CLIC Workshop 2008

CLIC damping rings overview

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October 15th, 2008

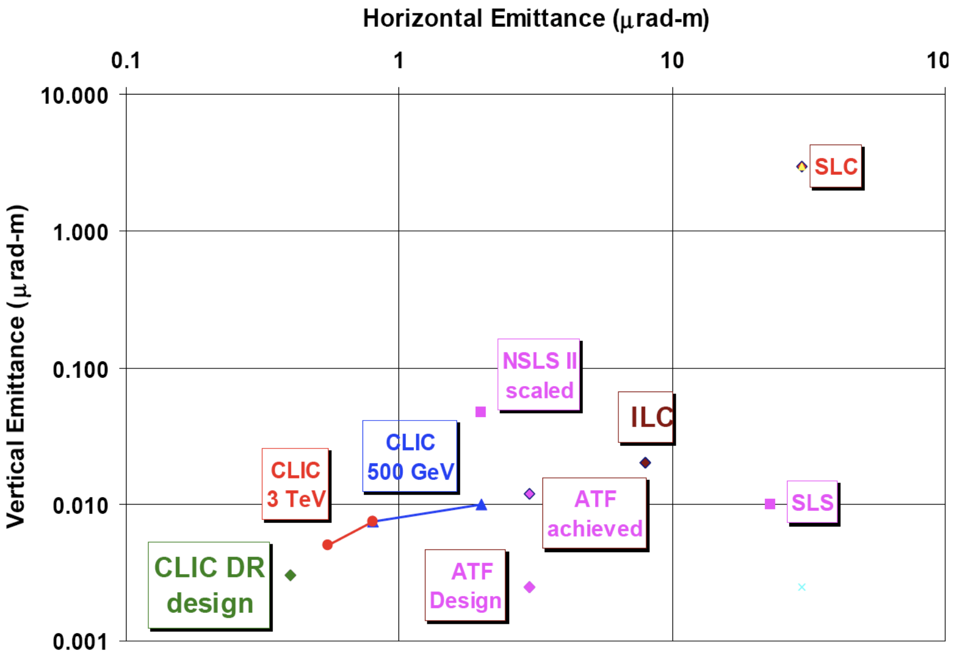
Outline

- 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
- Chromaticity correction and non-linear dynamics
- Low emittance tuning in the presence of coupling (tolerances)
- e-cloud and other collective effects (IBS)
- Parameter scan for damping rings
- Diagnostics
- CLIC DR activities
- Summary

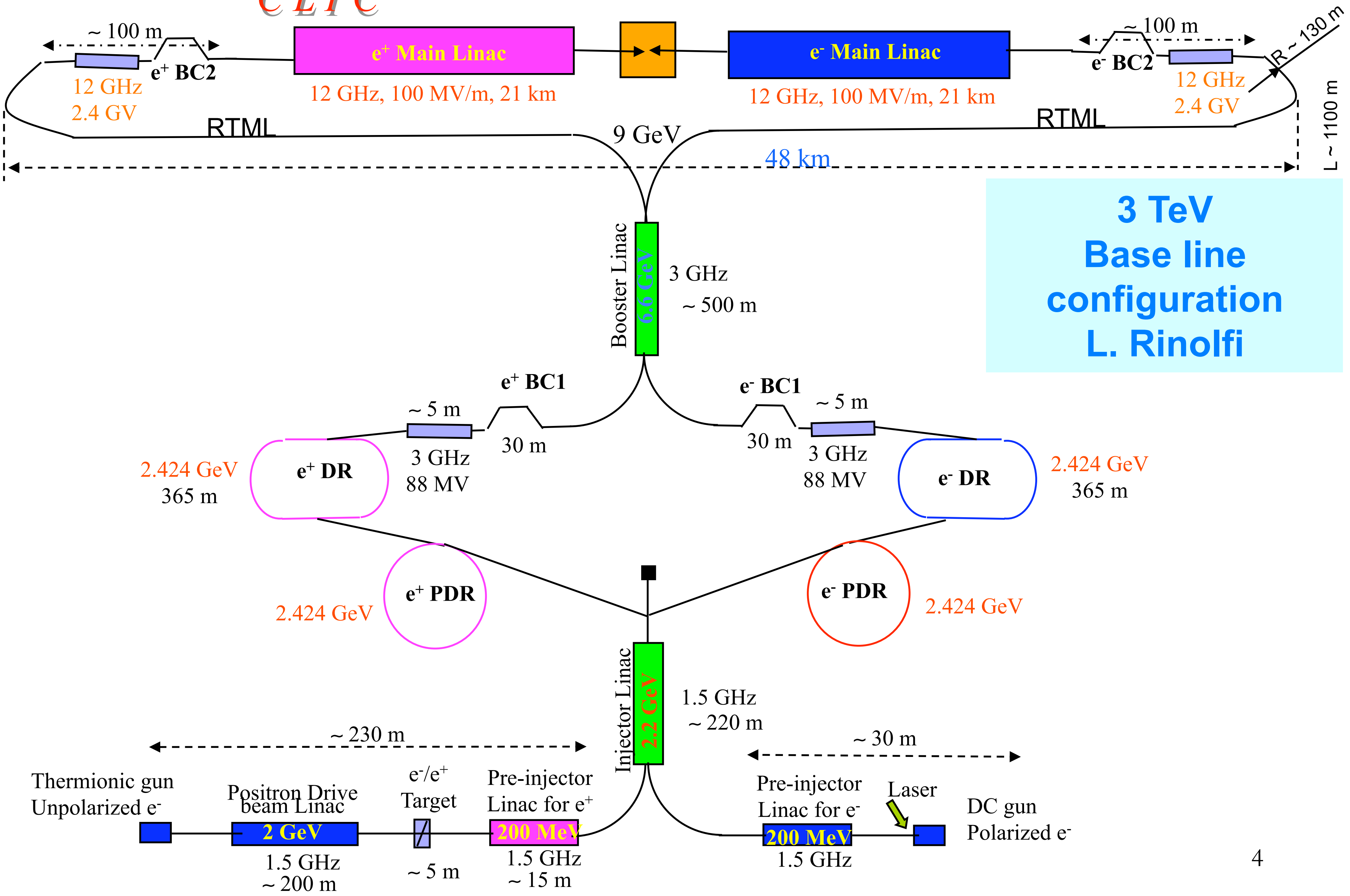
Damping ring design goals



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

- Ultra-low emittance + high beam polarisation cannot be produced by conventional particle sources:
  - 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, fast ion instability) 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

Injector complex



~ 100 m

e^+ BC2

12 GHz
2.4 GV

e^+ Main Linac

12 GHz, 100 MV/m, 21 km

e^- Main Linac

12 GHz, 100 MV/m, 21 km

~ 100 m

e^- BC2

12 GHz
2.4 GV

R ~ 130 m

L ~ 1100 m

RTML

RTML

9 GeV

48 km

Booster Linac

6.6 GeV

3 GHz
~ 500 m

e^+ BC1

~ 5 m

30 m

3 GHz
88 MV

e^- BC1

~ 5 m

30 m

3 GHz
88 MV

2.424 GeV
365 m

e^+ DR

e^- DR

2.424 GeV
365 m

2.424 GeV

e^+ PDR

e^- PDR

2.424 GeV

Injector Linac

2.2 GeV

1.5 GHz
~ 220 m

~ 230 m

Thermionic gun
Unpolarized e^-

Positron Drive
beam Linac

2 GeV

1.5 GHz
~ 200 m

e^-/e^+
Target

~ 5 m

Pre-injector
Linac for e^+

200 MeV

1.5 GHz
~ 15 m

~ 30 m

Pre-injector
Linac for e^-

200 MeV

1.5 GHz

Laser

DC gun
Polarized e^-

3 TeV
Base line
configuration
L. Rinolfi

DR parameters evolution

- 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		312
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

CLIC Pre-damping rings

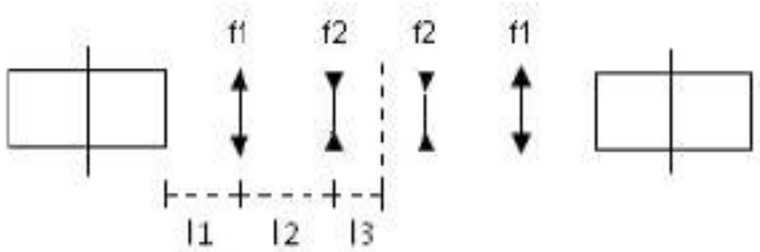
- Most critical the e^+ PDR
  - ☐ Injected e^+ emittance ~ 2 orders of magnitude larger than for e^-, i.e. aperture limited if injected directly into DR
- PDR for e^- beam necessary as well
  - ☐ A "zero current" linac e^- beam (no IBS) would need ~ 17ms to reach equilibrium in DR, (very close to repetition 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)

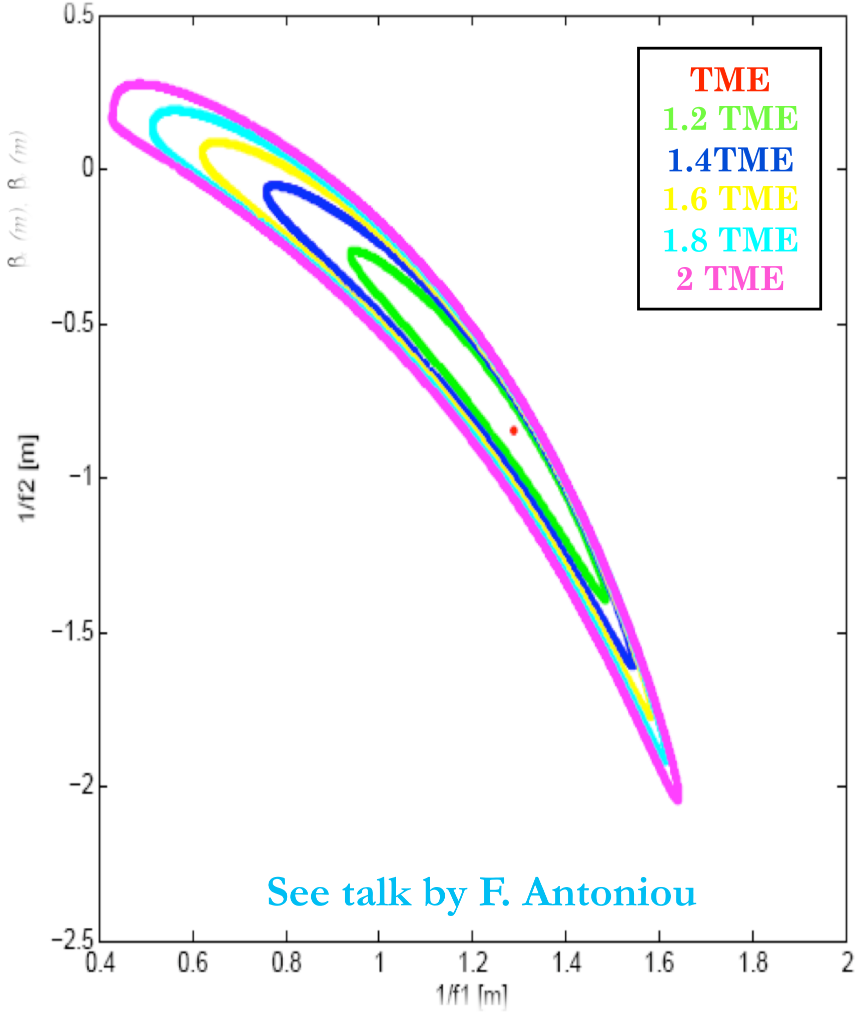
PDR Extracted Parameters	**CLIC**	**NLC**
Energy [GeV]	2.424	1.98
Bunch population [10^9]	4.1-4.4	7.5
Bunch length [mm]	10	5.1
Energy Spread [%]	0.5	0.09
Hor. Norm. emittance [nm]	63000	46000
Ver. Norm. emittance [nm]	1500	4600

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 x 10^3	9.3 x 10^6

See talks by L. Rinolfi, A. Vivoli and F. Zimmermann

Analytical solution for TME cells





See talk by F. Antoniou

- For a general TME cells the focal lengths of the quads (under thin lens approximation) can be written

$$f_1 = \frac{L_d(2(l_1+l_2)+L_d)+2(-\eta_s+\eta_x^{cd})\rho}{l_2(2l_1L_d+L_d^2+2\eta_x^{cd}\rho)}$$

$$f_2 = \frac{2l_1L_d+L_d^2-2\eta_s\rho+2\eta_x^{cd}\rho}{2l_2\eta_s\rho}$$

with η_s the dispersion function at the center of the cell (function of dipole parameters and drifts)

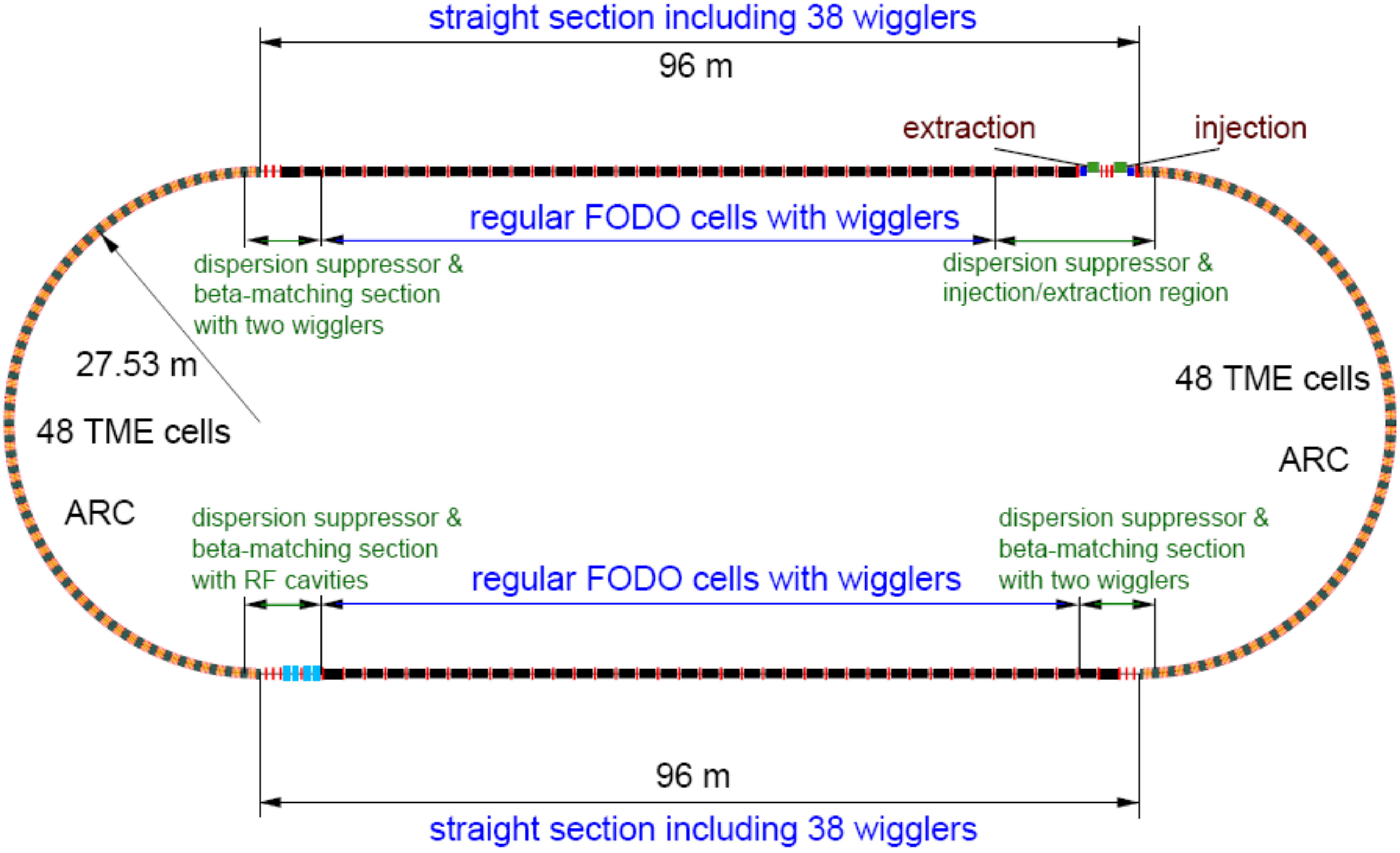
- All optics **uniquely** defined, parameterized by the drifts
- Only certain solutions are stable in both planes
- Guide to design optimal CLIC (P)DRs

