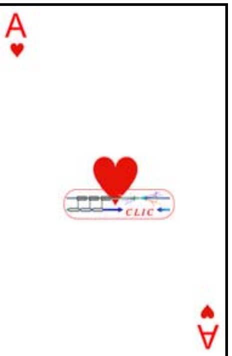
Low emittance generation in Damping rings

Specifications, status and plans of R&D until the CDR

Yannis PAPAPHILIPPOU

For the CLIC Damping Ring design team

May 27th, 2009



Contributors

F. Antoniou, M. Barnes, S. Bettoni, S. Calatroni, A. Grudiev, R. Maccaferri, M. Martini, G. Rumolo, M. Taborelli, A. Vivoli, F. Zimmermann (CERN), A. E. Bol'shakov, P. R. Zenkevich (ITEP), E.B. Levichev, S.V. Sinyatkin, P. Vobbly, K.V. Zolotarev (BINP), M. Palmer (Cornell), M. Korostelev (CI), C. Skokos (MPI Dresden), W. Bruns (GDFIDL), H.H. Braun (CERN – PSI), P. Raimondi (INFN-LNF)

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P. Chiggiato, R. Corsini, J.-P. Delahaye, T. Fowler, B. Jeanneret, M. Karpinnen, T. Lefevre, L. Rinolfi, D. Quatraro, G. Riddone, H. Schmickler, D. Schulte, F. Stulle, R. Tomas, J. Uythoven (CERN), R. Tucker (Un. Lancaster), A. Wolski (CI), A. Bernard, P. Peiffer, R. Rossmanith, D. Wollmann (Un. Karlsruhe), A. Streun (PSI), A. Andersson (PSI - Lund) J. Urakawa (KEK), S. Guiducci (INFN-LNF), M. Pivi, T. Raubenheimer (SLAC), V. Shiltsev M. Wendt (FNAL) …

Apologies to those I may have forgotten

Outline

- CLIC Damping Rings (DR) design goals
  - Energy revision
- Pre-Damping Rings (PDR) design
- Lattice revision for **Intra-beam Scattering (IBS)** reduction
- Wiggler design
  - Wiggler modelling and **prototyping**
  - Power absorption studies
- Collective effects
  - e$^-$-cloud, Fast Ion Instability
- RF design considerations and **challenges**
- Kicker **specifications**
- Low emittance tuning
- Beam instrumentation
- **Collaboration** with ILC
- DRs for **CLIC@500GeV**
- Summary

DR design goals and challenges

PARAMETER	NLC	CLIC
bunch population (10^9)	7.5	4.1
bunch spacing [ns]	1.4	0.5
number of bunches/train	192	312
number of trains	3	1
Repetition rate [Hz]	120	50
Extracted hor. normalized emittance [nm]	2370	<**500**
Extracted ver. normalized emittance [nm]	<30	<**5**
Extracted long. normalized emittance [keV.m]	10.9	<**5**
Injected hor. normalized emittance [µm]	150	63
Injected ver. normalized emittance [µm]	150	1.5
Injected long. normalized emittance [keV.m]	13.18	1240

- Design parameters dictated by target performance of the collider (e.g. luminosity), injected beam characteristics or compatibility with the downstream system parameters
- Most parameters are **driven** by the main linac RF optimization
- In order to reach ultra-low emittance, CLIC DR design is based on the inclusion **super-conducting wigglers**
- Output emittance is **dominated by IBS** due to high bunch charge density
- Instabilities may be triggered due to a number of collective effects (e.g. e^--cloud, fast ion instability)

DR parameters' evolution

CLIC parameter note 2005

↓

M. Korostelev, PhD thesis, 2006

↓

CLIC parameter note 2008

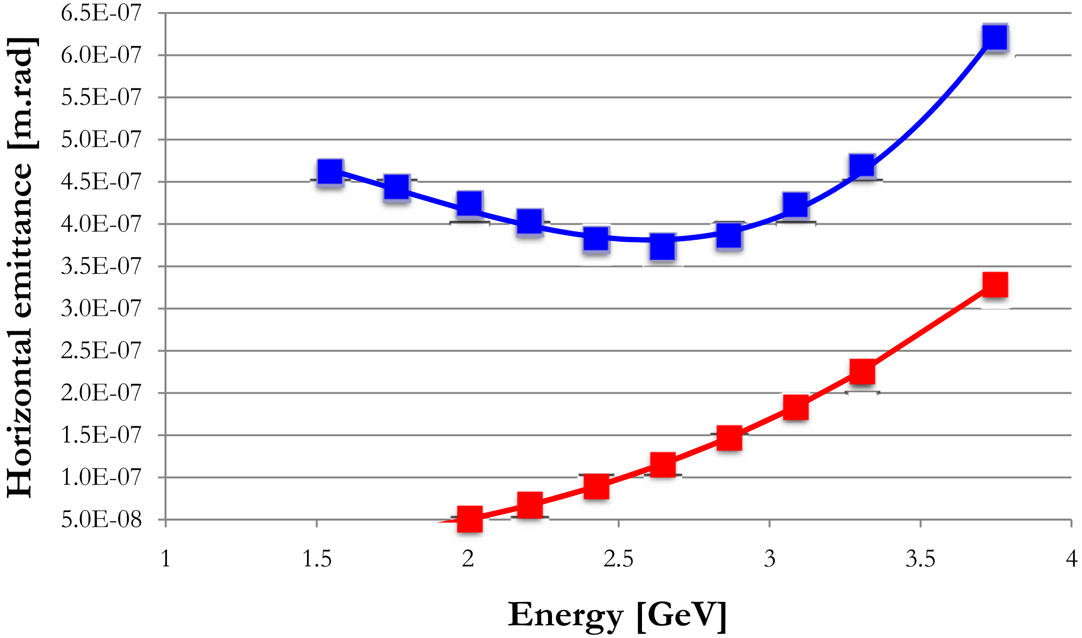
↓

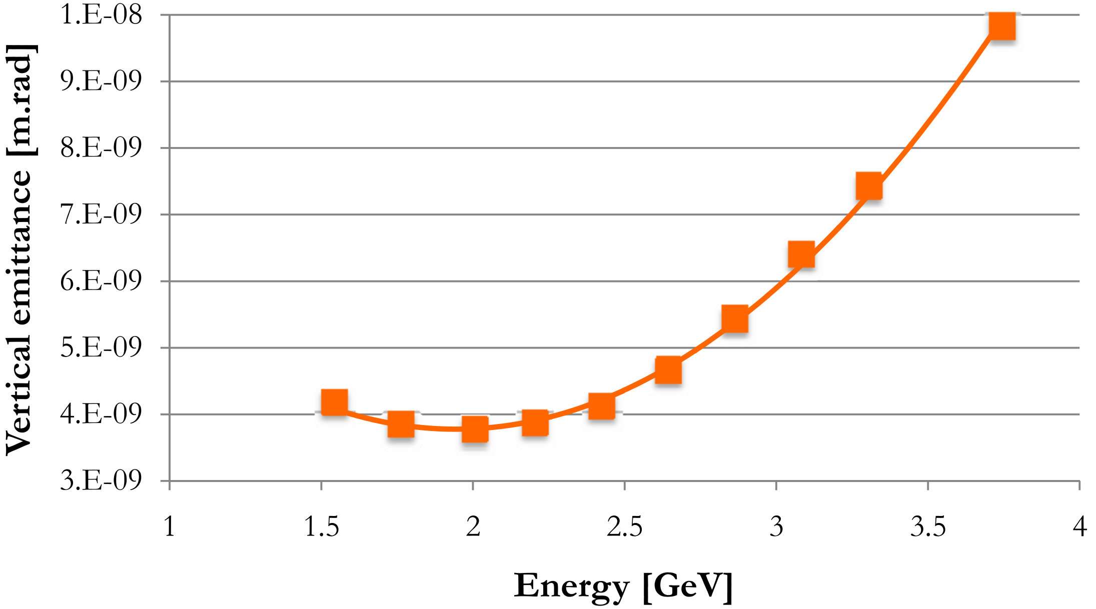
Design optimisation for CDR (2010)

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

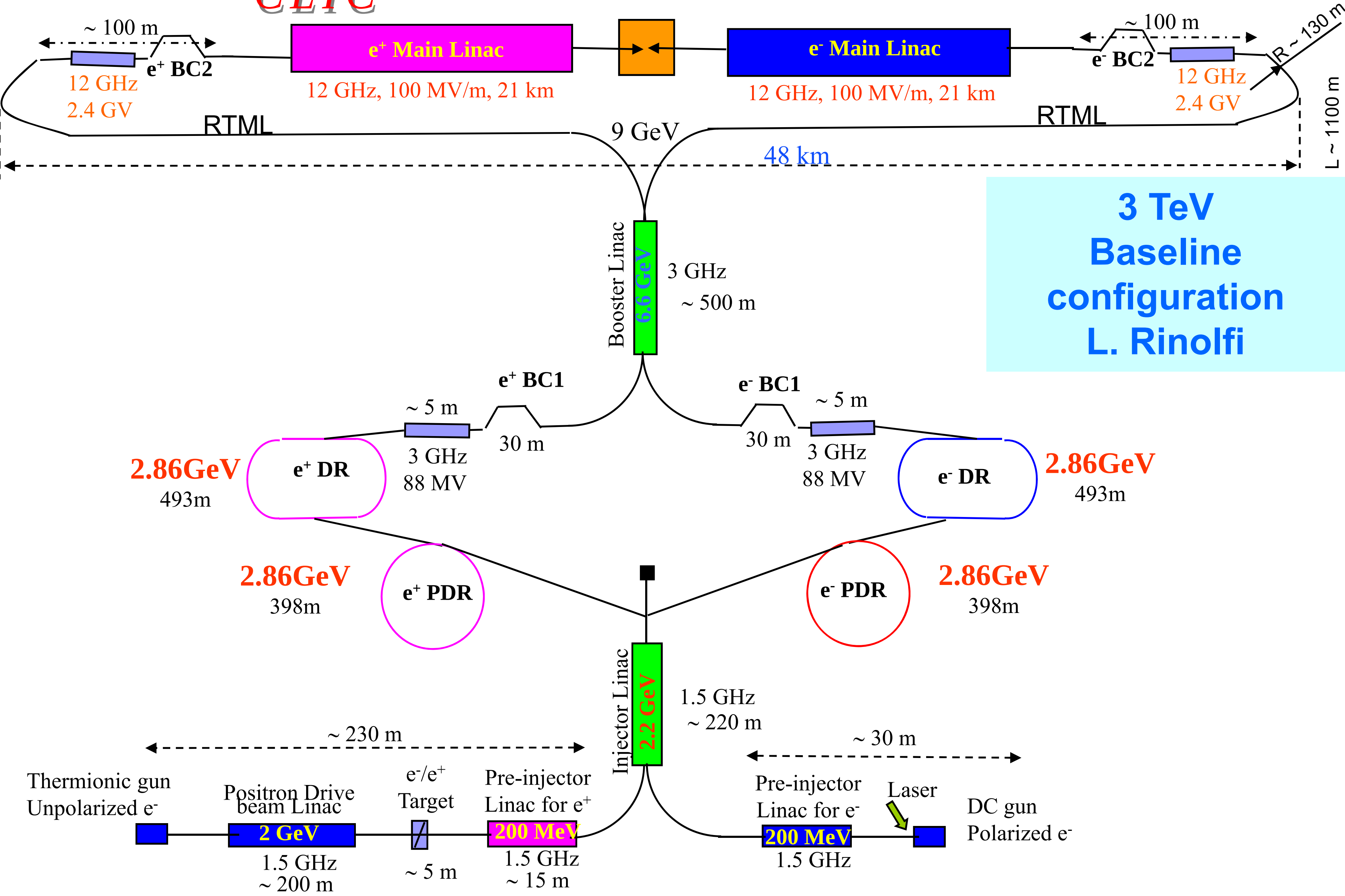
Damping ring energy

- Horizontal emittance has a broad **minimum** between 2 and 3GeV (constant longitudinal emittance)
- Higher energy reduce ratio between zero current and IBS dominated emittance
- Vertical emittance increased (tighter alignment and low emittance tuning tolerances)
- Slight decrease of geometrical aperture (compensating increase of magnet strength)
- Increase of energy loss per turn and radiated power (increased RF voltage, higher beam loading)
- Collective effects get relaxed (especially space-charge)
- Increase the DR energy to **2.86GeV**





