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Lattice options for PS2

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Outline

- PS2 design goals and optics constraints
- All FODO cell ring
  - Transition crossing optics
- Negative (Flexible) Momentum Compaction modules
  - Design principle
  - NMC rings
    - With dispersion suppressor
    - Resonant
    - Hybrid
  - Tunability and optics' parameter space scan
  - Chromaticity correction and Dynamic aperture
- Comparison and perspectives

Optics constraints for PS2 ring

Basic beam parameters	PS	PS2
Injection kinetic energy [GeV]	1.4	4
Extraction kinetic energy [GeV]	13/25	50
Circumference [m]	200π	1346
Transition energy [GeV]	6	8-12(i)
Dipole function type	Combined	Separated
Dipole length [m]	5	3-4
Maximum bending field [T]	1.2	1.8
Maximum quadrupole gradient [T/m]	5	17
Maximum beta functions [m]	23	60
Maximum dispersion function [m]	3	6
Minimum drift space for dipoles [m]	1	0.5
Minimum drift space for quads [m]		0.8
Layout	Circle	Racetrack
Maximum arc length [m]		~510

Incoherent space charge tune-shift $\Delta Q_{sc} \propto \frac{N_b}{\epsilon_n \beta \gamma^2 B_f} < 0.2$

Improve SPS performance

Analysis of possible bunch patterns: $C_{PS2} = (15/77)\ C_{SPS} = (15/7)\ C_{PS}$

Time for bunch splitting with 10MHz RF systems

Operational flexibility and low cost

Normal conducting magnets

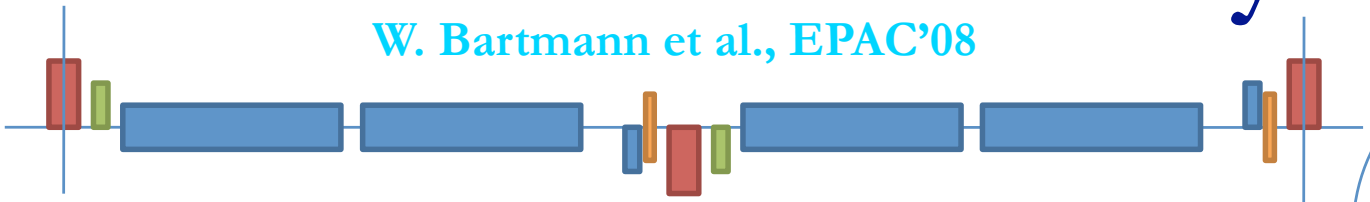
Aperture considerations for high intensity SPS physics beam

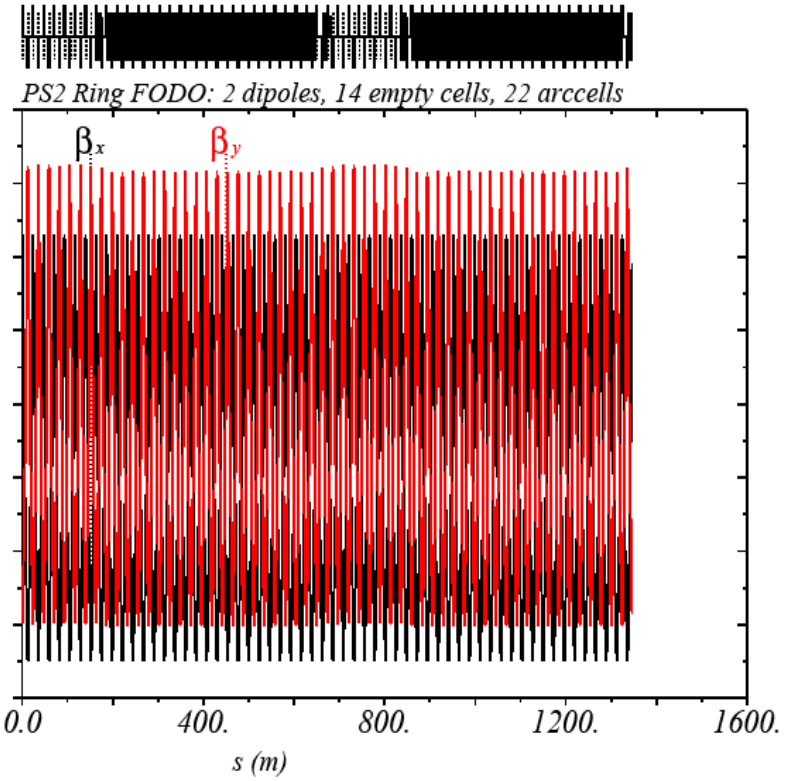
Space considerations

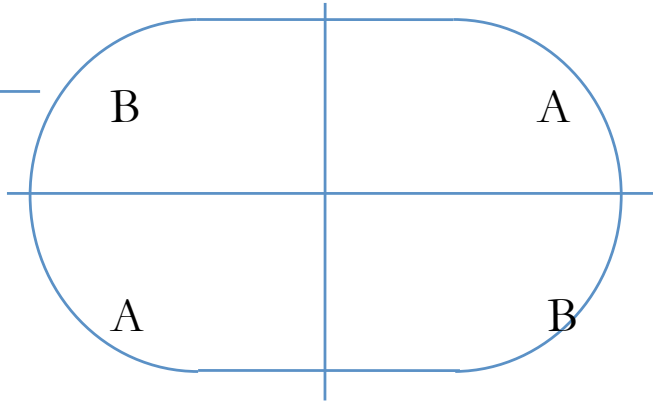
Long straight section minimum length for injection and extraction elements

Basic cell and lattice symmetry

W. Bartmann et al., EPAC'08

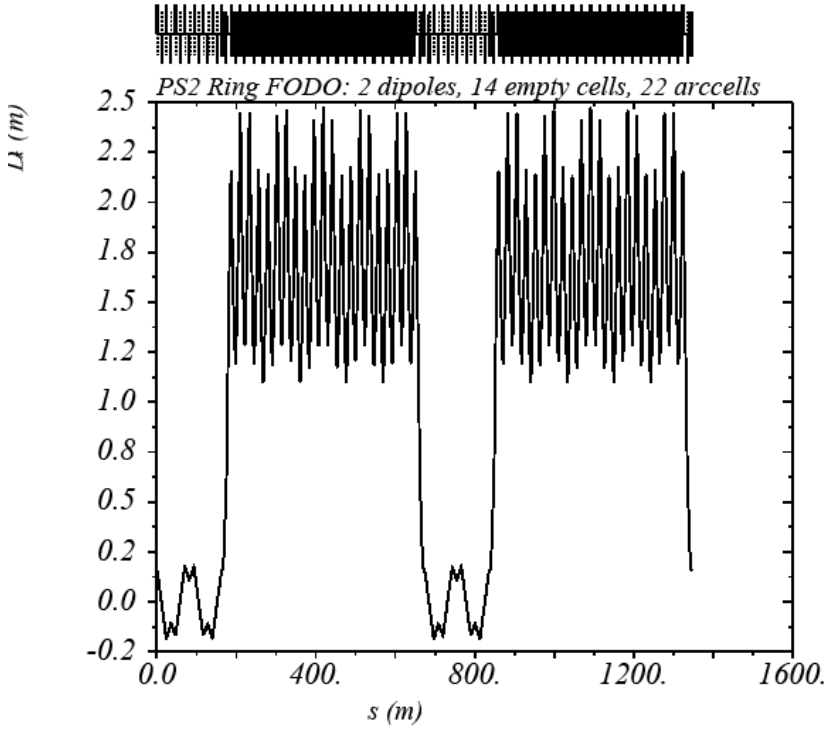






$Q_x = 14.26, \quad \mu_x = 88.5°$

$Q_y = 11.30, \quad \mu_Y = 70.1°$



Asymmetric dipole position in the cell

7 empty cells per LSS

20 full cells per ARC

4 Dispersion Suppressors with missing magnet

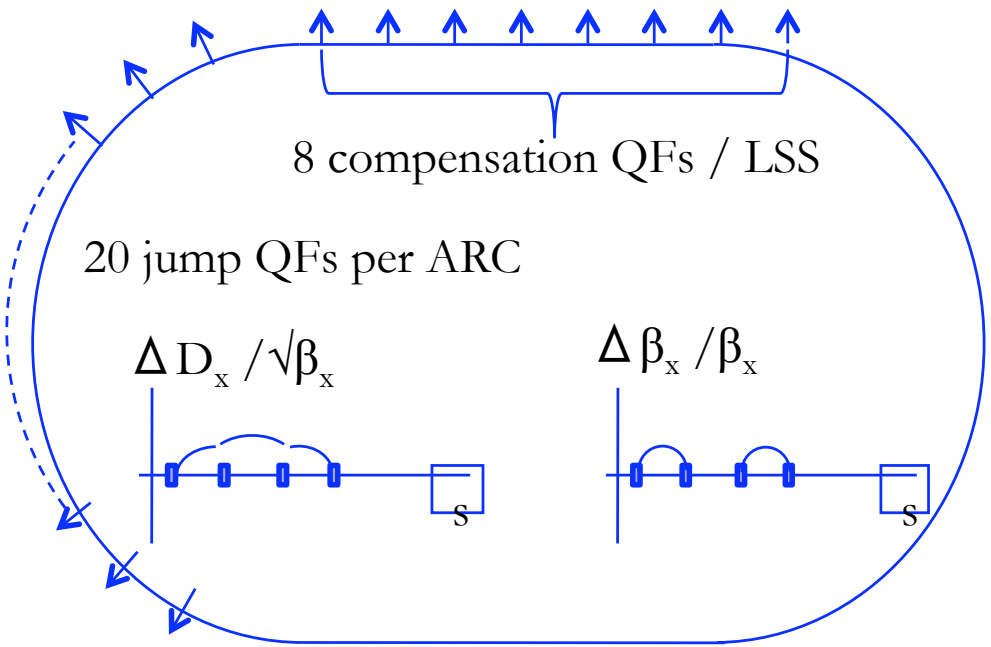
Transition Crossing Schemes

	nTOF (10/20 MHz)	FT (10/40MHz)	LHC (10/40 MHz)	LHC 50 ns (20 MHz)
$\Delta\gamma_{tr}$	-6.85/-1.38	**-2.91/-2.68**	-2.44/-0.95	-1.41

W. Bartmann et al., EPAC'08

- First order jump T. Risselada, 1990

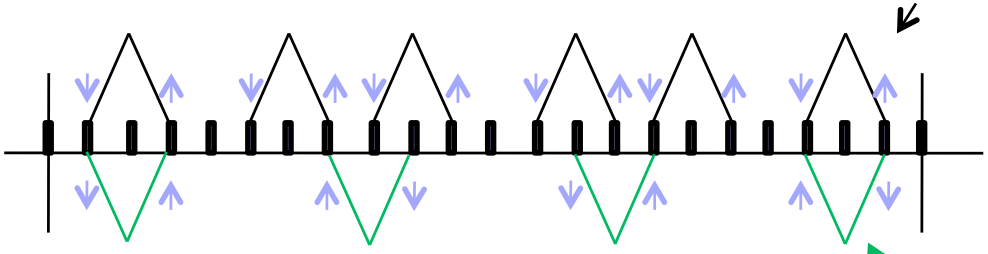
$$\Delta\gamma_{tr} = \gamma_{tr}^3 / (2C) \cdot \sum_i K_i \cdot D_i^2$$



- Second order jump

W. Hardt et al., PAC 1971

$\Delta\gamma_{tr} = - 0.065 \cdot \psi^2 \cdot 2M \cdot \cot(\theta)$ $\quad \Delta\gamma_{tr} > 0$



$\Delta\gamma_{tr} = 0.065 \cdot \psi^2 \cdot [2(M-1) \cdot \tan(\theta) - 2]$ $\quad \Delta\gamma_{tr} < 0$

