Overview of CLIC damping rings, design challenges, and main parameters of CLIC damping wigglers

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CERN

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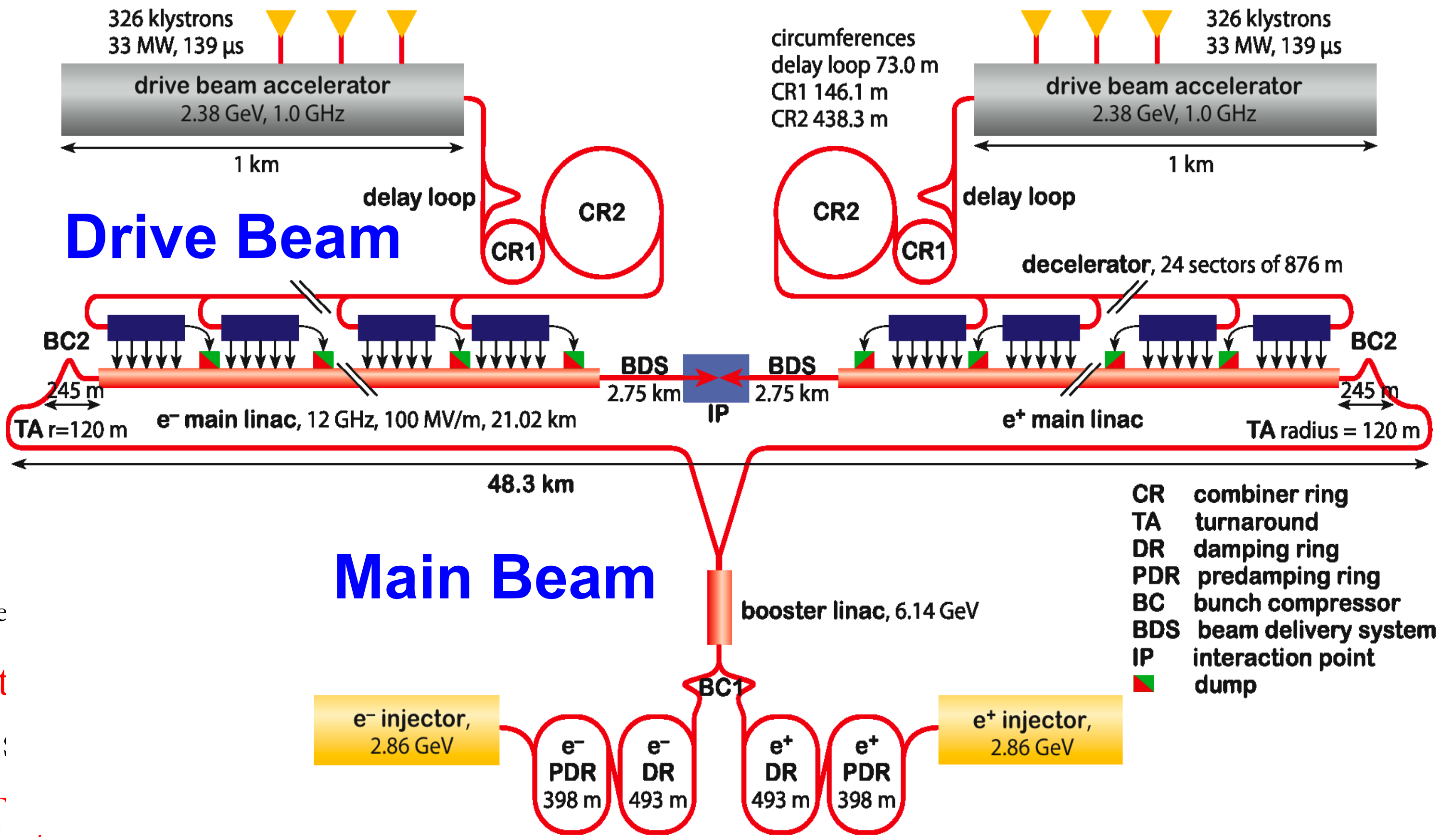
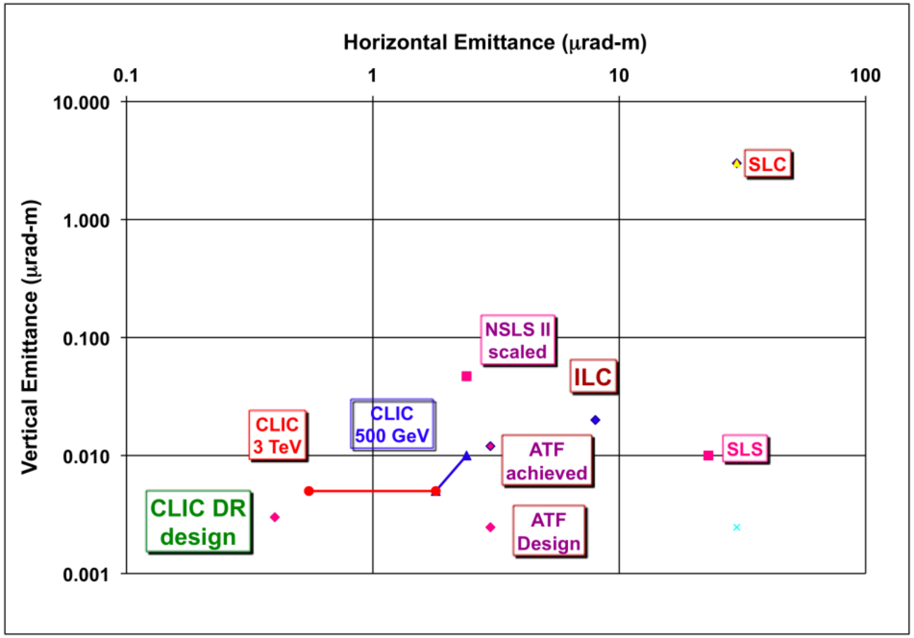
CLIC – in a nutshell

- Compact Linear Collider
- e+/e- collider for up to 3 TeV
- Luminosity $6 \cdot 10^{34} cm^{-2} s^{-1}$ (3 Te
- Normal conduct RF accelerating
- Gradient 100 M
- RF frequency 12 GHz
- Two beam acceleration principle for cost minimisation and efficiency
- Many common points with ILC, similar elements, but different parameters



DR 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	**<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

