SPS Upgrade Study

POSSIBLE REDUCTION OF TRANSITION ENERGY IN THE SPS

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Thanks to Gianluigi ARDUINI and Hannes BARTOSIK

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SPS Upgrade study team meeting
29/07/2010

Outline

- The background
  - Benefits for reducing transition energy in the SPS
  - Old proposals and results
    - Extra quadrupoles
    - Resonant tune
- SPS Hardware constraints
  - Quadrupole gradient
  - Sextupole strengths
- "Resonant" arc
  - Optics solutions and parameterization
- Doublet arc cells
  - Optics solution and phase advance scan
- Negative Momentum Compaction arc cells
  - Optics solutions
- Summary and perspectives

Reducing the transition energy

- Transition energy reduction benefits
  - Instability thresholds (e.g. microwave, TMCI) are usually linear with the slippage factor,

    $$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

    i.e. can be increased by lowering transition energy (almost quadratically for high energies)
  - Higher slippage factor translates to faster longitudinal motion, i.e. faster damping times for instabilities and longitudinal beam manipulation
  - For constant synchrotron frequency, increasing slippage factor allows lowering RF voltage (but larger bunch length)
  - High intensity beams can be injected in the SPS above transition avoiding losses and operational complexity of transition jump scheme

A very interesting option for reaching and building necessary parameter margin in order to achieve ultimate LHC beam density and beyond (LHC upgrade).

Transition energy manipulation

- Transition energy (or momentum compaction factor) is defined as

$$\frac{1}{\gamma_t^2} = \alpha_p = \frac{1}{C}\oint \frac{D(s)}{\rho(s)}ds$$

- The higher the dispersion oscillation in the bends, the lower the transition energy

Quadrupoles

- Note also that, for FODO cells, $\gamma_t \approx Q_x$, meaning that lowering the transition energy means lowering the horizontal tune

Past proposals: Extra quadrupoles

P. Collier (ed.), CERN/SL/97-07/DI, 1997

- Preliminary studies suggesting introducing 2 pairs of small quadrupoles evenly spaced in all SPS arcs
- If separated by $\mu_x, \mu_y = (2k+1)\pi$, there is no effect in the tune and optics (every two cells for minimizing orbit distortion)
- Other applications include raising transition energy at extraction (shortening LHC bunches), faster transition jump, smoothing dispersion (increasing momentum aperture) or tune feedback loop

K. Cornelis, Chamonix 1999

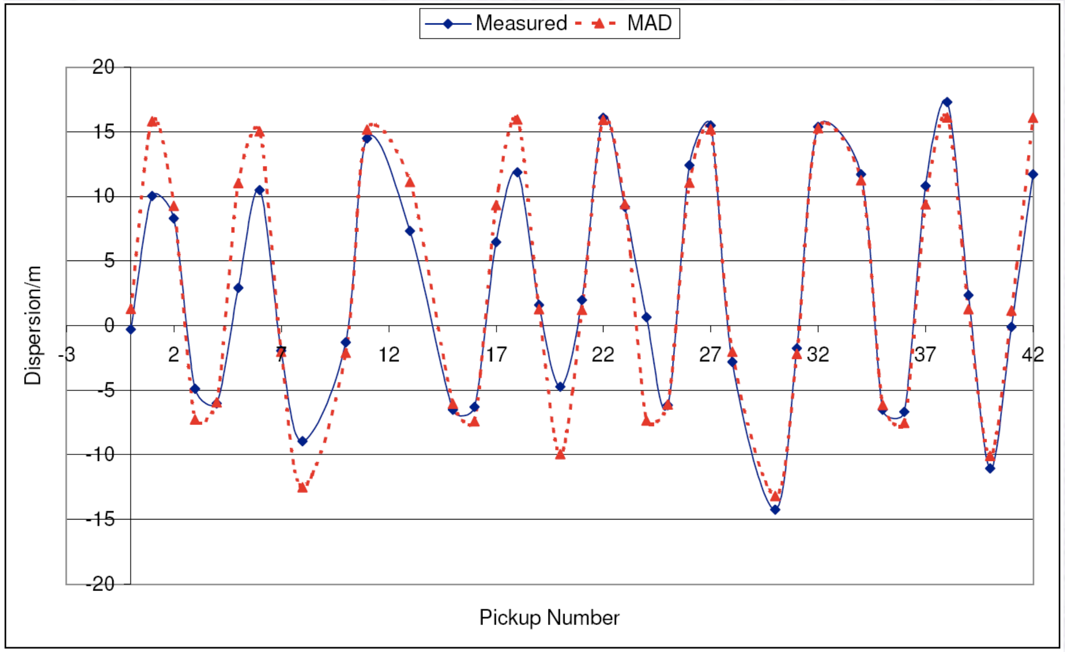
Maximum Gradient, G	7	T/m
Field Length, L	0.3	m
Inner Radius, r	44	mm
Ampere Turns, NI	5600	At
Coil Conductor (water cooled)	8x8	mm^2
Coil Length ,l	35	m
Coil resistance, R	58	mΩ
Dissipated Power, P	2.3	kW
Power Supply	12V,200A	

- Series of investigations were necessary for qualifying the feasibility of the scheme including machine experiments with "**resonant tune**" of 24 in the SPS

Resonant tune

G. Arduini et al., CERN/SL-Note 98-001 (MD), 1998

- By setting the SPS integer tune to a multiple of 6, large dispersion wave can be introduced (dispersion becomes even negative) by overall reducing transition energy
- Successfully establishing cycle in the SPS and measuring dispersion very close to the one of MAD
- 3-fold increase of the slippage factor can be achieved (model)
- "Difficult" beam conditions

