John Adams Institute Lecture

Optics solutions for the PS2 ring

Y. Papaphilippou
CERN

February 7th, 2008

Contributors

- **W. Bartmann**, M. Benedikt, C. Carli, J. Jowett (CERN)

Acknowledgements

- G. Arduini, R. Garobi, B. Goddard, S. Hancock (CERN), Y. Senichev (FZ Jülich), D. Trbojevic (BNL)

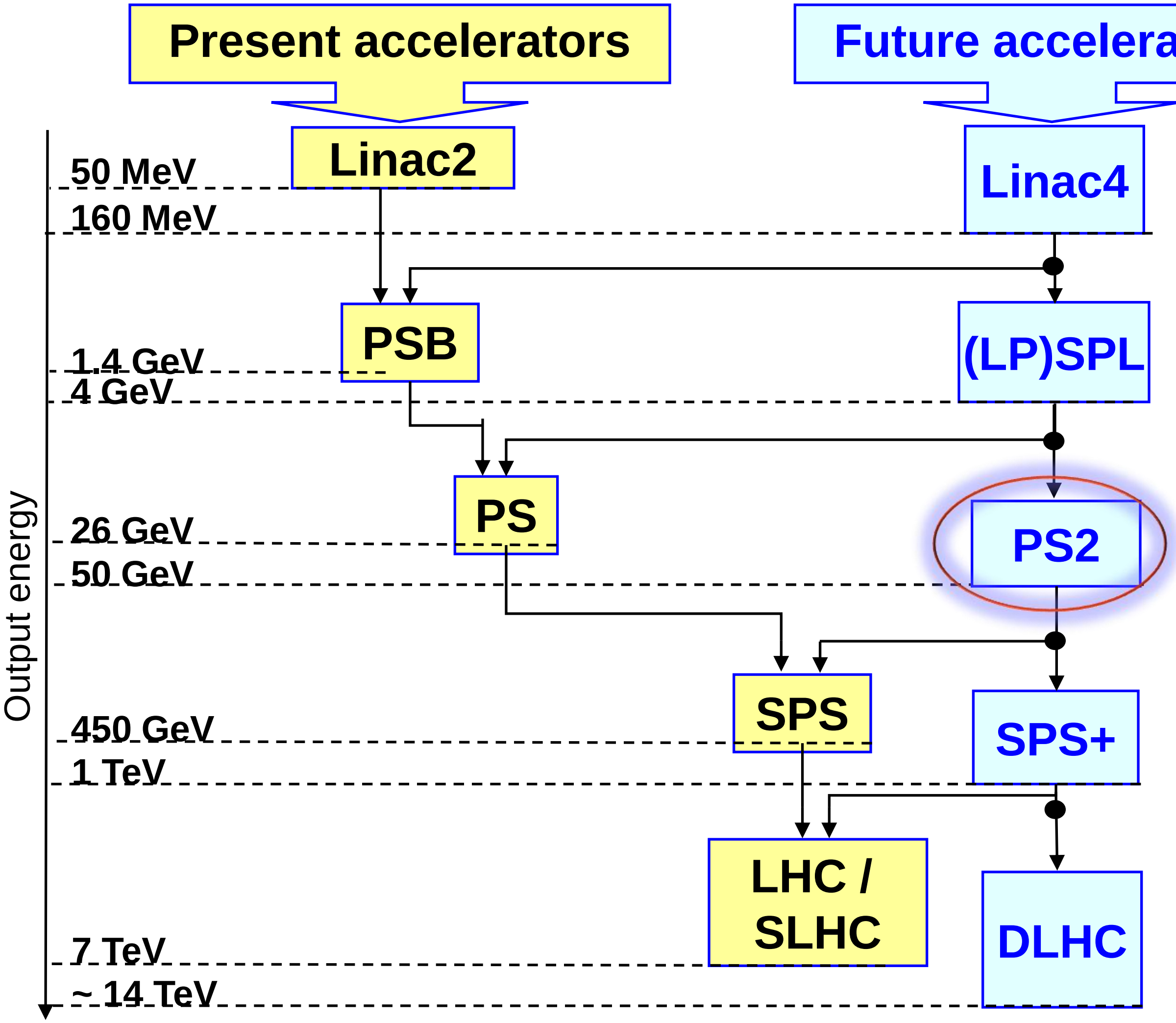
Outline

- Motivation and design constraints for PS2
- FODO lattice
- Doublet/Triplet
- Flexible (Negative) Momentum Compaction modules
  - High-filling factor design
  - Tunability and optics' parameter space scan
  - "Resonant" NMC ring
  - Hybrid solution
- Comparison and perspectives

Motivation – LHC injectors' upgrade

- Upgrade injector complex.
  - Higher injection energy in the SPS => better SPS performance
  - Higher reliability

R. Garoby, BEAM' 07



(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Super-luminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

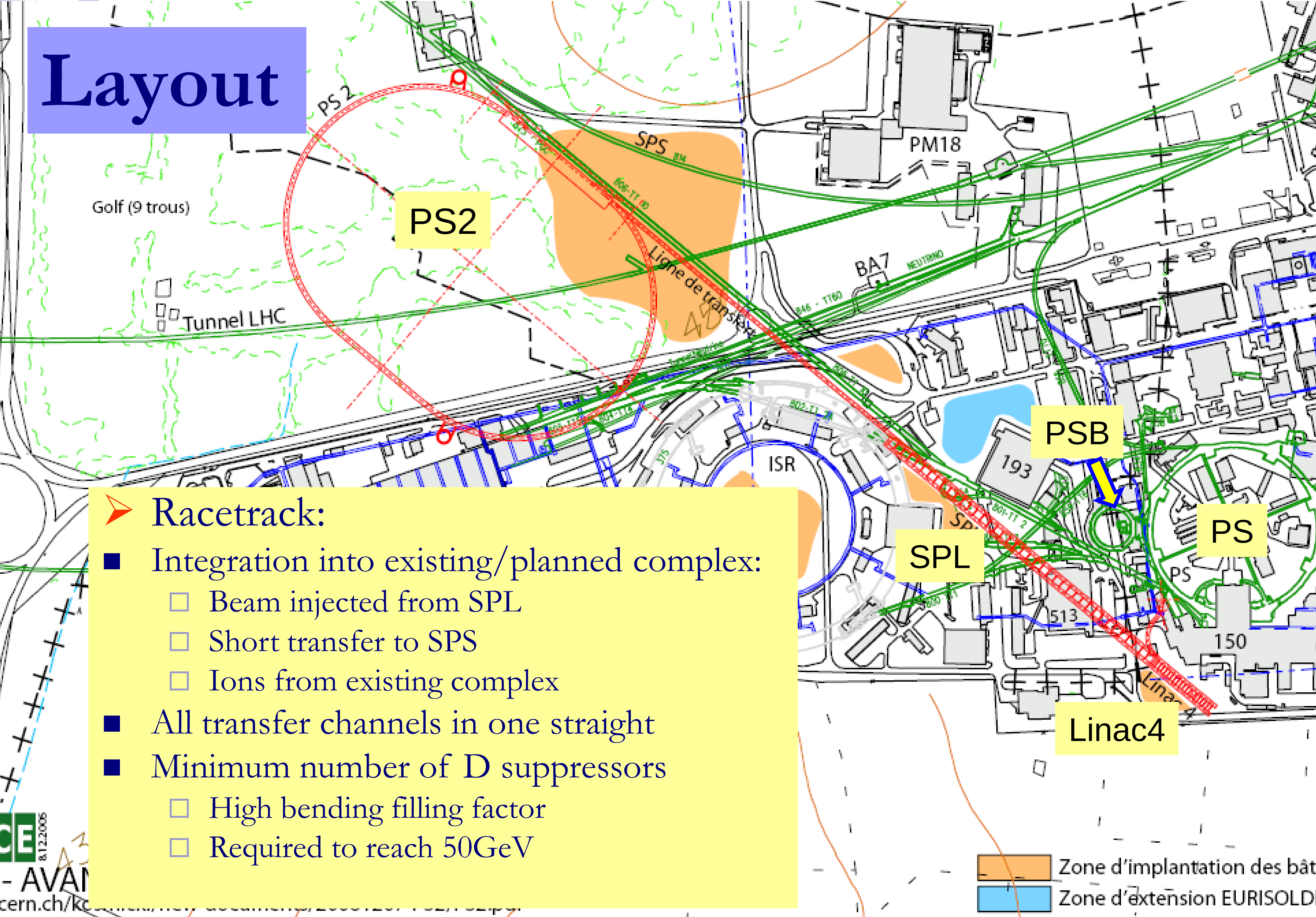
Design and optics constraints for PS2 ring

- Replace the ageing PS and improve options for physics
  - Provide 4×10^{11} protons/bunch for LHC (vs. 1.7×10^{11})
  - Higher intensity for fixed target experiments
- Integration in existing CERN accelerator complex
- Versatile machine:
  - Many different beams and bunch patterns
  - Protons and ions

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	~10/10i
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
Maximum arc length [m]		510

- Injection kinetic energy: Constrained by incoherent space charge tune-shift $\Delta Q_{sc} \propto \frac{N_b}{\epsilon_n \beta \gamma^2 B_f} < 0.2$
- Extraction kinetic energy: Improve SPS performance
- Circumference: Analysis of possible bunch patterns: $C_{PS2} = (15/77)\ C_{SPS} = (15/7)\ C_{PS}$
- Transition energy: Longitudinal aspects
- Maximum bending field, maximum quadrupole gradient: Normal conducting magnets
- Maximum beta functions, maximum dispersion function: Aperture considerations for high intensity SPS physics beam
- Minimum drift spaces, maximum arc length: Space considerations

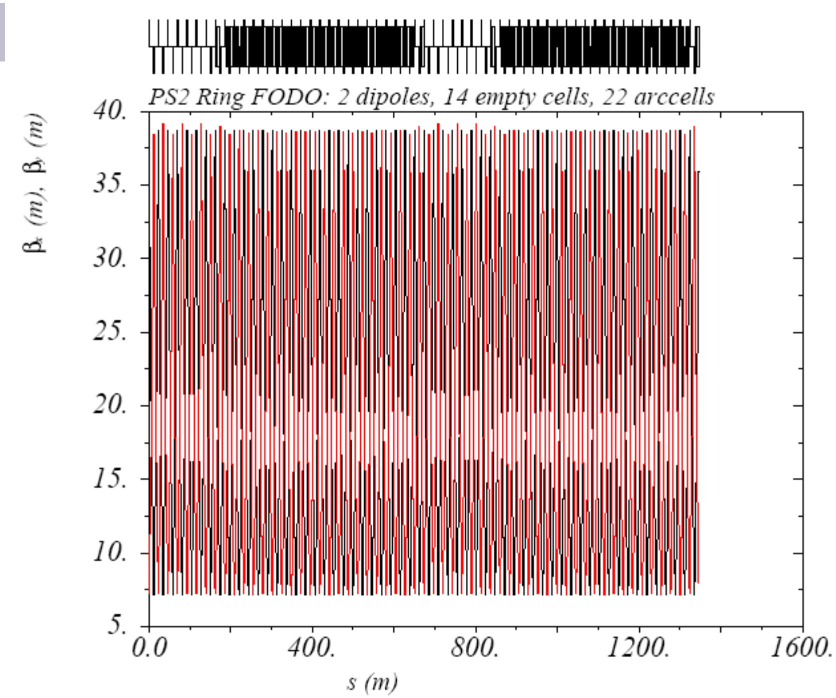
Layout

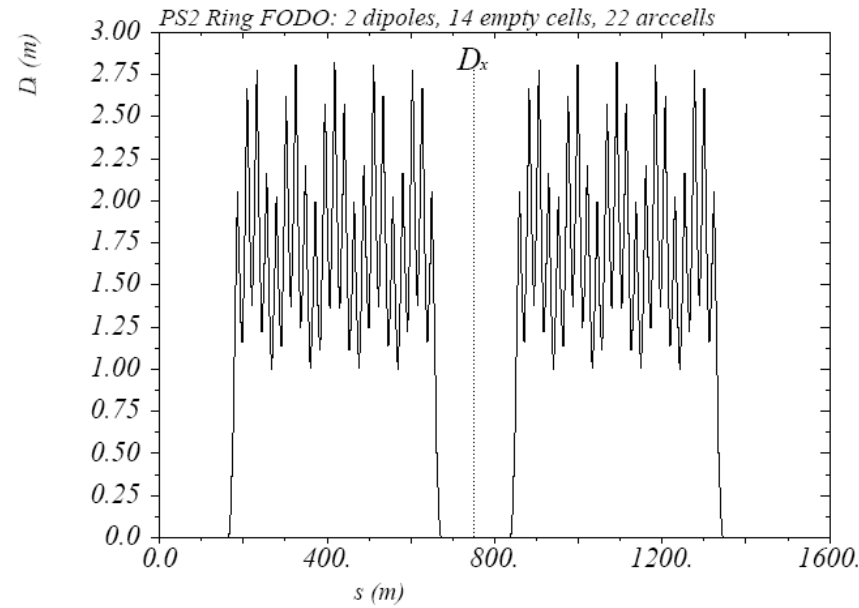


- ➢ Racetrack:
  - Integration into existing/planned complex:
    - Beam injected from SPL
    - Short transfer to SPS
    - Ions from existing complex
  - All transfer channels in one straight
  - Minimum number of D suppressors
    - High bending filling factor
    - Required to reach 50GeV

