C L I C

ILC'08 Workshop

CERN

CLIC damping rings overview

Yannis PAPAPHILIPPOU
CERN

November 18th, 2008

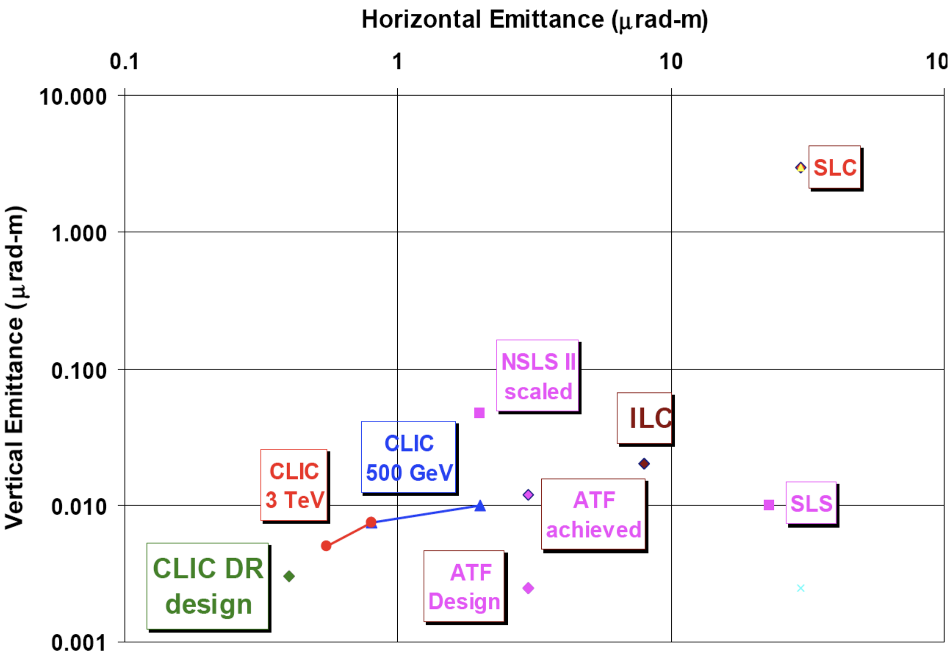
Outline

- CLIC damping rings (DR) design goals and challenges
- Design parameters' evolution

CLIC parameter note 2005	→	M. Korostelev, PhD thesis, 2006	→	CLIC parameter note 2008	→	Design optimisation for CDR (2010)

- Lattice choice, optics revision and magnet design
- Wiggler design and power absorption
- Non-linear dynamics
- Low emittance tuning
- e-cloud and other collective effects (IBS)
- Diagnostics
- CLIC DR activities
- Summary

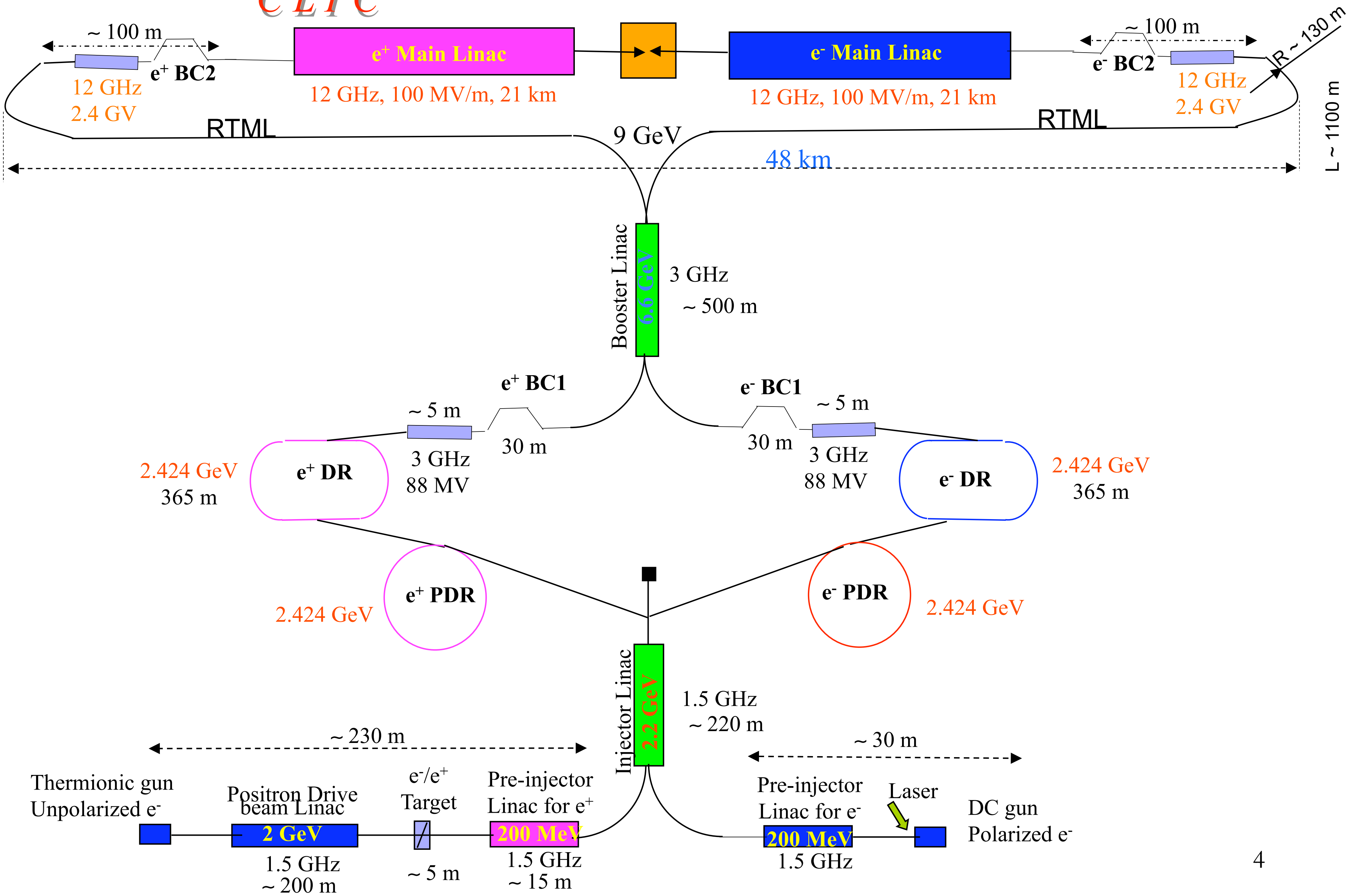
Damping ring design goals



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	<550
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

- Starting parameter dictated by design criteria of the collider (luminosity), injected beam characteristics or downstream system tolerances
- Intra-beam scattering due to high bunch current blows-up the beam
  - Equilibrium "IBS dominated" emittance has to be reached fast to match collider high repetition rate
- Other collective effects (e.g. e^--cloud, fast ion instability) may increase beam losses

Injector complex



CLIC Pre-damping rings

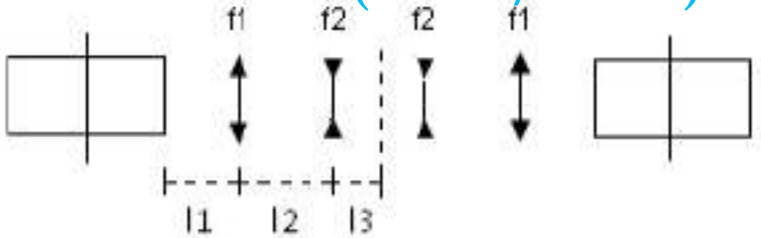
- Most critical the e^+ PDR
  - Injected e^+ emittance ~ 2 orders of magnitude larger than for e^-, i.e. aperture limited if injected directly into DR
- PDR for e^- beam necessary as well
  - A "zero current" linac e^- beam (no IBS) would need ~ 17ms to reach equilibrium in DR, (very close to repetition time of 20ms)
- PDR main challenges
  - Large input momentum spread necessitates large longitudinal acceptance for good injection efficiency
  - Polarised positron stacking time long compared to repetition rate (need fast damping and/or staggered trains)

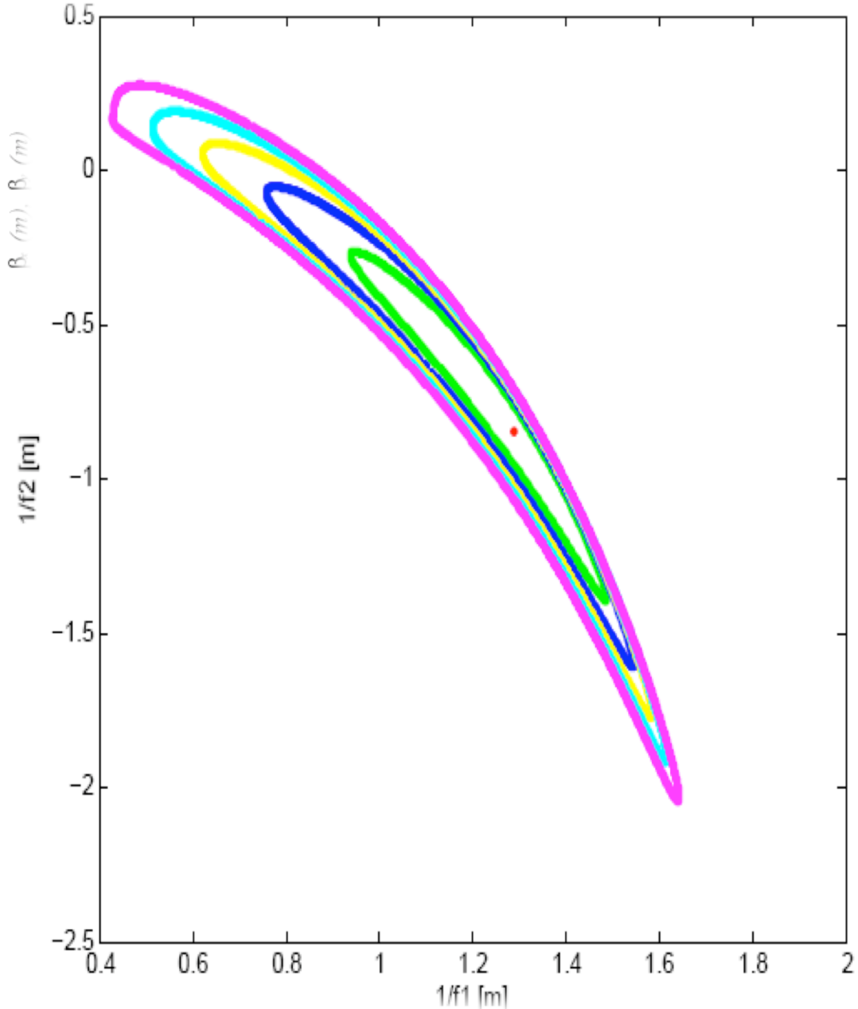
PDR Extracted Parameters	**CLIC**	**NLC**
Energy [GeV]	2.424	1.98
Bunch population [10^9]	4.1-4.4	7.5
Bunch length [mm]	10	5.1
Energy Spread [%]	0.5	0.09
Hor. Norm. emittance [nm]	63000	46000
Ver. Norm. emittance [nm]	1500	4600

