DR developments in view of CLIC re-baselining

Y. Papaphilippou,

for the DR team

CLIC workshop 2016

Adapting the DR complex to a new CLIC baseline

- Pre-damping rings revision
  - Potentially remove the electron pre-damping ring
  - Potentially replace the positron pre-damping ring with a booster ring
- Review DR based on recent design developments and collaboration effort in the low emittance rings community (both beam dynamics and technology)
    - New DR arc cell (longitudinally varying bends) and SC wigglers for circumference reduction (collective effects)
    - RF frequency choice and LLRF technical development
    - Stripline kicker + pulser tests
    - SC wiggler tests and developments

CLIC DR complex challenges

Injected Parameters	e^-	e^+
Bunch population [10^9]	4.7	6.4
Repetition frequenzy [Hz]	50	50
Bunch length [mm]	1	9
Energy Spread [%]	0.1	1
Long. emittance [eV.m]	2000	257000
H/V norm. emittance [nm-rad]	100 x 10^3	7 x 10^6

Extracted Parameters	PDR e^-/e^+	DR e^-/e^+
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-rad]	63000	500
Ver. Norm. emittance [nm-rad]	1500	5

- DR complex challenges
  - Large injected emittances and energy spread → Requirement of large DA and MA
  - Ultra low emittance at extraction
  - Repetition time of 20 ms → Fast damping requirement
- **PDR** → efficient injection of the large incoming beams
- **Main DR** → ultra-low emittance generation
- The positron beam needs at least 8 damping times to reach equilibrium (w/o taking into account injection, IBS, etc)

  → **The positron PDR is necessary!**

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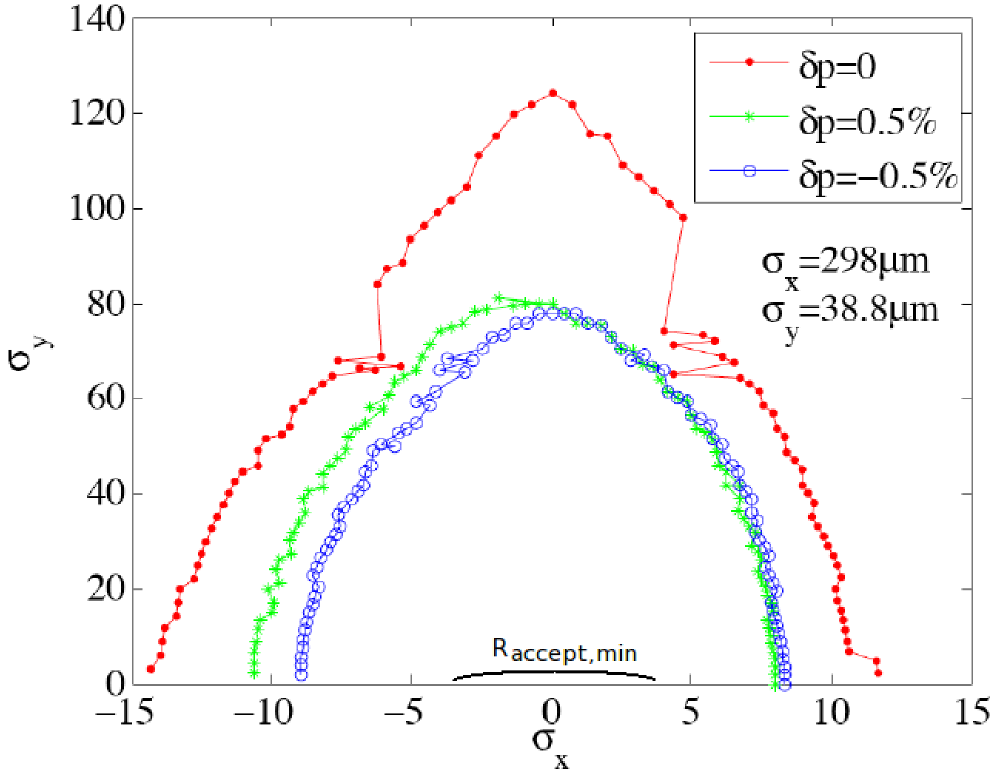
Electron linac requirements

DA of the main DR



- For non-Gaussian beams the minimum required acceptance:

$$R_{\min} = \sqrt{2\beta\varepsilon_{\max}} + D(\delta p/p_0)_{\max}$$

- To avoid an e⁻ PDR:
  - In horizontal R_{min} < 1 mm-rad
  - In vertical R_y^{min} < 1.2 mm-rad
- Required emittances from the electron injection linac **in order to remove electron PDR**

ε_x^{rms}= 25 μm-rad

ε_y^{rms}= 50 μm-rad

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CLIC DR challenges and adopted solutions