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

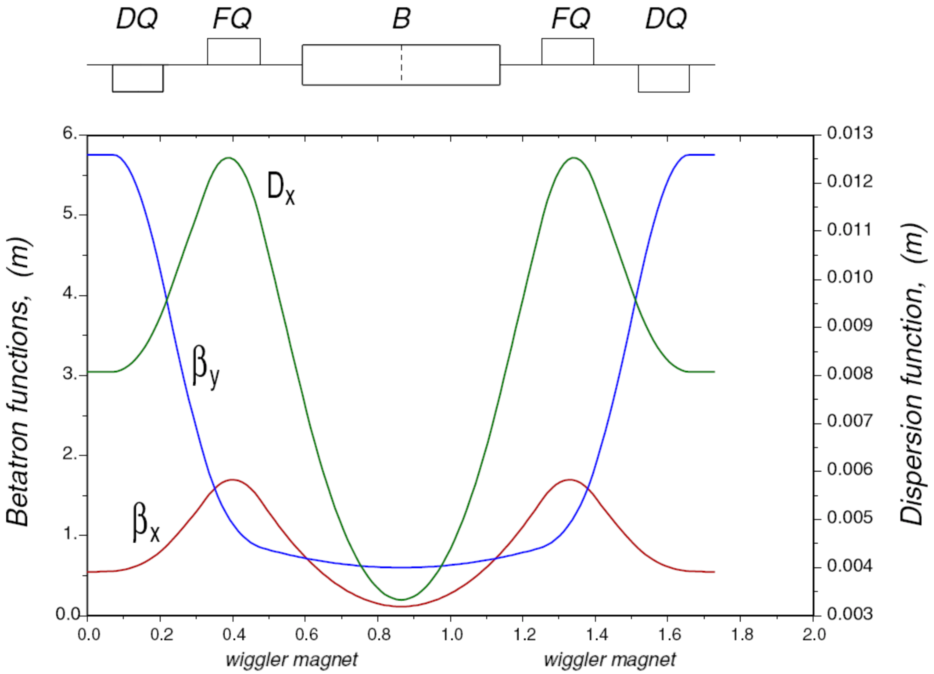
CLIC damping ring layout

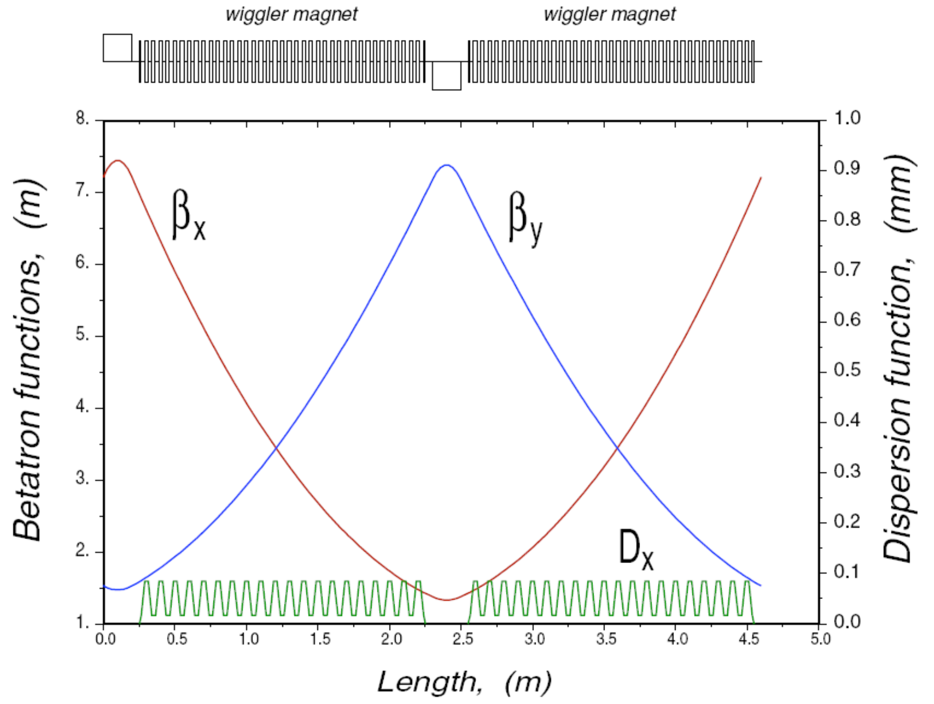


M. Korostelev, PhD thesis, EPFL 2006

Arc and wiggler cell

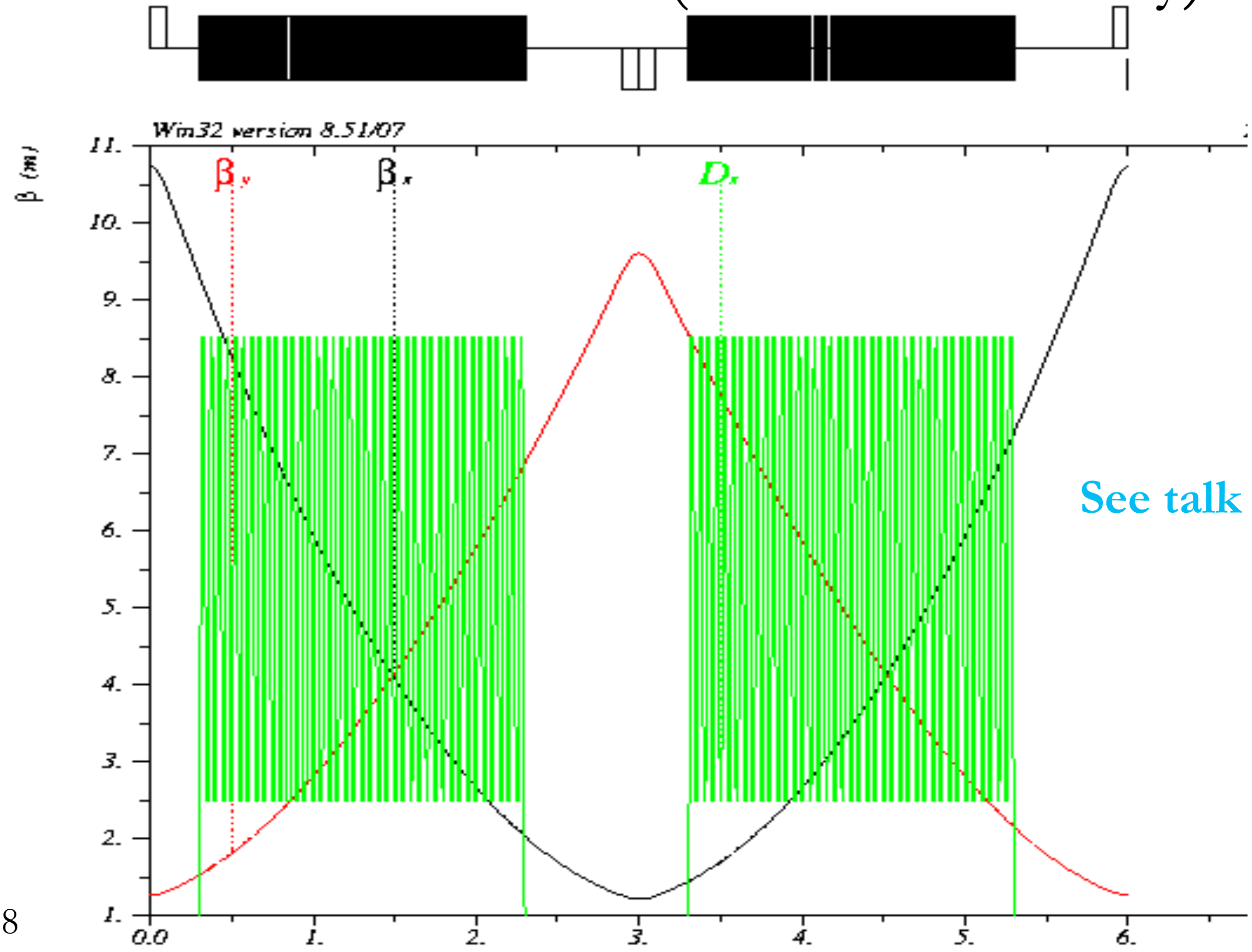
- TME arc cell chosen for compactness and efficient emittance minimisation over Multiple Bend Structures used in light sources
  - ☐ Large phase advance necessary to achieve optimum equilibrium emittance
  - ☐ Very low dispersion
  - ☐ Strong sextupoles needed to correct chromaticity
  - ☐ Impact in 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 wiggler cell

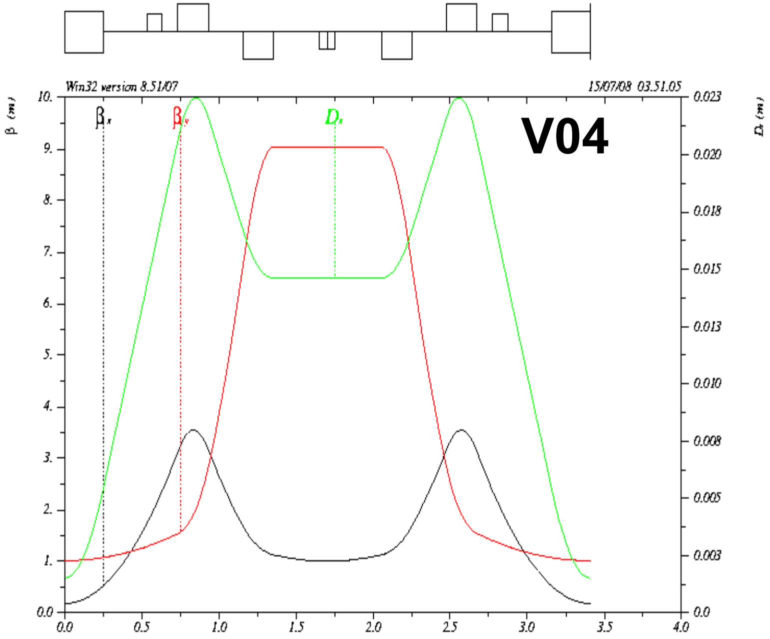
- Added space between wiggler and downstream quadrupoles for accommodating absorbers
- 30% increase of the wiggler section length
- Slight increase of beta maxima (and chromaticity)

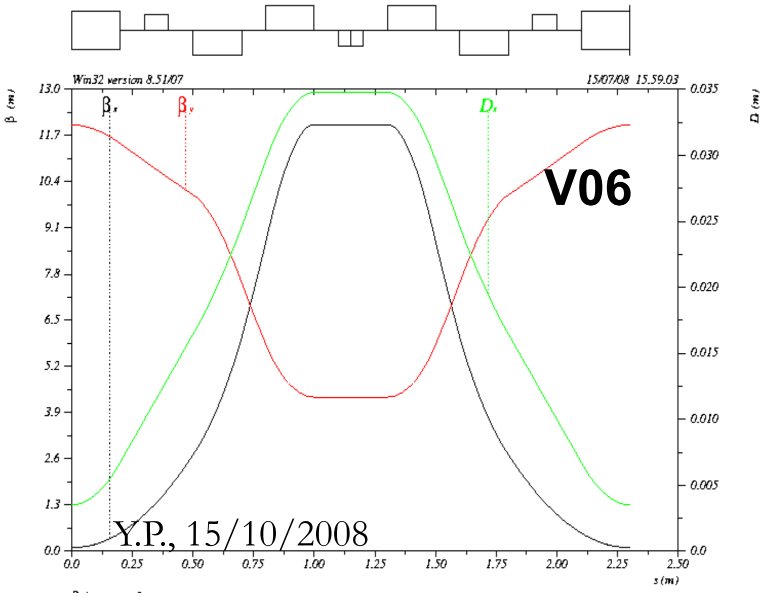


See talk of K. Zolotarev

Proposed arc cells

See talk of K. Zolotarev

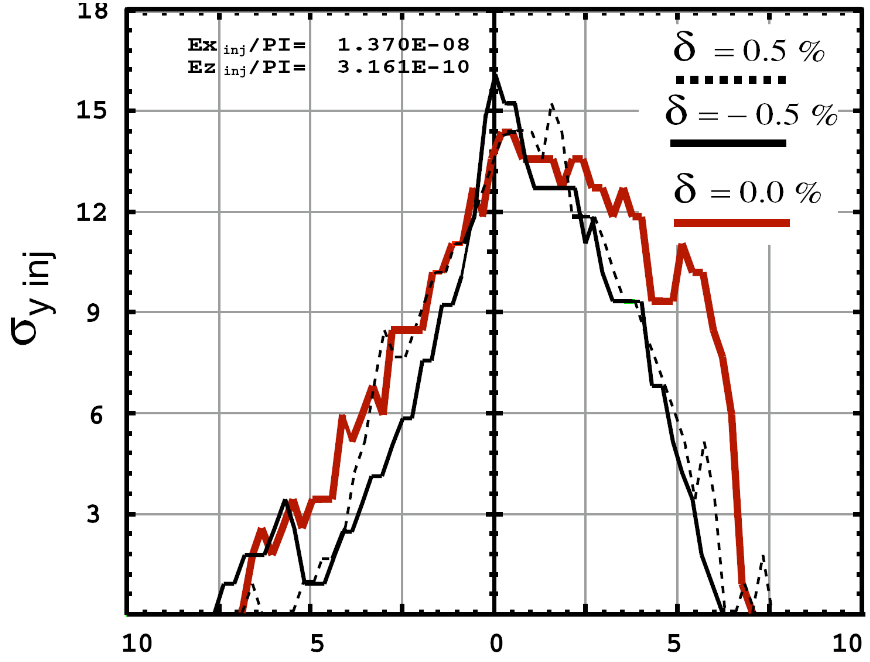


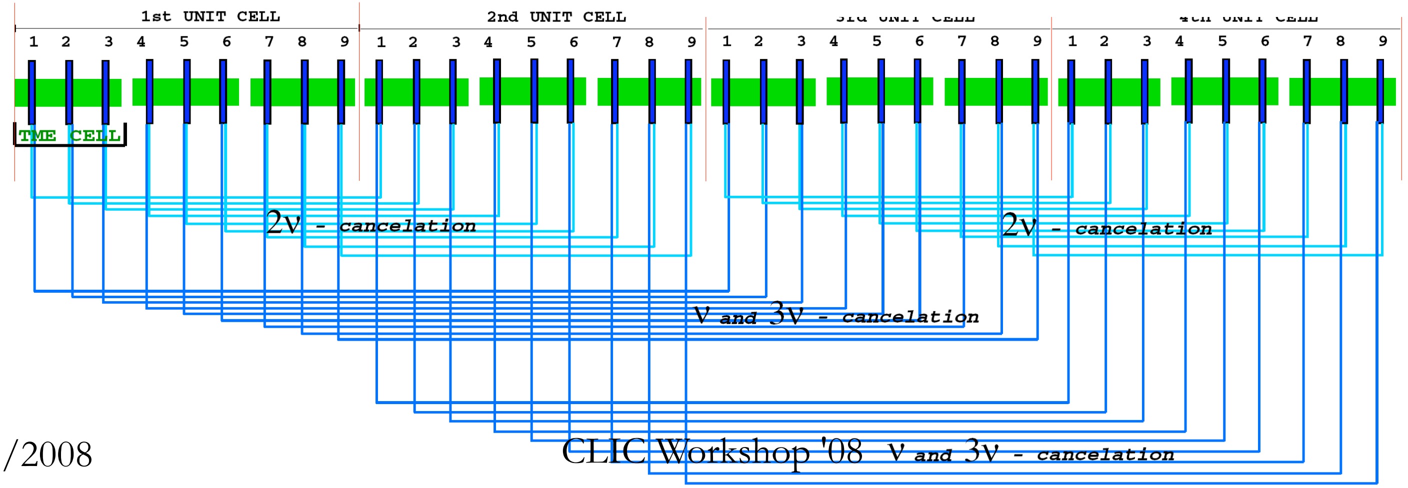


Structure version	Original	V04	V06
Energy [GeV]	2.424		
Circumference [m]	365.21	534	493.05
Coupling	0.0006		
Losses per turn [MeV/turn]	3.8600	3.9828	3.9828
RF voltage [MV]	4.38	4.35	4.601
Natural chromaticity x / y	-103 / -136	-186/ -118	-148.8 / -79.0
Compaction factor	8.0213E-05	4.56E-05	6.4427E-05
Damping time x / s [ms]	1.53 / 0.76	2.17 / 1.09	1.99 / 1.01
Dynamic aperture a/σ_{inj} x / y	±3.5 / 6	±1.5 / 5	±12 / 50
Number of arc cells	100		
Number of wigglers	76		
Cell length [m]	1.729	2.729	2.300
Dipole length [m]	0.544944	0.4	
Bend field [T]	0.93	1.27	
Bend gradient [1/m^2]	0	0	-1.10
Max. Quad. gradient [T/m]	220	107.7	60.3
Max. Sext. strength [T/m^2]*10^3	80	24.1	6.59
Phase advance x / z	0.581 / 0.248	0.524 / 0.183	0.442 / 0.045
Bunch population, N*10^9	4.1		
IBS gain factor	5.1831	3.62	2.89
Normalized Emittance [nm*rad]	449	439.26	428.4
Bunch length [mm]	1.402	1.450	1.380
Longitudinal emmitance [eVm]	5339	5694	5188

