# Lecture A3a: Damping Rings

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**Eighth International Accelerator School for Linear Colliders**
4-15 December 2013, Antalya

# Primary purpose and outline

- Overview of the beam physics processes and associated technology driving the design of linear collider damping rings
  - 12 hours of lectures covering the following areas
- Damping rings' design guidelines and challenges (~1.5h)
  - Role of the damping rings in the LC accelerator complex, review parameters and constraints of LC damping rings , identify key challenges
- Linear beam dynamics overview (~1.5h)
- Beam dynamics with radiation damping (~1.5h)
  - Radiation Damping and Synchrotron Motion, Quantum Excitation and Equilibrium Emittance, summary of Beam Parameters and Radiation Integrals
- Lattice design and non-linear dynamics for low emittance rings (~1.5h)
  - FODO, DBA, TBA, MBA, TME, chromaticity, non-linear dynamics, ID effects
- Ultra-low vertical emittance tuning (~1.5h)
  - Linear imperfections, Coupling, vertical dispersion, alignment tolerances
- Collective effects (~3h)
  - Single and multi-bunch bunch instabilities, Two stream instabilities, Intrabeam scattering, Touschek effect and space-charge
- Damping rings technology (~1.5h)
  - Damping wigglers, kickers, vacuum, instrumentation, feedback

# General Bibliography


- Accelerator physics books
  - K. Wille, The Physics of Particle Accelerators, an introduction, Oxford University press, 2000
  - S.Y. Lee, Accelerator Physics, 2nd edition, World Scientific, 2004
  - H. Wiedemann, Particle accelerator physics, 3rd edition, Springer 2007
- Lecture notes
  - L. Rivkin, Electron dynamics, CERN Accelerator School in Synchrotron Radiation and free-electron lasers, 2003; Intermediate CERN Accelerator School, 2007.
  - A. Wolski, Low emittance machines, CERN Accelerator School, September 2007.
  - M. Sands, The physics of electron storage rings, an introduction, Proc. Int. School of Phys. E. Fermi, (ed. B. Touschek), 1971.
- Design reports
  - A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report, CERN-2012-007
  - International Linear Collider Technical Design Report, Vol. 3
- Lectures on damping rings
  - A. Wolski, Lectures on Damping Rings, 4th International Accelerator School for Linear Colliders, Beijing, China, 2009.
  - M. Palmer, Lectures on Damping Rings, 5th International Accelerator School for Linear Colliders, Villars-sur-Ollon, Switzerland, 2010
  - S. Guiducci, Lectures on Damping Rings, 7th International Accelerator School for Linear Colliders, Indore, India, 2012

# Damping rings' design guidelines and challenges

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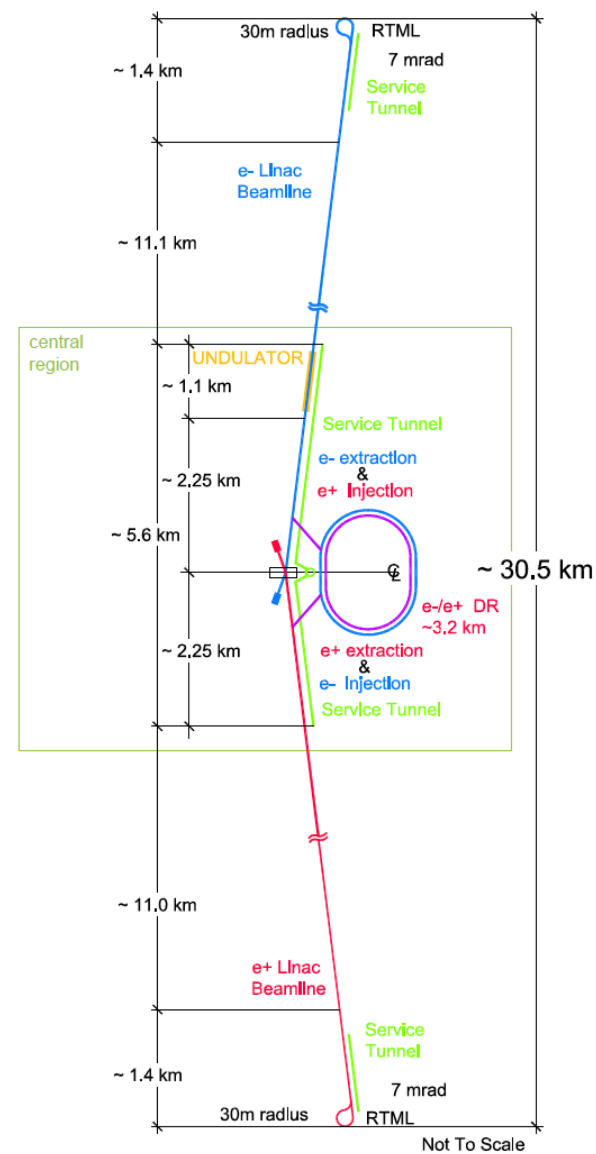
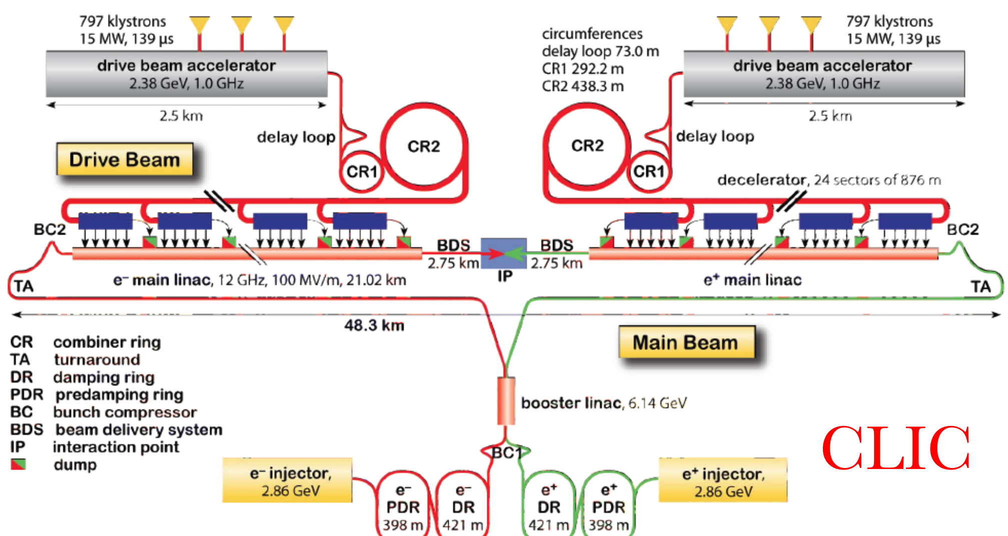
- Role of Damping Rings
- The CLIC and ILC design parameters
- DR Parameter Requirements
  - Luminosity and emittance
  - Bunch compressors
  - Main Linac
  - Injected emittance
- Examples of parameter optimization
- ILC and CLIC Damping Rings parameters and challenges

# Role of the Damping Rings

- **Accept** e$^+$ and e$^-$ beams with **large** transverse and longitudinal **emittances** and **damp** them by several orders of magnitude producing **ultra-low emittance** beams necessary for high luminosity collisions at the interaction point (IP), **within** the (fast) **repetition rate** imposed by the collider
- **Damp** longitudinal and transverse **jitter** in the incoming beams to provide very stable beams for delivery to the IP
- **Delay bunches** from the source to **allow** feed-forward systems **to compensate** for **pulse-to-pulse variations**