FODO Ring

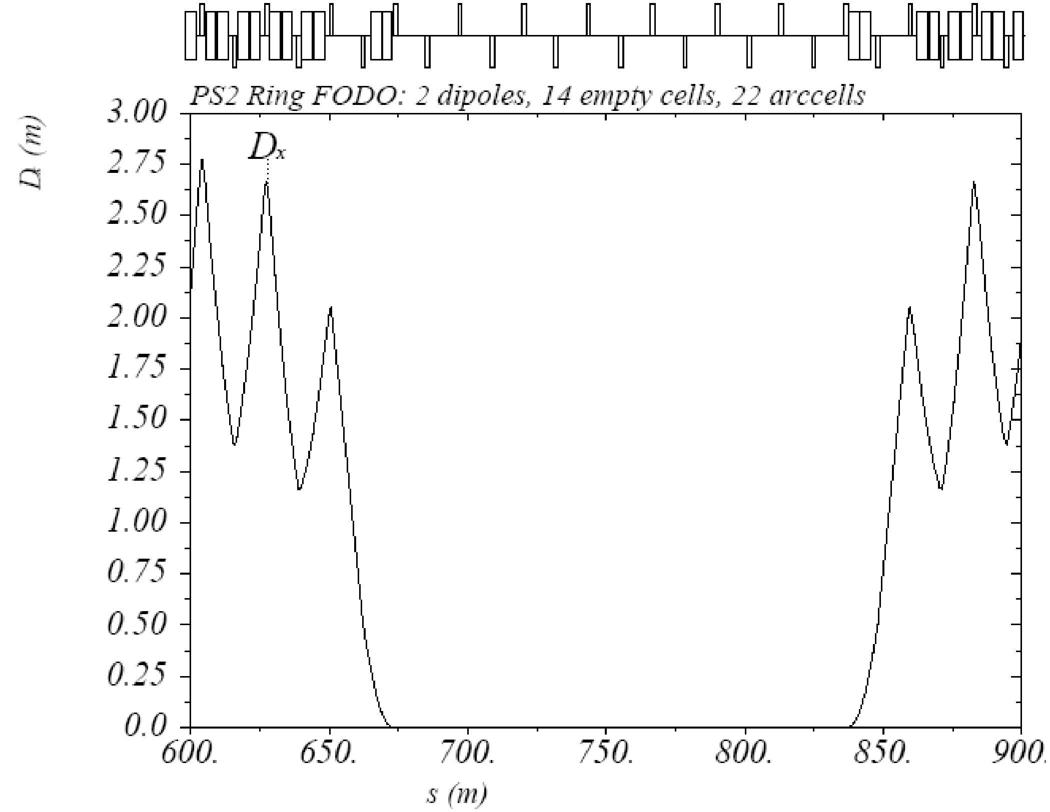
- Conventional Approach:
  - FODO with missing dipole for dispersion suppression in straights
  - 7 LSS cells, 22 asymmetric FODO arc cells, 2 dipoles per half cell, 2 quadrupole families
  - Phase advance of **88º**, γ_{tr} of **11.4**
  - 7 cells/straight and 22 cells/arc -> in total 58 cells
  - $Q_{H,V}$ = **14.1-14.9**
  - Alternative design with matching section and increased number of quadrupole families
  - Transition jump scheme under study

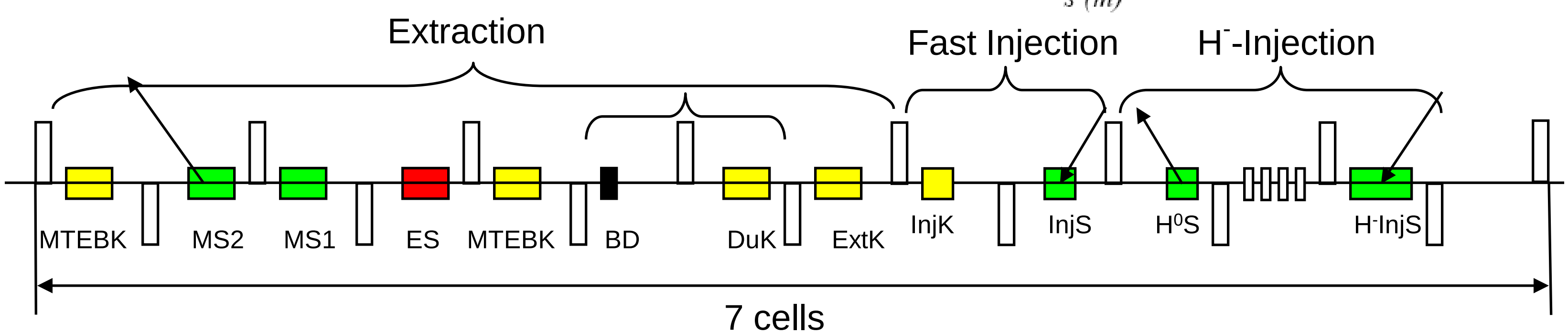




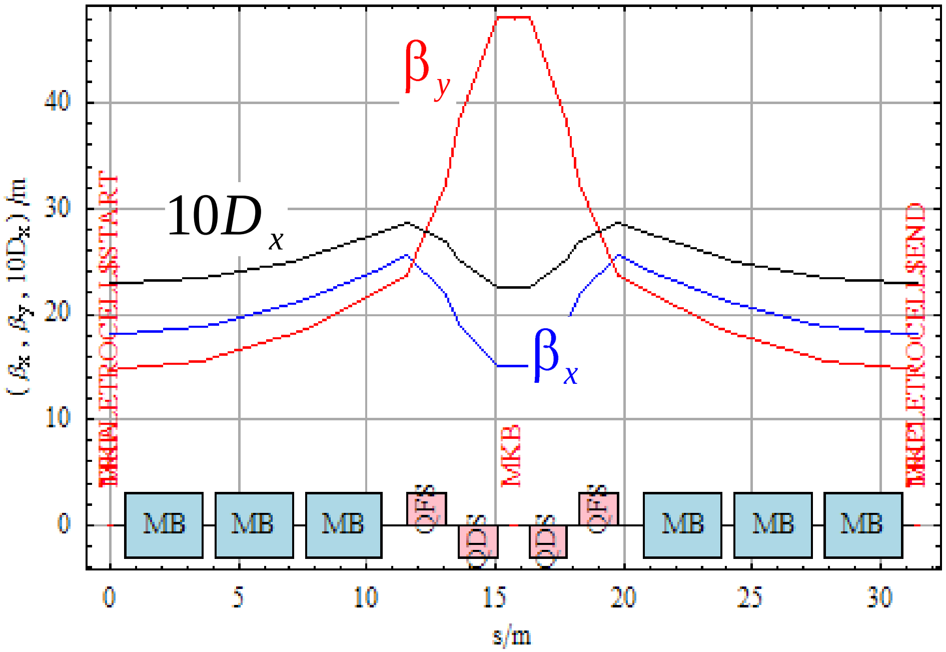
Dispersion suppressor and straight section

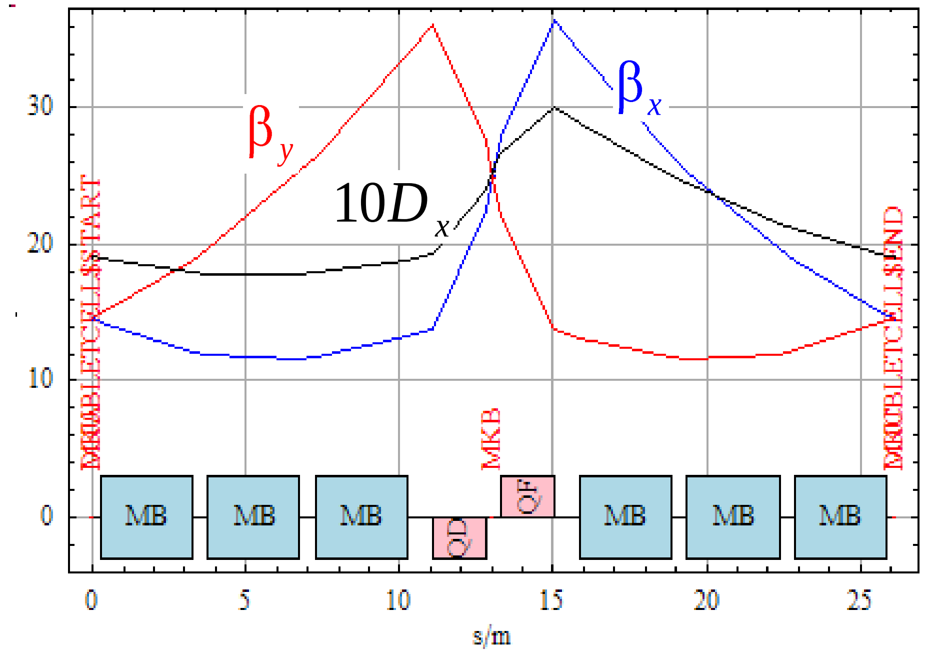
Cell length [m]	23.21
Dipole length [m]	3.79
Quadrupole length [m]	1.49
LSS [m]	324.99
Free drift [m]	10.12
# arc cells	22
# LSS cells:	7
# dipoles:	168
# quadrupoles:	116
# dipoles/half cell:	2





Doublet and Triplet arc cells





- Advantages
  - Long straight sections and small maximum ß's in bending magnets (especially for triplet)
- Disadvantage
  - High focusing gradients

Flexible Momentum Compaction Modules

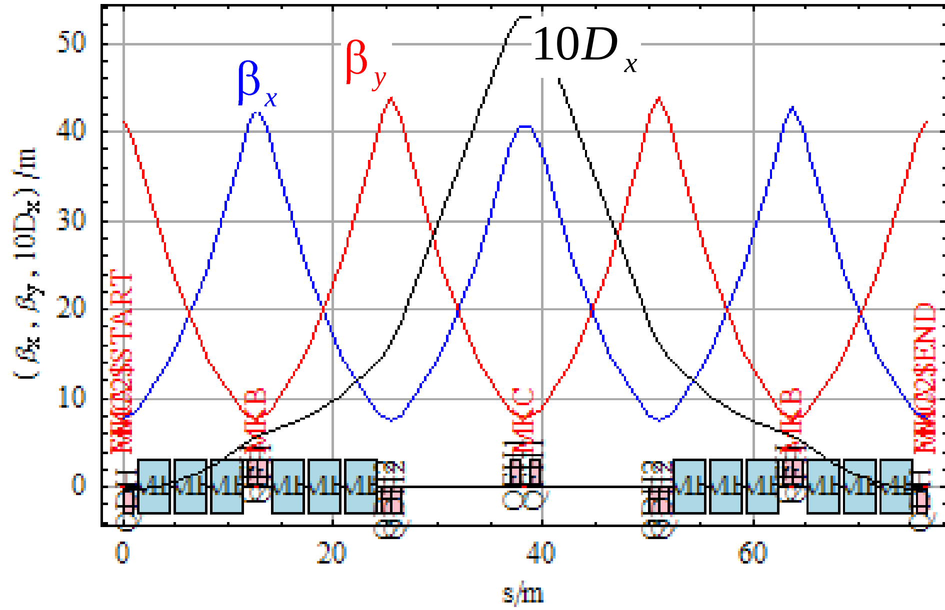
- Aim at negative momentum compaction (NMC modules), i.e.