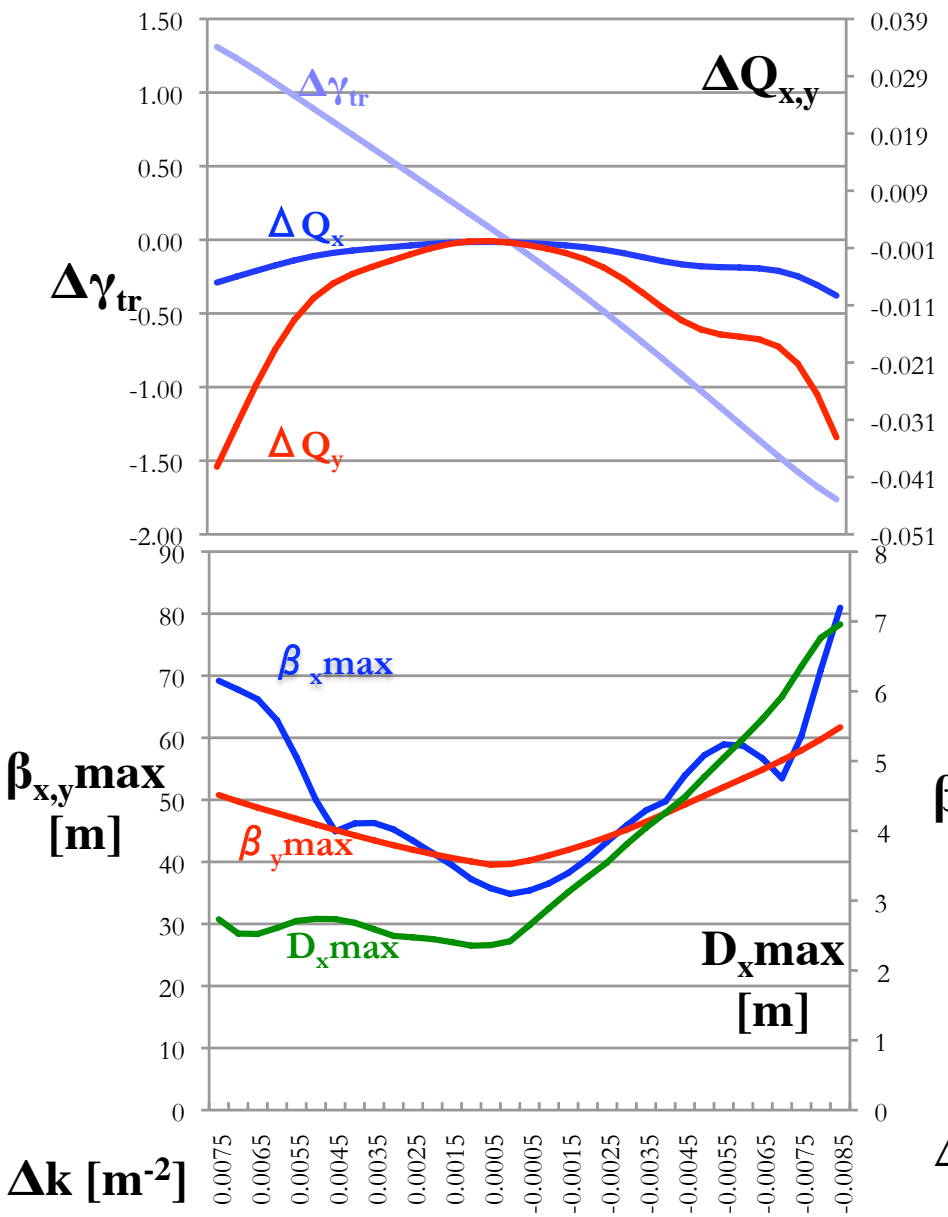
$\Psi_i = \beta_{0i} \cdot \int K_i \cdot dl$

M = # doublet arrays

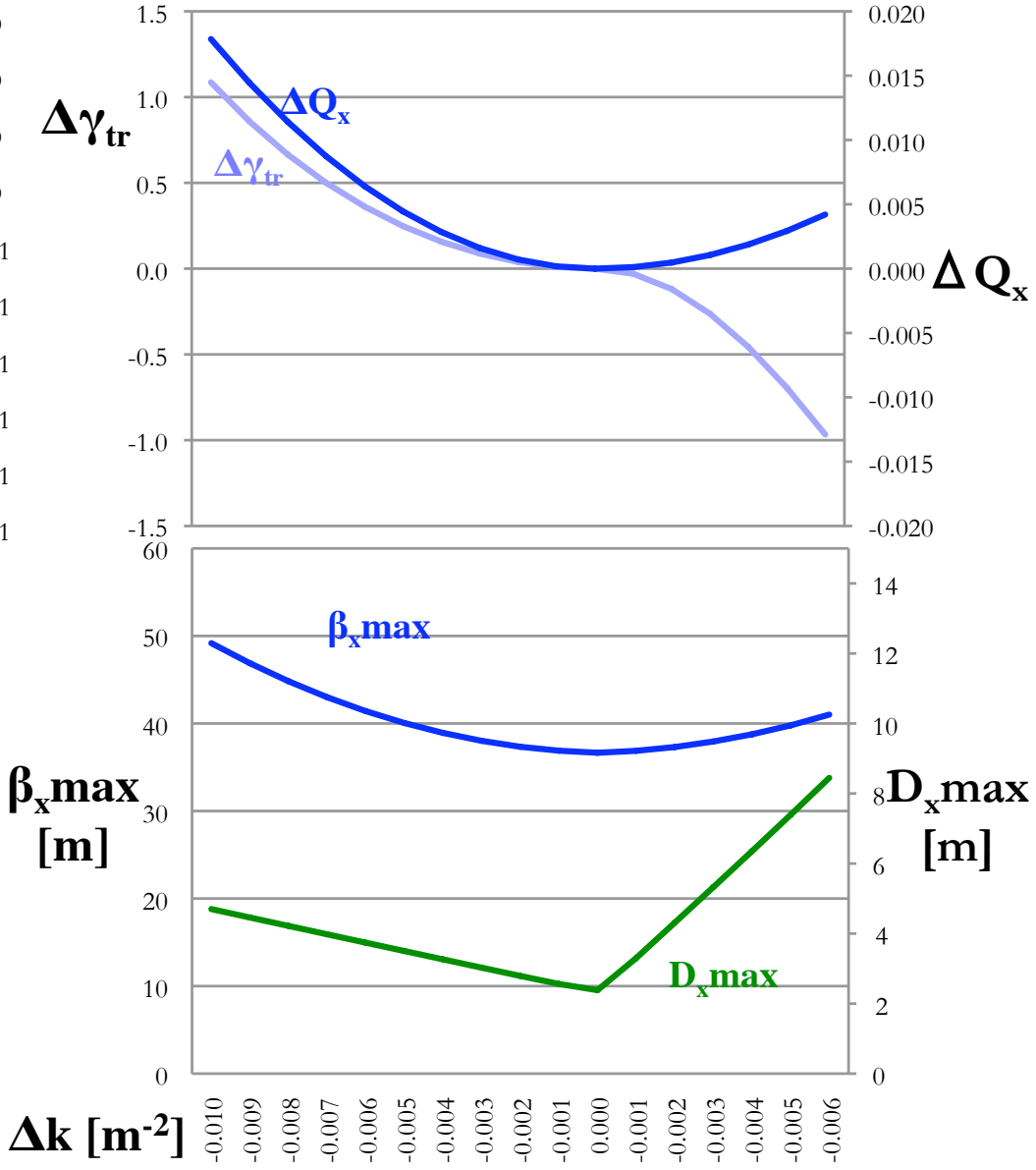
$2\theta = 2\pi Q_0 / M$

Optics during transition crossing

- First order jump



- Second order jump



Negative Momentum Compaction modules

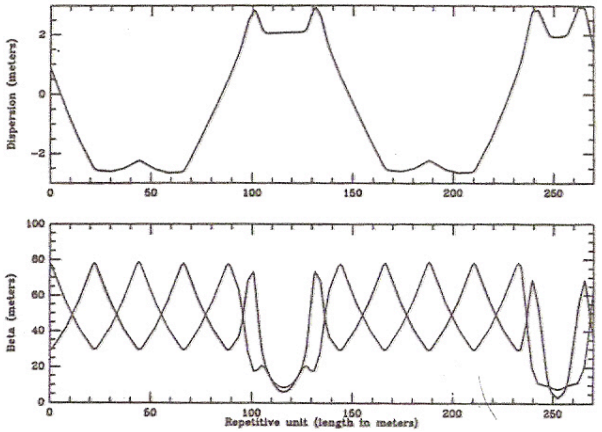
- Avoid transition crossing (beam instabilities and losses)
- Aim at negative momentum compaction

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

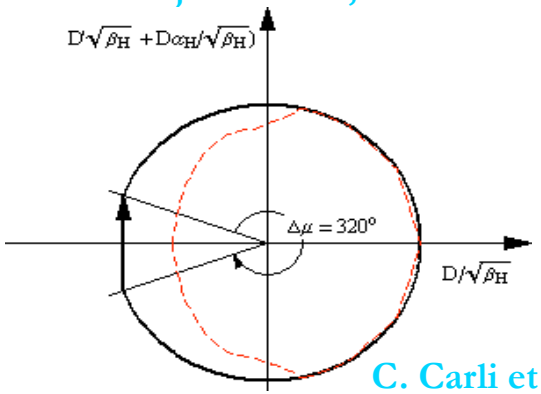
- Modulate dispersion using cells with different bending power
- Normalized coordinates

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

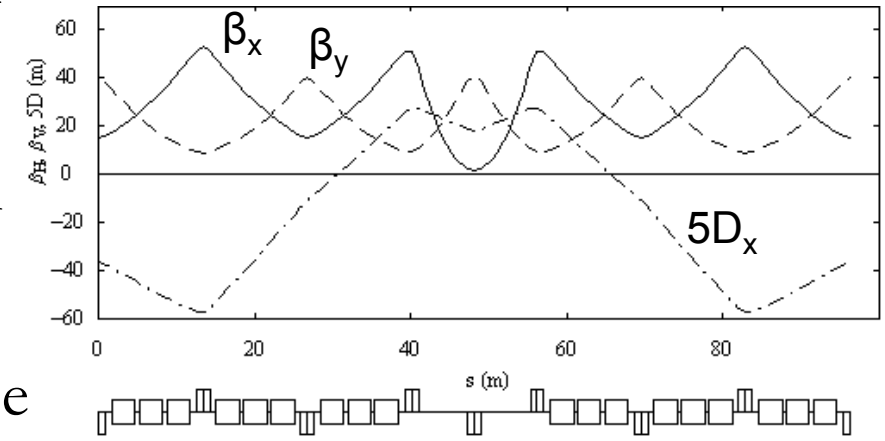
- Dispersion vector (χ, ξ) is invariant outside bends, i.e. vary it with bends in areas of negative dispersion to get NMC
- Similar approach used for J-PARC high energy ring lattices
- **Main difficulty in PS2**: extremely low $\gamma_t \approx 10i$ (high dispersion) in limited space



