Optics design considerations for minimum emittance lattices

Application to CLIC pre-damping rings

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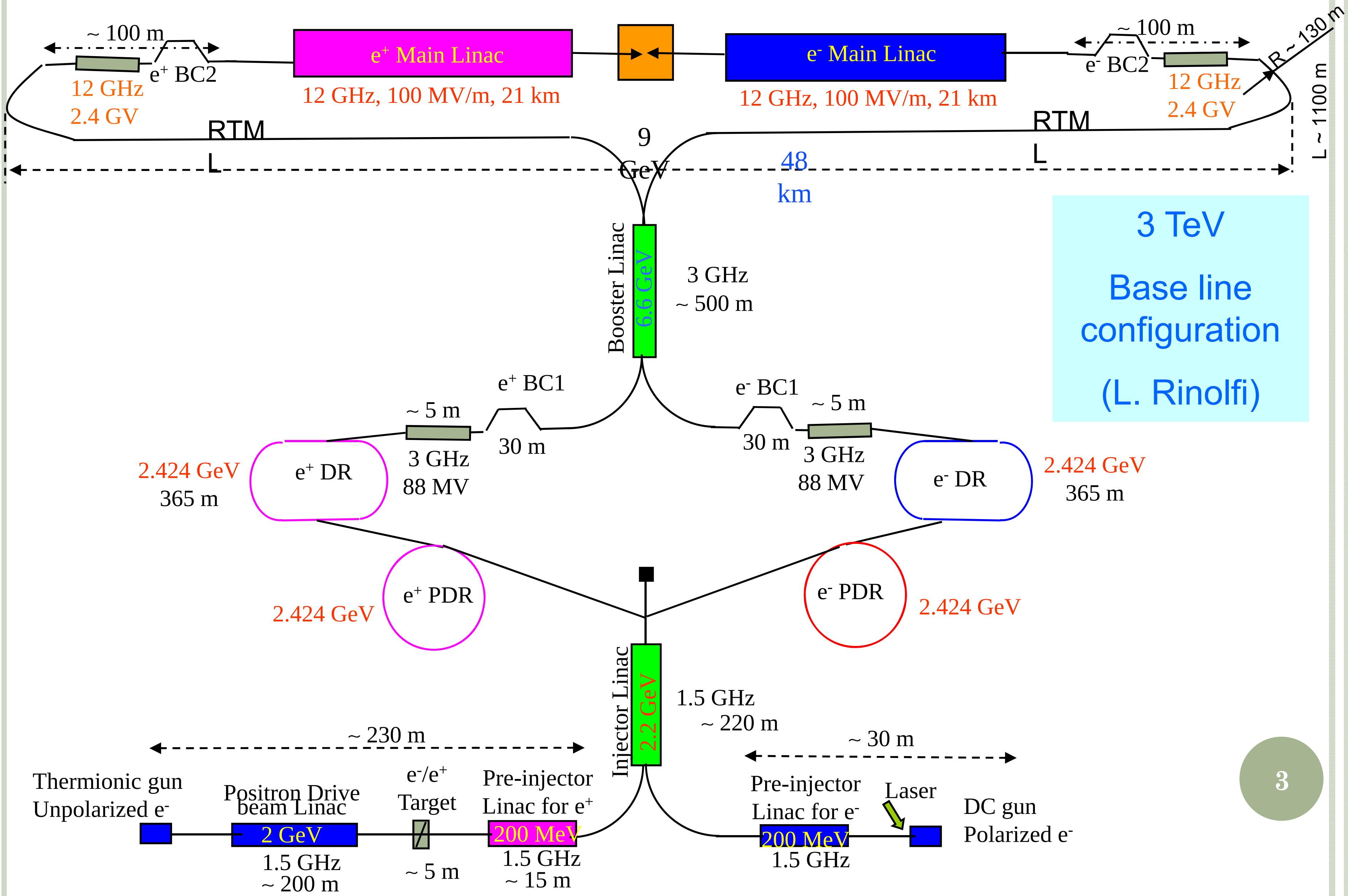
Outline

- *CLIC PDR*
  - *PDR Parameters*
- *Analytical Solution for the TME cells*
  - *TME cells*
  - *Constraints*
  - *Stability criteria*
  - *Parameterization*
- *Application to the CLIC PDRs*

CLIC INJECTOR COMPLEX



CLIC Pre-damping Rings

- The pre-damping rings (PDR) are an essential part of the CLIC injector complex.
- Most critical the e^+ PDR
  - Injected e^+ emittance ~ 2 orders of magnitude larger than for e^-, i.e. aperture limited if injected directly into DR
- PDR for e^- beam necessary as well
  - A "zero current" linac e^- beam (no IBS) would need ~ 17ms to reach equilibrium in DR, (very close to repetition time of 20ms)
- CLIC PDR parameters at extraction close to those of NLC PDR

(I. Raichel and A. Wolski, EPAC04)

PDR Extracted Parameters	CLIC	NLC
Energy [GeV]	2.424	1.98
Bunch population [10^9]	4.1-4.4	7.5
Bunch length [mm]	10	5.1
Energy Spread [%]	0.5	0.09
Long. emittance [eV.m]	121000	9000
Hor. Norm. emittance [nm]	63000	46000
Ver. Norm. emittance [nm]	1500	4600

Injected Parameters	e^-	e^+
Bunch population [10^9]	4.4	6.4
Bunch length [mm]	1	5
Energy Spread [%]	0.1	2.7
Long. emittance [eV.m]	2400	181000
Hor.,Ver Norm. emittance [nm]	100 x 10^3	9.3 x10^6

Analytical Solution For The TME Cells

THEORETICAL MINIMUM EMITTANCE CELL

- The TME cell is the most compact and efficient module for getting the lowest possible emittance.

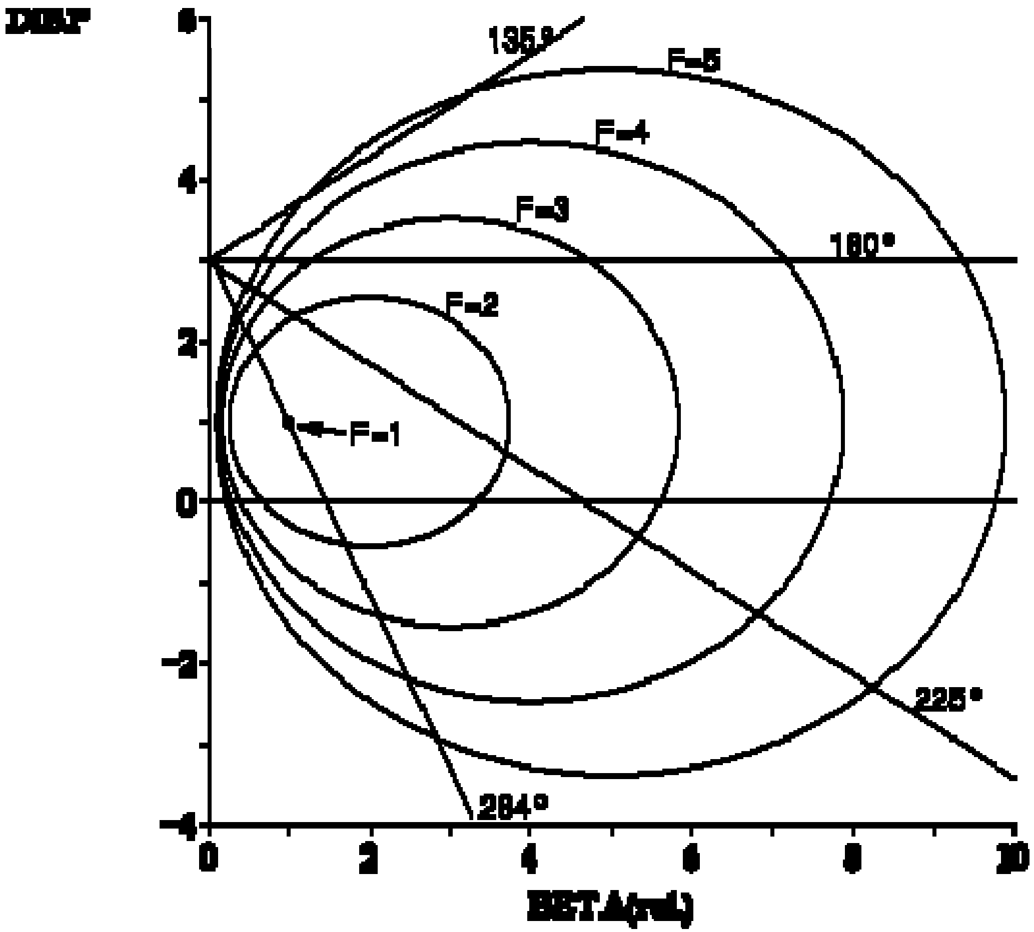
- The beta function and the dispersion function have minima in the center of the bending magnet.