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

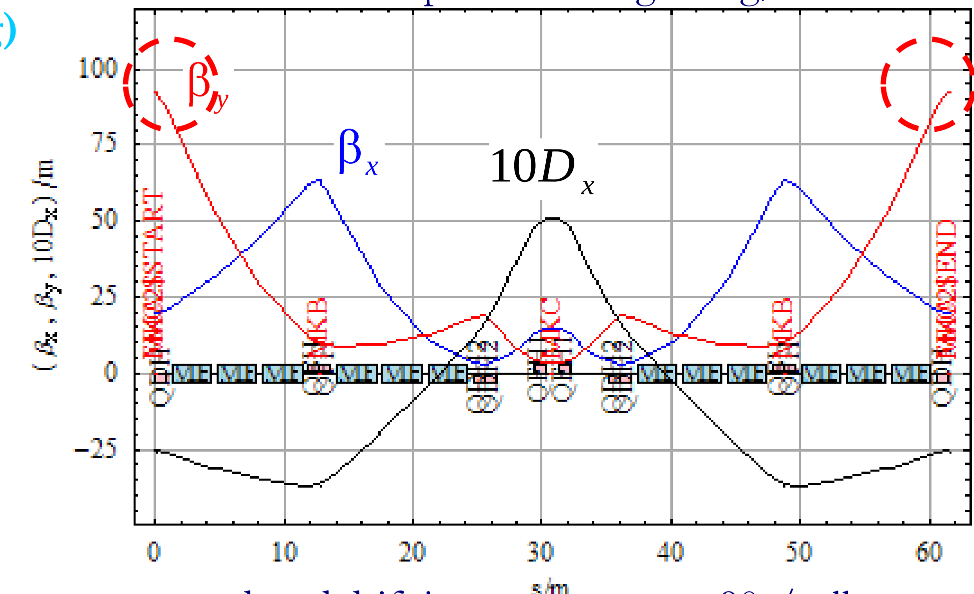
- Similar to and inspired from existing modules

(SY. Lee et al, PRE, 1992, J-PARC high energy ring)

- First approach
  - Module made of three FODO cells
  - Match regular FODO to 90° phase advance
  - Reduced central straight section without bends
  - Re-matched to obtain phase advance (close to three times that of the FODO, i.e. 270°)
- Disadvantage: Maximum vertical β above **80m**



regular FODO 90°/cell
-> zero dispersion at beginning/end

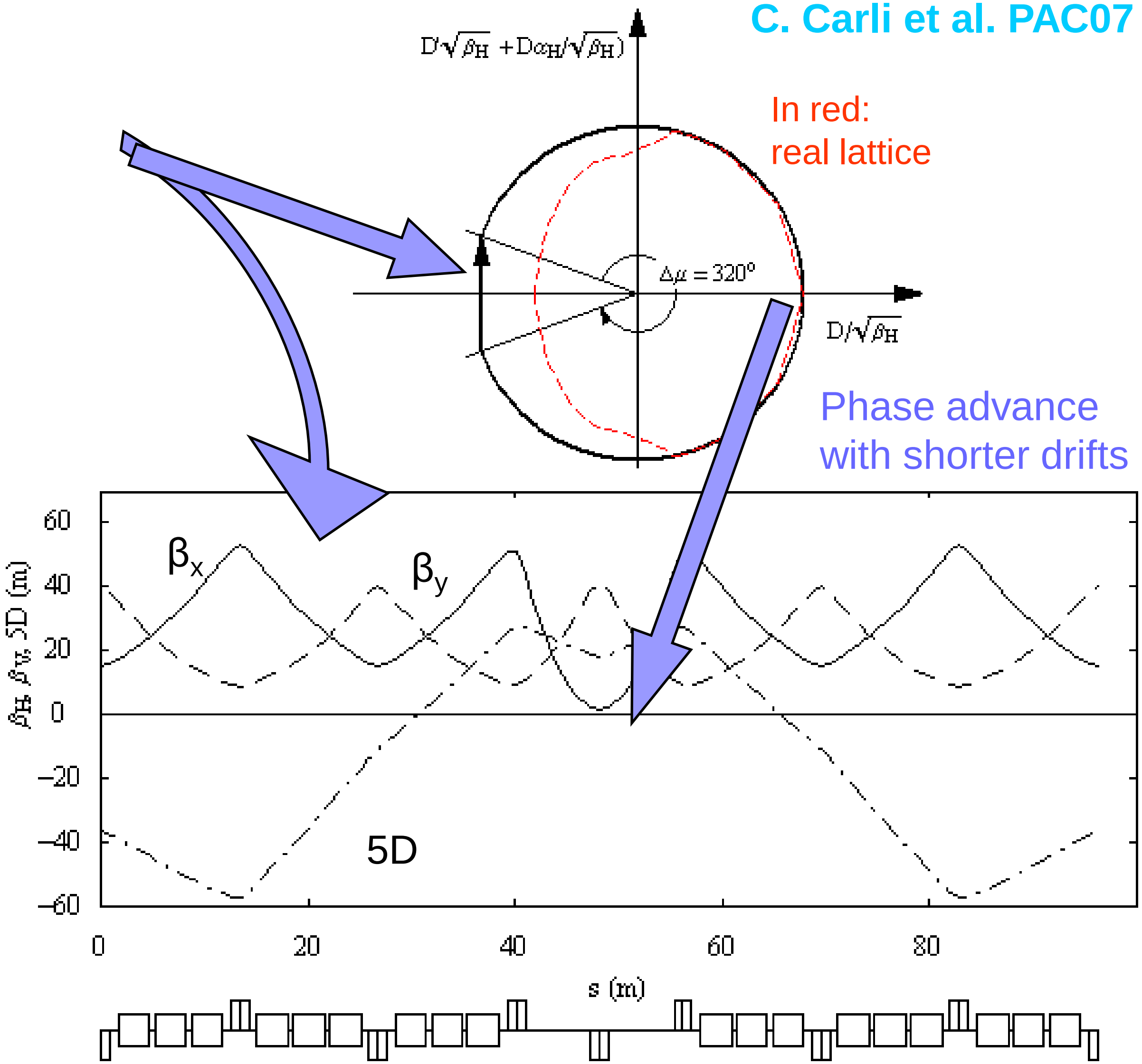


reduced drift in center, average 90°/cell
-> negative dispersion at beginning/end
$\gamma_{tr} \sim 10i$

NMC modules with high filling factor

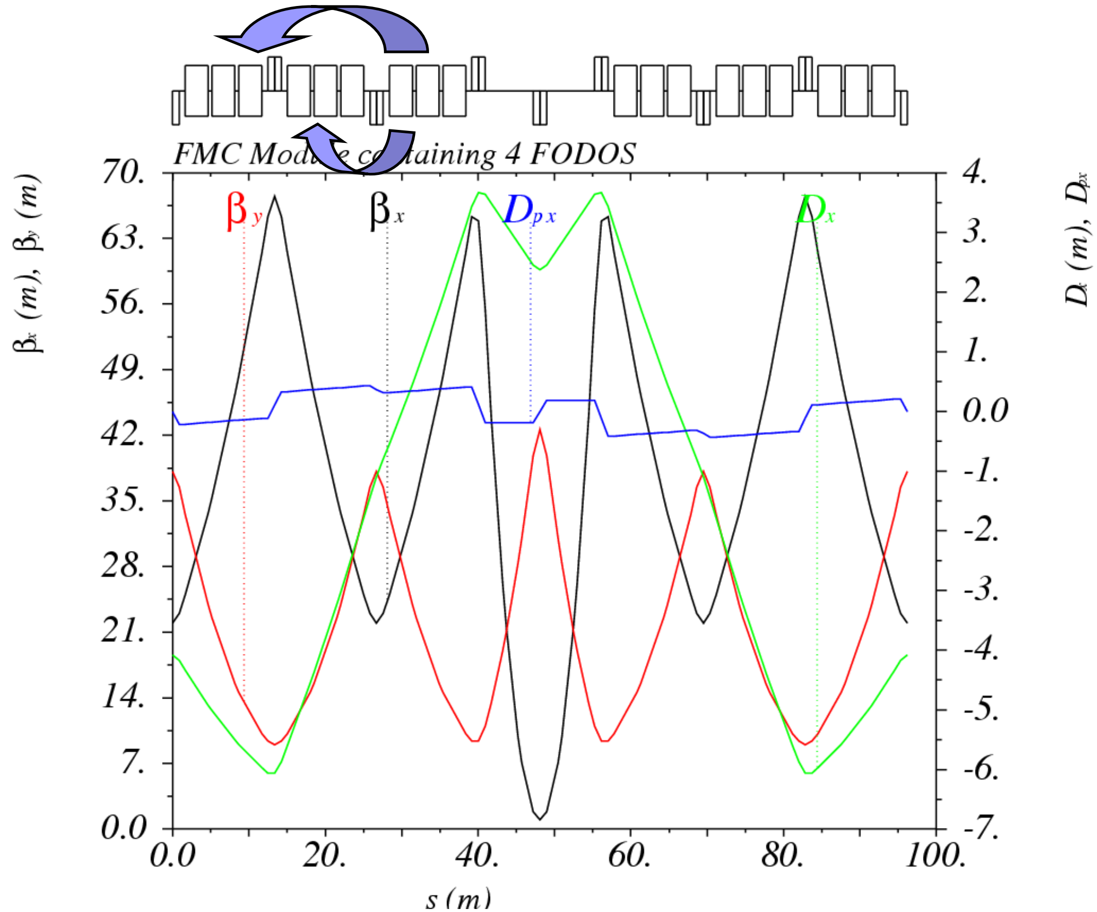
- Improve filling factor: four FODO per module
- Dispersion beating excited by "kicks" in bends
- Resonant behavior: total phase advance < 2π
- Large radii of the dispersion vector produce negative momentum compaction
- High phase advance is necessary

C. Carli et al. PAC07



Improving the high filling factor FMC

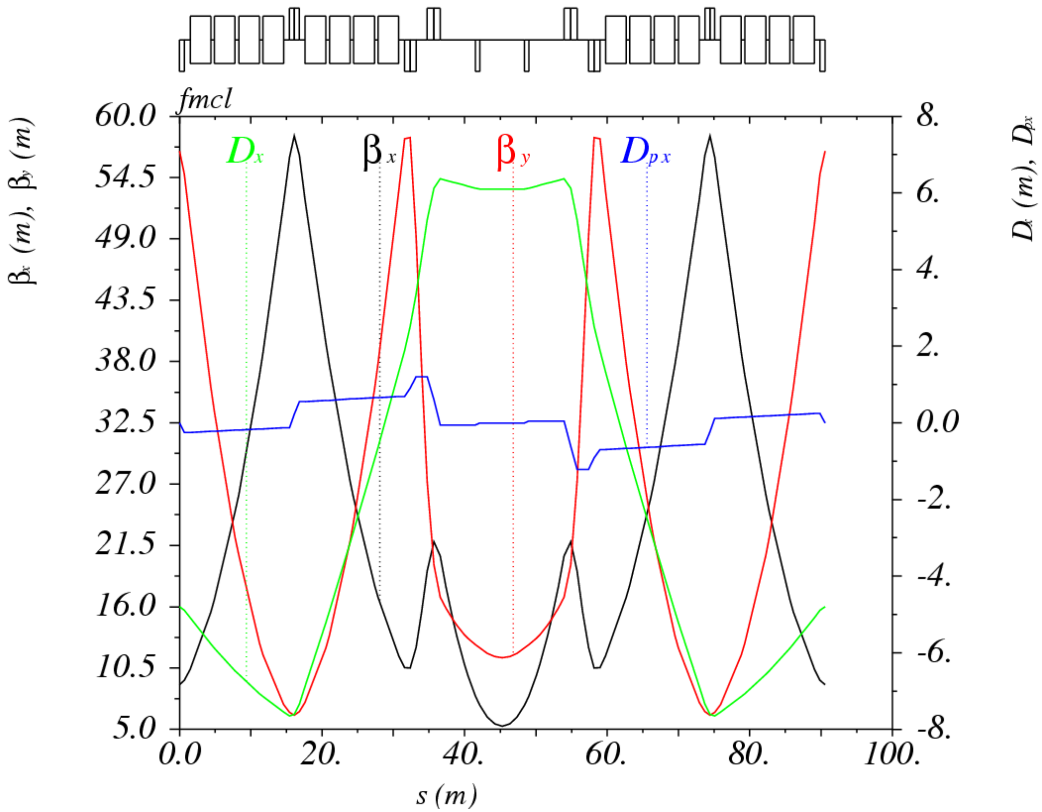
- The "high-filling" factor arc module
  - Phase advances of **280°,320°** per module
  - γ_t of **8.2i**
  - Four families of quads, with max. strength of **0.095m^{-2}**
  - Max. horizontal beta of **67m** and vertical of **43m**
  - Min. dispersion of -6m and maximum of 4m
  - Chromaticities of **-1.96,-1.14**
  - Total length of **96.2m**
- Slightly high horizontal β and particularly long module, leaving very little space for dispersion suppressors and/or long straight sections