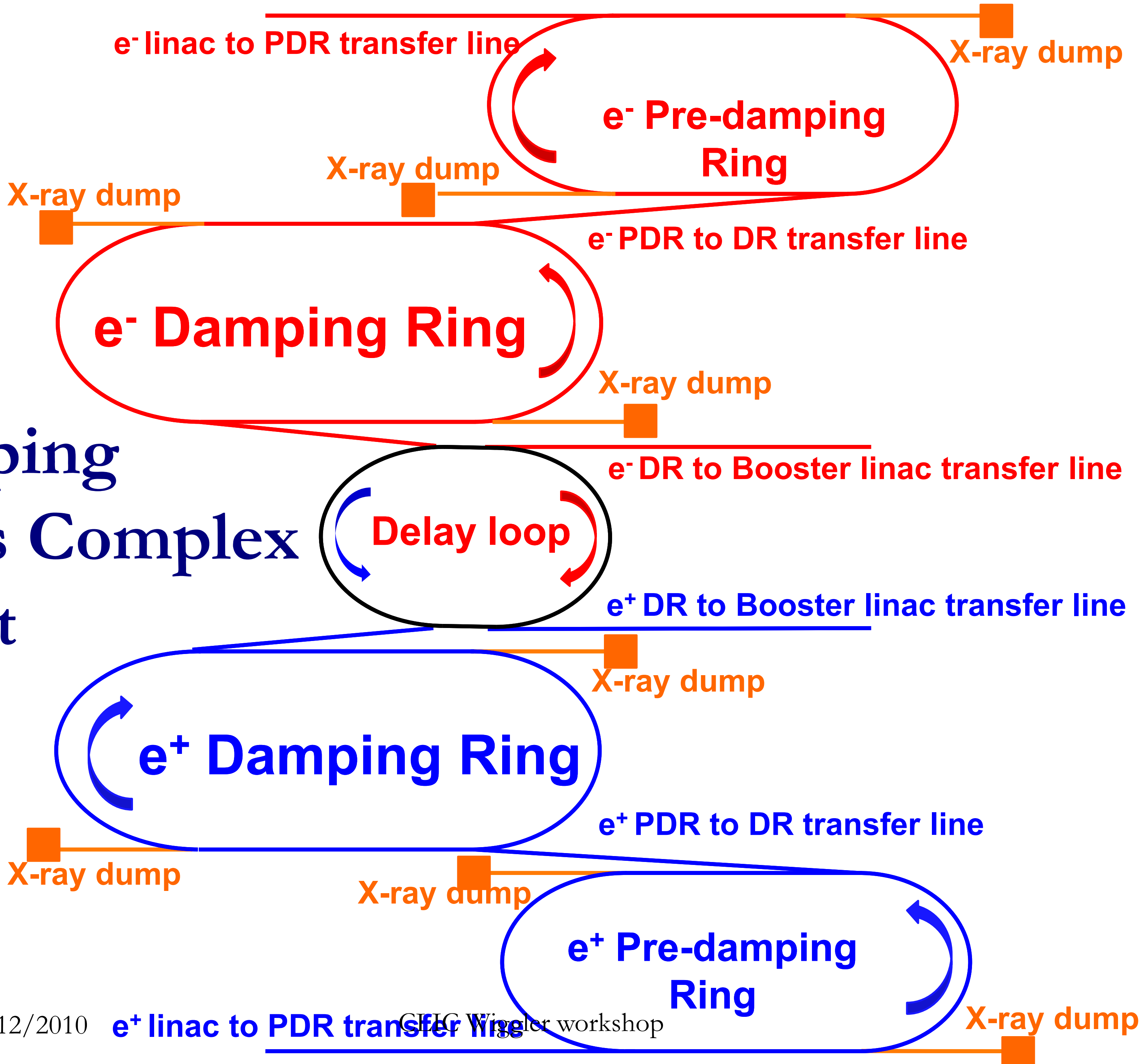
- Damping ring necessary to "cool" the beam to an extremely low emittance in all three dimensions
- Design parameters dictated by target performance of the collider (e.g. luminosity), injected beam characteristics or compatibility with the downstream system parameters
- Most parameters are **driven**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

DR challenges and adopted solutions

Design Parameters	CLIC
Energy [GeV]	2.86
Circumference [m]	420.56
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Compaction factor	$8x10^{-5}$
Damping time x / s [ms]	1.88/0.96
No bends / wigglers	100/52
Dipole/ wiggler field [T]	1.4/2.5

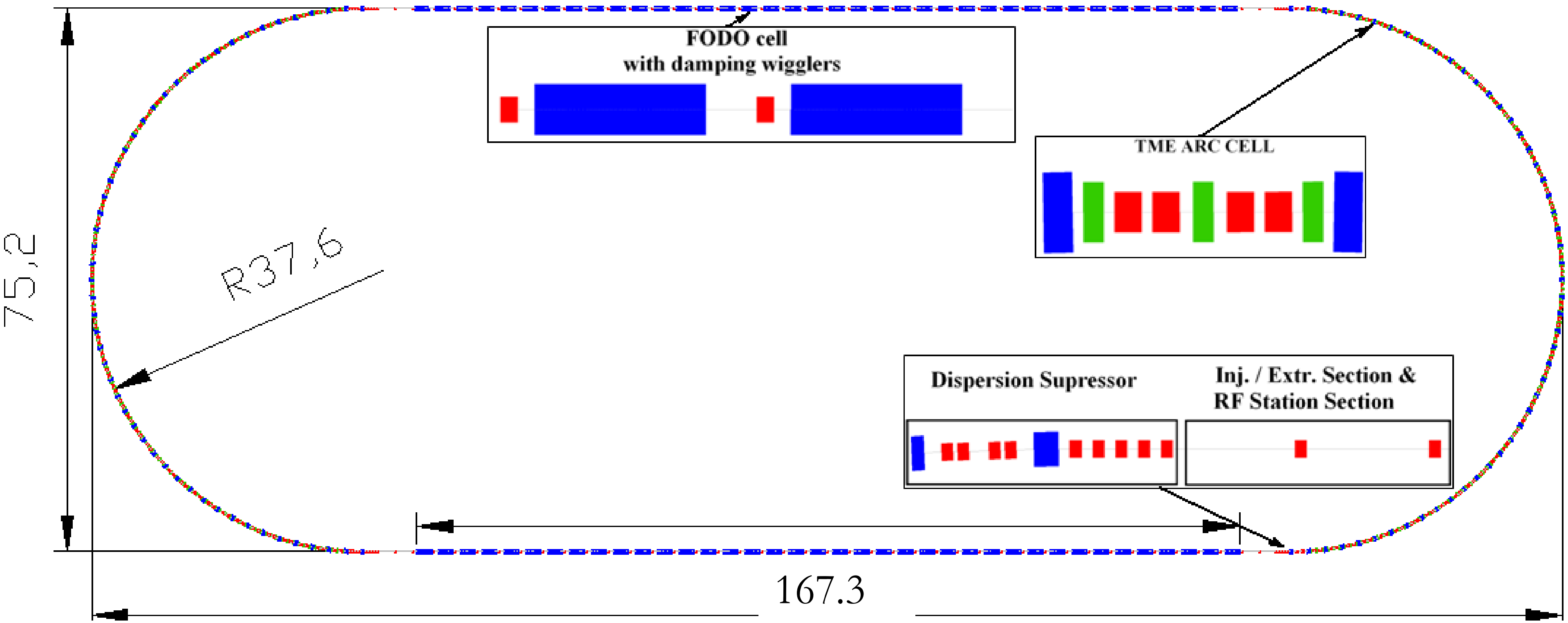
- High-bunch density
  - Emittance dominated by **Intrabeam Scattering**, driving energy, lattice, **wiggler technology choice** and alignment tolerances
  - **Electron cloud** in e^+ ring imposes chamber coatings and efficient photon absorption
  - **Fast Ion Instability** in the e^- ring necessitates 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

