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University of Texas at Arlington, USA
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Low Emittance Generation and Preservation: Damping Rings

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Emittance Preservation in ILC Damping Ring

Problems come from electron cloud and fast ion instability. Regarding with bunch-by-bunch extraction, we have to make a careful beam optical matching and a smooth impedance design. This issue was already confirmed by ATF extraction beam tuning (10pm, not 2pm.)

ILC Damping Ring Layout

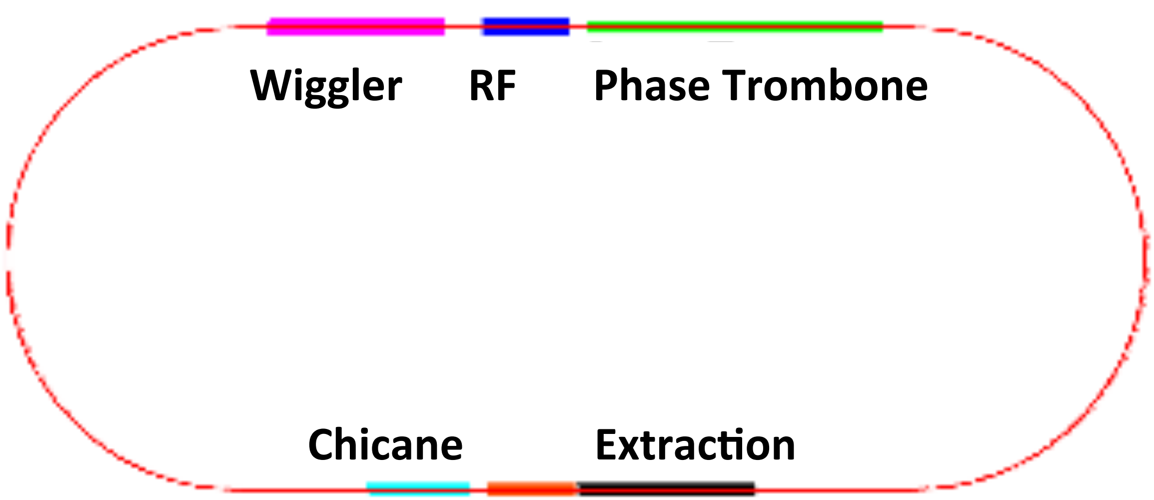


Figure 8.1. Damping ring layout: the circumference is 3238.7 m; the length of each straight is 710.2 m.

DTC lattice parameters for 5 Hz Low Power (baseline) and High Luminosity (upgrade) operating modes and 10 Hz repetition rate (baseline) operation

			TDR Operational Baseline				Upgrade	
			Nominal 5 Hz mode		10 Hz mode for low E_{cm} running		Luminosity upgrade (5Hz)	
			e−	e+	e−	e+	e−	e+
Number of damping rings			1		1		1	2
Number of bunches per ring	n_b		1312		1312		2625	1312
Particles per bunch	N	$\times 10^{10}$	2.0		2.0		2.0	
Average bunch separation		ns	8.23		8.23		4.12	8.23
Average current		mA	389.2		389.2		778.6	389.2
Extracted beam								
Extracted horizontal emittance	ε_x	nm	0.57	0.57	0.60	0.61	0.57	0.57
	$\gamma\varepsilon_x$	µm	5.5	5.5	5.9	6.0	5.5	5.5
Extracted vertical emittance*	ε_y	pm	2.00	2.04	2.06	2.14	2.00	2.04
	$\gamma\varepsilon_y$	nm	19.6	20.0	20.1	20.9	19.6	20.0
RMS rel .energy spread		%	0.110		0.12	0.137	0.110	
RMS bunch length		mm	6.0		6.0	6.0	6.0	
Maximum allowed transverse jitter		$\sigma_{x,y}$	0.1		0.1		0.1	
* Calculated assuming each ring is corrected to 2pm equilibrium vertical emittance								
Damping times & Equilibrium Emittance								
Vertical damping time	τ_y	ms	23.9		17.7	12.9	23.9	
Horizontal damping time	τ_x	ms	23.9		17.7	12.9	23.9	
Longitudinal damping time	τ_s	ms	11.9		8.8	6.4	11.9	
Equilibrium horizontal emittance	ε_x	nm	0.57		0.60	0.64	0.57	
Normalized eq. horizontal emittance	$\gamma\varepsilon_x$	µm	5.5		5.9	6.3	5.5	
Equilibrium vertical emittance	ε_y	pm	2.0		2.0		2.0	
Normalized eq. vertical emittance	$\gamma\varepsilon_y$	nm	19.6		19.6		19.6	
RF & Wiggler								
Total energy loss per turn		MeV	4.5		6.1	8.40	4.53	
Wiggler energy loss per turn		MeV	3.8		5.4	7.66	3.79	
Arc energy loss per turn		MeV	0.7		0.7	0.74	0.74	
Ring Duty Cycle		%	100%		100%	50%	100%	
Beam power		MW	1.76		2.38	1.63	3.53	1.76
Wiggler period		m	0.30		0.30		0.30	
Wiggler length		m	2.10		2.10		2.10	
Number of wigglers			54		54		54	
Total length of wiggler		m	113.4		113.4		113.4	
Wiggler field	B	T	1.51		1.8	2.16	1.51	
Momentum compaction	α_p		3.3E-04		3.3E-04	3.3E-04	3.3E-04	
Total RF voltage	V_{RF}	MV	14.0		17.0	22.0	14.0	

Three ILC operating modes correspond to four DR configurations, Two utilize a 5 Hz repetition rate: low power baseline (1312 bunches/ring); and high luminosity upgrade (2625 bunches. Third operating mode is at 10 Hz and e- linac operated with alternating pulses: high energy for e+ production followed by low energy for collisions. Shorter damping times in necessary to achieve the same extracted vertical emittance in half the nominal storage time

