A decorative graphic on the left side of the slide, consisting of a grid of squares in various shades of blue and purple, arranged in a stepped pattern.

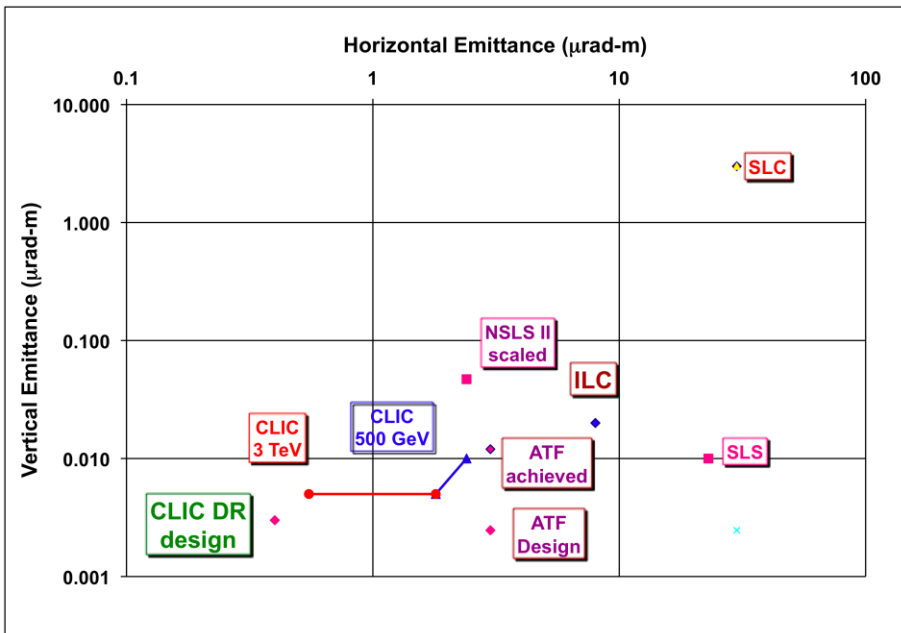
Conceptual Design of the CLIC Damping Rings

Yannis PAPAPHILIPPOU

CERN

October 20th, 2010

- CLIC Damping Rings (DR)
design goals
- 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
- **LER collaboration**
- Summary



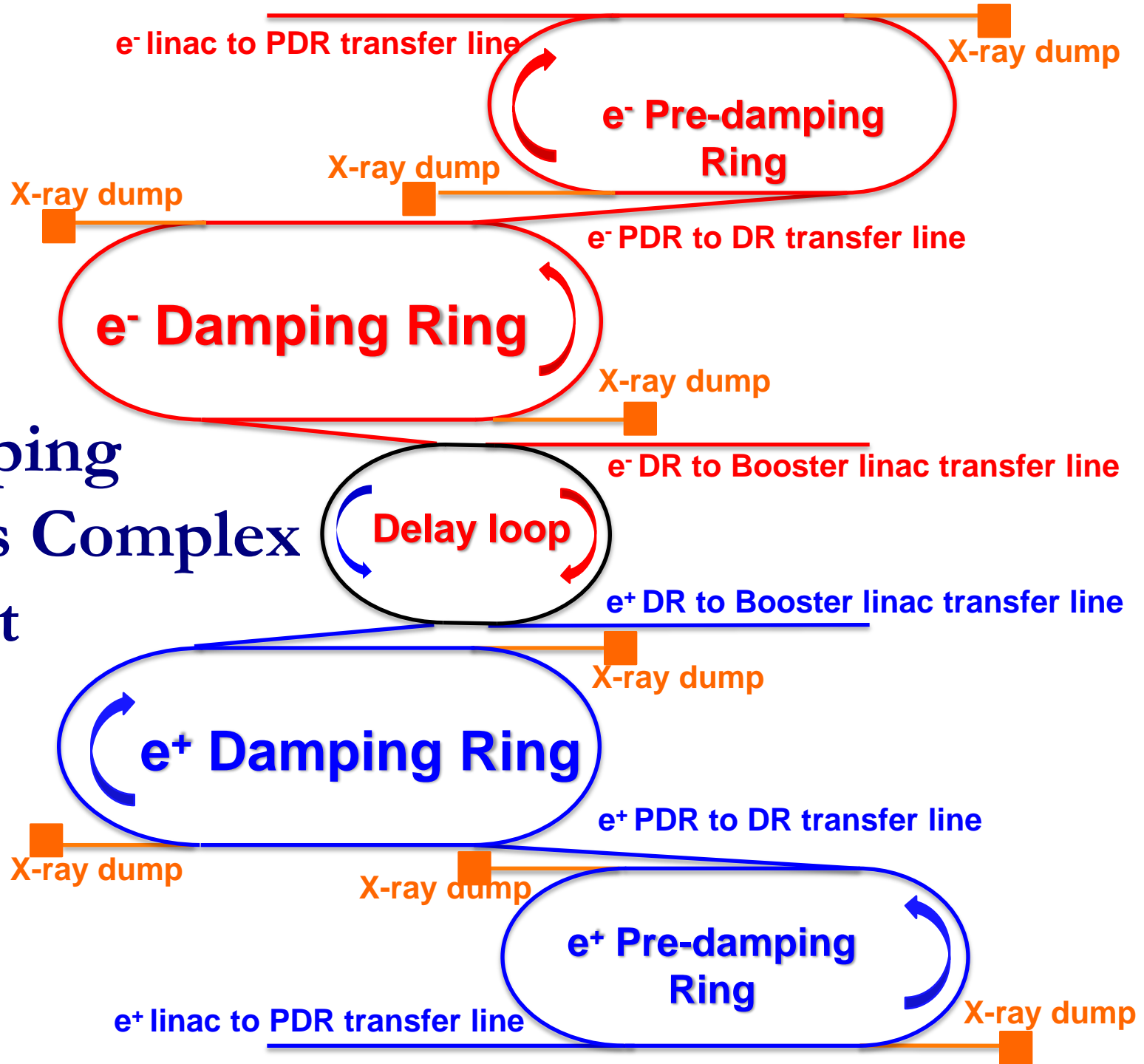
PARAMETER	NLC	CLIC
bunch population (10^9)	7.5	4.1
bunch spacing [ns]	1.4	0.5
number of bunches/train	192	312
number of trains	3	1
Repetition rate [Hz]	120	50
Extracted hor. normalized emittance [nm]	2370	<500
Extracted ver. normalized emittance [nm]	<30	<5
Extracted long. normalized emittance [keV.m]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

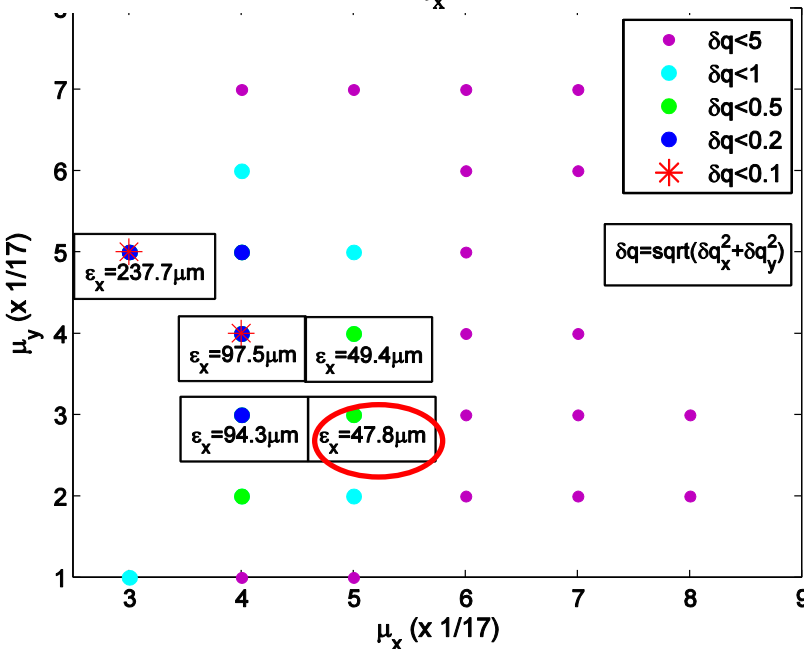
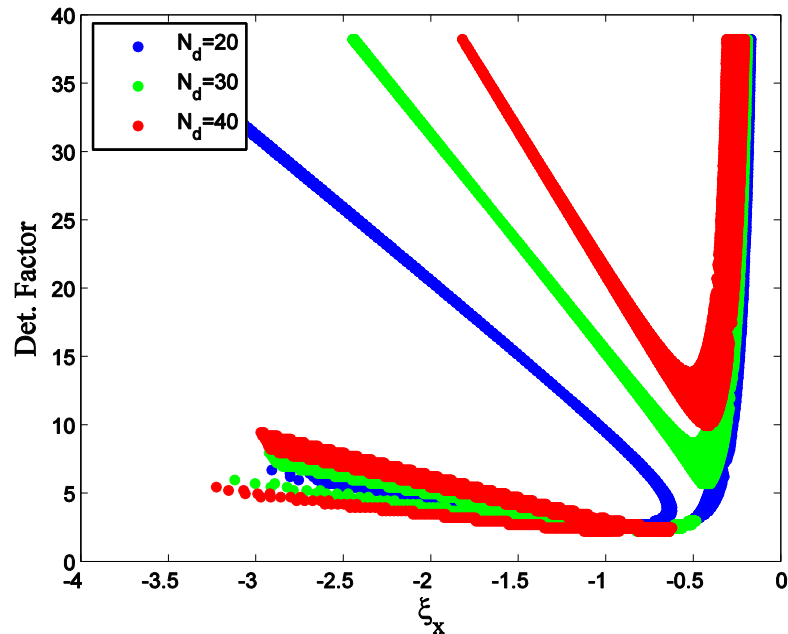
- Damping ring necessary to “cool” the beam to an extremely low emittance in all three dimensions
- Design parameters dictated by target performance of the collider (e.g. luminosity), injected beam characteristics or compatibility with the downstream system parameters
- Most parameters are **driven** by the main linac RF optimization (efficiency)

