Non linear optimization of the CLIC pre-damping rings

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Outline

- CLIC Damping-Rings' (DR) and Pre-Damping Rings' (PDR) requirements.
- PDR design guidelines & Layout
- Analytical Solution for the TME cells
- Dynamic aperture (DA) optimization
- Current PDR parameters
- Conclusions

CLIC DR and PDR requirements

Injected Parameters	e^-	e^+
Bunch population [10^9]	4.6	4.6
Bunch length [mm]	1	9
Energy Spread [%]	0.1	1
Long. emittance [eV.m]	2000	257000
Hor.,Ver Norm. emittance [nm]	100 x 10^3	7 x 10^6

PDR Extracted Parameters	PDR e^-/e^+	DR e^-/e^+
Energy [GeV]	2.86	2.86
Bunch population [10^9]	4.1-4.4	4.1
Bunch length [mm]	10	1.4
Energy Spread [%]	0.5	0.1
Long. emittance [eV.m]	143000	5000
Hor. Norm. emittance [nm]	63000	500
Ver. Norm. emittance [nm]	1500	5

Why Damping Rings (DR) ?

- To achieve the very low emittance needed for the Luminosity requirements of CLIC.

Why PDR?

- Large injected e^+ emittances
  - ➔ aperture limitations if directly injected to the Damping Ring
- e- beam needs at least 17 ms to reach equilibrium in the DR (w/o IBS)
  - ➔ very close to the repetition rate of 50 Hz

➢ **Most critical the design of the positron ring**

PDR design guidelines

- ❑ Large input beam sizes due to large injected emittances in both horizontal and vertical planes, especially for the positron beam.
- ❑ Large energy spread
- ❑ Required output horizontal and vertical emittances

- ➢ The output emittances not extremely small
  - the emittance is not the crucial parameter as in the case of the DR
- ➢ The large energy spread of the injected positron beam necessitates large momentum acceptance
  - Small momentum compaction factor and/or large RF Voltage needed
- ➢ The large beam sizes (h & v) require large dynamic aperture (DA)
  - Minimization of the non-linear effects

- ❑ Similar geometry with the DR (fit in the same tunnel ?)

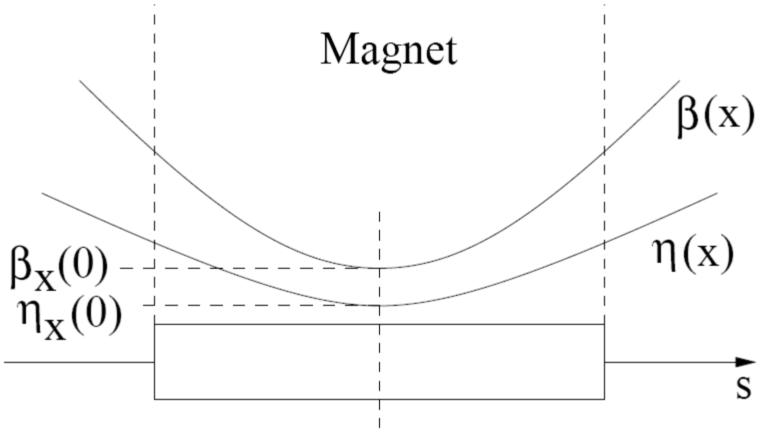
PDR layout

- Racetrack configuration similar with the DR with 2 arc sections and 2 long straight sections
- The arc sections filled with theoretical minimum emittance cells (TME)
- The straight sections composed with FODO cells filled with damping wigglers

- The low emittance and damping times are achieved by the strong focusing of the TME arcs and the high field normal conducting damping wigglers in the long straight sections

Analytical parameterization of the Theoretical Minimum Emittance (TME) cells

Analytical solution of the TME cell



$$\beta_x(0) = \frac{1}{2\cdot\sqrt{15}}\cdot L \qquad \eta_x(0) = \frac{L^2}{24\cdot\rho}$$

$$\varepsilon_{x0} = C_q\cdot\gamma^2\cdot\frac{1}{J_x}\cdot\frac{1}{3\cdot 4\sqrt{15}}\cdot\varphi^3$$

Behavior of the machine functions at a bending magnet to reach the theoretical minimum emittance.

D. Einfeld, J. Schaper, M. Plesko, EPAC96

- An analytical solution for the quadrupole strengths based on thin lens approximation was derived in order to understand the properties of the TME cells.

$$f_1 = \frac{l_2(4l_1L_d + L_d^2 + 8\eta_{x,cd}\rho)}{4l_1L_d + 4l_2L_d + L_d^2 - 8\eta_s\rho + 8\eta_{x,cd}\rho}$$

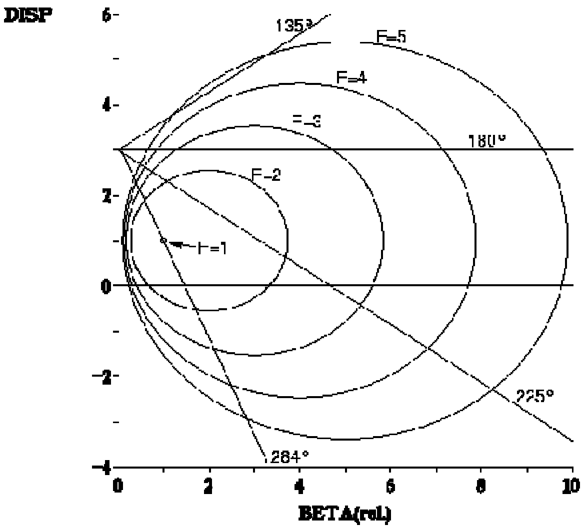
$$f_2 = \frac{8l_2\eta_s\rho}{-4l_1L_d - L_d^2 + 8\eta_s\rho - 8\eta_{x,cd}\rho}$$

$$\eta_s = f(l_1, l_2, l_3, L_d, \rho, \eta_{x,cd}, \beta_{x,cd})$$

(l_1, l_2, l_3: Drift lengths; L_d, ρ: Dipole length and bend. angle; $\eta_{x,cd}, \beta_{x,cd}$: Initial optics functions)