$$\beta_{cd} = \frac{L_d}{2\sqrt{15}}, \quad \eta_{cd} = \frac{\theta L_d}{24}$$

- The Normalized TME is : $\epsilon_{TME} = F C_q \gamma_1^3 \theta^3$

where $F = \frac{1}{12\sqrt{15}J_x}$, $C_q = 3.84 \cdot 10^{-3}$ m and $J_x \approx 1$ in the case of isomagnetic, separated function ring

Theoretical Minimum Emittance Cell

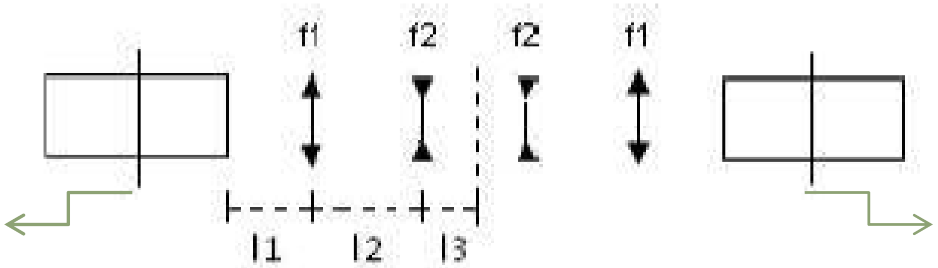


Andrea Streun
http://slsbd.psi.ch/pub/cas/cas/node41.html

- TME cells provide 3 times lower horizontal emittance than DBA cells.
- A unique pair of (η,β) values can achieve the Theoretical Minimum Emittance.
- Higher emittance values can be achieved by several pairs of (η,β)

ANALYTICAL SOLUTION CONSIDERATIONS

$$\beta_{cd} = \frac{L_d}{2\sqrt{15}} \qquad \eta_{cd} = \frac{\theta L_d}{24}$$



$$\beta_{cd} = \frac{L_d}{2\sqrt{15}} \qquad \eta_{cd} = \frac{\theta L_d}{24}$$

- For achieving a certain emittance in a standard TME cell, there are **two** independent horizontal optical parameters to be fixed at the entrance (and exit) of the cell
- **Two** quadrupole families are needed to achieve this
  - The vertical plane is not controlled and, for this, additional quadrupoles may be needed
- The quadrupole strengths can be computed analytically using thin lens approximation
- Parameterization of the quadrupole strengths and optics solutions with respect to the drift lengths (for constant emittance) and with the emittance (for constant drift lengths)

Solutions And Constraints

- The general solutions for the focusing strengths are:

$$f_1 = \frac{L_d(2(l_1 + l_2) + L_d) + 2(-\eta_s + \eta_x^{cd})\rho}{l_2(2l_1L_d + L_d^2 + 2\eta_x^{cd}\rho)}$$

$$f_2 = \frac{2l_1L_d + L_d^2 - 2\eta_s\rho + 2\eta_x^{cd}\rho}{2l_2\eta_s\rho}$$

- η_s is the dispersion function in the center of the cell and it is a complicated function of the horizontal beta and dispersion at the center of the dipole and the drift lengths.
  - There are 2 solutions for $\boldsymbol{\eta_s}$
  - One of them results in horizontal focusing for both $\boldsymbol{f_1}$ and $\boldsymbol{f_2}$
  - This solution is unstable in the vertical plane and is rejected

STABILITY CRITERIA

- Trace(M)=2 cosμ

  where **M** is the transfer matrix of all the cell and

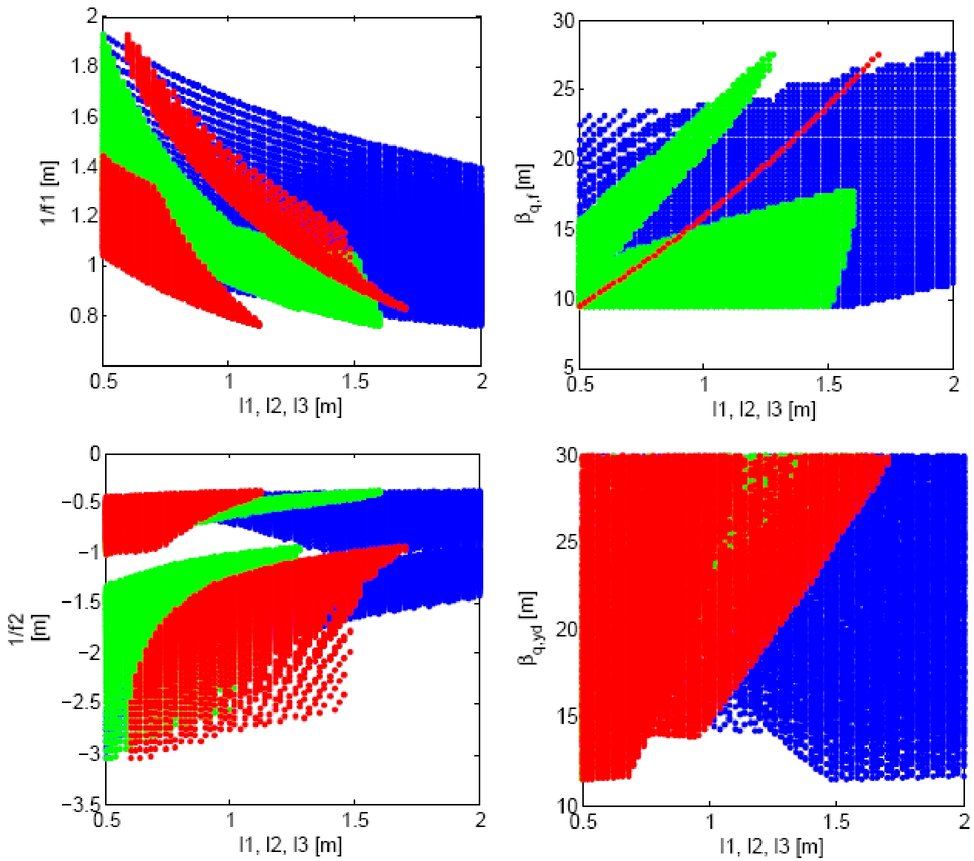
  μ the phase advance per cell.