- High-bunch density
 - Emittance dominated by **Intrabeam Scattering**, driving energy, lattice, wiggler technology choice and alignment tolerances
 - **Electron cloud** in e^+ ring imposes chamber coatings and efficient photon absorption
 - **Fast Ion Instability** in the e^- ring necessitates low vacuum pressure
 - **Space charge** sets energy, circumference limits
- Repetition rate and bunch structure
 - **Fast damping** achieved with wigglers
 - RF frequency reduction considered due to many challenges @ **2GHz** (power source, high peak and average current)
- Output emittance stability
 - Tight **jitter tolerance** driving kicker technology
- Positron beam dimensions from source
 - Pre-damping ring challenges (**energy acceptance**, **dynamic aperture**) solved with lattice design

Design Parameters	CLIC
Energy [GeV]	2.86
Circumference [m]	420.56
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Compaction factor	8×10^{-5}
Damping time x / s [ms]	1.88/0.96
No bends / wigglers	100/52
Dipole/ wiggler field [T]	1.4/2.5

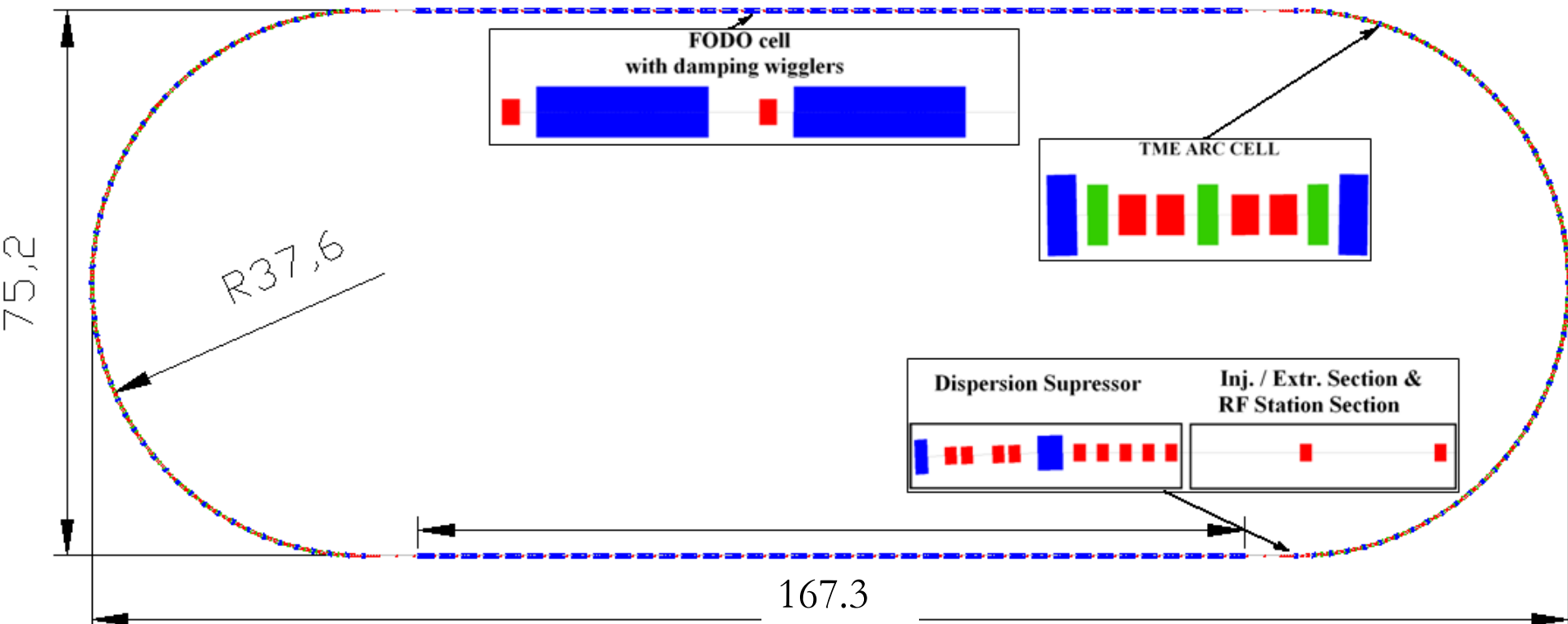
Damping Rings Complex layout



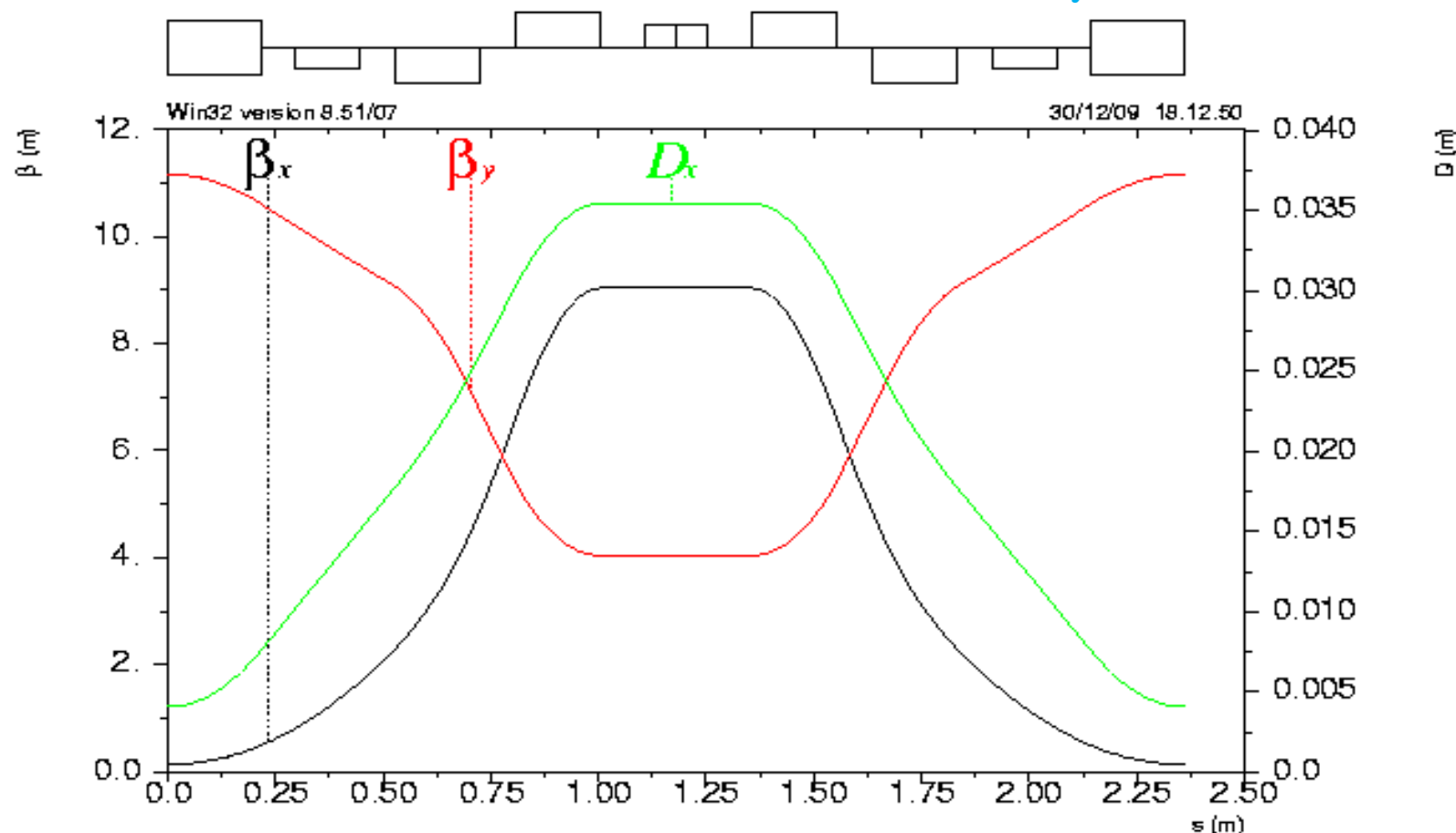


Injected Parameters	e^-	e^+
Bunch population [10^9]	4.4	6.4
Bunch length [mm]	1	10
Energy Spread [%]	0.1	8
Hor., Ver Norm. emittance [nm]	100×10^3	7×10^6

- 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)