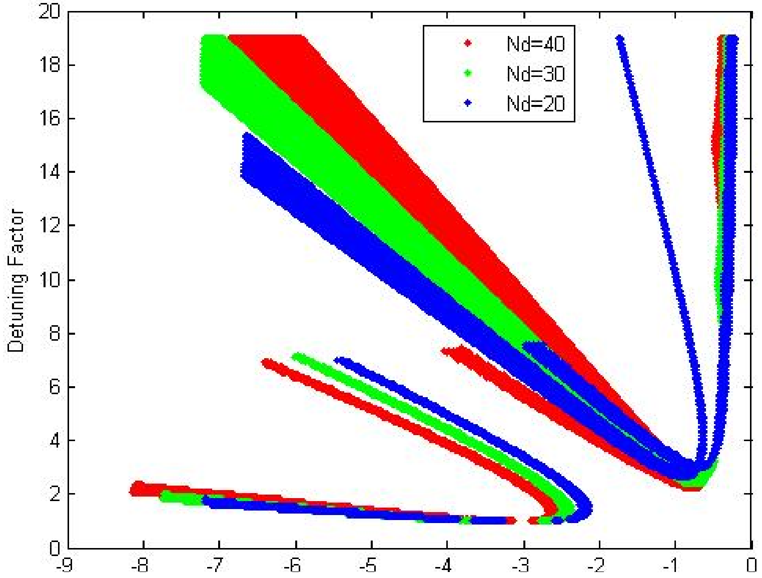
Injector complex

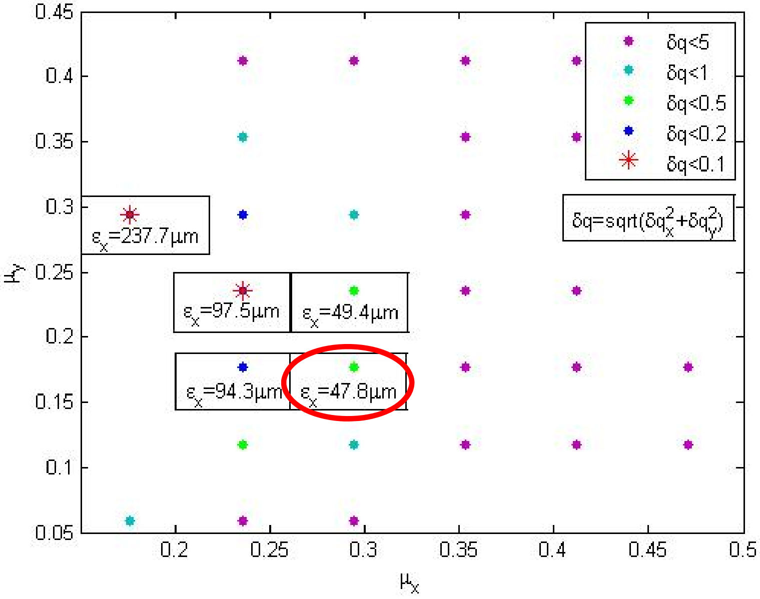


3 TeV
Baseline
configuration
L. Rinolfi

PDR design

F. Antoniou, et al., 2009

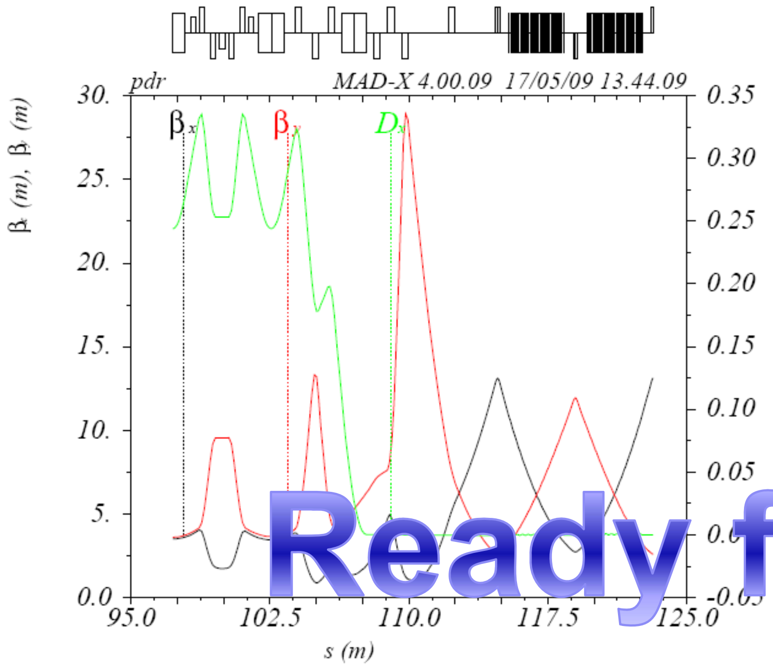


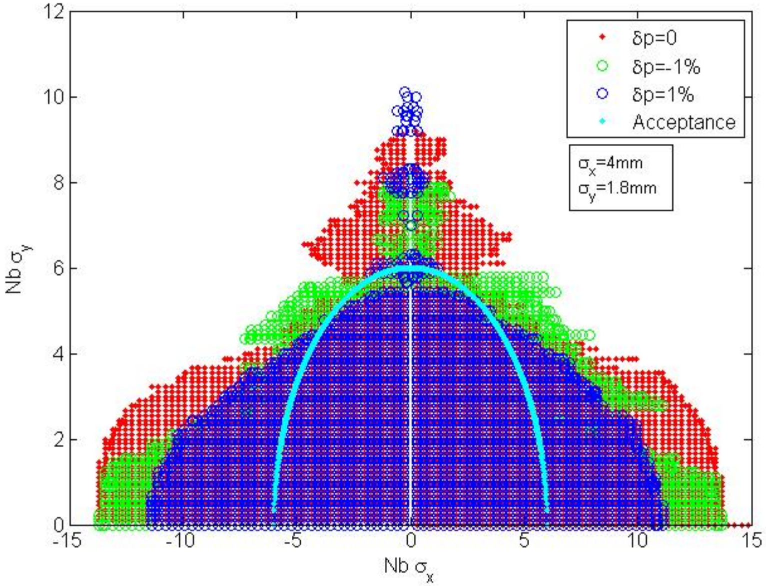


Injected Parameters	**e$^-$**	**e$^+$**
Bunch population [10^9]	4.4	6.4
Bunch length [mm]	1	5
Energy Spread [%]	0.1	2.7
Hor.,Ver Norm. emittance [nm]	100 x 10^3	7 x 10^6

- Main challenge
  - Large input emittances especially for positrons to be damped by several orders of magnitude
- Design optimization following analytical parameterization of TME cells
- Detuning factor (achieved emittance/TME)> 2 needed for minimum chromaticity
- Target emittance reached with the help of conventional high-field wigglers (PETRA3)
- Non linear optimization based on phase advance scan (minimization of resonance driving terms and tune-shift with amplitude)

PDR parameters

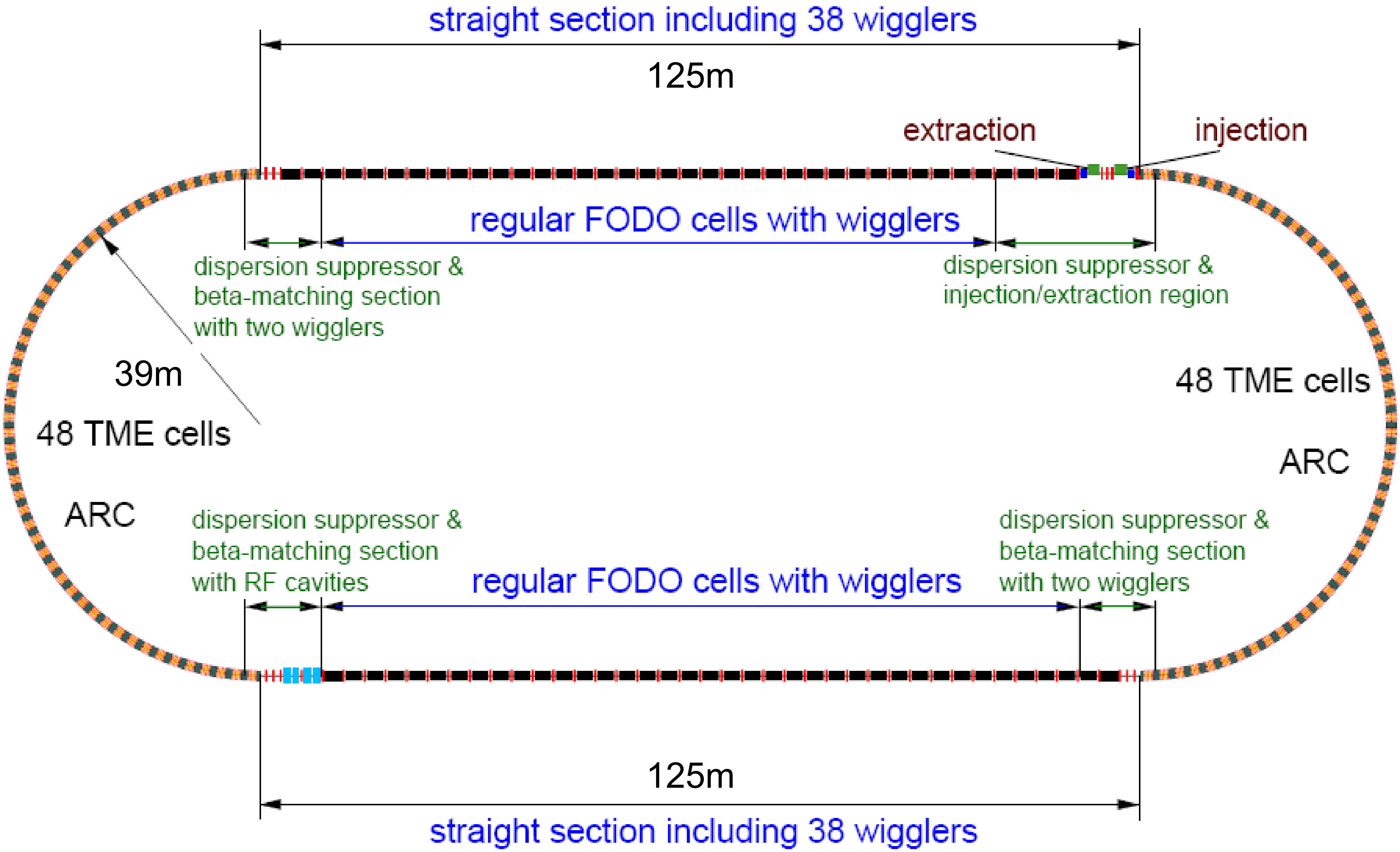




Ready for CLIC CDR

Parameter [unit]	Value
beam energy [GeV]	2.86
circumference [m]	397.6
bunch population [10^9]	4.7
bunch spacing [ns]	0.5
bunches per train	312
rms bunch length [mm]	3.3
rms momentum spread [%]	0.1
hor. norm. emittance [nm.rad]	47850
no. of arc bends	38
arc-dipole field [T]	1.2
length of arc dipole [m]	1.3125
number of wigglers	40
wiggler field [T]	1.7
length of wiggler [m]	3
wiggler period [cm]	30
mom. compaction [10^{-3}]	3.83
RF frequency [GHz]	2
energy loss/turn [MeV]	3.27
RF voltage [MV]	10
Harmonic number	2652
RF acceptance [%]	1.1
h/v/l damping times [ms]	2.32/2.32/1.15
Revolution time [ns]	1326
Tunes (h/v/l)	18.44/12.41/0.07
Nat. chromaticity (h/v)	-18.98/-22.81