- The beta functions at the quads have values smaller than 30m

All the optics functions are thus uniquely determined for both planes and can be optimized by varying the drifts

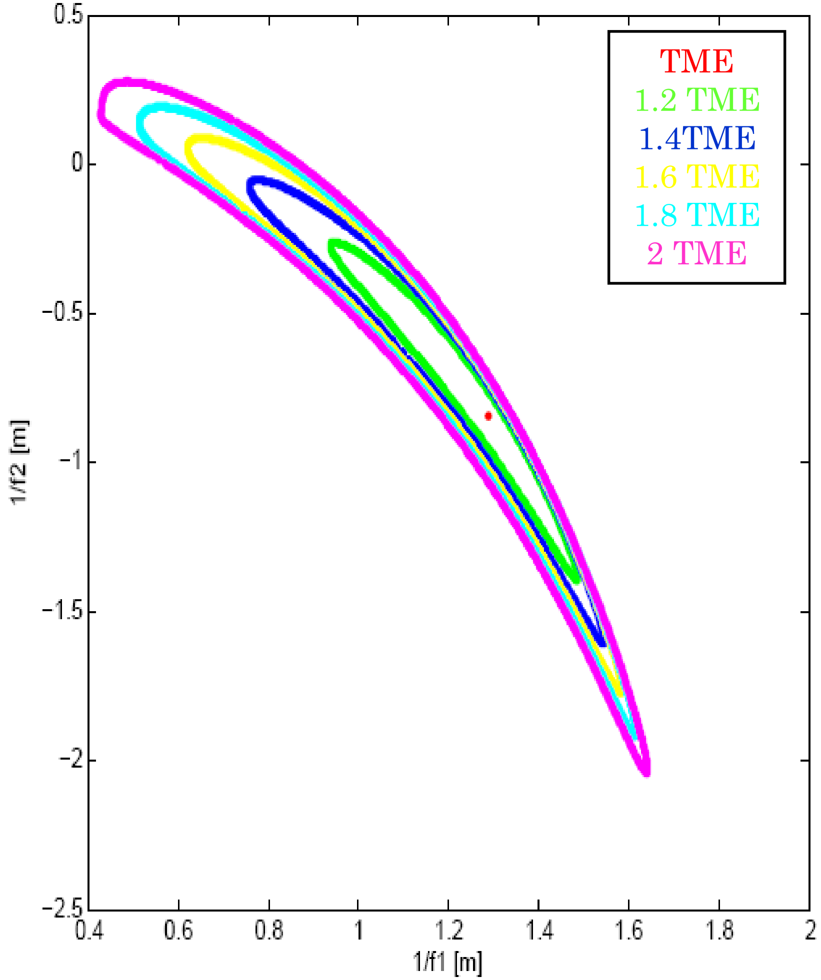
DRIFT LENGTHS PARAMETERIZATION

- Minimum number of dipoles (18) to achieve target PDR emittance with a TME cell (with a 30% margin)
- A constant emittance is first considered (the TME one)
- Focusing strengths and beta functions on the quads, for l_1, l_2, l_3 (between 0.5 and 2m).



- No restrictions for l_3.
- l_1 is bounded to values smaller than 1.7 m and l_2 to values smaller than 1.6 m.
- The limits are set by the constraint in the beta functions (<30m)

EMITTANCE PARAMETERIZATION



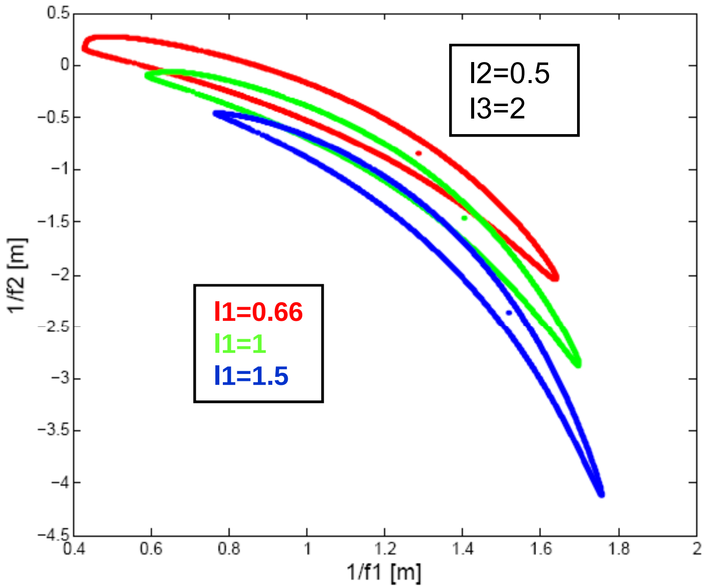
A possible configuration for the l_1, l_2, l_3 for low chromaticity (and small focusing strengths) at both the planes is chosen for the TME:

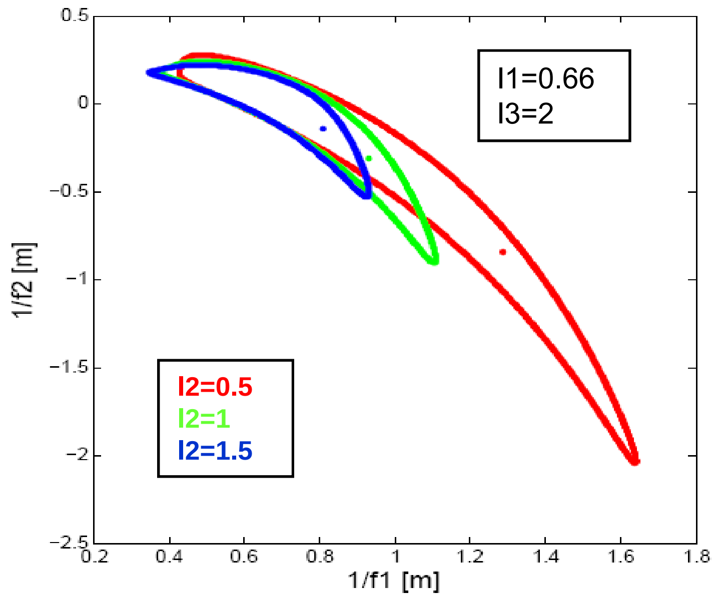
$$l_1 = 0.66,\ l_2 = 0.5,\ l_3 = 2$$

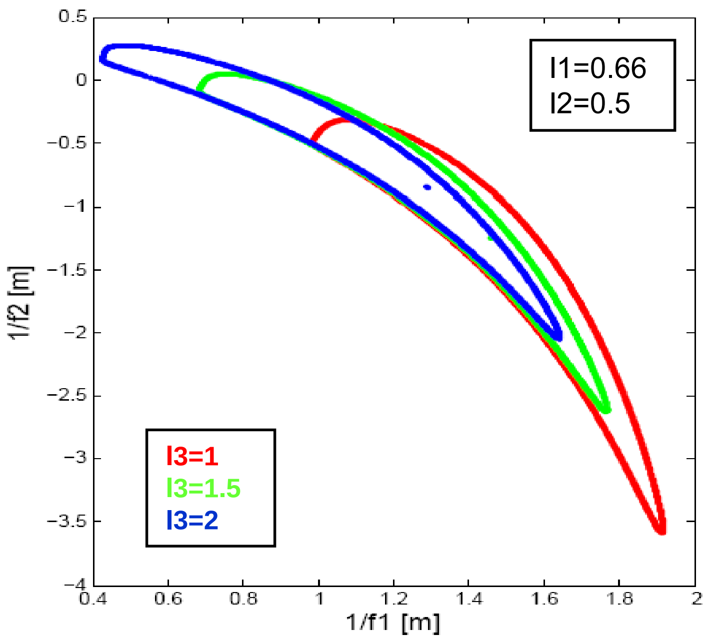
The choice of the drift lengths can be done according to what we want to minimize or succeed.