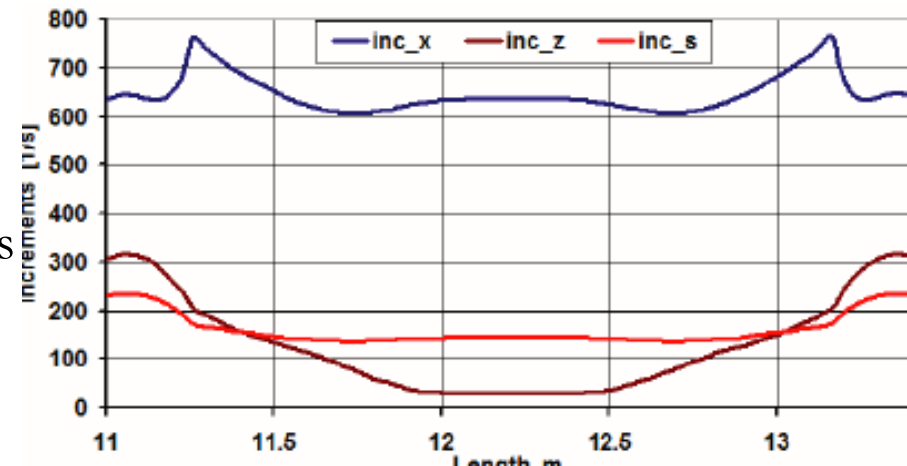
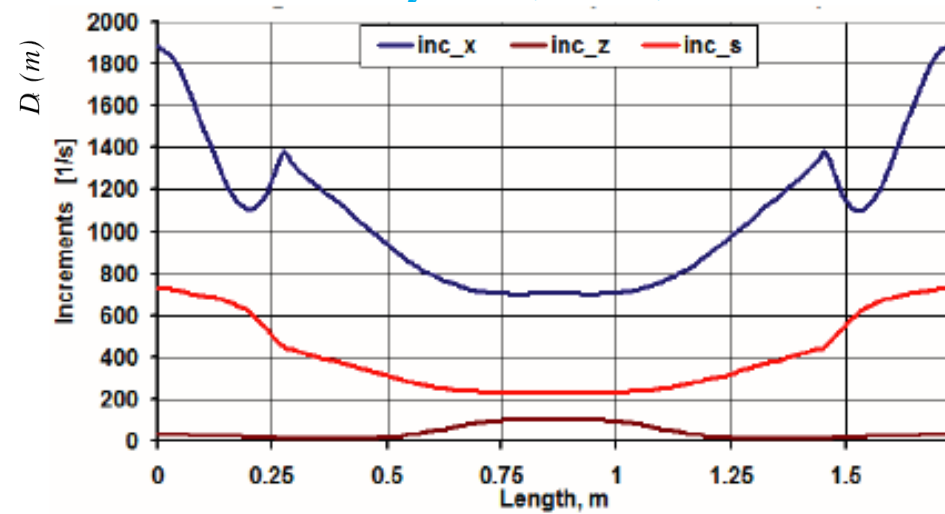
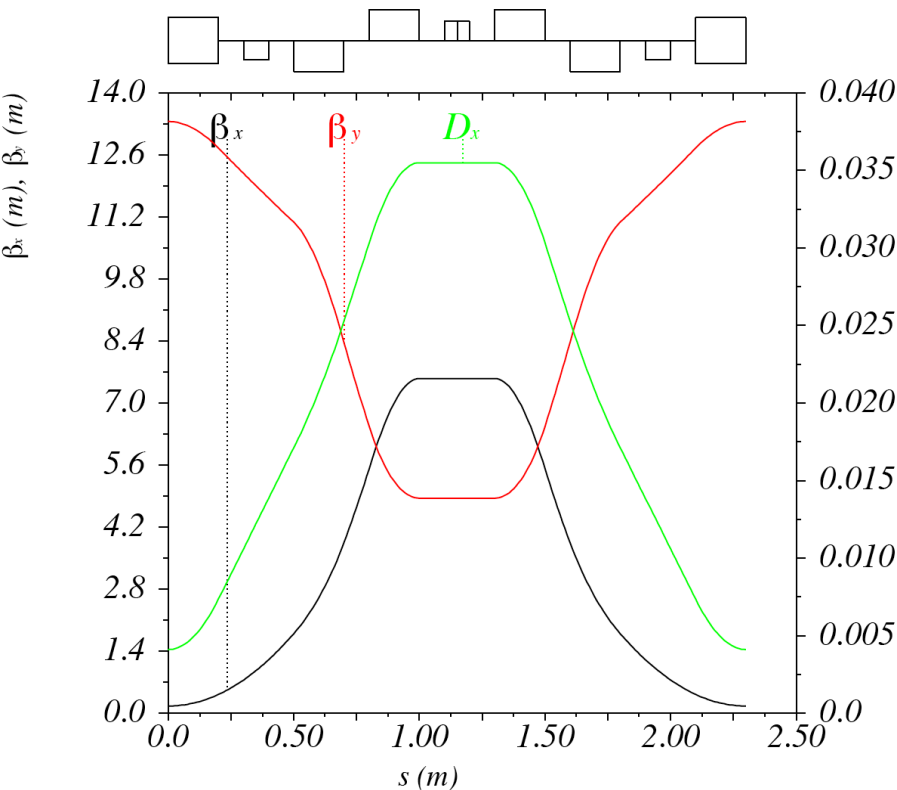


- Racetrack shape with
 - 96 TME arc cells (4 half cells for dispersion suppression)
 - 26 Damping wiggler FODO cells in the long straight sections (LSS)
 - Space reserved upstream the LSS for injection/extraction elements and RF cavities

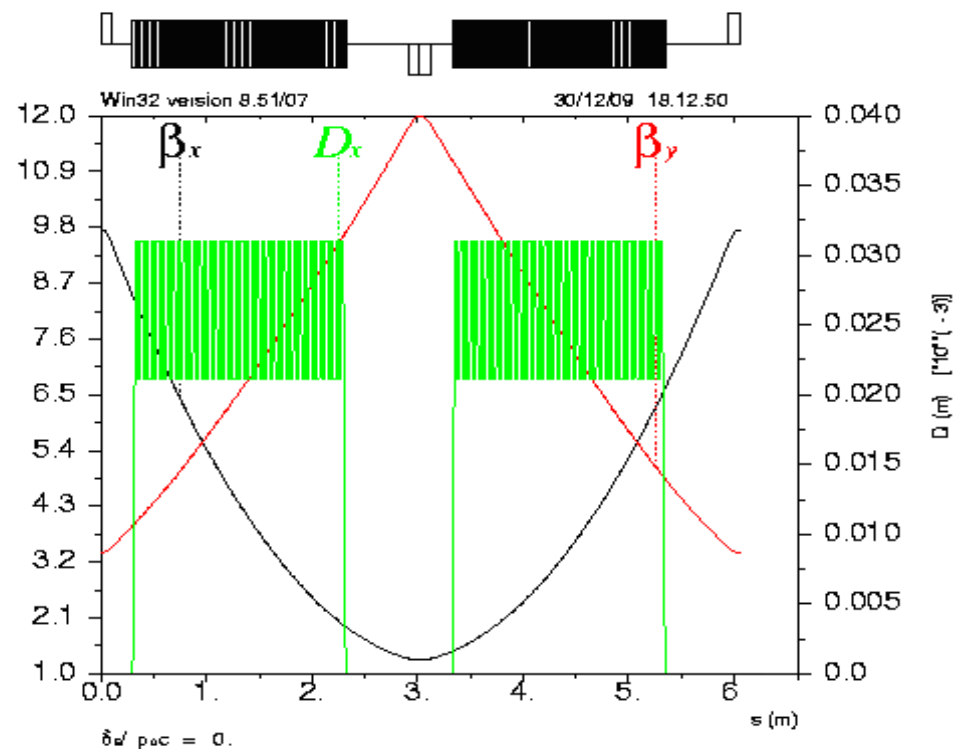
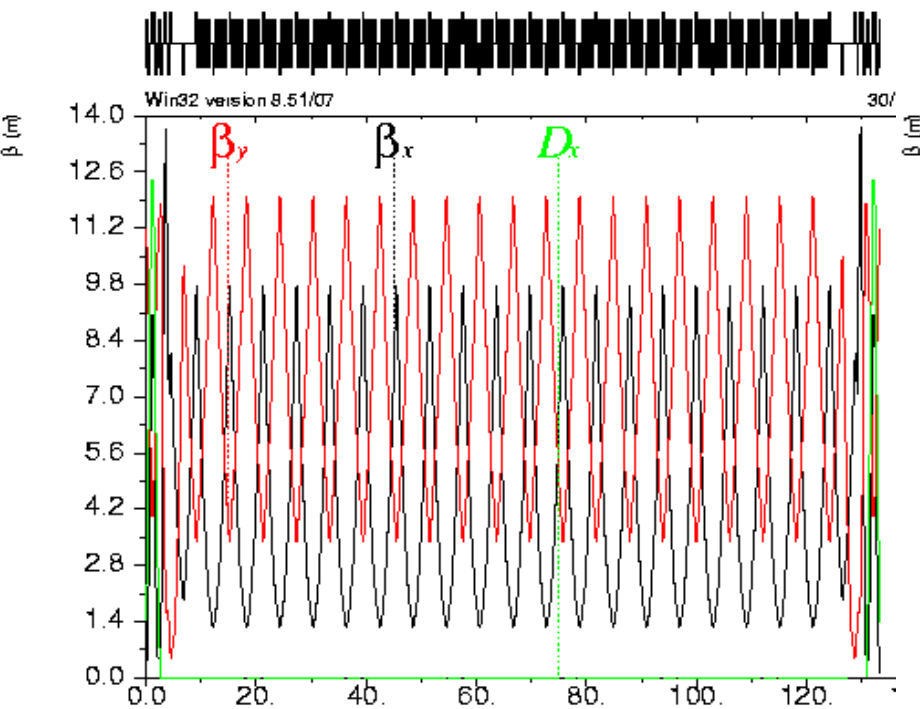


- 2.36m-long TME cell with bends including small gradient (as in NLC DR and ATF)
- Phase advances of 0.452/0.056 and chromaticities of -1.5/-0.5
- IBS growth rates reduced due to optics function inversion