Damping Rings Complex layout



DR layout

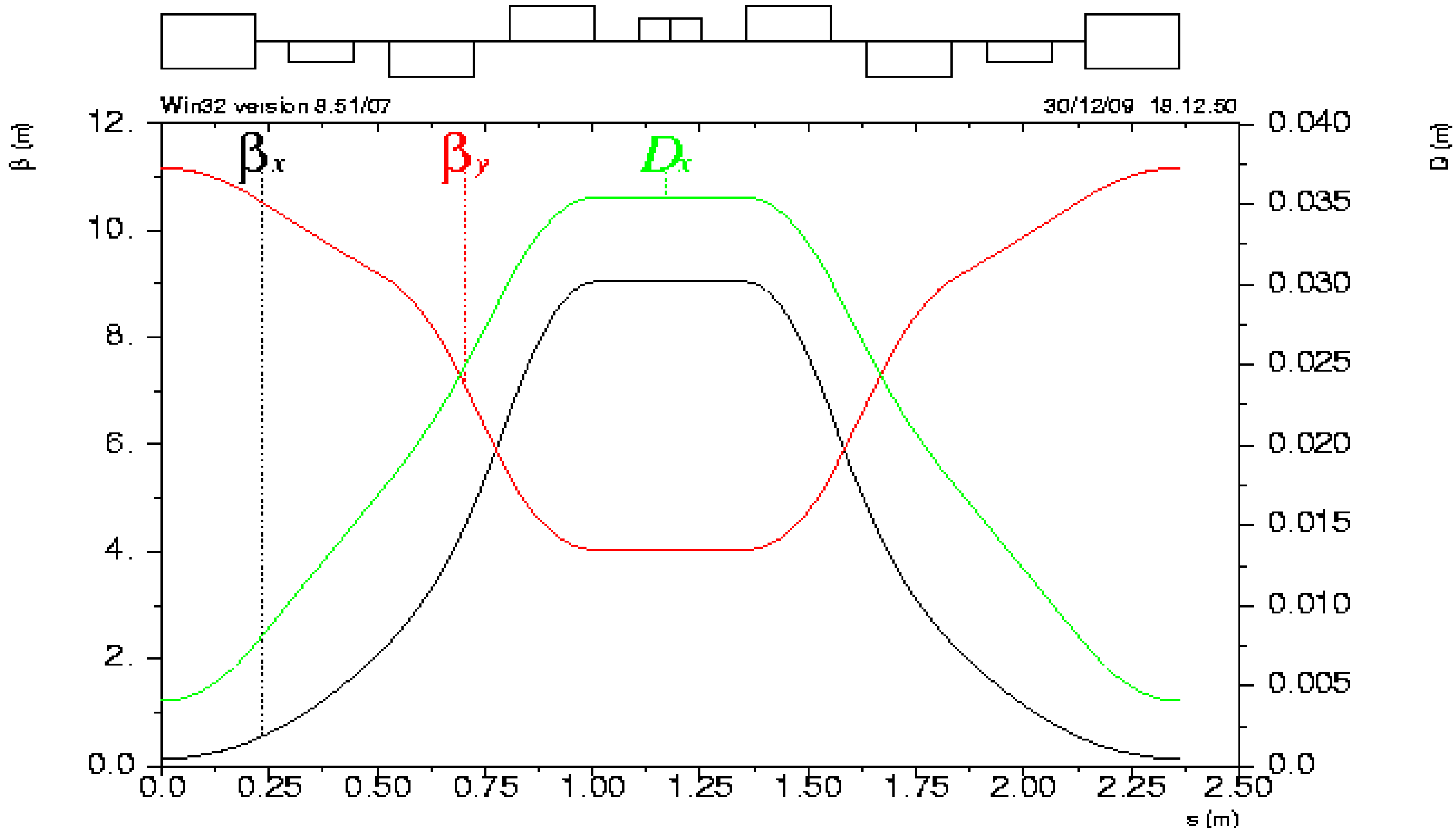
S. Sinyatkin, et al., LER 2010



- 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

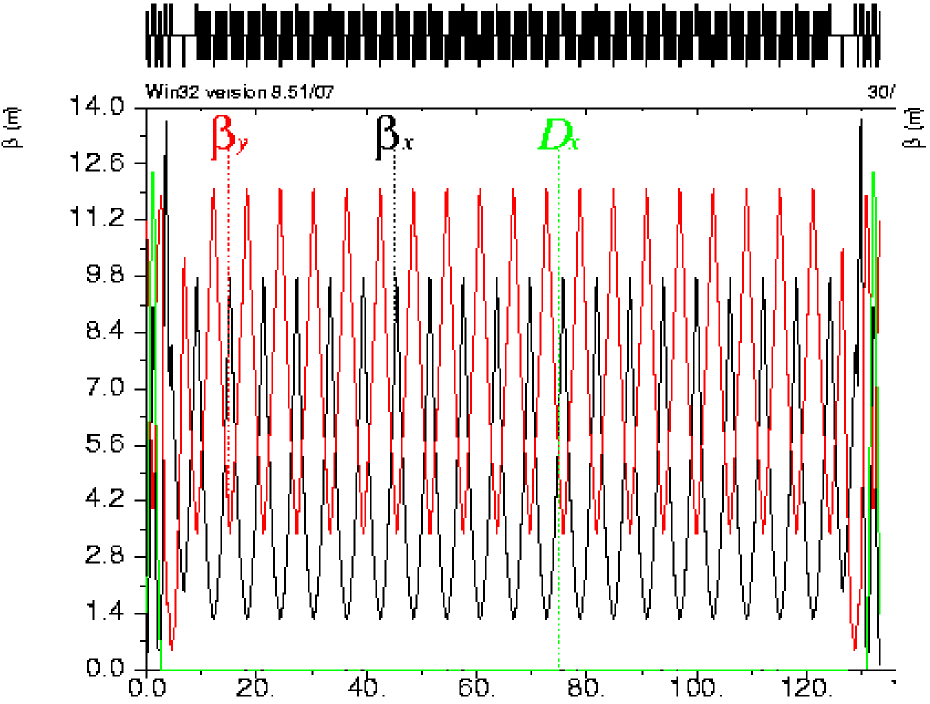
Arc cell

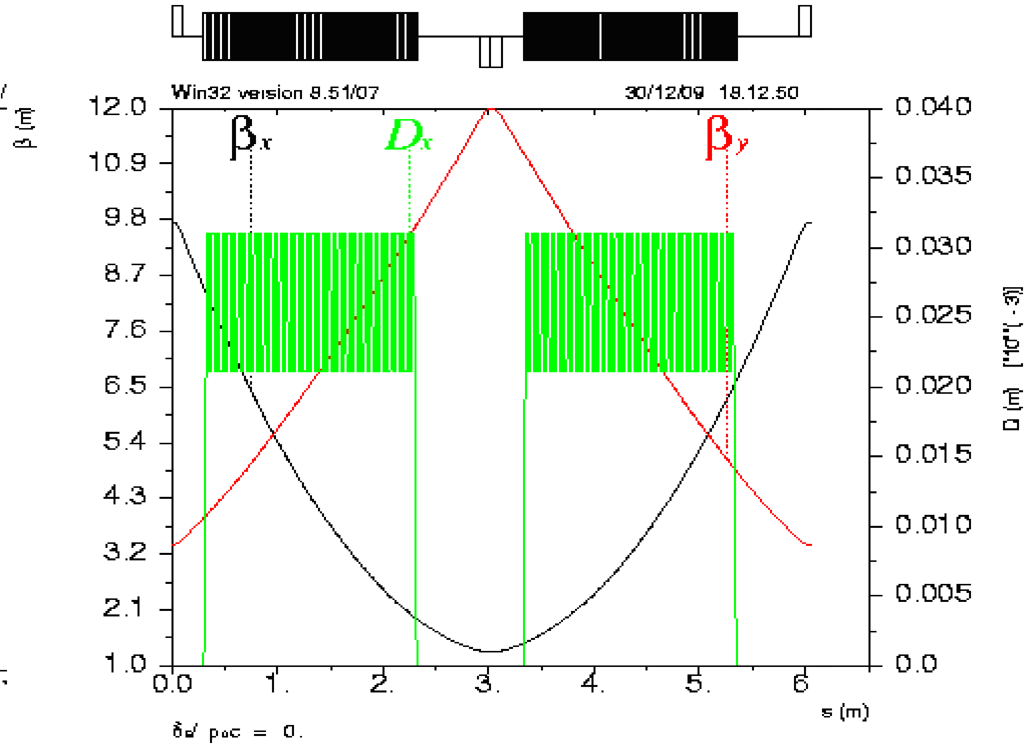
S. Sinyatkin, et al., LER 2010



- 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

Wiggler cell and LSS





- LSS filed with wiggler FODO cells of around ~6m
- Horizontal phase advance optimised for minimizing emittance with IBS, vertical phase advance optimised for aperture
- Drifts of 0.6m downstream of the wigglers may need to be increased (~1m) for absorbers, vacuum equipment and instrumentation

DR parameters

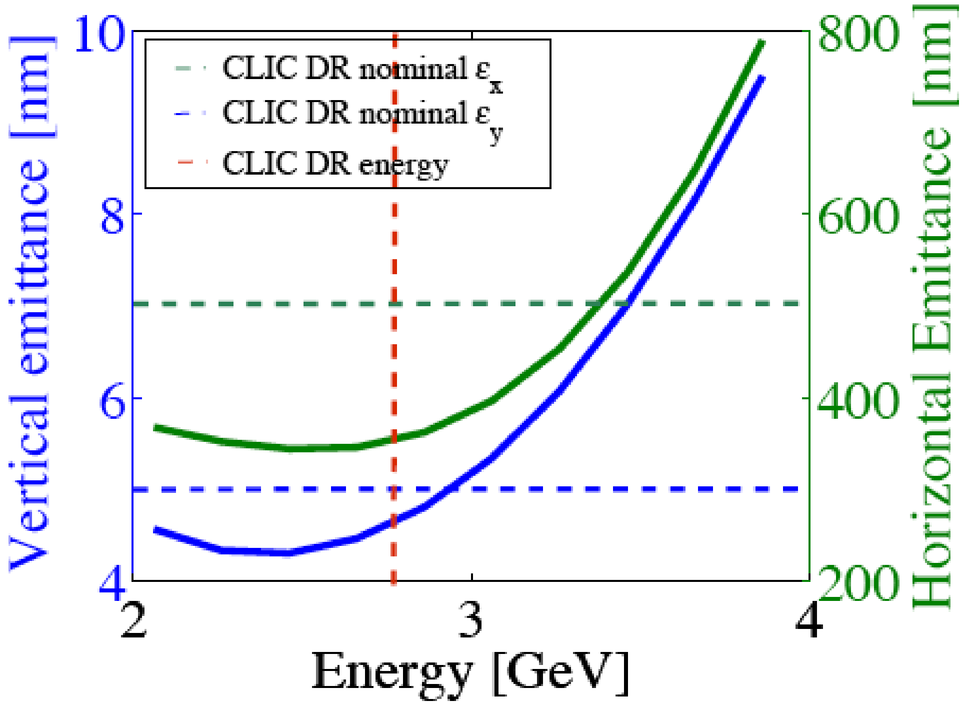
- Reasonable magnet strengths (magnet models already studied) and space constraints
- DA significantly increased
- TME optics with gradient in the bend and energy increase reduces IBS growth factor to 1.4 (as compared to 5.4 in original DR design)
- Further optics optimization with respect to IBS (F.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

