CLICWEEK2019

January 21-25 2019

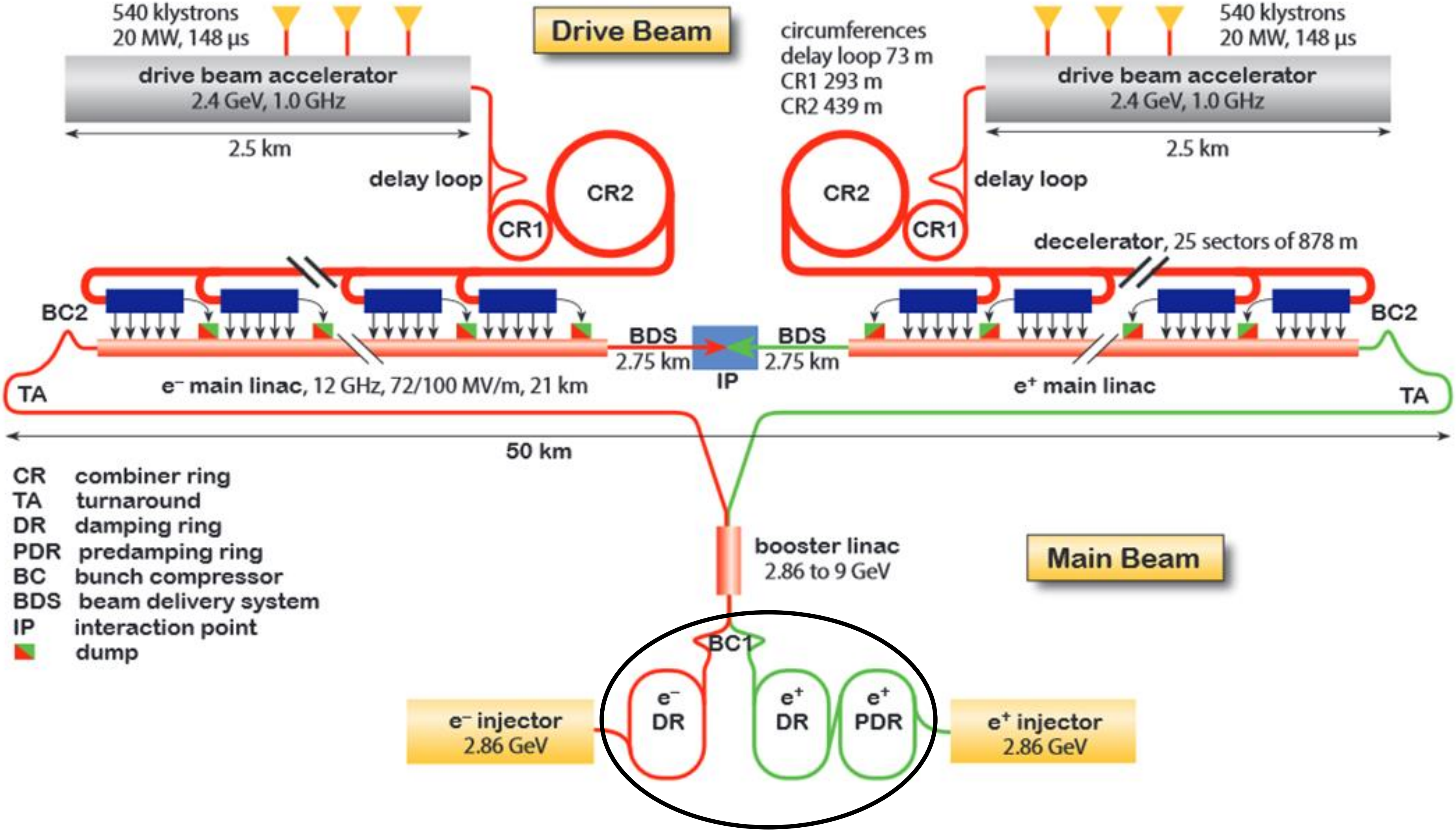
Reaching ultra-low emittance in the CLIC damping rings

Beam dynamics and technology

Y. Papaphilippou

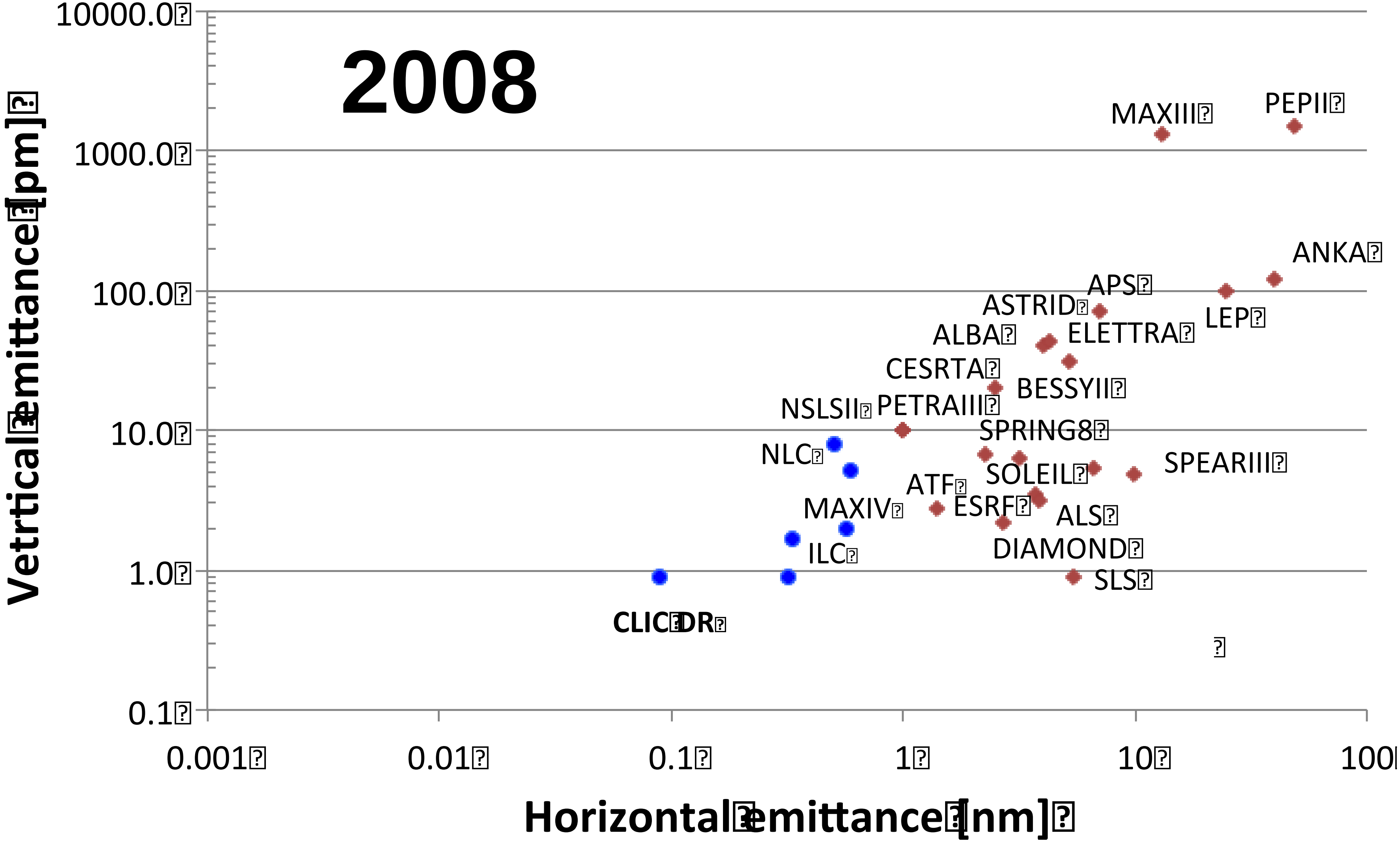
Thanks to F. Antoniou, M. Barnes, C. Belver, A. Grudiev, P. Ferracin, S. Papadopoulou, D. Schörling, P. Zisopoulos (CERN), H. Ghasem (Diamond), L. Fajardo (LBNL), A. Bernard (KIT-ANKA), F. Torral, M. Dominguez (CIEMAT), J. Holma, M. Pont, F. Perez (ALBA), T. Mastorides (CalPoly)