Damping Ring Arc Magnet Layout

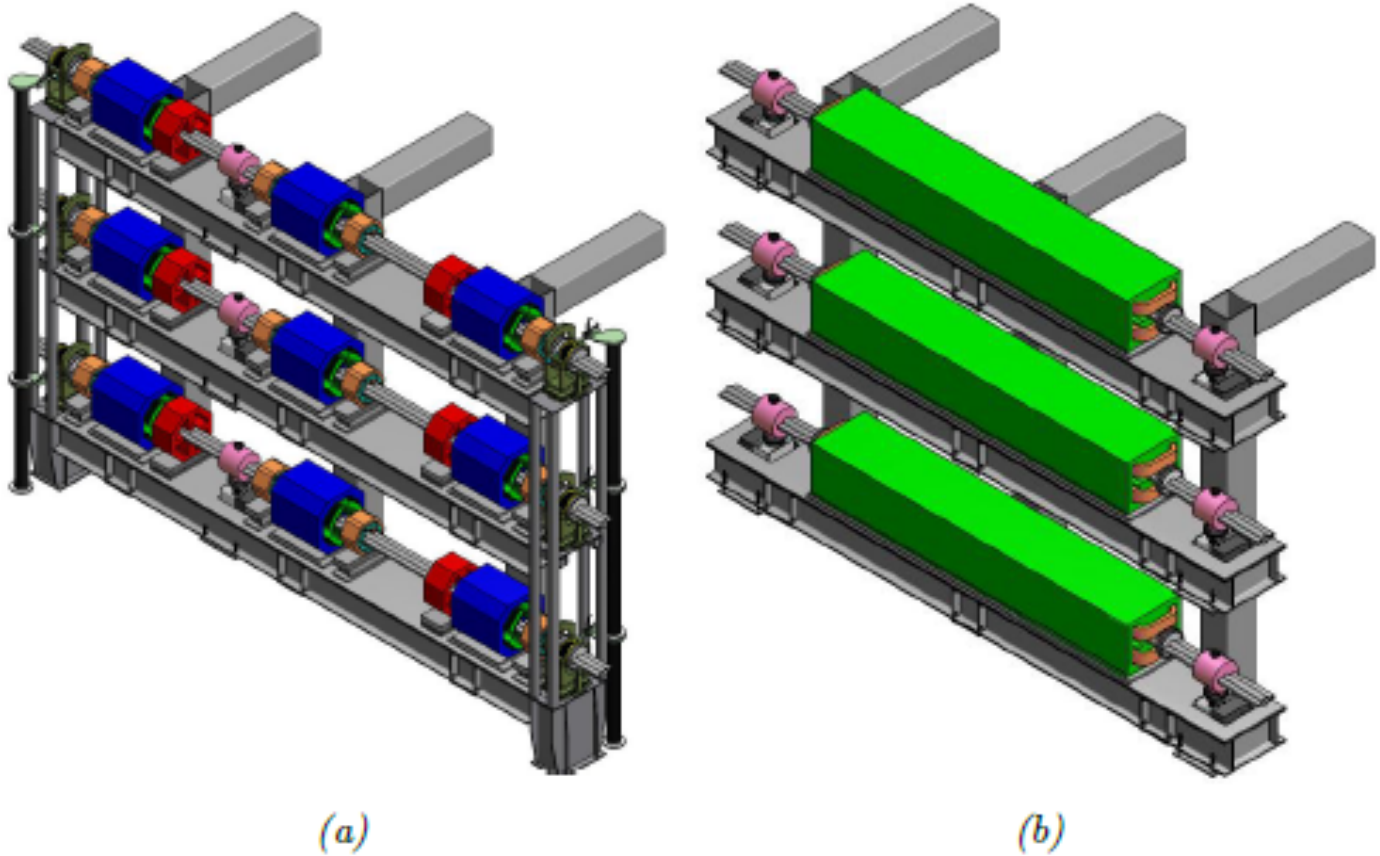
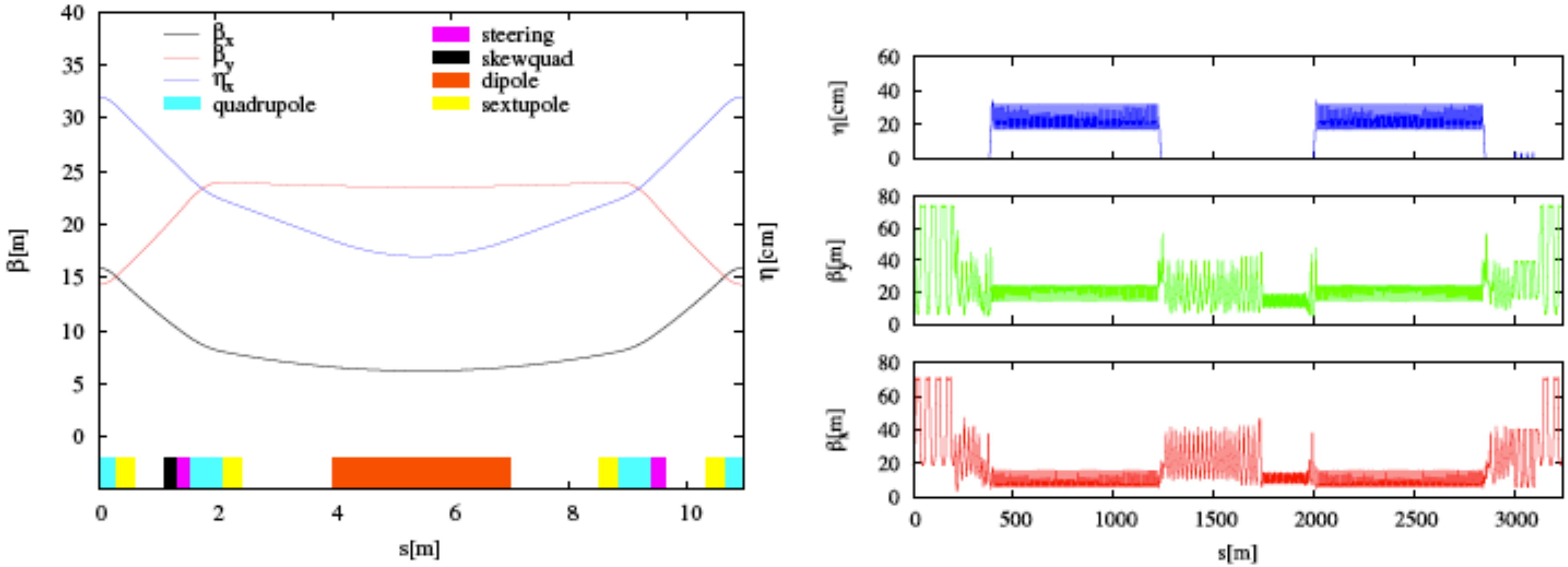


Figure 8.2. Damping ring arc magnet layout with positron ring at the bottom and electron ring directly above. A second positron ring would be placed above the electron ring if required: arc a) quadrupole section layout and b) dipole section layout.

Doubling of current in e+ DR for high luminosity upgrade poses concern for electron cloud effects. If mitigation techniques are not sufficient, possibility of installing a second e+ ring in the same tunnel.

Arc Cell and Damping Ring Lattice Functions



(a) *(b)*

Figure 8.3. a) Arc cell. The cell boundaries are at the midpoint of the focusing quadrupole. There is one each vertical and horizontal dipole corrector and a skew quad corrector in each cell, and two beam position monitors adjacent to the defocusing sextupoles. b) Damping ring lattice functions. From left to right extraction, arc, phase trombone, RF, wigglers, arc, circumference chicane, and injection

BPM, Magnet Alignment Tolerances and Dynamic Aperture, Specified Geometric Vertical Emittance of 2pm-rad

Table 8.3. BPM and magnet alignment tolerances.

Parameter	RMS
BPM Differential resolution†	2 µm
BPM Absolute resolution	100 µm
BPM Tilt	10 mrad
BPM differential button gain	1%
Quad & Sextupole Offset (H&V)	50 µm
Quadrupole Tilt	100 µrad
Dipole Roll	100 µrad
Wiggler vertical Offset	200 µm
Wiggler - Roll	200 µrad

† Reproducibility of single pass measurement

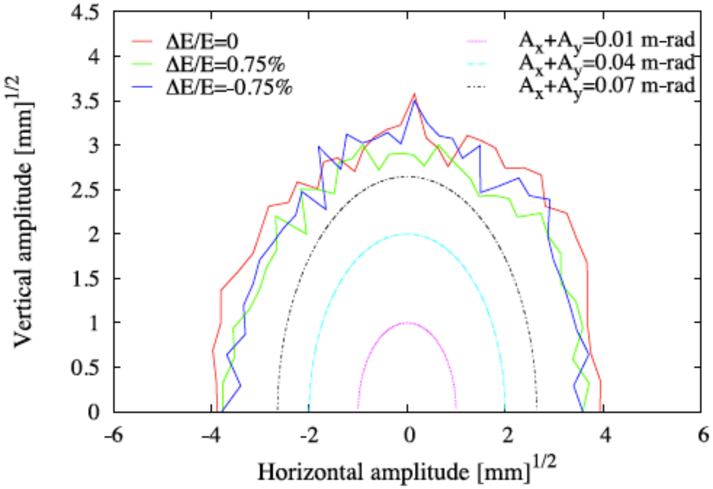
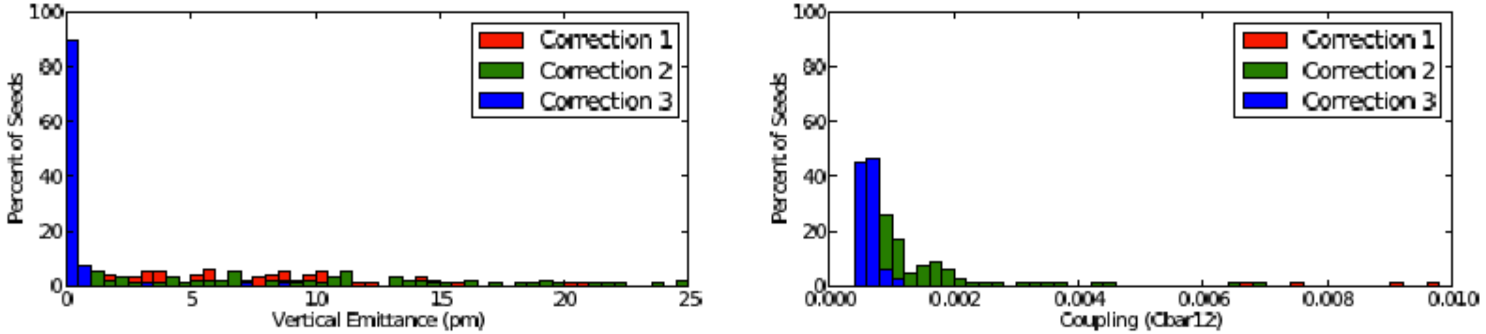


Figure 8.5. Dynamic aperture including multipoles, wiggler nonlinearities and magnet misalignments. Defined as the largest stable amplitude after tracking 1000 turns.



(a) (b)

Figure 8.4. Histogram of the a) vertical emittance and b) rms coupling ($\overline{C}_{12}$) at the conclusion of each step in the low emittance tuning procedure for 100 lattice files with randomly chosen misalignments and multipole errors.

Electron Cloud Mitigations and Modeling Results

Table 8.4. EC mitigations specified for the positron DR.