D. Trbojevic et. all, EPAC 90.

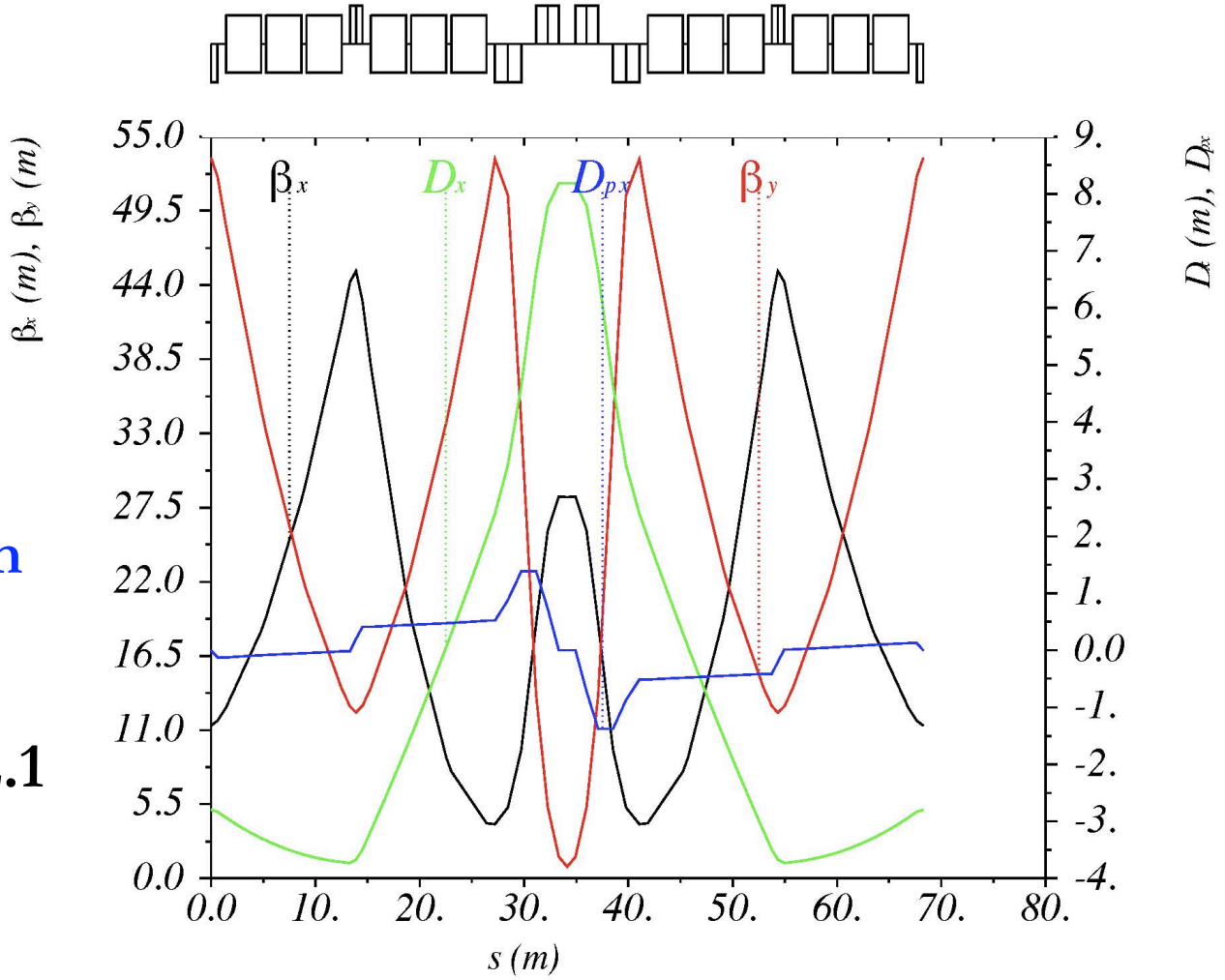


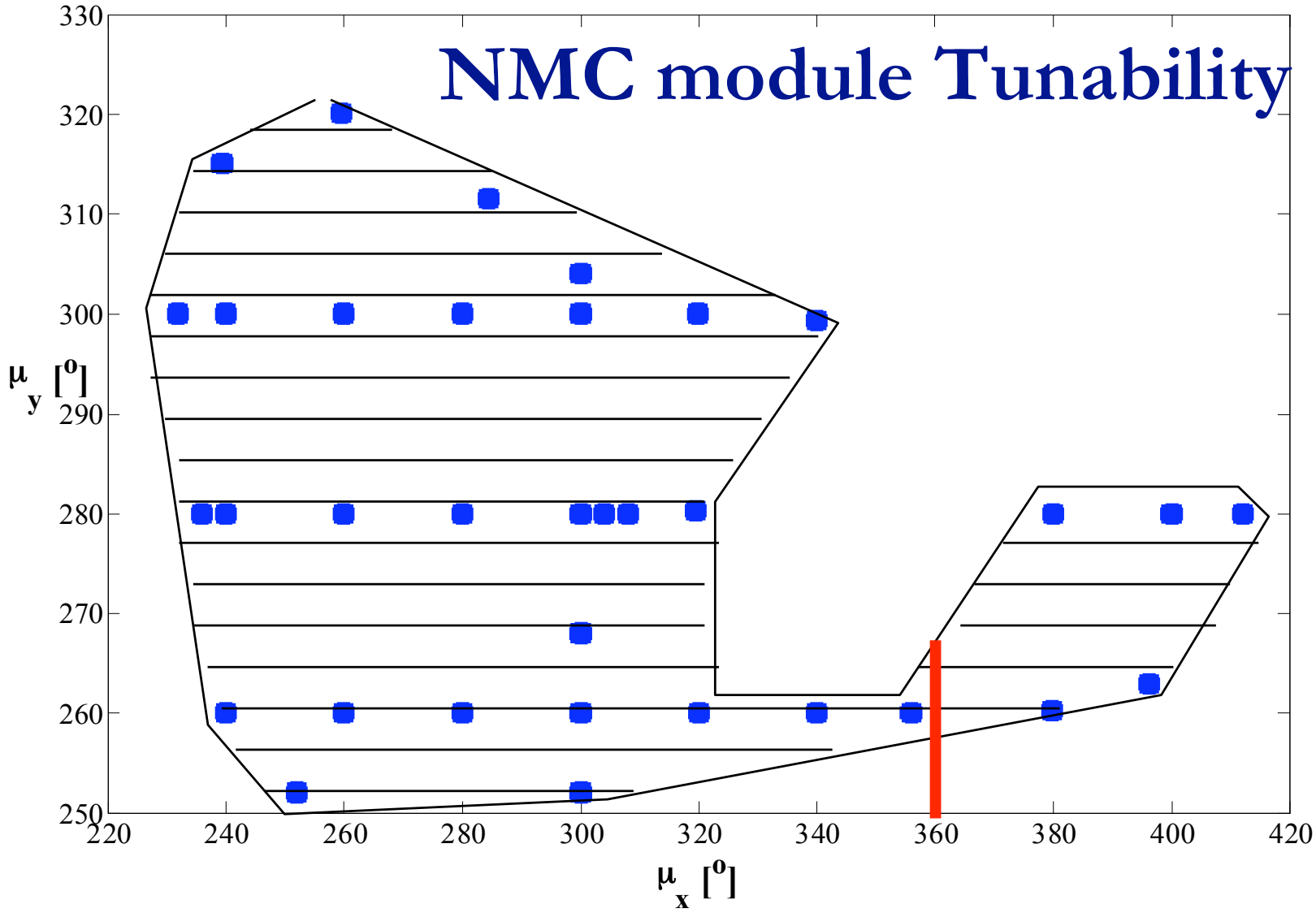
C. Carli et al. PAC07



The "short" NMC module

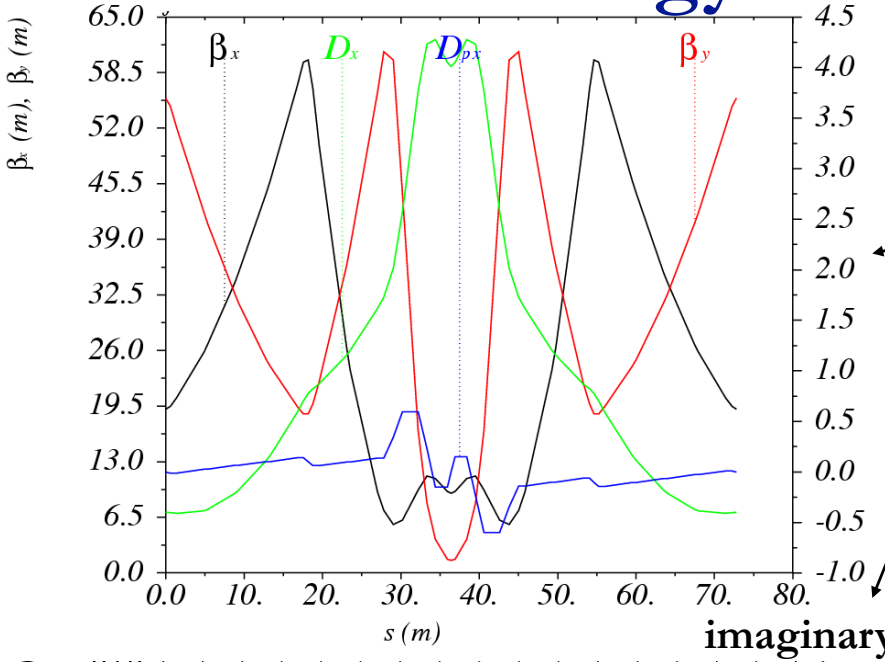
- 1 DOFO cell with 3 + 3 bends and a low-beta doublet
- γ_t of **8.1i**
- Phase advances of **306°** and **288°** per module
- Four families of quads, with max. strength of **0.1m^{-2}**
- Max. beta of **44** and **53m**
- Min. dispersion of **-4m** and maximum of **8m**
- Chromaticities of **-1.3,-2.1**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

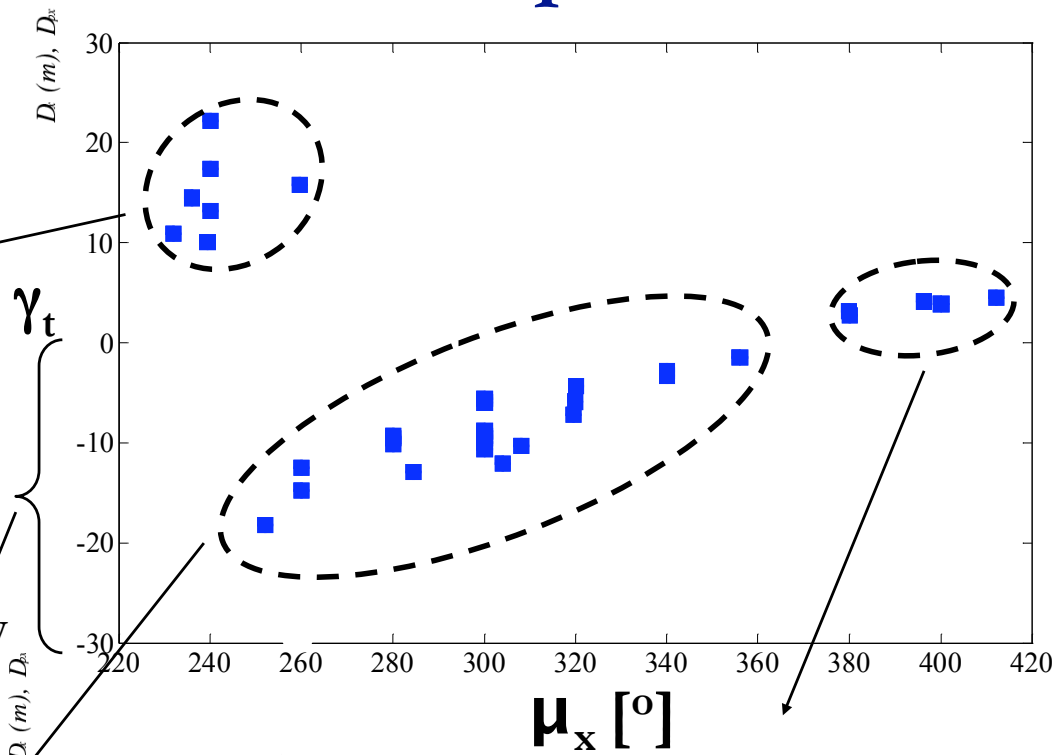




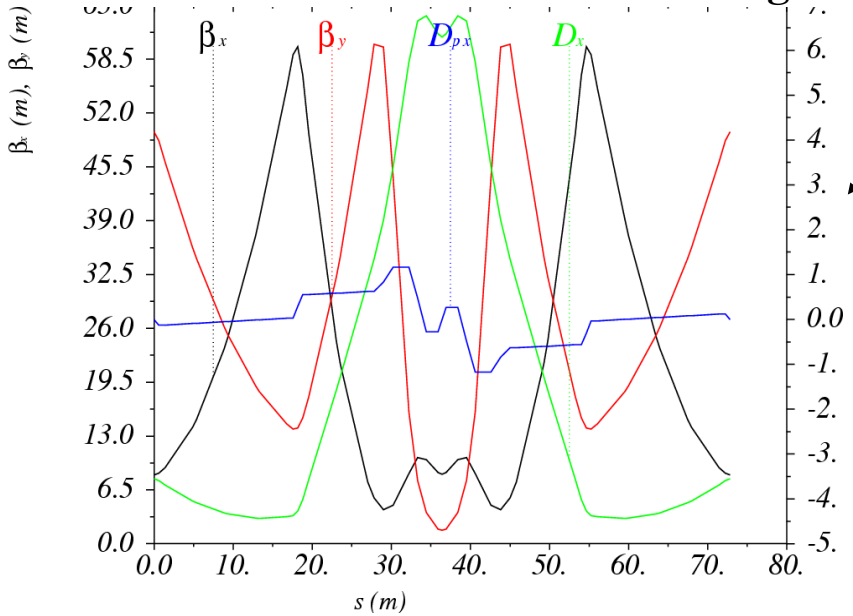
- Phase advance tunable between **240°** and **420°** in the horizontal and between **250°** and **320°** in the vertical plane

