Damping Ring Issues

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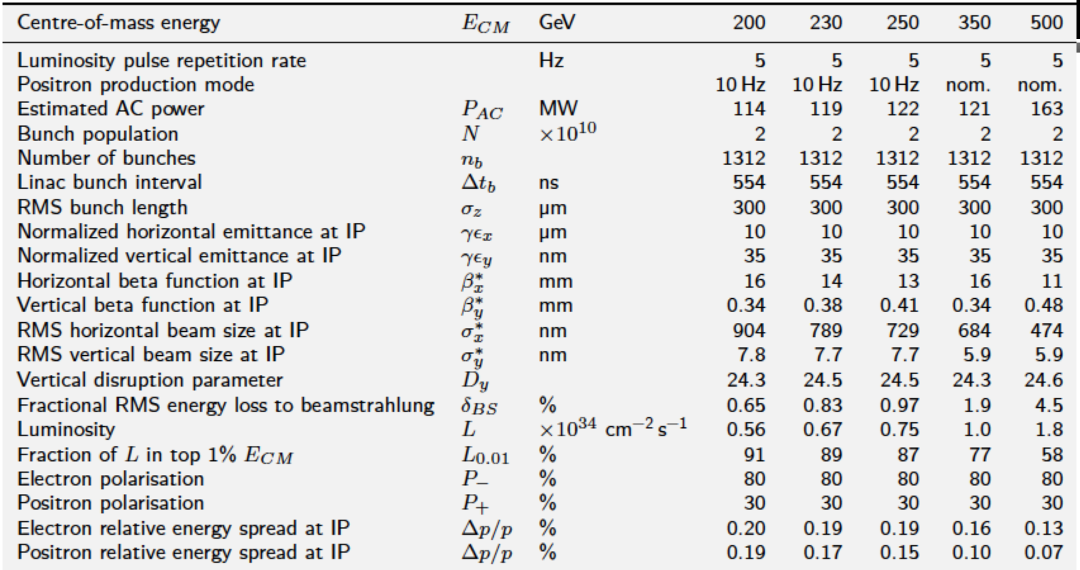
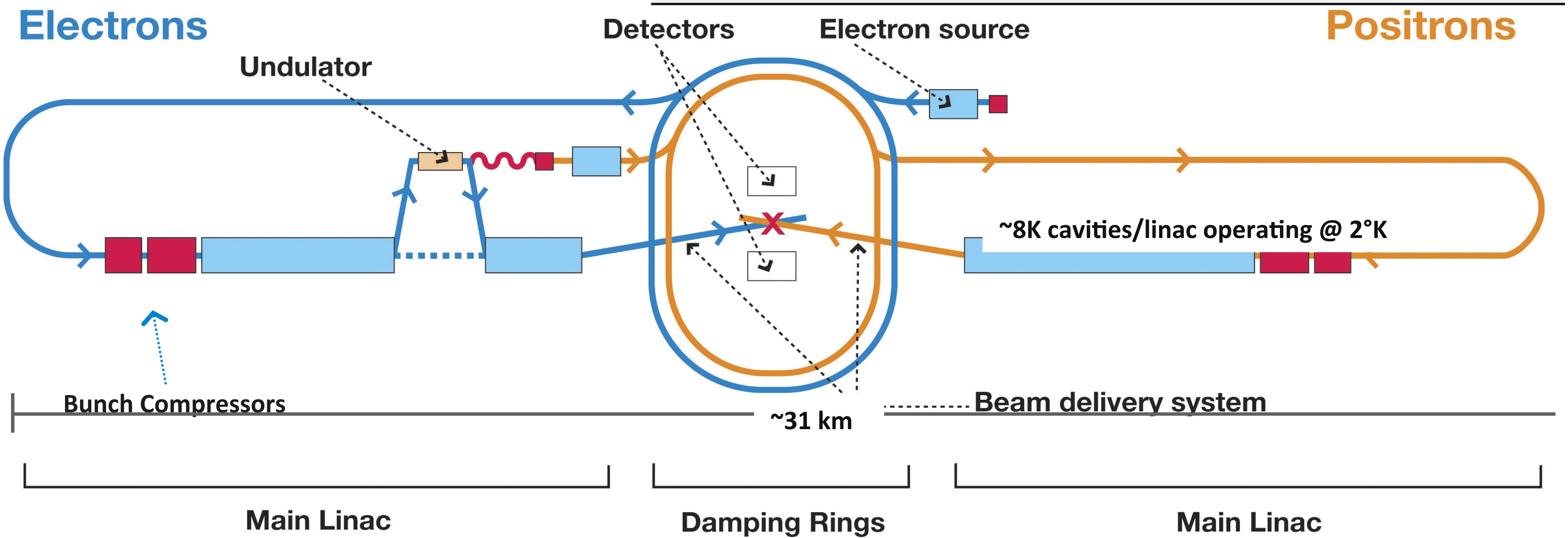
The ILC Design

- Machine Configuration for **500GeV** center of mass energy
  - Helical undulator polarized e+ source
  - Two **~3.2 km damping rings** in the same tunnel
  - RTML running length of linac
  - Two **11.2km main linacs** with super-conducting cavities
  - Single Beam Delivery System
  - 2 Detectors in Push-Pull configuration



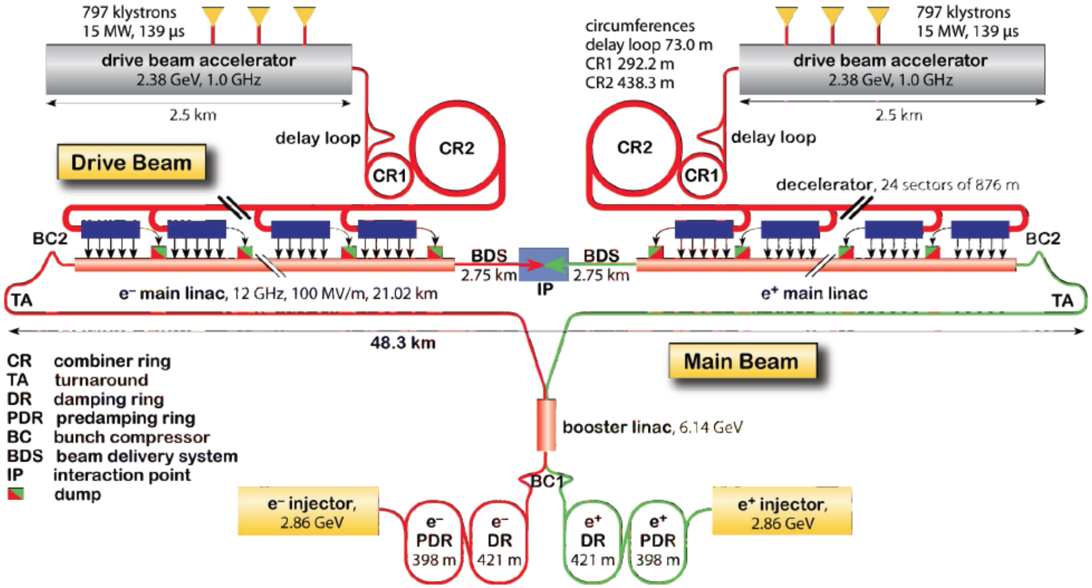
Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	µm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	µm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07



The CLIC Design

- Machine Configuration for 0.5and 3TeV center of mass energy
  - Non-polarised e^+ source
  - Two **~430m** damping rings + two **~400m** pre-damping rings
  - RTML running length of linac
  - Two **~21km main linacs** with copper cavities
  - **Drive beam complex** for R power production
  - Single Beam Delivery System
  - Two Detectors in Push-Pul configuration

Description [units]	**500 GeV**	**3 TeV**
Total (peak 1%) luminosity	$2.3\ (1.4)\times10^{34}$	$5.9\ (2.0)\times10^{34}$
Total site length [km]	13.0	48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	50	
Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m]	2.4/25	0.66/20
Hor./vert. IP beam size [nm]	202/2.3	40/1
Beamstrahlung photons/electron	1.3	2.2
Hadronic events/crossing at IP	0.3	3.2
Coherent pairs at IP	200	6.8×10^{8}



Luminosity Requirements

- The principle parameter driver in a collider is the production of luminosity at the collision point

$$\boxed{\mathcal{L} = \frac{N^2 f_{\mathrm{rep}} n_b}{4\pi\sigma_x\sigma_y}\mathcal{H}_{\mathcal{D}}}$$

  - N, the number of particles per bunch
  - σ_x and σ_y, the horizontal and vertical beam sizes
  - f_{rep}, the collision rate at the interaction point (IP)
  - n_b, the number of bunches
  - $\mathcal{H}_{\mathcal{D}}$, represents combined effect of "hour glass" (longitudinal beta function change over IP) and disruption enhancement (attractive force of colliding bunches)