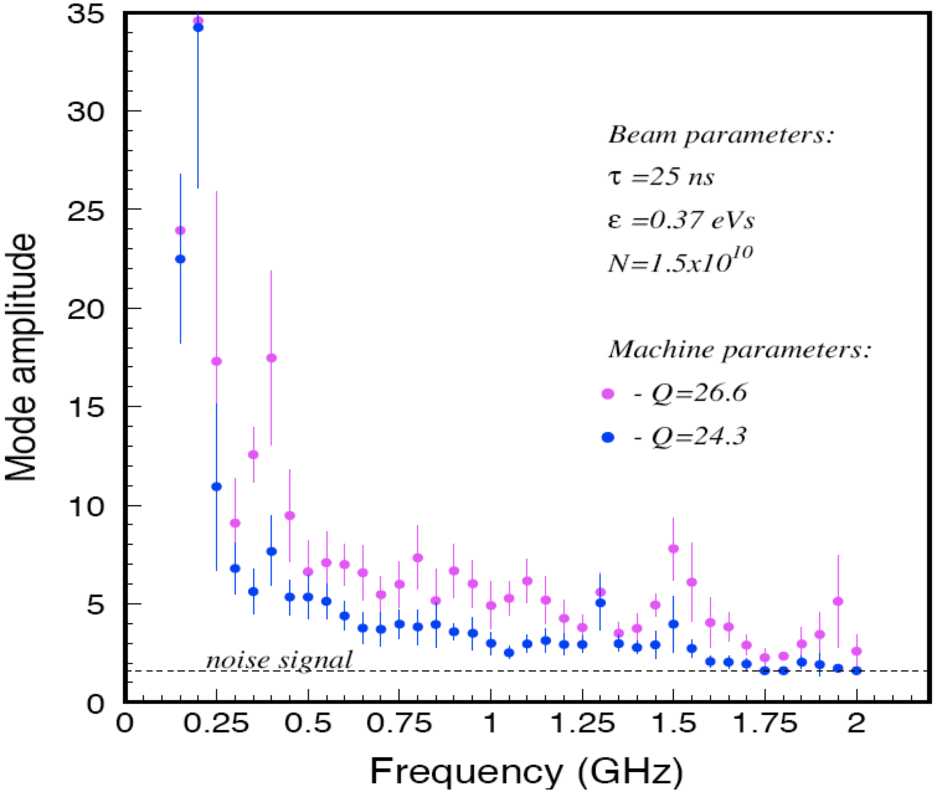


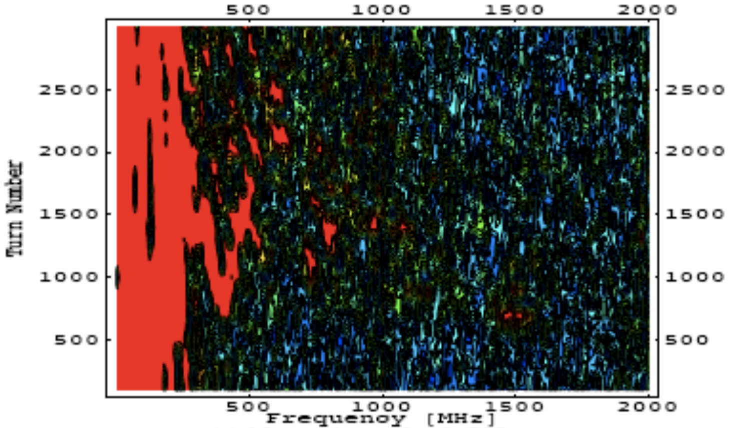
Q_h	Q_v	γ_{tr}	$\eta\ (10^{-3}$
24.18	24.22	18.54	1.61
24.29	24.32	19.59	1.30
26.62	26.58	23.23	0.551

Lower transition and microwave instability

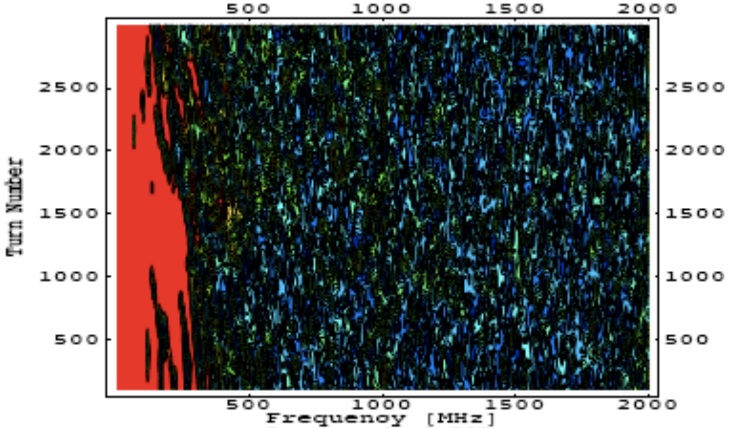
T. Bohl et al., EPAC 1998

- Machine experiments at the SPS showed reduction of the unstable modes amplitudes (apart from 200MHz) by a factor of 1.5-2.5 when running with lower transition energy





(a) Normal γ_{tr} 0 - 2 GHz



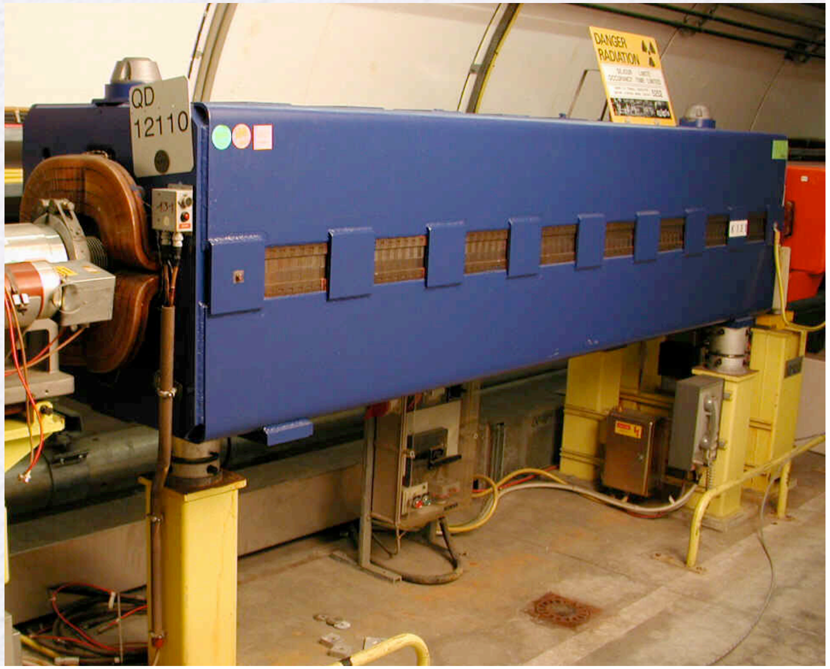
(b) Low γ_{tr} 0 - 2 GHz

SPS quadrupoles

- 216 quadrupoles (102 QF, 100 QD, 6 QFA and 8 QDA)
- Maximum gradient of 22T/m, corresponding to a normalized gradient of 0.01466m^{-2}
- Normal operation necessitates almost the full gradient @ 450 GeV

