Linear Collider Damping Rings

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ALCPG Seminar

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Outline

- The need for damping rings in a linear collider
  - Configurations: NLC/JLC and TESLA
- Principles of radiation damping
  - Longitudinal and transverse dynamics
  - Quantum excitation and equilibrium emittance
- Design issues
  - Key parameters for damping rings
  - Design constraints
- Operational and performance issues
  - Single particle effects
  - Collective effects
- Research and development priorities

Why do we need damping rings?

- The beam from the source is too large to make the luminosity
  - Interaction point parameters specify transverse emittance:
    - 3.6 μm × 0.04 μm for NLC/JLC
    - 10 μm × 0.03 μm for TESLA
  - Need to allow some budget for dilution
- Stability requirements of main linacs, beam delivery system and final focus are extremely demanding

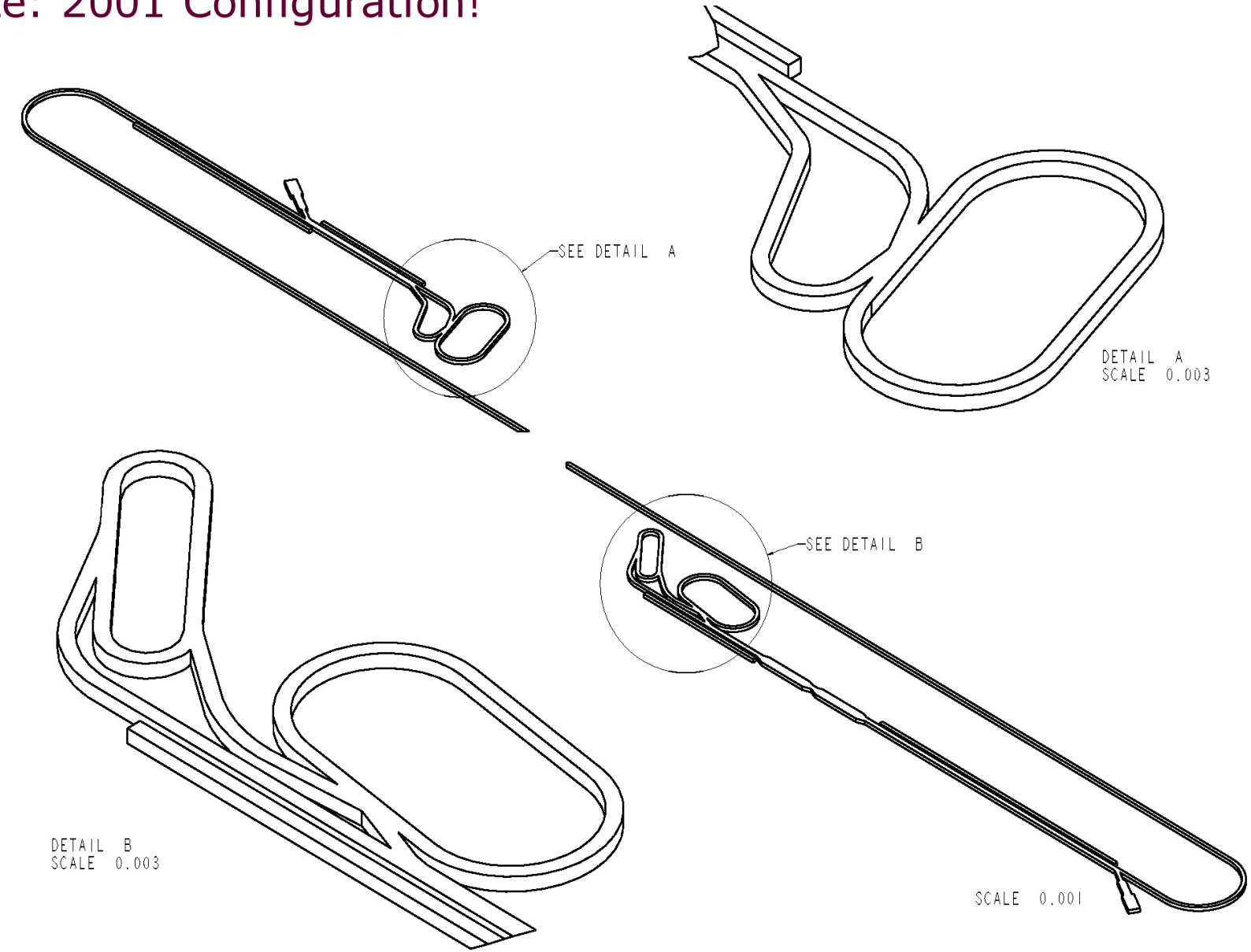
	NLC MDR	TESLA e^+
Injected $\gamma\varepsilon$	150 μm rad	10 000 μm rad
Extracted Horizontal $\gamma\varepsilon$	3 μm rad	8 μm rad
Extracted Vertical $\gamma\varepsilon$	0.02 μm rad	0.02 μm rad
Injected Energy Spread	1% full width	1% full width
Extracted Energy Spread	0.1% rms	0.13%
Extracted Bunch Length	4 mm	6 mm
Bunch Spacing	1.4 ns	20 ns
Bunches per Train	192	2820
Repetition Rate	120 Hz	5 Hz

Can we do without damping rings?

- RF photocathode guns are capable of producing electron beams with the necessary 6 dimensional emittance
  - Only capable of making unpolarized beams at present
  - Positron beams…
- Beam extracted from a storage ring is much more stable than that direct from the source
  - Low transverse and longitudinal jitter are crucial for performance of systems downstream, from bunch compressors to the interaction point
- Damping rings delay the beam, allowing feed-forward systems to compensate variations in parameters
  - For example, RF power in linac must be adjusted in response to bunch charge
- *Damping rings look like the best technical solution at present*