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]	100×10^3	9.3×10^6

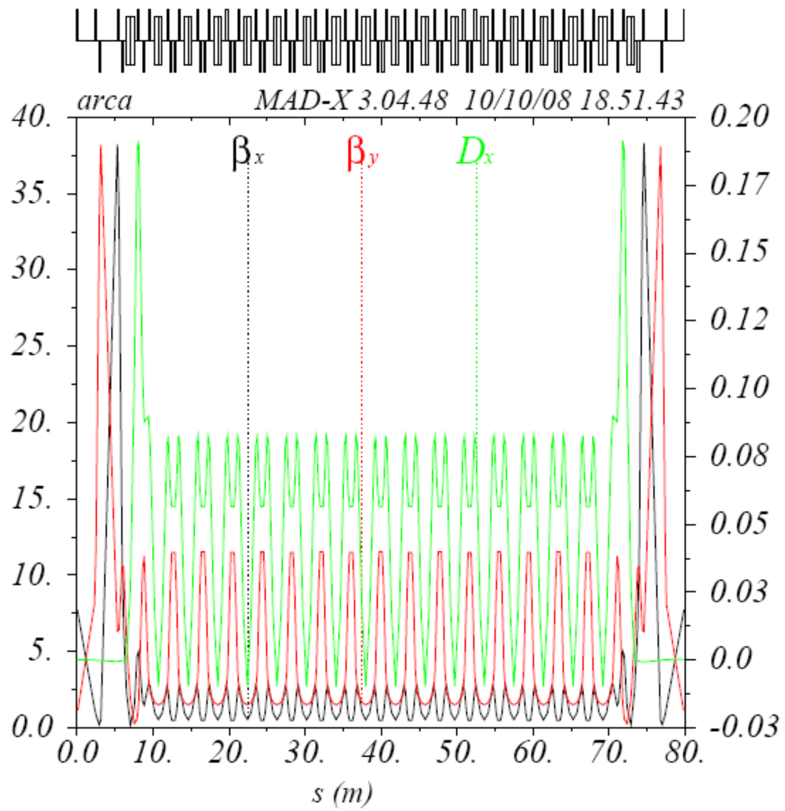
Analytical solution for TME cells

F. Antoniou (NTUA/CERN)





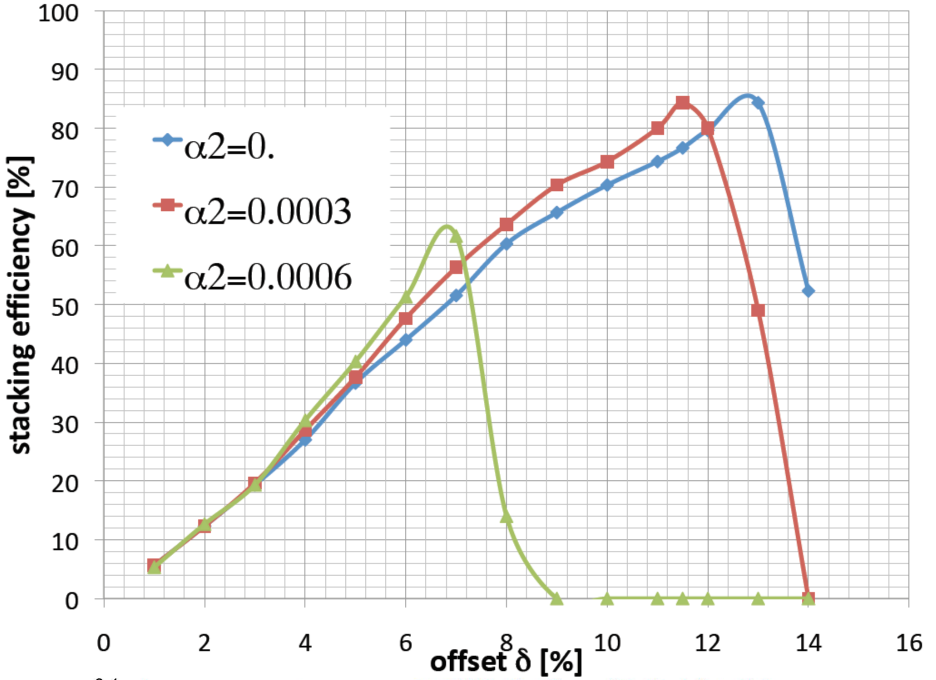
- For general TME cells the focal lengths (under thin lens approximation) can be written as a function of the drifts and the transverse emittance
- Enables optimization of any type of optics parameter
- Guide to design optimal CLIC (P)DRs
- Example: optics design of PDR

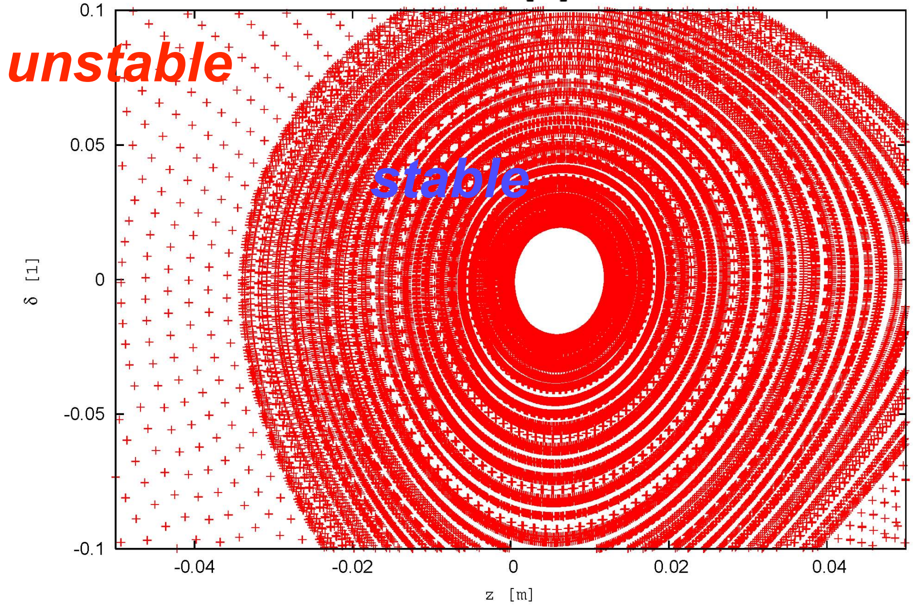


Stacking of polarized e^+ into the PDR

F. Zimmermann (CERN)

- ➢ CLIC Compton source using ERL or CR
- ➢ e+ emittance preservation after capture
- ➢ CLIC PDR parameters should have a **low** a_2 (4e-4) and **high** V_{RF} (~16MV)
- ➢95% efficiency can be achieved with off-momentum off-phase injection
- ➢ Needs **10% of momentum acceptance** in PDR (off momentum DA)
- ➢ Quite some flexibility (# optical cavities vs. e- bunch charge) but a few challenges for PDR design



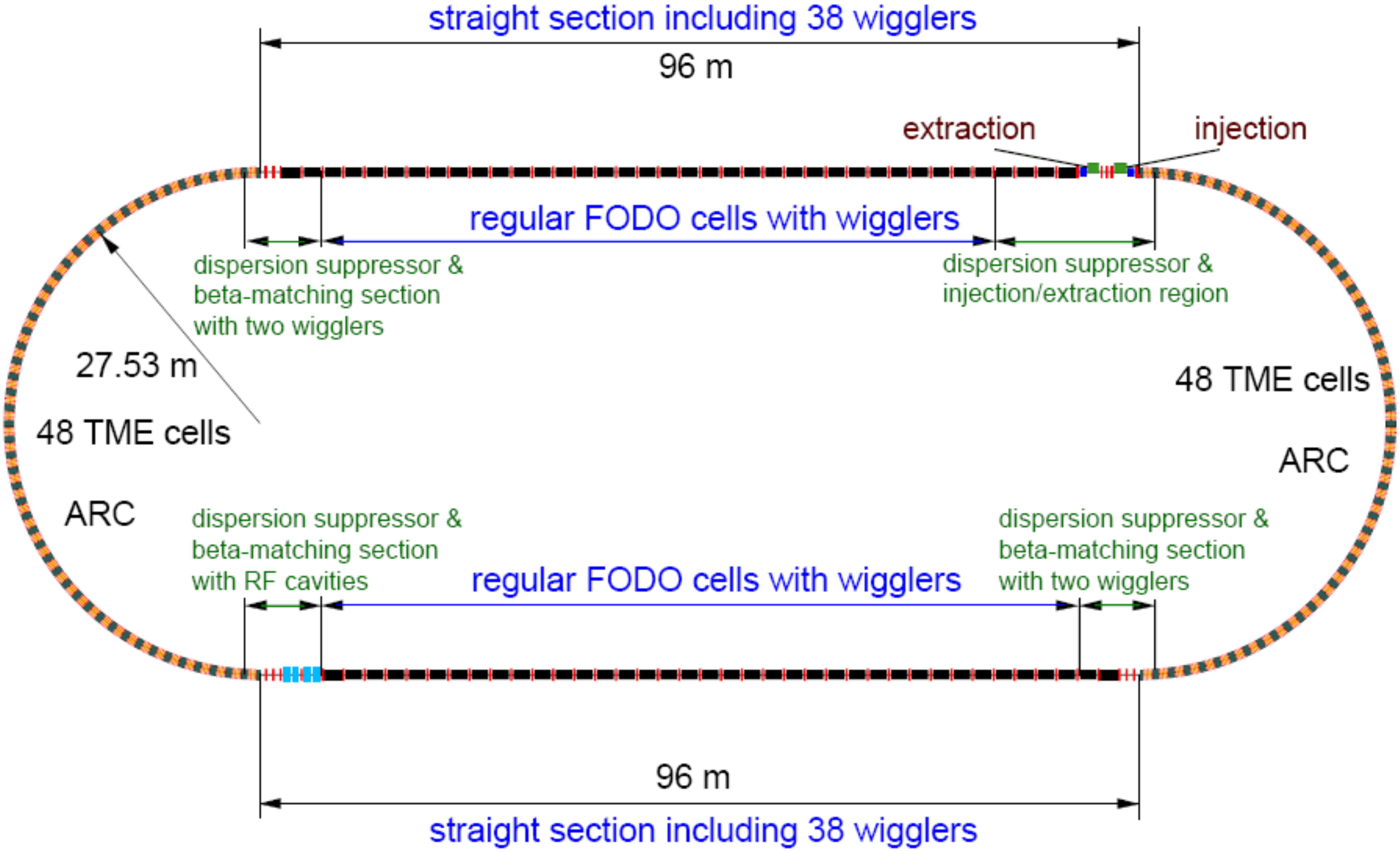


CLIC damping rings lattice

- Two rings of racetrack shape at energy of **2.424GeV**
- Arcs filled with **1.8m long TME cells** and straight sections contain FODO cells with damping wigglers, giving **total length** of **365.2m**
- Phase advance per TME cell was kept to **210°** in the horizontal and **90°** in the vertical plane, providing a detuning factor of 1.8
- The chromaticity is controlled by two sextupole families.

