CLIC Pre-damping rings overview

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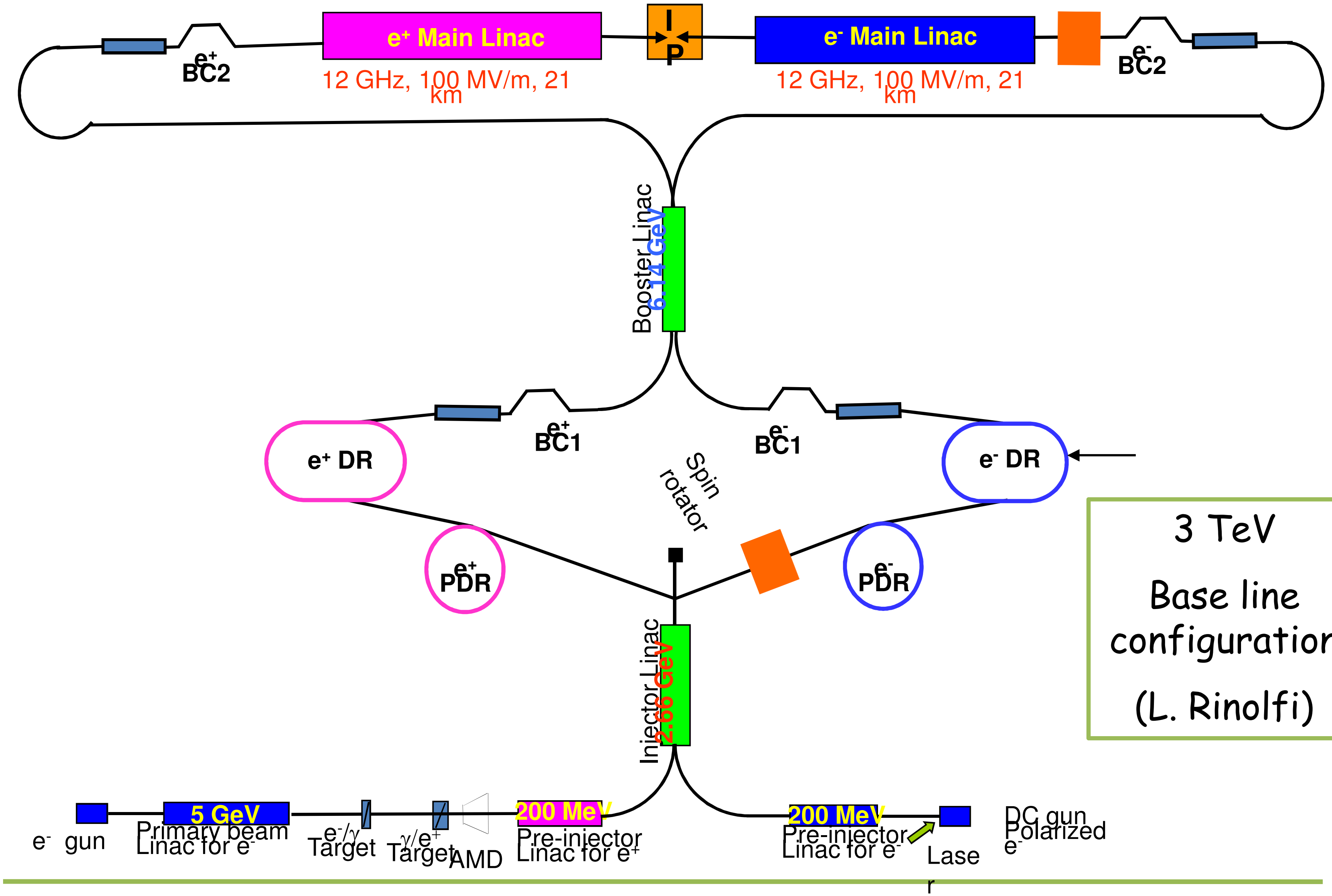
Outline

- ☐ CLIC Pre-Damping Rings' parameters
- ☐ Parameters guiding the design
- ☐ PDR Layout
- ☐ Analytical Solution for the TME cells
- ☐ Low momentum compaction factor lattice
- ☐ Lattice with optimized dynamic aperture (DA)
- ☐ Current PDR parameters
- ☐ Conclusions

The CLIC injector complex



3 TeV

Base line configuration

(L. Rinolfi)

CLIC PDR Parameters

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	**e^-/e^+**
Energy [GeV]	2.86
Bunch population [10^9]	4.1-4.4
Bunch length [mm]	10
Energy Spread [%]	0.5
Long. emittance [eV.m]	143000
Hor. Norm. emittance [nm]	63000
Ver. Norm. emittance [nm]	1500

Why PDR?

- Large injected e^+ emittances
  - ➔ aperture limitations if directly injected to the DR
- 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

Parameters Guiding the design

- ❑ 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

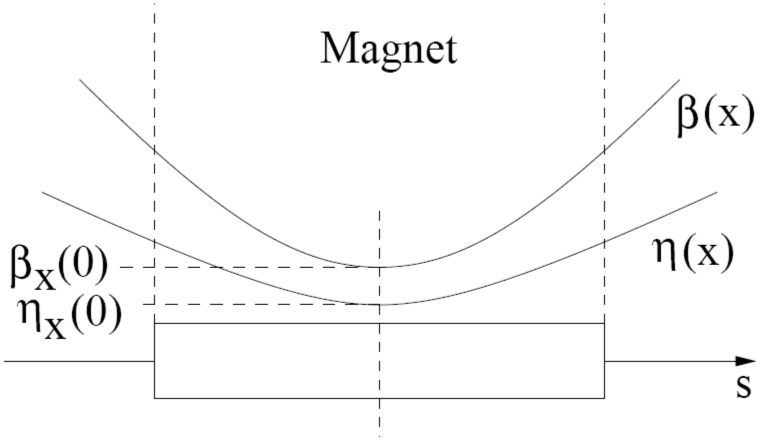
- ❑ Similar geometry with the DR (fit in the same tunnel ?)