Magnetic Region	Primary Mitigation	Secondary Mitigation
Drift	TiN Coating	Solenoid Windings
Dipole	Grooves wtih TiN Coating	Antechamber
Wiggler	Clearing Electrodes	Antechamber
Quadrupole	TiN Coating	—

Table 8.5. POSINST modeling results for EC densities N_e (10^{11} m^{-3}) in the dipole regions of the DTC and DSB3 lattices

	DSB3		DTC	
Cloud Densities	SEY=0	SEY=1.0	SEY=0	SEY=0.94
At end of a 34-bunch train	~ 0.2	~ 0.4	~ 0.5	~ 1.2
20-σ peak during train	~ 0.1	~ 0.2	~ 0.2	~ 0.5
20-σ prior to bunch passage	~ 0.1	~ 0.2	~ 0.2	~ 0.4

Measurements in CESRTA, simulations with several codes for various bunch configurations, chamber geometries and coatings (ILC e-cloud WG). Recommendations for mitigations include coating, grooves, clearing electrodes, solenoids and antechambers

Fast Ion Instability in Electron Damping Ring

Simulation Codes based on week strong model predict confirmed by Experimental result very fast rise of vertical emittance due to FII. Growth rate reduced when introducing train mini-gaps

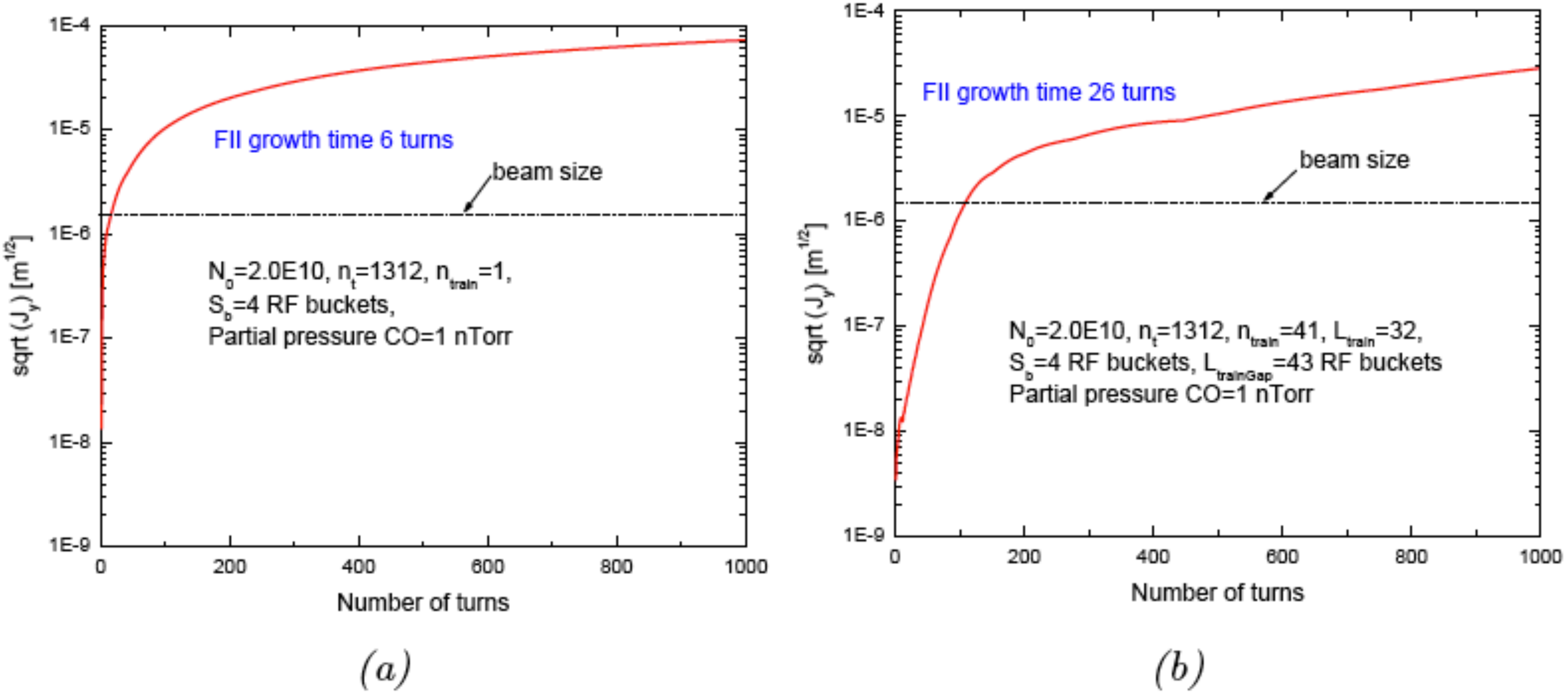
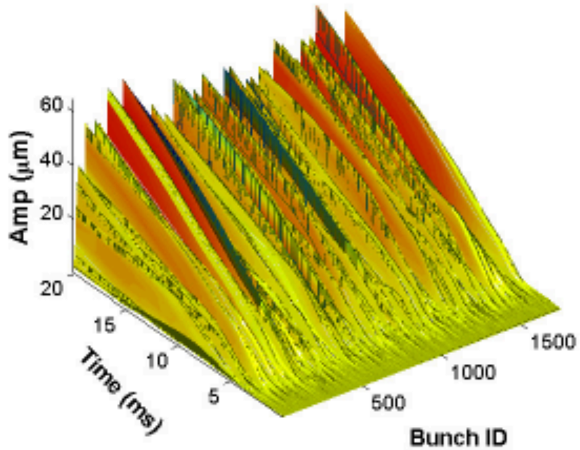


Figure 8.6. Simulated vertical amplitude vs number of turns for a) 1312 bunches in a single train at 1 nT CO and b) for 41 trains of 32 bunches.

Simulated Vertical Amplitude versus time due to Fast Ion Instability



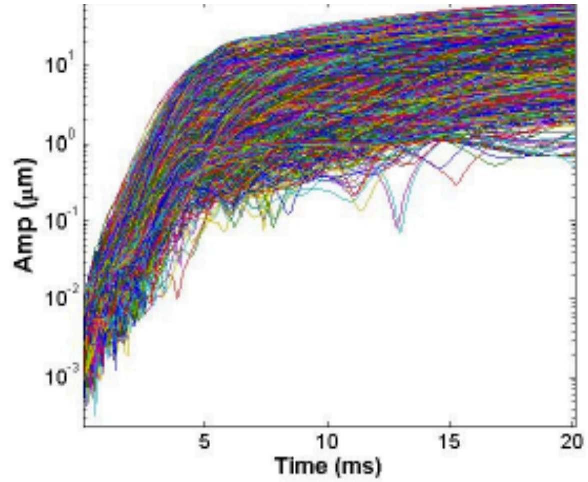
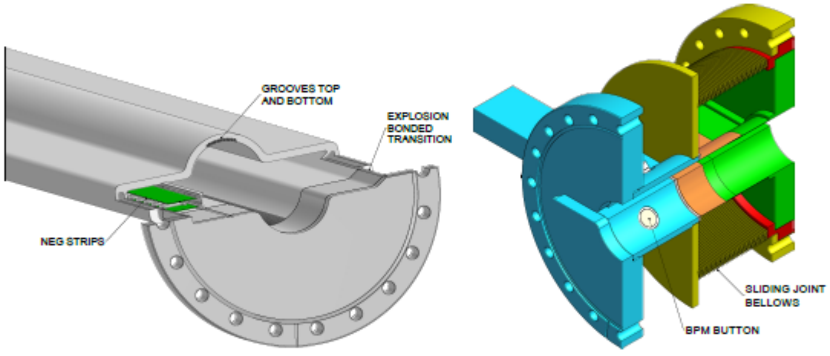


Figure 4. Simulated vertical beam ion instability in KCS configuration. The vertical oscillation amplitude in the left plot is in linear scale, while it is in logarithmic scale in the right plot. The different lines in the plots are for different bunches. The vertical instability growth time is 0.61 ms.