Parameter [unit]	symbol	old value (2005)	new value (2007)
beam energy [GeV]	E_b	2.424	2.424
circumference [m]	C	360	365.2
bunch population [10^9]	N	2.56	3.70 $\times$1.1
bunch spacing [ns]	$T_{\rm sep}$	0.533	0.5
bunches per train	$N_{\rm b}$	110	312
number of trains	$N_{\rm train}$	4	1
store time / train [ms]	$t_{\rm store}$	13.3	20
rms bunch length [mm]	σ_z	1.547	1.53
rms momentum spread [%]	σ_δ	0.126	0.143
final hor. emittance [nm]	$\gamma\epsilon_x$	550	381
hor. emittance w/o IBS [nm]	$\gamma\epsilon_{x0}$	134	84
final vert. emittance [nm]	$\gamma\epsilon_y$	3.3	4.1
coupling [%]	κ	0.6	0.13
vertical dispersion invariant	$\mathcal{H}_y$	0	0.248
no. of arc bends	$n_{\rm bend}$	96	100
arc-dipole field [T]	$B_{\rm bend}$	0.932	0.932
length of arc dipole [m]	$l_{\rm bend}$	0.545	0.545
arc beam pipe radius [cm]	$b_{\rm arc}$	2	2
number of wigglers	$n_{\rm w}$	76	76
wiggler field [T]	$B_{\rm w}$	1.7	2.5
length of wiggler [m]	$l_{\rm w}$	2.0	2.0
wiggler period [cm]	λ_w	10	5
wiggler half gap [cm]	b_w	0.6	0.5
mom. compaction [10^{-4}]	α_c	0.796	0.804
synchrotron tune	Q_s	0.005	0.004
horizontal betatron tune	Q_x	69.82	69.84
vertical betatron tune	Q_y	34.86	33.80
RF frequency [GHz]	$f_{\rm RF}$	1.875	2
energy loss / turn [MeV]	U_0	2.074	3.857
RF voltage [MV]	$V_{\rm RF}$	2.39	4.115
h/v/l damping time [ms]	$\tau_x/\tau_y,/\tau_s$	2.8/2.8/1.4	1.5/1.5/0.76
revolution time [μs]	$T_{\rm rev}$	1.2	1.2
repetition rate [Hz]	$f_{\rm rep}$	150	50

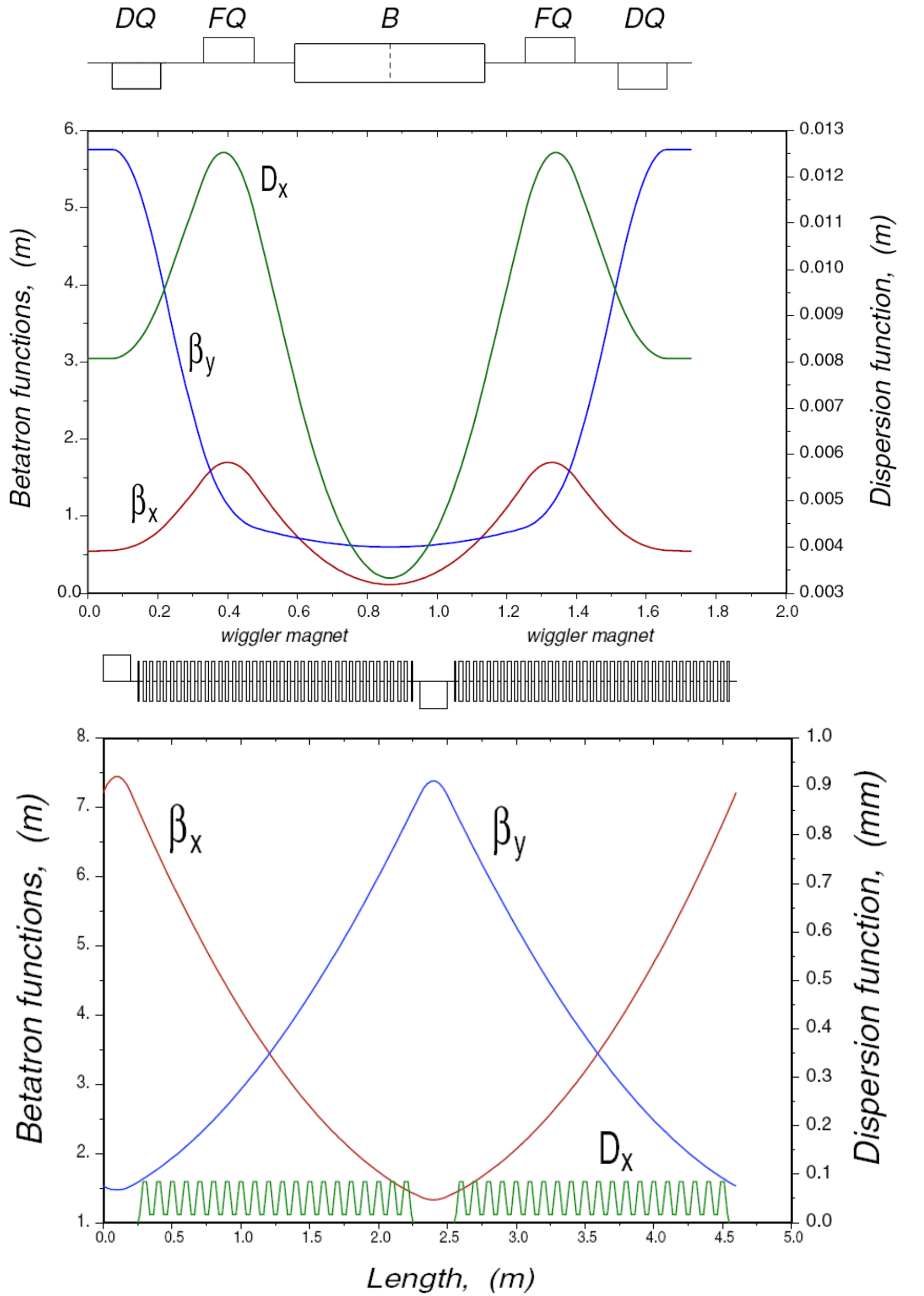
CLIC damping ring layout



M. Korostelev, PhD thesis, EPFL 2006

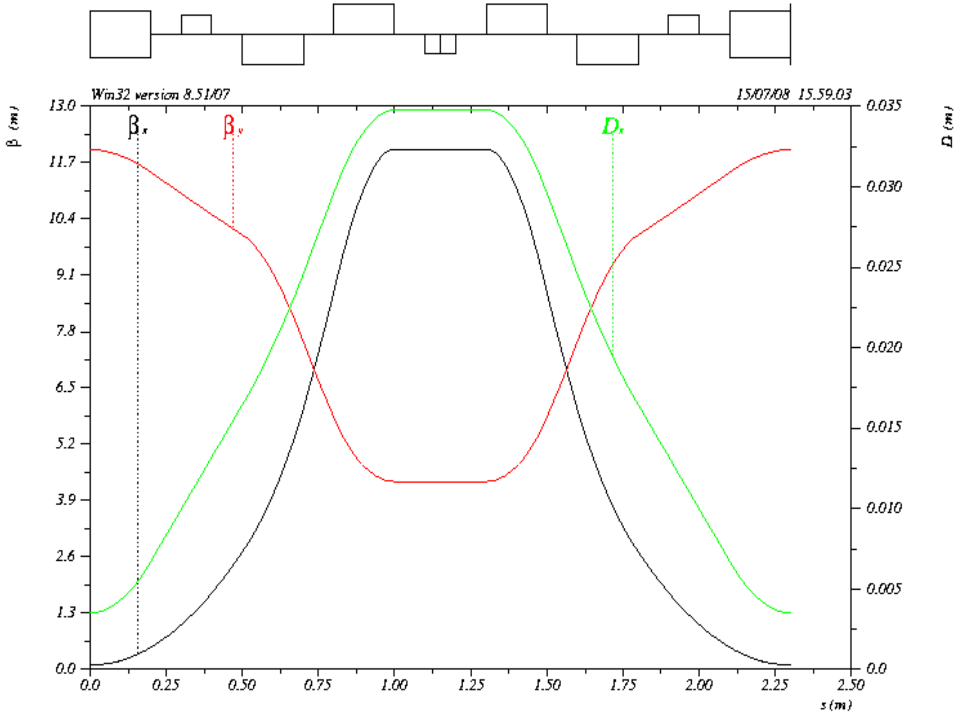
Arc and wiggler cell

- TME arc cell chosen for compactness and efficient emittance minimisation over Multiple Bend Structures 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
  - Very limited space
  - Extremely high quadrupole and sextupole strengths
- FODO wiggler cell with phase advances close to 90° giving
  - Average β's of ~ 4m and reasonable chromaticity
  - Quad strength adjusted to cancel wiggler induced tune-shift
  - Limited space for absorbers



New arc cells optics

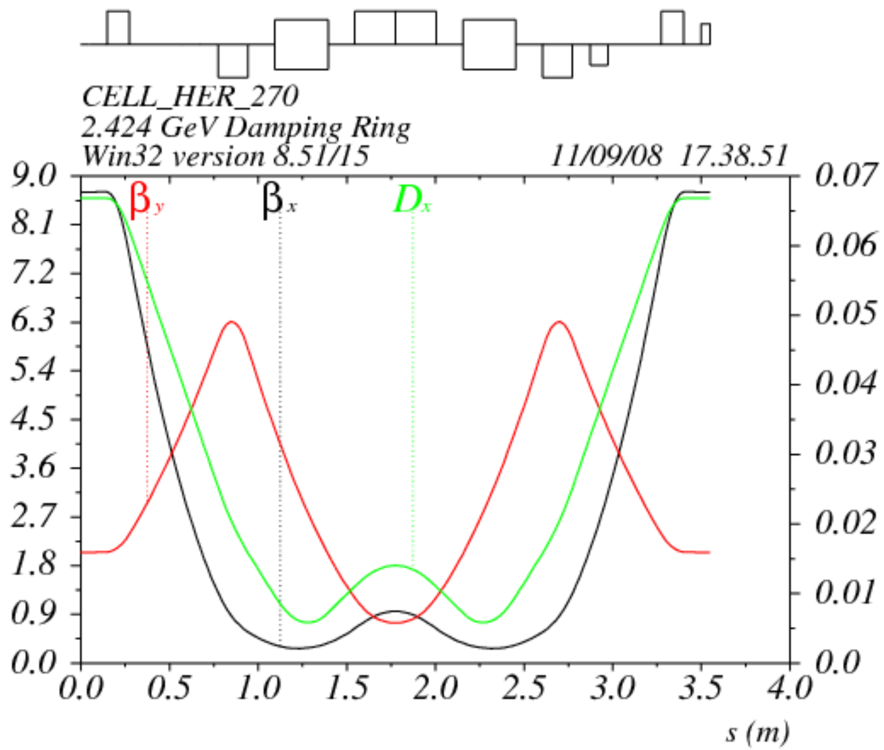
S. Sinyatkin, et al., BINP



- New arc cell design
  - Increasing space between magnets, reducing magnet strengths to realistic levels
  - Reducing chromaticity, increasing DA
  - Even if equilibrium emittance is increased (0 current), IBS dominated emittance stays constant!
  - Dipoles have quadrupole gradient (as in ATF!).