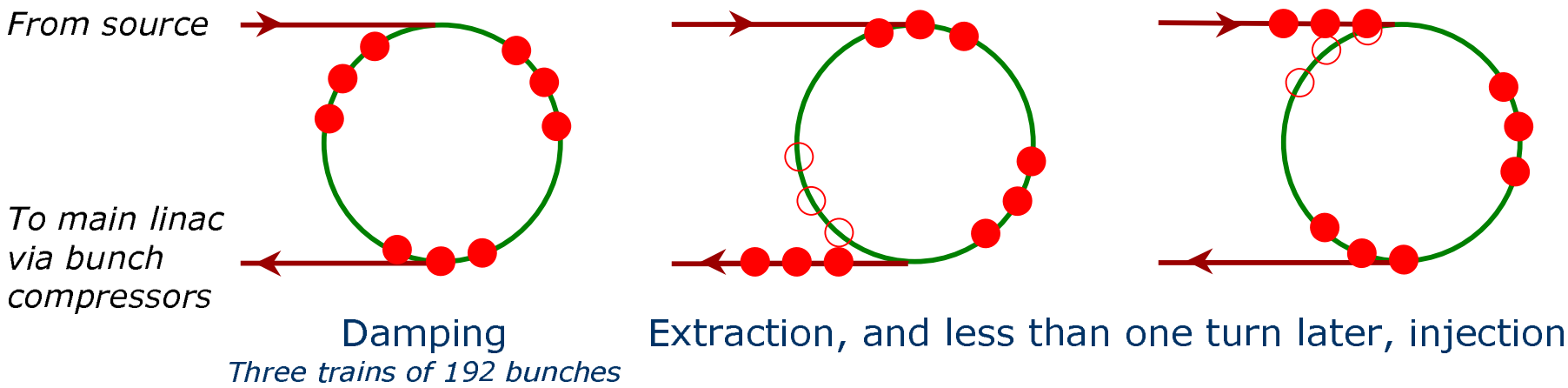
NLC Injector Systems Scheme

Note: 2001 Configuration!