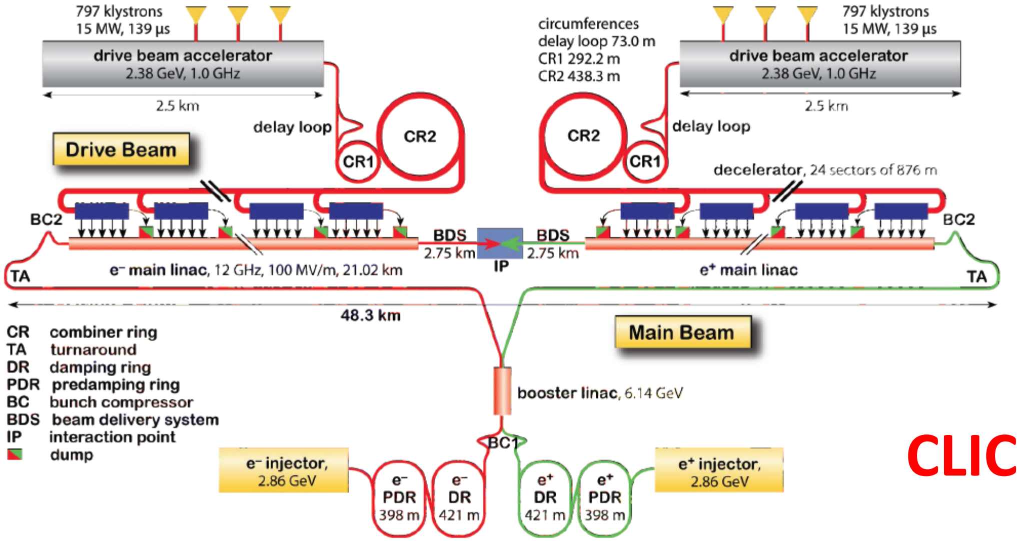
} Assumed equal for all bunches and both beams

- Ideally the target is
  - High intensity bunches
  - Small transverse beam size
  - High repetition rate
  - Large number of bunches

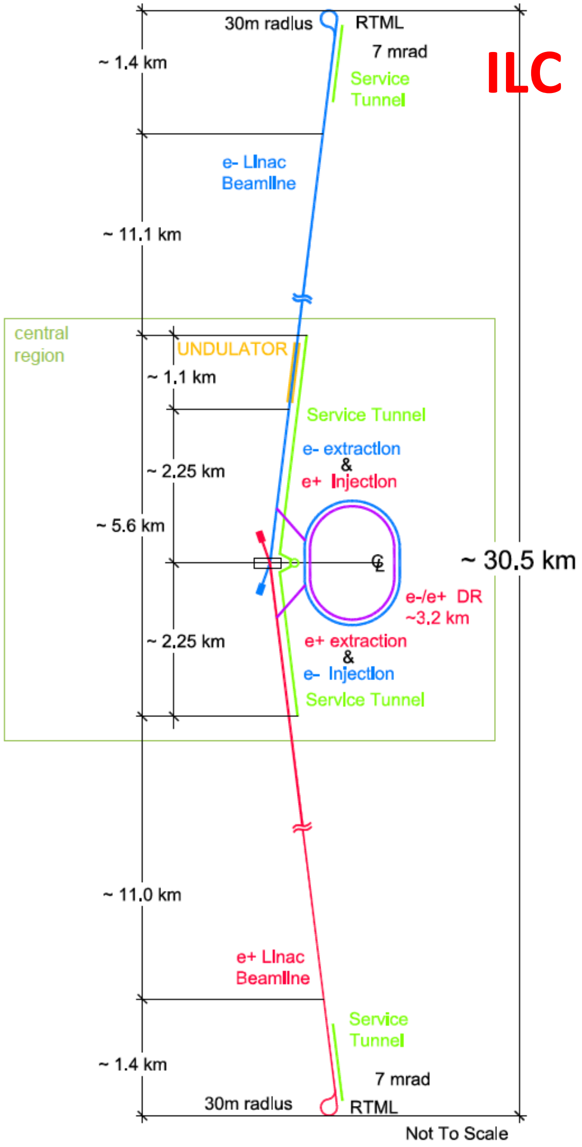
} High brightness

Role of Damping Rings

- **Accept** e^+ and e^- beams with **large** transverse and longitudinal **emittances** and **damp** them by several orders of magnitude producing **ultra-low emittance** beams necessary for high luminosity collisions at the interaction point (IP), **within** the (fast) **repetition rate** imposed by the collider
- **Damp** longitudinal and transverse **jitter** in the incoming beams to provide very stable beams for delivery to the IP
- **Delay bunches** from the source to **allow** feed-forward systems **to compensate** for **pulse-to-pulse variations**



CLIC



LC Damping Ring Design Constraints

- DR parameters are constrained due to LC physics performance requirements (**luminosity**), the downstream systems (mainly **main linac RF**, but also **RTML**), the upstream systems (particle **sources**, mainly e^+)
- They impact damping rings beam dynamics but also technology

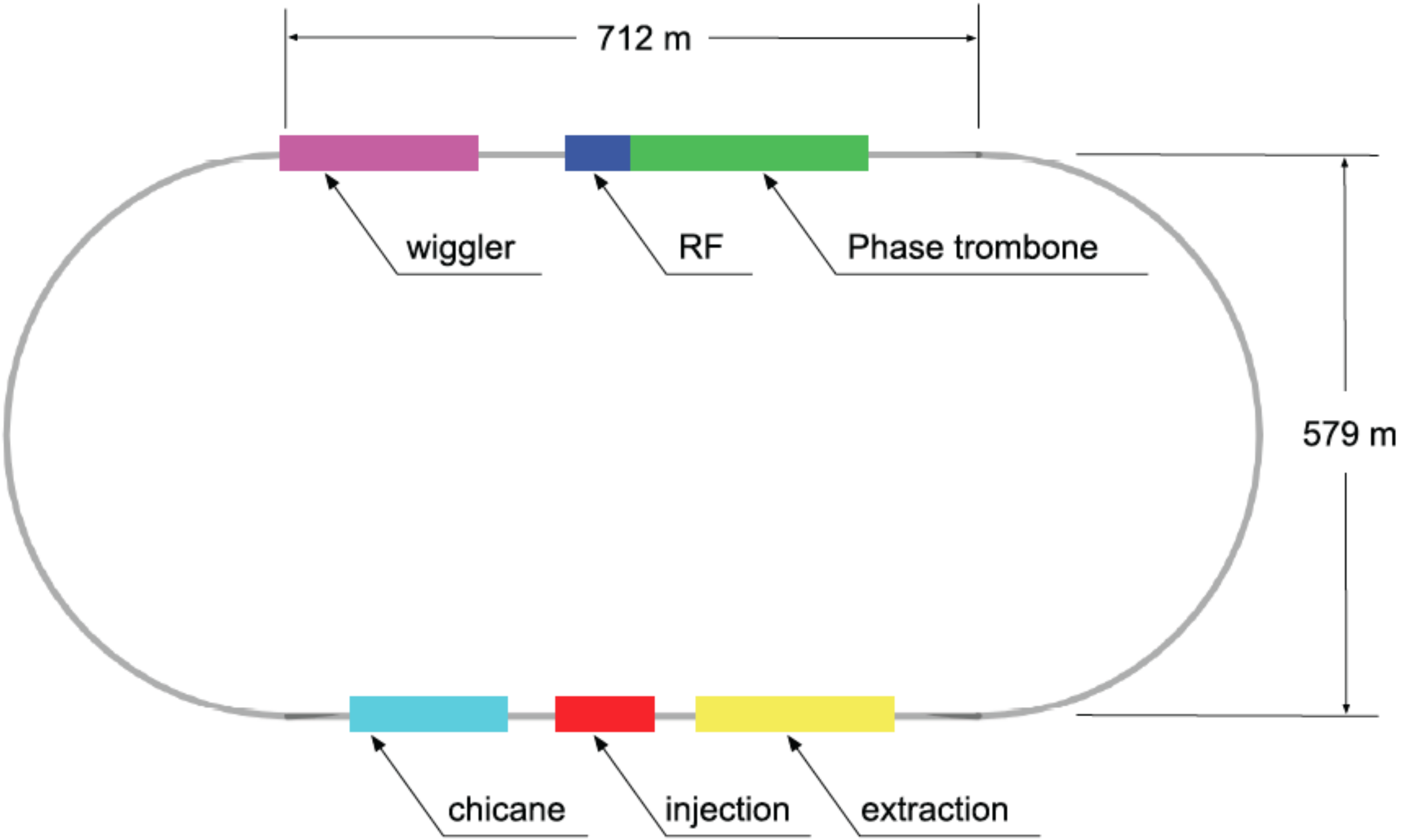
Parameters	CLIC	ILC	Constraints	Impact on DR design
Particles per bunch	4×10^{9}	2×10^{10}	Maximum set by disruption at IP, and linac short range wakefields, minimum set by luminosity target and RF to beam efficiency	Single bunch Collective effects, impedance budgets, vacuum, feedback
Machine repetition rate [Hz]	50	5	Set by cryogenic cooling capacity in ILC, partially determines required damping time	Lattice design, layout, damping wigglers parameters
Linac RF pulse length [μs]	0.156	1600	Upper limit set by RF technology and RF to beam efficiency	Layout, collective effects, extraction kicker design, RF system design (including LLRF)
Bunch spacing in linac/DR [ns]	0.5/1	554/6		
Particles per machine pulse	1.3×10^{12}	5.3×10^{13}	Lower limit set by luminosity target	Collective effects
Injected normalized emittance (e^+) [μm.rad]	7000	8	Set by positron source, influences damping time requirement	Number of damping stages, layout, lattice design, dynamic aperture, magnet tolerances
Injected rms energy spread [%]	±4.5	±0.75	Set by positron source	Momentum (dynamic) acceptance, magnet tolerances
H/V Extracted normalized emittances [nm]	500/5	5000/20	Set by luminosity goal and emittance growth budget in downstream systems	Lattice design, alignment tolerances, collective effects
Extracted rms bunch length [mm]	1.8	6	Upper limit set by downstream bunch compressors	RF system, collective effects
Extracted rms energy spread [%]	0.1	0.15		