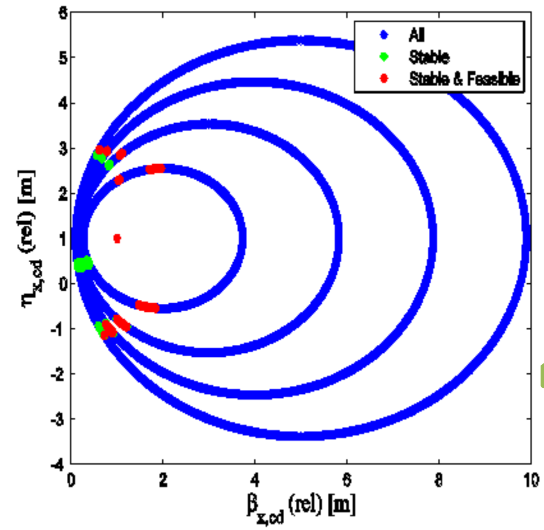
- ✓ Multi-parametric space describing all the cell properties (optical and geometrical)
- ✓ Stability and feasibility criteria can be applied for both planes
- ✓ The cell can be optimized according to the requirements of the design

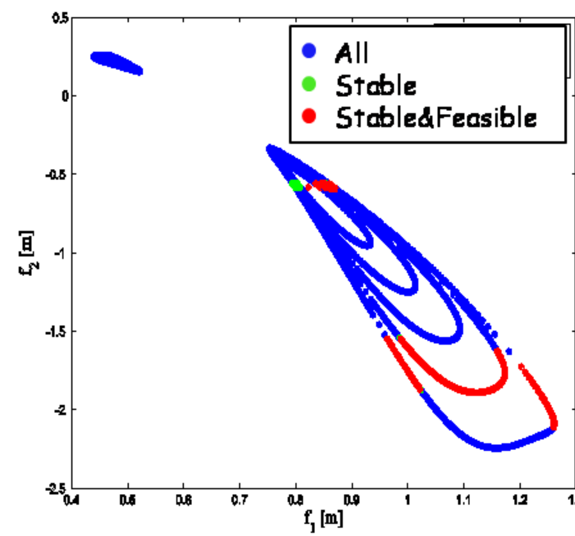
Analytical solution for the TME cell



Andrea Streun
http://slsbd.psi.ch/pub/cas/cas/node41.html

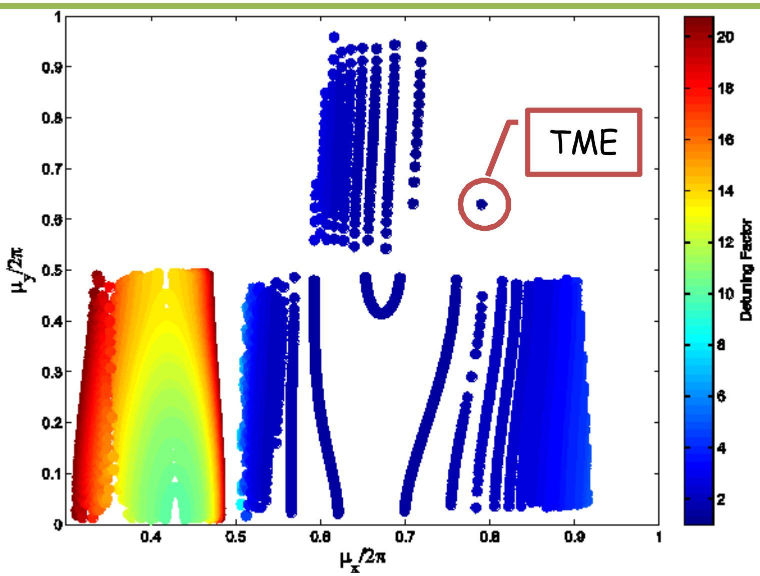
Applying the analytical parameterization with the stability and feasibility constraints



