CLIC damping rings overview and open issues

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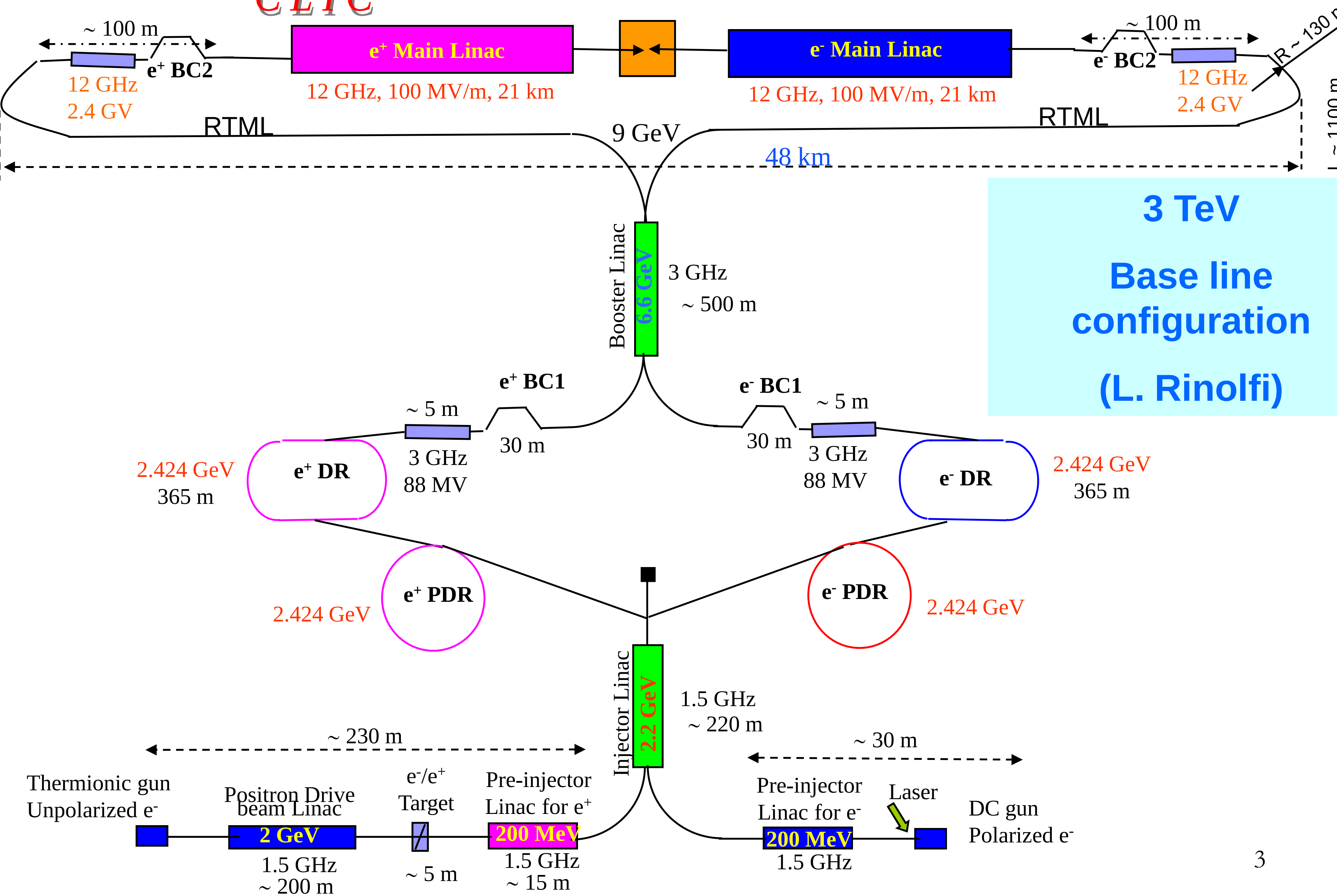
Outline

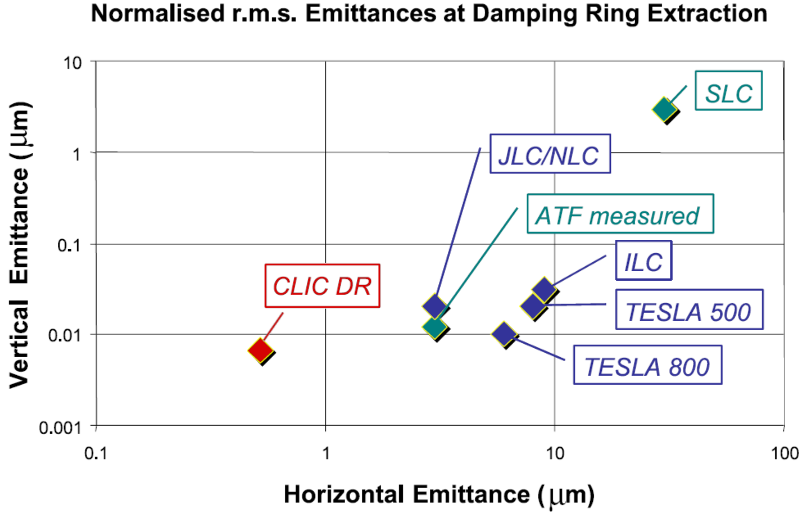
- CLIC damping rings design and open issues → M. Korostelev (PhD thesis, EPFL 2006)
  - Design goals and challenges
  - Input parameters - Pre-damping rings
  - Lattice choice and optics optimisation
  - Circumference (realistic drift space and magnets)
  - Wiggler design and parameter scan (prototypes)
  - Synchrotron radiation absorption
  - Chromaticity correction and dynamic aperture
  - Low emittance tuning in the presence of coupling (tolerances)
  - e-cloud and other collective effects
- Summary

Injector complex



Damping ring design goals

- Ultra-low emittance and high beam polarisation impossible to be produced by conventional particle source:
  - Ring to damp the beam size to desired values through synchrotron radiation
- Intra-beam scattering due to high bunch current blows-up the beam
  - Equilibrium "IBS dominated" emittance should be reached fast to match collider high repetition rate
- Other collective effects (e.g. e⁻-cloud) may increase beam losses
- Starting parameter dictated by design criteria of the collider (e.g. luminosity), injected beam characteristics or compatibility with the downstream system parameters (e.g. bunch compressors)



PARAMETER	NLC	CLIC
bunch population (10^9)	7.5	4.1
bunch spacing [ns]	1.4	0.5
number of bunches/train	192	316
number of trains	3	1
Repetition rate [Hz]	120	50
Extracted hor. normalized emittance [nm]	2370	<680
Extracted ver. normalized emittance [nm]	<30	< 20
Extracted long. normalized emittance [eV m]	10890	<5000
Injected hor. normalized emittance [μm]	150	63
Injected ver. normalized emittance [μm]	150	1.5
Injected long. normalized emittance [keV m]	13.18	1240

CLIC Pre-damping rings

- Pre-damping rings needed in order to achieve injected beam size tolerances at the entrance of the damping rings
- Most critical the positron damping ring
  - Injected emittances ~ 3 orders of magnitude larger than for electrons
- CLIC PDR parameters very close to those of NLC