CLIC complex

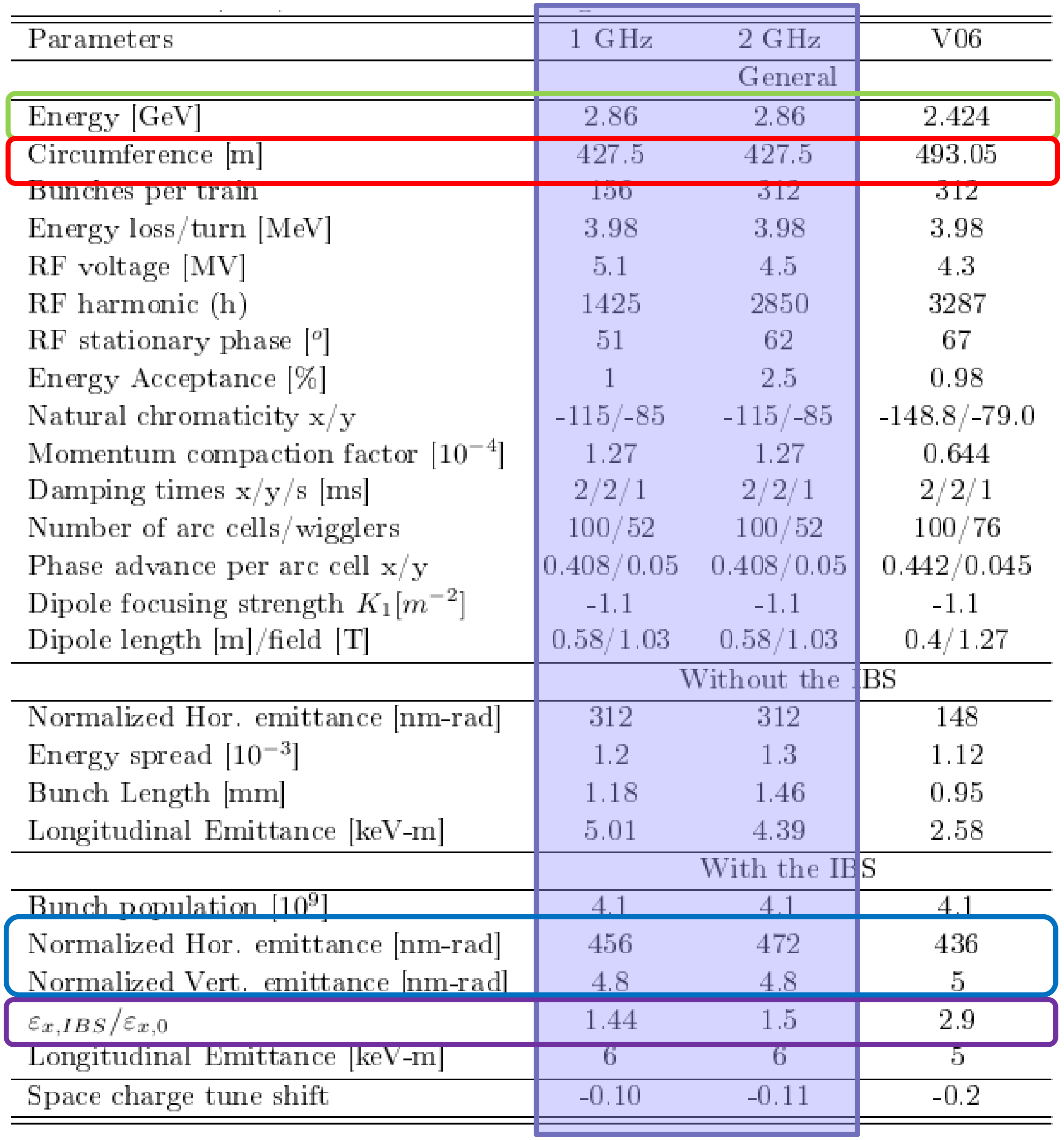


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Emittance targets



The CLIC DR CDR design

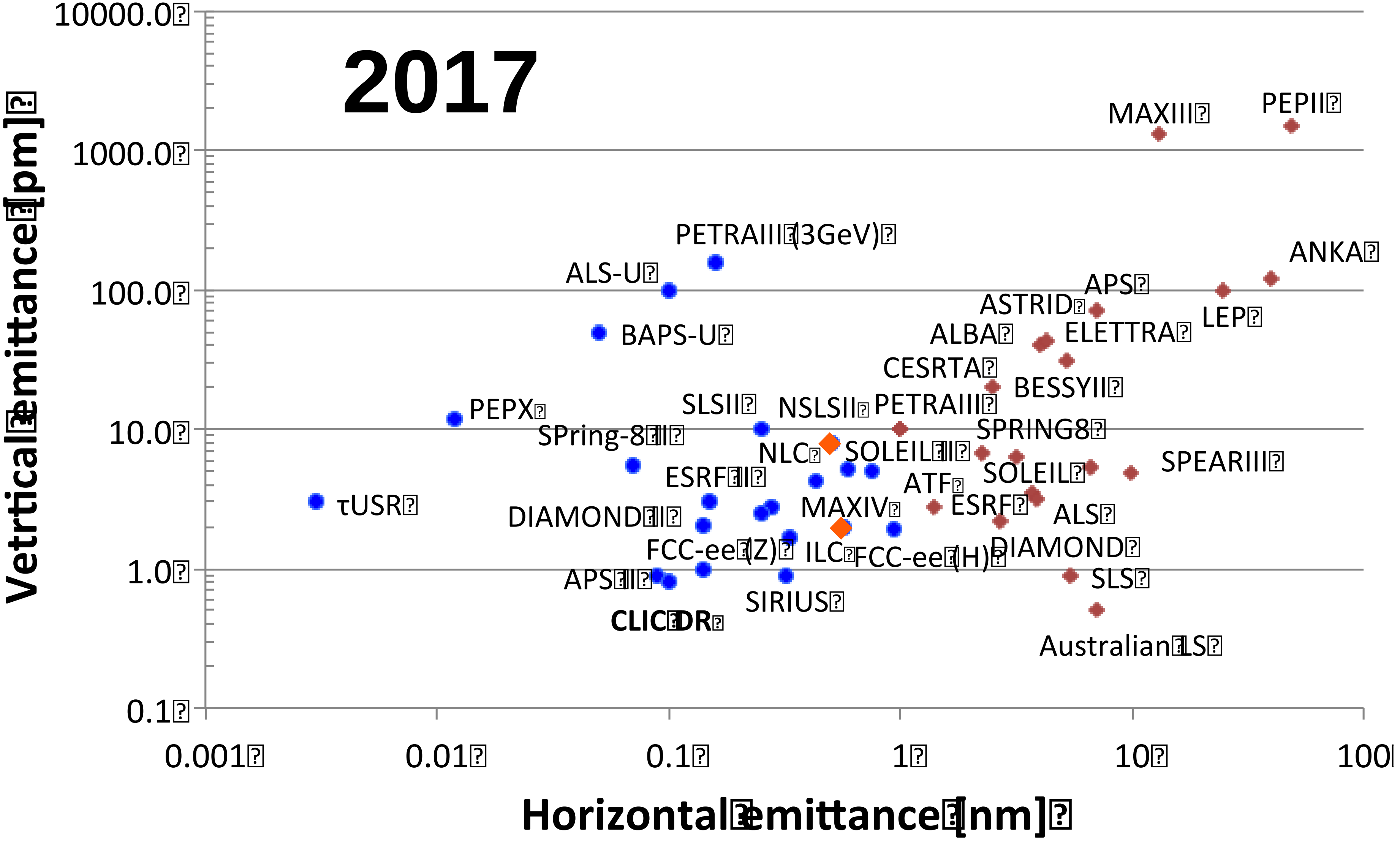


Parameters	1 GHz	2 GHz	V06
		General	
Energy [GeV]	2.86	2.86	2.424
Circumference [m]	427.5	427.5	493.05
Bunches per train	156	312	312
Energy loss/turn [MeV]	3.98	3.98	3.98
RF voltage [MV]	5.1	4.5	4.3
RF harmonic (h)	1425	2850	3287
RF stationary phase [^{o}]	51	62	67
Energy Acceptance [%]	1	2.5	0.98
Natural 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

Emittance targets



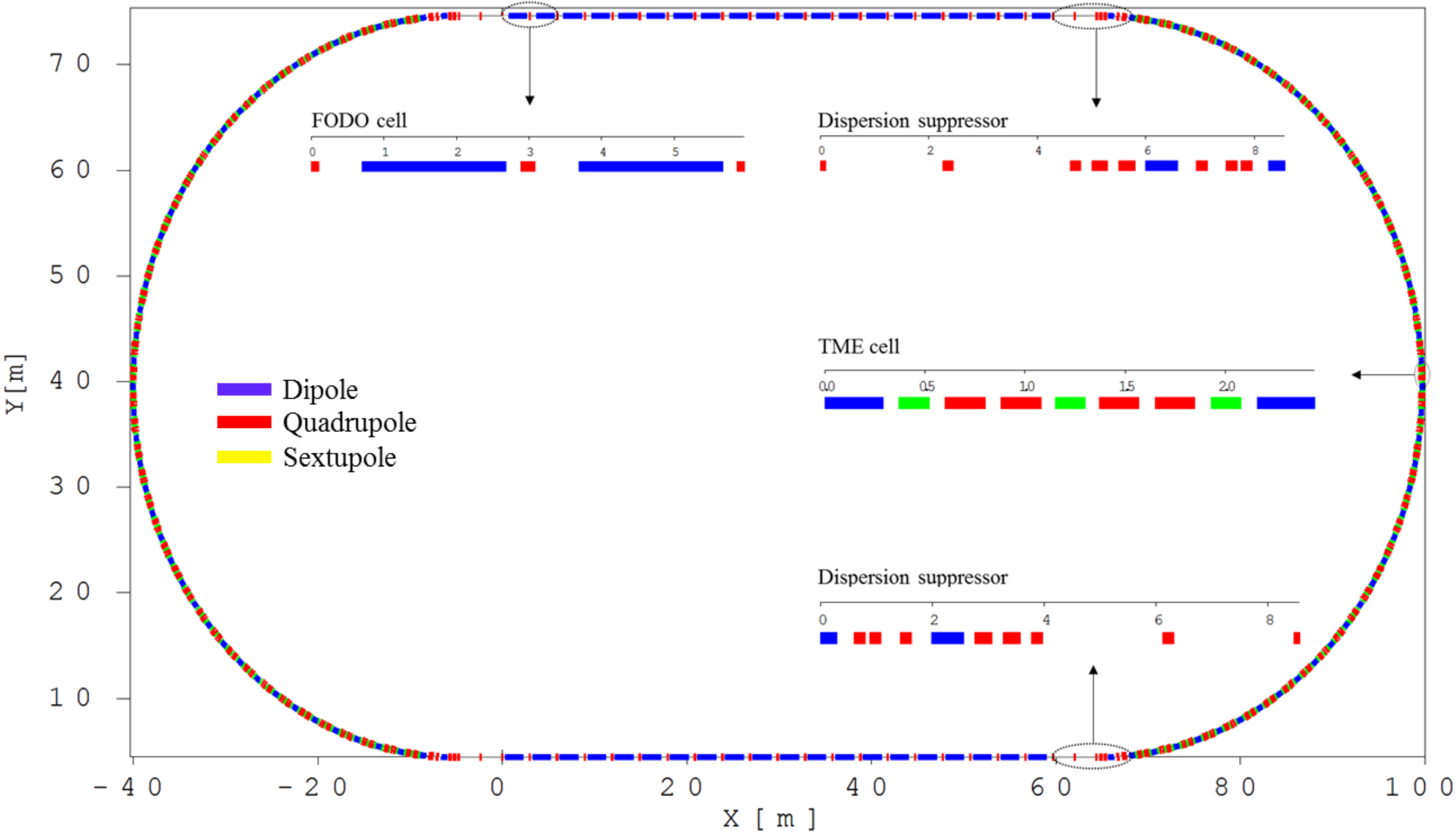
Adapting the DR complex to a new CLIC baseline

- Pre-damping rings **revision**
  - ☐ Remove the electron pre-damping ring
  - ☐ Potentially replace the positron pre-damping ring with a **booster ring** (design still pending)

Adapting the DR complex to a new CLIC baseline

- Pre-damping rings **revision**
  - ☐ Remove the electron pre-damping ring
  - ☐ Potentially replace the positron pre-damping ring with a **booster ring** (design still pending)
- Reviewed 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 layout



- Racetrack shape with TME arc cells and FODO straight sections filled with high field super conducting damping wigglers

Revising CLIC DR design

CDR design of the main CLIC DRs

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 with longitudinally variable bends

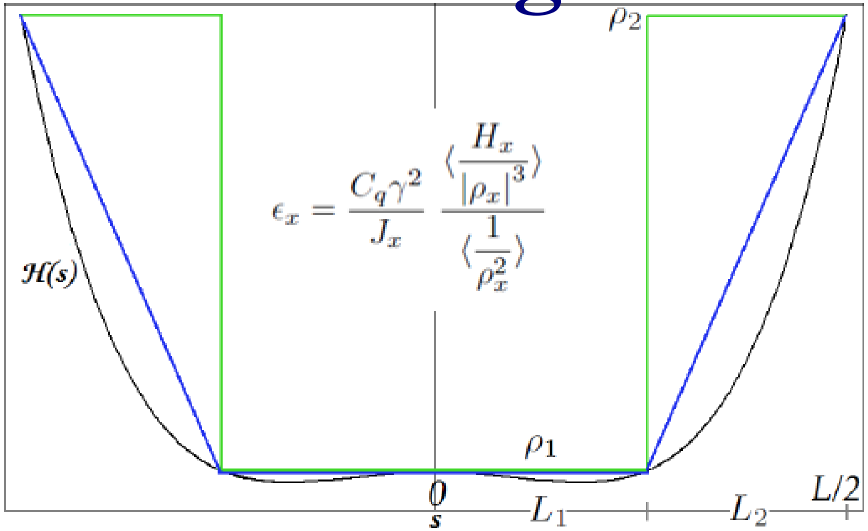
Reduce the number of wiggler using higher wiggler field

500 nm (700 nm) 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

S. Papadopoulou



$$\epsilon_x = \frac{C_q\gamma^2}{J_x}\frac{\langle\frac{H_x}{|\rho_x|^3}\rangle}{\langle\frac{1}{\rho_x^2}\rangle}$$

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

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

Bending radii ratio

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

Lengths ratio

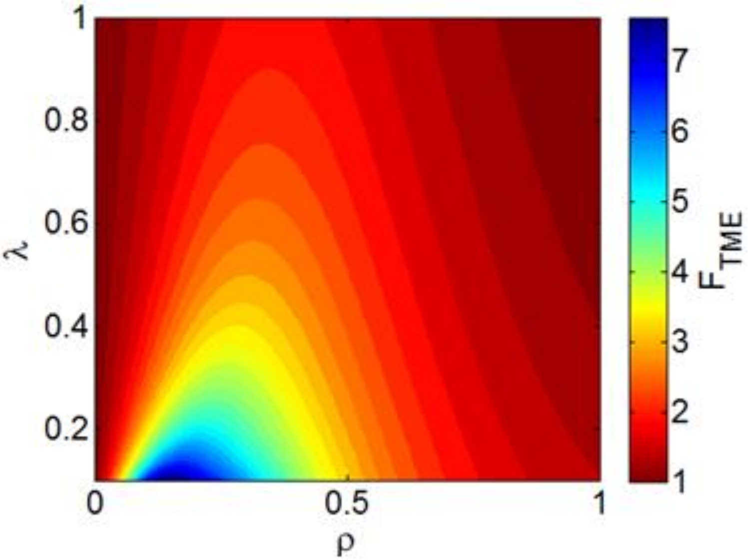
$$\lambda = \frac{L_1}{L_2}$$

Emittance reduction factor

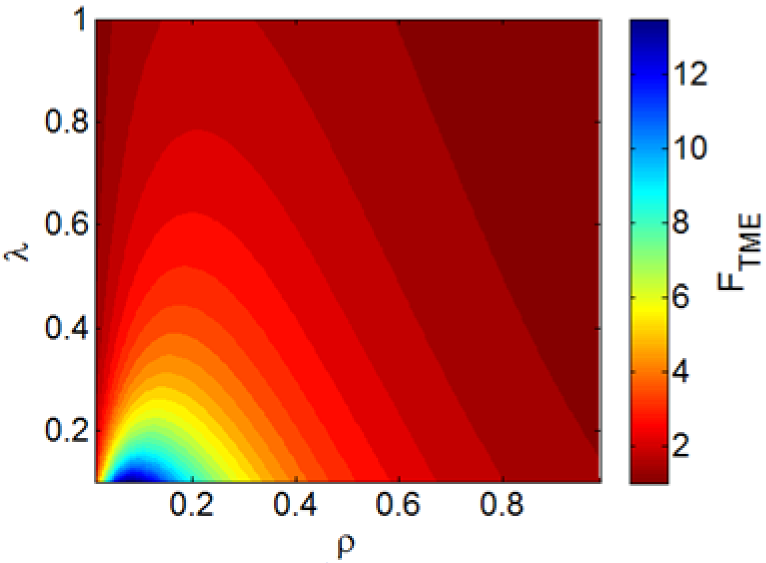
$$F_{TME} = \frac{\epsilon_{TME_{uni}}}{\epsilon_{TME_{var}}}$$

$$F_{TME} > 1$$

Step profile



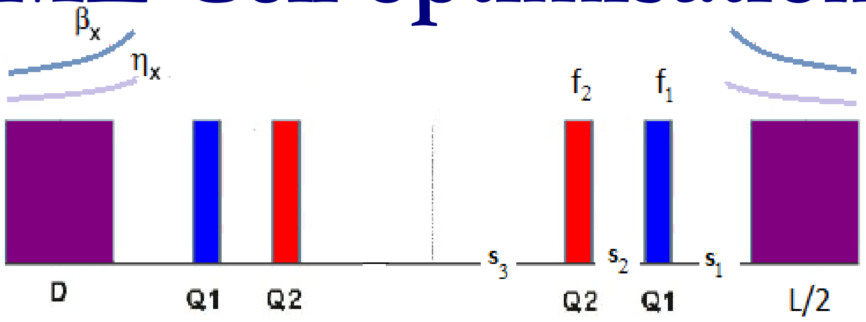
Trapezium profile



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.