ILC DR Design

- The ILC DR baseline configuration is able to meet the key design parameters required for the baseline design
  - Validation of the various design choices continues
  - Major limiting areas of operational concern identified for further R&D included
    - Achievement of 2pm vertical emittance
    - Electron Cloud effects
    - Fast Ion effects
    - Ability to stably inject and extract closely spaced bunches
  - An aggressive R&D program has been underway for address these issues at CESRTA and ATF

The TDR ILC Damping Ring Layout

- DTC4 – Racetrack shape, Circumference 3.2 km, energy of 5GeV
- TME style lattice in the arcs
- Straight sections filled mostly with FODO cells and include damping wigglers, RF and beam transfer equipment, circumference chicane and phase trombone



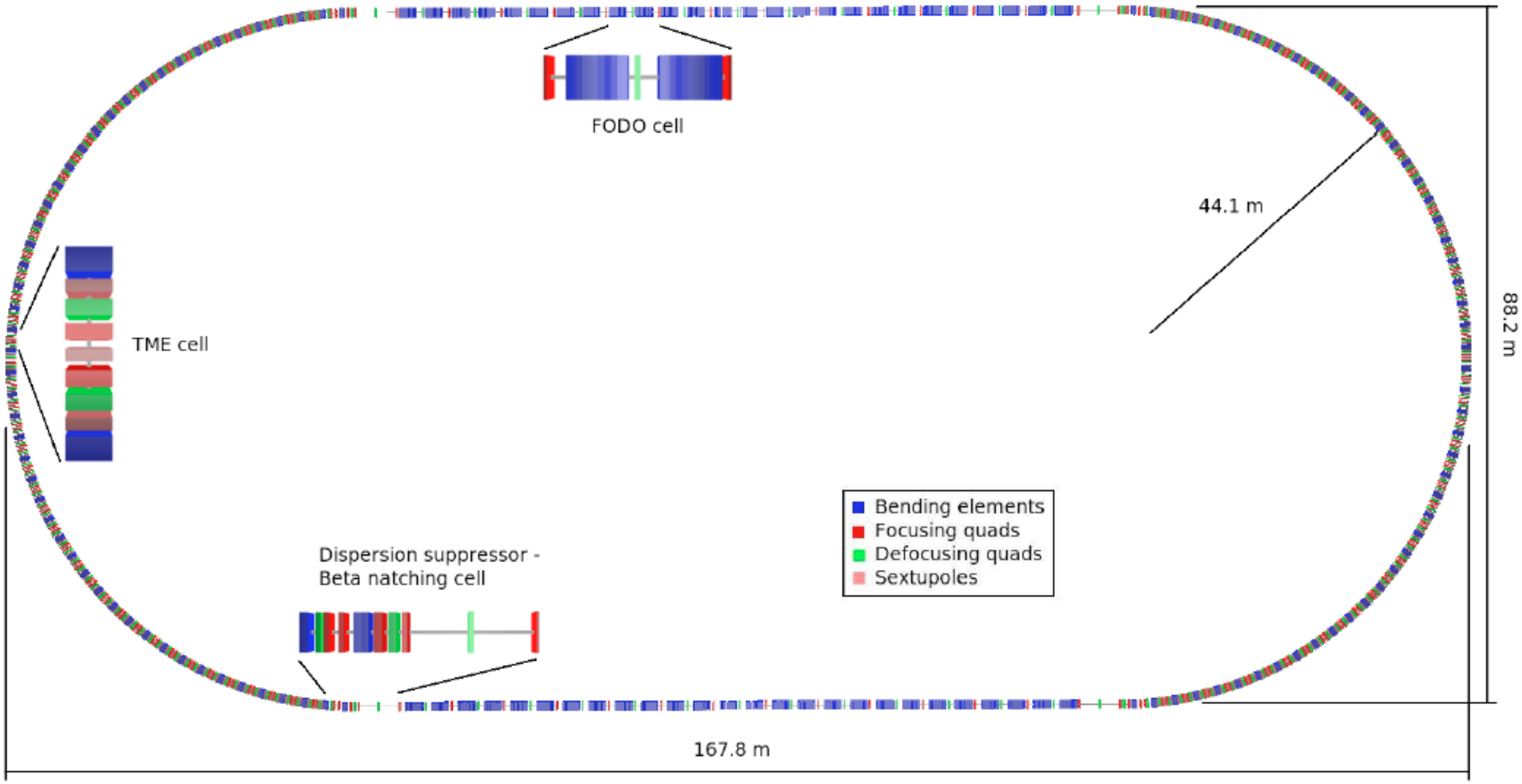
CLIC DR challenges and adopted solutions

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

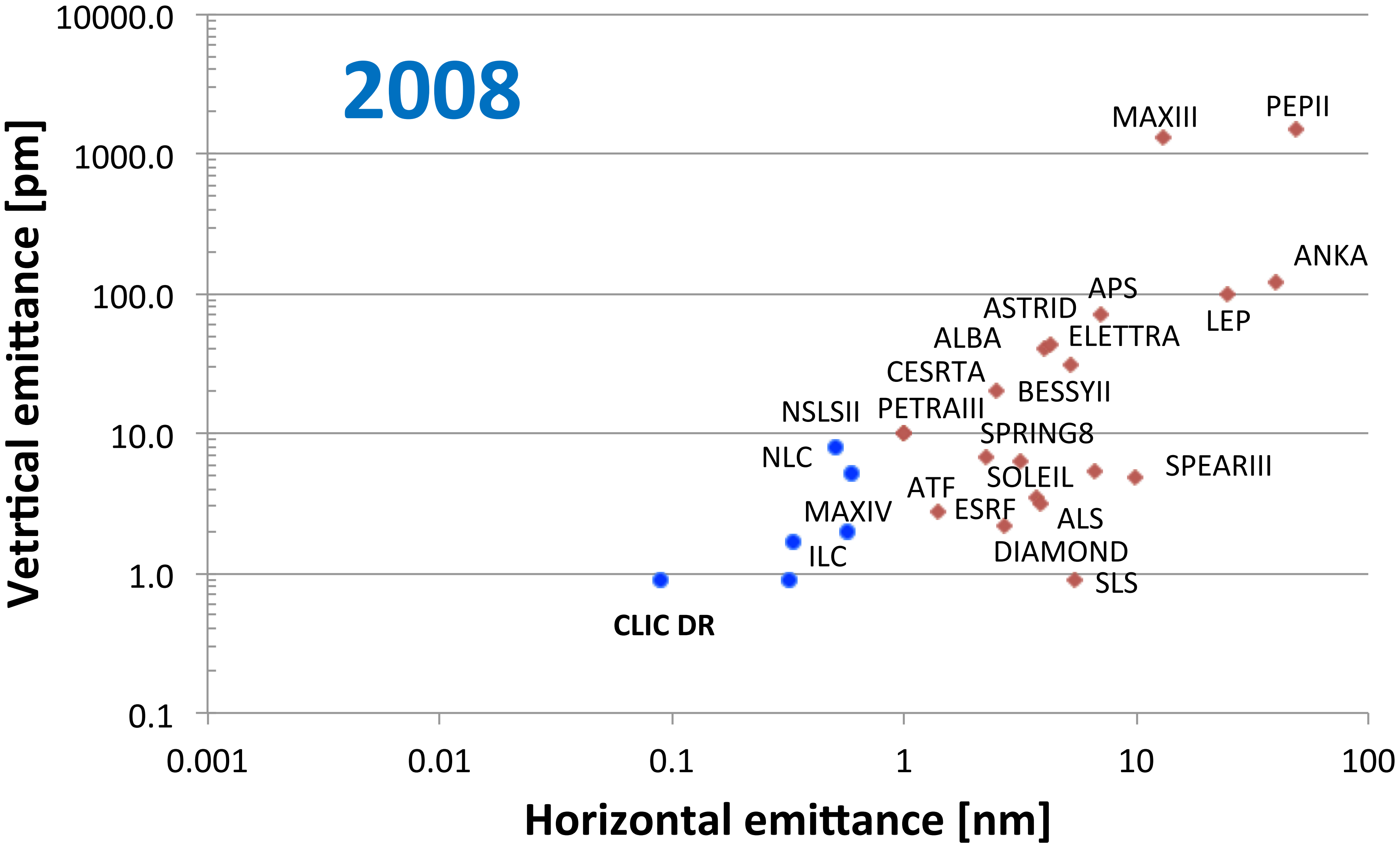
- High-bunch density in all three dimensions
  - **Intrabeam Scattering** effect reduced by choice of ring energy, lattice design, wiggler technology and alignment tolerances
  - **Electron cloud** in e$^+$ ring mitigated by chamber coatings and efficient photon absorption
  - **Fast Ion Instability**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