The focal strengths can be now parameterized with respect to the achievable emittance

- These solutions do not necessarily provide stability in the vertical plane

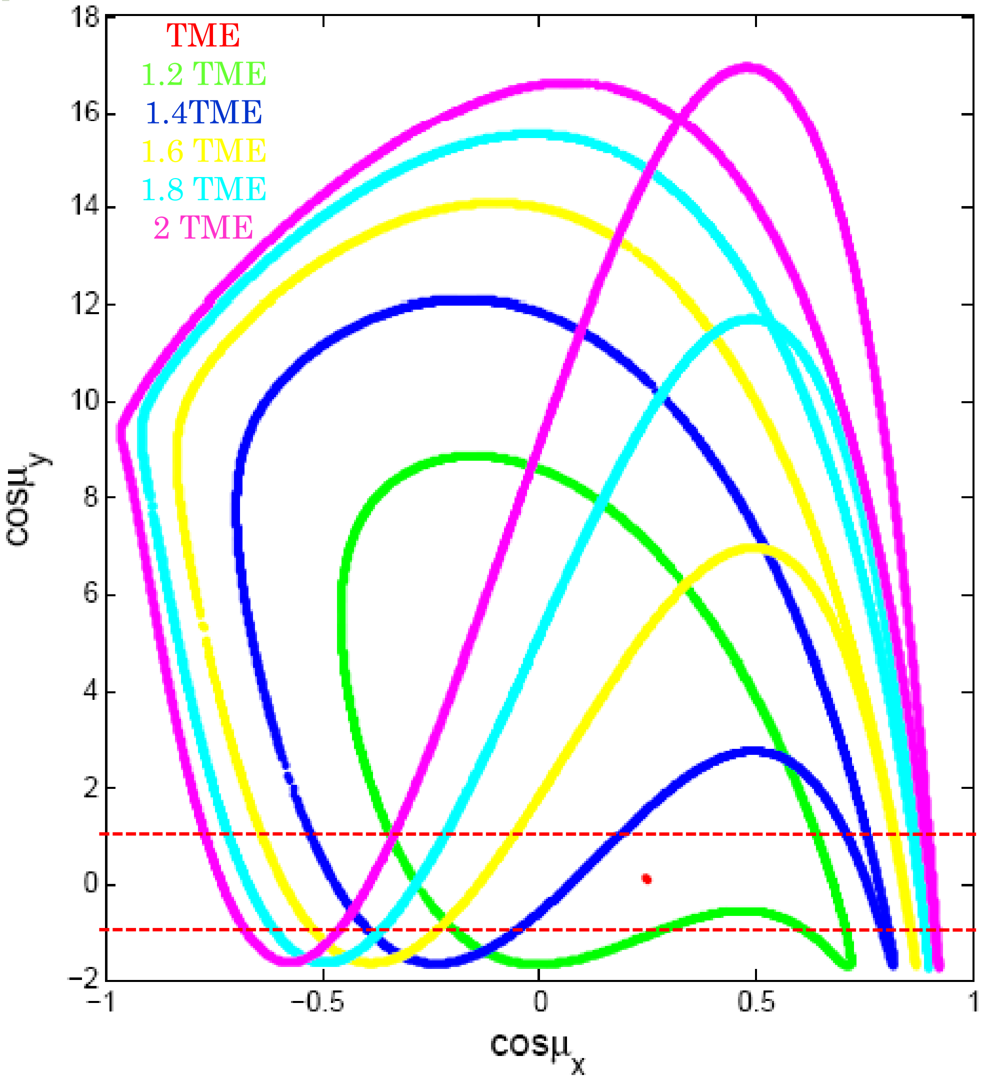






- Solution dependence on each drift length.
  - For higher values of l_1 greater values of $1/f_1$ and $1/f_2$ are needed in order to achieve the TME
  - For higher values of l_2 or l_3 smaller values of $1/f_1$ and $1/f_2$ are needed in order to achieve the TME

STABILITY REGIONS



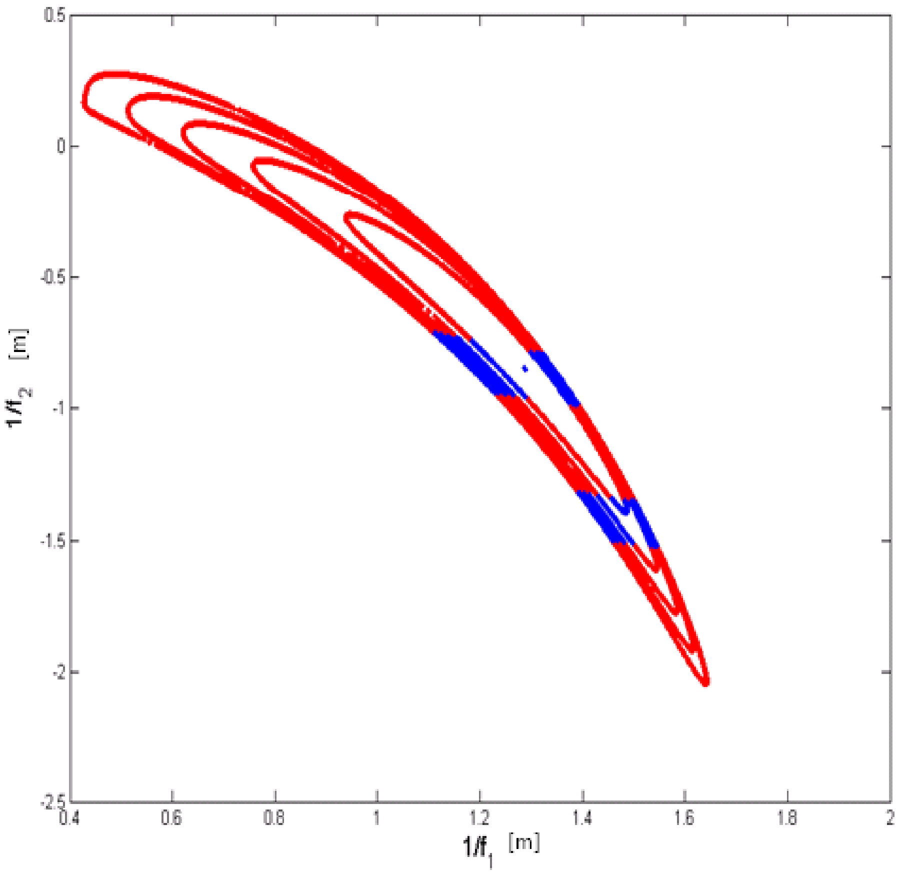
- ❑ Phase advance curves in the horizontal and vertical plane for the solutions

- There is always stability in the horizontal plane (by construction) but only very few solutions are stable in the vertical plane

- The horizontal phase advance for the TME is 284.5 ° and is independent of the cell details