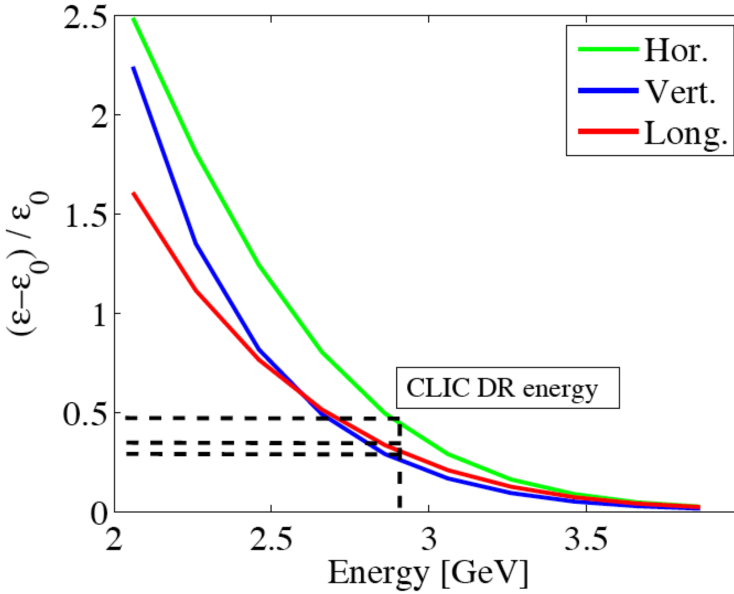
Parameters	Value
Energy [GeV]	2.86
Circumference [m]	420.56
Coupling	0.0013
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Natural chromaticity x / y	-168/-60
Momentum compaction factor	8e-5
Damping time x / s [ms]	1.9/ 0.96
Dynamic aperture x / y [σ_{inj}]	30 / 120
Number of dipoles/wigglers	100/52
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 [keVm]	5.5

Damping ring energy

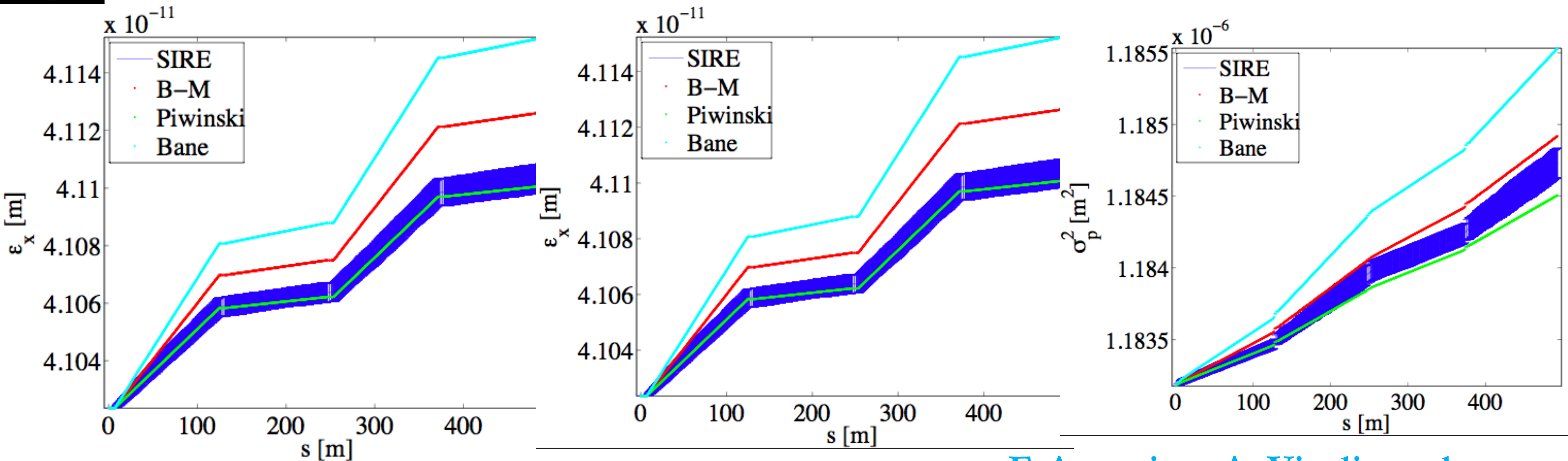
F. Antoniou, et al. IPAC10

- Scaling of emittances with energy obtained with analytical arguments and including IBS effect (constant longitudinal emittance)
- Broad **minimum** for horizontal emittance ~2-3GeV
- 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. CESRTA)
- Choice of 2.86GeV in order to relax collective effects while achieving target emittances





IBS tracking code



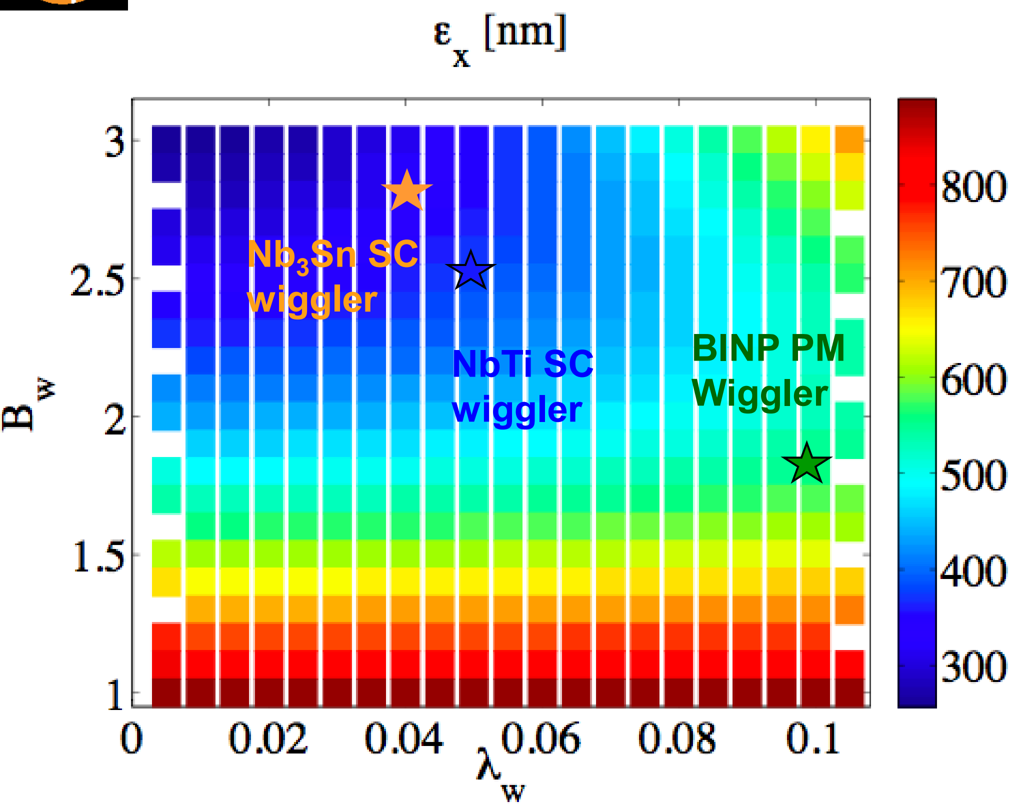
	$1/T_x$ (s^{-1})	$1/T_y$ (s^{-1})	$1/T_z$ (s^{-1})
MADX (B-M)	1476.7	952.9	1010.6
Bjorken-Mtingwa (Martini)	1579.4	739.1	968.5
SIRE (compressed)	1224.6	732.5	815.6
SIRE (not compressed)	1181.1	691.8	802.0
Mod. Piwinski	1299.5	625.7	775.2