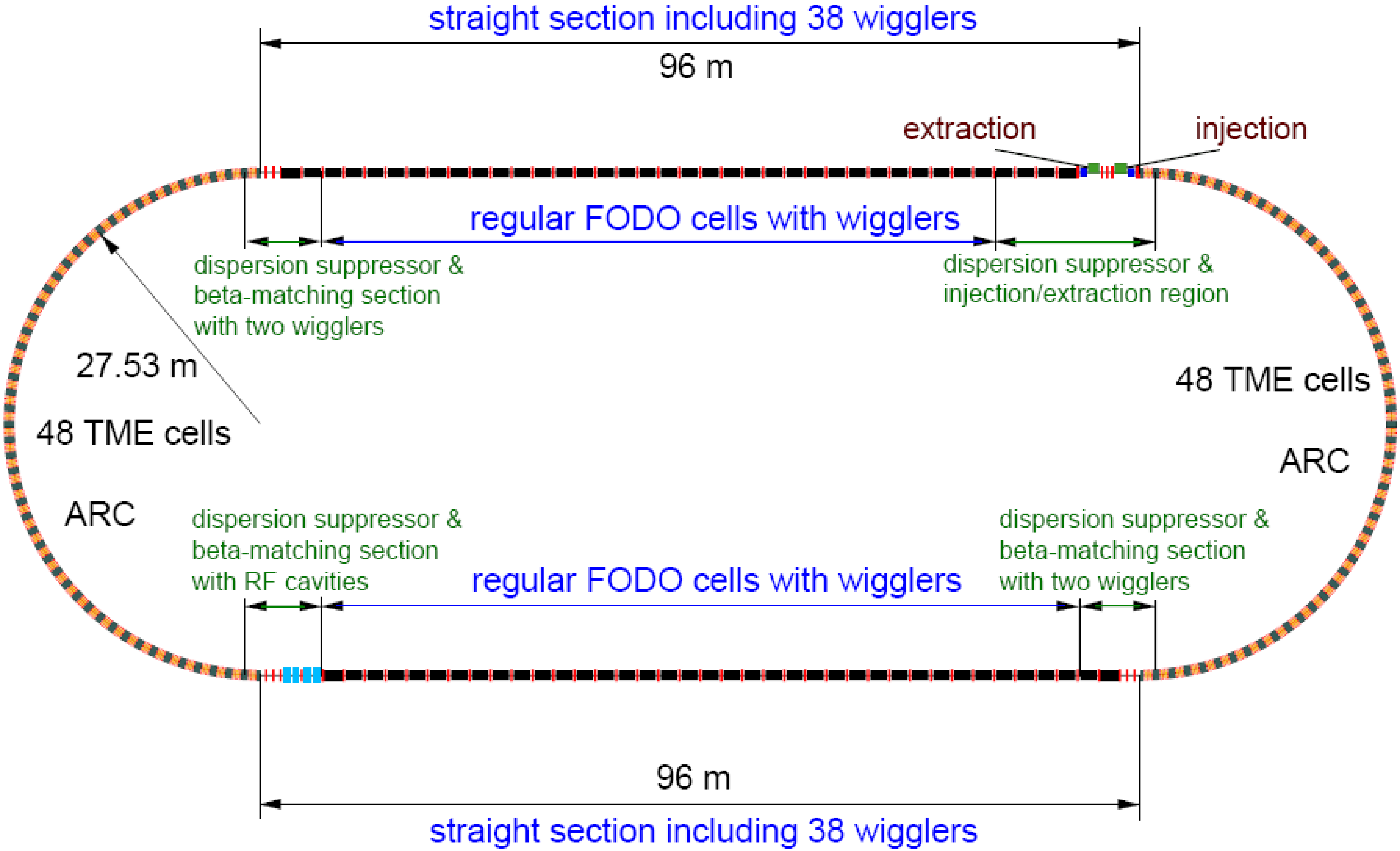
  (I. Raichel and A. Wolski, EPAC04)
- Similar design may be adapted to CLIC
  - Lower vertical emittance
  - Higher energy spread

PDR Parameters	CLIC	PDR
Energy [GeV]	2.424	1.98
Bunch population [10^9]	4.5	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]	4.7	6.4
Bunch length [mm]	1	5
Energy Spread [%]	0.07	1.5
Long. emittance [eV.m]	1700	240000
Hor.,Ver Norm. emittance [nm]	100 x 10^3	9.7 x 10^6

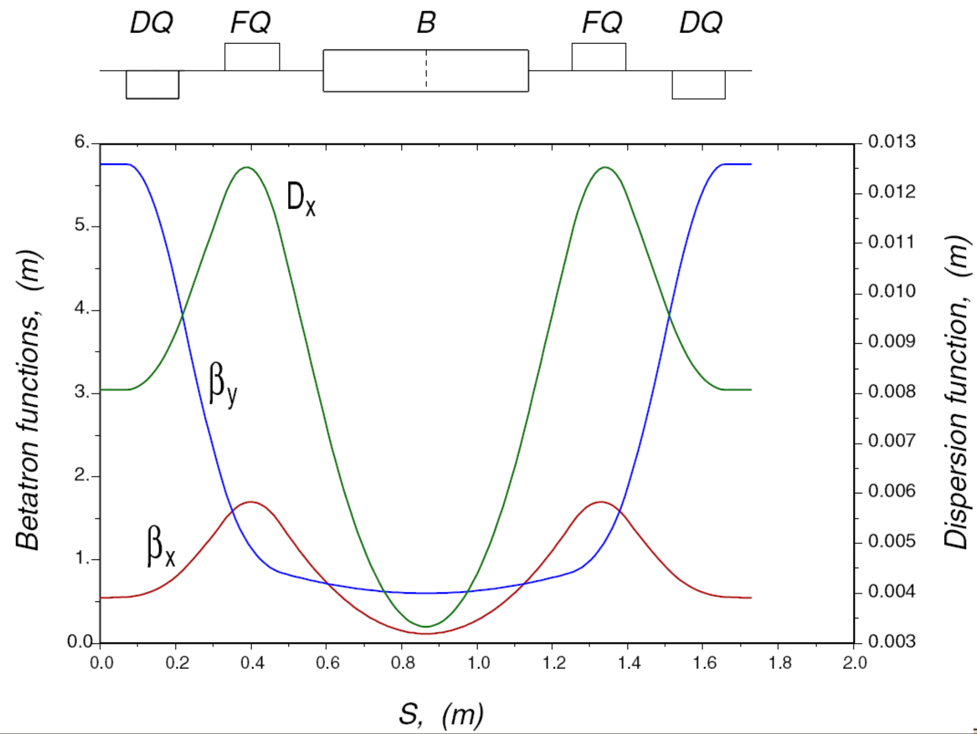
L. Rinolfi

CLIC damping ring layout



TME arc cell

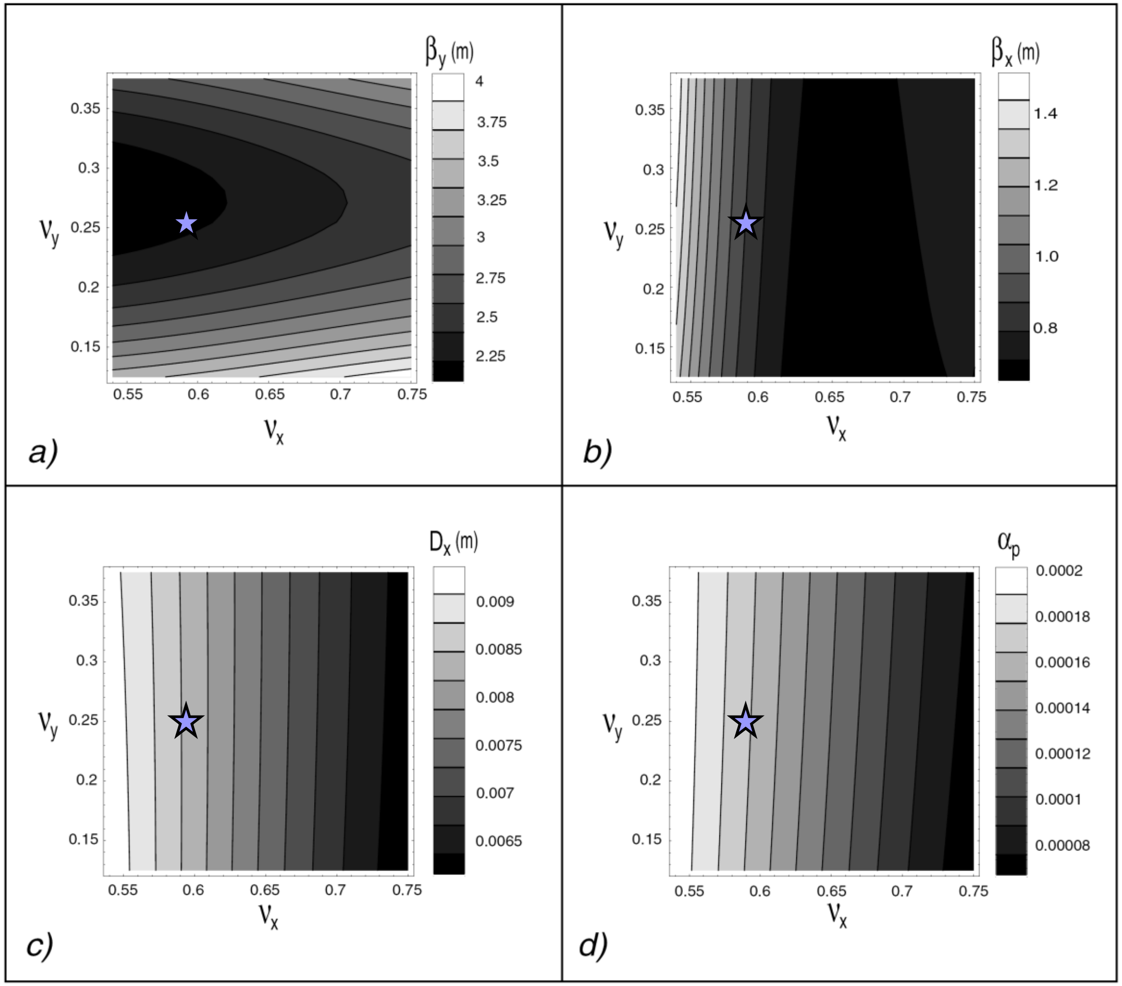
- TME cell chosen for compactness and efficient emittance minimisation over Multiple Bend Structures (or achromats) used in light sources
- Large phase advance necessary to achieve optimum equilibrium emittance
- Very low dispersion
- Strong sextupoles needed to correct chromaticity
- Impact in dynamic aperture