ILC



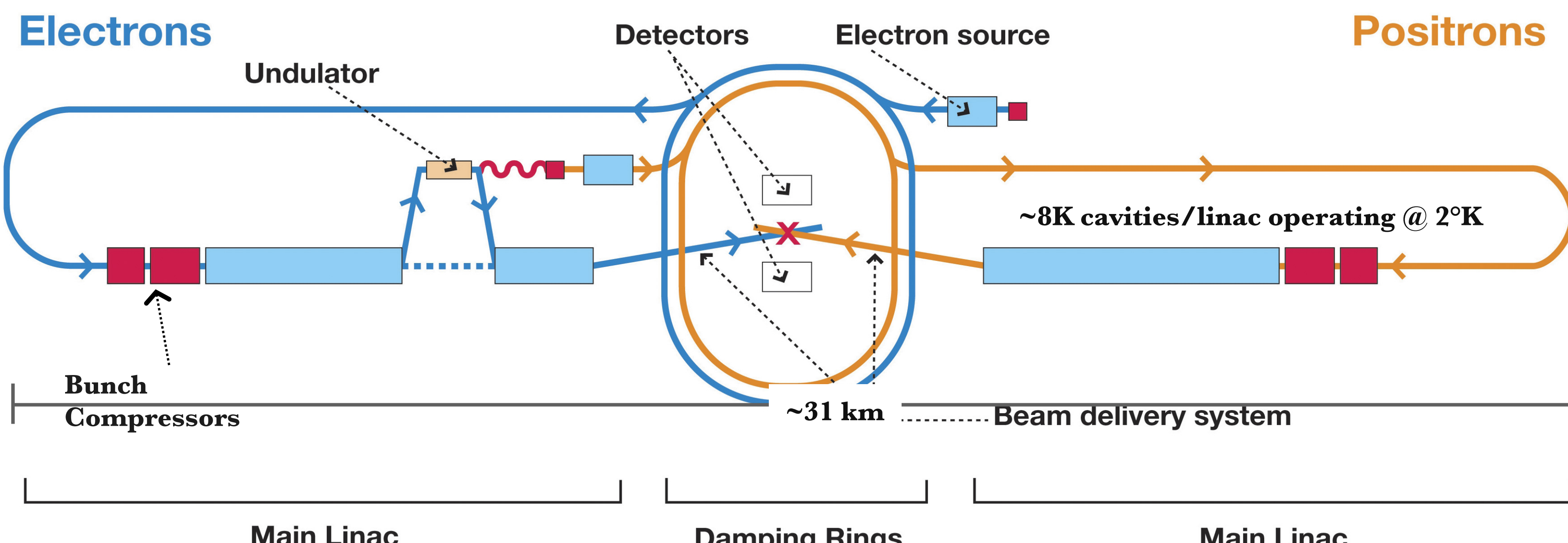




CLIC

# The ILC Design

- Machine Configuration for **500GeV** center of mass energy
  - Helical undulator polarized $e^+$ source
  - Two **~3.2 km damping rings** in the same tunnel
  - RTML running length of linac
  - Two **11.2km main linacs** with super-conducting cavities
  - Single Beam Delivery System
  - 2 Detectors in Push-Pull configuration

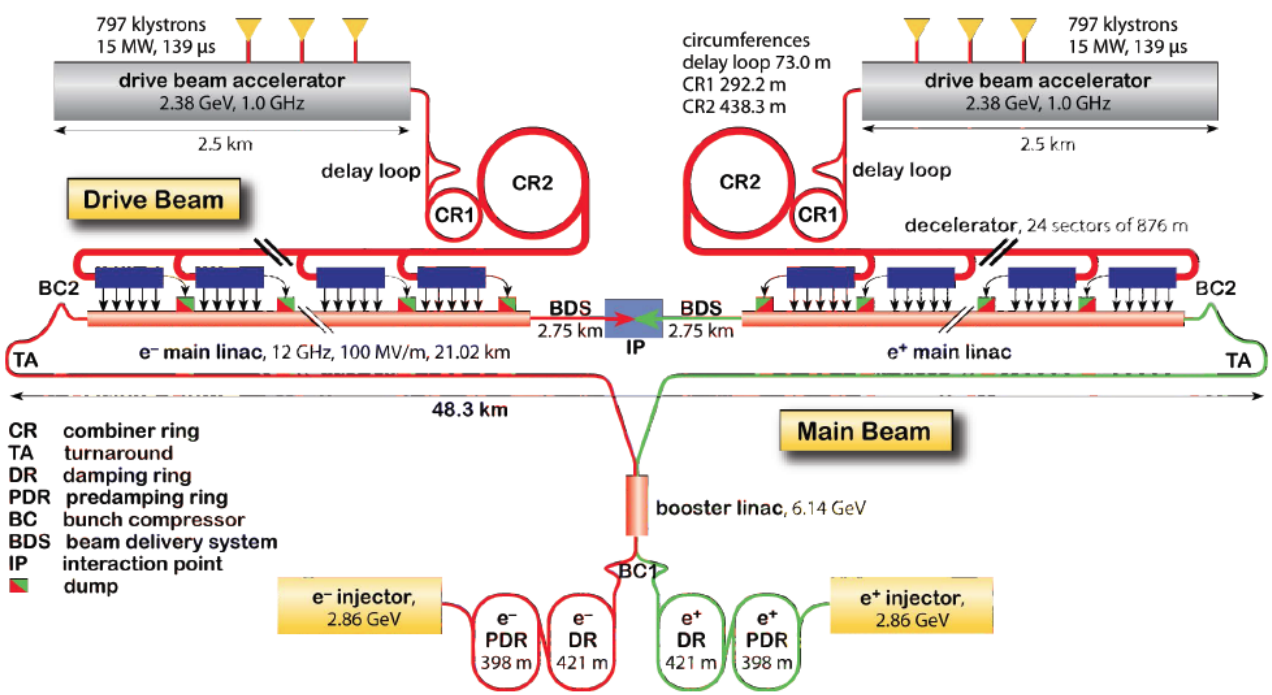
| Centre-of-mass energy | $E_{CM}$ | GeV | 200 | 230 | 250 | 350 | 500 |
|---|---|---|---|---|---|---|---|
| Luminosity pulse repetition rate | | Hz | 5 | 5 | 5 | 5 | 5 |
| Positron production mode | | | 10 Hz | 10 Hz | 10 Hz | nom. | nom. |
| Estimated AC power | $P_{AC}$ | MW | 114 | 119 | 122 | 121 | 163 |
| Bunch population | $N$ | $\times 10^{10}$ | 2 | 2 | 2 | 2 | 2 |
| Number of bunches | $n_b$ | | 1312 | 1312 | 1312 | 1312 | 1312 |
| Linac bunch interval | $\Delta t_b$ | ns | 554 | 554 | 554 | 554 | 554 |
| RMS bunch length | $\sigma_z$ | μm | 300 | 300 | 300 | 300 | 300 |
| Normalized horizontal emittance at IP | $\gamma\epsilon_x$ | μm | 10 | 10 | 10 | 10 | 10 |
| Normalized vertical emittance at IP | $\gamma\epsilon_y$ | nm | 35 | 35 | 35 | 35 | 35 |
| Horizontal beta function at IP | $\beta_x^*$ | mm | 16 | 14 | 13 | 16 | 11 |
| Vertical beta function at IP | $\beta_y^*$ | mm | 0.34 | 0.38 | 0.41 | 0.34 | 0.48 |
| RMS horizontal beam size at IP | $\sigma_x^*$ | nm | 904 | 789 | 729 | 684 | 474 |
| RMS vertical beam size at IP | $\sigma_y^*$ | nm | 7.8 | 7.7 | 7.7 | 5.9 | 5.9 |
| Vertical disruption parameter | $D_y$ | | 24.3 | 24.5 | 24.5 | 24.3 | 24.6 |
| Fractional RMS energy loss to beamstrahlung | $\delta_{BS}$ | % | 0.65 | 0.83 | 0.97 | 1.9 | 4.5 |
| Luminosity | $L$ | $\times 10^{34}$ cm$^{-2}$ s$^{-1}$ | 0.56 | 0.67 | 0.75 | 1.0 | 1.8 |
| Fraction of $L$ in top 1% $E_{CM}$ | $L_{0.01}$ | % | 91 | 89 | 87 | 77 | 58 |
| Electron polarisation | $P_-$ | % | 80 | 80 | 80 | 80 | 80 |
| Positron polarisation | $P_+$ | % | 30 | 30 | 30 | 30 | 30 |
| Electron relative energy spread at IP | $\Delta p/p$ | % | 0.20 | 0.19 | 0.19 | 0.16 | 0.13 |
| Positron relative energy spread at IP | $\Delta p/p$ | % | 0.19 | 0.17 | 0.15 | 0.10 | 0.07 |