F. Antoniou, A. Vivoli, et al.

	$\gamma\varepsilon_x$ (m)	$\gamma\varepsilon_y$ (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

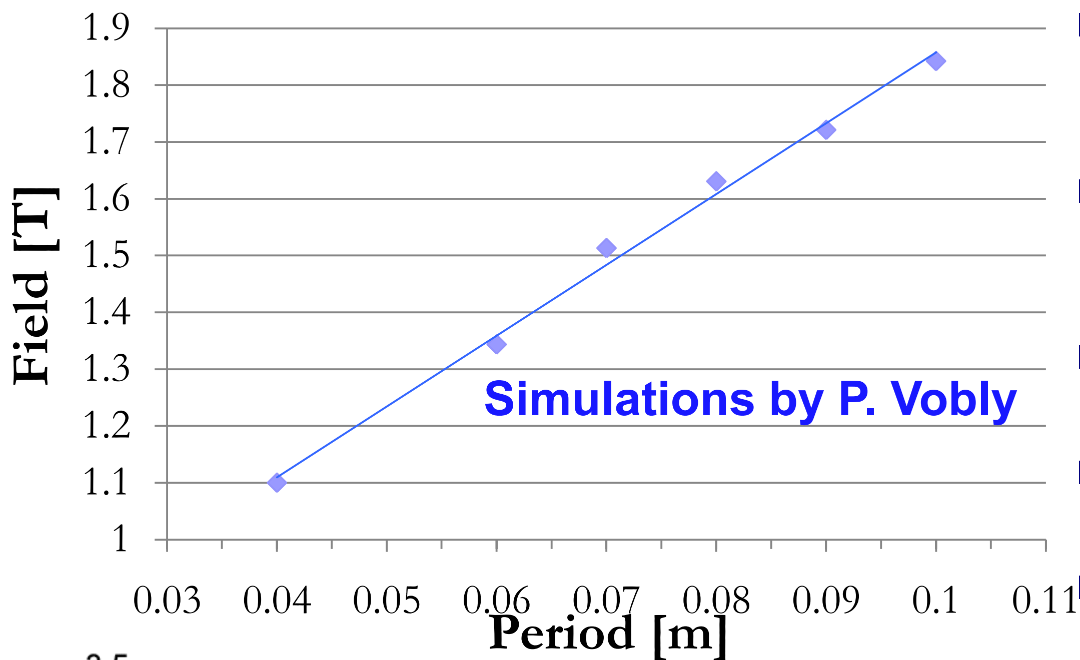
Wigglers' effect with IBS

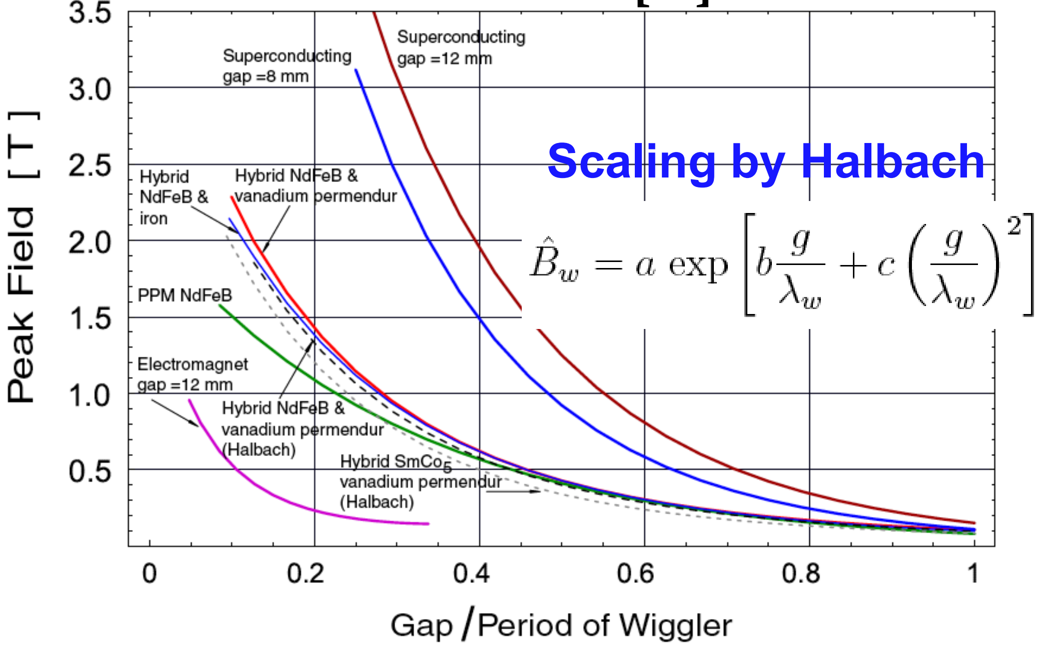


Parameters	BINP	CERN
B_{peak} [T]	2.5	2.8
λ_W [mm]	50	40
Beam aperture full gap [mm]	13	
Conductor type	NbTi	Nb_3Sn
Operating temperature [K]	4.2	

- 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
- Nb_3Sn 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

Permanent magnet performance



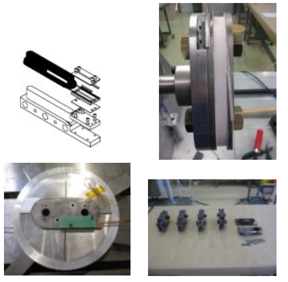


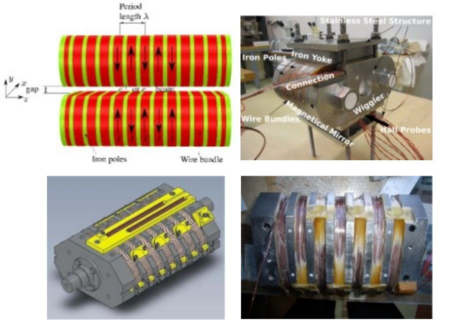
- Pure permanent magnet not able to reach very high field (i.e. 1.2T for Sm_2Co_{17})
- Pole concentrators used (e.g. vanadium permendur) to enhance pole field to a max value of 2.3T
- Not more than 1.1T reached for 40mm period and 14mm gap
- Higher field of 1.8T reached for 100mm period
- Max field of 2.3T can be reached for a gap/period ratio of ~0.1, (140mm period for 14mm gap)
- In that case, output emittance gets more than doubled (>800nm)
- In order to reach target DR performance, number of wigglers has to be increased by more than a factor of 2, i.e. ~40% of ring circumference increase
- **Only way** to reach high field for high gap/period ratio is by using **super-conducting wigglers**

Nb$_3$Sn Technology

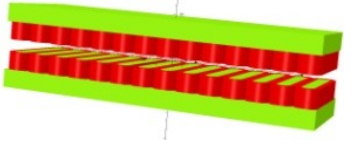
D. Schoerling, S. Russenchuck, et al.

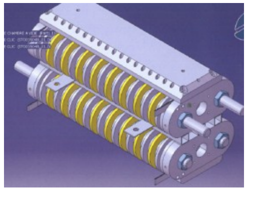
Nb-Ti Technology



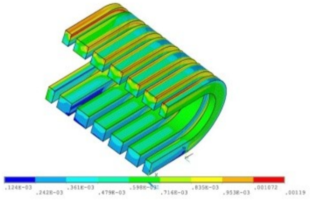


CDR





SCU14 in ANKA



TDR

DEPENDING ON APPROVED FUNDING!