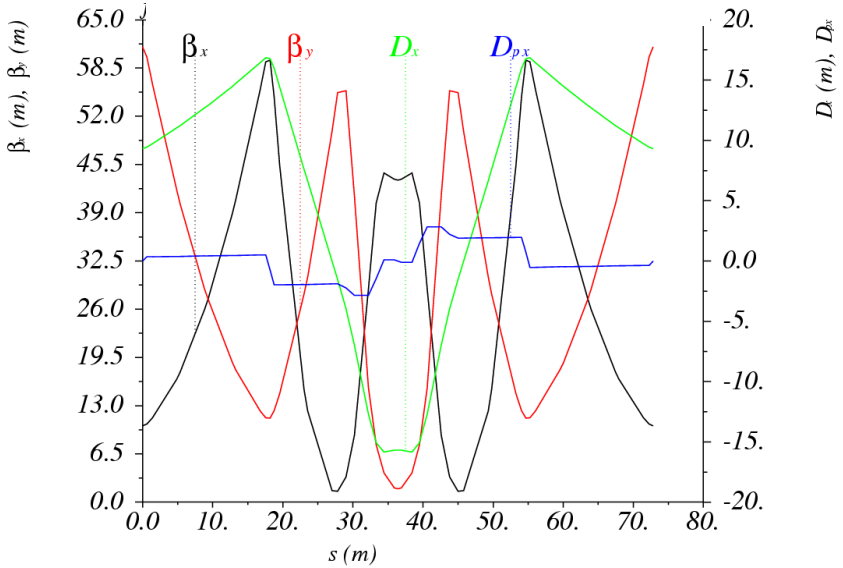
Transition energy versus horizontal phase advance



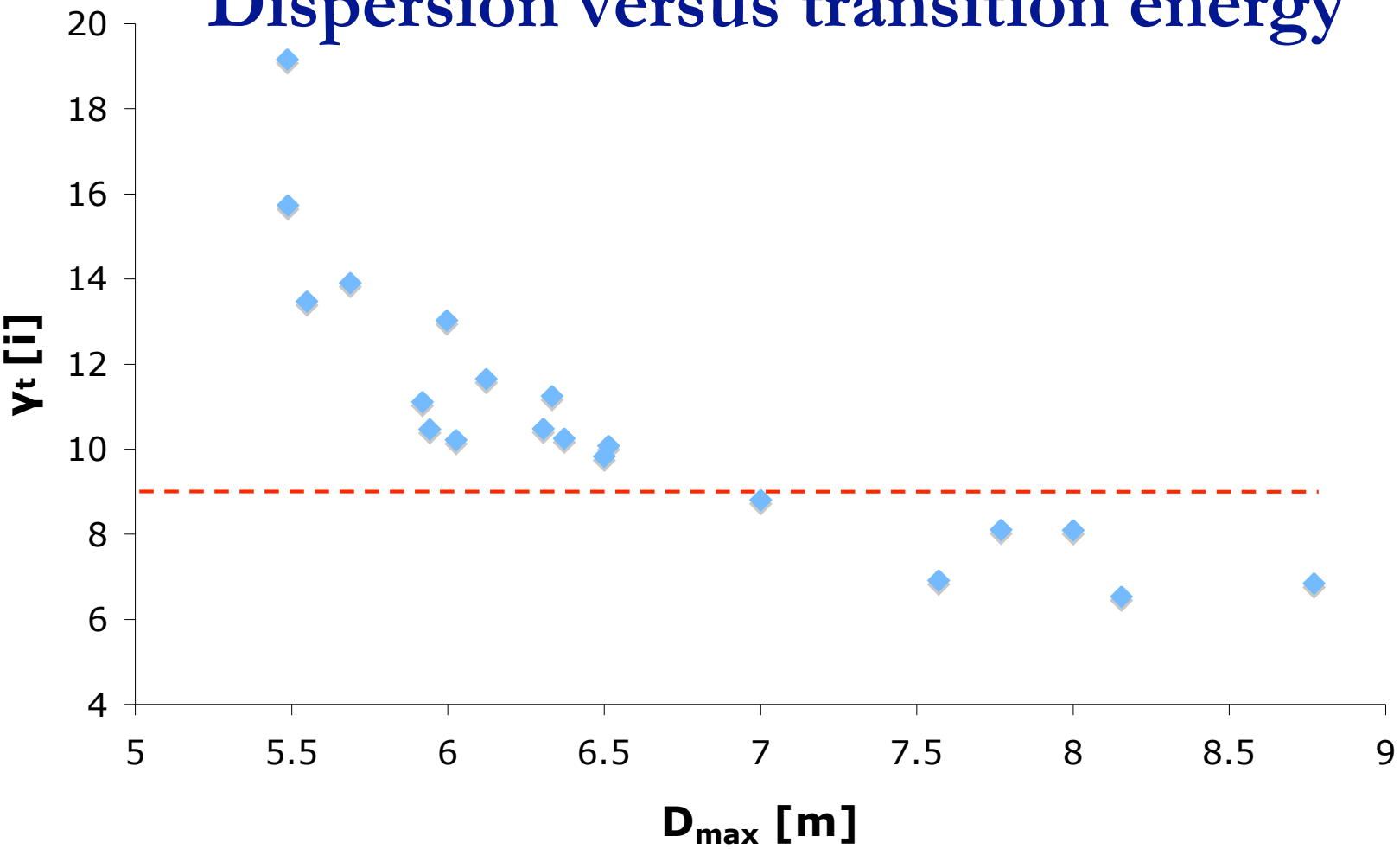


imaginary





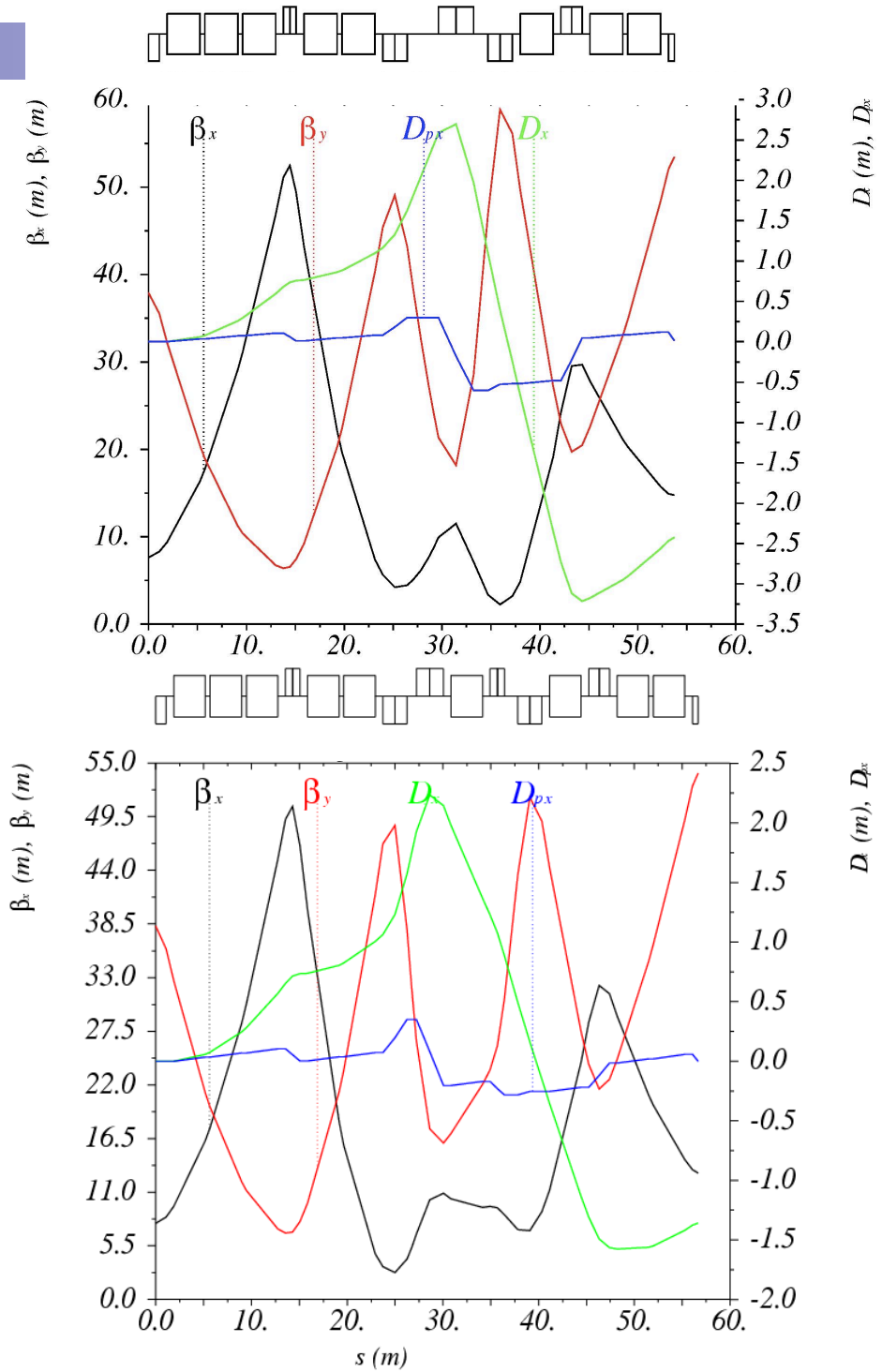
Dispersion versus transition energy



- 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
- Same tendency for beta functions and chromaticity