# The CLIC Design

- Machine Configuration for 0.5and 3TeV center of mass energy
  - Non-polarised e+ source
  - Two **~430m** damping rings + two **~400m** pre-damping rings
  - RTML running length of linac
  - Two **~21km main linacs** with copper cavities
  - **Drive beam complex** for RF power production
  - Single Beam Delivery System
  - Two Detectors in Push-Pull configuration

| **Description** [units] | **500 GeV** | **3 TeV** |
|---|---|---|
| Total (peak 1%) luminosity | $2.3\ (1.4) \times 10^{34}$ | $5.9\ (2.0) \times 10^{34}$ |
| Total site length [km] | 13.0 | 48.4 |
| Loaded accel. gradient [MV/m] | 80 | 100 |
| Main Linac RF frequency [GHz] | 12 | |
| Beam power/beam [MW] | 4.9 | 14 |
| Bunch charge [$10^9$ $e^+/e^-$] | 6.8 | 3.72 |
| Bunch separation [ns] | 0.5 | |
| Bunch length [$\mu$m] | 72 | 44 |
| Beam pulse duration [ns] | 177 | 156 |
| Repetition rate [Hz] | 50 | |
| Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m] | 2.4/25 | 0.66/20 |
| Hor./vert. IP beam size [nm] | 202/2.3 | 40/1 |
| Beamstrahlung photons/electron | 1.3 | 2.2 |
| Hadronic events/crossing at IP | 0.3 | 3.2 |
| Coherent pairs at IP | 200 | $6.8 \times 10^8$ |



# DR Design Parameters

- Main goal of this course is to understand why parameters have the specified values and why they are different in the two LC design

CLIC

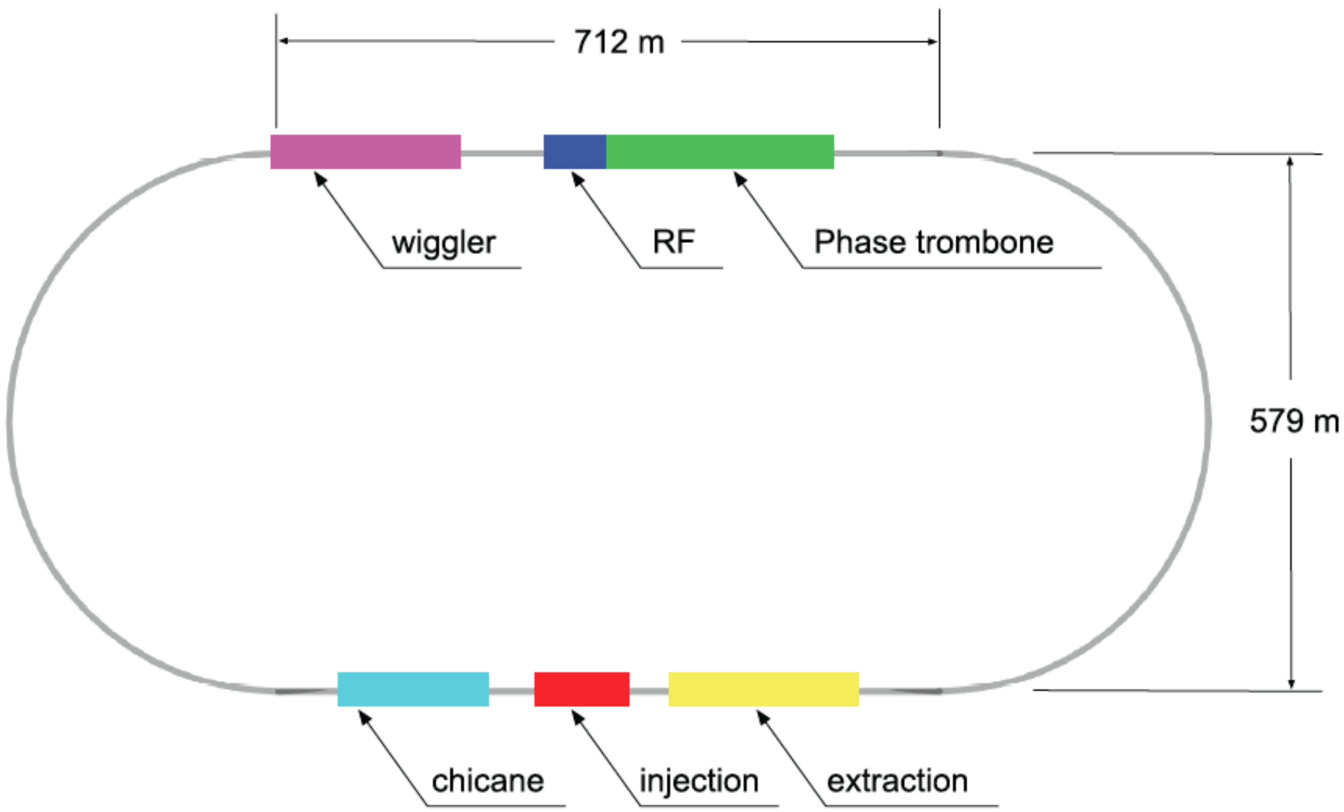
| Parameters, Symbol [Unit] | 2 GHz | 1 GHz |
|---|---|---|
| Energy, $E$ [GeV] | 2.86 | |
| Circumference, $C$ [m] | 427.5 | |
| Bunch population, $N$ [$10^9$] | 4.1 | |
| Basic cell type in the arc/LSS | TME/FODO | |
| Number of dipoles, $N_d$ | 100 | |
| Dipole Field, $B_0$ [T] | 1.0 | |
| Norm. gradient in dipole [$m^{-2}$] | -1.1 | |
| Horizontal and vertical tune, ($Q_x$,$Q_y$) | (48.35,10.40) | |
| Horizontal and vertical chromaticity, ($\xi_x$,$\xi_y$) | (-115,-85) | |
| Number of wigglers, $N_w$ | 52 | |
| Wiggler peak field, $B_w$ [T] | 2.5 | |
| Wiggler length, $L_w$ [m] | 2 | |
| Wiggler period, $\lambda_w$ [cm] | 5 | |
| Hor., vert. and long. damping time, ($\tau_x,\tau_y,\tau_l$) [ms] | (2.0,2.0,1.0) | |
| Momentum compaction factor, $\alpha_c$ [$10^{-4}$] | 1.3 | |
| Energy loss/turn, $U$ [MeV] | 4.0 | |
| Norm. horizontal emittance, $\gamma\epsilon_x$[$\mu$m] | 472 | 456 |
| Norm. vertical emittance, $\gamma\epsilon_y$[$\mu$m] | 4.8 | 4.8 |
| Energy spread (r.m.s.), $\sigma_\delta$ [%] | 0.1 | 0.1 |
| Bunch length (r.m.s.), $\sigma_s$ [mm] | 1.6 | 1.8 |
| Longitudinal emittance, $\epsilon_l$ [keVm] | 5.3 | 6.0 |
| IBS growth factors hor./ver./long. | 1.5/1.1/1.2 | 1.5/1.1/1.2 |
| RF Voltage, $V_{RF}$ [MV] | 4.5 | 5.1 |
| Stationary phase [$^o$] | 62 | 51 |
| Synchrotron tune, $Q_s$ | 0.0065 | 0.0057 |
| Bunches per train, $n_b$ | 312 | 156 |
| Bunch spacing, $\tau_b$ [ns] | 0.5 | 1 |
| RF acceptance, $\epsilon_{RF}$ [%] | 1.0 | 2.4 |
| Harmonic number, $h$ | 2851 | 1425 |

ILC

| Parameter | 5 Hz Mode Low Power | 5 Hz Mode High Lumi |
|---|---|---|
| Circumference [km] | 3.238 | |
| Number of bunches | 1312 | 2625 |
| Particles per bunch [$\times 10^{10}$] | 2 | 2 |
| Maximum beam current [mA] | 389 | 779 |
| Transverse damping time $\tau_x,\tau_y$ [ms] | 23.95 | |
| Longitudinal damping time $\tau_z$ [ms] | 12.0 | |
| Bunch length $\sigma_z$ [mm] | 6.02 | |
| Energy spread $\sigma_E/E$ [%] | 0.11 | |
| Momentum compaction factor $\alpha_p$ [$\times 10^{-4}$] | 3.3 | |
| Normalized horizontal emittance $\gamma\epsilon_x$[μm] | 5.7 | |
| Horizontal chromaticity $\xi_x$ | −51.3 | |
| Vertical chromaticity $\xi_y$ | −43.3 | |
| Wiggler Field [T] | 1.51 | |
| Number of Wigglers | 54 | |
| Energy loss/turn [MeV] | 4.5 | |
| **RF Specifications:** | | |
| Frequency [MHz] | 650 | |
| Number of cavities | 10† | 12 |
| Total voltage [MV] | 14.0 | |
| Voltage per cavity [MV] | 1.40 | 1.17 |
| RF synchronous phase [°] | 18.5 | |
| Power per RF coupler [kW]‡ | 176 | 294 |