The CDR CLIC Damping Ring Layout

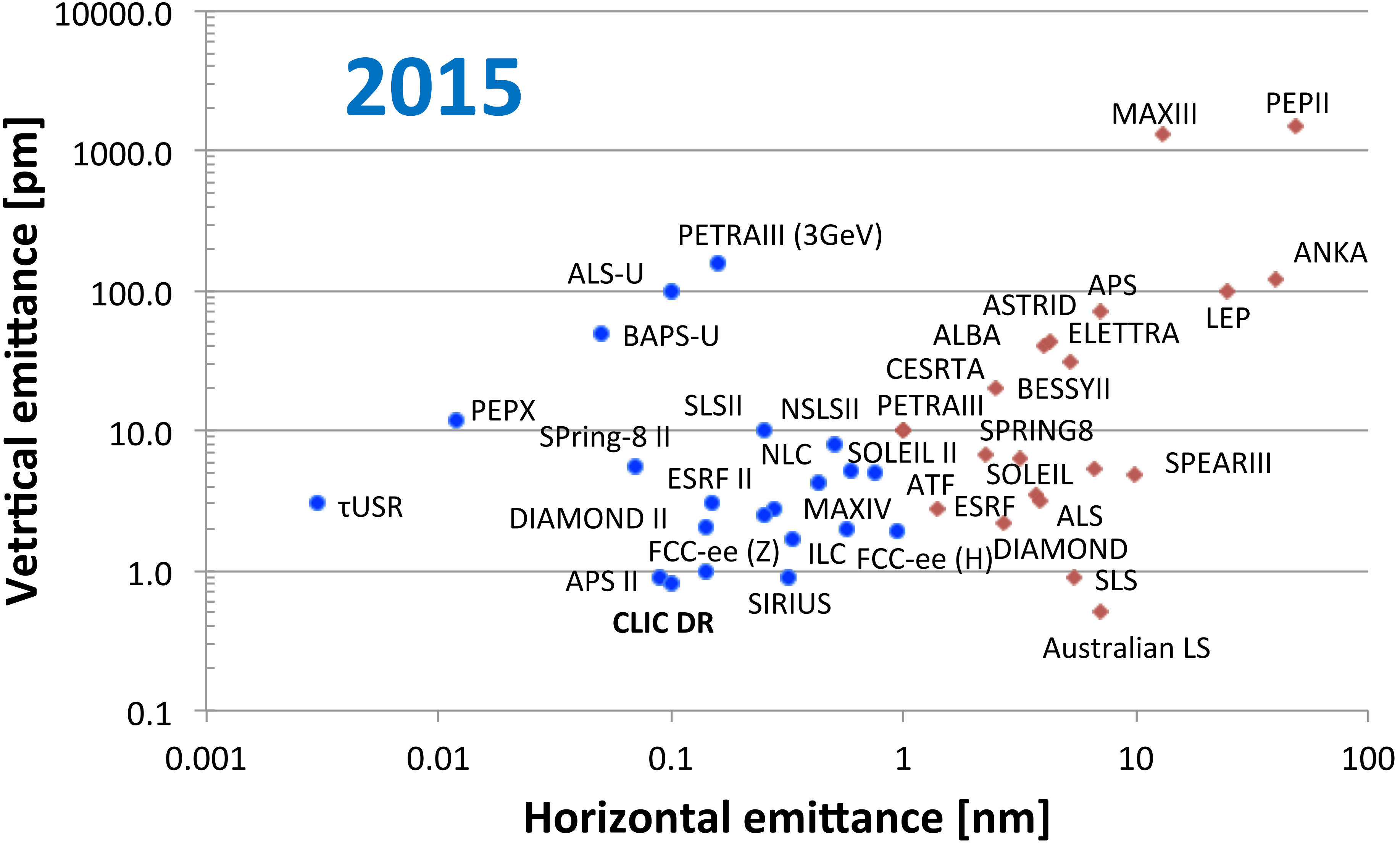
- Racetrack shape, Circumference 427.5 m, energy of 2.86GeV
- TME in the arcs with gradient dipole
- Straight sections filled with FODO cells and include damping wigglers, RF and beam transfer equipment



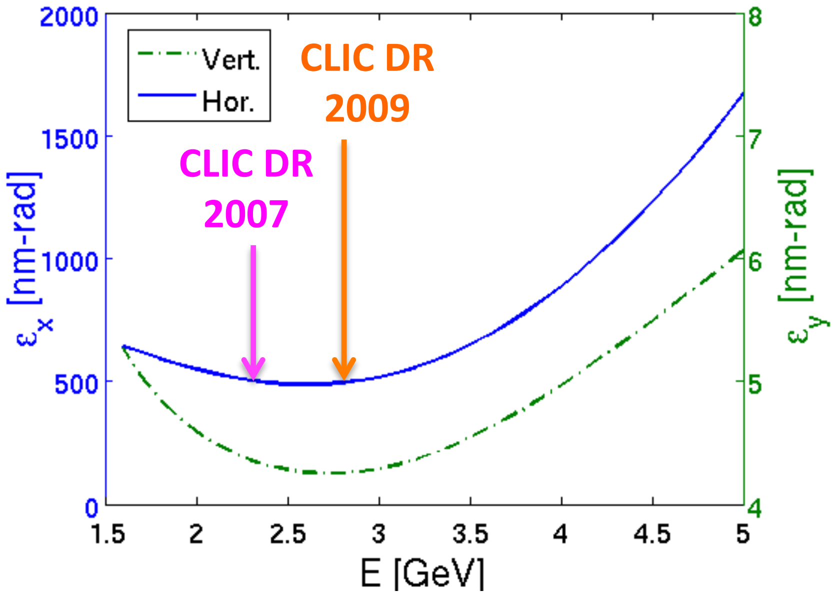
Emittance targets

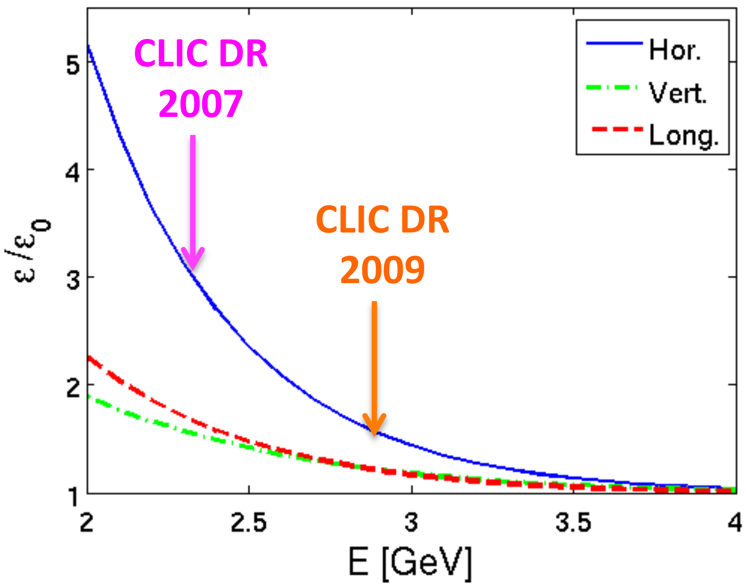


Emittance targets



Optimal energy for IBS reduction





- Steady state (normalised) emittance as a function of the energy (including IBS)
- Broad minimum at around 2.5 GeV

See talk of F. Antoniou

- Strong horizontal beam blow-up for lower energies
- Increased energy from **2.42** to **2.86** GeV resulted in reduction of horizontal emittance blow-up by a **factor of 2**

Parameterization of TME cells

$$f_1 = \frac{s_2(4s_1 l_d + l_d^2 + 8D_{xc}\rho)}{4s_1 l_d + 4s_2 l_d + l_d^2 - 8D_s\rho + 8D_{xc}\rho}$$

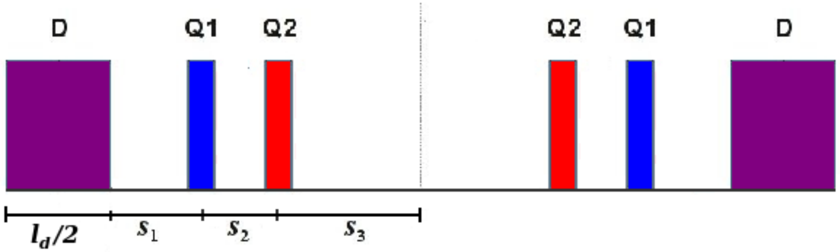
$$= \frac{l_d s_2\left(12 s_1 + l_d\left(D_r + 3\right)\right)}{12 l_d\left(s_1 + s_2\right) + l_d^2\left(D_r + 3\right) - 24 D_s \rho}$$

$$f_2 = \frac{8 s_2 D_s \rho}{-4 s_1 l_d - l_d^2 + 8 D_s \rho - 8 D_{xc}\rho}$$

$$= \frac{24 s_2 D_s \rho}{12 l_d s_1 + l_d^2\left(D_r + 3\right) - 24 D_s \rho}$$

$$D_r = \frac{D_{xc}}{D_{xc}^{\min}}, \beta_r = \frac{\beta_{xc}}{\beta_{xc}^{\min}}, \varepsilon_r = \frac{\varepsilon_{xc}}{\varepsilon_{xc}^{\min}}$$