- Reduce further the transition energy by moving bends towards areas of negative dispersion and shorten the module

Alternative NMC module

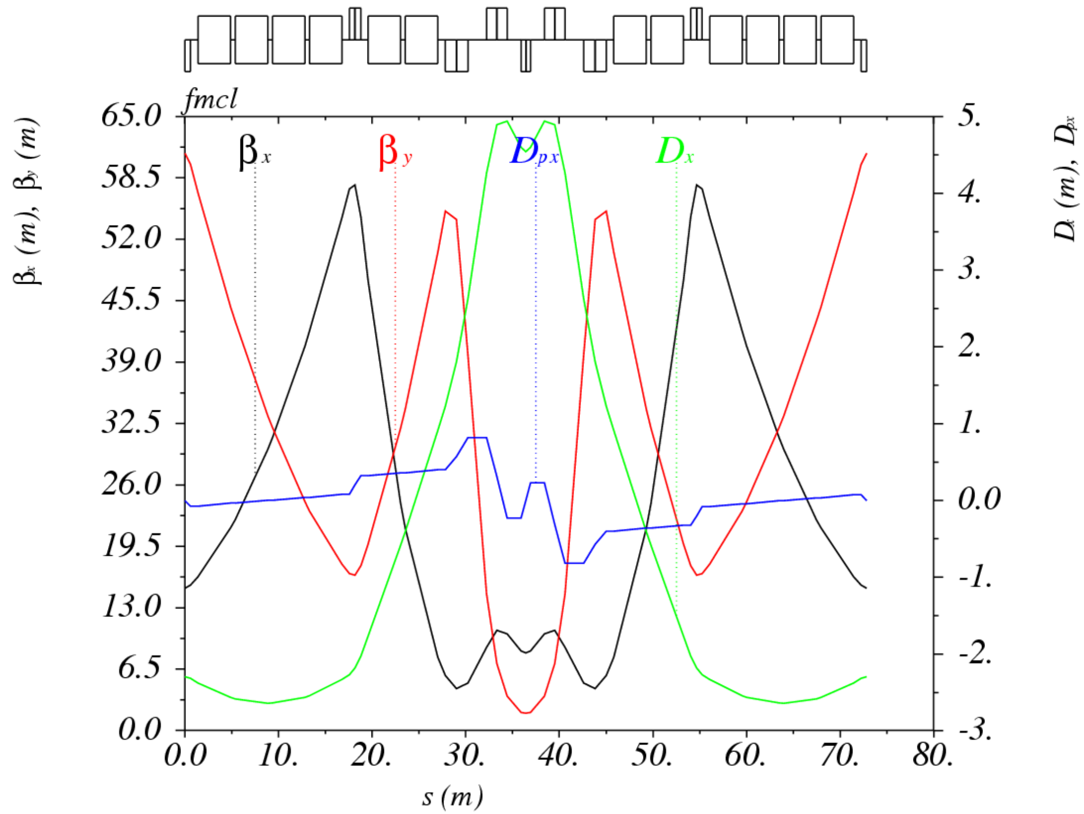
- 1 FODO cell with 4 + 4 bends and an asymmetric low-beta triplet
  - Phase advances of **320º,320º** per module
  - γ_t of **6.2i**
  - Five families of quads, with max. strength of $\mathbf{0.1m^{-2}}$
  - Max. beta of **58m** in both planes
  - Min. dispersion of **-8m** and maximum of **6m**
  - Chromaticities of **-1.6,-1.3**
  - Total length of **90.56m**
- Fifth quad family not entirely necessary
- Straight section in the middle can control γ_t
- Phase advance tunable between **240º** and **330º**



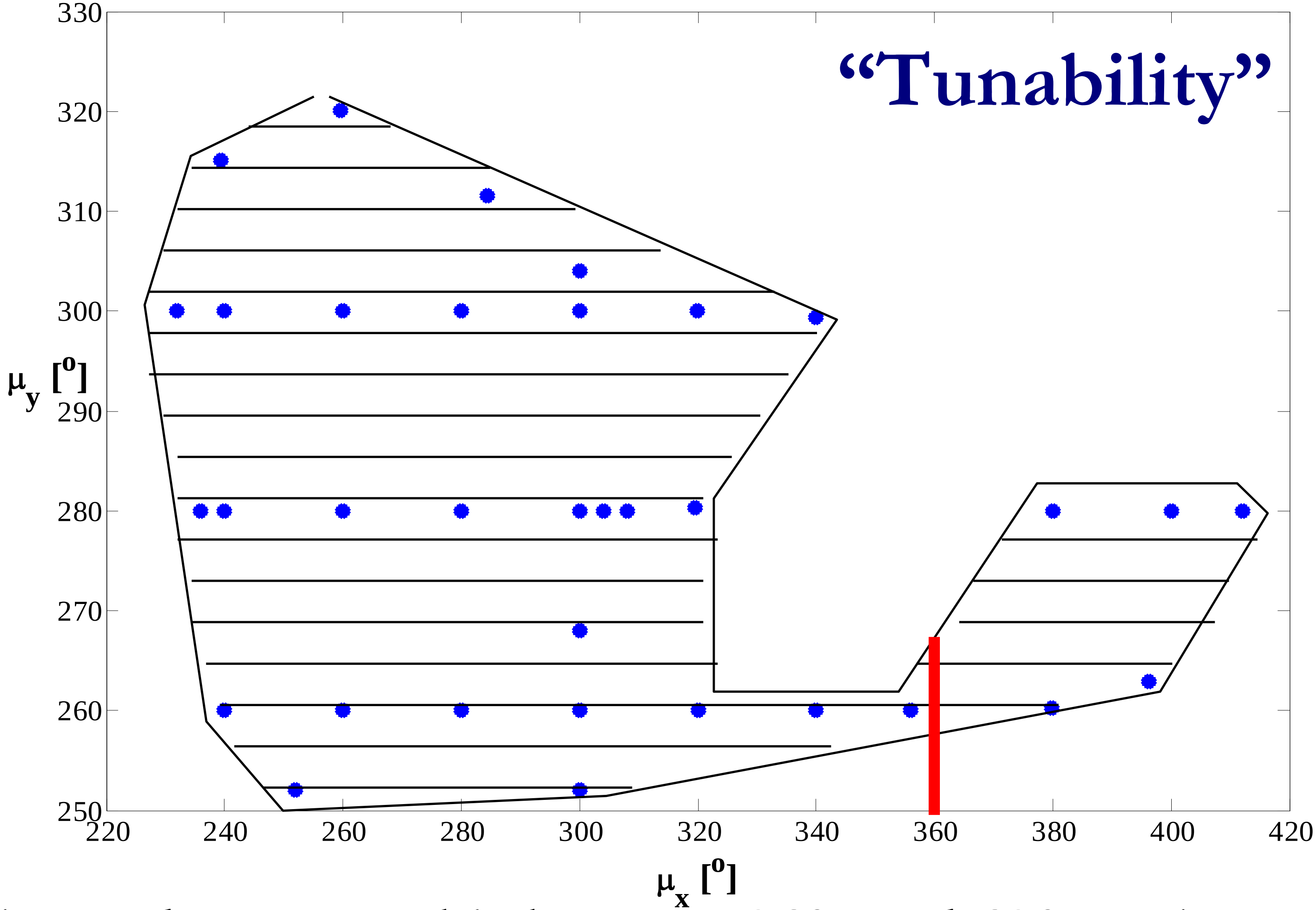
- Main disadvantage the length of the module, giving an arc of around **560m** (5 modules + dispersion suppressors), versus **510m** for the FODO cell arc

The "short" NMC module

- Remove middle straight section and reduce the number of dipoles
- 1 asymmetric FODO cell with 4 + 2 bends and a low-beta doublet
  - Phase advances of 272°,260° per module
  - γ_t of **10i**
  - Five families of quads, with max. strength of **0.1m^{-2}**
  - Max. beta of around **60m** in both planes
  - Min. dispersion of **-2.3m** and maximum of **4.6m**
  - Chromaticities of -1.1,-1.7
  - Total length of **71.72m**

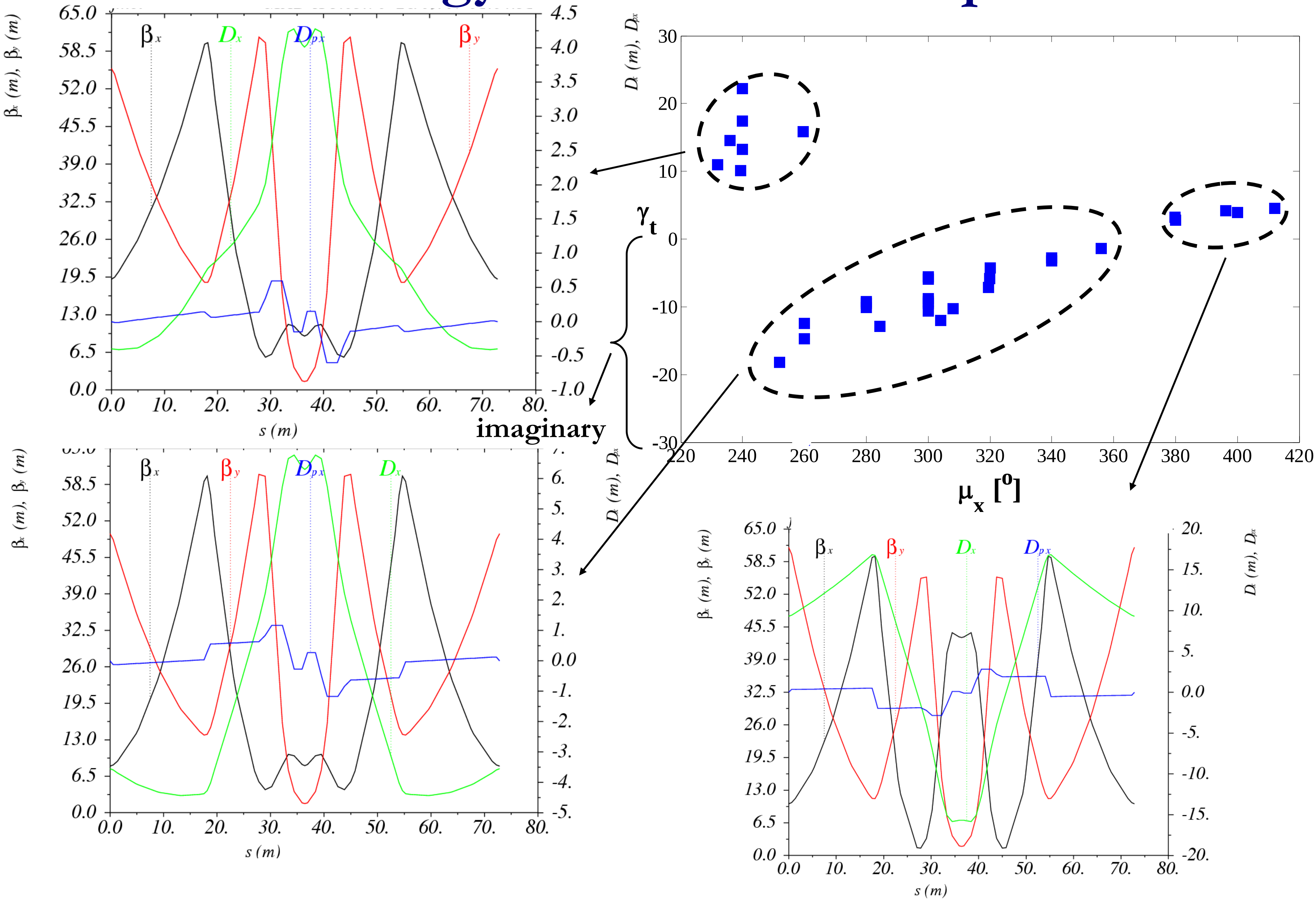


- Considering an arc of 6 modules + 2 dispersion suppressors of similar length, the total length of the arc is around **510m**