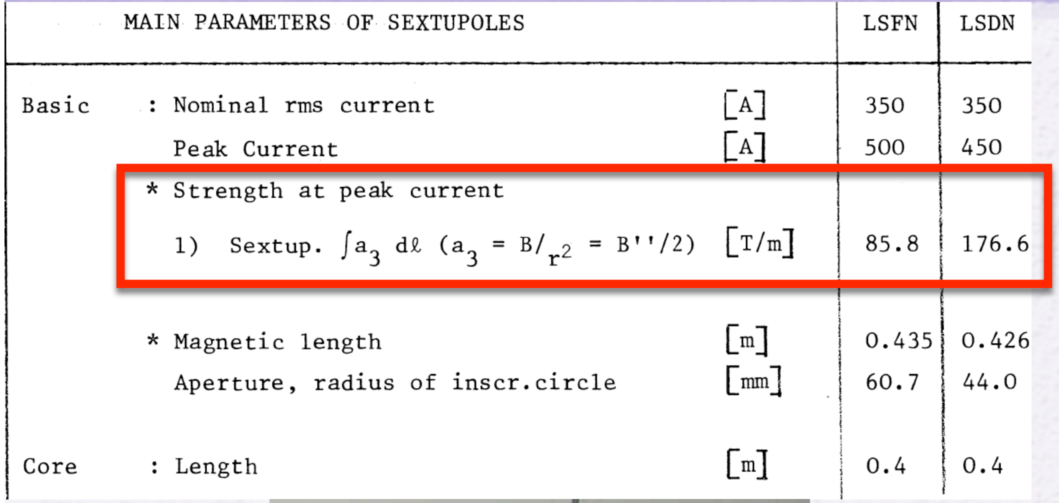
D. Tommasini CERN/TE-Note-2010-003

Number of magnets	216
Year of 1st operation	1976
Maximum gradient [T/m]	22
Physical vertical aperture [mm]	88
Yoke assembly [Solid,Laminated,Welded,Glued]	L,W
Coil technology [Copper,Aluminium,Glass-epoxy,Mica,Other]	C,G
Maximum voltage to ground [V]	3450
Operation	Cycled
Maximum cooling water velocity [m/s]	3.6
Operational temperature [C°]	40



SPS sextupoles

M. Giesch, CERN/SPS/80-3/AMS, 1980

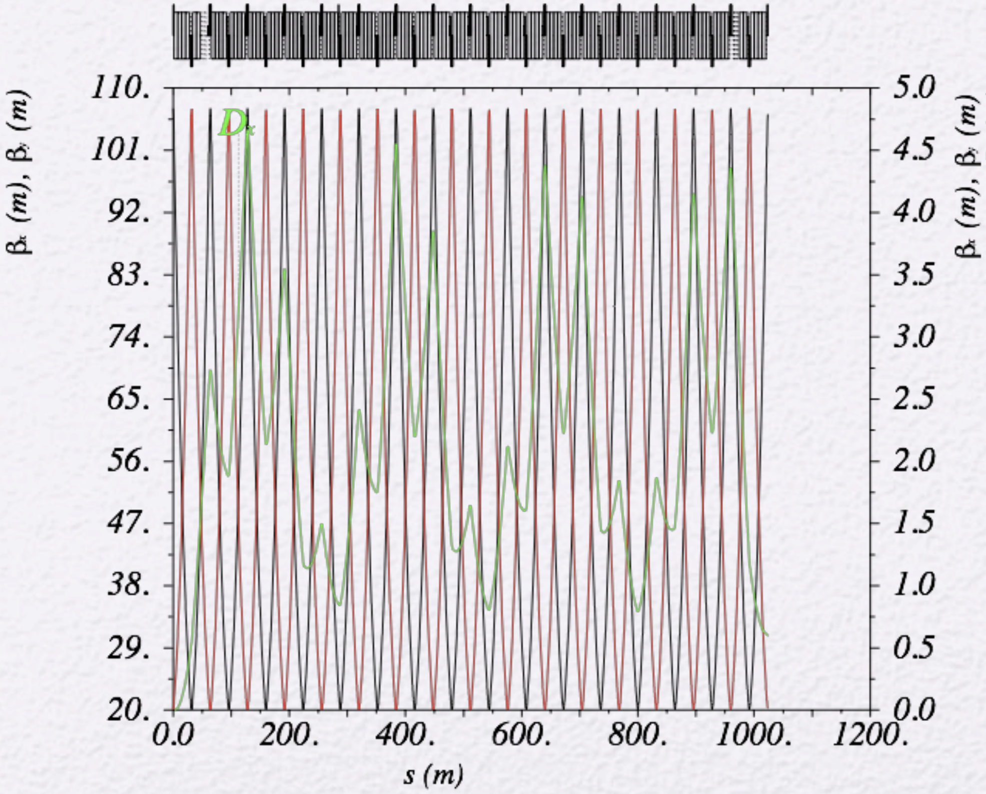


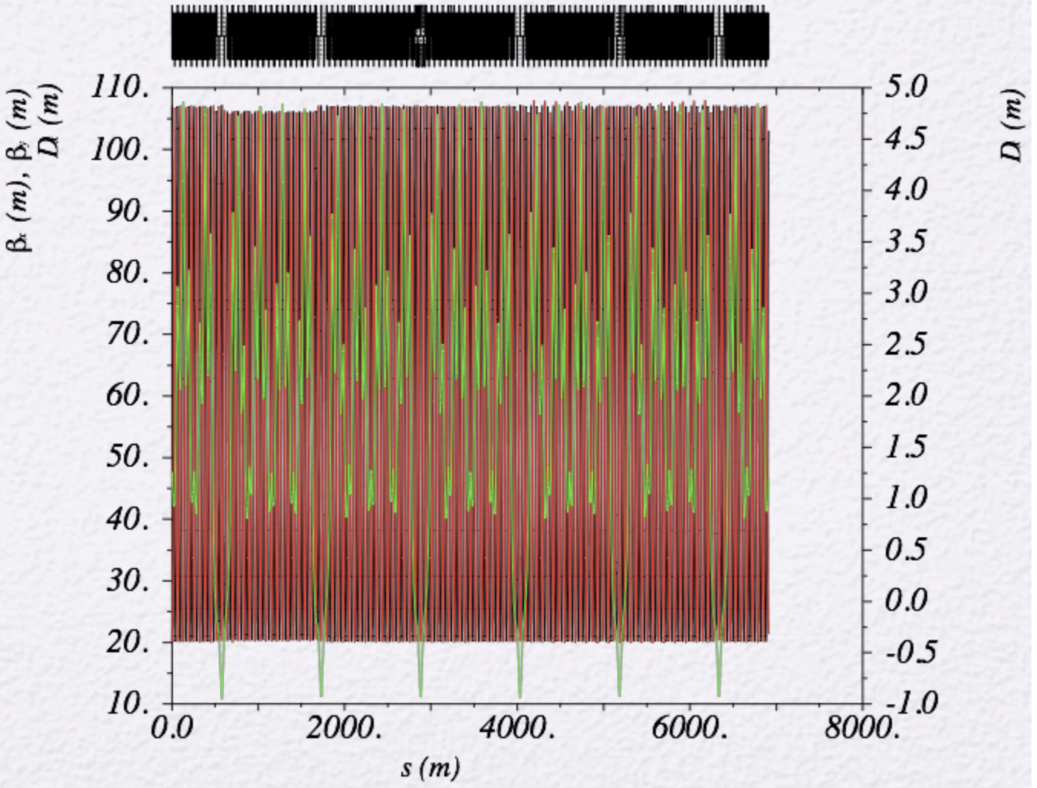
MAIN PARAMETERS OF SEXTUPOLES			LSFN	LSDN
Basic	: Nominal rms current	[A]	350	350
	Peak Current	[A]	500	450
	* Strength at peak current			
	1) Sextup. $\int a_3 \, d\ell$ ($a_3 = B/r^2 = B''/2$)	[T/m]	85.8	176.6
	* Magnetic length	[m]	0.435	0.426
	Aperture, radius of inscr.circle	[mm]	60.7	44.0
Core	: Length	[m]	0.4	0.4