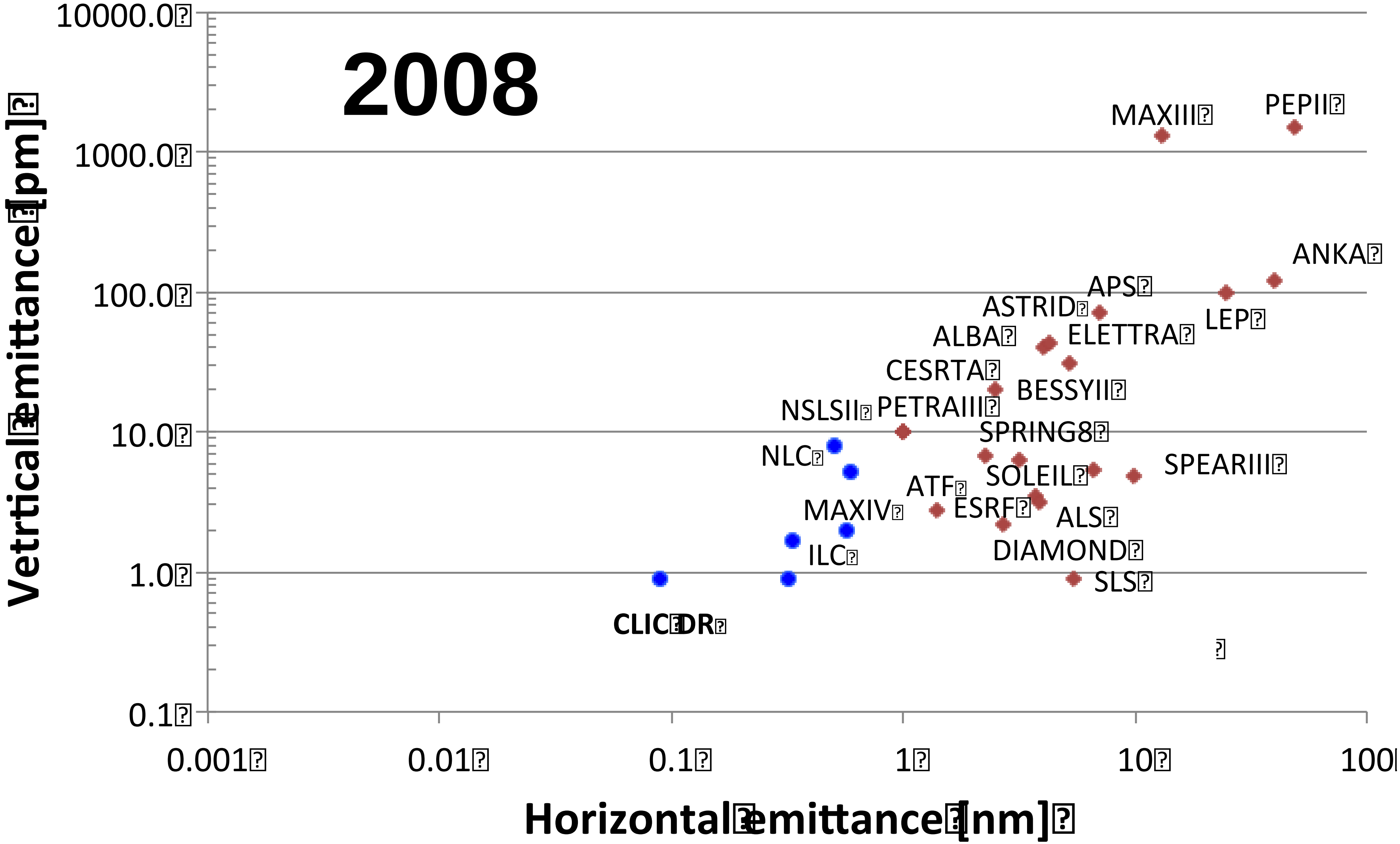
Parameters, Symbol [Unit]	2 GHz	1 GHz
Energy, E [GeV]	2.86	
Circumference, C [m]	427.5	
Bunch population, N [10^9]	4.1	
Basic cell type in the arc/LSS	TME/FODO	
Number of dipoles, N_d	100	
Dipole Field, B_0 [T]	1.0	
Norm. gradient in dipole [m^{-2}]	-1.1	
Hor., ver. tune, (Q_x,Q_y)	(48.35,10.40)	
Hor., ver. chromaticity, (ξ_x,ξ_y)	(-115,-85)	
Number of wigglers, N_w	52	
Wiggler peak field, B_w [T]	2.5	
Wiggler length, L_w [m]	2	
Wiggler period, λ_w [cm]	5	
Damping times, (τ_x, τ_y, τ_l) [ms]	(2.0,2.0,1.0)	
Momentum compaction, α_c [10^{-4}]	1.3	
Energy loss/turn, U [MeV]	4.0	
Norm. hor. emittance, $\gamma\epsilon_x$ [mm·mrad]	472	456
Norm. ver. emittance, $\gamma\epsilon_y$ [mm·mrad]	4.8	4.8
Energy spread (rms), σ_δ [%]	0.1	0.1
Bunch length (rms), σ_s [mm]	1.6	1.8
Long. emittance, ϵ_l [keVm]	5.3	6.0
IBS factors hor./ver./long.	1.5/1.1/1.2	1.5/1.1/1.2
RF Voltage, V_{RF} [MV]	4.5	5.1
Stationary phase [^{o}]	62	51
Synchrotron tune, Q_s	0.0065	0.0057
Bunches per train, n_b	312	156
Bunch spacing, τ_b [ns]	0.5	1
RF acceptance, ϵ_{RF} [%]	1.0	2.4
Harmonic number, h	2851	1425

- High-bunch density in all three dimensions
  - **Intrabeam Scattering** effect reduced by choice of ring energy, lattice design, wiggler technology and alignment tolerances
  - **Electron cloud** in e$^+$ ring mitigated by chamber coatings and efficient photon absorption
  - **Fast Ion Instability** in the e$^-$ ring reduced by low vacuum pressure and large train gap
  - **Space charge vertical tune-shift** limited by energy choice, reduced circumference, bunch length increase
  - Other **collective instabilities** controlled by low – impedance requirements on machine components
- Repetition rate and bunch structure
  - Fast damping times achieved with SC wigglers
  - RF frequency reduction @ 1GHz considered due to many challenges @ 2GHz (power source, high peak and average current, transient beam loading)
- Output emittance stability
  - Tight jitter tolerance driving kicker technology
- Positron beam dimensions from source
  - Pre-damping ring challenges (energy acceptance, dynamic aperture) solved with lattice design

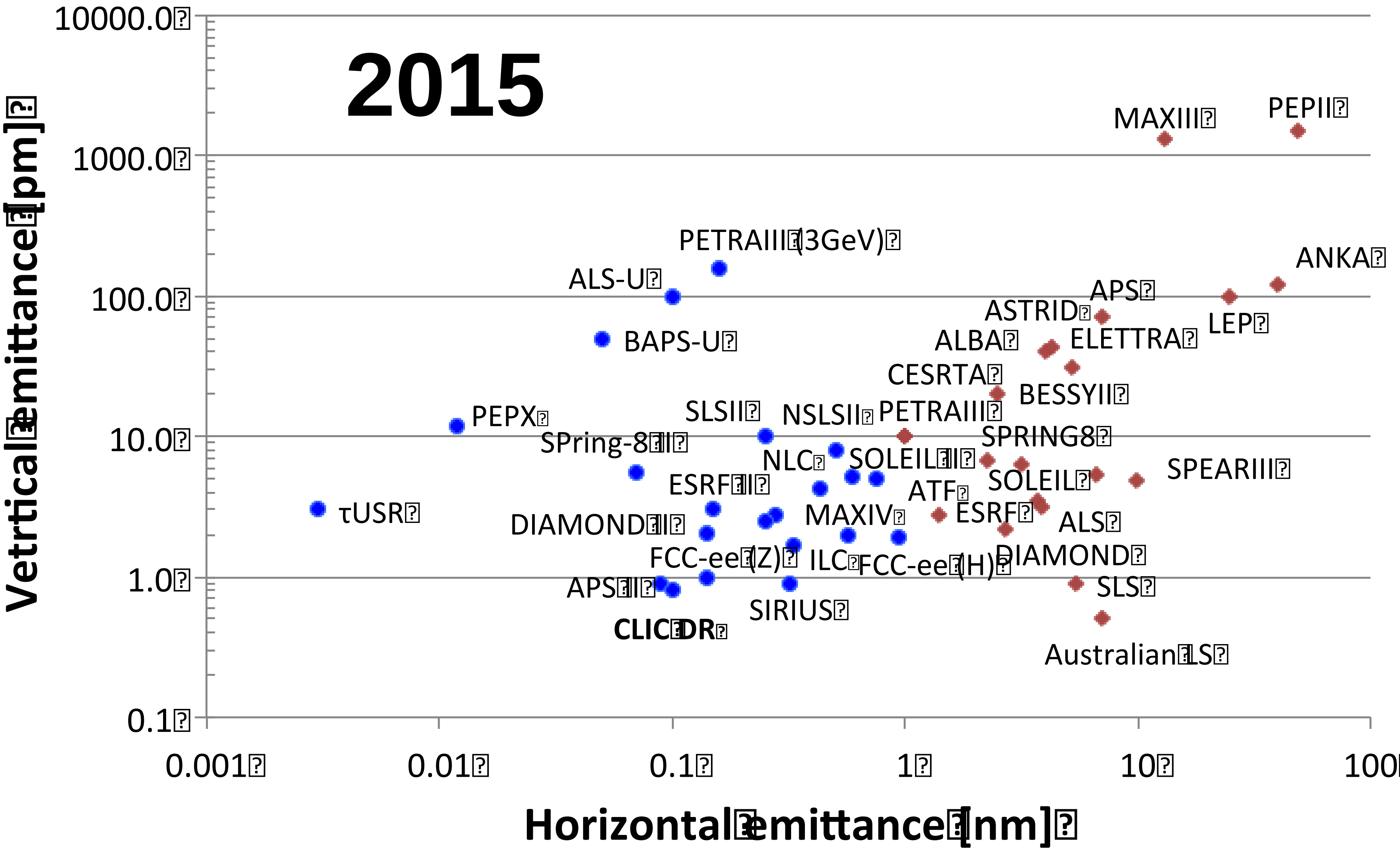
1 vs. 2 GHz RF system

- The cost difference due to the RF frequency choice in the DR (scaled with the total voltage) is minor
- The cost impact of an additional delay loop for 1GHz is small (but non negligible)
- The technological risk of choosing the 2GHz option, after conceptual design of A. Grudiev, seems equivalent with the train recombination for the 1GHz option
- Choose 2GHz as baseline and work with low emittance rings community to prove efficient handling of beam loading transients
  - Collaboration with ALBA (F. Perez et al.) and LBNL (J. Byrd et al.) for the conceptual design of a 1.5GHz active RF system, including LLRF