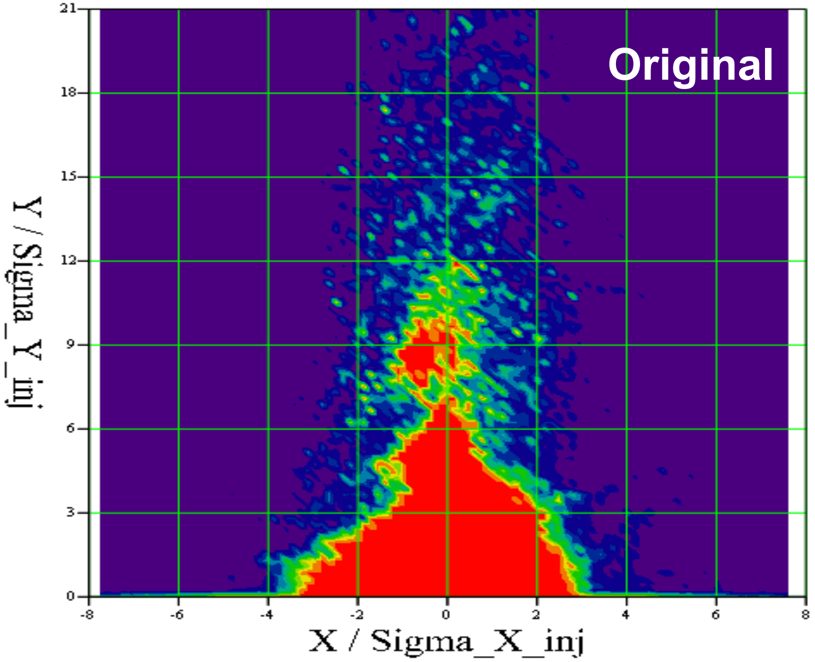
Non-linear dynamics

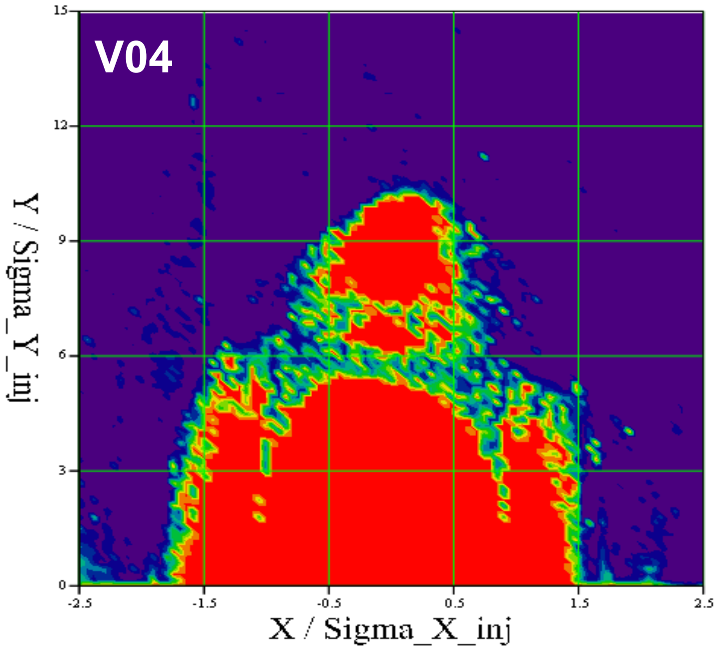
- Two sextupole schemes
  - ☐ 2 and 9 families of sextupoles
- With the 9 family scheme tha Dynamic aperture is $9\sigma_x$ in the horizontal and $14\sigma_y$ in the vertical plane (comfortable for injection)



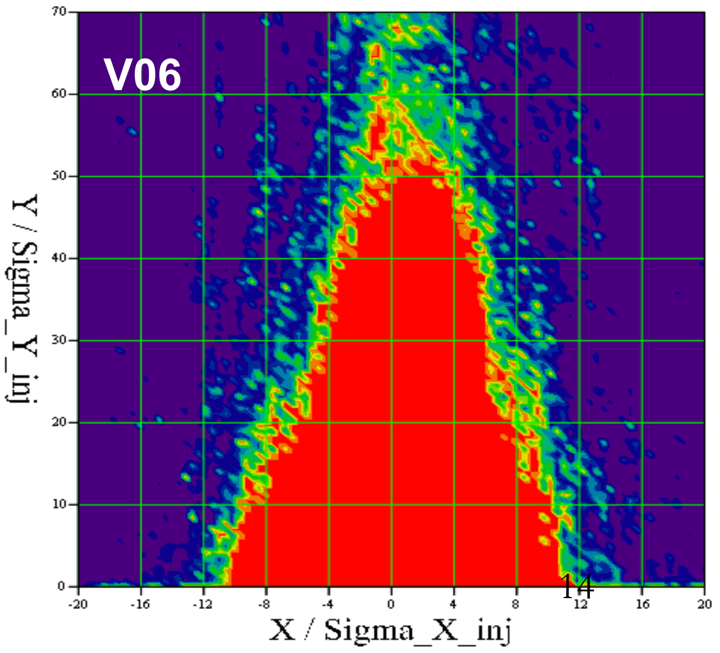


Dynamic aperture





- 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, ...)

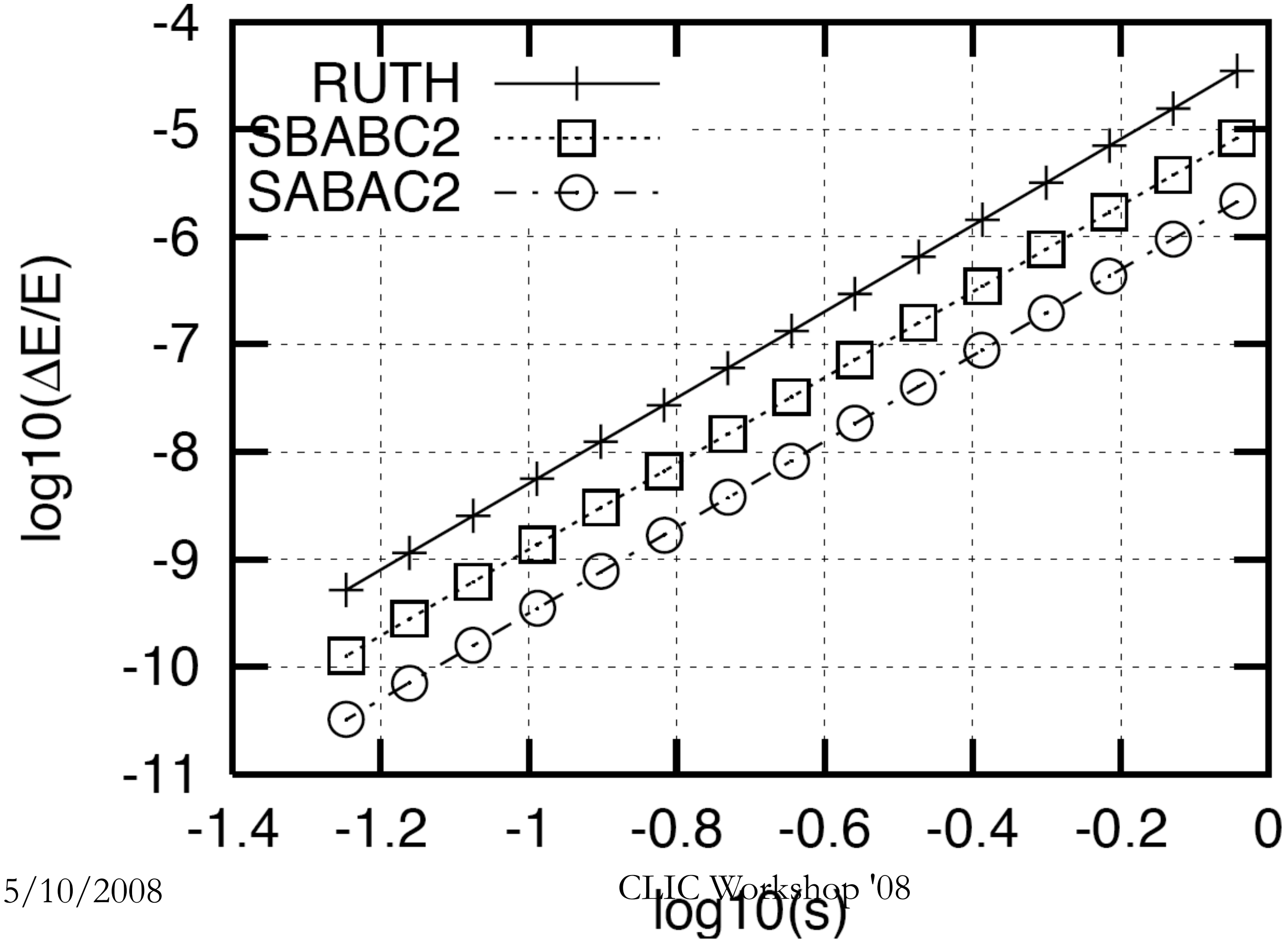


S. Sinyatkin, et al. 2008

SABA$_2$ integrator performance

- The accuracy of the SABA$_2$C was proved an order of magnitude more precise than the Forest-Ruth 4th order integrator

Nadolski and Laskar, EPAC 2002



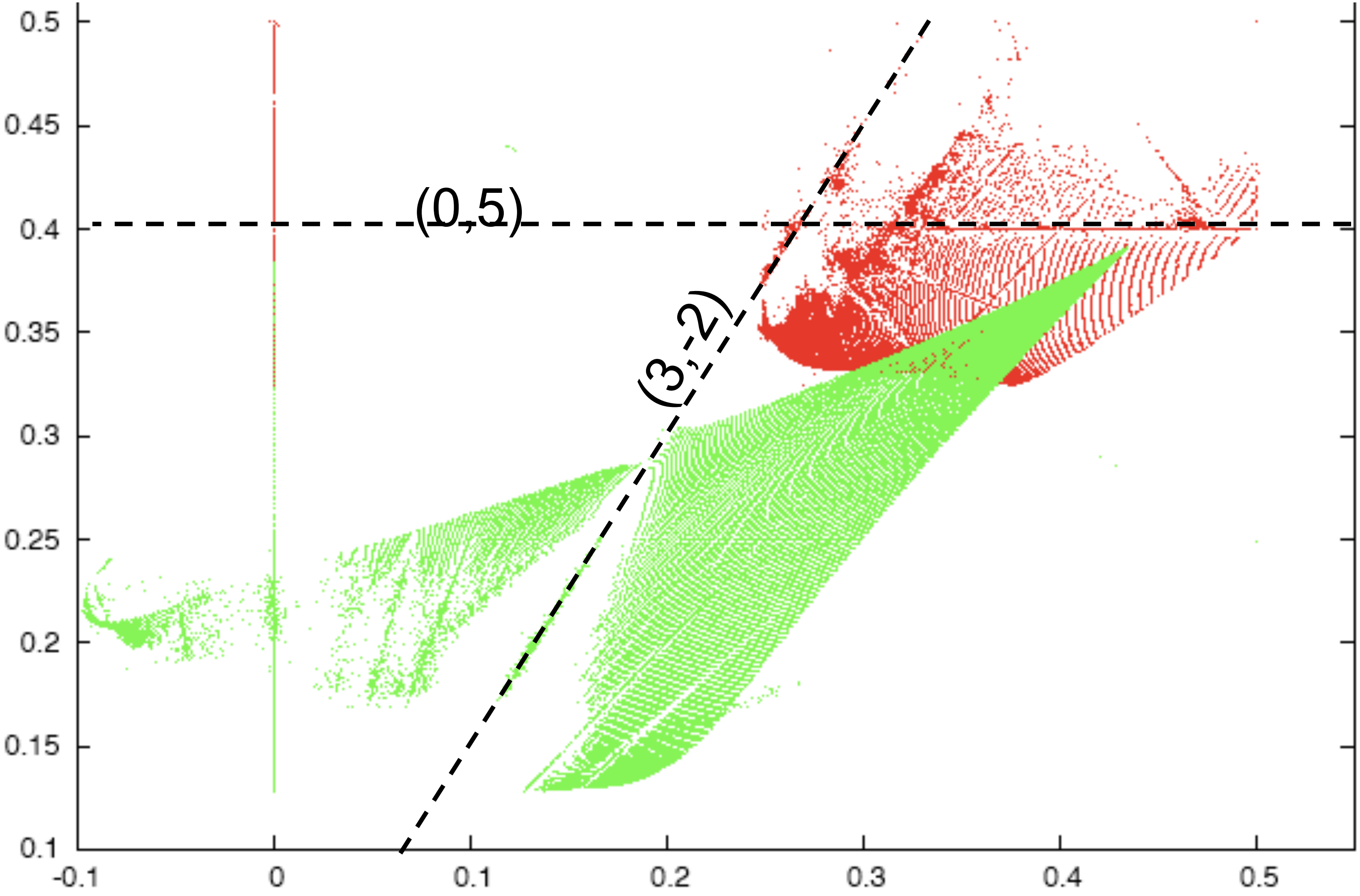
Application to the ESRF

C. Skokos, et al. 2008

- Consider the old ESRF "ideal" lattice, i.e. perfectly symmetric (periodicity of 16) with the only non-linearity coming from the sextupoles
- Integrate the equations of motions with three different methods
  - "Drift-Kick" method by splitting the 0.4m sextupoles in a drift + kick + drift
  - Splitting the sextupoles in 10*(drift + kick) + drift
  - Using the $\mathrm{SABA}_2\mathrm{C}$ symplectic integrator
- Produce frequency maps by using Laskar's NAFF algorithm and compare