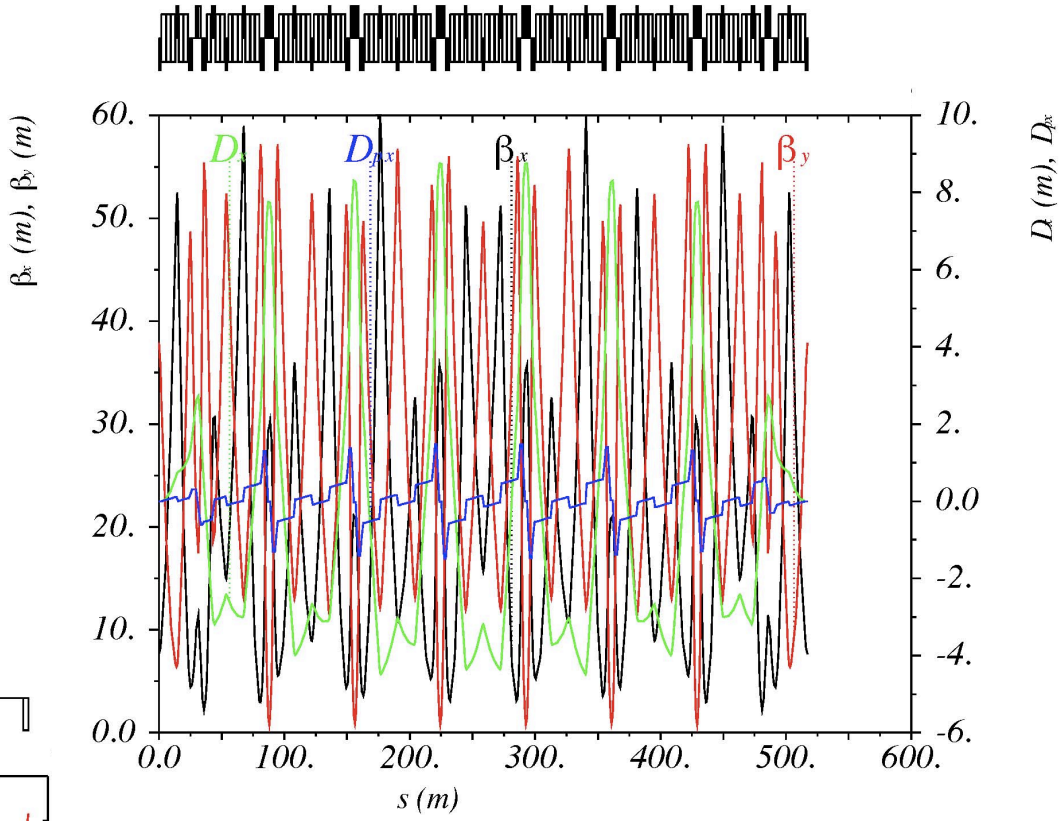
Dispersion suppressor and matching cell

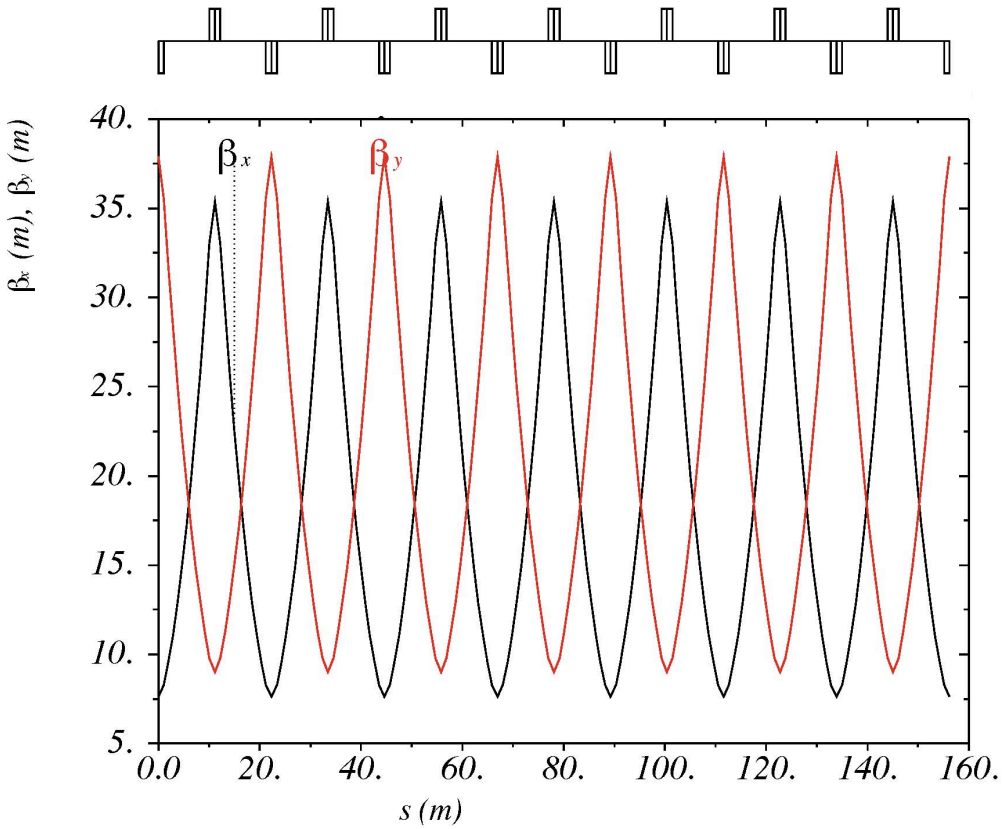
- Similar half module as for the NMC with **3+2** dipoles for suppressing dispersion and matching cell with **1 (+1)+2** dipoles
- Using **5** (or **6**) families of quads with strengths within the imposed limits (sharing two half quads with the straight section and arc module)
- Maximum beta within imposed limits
- Total length of around **60m**



Arc and long straight section

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

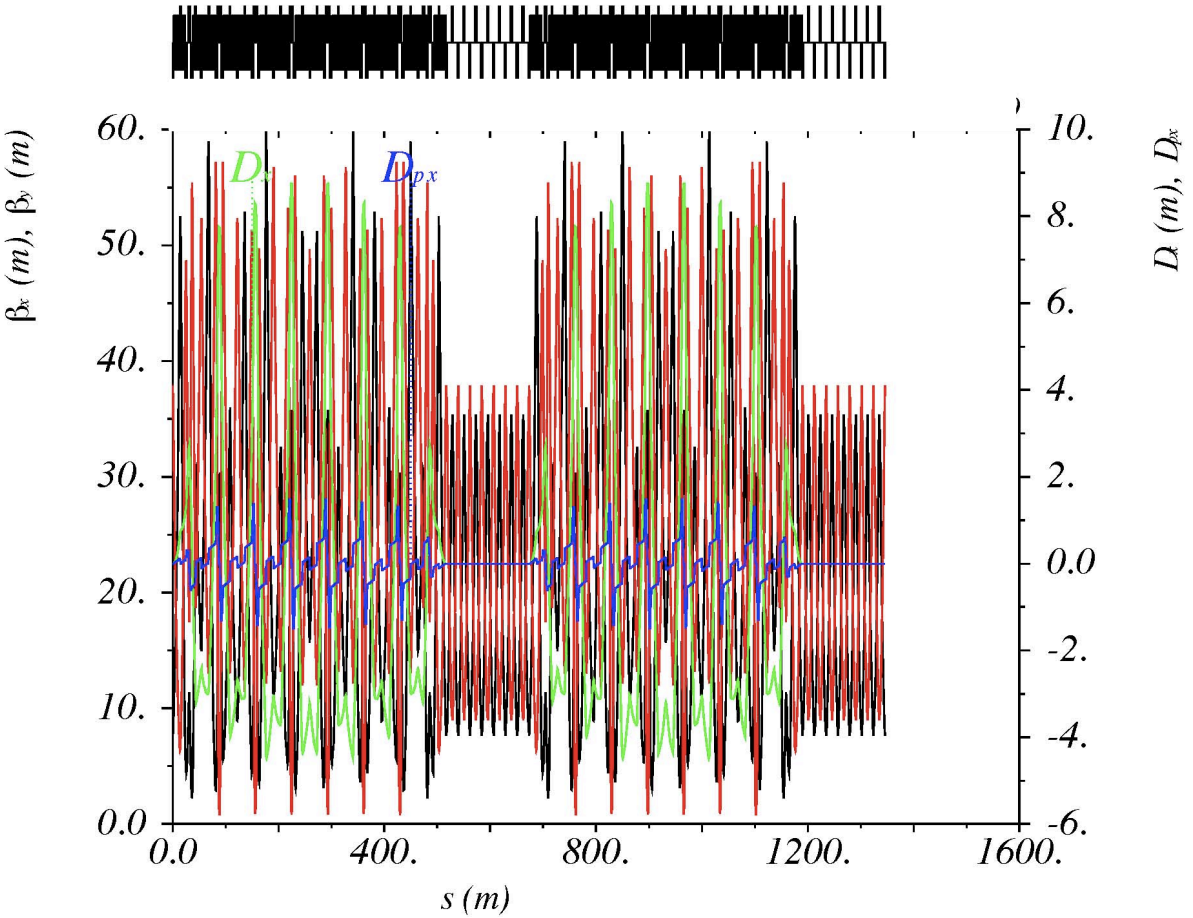




- Straight section with 7 FODO cells with horizontal phase advance of **85.25°** and vertical of **74°**
- Straight section drift of **9m**
- Only two families of quadrupoles are used
- Extra two families can be added for internal phase adjustments
- Total length of **156.2m**

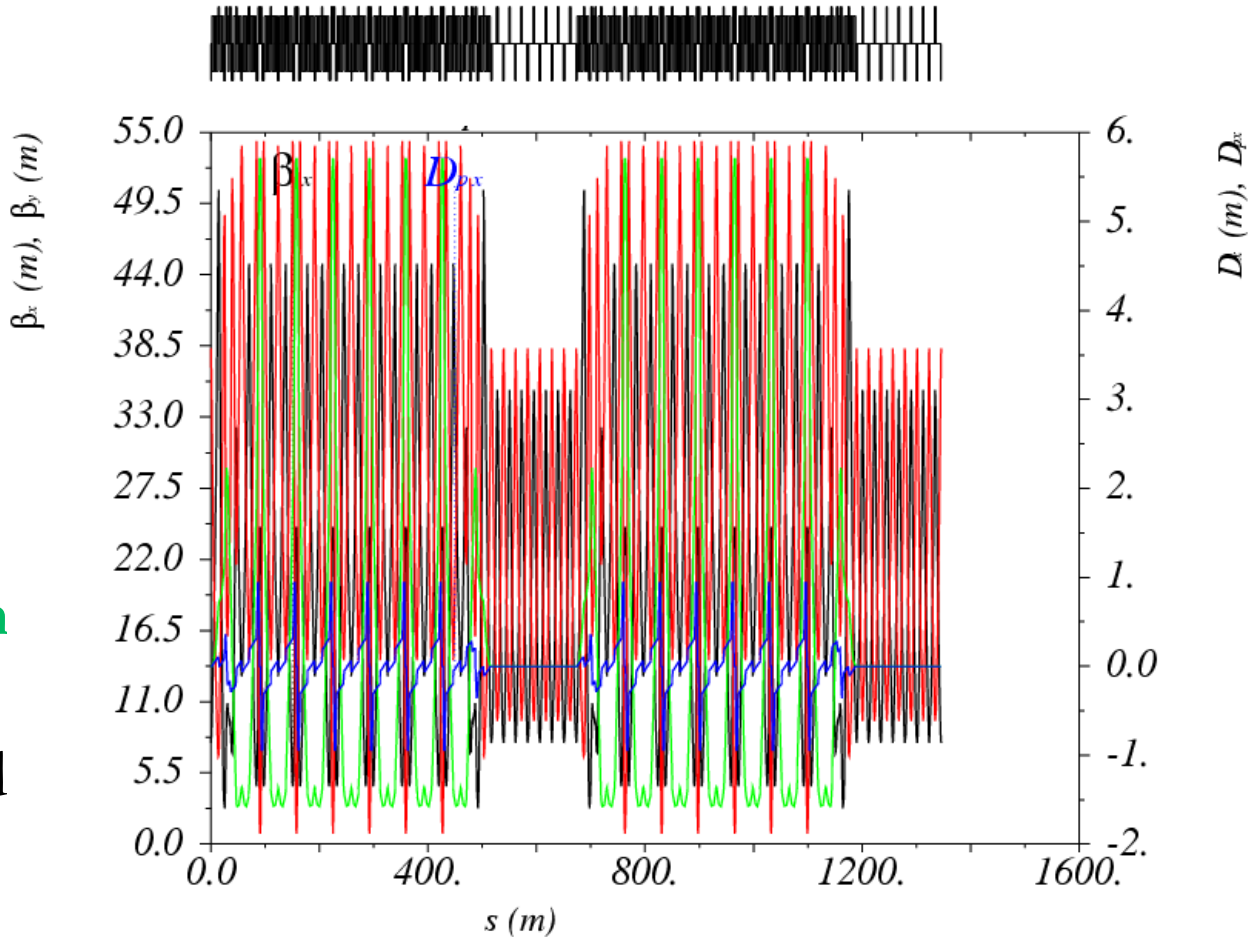
The NMC with dispersion suppressor ring I