Emittance targets



Emittance targets



The CLIC DR CDR design

Parameters	1 GHz	2 GHz	V06
		General	
Energy [GeV]	2.86	2.86	2.424
Circumference [m]	427.5	427.5	493.05
Bunches per train	156	312	312
Energy loss/turn [MeV]	3.98	3.98	3.98
RF voltage [MV]	5.1	4.5	4.3
RF harmonic (h)	1425	2850	3287
RF stationary phase [^{o}]	51	62	67
Energy Acceptance [%]	1	2.5	0.98
Natural chromaticity x/y	-115/-85	-115/-85	-148.8/-79.0
Momentum compaction factor [10^{-4}]	1.27	1.27	0.644
Damping times x/y/s [ms]	2/2/1	2/2/1	2/2/1
Number of arc cells/wigglers	100/52	100/52	100/76
Phase advance per arc cell x/y	0.408/0.05	0.408/0.05	0.442/0.045
Dipole focusing strength $K_1[m^{-2}]$	-1.1	-1.1	-1.1
Dipole length [m]/field [T]	0.58/1.03	0.58/1.03	0.4/1.27
		Without the IBS	
Normalized Hor. emittance [nm-rad]	312	312	148
Energy spread [10^{-3}]	1.2	1.3	1.12
Bunch Length [mm]	1.18	1.46	0.95
Longitudinal Emittance [keV-m]	5.01	4.39	2.58
		With the IBS	
Bunch population [10^9]	4.1	4.1	4.1
Normalized Hor. emittance [nm-rad]	456	472	436
Normalized Vert. emittance [nm-rad]	4.8	4.8	5
$\varepsilon_{x,IBS}/\varepsilon_{x,0}$	1.44	1.5	2.9
Longitudinal Emittance [keV-m]	6	6	5
Space charge tune shift	-0.10	-0.11	-0.2

- **Performance parameters** of the CLIC DR for the **1 GHz** and **2 GHz** options in comparison to the V06
  - Increased energy (2.424→2.86 GeV)
  - Reduce the circumference by 15%
  - Ultra-low emittances in all 3 planes
  - Reduced IBS effect (from 3 to 1.5)
  - Reduced space charge tune shift (-0.2 → -0.1)
  - Lower RF stable phase (70°→51° (62°))

F.Antoniou

A new design of the CLIC DR based on variable dipole bends and high field wigglers

CLIC Workshop
Geneva, 21/1/2016

Stefania Papadopoulou* +, Fanouria Antoniou *, Yannis Papaphilippou*
*CERN, +University of Crete

Contents

- The aim
- Longitudinally variable bends
  - -General case
  - -Fixed dipole characteristics
- Optimization of the arc TME cell
  - -Parametrization with the drift space lengths
  - -Parametrization with the phase advances
- Optimization of the wiggler FODO cell
  - -A new working point for a high field wiggler
- Conclusion: Design parameters of the main CLIC DRs

The aim

Current design of the main CLIC DRs, E=2.86 GeV

Parameters, Symbol [Unit]	uniform
Circumference, C [m]	427.5
Norm. horiz. emittance , $\gamma\varepsilon_x$ [nm-rad] *	657

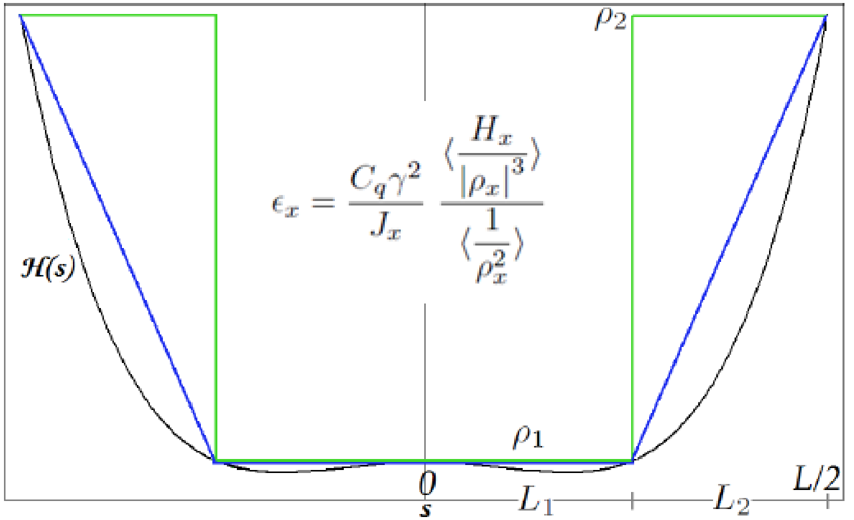
Reduce the number of arc TME cells->longitudinally variable bends

Reduce the number of wigglers->higher wiggler field

500nm required output emittance

*The emittance is calculated using the Bjorken-Mtingwa formalism through MADX.
Using the Piwinski form., the original design (with the uniform dipoles) reaches the target horizontal emittance.

Longitudinally variable bends[1]



$$\rho_{st}(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_2, & L_1 < s < L_1 + L_2 \end{cases}$$

$$\rho_{\mathrm{tr}}(s) = \begin{cases} \rho_1, & 0 < s < L_1 \\ \rho_1 + \frac{(L_1 - s)(\rho_1 - \rho_2)}{L_2}, & L_1 < s < L_1 + L_2 \end{cases}$$

Bending radii ratio

$$\rho = \frac{\rho_1}{\rho_2}$$

Lengths ratio

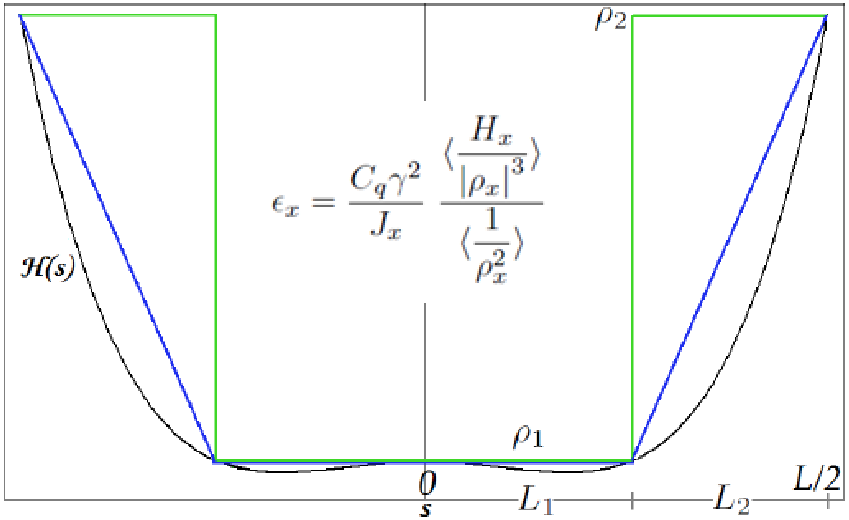
$$\lambda = \frac{L_1}{L_2}$$

Emittance reduction factor

$$F_{TME} = \frac{\epsilon_{TME_{uni}}}{\epsilon_{TME_{var}}}$$

$$F_{TME} > 1$$

Longitudinally variable bends[1]