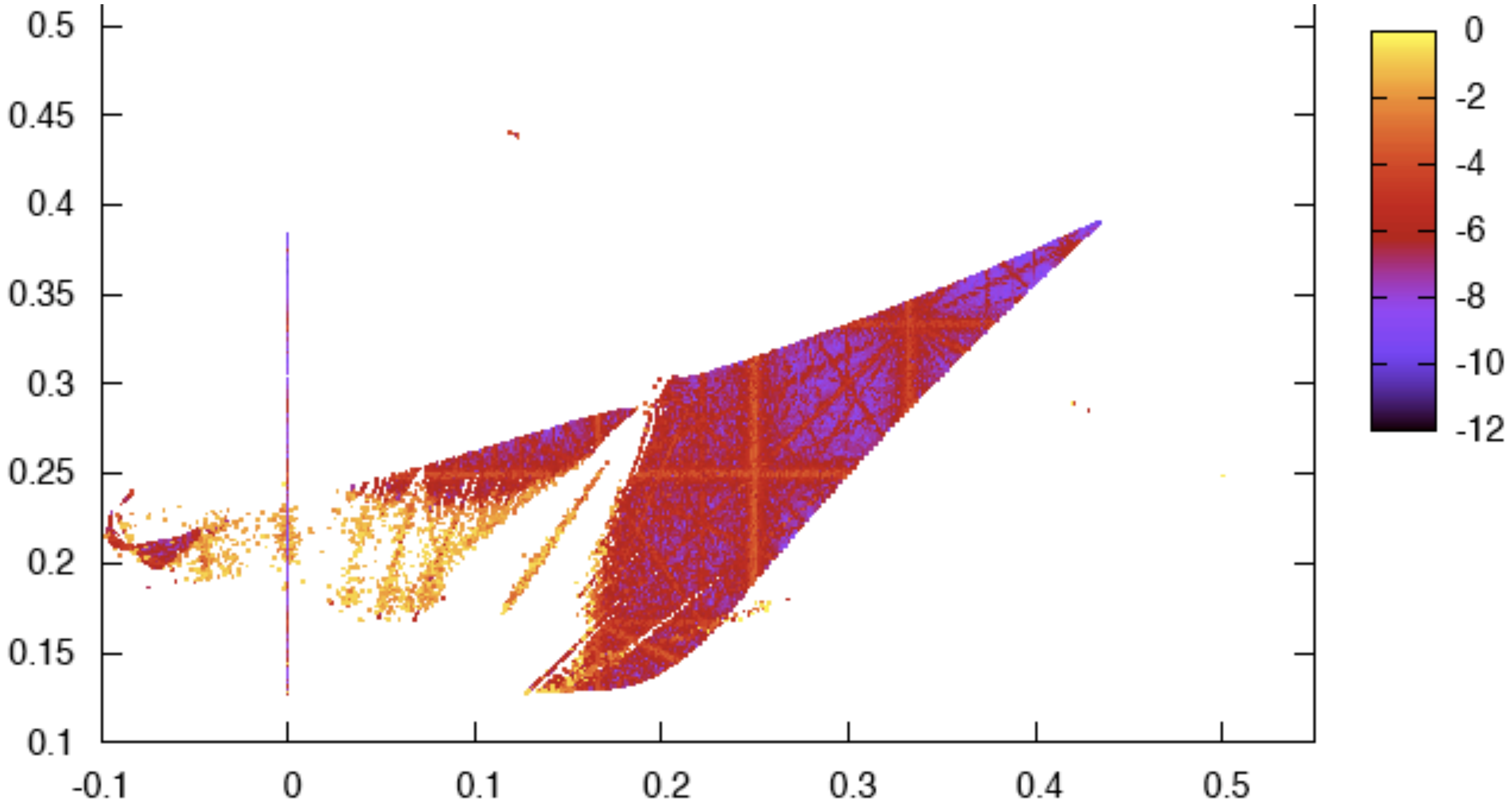
Frequency map I

- Comparison between frequency maps produced by "drift-kick" 1 kick versus 10 kicks

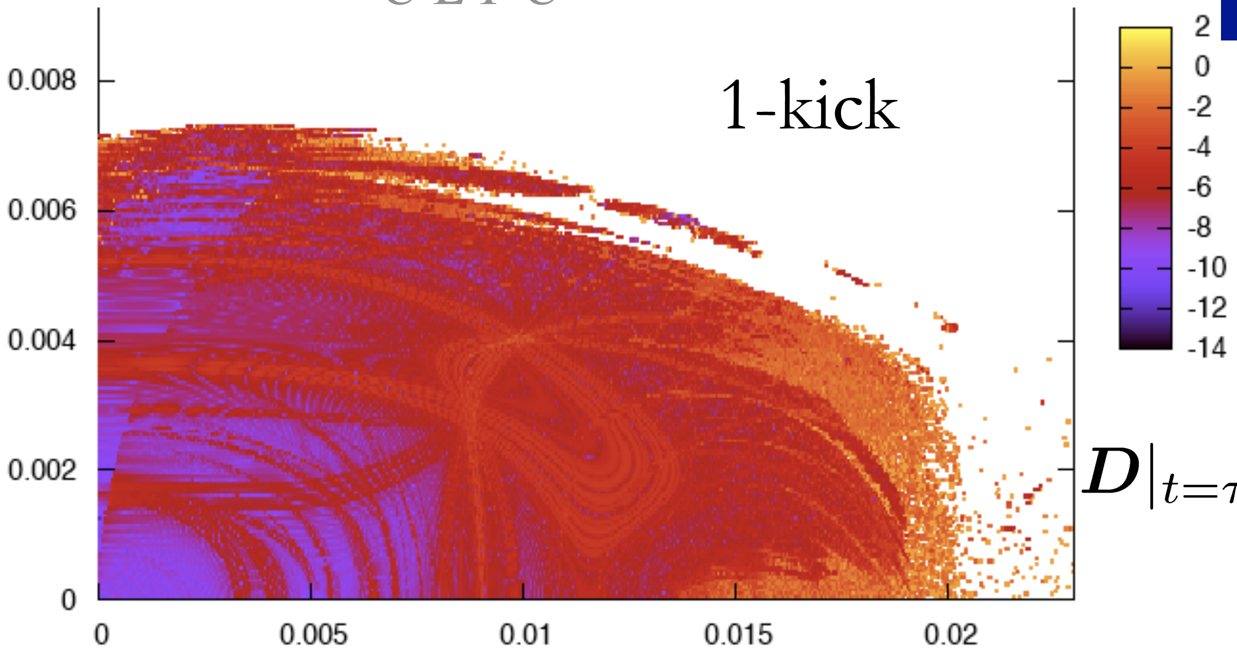


Frequency map II

- Frequency map using the SABA$_2$C symplectic integrator reproduces the "10-kick" case



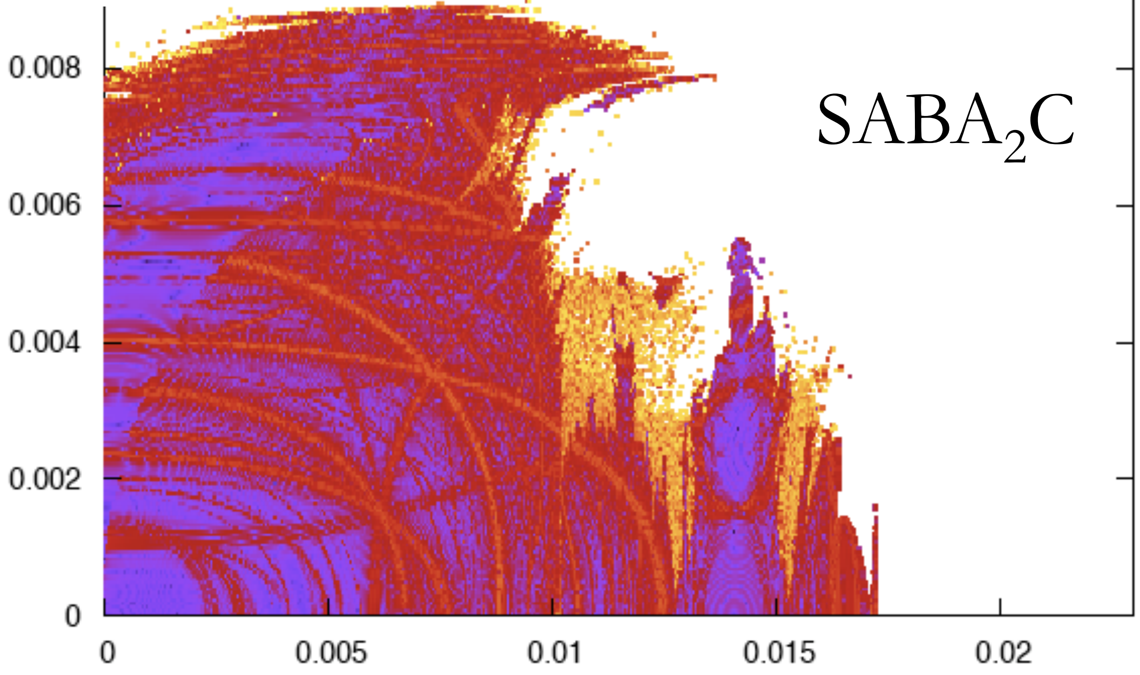
Diffusion maps



- Colour coding following the logarithm of the diffusion vector amplitude

$$\boldsymbol{D}|_{t=\tau} = \boldsymbol{\nu}|_{t\in(0,\tau/2]} - \boldsymbol{\nu}|_{t\in(\tau/2,\tau]}$$

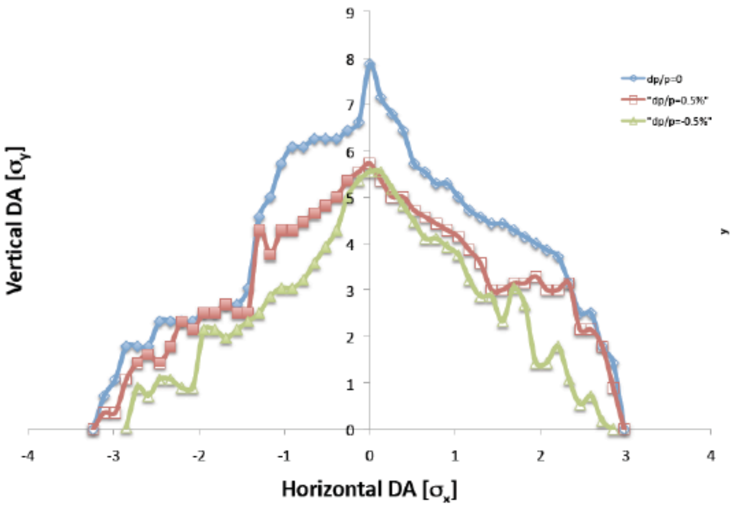
- Diffusion map using the SABA$_2$C symplectic integrator shows lower horizontal and slightly higher vertical DA than 1-kick integrator

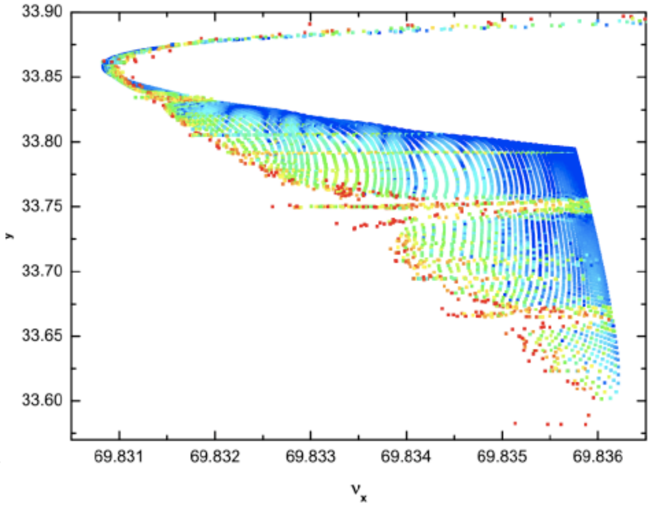


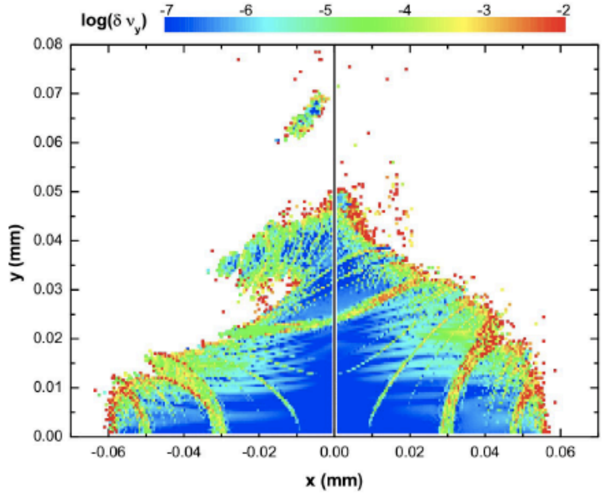
C L I C

Frequency maps

Ch. Skokos and Y. Papaphilippou, EPAC08

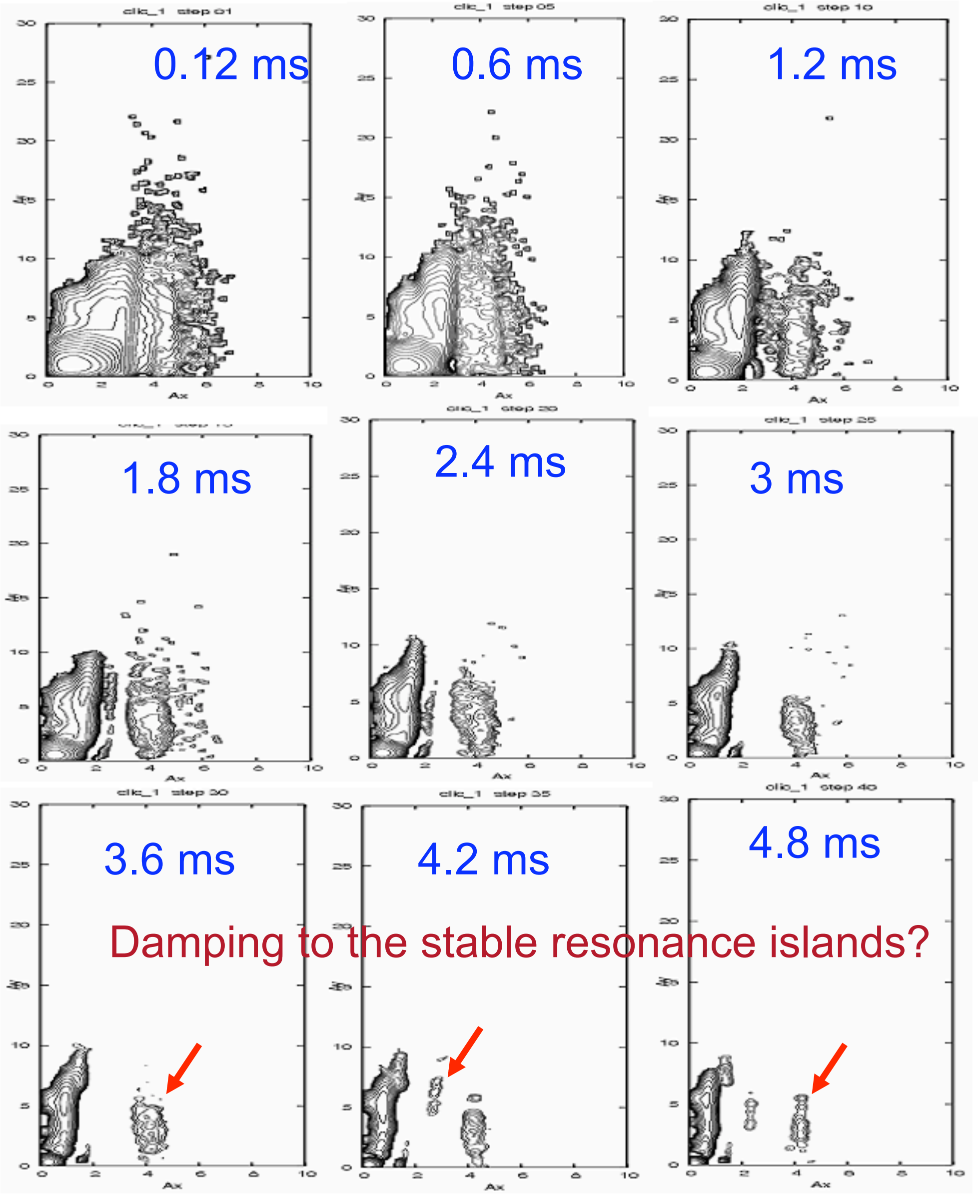




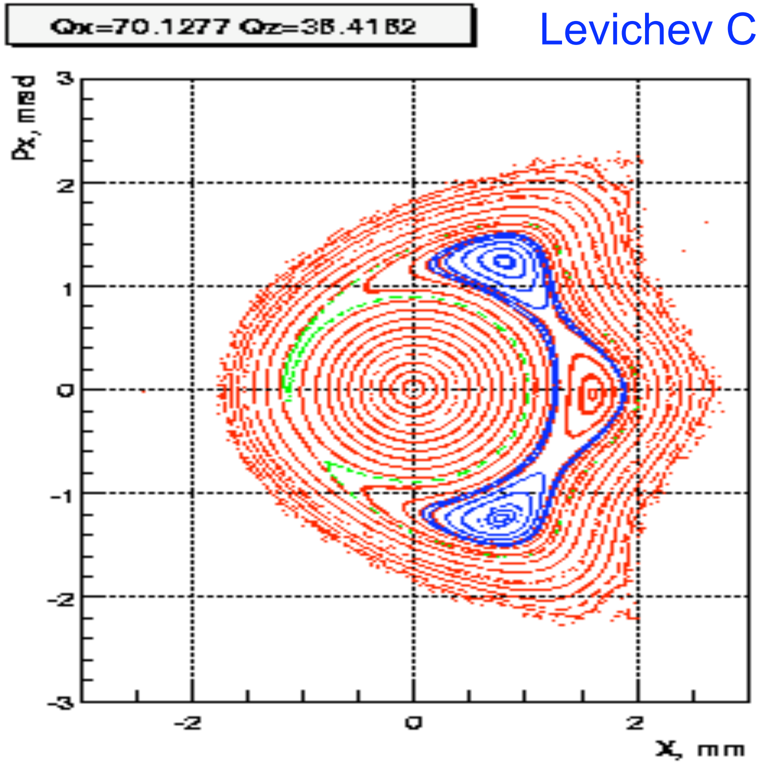


- Only sextupole non-linearity considered (two families)
- Small DA confirmed by both tracking with symplectic integrator SABA$_2$C and MADX-PTC
- First on-momentum frequency map reveals wide vertical tune spread and crossing of a multitude of resonances (especially 4th order for present working point)
- 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



Damping to the stable resonance islands?