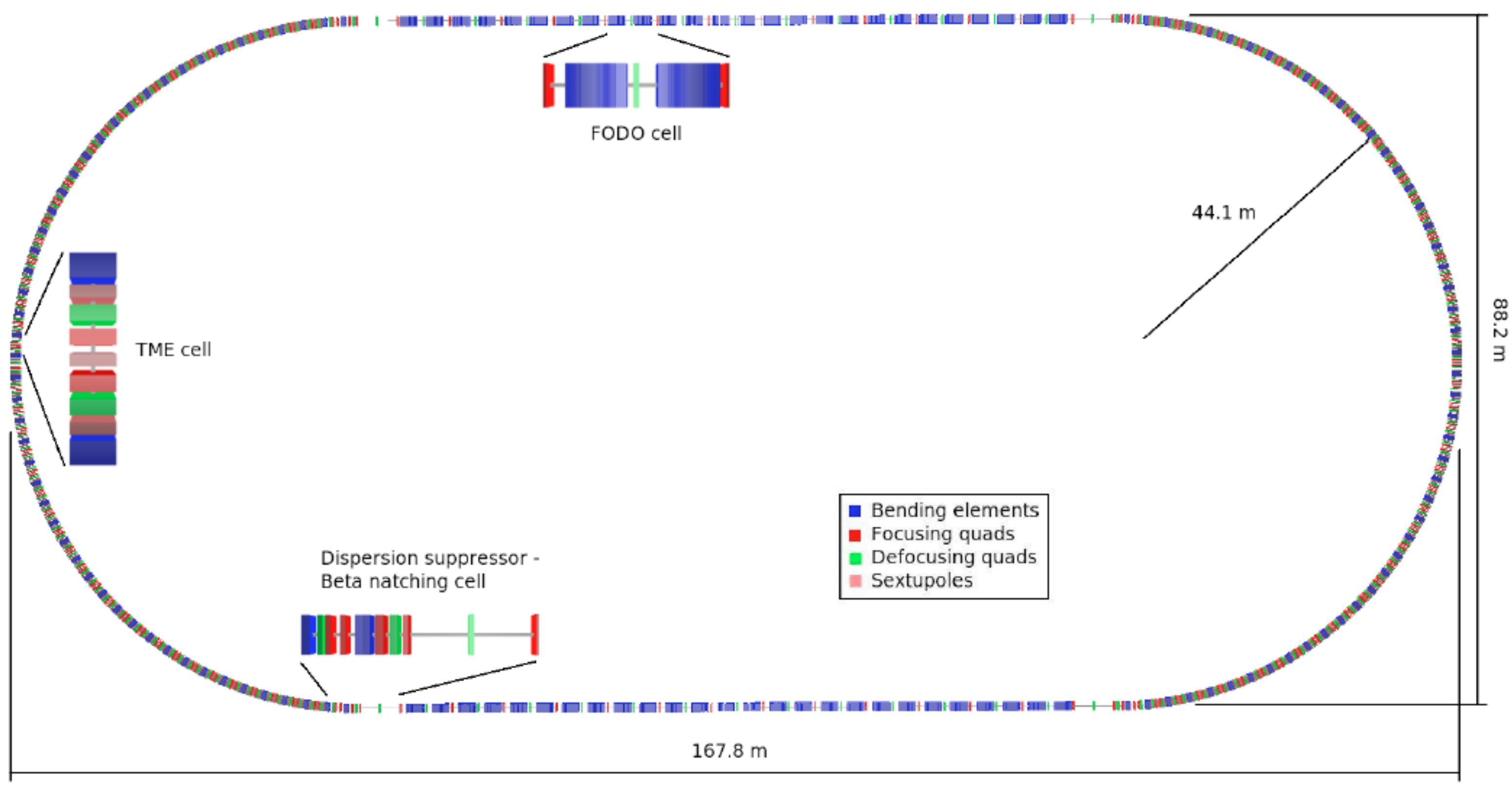
# The TDR ILC Damping Ring Layout

- DTC4 – Racetrack shape
- Circumference 3.2 km, energy of 5GeV
- TME style lattice in the arcs
- Straight sections filled mostly with FODO cells and include damping wigglers, RF and beam transfer equipment, circumference chicane and phase trombone



# The CDR CLIC Damping Ring Layout

- Racetrack shape
- Circumference 427.5 m, energy of 2.86GeV
- TME in the arcs with gradient dipole
- Straight sections filled with FODO cells and include damping wigglers, RF and beam transfer equipment



# LC Damping Ring Design Inputs

- A number of parameters are design **inputs** for the damping rings
- They are constrained due to LC physics performance requirements (**luminosity**), the downstream systems (mainly **main linac RF**, but also **RTML**), the upstream systems (particle **sources**, mainly $e^+$)
- They impact damping rings beam dynamics but also technology

| Parameters | CLIC | ILC | Constraints | Impact on DR design |
|---|---|---|---|---|
| Particles per bunch | $4\times10^9$ | $2\times10^{10}$ | Maximum set by disruption at IP, and linac short range wakefields, minimum set by luminosity target and RF to beam efficiency | Single bunch Collective effects, impedance budgets, vacuum, feedback |
| Machine repetition rate [Hz] | 50 | 5 | Set by cryogenic cooling capacity in ILC, partially determines required damping time | Lattice design, layout, damping wigglers parameters |
| Linac RF pulse length [ns] | 156 | 1600 | Upper limit set by RF technology and RF to beam efficiency | Layout, collective effects, extraction kicker design, RF system design (including LLRF) |
| Bunch spacing in linac/DR [ns] | 0.5/1 | 554/6 | | |
| Particles per machine pulse | $1.3\times10^{12}$ | $5.3\times10^{13}$ | Lower limit set by luminosity target | Collective effects |
| Injected normalized emittance ($e^+$) [μm.rad] | 7000 | 8 | Set by positron source, influences damping time requirement | Number of damping stages, layout, lattice design, dynamic aperture, magnet tolerances |
| Injected rms energy spread [%] | ±4.5 | ±0.75 | Set by positron source | Momentum (dynamic) acceptance, magnet tolerances |
| H/V Extracted normalized emittances [nm] | 500/5 | 5000/20 | Set by luminosity goal and emittance growth budget in downstream systems | Lattice design, alignment tolerances, collective effects |
| Extracted rms bunch length [mm] | 1.8 | 6 | Upper limit set by downstream bunch compressors | RF system, collective effects |
| Extracted rms energy spread [%] | 0.1 | 0.15 | | |

# Luminosity Requirements

- The principle parameter driver is the production of luminosity at the collision point

where

$$\mathcal{L} = \frac{N^2 f_{\mathrm{rep}} n_b}{4\pi\sigma_x\sigma_y}\mathcal{H}_\mathcal{D}$$

  - $N$, the number of particles per bunch
  - $\sigma_x$ and $\sigma_y$, the horizontal and vertical beam sizes

  } Assumed equal for all bunches and both beams

  - $f_{\mathrm{rep}}$, the collision rate at the interaction point (IP)
  - $n_b$, the number of bunches
  - $\mathcal{H}_\mathcal{D}$, the luminosity factor representing combined effect of "hour glass" (longitudinal beta function change over IP) and disruption enhancement (mutual attractive force of colliding bunches)

- Ideally the target is
  - High intensity bunches
  - Small transverse beam size

  } High brightness

  - High repetition rate
  - Large number of bunches

# Parameters at the ILC Interaction Point

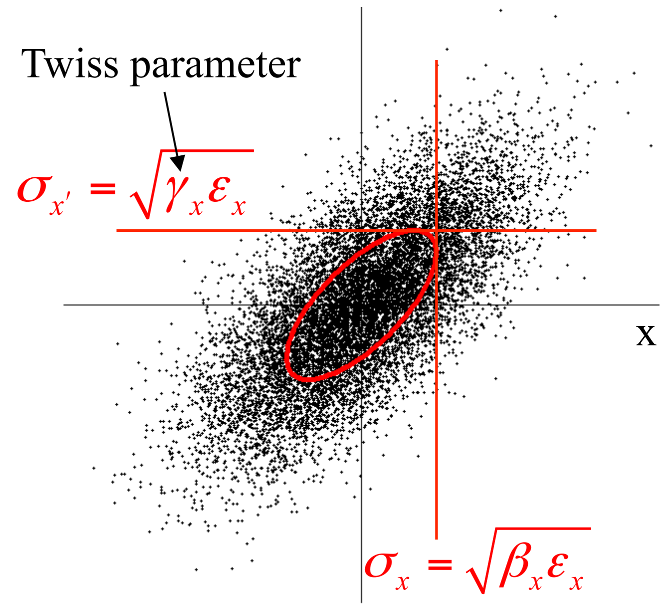
- The parameters at the interaction point have been chosen to provide a nominal luminosity of $2\times10^{34}$ $cm^{-2}s^{-1}$ for ILC
- The bunch charge is $N = 2\times10^{10}$ particles/bunch and we consider 1 bunch
- The horizontal beam size $\sigma_x \sim 474$ nm with $\beta_x^* = 11$ mm which requires a **geometrical** emittance of $\varepsilon_x = 20$ pm-rad
- The vertical beam size $\sigma_y \sim 5.9$ nm with $\beta_y^* = 0.48$ mm which requires a **geometrical** emittance of $\varepsilon_y = 0.07$ pm-rad
- The luminosity factor $\mathcal{H}_D \sim 2$
- For the required luminosity a collision rate of **7kHz** is required.
- **Question**: How the 1 bunch consideration and the 7kHz collision rate can be compatible with the ILC damping ring parameters (1312 bunches and 5Hz machine repetition rate)
- **Answer** in a few slides…