Energy	2.42 GeV
Field of the bending magnet, B_a	0.932 T
Length of the bending magnet	0.545 m
Bending angle	$2\pi/100$
Bending radius	8.67 m
Length of the cell, L_{TME}	1.73 m
Horizontal phase advance, μ_x	210°
Vertical phase advance, μ_y	90°
Emittance detuning factor, ϵ_r	1.8
Horizontal chromaticity, $\partial\nu_x/\partial\delta$	-0.84
Vertical chromaticity, $\partial\nu_y/\partial\delta$	-1.18
Average horizontal beta function, $\langle\beta_x\rangle$	0.847 m
Average vertical beta function, $\langle\beta_y\rangle$	2.22 m
Average horizontal dispersion, $\langle D_x\rangle$	0.0085 m
Relative horizontal beta function, $\beta_r = \beta^*/\beta^*_m$	$0.113/0.07 = 1.6$
Relative horizontal dispersion, $D_r = D^*/D^*_m$	$0.00333/0.00143 = 2.33$

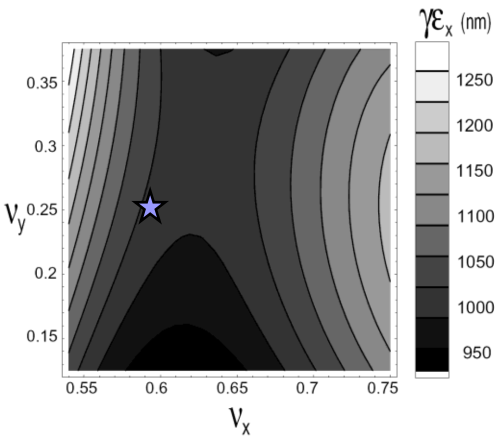
Phase advance choice

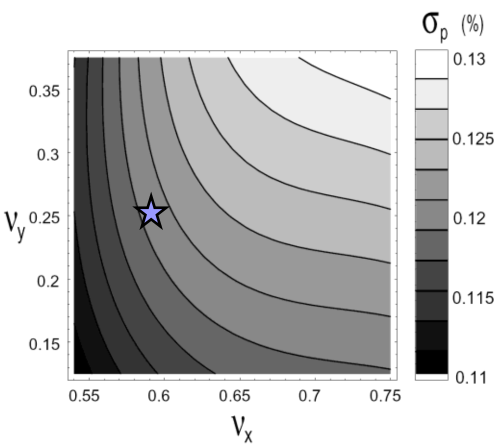
- Optimum horizontal phase advance of cells for minimising zero current emittance is fixed (284° for TME cells)
- Vertical phase advance is almost a free parameter
- First iteration based on lattice considerations, i.e. comfortable beta functions and relaxed quadrupole strengths and chromaticity
- Low horizontal phase advance gives increased momentum compaction factor (high dispersion) but also chromaticity

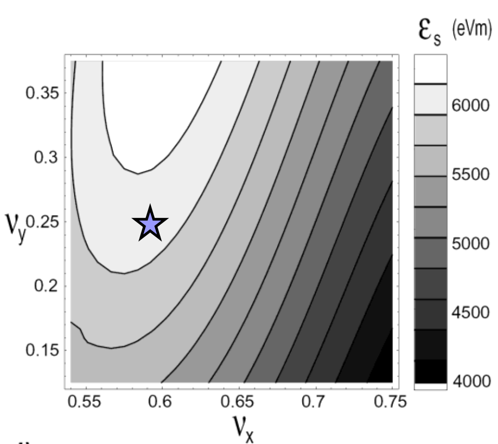


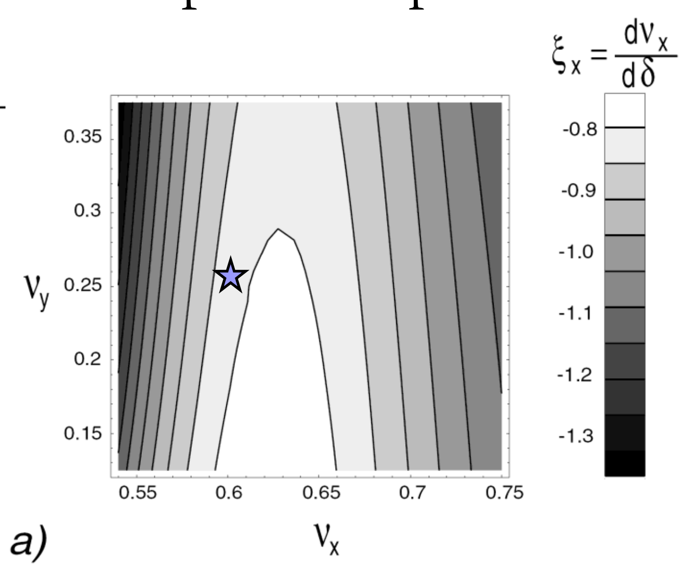
Phase advance with IBS

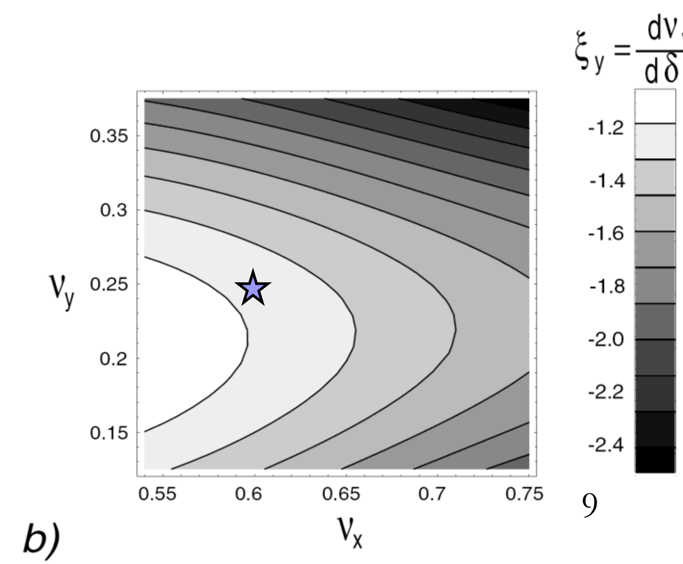
- Horizontal phase advance for minimum horizontal emittance with IBS, is found in an area of small horizontal beta and moderate dispersion functions (between 1.2-1.3π, for CLIC damping rings)
- Optimal vertical phase advance quite low (0.2π)
- The lowest longitudinal emittance is achieved for high horizontal and low vertical phase advances
- The optimal point has to be compromised due to chromaticity considerations and dynamic aperture optimisation