DR layout



straight section including 38 wigglers

125m

extraction

injection

regular FODO cells with wigglers

dispersion suppressor &
beta-matching section
with two wigglers

dispersion suppressor &
injection/extraction region

39m

48 TME cells

ARC

48 TME cells

ARC

dispersion suppressor &
beta-matching section
with RF cavities

regular FODO cells with wigglers

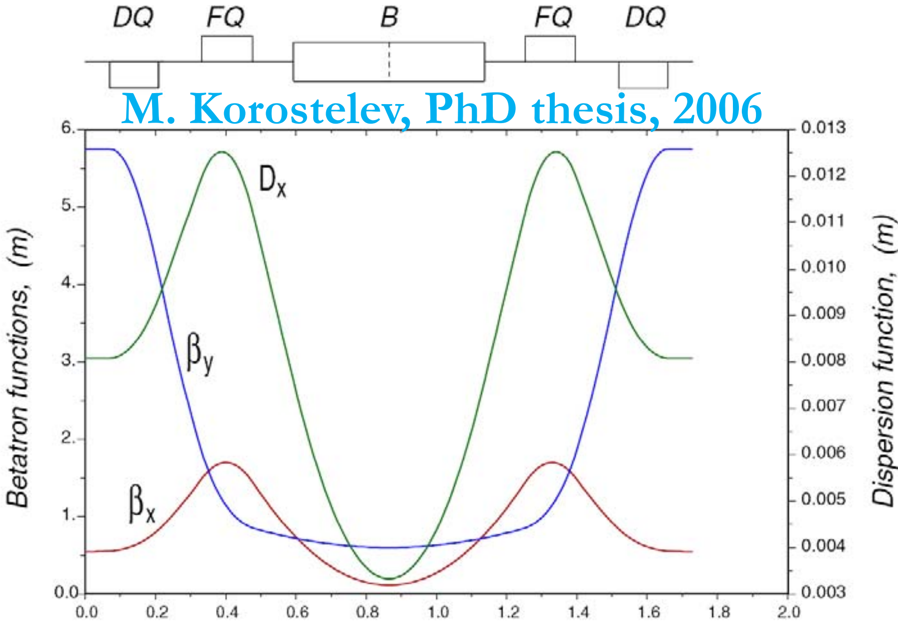
dispersion suppressor &
beta-matching section
with two wigglers

125m

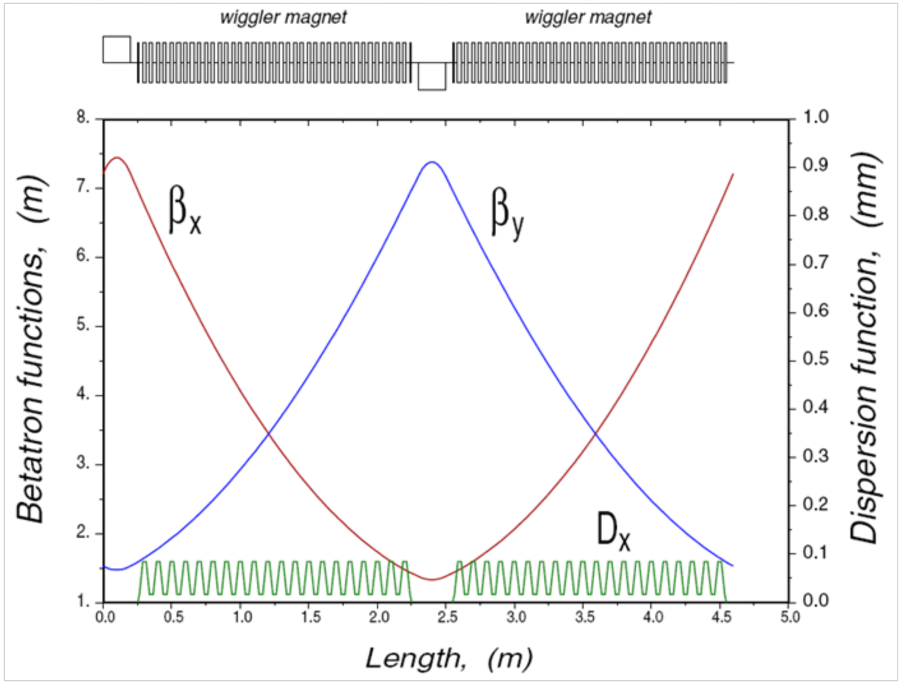
straight section including 38 wigglers

Original DR optics

- TME arc cell chosen for compactness
  - Large phase advance necessary to achieve optimum equilibrium emittance
  - Low dispersion and strong sextupoles needed to correct chromaticity, reducing DA
  - Limited magnet to magnet space
  - Extremely high magnet strengths
  - **Large IBS growth rates** due to small h/v beam size in the bend
- FODO wiggler cell with phase advances close to 90° giving
  - Limited space for absorbers



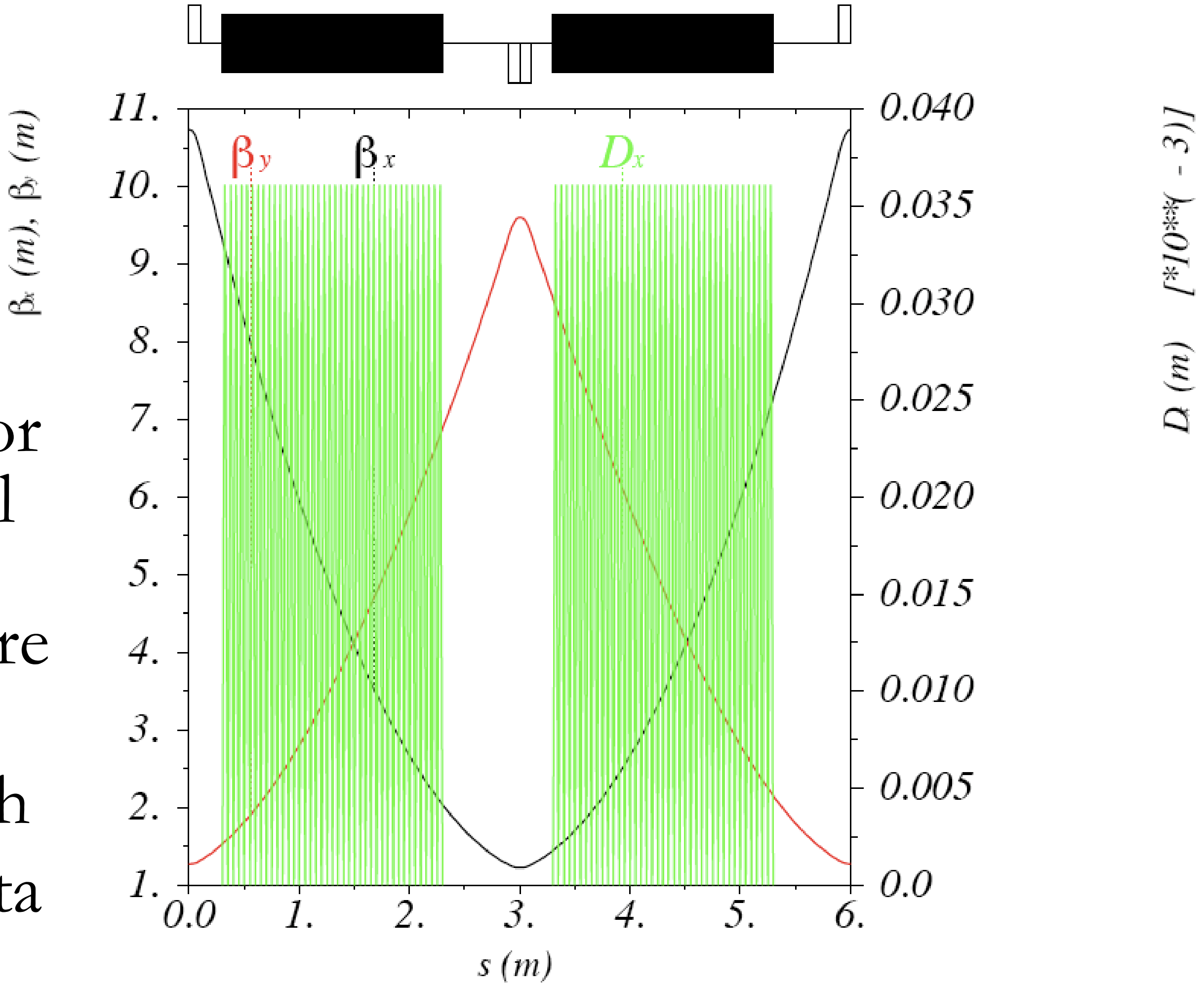
M. Korostelev, PhD thesis, 2006



New wiggler cell

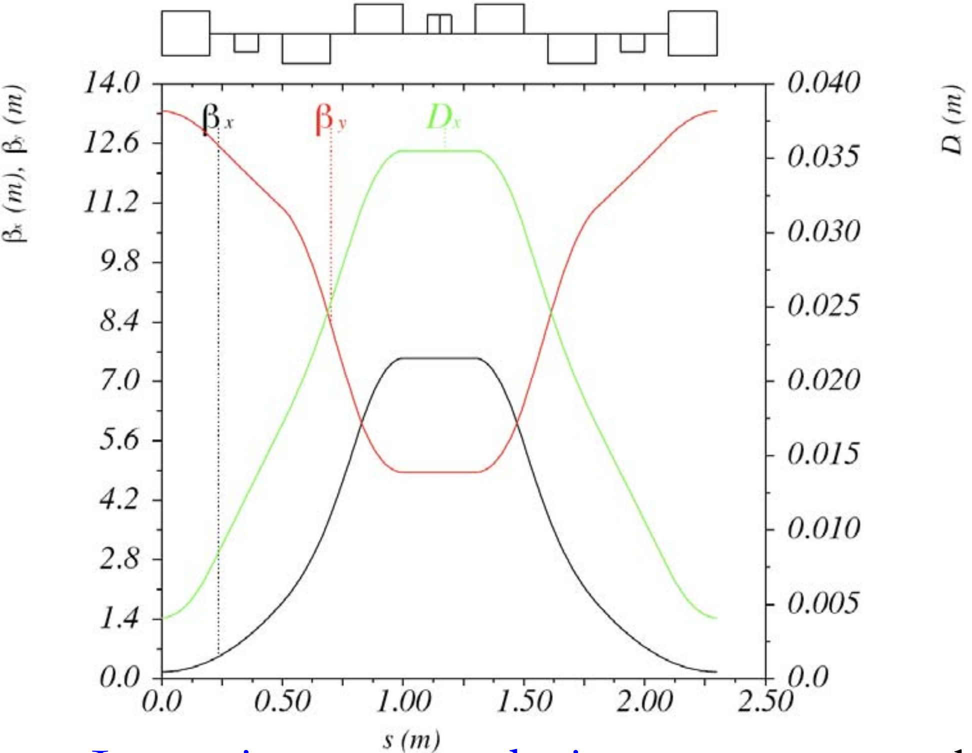
- Added space between wiggler and downstream quadrupoles for accommodating absorbers
- Horizontal phase advance optimised for lowering IBS, vertical phase advance optimised for aperture
- 30% increase of the wiggler section length
- Slight increase of beta maxima (and chromaticity)