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

The TME cell option



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

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

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

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

- ✓ Compact cells.
- ✓ Achieving the lowest emittance.

- ✗ Intrinsically high chromaticity due to strong focusing and thus low dispersion, for minimum emittance.
- ✗ Difficult to tune in their extreme minimum, if it exists.

- ➢ Relaxed emittance and low chromaticity needed in the case of the PDR → More general understanding of the behavior of the cell needed.

Analytical solution of the TME cell

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

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

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

$$\eta_s = f(\underbrace{l_1, l_2, l_3}_{\text{Drift lengths}}, \underbrace{L_d, \rho}_{\text{Dipole length and bend. angle}}, \underbrace{\eta_{x,cd}, \beta_{x,cd}}_{\text{Initial optics functions}})$$

- ✓ 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 of the TME cell

❑ Stability constraint

$$\mathrm{Trace}(M_{x,y}) = 2\cos\mu_{x,y} < 2$$

Cell transfer matrix

Phase advance per cell

❑ Feasibility constraints

Quad. maximum pole tip field

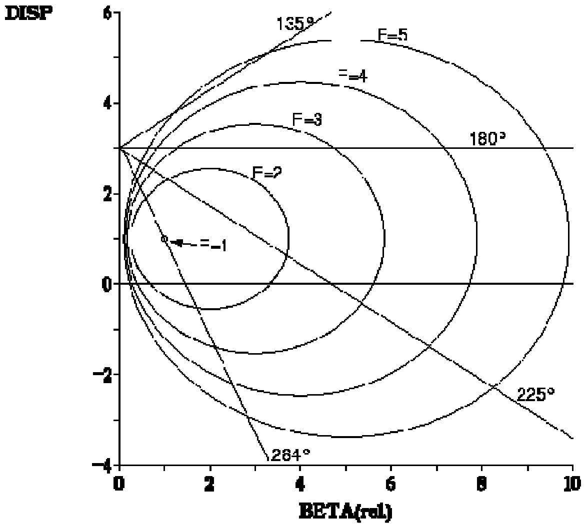
Quads: $g \le \frac{B^{max}_{pt,q}}{R^{min}_{acc}} \Rightarrow \frac{1}{f l_q} = k \le \frac{1}{(B\rho)} \frac{B^{max}_{pt,q}}{R^{min}_{acc}}$

$$R_{x,y} = \sqrt{\beta_{x,y}\epsilon_{edge,x,y}} + (\delta p/p)_{k\sigma_l} \cdot \eta_{x,y}$$

Minimum geometrical acceptance

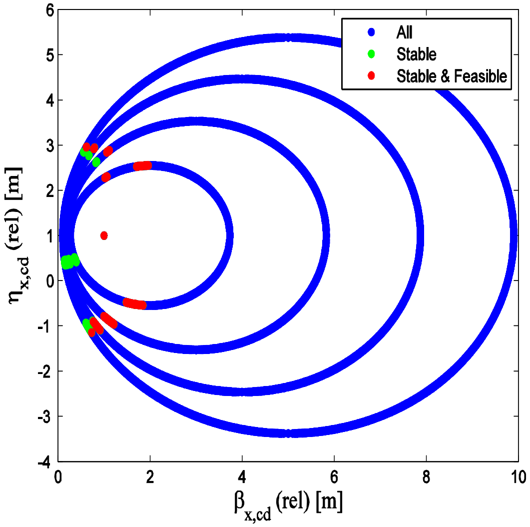
Sextupoles: $S \le \frac{2B^{max}_{pt,sext}}{R^2} \frac{1}{(B\rho)}$

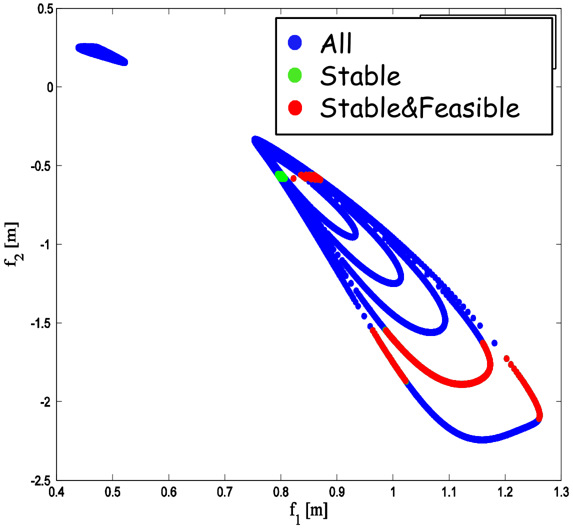
Analytical solution for the TME cell



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

Applying the analytical parameterization with the stability and feasibility constraints