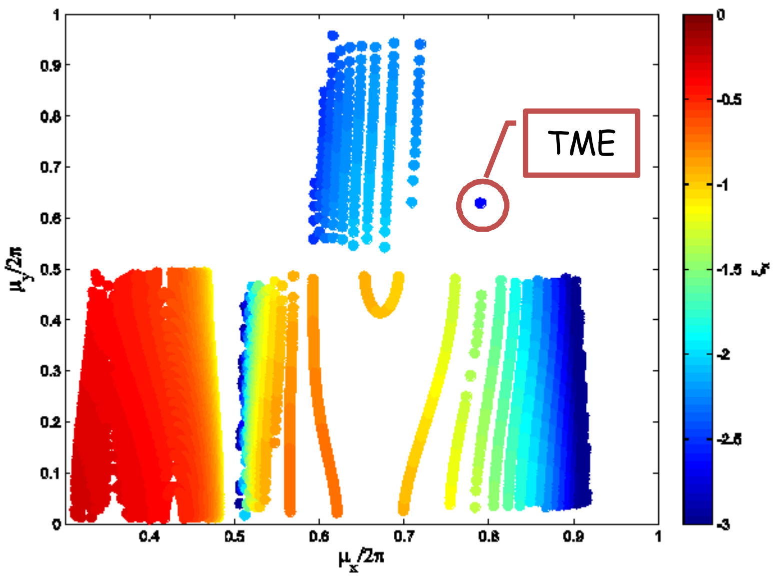


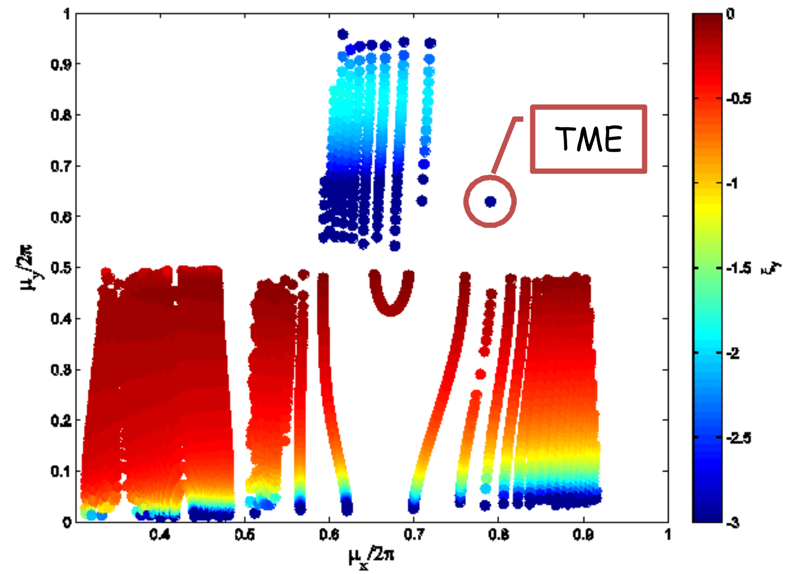
- ✓ Only one pair of values for the initial optics functions and the quad strengths can achieve the TME
- ✓ Several pair of values for larger emittances, but only small fraction of them stable.
- ✓ Similar plots for all the parameters

Analytical solution for the TME cell

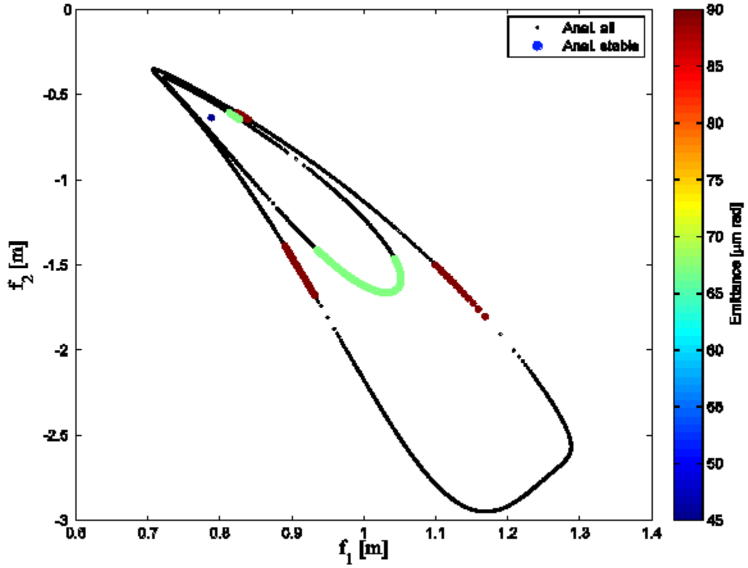


- Detuning factor (up) and chromaticities (down) as a function of the horizontal and vertical phase advances.
- Large detuning factor and small phase advances needed for small chromaticities