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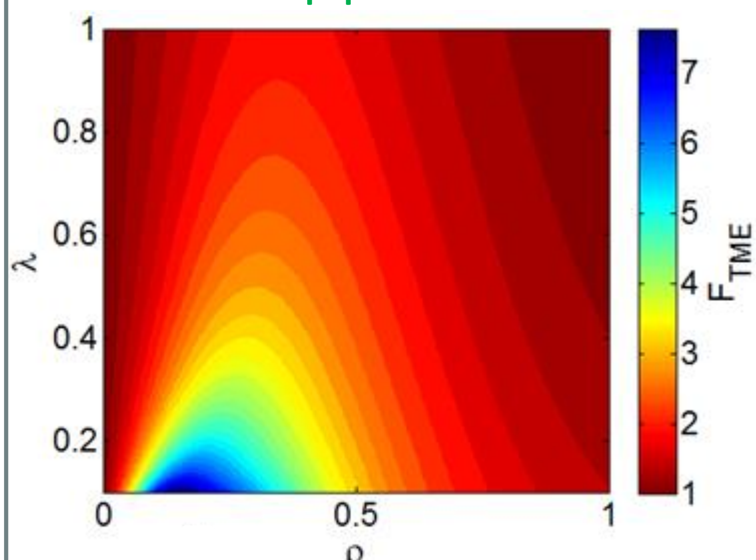
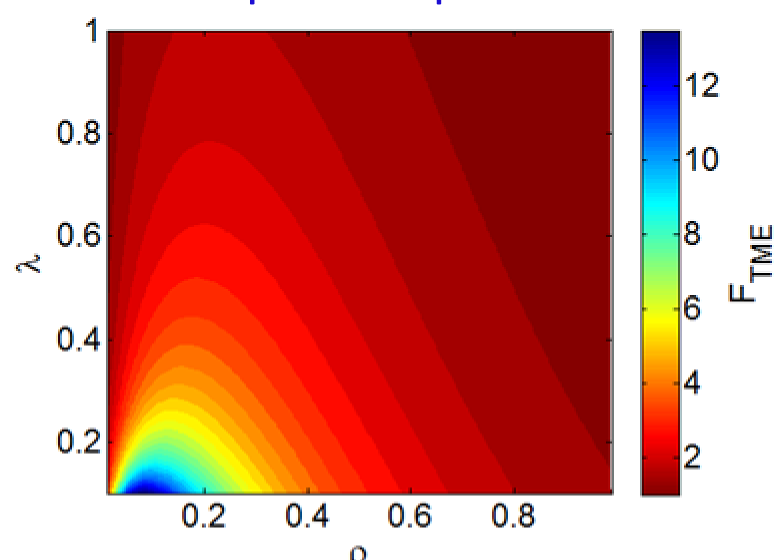
Step profile



Trapezium profile



The parameterization of the emittance reduction factor F_{TME} with the bending radii ratio ρ and the lengths ratio λ, always for λ>0.1.

Fixing the dipole's characteristics (bending angle, length and minimum bending radius)

step

$$\theta = \frac{L(\lambda + \rho)}{\rho_1(1+\lambda)}$$

trapezium

$$\theta = \frac{L(\lambda(-1+\rho) + \rho \log \rho)}{\rho_1 \; (-1+\rho)(1+\lambda)}$$

$\longrightarrow \lambda(\rho)$ or $\rho(\lambda) \xrightarrow{F_{TME}(\rho,\lambda)} F_{TME}(\rho)$ or $F_{TME}(\lambda)$

Fixing the dipole's characteristics (bending angle, length and minimum bending radius)

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$$\theta = \frac{L(\lambda+\rho)}{\rho_1(1+\lambda)}$$

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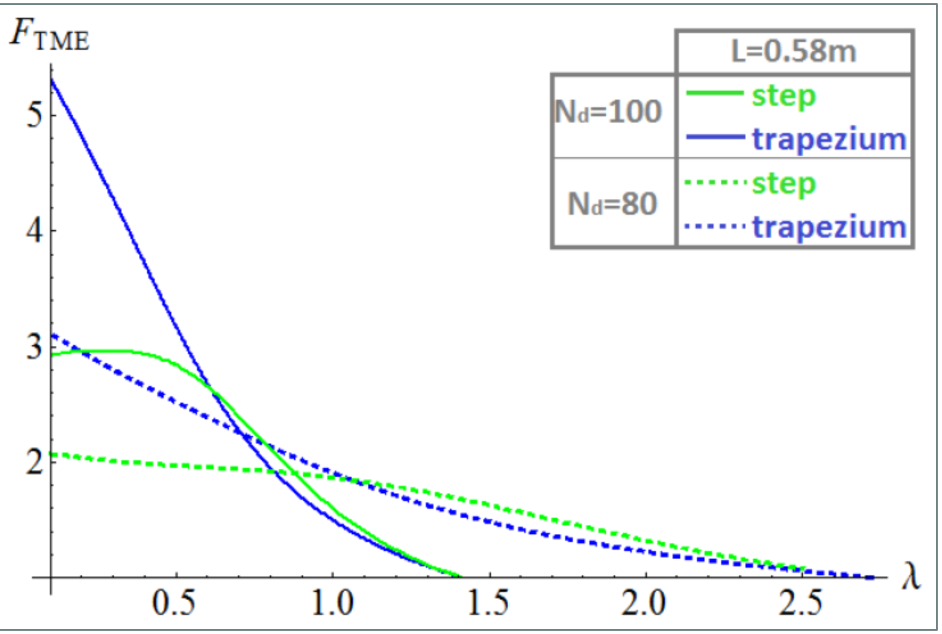
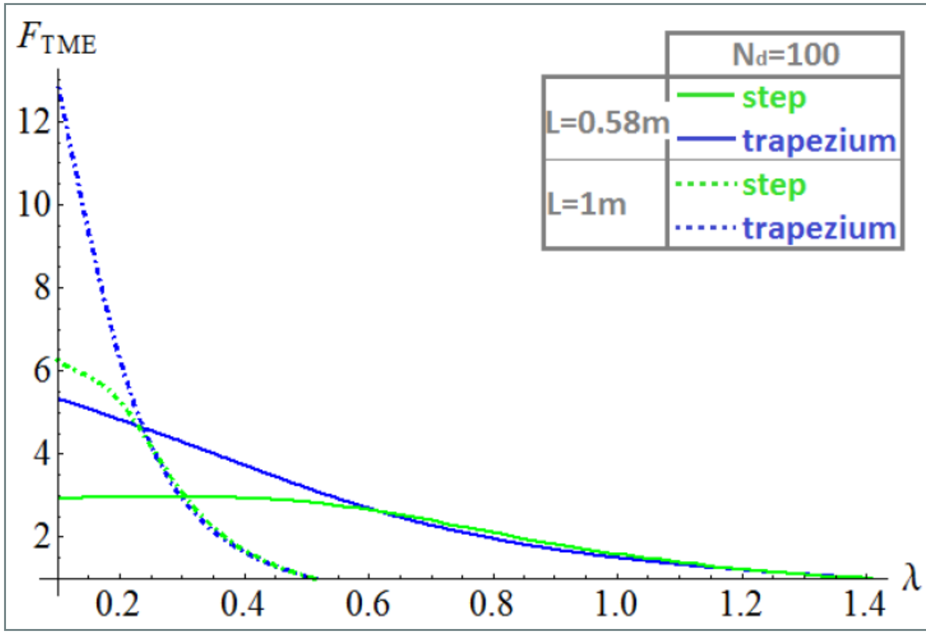
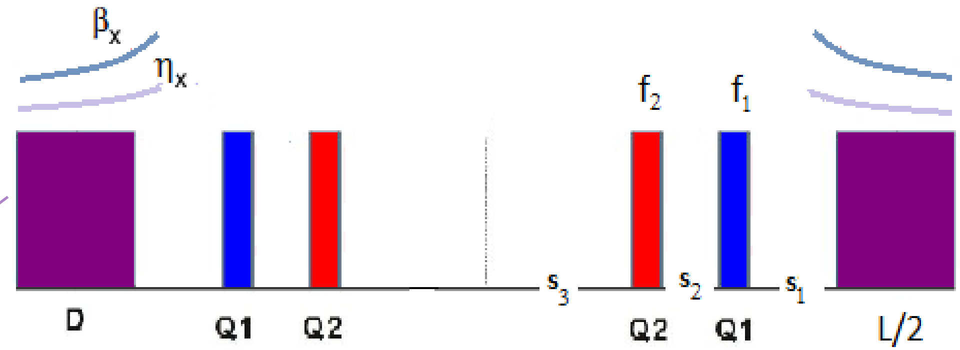