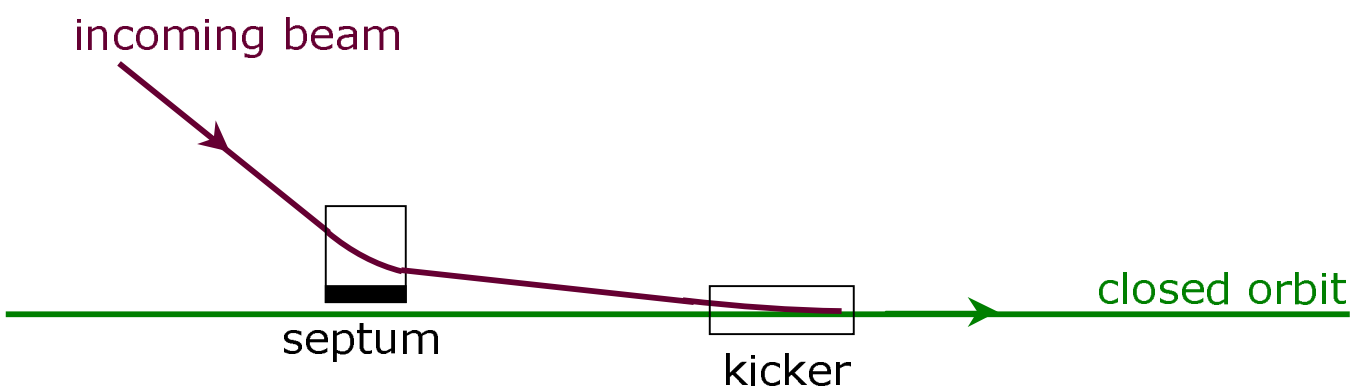


Damping Rings in NLC/JLC

- NLC/JLC Main Damping Rings store three bunch trains at once

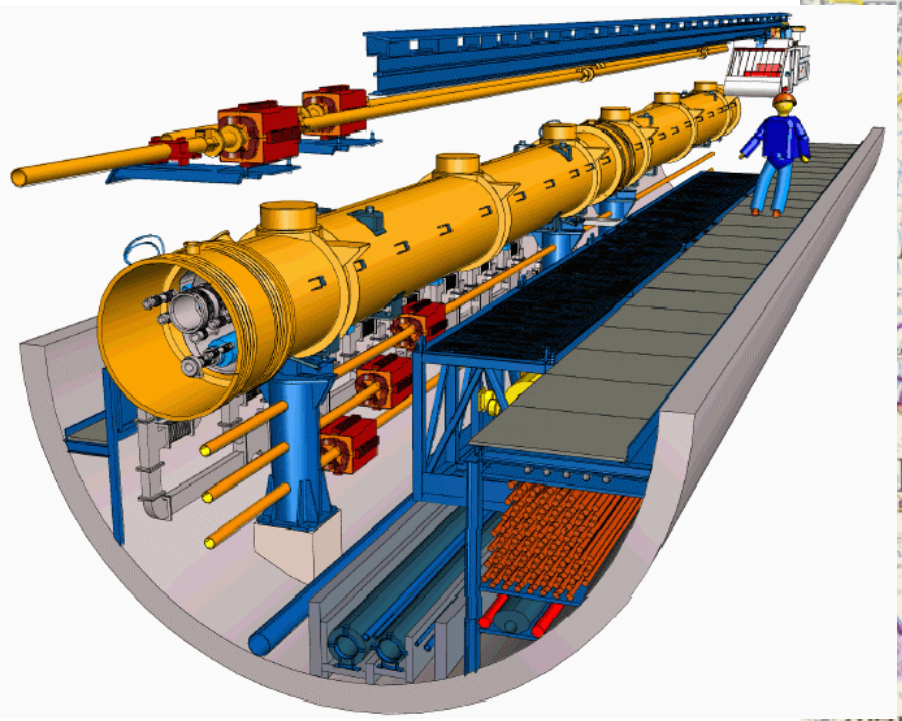


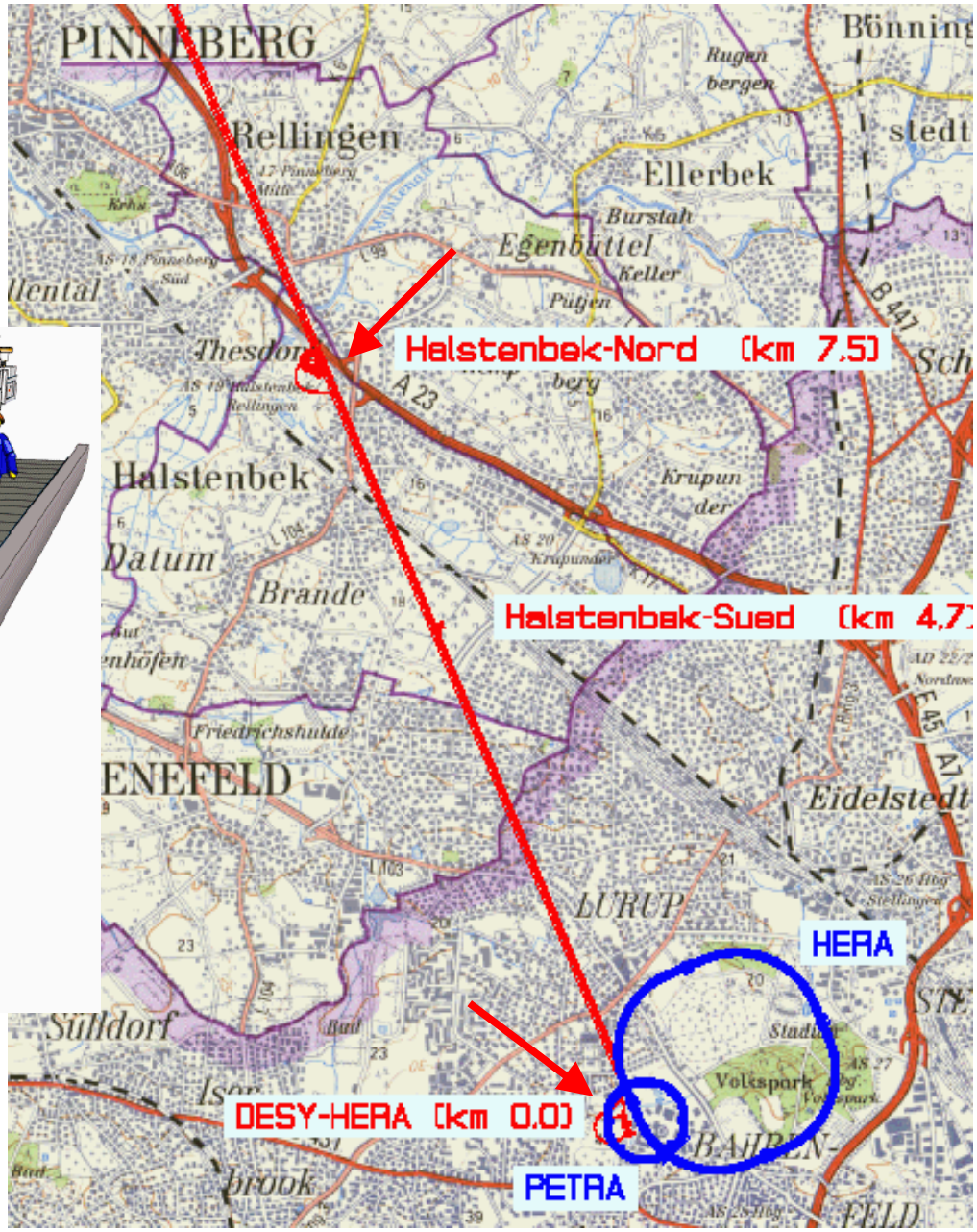
- On-axis injection needed, so current cannot be “stacked”



TESLA Damping Rings

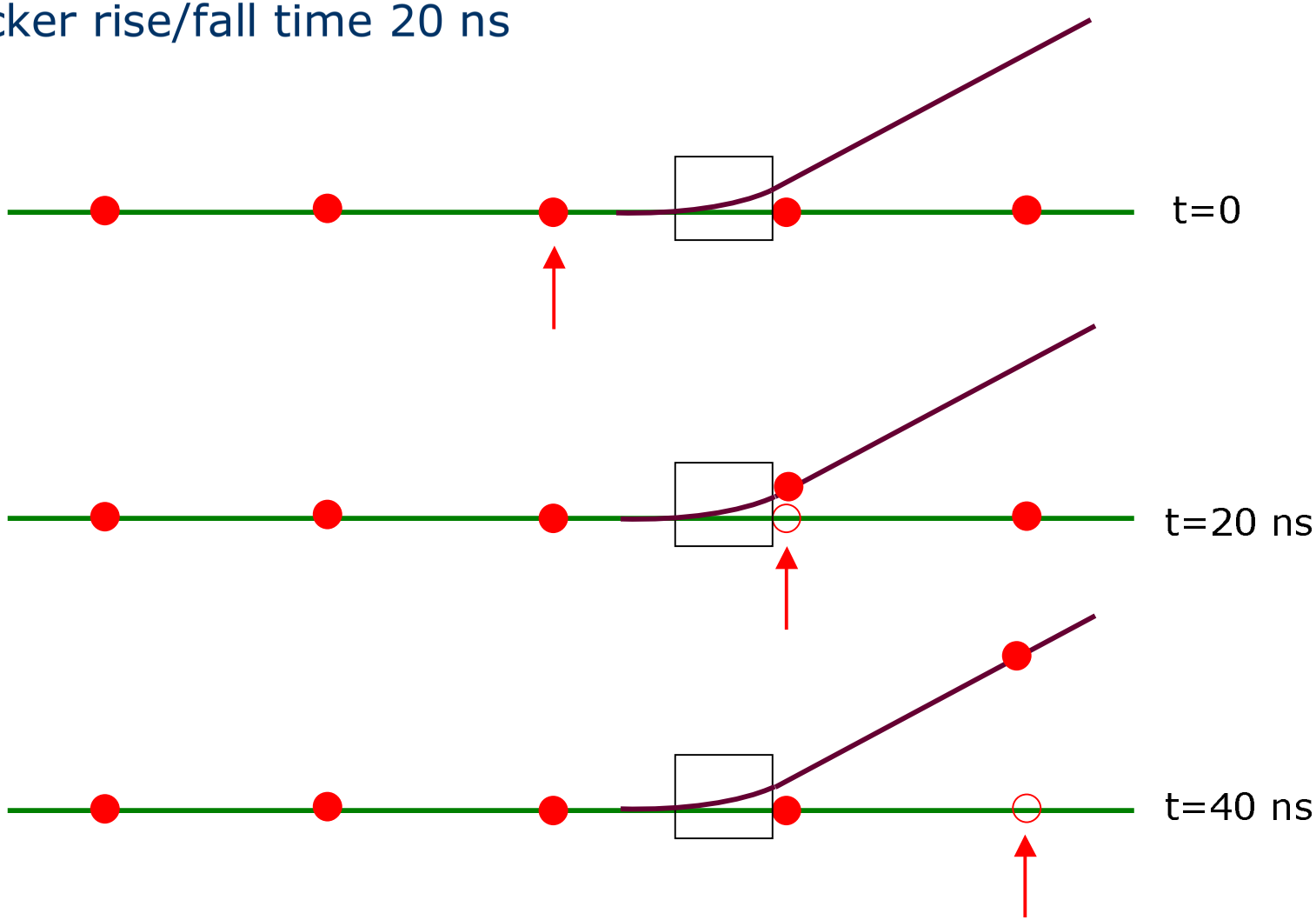
- Damping Rings are placed in the main tunnel with the linac