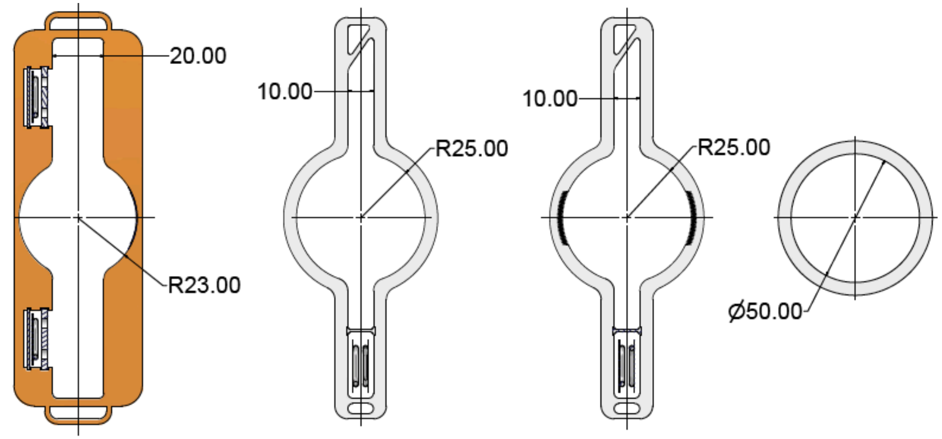
Simulation Codes confirmed by experimental results at ATF-DR, CesrTA, SPEAR3 and low emittance SR Rings predict that fast ion instability can be mitigated with good vacuum level less than 1nT, many train operation with train gap and b-by-b feedback system.

Vacuum System



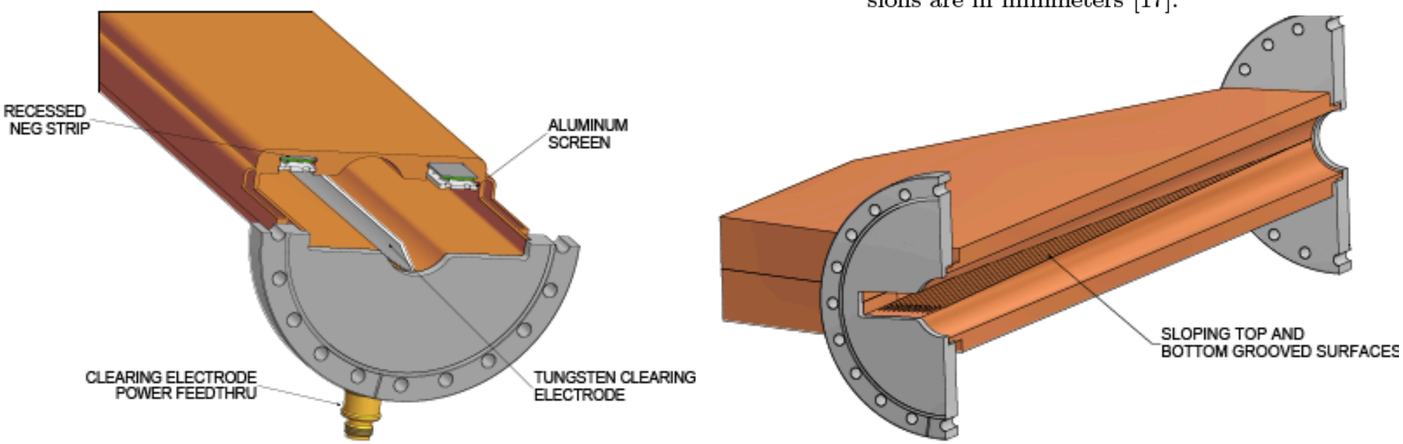
(a) *(b)*

Figure 8.8. (a) Dipole Chamber with grooved top and bottom surfaces, radially inside antechamber with NEG strips, and radially outside antechamber with sloped wall. (b) BPM and sliding joint assembly. [17].



(a) WIGGLER CHAMBER (b) ARC CHAMBER (c) DIPOLE CHAMBER (d) DRIFT CHAMBER

Figure 8.10. Side-by-side comparison of ILC DR vacuum chamber profiles. Dimensions are in millimeters [17].



(a) *(b)*

Figure 8.9. (a) Wiggler vacuum chamber with clearing electrode and 20 mm tall antechambers with recessed NEG strips. (b) Wiggler section photon stop showing sloping and grooved photon-absorbing walls [17].

Extraction Kicker

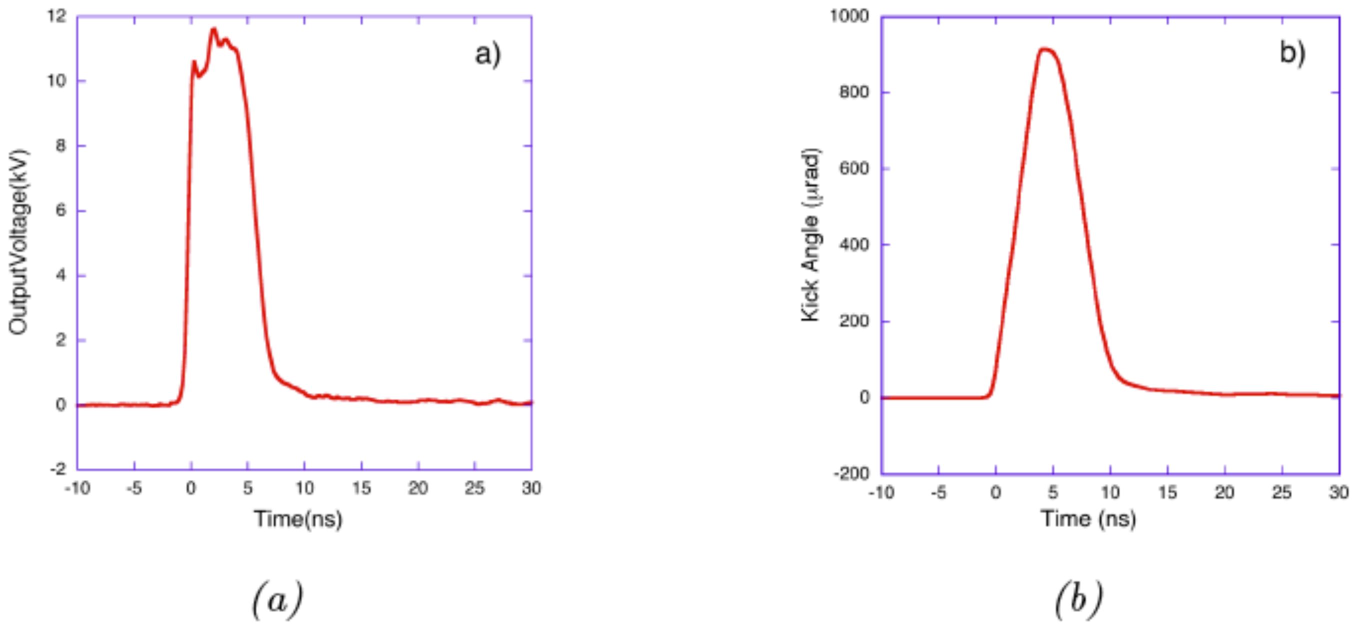
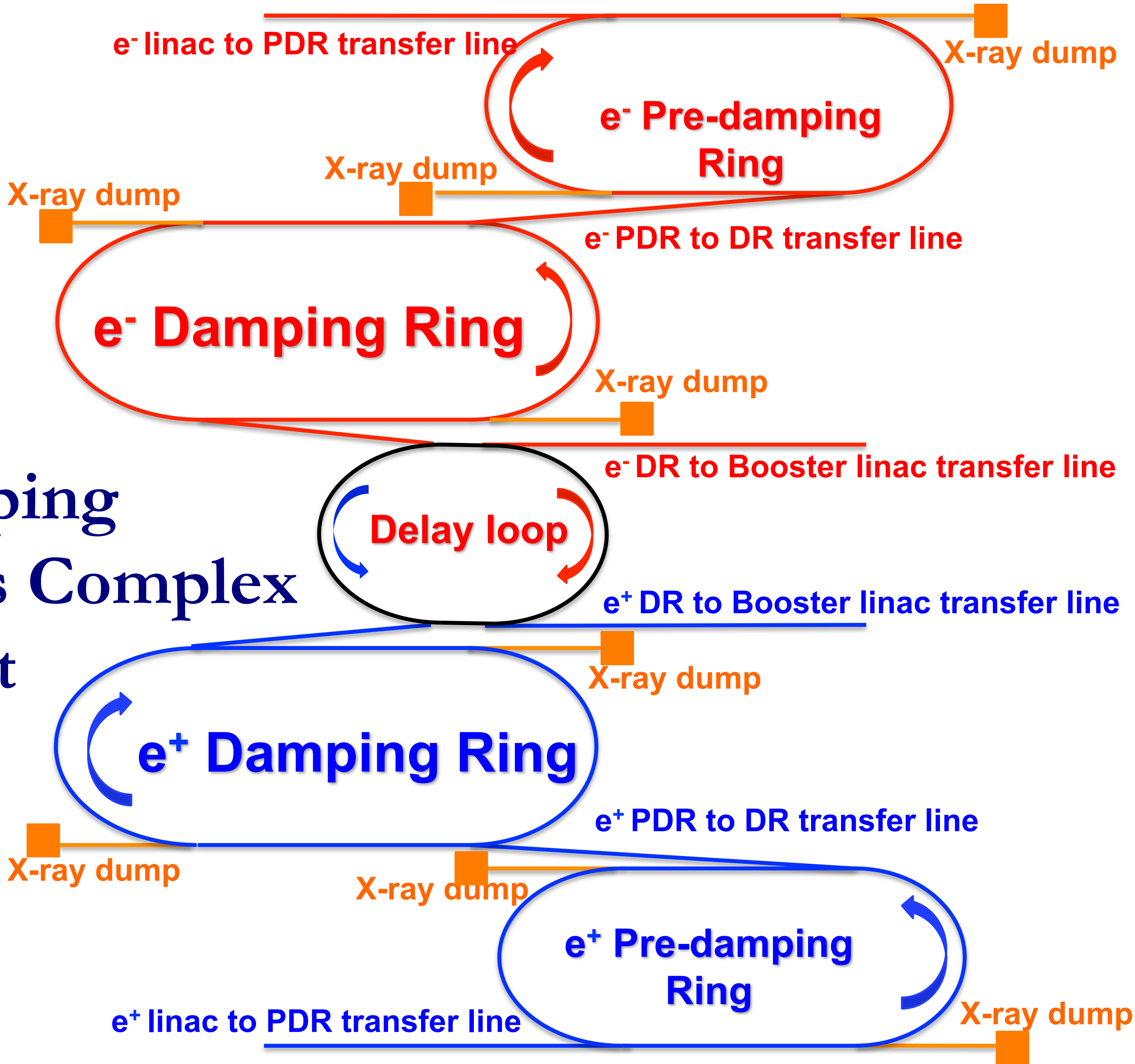