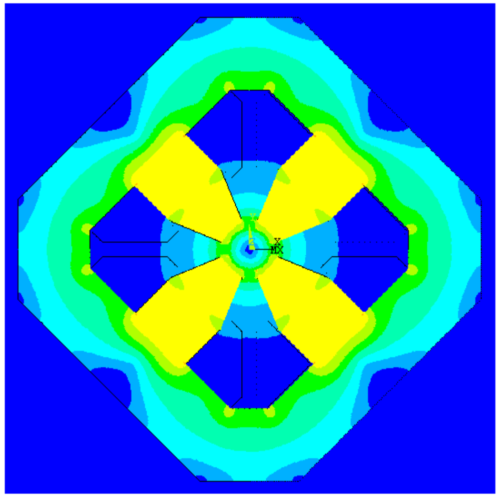
Levichev CLIC07

- 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

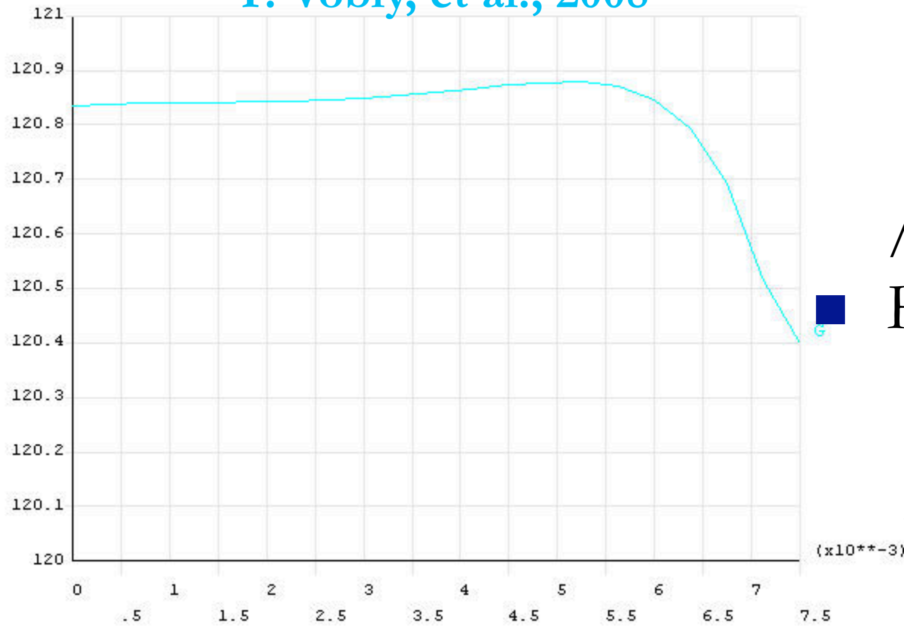
Arc magnet design

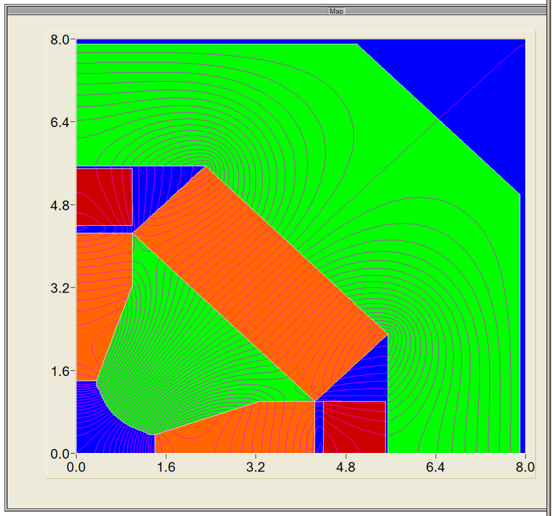
P. Vobly, et al., 2008

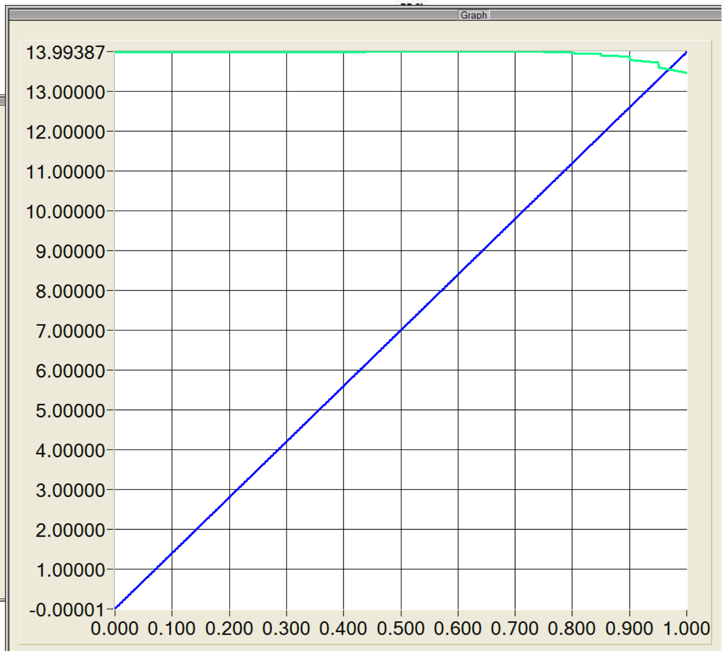
- High gradient quadrupole model using conventional technology (120 T/m, r=10mm)
- Hybrid quadrupole and sextupole designs for even higher field (140-160 T/m and 28 T/m^2)

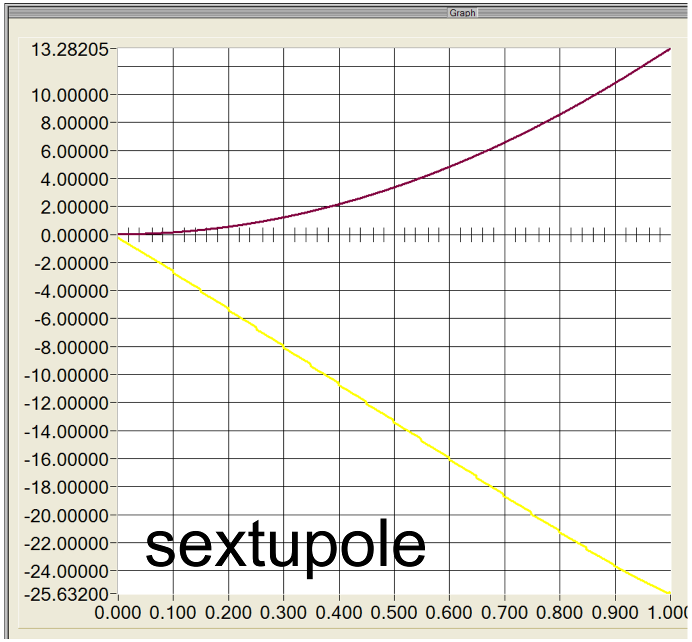


Quadrupoles

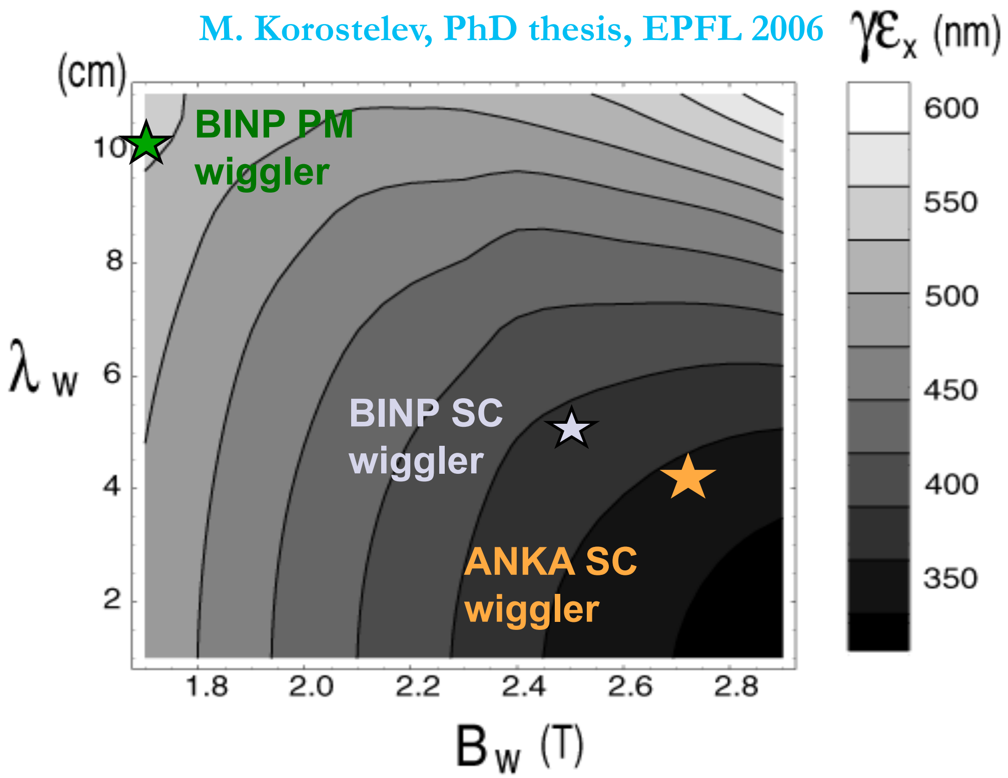








Wigglers' effect with IBS


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

See talks by R. Maccaferri, R. Rossmanith, P. Vobly and K. Zolotarev

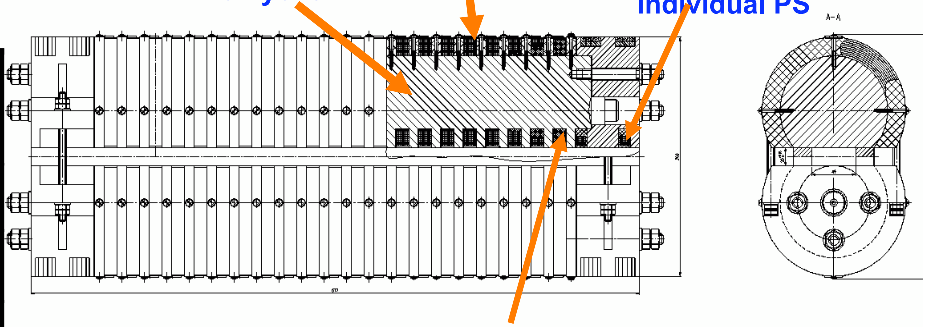
NbTi wiggler design

See talk by P. Vobly

Parameter	CLIC-DR
Energy	2.424 GeV
Beam Current	170 mA

Parameter	BINP wiggler	CERN wiggler
Coils material	NbTi	Nb$_3$Sn
Maximal magnetic field, T	2.5	2.8
Period of wiggler, cm	5	4
Magnetic gap of wiggler, mm	20*	24*
Number of periods	40	50
SR critical energy, keV	9.62	10.8
Deflection parameter	11.7	10.5
SR power, kW	7.90	9.91
VC temperature, K	60 (LN)	4.2 (LHe)
Critical longitudinal power density over VC, W/m	10	1
VC vertical aperture, mm	12	16
Length of wiggler, m	2	2

General view for BINP wiggler prototype



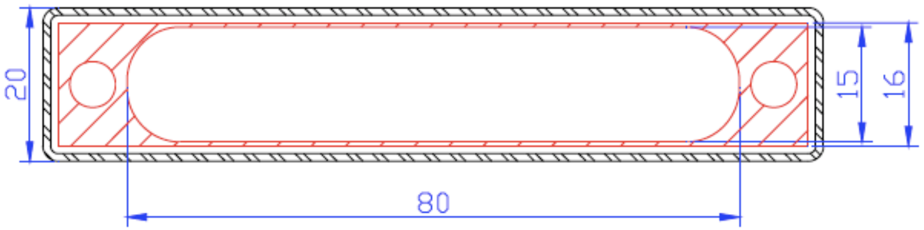
Regular coil

Corrector coils with individual PS

Iron yoke

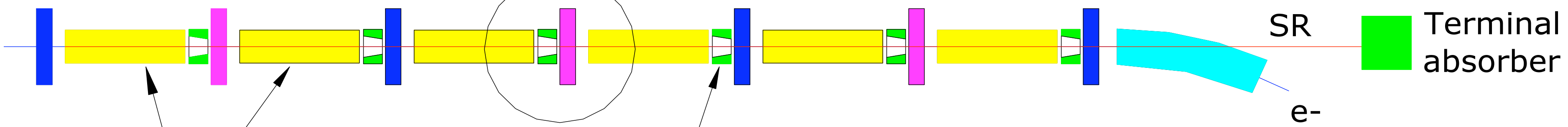
End coils to compensate the first and the second integral

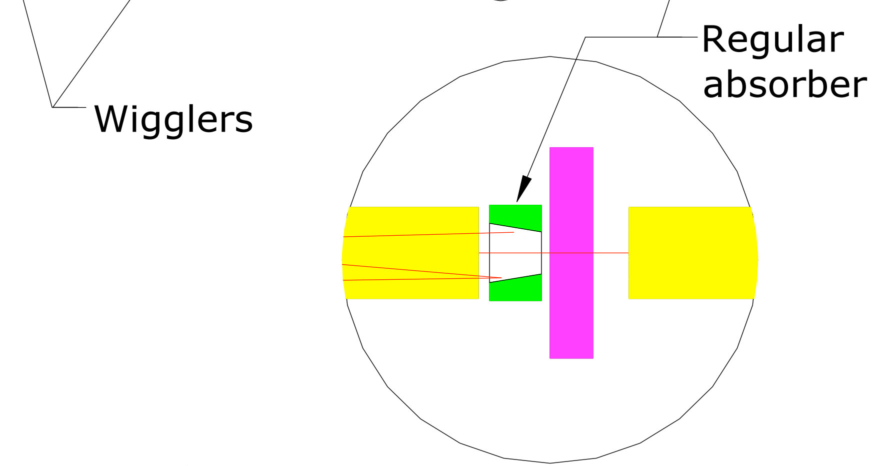
Internal Cu liner with LN temperature protects LHe elements from SR



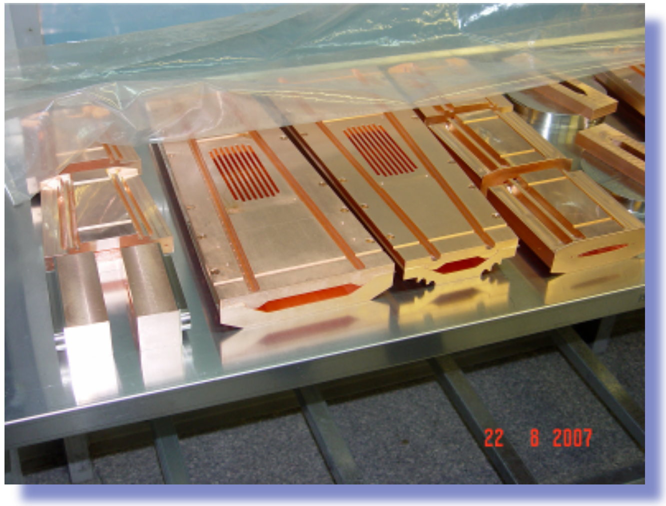
A cryogenic cooler SUMITOMO SRDK 408S2 permits evacuate up to 50 W power from 60 K liner.