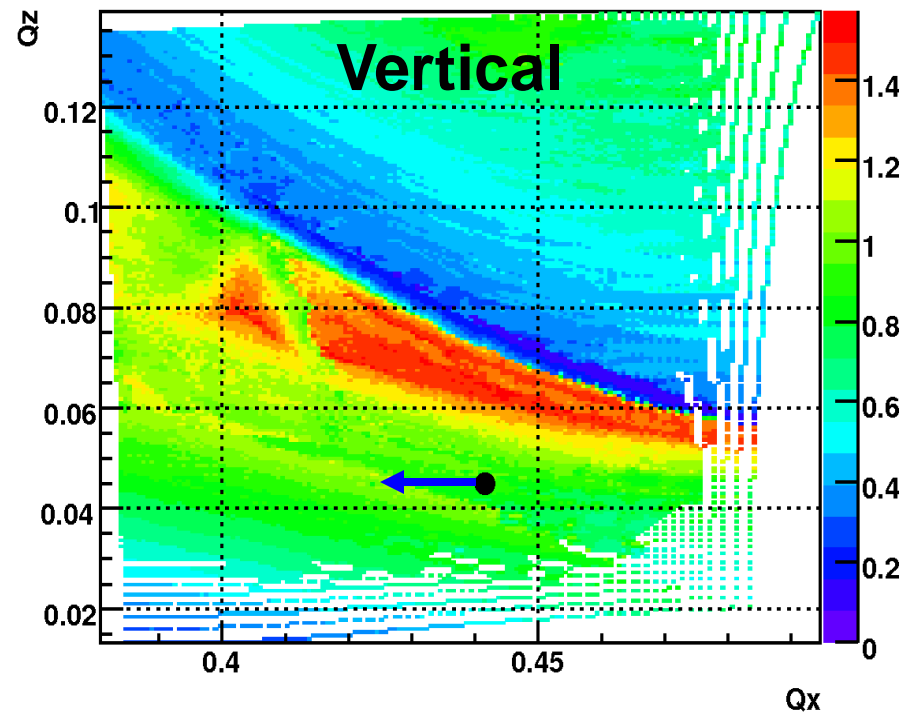
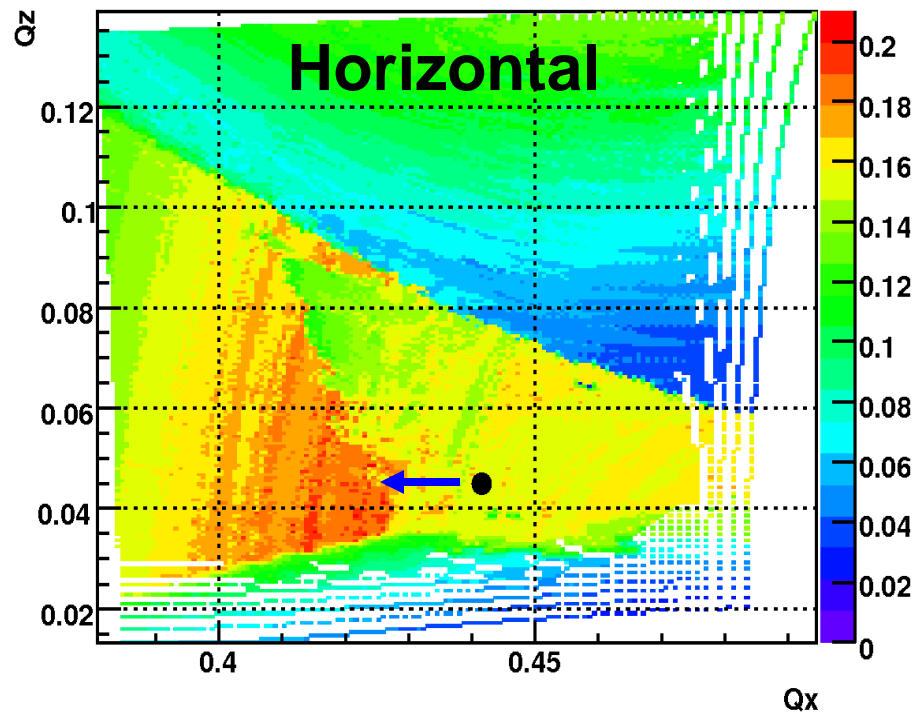
S. Sinyatkin, et al., EPAC 2009



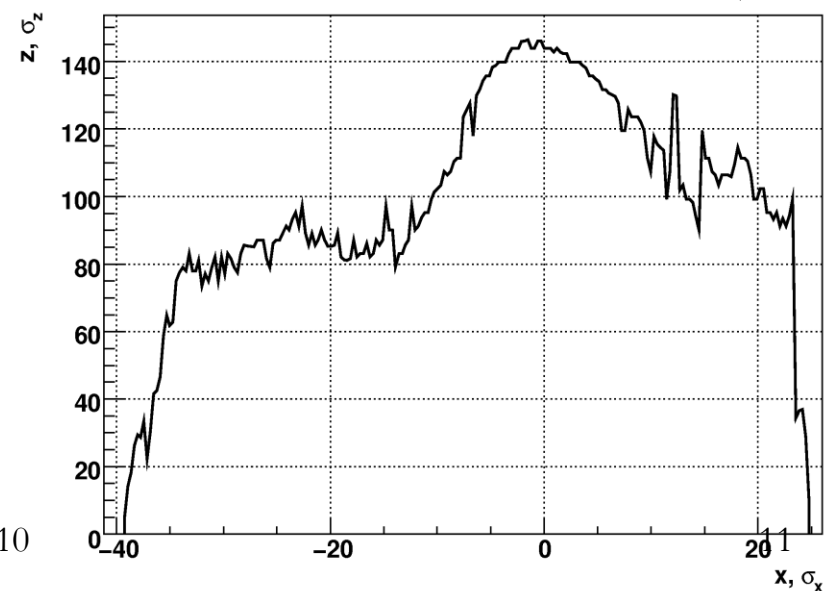
- Increasing space, reducing magnet strengths
- Reducing chromaticity, increasing DA
- IBS growth rates reduced, i.e. zero current equilibrium emittance increased but IBS dominated emittance not changed
- Combined function bends with small gradient (as in NLC DR and ATF)



- LSS filled with wiggler FODO cells of around $\sim 6\text{m}$
- Horizontal phase advance optimised for minimizing emittance with IBS, vertical phase advance optimised for aperture
- Drifts of 0.6m downstream of the wigglers, long enough for absorbers, vacuum equipment and instrumentation



- Arc cell phase advance scan to optimize horizontal and vertical DA
- Very large in both planes especially in vertical
- Further DA optimisation needed (including misalignments, magnetic errors and wiggler effects)



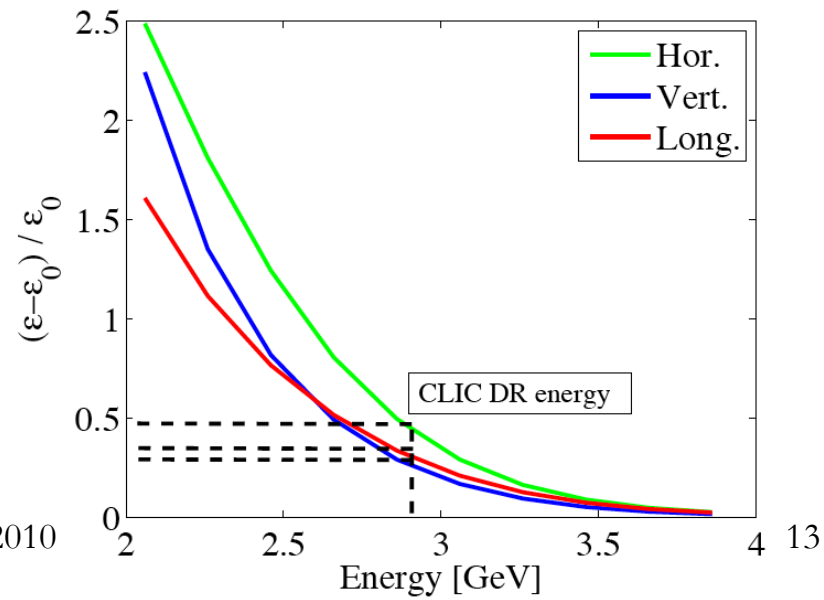
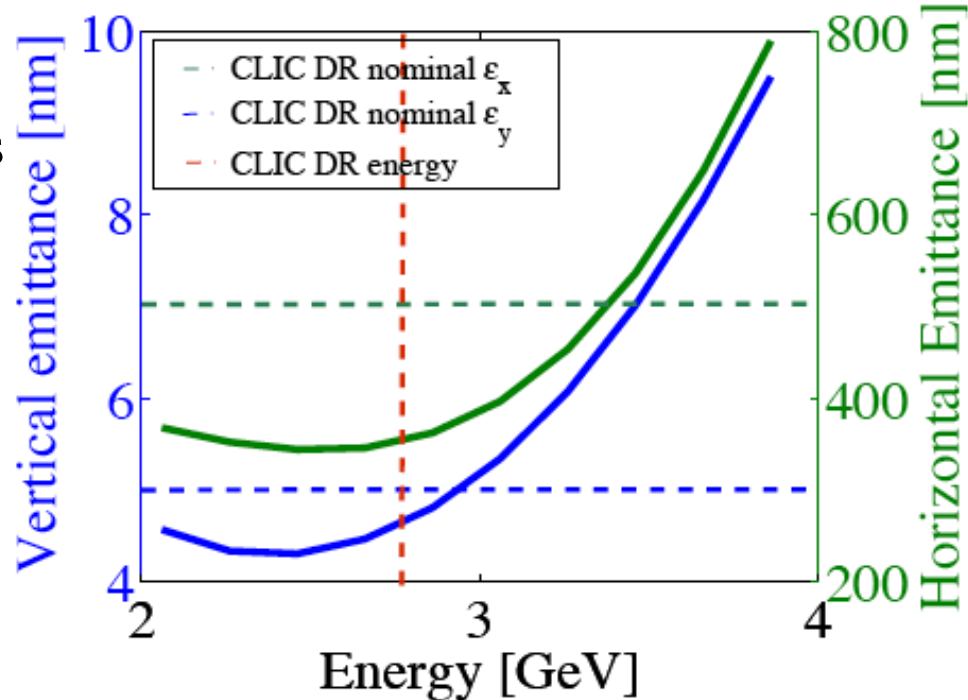
- Reasonable magnet strengths (magnet models already studied) and space constraints
- DA significantly increased
- TME optics with gradient in the bend and energy increase reduces IBS growth factor to **1.4** (as compared to **5.4** in original DR design)
- Further optics optimization with respect to IBS (F. Antoniou PhD thesis) and tracking code for comparaison with analytical theory

Parameters	Value
Energy [GeV]	2.86
Circumference [m]	420.56
Coupling	0.0013
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Natural chromaticity x / y	-168/-60
Momentum compaction factor	8e-5
Damping time x / s [ms]	1.9/ 0.96
Dynamic aperture x / y [σ_{inj}]	30 / 120
Number of dipoles/wigglers	100/52
Cell /dipole length [m]	2.36 / 0.43
Dipole/Wiggler field [T]	1.4/2.5
Bend gradient [$1/m^2$]	-1.10
Max. Quad. gradient [T/m]	73.4
Max. Sext. strength [kT/m^2]	6.6
Phase advance x / z	0.452/0.056
Bunch population, [10^9]	4.1
IBS growth factor	1.4
Hor./ Ver Norm. Emittance [nm.rad]	400 / 4.5
Bunch length [mm]	1.6
Longitudinal emittance [keV.m]	5.5