# Parameters at the CLIC Interaction Point

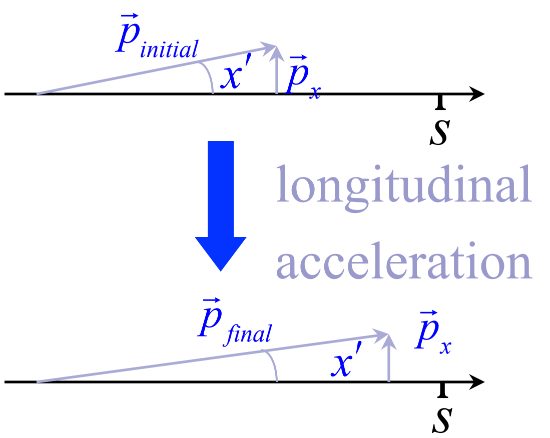
- The parameters at the interaction point have been chosen to provide a nominal luminosity of $6\times10^{34}$ cm$^{-2}$s$^{-1}$ for CLIC
- The bunch charge is $N = 3.72\times10^9$ particles/bunch for a total of 312 bunches
- The horizontal "core" beam size $\sigma_x$ ~ 45 nm (**rms** of 33.5nm) with $\beta_x^* = 6.9$ mm which is given by a **geometrical** emittance of $\varepsilon_{xn} = 0.1$ pm-rad
- The vertical "core" beam size $\sigma_y$ ~ 0.9 nm (**rms** of 0.5nm) with $\beta_y^* = 0.068$ mm which is given by a **geometrical** emittance $\varepsilon_{yn} = 0.003$ pm-rad!
- The collision rate now is equal to the machine repetition rate of **50Hz**
- For reaching the target luminosity, factor $\mathcal{H}_D$ has to be equal to 0.6
- The beta functions at the IP are optimized in final focus system
- Note: LC Luminosity cannot be just a matter of simple scaling. There is an interplay of several effects, such as beam-beam enhancement and disruption, beamstrahlung producing losses and detector background, the hour glass effect, which are usually simulated with dedicated codes

# Emittance Transport from the DR to IP

- Having the required geometric emittances at the IP, the emittance at the damping rings can be projected by using a relativistic invariant quantity, the **normalized emittance** (more details in 2nd lecture)



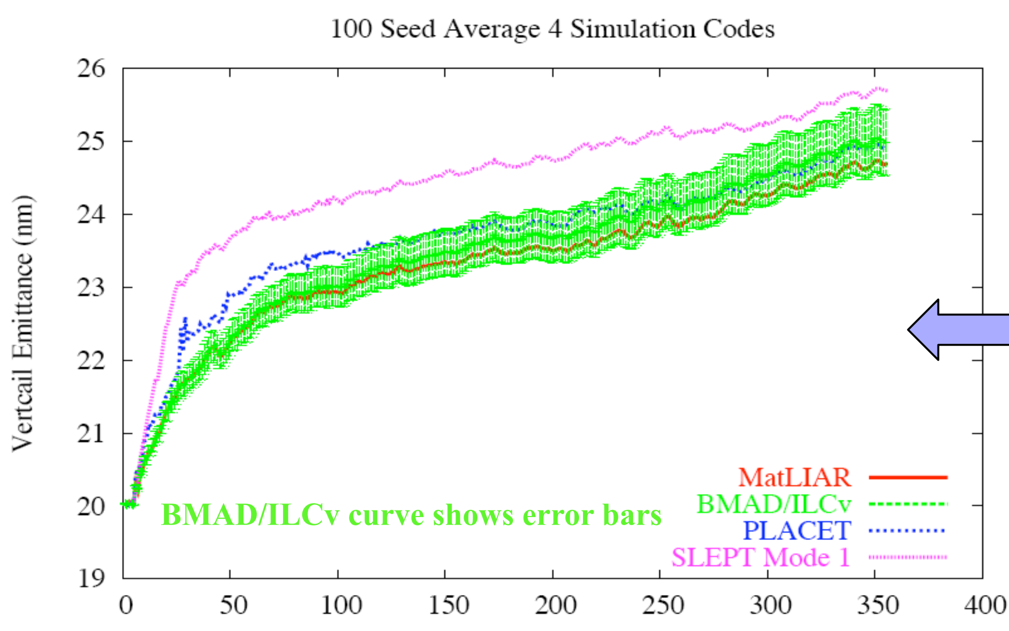

- By using the conjugate phase space coordinated $(x,px)$ instead of $(x,x')$ gives: $p_x = p\,x' = mc\beta\gamma x'$




- The normalized emittance is defined as $\varepsilon_n = \beta\gamma\varepsilon_{geo} \approx \gamma\varepsilon_{geo}$ for ultra-relativistic particles

# Emittance Transport from DR to the IP

- From the target normalized emittance at the IP and the estimated emittance growth in the main linac and the RTML, the emittance requirements at the DR extraction can be inferred
- For CLIC, the normalized horizontal and vertical emittances at the IP are **660** and **20 nm.rad**, respectively
- Considering 10% horizontal and 100% vertical emittance growth in the main linac and another 20% and 100% in the RTML, the normalized emittance requirement at the exit of the CLIC DR is **500** and **5 nm.rad**
- Following the same route for the ILC DR (considering 100% emittance growth in both planes from linac and RTML) the emittance targets at its exit are **5000** and **20** nm.rad, i.e. an order of magnitude higher




Low Emittance Tuning simulation Benchmarking in ILC Main LINAC

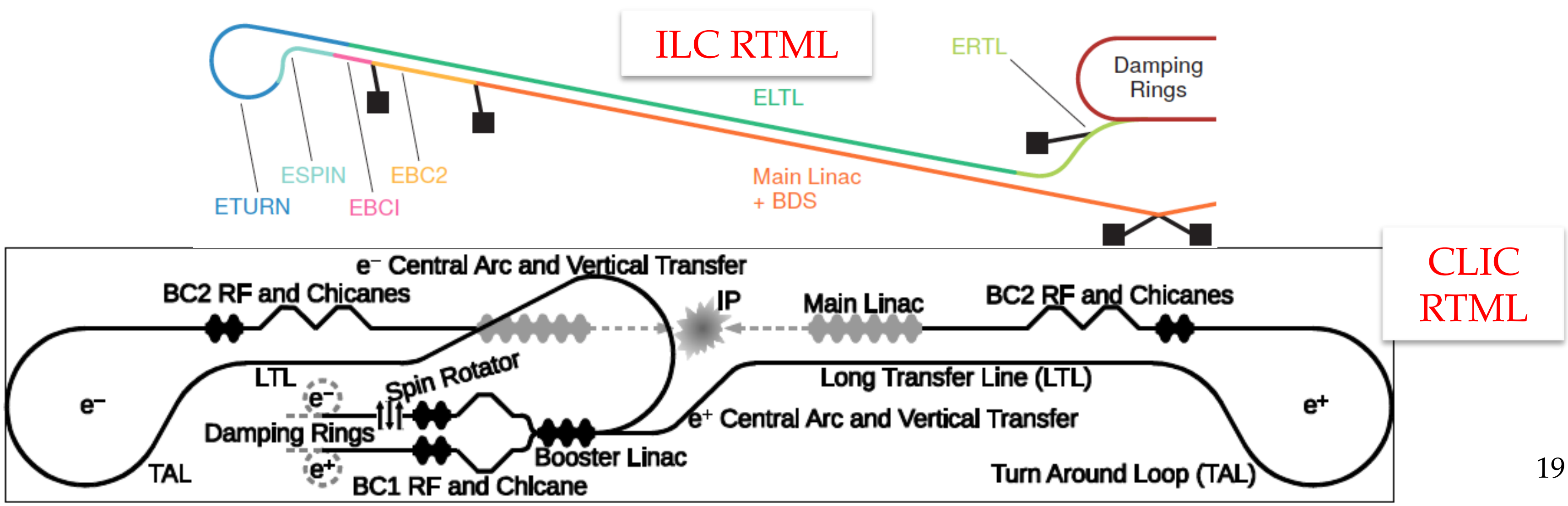
(J. Smith)