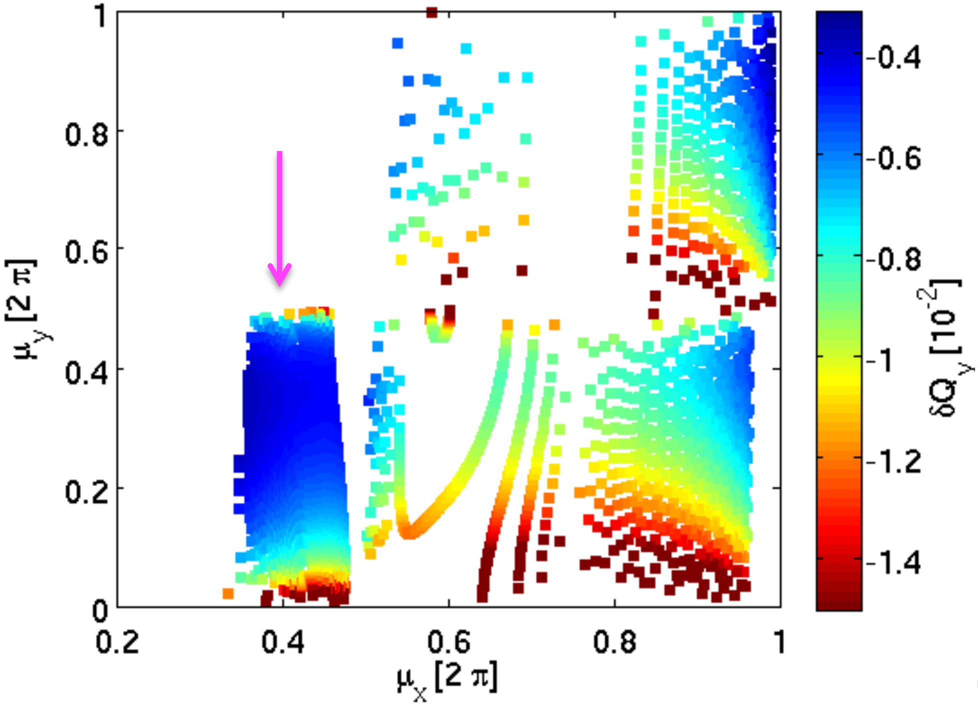
$$D_s = g(s_1, s_2, s_2, l_d, \beta_r, D_r)$$



- Analytical representation of TME quadrupole focal lengths (thin lens)
  - Depending on horizontal optics conditions at dipole center (horizontal emittance) and drift lengths
  - Multi-parametric space for applying optics stability criteria, magnet constraints, non-linear optimization, **IBS reduction,…**

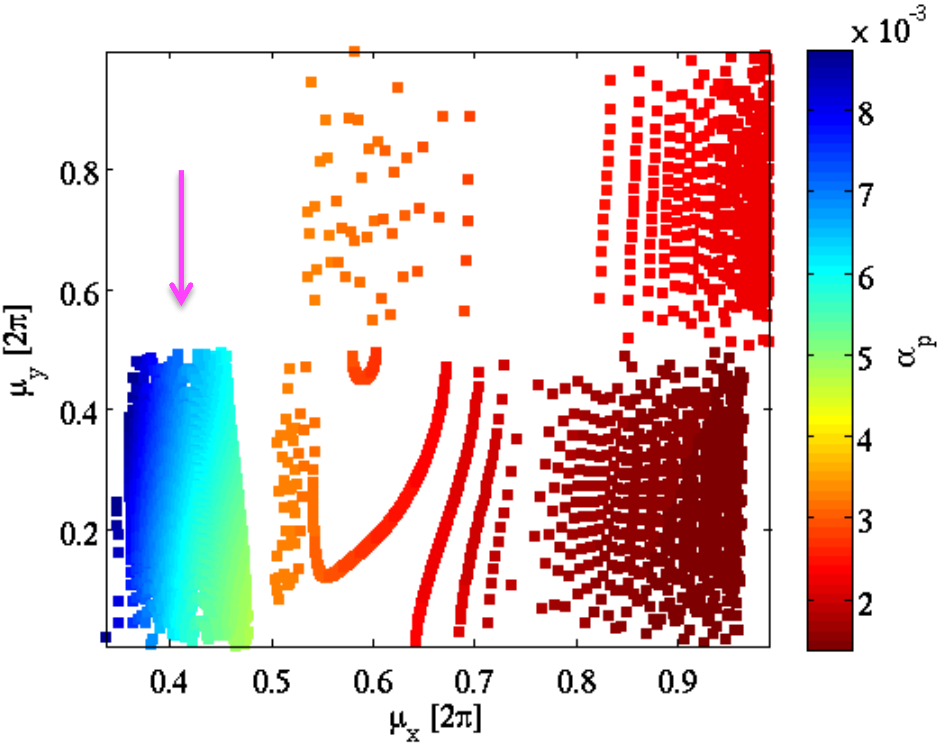
F. Antoniou and Y.P, PRSTAB 17 (6), 064002, 2014

TME optimization for reducing IBS



❑ **Low cell phase advances** can minimize **IBS growth rates**

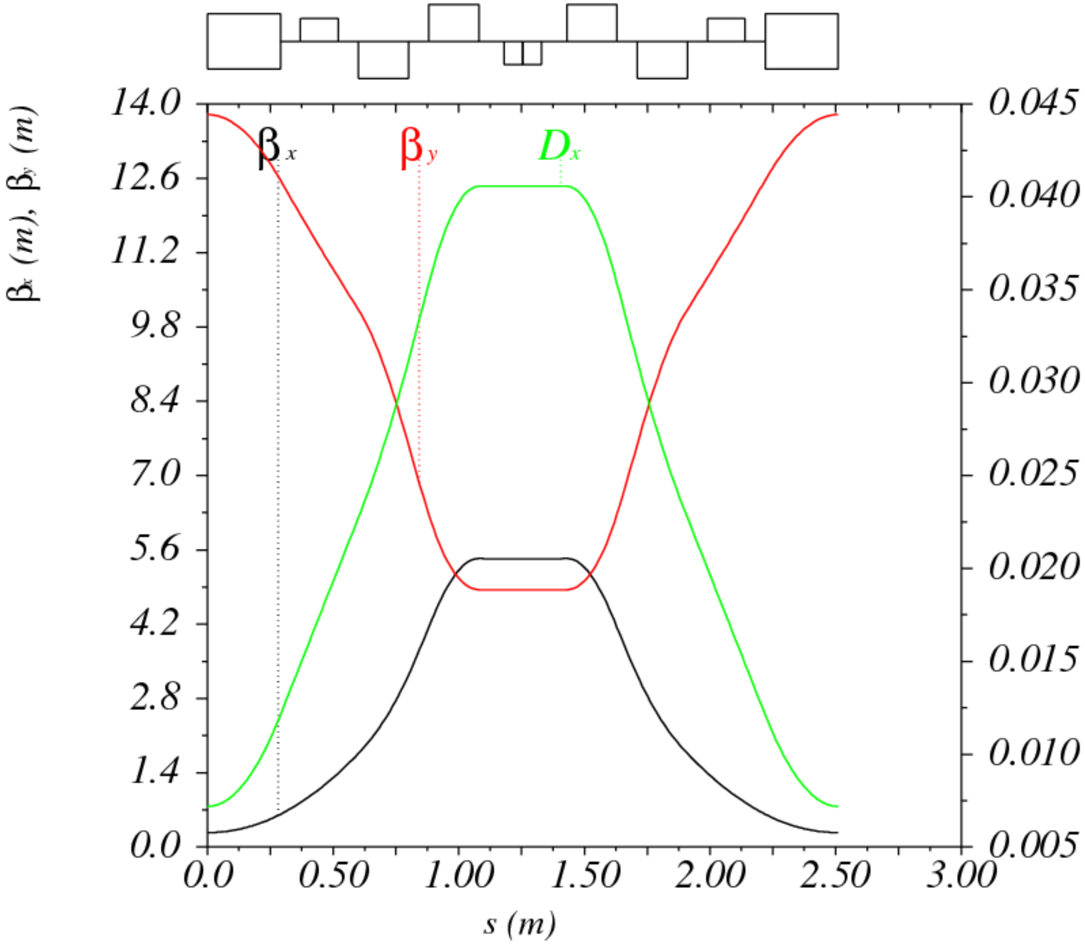
❑ Correspond to large **deviation** from absolute theoretical emittance minimum



❑ Optimal also for minimizing **space-charge** tuneshift and increase **momentum compaction factor**