F. Antoniou, et al. IPAC10

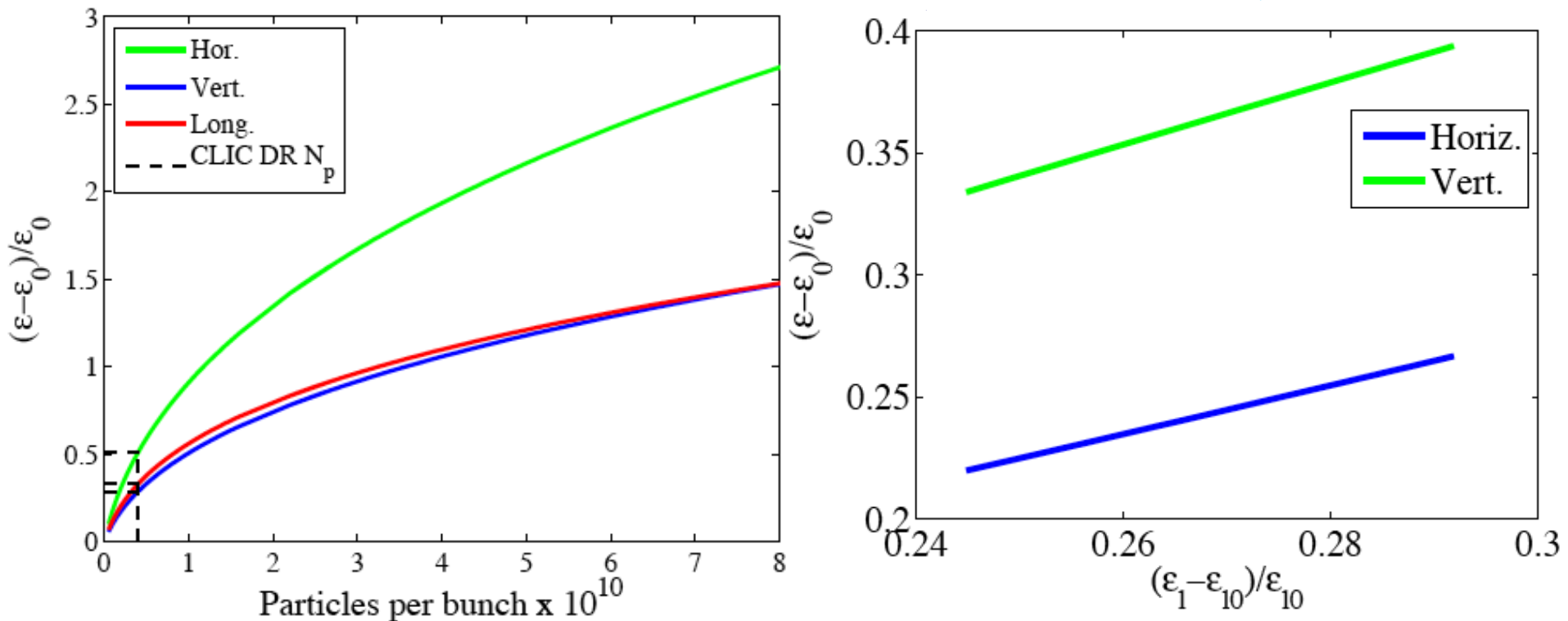
- Scaling of emittances with energy obtained with analytical arguments and including IBS effect (constant longitudinal emittance)
- Broad **minimum** for horizontal emittance $\sim 2\text{-}3\text{GeV}$
- Higher energy reduces ratio between zero current and IBS dominated emittance
- Vertical emittance increases linearly with energy
- Similar results obtained for other machines (e.g. CESR TA)
- Choice of 2.86GeV in order to relax collective effects while achieving target emittances

Y.P., 20/10/2010

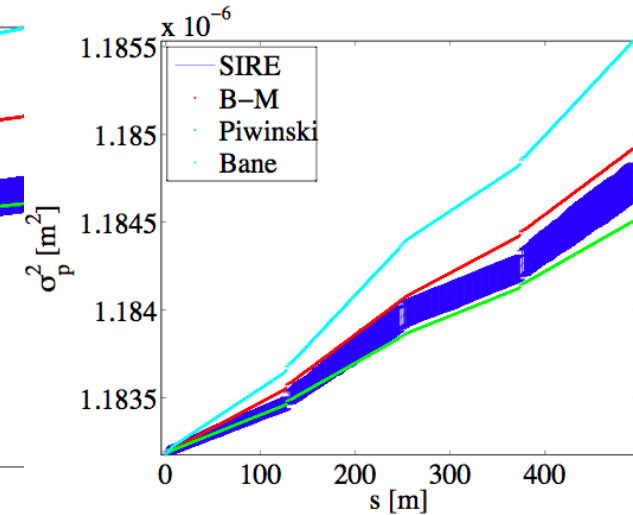
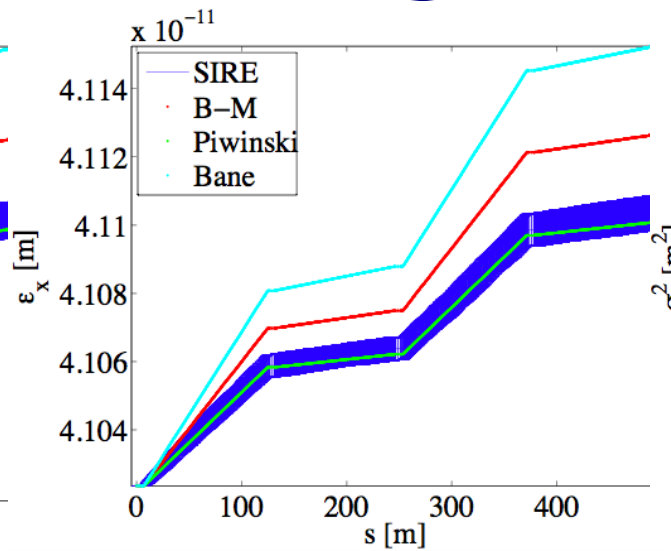
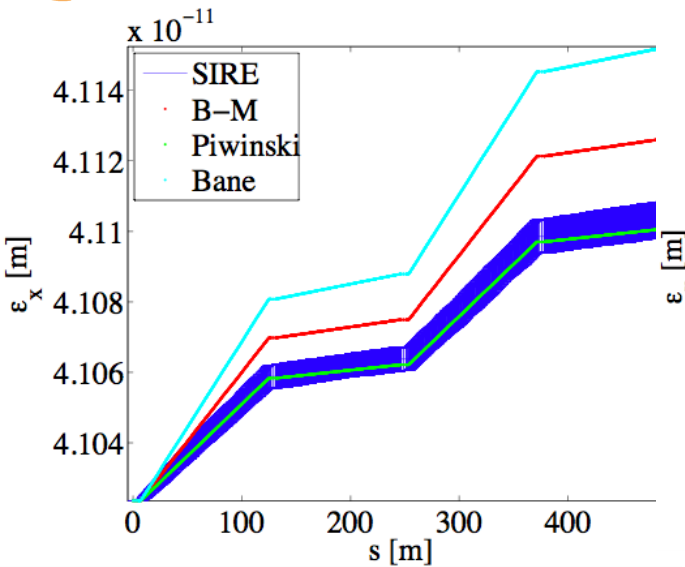


Bunch charge and longitudinal emittance

F. Antoniou, et al. IPAC10



- **Emittances** scale as a power law of the bunch charge
- **Vertical** and **longitudinal emittance** have weaker dependence to **bunch charge** (of the same order) confirming that **vertical emittance** dominated by **vertical dispersion**.
- Linear dependence between transverse and longitudinal emittance

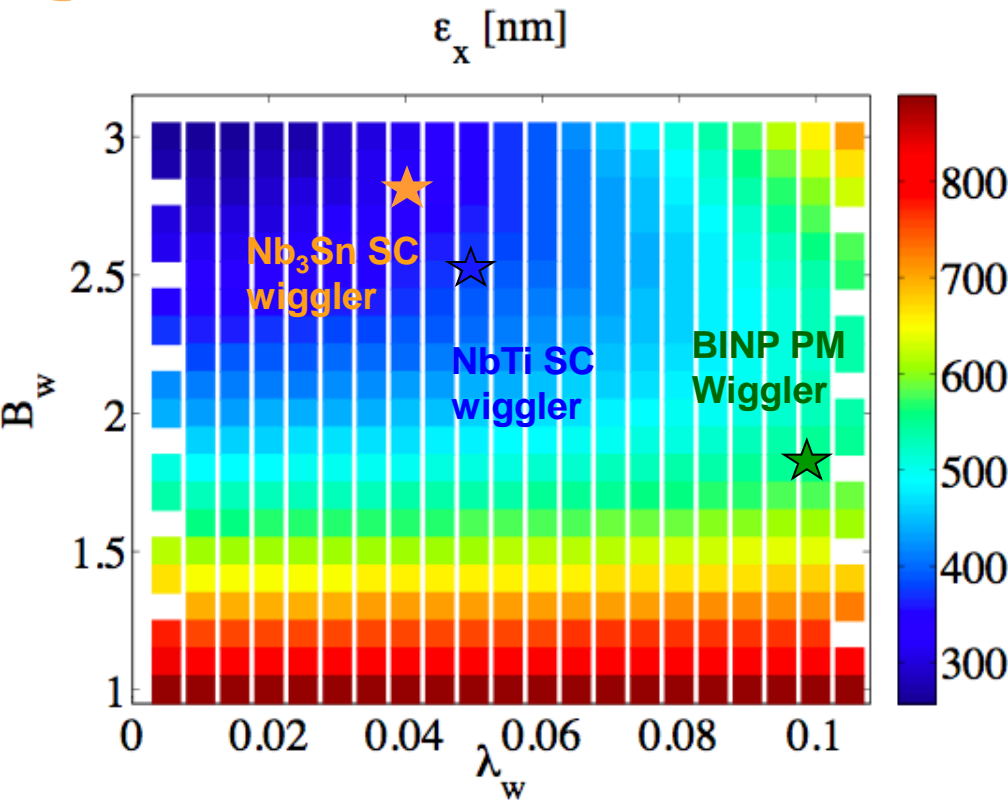


F. Antoniou, A. Vivoli, et al.

	1/Tx (s ⁻¹)	1/Ty (s ⁻¹)	1/Tz (s ⁻¹)
MADX (B-M)	1476.7	952.9	1010.6
Bjorken-Mtingwa (Martini)	1579.4	739.1	968.5
SIRE (compressed)	1224.6	732.5	815.6
SIRE (not compressed)	1181.1	691.8	802.0
Mod. Piwinski	1299.5	625.7	775.2