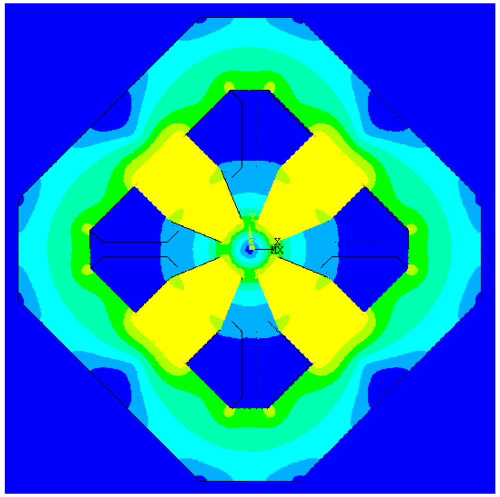
P. Raimondi (INFN-LNF)

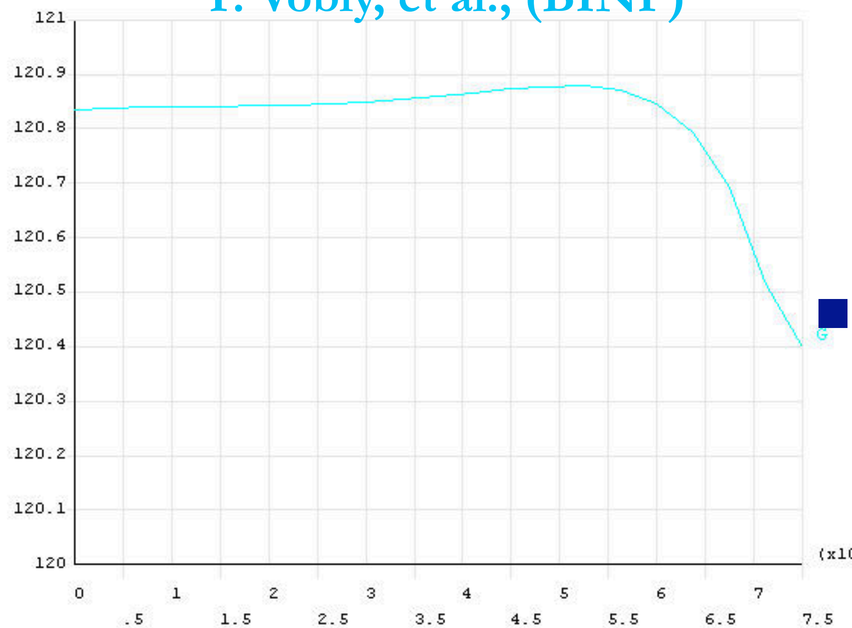
- Alternative cell based on SUPERB lattice
  - Using 2 dipoles per cell with a focusing quadrupole in the middle
  - Good optics properties
  - To be evaluated for performance when IBS is included



Arc magnet design

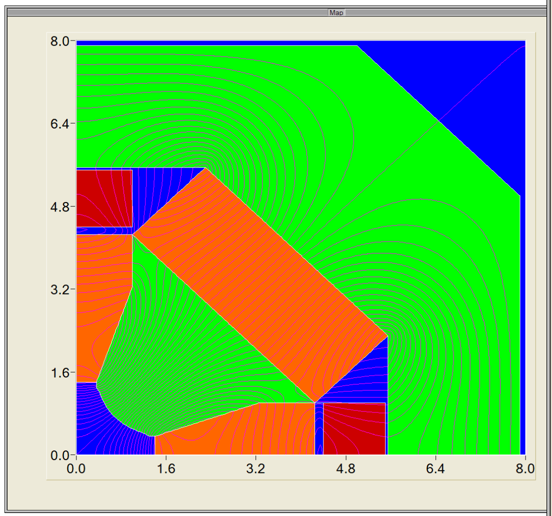
P. Vobly, et al., (BINP)

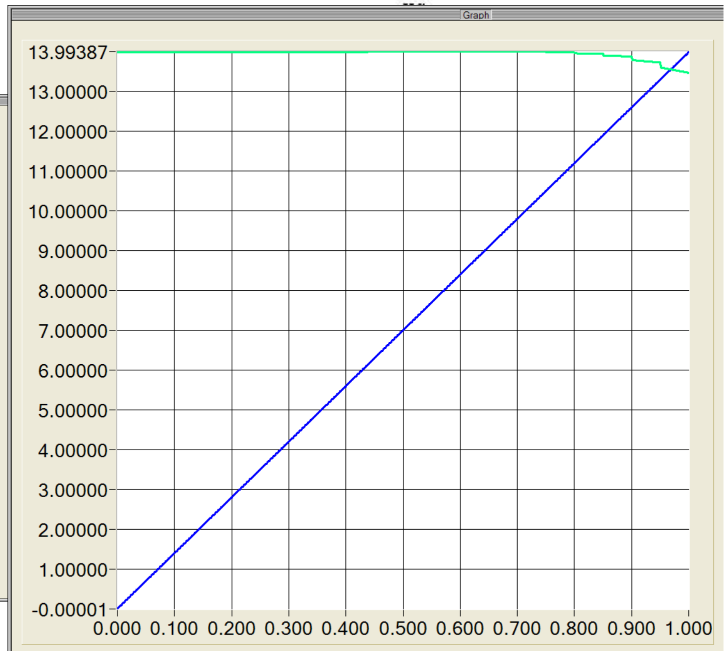


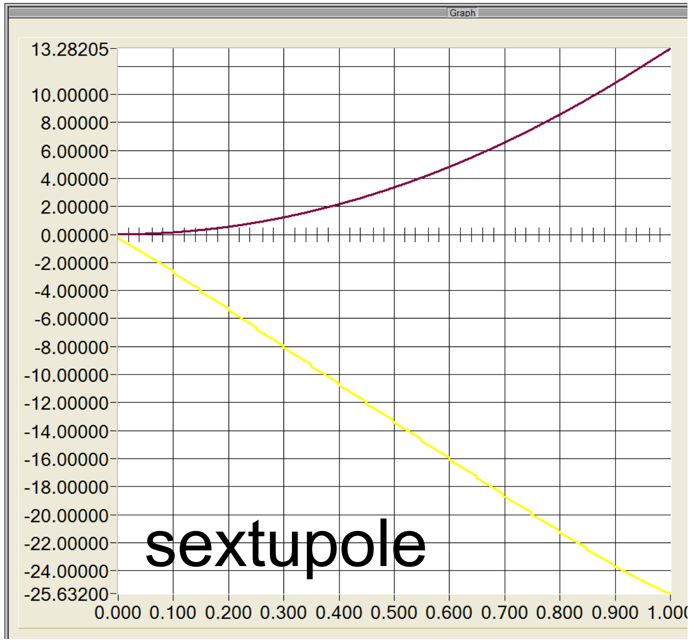


- High gradient quadrupole model using conventional technology (120 T/m, r=10mm)
- Hybrid quadrupole and sextupole designs for even higher field (140-160 T/m and 28 T/m^2)

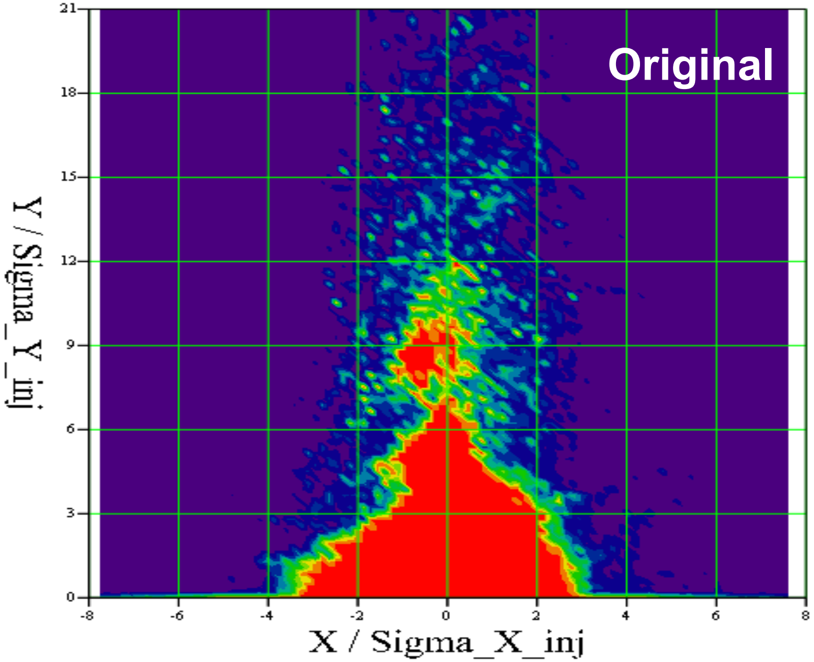
Quadrupoles

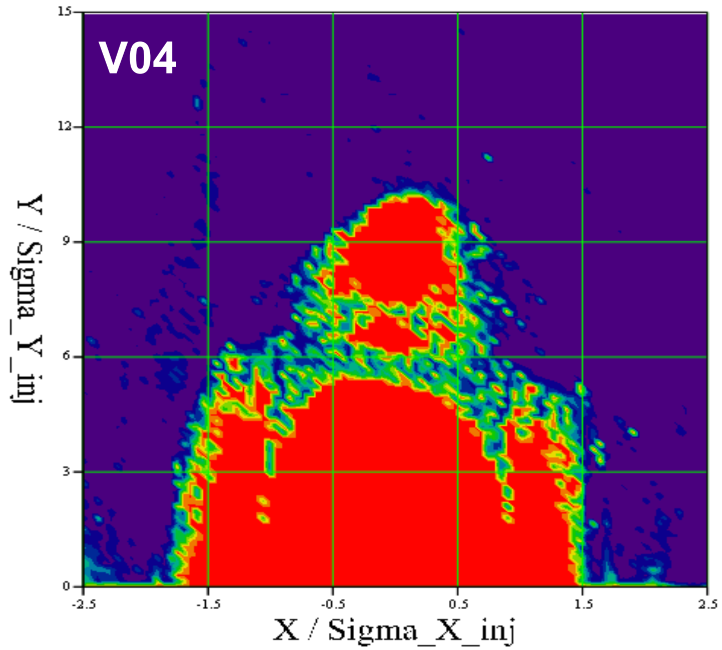




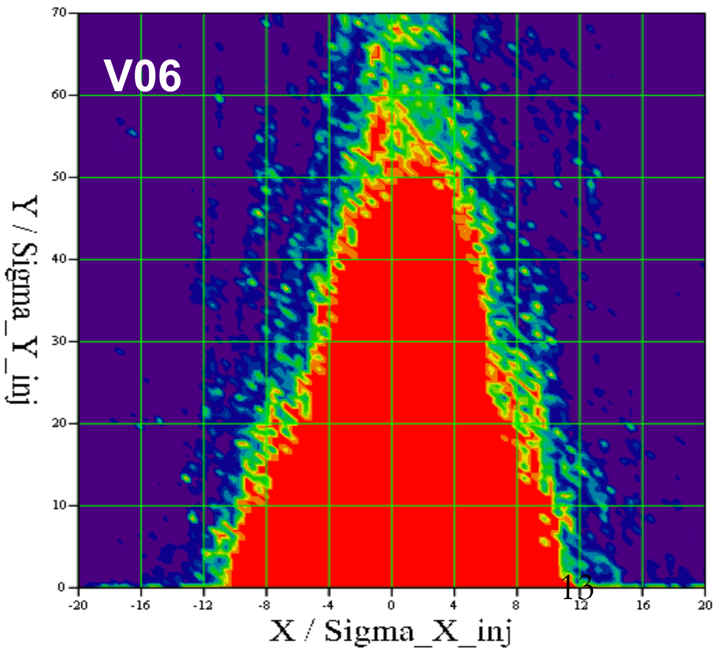


Dynamic aperture





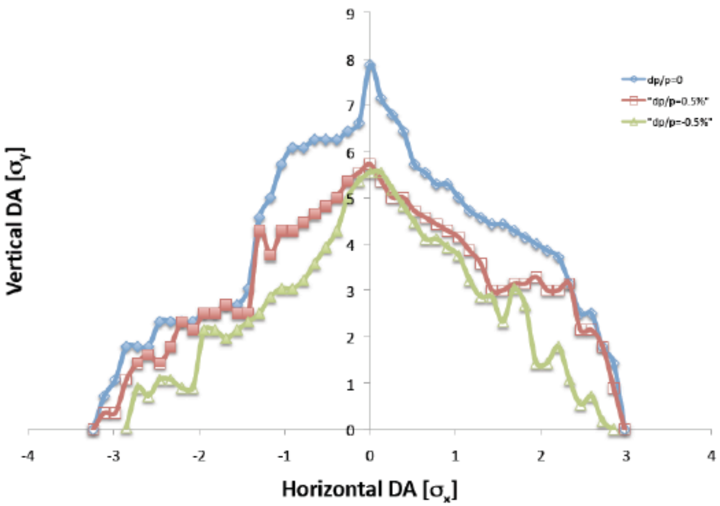
- Original and V04 lattices have very small DA
- The V06 lattice has a more comfortable DA
- Error tables for all magnets including superconducting wigglers to be considered and optimised
- Resonance correction and DA optimisation with sextupoles and/or octupoles using modern techniques (normal forms, frequency maps, ...)