Figure 8.11. (a) Pulse waveform of the FID pulser; and (b) estimated kick obtained using the 60 cm stripline kicker in the KEK-ATF beamline.

Very tight kicker jitter tolerance performance (<5e-4) confirmed in ATF experimental results (single bunch extraction for train of 10 bunches with spacing of 5.6 ns). Need to address impedance issues for 42 strip-line kickers (30cm long, 30mm gap)

CLIC Damping Rings Complex layout



CLIC DR challenges and adopted solutions

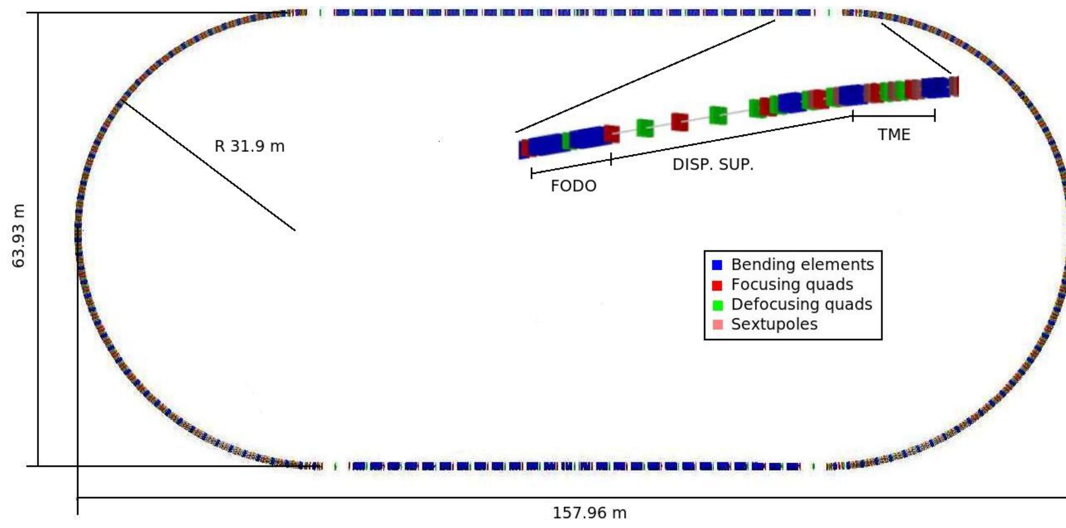
Target parameters	CLIC
Bunch population (10^9)	4.1
bunch spacing [ns]	0.5
number of bunches	312
Repetition rate [Hz]	50
Norm. emit. h/v [nm]	500/5
Norm. emit. l [keV.m]	6

Design Parameters	CLIC DR
Energy [GeV]	2.86
Circumference [m]	427.5
Energy loss/turn [MeV]	4.0
RF voltage [MV]	5.1-4.5
Compaction factor	1.3×10^{-4}
Damping time x / s [ms]	2.0/1.0
No bends / wigglers	100/52
Dipole/ wiggler field [T]	1.0/2.5

- High-bunch density in all three dimensions
  - **Intrabeam Scattering** effect reduced by choice of ring energy, lattice design, wiggler technology and alignment tolerances
  - **Electron cloud** in e^+ ring mitigated by chamber coatings and efficient photon absorption
  - **Fast Ion Instability** in the e^- ring reduced by low vacuum pressure and large train gap
  - **Space charge vertical tune-shift** limited by energy choice, reduced circumference, bunch length increase
  - Other collective instabilities controlled by low – impedance requirements on machine components
- Repetition rate and bunch structure
  - Fast damping times achieved with SC wigglers
  - RF frequency reduction @ 1GHz considered due to many challenges @ 2GHz (power source, high peak and average current, transient beam loading)
- Output emittance stability
  - Tight jitter tolerance driving kicker technology
- Positron beam dimensions from source
  - Pre-damping ring challenges (energy acceptance, dynamic aperture) solved with lattice design

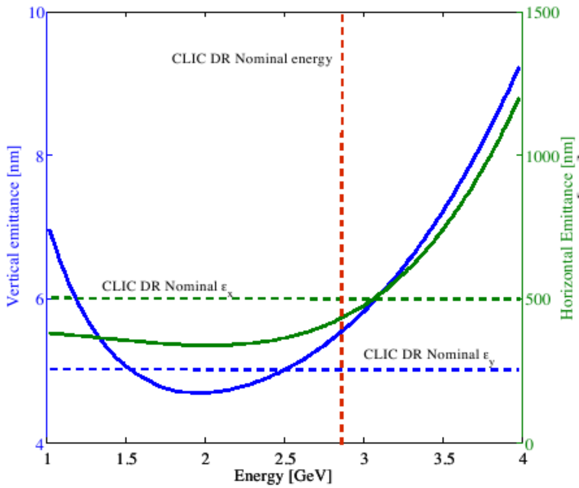
CLIC DR layout and parameters

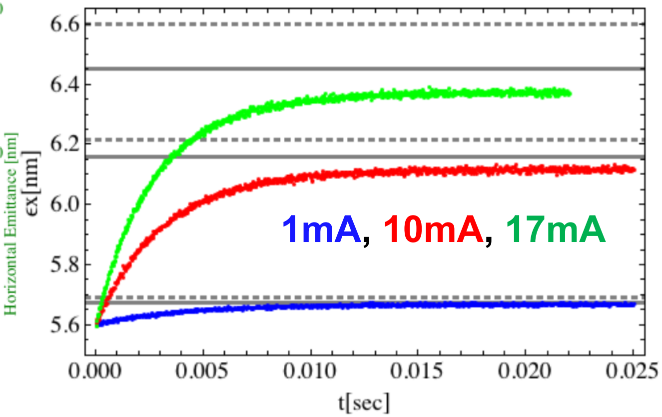
Parameters	1GHz	2GHz
Energy [GeV]	2.86	
Circumference [m]	**427.5**	
Energy loss/turn [MeV]	**4.0**	
RF voltage [MV]	**5.1**	**4.5**
Stationary phase [°]	**51**	**62**
Natural chromaticity x / y	**-115/-85**	
Momentum compaction factor	**1.3e-4**	
Damping time x / s [ms]	**2.0/1.0**	
Number of dipoles/wigglers	100/52	
Cell /dipole length [m]	**2.51 / 0.58**	
Dipole/Wiggler field [T]	**1.0**/2.5	
Bend gradient [1/m2]	-1.1	
Phase advance x / z	**0.408/0.05**	
Bunch population, [e9]	4.1	
IBS growth factor x/z/s	**1.5/1.4/1.2**	
Hor./ Ver Norm. Emittance [nm.rad]	**456/4.8**	**472/4.8**
Bunch length [mm]	**1.8**	**1.6**
Longitudinal emittance [keVm]	**6.0**	**5.3**
Space charge tune shift	**-0.10**	**-0.11**



- 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 (optics design ready) and RF cavities
- Circumference reduced (30% less wigglers)