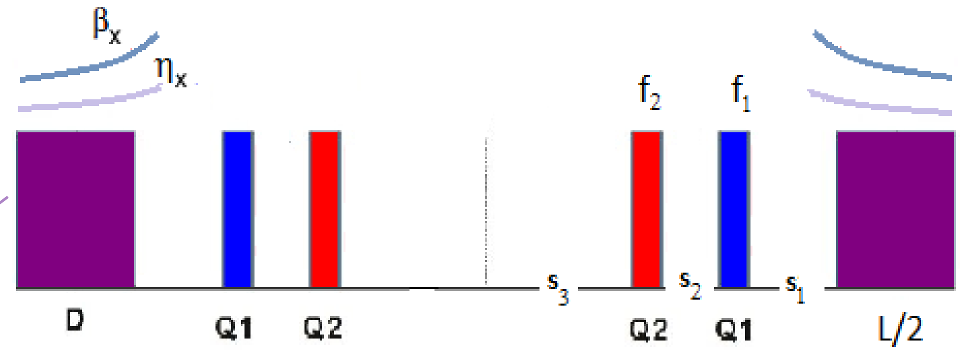
$\downarrow N_d \rightarrow \downarrow F_{TME}$ $\downarrow L \rightarrow \downarrow F_{TME}$

Optimization of the arc TME cell



After fixing the dipoles' characteristics (bending radii ratio ρ and lengths ratio λ, dipole's length L and bending angle θ or else the total number of dipoles N_d) in order to get a large F_{TME}

Optimization of the arc TME cell



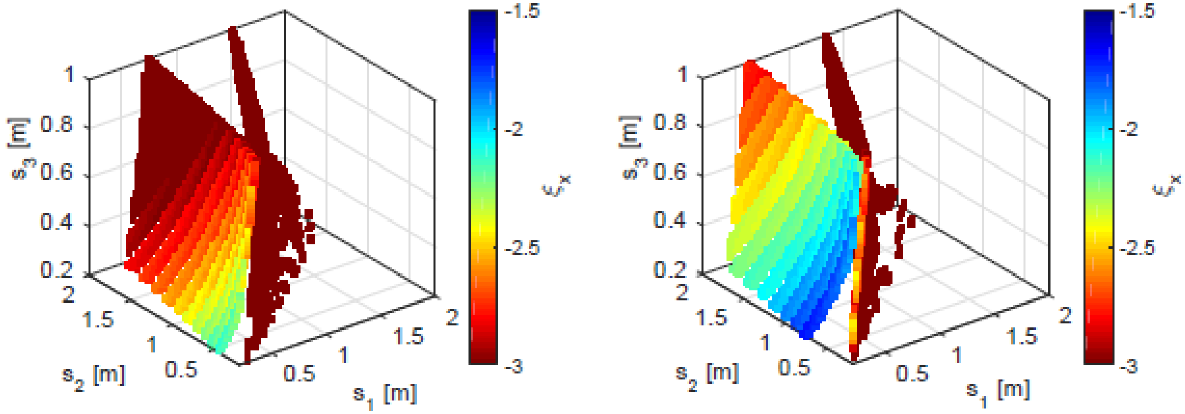
After fixing the dipoles' characteristics (bending radii ratio ρ and lengths ratio λ, dipole's length L and bending angle θ or else the total number of dipoles N_d) in order to get a large F_{TME}

Aiming to reduce the DR's circumference and get the required output parameters, it is necessary to find the:

- the elements' and drifts' lengths that result in a compact cell.
- the optimal phase advances for which:
  - -the horizontal and vertical emittances are $\gamma\varepsilon_x$ <500nm, ε_l <6 keV m
  - -the low chromaticities in both planes guarantee an adequate dynamic aperture
  - -and the quadrupole strengths are k_1,k_2<100 T/m.

Optimization of the arc TME cell

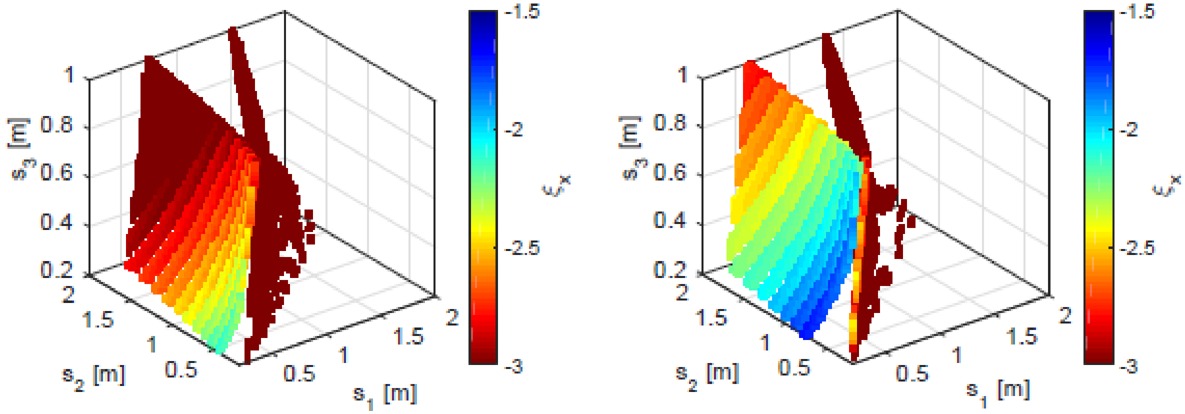
Parametrization with the drift lengths



The horizontal chromaticity ξ_x is parameterized with the drift lengths s_1, s_2, s_3 for the TME, for the step (left) and the trapezium (right) profile