- 54 "focusing" and 54 "defocusing" sextupoles in two (three for F) families (24 and 30)
- Maximum normalized sextupole strength of 0.13m^{-3} for LSFs and 0.28m^{-3} for LSDs
- Around 80% and 60% in operational conditions
- Other elements (correctors, skew quadrupoles, octupoles, extraction elements…) need also to be checked

Resonant arc: A different approach

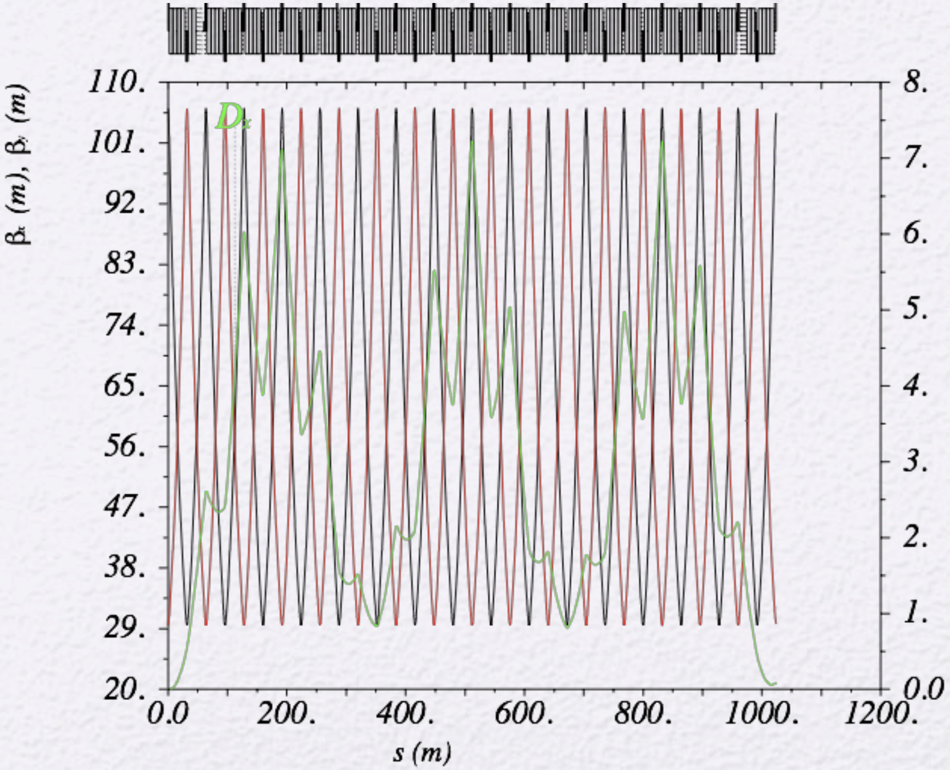
- The SPS arc horizontal phase advance can be tuned to a multiple of 2π (phase advance of the cell a multiple of 1/16)
- In that way, dispersion is almost suppressed (small perturbation due to missing bends at arc extremities)
- Operational point at cell phase advance of around **4/16 = 0.25 = π/2**