Synchrotron radiation absorption

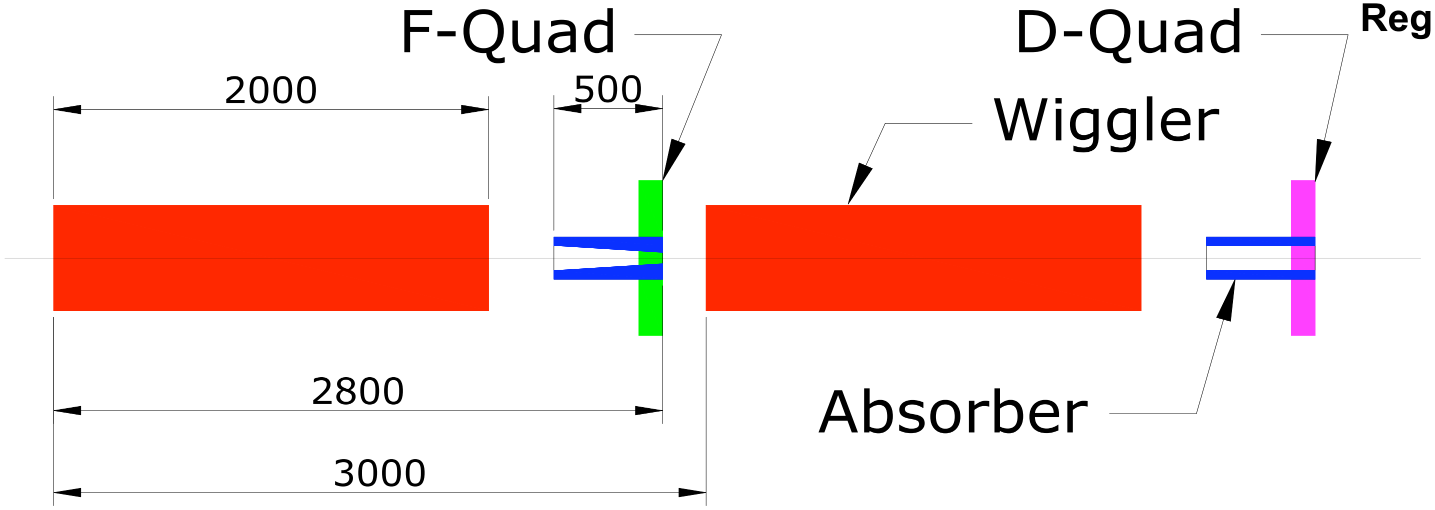




See talk by K. Zolotarev



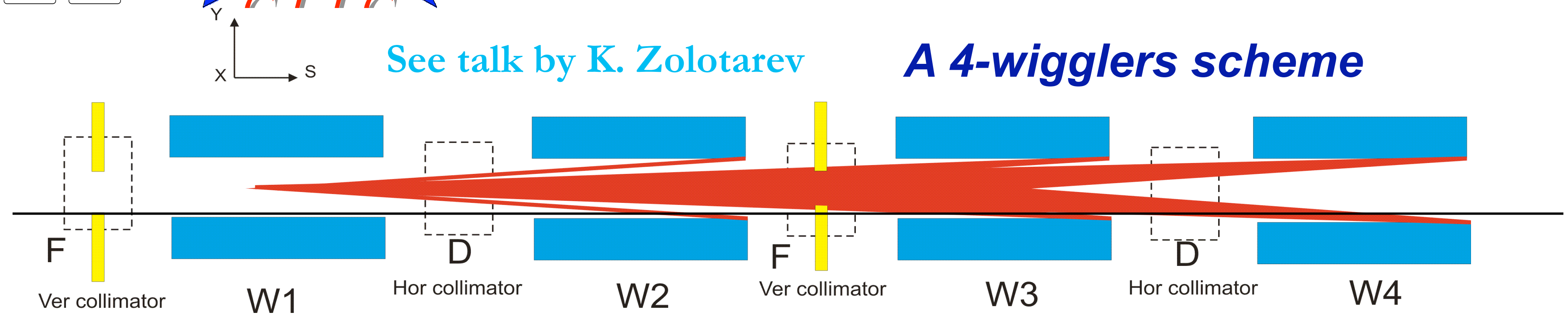
Regular absorbers of 26kW for PETRA-III project



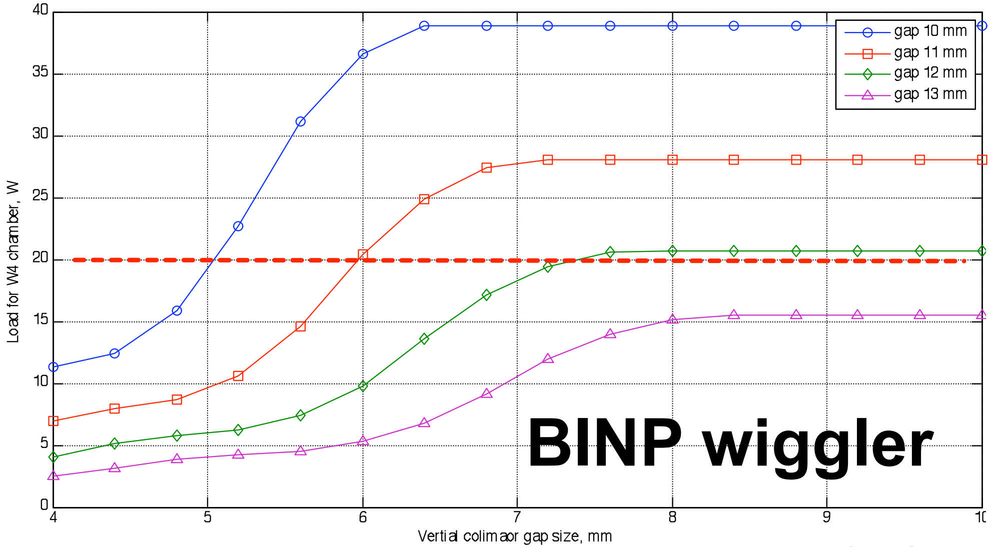
Wiggler gap and vertical collimator size

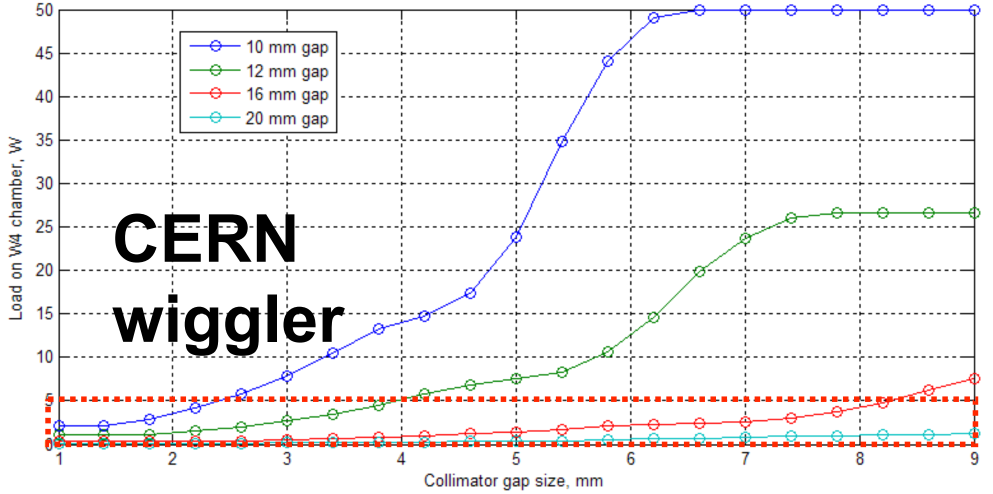
See talk by K. Zolotarev

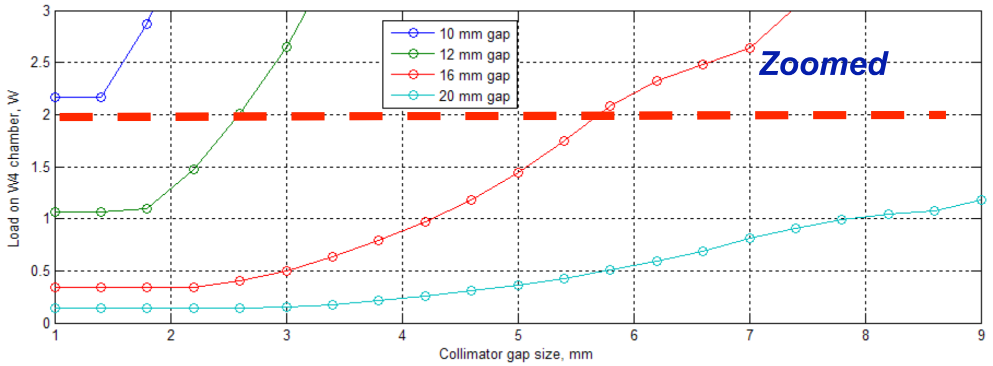
A 4-wigglers scheme



- CERN wiggler more challenging due to 1W/m power limit
- Gap of 13mm for NbTi wiggler and 20mm for Nb3Sn design



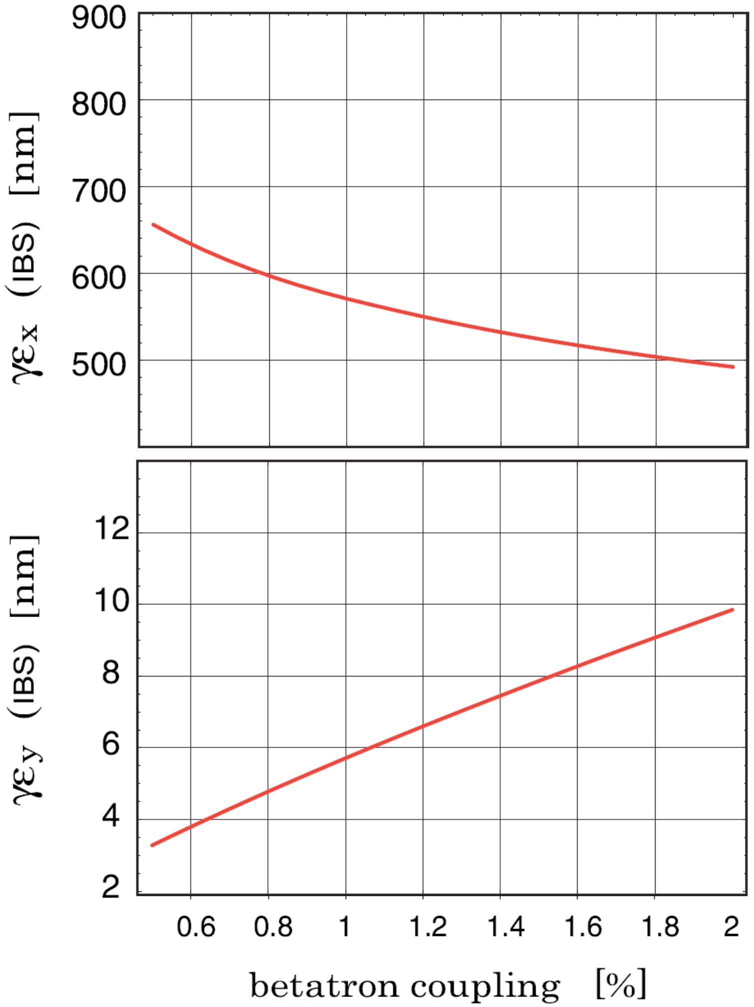




Coupling correction

- Dispersion free steering for 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 DR, vertical dispersion is dominant (0.1% of coupling and 0.25μm of dispersion invariant)
- Effect of wiggler field errors to be included
- Review of linear correction systems for new lattice design
- Experimental low-emittance tuning foreseen @ SLS

M. Kolosterev PhD thesis



Imperfection	σ [unit]
Quadrupole misalignment	90 μm
Sextupole misalignment	40 μm
Quadrupole misalignment	100 μrad
Dipole rotation	100 μrad
BPM resolution	2 μm

e^--cloud effect

- Simulations with ECLOUD revealed importance of the effect in both CLIC and TESLA DRs

D. Schulte, R. Wanzerberg , F. Zimmerman, ECLOUD'04

- Simulations using the FAKTOR2 code confirmed the importance of the effect

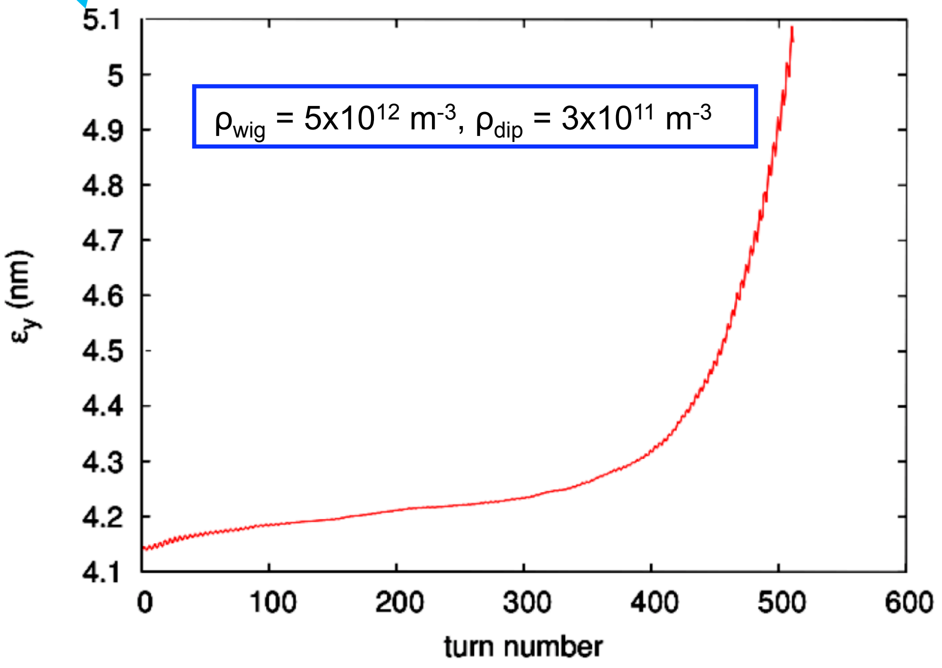
G. Rumolo et al., EPAC08

  - ☐ 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 to be carried out for newest parameter set including 3D photon distribution in wiggler section

See talk by G. Rumolo

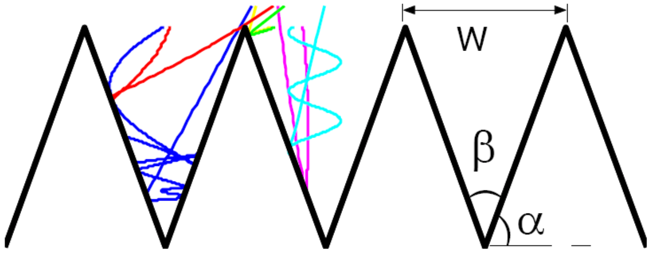
Chambers	PEY	SEY	ρ [10^{12} e^-/m^3]
Dipole	0.000576	1.3	0.04
		1.8	2
	0.0576	1.3	7
		1.8	40
Wiggler	0.00109	1.3	0.6
	0.109	1.3	45
		1.5	70
		1.8	80