Synchrotron radiation

- 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

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

- Radiation opening angle

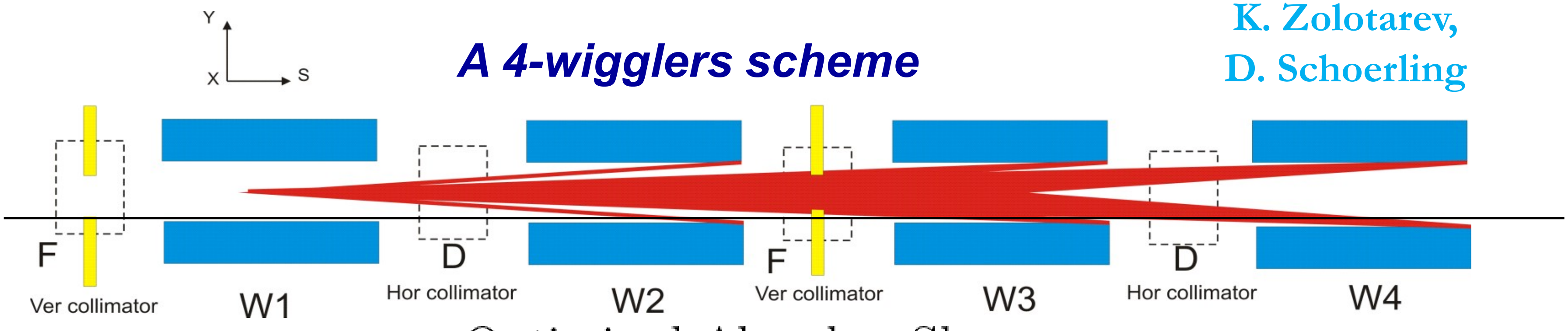
$$\theta_y = \frac{0.608}{\gamma}$$

DR radiation parameters	Value
Power per dipole [kW]	1.3
Power per wiggler [kW]	18.7
Total power [MW]	0.61
Critical energy for dipole [keV]	19.0
Critical energy for wiggler [keV]	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)

Radiation absorption scheme

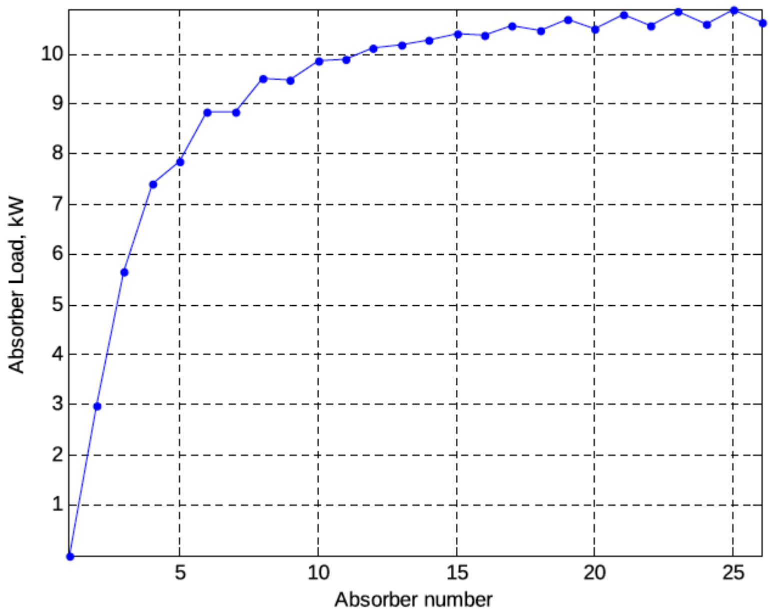
K. Zolotarev,
D. Schoerling



Optimized Absorber Shapes

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)

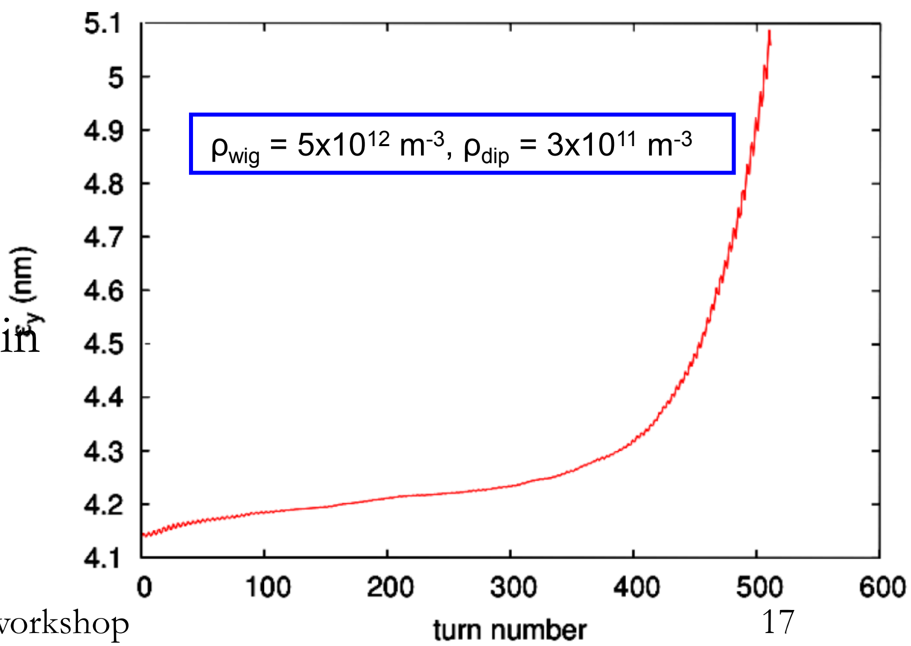


Collective effects in the DR

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 0.1nTorr)
- 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)

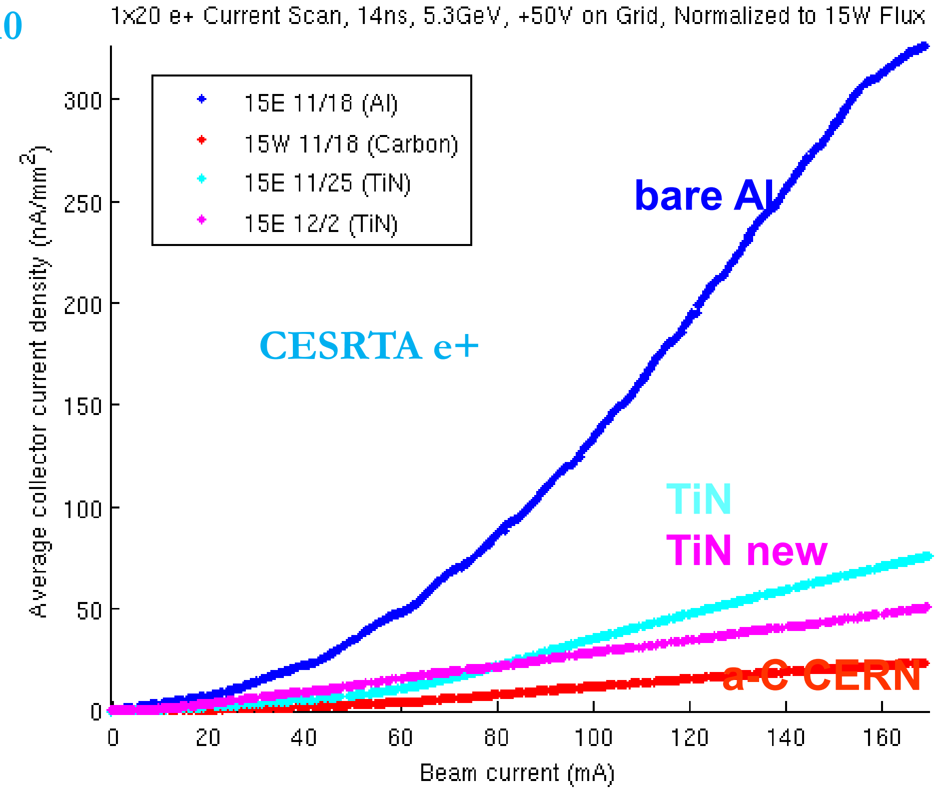
Chambers	PEY	SEY	ρ [10^{12} e^-/m^3]
Dipole	0.000576	1.3	0.04
		1.8	2
	0.0576	1.3	7
		1.8	40
Wiggler	0.00109	1.3	0.6
	0.109	1.3	45
		1.5	70
		1.8	80