- 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 NMC with dispersion suppressor ring Ib

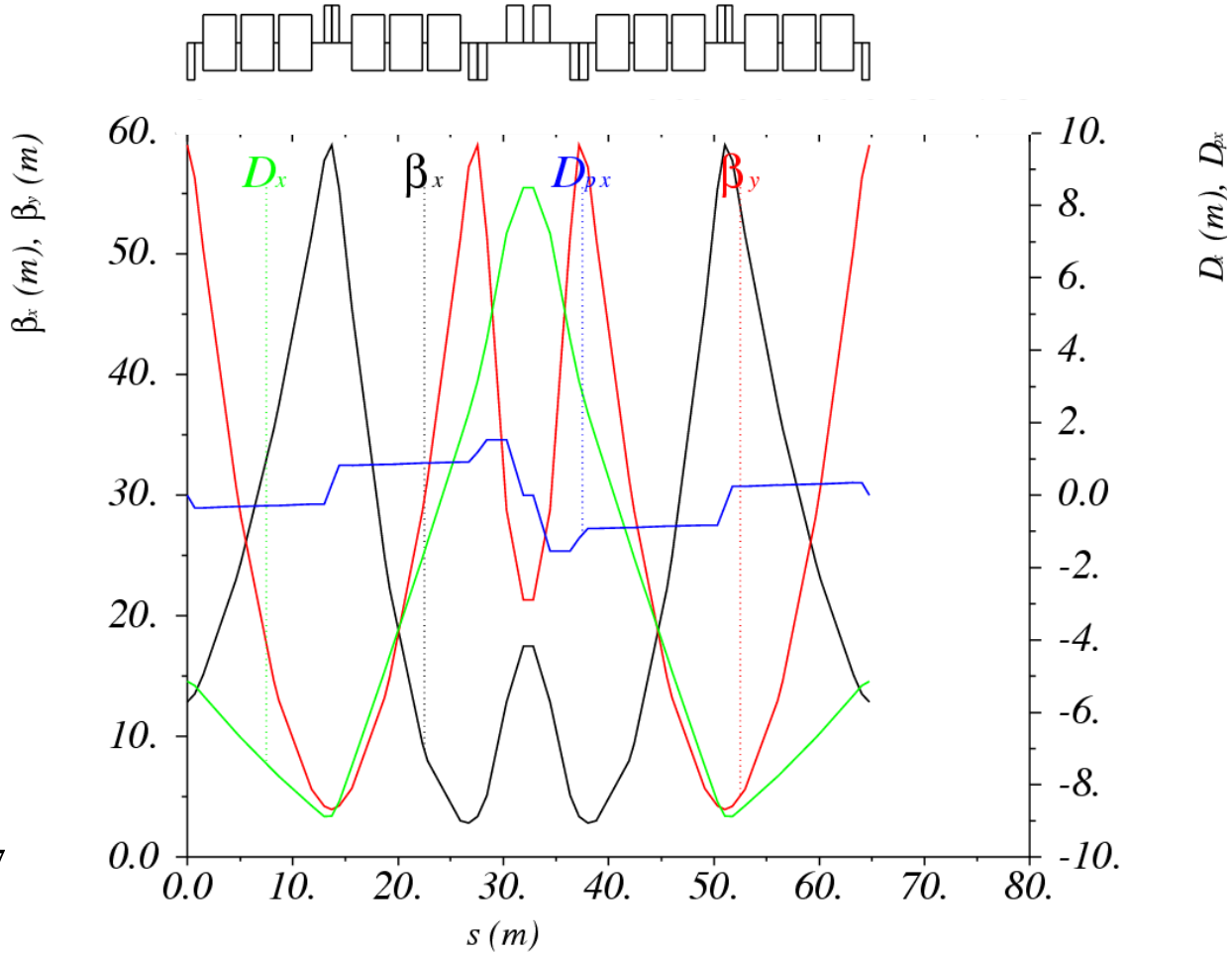
- γ_t of **19.8i**
- Tunes of **15.75** and **13.75**
- **180** dipoles**,** **3.3m** long
- **134** quadrupoles in **12** **(+ 2)** families of **5** types with max. strength of **0.1m^{-2}**
- Max. beta of **51m** in horizontal and **54m** in the vertical plane
- Dispersion min. of **-1.5m** and max.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



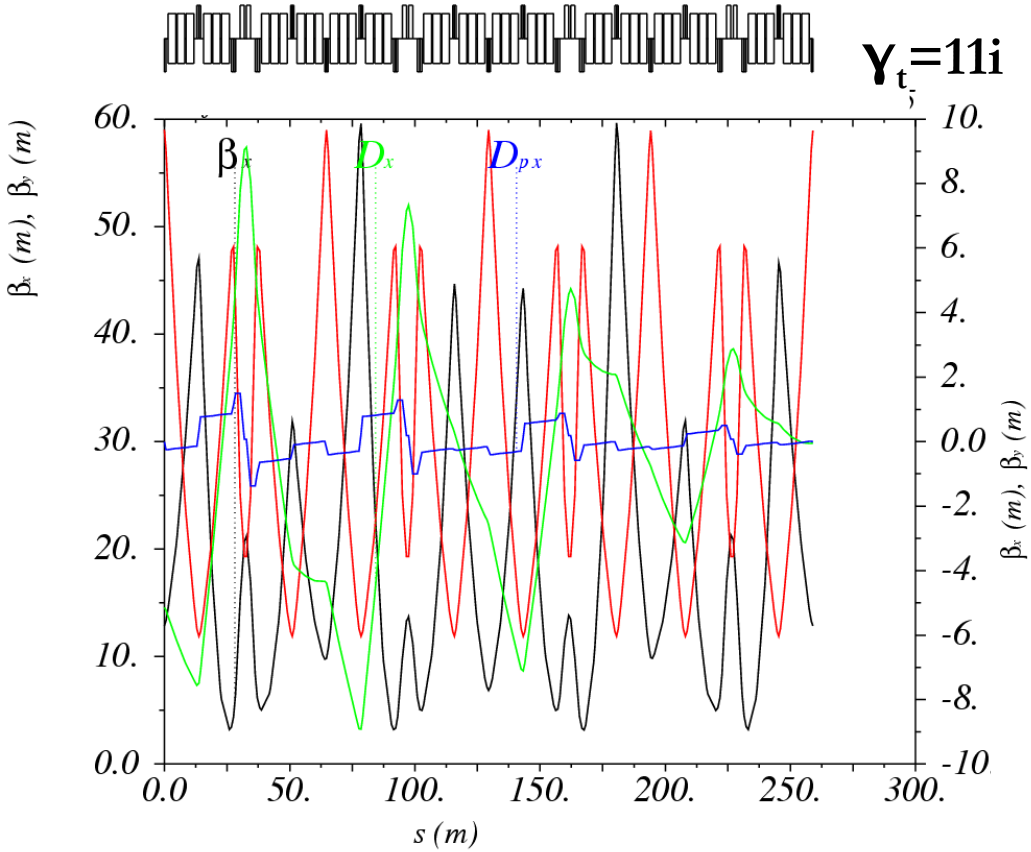
The resonant NMC module

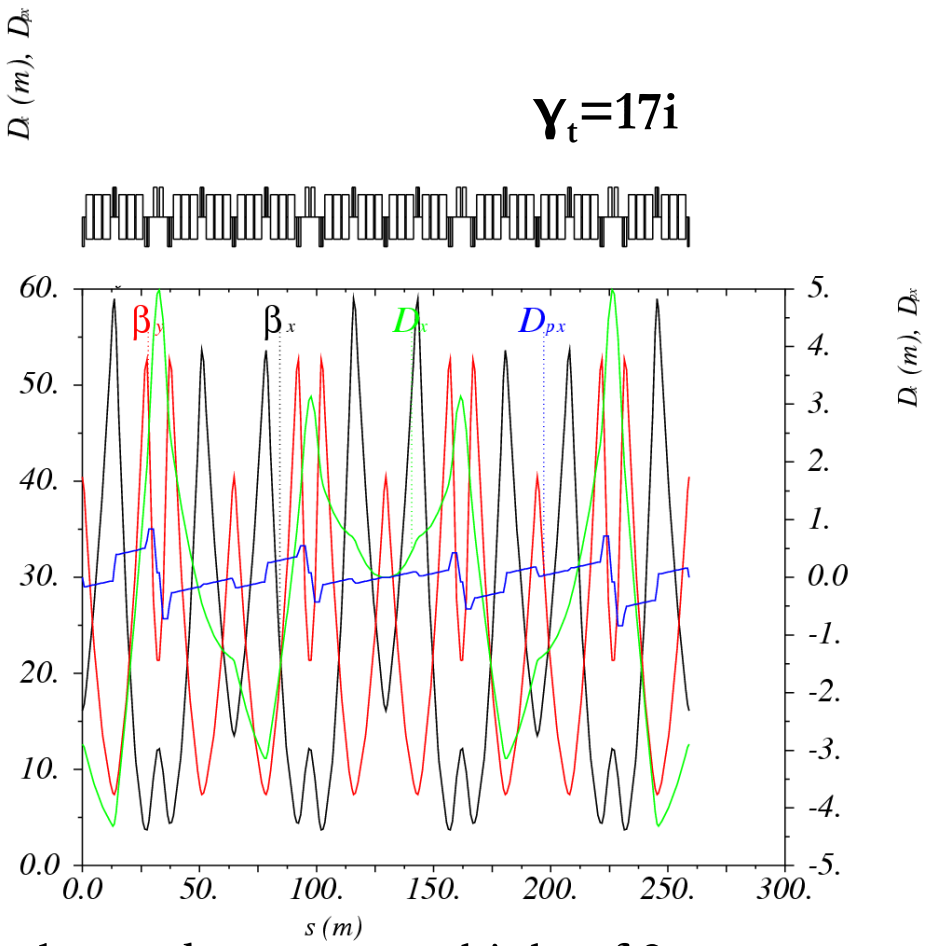
e.g. Y. Senichev BEAM'07, and J-PARC main ring lattice

- 1 symmetric FODO cell with 3 + 3 bends and a low-beta doublet
  - Phase advances of 315°, 270° per module
    - **8 x** 315°->7 x 2π
    - **8 x** 270°->6 x 2π
  - γ_t of **5.7i!!!**
  - **Four** families of quads, with max. strength of $0.1 m^{-2}$
  - 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