TME Cell optimisation

S. Papadopoulou



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

With the variable bends, lower emittances are reached, providing flexibility to reduce the number of TME cells, for reaching target emittance in a shorter ring.

procedure followed in MADX

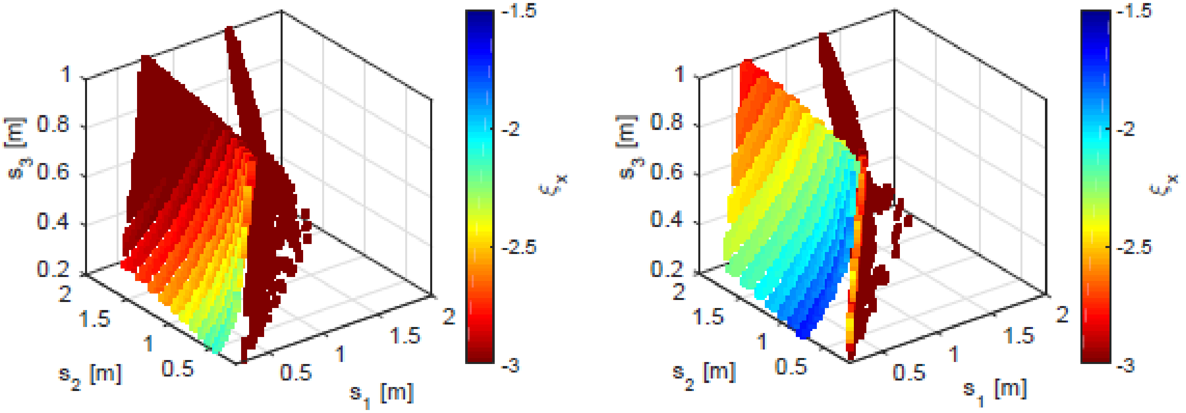
removing TME cells
checking the output parameters

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.

TME Cell optimisation

S. Papadopoulou

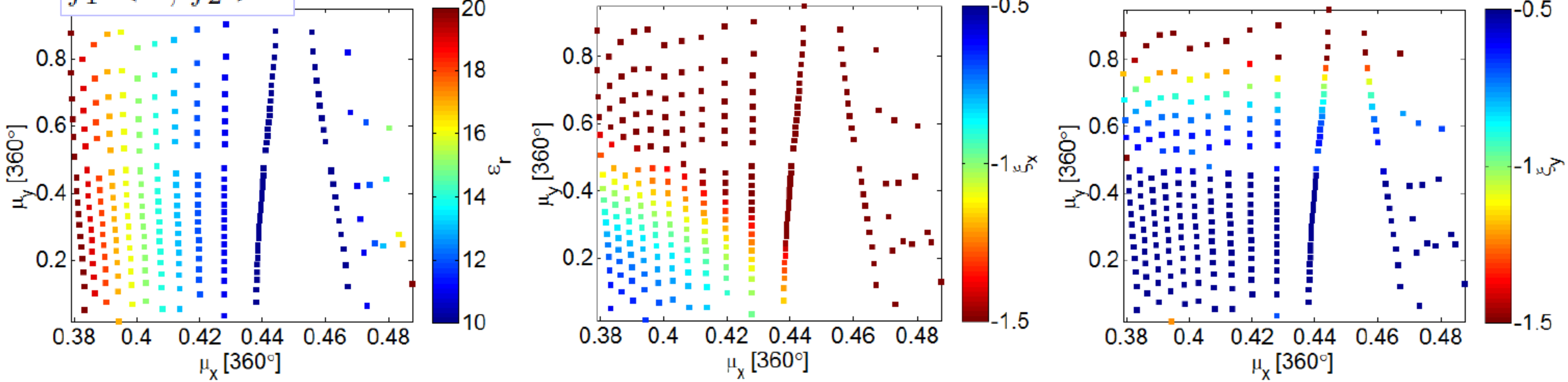
Parametrization with the drift lengths



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

$f_1 < 0,\ f_2 > 0$

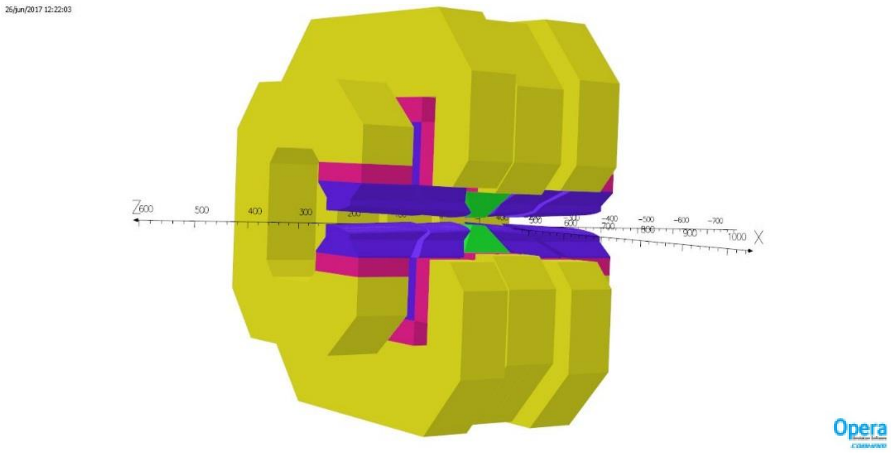


The parameterization of the detuning factor ε_r ($\varepsilon_r = \varepsilon_x/\varepsilon_{TME}$) and of the horizontal and vertical chromaticities (ξ_x and ξ_y) with the horizontal and vertical phase advances μ_x and μ_y , only for the trapezium profile.

TME Cell optimisation

-Based on the trapezium profile, the designed dipole has a total length of 56 cm and bends the beam by 4 degrees.

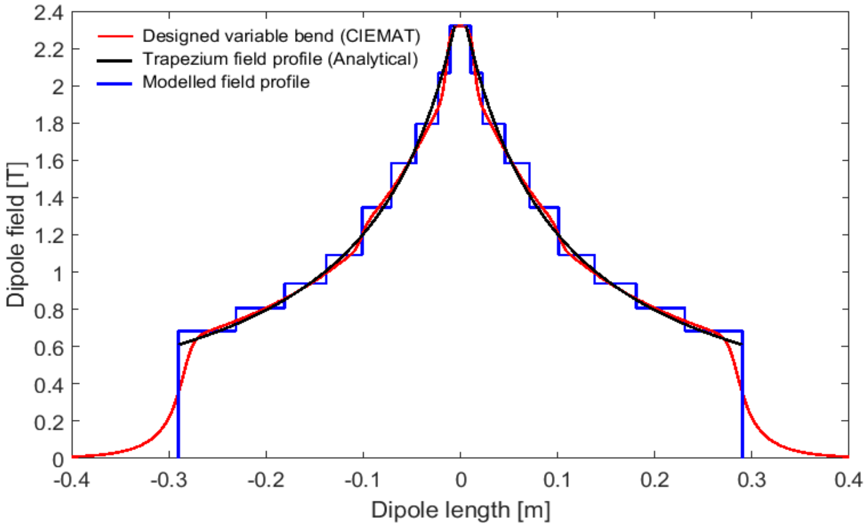
- A maximum field of 2.3 T is reached. The λ and ρ values achieved are 0.04 and 0.29 respectively, corresponding to a F_{TME}=7.



M. A. Domínguez, F. Toral (CIEMAT, Spain)

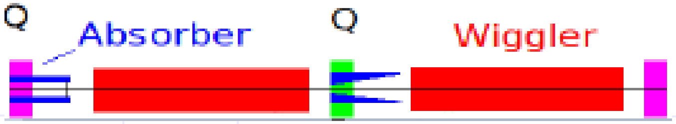
see "Design of a Dipole with Longitudinally Variable Field using Permanent Magnets for CLIC DRs"

Parameters	Highest field section	Lowest field section
Length (cm)	2.143	5.900
Field (T)	2.321	0.685
Radius (m)	4.111	13.937
K (m^{-2})	-1.100	-1.100



M. Dominguez, F. Toral

Optimisation of Wiggler FODO



Results obtained after optimization of the arc TME cell.

+

When increasing the wigglers' peak field B_w, the emittance and the IBS effect are lowered [3].