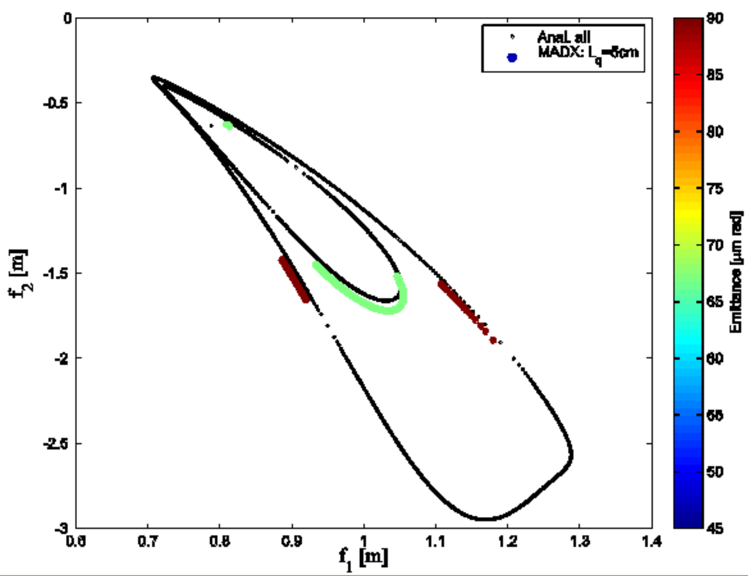


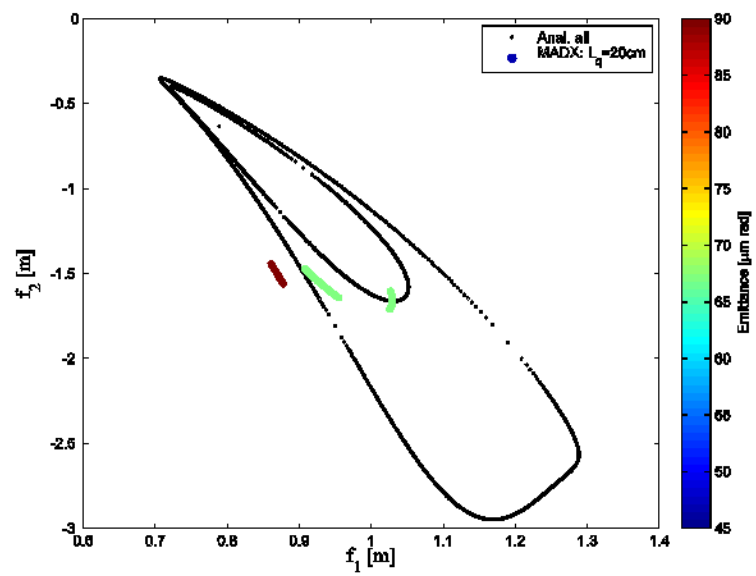


Comparison with MADX



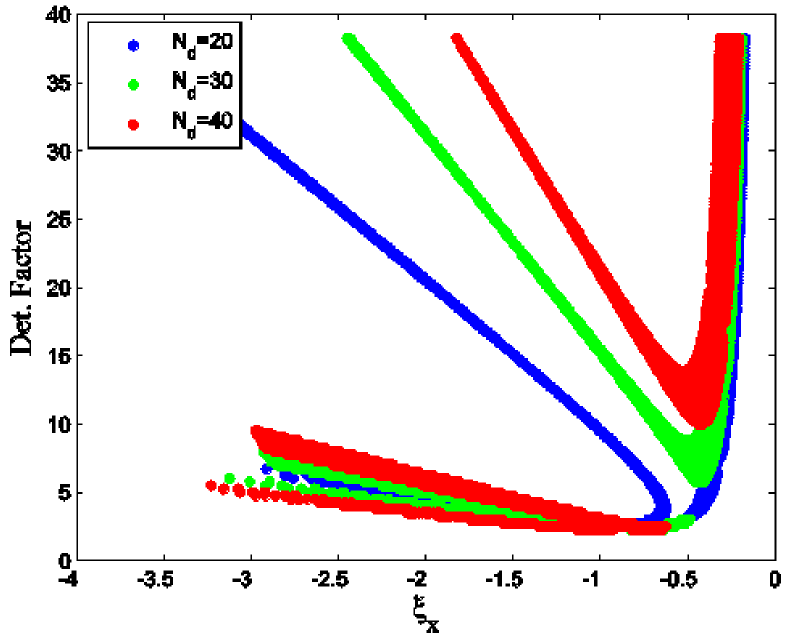
Emittance parameterization curves for TME, 1.5 TME and 2 TME. With black are shown all the solutions while the colormaps show the stable solutions of the analytical solution (up) and the results from MADX for quad. lengths l_q=5 cm (down-left) and l_q=20 cm (down-right)





PDR Dynamic Aperture optimization

Arc optimization



Detuning factor: the ratio of the achieved emittance and the theoretical minimum emittance.

- The current design is focused on the Dynamic Aperture (DA) optimization
- Minimum chromaticity, ξ, required in order to minimize the sextupole strengths for the natural chromaticity correction
- A detuning factor greater than 2 needed for minimum ξ_x
- Scanning on the drift space ➔ Optimal drifts for minimum chromaticity and compact enough cell:

$$l_1 = 0.9,\ l_2 = 0.6,\ l_3 = 0.5$$

Nonlinear optimization considerations

- Reference: "Resonance free lattices for A.G machines", A. Verdier, PAC99
- The choice of phase advances per cell, crucial for the minimization of the resonance driving terms
- The resonance driving term [at first order] associated with the ensemble of N_c cells vanishes if the resonance amplification factor is zero:

$$N_c(n_x\mu_{x,c} + n_y\mu_{y,c}) = 2k\pi$$
$$n_x\mu_{x,c} + n_y\mu_{y,c} \neq 2k'\pi$$

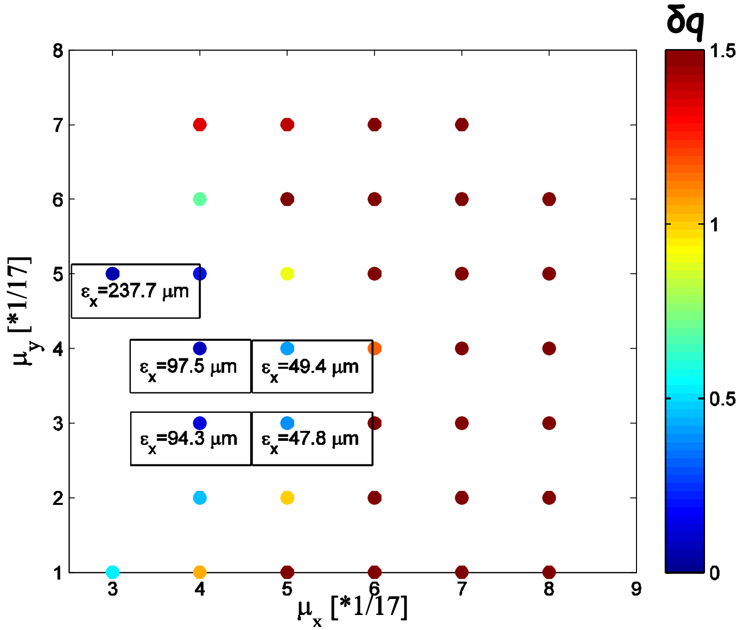
"A part of a circular machine containing N_c identical cells will not contribute to the excitation of any non-linear resonance, except those defined by $n_x+n_y = 2k_3\pi$, if the phase advances per cell satisfy the conditions :

- $N_c\mu_{x,c} = 2k_1\pi$ (cancellation of one-D horizontal non-linear resonances)
- $N_c\mu_{y,c} = 2k_2\pi$ (cancellation of one-D vertical nonlinear resonances)
- k_1 k_2 and k_3 being any integers."

Non linear optimization considerations

- For prime numbers of N_c, less resonances satisfying both conditions simultaneously.
- In our case N_c is the number of TME cells per arc.
- Some convenient numbers for N_c are 11, 13, 17 (26, 30 and 38 dipoles in the ring respectively, including the dispersion suppressors' last dipole).
- The largest number of cells is better for increasing the detuning factor and the reduction of largest number of resonance driving terms.
- A numerical scan indeed showed that the optimal behavior is achieved for the case of 17 TME / arc.