Damping Rings in TESLA

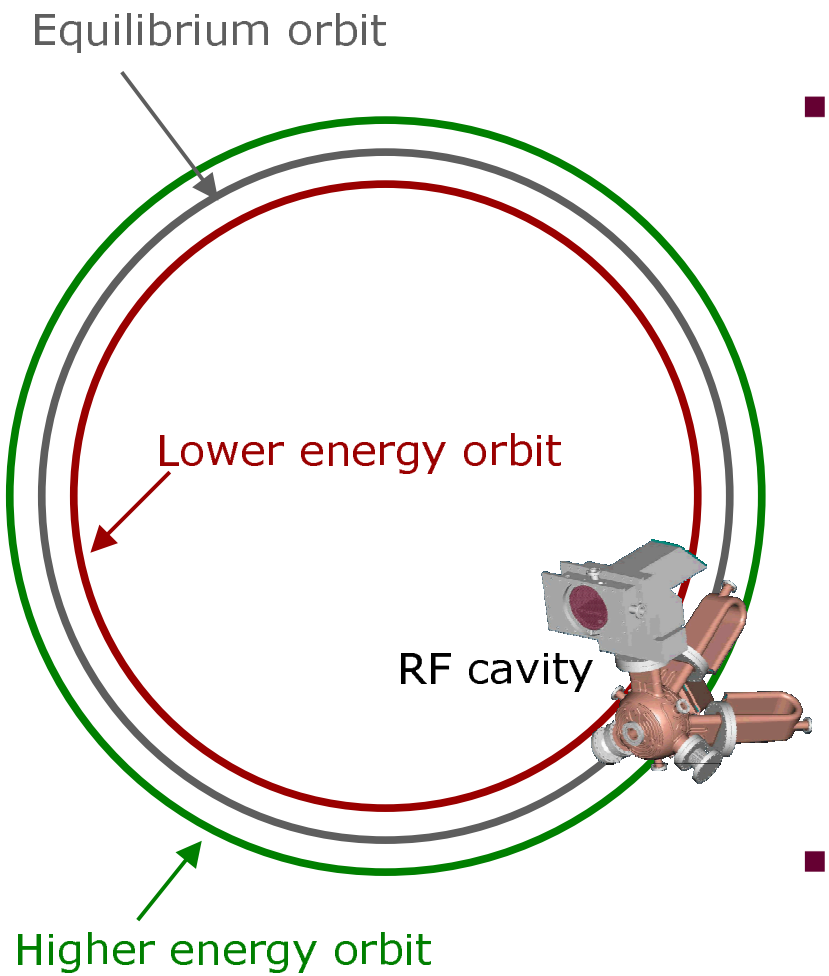
- Bunch trains of 2820 bunches with 330 ns spacing (280 km), must be compressed in the damping rings (17 km)
- Bunches injected/extracted individually
  - Kicker rise/fall time 20 ns



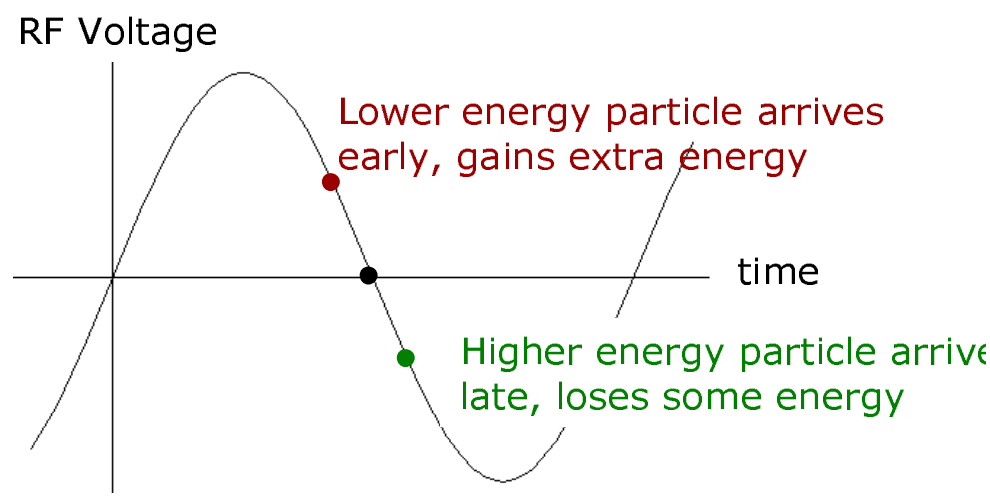
Radiation Damping

- In *symplectic* transport through magnets, the phase space volume (geometric emittance) is constant
  - The same is true of the *normalized* emittance under acceleration in RF cavities
- We need some other process to damp the emittance
  - Must be non-symplectic, to get round Liouville's theorem
- Radiation damping is appropriate for a linear collider
  - Can operate sufficiently fast
  - Well understood, from experience with circular colliders, and synchrotron light sources and
- Mechanism of radiation damping is somewhat different in the longitudinal and transverse directions