See talk of F. Antoniou

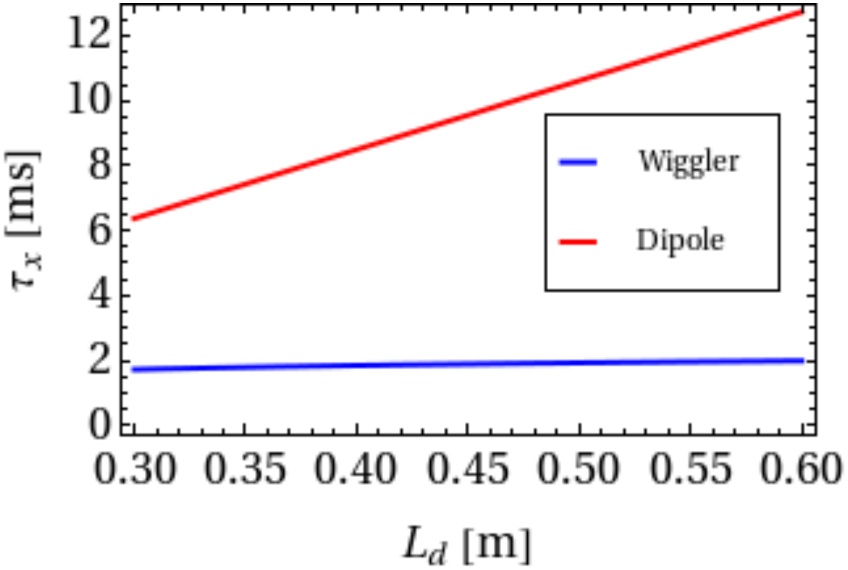
Optimized TME cell

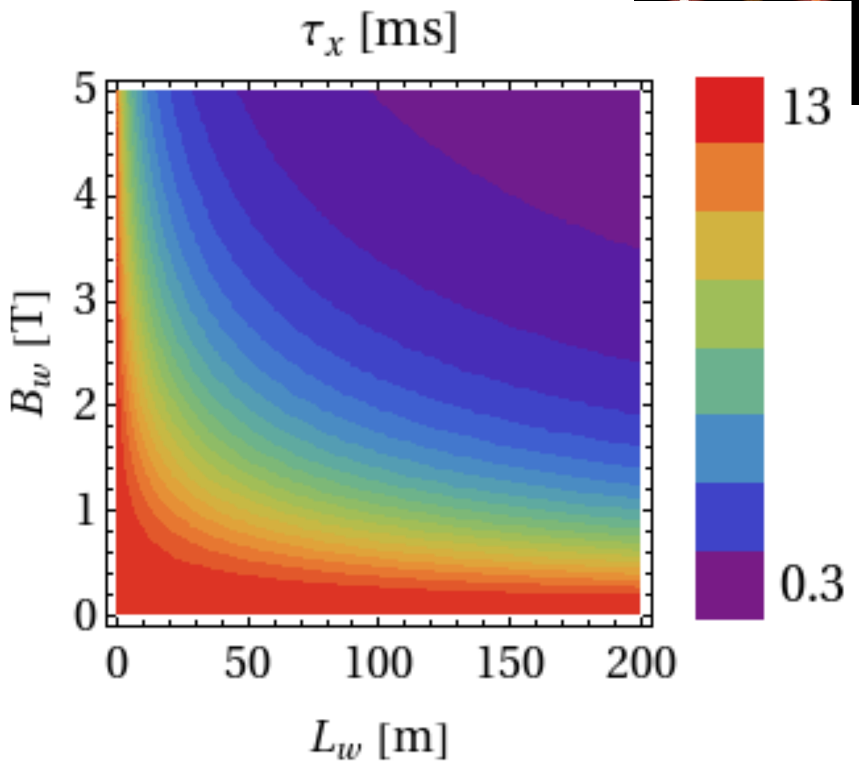


- TME cell with defocusing gradient along the dipole length
  - Reduction of the IBS effect
- Dipole length increased
  - l_d=0.58m (from 0.43m)
- Horizontal phase advance reduced
  - μ_{xTME}=0.408 (from 0.452)
- RF voltage decreased
  - V_{RF}=5.1MV (from 4.5MV)

CLIC DR damping times

F. Antoniou, PhD thesis, NTUA 2013

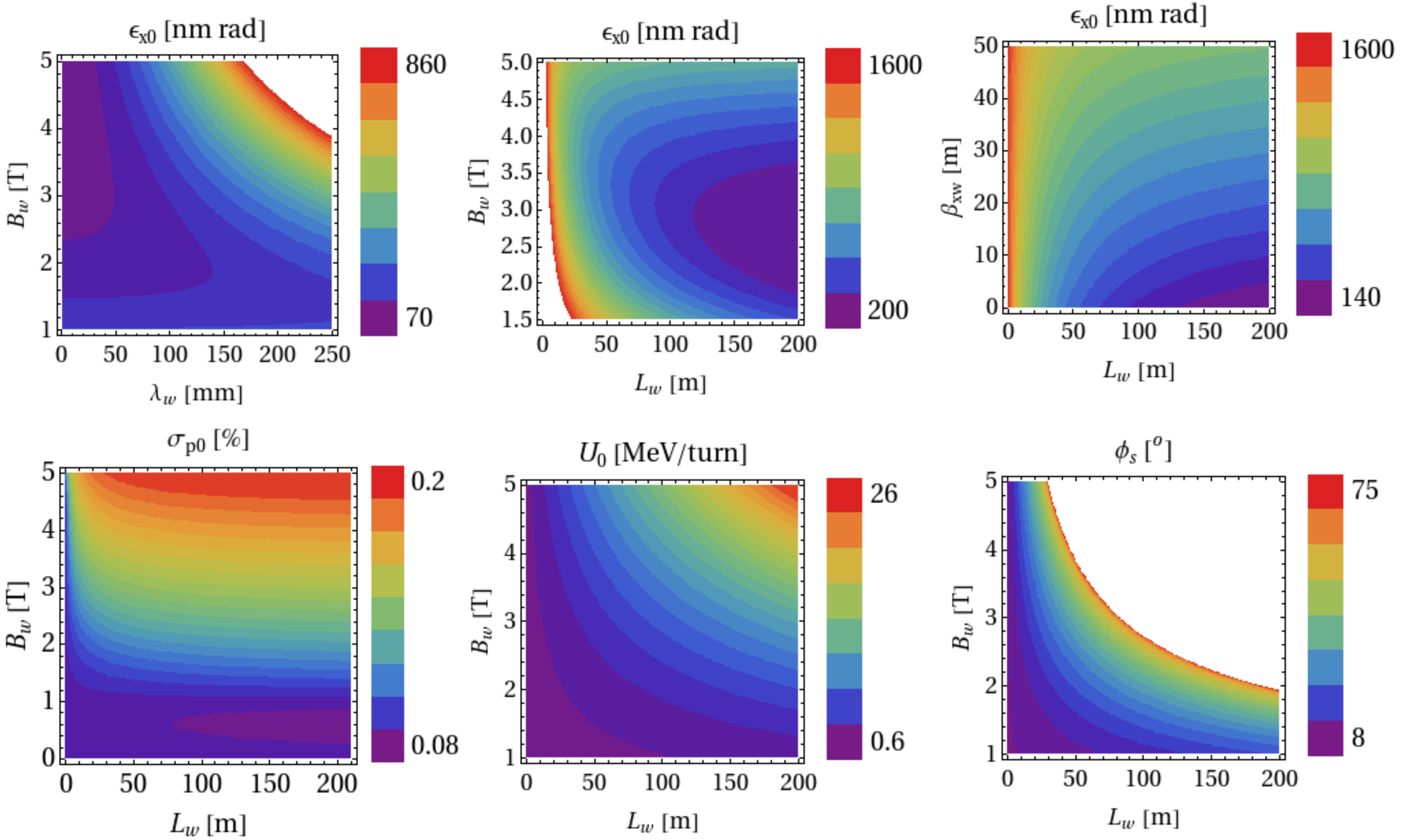




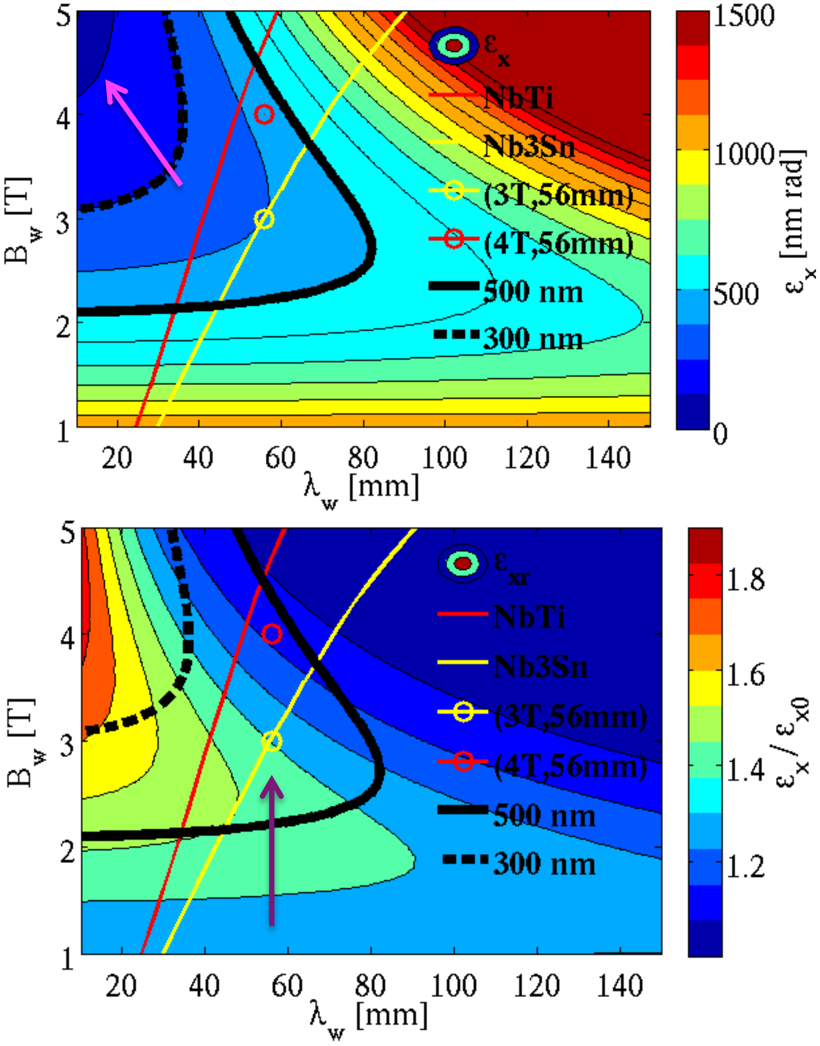
- To damp the beam from 63 μm-rad to 500 nm-rad in less than 20 ms a maximum damping time of 4 ms is required →
- Large dipole fields (or very small dipole length)
  - Cannot be achieved by normal conducting dipoles
- Fast damping times can be achieved for large wiggler fields and/or large wiggler total length