	$\gamma\epsilon_x$ (m)	$\gamma\epsilon_y$ (m)	ϵ_z (eV m)
Injection	74e-6	1.8e-6	130589
Extraction	498e-9	4.3e-9	3730
Equilibrium (NO IBS)	254e-9	3.7e-9	2914

- Developed Monte-Carlo tracking code for IBS including synchrotron radiation damping and quantum excitation (**SIRE**, based on MOCAC)
- Agreement between analytical emittance growth and the mean values obtained by 20 SIRE runs
- Final emittances obtained by SIRE are just within the CLIC DR budget but for lower longitudinal emittance

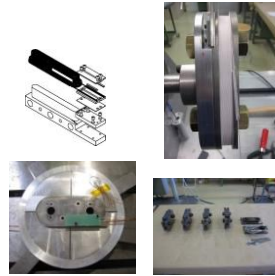


- Stronger wiggler fields and shorter wavelengths necessary to reach target emittance due to strong IBS effect
- Current density can be increased by different conductor type
- Nb₃Sn can sustain higher heat load (potentially 10 times higher than NbTi)
- Two wiggler prototypes
 - 2.5T, 5cm period, built and currently tested by BINP
 - 2.8T, 4cm period, designed by CERN/Un. Karlsruhe
- Mock-ups built and magnetically tested
- Prototypes to be installed in a storage ring for beam measurements

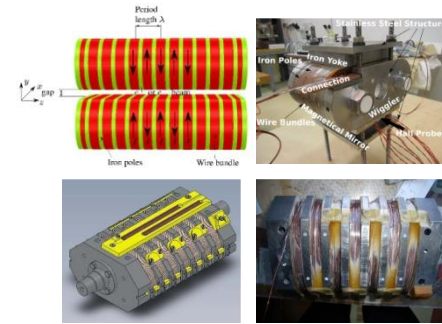
Parameters	BINP	CERN
B_{peak} [T]	2.5	2.8
λ_w [mm]	50	40
Beam aperture full gap [mm]	13	
Conductor type	NbTi	Nb ₃ Sn
Operating temperature [K]	4.2	

Nb₃Sn Technology

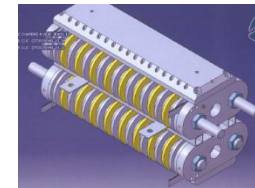
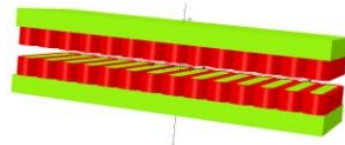
D. Schoerling,
S. Russenchuck, et al.



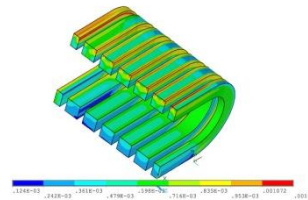
Nb-Ti Technology



CDR



SCU14 in ANKA



TDR

DEPENDING ON APPROVED FUNDING!

- Synchrotron radiation power from bending magnets and wigglers

$$P_{bend} = \frac{2c^2 r_e}{3m_0^3} E^2 l_b B^2 I$$

$$P_w = \frac{2c^2 r_e}{3m_0^3} E^2 l_w B_w^2 I$$

- Critical energy for dipoles and wigglers

$$E_c = \frac{3hc}{2m_0^3} \frac{E^3}{\rho} \quad E_{cw} = \frac{3hc^2}{2m_0^3} B_w E^2$$

- Radiation opening angle

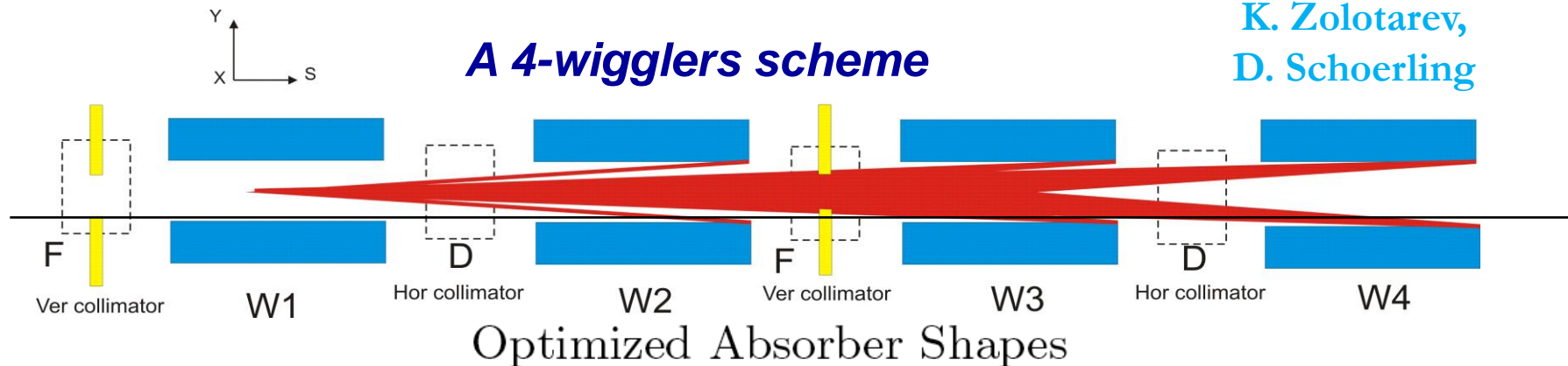
$$\theta_y = \frac{0.608}{\gamma}$$

DR radiation parameters	PD R	DR
Power per dipole [kW]	3.3	1.3
Power per wiggler [kW]	15.2	18.7
Total power [MW]	0.7	0.61
Critical energy for dipole [keV]	16.0	19.0
Critical energy for wiggler [keV]	27.7	40.7
Radiation opening angle [mrad]	0.11	

- 90% of radiation power coming from the 52 SC wigglers
- Design of an absorption system is necessary and critical to protect machine components and wigglers against quench
- Radiation absorption equally important for PDR (but less critical, i.e. similar to light sources)

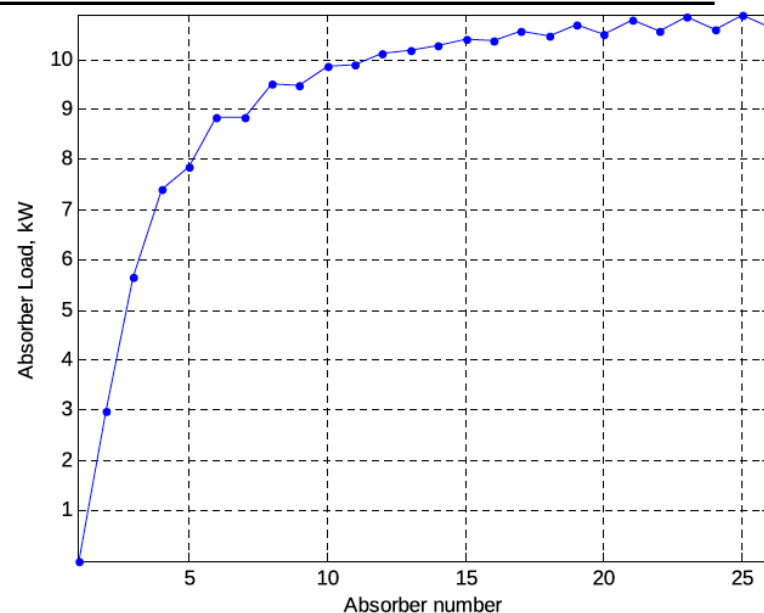
K. Zolotarev,
D. Schoerling

A 4-wigglers scheme



Element	Length [m]	V [mm]	H [mm]	Shape
Horizontal Absorber	0.5	13.5	12.3	Rectangular
Vertical Absorber	0.5	9.5	12.5	Rectangular

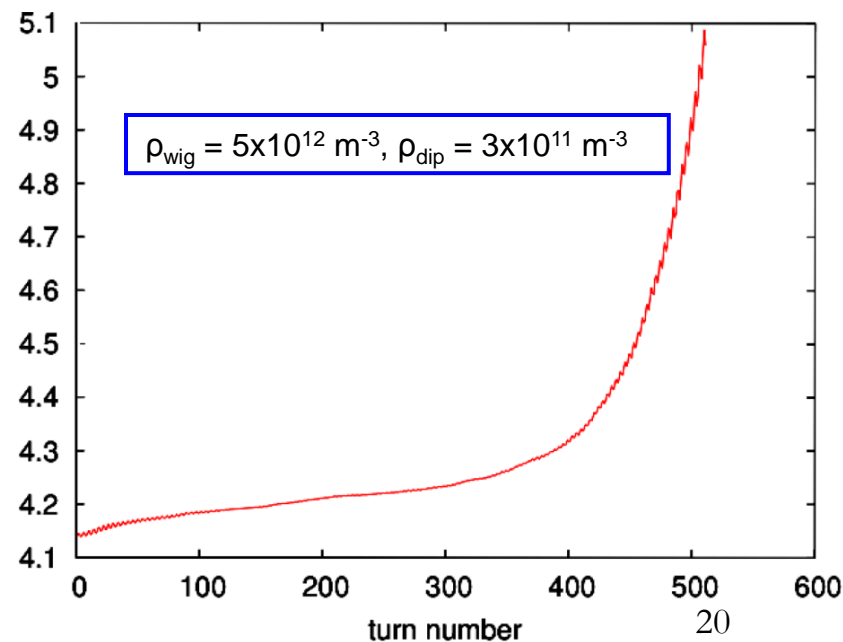
- Gap of 13mm (10W/m)
- Combination of collimators and absorbers (PETRAIII type, power density of up to 200W/cm)
- Terminal absorber at the end of the straight section (10kW)