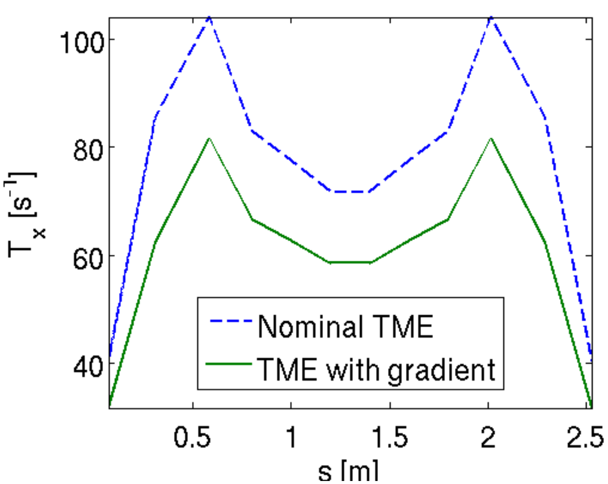
Intrabeam Scattering theory, simulations and measurements

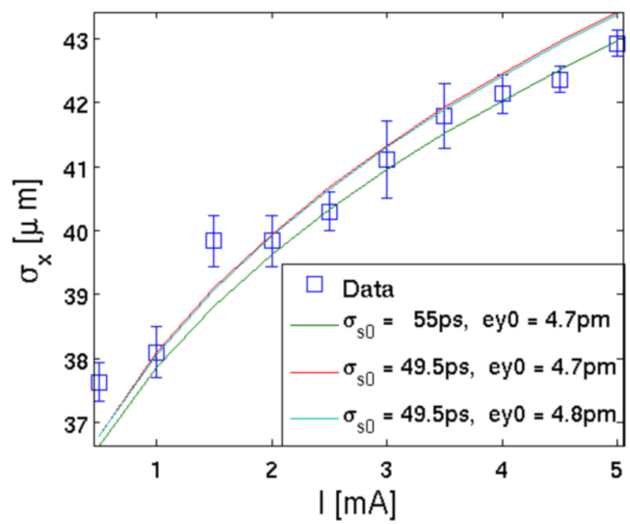




F. Antoniou, et al.

- Energy choice and lattice design for reducing effect from IBS
- Monte-Carlo tracking codes developed based on Ratherford Coulomb scattering cross section
  - Code agreement for lower currents, more divergence at high currents
- First measurements at SLS-PSI with good agreement with theoretical predictions



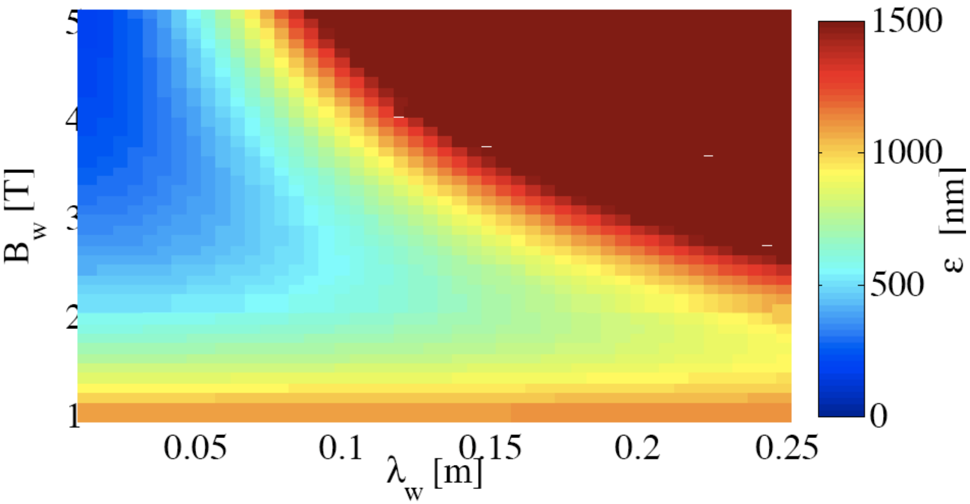


Other collective effects

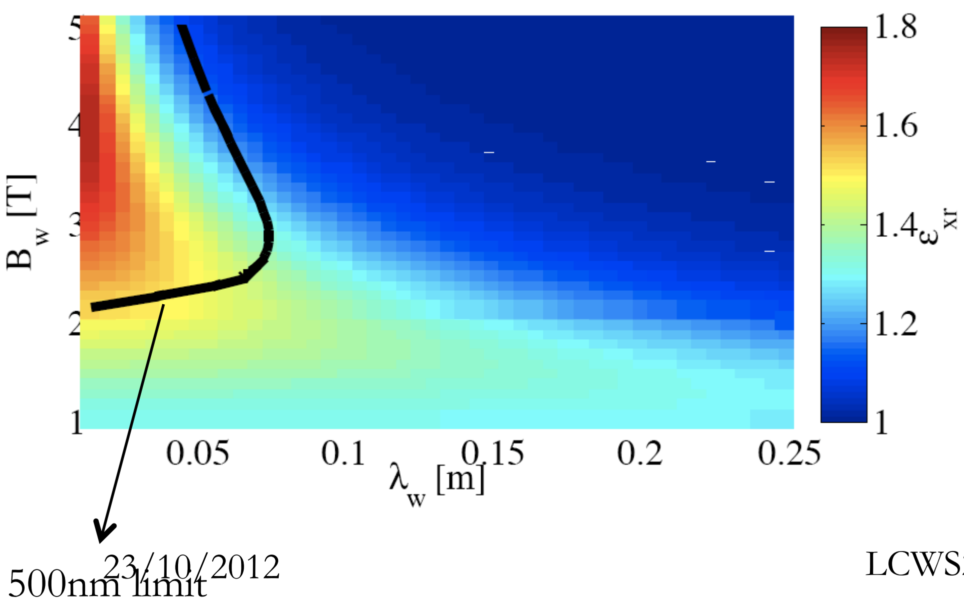
E. Koukovini-Platia, G. Rumolo, et al.

- Space-charge reduced <0.1 with combined circumference reduction and bunch length increase
- e-cloud in the e^+ DR imposes limits in PEY (99.9%) and SEY (<1.3) achieved with wiggler absorption scheme and chamber coatings (amorphous carbon)
- Fast ion instability in e^- DR constrains vacuum pressure to around 0.1nTorr (large train gap also helps)
- Single bunch instabilities avoided with smooth vacuum chamber design
  - Simulations for instability thresholds for resistive wall
- Resistive wall coupled bunch controlled with feedback
  - Conceptual design of 1-2GHz b-b-b feedback by **T. Nakamura** (SPring8)
- Impedance estimates for effect of multiple material layers
- Coherent synchrotron radiation estimates do not