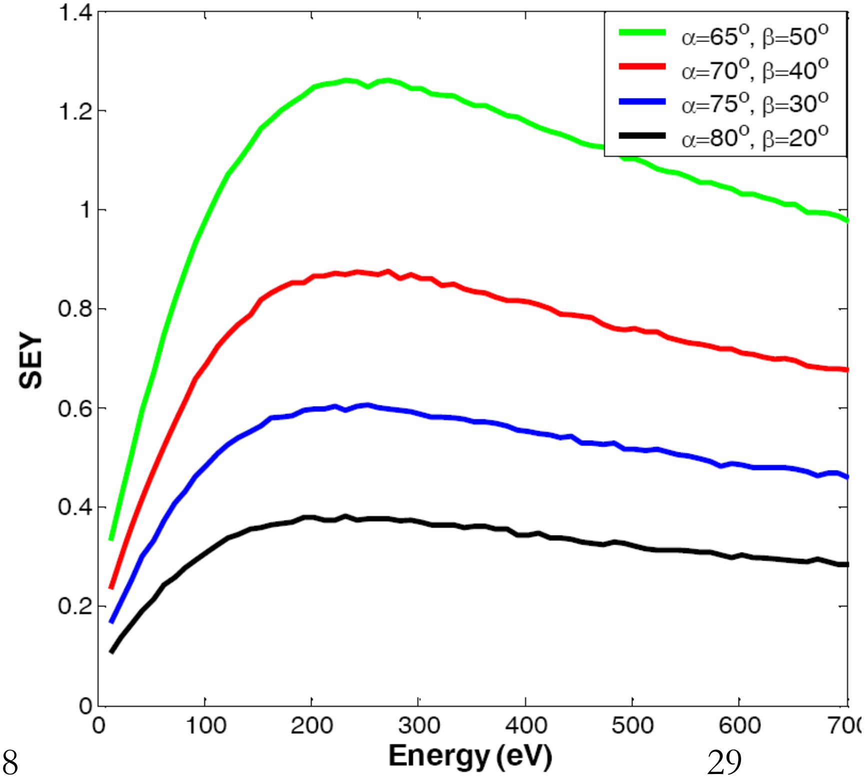
e$^-$-cloud countermeasures

See talks by G. Rumolo and M. Taborelli

- Coating of vacuum chambers by a material (e.g. NEG, CNe) for lowering secondary emission yield (tested in SPS)
- 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

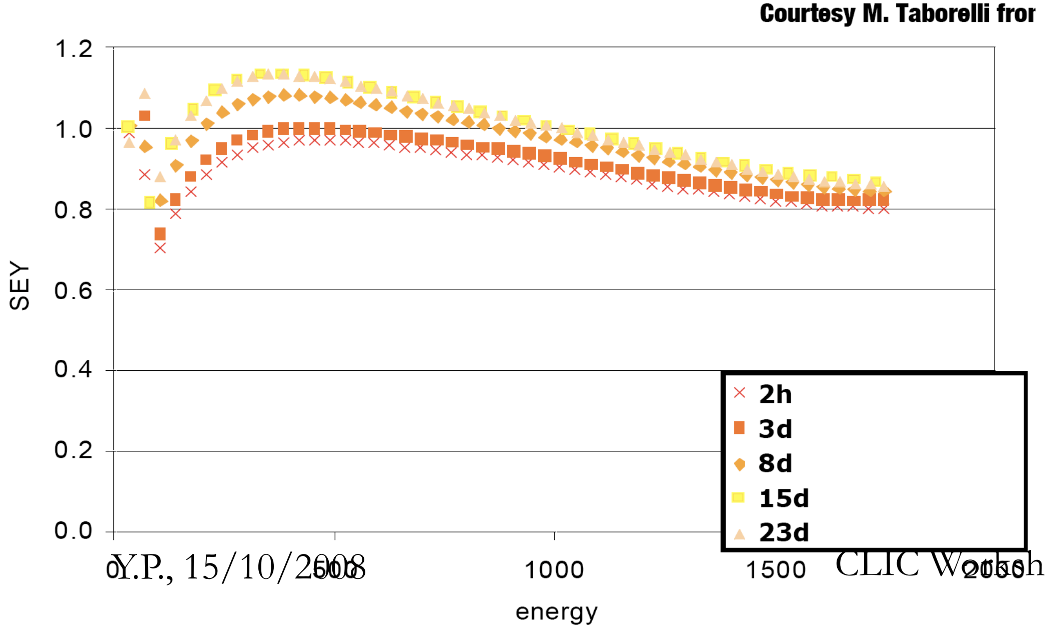


L. Wang et al., PAC2007



courtesy by M. Pivi

SEY of CNe



Other collective effects

See talk by G. Rumolo

- Longitudinal and transverse broad band impedance requirements not too stringent
  - Based on analytical estimates, a few Ohms in longitudinal and MOhms in transverse are acceptable for stability
  - Detailed vacuum chamber design and impedance budget are needed
- Coherent Synchrotron radiation has a minor effect in bunch lengthening
- Vertical incoherent space-charge tune-shift

$$\Delta Q_y = \frac{N_b r_e C}{(2\pi)^{3/2}\gamma^3\sigma_z}\sqrt{\frac{1}{\epsilon_y}} \cdot \langle \frac{\sqrt{\beta_y}}{\sqrt{\beta_x\epsilon_x + D_x^2\sigma_\delta^2} + \sqrt{\beta_y\epsilon_y}} \rangle \simeq 0.188$$

  higher than the acceptable value of 0.1
  - To be taken into account in non-linear dynamics and working point choice
  - Pessimistic estimates from HEADTAIL simulations show a 10% emittance increase
- Fast ion instabilities necessitates vacuum pressure of < 0.1nTorr
- Touschek lifetime large enough compared to store time
- Resistive wall multi-bunch effects are associated to rise times of around 1ms and can be damped with a multi-bunch feedback
- Couple bunch instabilities have to be avoided with HOM free cavities

Intrabeam scattering

See talk by M. Martini

IBS'07
Intra Beam Scattering Mini Workshop

The Cockcroft Institute, Daresbury, UK. 28th - 29th August 2007

- In the case of IBS dominated beams, all lattice parameters can be optimised for reaching the target emittance including IBS effect through semi-analytical approach (modified Piwinski or Bjorken-Mtingwa formalism)
  - The effect of IBS is evaluated “a posteriori”, i.e. after setting up the basic features of the lattice
  - An iterative process can be used in order to scan the full parameter space and reach the optimum, using numerical tools
  - Lack of a unique tool for executing all the optimisation steps and reiterate if needed.
  - 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

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 relaxed
- Detailed design of RF cavity and injection/extraction elements is **pending**

See talk by A. Grudiev

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 **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)

- LBNL colleagues showed interest to work on certain items during CLIC workshop 2007

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)

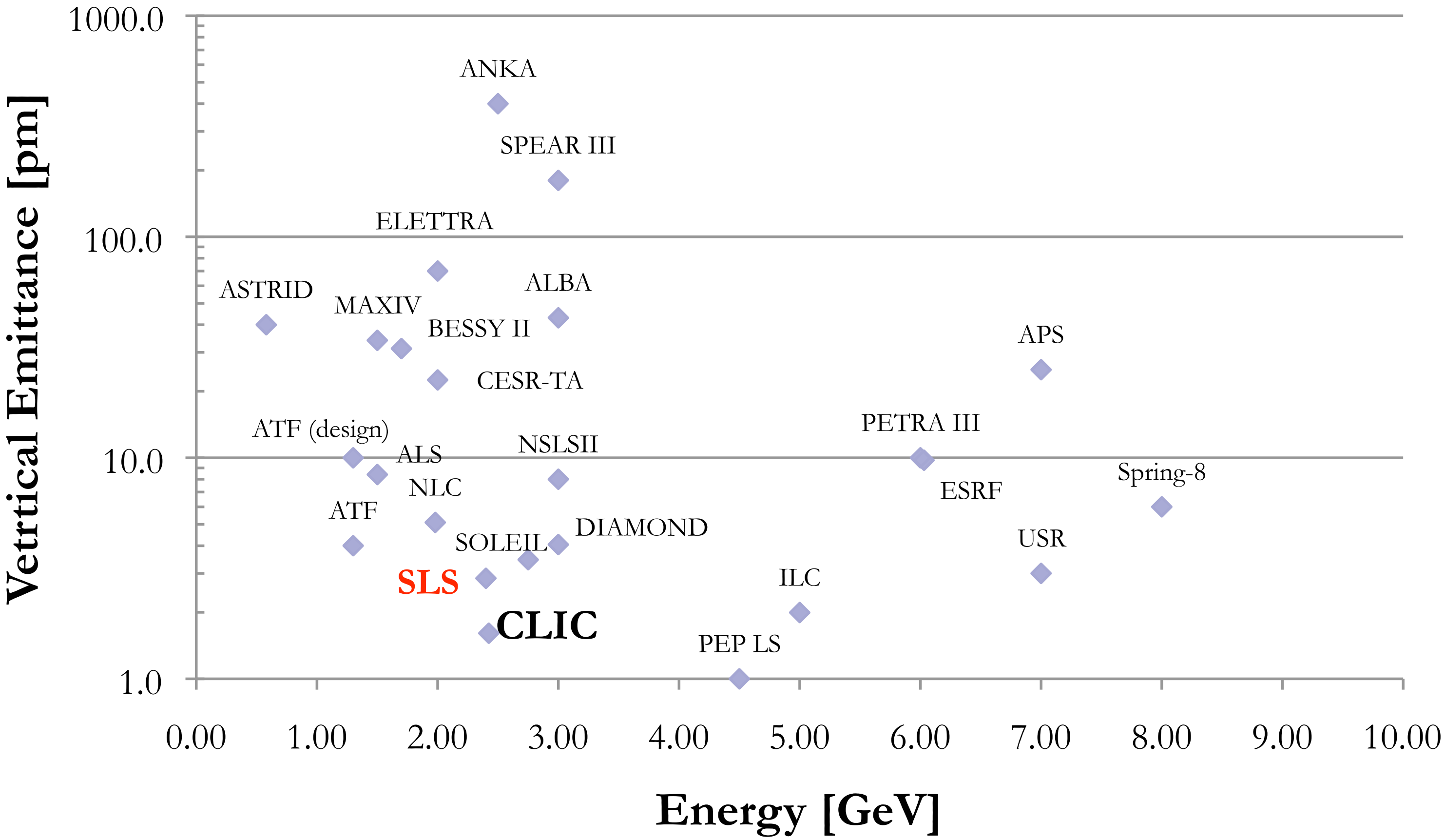
Summary

- 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 for becoming less challenging with respect to space 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
- Parameter scan for conservative beam emittances for 500GeV collider
- Work in progress
  - Pre-damping rings optics design
  - IBS theory, numerical tools and experimental demonstration of low emittance
  - Vacuum chamber design and impedance budget
  - Injection and extraction elements
  - Design of HOM free high frequency RF cavities
  - Diagnostics and feedback
  - Route from 500GeV to 3TeV

Scaling of DR parameters

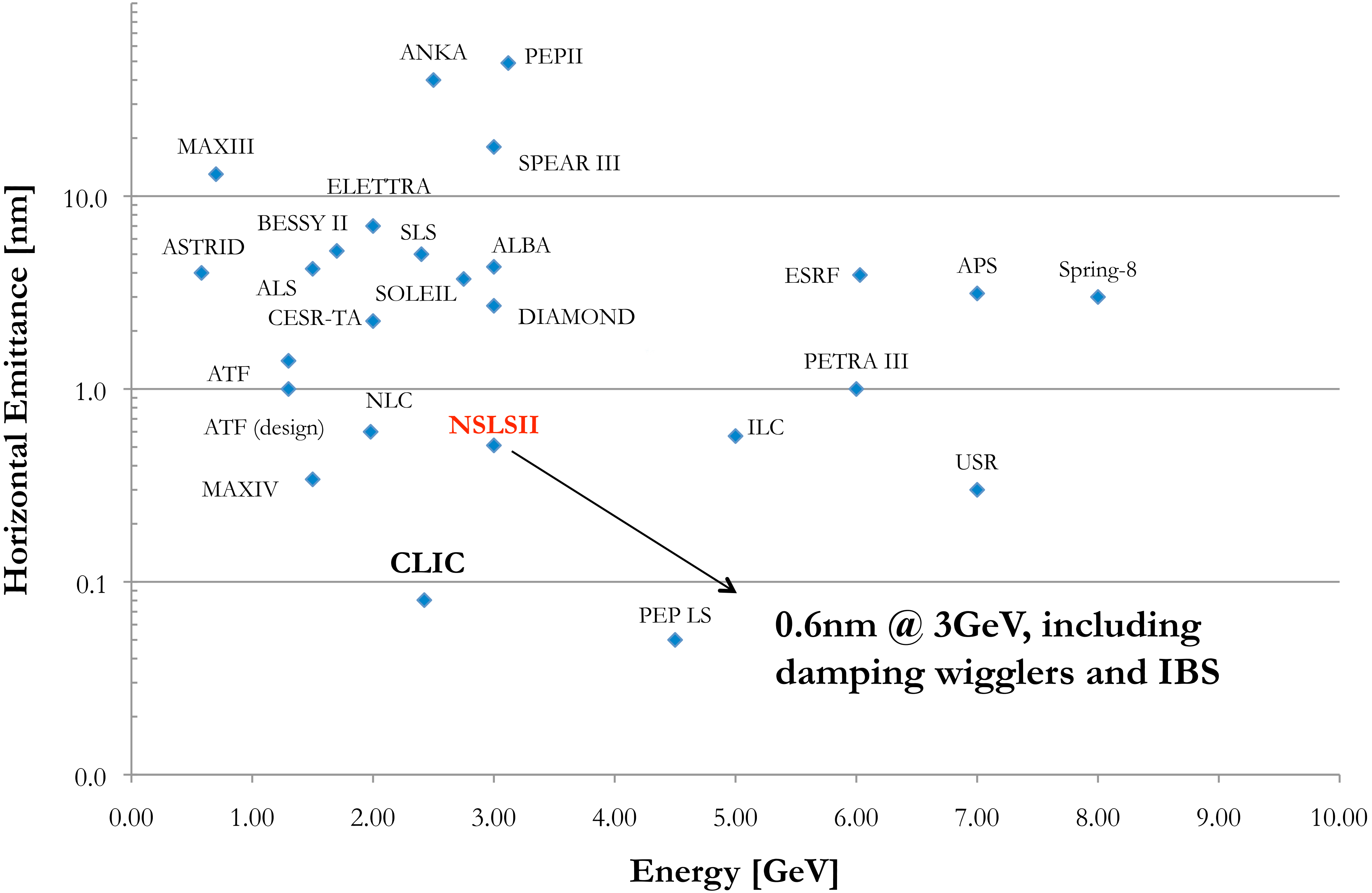
Conservative parameters for CLIC@500GeV

Conservative vertical emittance



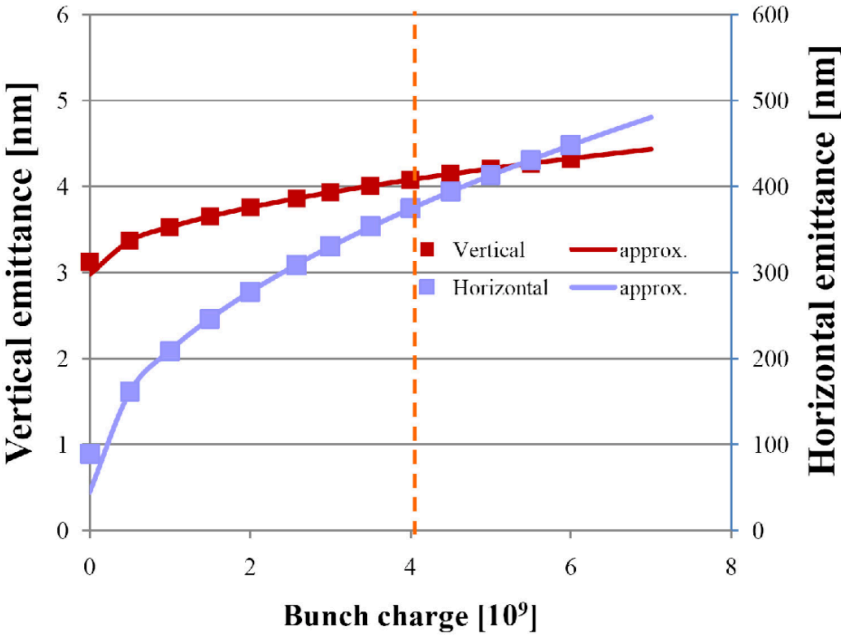
- Swiss Light Source achieved **2.8pm**, the lowest geometrical vertical emittance, at 2.4 GeV, corresponding to ~**10nm** of normalised emittance
- Below 2pm, necessitates challenging alignment tolerances and low emittance tuning (coupling + vertical dispersion correction)
- Seems a “safe” target vertical emittance for CLIC damping rings