G. Rumolo

- Electron cloud in the e^+ DR imposes limits in PEY (99.9% of synchrotron radiation absorbed in the wigglers) and SEY (<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 0.1 nTorr)
- Other collective effects in DR
 - Vertical Space charge tune-shift reduced to 0.12 by combined circumference reduction and bunch length increase
 - 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 (100s of turns rise time)

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
		1.3	45
	0.109	1.5	70
		1.8	80



M. Taborelli LER2010

Bakeable system

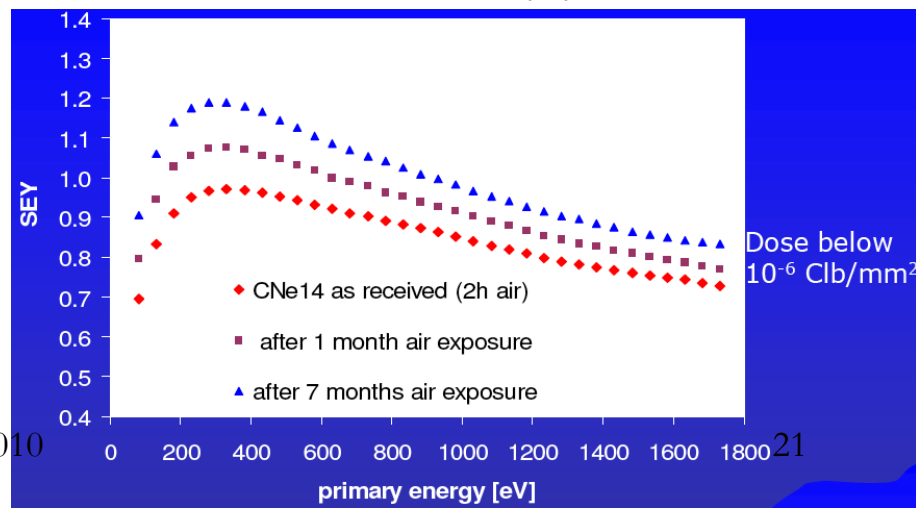
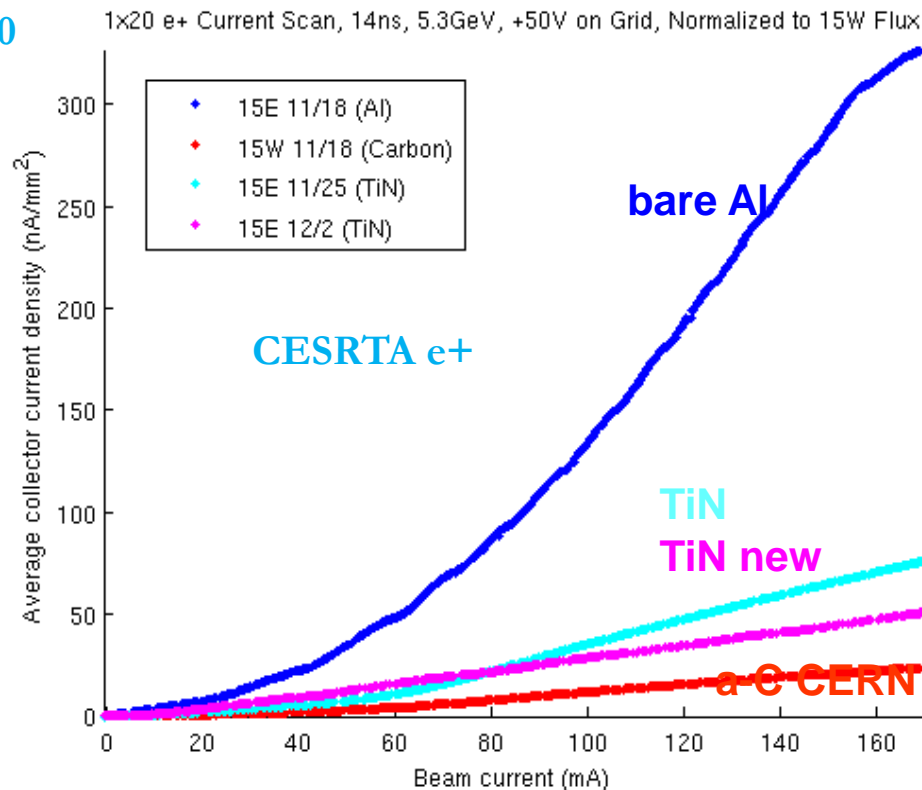
- NEG gives $SEY < 1.3$ for baking @ $> 180^\circ\text{C}$
- Evolution after many venting cycles should be studied
- NEG provides pumping
- Conceivable to develop a coating with lower activation T

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
- No particles and peel-off
- Very good results obtained at CESR-TA (although contaminated by silicon from kapton adhesive tape)

Y.P., 26/10/2010

IWLC2010

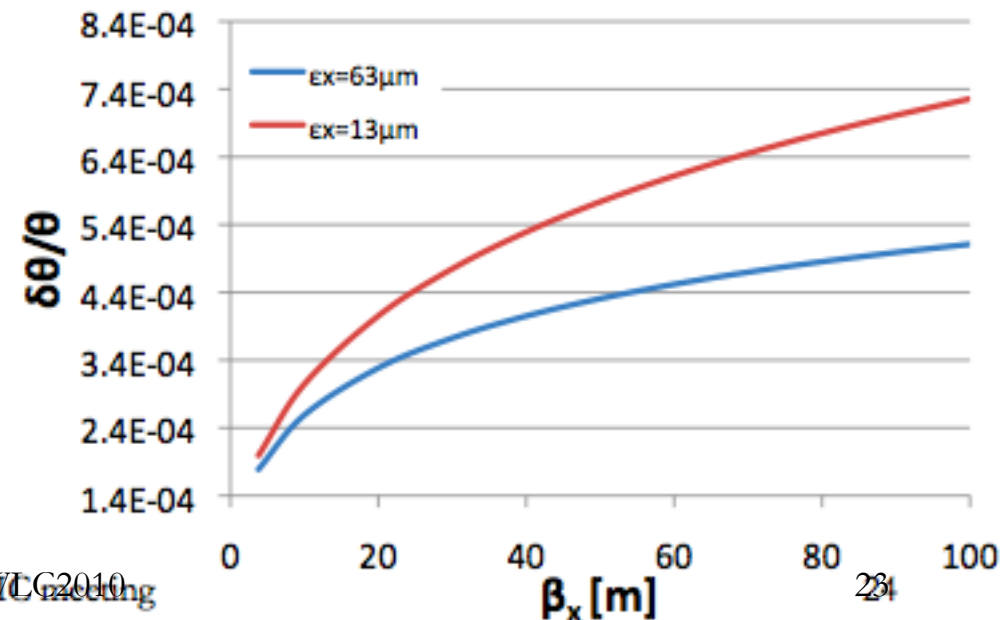
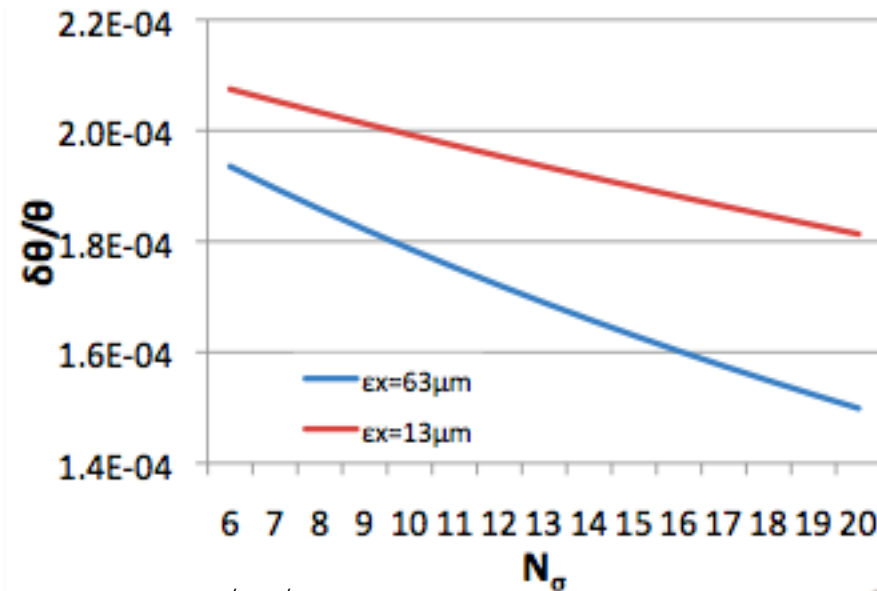


- RF frequency of **2GHz**
 - R&D needed for power source
 - High peak and average power introducing strong transient beam loading to be handled by non-conventional LLRF system
- The **1GHz** frequency eases beam dynamics and drives the RF system to more conventional parameters for power source and LLRF
 - Extra complication with train recombination and RF deflector stability
 - Some schemes with longer bunch trains for 1TeV operation of the collider are not compatible with this bunch structure and PDR circumference
- Scaling for both frequencies suggest that total transverse impedance is 10 times below threshold (but these are only the cavities...)