Wiggglers' effect with IBS



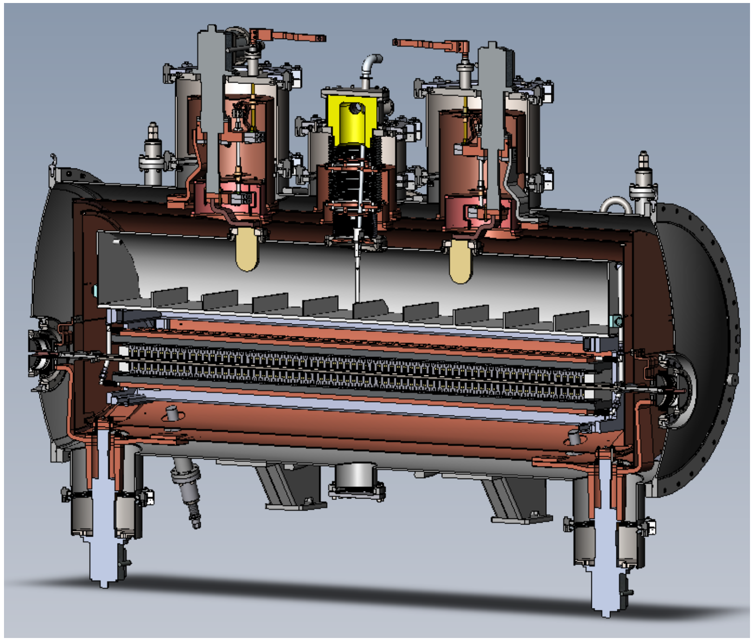
F. Antoniou

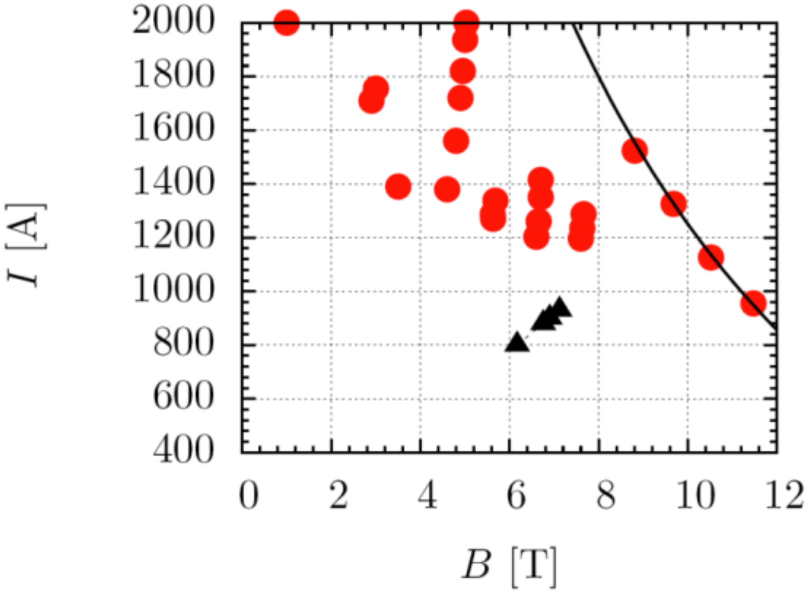


- Stronger wiggler fields and shorter wavelengths necessary to reach target emittance due to strong IBS effect
- Stronger field and moderate wavelength reduces IBS effect while reaching target emittance
- Current density can be increased by different conductor type
- Nb_3Sn can sustain higher heat load (~10 times higher than NbTi)
- Two wiggler mock-ups
  - 2.5T, 5cm period NbTi (CERN/ BINP)
  - 2.8T, 4cm period, Nb_3Sn (CERN)
  - Magnetically tested achieving required performance

SC wiggler development

A. Bernard, P. Ferracin, N. Mesentsev, D. Schoerling, et al.

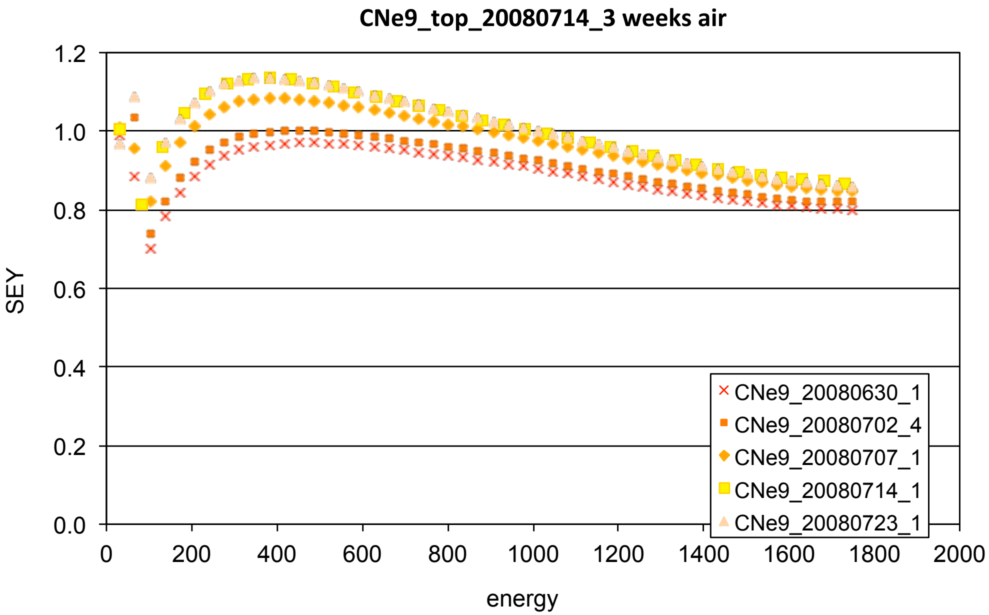


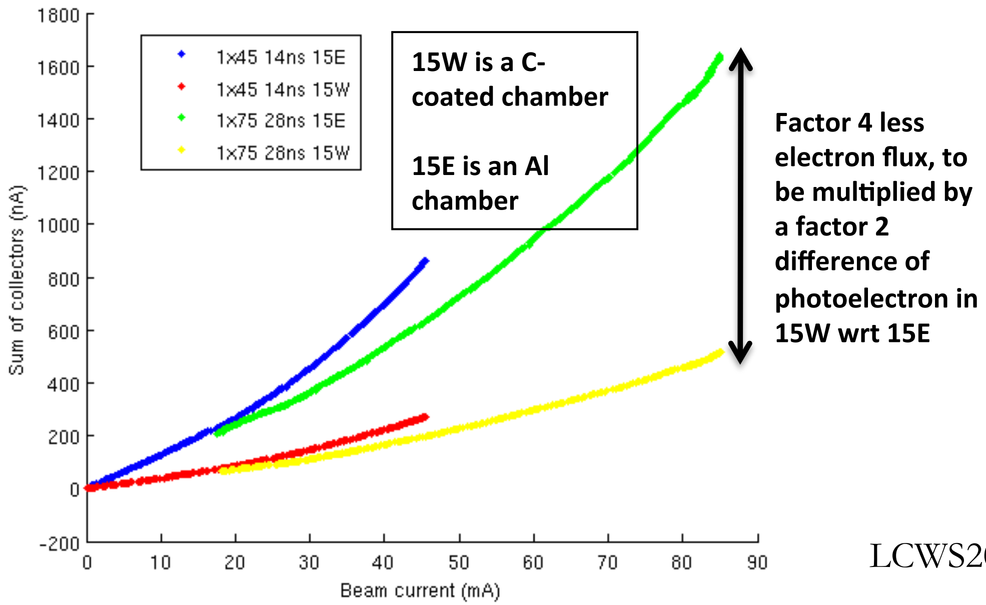


- Two paths of R&D
  - NbTi wire, horizontal racetrack, conduction cooled (BINP/KIT collaboration)
  - Nb_3Sn wire, vertical racetrack, conduction cooled (CERN)
- Full NbTi length prototype
  - Higher than 3T, 5.1cm period, magnetic gap of 18mm
  - Under production by BINP to be installed in 2014 in ANKA for beam tests
  - Operational performance, field quality, cooling concept
- First vertical racetrack magnet (3-period) tested in 2011
  - Reached 75% of max. current
  - Limited by short coil-to-structure
  - Still higher than NbTi (900 A vs. 700 A)

Vacuum technology

S. Calatroni, M.Palmer, G. Rumolo, M. Taboreli et al.





- Amorphous-C coating shows maximum SEY starting from below 1 and gradually growing to slightly more than 1.1 after 23 days of air exposure
  - Peak of the SEY moves to lower energy
- Experimental tests
  - Huge amount of data at SPS
  - Run with 5 GeV positrons at CESRTA, for different intensities and bunch spacings
  - The total electron current reduced significantly (1 order of magnitude) as compared to Al
  - Continuing collaboration with ESRF for PEY tests in a dedicated beamline

A. Grudiev

RF system

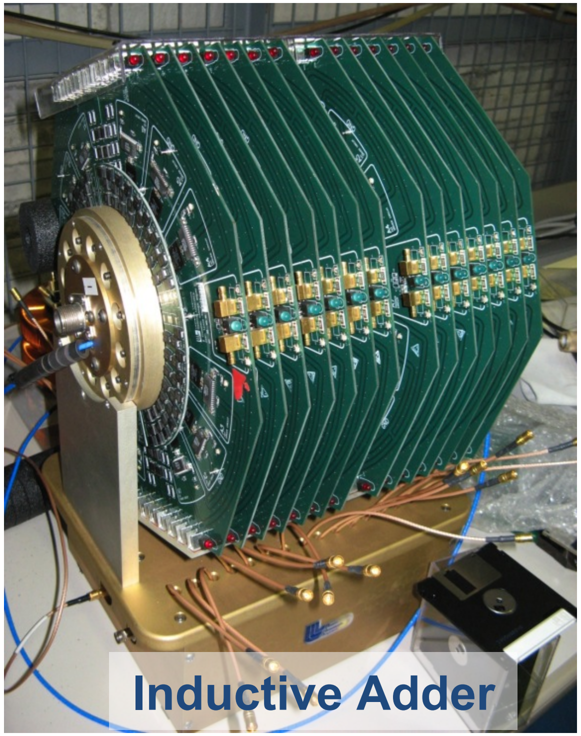
- Single train of 312 bunches spaced at 0.5ns necessitates 2GHz system
  - R&D needed for power source
  - Large average and peak current/power introduces important transient beam loading
- Considered 1GHz system
  - Straight-forward RF design but train recombination in a delay loop is needed