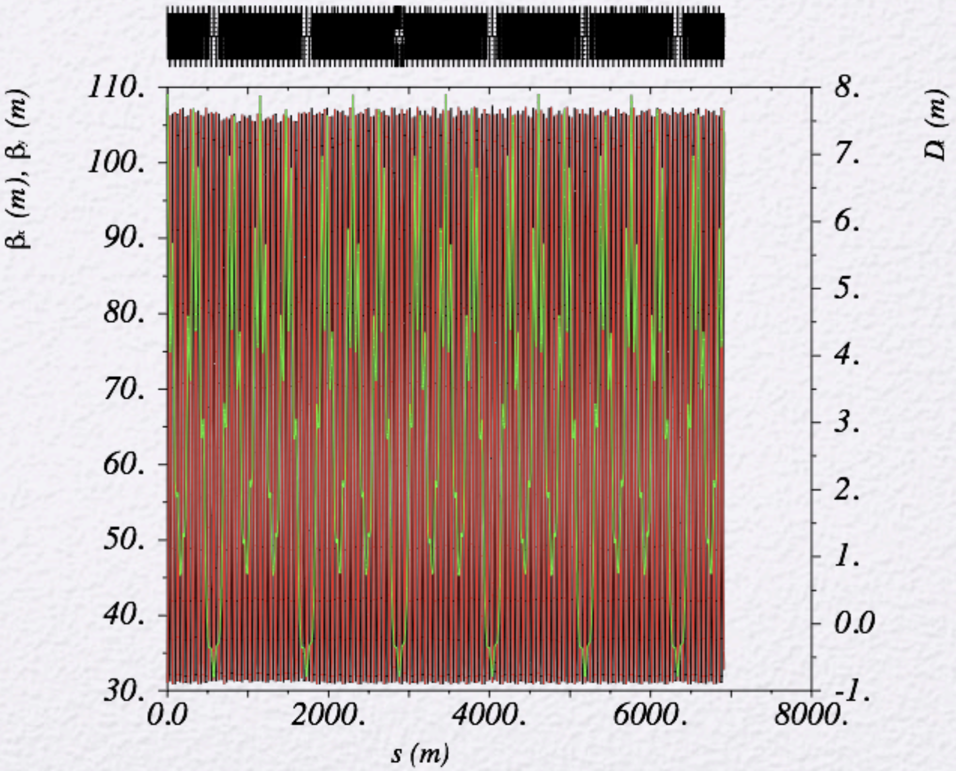




Resonant arc:
Cell phase advance of 3/16

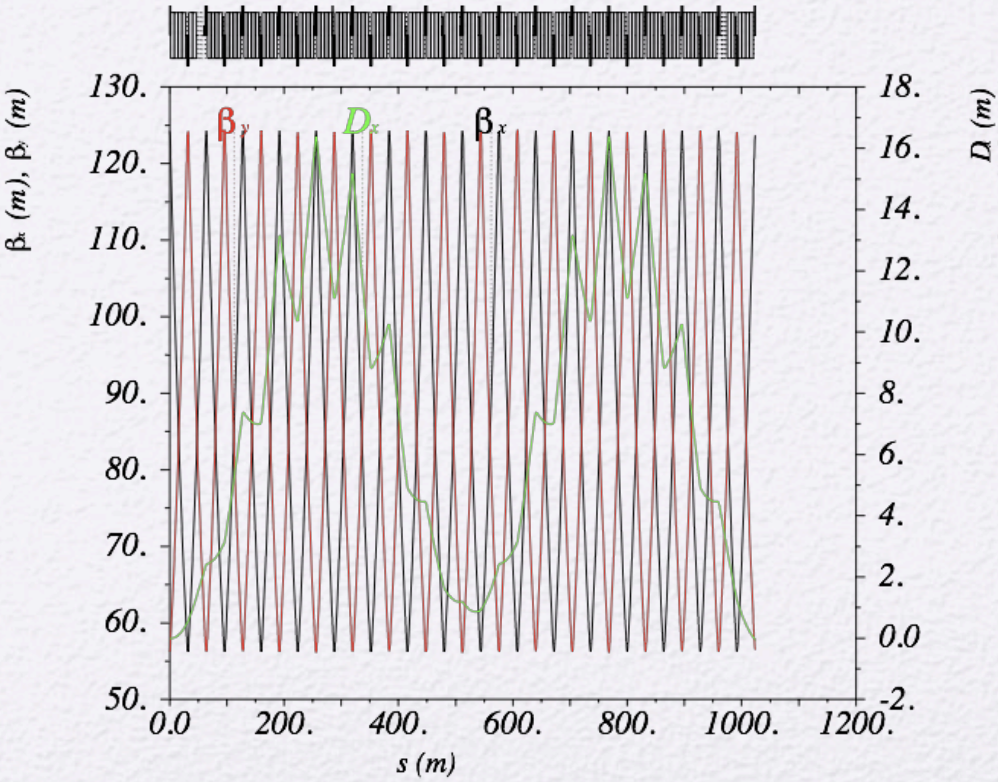
- Very smooth optics for cell phase advance of 3/16
- Ring tunes of 20.25 shown here, but vertical tune can be varied to different integers
- Dispersion max. slightly increased to 8m (from 5m) but beta max. below 110m
- Quad. strengths reduced by almost 30%
- Same trend for natural chromaticity (-23) and chromaticity sextupole strengths
- Transition energy reduced to **18 (from 23), i.e. slippage factor increased by a factor of 3.5**

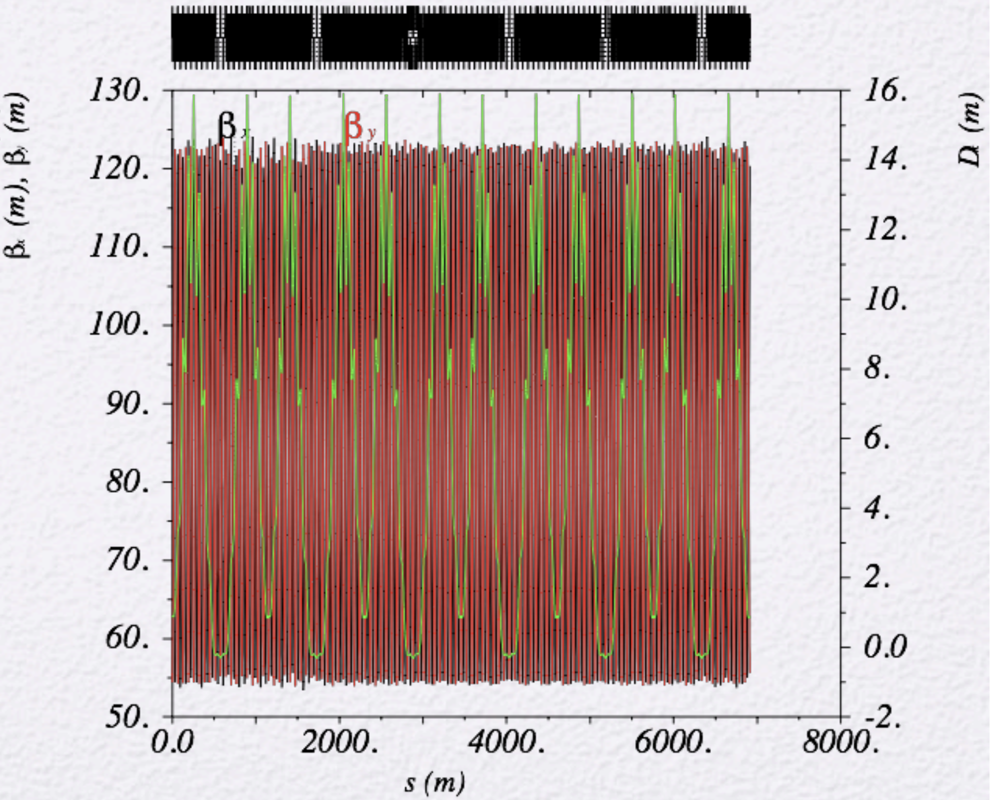




Resonant arc:
Cell phase advance of 2/16

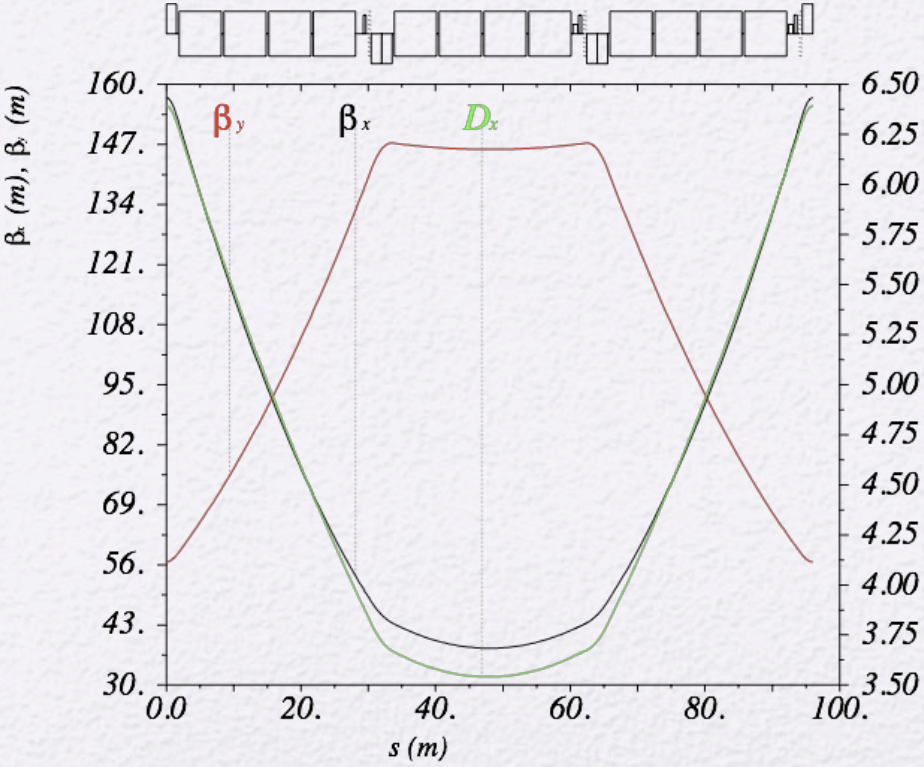
- Smooth optics for cell phase advance of 2/16
- Ring tunes of 13.8, with dispersion max. at 16m (can be further reduced) and beta max. around 120m
- Quad. strengths reduced by 50%
- Very low natural chromaticity of-14 (from -33) and chromaticity sextupole strengths
- **Transition energy reduced to 12.6, i.e. slippage factor increased by a factor of 11**