Longitudinal Oscillations and Damping



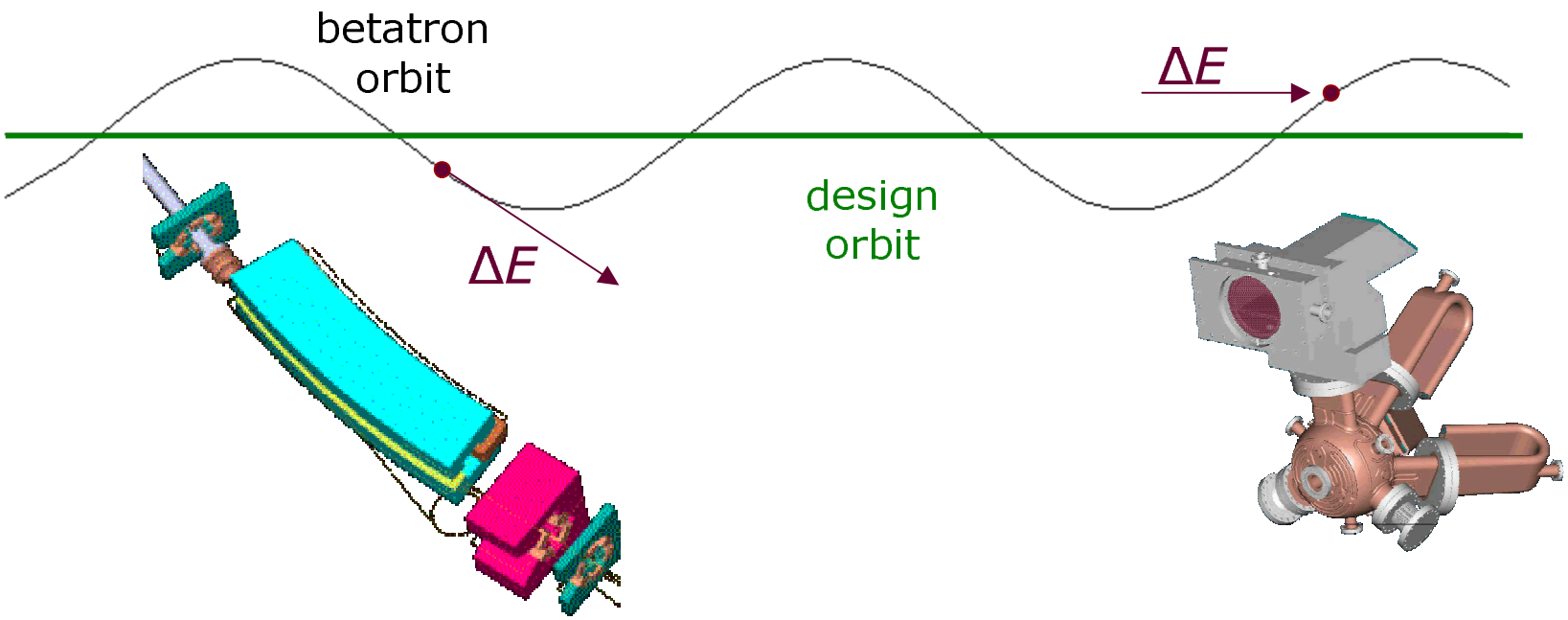
- Higher energy particles follow a longer orbit
- Particles perform synchrotron oscillations in the RF potential



- *In addition*, particles emit synchrotron radiation dependent on their energy
- This acts as a "frictional" force, damping the synchrotron oscillation

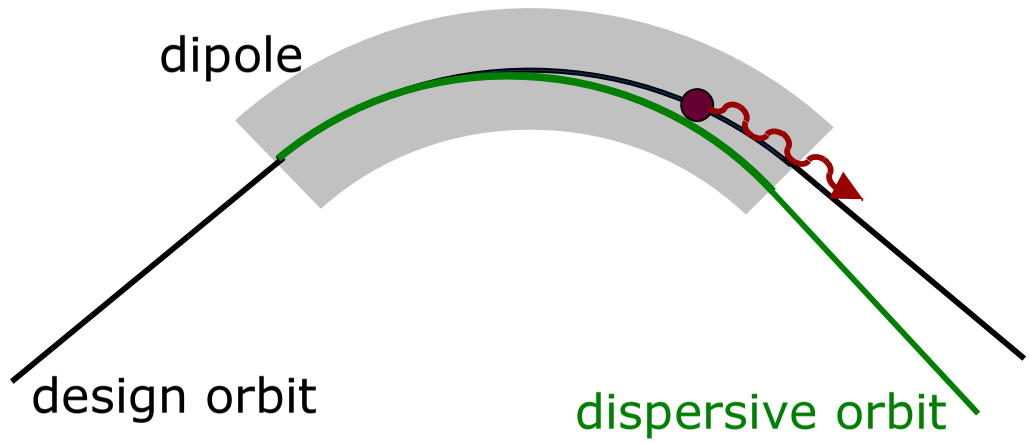
Transverse Oscillations and Damping

- Synchrotron radiation emitted in narrow cone (of width ~ $1/\gamma$) around instantaneous direction of motion
  - Particles receive a transverse momentum kick proportional to the amplitude of betatron motion
- Energy lost through synchrotron radiation is replaced in the RF cavities
  - Field is such that there is no transverse momentum kick



Quantum Excitation

- If the synchrotron radiation were continuous ($h \rightarrow 0$) then the six-dimensional emittance would damp to zero
- Emission of a photon will excite synchrotron and betatron oscillations



- Equilibrium emittance (longitudinal and transverse) is a balance between radiation damping and quantum excitation

Some Useful Results

- The emittance of the beam damps exponentially:

$$\frac{\mathrm{d}\gamma\varepsilon}{\mathrm{d}t} = \gamma\varepsilon_{\mathrm{inj}}\mathrm{e}^{-2t/\tau} + \gamma\varepsilon_{\mathrm{equ}}\left(1-\mathrm{e}^{-2t/\tau}\right)$$

- The damping times are simply related to the time it would take for a particle to lose all its energy:

$$\mathcal{J}_x\tau_x = \mathcal{J}_y\tau_y = \mathcal{J}_E\tau_E = 2\frac{E}{U}T \qquad U = C_\gamma\frac{E^4}{\rho} \qquad \mathcal{J}_x + \mathcal{J}_y + \mathcal{J}_E = 4$$

- The equilibrium (natural) energy spread depends only on the beam energy and the dipole fields:

$$\sigma_\delta^2 = C_q\frac{\gamma^2}{\rho}$$

- The equilibrium horizontal emittance scales as the square of the energy, and is also a complicated function of the lattice:

$$\gamma\varepsilon_0 = C_q\gamma^3\frac{I_5}{\mathcal{J}_x I_2}$$

- The equilibrium vertical emittance *in a perfect lattice* is limited only by the opening angle of the radiation