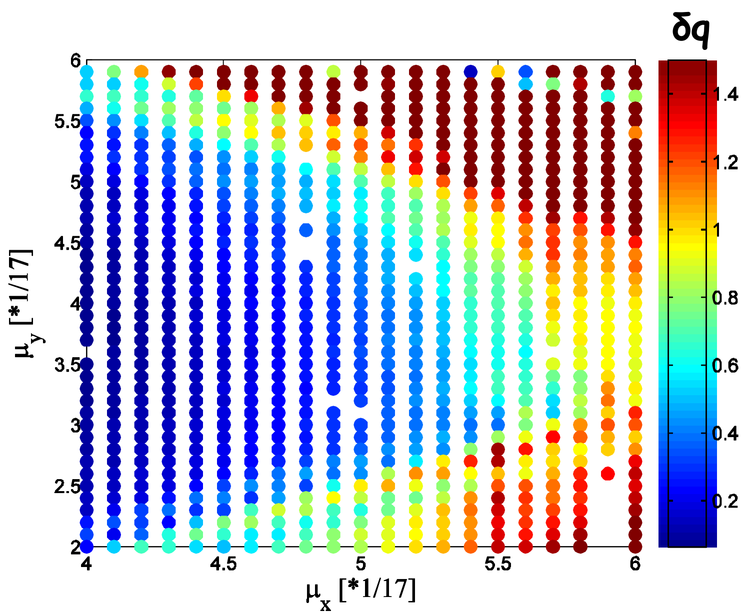
Non linear optimization considerations



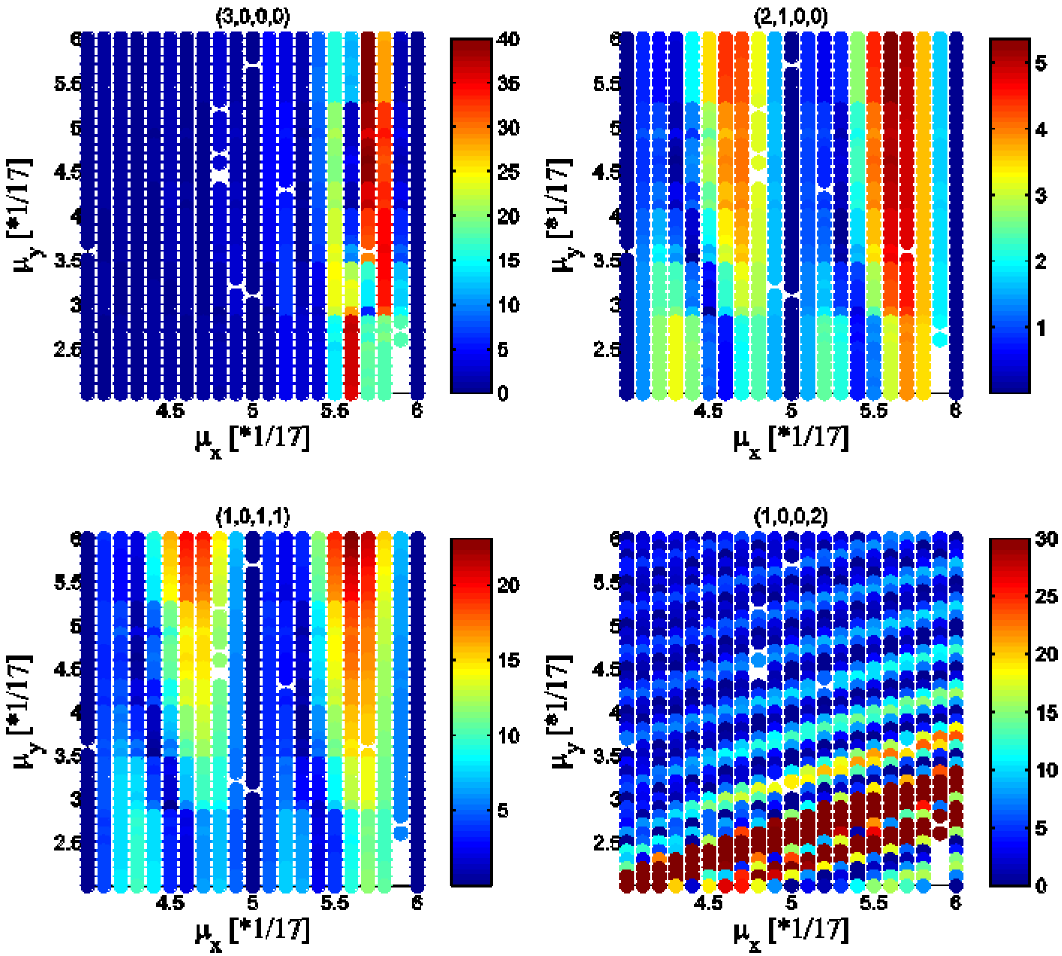
- Phase advance scan in horizontal μ_x and vertical μ_y phase advances for μ_x and μ_y integer multiples of 1/17.
- Different colors indicate the **first order tune shift with amplitude, δq,** levels where $\delta q=\sqrt{(\delta q_x^2+\delta q_y^2)}$

✓ Optimal pair of values: $(\mu_x,\mu_y)=(0.2941=5/17,0.1765=3/17)$

- Finer phase advance scan around the chosen values
- The tune shift with amplitude is getting larger as μ_x is getting large
- The pair originally chosen is the optimum.