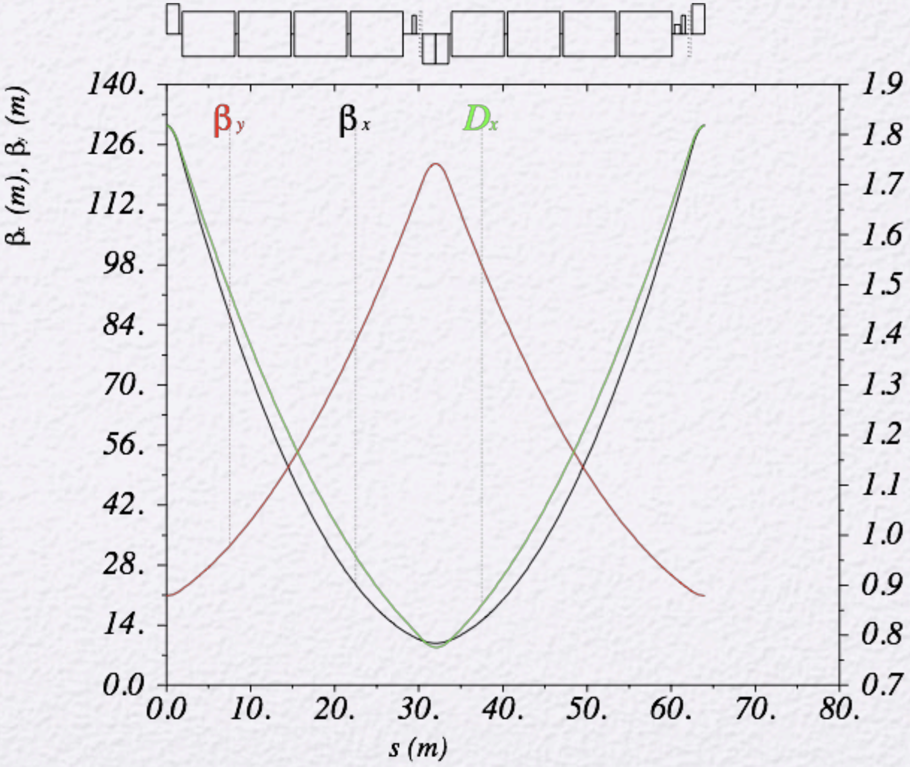




The FODODOFO cell

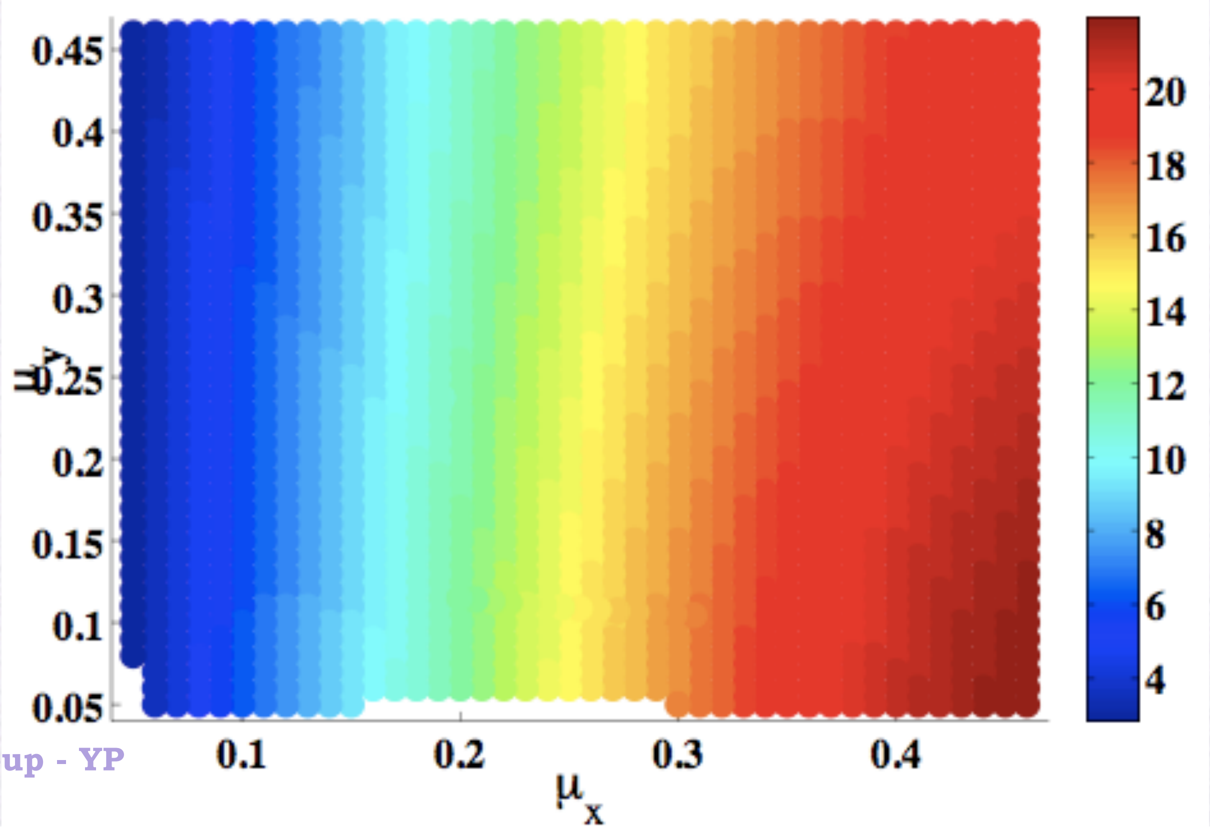
- By flipping the polarity of the last two quadrupoles in 2 consecutive arc cells (from FODOFODO to FODODOFO), a larger dispersion oscillation is produced, providing lower transition energy (lowering overall arc phase advance)
- The optics is quite smooth and tunable, although beta functions get slightly larger
- Necessitates bipolar power supplies in all quads and some additional ones to provide flexibility for dispersion suppression





