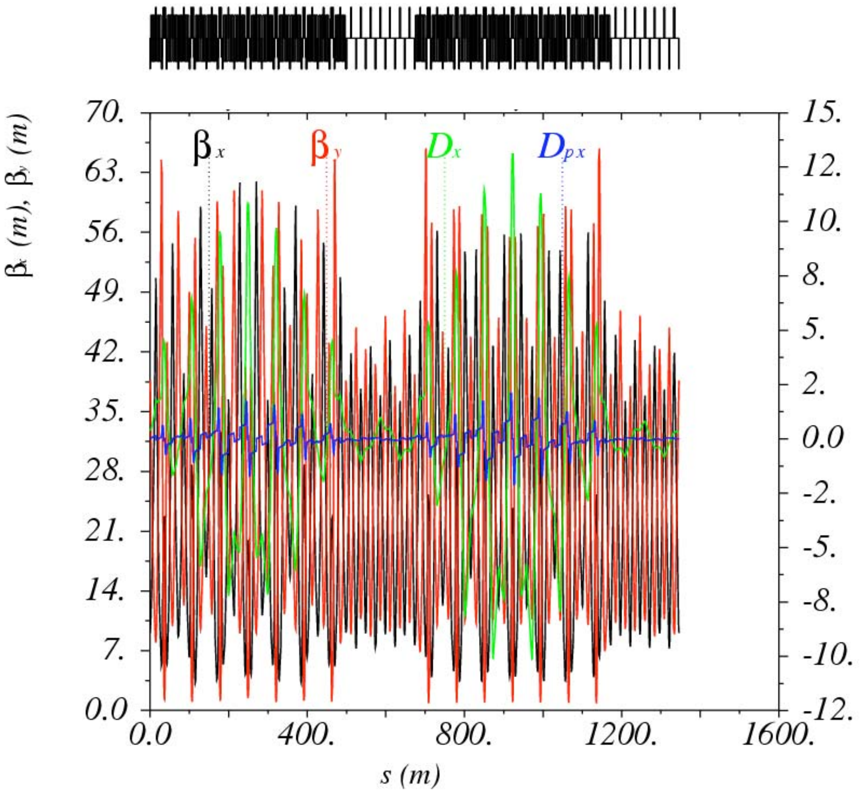


δp/p=0.5%

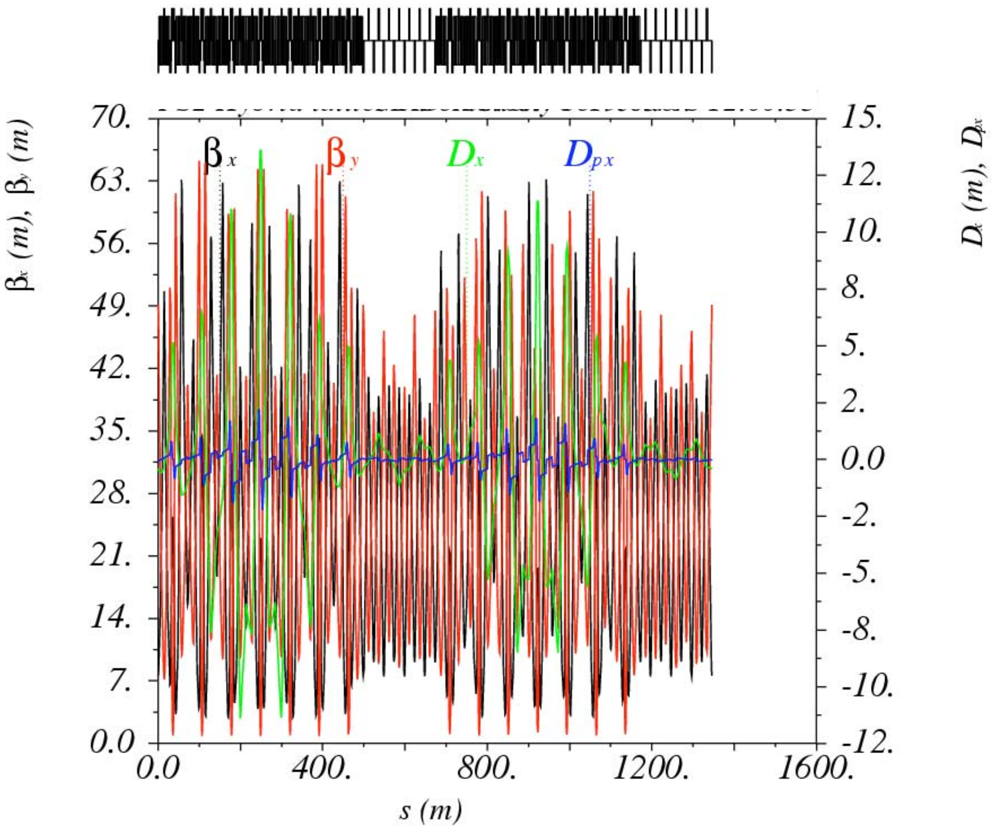
Chromaticity correction

- Using 8 sextupole families to minimize 2nd order chromaticity and off-momentum beta variation in both planes