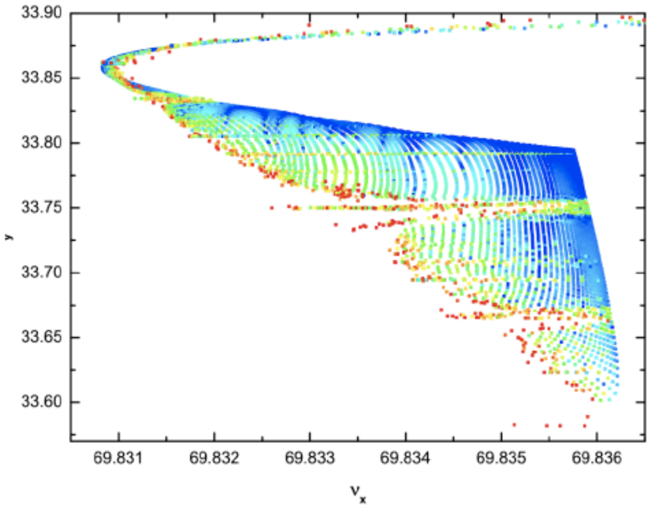


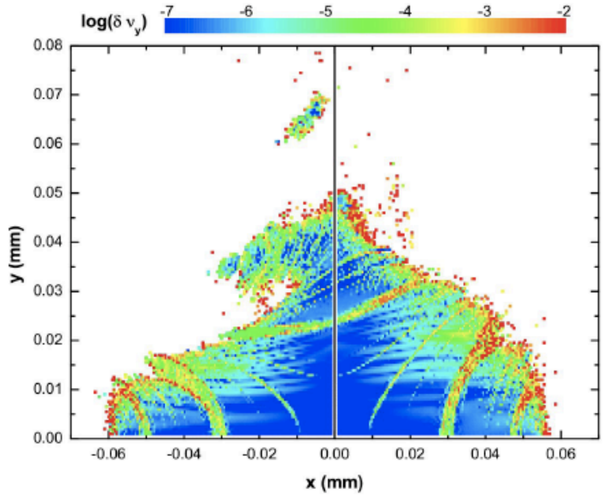
S. Sinyatkin, et al. 2008

Frequency maps

Ch. Skokos and Y. Papaphilippou, EPAC08

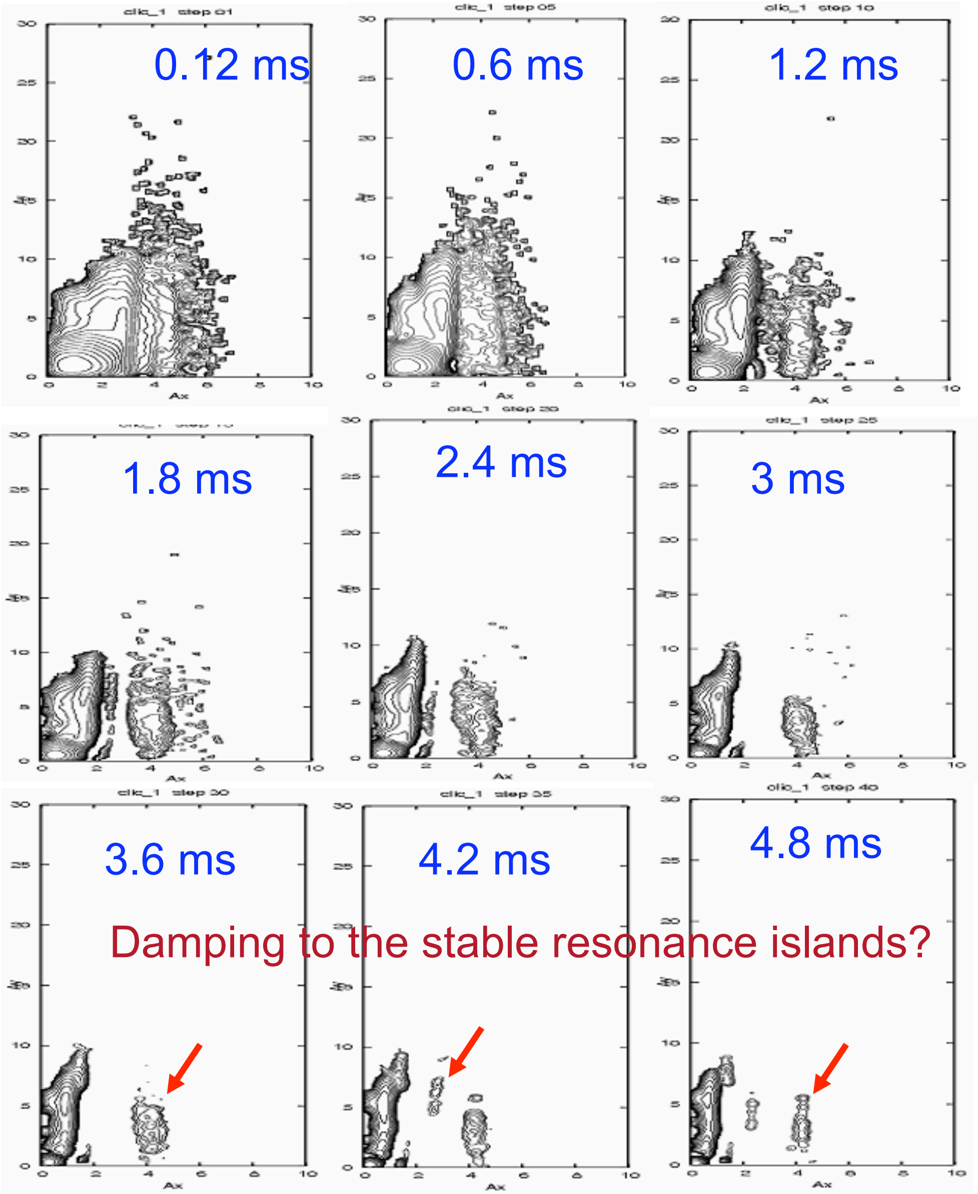




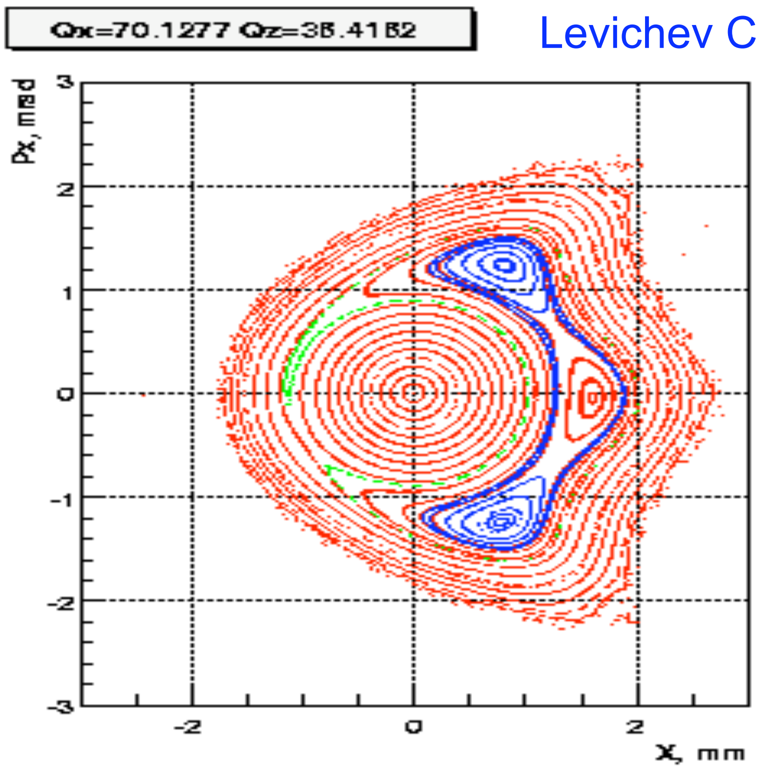


- Only sextupole non-linearity considered (two families)
- Small DA confirmed by both tracking with symplectic integrator $SABA_2C$ and MADX-PTC
- First on-momentum frequency map reveals wide vertical tune spread and crossing of a multitude of resonances (especially 4th order for present working point)
- On-going effort to include in tracking all relevant effects (dipole and quadrupole fringe fields, wigglers, magnet errors, space-charge, radiation damping)

Effect of radiation damping



Levichev CLIC07



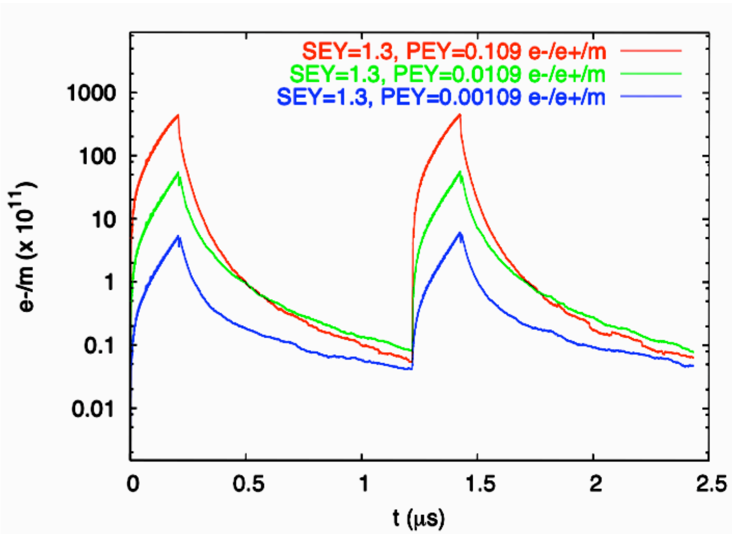
- Including radiation damping and excitation shows that 0.7% of the particles are lost during the damping
- Certain particles seem to damp away from the beam core, on resonance islands

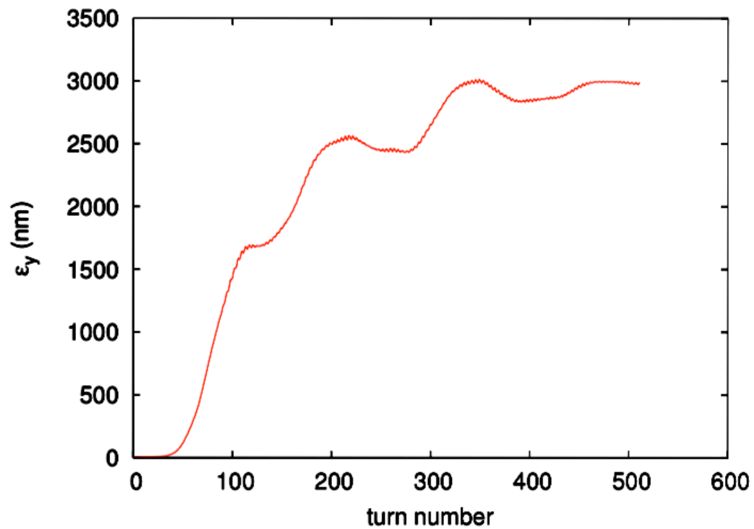
Collective effects

- The electron cloud in the e^+ DR impose limits in PEY (99.9% of synchrotron radiation absorbed in the wigglers) and SEY (below 1.3) and can be cured with special **chamber coatings**
- Fast ion instability in :
  - 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 0.188 and 10% emittance growth)
  - Single bunch instabilities avoided with smooth impedance design and resistive wall coupled bunch can be controlled with feedback