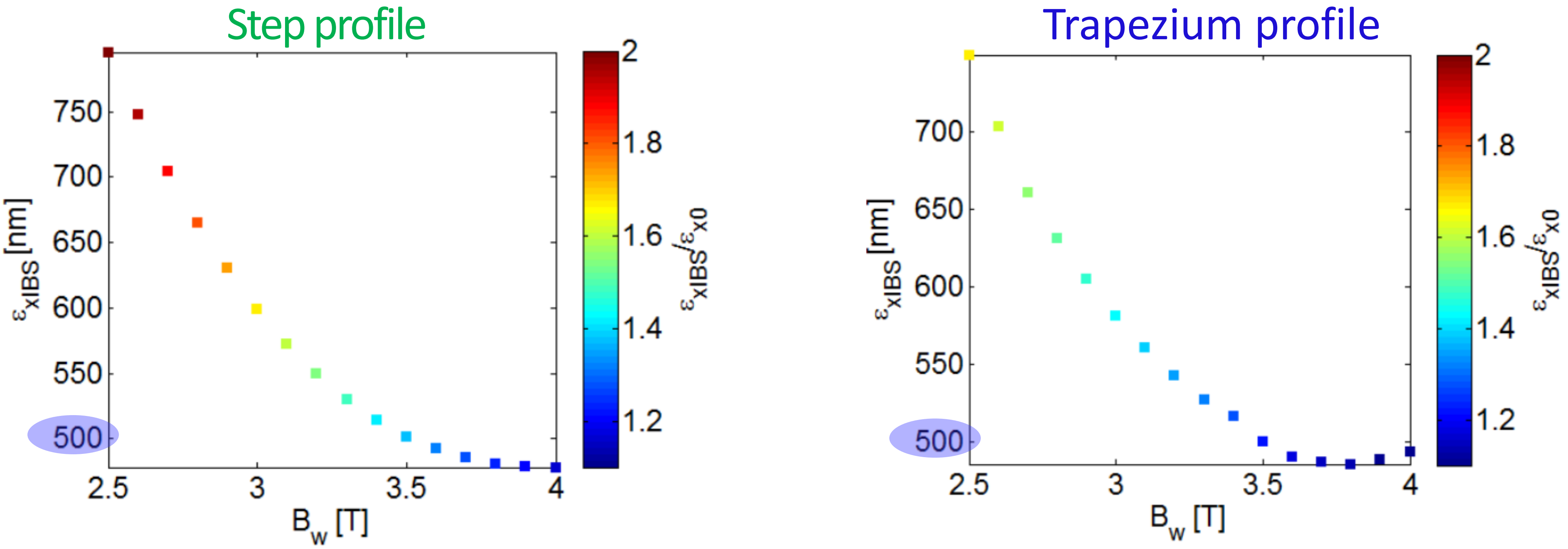
+

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

→

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

N_{FODO}=10 per straight section


Step profile

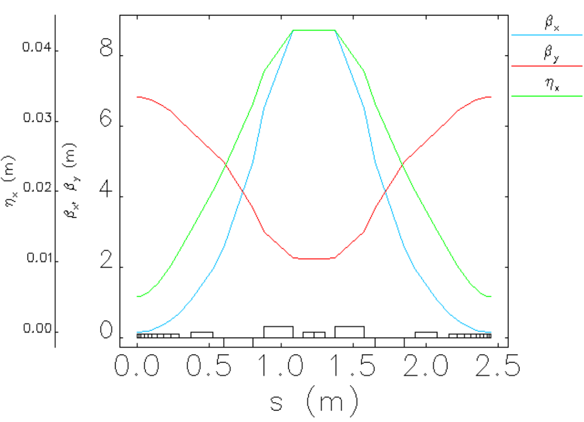
Trapezium profile

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

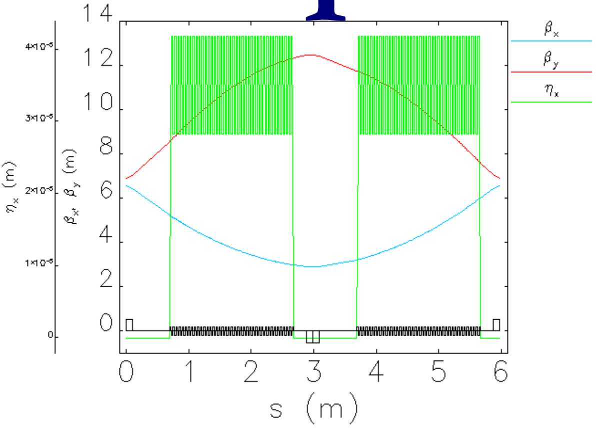
CLIC DR Design parameters

	Nb=4.07e+09			Nb=5.7e+09
Parameters, Symbol [Unit]	uniform	step	trapezium	trapezium
Number of arc cells/wigglers	100/52	96/40	90/40	90/40
Dipole field (max/min), B [T]	0.97/0.97	1.77/1.01	1.77/0.73	1.77/0.73
horiz. /vert. chromaticities ξ_x/ξ_y	-113/-82	-135/-76	-126/-72	-134/-41
Wiggler peak field B_w [T] for length L_w=2m	2.5	3.5	3.5	3.5
Wiggler period, λ_w [cm]	5.0	4.9	4.9	4.9
Mom. compaction, α_c [10^{-4}]	1.3	1.3	1.2	1.2
Energy loss/turn, U [MeV/turn]	4	5.7	5.7	5.8
Energy spread (rms), σ_δ [%]	0.12	0.13	0.13	0.13
Bunch length (rms), σ_s [mm]	1.8	1.6	1.6	1.3
Long. emittance , ε_l [keV m]	5.9	6.1	6.0	5.0
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)	(1.2, 1.2, 0.6)
IBS factors hor./ver./long.	2.2/1.5/1.2	1.4/1.5/1.1	1.4/1.5/1.1	1.4/2.0/1.1
Norm. horizontal emittance (with IBS), $\gamma\varepsilon_x$ [nm]	681	502	500	579
Norm. vertical emittance (with IBS), $\gamma\varepsilon_y$ [nm]	5	5	5	6.7
Circumference, C [m]	427.5	374.1 (-14%)	359.4 (-19%)	359.4 (-19%)

CLIC DR Optics

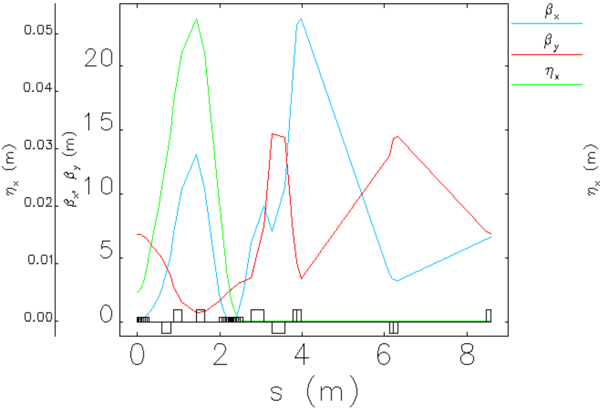


TME cell;
Length= 2.45 m
$\psi_x/2\pi$= 0.442
$\psi_y/2\pi$= 0.1

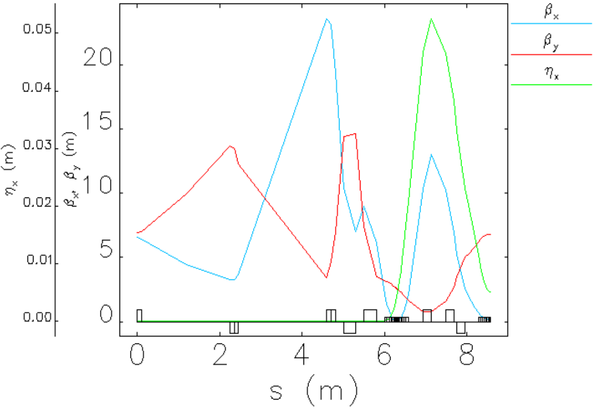


FODO cell;
Length= 5.969
$\psi_x/2\pi$= 0.238
$\psi_y/2\pi$= 0.096
Wiggler (l=2 m, B=3.5 T, L_λ=49 mm)

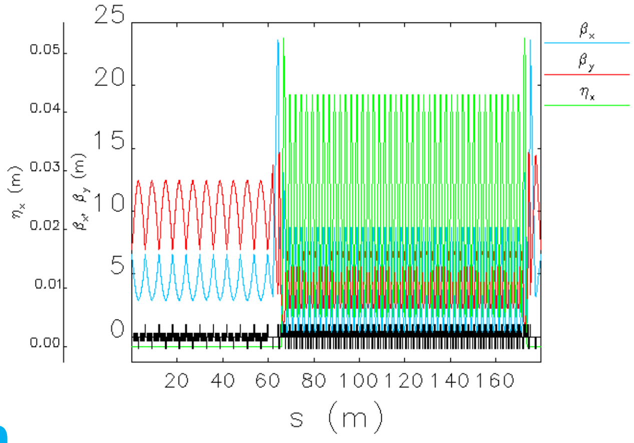
Parameters	Value
Energy [GeV]	2.86
Circumference [m]	359.44
No. of Dipole/wiggler	90/40
Hor./Ver. Tune	45.27/13.33
Nat./nor. emittance [pm/nm]	79.00/442.18
Nat. chromaticity	-134.42/-41.63
1st order mom. compaction	1.17E-4
Energy spread	1.28E-3
Energy loss per turn [MeV]	5.79
Damping time [ms/ms/ms]	1.17/1.19/0.60
Radio frequency [GHz]	2
RF voltage [MV]	6.5
Bunch length/charge [mm/nC]	1.26/0.91
Number of particles per bunch	5.7E10
Natural emittance+ IBS [pm]	110
Energy spread + IBS	1.33E-3
Bunch length + IBS [mm]	1.31



Dispersion suppressor;
Length=8.57
$\psi_x/2\pi$= 0.85
$\psi_y/2\pi$=0.757

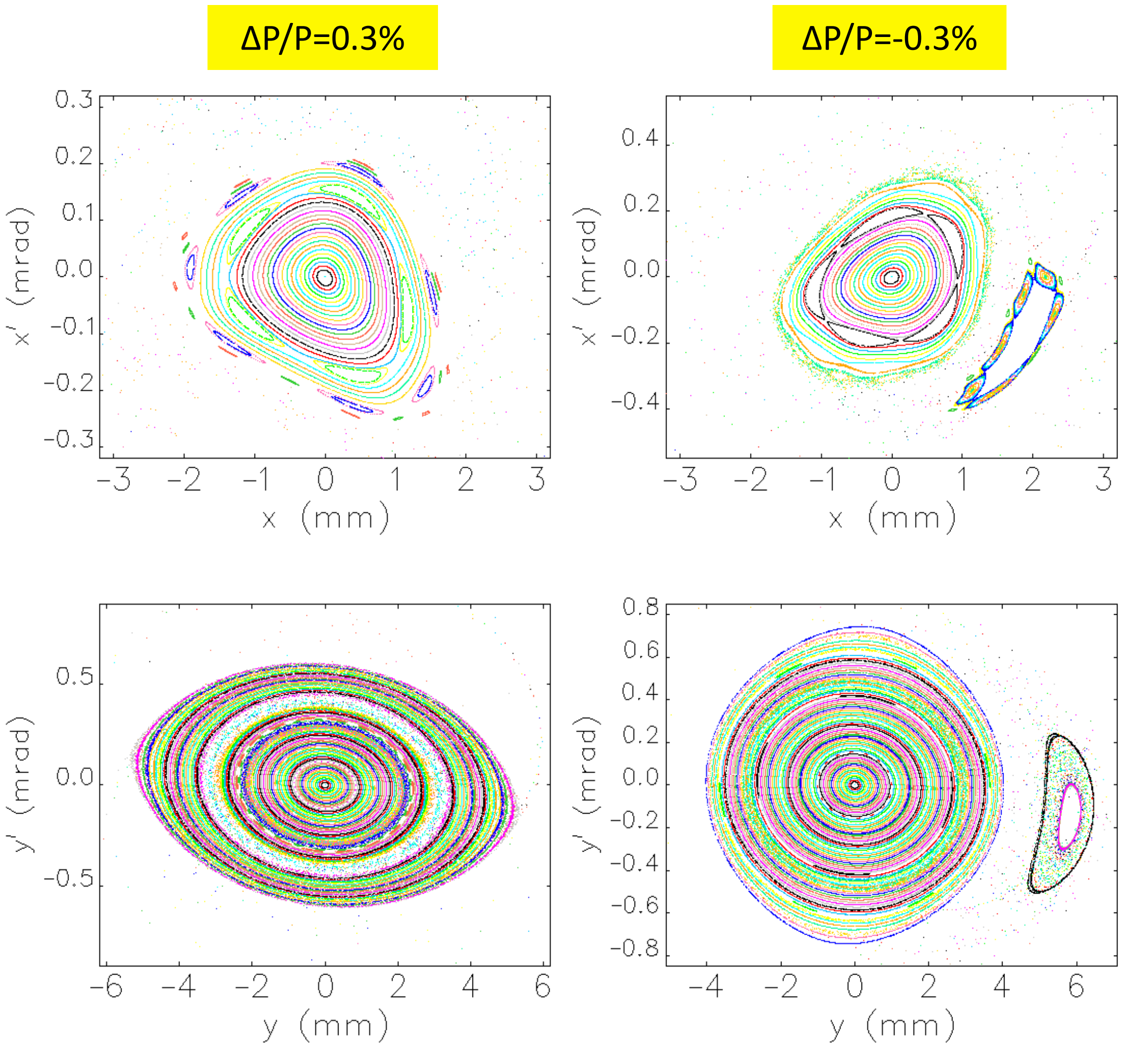


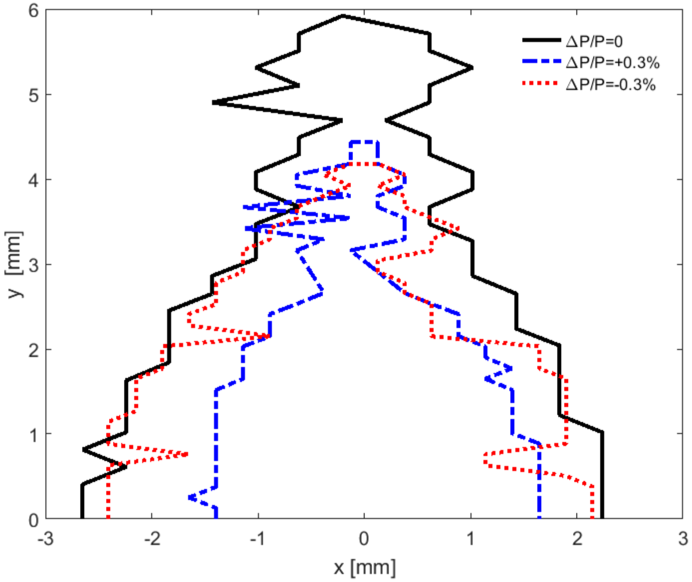
Dispersion suppressor;
Length= 8.56
$\psi_x/2\pi$= 0.85
$\psi_y/2\pi$= 0.748