# Emittance targets for LC DR

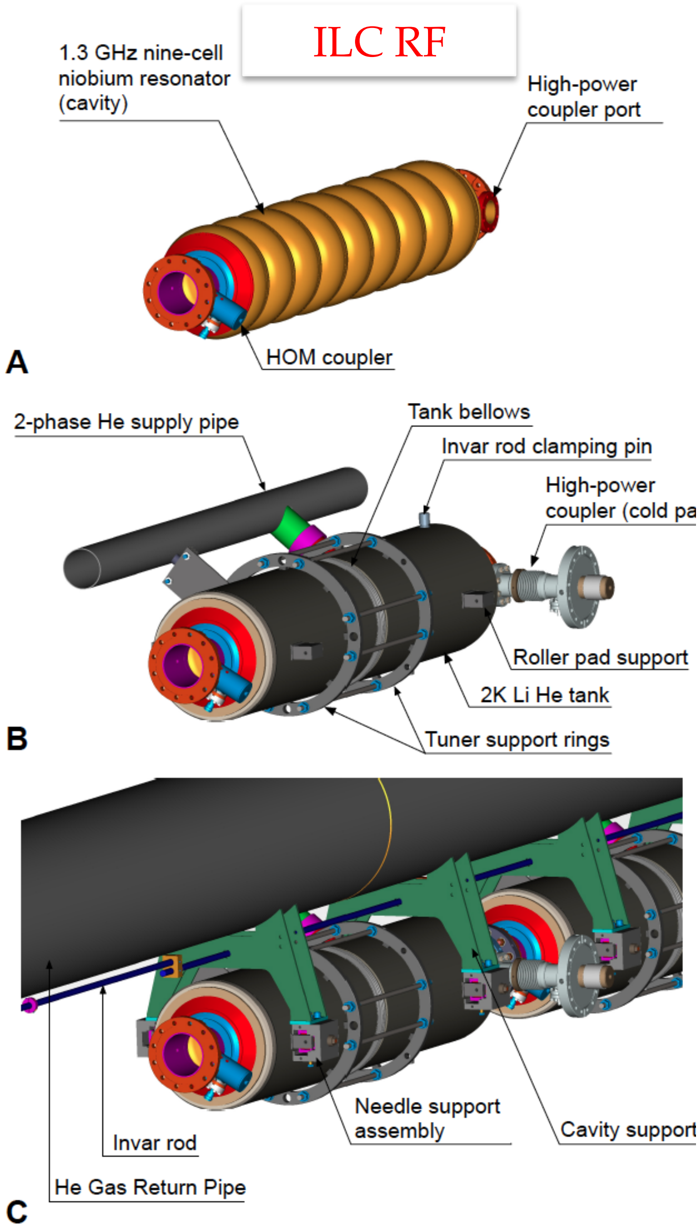
- Computing back the geometrical emittance target for CLIC DR (energy of 2.86 GeV), we obtain **90** and **0.9** pm.rad in the horizontal and vertical plane
- For the ILC damping rings (@ 5 GeV), the geometrical emittances are **500** and **2** pm.rad, i.e. still higher but with factors of 2 to 6
- Similar vertical emittances have been achieved today in various low emittance rings, with SLS storage ring holding the record by having reached the CLIC target
- The horizontal emittance is unprecedented but several synchrotron light source projects ("Ultimate storage rings") are targeting even lower emittances
- The main difference with other low emittance rings is that DR (especially CLIC) necessitate to have also very small longitudinal emittance (bunch length and energy spread) as explained in the next slide
- This makes the DR beam dynamics (especially for CLIC) largely dominated by collective effects

# Bunch Compressors

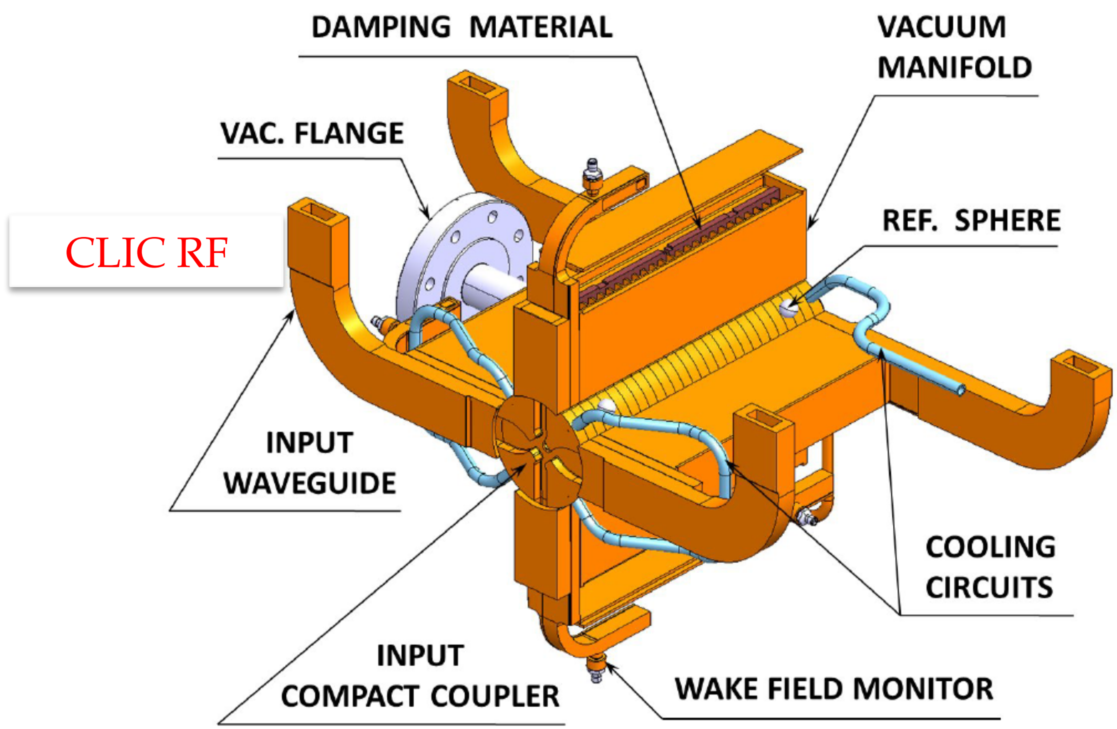
- After extraction from DRs, beam goes through bunch compressors, which manipulate phase space so as to shrink the bunch length from **a few mm** down tens or hundreds of **μm** as required by main linac and IP
- Both ILC and CLIC are considering 2 bunch compression stages taking the bunch length from **6** and **1.8 mm** down to **300** and **40 μm** respectively
- From the downstream point of view, lowering the bunch length means cheaper and simpler bunch compression schemes
- From the DR point of view, shorter bunches require smaller values of the momentum compaction (lattice design) or higher RF voltage (more RF units, hence greater cost). Shorter bunches indeed imply bigger sensitivity to collective effects



# Main Linac RF system impact




- The bunch-train structure is largely determined by the design and performance of the RF system of the Main Linac (ML)
- Due to the different technology of CLIC and ILC main RF (superconducting vs. normal conducting), the design of the two DRs, vary significantly