G. Rumolo et al. (CERN)

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



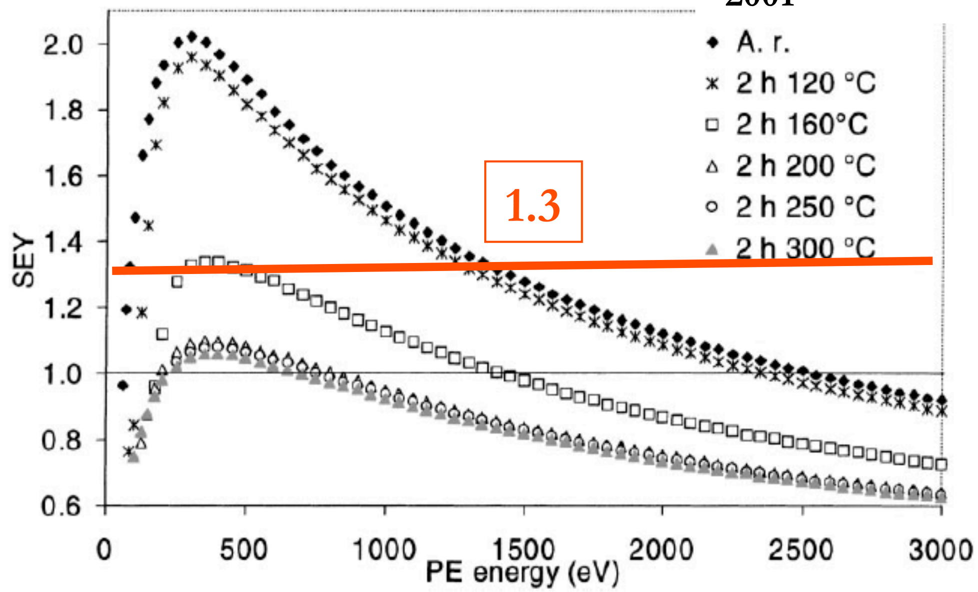


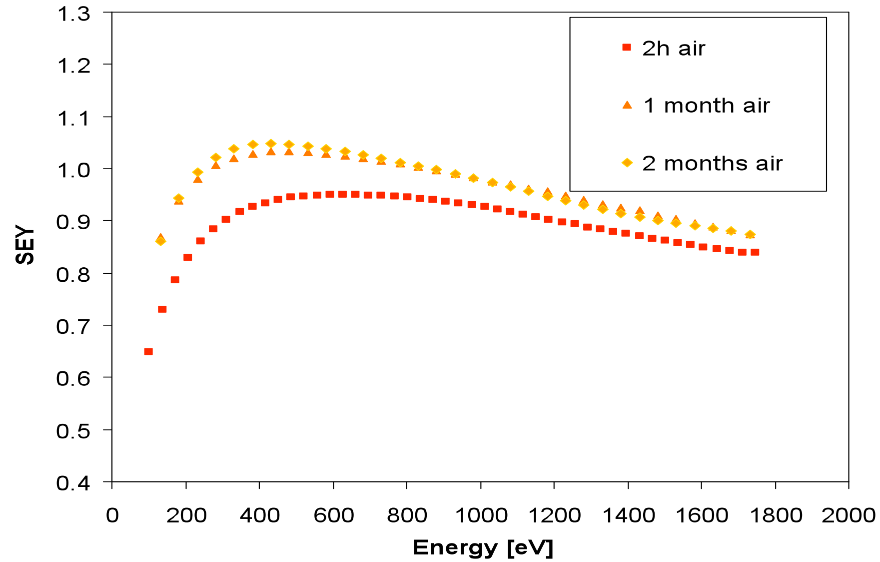
Surface Treatment for e- Cloud Mitigation

M. Taborelli et al. (CERN)

Bakeable system
-NEG gives SEY<1.3 for baking @ > 180C
-the evolution after many venting cycles should be studied
-NEG provides pumping
-it is also 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
-pumpdown curves can be 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

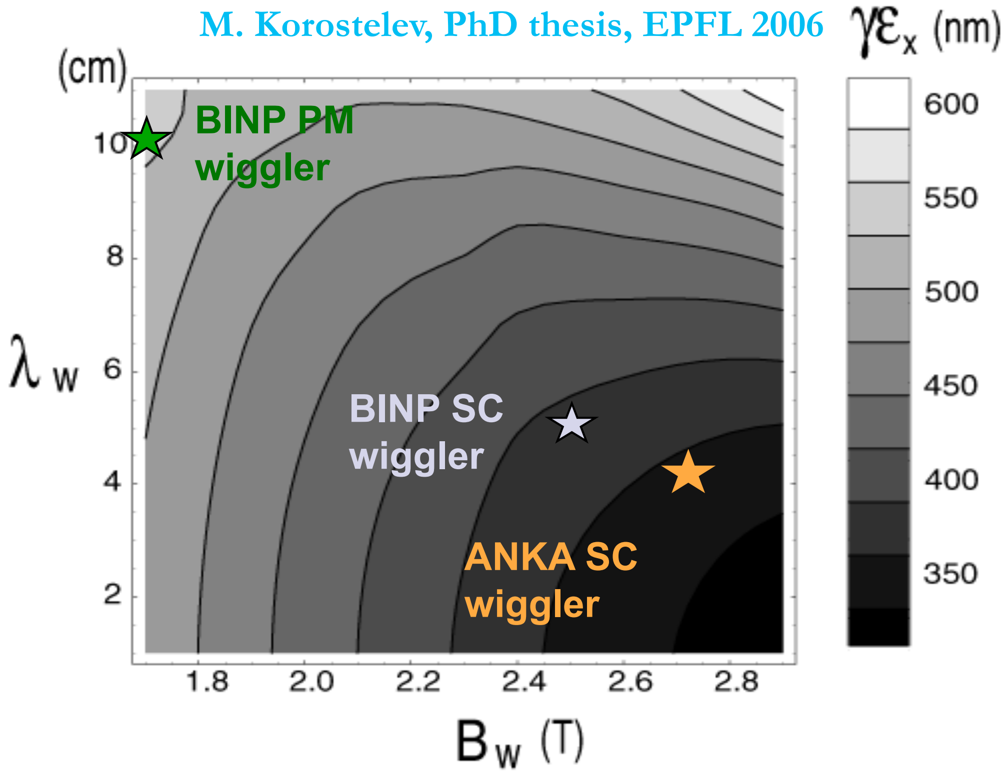
Henrist et al. Appl.Surf.Sci, 2001





Wigglers' effect with IBS

M. Korostelev, PhD thesis, EPFL 2006



- With super-conducting wigglers of **2.5T** and **5cm** period, the achieved normalized horizontal emittance drops below **400nm**
  - Super-conducting magnets have to be designed, built and tested

- Stronger wiggler fields and shorter wavelengths necessary to reach target emittance due to strong IBS effect

Parameters	**BINP**	**ANKA/CERN**
B_{peak} [T]	2.5	2.8
λ_W [mm]	50	40
Beam aperture full gap [mm]	20*	24*
Conductor type	NbTi	$NbSn_3$
Operating temperature [K]	4.2	4.2

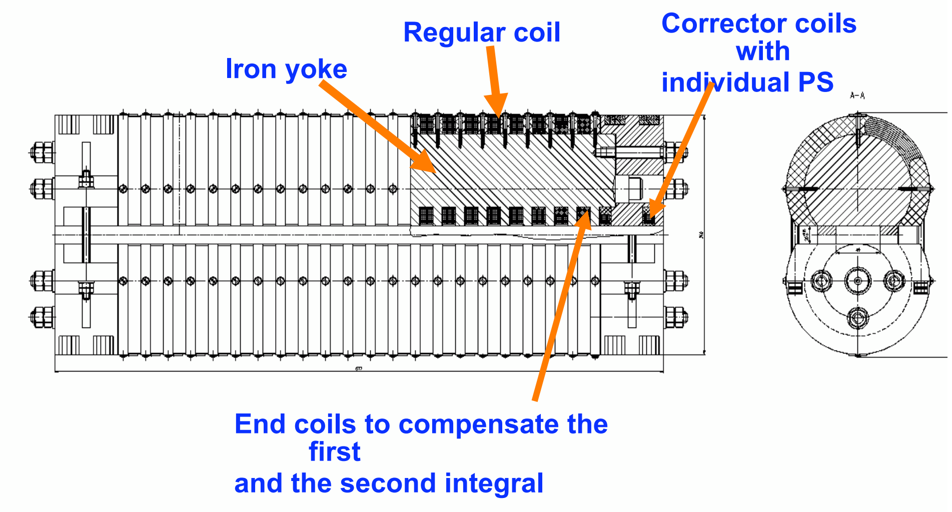
- Two wiggler prototypes
  - 2.5T, 5cm period, NbTi coil, built by BINP
  - 2.8T, 4cm period, Nb_3Sncoil, built by CERN/ANKA
- Aperture fixed by radiation absorption scheme
- Short version to be installed and tested at ANKA

NbTi Wiggler Design

- Present design uses NbTi wet wire in separate poles clamped together (2.5T, 5cm period)
- Performance tests by the end of the year on short prototype
- Magnetic tolerances needed to refine design (e.g. taken from PETRA III wiggler)
- Alternative design allows using Nb3Sn dry wire substantially reducing time and cost

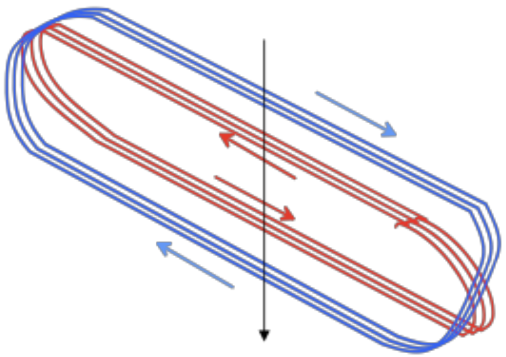
P. Vobly (BINP)