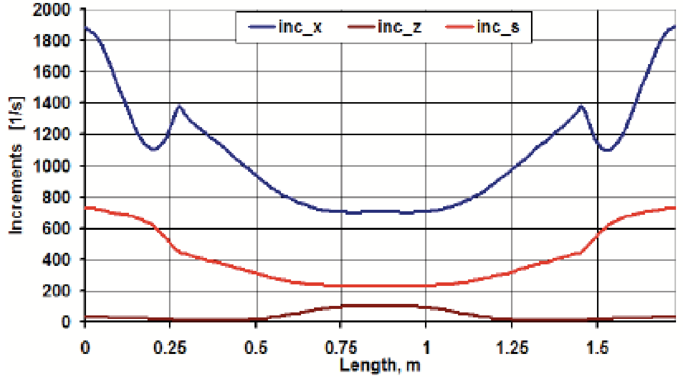
S. Sinyatkin, et al., 2008

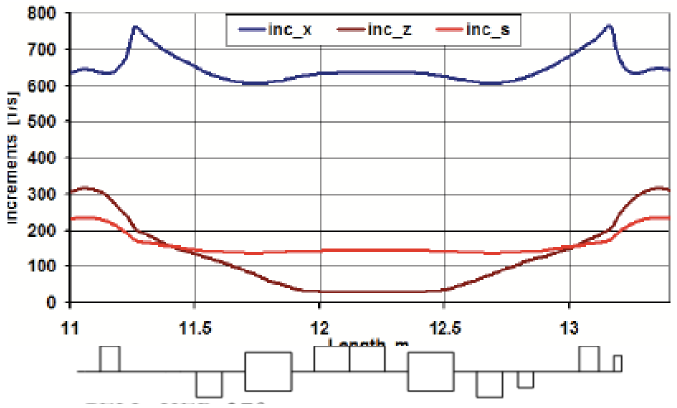


New DR arc cell

S. Sinyatkin, et al., 2008

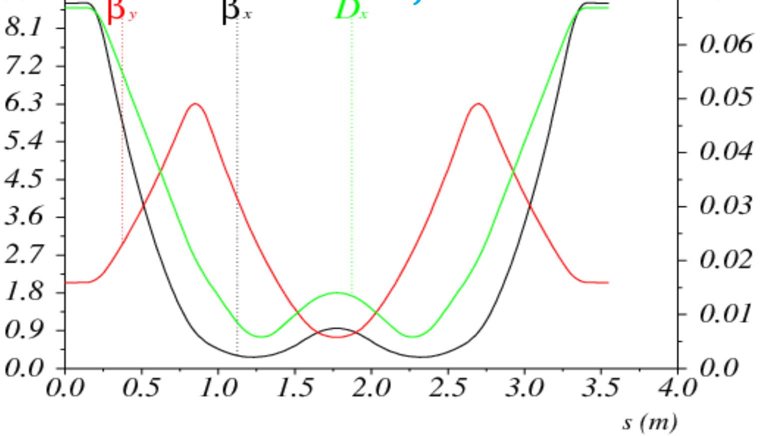






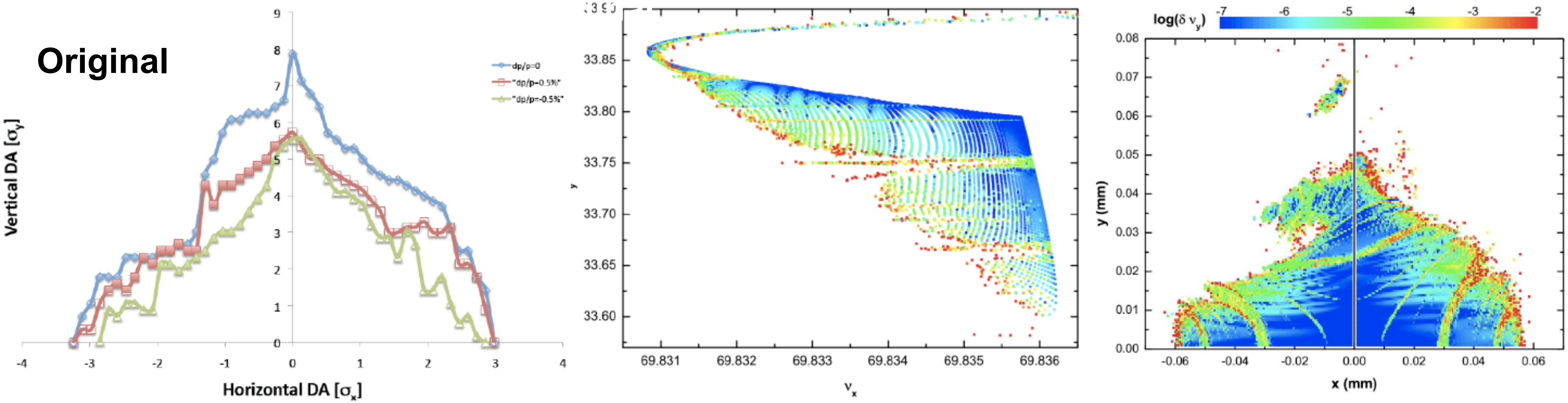
- Increasing space, reducing magnet strengths
- Reducing chromaticity, increasing DA
- IBS growth rates reduced, i.e. zero current equilibrium emittance increased but IBS dominated emittance not changed
- Combined function bends with small gradient (as in NLC DR and ATF)
- Alternative design based on SUPERB cell

P. Raimondi, CLIC08

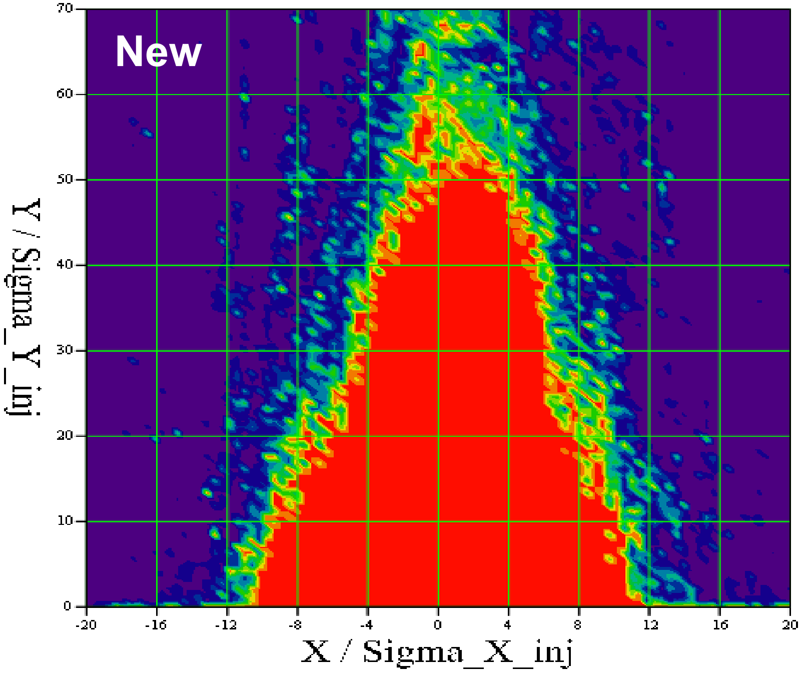


Dynamic aperture

Ch. Skokos and Y. Papaphilippou, EPAC08



- Very small DA in the original lattice due to large tune-shift with amplitude and crossing of multitude of resonances
- The new lattice has comfortable DA
- More detailed non-linear optimisation for CDR, including magnet errors and wiggler effects



S. Sinyatkin, et al. 2008

New DR parameters

CLIC

- New DR increased circumference by 30% and energy by 20%
- DA significantly increased
- Magnet strength reduced to reasonable levels (magnet models already studied)
- Combined function bend increases significantly vertical beta on dipoles
- TME optics modification and energy increase reduces IBS growth factor to 2 (as compared to 5.4)
- **Ready for CDR**
- Further optimization with respect to IBS (F. Antoniou PhD thesis)

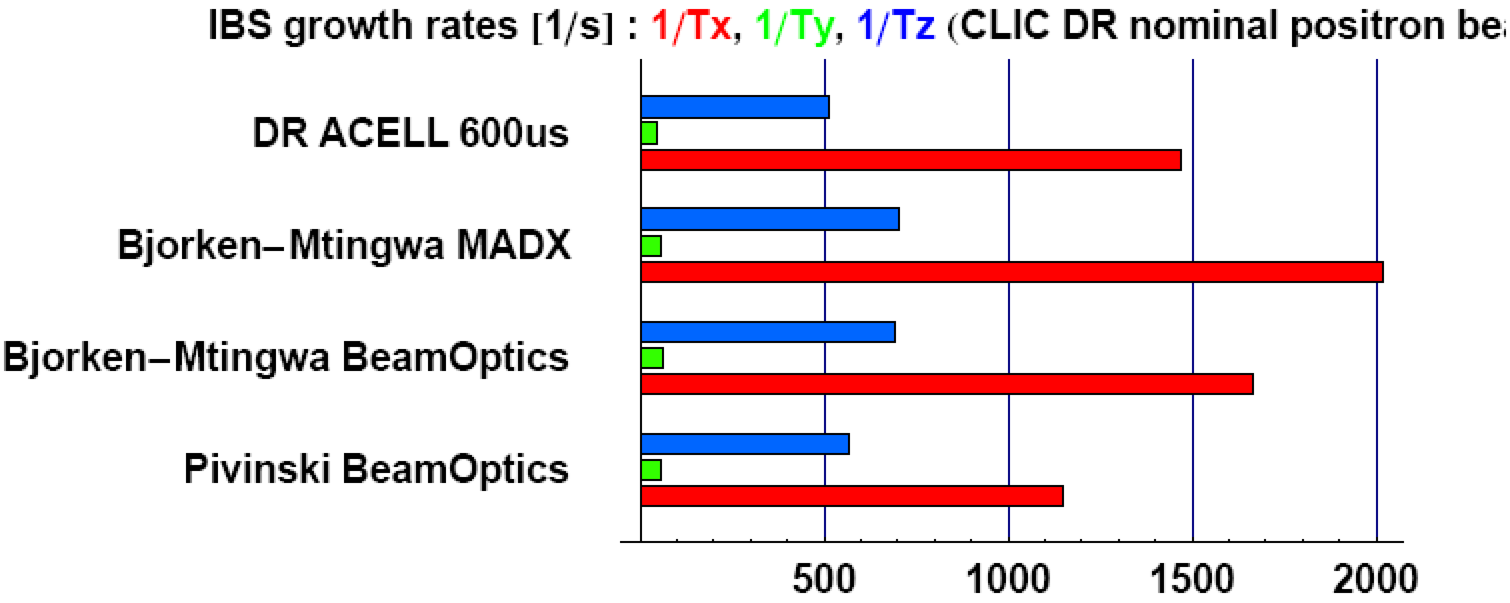
Lattice version	**Original**	**New**
Energy [GeV]	2.42	2.86
Circumference [m]	**365.21**	**493.05**
Coupling	0.0013	
Energy loss/turn [Me]	3.86	5.04
RF voltage [MV]	5.0	6.5
Natural chromaticity x / y	-103 / -136	-149 / -79
Compaction factor	8E-05	6e-5
Damping time x / s [ms]	1.53 / 0.76	1.87 / 0.94
Dynamic aperture x / y [σ_{inj}]	**±3.5 / 6**	**±12 / 50**
Number of arc cells	100	
Number of wigglers	76	
Cell /dipole length [m]	1.729/0.545	2.30 / 0.4
Bend field [T]	0.93	1.27
Bend gradient [1/m^2]	0	-1.10
Max. Quad. gradient [T/m]	**220**	**60.3**
Max. Sext. strength [T/m^2 10^3]	**80**	**6.6**
Phase advance x / z	0.58 / 0.25	0.44/0.05
Bunch population, [10^9]	4.1	
IBS growth factor	**5.4**	**2.0**
Hor. Norm. Emittance [nm.rad]	**470**	**495**
Ver. Norm. Emittance [nm.rad]	**4.3**	**4.9**
Bunch length [mm]	1.4	1.4
Longitudinal emmitance [eVm]	3500	3957