Effect of damping wigglers on CLIC DR

F. Antoniou, PhD thesis, NTUA 2013



Wiggler parameter choice

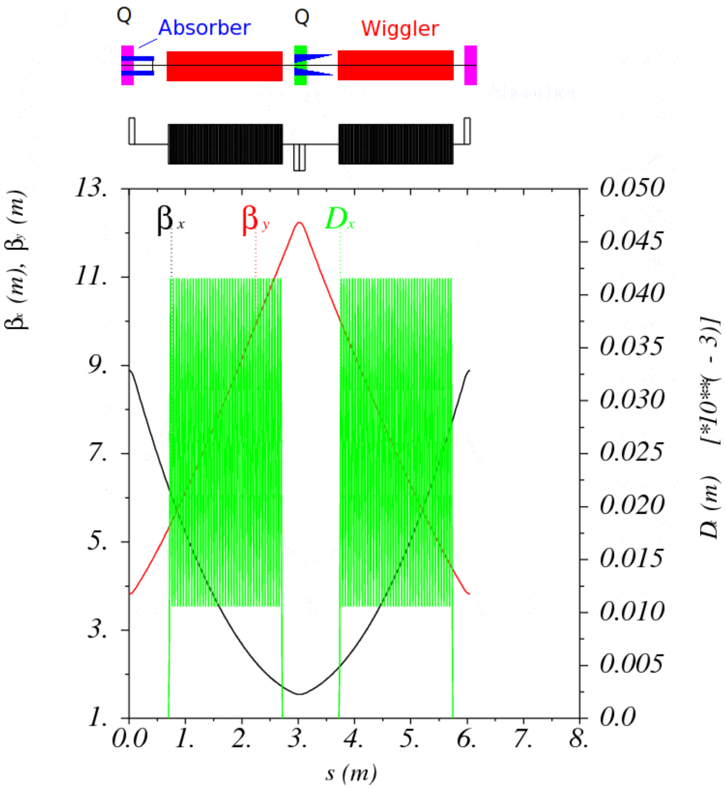


Courtesy F. Antoniou

- The **highest field** and **smallest period** provide the smallest emittance
- Lower emittance blow-up due to IBS for **high-field** but **moderate period** (within CLIC emittance targets)
- Wiggler prototype in NbTi with these specs, built at BINP, for installation to ANKA (KIT)
  - Serving X-ray user community but also beam tests
- Development of higher-field short models in Nb3Sn at CERN

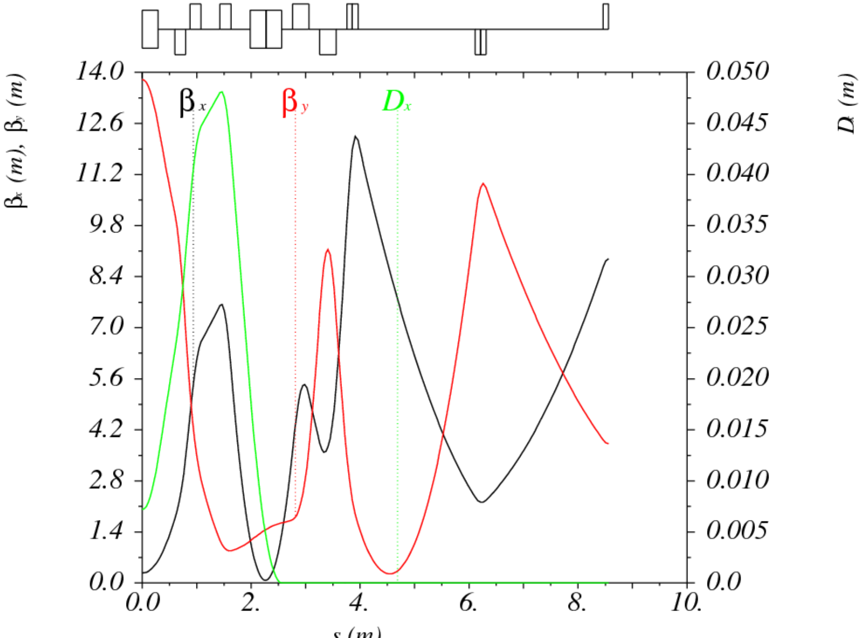
D. Schoerling et al., PRST-AB 15, 042401, 2012

CLIC DR FODO and DS-BM cells



- FODO cells accommodate the damping wigglers (2 wigglers / cell)
- Space is reserved for the **absorption scheme** of synchrotron radiation

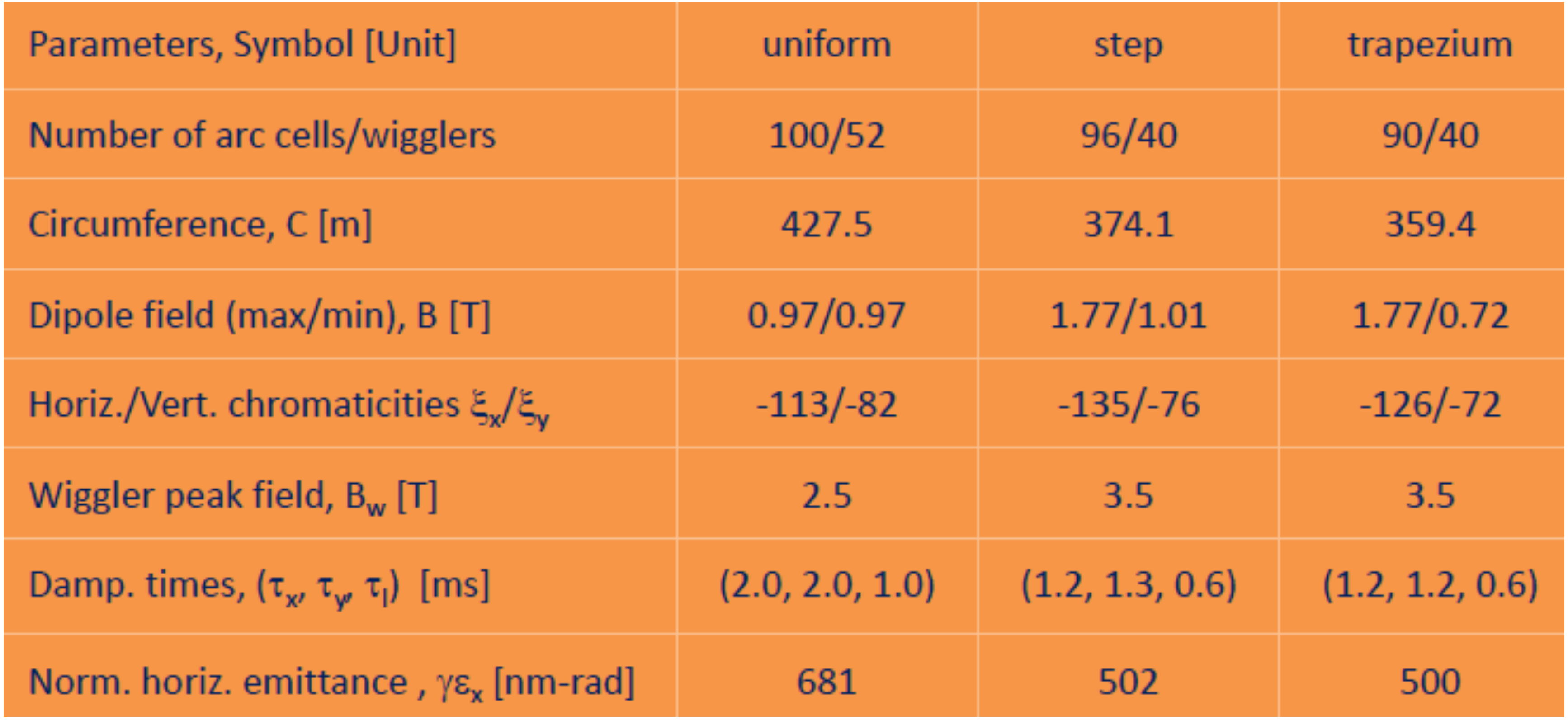
- Dispersion suppression – beta matching cell optics
- Space is reserved for **injection/ extraction** elements and **RF cavities**



Ring Circumference

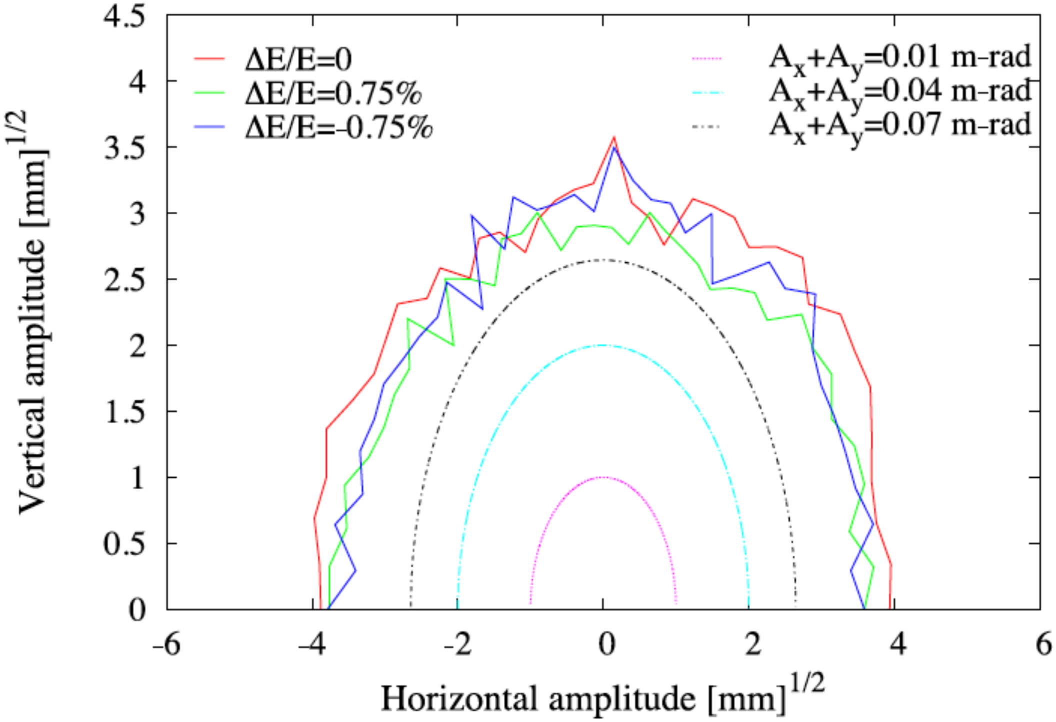
- Large circumference implies that collective effects (IBS, space charge) are more severe
- Small circumference implies fewer components and smaller tunnel so cheaper and potentially better net hardware reliability
- Effort to reduce circumferance in CLIC damping rings through variable dipoles and new higher field wigglers