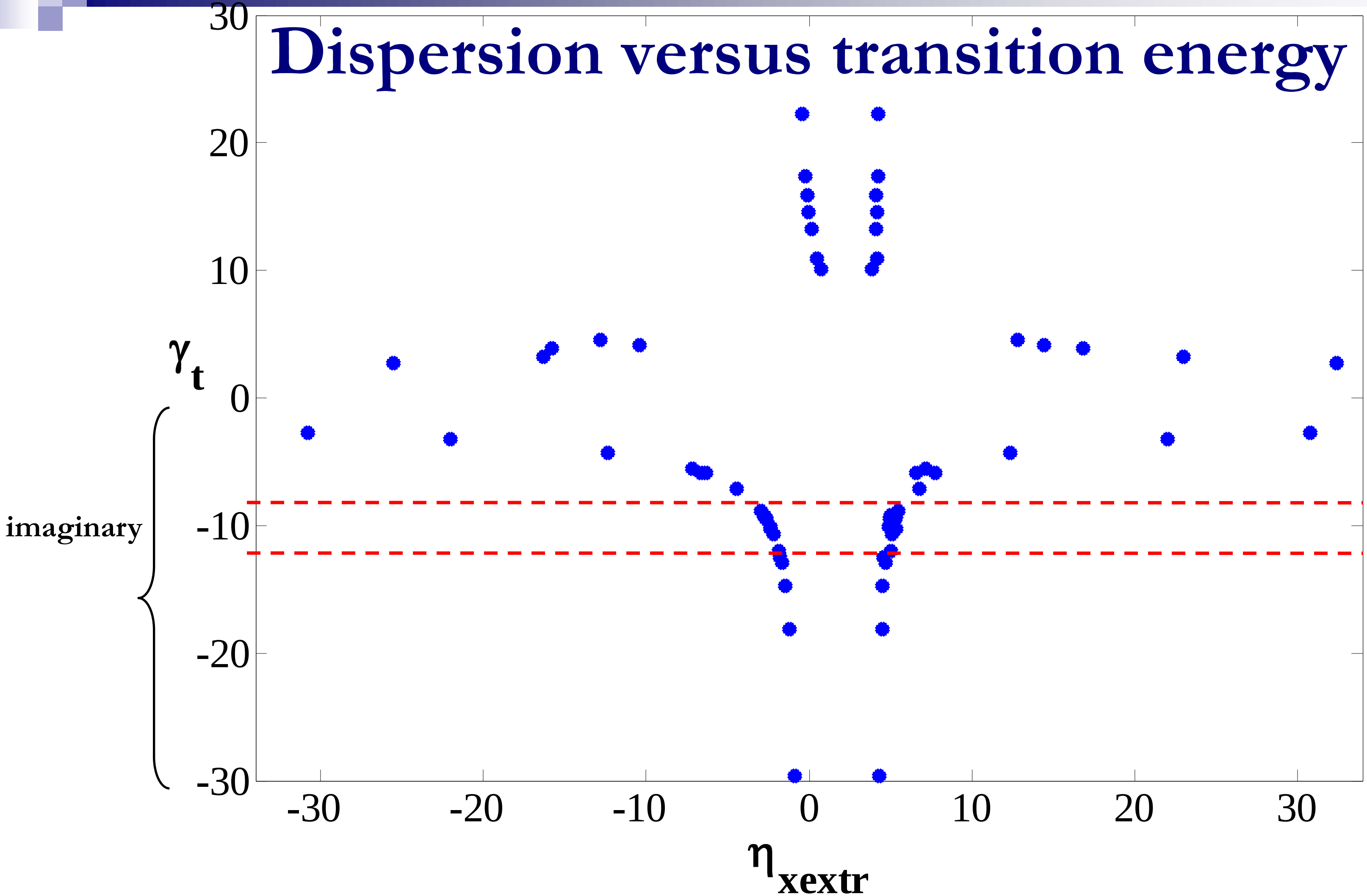


- Phase advance tunable between **240°** and **420°** in the horizontal and between **250°** and **320°** in the vertical plane

Transition energy versus horizontal phase advance

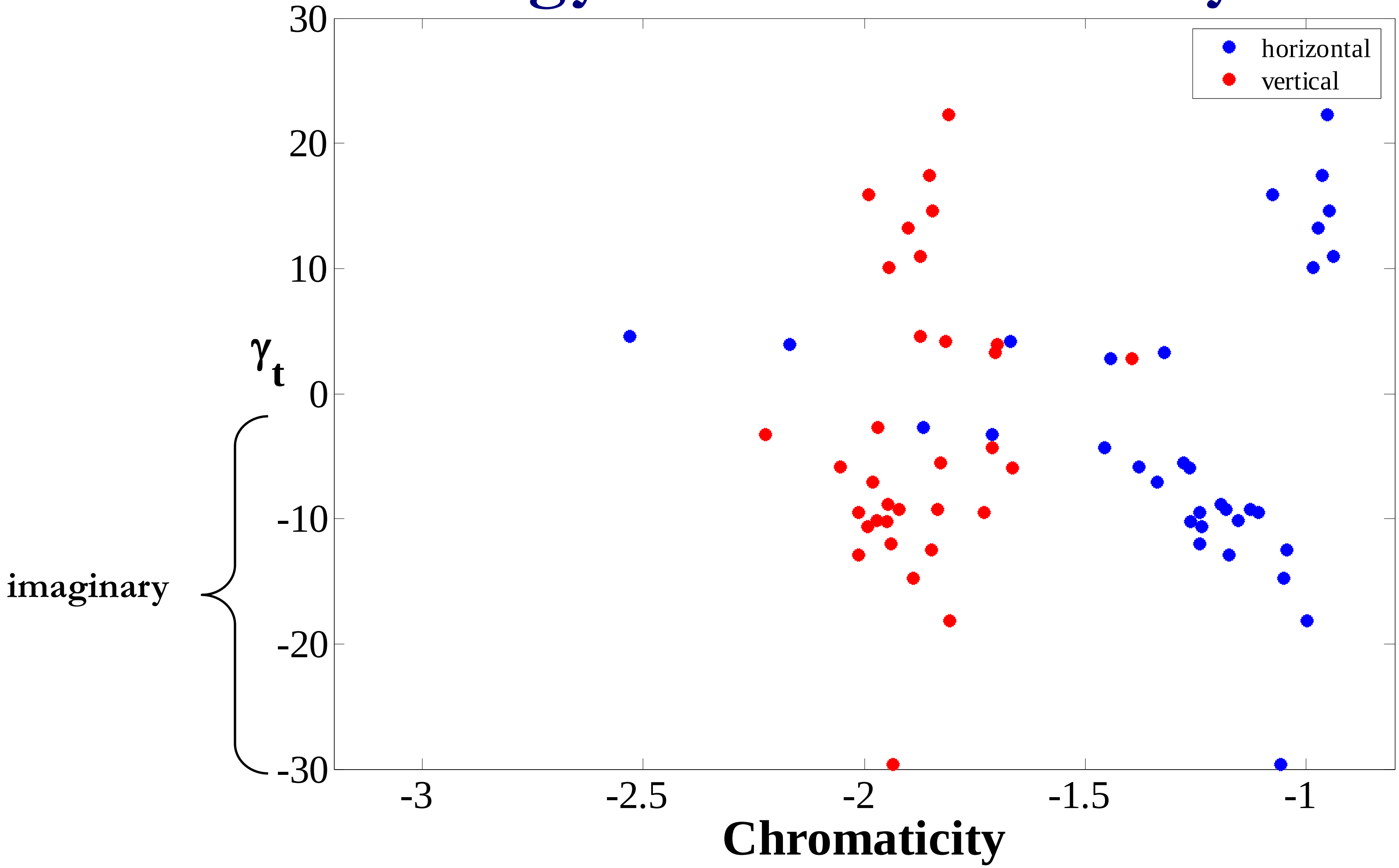


Dispersion versus transition energy



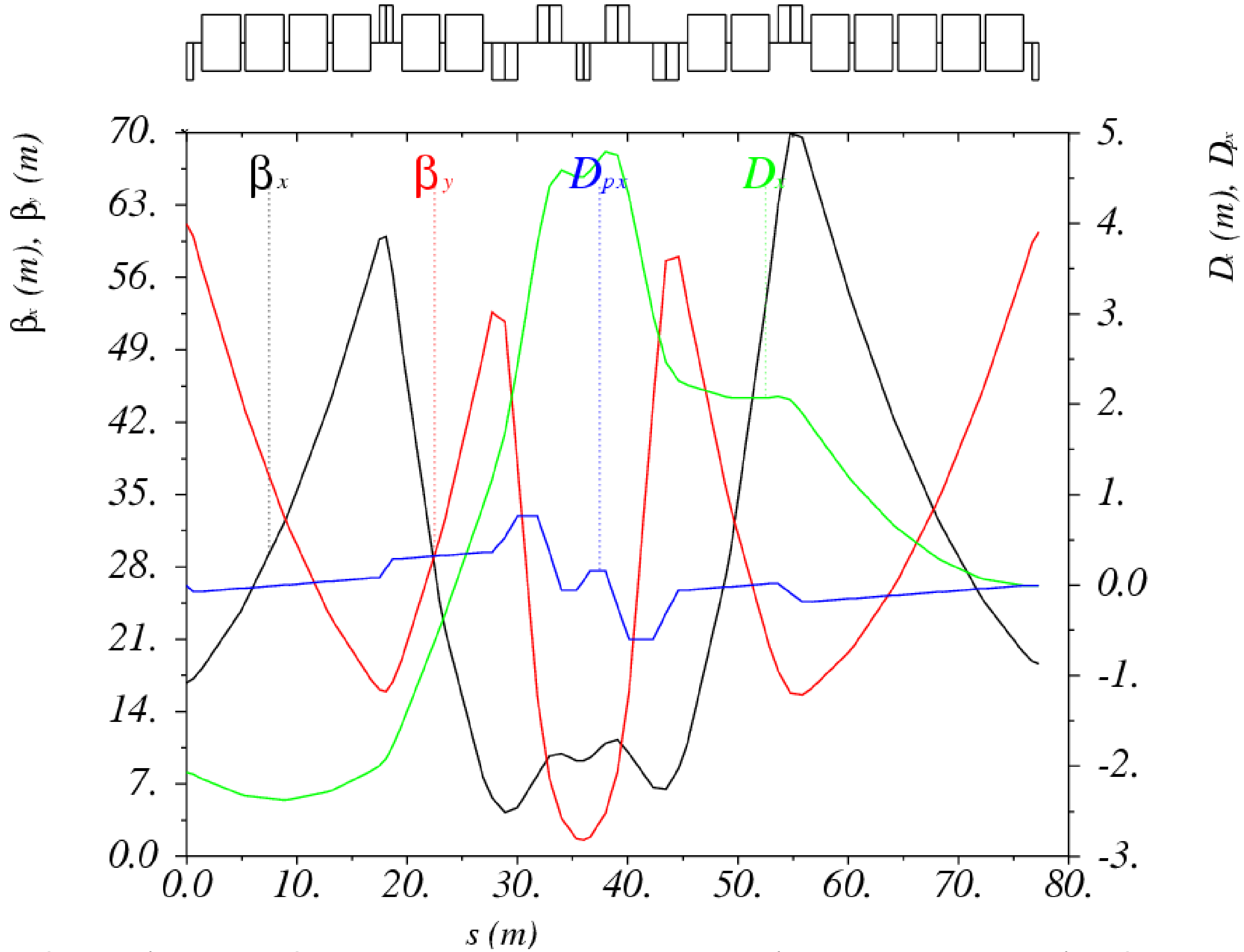
- Almost linear dependence of momentum compaction with dispersion min/max values
- Higher dispersion variation for γ_t closer to 0
- Smaller dispersion variation for higher γ_t