Transition energy dependence

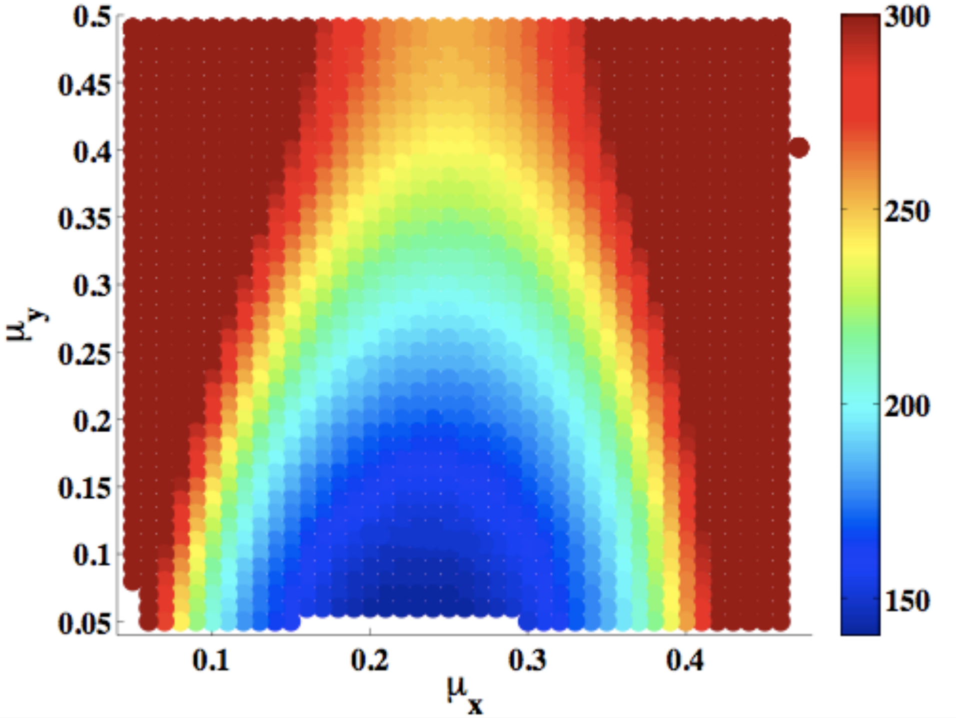
- Transition energy between 4 to above 20
- Lower transition energy for lower horizontal phase advances, as expected
- Almost no dependence on vertical phase advance
- Good compromise at phase advances of around 0.2/cell in both planes (transition energy of 12)



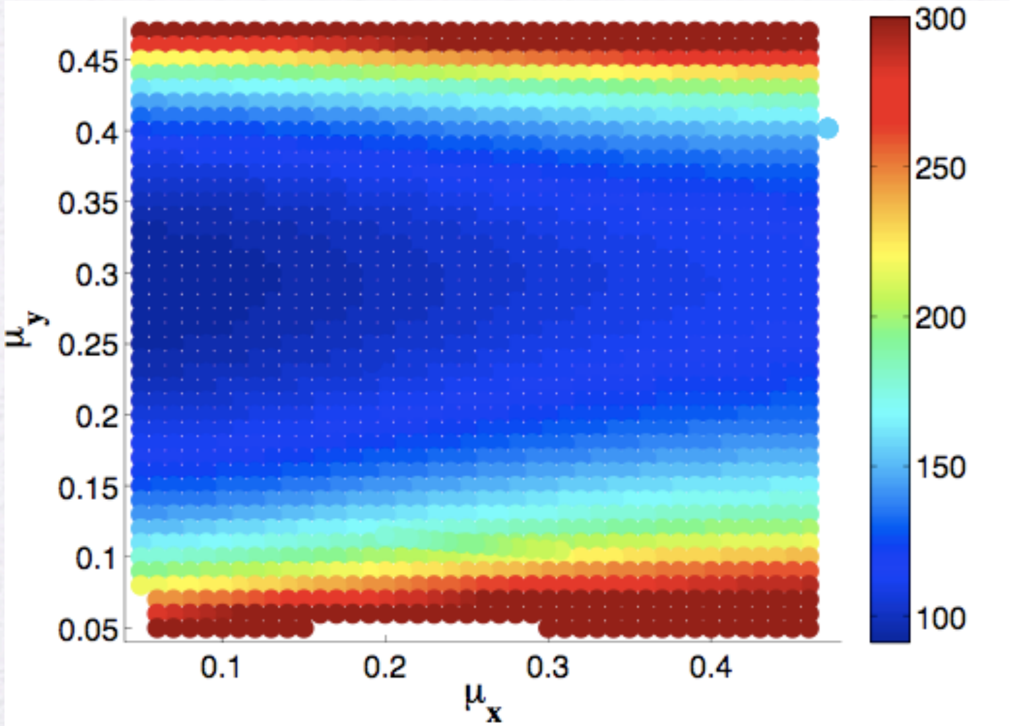
Beta functions

- Low vertical and moderate horizontal phase advance for lower horizontal beta
- Vertical beta has opposite trend but smoother variation (apart from extremities)