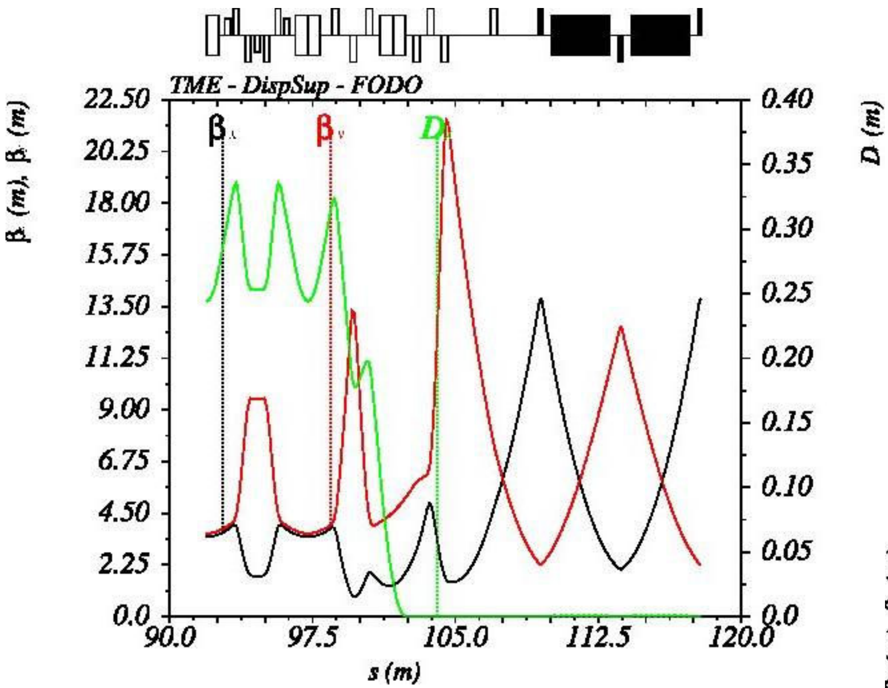


Non linear optimization considerations

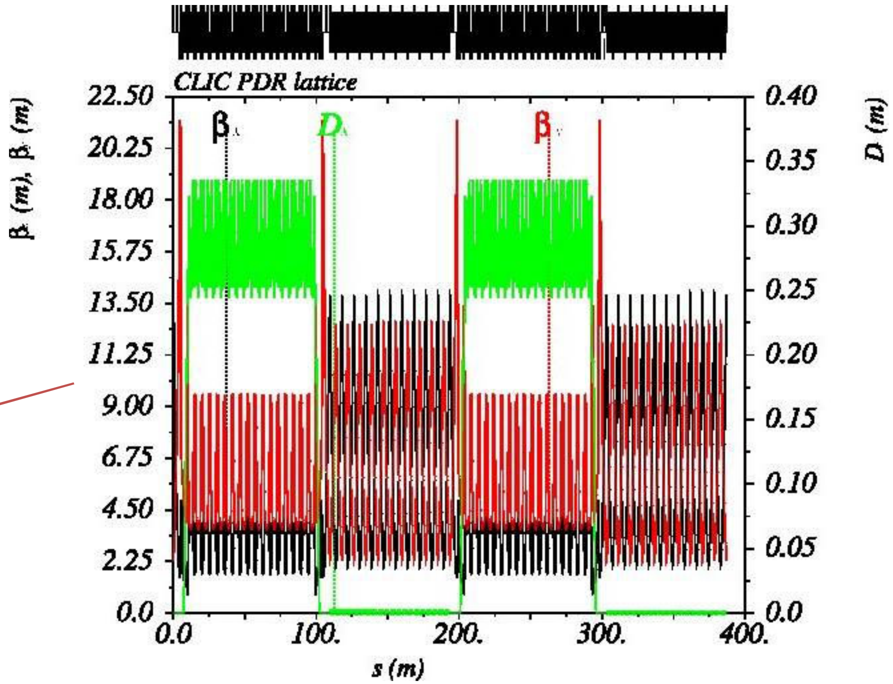


3rd order Resonance driving terms amplitudes as a function of the horizontal and vertical phase advances for the different components of the third order resonance.

Optics of the ring

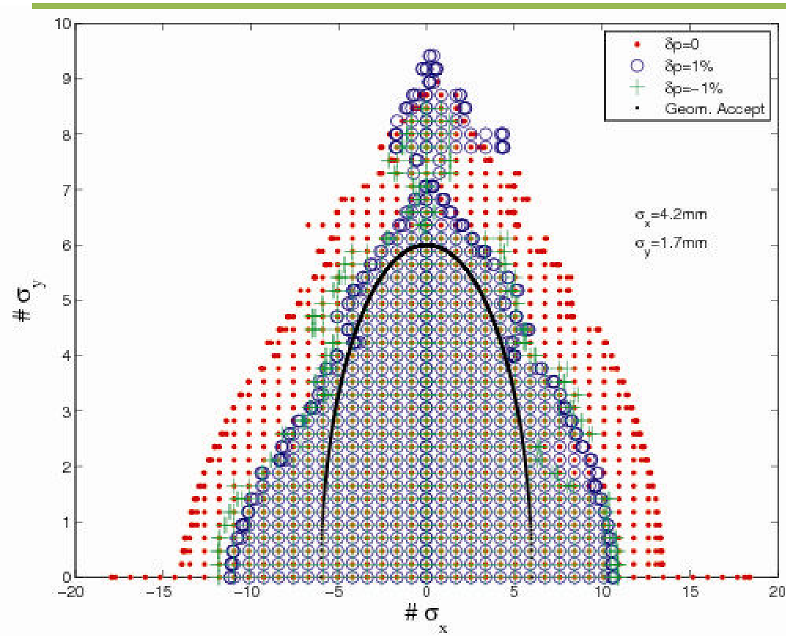


Optics of the TME arc cell, the dispersion suppressor – beta matching cell and the FODO straight section cell



Optics of the current design of the PDR.