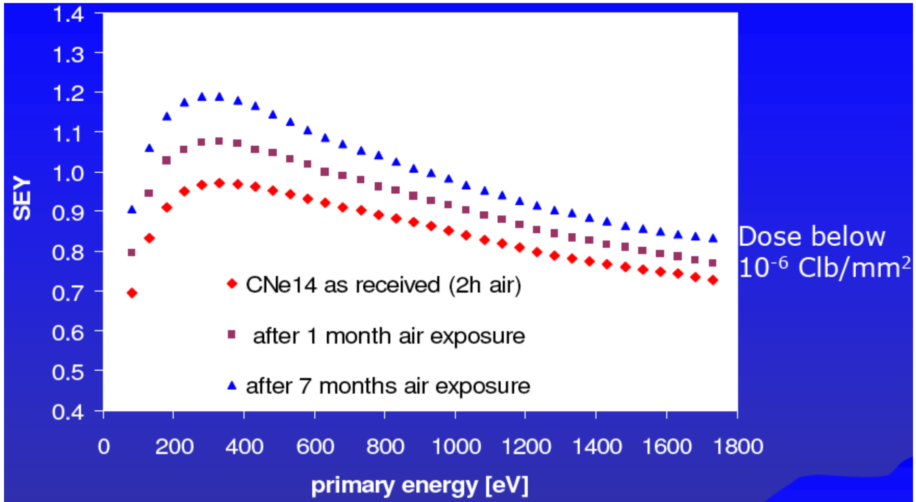


Coatings for e- Cloud Mitigation

M. Taborelli LER2010

- Bakeable system
  - NEG gives SEY<1.3 for baking @ > 180C
  - Evolution after many venting cycles should be studied
  - NEG provides pumping
  - Conceivable to develop a coating with lower activation T
- Non-bakeable system
  - a-C coating provides SEY< 1 (2h air exposure), SEY<1.3 (1week air exposure)
  - After 2 months exposure in the SPS vacuum or 15 days air exposure no increase of e-cloud activity
  - Pump-down curves are as good as for stainless steel
  - No particles and peel-off
  - Very good results obtained at CESR-TA (although contaminated by silicon from kapton adhesive tape)





RF system

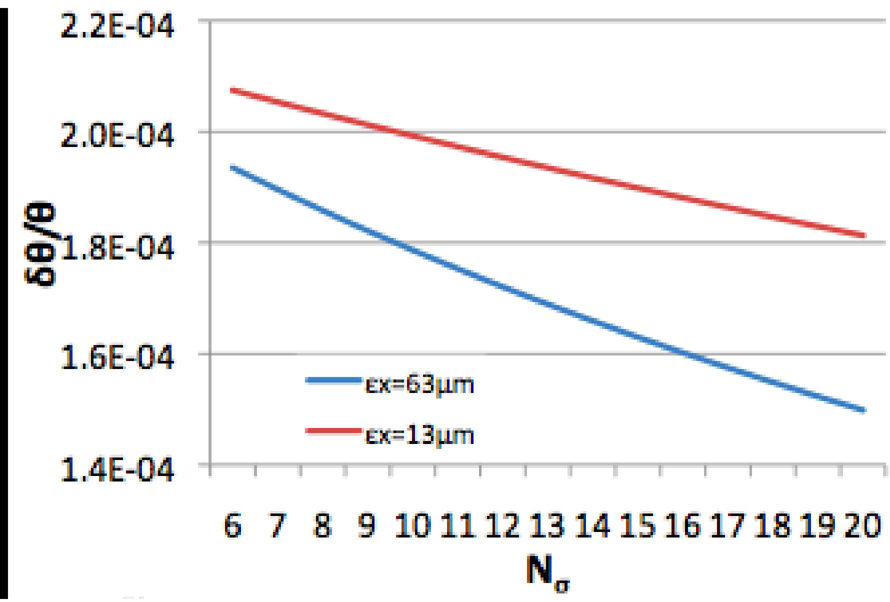
A. Grudiev

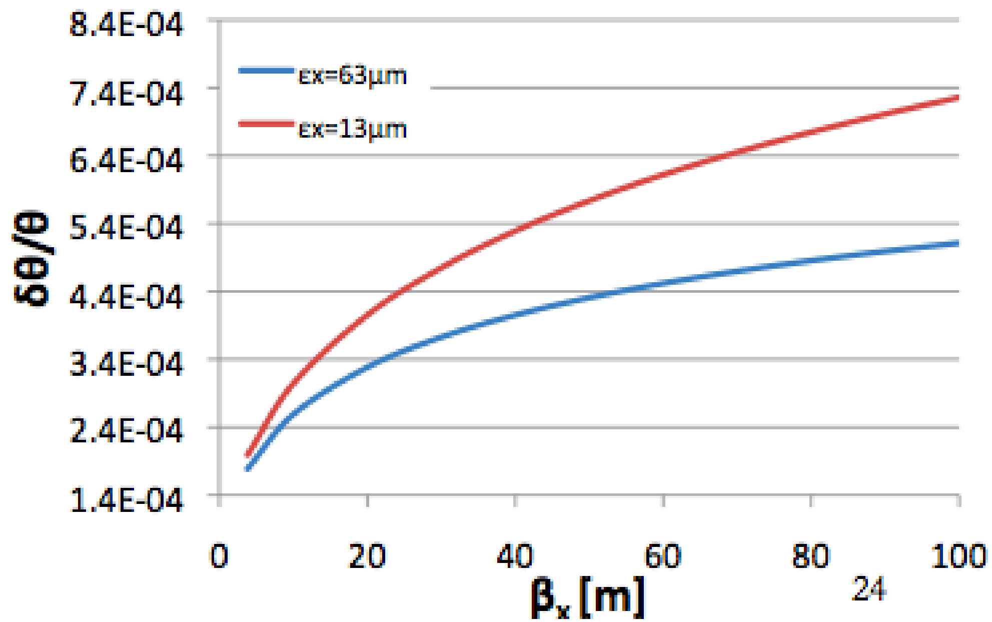
- RF frequency of **2GHz**
  - R&D needed for power source
  - High peak and average power introducing strong transient beam loading to be handled by non-conventional LLRF system
- The **1GHz** frequency eases beam dynamics and drives the RF system to more conventional parameters for power source and 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	$8x10^{-5}$	
Energy loss/turn [MeV]	**4.2**	
RF voltage [MV]	4.9	**4.4**
RF frequency [GHz]	1.0	**2.0**
Peak/Aver. current [A]	0.66/0.15	1.3/0.15
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 $\boldsymbol{\sigma_{jit} \leq 0.1\sigma_x}$ is needed
- Translated in a relative deflection stability requirement as $\frac{\delta\theta_{\mathrm{kick}}}{\theta_{\mathrm{kick}}} \leq \frac{\sigma_{\mathrm{jit}}}{x_{\mathrm{sep}}}$
- For higher positions at the septum (larger injected emittances or lower beta functions) the stability tolerance becomes tighter
- The tolerance remains typically to the order of $\mathbf{10^{-4}}$
- Available drift space has been increased to reduce kicker voltage spec.