Key Parameters

- Damping time
  - Requirement determined by specified injected and extracted emittance and machine rep rate
  - Scales as $\rho C E^{-3}$
    - Circumference should be as short as possible…
    - …but limited by train structure and kicker parameters
    - Higher energy is better
- Natural emittance
  - Specified by interaction point parameters
  - Scales (with N bending magnets) as E^3/N
    - Lower energy is better
- Natural energy spread
  - Gets converted to bunch length in the bunch compressor
  - Scales as $E\rho^{-1/2}$
    - Lower energy is better

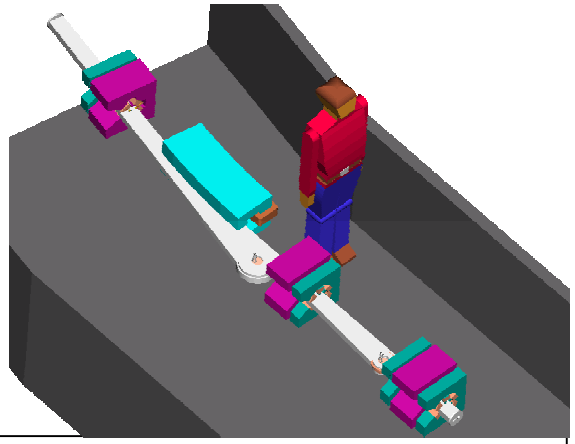
- *Use a fairly low energy for the emittance…*
- *…and a wiggler to reduce the damping time*

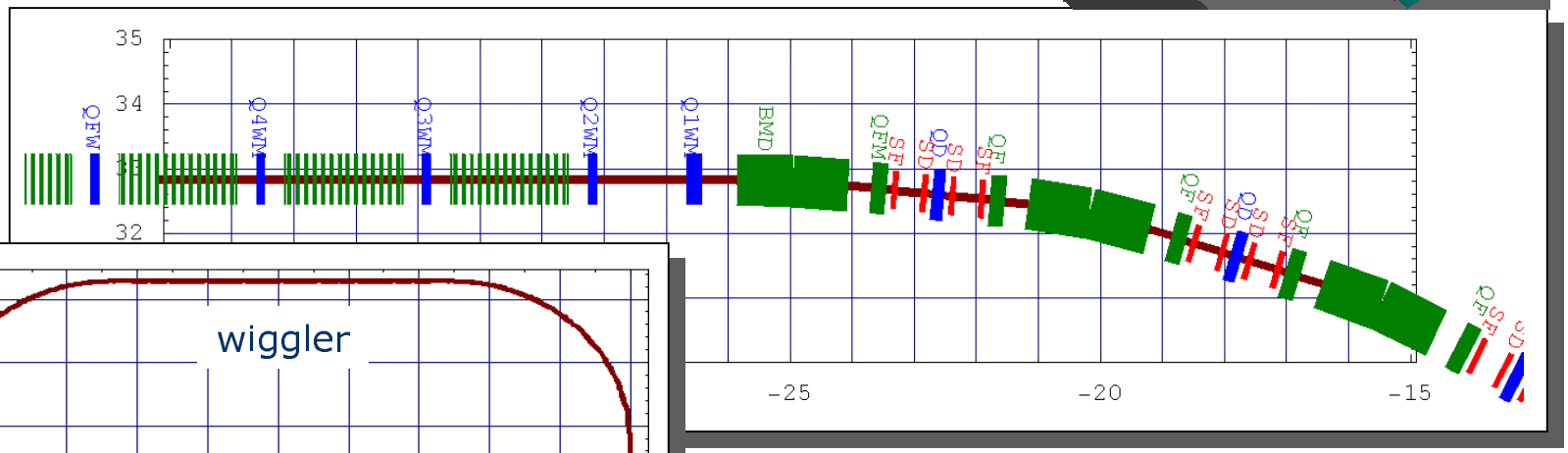
Lattice Design Steps

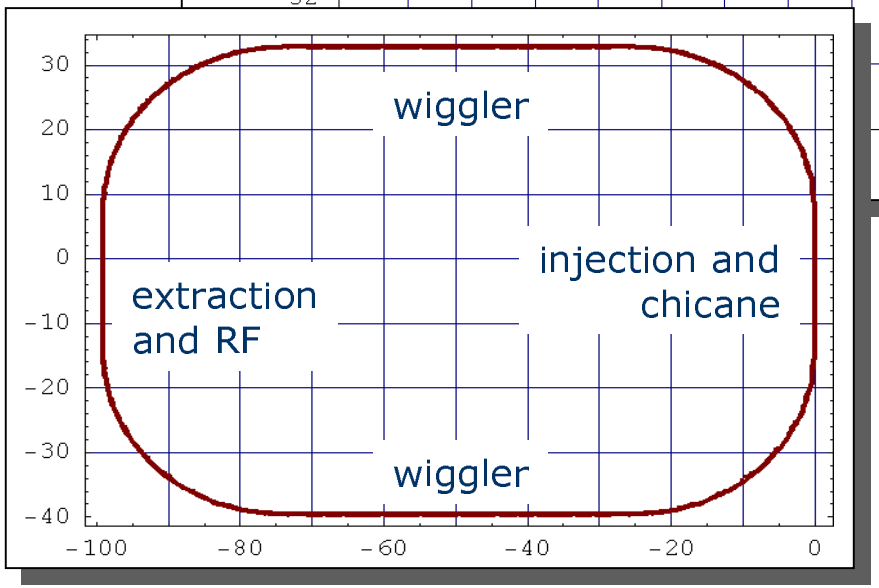
- Key parameters are used to determine an appropriate energy
  - Also need to avoid depolarization resonances
- Basic lattice arc cell is constructed to meet requirements for transverse emittance
  - More cells means a lower emittance
  - Space is also needed for injection/extraction, RF etc.
  - For NLC/JLC, circumference is an issue at this stage
- Wiggler parameters are determined by the damping time requirements
- Final lattice (with appropriate circumference) includes:
  - arcs
  - wiggler
  - injection and extraction systems
  - RF cavities
  - chicane for circumference correction
  - more…

The NLC Main Damping Ring

- 1.98 GeV beam energy
- 36 arc cells
- 300 m circumference
  - 3 bunch trains, 192 bunches × 1.4 ns
  - 65 ns kicker rise/fall time
- 62 m of 2.15 T wiggler