See talk of S. Papadopoulou



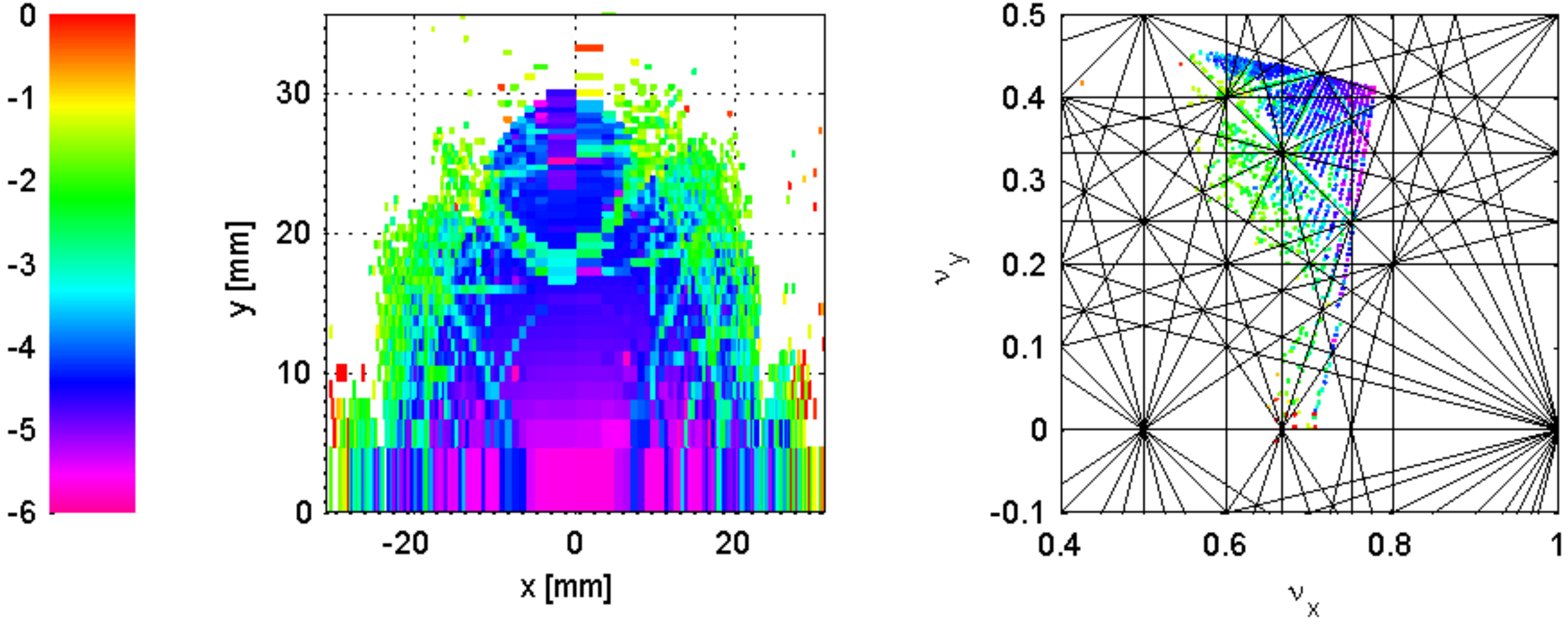
Parameters, Symbol [Unit]	uniform	step	trapezium
Number of arc cells/wigglers	100/52	96/40	90/40
Circumference, C [m]	427.5	374.1	359.4
Dipole field (max/min), B [T]	0.97/0.97	1.77/1.01	1.77/0.72
Horiz./Vert. chromaticities ξ_x/ξ_y	-113/-82	-135/-76	-126/-72
Wiggler peak field, B_w [T]	2.5	3.5	3.5
Damp. 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)
Norm. horiz. emittance , $\gamma\varepsilon_x$ [nm-rad]	681	502	500

ILC DR Dynamic Aperture



- Dynamic aperture for lattice with specified misalignments, multipole errors, and wiggler nonlinearities
- Specification for the phase space distribution of the injected positron bunch is an amplitude of **A**x + **A**y = 0.07m rad (normalized) and an energy spread of **E/E** 0.75%
- DA is larger then the specified beam acceptance

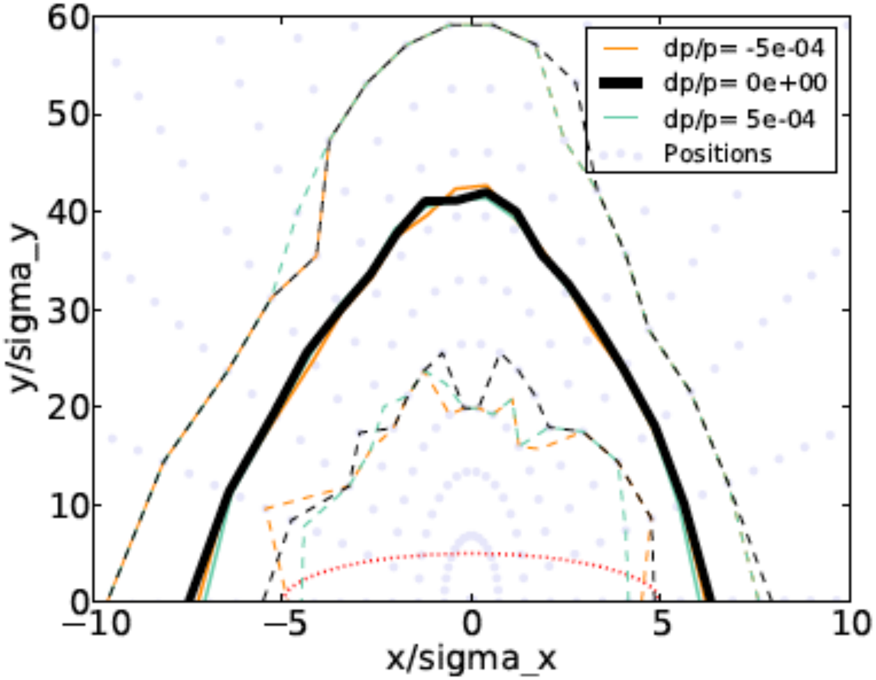
Frequency maps for the ILC DR

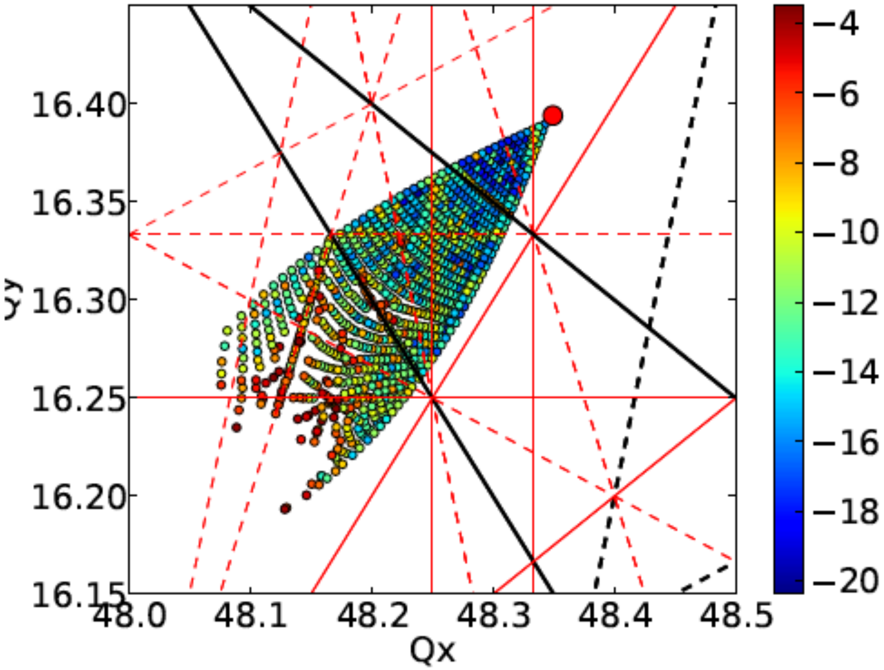


- Frequency maps enabled the comparison and steering of different lattice designs with respect to non-linear dynamics
  - Working point optimisation, on and off-momentum dynamics, effect of multi-pole errors in wigglers

Dynamic aperture for CLIC DR

See talk of 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

Summary

- DR design has to comply with numerous constraints and design requirements imposed by upstream and downstream systems
- The optimization process involves complicated trade-offs to meet physics specifications
- DR offer a wide spectrum of challenges both for beam dynamics and the required hardware
- A large number of these challenges are shared with the X-ray storage rings and e+/e- ring colliders (and their injector systems)

THANK YOU
for your
attention