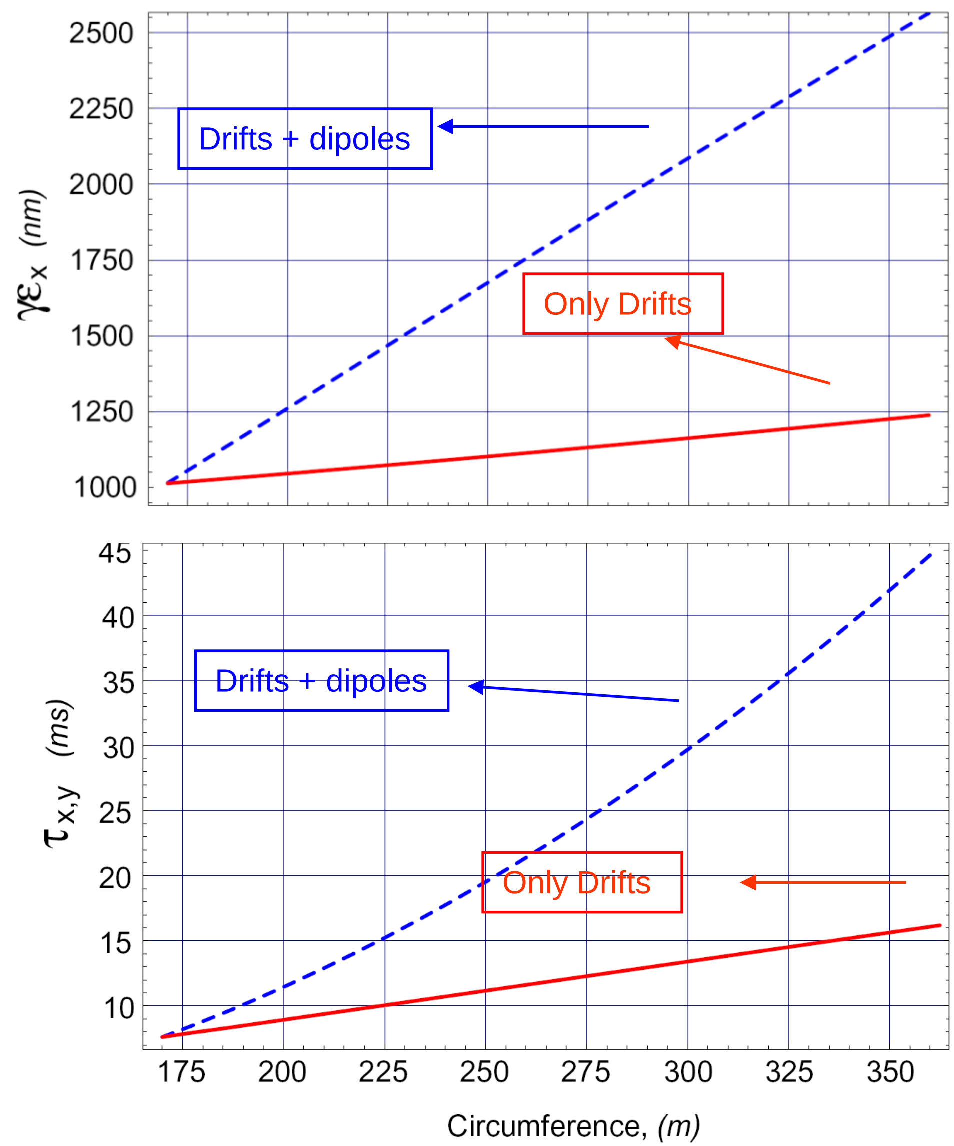






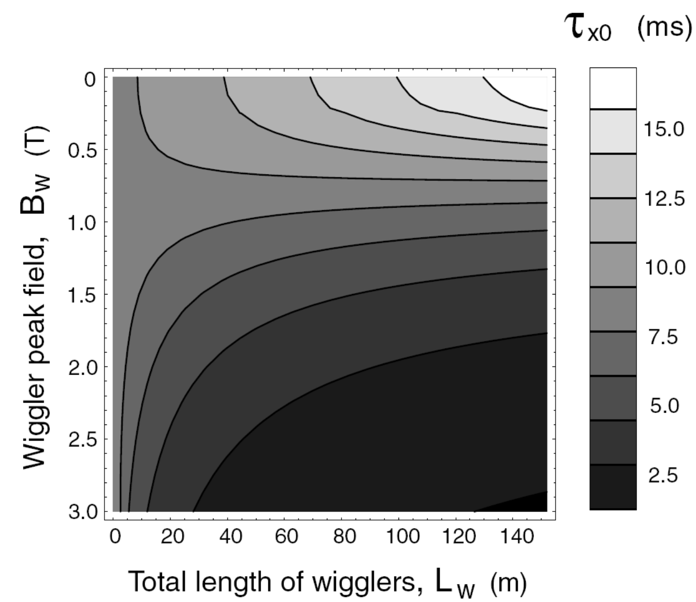
Circumference

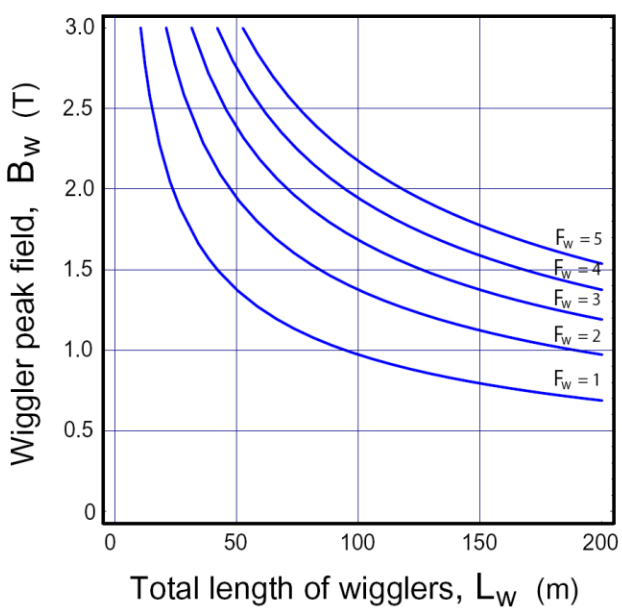
- Big enough to accommodate bunch train
- Drift space increase essential for establishing realistic lattice, reserving enough space for instrumentation and other equipment
- For constant number of dipoles (TME cells), zero equilibrium emittance is independent of circumference
- Normalised emittance with IBS increases with circumference (no wigglers)
  - When dipole lengths increase with drifts, emittance grows due to increase of damping time (inversely proportional to radiation integral I_2 which decreases with length)
  - When only drifts increase, smaller emittance growth due to increase of optics functions
  - Impact on chromaticity + dynamic aperture
- Compensation may be achieved due to increase of bunch length with circumference (momentum compaction)
- Linear optics has to be reviewed with realistic magnet parameters

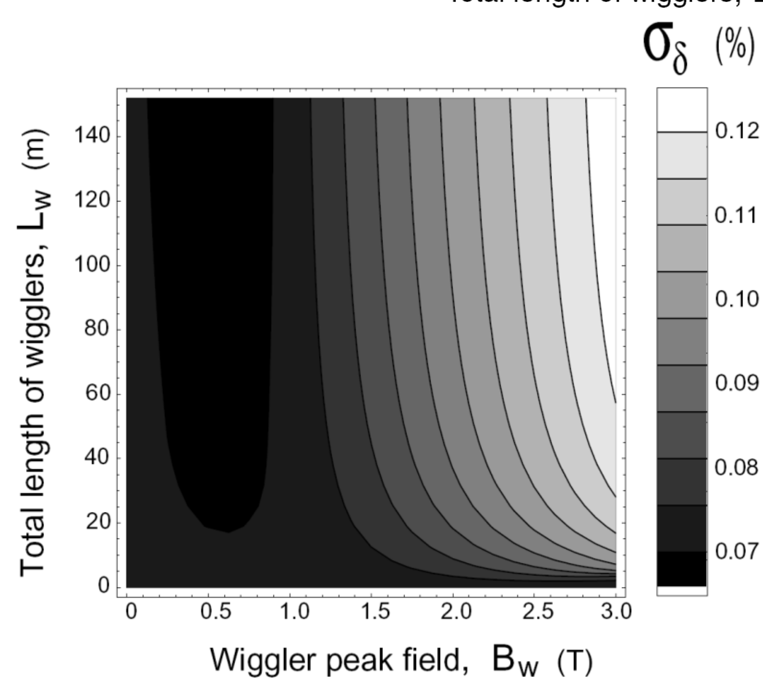


Damping wigglers

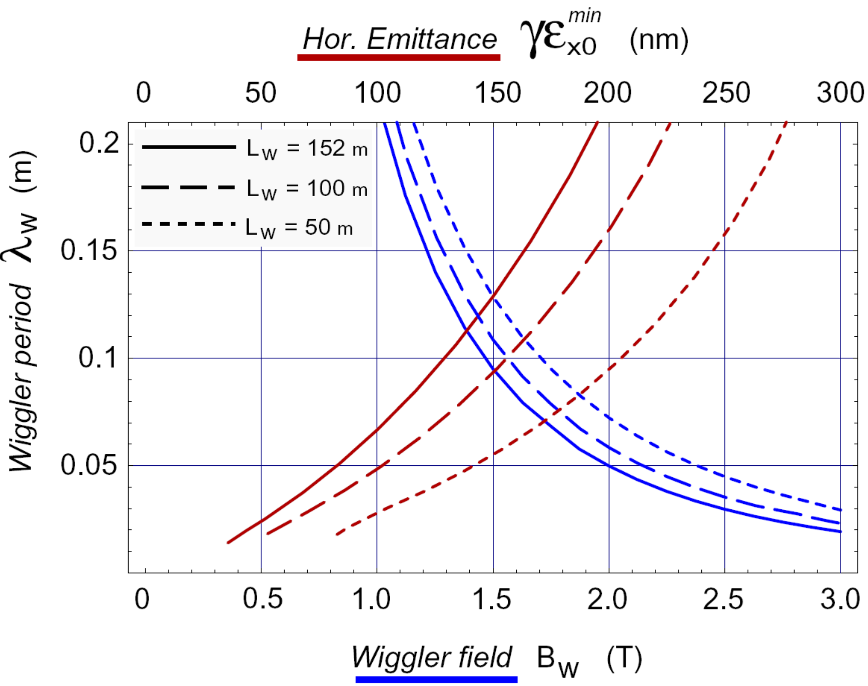
- Damping wigglers are used to increase radiation damping and reduce the effect of IBS in order to reach target emittances
- The total length of wigglers is chosen by its dependence with the peak wiggler field and relative damping factor $\boldsymbol{F_w}$
- Higher damping factor can be achieved for higher fields and longer wiggler occupied straight section
- Relative momentum spread is independent of total length but increases with wiggler field