Dynamic Aperture

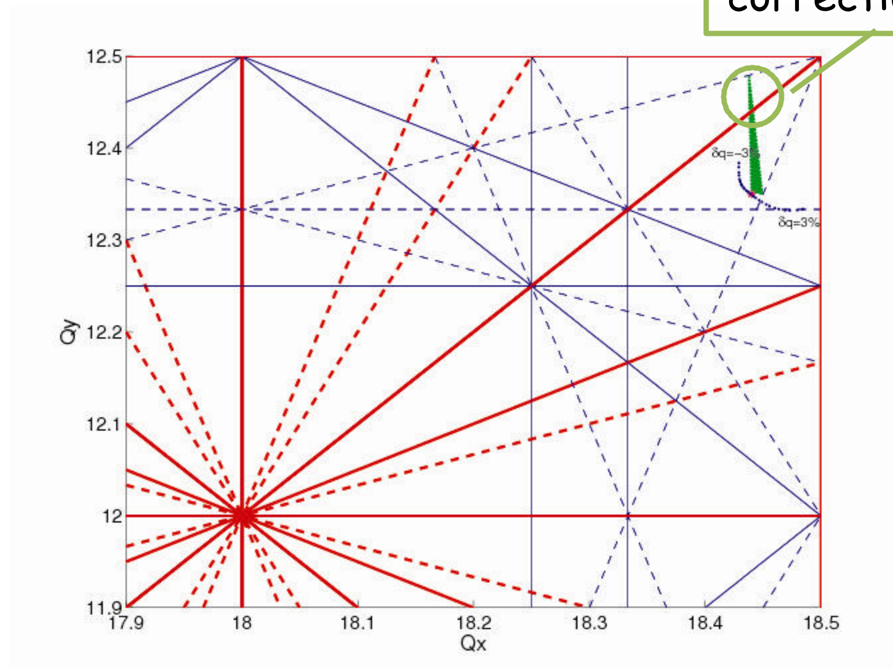


ptc-track (MADX) for 1000 turns

On and off-momentum dynamic aperture for δp = 0 (red), 1% (green) and -1% (blue) . The geometrical acceptance is also shown.

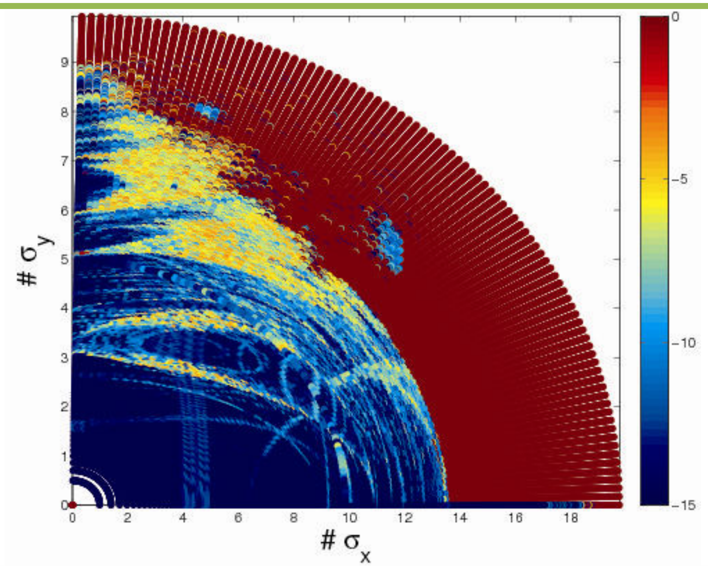
$$A = \sqrt{2\beta\epsilon_{edge}} + \eta\delta$$

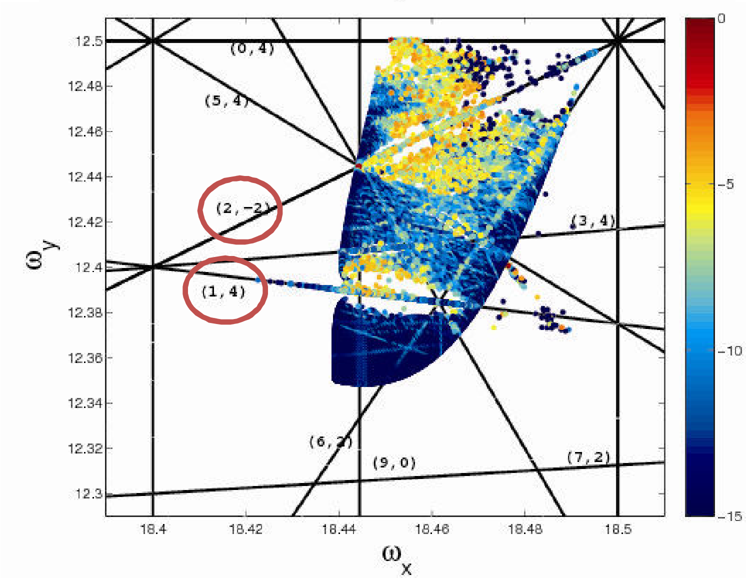
Octupole correction?



The working point in tune space (blue) for momentum deviations from -3% to 3% and the first order tune shift with amplitude (green) at 6 $\sigma_{x,y}$. The on momentum working point is (18.44, 12.35)