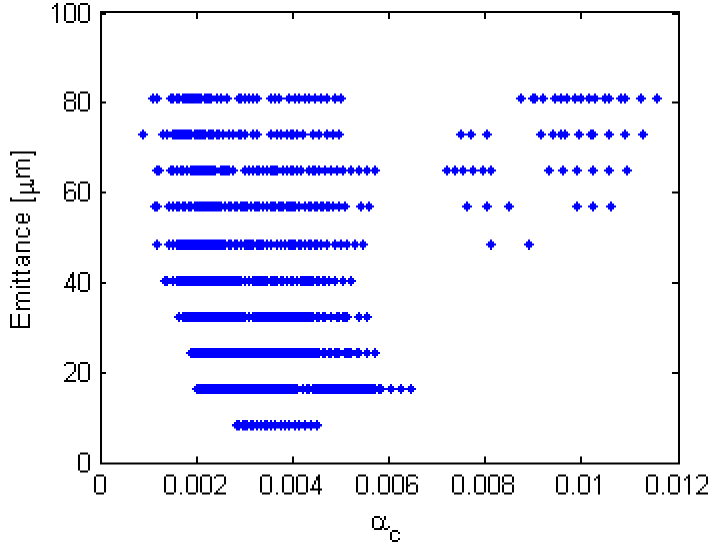


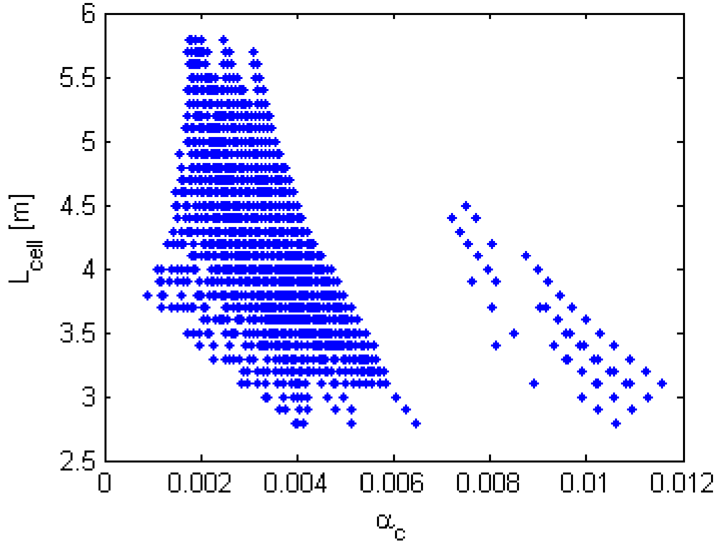
- ✓ Only one pair of values for the initial optics functions and the quad strengths can achieve the TME
- ✓ Several pair of values for larger emittances, but only small fraction of them stable.
- ✓ Similar plots for all the parameters

PDR Lattice version 0

Initial design aiming to achieve low momentum compaction factor

Choice of parameters for v0



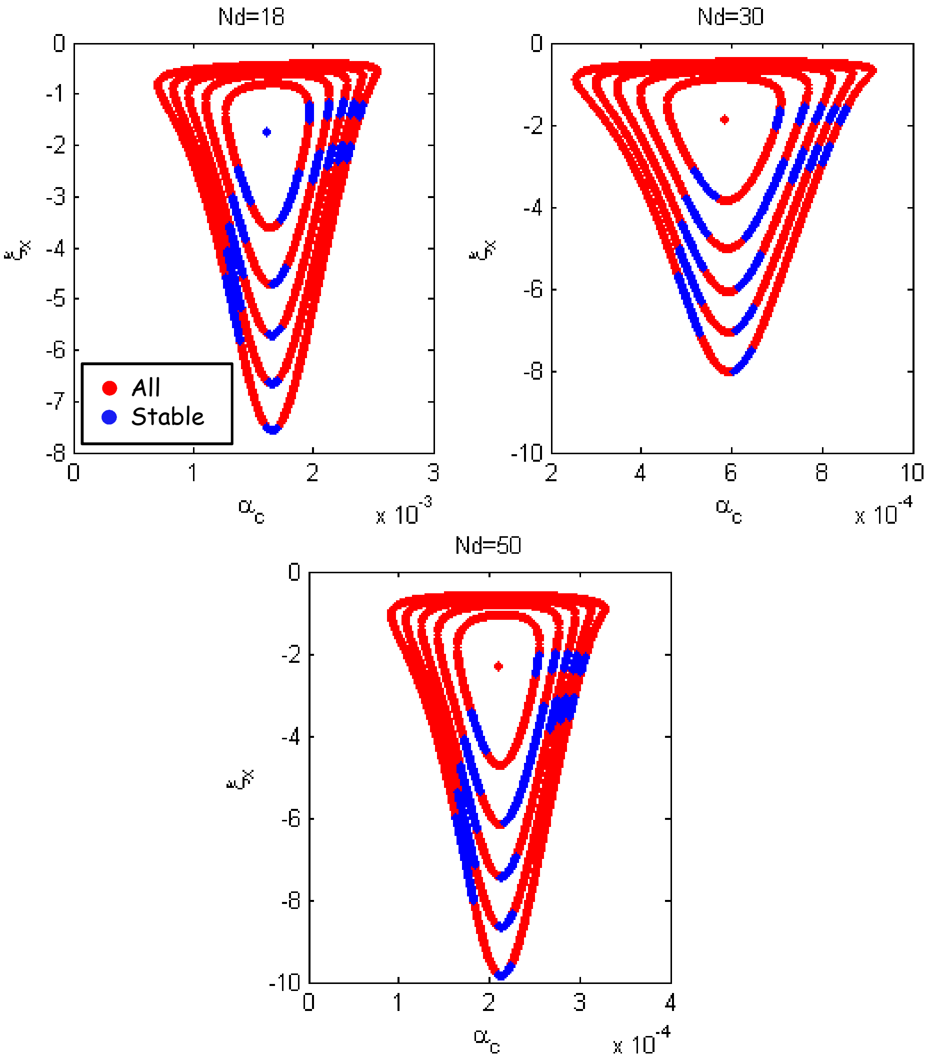


- ❑ A first attempt of the design was aiming to the minimization of the momentum compaction factor $\boldsymbol{\alpha_c}$ for maximum momentum acceptance and stacking purposes.