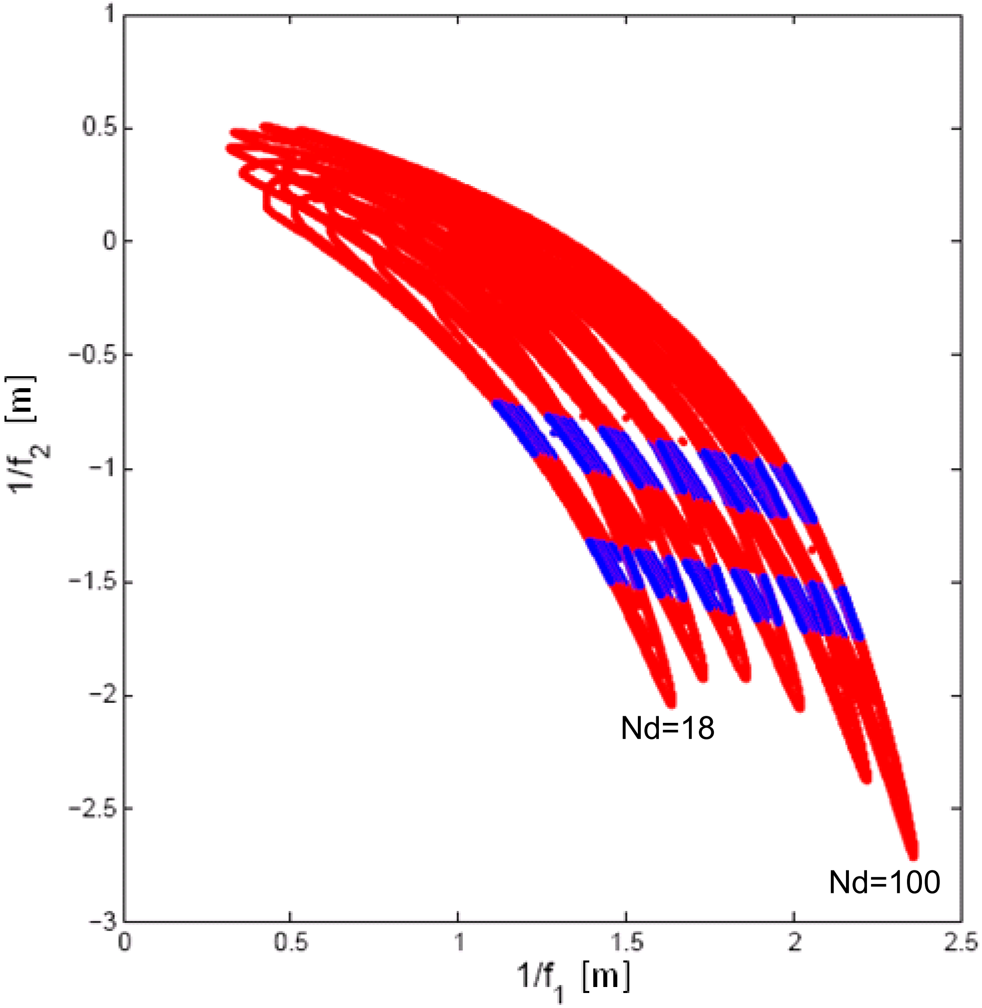
- The vertical phase advance depends on the drift lengths and for this cell is 277.16 °

Stability Regions



- Applying also the stability criterion for the vertical plane in all the solutions, we get the stable solutions for both the planes.
- Two bands of solutions
- The stability region for f_2 almost constant for all the values of emittances.

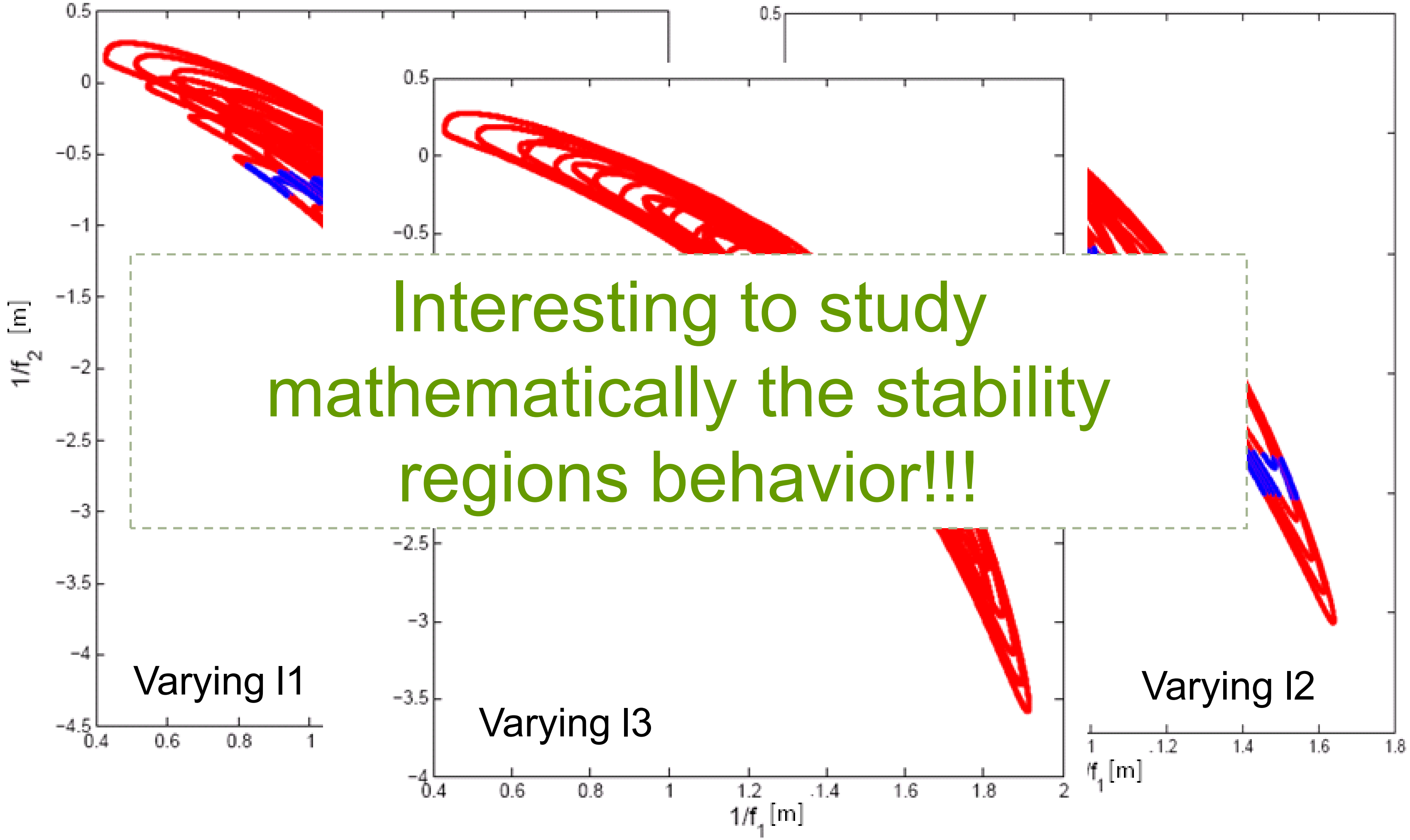
Stability Regions



- The stability regions are studied for different values of TME (increasing the number of the dipoles, the TME is reduced)
- The stability region for f_2 is almost the same in all cases.