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

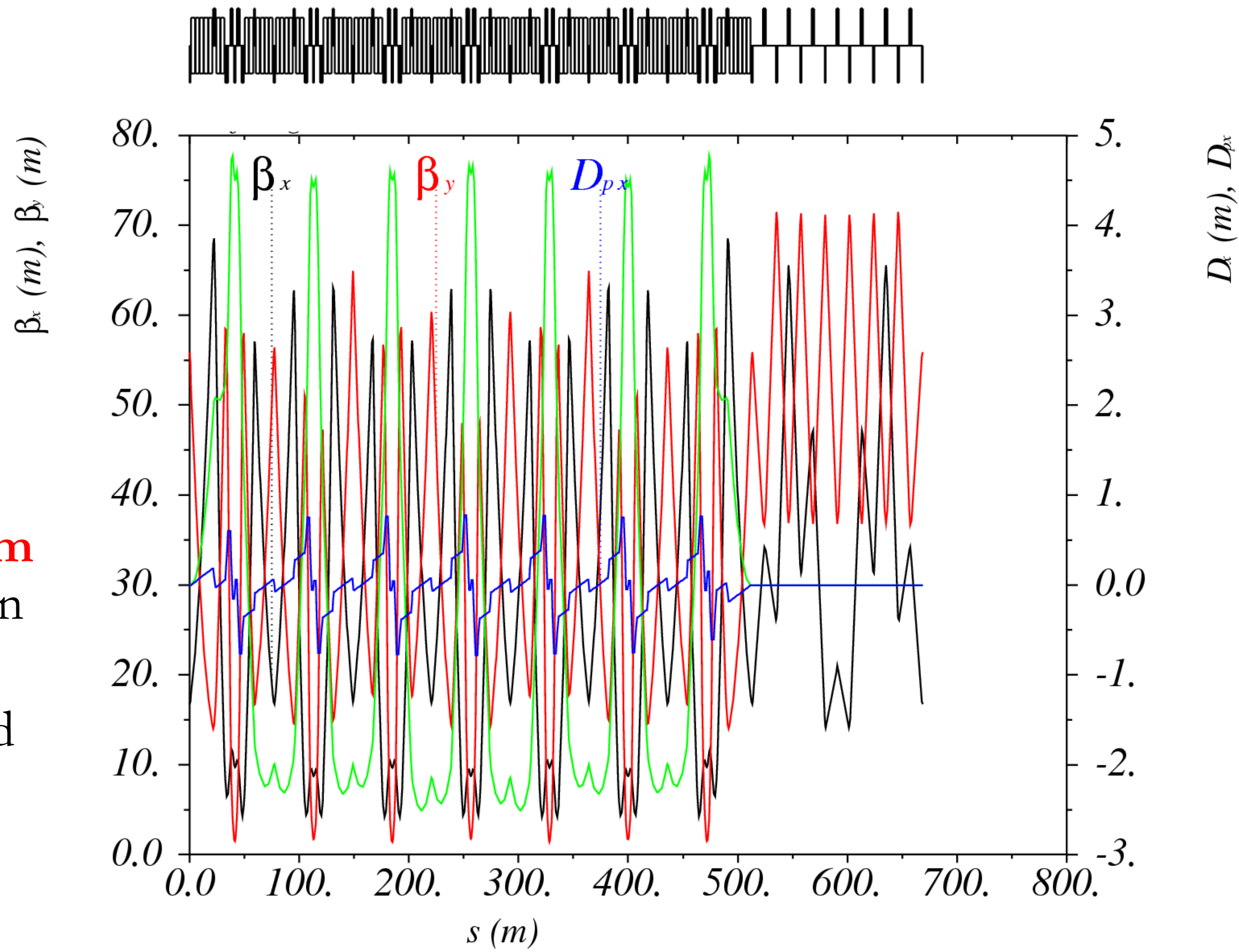
Dispersion suppressor cell



- Similar half module as for the NMC with **2+5** dipoles (instead of 2+4)
- Using 4 families of quads to suppress dispersion, while keeping beta functions "small"
- Maximum beta of **70m**
- Total length of **77.31m**

The ring I

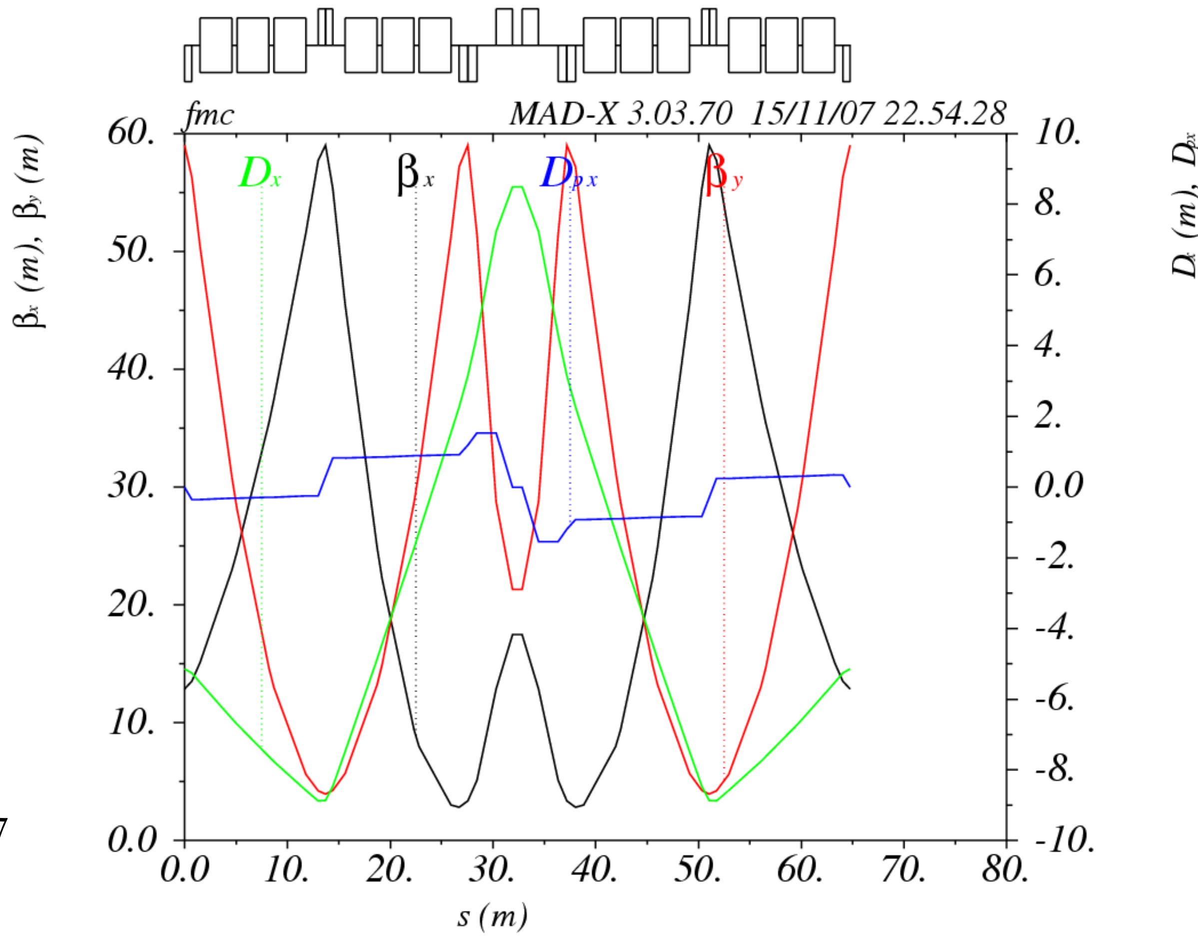
- Adding a straight section with 7 FODO cells, using 2 matching quadrupoles
  - Straight drift of **9.5m**
  - Tunes of (12.1,11.4)
  - γ_t of **12.9i**
  - 13 families of quads, with max. strength of 0.1m^{-2}
  - Max. beta of around **71m** in horizontal and **68m** in the vertical plane
  - Dispersion of -2.3m and maximum of **4.6m**
  - Chromaticities of -16.7, -25.8
  - Total length of **1346m**



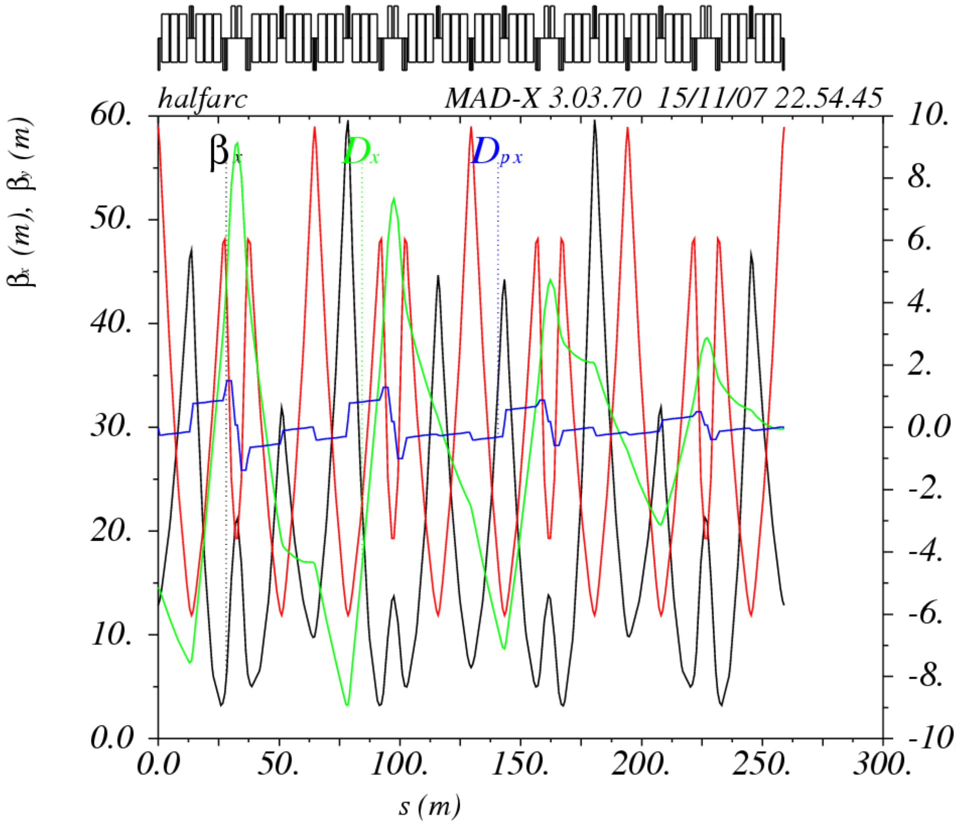
The resonant NMC module

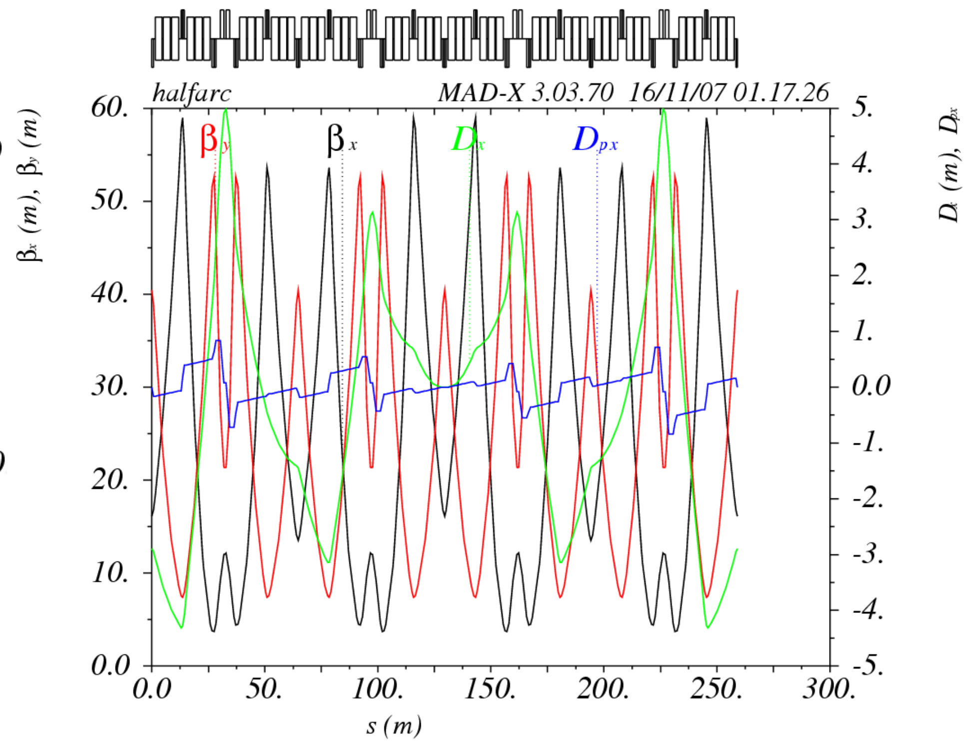
e.g. Y. Senichev BEAM'07

- 1 symmetric FODO cell with 3 + 3 bends and a low-beta doublet
  - Phase advances of 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 0.1m^{-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