- ➢ Emittance and Cell Length Vs α_c for a certain cell (N_d = 30).
- ➢ Smaller values of α_c if the cell is detuned.
- Plots from the analytical solution

- ✓ Optimal solution for:
  - *l_1=0.7, l_2=0.45, l_3=0.3*
  - *Lcell = 3.8961 m (for B=1.7 T)*

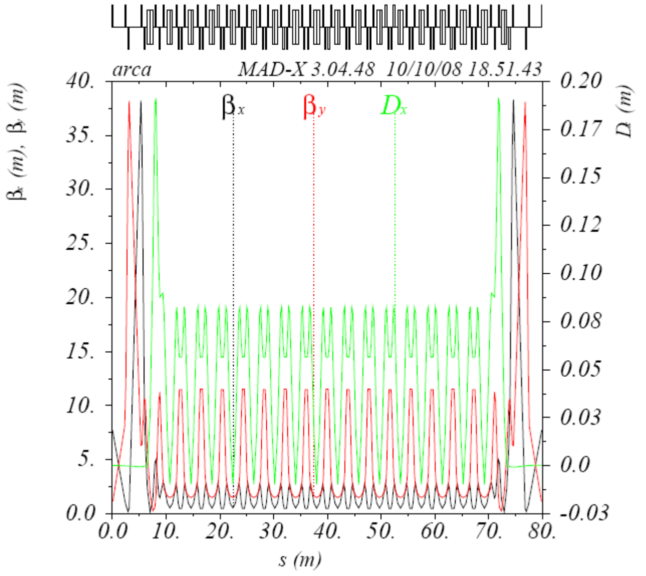
Choice of parameters for v0

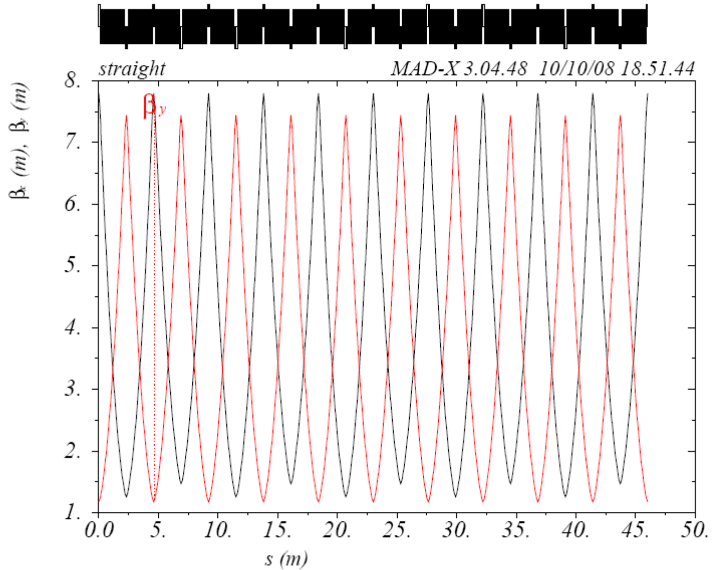


- ☐ Plots of α_c versus the horizontal chromaticity ξ_x for several bending angles (different achievable minimum emittances).
  - The outer curve corresponds to twice the TME
  - The only stable solutions are the blue ones

- ➢ The α_c factor decreases as the number of cells is decreased.
- ➢ For smaller values of the α_c higher values of ξ_x!!!
- ✓ Choice of 30 dipoles

Choice of parameters for v0





ARC:

- 13 TME cells/arc
  - Ldip = 0.9961 m
  - Bdip = 1.7 T
  - Bend. ang. = 0.2094 rad
  - Lcell = 3.896 m
  - Quad. Coefficients: $k_1/k_2 = (10.69/-6.32)\mathrm{m}^{-2}$
- 2 Dispersion Suppressor sections
- 2 Beta Matching sections

STRAIGHT SECTION:

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

Table of parameters for v0

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}

- ☐ A very preliminary design which had as a goal to provide very low a_c.
- ✓ It provides the very low a_c **BUT**
- ✗ Very limited dynamic aperture
  - ✗ Less than 2 sigma both horizontal and vertical!!