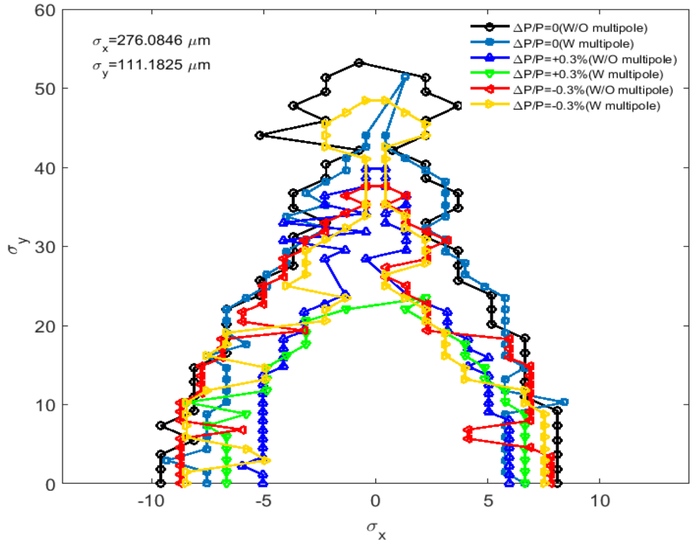


H. Ghasem

Dynamic aperture with errors







The injected positron beam specification
(ε_{xn}=65 µm and ε_{yn}=10 µm, δ=0.3%)

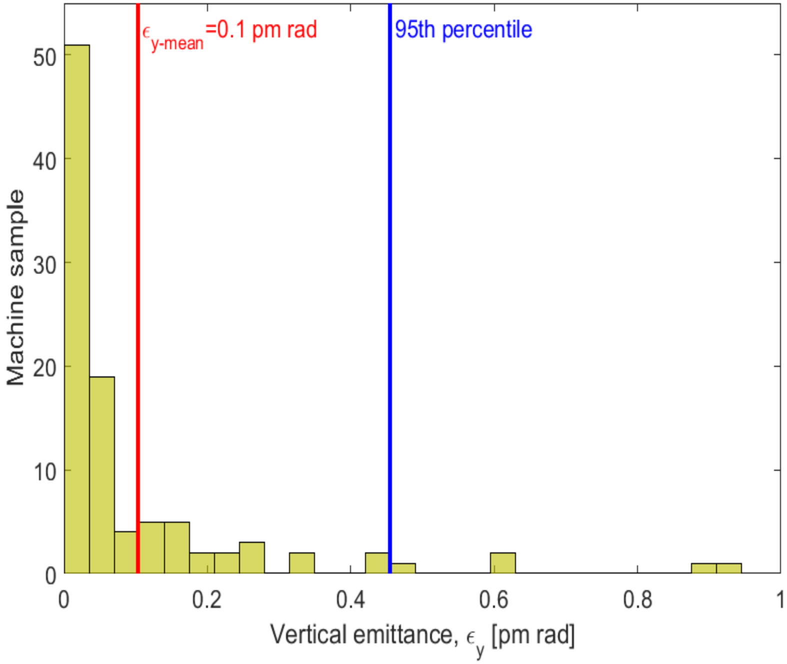
H. Ghasem

Vertical emittance tuning

- Vertical emittance in the CLIC DR including all errors, specified misalignments and BPM offsets, rolls and noise jitter (100 random seeds)

Error	Unit	Value
Dipole/quadrupole/sextupole/BPM vertical misalignment	µm	40/16/70/70
Dipole/quadrupole/sextupole roll	µrad	70/50/100
BPM roll	µrad	70
BPM noise	nm	200

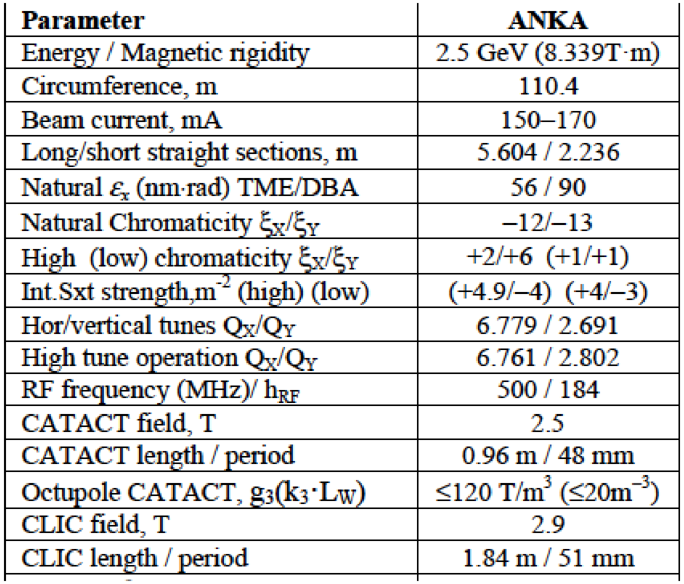
- The mean value of the vertical emittance for 100 seeds is around 0.1 pm rad and fc 95% of machine samples, the vertical emittance is below 0.5 pm rad.



H. Ghasem

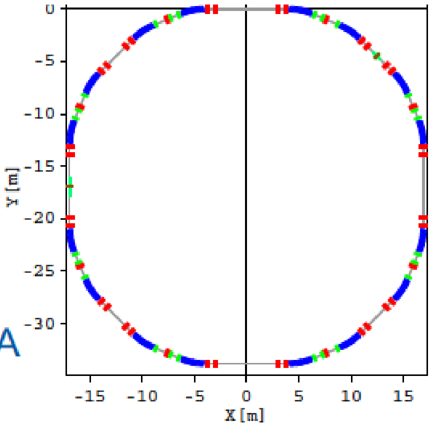
NbTi Wiggler tests at ANKA

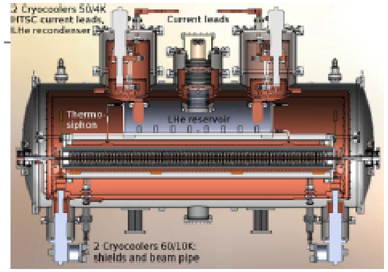
A. Bernard, P. Zisopoulos



Parameter	ANKA
Energy / Magnetic rigidity	2.5 GeV (8.339T·m)
Circumference, m	110.4
Beam current, mA	150–170
Long/short straight sections, m	5.604 / 2.236
Natural ε_x (nm·rad) TME/DBA	56 / 90
Natural Chromaticity ξ_X/ξ_Y	–12/–13
High (low) chromaticity ξ_X/ξ_Y	+2/+6 (+1/+1)
Int.Sxt strength,m^{-2} (high) (low)	(+4.9/–4) (+4/–3)
Hor/vertical tunes Q_X/Q_Y	6.779 / 2.691
High tune operation Q_X/Q_Y	6.761 / 2.802
RF frequency (MHz)/ h_{RF}	500 / 184
CATACT field, T	2.5
CATACT length / period	0.96 m / 48 mm
Octupole CATACT, $g_3(k_3 \cdot L_W)$	≤120 T/m^3 (≤20m^{-3})
CLIC field, T	2.9
CLIC length / period	1.84 m / 51 mm

- ANKA (recently renamed KARA) is a 4-fold DBA ring with very flexible optics, able to serve 19 beamlines
- The CLIC SC Nb-Ti Wiggler prototype was installed at KIT-ANKA in 2016.
- This project is the result of a fruitful collaboration between KIT, BINP and CERN
- Several ongoing studies to characterize the impact of the wiggler on beam dynamics





Cross-section of the assembled wiggler cryostat. Mezentsev N.A., 2012

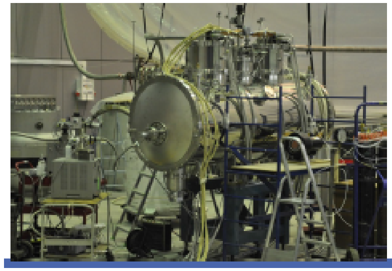


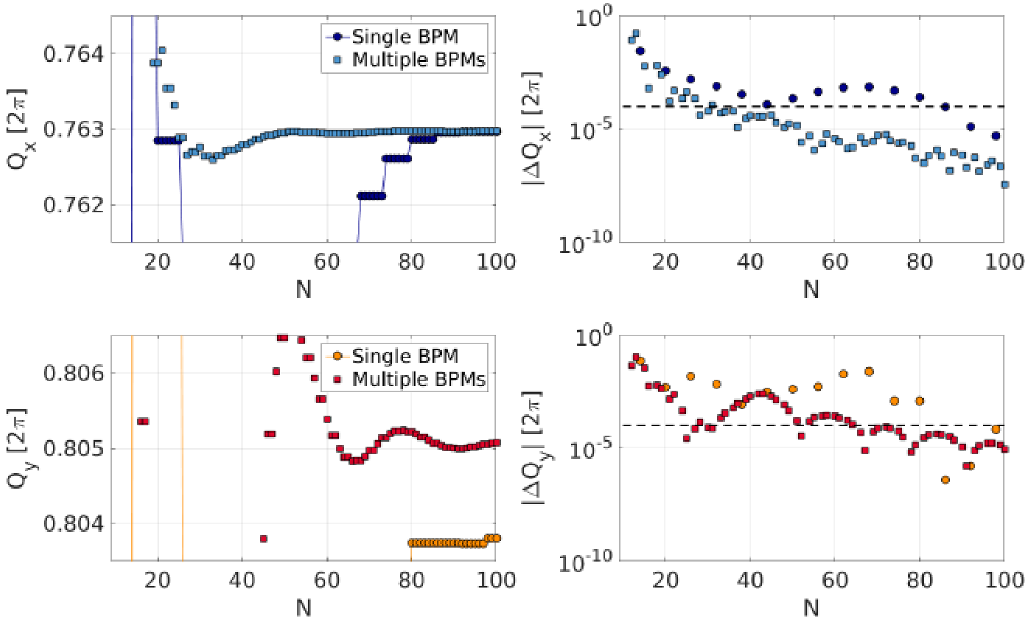
Photo taken during FAT at BINP

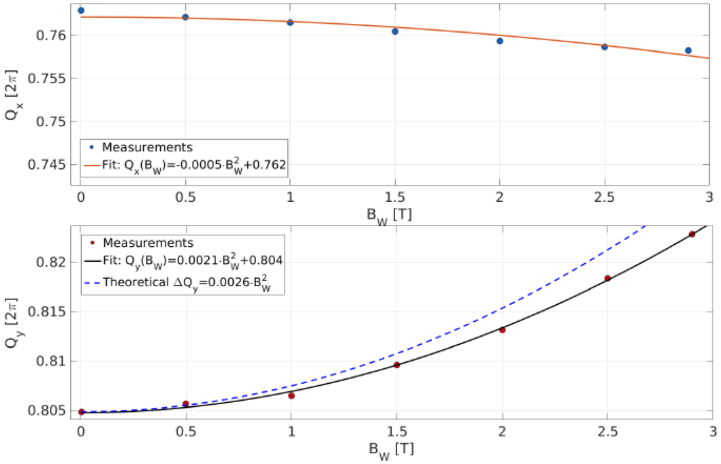
J. Gethmann et al, IPAC 2017, WEPIK068, p.3087-3089

A. Bernhard et al, IPAC 2016, WEPMW002, p.2412-2415

NbTi Wiggler tests at ANKA

P. Zisopoulos

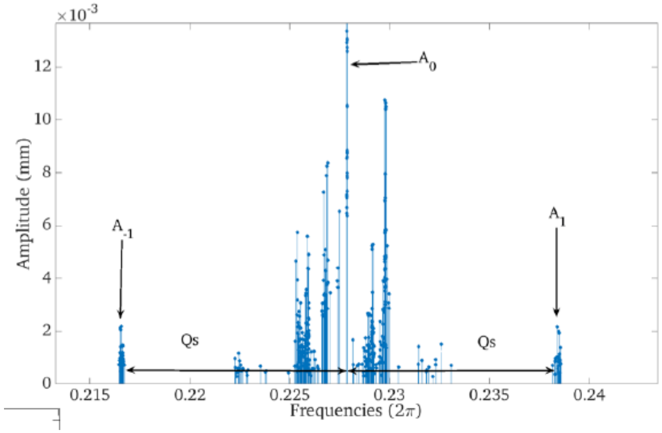




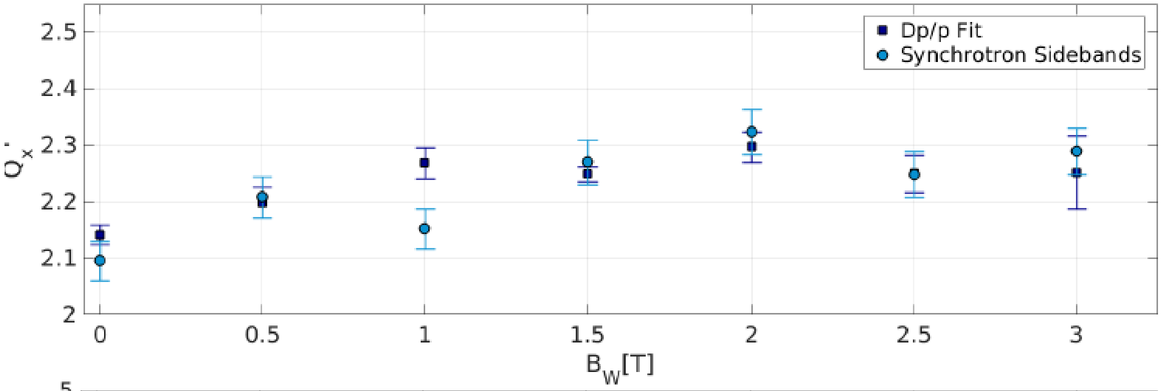
- By using the mixed BPMs scheme the tunes were also measured during each ramp of the wiggler with the beam at the nominal chromatic orbit.
- Precision is increased in both cases and it is at the level of 10^{-4} at around 30 turns.
- The measurements were fitted with quadratic models.
- The horizontal tune-shift is not expected but it is present, possibly due to sextupolar feed-downs.
- The expected vertical tune-shift is relatively close to the theoretical predicted value.
- (ΔQx/Qx, ΔQy/Qy) ~ (0.5%, 2%) at 2.9 T