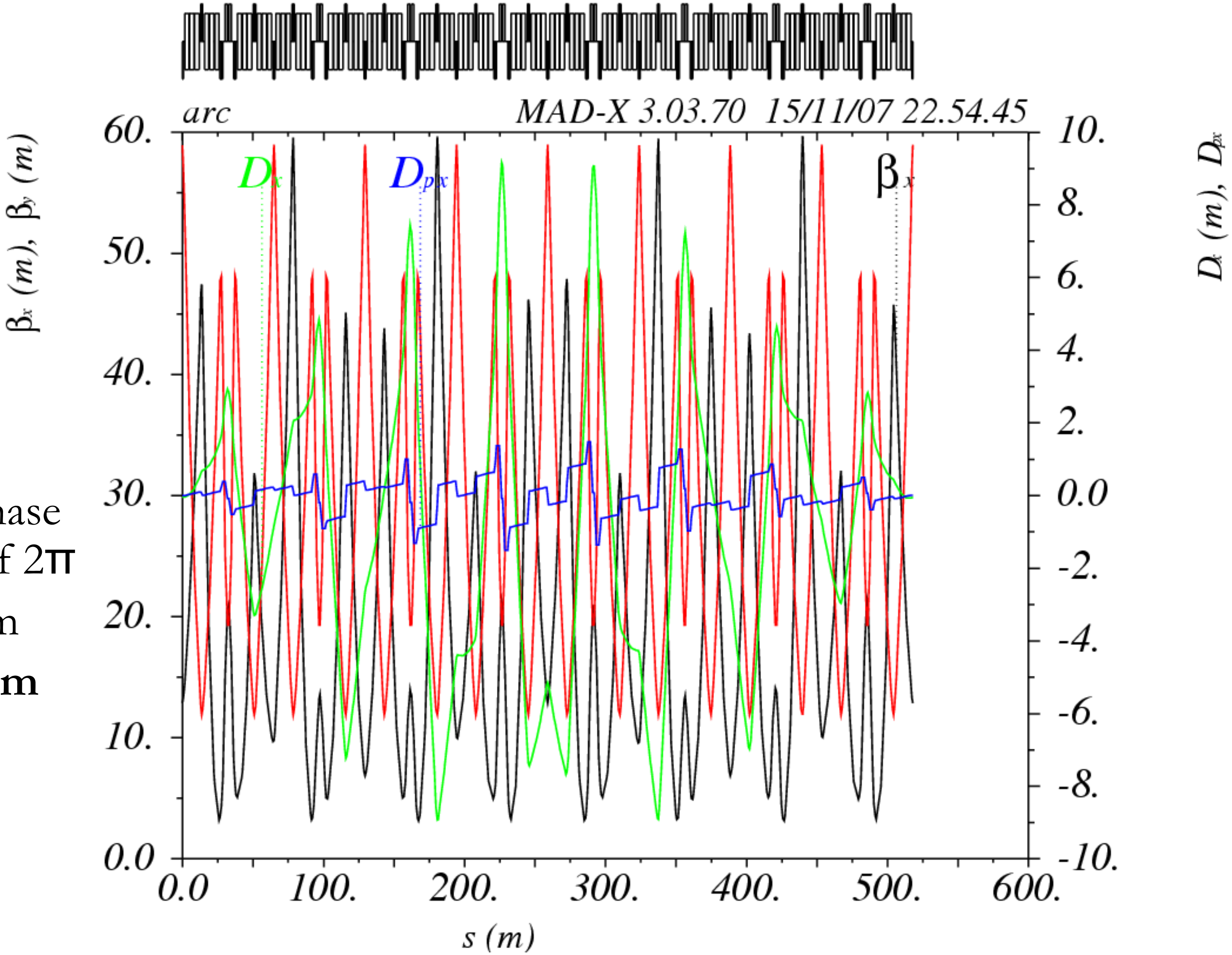




- Dispersion is suppressed by fixing horizontal phase advance to multiple of 2π
- Solution with **odd** number of 2π multiples is preferable for getting **lower imaginary γt**