Due to:

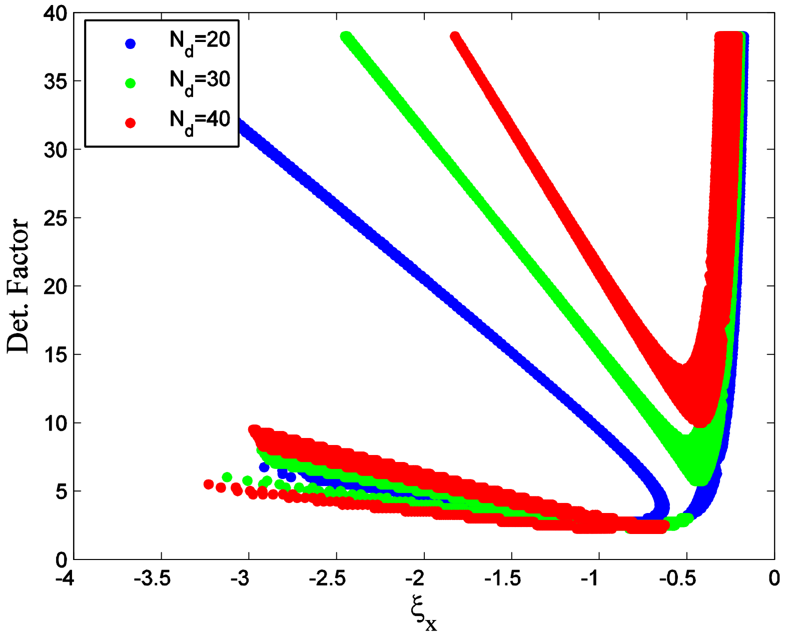
- Non linear effects because of the strong sextupoles for chromaticity correction.
- Large injected beam

σ_x = 3.84 mm & σ_y = 1.71 mm

PDR Lattice version 1

Current design, focused on dynamic aperture optimization

Arc Choice of parameters for v1



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

- Following: "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 associated with the ensemble of N_c cells vanishes if the resonance amplification factor is zero:

$$\left|\sum_{p=0}^{N_c-1} e^{ip(n_x\mu_{x,c}+n_y\mu_{y,c})}\right| = \sqrt{\frac{1-\cos[N_c(n_x\mu_{x,c}+n_y\mu_{y,c})]}{1-\cos(n_x\mu_{x,c}+n_y\mu_{y,c})}} = 0 \quad \Bigg\}$$

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

Non linear optimization considerations

- Setting the phase advances to the values:

$\mu_{xc}/2\pi = k_1/N_c$ and $\mu_{yc}/2\pi = k_2/N_c$ ➔ $n_x k_1 + n_y k_2 = k$

where: n_x, n_y, k_1, k_2, k integers

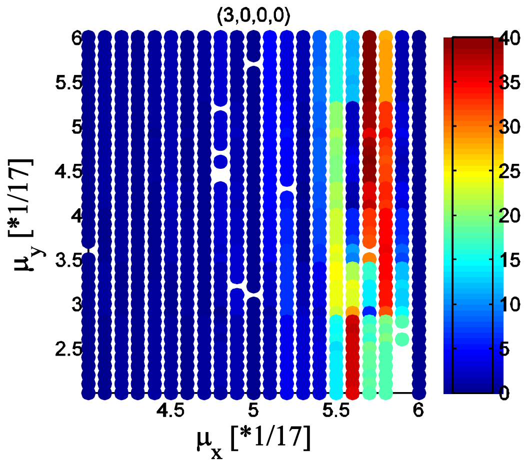
"A part of a circular machine containing N_c identical cells will not contribute to the excitation of any non-linear resonance, except those defined by $n_x + n_y = 2k_3\pi$, if the phase advances per cell satisfy the two conditions :

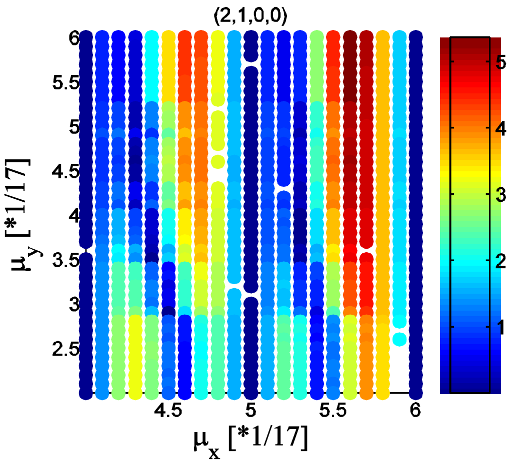
- $N_c\mu_{x,c} = 2k_1\pi$ (cancellation of one-D horizontal non-linear resonances)
- $N_c\mu_{y,c} = 2k_2\pi$ (cancellation of one-D vertical nonlinear resonances)
- k_1 k_2 and k_3 being any integers."

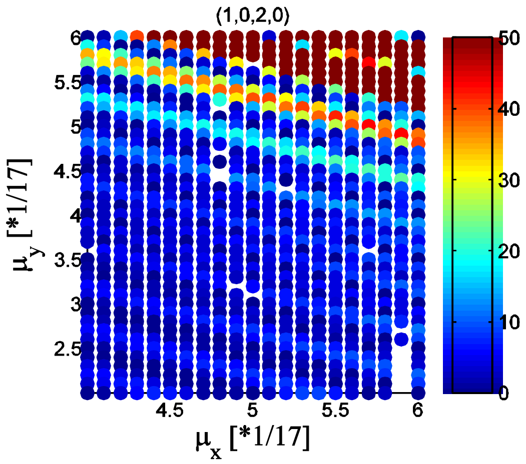
Non linear optimization considerations

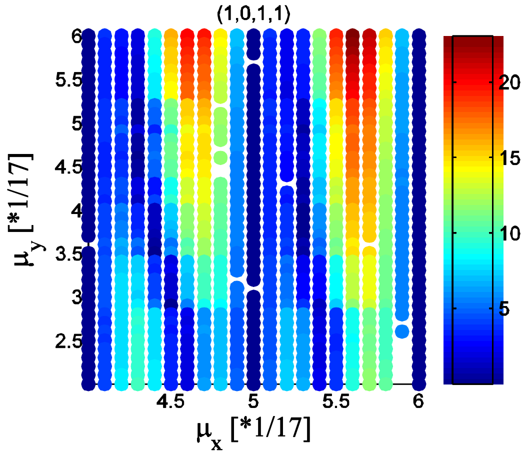
- ❑ For prime numbers of N_c, less resonances satisfying both conditions simultaneously.
- ❑ In our case N_c is the number of TME cells per arc.
- ❑ Some convenient numbers for N_c are 11, 13, 17 (26, 30 and 38 dipoles in the ring respectively, including the dispersion suppressors' last dipole).
- ❑ 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.