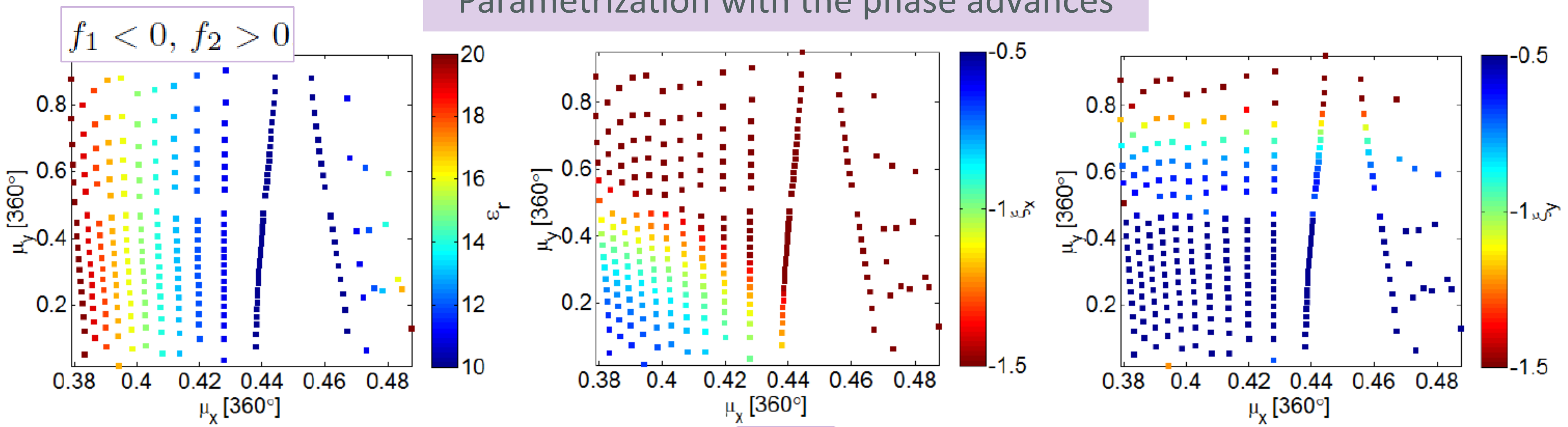
Optimization of the arc TME cell

Parametrization with the drift lengths



The horizontal chromaticity ξ_x is parameterized with the drift lengths s_1, s_2, s_3 for the TME, for the step (left) and the trapezium (right) profile

Parametrization with the phase advances



The parameterization of the detuning factor ε_r ($\varepsilon_r = \varepsilon_x/\varepsilon_{TME}$) and of the horizontal and vertical chromaticities (ξ_x and ξ_y) with the horizontal and vertical phase advances μ_x and μ_y , only for the trapezium profile.

Optimization of the arc TME cell

$$\frac{\epsilon_{var}}{\epsilon_{uni}} < 1 \Rightarrow \frac{\epsilon_{var}}{\epsilon_{uni}} = \frac{\epsilon_{r_{var}} \epsilon_{TME_{var}}}{\epsilon_{r_{uni}} \epsilon_{TME_{uni}}} = \frac{\epsilon_{r_{var}}}{\epsilon_{r_{uni}}} \frac{1}{F_{TME}} \Rightarrow \frac{\epsilon_{r_{var}}}{\epsilon_{r_{uni}}} < F_{TME}$$

Optimization of the arc TME cell

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When properly using the variable bends, lower emittances than the current design's ones are reached. This gives us the flexibility to reduce the existing arcs' TME cells, till the point we get the required output parameters (because the aim was not a lower emittance than the one that already exists, but a shorter ring).

procedure followed in MADX

removing TME cells
checking the output parameters

Optimization of the arc TME cell

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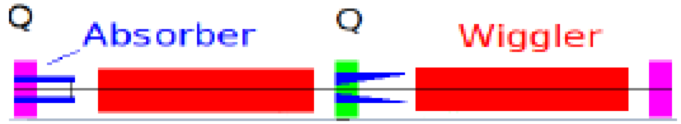
procedure followed in MADX

removing TME cells
checking the output parameters

The optimal solutions are found to be N_d=96 for the step and N_d=90 for the trapezium profile, instead of the existing arc's cell that are N_d=100.

Optimization of the wiggler FODO cell



Results obtained after the optimization of the arc TME cell.

+

When increasing the wigglers' peak field B_w up to a certain point, the emittance and the IBS effect are lowered [3].

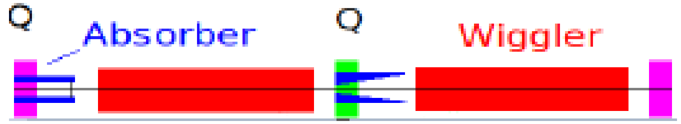
+

Based on the technological restrictions, a new working point for the damp. wiggler is proposed to be at **3.5T** (prev. 2.5T), with 49mm period length[4]

→

Removing some FODO cells from the existing straight section (N_{FODO}=13 per section) is possible.

Optimization of the wiggler FODO cell



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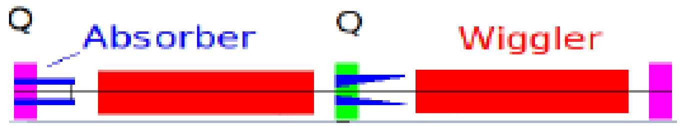
N_{FODO}=10 per straight section

Optimization of the wiggler FODO cell



Results obtained after the optimization of the arc TME cell.	+	When increasing the wigglers' peak field B_w up to a certain point, the emittance and the IBS effect are lowered [3].	+	Based on the technological restrictions, a new working point for the damp. wiggler is proposed to be at **3.5T** (prev. 2.5T), with 49mm period length[4]	→	Removing some FODO cells from the existing straight section (N_{FODO}=13 per section) is possible.