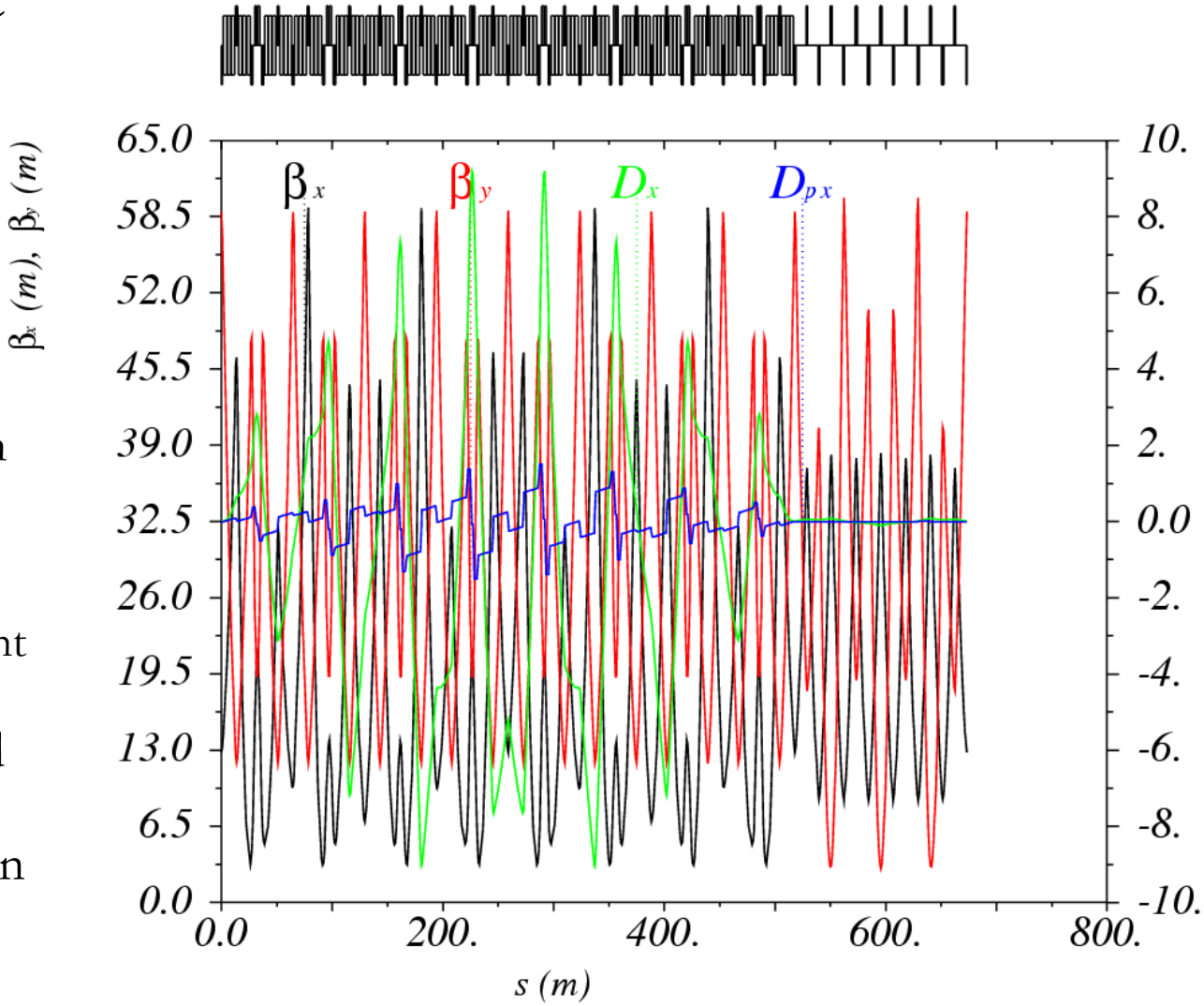




- Dispersion is suppressed by fixing horizontal phase advance to multiple of 2π
- Solution with **odd** number of 2π multiples preferable for getting **lower imaginary γ_t**

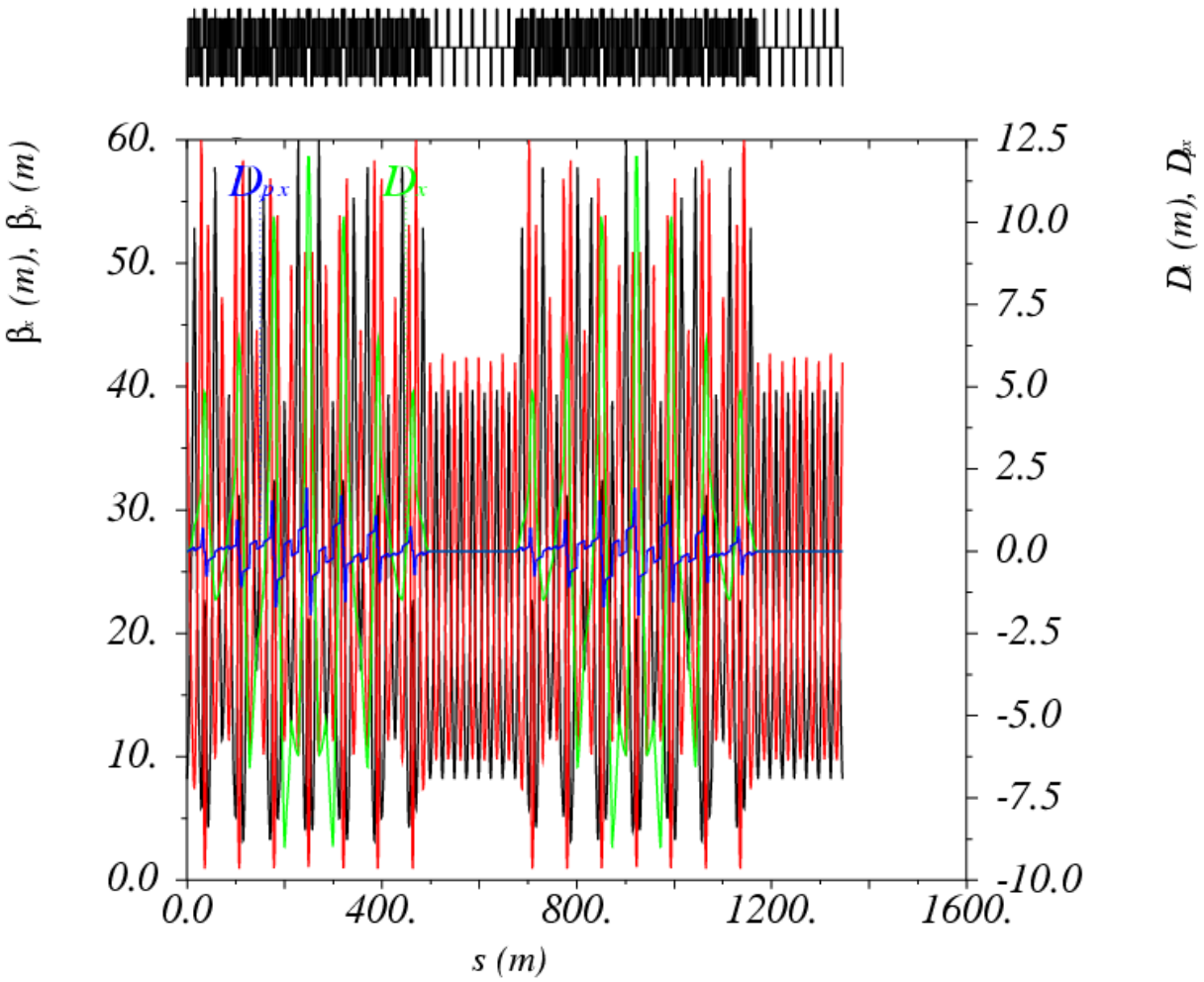
The "resonant" NMC ring II

- 8NMC modules per arc
- 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**



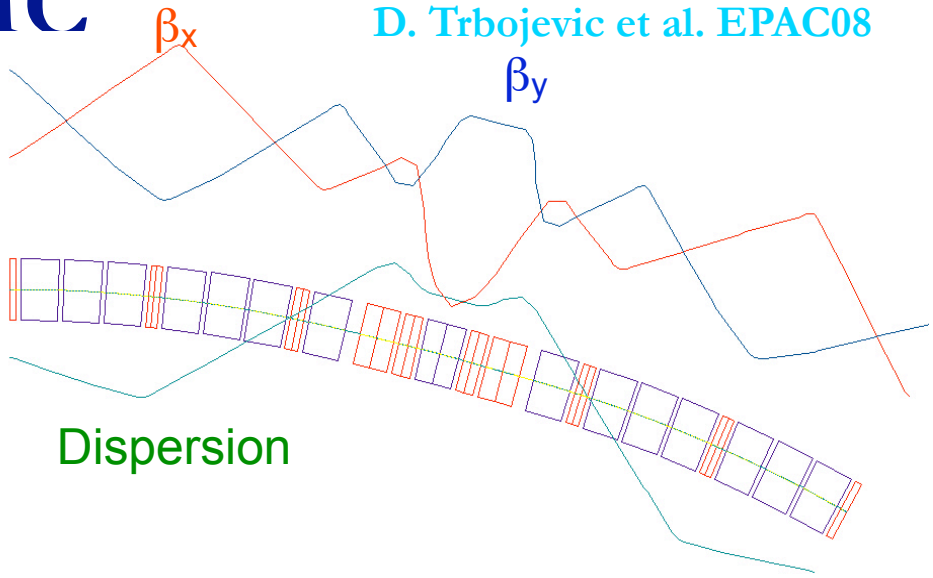
The "hybrid" NMC ring III

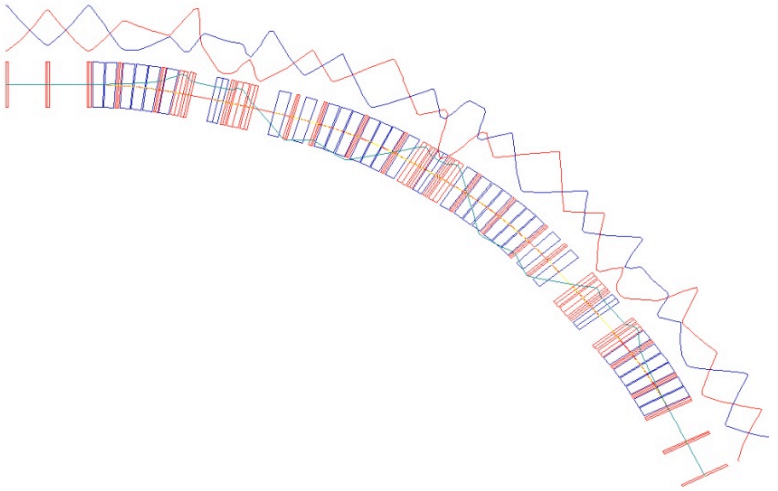
- Three types of 8 (+2) quadrupole families (max. strength of $0.1m^{-2}$) for a length of **1346.4m**
- γ_t of **11i**
- Tunes matched to **(14.8,15.2)**
- Max. β's of around **60m** both planes
- Dispersion of **-9m** and maximum of **12m**
- Tunability between **14** and **16** in both planes but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