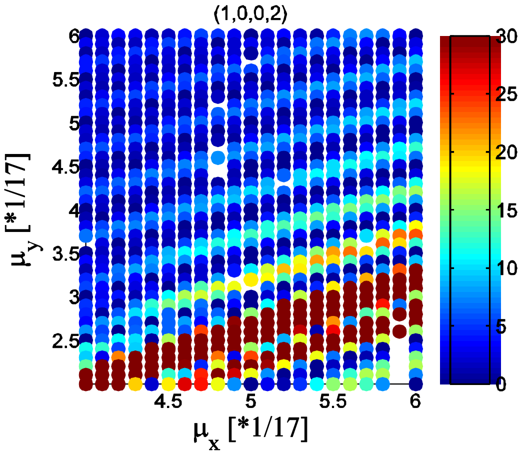
Non linear optimization considerations





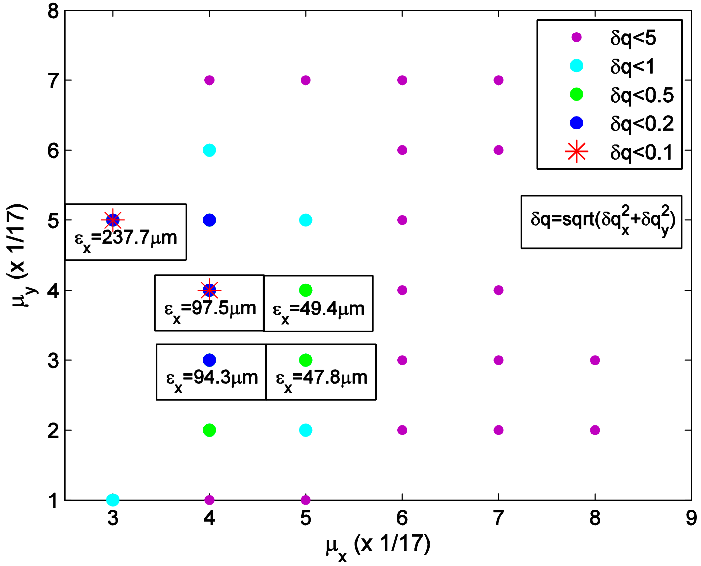




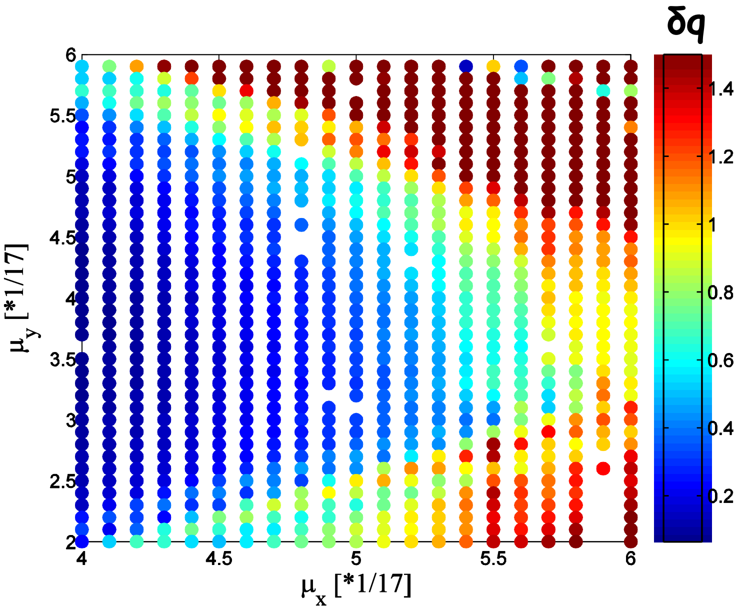


Resonance driving terms amplitudes with the horizontal phase advance for the different components of the third order resonance.