Y.P., 27/05/2009

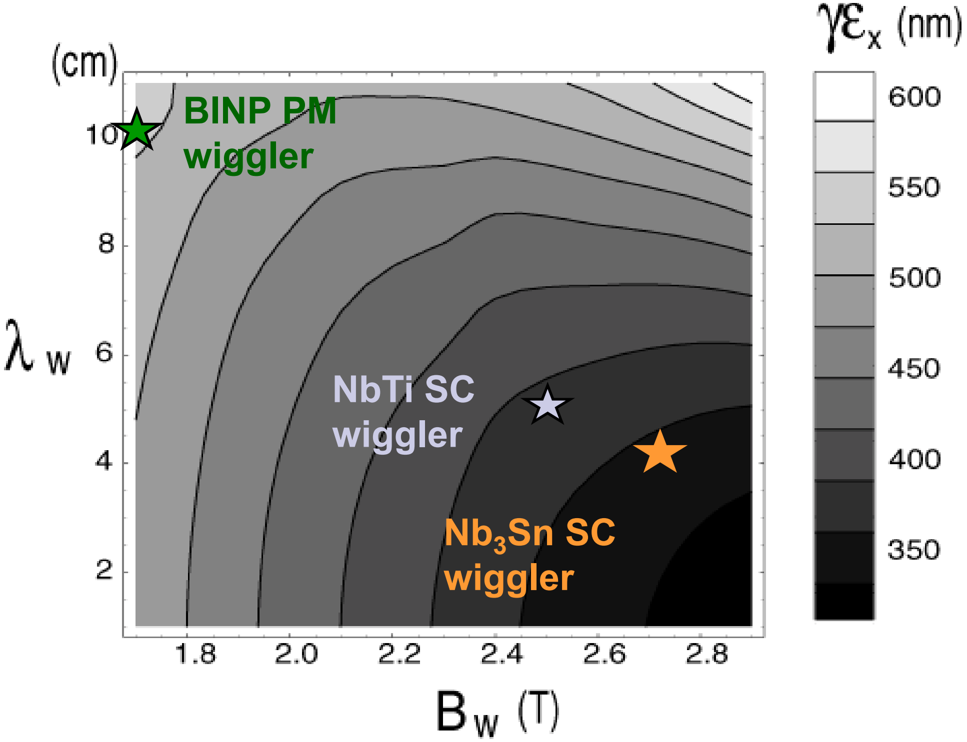
Intrabeam Scattering

M. Martini and A. Vivoli, 2009

- Conventional IBS growth rate calculations (Piwinski, Bjorken-Mtingwa) assume Gaussian beam distribution, which may not be true in extreme IBS regimes
- Tracking code following arbitrary particle distribution evolution during damping, taking into account IBS and quantum excitation
- Zenkevich and Bolshakov have developed such code (MOCAC)
- Serious code cleaning and debugging performed at CERN
- Benchmarking of the simulations with semi-analytical models, with first encouraging results when applied to original TME cell of CLIC DR
- Further steps include IBS kick revision, inclusion of damping process, parallelization and full scale DR simulations



Wigglers' effect with IBS



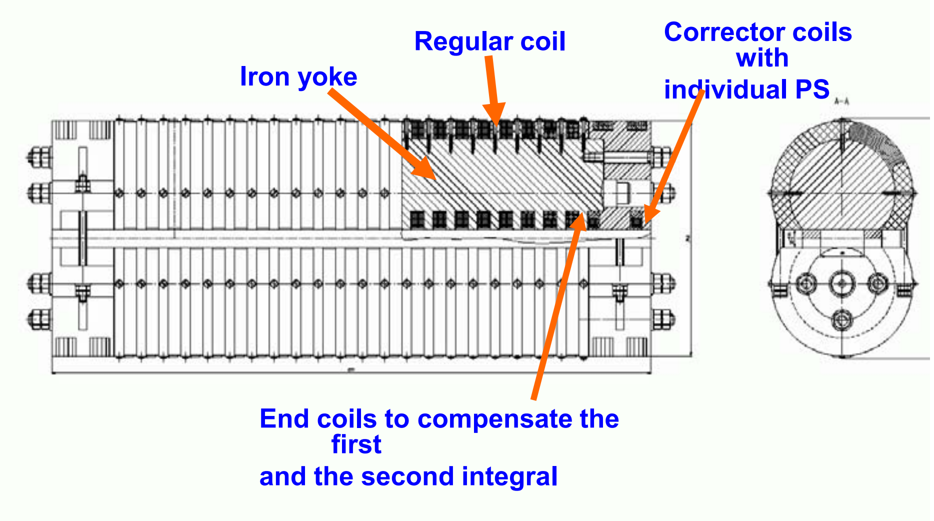
Parameters	**BINP**	**CERN**
B_{peak} [T]	2.5	2.8
λ_W [mm]	50	40
Beam aperture full gap [mm]	13	13
Conductor type	NbTi	$NbSn_3$
Operating temperature [K]	4.2	4.2

- Stronger wiggler fields and shorter wavelengths necessary to reach target emittance due to strong IBS effect
- Two wiggler prototypes
  - ☐ 2.5T, 5cm period, built and currently tested by BINP
  - ☐ 2.8T, 4cm period, designed by CERN/Un. Karlsruhe
- Current density can be increased by using different conductor type
- Prototypes built and magnetically tested (at least one by CDR)
- Installed in a storage ring (ANKA, CESR-TA, ATF) for beam measurements (IBS/wiggler dominated regime)

NbTi Wiggler Design

- Present design uses NbTi wet wire in separate poles clamped together (2.5T, 5cm period)
- Wire wound and impregnated with resin in March
- Prototype assembled including corrector coil and quench protection system by end of April
- Currently put in test cryostat and being cooled down
- Field measurement expected in a few days…
- Major DR performance item

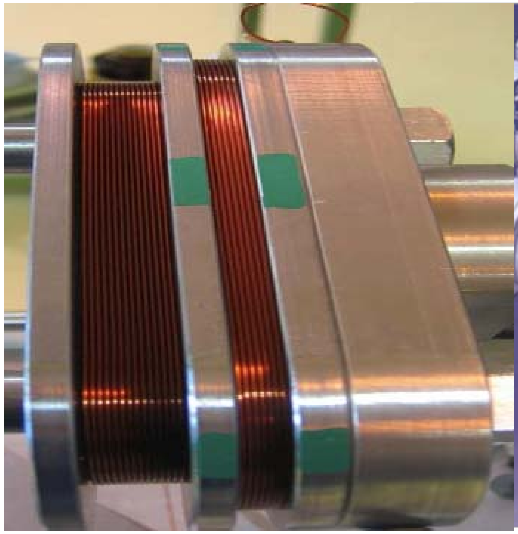
P. Vobly, et al., 2008

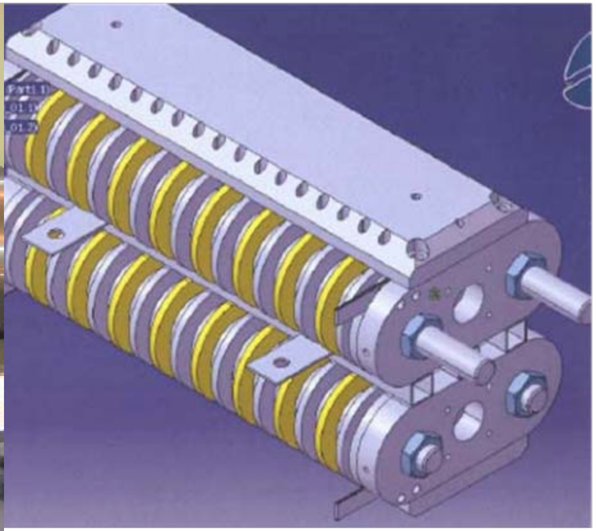


Nb_3Sn Wiggler Design

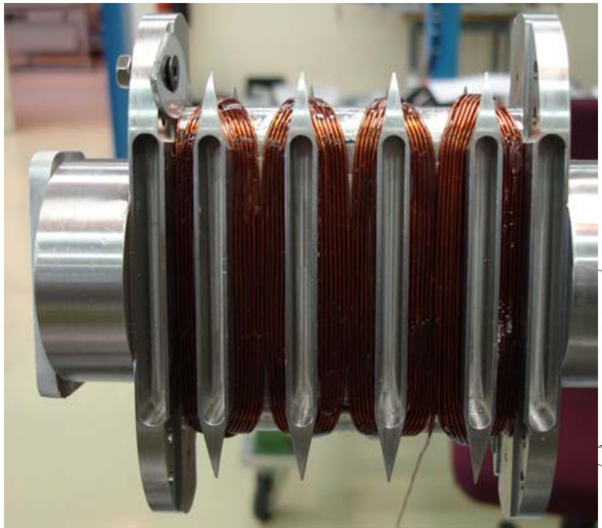
R. Maccaferi and S. Bettoni, 2009

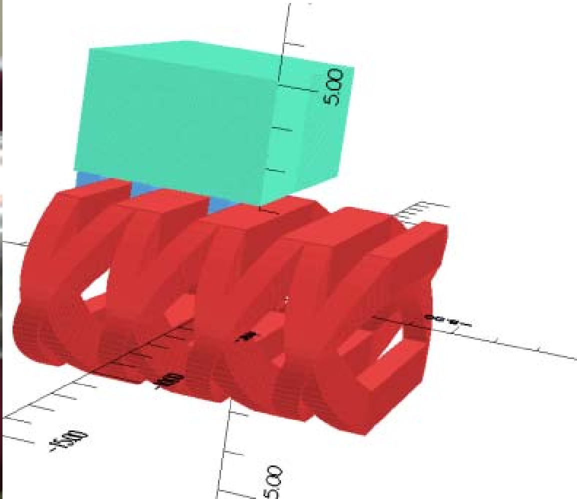
- Two models (2.8T, 40mm period)
  - Vertical racetrack (VR)
  - Double helix (WH), can reach 3.2T with Holmium pole tips
- Nb3Sn can sustain higher heat load (10W/m) than NbTi (1W/m)
- Between 2009-2010, 2 short prototypes will be built, tested at CERN and measured at ANKA
- 3D modelling in progress