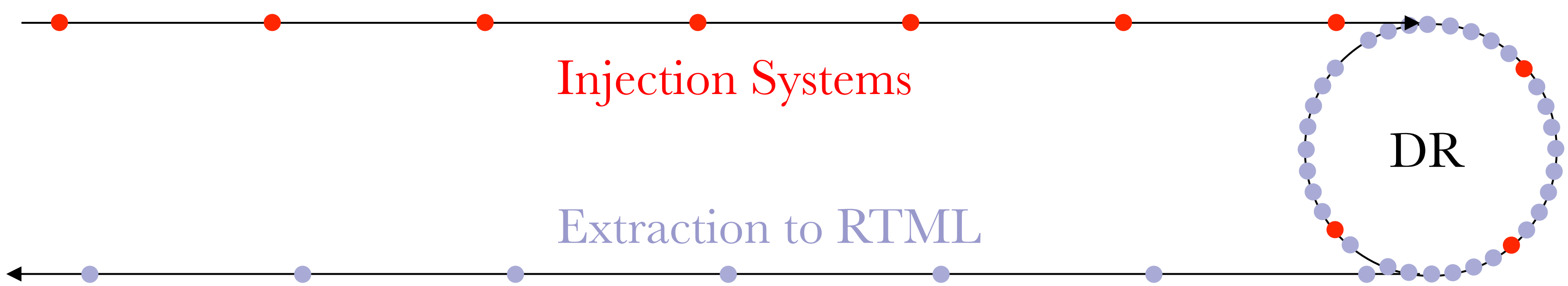


# ILC Main Linac RF system impact

- For the ILC DRs, the RF power system (1.3GHz klystrons of 10MW) imposes the total RF pulse of 1.6ms and considering the filling time of the cavity of 0.87ms, the beam pulse length is **0.73ms**
- At the same time, due to RF peak power requirements, the **nominal average current** for each beam pulse should be **5.8 mA**
- The dynamic cryogenic load (refrigeration) is a cost driver and imposes the nominal machine **repetition rate** of **5 Hz**
- Considering the bunch population to be $\mathbf{2x10^{10}}$ particles, leads to the nominal bunch train number of **1312 bunches** per pulse and thereby the **bunch spacing** of **554 ns** for uniform loading through the pulse
- The resulting collision rate at the IP is then **7kHz** consistent with the target luminosity
- The 5 Hz repetition rate places the primary constraint on the **DR damping times**
  - In order for the bunches in each pulse to experience 8 full damping cycles, a **transverse damping time of ≤25 ms** is required.

# ILC Bunch Train structure

- The basic ILC bunch train structure of 0.73ms with 1312 uniformly spaced bunches with 554ns between them results to a train length of **220km**, which cannot fit to a reasonable ring circumference
- Thus, the damping rings must act as a *reservoir* to store the full train
- The long bunch train has to be folded (or **compressed**) into a much shorter ring, and it has to be **decompressed** while extracted, through a bunch-by-bunch extraction scheme

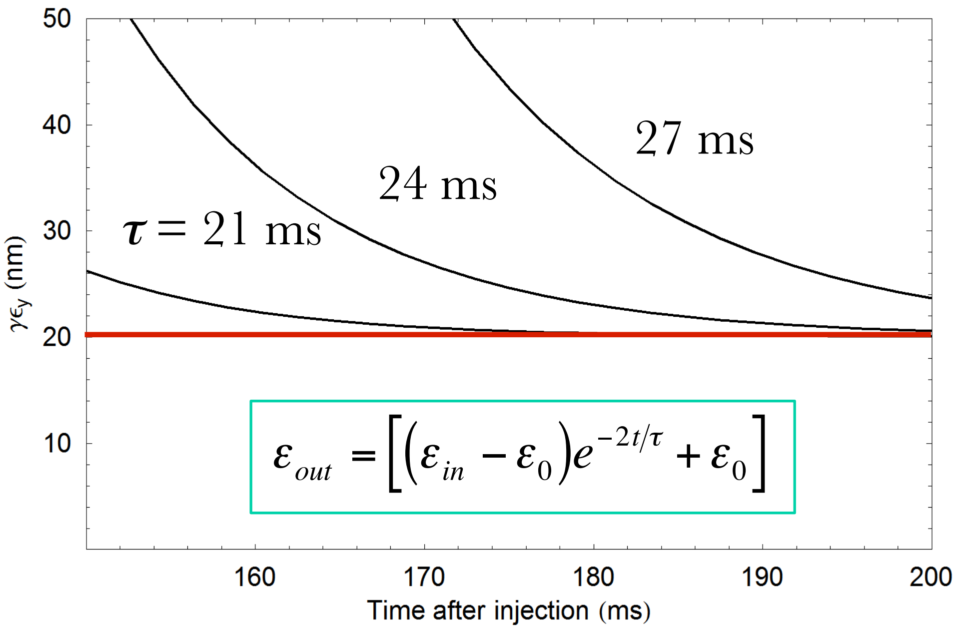



- A "trade-off" is necessary between the bunch spacing in the ring (the longest possible for reducing e-cloud build-up and increasing the extraction kicker rise/fall times) and its circumference (the shortest possible for cost but also reduction of single bunch collective effects, as space-charge and IBS)
- There is significant overlap between the injection and extraction cycles for maintaining constant beam loading and each extracted bunch position is filled by the injected bunch

- A scaling law between RF pulse length, accelerating field and break-down rates of the CLIC ML X-band RF cavities necessitates very short pulse lengths of **156 ns**
- A short bunch spacing is also favored in order to improve the RF-to-beam efficiency and a value of **0.5 ns** (6 cycles of the 12GHz RF system)
- The resulting train of **312 bunches** can easily fit to a ring of circumference of around **100m**, even taking into account confortable injection/extraction kicker rise/fall times
- This circumference is quite low though for realizing an ultra-low emittance magnet structure with reasonable magnet-to-magnet distances and also get the ultra-low damping times for fitting to the machine pulse of **20ms** (50Hz repetition rate)
- Thus the ring circumference is ~400m around an order of  longer than the bunch train
- On the other hand, a **2GHz** RF system is imposed to the DRs which is extremely challenging with respect to the power source, the high and average and peak current and the associated LLRF system dealing with severe transient beam loading

# Injected emittance and damping time

- Positron production via a heavy metal target results in much larger emittances due to scattering in the target for positrons
- Electrons can be produced with much smaller emittances through an optimized design of the injector gun and its cathode
- The ($e^+$) injected emittance partially determines damping time
- The approach to the target extraction emittance of the ILC DR (20nm.rad) is shown for various damping times assuming the target $e^+$ injected emittance ($\varepsilon_n = 0.01$ m.rad) and for "zero-current" beam (no collective effects)



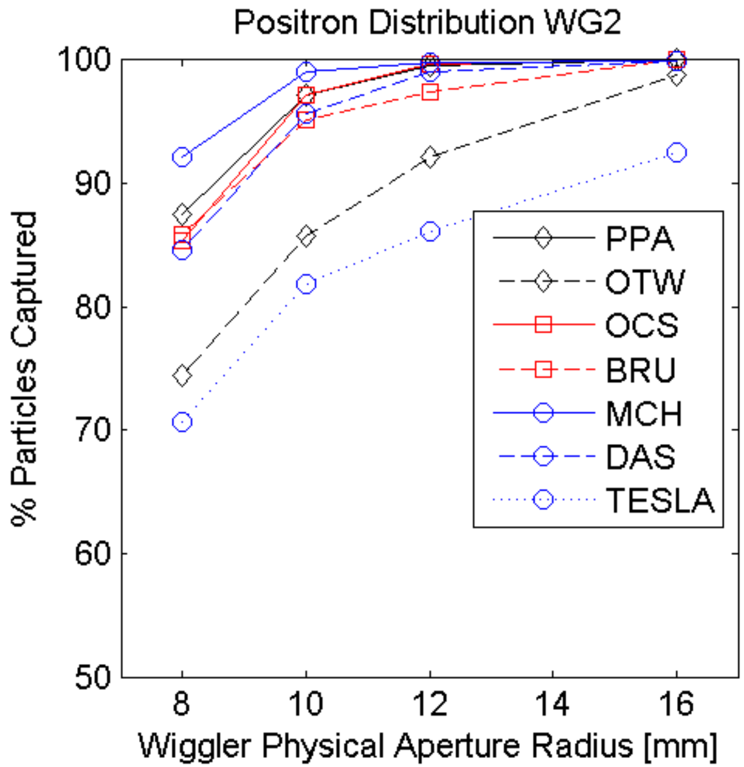

$$\varepsilon_{out} = \left[\left(\varepsilon_{in} - \varepsilon_0\right)e^{-2t/\tau} + \varepsilon_0\right]$$

- This justifies the consideration of damping times < 25ms

$t_c/\tau$
200/27 = 7.4
200/24 = 8.3
200/21 = 9.5

# Injected emittance and acceptance

- The injected beams have large betatron amplitudes and energy spread
- This requires that the acceptance of the DR to be sufficiently large to accommodate these beams
- It places important constraints on the minimum aperture of the vacuum system and the minimum good field regions of all of the magnets but also magnetic error tolerances and non-linear optimisation for adequate dynamic aperture
- In the case of CLIC, the injected emittance cannot be digested directly to the DRs, necessitating pre-damping rings, even for electrons (especially due to the very short beam cycle of 20ms)




Particle capture rates assuming that the limiting physical aperture in the ILC DRs is due to the vacuum chambers in the wiggler regions. The choice of a superferric wiggler design, with large physical aperture, allows for a DR design with full acceptance.