δp/p=-0.5%

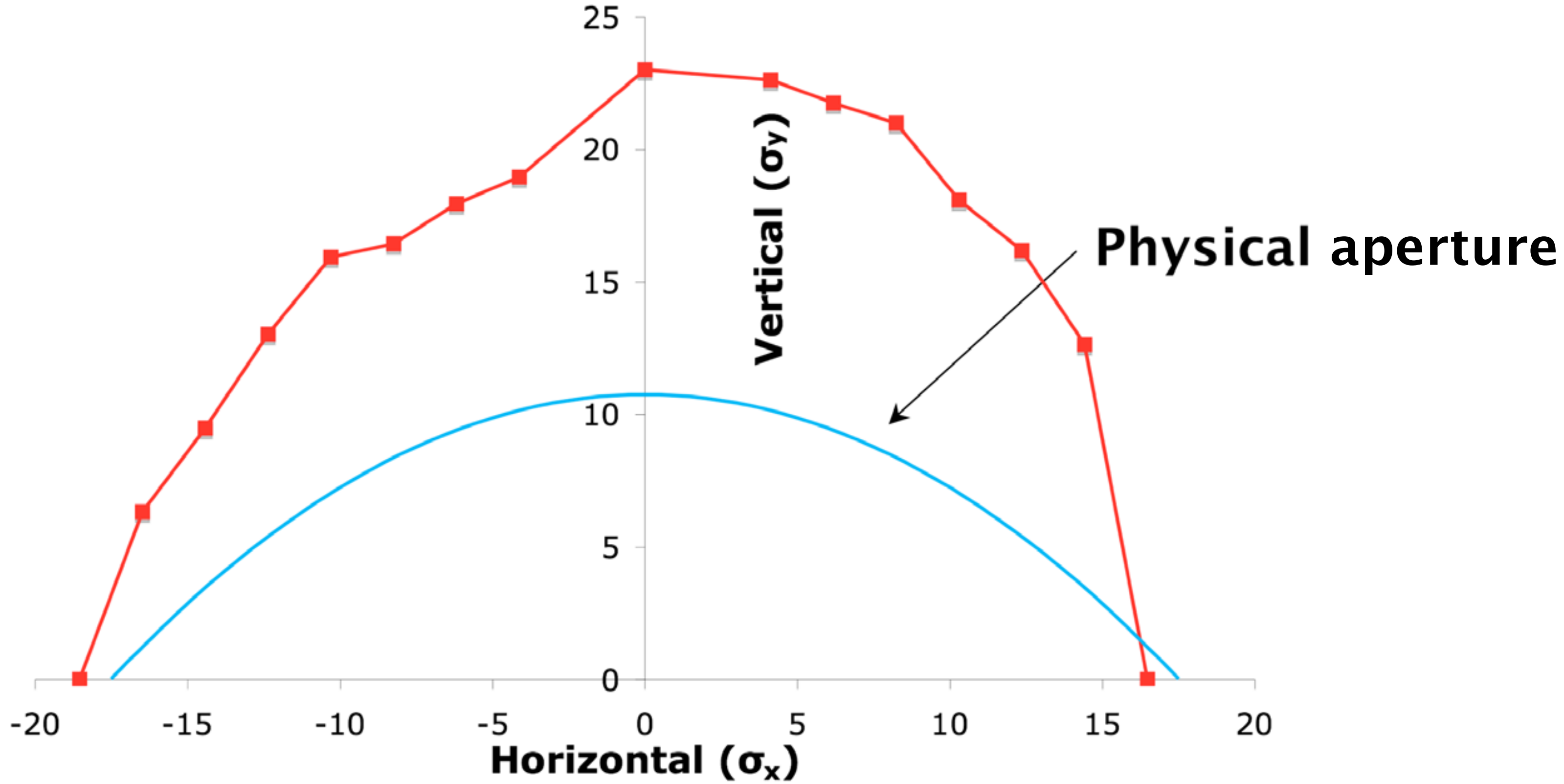


δp/p=0.5%



Dynamic aperture (preliminary)

- On momentum tracking using SIXTRACK for the hybrid lattice
- Only non-linearity included: chromaticity sextupoles
- Large vertical and slightly smaller horizontal DA
- Tune optimization necessary



Comparison

Parameters	NMC with DS RING Ia	NMC with DS RING Ib	NMC resonant RING II	NMC hybrid RING III
Transition energy	10.9i	**19.8i**	10.7i	11i
Number of dipoles	176	180	192	168
Dipole length [m]	3.4	3.3	3.1	3.5
Arc module length [m]	68.3	67.3	64.8	71.2
Number of arc modules	6+2	6+2	8	7
Arc length [m]	517	517	518	500
Straight section drift length [m]	9	9	9.4	10.2
Quadrupole families	11	12	6	8
Arc phase advance [2π]	6.7/5.7	6.2/5.5	7/6	5.7/6.1
Max. beta functions [m]	60/57	**51/54**	61/61	60/60
Max. dispersion function [m]	8.8	**5.7**	8.9	12
Tunes	16.75/14.2	15.75/13.75	16.8/9.8	14.8/15.2
Chromaticity	-24.1/-32.1	-20.6/-30.9	-21.7/-19.8	-21.6/-32.2

Conclusions

- Thorough optics design of several NMC modules with low imaginary transition energy
  - NMC with dispersion suppressor is my **preferred** solution
  - NMC hybrid ring a good **alternative**
  - NMC resonant ring has **limited tunability**
- Relaxing the transition energy constraint (to around **20i**) is an advantage:
  - Reduces the optics functions maxima (less chromaticity, more aperture)
  - Leaves margin for tuning and operational flexibility
  - For example, the J-PARC high energy ring lattice is tuned for a transition energy of **30i**
- Lattice choice based on detailed comparison of performance with respect to beam losses
  - Collimation system, non-linear dynamics, collective effects