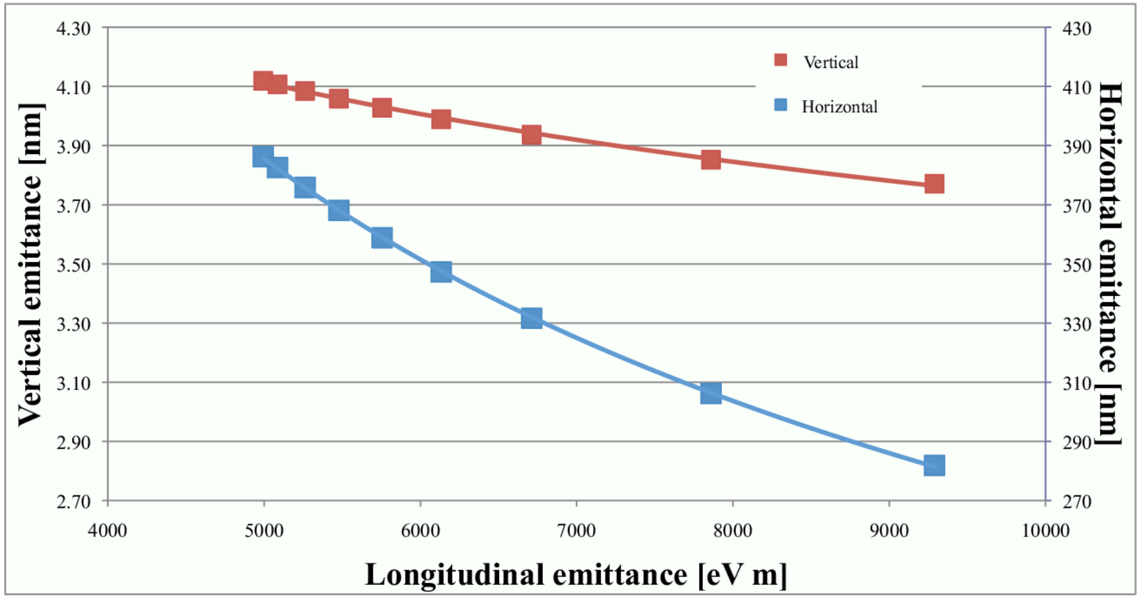
Horizontal emittance vs. energy



0.6nm @ 3GeV, including damping wigglers and IBS

Bunch charge and longitudinal emittance





- Horizontal **emittance** scales as $\gamma\epsilon_x \propto \sqrt{N_b/\sigma_z}$
- Vertical and **longitudinal emittance** have **weaker dependence** to **bunch charge** (of the same order) confirming that **vertical emittance dominated** by **vertical dispersion.**
- When **relaxing longitudinal emittance constraint of 5keV.m** (decreasing RF voltage), **horizontal emittance presents inverse square root dependence** (reduced by 25%)
- Vertical emittance dependence is much weaker

Horizontal emittance vs. energy

- The horizontal emittance is $\epsilon_{x;0} = \frac{C_q \gamma^2}{12(\mathcal{J}_x + \mathcal{F}_w)} \left(\frac{\theta^3}{\sqrt{15}} \epsilon_r + \frac{\mathcal{F}_w |B_w^3| \lambda_w^3 \langle \beta_x \rangle}{16 (B\rho)^3} \right)$

  relative damping factor $\mathcal{F}_w = \frac{L_w B_w^2}{4\pi (B\rho) B}$
- Assume the damping partition number $\mathcal{J}_x = 1$ (i.e. no gradient in dipoles) and constant bending angle $\theta = \frac{L}{\rho} = constant$ and dipole field. As $\rho \propto \gamma$, the dipole length and the circumference should be scaled as well with energy $C \propto \gamma \; and \; L \propto \gamma$
- Scaling the total wiggler length with energy $L_w \propto \gamma$ makes the relative damping factor energy independent
- The average beta function in a wiggler FODO cell is $\langle \beta_x \rangle = 2 \frac{3f^2 - L_w^2}{3\sqrt{f^2 - L_w^2}}$ and scales as the wiggler length or the energy, considering constant focal length
- Keeping the wiggler characteristics (field, period) constant, the first term is scaled with the square of the energy whereas the second is energy independent
- Finally, the **horizontal normalized emittance** is $\epsilon_{xn;0} \propto \gamma^3$
- Note also that the horizontal damping time is inversely proportional to the energy

Longitudinal emittance vs.energy

- The longitudinal normalised emittance can be defined as $\epsilon_s = \gamma \sigma_s \sigma_\delta m_0 c^2$
- The slippage factor is approximately equal to the momentum compaction factor which can be written as

$$\eta \approx \alpha_p = \frac{3\pi}{2}\left(\frac{4\sqrt{15}}{9}\right)^{2/3} \frac{(B\rho)(1+\mathcal{F}_w)^{2/3}}{C|B|\gamma^2}\left(\frac{\gamma\epsilon_{x;0}}{C_q} - \frac{\mathcal{F}_w |B_w^3| \lambda_w^2 \langle\beta_x\rangle \gamma^3}{192(B\rho)^3(\mathcal{J}_w+\mathcal{F}_w)}\right)^{2/3} \frac{\sqrt{5}+\sqrt{\epsilon_r^2-1}}{\epsilon_r^{2/3}}$$

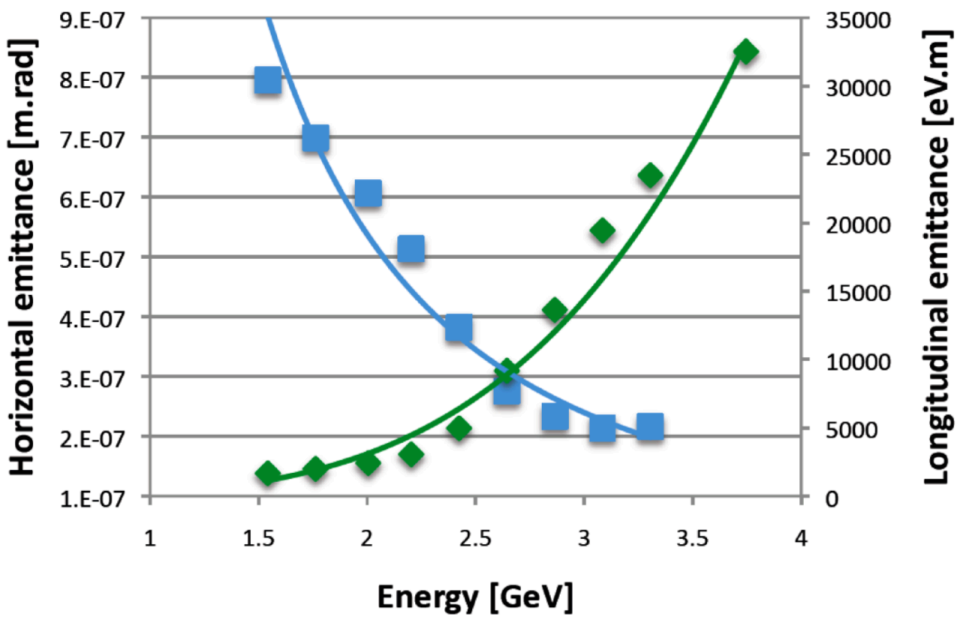
- Under the previous assumptions the momentum compaction factor is energy independent
- The synchrotron frequency is $\omega_s = \frac{c}{C}\sqrt{\frac{2\pi h \alpha_p (e\hat{V}^2 - U_0^2)^{1/2}}{m_0 c^2}}$ and taking into account that the harmonic number is $h \propto C \propto \gamma$, the synchrotron frequency is

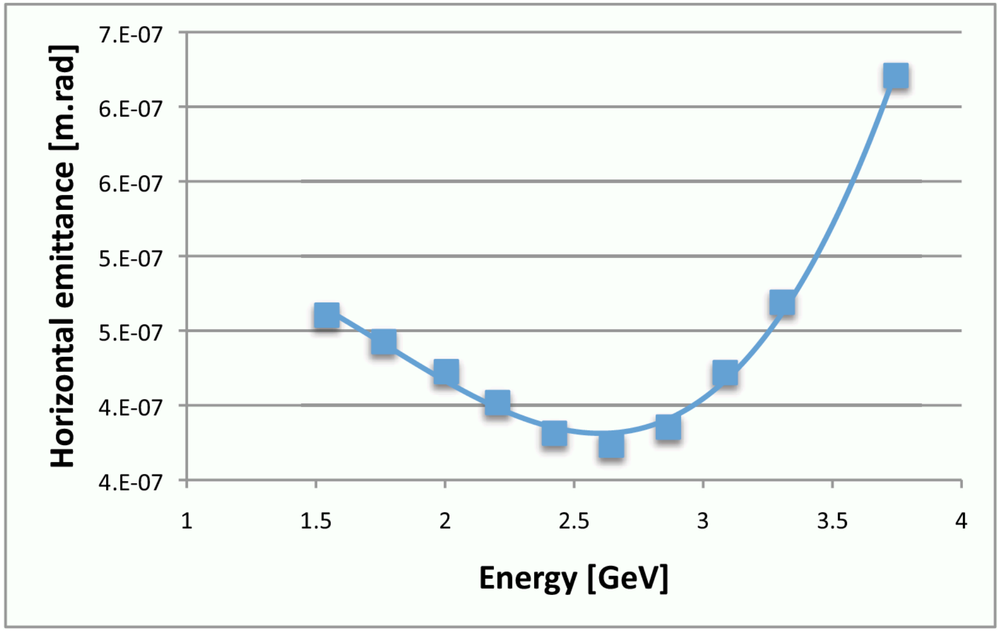
$$\omega_s \propto \frac{1}{\sqrt{\gamma}}$$ assuming an increase of the RF voltage with the energy loss per turn

- The bunch length is $\sigma_s = \frac{c|\eta|}{\omega_s}\frac{\sigma_\delta}{m_0 c^2}$
- The momentum spread $\frac{\sigma_\delta}{m_0 c^2} = \sqrt{\frac{C_q \gamma^2}{\mathcal{J}_s \rho}} \propto \sqrt{\gamma}.$
- Finally the longitudinal normalised emittance is $\epsilon_{s;0} \propto \gamma^{5/2}$

IBS dominated emittances vs.energy

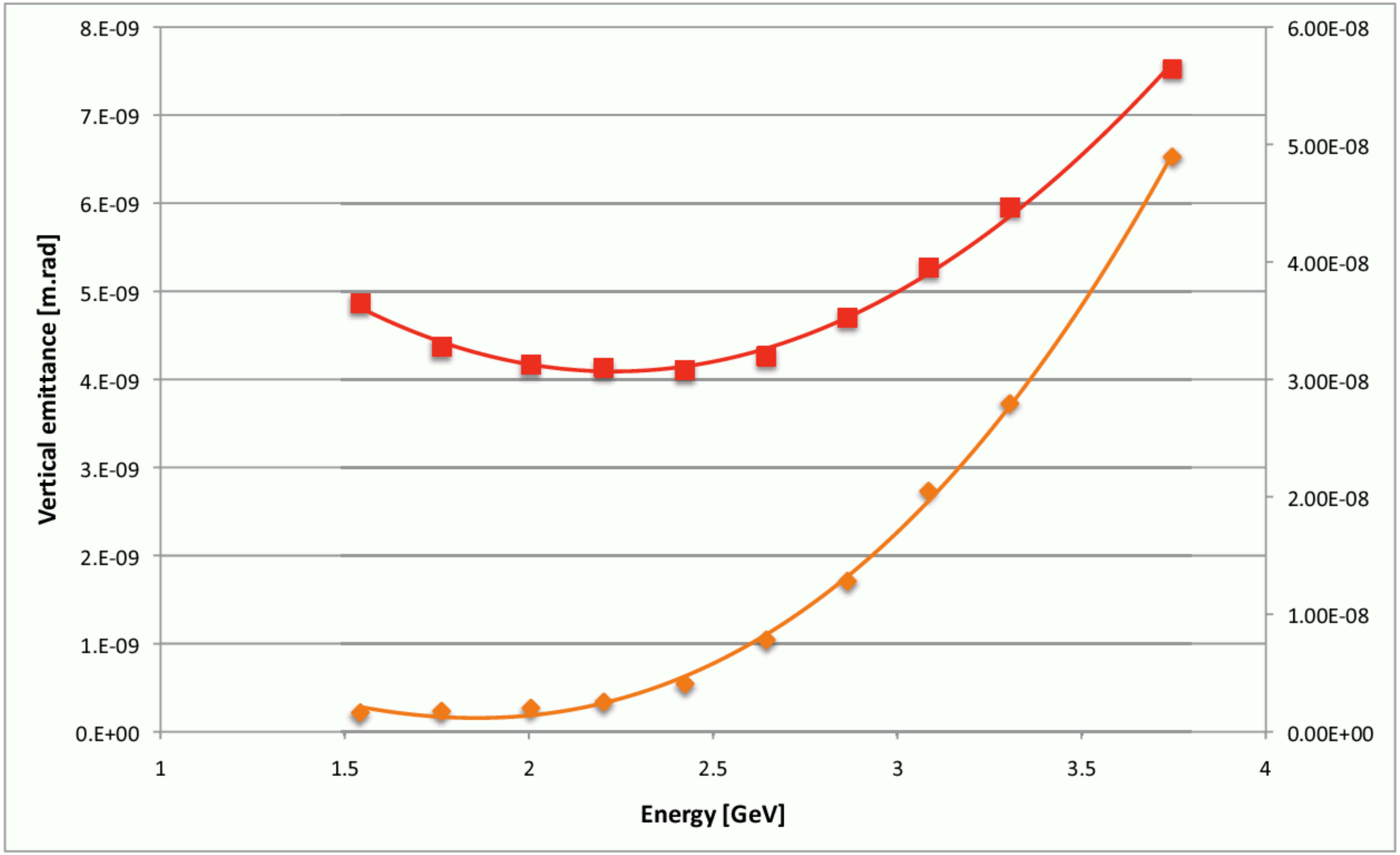
- **Numerical scaling** obtained, by integrating coupled difference equations of standard IBS theory.
- **Longitudinal** and **horizontal** **emittance** scale approximately as $\epsilon_s \propto \gamma^4$ and $\epsilon_x \propto \gamma^{-2}$
- For **constant longitudinal emittance**
  - **high energies** (small effect of IBS): horizontal emittance follows power law similar to the one of zero current emittance
  - **low energies** (IBS dominates): is inversely proportional to the energy





IBS dominated emittances vs.energy

- **Vertical emittance** follows a **quadratic polynomial law**
- For **constant longitudinal emittance**, it scales **linearly with energy** for **high energies**. For **low energies saturates to constant value.**



Scaling of NSLS II parameters

- The “zero-current” equilibrium emittance scaled to CLIC DRs energy is **1.6μm**
- Under previous assumptions, give longitudinal normalized emittance of **6256eV.m** @ 2.424 GeV
- Taking into account scaling of horizontal emittance with bunch population and longitudinal emittance the hor. norm. emittance for CLIC DR parameters ($4.1\text{x}10^9$p/bunch and 5000eV.m) is **1.3μm**
- The final horizontal emittance after scaling the IBS growth with the energy and the vertical emittance, is **2.4μm**
- In this respect the final value may lie around **2μm** providing a safe compromise

PARAMETER	Values
energy [GeV]	3
circumference [m]	791.5
bunch population [10^9]	7.9
bunch spacing [ns]	1.9
number of bunches	1056
rms bunch length [mm]	2.9
rms momentum spread [%]	0.1
hor. normalized emittance [μm]	2.99
ver. normalized emittance [nm]	47
lon. normalized emittance [eV.m]	10395
coupling [%]	0.64
wiggler field [T]	1.8
wiggler period [cm]	10
RF frequency [GHz]	0.5