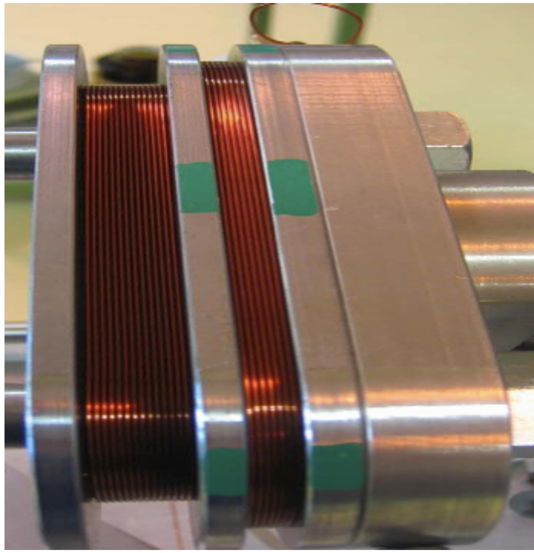
General view for BINP wiggler prototype

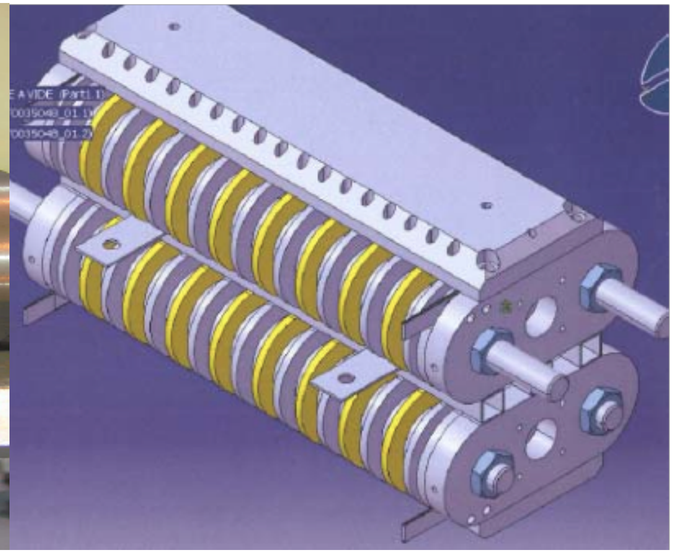


Nb3Sn Wiggler Design

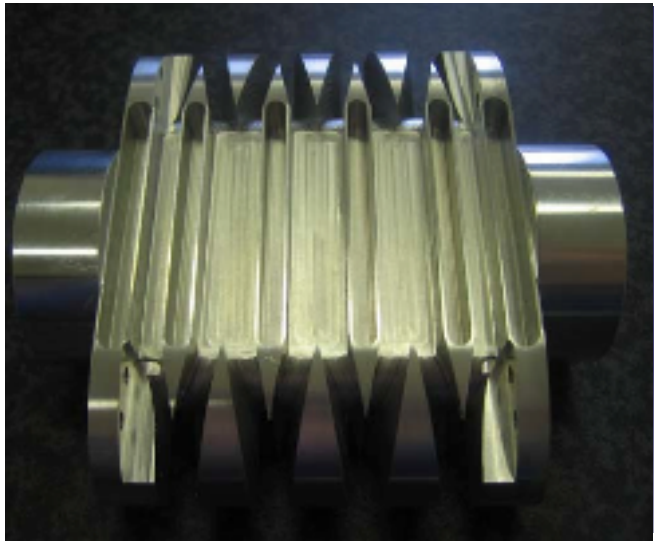
- Two models (2.8T, 40mm period)
  - Vertical racetrack (WR)
  - Double helix (WH), can reach 3.2T with Holmium pole tips
- Apart from higher field Nb3Sn can sustain higher heat load (10W/m) than NbTi (1W/m)
- Between 2009-2010, two short prototypes will be built, tested at CERN and magnetically measured at ANKA

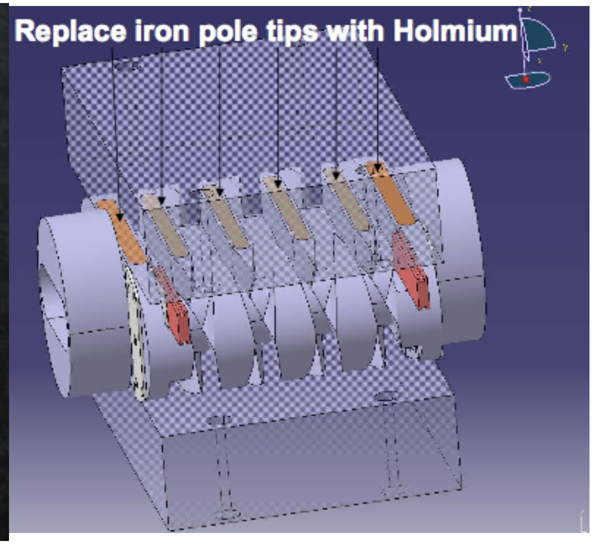






R. Maccaferri (CERN)

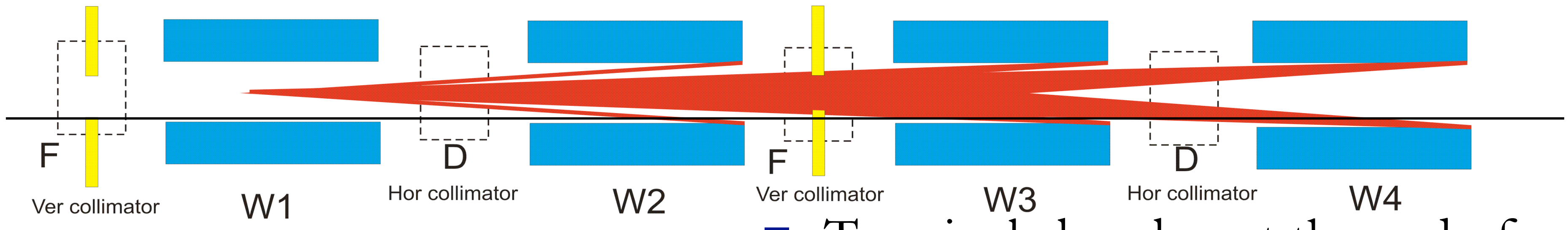




Radiation absorption scheme

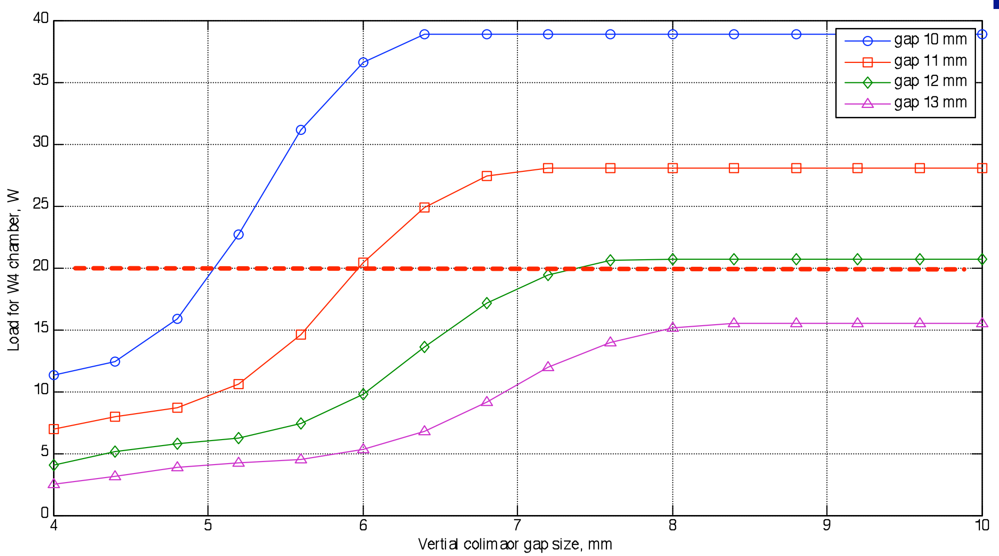
K. Zolotarev (BINP)

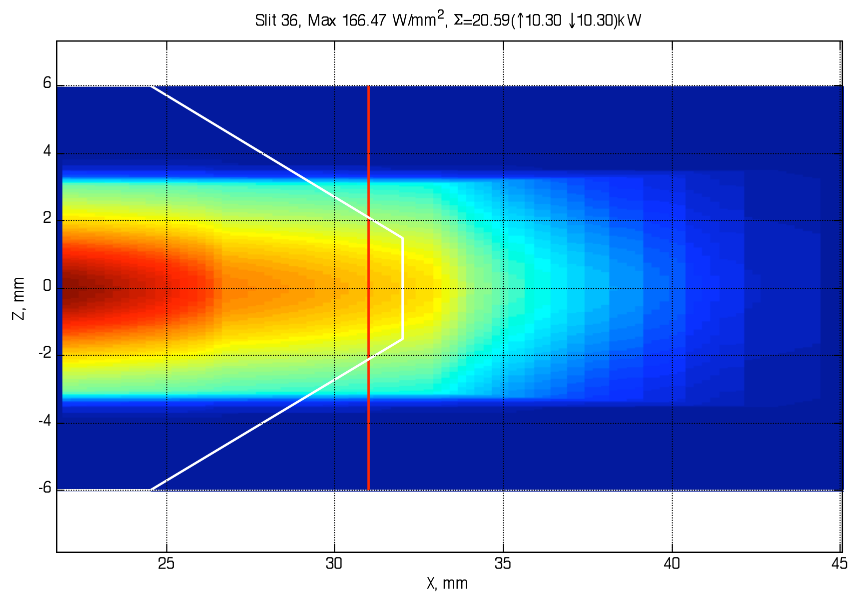
A 4-wigglers scheme



- Terminal absorber at the end of the straight section
- 3D radiation distribution to be used for e-cloud built up
- Impedance estimation

- Gap of 13mm for NbTi wiggler and 20mm for Nb3Sn design (1W/m) or 13mm (10W/m)

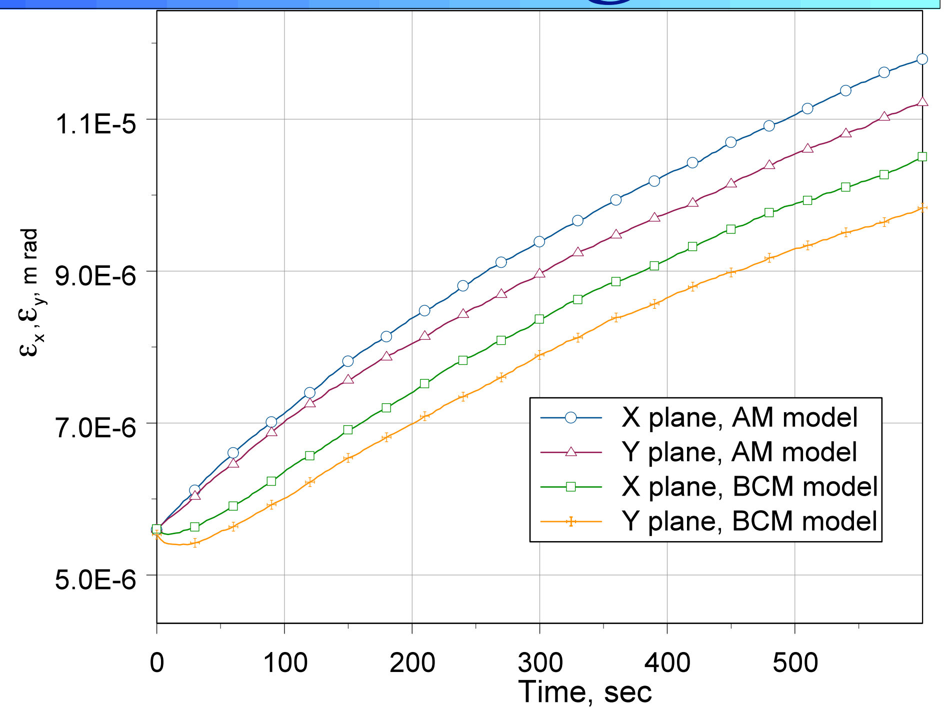


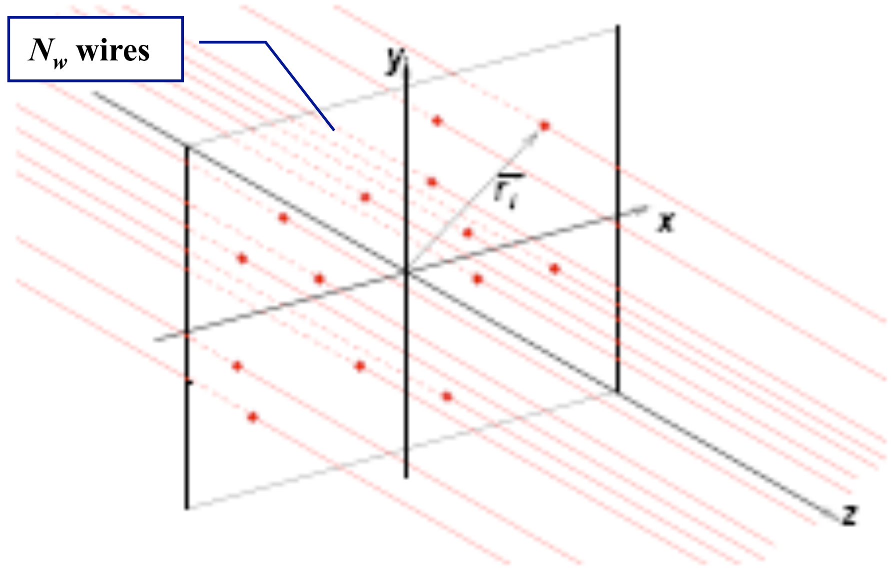


Intrabeam scattering

M. Martini and A. Vivoli (CERN)

- IBS effect evaluated through semi-analytical approach (modified Piwinski or Bjorken-Mtingwa formalism)
  - Derive analytically the optics parameters for reaching minimum IBS dominated emittance in selected lattices (FODO, TME,…)
- Numerical or analytical approach for effect of strong IBS producing non-Gaussian tails including radiation damping is missing
  - Codes for non-Gaussian beams exist (e.g. MOCAC) but not all effects included
  - Use of stochastic diffusion equation approach may be an alternative (presently used for coasting beams)