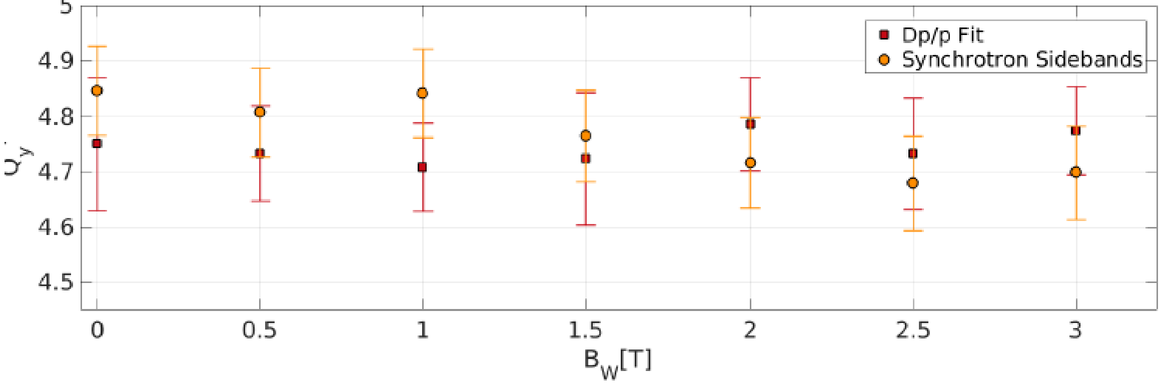
NbTi Wiggler tests at ANKA

P. Zisopoulos



$$Q' = \frac{Q_s}{\sigma_\delta}\sqrt{\frac{A_1+A_{-1}}{A_0}}$$





- The synchrotron tune at ANKA is Qs=0.013.
- The chromaticity was extracted from the Fourier spectra of 4/Qs turns and from a fit with the dp/p.
- The measurements indicate a slight increase of Q^{*}_{x}
- For Q^{*}_{y} the uncertainty in the vertical plane is larger so a clear trend is not evident.

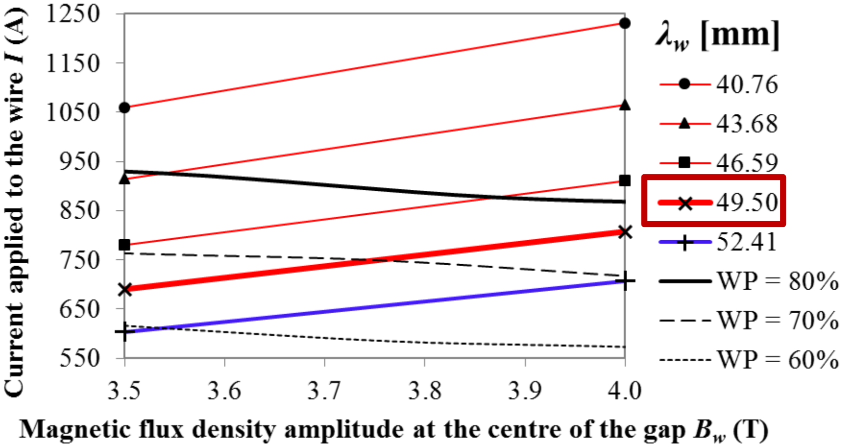
Nb$_3$Sn wiggler Design

L. Fajardo

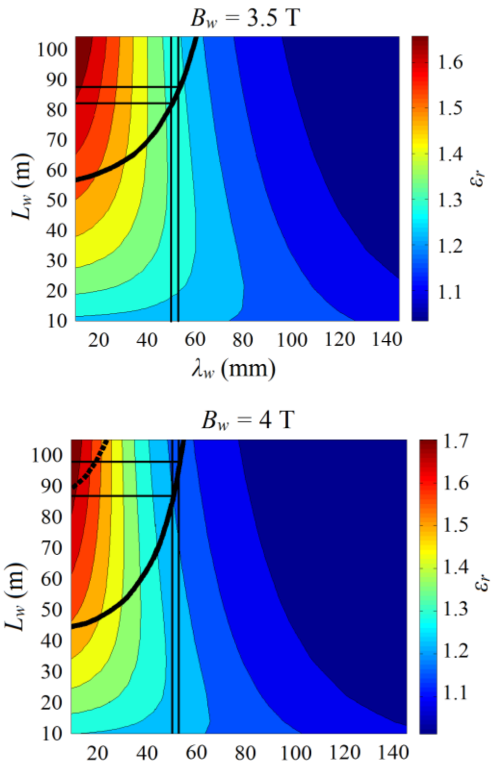
ADDITIONAL RESTRICTION:

Keeping the working point (*WP*) below 80% of the magnet's current limit for all $3.5\ \mathrm{T} \leq B_w \leq 4\ \mathrm{T}$

Scenarios for achieving $3.5\ \mathrm{T} \leq B_w \leq 4\ \mathrm{T}$ with $40\ \mathrm{mm} \leq \lambda_w \leq 55\ \mathrm{mm}$ values:

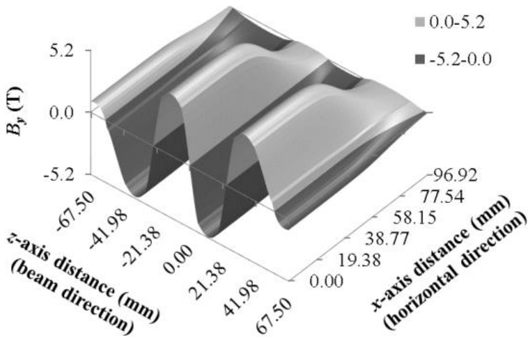


Larger potential L_w reduction with λ_w = 49.5 mm

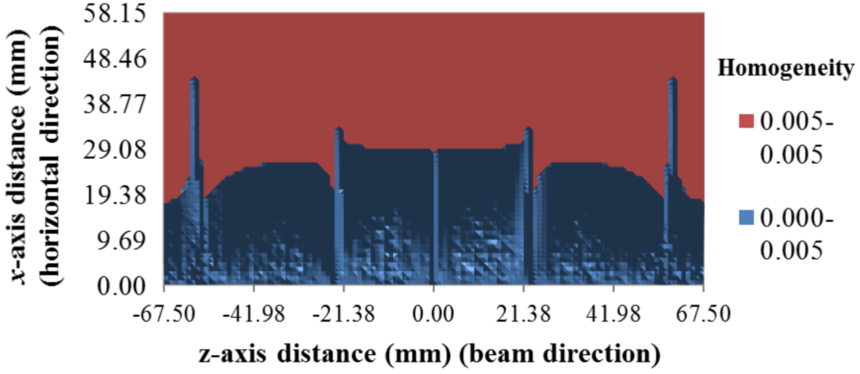


SELECTED λ_w FOR $3.5\ \mathrm{T} \leq B_w \leq 4\ \mathrm{T}$

Field map: Vertical component of the magnetic flux density B_y at the centre of the gap

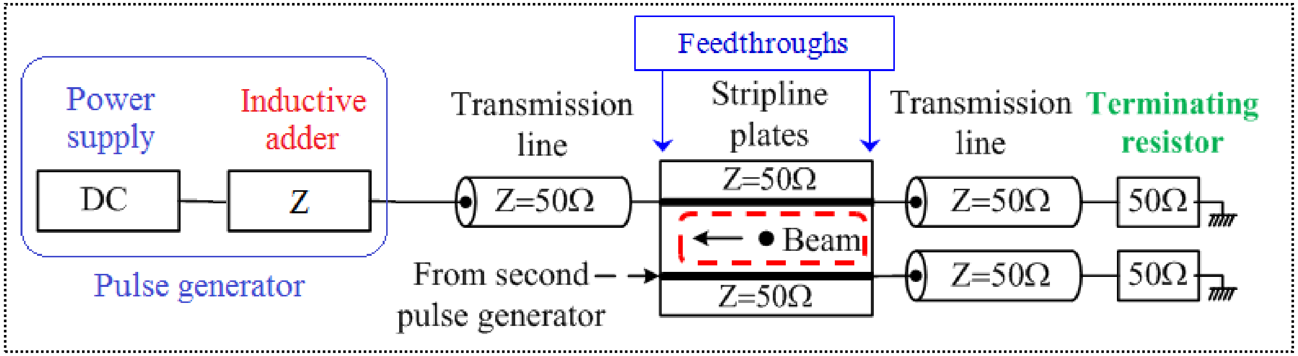


Field homogeneity map: $|(B_y(0) - B_y(x))/B_y(0)|$



Extraction Kicker System

Previous studies demonstrated that the stripline kicker is the most suitable technology.



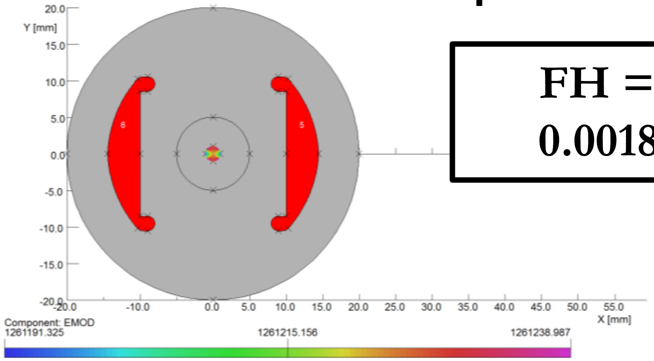
Striplines parameters	Values	Inductive adder parameters	Values
Beam energy	2.86 GeV	Pulse rise and fall time	100 ns
Deflection angle	1.5 mrad	Pulse flat-top	900 ns
Aperture	20 mm	Extraction stability	± 0.02%
Effective length	1.7 m	Repetition rate	50 Hz
Extraction inhomogeneity	± 0.01%		

M. Barnes, C. Belver, J. Holma

Kicker System challenges

Striplines

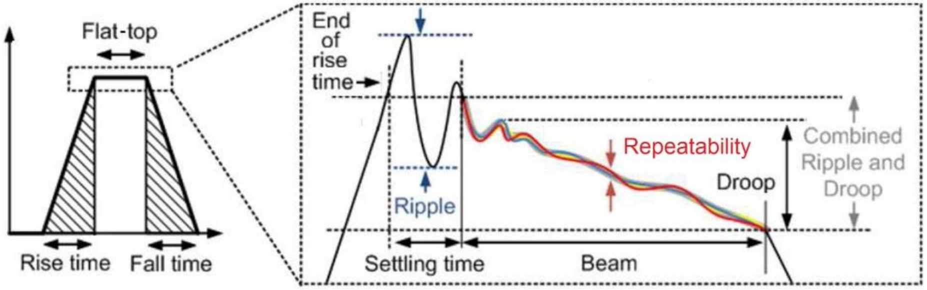
- Excellent field homogeneity: ± 0.01% over 1 mm radius.
- Very low reflections: $S_{11} < 0.1$ up to 10 MHz.
- Very low beam coupling impedance: 0.05 Ω/n in the longitudinal plane and 200 kΩ/m in the transverse plane.



FH = ± 0.0018%

Inductive Adder

- Extremely tight requirements for flat-top stability and repeatability:
  - Flat-top repeatability: ± 0.01%
  - Flat-top stability: ± 0.02%
- Rise/fall times ≤ 100 ns desired.