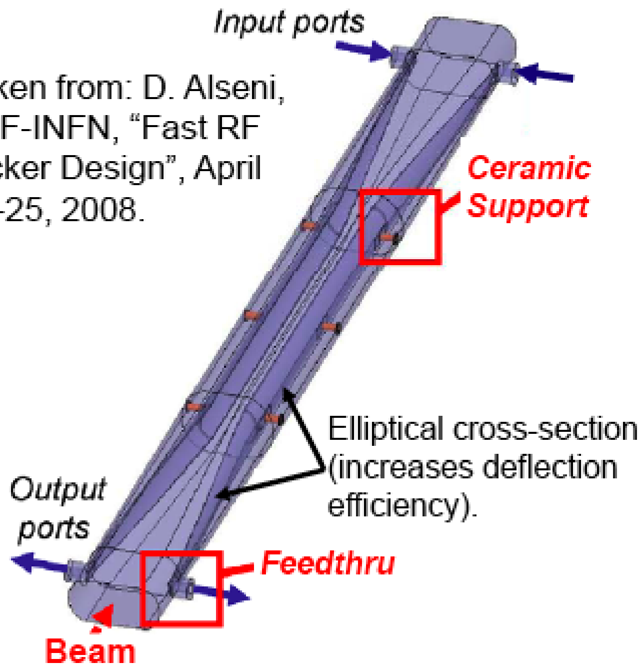


Kicker design

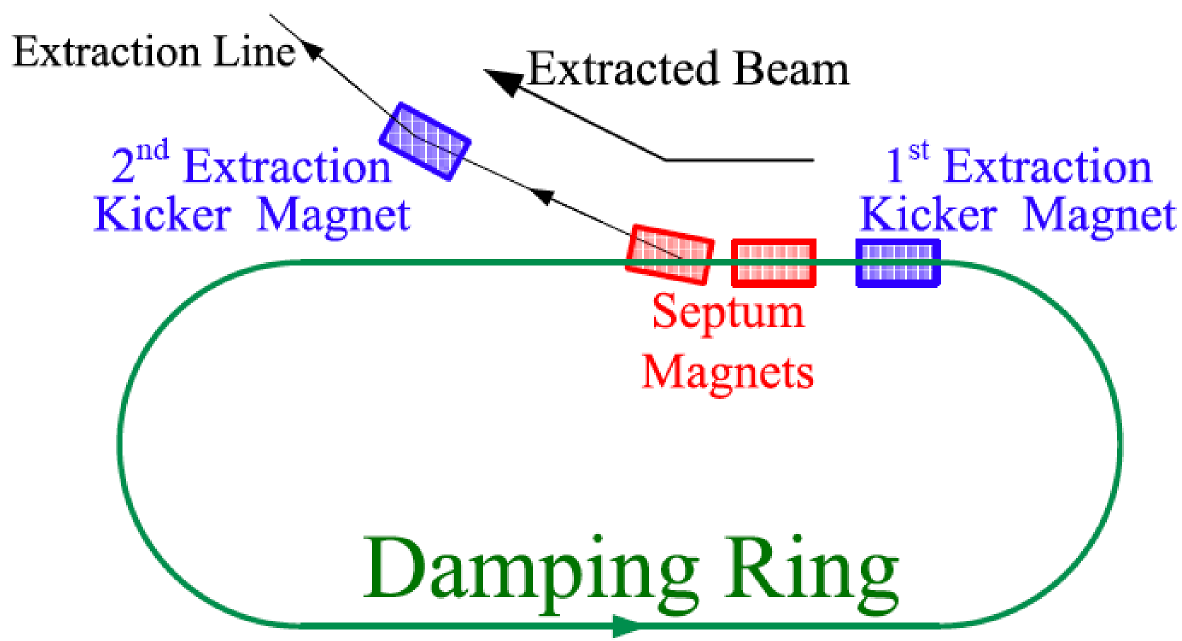
M. Barnes

- 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

Taken from: D. Alseni, LNF-INFN, "Fast RF Kicker Design", April 23-25, 2008.



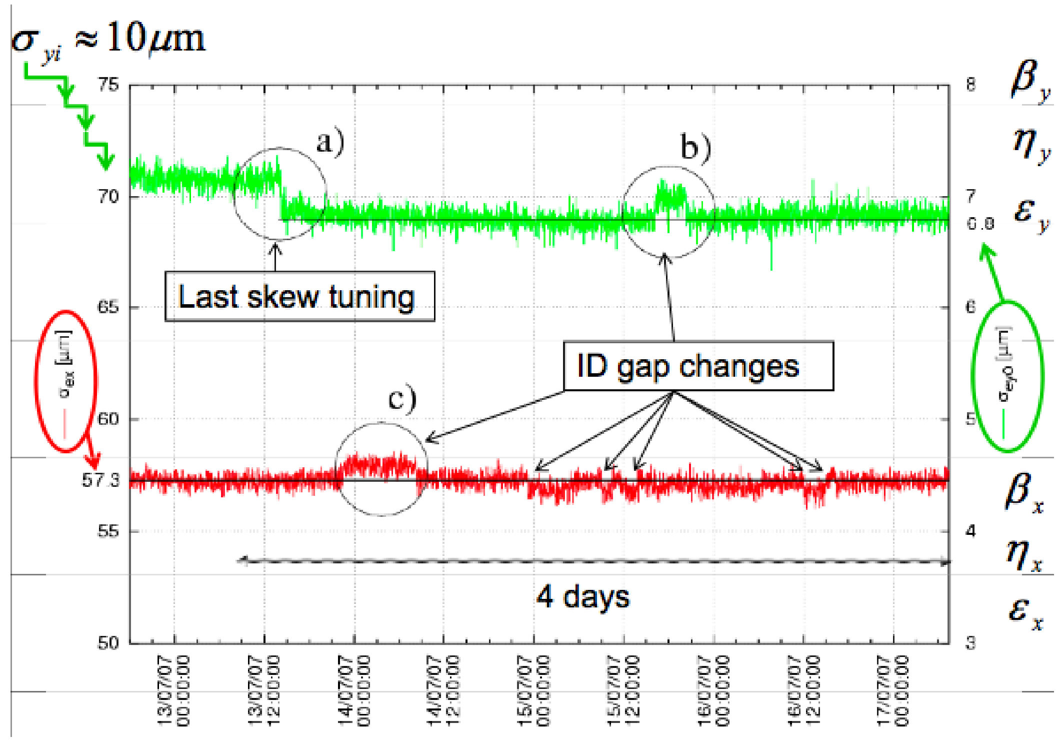
DAΦNE Stripline (~0.94m)



Low emittance tuning

- 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

M. Boege, LER2010



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

Damping Rings diagnostics

- **300PUs**, turn by turn (every **1.6μs**)
  - **10μm** 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 $\mathbf{10^{-4}}$, critical for resolving instabilities (i.e. synchrotron side-bands, ions)
- Turn by turn transverse profile monitors (X-ray?) with a wide dynamic range:
  - Hor. geometrical emittance varies from **11nm.rad** @ injection to **90pm.rad** @ extraction and the vertical from **270pm.rad** to **0.9pm.rad**.
  - Capable of measuring **tails** for IBS
  - This would probably be the most challenging item
- Longitudinal profile monitors
  - Energy spread of **0.5%** to **0.1%** and bunch length from **10** to **0.1mm**.
  - Note that the dispersion around the ring is extremely small (<12mm).
- Fast beam loss monitoring and bunch-by-bunch current measurements
- E-cloud + ion diagnostics

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 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),…

Damping wiggler experiments

- Need to test the wiggler on real beam conditions
  - Validate cryogenic performance, reliability and heat load evacuation (absorber)
  - Test quench performance under presence of beam and synchrotron radiation (especially for Nb_3Sn)
  - Validate measured field quality (wiggler should be transparent to beam stability)
  - Can be combined with vacuum chamber tests (photo-emission yield, desorption)
- Experimental set-up
  - Storage ring with available straight section of ~3m for installing wiggler and absorber downstream of a dipole or other insertion device
  - Ability to install the cryogenic system
  - Average current of ~200mA for testing absorber in similar radiation conditions
  - For using wiggler as an X-ray user insertion device, ***K*-**parameter can be adjusted by reducing wiggler field (need to have good field quality at lower currents)

Low Emittance Rings collaboration

- 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**

Concluding remarks

- Super-conducting wigglers fundamental for DR performance
  - Mock-up on "conventional" wire technology built achieving target parameters
  - More challenging wire technologies and wiggler designs studied at CERN and KIT/ANKA and measurements from short prototypes are expected
- Profit from installation of SC wiggler at ANKA for IMAGE beam line in order to perform experimental tests
- Discuss and converge
  - Magnet parameters
  - Schedule and cost
  - Collaboration set-up (CERN, KIT, BINP, BNG)
  - Technological implications or synergies for vacuum (coating), cryogenics, radiation absorption,…
  - Experimental conditions and plan (machine parameters, measurement set-up, associated instrumentation,…)