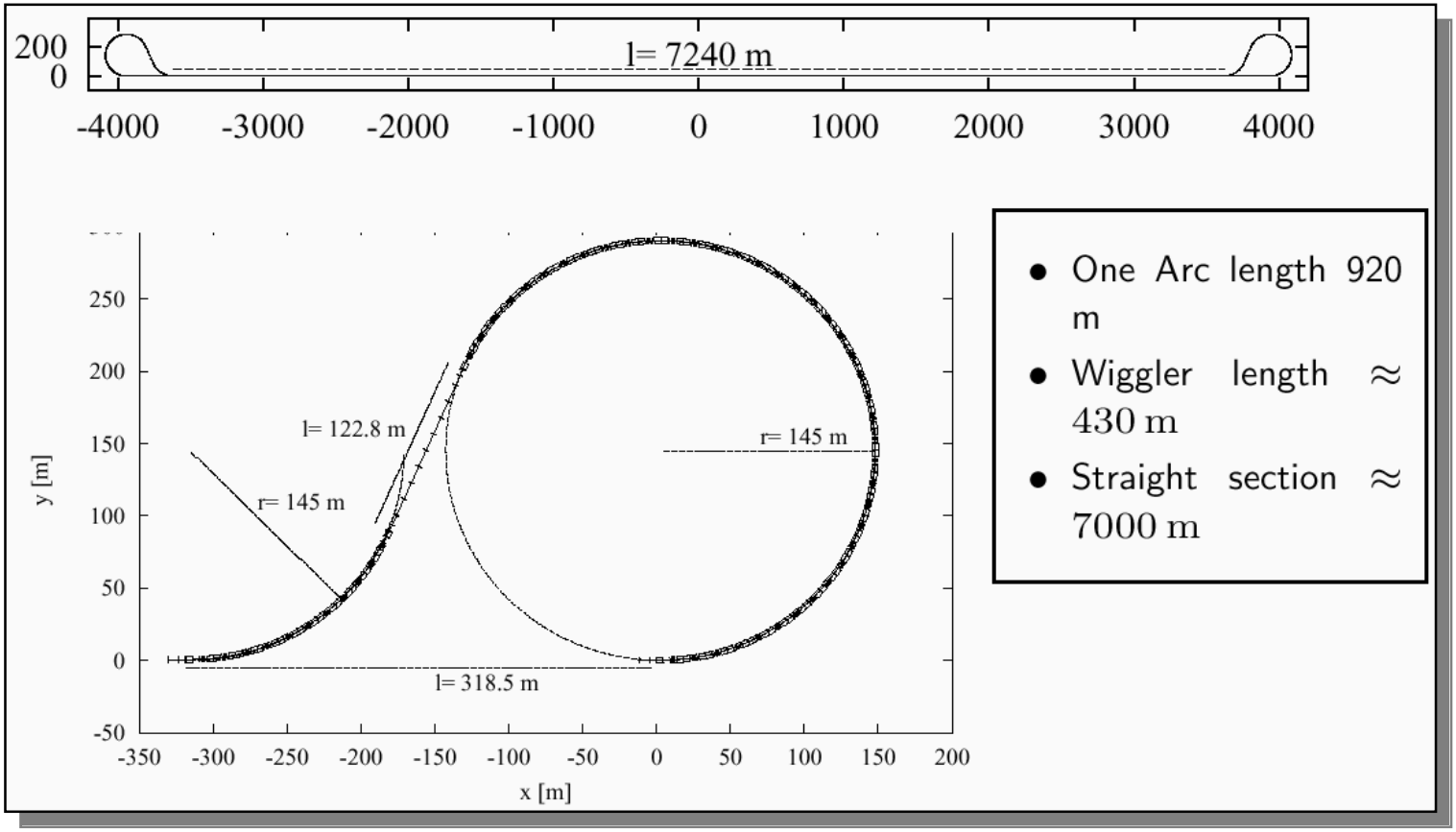






The TESLA Damping Rings

- 5 GeV beam energy
- 17 km circumference
  - 1 compressed bunch train, 2820 bunches
  - 20 ns kicker rise/fall time
- 430 m of 1.6 T wiggler in the positron ring