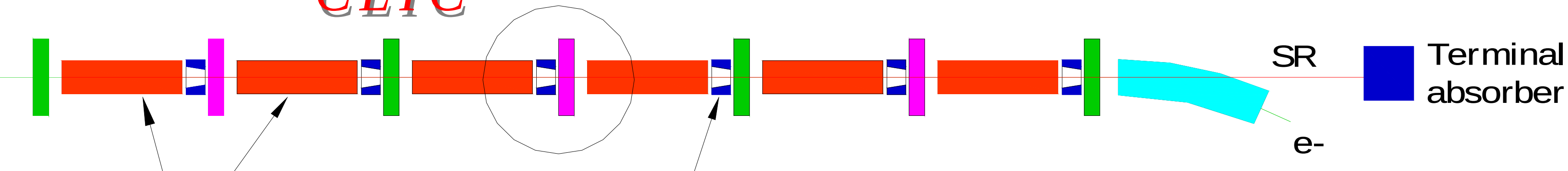


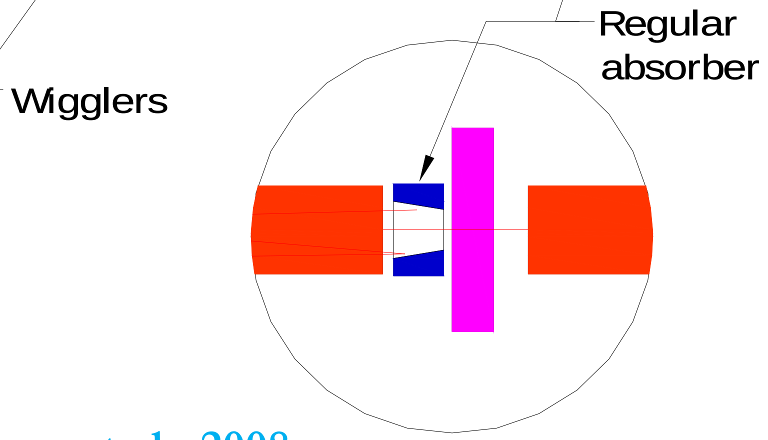
Type	Bmax	Period	Gap
Nb_3Sn	2.8 T	40 mm	16 mm
NbTi	2.0 T	40 mm	16 mm
Nb_3Sn	2.8 T	30 mm	10 mm
NbTi	2.2 T	30 mm	10 mm



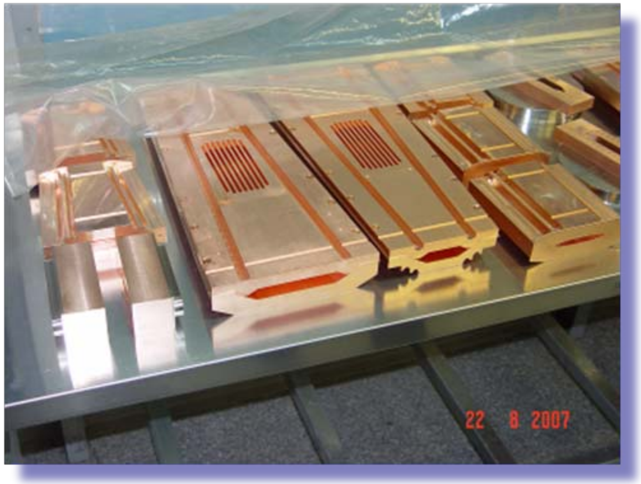


Synchrotron radiation absorption

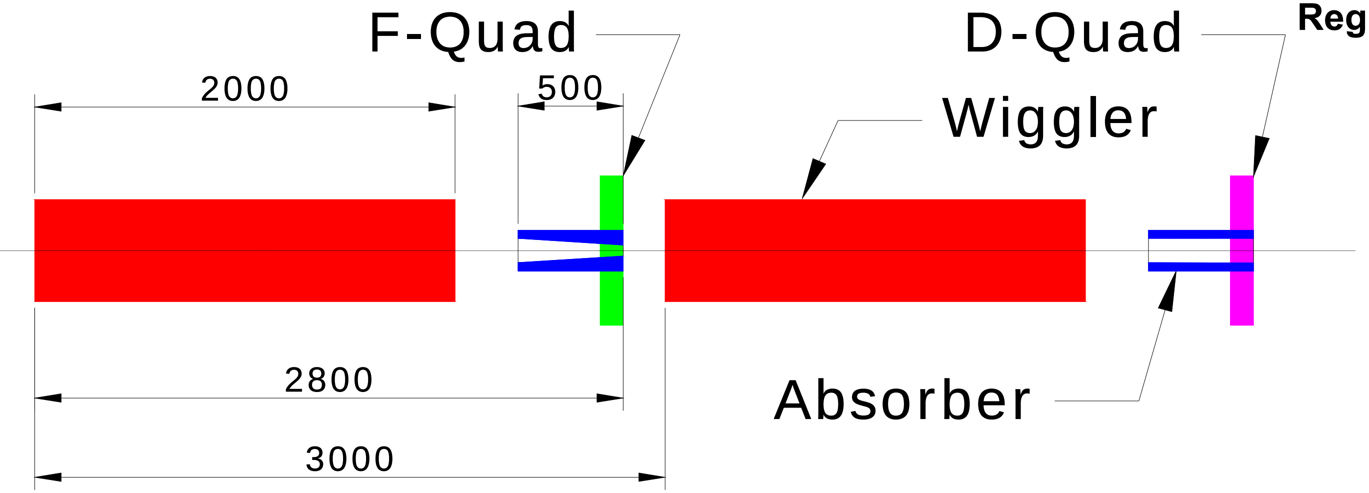




K. Zolotarev, et al., 2008



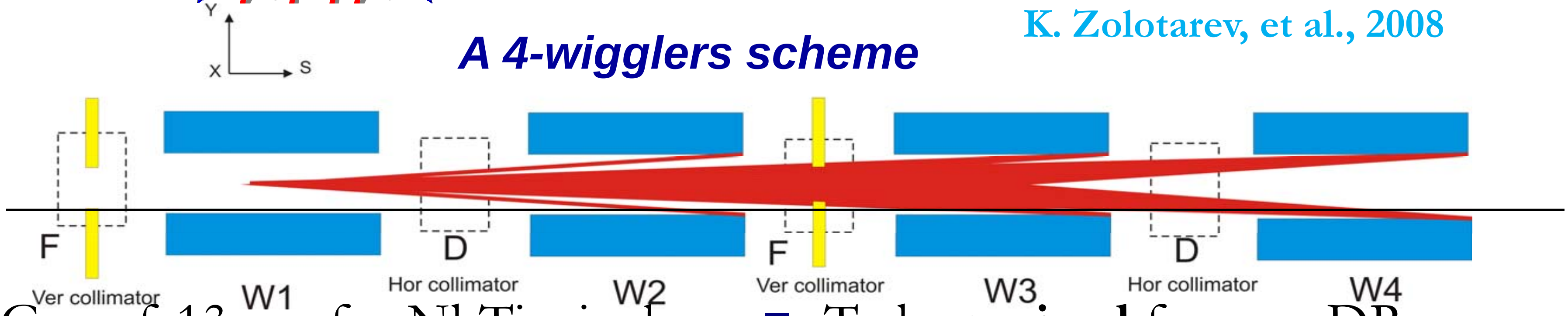
Regular absorbers of 26kW for PETRA-III project



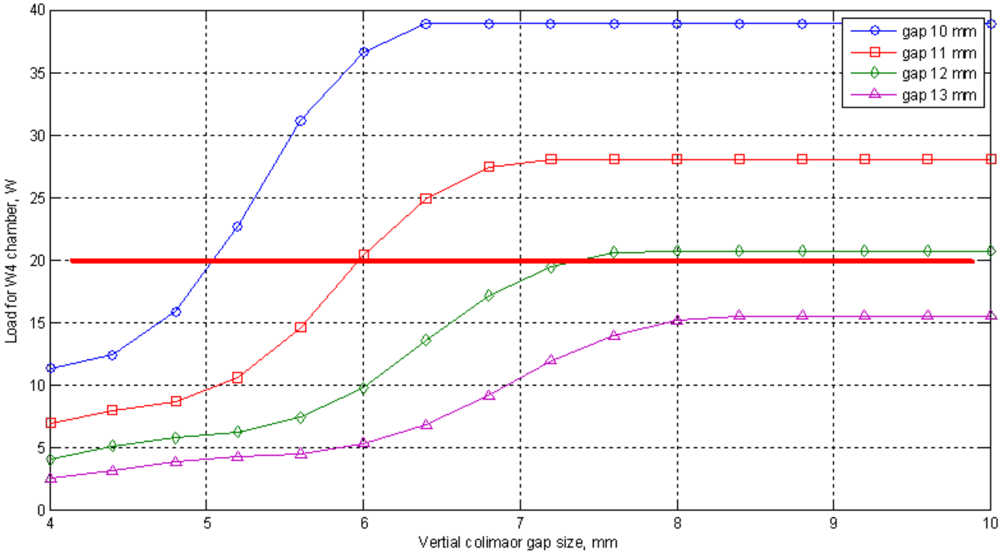
Radiation absorption scheme

K. Zolotarev, et al., 2008

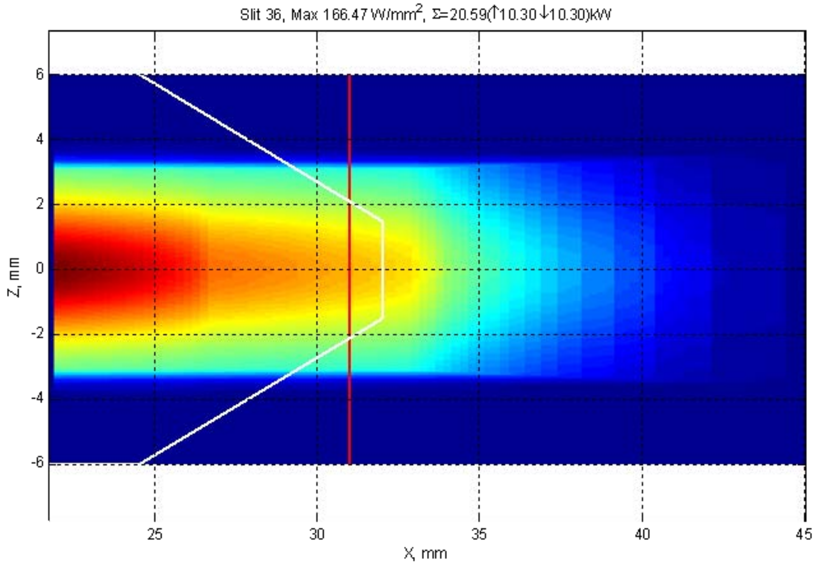
A 4-wigglers scheme



- Gap of 13mm for NbTi wiggler and 20mm for Nb3Sn design (1W/m) or 13mm (10W/m)
- Terminal absorber at the end of the straight section



- To be **revised** for new DR energy
- 3D radiation distribution to be used for e-cloud built up
- Impedance estimation for the CDR

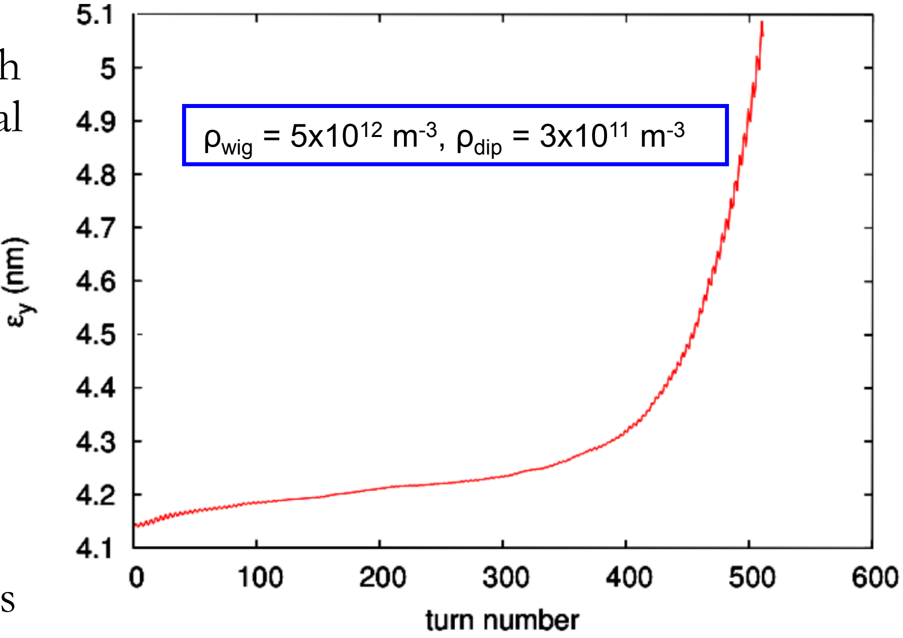


Collective effects in the DR

- Electron cloud in the e^+ DR imposes limits in PEY (99.9% of synchrotron radiation absorbed in the wigglers) and SEY (below 1.3)
  - Cured with special **chamber coatings**
- Fast ion instability in e^- DR, molecules with A>13 will be trapped (constrains vacuum pressure to around 0.1nTorr)
- Other collective effects in DR
  - Space charge (large vertical tune spread of 0.19 and 10% emittance growth)
  - Single bunch instabilities avoided with smooth impedance design (a few Ohms in longitudinal and MOhms in transverse are acceptable for stability)
  - Resistive wall coupled bunch controlled with feedback (1ms rise time)
- For CDR
  - Update studies with newest parameter set including 3D photon distribution in wiggler section
  - Estimate impedance of a few key components