# Reaching an optimized DR design

- Taking into account the requirements previously mentioned
  - Train structure
  - Equilibrium emittance requirements
  - Bunch length requirements
  - Bunch current
  - Acceptance of ring
  - Timing structure
- Choose adequate parameters for reaching desired DR performance
  - Design typically implies various compromises between parameters
  - Parameters must be robust and flexible enough to match paths of evolution of the overall machine design (e.g. future upgrades)

# Example: Ring Circumference

- Large circumference implies that collective effects (IBS, space charge) are more severe
- If collective effects are significant, higher energy is desirable
- Higher energy means larger equilibrium emittance due to quantum excitation but also larger ring…
- Small circumference implies fewer components and smaller tunnel so cheaper and potentially better net hardware reliability
- On the other hand, the folding of linac bunch train into ring requires more closely spaced bunches
- Closely spaced bunches more challenging bunch-by-bunch injection and extraction and electron cloud and fast ion effects more severe

# Example: Beam Ring Energy

- For higher energy, sensitivity to collective effects (beam instabilities, intrabeam scattering, space charge, etc) is weakened
- Higher energy provides increased damping rates due to higher synchrotron radiation
- For a given normalized emittance from the sources, higher energy provides smaller geometrical emittance due to adiabatic damping from the initial beam acceleration and the ring acceptance issues are eased
- Lower energy provides a smaller equilibrium emittance but without taking into consideration collective effects
- Lower energy implies weaker magnets and lower field RF cavities to focus the beam, hence cheaper (and often more reliable) hardware

# Example: High Voltage Kickers

- Wide kicker pulse is typically more stable, hence better for uniform injection/extraction
- Wide kicker pulse requires a large ring circumference to allow bunch-by-bunch injection and extraction (bunch spacing)
- Wide kicker pulse necessitates relatively fewer kicker structures (matched to pulse width), minimizing impedance issues, improving reliability, minimize cost…
- Wide kicker pulse works well in a scenario with full train injection/extraction
- Narrow kicker pulse implies higher bandwidth which requires careful impedance matching with kicker structure
- Many short kicker structures are required for a narrow kicker pulse (reliability and cost concerns)
- Narrow kicker pulse combined with high voltage pulses may be quite challenging

# Example: Damping Wigglers

- Competing technologies:
  - Permanent magnet
  - Normal conducting electromagnet
  - Superconducting electromagnet
- Performance issues:
  - Aperture
  - Allowable field strength
  - Field quality
  - Sensitivity to radiation damage
  - Operating cost
- ILC design choice:
  - Employ only a damping ring with no pre-damping ring
  - Places significant weight on aperture and field quality issues in order to handle the large input beams from the positron source
- CLIC choice:
  - Use pre-damping rings, easing aperture requiremens of DR
  - Use SC damping wigglers for reaching target emittance within ultra-fast beam cycle

# Example: Physics requirements

- Provide wider energy range for producing luminosity
- This affects the polarised positron production mode for ILC and increases significantly bunch charge and train length for CLIC
- ILC positron production is at fixed energy point in main linac
- A lower energy ILC needs to produce positrons on one pulse and then change the acceleration in the ML for collisions on a separate pulse
- For this two pulse configurations, the positron damping ring only filled 50% of time which means new RF system design and increase of damping rate so that 5Hz pulses for collision can be maintained
- Lower positron production energy means lower production yield and inability to achieve desired standard operating parameters
- Lower positron production energy has potentially unacceptable impact on the positron target design

# ILC DR Design

- The ILC DR baseline configuration is able to meet the key design parameters required for the baseline design
  - Validation of the various design choices continues
  - Major limiting areas of operational concern identified for further R&D included
    - Achievement of 2pm vertical emittance
    - Electron Cloud effects
    - Fast Ion effects
    - Ability to stably inject and extract closely spaced bunches
  - An aggressive R&D program has been underway for address these issues at CESRTA and ATF

# CLIC DR challenges and adopted solutions

| Parameters, Symbol [Unit] | 2 GHz | 1 GHz |
|---|---|---|
| Energy, $E$ [GeV] | 2.86 | |
| Circumference, $C$ [m] | 427.5 | |
| Bunch population, $N$ [$10^9$] | 4.1 | |
| Basic cell type in the arc/LSS | TME/FODO | |
| Number of dipoles, $N_d$ | 100 | |
| Dipole Field, $B_0$ [T] | 1.0 | |
| Norm. gradient in dipole [$m^{-2}$] | -1.1 | |
| Hor., ver. tune, ($Q_x$,$Q_y$) | (48.35,10.40) | |
| Hor., ver. chromaticity, ($\xi_x$,$\xi_y$) | (-115,-85) | |
| Number of wigglers, $N_w$ | 52 | |
| Wiggler peak field, $B_w$ [T] | 2.5 | |
| Wiggler length, $L_w$ [m] | 2 | |
| Wiggler period, $\lambda_w$ [cm] | 5 | |
| Damping times, ($\tau_x$, $\tau_y$, $\tau_l$) [ms] | (2.0,2.0,1.0) | |
| Momentum compaction, $\alpha_c$ [$10^{-4}$] | 1.3 | |
| Energy loss/turn, $U$ [MeV] | 4.0 | |
| Norm. hor. emittance, $\gamma\epsilon_x$ [mm·mrad] | 472 | 456 |
| Norm. ver. emittance, $\gamma\epsilon_y$ [mm·mrad] | 4.8 | 4.8 |
| Energy spread (rms), $\sigma_\delta$ [%] | 0.1 | 0.1 |
| Bunch length (rms), $\sigma_s$ [mm] | 1.6 | 1.8 |
| Long. emittance, $\epsilon_l$ [keVm] | 5.3 | 6.0 |
| IBS factors hor./ver./long. | 1.5/1.1/1.2 | 1.5/1.1/1.2 |
| RF Voltage, $V_{RF}$ [MV] | 4.5 | 5.1 |
| Stationary phase [$^o$] | 62 | 51 |
| Synchrotron tune, $Q_s$ | 0.0065 | 0.0057 |
| Bunches per train, $n_b$ | 312 | 156 |
| Bunch spacing, $\tau_b$ [ns] | 0.5 | 1 |
| RF acceptance, $\epsilon_{RF}$ [%] | 1.0 | 2.4 |
| Harmonic number, $h$ | 2851 | 1425 |

- 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

# Some ILC-CLIC Comparisons

| Parameter | Units | ILC DR (RDR) | CLIC DR |
|---|---|---|---|
| Energy | GeV | 5.0 | 2.86 |
| Circumference | km | 3.238 | 0.428 |
| Nominal # of bunches & particles/bunch | | $1312@2.0\times10^{10}$ | $312@0.41\times10^{10}$ |
| Macropulse Repetition Rate | Hz | 5 | 50 |
| Average current | A | 0.4 | 0.15 |
| Energy loss per turn | MeV | 4.5 | 4.0 |
| RF Frequency | MHz | 650 | 2000 (1000) |
| Total RF voltage | MV | 14 | 10 |
| Equilibrium normalized emittance, $\gamma\varepsilon_x$ | μm·rad | 5.7 | 0.46 |
| Natural Chromaticity, $\chi_x/\chi_y$ | | -51/-43 | -115/-85 |
| Momentum compaction, $\alpha_c$ | | $3.3\times10^{-4}$ | $1.3\times10^{-4}$ |
| Bunch length, $\sigma_z$ | mm | 6.0 | 1.6 (1.8) |
| Momentum spread, $\sigma_p/p$ | | $1.1\times10^{-3}$ | $1.0\times10^{-3}$ |
| Horizontal damping time, $\tau_x$ | ms | 24.0 | 2.0 |
| Longitudinal damping time, $\tau_z$ | ms | 12.0 | 1.0 |

# Summary

- Overview of some of the key design issues for the CLIC and ILC damping rings
- DR design has to comply with numerous constraints and design requirements imposed by upstream and downstream systems
- DR offer a wide spectrum  of challenges both for beam dynamics and the required hardware
- The optimization process involves complicated trade-offs to meet physics specifications
- The rest of the course will cover as much as possible the beam physics of LC DRs and its impact to the associated technology