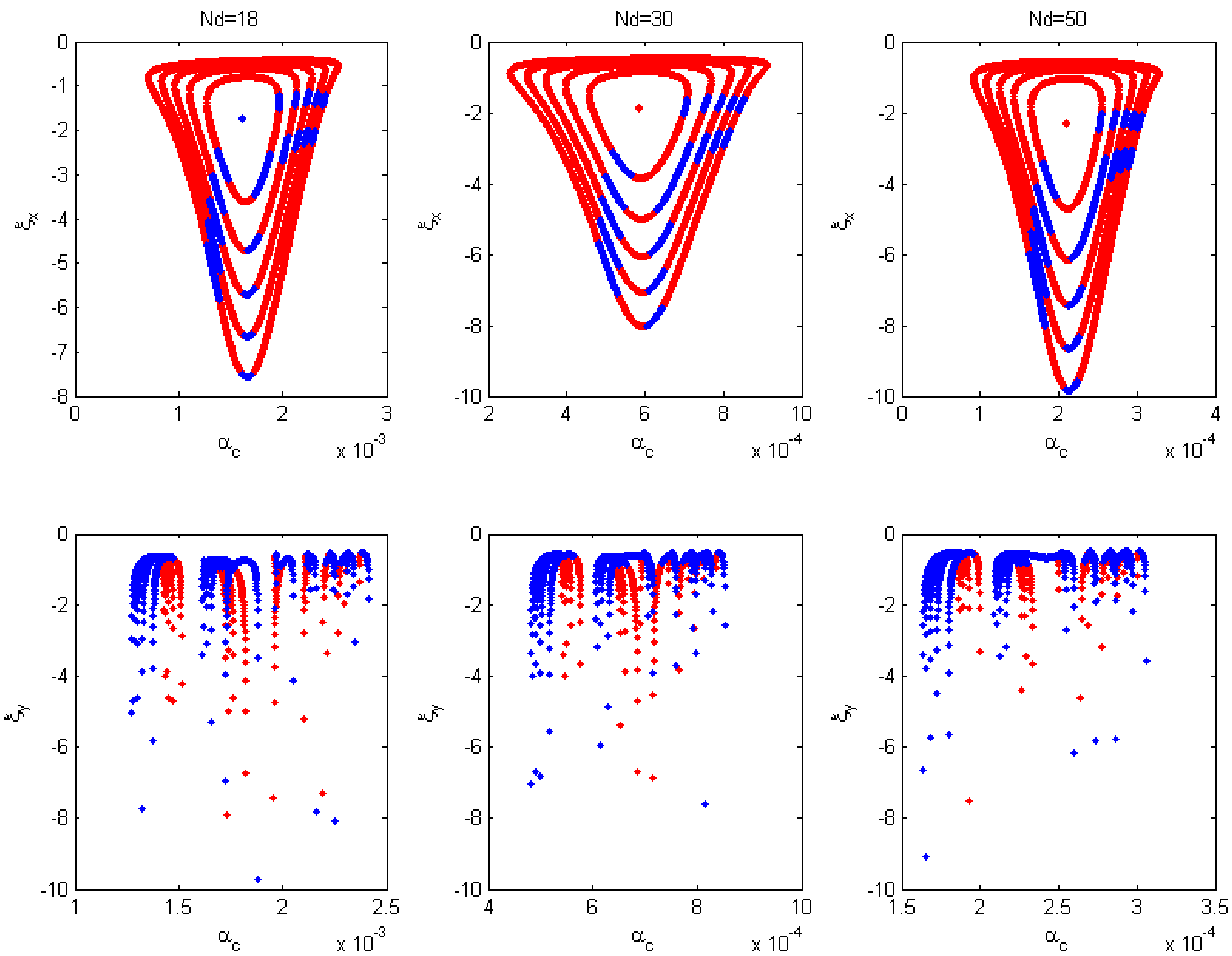
Stability Regions

- The stability region dependence on each drift length



Interesting to study mathematically the stability regions behavior!!!

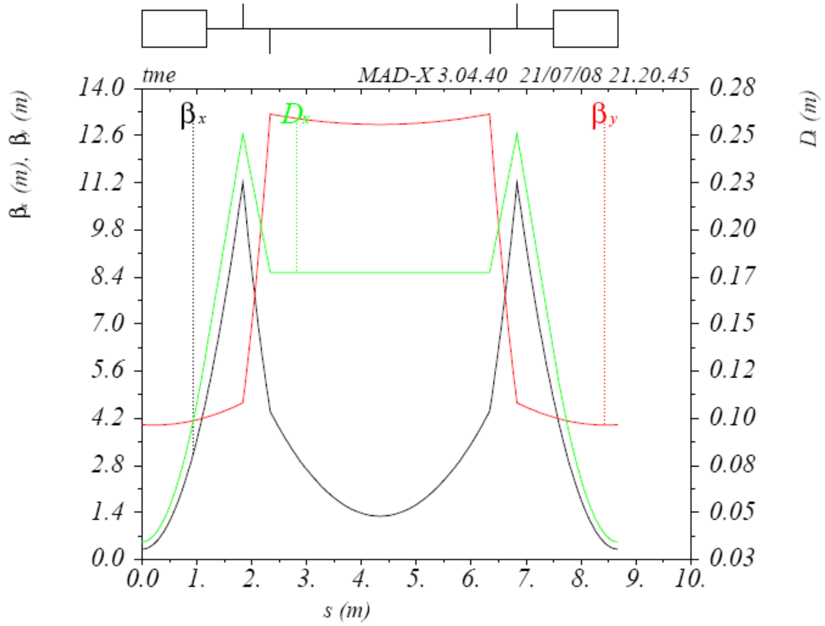
Momentum Compaction factor And Chromaticity Minimization

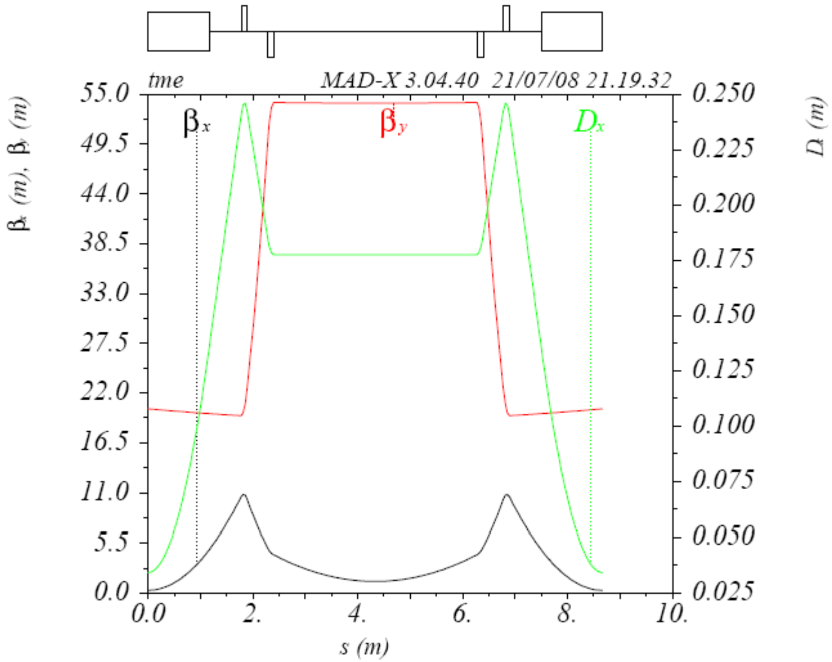


- Same color convention with the previous plots.
- The α_c factor is decreased as the number of cells is increased.
- For smaller values of the α_c, higher values of horizontal chromaticities!!!!

Comparison With MADX

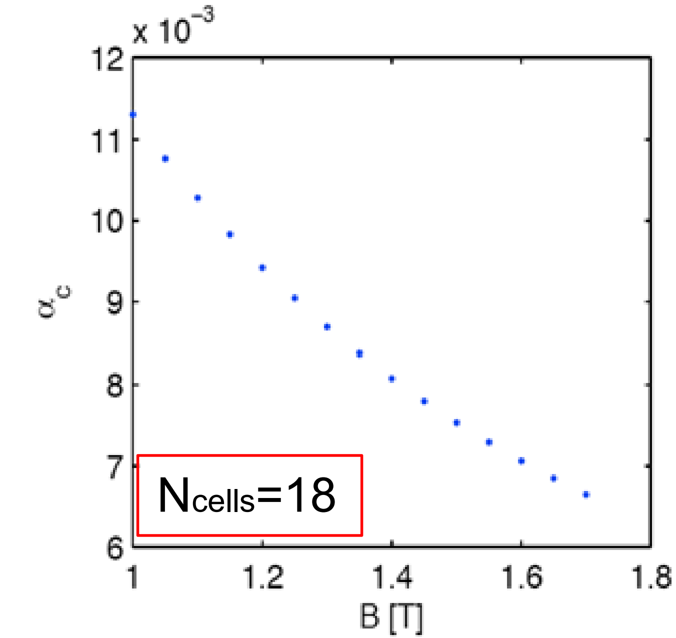
- The solution is also applied to MADX
- Very good agreement in the case of the thin lens approximation
- Growing the quadrupole length the beta function at the vertical plane is growing rapidly
- The convergence of the solution becomes quite difficult
- However, the solution gives a very good starting point!!