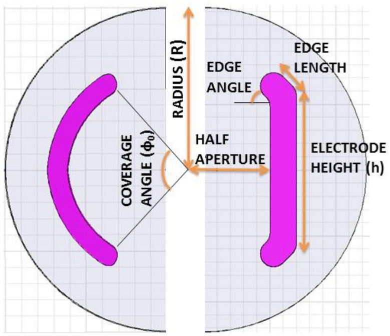
RF design concepts	1 GHz	2 GHz **no train interleaving after DR**
Classical RF system based on the NC ARES-type cavities	Baseline P_{RF} = 3.8 MW; L = 32 m; Cavity design: OK	Alternative 2.0 P_{RF} = 5.9 MW; L = 48 m; Cavity design: ok?
Classical RF system based on the SCC cavities	Alternative 1.1 P_{RF} = **0.6** MW; L = 108 m; Cavity design: **ok?**	Alternative 2.1 P_{RF} = **0.6** MW; L = **800** m; Cavity design: **NOT OK**
RF system with RF frequency mismatch	Alternative 1.2 P_{RF} = **1.3** MW; L = **16** m; Cavity design: **OK**	Alternative 2.2 P_{RF} = 2.1 MW; L = 24 m; Cavity design: OK
"A-la-linac" RF system with strong input power modulations	Alternative 1.3 P_{RF} = 3.3 MW; L = **8** m; Cavity design: **OK**	Alternative 2.3 P_{RF} = 5.8 MW; L = **12** m; Cavity design: **OK**

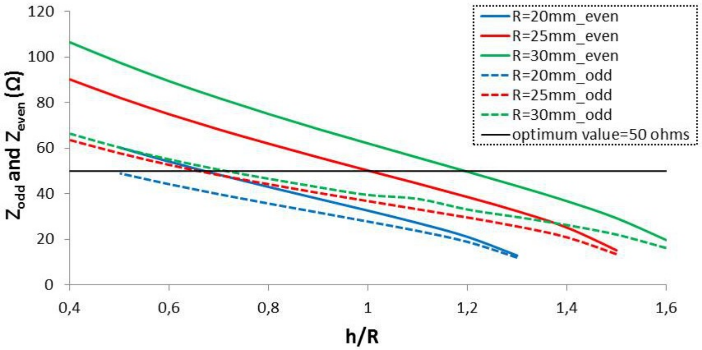
Extraction kicker design

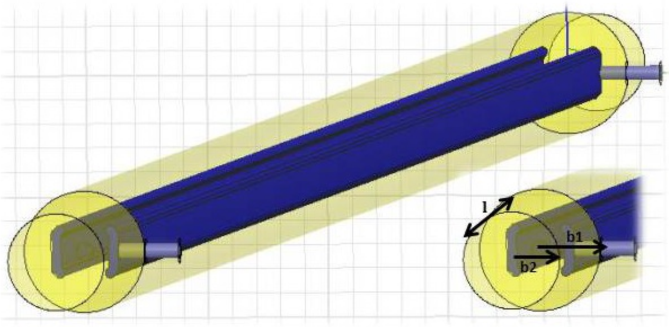
M. Barnes, C. Belver- Aguilar, A. Faus Golfe et al.

- Kicker jitter tolerance ~ few 10^{-4}
- Striplines required for achieving low longitudinal coupling impedance
- Significant R&D needed for PFL (or alternative), switch, transmission cable, feed-throughs, stripline, terminator
  - Prototyped under the Spanish Program "Industry for Science"
  - Collaboration is set-up with ALBA synchrotron and ATF for beam tests

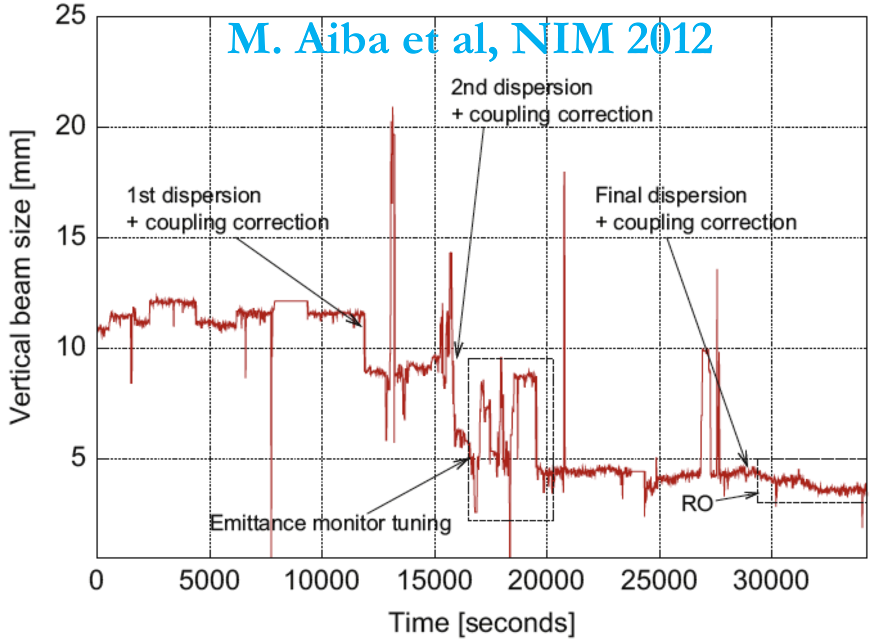








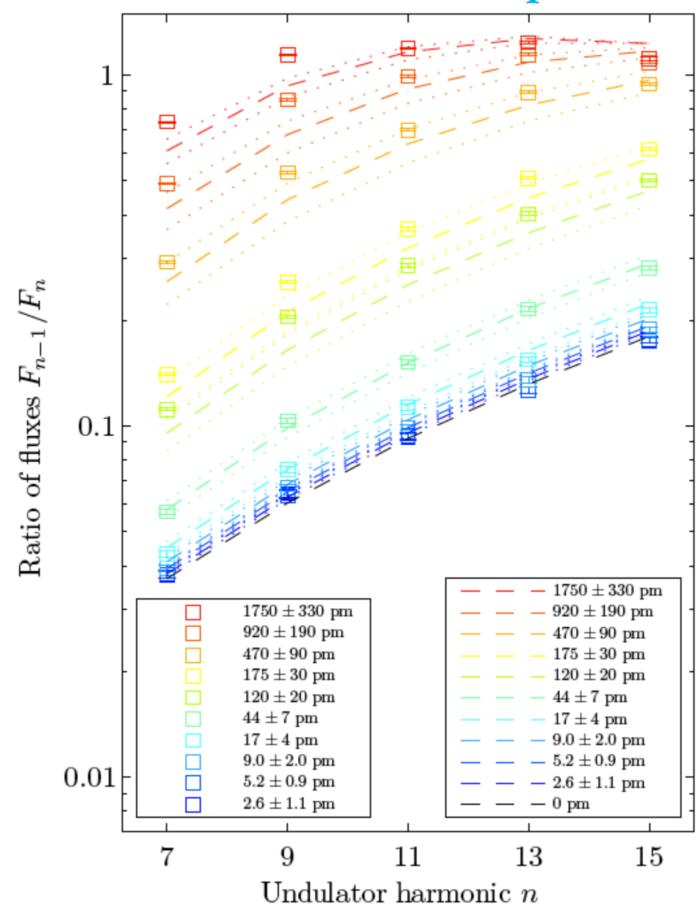
Reaching Quantum L_{imit} O_f $V_{ertical}$ $E_{mittance}$



- EU collaboration between PSI-SLS (Maxlab), INFN-LNF and CERN (TIARA-SVET) for low emittance tuning techniques and instrumentation
  - SLS achieved ε_y record of 0.9 ± 0.4pm (confirmed with different techniques)
  - New emittance monitor for resolutions below 3μm (vertical polarized light) under installation for measurements in 2013

- Tousheck lifetime vs. RF voltage in ASLS points to ε_y = 1.24 ± 0.3pm
  - New technique for resolving ultra-low beam sizes using vertical undulator

K. Wootton, et al, PRL, accepted



DR technology and experimental program

- **Super-conducting wigglers**
  - Demanding magnet technology combined with cryogenics and high heat load from synchrotron radiation (absorption)
- **High frequency RF system**
  - 1-2GHz 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 system

- 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),…
- Ideas for a DR test facility within a future LC test facility

Low Emittance Rings' Collaboration

- Initiated by the ILC-CLIC working group on damping rings and catalyzed by the organization of two workshops (01/2010 @ CERN, 10/2011 @ Heraklion)
  - Common beam dynamics and technology items for synchrotron light sources, linear collider damping rings, b-factories
- Formed a EU network within EUCARD2
  - Coordinated by EU labs
  - Extended collaboration board including colleagues from US and Japan
  - 30 participating institutes world wide
- Proposal approved with 330k€ allocated budget for 4 years starting 05/13