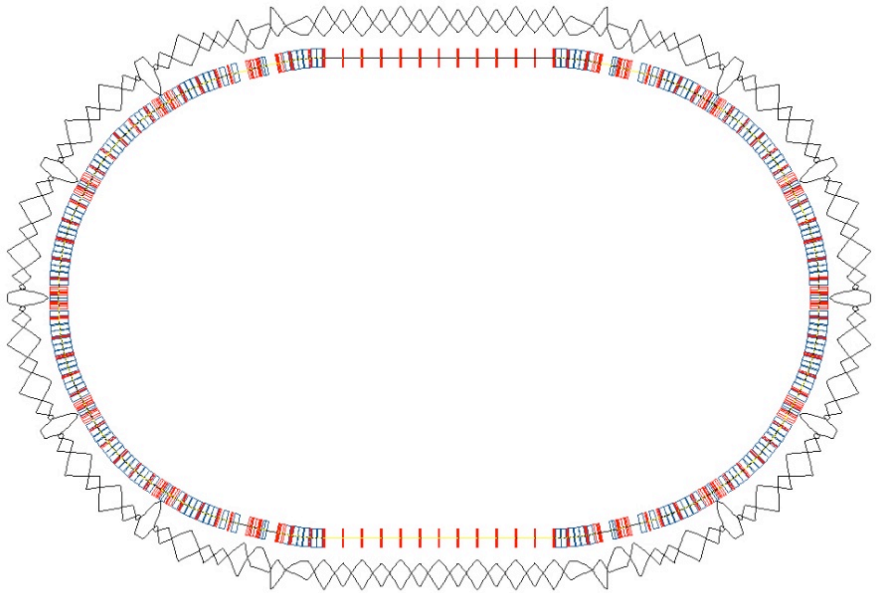


High filling factor NMC

- 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**



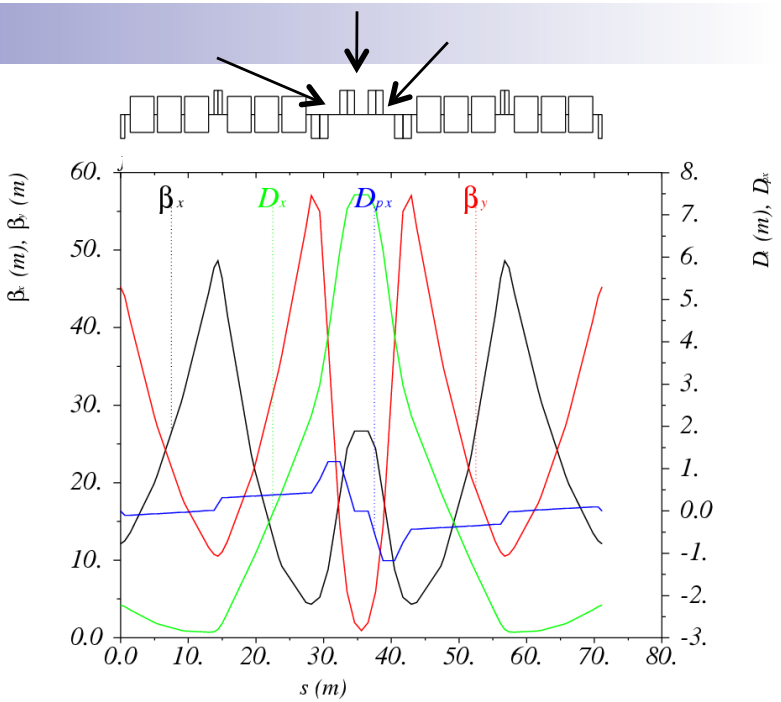




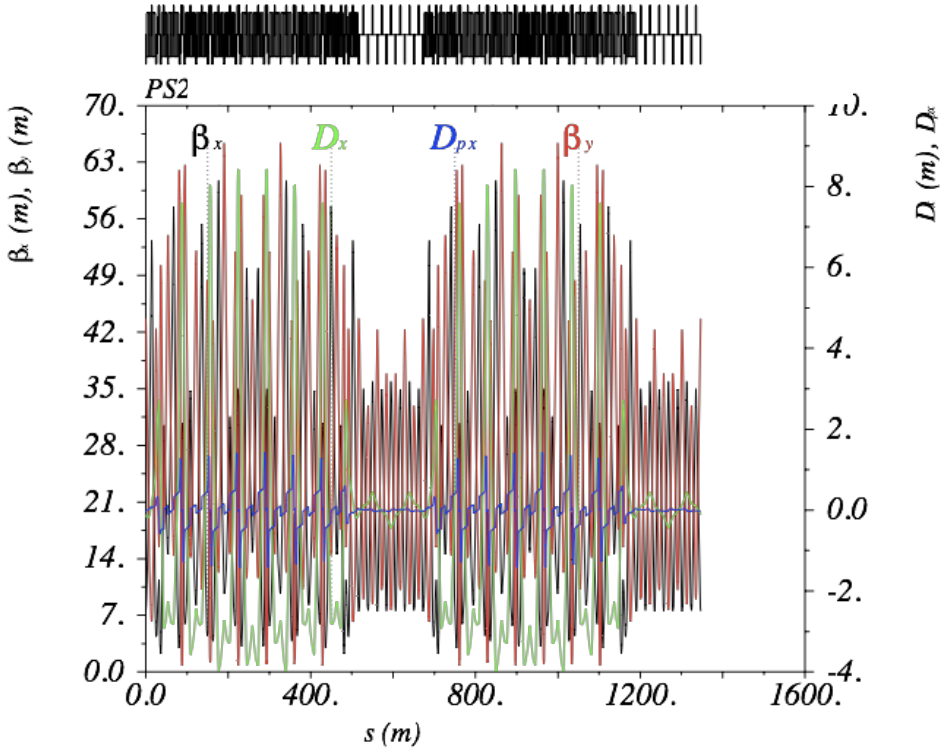
- Main disadvantage is the long arc: only **6** cells available for long straight sections

Chromaticity correction

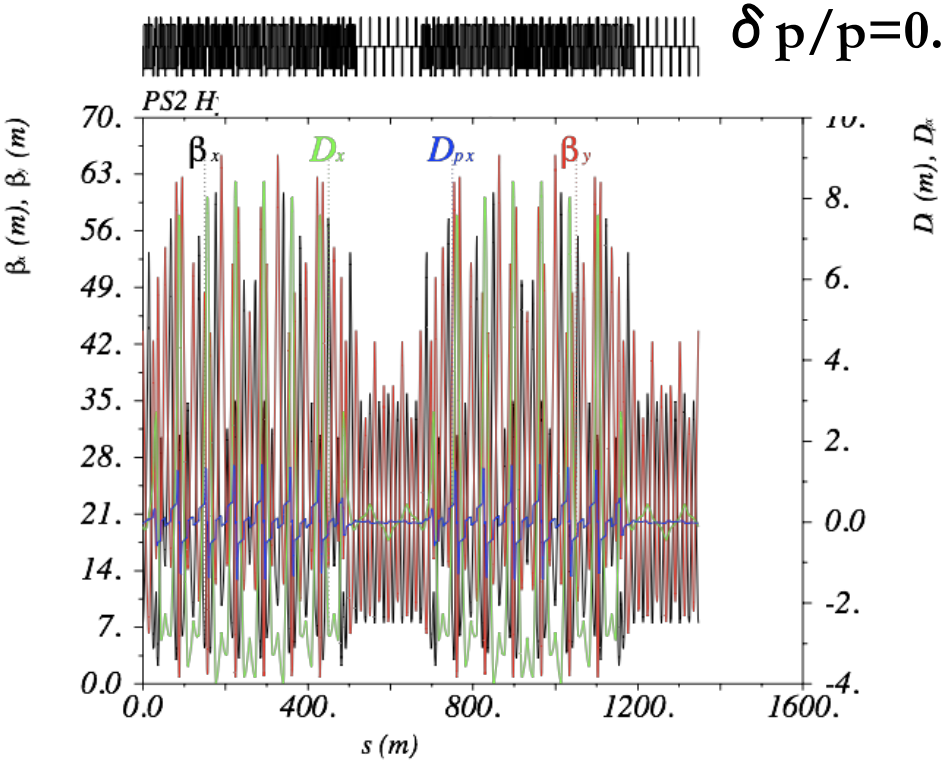
- Same approach for all three lattice types
- Sextupoles (0.4m) placed in low beta doublet
- 2 families needed for chromaticity control
- 8 sextupole families to minimize 2nd order chromaticity and off-momentum beta variation



δ p/p=-0.5%

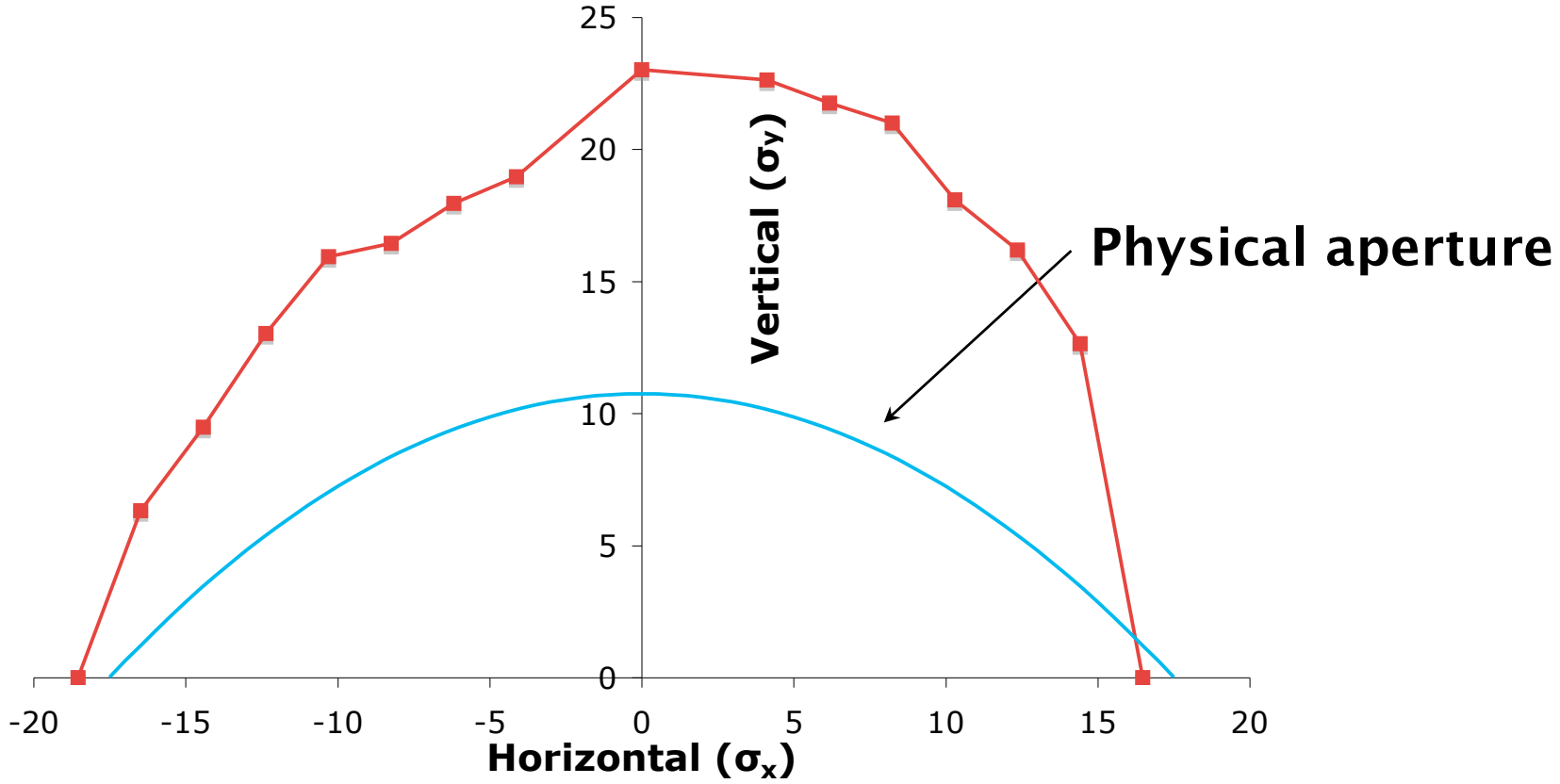


δ p/p=0.5%



Dynamic aperture

- 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 of NMC lattices

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

- Optics of FODO ring with real transition energy is straightforward
  - Transition crossing optics are quite distorted for large gamma jump amplitudes
- Thorough optics design of several NMC modules with low imaginary transition energy
  - NMC with dispersion suppressor is the **preferred** solution
  - NMC hybrid ring is a good **alternative**
  - NMC resonant ring with FODO straight has **limited tunability**
- Relaxing the transition energy constraint is an advantage:
  - Reduces the optics functions maxima (less chromaticity, more aperture)
  - Leaves margin for tuning and operational flexibility
  - For example, J-PARC main ring lattice is tuned for a transition energy of **30i**
  - R&D for wide range tunability RF system needed for proton and ion operation
- Lattice choice based on detailed comparison of performance with respect to beam losses
  - Collimation system, non-linear dynamics, collective effects