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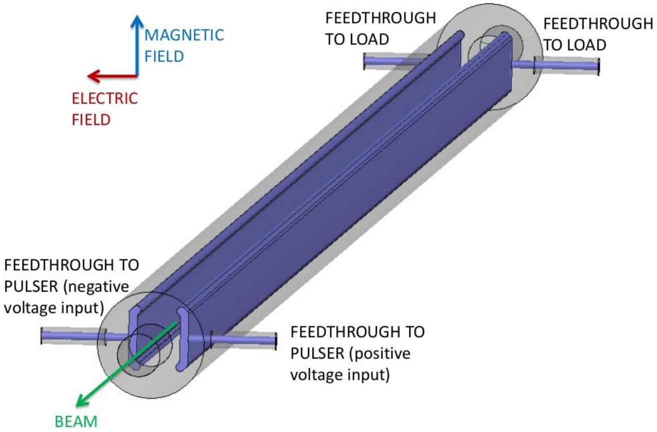
Stripline prototype



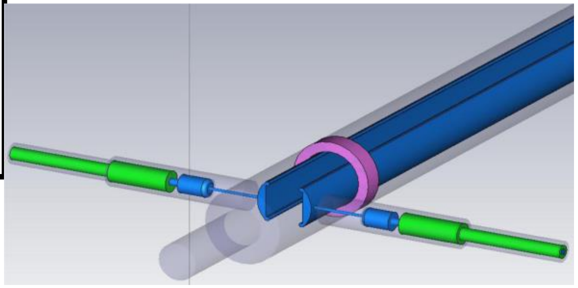
M. Barnes, C. Belver

Design studies & fabrication (VP):

- Impedance matching
- Field homogeneity
- Power transmission
- Beam coupling impedance
- High order modes
- Electrode heating
- Manufacturing tolerances

Laboratory test and measurements:

- Power reflection
- Beam coupling impedance
- HV DC conditioning



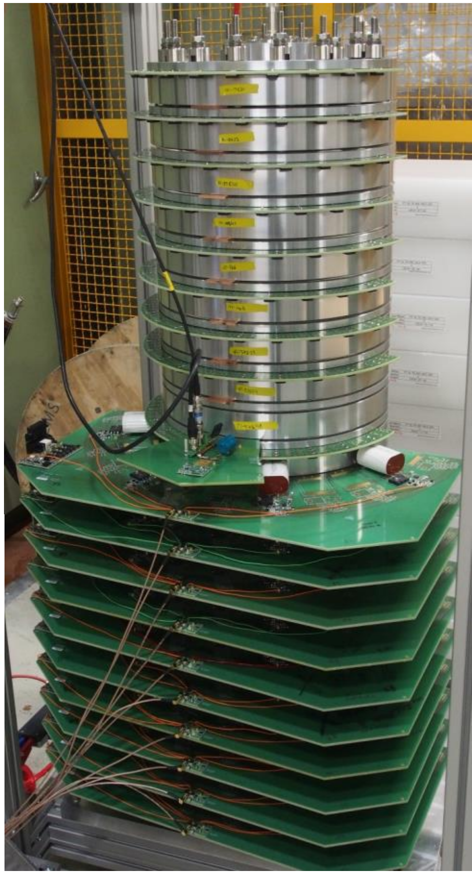
Further optimization studies:

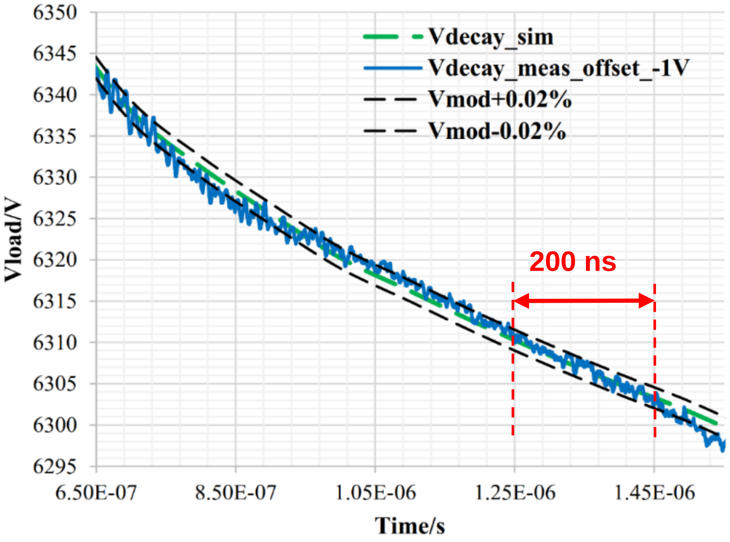
- New method for matching characteristic impedances
- Transient studies of the striplines
- Review of horizontal beam coupling impedance

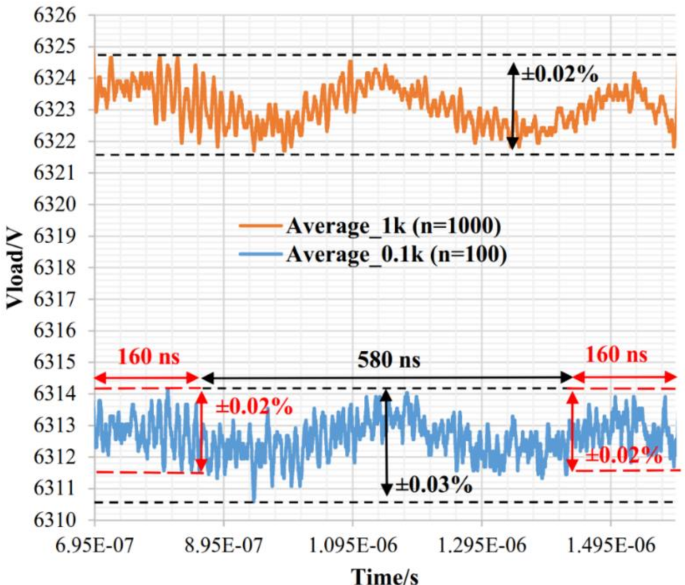
Inductive adder

J. Holma

- The first full-scale 20-layer, 12.5 kV, prototype inductive adder for CLIC DR extraction kicker system is currently under testing.
- The best measured flat-top/waveform stabilities until now:
  ±0.02 % over 900 ns for a flat-top pulse at 6.3 kV
  ±0.02 % over 160 ns for a “controlled decay waveform” at 6.3 kV.
- Future measurements of two 12.5 kV inductive adders with a stripline kicker installed in a beamline in an accelerator test facility (at Alba in Spain, in January 2019).



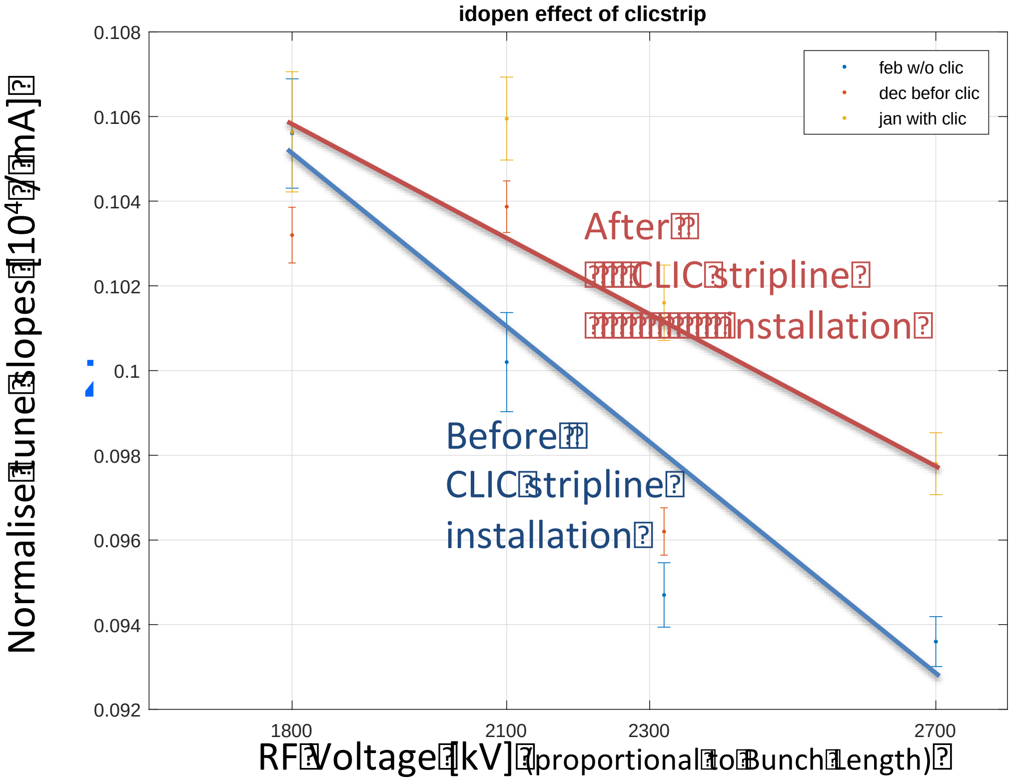




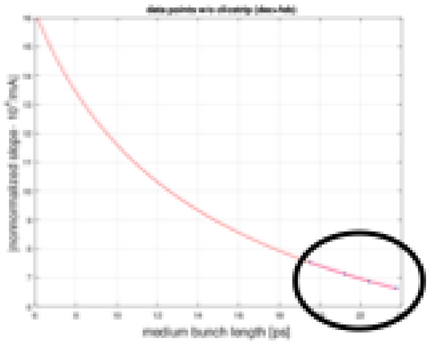
Impedance measurements @ ALBA

1) **<u>Measurements without HV DC power supplies</u>: Transverse coupling impedance**

- ❑ Measurements pending to be fully analysed, but first estimated



$Z_{CLIC\text{-}meas}$ = 21 ± 12 kOhm/m



global view of fit function

F. Perez, M. Pont

Next steps

- Complete analysis of non-linear dynamics and **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
  - **Prototyping** of variable dipole bends with CIEMAT (F. Toral)
  - Continue **wiggler tests** at ANKA and finalise Nb_3Sn short wiggler model
  - Test stripline and pulser at ALBA
  - Design a 2 GHz CLIC DR RF system including LLRF

Thank You

Reserve

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

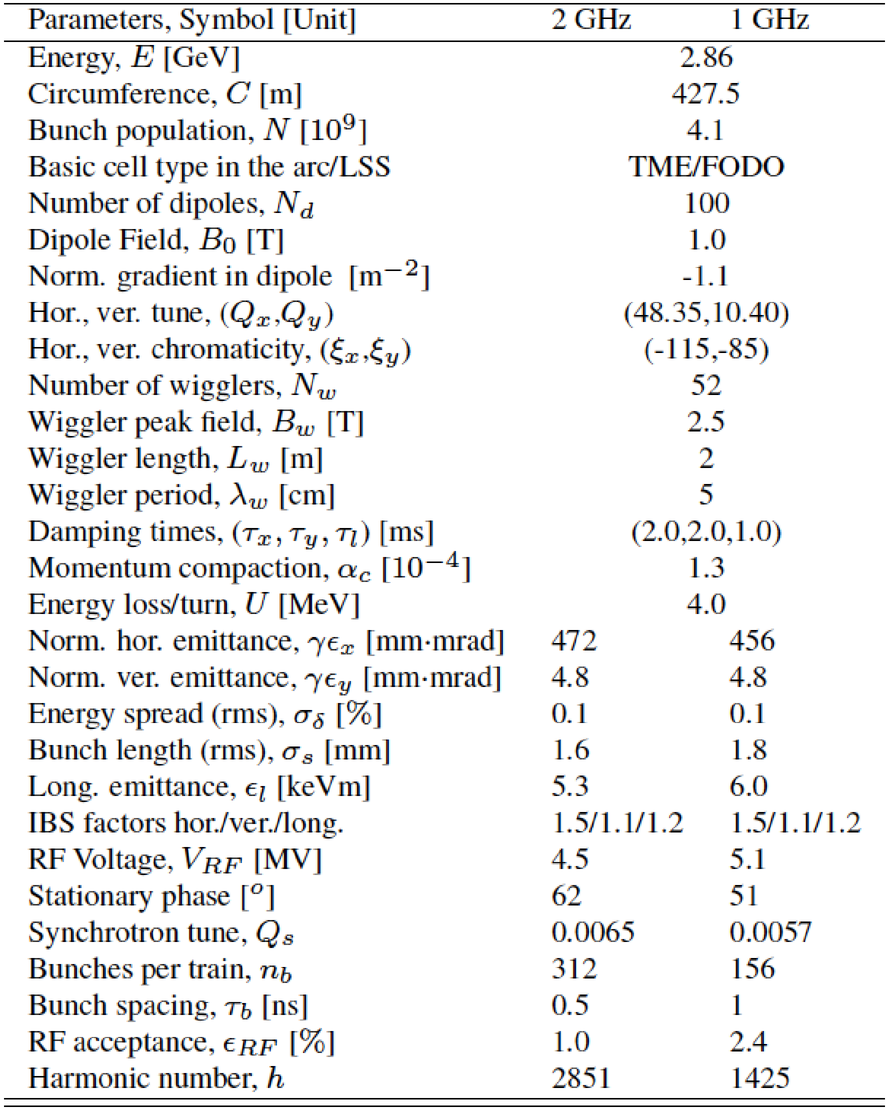
Extracted Parameters	**PDR e^-/e^+**	**DR e^-/e^+**
Bunch population $[10^9]$	4.1-4.4	4.1
Bunch length [mm]	10	1.4
Energy Spread [%]	0.5	0.1
Long. emittance [eV.m]	143000	5000
Hor. Norm. emittance [nm-rad]	63000	500
Ver. Norm. emittance [nm-rad]	1500	5