Non linear optimization considerations

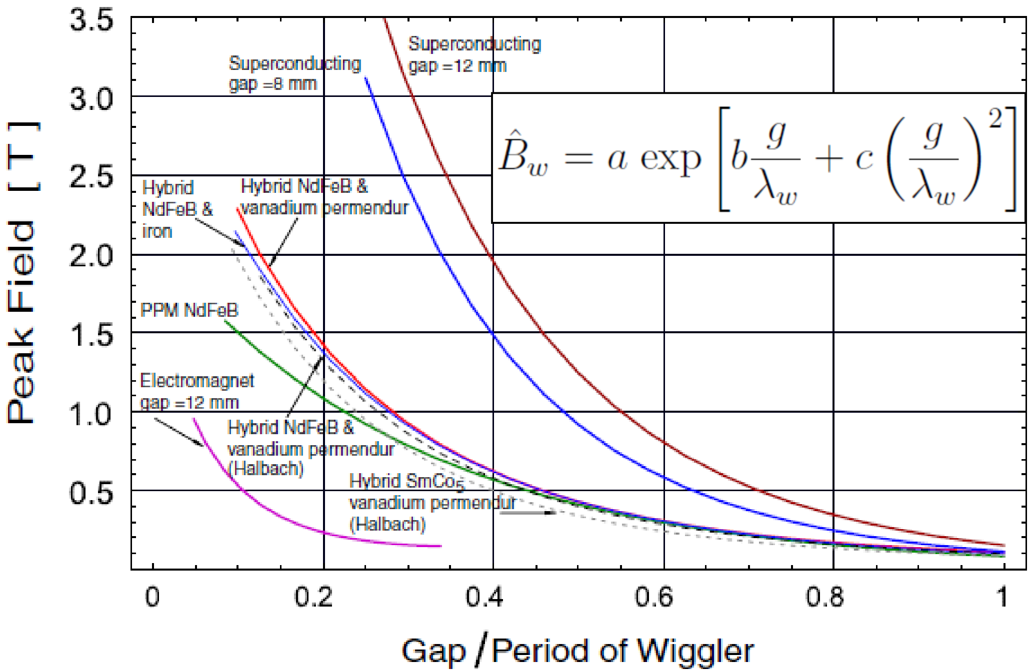


- Phase advance scan in horizontal μ_x and vertical μ_y phase advances for μ_x and μ_y integer multiples of 1/17.
- Different colors indicate the **first order tune shift with amplitude, δq,** levels.
- ✓ Optimal pair of values: $(\mu_x,\mu_y)=(0.2941=5/17,0.1765=3/17)$



- ❑ 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.

Wiggler parameters

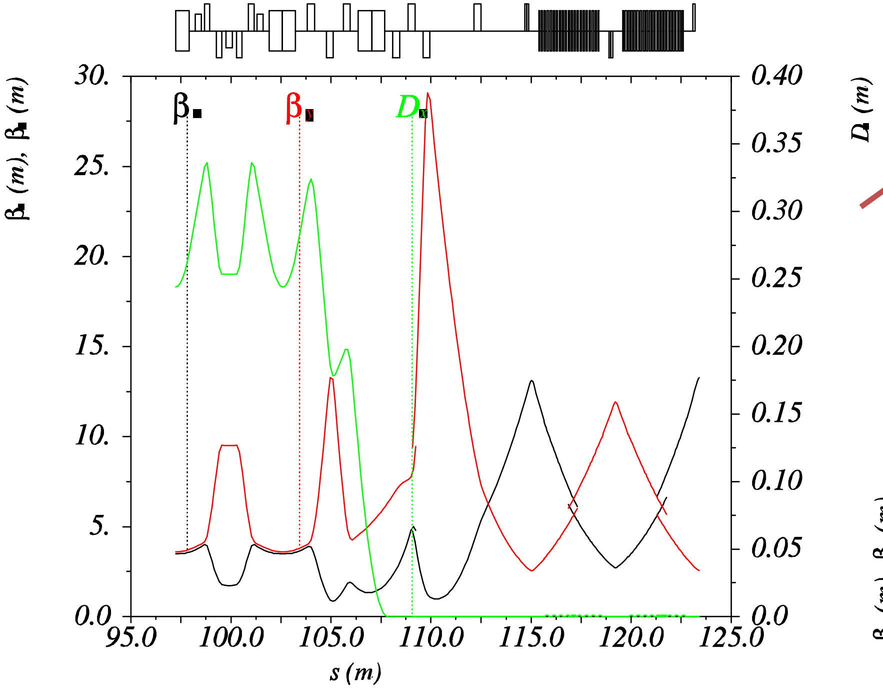


Peak field versus gap/period approximated by Eq. 6.1 with parameters taken from Table 6.2.

M. Korostelev thesis

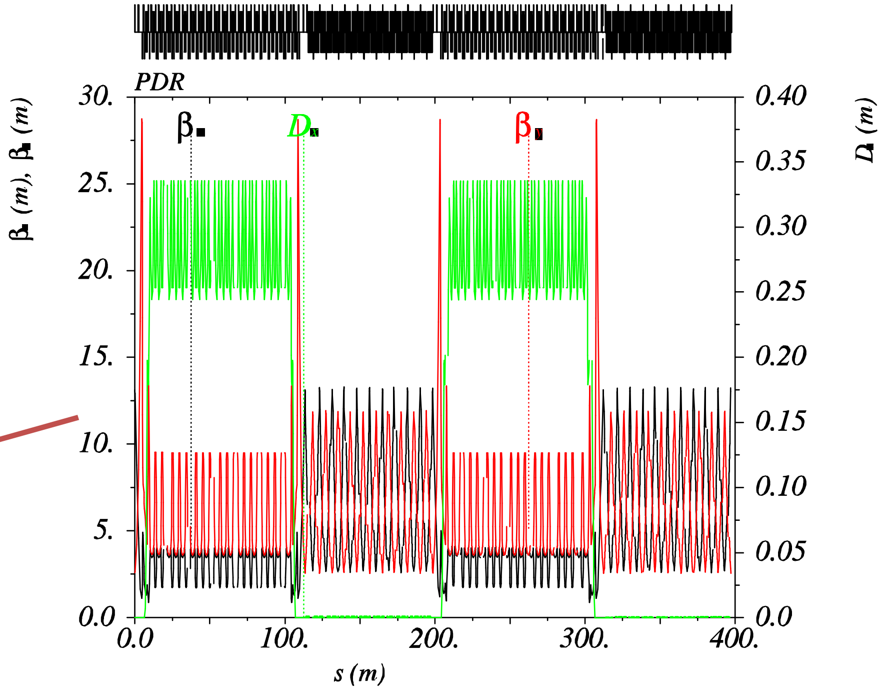
- For the permanent magnet wiggler at B_w = 1.7 T the gap/period = 0.15
- In order to have 6σ aperture we need a gap of around 50 mm and that defines the wiggler period to be λ_w = 30 cm
- However detailed studies needed considering power consumption and field quality.