G. Rumolo et al., EPAC08

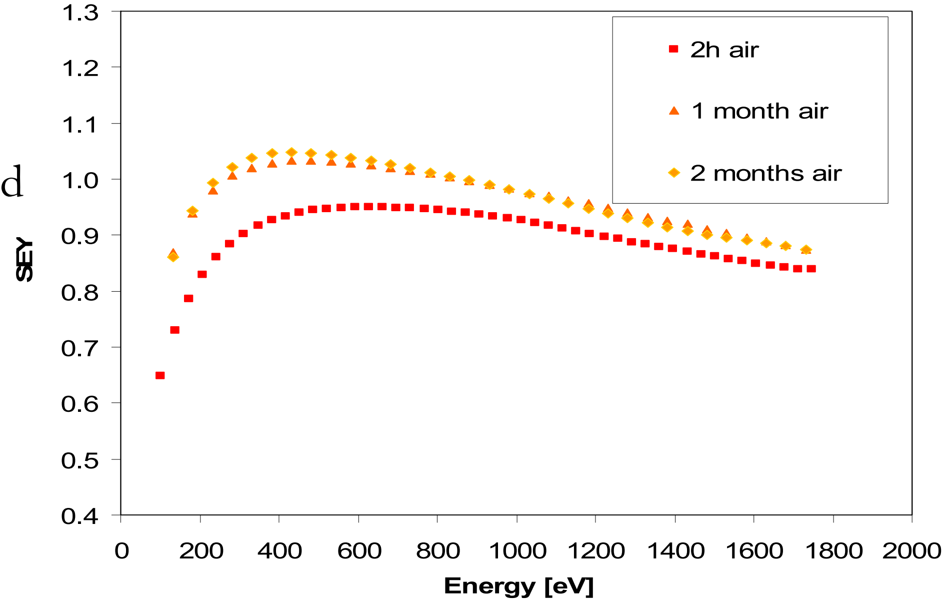
Chambers	PEY	SEY	ρ $[10^{12}\ e^-/m^3]$
Dipole	0.000576	1.3	0.04
		1.8	2
	0.0576	1.3	7
		1.8	40
Wiggler	0.00109	1.3	0.6
	0.109	1.3	45
		1.5	70
		1.8	80

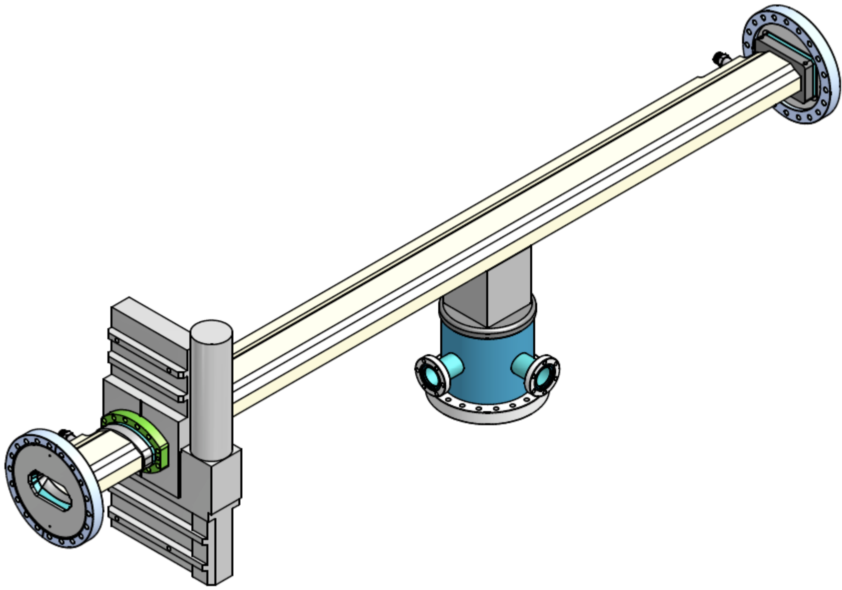


Coatings for e- Cloud Mitigation

- Bakeable system
  - NEG gives SEY<1.3 for baking @ > 180C
  - Evolution after many venting cycles should be studied
  - NEG provides pumping
  - Conceivable to develop a coating with lower activation T
- Non-bakeable system
  - a-C coating provides SEY< 1 (2h air exposure), SEY<1.3 (1week air exposure)
  - After 2 months exposure in the SPS vacuum or 15 days air exposure no increase of e-cloud activity
  - Pump-down curves are as good as for stainless steel (measurements in progress in lab and ESRF)
  - No particles and peel-off
  - to be characterized for impedance and PEY
  - Chamber delivered at CERN to be coated and installed back to CESR-TA for measurements during the summer run

S. Calatroni et al., 2009





DR RF system

A. Grudiev, CLIC08

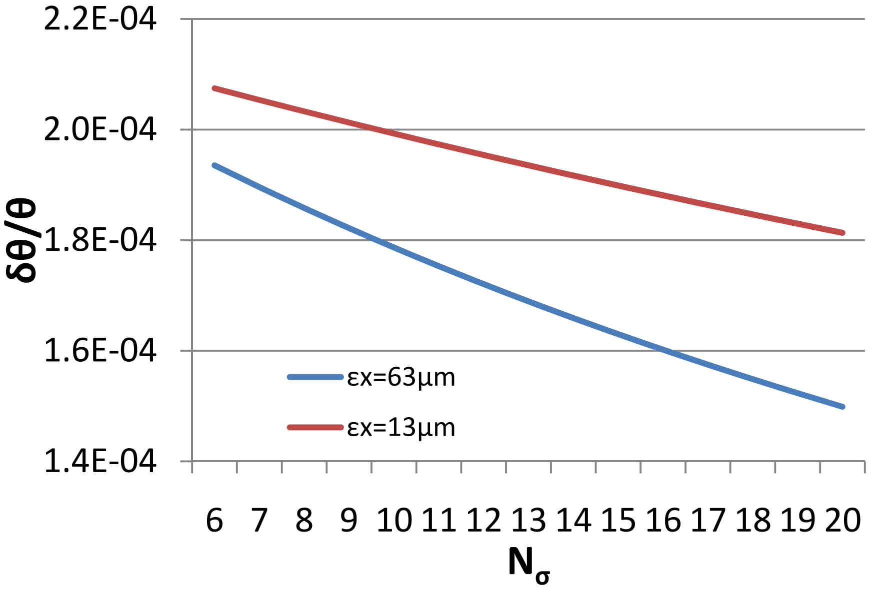
- RF frequency of **2GHz**
  - Power source is an R&D item at this frequency
- High peak and average power of **6.6** and **0.6MW**
- Strong beam loading transient effects
  - Beam power of ~6.6MW during 156 ns, no beam during other 1488 ns
  - Small stored energy at 2 GHz
- Wake-fields and HOM damping should be considered
- A conceptual RF design should be ready for the CDR

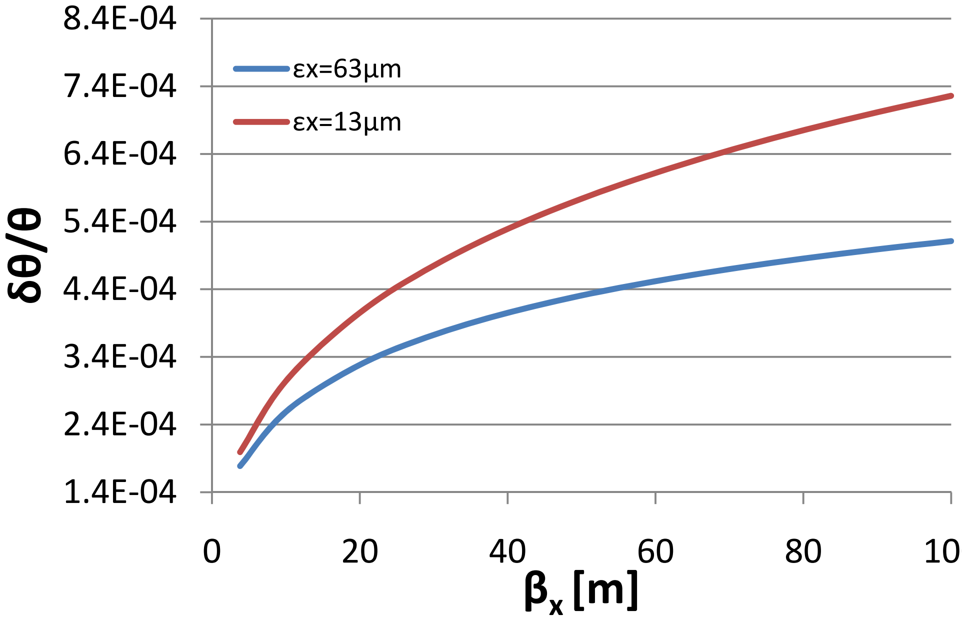
CLIC DR parameters	
Circumference [m]	493.5
Energy [GeV]	2.86
Momentum compaction	0.6×10^{-4}
Energy loss per turn[MeV]	**5.04**
Maximum RF voltage [MV]	**6.5**
RF frequency [GHz]	**2.0**

- High energy loss per turn at relatively low voltage (keeping longitudinal emittance at 5keV.m) results in large φ_s
  - Bucket becomes **non-linear**
  - Small energy acceptance
  - RF voltage increased to **6.5MV** (energy acceptance of **2.6%**)
  - As longitudinal emittance is decreased (3.9 keV.m), horizontal emittance **increased** to **495nm**

Kicker stability

- Kicker jitter is translated in a beam jitter in the IP.
- Typically a tolerance of $\boldsymbol{\sigma_{jit} \leq 0.1\sigma_x}$ is needed
- Translated in a relative deflection stability requirement as $\frac{\delta\theta_{\mathrm{kick}}}{\theta_{\mathrm{kick}}} \leq \frac{\sigma_{\mathrm{jit}}}{x_{\mathrm{sep}}}$
- For higher positions at the septum (larger injected emittances or lower beta functions) the stability tolerance becomes tighter
- The tolerance remains typically to the order of $\mathbf{10^{-4}}$
- Available drift space has been increased to reduce kicker voltage spec.