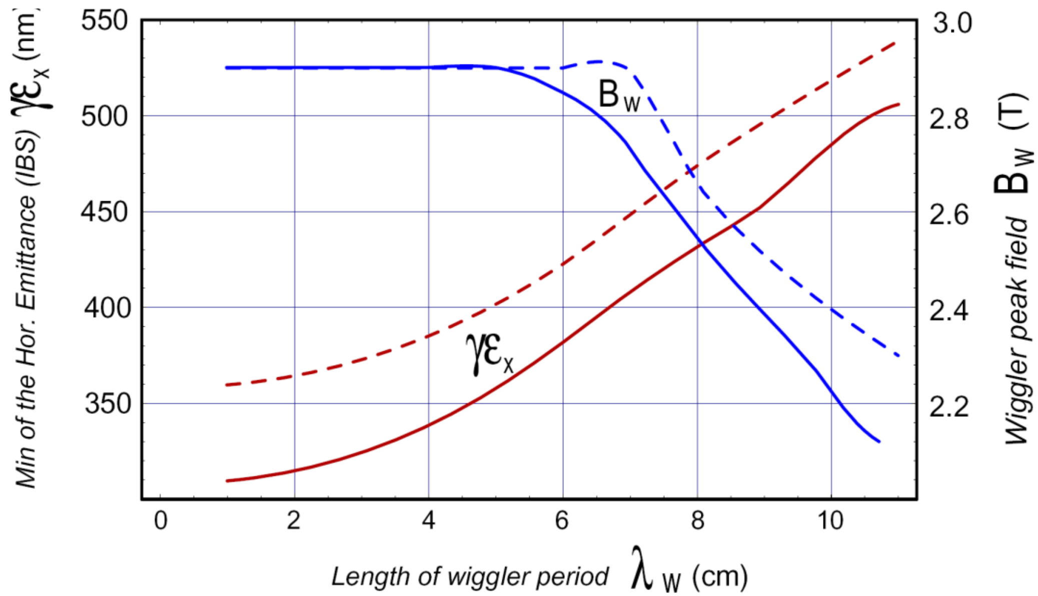






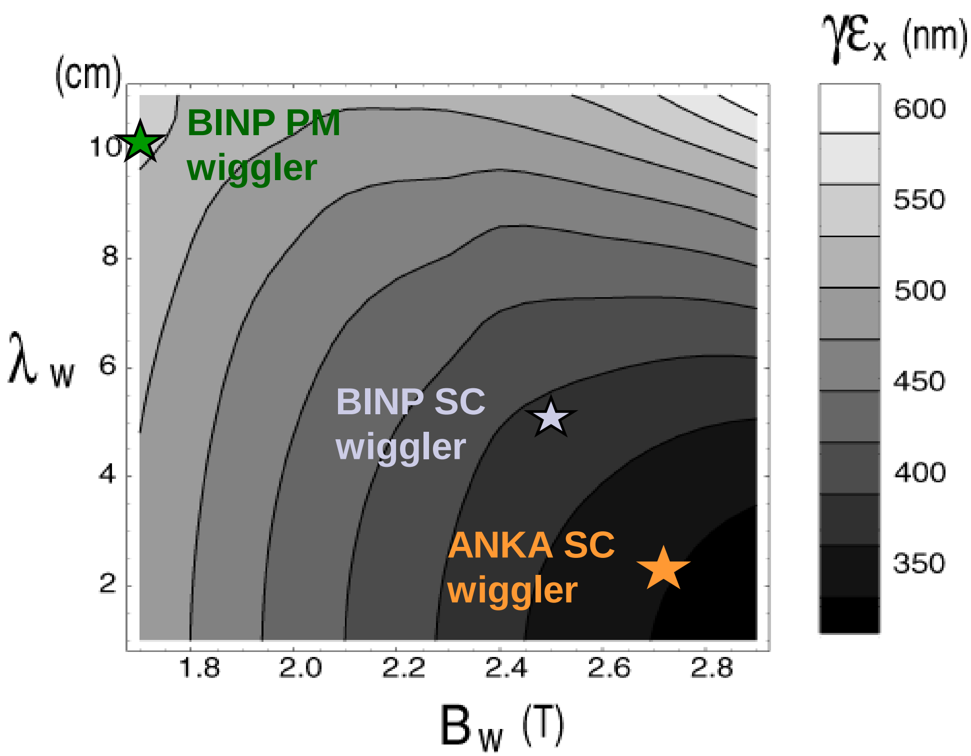
Wigglers effect in emittance





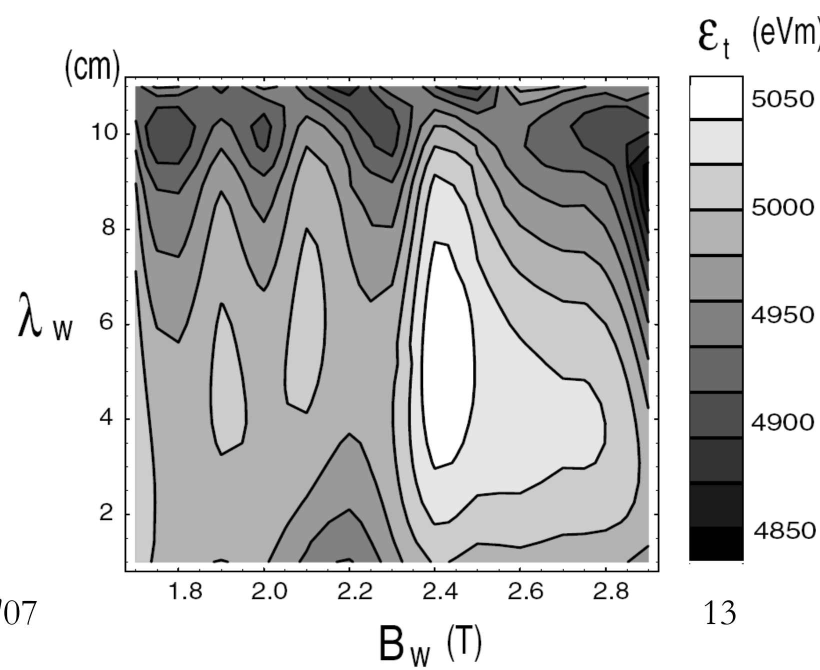
- For fixed value of wiggler period, equilibrium emittance minimum for particular value of wiggler field
- By reducing total length, optimal values necessitate higher fields and lower wiggler periods
- Optimum values change when IBS included, necessitating higher fields
- Damping rings cannot reach 450nm with normal conducting wigglers

Wigglers' effect with IBS



- For higher wiggler field and smaller period the transverse emittance computed with IBS gets smaller
- The longitudinal emittance has a different optimum but it can be controlled with the RF voltage

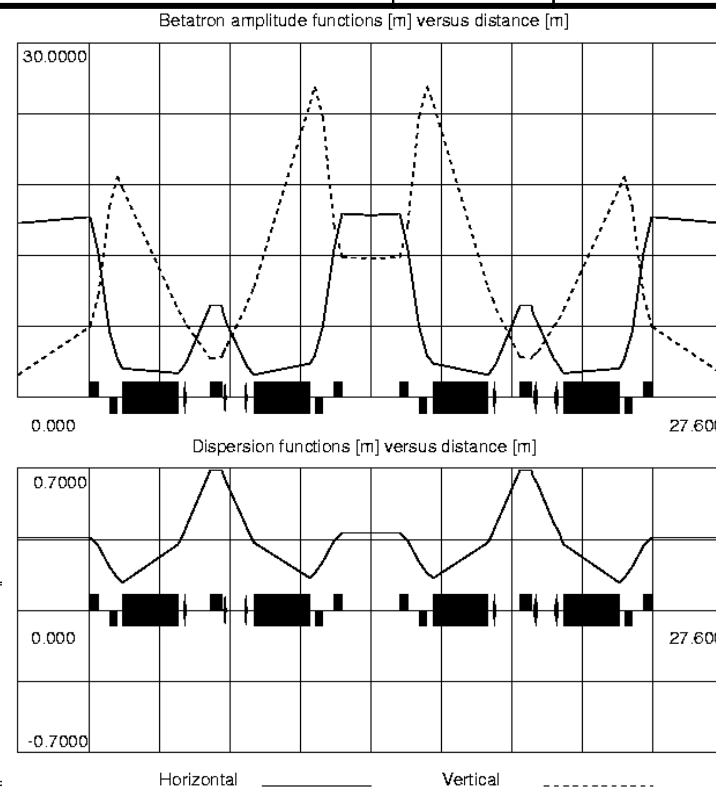
- The choice of the wiggler parameters is finally dictated by their technological feasibility.
  - Normal conducting wiggler of 1.7T can be extrapolated by existing designs
  - Super-conducting options have to be designed, built and tested

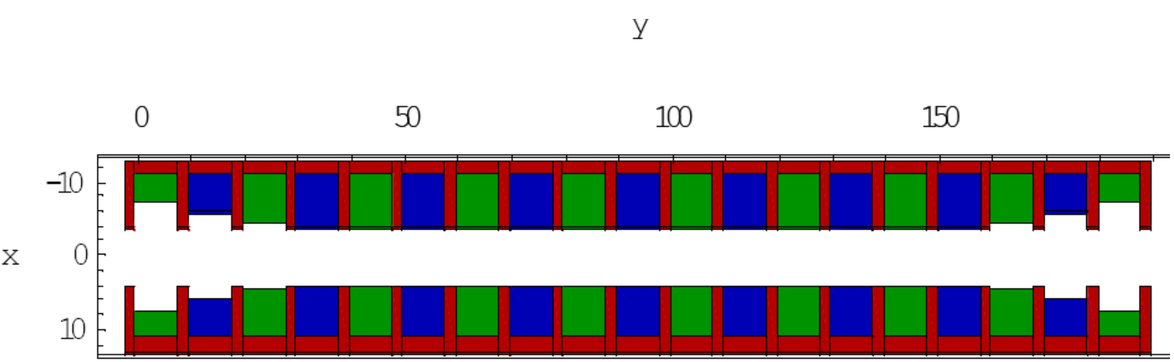


Wiggler prototypes

- Two wiggler prototypes
  - 2.5T, 5cm period, built by BINP
  - 2.7T, 2.1cm period, built by ANKA
- Wiggler prototype of 2.6T, 4cm period
- Aperture of 8-10mm
- Current density can be increased by using different conductor type
- Establish field error tolerances for both designs
- Short version to be installed and tested at ANKA (GADGET)
- Measurements of emittance growth due to IBS in a wiggler dominated ring (ANKA at injection energy of 0.5 GeV)