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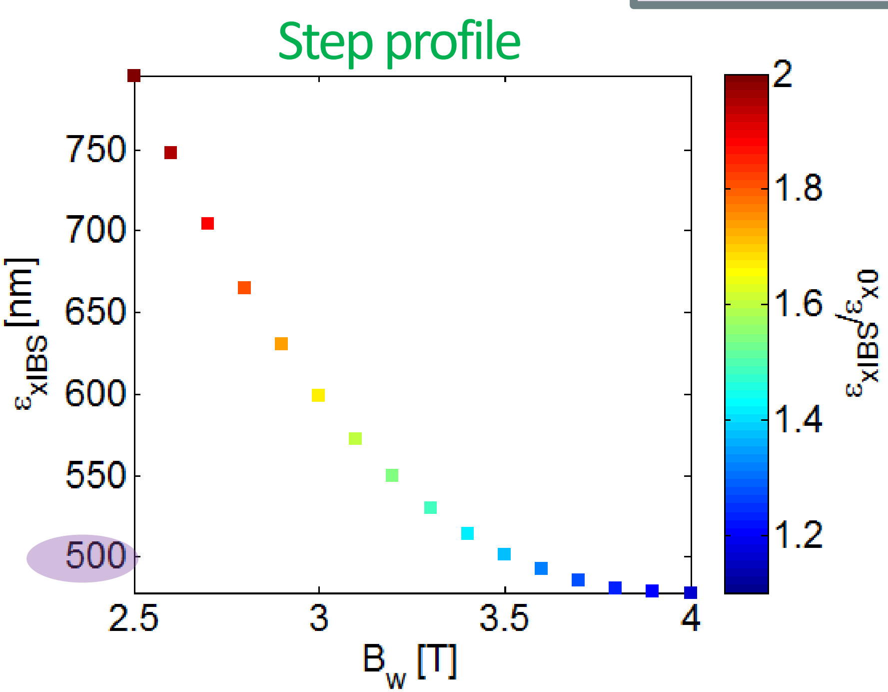
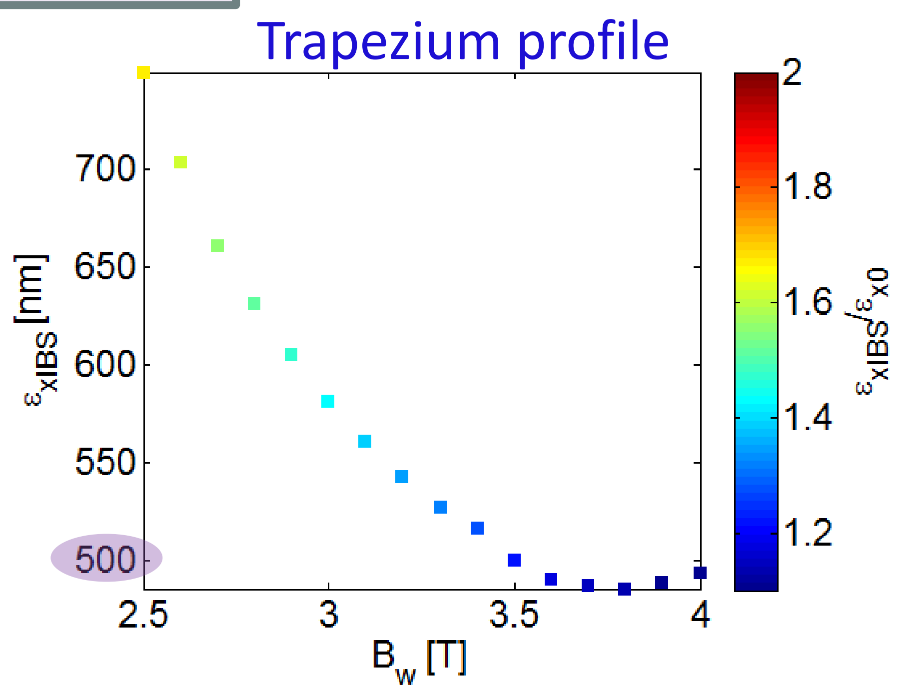




Parametrization of the steady state emittance and the IBS effect with the wiggler's peak field B_w

Design parameters for the main DRs, E=2.86 GeV , 2GHz

Parameters, Symbol [Unit]	uniform	step	trapezium
Number of arc cells/wigglers	100/52	96/40	90/40
Circumference, C [m]	427.5	374.1 (-14.3%)	359.4 (-18.9%)
Dipole field (max/min), B [T]	0.97/0.97	1.77/1.01	1.77/0.73
Horiz./Vert. chromaticities ξ_x/ξ_y	-113/-82	-135/-77	-162/-83
Wiggler peak field, B_w [T]	2.5	3.5	3.5
Wiggler length, L_w [m]	2		
Wiggler period, λ_w [cm]	5.0	5.0	4.9
Damp. times, (τ_x, τ_y, τ_l) [ms]	(2.0, 2.0, 1.0)	(1.2, 1.3, 0.6)	(1.2, 1.2, 0.6)
Mom. compaction, α_c [10^{-4}]	1.3	1.3	1.2
Energy loss/turn, U [MeV]	4	5.7	5.7
Norm. horiz. emittance , $\gamma\varepsilon_x$ [nm-rad] *	657	502	500
Norm. vert. emittance, $\gamma\varepsilon_y$ [nm-rad]	5.0	5.0	5.0
Energy spread (rms), σ_δ [%]	0.11	0.13	0.13
Bunch length (rms), σ_s [mm]	1.8	1.6	1.6
Long. emittance , ε_l [keVm]	6.0	6.1	6.0
IBS factors hor./ver./long.	2.1/1.5/1.2	1.4/1.5/1.1	1.2/1.5/1.1
RF Voltage, V_{RF} [MV]	4.2	6.1	6.1
Stationary phase [°]	70	68	71

*Both lattices[5] reach the target emittances including IBS, as calculated by the Bjorken-Mtingwa formalism through MADX. Using the Piwinski form., the original design[6] (with the uniform dipoles) was also reaching the target horizontal emittance.

Low emittance tuning algorithm

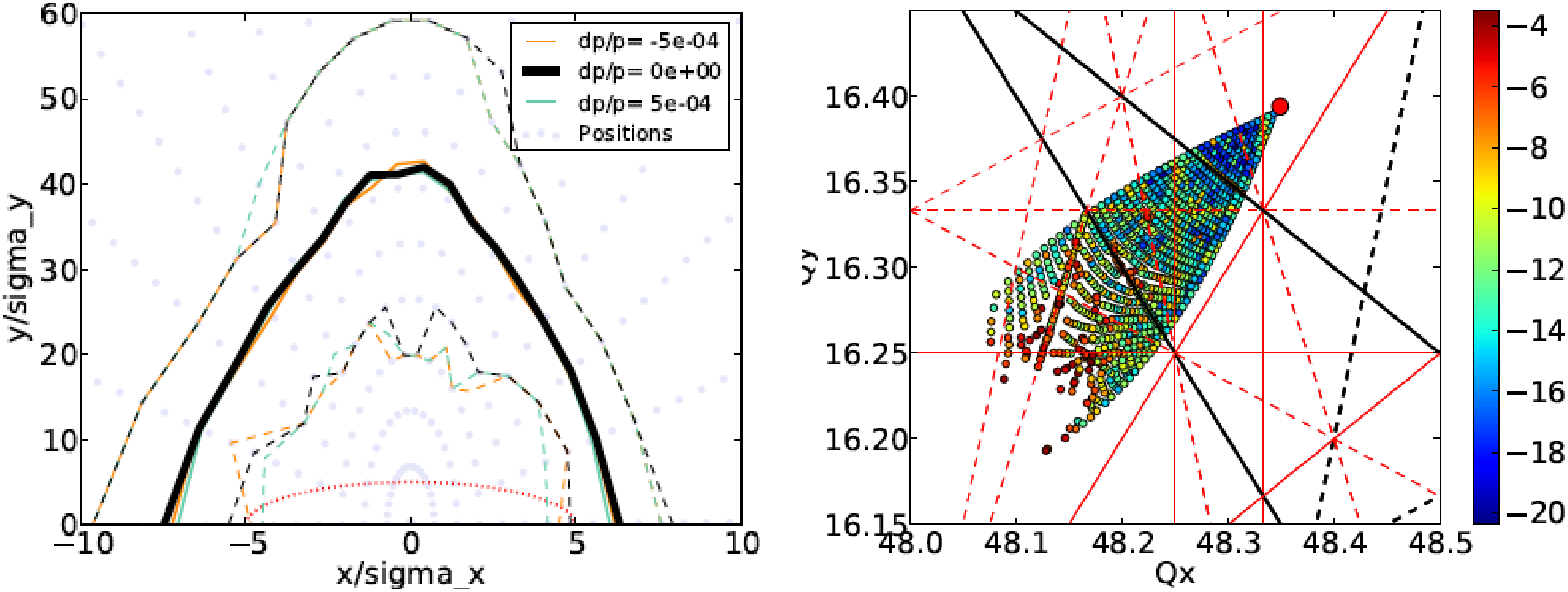
J. Alabau Gonzalvo

- Feed misalignments
- H&V CO correction
- Coupling and dispersion correction
- RF Matching
- Chromaticity correction
- Measure equilibrium emittance