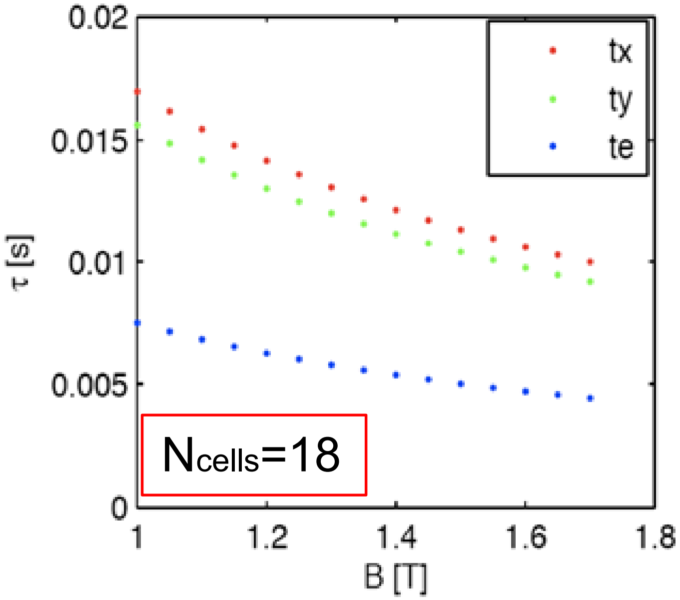




APPLICATION TO THE CLIC PRE DAMPING RINGS

PDR DESIGN CHALLENGES





- **Momentum compaction factor (up)**

$$\alpha_c = \frac{1}{C}\sum_i \langle D \rangle_i \, \theta_i = \frac{1}{C} N_d \left(2\eta_{cd} + 7\,\frac{L_d^{\,2}}{12\,\rho} \right) \frac{L_d}{\rho}$$

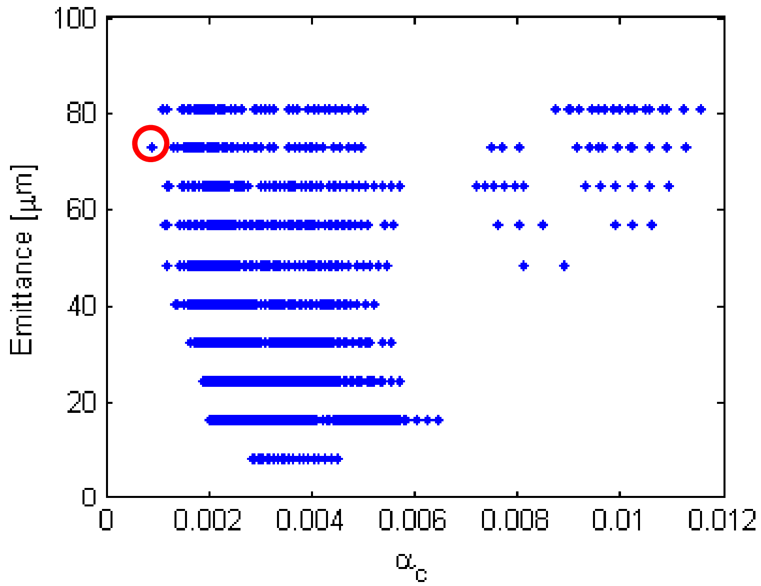
$$\alpha_{c,TME} = \frac{12\,\theta^3 \rho}{C}$$

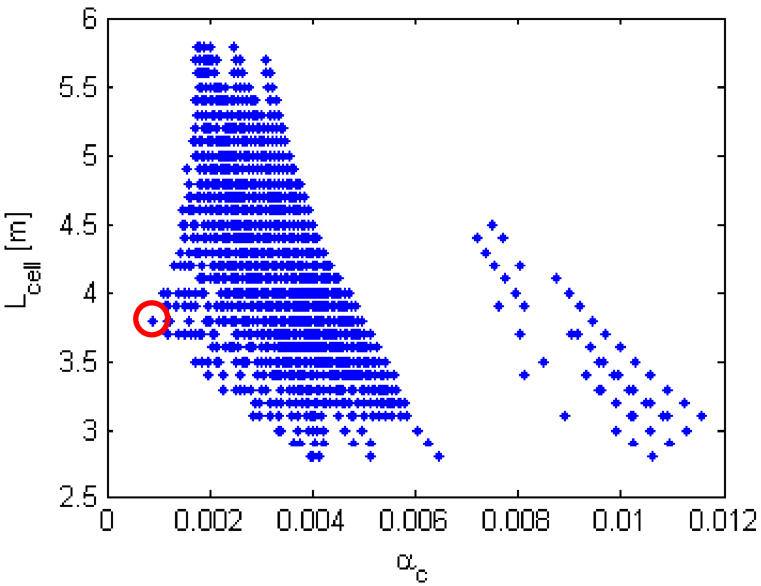
- For increasing momentum acceptance:

$$\frac{\delta p}{p} = \sqrt{\frac{V_{rf}\left(2\cos\varphi_s + (2\varphi_s - \pi)\sin\varphi_s\right)}{\pi h |\alpha_c| E_n}}$$

- **Damping times (down)** quite long:
  - Incompatible with polarized positron stacking of 12ms
  - It should be twice faster than in the DR and cannot be achieved with damping wigglers
  - Staggered trains injection scheme
  - High beam power handling (radiation absorption, HOM free cavities, other collective effects)