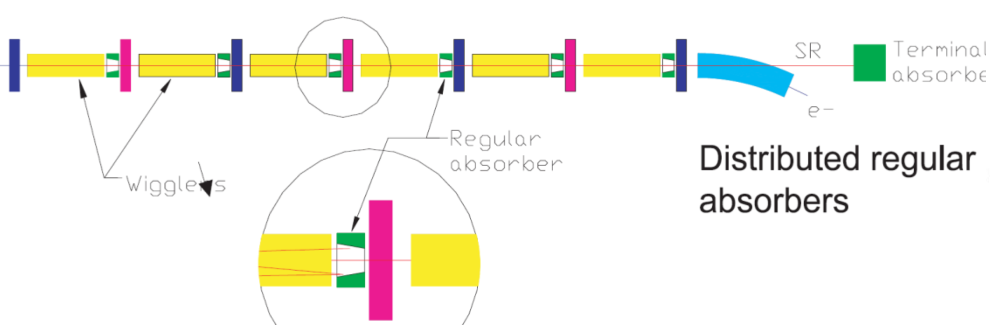
Parameters	BINP	ANKA
B_{peak} [T]	2.5	2.7
λ_W [mm]	50	21
Beam aperture full height [mm]	12	5
Conductor type	NbTi	$NbSn_3$
Operating temperature [K]	4.2	4.2



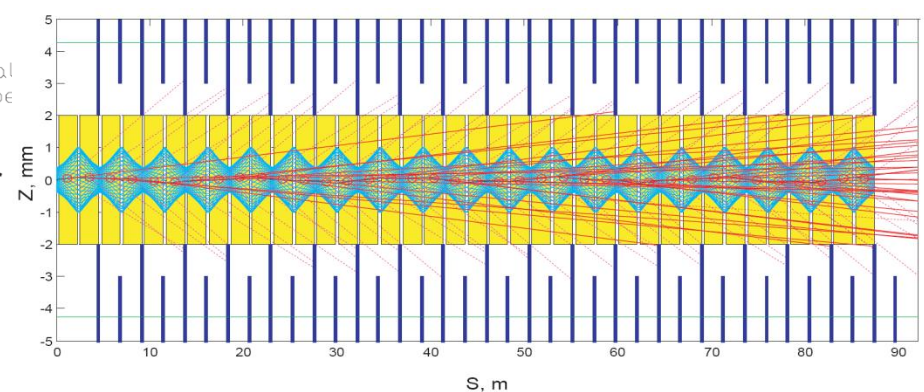


Synchrotron Radiation and losses

- Regularly distributed short absorbers with apertures of 4-6mm considered for SR power of around 11kW based on the old parameters (reduced bunch charge, increased number of bunch trains, permanent magnet wiggler)
- Need of a terminal absorber at the end of the straight for absorbing **90 kW**
- For the new parameters, beam current of **0.17A** produces synchrotron radiation of around **9.2kW** in the high-field superconducting wiggler (**7.9kW** for the lower field)
- Considering a scheme with a long bunch train filling the whole ring, the above values are raised by a factor of **7!**
- Review absorber design, considering super-conducting wiggler quench protection and fit it into ring layout



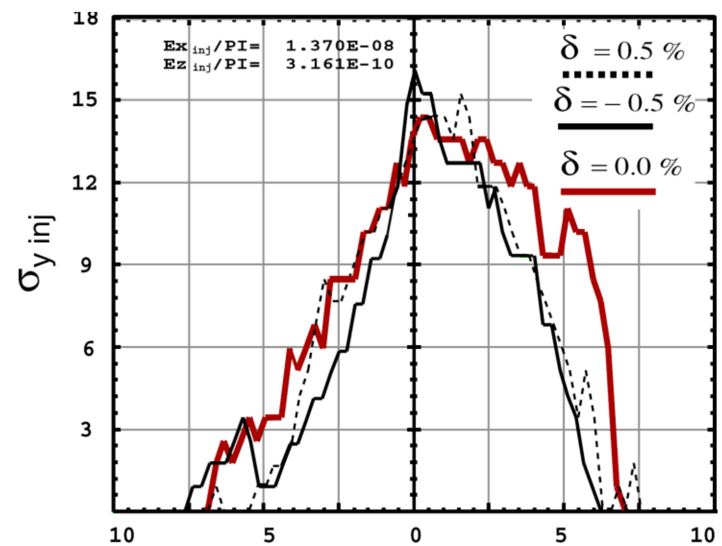
Distributed regular absorbers

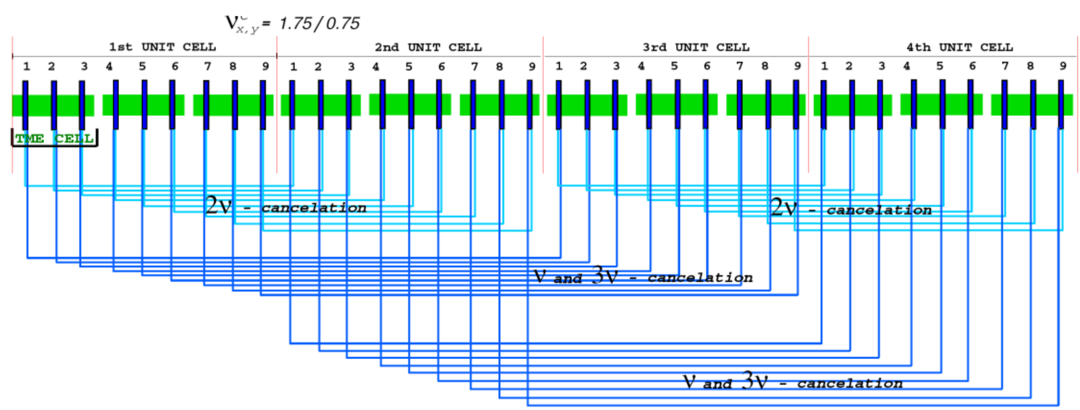


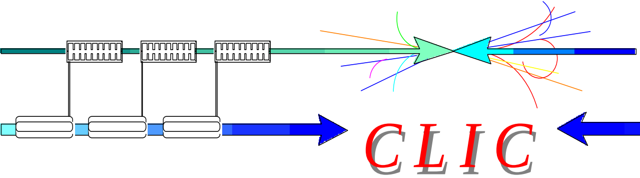
Non-linear dynamics

CLIC

- Two sextupole schemes
  - 2 and 9 families of sextupoles
- Dynamic aperture is $9\sigma_x$ in the horizontal and $14\sigma_y$ in the vertical plane (comfortable for injection)
- Error tables for all magnets including superconducting wigglers should be considered and optimised
- Resonance correction and DA optimisation with sextupoles and/or octupoles using modern techniques (normal forms, frequency maps, ...)

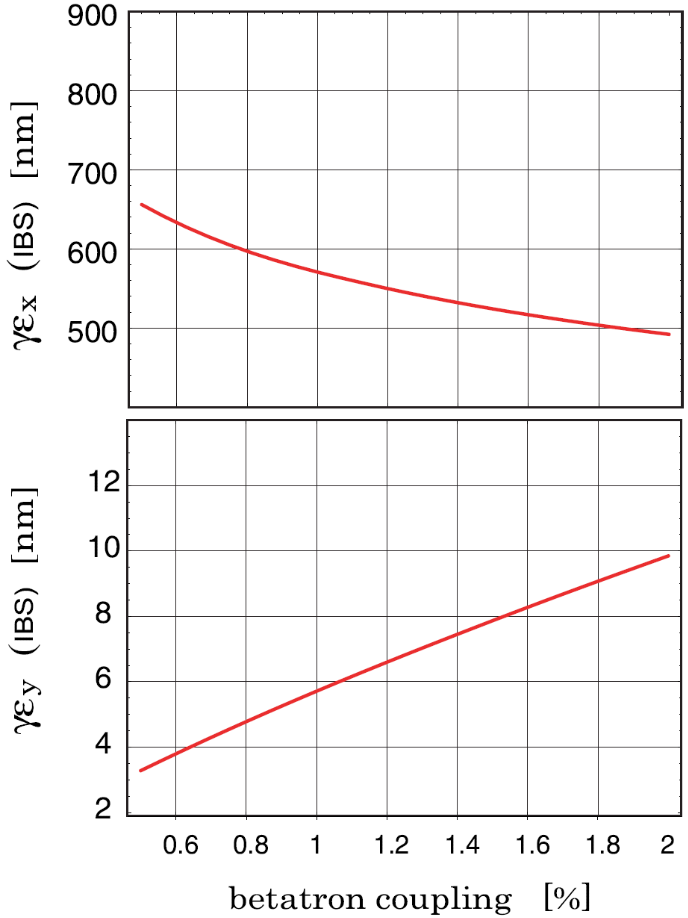






Coupling correction

- Correction with dispersion free steering (orbit and dispersion correction)
- Skew quadrupole correctors for correcting dispersion in the arc and emittance minimisation
- Iteration of dynamic aperture evaluation and optimisation after correction
- In CLIC damping rings, the effect of vertical dispersion is dominant (0.1% of coupling and 0.25μm of dispersion invariant)
- Effect of super-conducting wigglers field errors
- Review of linear correction systems (orbit, beta variation, coupling) with realistic magnet parameters and re-establishment of alignment tolerances