Betax



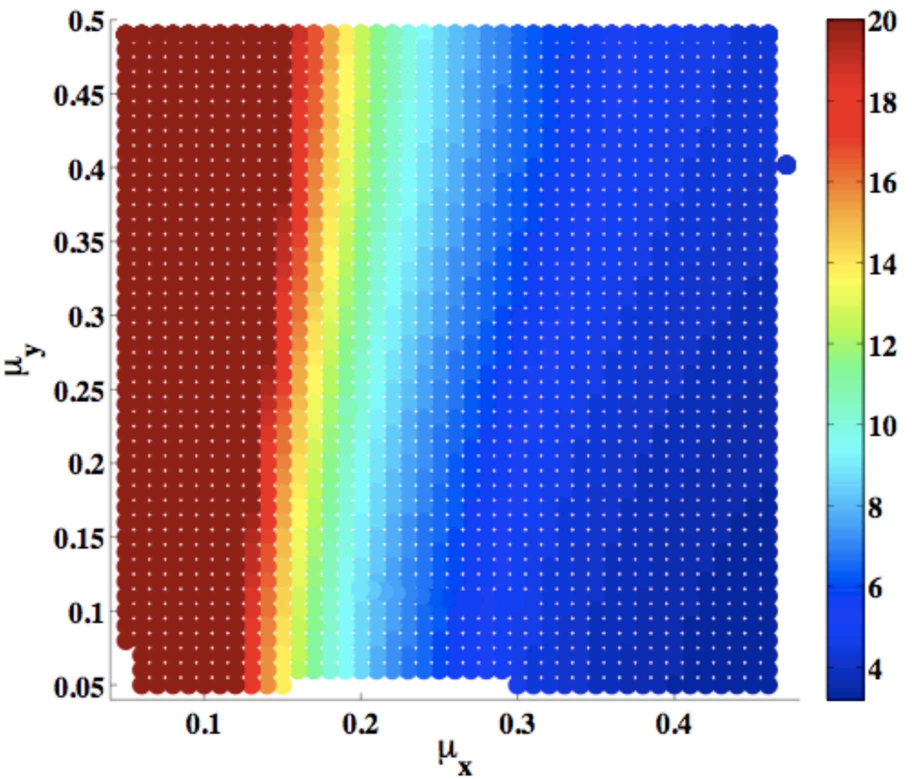
Betay



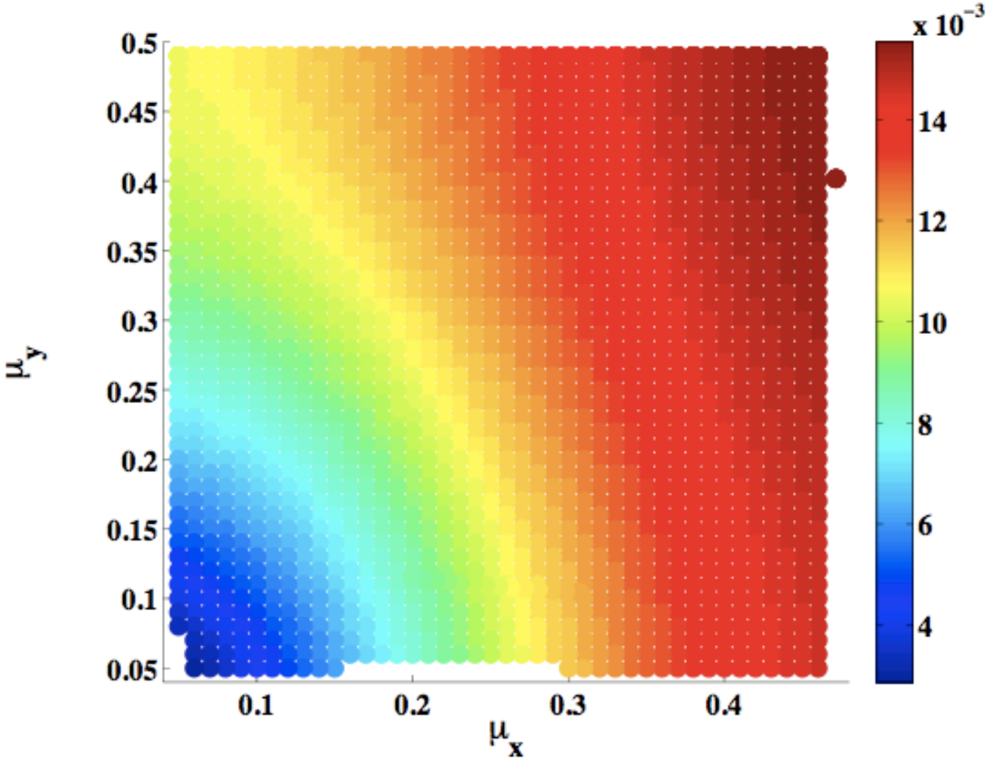
Dispersion and quad strengths

- Low dispersion values for horizontal phase advances above 0.15, and dropping rapidly at around 0.2
- Overall low quadrupole gradient apart for large phase advances in both planes

Dx

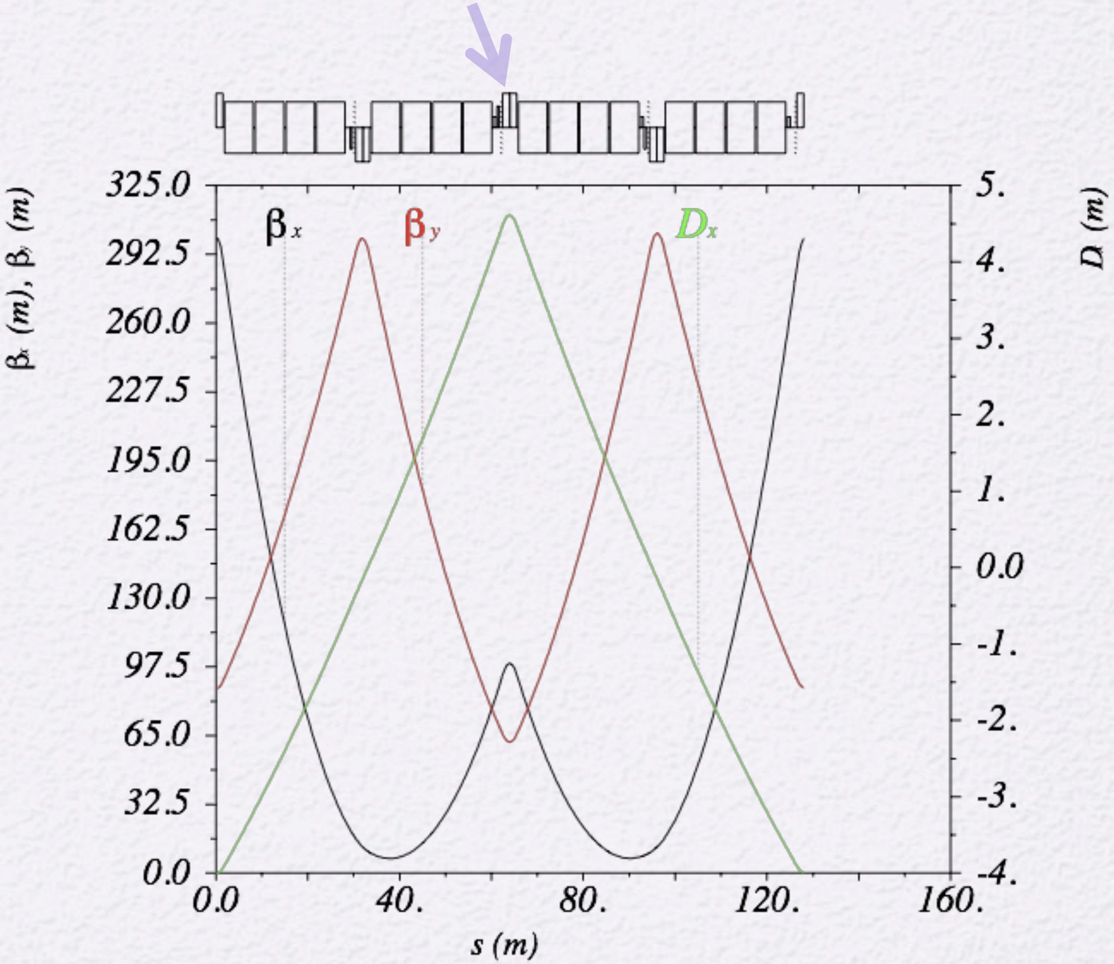


Max. Gradient



Imaginary transition energy

- Excite dispersion oscillations by powering individually central focusing quad in two consecutive FODO cells
- High imaginary transition energy of 200i for this example
- Dispersion maximum below 5m, but high beta function maxima (300m)
- Focusing quadrupole gradients quite high (30% more than max. allowed) as horizontal phase advance is large
- Quite academic…



Summary and perspectives

- Several optics solutions for manipulating the transition energy of the SPS are possible
- "Resonant arc" seems the most promising as it does not necessitate any hardware change
- Optics looks smoother as compared to previous attempts
- This option can be tested experimentally in the SPS
- FODODOFO optics looks very good with respect to tunability, aperture and quadrupole strengths
- Requires hardware changes (extra bi-polar power convertors)
- Needs still further optics optimization for dispersion suppression and general ring tuning
- High imaginary transition energy can be achieved but aperture and quadrupole strengths are a serious obstacle