APPLICATION TO THE CLIC PDR

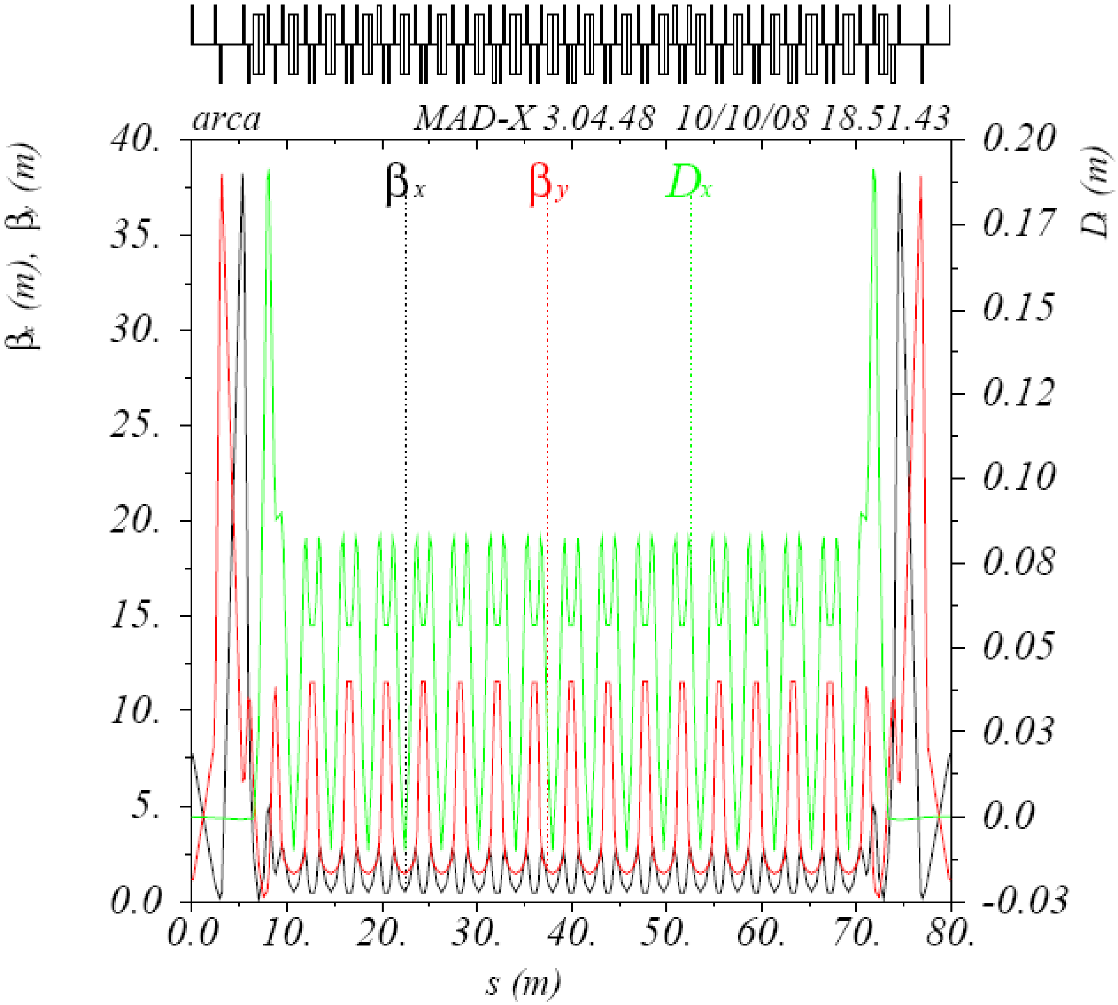




- The previous analysis was applied in the case of the CLIC PDR
- Minimization of the momentum compaction factor
- 30 TME cells (Minimum Emittance that can achieve = 8.1 µm) and moving to one of the upper curves of higher emittance of the plots.

➢ Optimal solution for:
  - $l_1 = 0.7$, $l_2 = 0.45$, $l_3 = 0.3$
  - *Emittance = 73 µm*
  - *Lcell = 3.8961 m (for B=1.7 T)*

ARCS OF THE PDR

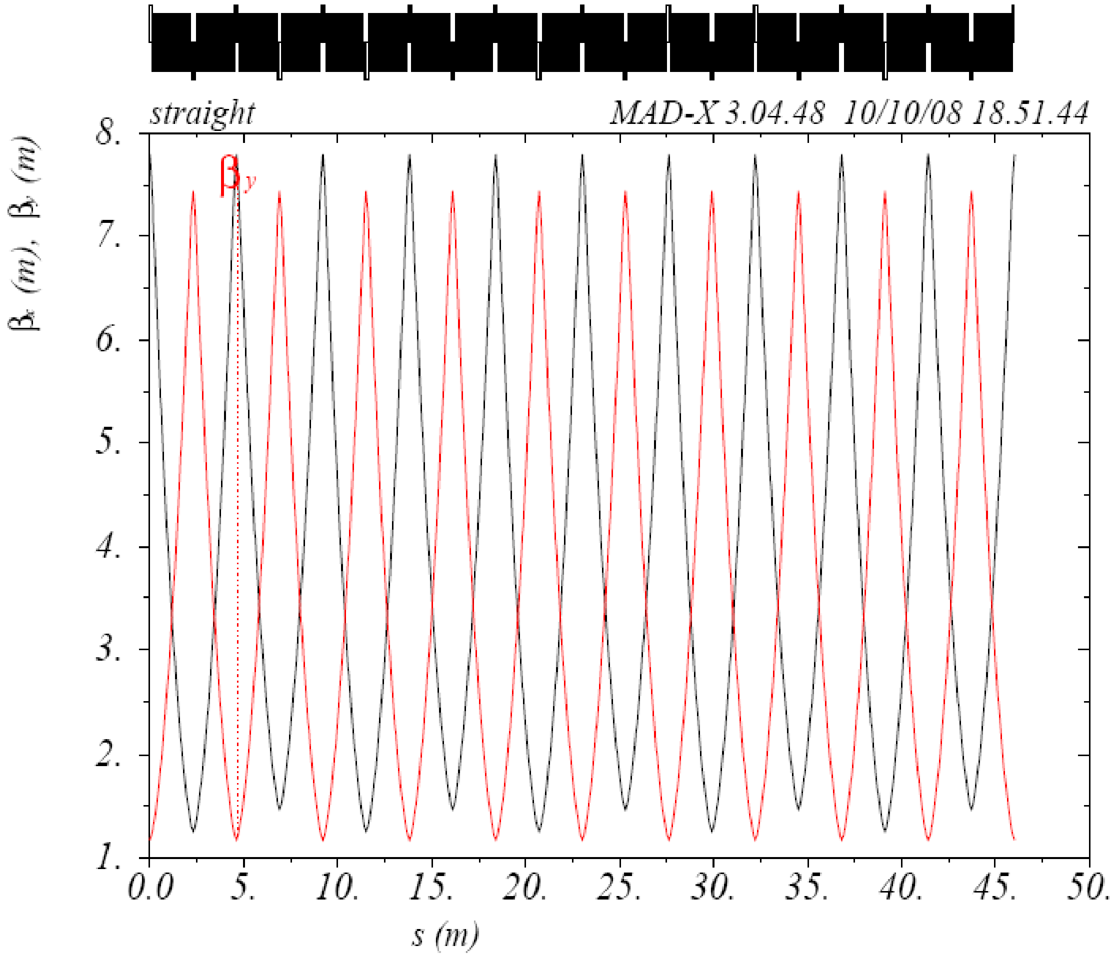


For the Arcs:

- 15 TME cells/arc
  - L_{dip} = 0.9961 m
  - B_{dip} = 1.7 T
  - Bend. ang. = 0.2094 rad
  - L_{cell} = 3.896 m
  - Quad. Coefficients

    k1/k2 = (10.69/-6.32)m^{-2}
- 2 Dispersion Suppressor sections (one in each side)
- 2 Beta Matching sections (one in each side).

STRAIGHT SECTION



For the Straight sections:

- 10 FODO cells (per straight section) are used
- Each FODO cell contains 2 wigglers (40 wigglers on total)
- Wiggler Parameters:
  - B_W = 1.7 T
  - L_W = 2 m
  - λ_W = 5 cm

PDR PARAMETERS

Parameters	CLIC PDR
Energy [GeV]	2.424
Circumference [m]	251.6
Normalized Emittance [μm rad]	18.6
Energy Loss per turn [MeV/turn]	1.6
RF Voltage [MV]	2 (5)
Harmonic Number	1677
Long. Damping time [msec]	1.25
Eq. Momentum spread [%]	0.095
Eq. bunch length [mm]	0.786 (0.952)
Momentum acceptance [%]	2.94 (6.88)
Quad coefficient K1[1/m^2] k1/k2	10.69/-6.32
Mom. Compaction factor, a_c	8.98E-05

- Parameters obtained from a preliminary design.

OUTLOOK

- A complete parameterization of the TME cells optics has been shown with respect to the emittance and the drift lengths
- It can be extended to any type of minimum emittance cell.
- Using this analytical approach, the cell design can be optimized for any target parameter (chromaticity, cell length, momentum compaction (1st or 2nd order), geometrical aperture…)
- An optimal solution for the minimization of the 1st order momentum compaction factor has been chosen for CLIC Pre Damping Rings.
- A preliminary design of the positron PDR
- Next steps
  - Optimize longitudinal parameters for increased momentum acceptance and small higher order momentum compaction factor
  - Chromaticity correction and dynamic aperture