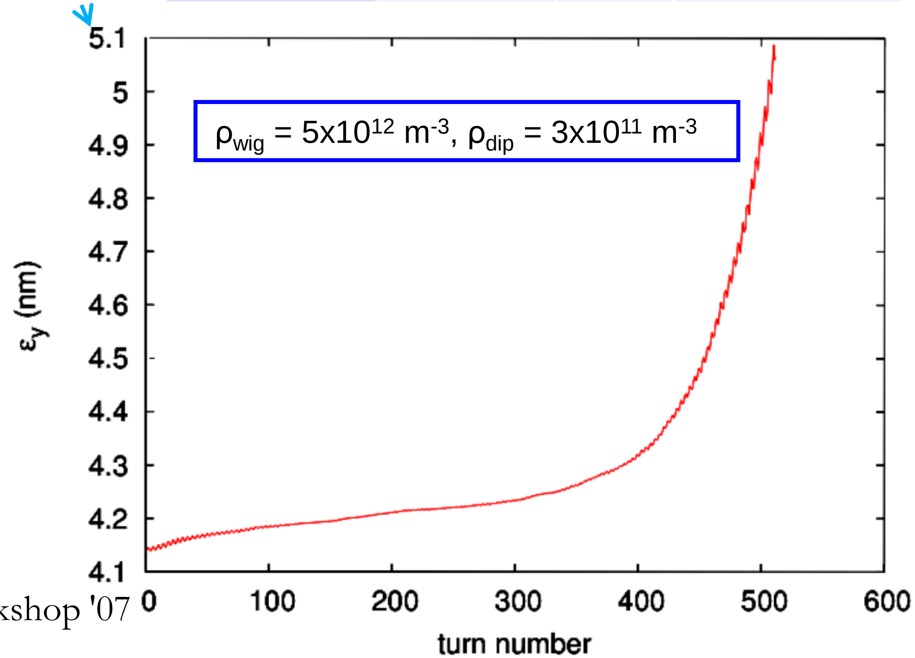
Imperfections	Simbol	1 r.m.s.
Quadrupole misalignment	$\langle \Delta Y_{\rm quad} \rangle, \langle \Delta X_{\rm quad} \rangle$	90 μm.
Sextupole misalignment	$\langle \Delta Y_{\rm sext} \rangle, \langle \Delta X_{\rm sext} \rangle$	40 μm
Quadrupole rotation	$\langle \Delta \Theta_{\rm quad} \rangle$	100 μrad
Dipole rotation	$\langle \Delta \Theta_{\rm dipole\ arc} \rangle$	100 μrad.
BPMs resolution	$\langle R_{\rm BPM} \rangle$	2 μm.

e⁻-cloud effect

CLIC

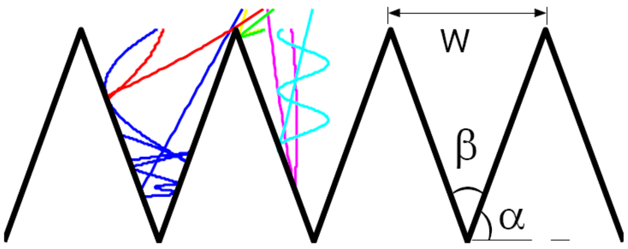
- Simulations with ECLOUD code revealed the importance of the effect in both CLIC and TESLA damping rings
  D. Schulte, R. Wanzerberg , F. Zimmerman, ECLOUD'04
- Simulations using the FAKTOR2 code confirmed the importance of the effect
  (W. Bruns and G. Rumolo, CLIC meeting 06/06/2007)
  - Ante-chambers in dipoles and wigglers need to absorb **99.9%** of photon flux
  - Secondary emission yield has to be less than 1.3
  - e-cloud density of 3-5x10^{12} m^{-3} in the wigglers (independently of density in dipoles) for beam to be stable
- Simulations have to be carried out for the newest parameter set
  - Bunch population of 4.1x10^{9}
  - Bunch spacing from 0.667 to 0.5ns
  - Wiggler field of 2.5T (or 2.7T)
- Inclusion of linear optics in HEADTAIL simulations and effect of non-linear chromaticity

Chambers	PEY	SEY	ρ [10^{12} e$^-$/m^3]
Dipole	0.000576	1.3	0.04
		1.8	2
	0.0576	1.3	7
		1.8	40
Wiggler	0.00109	1.3	0.6
	0.109	1.3	45
		1.5	70
		1.8	80

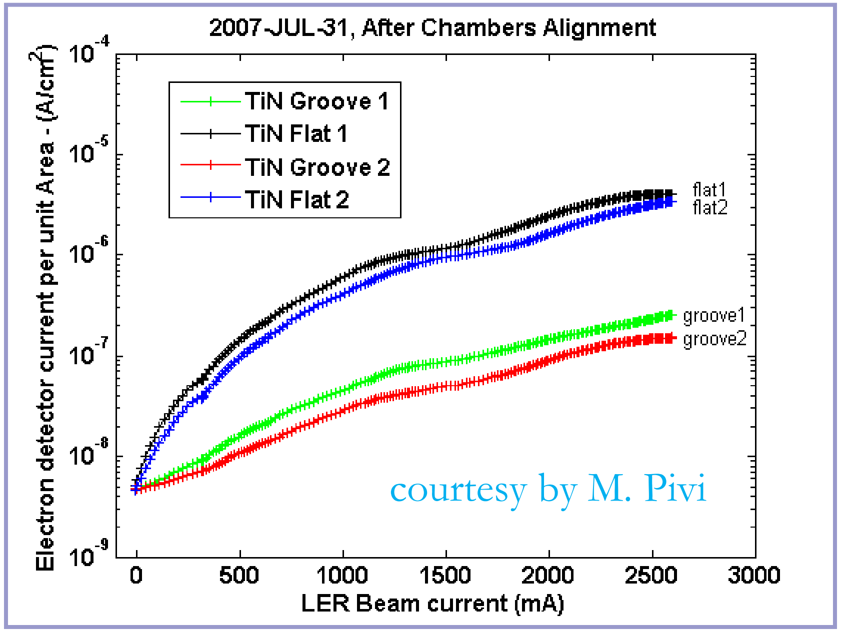


e⁻-cloud countermeasures

- Coating of vacuum chambers by a material (e.g. NEG) for lowering secondary emission yield (GADGET)
- Clearing electrodes
- Solenoids in field-free regions
- Grooved surface of vacuum chamber
  - Simulations showing reduction of SEY
  - Verified experimentally in PEPII
  - Slight resistive wall impedance increase



L. Wang et al., PAC2007



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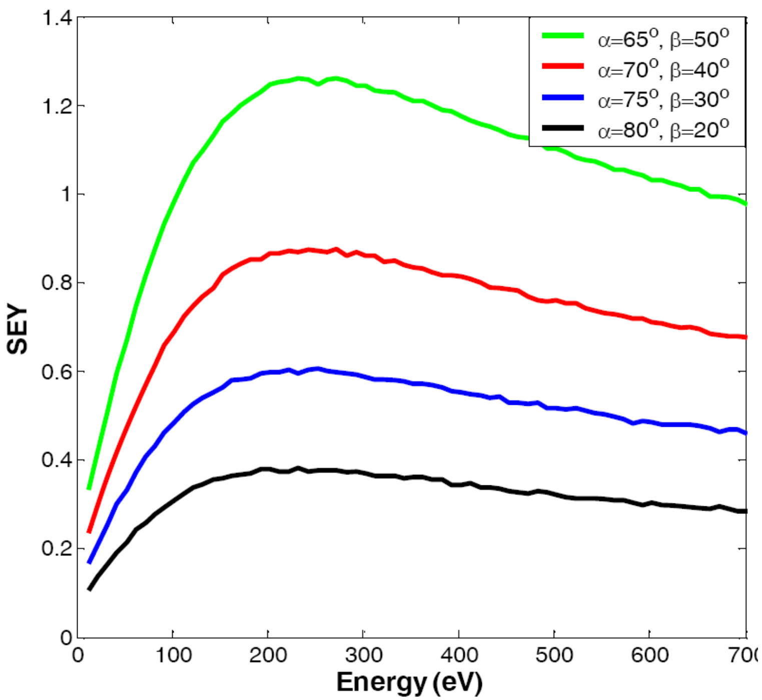