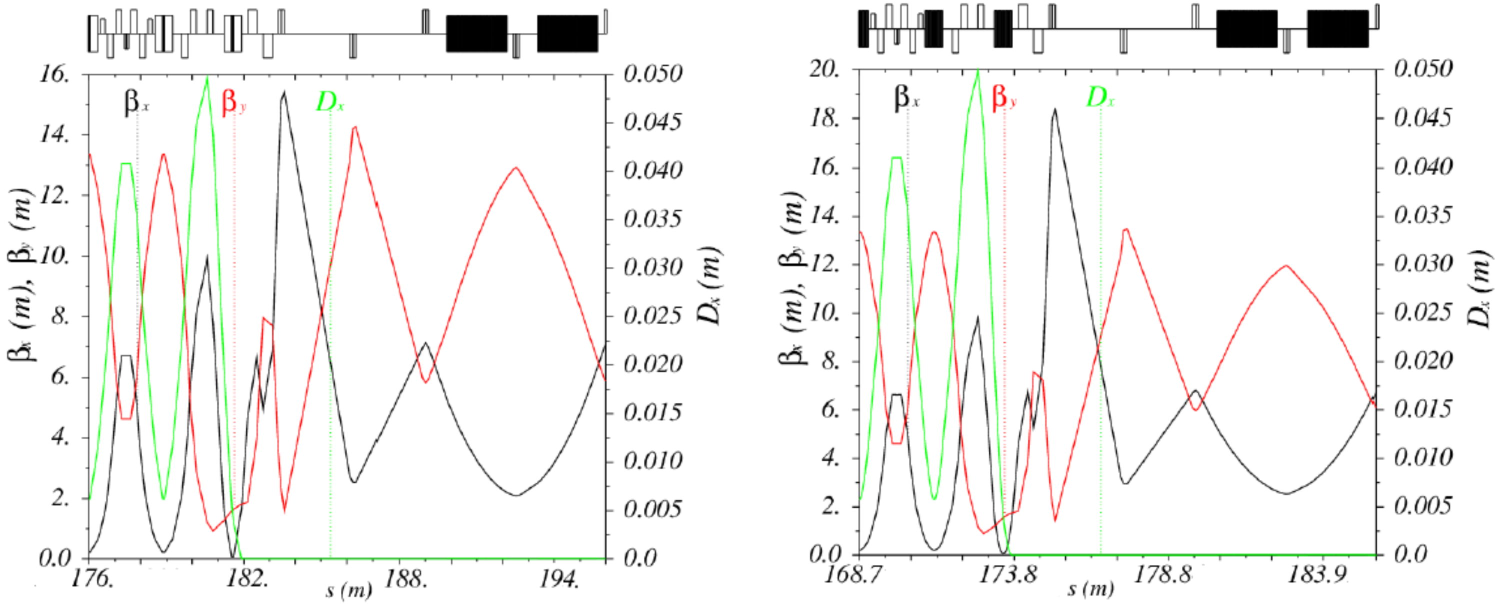
Tolerances $(95\%\ \varepsilon_y < 1pm \cdot rad)$		
Quadrupole Vertical Offset	18	µm
Quadrupole Roll	138	µrad
Dipole Roll	180	µrad
Sextupole Vertical Offset	78 (20)	µm
BPM resolution	200	nm

Dynamic aperture

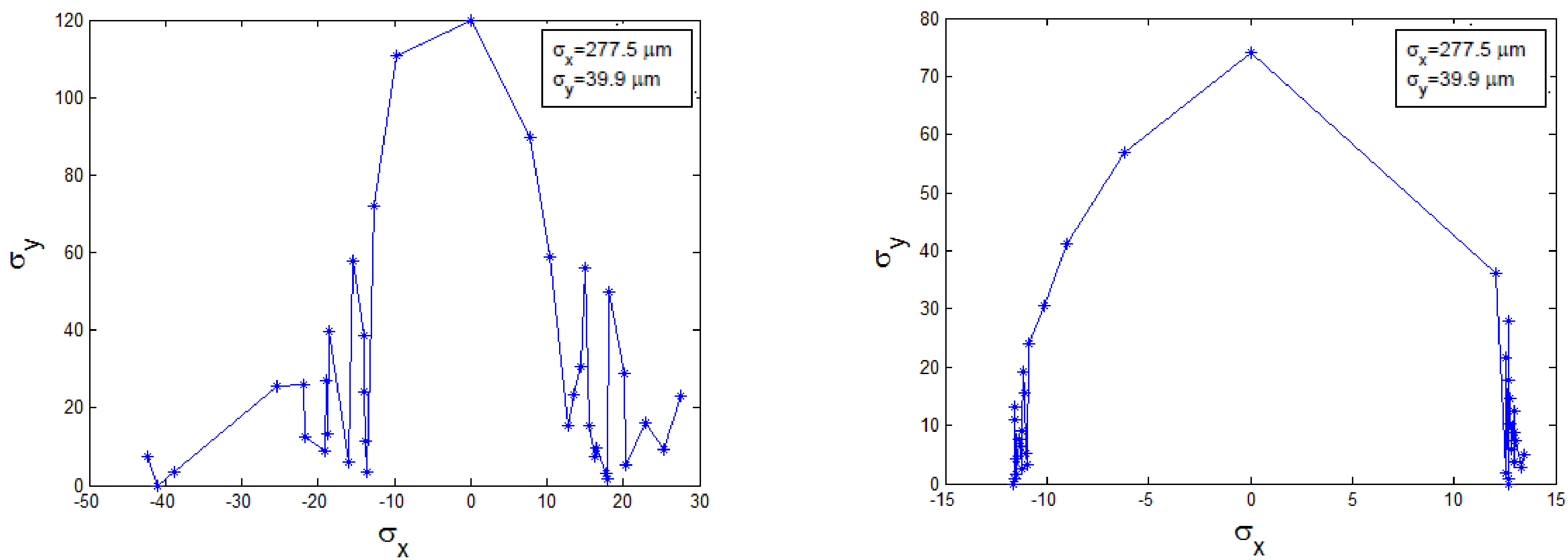
J. Alabau-Gonzalvo



- Dynamic aperture (including SR damping) and frequency map including alignment errors and wiggler field imperfections
- Comfortable DA in the vertical plane tighter in the horizontal
- Need a working optimisation and (tune-spread) correction



Optical functions of one TME cell, the dispersion suppressor-beta matching section and one FODO cell when using in the arcs the step (left) and the trapezium (right) profile.



The on momentum dynamic aperture of the DR for the step (left) and the trapezium(right) profile.

Next steps

- Repeat low emittance tuning and non-linear analysis with new design
  - Including effect of variable bends and wigglers
  - Including space-charge
- Complete analysis of collective effects with new DR parameters
  - Ions, space-charge, e-cloud, impedance budget, feedback specs
- Investigate the possibility to replace e-linac by a booster
- Continue collaboration with low emittance rings community for experimental tests
  - Modeling and protyping of variable dipole bends with CIEMAT (F. Toral)
  - Test existing wiggler at ANKA and finalise Nb_3Sn short wiggler model
  - Test stripline and pulser at ALBA
  - Design of a 1.5 GHz active harmonic RF system for ALBA and adapt it to 2 GHz CLIC DR RF system