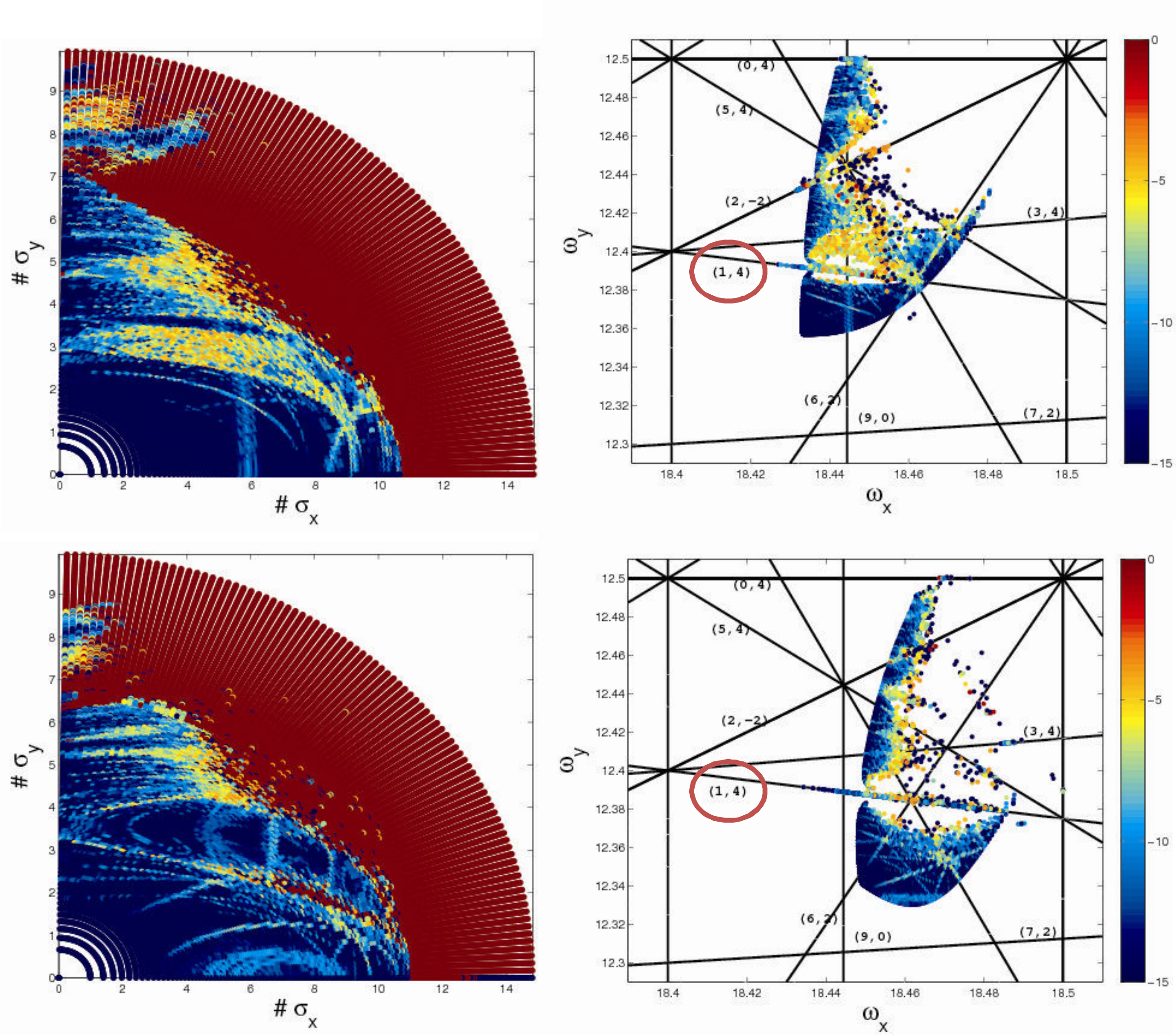
Frequency maps





- Frequency maps produced for 1056-turn ptc tracking, including only sextupoles and fringe-fields (perfect lattice) ($\delta p=0$)
- It reveals that the main limitation of the (vertical) dynamic aperture is a 5^{th} order resonance (which is not eliminated by the phase advance choice for resonance free lattice)
- For higher vertical amplitudes, limited by (2,-2) (quadrupole fringe fields?)
- Other higher order resonances visible
- Vertical tune-shift is large whereas horizontal is small, maybe a second linear optics iteration for equilibrating the two is needed
- Lowering the vertical tune may help (skew sextupole resonance?)

Frequency maps



- Frequency maps produced for 1056-turn ptc tracking, including only sextupoles and fringe-fields (perfect lattice) (δp=1% (up) and δp=-1% (down))
- Main resonances the same with the case of δp=0.
- The 5th order resonance the main limitation.

Table of parameters

Parameters, Symbol [Unit]	Value
Energy, E_n [GeV]	2.86
Circumference, C [m]	386.95
Bunches per train, N_b	312
Bunch population [10^9]	4.2
Bunch spacing, τ_b [ns]	0.5
Basic cell type	TME
Number of dipoles, N_d	38
Dipole Field, B_a [T]	1.2
Tunes (hor./ver./sync.),($Q_x/Q_y/Q_s$)	18.44/12.35/0.07
Nat. chromaticity (hor./vert.),(ξ_x/ξ_y)	-18.99/-22.85
Norm. Hor. Emit.,$\gamma\varepsilon_0$[mm mrad]	45.87
Damping times, ($\tau_x/\tau_y/\tau_\varepsilon$),[ms]	2.3/2.29/1.14
Mom. Compaction Factor, α_c [10^{-3}]	3.72
RF Voltage, V_{rf} [MV]	10
RF acceptance, ε_{rf} [%]	1.12
RF frequency, f_{rf} [GHz]	2
Harmonic Number, h	2652
Equil. energy spread (rms), σ_δ [%]	0.1
Equil. bunch length (rms), σ_s [mm]	3.2
Number of wigglers, N_{wig}	40
Wiggler peak field, B_w [T]	1.7
Wiggler length, L_{wig} [m]	3
Wiggler period, λ_w [cm]	30

- Table of parameters for the current PDR design.
- Emittance achieved without wigglers:
  $\varepsilon_{x,arc}$ = 197.087 μm
  F_w ✍ 4
- Detuning Factor:
  F_{TME} ✍ 30

Conclusions

- An analytical solution for the TME cell can be useful for the lattice optimization.
- The “resonance free lattice” concept can be very efficient for first order non linear optimization.
- The present design achieves the CLIC base line configuration requirements (no polarized positrons) for the output parameters and an adequate (but tight) DA.
- A working point analysis and optimization is in progress.
- A necessary final step of the non-linear optimization, is the inclusion of errors in the main magnets and wigglers.
- Further non-linear optimization studies needed
  - Families of correcting sextupoles and/or octupoles

Thanks for your attention!!!

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