Other collective effects

- Longitudinal and micro-wave instability
  - Keil-Schnell-Boussard threshold $\frac{Z_{||}}{n} = Z_0 \sqrt{\frac{\pi}{2}} \frac{\gamma \alpha_p \sigma_\delta^2 b^2}{N_{bp} r_0 \sigma_s} = 1.75\Omega$ is higher than scaled values from the KEKB LER
  - Transverse coasting beam instability associated with transverse impedance $$Z_\perp = Z_0 \frac{\gamma \alpha_p \sigma_\delta \sigma_s \nu_y \omega_0}{N_{bp} r_0 C} = 11.1 M\Omega/m$$
  - Detailed vacuum chamber design and impedance budget
- Coherent Synchrotron radiation has a minor effect of only 5% of bunch lengthening not causing any emittance blow-up or microwave instability
- Space-charge tune-shift is higher than the acceptable value of 0.1 $\Delta\nu_y = \frac{N_{bp} r_0}{(2\pi)^{3/2} \gamma^3 \sigma_s} \oint \frac{\beta_y}{\sigma_y(\sigma_x + \sigma_y)} ds \approx 0.15$
  - To be taken into account in non-linear dynamics and working point choice
- Fast ion instabilities
  - Analytical estimates and simulations for old parameter set assuming total pressure of 1nTorr (20% CO, the rest hydrogen)
  - Ionisation cross-section of 0.2nTorr and 30% ion frequency spread
  - Ion accumulation avoided for train gap of a few meters
  - Review with new parameter set
- Toushek lifetime large enough compared to store time
- Resistive wall growth time estimated to around 2ms
- Couple bunch instabilities have to be avoided with design of HOM free RF cavities

Damping rings' parameters

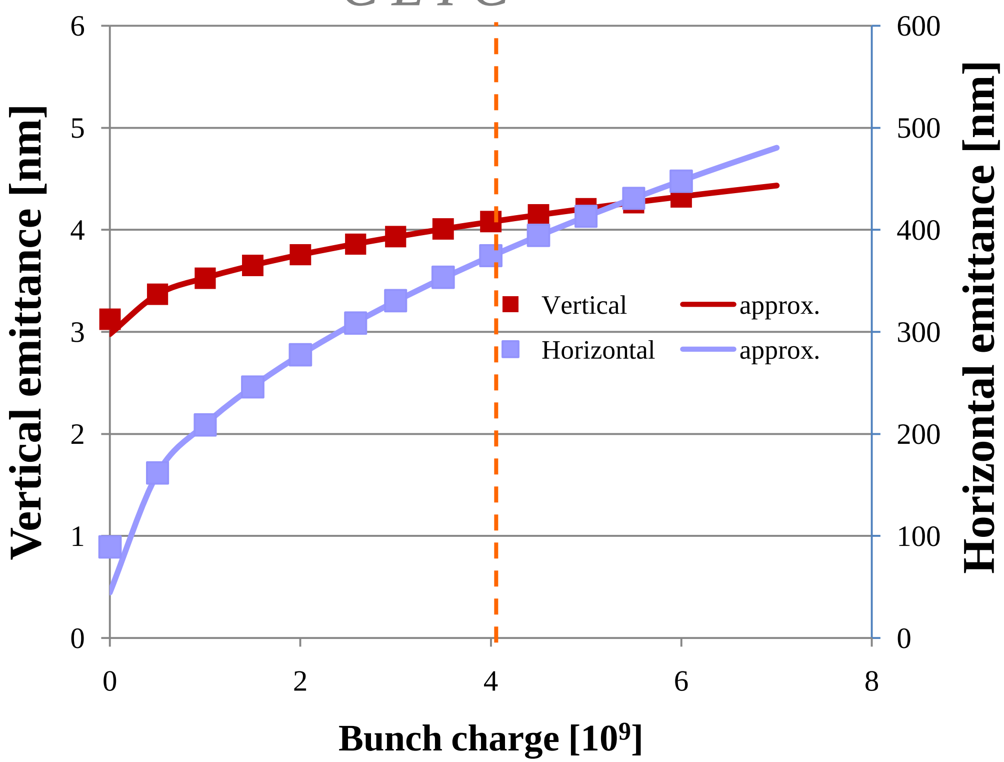
CLIC

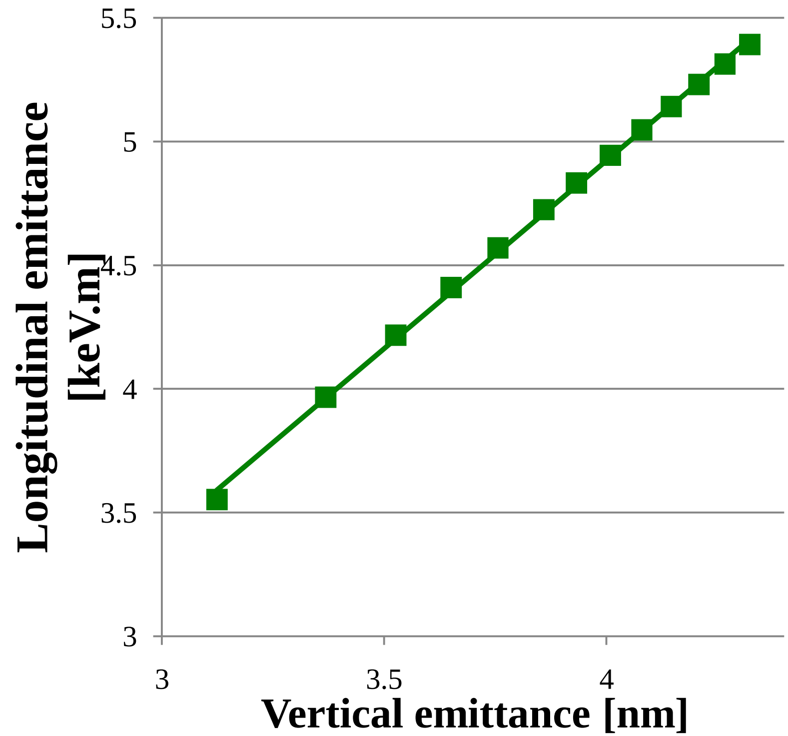
- 2005: original ring
- 2006a: super-conducting wiggler considered
- 2006b: vertical dispersion included
- 2007a: 12GHz structure
- 2007b: reduced bunch population
- 2007c: CLIC_G structure

PARAMETER	2005	2006a	2006b	2007a	2007b	2007c
energy [GeV]	2.424					
circumference [m]	360	365.2				
bunch population [E+09]	2.56+5%			5.20+5%	4.00+10%	3.70+10%
bunch spacing [ns]	0.533			0.667		0.500
number of bunches/train	110			311		316
number of trains	4			1		1
store time/train [ms]	13.3			20		20
rms bunch length [mm]	1.55	1.51	1.59	1.49	1.53	1.53
rms momentum spread [%]	0.126	0.136	0.130	0.138	0.135	0.134
hor. normalized emittance [nm]	540	380	308	455	395	381
ver. normalized emittance [nm]	3.4	2.4	3.9	4.4	4.2	4.1
lon. normalized emittance [eV.m]	4725	5000	4982	4998	4993	4996
(horizontal, vertical) tunes	(69.82, 34.86)	(69.82, 33.80)				
coupling [%]	0.6		0.13			
ver. dispersion invariant [μm]	0		0.248			
wiggler field [T]	1.7	2.5				
wiggler period [cm]	10	5				
energy loss/turn [MeV]	2.074	3.903				
hor./ver./lon./ damping times [ms]	2.8/2.8/1.4	1.5/1.5/0.75				
RF Voltage [MV]	2.39	4.25	4.185	4.345	4.280	4.115
number of RF cycles	2			1		
repetition rate [Hz]	150			50		
RF frequency [GHz]	1.875			1.499		2.00

Y.P., 18/10/2007

Bunch charge





- For the CLIC damping rings, the horizontal normalized emittance scales approximately as $\gamma\epsilon_x \propto \sqrt{N_b/\sigma_z}$
- The above relationship is even more exact when the longitudinal emittance is kept constant (around 5000 eV.m, in the case of the CLIC damping rings)
- Vertical and longitudinal emittance weakly dependent on bunch charge, and linear with each other
- Numerical tools have to be optimised for evaluation of final emittance with IBS
- IBS theory and numerical tools have to be reviewed for non-Gaussian tails
- Demonstration of low-emittance in the presence of IBS needs to be proved experimentally

Concluding remarks

- Detailed and robust design of the CLIC damping rings, delivering target emittance with the help of super-conducting wigglers
  - Prototype to be built and tested at ANKA synchrotron
  - Radiation absorption and quench protection
- Areas needing further optimisation and/or detailed studies
  - Pre-damping ring optics design
  - Realistic damping ring cell length and magnet parameters
  - Sextupole optimisation and non-linear dynamics including wiggler field errors
    - Linear and non-linear correction schemes
  - Low emittance tuning and alignment tolerances
  - IBS theory, numerical tools and experimental demonstration of low emittance
  - Collective effects including electron cloud and fast ion instability
    - Detailed vacuum chamber design – impedance budget
  - Injection and extraction elements
  - Design of HOM free high frequency RF cavities
  - Diagnostics and feedback