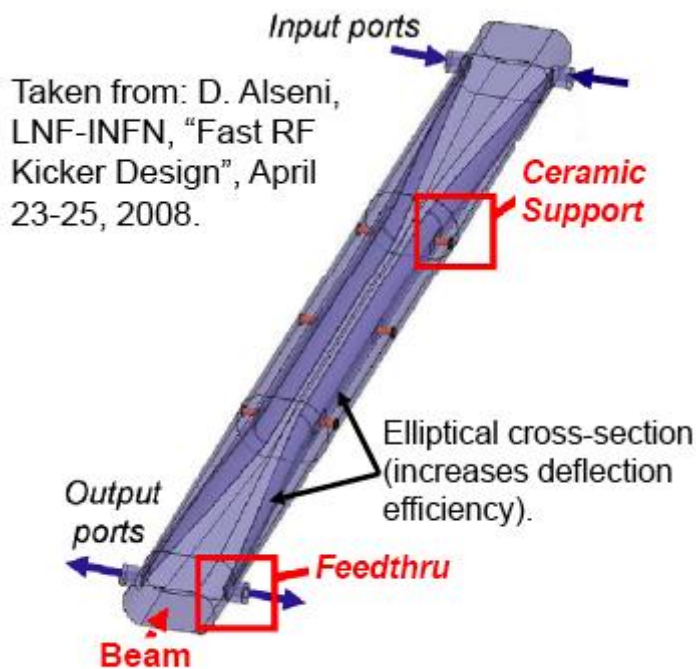
CLIC DR parameters		
Circumference [m]	420.56	
Energy [GeV]	2.86	
Momentum compaction	8×10^{-5}	
Energy loss/turn [MeV]	4.2	
RF voltage [MV]	4.9	4.4
RF frequency [GHz]	1.0	2.0
Peak/Aver. current [A]	0.66/0.1 5	1.3/0.1 5
Peak/Aver. power [MW]	2.8/0.6	5.5/0.6

Kicker stability

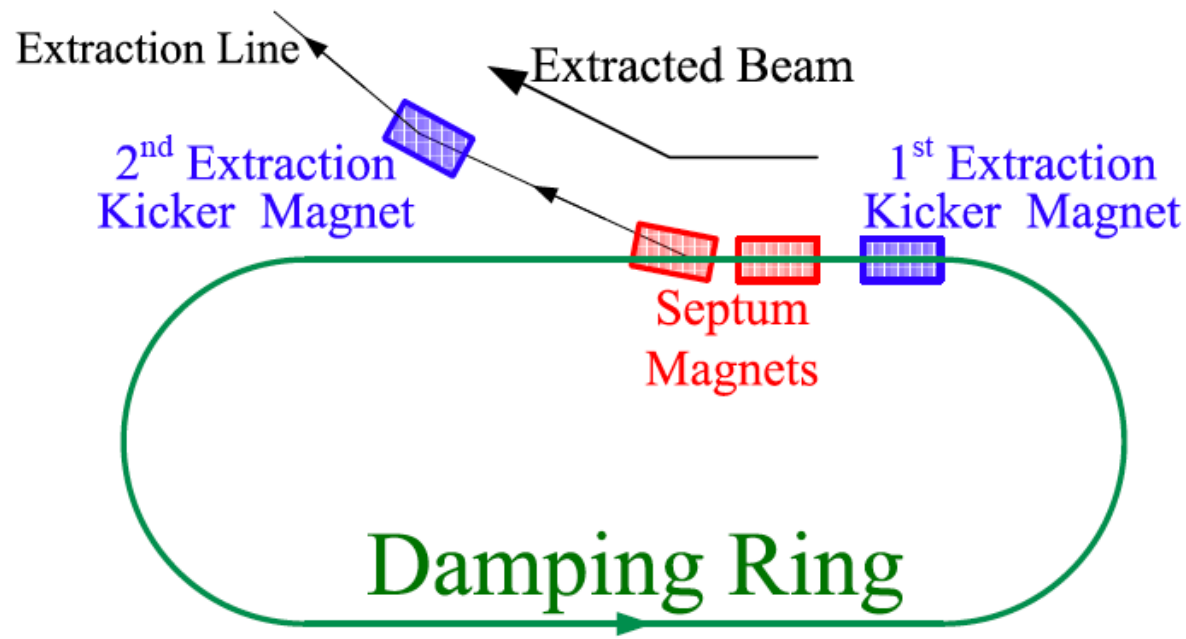
- Kicker jitter is translated in a beam jitter in the IP.
- Typically a tolerance of $\sigma_{jit} \leq 0.1\sigma_x$ is needed
- Translated in a relative deflection stability requirement as $\frac{\delta\theta_{kick}}{\theta_{kick}} \leq \frac{\sigma_{jit}}{x_{sep}}$
- For higher positions at the septum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



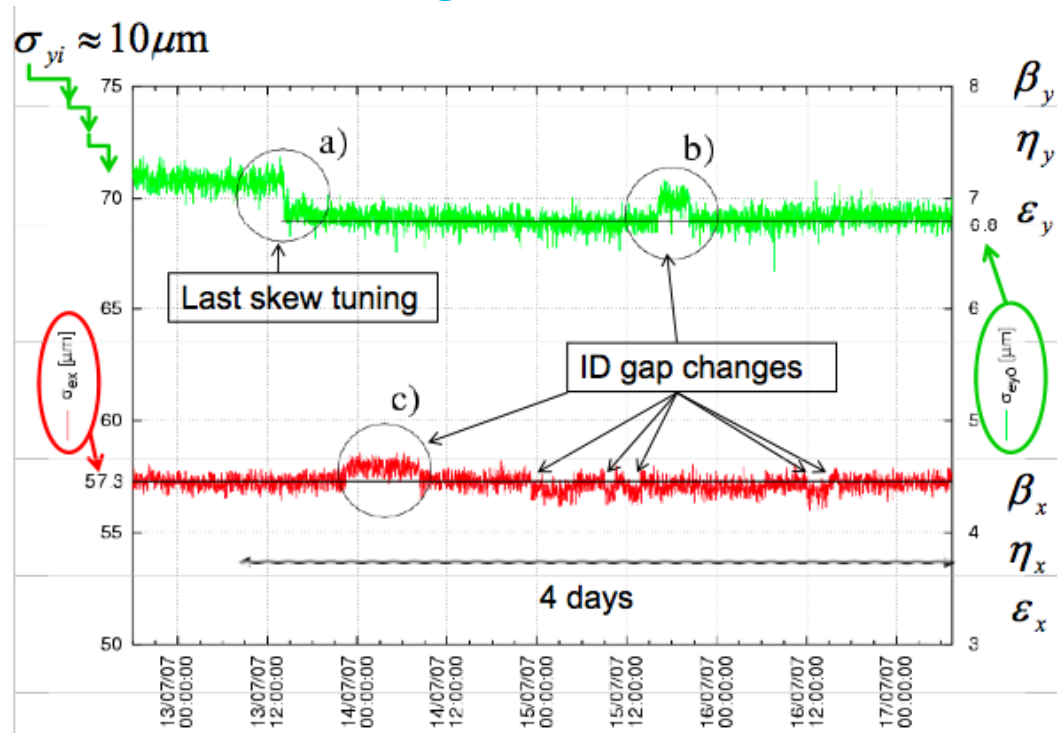
- Double kicker system relaxes requirement, i.e. ~ 3.3 reduction achieved @ATF
- Striplines required for achieving low longitudinal coupling impedance
- Significant R&D needed for PFL (or alternative), switch, transmission cable, feedthroughs, stripline, terminator (PhD thesis student at CERN)
- Should profit from collaborator with ILC and light source community



DAΦNE Stripline ($\sim 0.94\text{m}$)



- Present tolerances not far away from ones achieved in actual storage rings
- SLS achieved 2.8pm emittance
- DIAMOND claim 2.2pm and ASP quoting 1-2pm (pending direct beam size measurements)
- A collaboration with SLS and ASP is prepared



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

- **300PUs**, turn by turn (every **1.6μs**)
 - **10μm** precision, for linear and non-linear optics measurements.
 - **2μm** precision 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 precision (**~2μm**) 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. **synchronous 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

■ Super-conducting wigglers

- Demanding magnet technology combined with cryogenics and high heat load from synchrotron radiation (absorption)

■ High frequency RF system

- 1 or 2GHz RF system in combination with high power and transient beam loading

■ Coatings, chamber design and ultra-low vacuum

- Electron cloud mitigation, low-impedance, fast-ion instability

■ Kicker technology

- Extracted beam stability

■ Diagnostics for low emittance

- Profile monitors, feedback

■ Experimental program set-up for measurements in storage rings and test facilities

- ALBA (Spain), ANKA (Germany), ATF (Japan), Australia Synchrotron (Australia), CESRTA (USA), SOLEIL (France),...

- Initiated by the ILC-CLIC working group on damping rings
- Workshop organized in January 2010 at CERN identifying items of common interest among the low emittance rings community (synchrotron light sources, linear collider damping rings, b-factories)
- Low emittance rings working groups formed
- A EU network proposal is being prepared
- Next workshop to be organized during summer 2011

	Working groups
1	Low emittance cells design
2	Non-linear optimization
3	Minimization of vertical emittance
4	Integration of collective effects in lattice design
5	Insertion device, magnet design and alignment
6	Instrumentation for low emittance
7	Fast Kicker design
8	Feedback systems (slow and fast)
9	Beam instabilities
10	Impedance and vacuum design

- PDR optics design with adequate DA
- Revised DR lattice in order to be less challenging (magnets, IBS, RF, space charge)
- IBS theories and tracking code show excellent agreement
 - Benchmark with experiments will be tried in CESRTA
- DR performance based on super-conducting wigglers
 - Mock-up on “conventional” wire technology built achieving target parameters
 - More challenging wire technologies and wiggler designs studied at CERN and Un. Karlsruhe/ANKA and measurements from short prototypes are expected
 - Robust absorption scheme adapted to new parameters
- Collective effects (e-cloud, FII) remain major performance challenges
 - Measurement tests in CESR-TA for novel chamber coatings are very encouraging
 - Key component impedance estimation is undertaken and instability studies are underway
- RF system present challenges with respect to transients and power source at the DR frequency
 - Considered reduction of frequency
 - Conceptual design performed for both options

Summary (cont.)

- Stability of kickers challenging, as for all DRs and even modern storage rings for top-up operation
 - Conceptual design has been finalized
 - Results from ATF double kicker system encouraging
- Alignment tolerances revised
 - Participation in low emittance tuning measurement campaigns in light sources and test facilities
- Beam instrumentation wish-list and crude specs
 - Contacts established with light sources and ILC community
- CLIC/ILC working group on common issues for DR
 - Collaboration includes measurements in CESRTA (e-cloud, IBS) and ATF
 - Low emittance rings' workshop organised on January 2010 summing-up the present experience and challenges of DR design
 - Next workshop to be organised during summer next year