- 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!**

F. Antoniou

CLIC DR challenges and adopted solutions



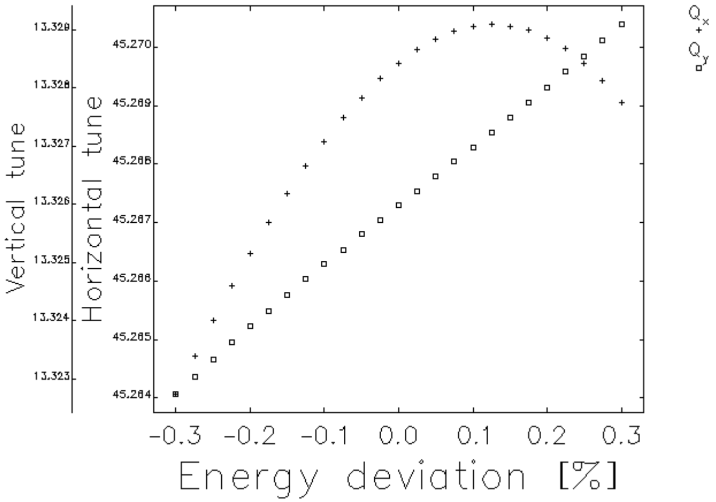
Parameters, Symbol [Unit]	2 GHz	1 GHz
Energy, E [GeV]	2.86	
Circumference, C [m]	427.5	
Bunch population, N [10^9]	4.1	
Basic cell type in the arc/LSS	TME/FODO	
Number of dipoles, N_d	100	
Dipole Field, B_0 [T]	1.0	
Norm. gradient in dipole [m^{-2}]	-1.1	
Hor., ver. tune, (Q_x,Q_y)	(48.35,10.40)	
Hor., 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

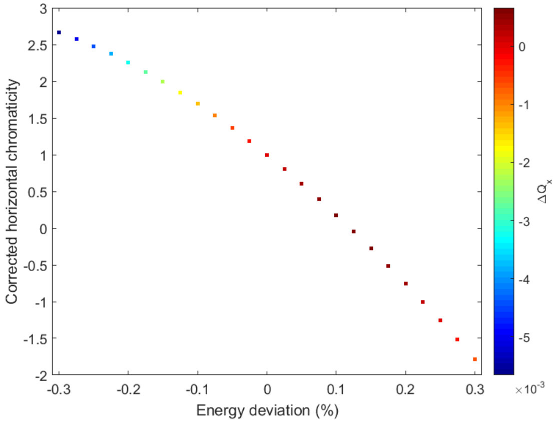
- High-bunch density in all three dimensions
  - **Intrabeam Scattering** effect reduced by choice of ring energy, lattice design, wiggler technology and alignment tolerances
  - **Electron cloud** in e^+ ring mitigated by chamber coatings and efficient photon absorption
  - **Fast Ion Instability** 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

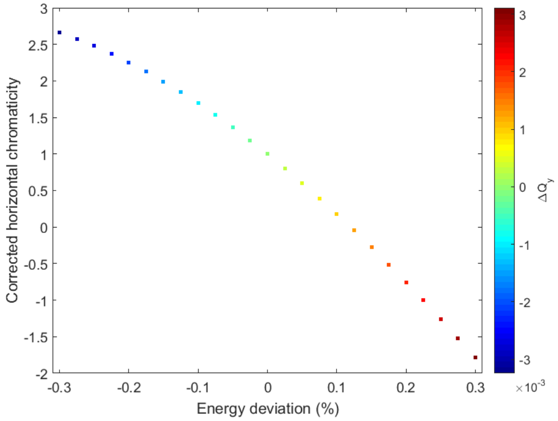
Chromaticity correction

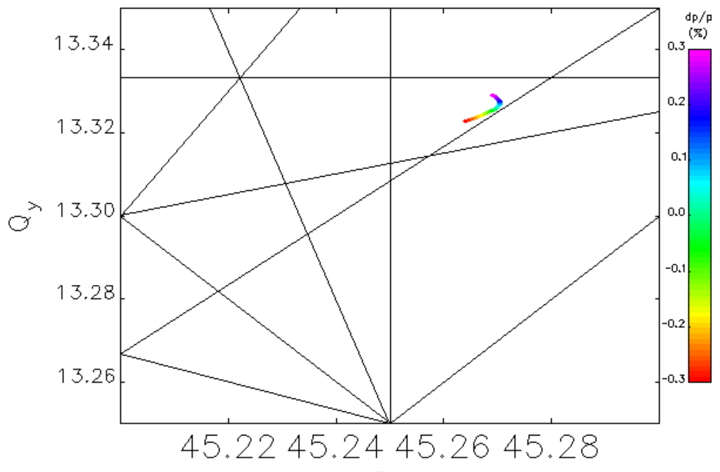
- Two families of sextupole magnets both with the same length of 15 cm in the TME cell are considered to correct the natural chromaticity of ring to +1.

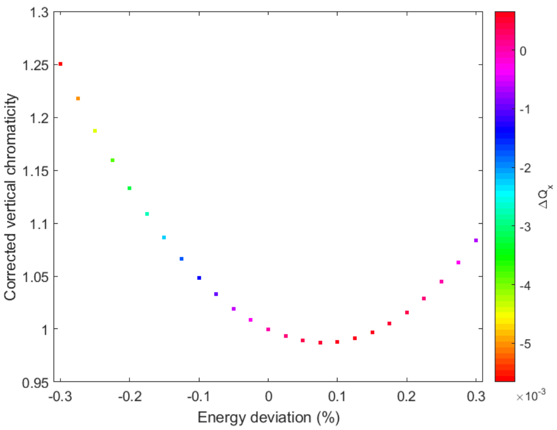
Parameters	SD	SF
Length [cm]	15	
Pole radius [mm]	15	
Sextupole strength [m^{-2}]	-449.84	421.10
B” (T/m^{-2})	-4291.36	4017.16
Pole tip field (T) [R=15 mm]	0.48	0.45

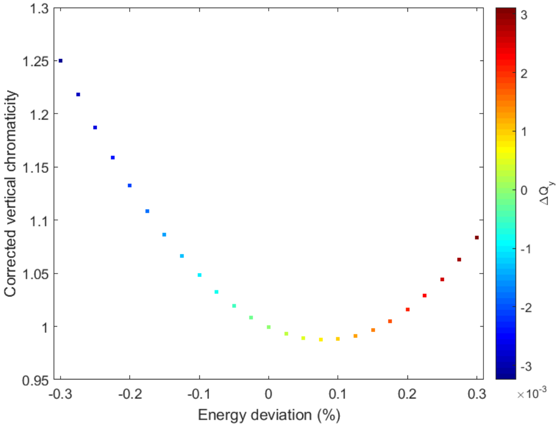








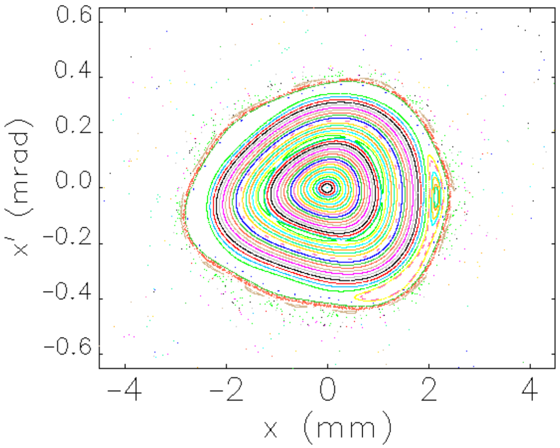


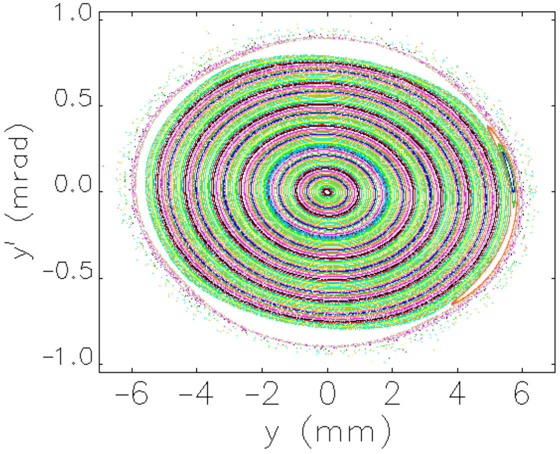


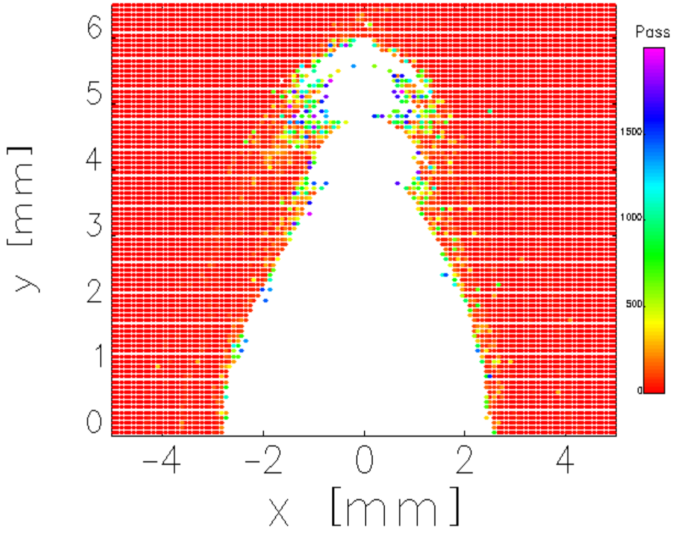
H. Ghasem

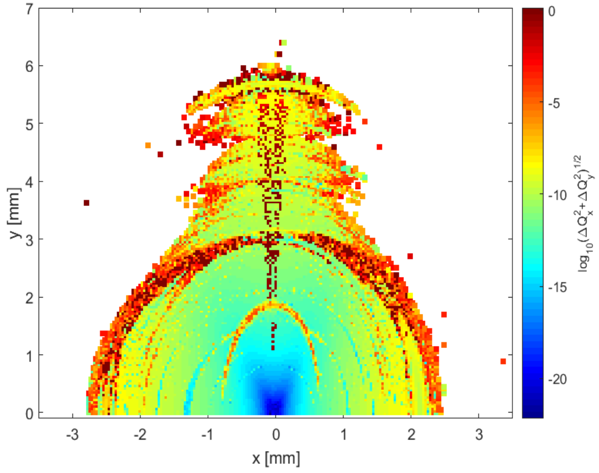
Dynamic aperture

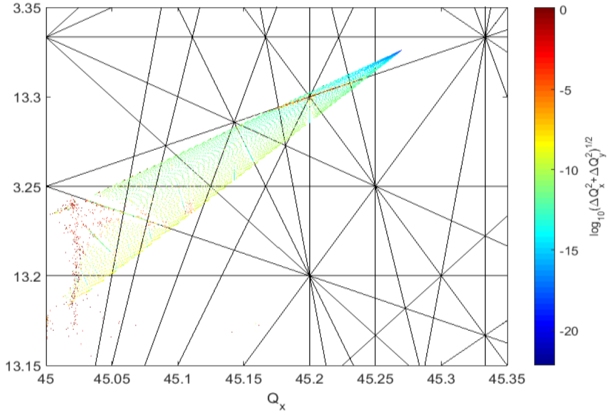
ΔP/P=0











H. Ghasem