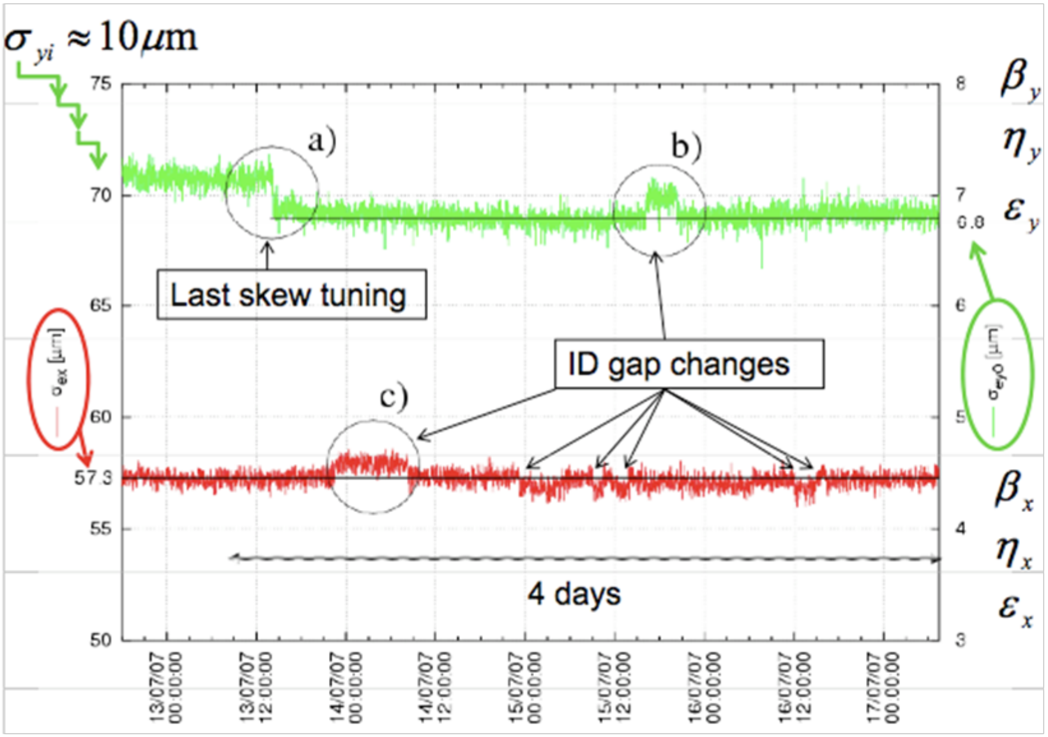




Low emittance tuning

A. Andersson, et al., CLIC08

- Present tolerance not far away from ones achieved in actual storage rings
- To be re-evaluated with new DR parameters for CDR
- Participate in low emittance tuning measurements in light sources (SLS) and CESR-TA



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.

Damping Rings diagnostics

- **300PUs**, turn by turn (every **1.6μs**)
  - **10μm** resolution, for linear and non-linear optics measurements.
  - **2μm** resolution for orbit measurements (vertical dispersion/coupling correction + orbit feedback).
- WB PUs for bunch-by-bunch (bunch spacing of **0.5ns** for **312** bunches) and turn by turn position monitoring with high resolution (**1μm**) for injection trajectory control, and bunch by bunch transverse feed-back.
- PUs for extraction orbit control and feed-forward.
- Tune monitors and fast tune feed-back with precision of **10^{-4}**, critical for resolving instabilities (i.e. synchrotron side-bands, ions)
- Turn by turn transverse profile monitors (X-ray?) with a wide dynamic range:
  - Hor. geometrical emittance varies from **11nm.rad** @ injection to **90pm.rad** @ extraction and the vertical from **270pm.rad** to **0.9pm.rad**.
  - Capable of measuring **tails** for IBS
  - This would probably be the most challenging item
- Longitudinal profile monitors
  - Energy spread of **0.5%** to **0.1%** and bunch length from **10** to **0.1mm**.
  - Note that the dispersion around the ring is extremely small (<12mm).
- Fast beam loss monitoring and bunch-by-bunch current measurements
- E-cloud + ion diagnostics

CLIC/ILC DR collaboration

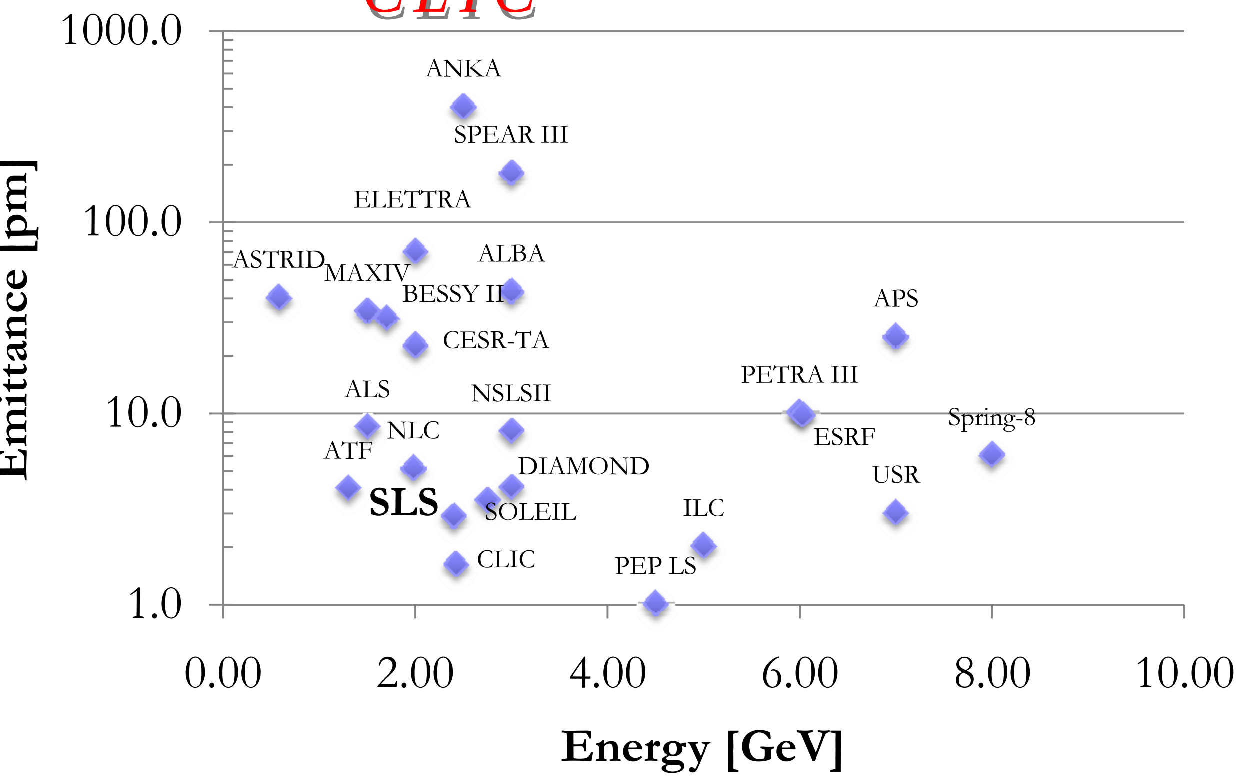
CLIC

S. Guiducci, CLIC'08

- ILC and CLIC DR differ substantially as they are driven by quite different main RF parameters
- Intense interaction between ILC/CLIC in the community working on the DR crucial issues: ultra low emittance and e$^-$-cloud mitigation.
- Common working group initiated
  - ☐ Co-chaired with **M. Palmer**
- Short term working plan includes chamber coatings and e-cloud measurements in CESR-TA, e-cloud and instability simulations with HEADTAIL

	ILC	CLIC
Energy (GeV)	5	2.4
Circumference (m)	6476	365
Bunch number	2700 - 5400	312
N particles/bunch	2×10^{10}	3.7×10^{9}
Damping time τ_x (ms)	21	1.5
Emittance $\gamma\varepsilon_x$ (nm)	4200	381
Emittance $\gamma\varepsilon_x$ (nm)	20	4.1
Momentum compaction	$(1.3 - 2.8)\times10^{-4}$	0.80×10^{-4}
Energy loss/turn (MeV)	8.7	3.9
Energy spread	1.3×10^{-3}	1.4×10^{-3}
Bunch length (mm)	9.0 - 6.0	1.53
RF Voltage (MV)	17 - 32	4.1
RF frequency (MHz)	650	2000

Emittances @ 500GeV



NSLSII PARAMETERS	Values
energy [GeV]	3
circumference [m]	791.5
bunch population [10^9]	11.8
bunch spacing [ns]	1.9
number of bunches	700
rms bunch length [mm]	2.9
rms momentum spread [%]	0.1
hor. normalized emittance [μm]	2.9
ver. normalized emittance [nm]	47
lon. normalized emittance [eV.m]	8700
coupling [%]	0.64
wiggler field [T]	1.8
wiggler period [cm]	10
RF frequency [GHz]	0.5

- SLS achieved **2.8pm**, the lowest geometrical vertical GeV, corresponding to ~**10nm** of normalised emittance
- **Below 2pm**, necessitates challenging alignment tolerances and low emittance tuning
- Seems a "safe" target vertical emittance for CLIC damping rings @ 500GeV
- Horizontal emittance of **2.4μm** is scaled from NSLSII parameters, a future light source ring with wiggler dominated emittance and 10% increase due to IBS

Route to 3TeV

- The 3TeV design can be relaxed by **including only a few super-conducting wigglers** (around 10%) and **relaxing the arc cell optics** (reduce horizontal phase advance)
- Another option may be operating a **larger number of super-conducting wigglers at lower field** of around 2T.
- The same route can be followed from conservative to nominal design, considering that some time will be needed for low-emittance tuning (reducing the vertical emittance)
- Considering the same performance in the pre-damping rings, the 500GeV design **relaxes the kicker stability requirements** by more than a factor of 2
- The **dynamic aperture** of the DR should be also more **comfortable** due to the relaxed arc cell optics
- **Energy loss/turn** will be **significantly reduced** (a factor of 4-5) and thereby the **total RF voltage needed**

Bunch charge @ 500 GeV

- Bunch charge of **1.1 x 6.8x10^9p** for 354 bunches corresponds to an average current of **350mA** (170mA for the CLIC DR baseline parameters)
- **Damping time** will be inevitably increased to **4-5ms** which is **quite long** for **50Hz** repetition rate
- **Staggered trains** may be needed (delay loop and recombination kicker)
- This corresponds to a beam current of at least **700mA**, i.e. good HOM damping design for RF cavities but also lower transients
- Rise time and flat top of kicker should be shortened (factor of 2)
- Absorption scheme has to be reviewed for higher radiation power per wiggler, but lower total power
- All collective instabilities increase with the bunch charge but there is a significant reduction due to the increased emittance (charge density is reduced)
- Total impedance will be lower due to less wiggler gaps and absorbers

Summary

- PDR design ready for CDR
- Revised DR lattice in order to be less challenging (magnets, IBS)
  - Some refinement in non-linear dynamics needed for the CDR
- IBS may be a key feasibility item
  - It may not be solved until CDR but a lot of work is on-going
- DR performance based on super-conducting wigglers
  - Prototype on "conventional" wire technology built and currently tested
  - More challenging wire technologies and wiggler designs are studies at CERN and Un. Karlsruhe/ANKA and measurements from short prototypes to be expected by the CDR
  - Robust absorption scheme to be adapted to new parameters
- Collective effects (e-cloud, FII) remain major performance challenges
  - Results from measurement tests in CESR-TA for novel chamber coatings expected during this summer
  - Key component impedance estimation
- RF system present challenges with respect to transients and power source at the DR frequency (true for the whole injector complex)
  - Conceptual design to be performed for CDR

Summary (cont.)

- Stability of kickers challenging (as for all DRs and even modern storage rings for top-up operation)
  - Collaboration with ILC and light sources but technical design will not be available for CDR
- Alignment tolerances to be revised for CDR based on analytical estimations
  - Participation in low emittance tuning measurement campaigns in light sources and CESR-TA
- Beam instrumentation wish list is good enough for CDR
  - Contacts to be established during the CLIC BI workshop next week
- Formed group on CLIC/ILC common issues for DR
  - Workshop to be organised next year to sum-up the present experience and challenges of DR design
- Established conservative and nominal DR parameters for CLIC @ 500GeV
  - Scaled design to be ready for CDR
  - Estimation of some collective effects but not detailed simulations