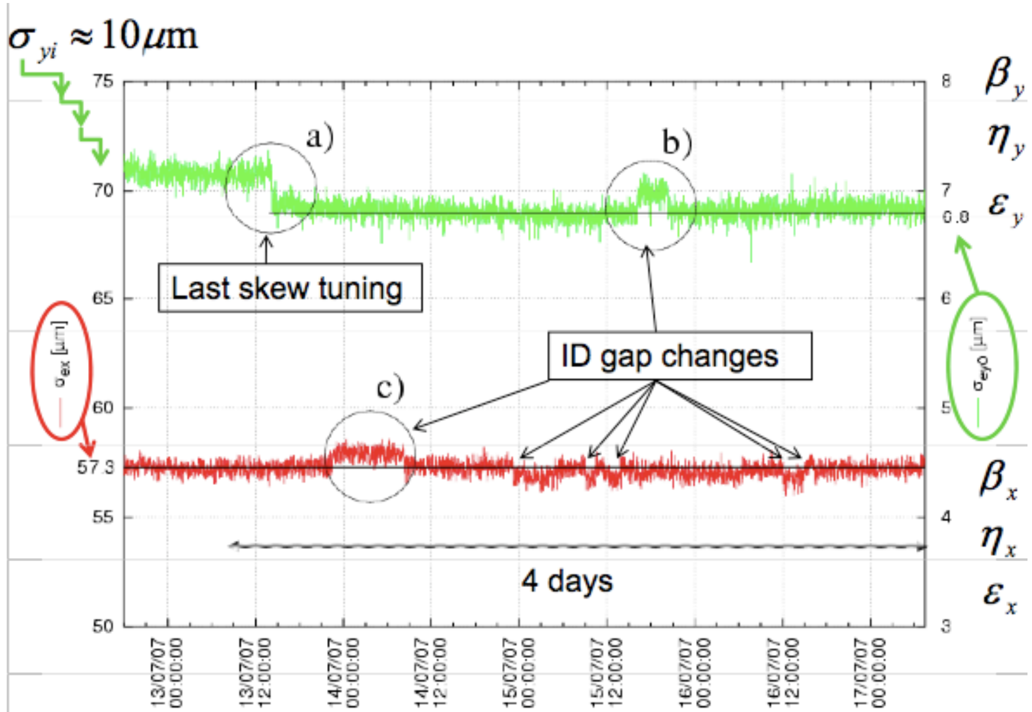


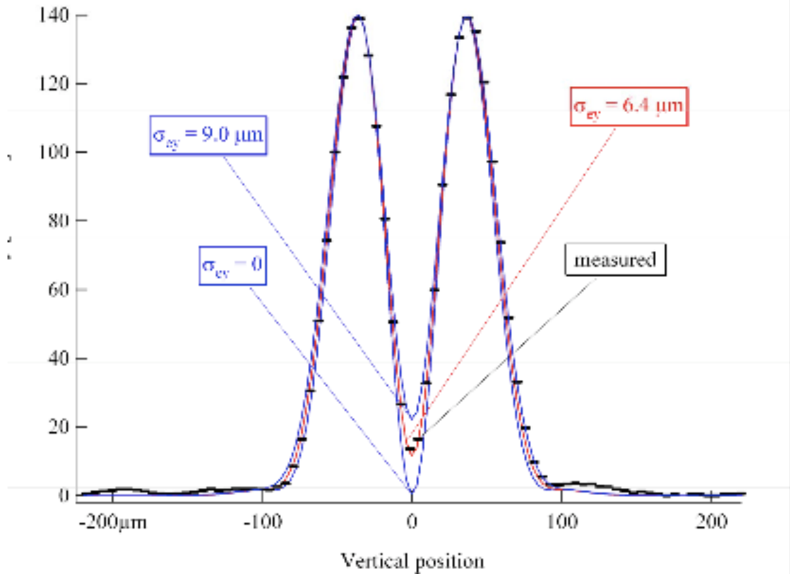
Coupling correction and low emittance measurement in SLS

CLIC

A. Andersson (PSI)

- Achieved 3pm vertical emittance
- Aggressive program for reaching absolute limit (0.55pm)
    - Correction of residual dispersion (3mm) induced by sextupole misalignments with skew quads in dispersive regions
- Beam size measurements using π polarization method
    - Beam image formed by vertically polarized visible-UV synchrotron radiation
    - Beam sizes of a few **microns** can be measured
    - Integration time of a 100-turns limited by response of CCD camera





Injection, extraction, timing, RF

- Interleaved bunch train scheme abandoned due to its complexity.
- Reduction of the repetition rate from 150 to 50Hz leaves enough time for the emittances to reach their equilibrium.
- Bunch spacing increased almost to the same level as for the interleaved scheme.
- **312** bunches with 0.5ns spacing, fill only **13%** of the rings.
- RF frequency of **2GHz** with voltage of **4.1MV** for enough energy recovery while keeping longitudinal emittance below **5000eV.m**
- Extraction kicker rise time is relaxed
- Detailed design of RF cavity and injection/extraction elements is **pending**

CLIC DR RF system

A. Grudiev (CERN)

1) Main issues:

- Frequency: 2 GHz
- Highest peak and average power
- Very strong beam loading transient effects (beam power of ~5 MW during 156 ns, no beam power during the other 1060 ns)
- Small stored energy at 2 GHz
- High energy loss per turn at relatively low voltage results in big sin $\phi_s = 0.95$ (see also LEP)
- Wake-fields
- Pulsed heating related problem (fatigue, …)

2) Recommendations:

- Reduce energy loss per turn and/or increase RF voltage
- Consider 1GHz frequency (RF system becomes conventional, RF power reduced, but delay loop for recombination is necessary and emittance budget is tight)

Damping Rings diagnostics

- Beam position from around **300PUs**, turn by turn (every **1.22µs**) all around the ring with a
  - **10µm** resolution, for linear and non-linear optics measurements.
  - **2µm** resolution for orbit measurements (needed for vertical dispersion/ coupling monitoring and correction and closed orbit feedback).
- A few wide band pick-ups able to do bunch-by-bunch (bunch spacing of **0.5ns** for **312** bunches) and turn by turn position monitoring with a high resolution (**1µm**) for injector trajectory control, and bunch by bunch transverse feed-back.
- Some pick-ups or profile monitors for the extraction transfer line for extraction orbit control and feed-forward.
- Tune monitors and fast tune feed-back precision of $\mathbf{10^{-4}}$). The vertical tune may move roughly by **0.2** due to space-charge. The precision of these monitors may be critical for resolving instabilities (i.e. synchrotron side-bands, ions)

Damping Rings diagnostics

- Turn by turn transverse profile monitors (X-ray?) with a wide dynamic range:
  - the horizontal geometrical emittance goes roughly from **13nm.rad** at injection to **80pm.rad** at extraction and the vertical from **300pm.rad** to **0.8pm.rad**.
  - Capable of measuring **tails** for an IBS dominated beam.
  - 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 (vacuum)

Damping ring activities

Y. Papaphilippou and H.H. Braun

Activity	Contacts	Commitment	Comment
DR parameters	Y. Papaphilippou (CERN)	Formal	
Lattice design	Y. Papaphilippou (CERN), S.V. Sinyatkin (BINP)	Formal	
Non-linear dynamics	Ch. Skokos (MPI-Dresden)	Informal	
	E. Levichev et al. (BINP)	Formal	
Correction systems	R. Tomas, G. Vanbavickhove (CERN)	Planned	PhD thesis
Intrabeam Scattering	M. Martini, A. Vivoli (CERN)	Formal	
	F. Antoniou (CERN, NTUA)	Planned	PhD Thesis
Polarization	F. Zimmermann (CERN)	Informal	
Machine experiments	A. Muller (ANKA)	Planned	ANKA
	A. Streun (PSI), L. Rivkin (PSI – EPFL)	Informal	PSI
	F. Zimmermann (CERN)	Formal	ATF contact
Magnet design	E. Levichev, P. Vobly (BINP)	Formal	

Damping ring activities

Activity	Contacts	Commitment	Comment
Super-conducting wiggler	R. Rossmanith (ANKA), R. Maccaferi (CERN)	Planned	Nb3Sn
	E. Levichev, P. Vobly (BINP)	Formal	NbTi
Radiation absorption	K. Zolotarev (BINP)	Formal	
Pre-damping rings	F. Antoniou (CERN, NTUA)	Formal	
Instrumentation	J. Byrd, S. de Santis (LBNL)	Planned	
	T. Lefevre (CERN)	Formal	
RF design	E. Jensen, A. Grudiev (CERN)	Planned	
	V. Serriere (ESRF)	Informal	
Harmonic cavities	S. De Santis (LBNL)	Informal	
Injection/Extraction	T. Fowler, M. Barnes (CERN)	Formal	
Alignment	J.P. Quesnel (CERN)	Planned	
Stabilization	C. Hauviller (CERN)	Planned	
Feed-back	To be confirmed		

Damping ring activities

Collective effects: G. Rumolo

Activity	Contacts	Commitment	Comment
e-cloud / ions	G. Rumolo (CERN), W. Bruns	Formal	
	M. Pivi (SLAC)	Planned	
Chamber coating	P. Chiggiato (CERN), R. Kersevan (ESRF)	Planned	Cut by EUCARD
Space-charge	D. Quatraro (CERN), E. Levichev (BINP)	Formal	
Impedances	A. Wolski, M. Korostelev (Cockcroft Institute)	Planned	
Instabilities	G. Rumolo , D. Quatraro (CERN)	Formal	
Vacuum design	To be confirmed		

36 contact persons from CERN(19), BINP(4), Cockroft(2), ESRF(2), SLAC(1), LBNL (2), ANKA(2), PSI(2), MPI(1), Private(1)

CLIC/ILC DR common issues

S. Guiducci (INFN-LNF)

- Intense interaction between ILC/ CLIC in the community working on the DR crucial issues: ultra low emittance and e-cloud mitigation.
- Common WEBX collaboration meetings already organized for CESRTA, ILC and CLIC DR (inscribe yourself in the mailing list)
- It is very important to strengthen the collaboration and include also other beam dynamics and technical aspects.

	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^{-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

Summary

- Detailed 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 protection
  - Collective effects evaluation including electron cloud and fast ion instability
- Lattice revision with respect to space and magnet parameters
- Parameter scan for conservative beam emittances for 500GeV collider
- Active collaboration with ILC, test facilities, B-factories, synchrotron light sources and other interested institutes
- Critical items for the performance of the damping rings
  - Super-conducting wigglers
  - E-cloud and fast ion instability
  - Low emittance tuning
  - Intra-beam scattering