Optics of the ring

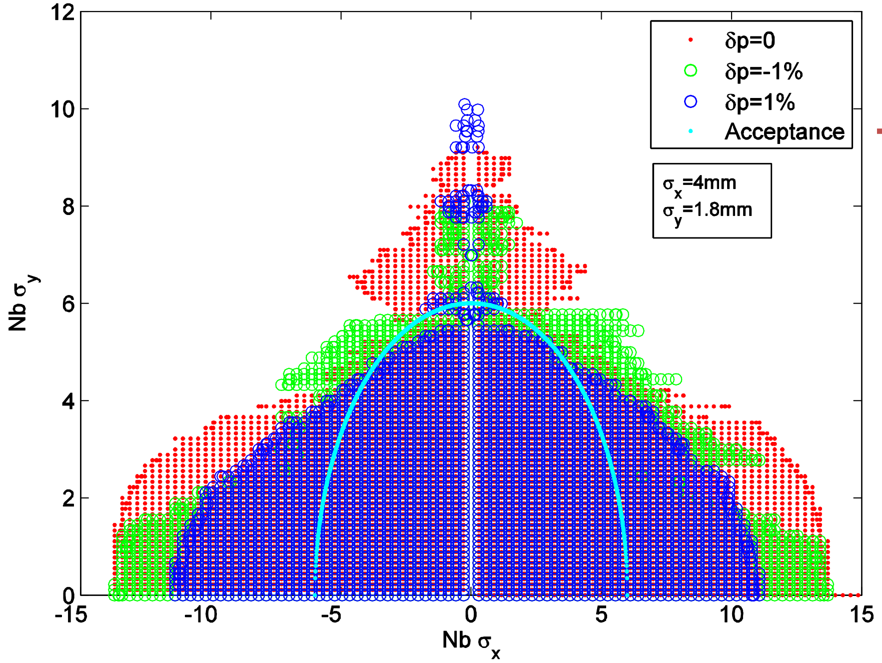


Optics of the TME arc cell, the dispersion suppressor – beta matching cell and the FODO straight section cell

Optics of the current design of the PDR.



Dynamic Aperture



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

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

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)

Octupole correction

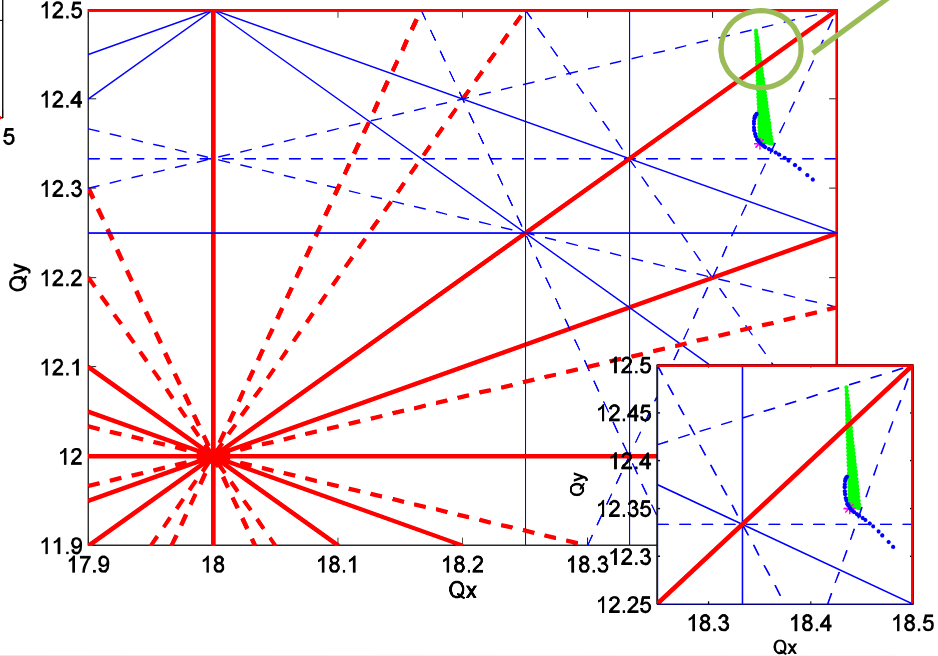


Table of parameters

Parameters, Symbol [Unit]	**Value**
Energy, E_n [GeV]	2.86
Circumference, C [m]	397.6
Bunches per train, N_b	312
Bunch population [10^9]	4.6
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.),($\xi_{x/}\xi_y$)	-16.88/-23.52
Norm. Hor. Emit.,$\gamma\varepsilon_0$[mm mrad]	47.85
Damping times, ($\tau_x/\tau_y/\tau_\varepsilon$),[ms]	2.32/2.32/1.16
Mom. Compaction Factor, α_c [10^{-3}]	3.83
RF Voltage, V_{rf} [MV]	10
RF acceptance, ε_{rf} [%]	1.1
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]	3.3
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

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 nonlinear errors in the main magnets and wigglers.
- Further non-linear optimization studies needed
    - Insertions of more families of sextupoles and/or octupoles

Thanks for your attention!!!