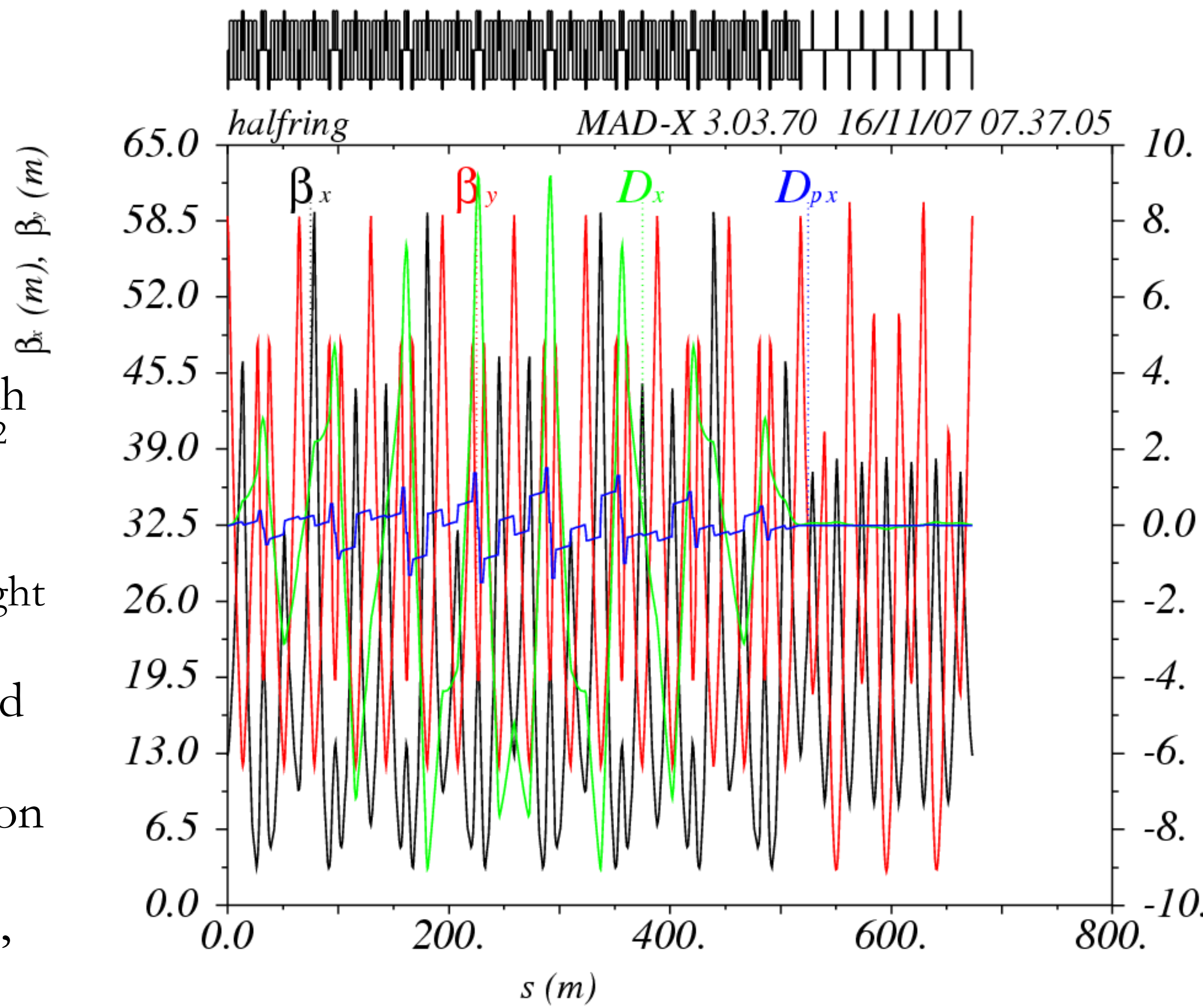
The “resonant” NMC arc

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



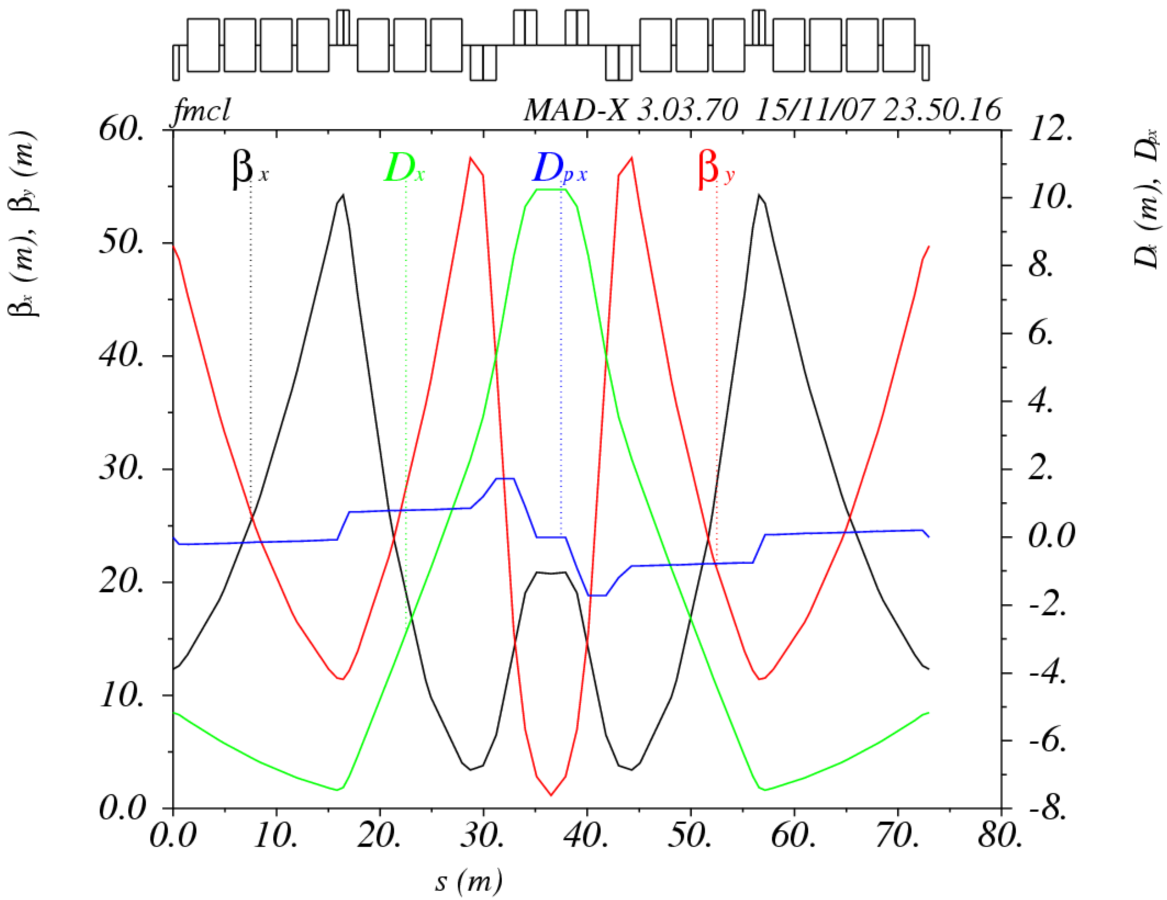
The "resonant" NMC ring II

- 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 **1346m**

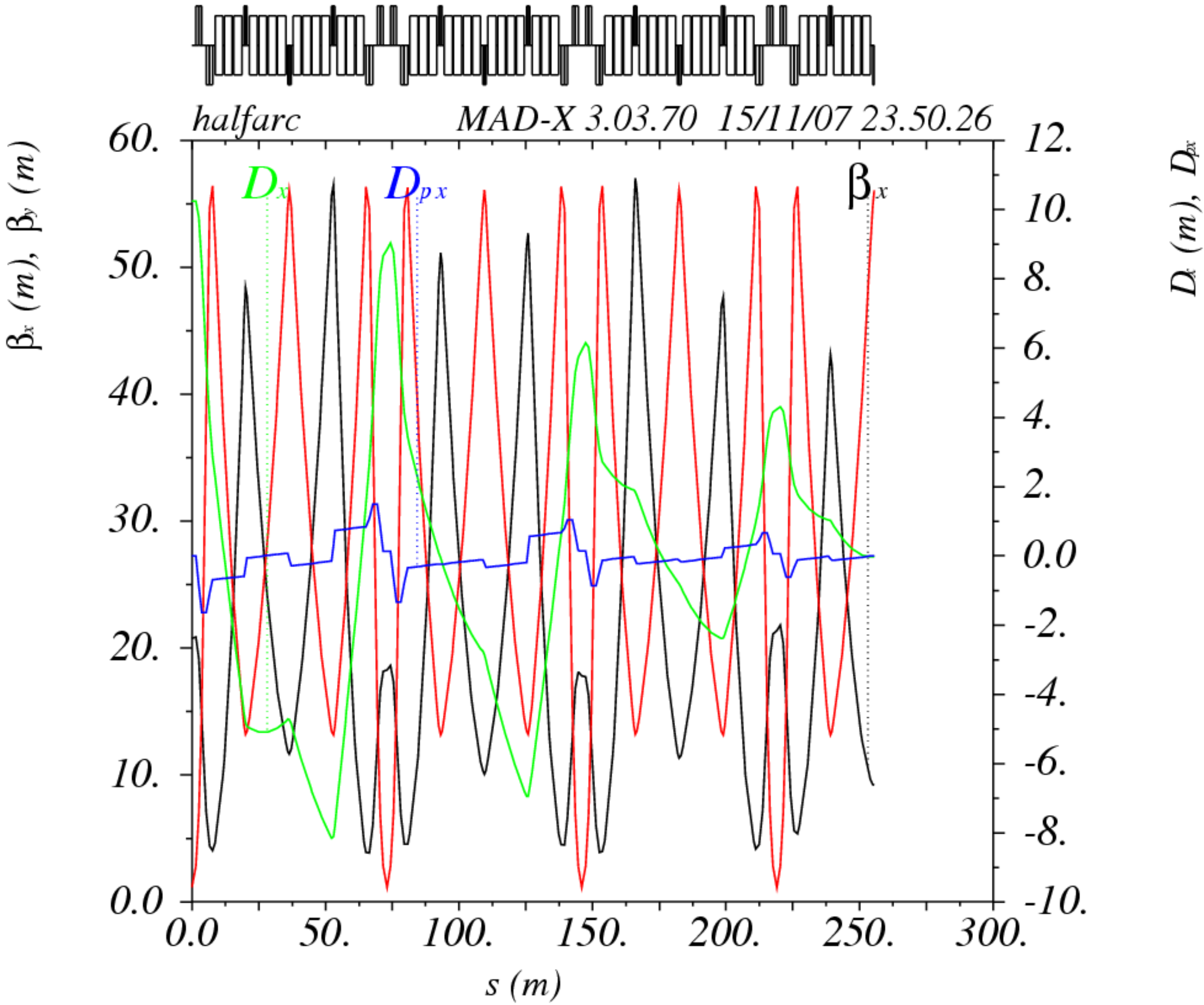


An optimized NMC module

- 1 asymmetric FODO cell with 4 + 3 bends and a low-beta doublet
  - Phase advances of 316°,300° per module
  - γ_t of **5.6i!!!**
  - **Four** families of quads, with max. strength of $0.1m^{-2}$
  - Max. beta of around **54m** and **58m**
  - Min. and max. dispersion of **-7.8m** and **10.2m**
  - Chromaticities of -1.3,-2
  - Total length of **73m**

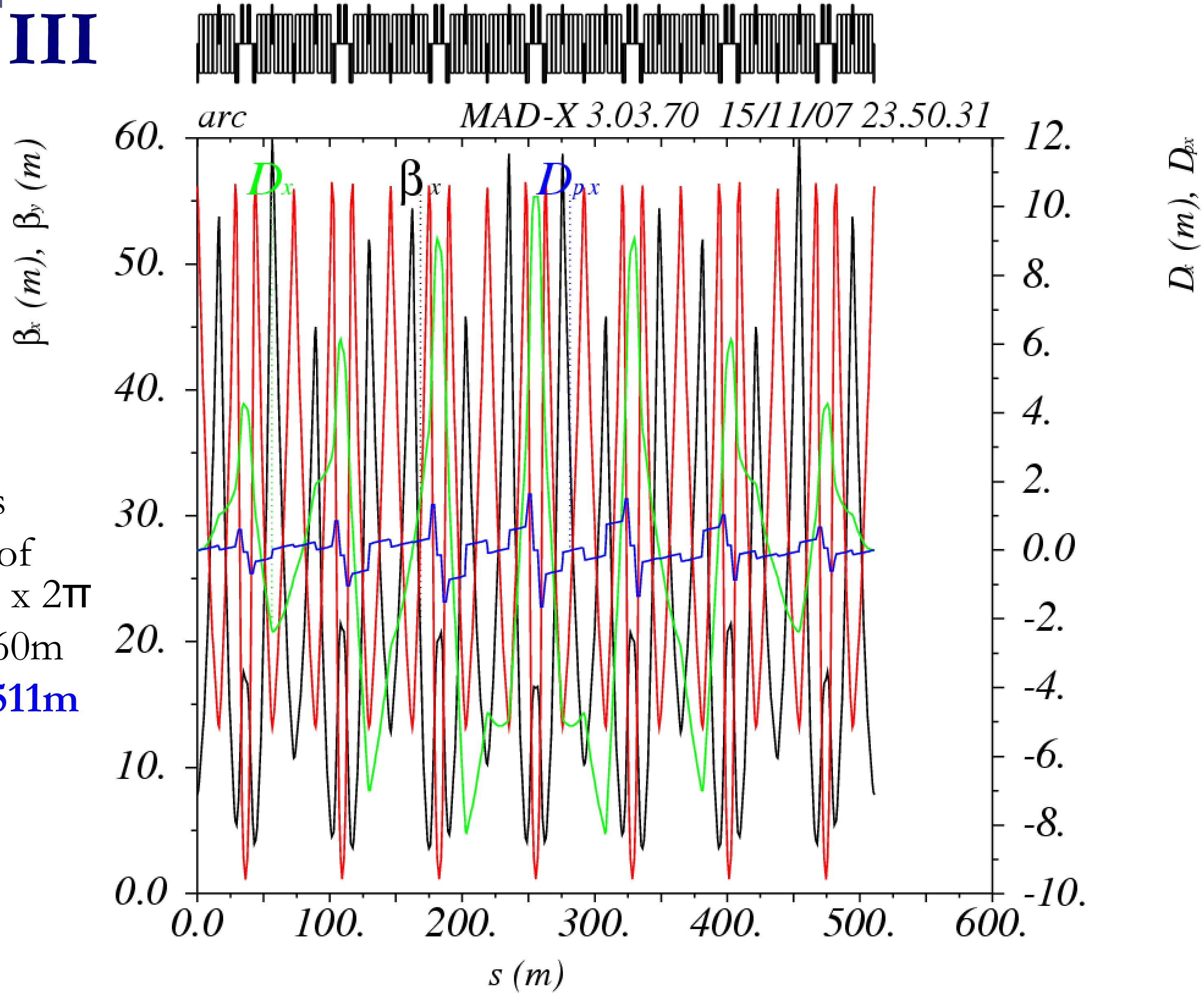


Suppressing dispersion



- Hybrid approach:
  - Phase advance close to multiple of 2π and 2 extra quad families

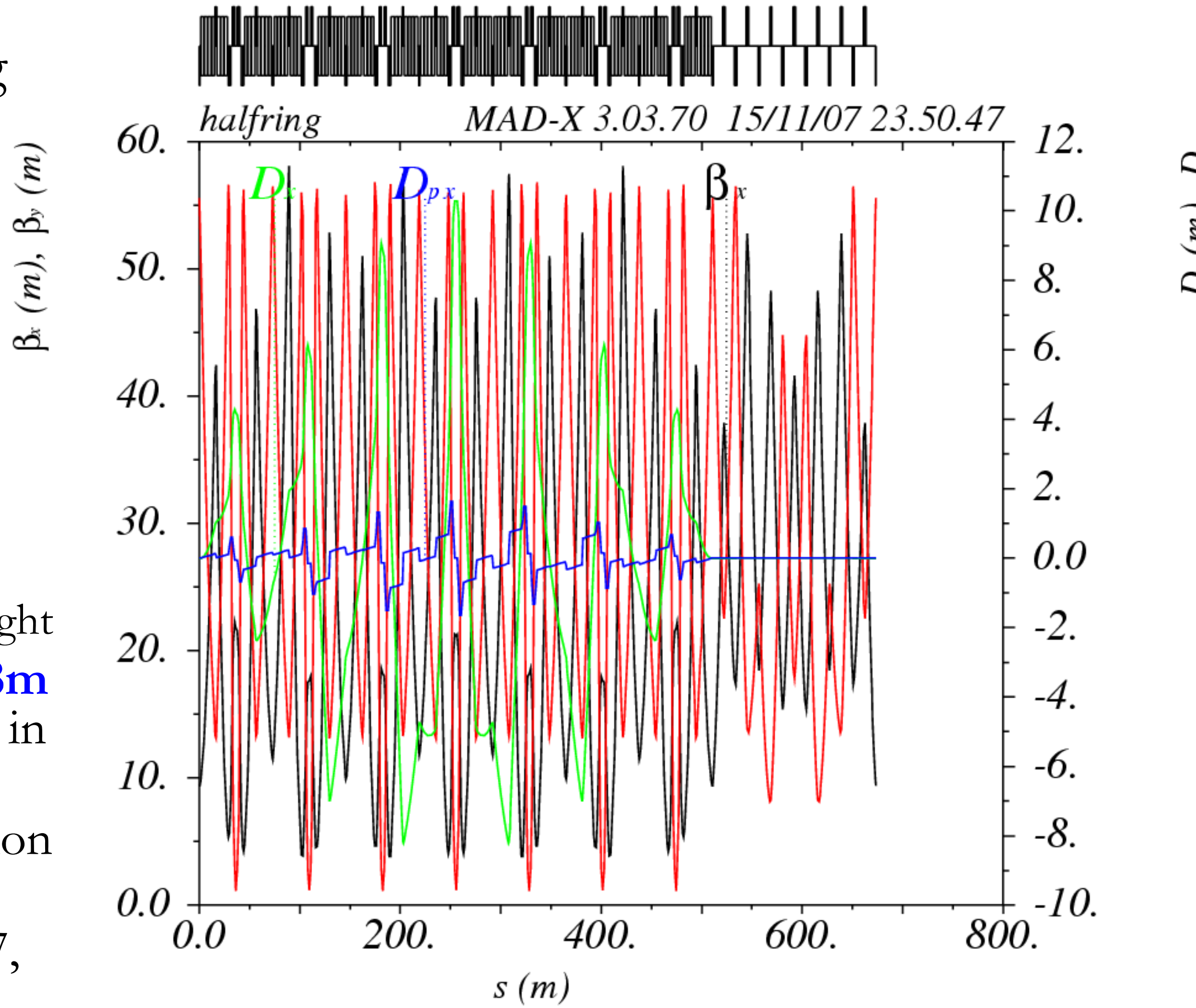
The arc III



- 7 NMC modules
- Phase advances of 5.8 x 2π and 5.5 x 2π
- Maximum β of 60m
- Total length of **511m**

The NMC ring III

- Adding a straight section with 7 FODO cells, using 2 matching quadrupoles
  - Straight drift of **9.5m**
  - Tunes of (13.8,13.4)
  - γ_t of **10.9i**
  - 10 families of quads, with max. strength of 0.1m^{-2}
    - Extra families for phase advance flexibility in the straight
  - Max beta of around **58m** in horizontal and **56m** in the vertical plane
  - Min. and max. dispersion of **-8.2m** and **10.2m**
  - Chromaticities of -18.7, -29.5
  - Total length of **1346m**



Comparison

Parameters	RING I	RING II	RING II
Transition energy	12.9i	10.7i	10.9i
Number of dipoles	172	192	196
Dipole length [m]	3.45	3.11	3.03
Arc module length [m]	71.7	64.8	73
Number of arc modules	5+2	8	7
Arc length [m]	513.5	518	511
Straight section drift length [m]	9.5	9.4	9.5
Quadrupole families	13	8	10
Arc phase advance [2π]	5.2/5.2	7/6	5.8/5.5
Maximum beta functions [m]	71/68	61/61	58/56
Maximum dispersion function [m]	4.7	8.9	10.2
Tunes	12.1/11.4	16.8/9.8	13.8/13.4
Chromaticity	-16.7/-26.8	-21.7/-19.8	-18.7/-29.5

Summary

- Different lattice types for PS2 optics investigated
  - FODO type lattice a straightforward solution
    - Challenge: Transition crossing scheme
  - NMC lattice possible alternative
    - No transition crossing
    - Challenge: low imaginary transition energy
- Perspectives:
  - Complete the lattice design including chromaticity correction and dynamic aperture evaluation
  - Detailed comparison based on performance with respect to beam losses
    - Collimation system
    - Non-linear dynamics
    - Collective effects