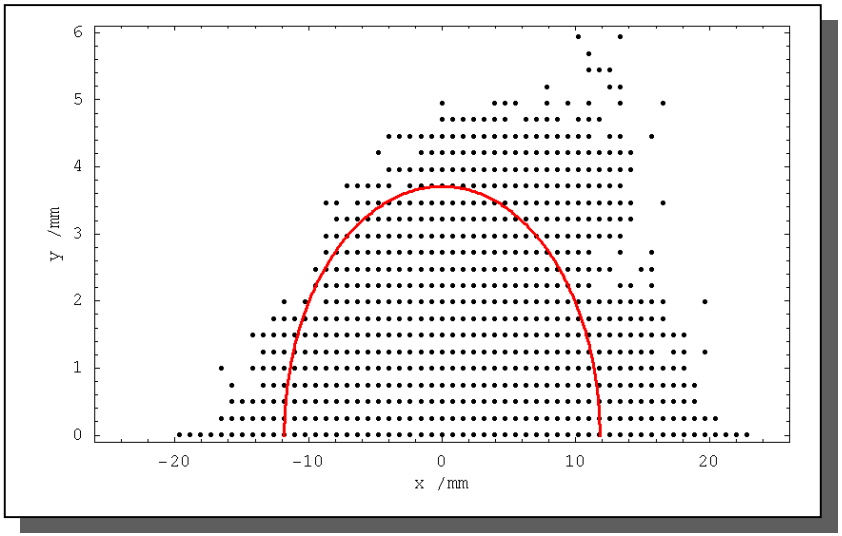


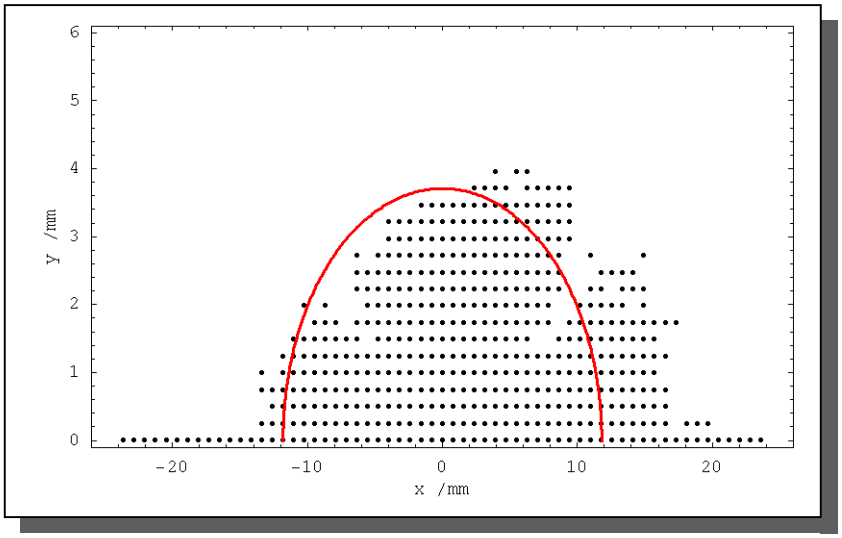
Design Issues

- Acceptance
  - Large mean injected beam power - even small losses could quickly damage vital components
    - 55 kW NLC
    - 226 kW TESLA
  - Transverse and longitudinal acceptance need to be as large as possible
    - Physical limits (beam pipe aperture)
    - Dynamical limits (dynamic aperture)
- Beam quality
  - Single particle effects
  - Collective effects
- Engineering challenges
  - Magnet requirements: field quality
  - Vacuum system
  - RF system
  - Diagnostics, etc.

Acceptance

- Dynamic aperture is limited by nonlinear magnetic fields
  - Sextupoles are needed to correct the chromaticity, and stabilize the dynamics for off-energy particles
  - Wigglers have intrinsic nonlinear fields
  - Dipoles and quadrupoles have (small) systematic and random nonlinear components
- An important and challenging issue for all modern storage rings
  - A variety of powerful tools have been developed to characterize and help optimize storage ring dynamics

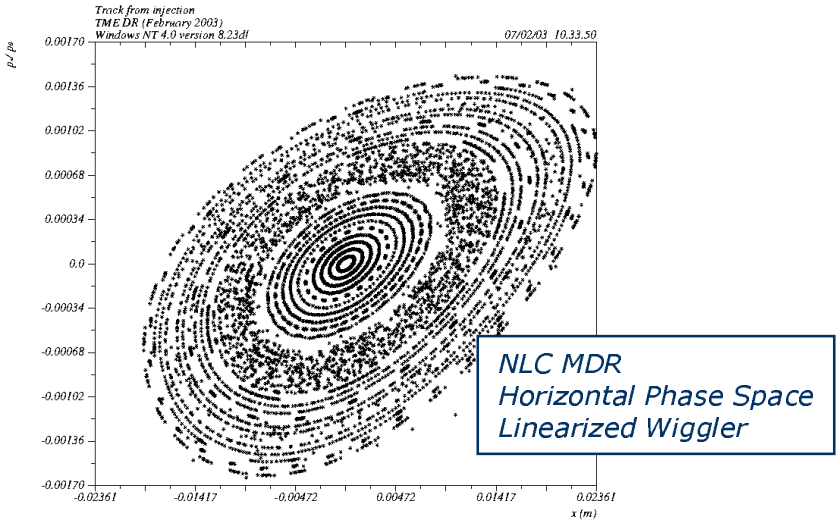


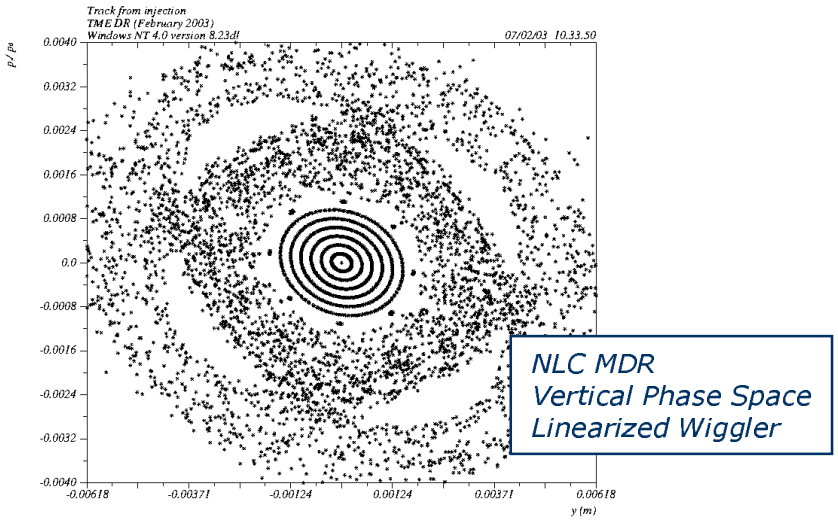


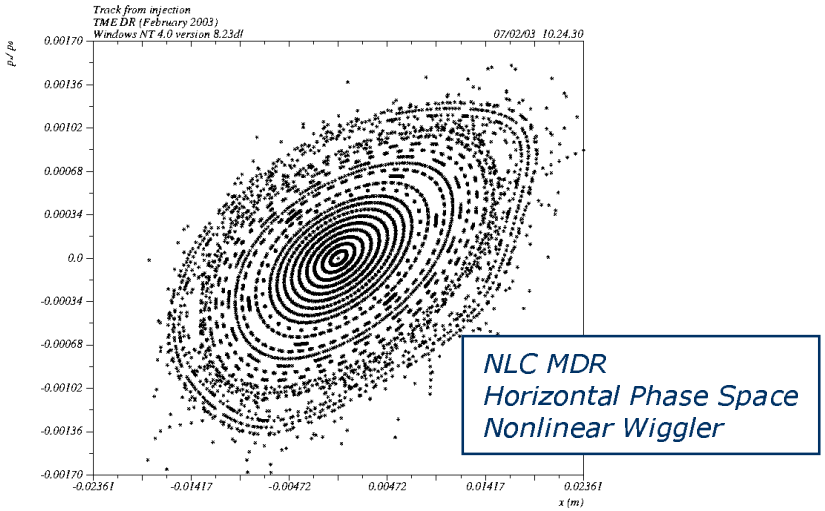
Dynamic aperture of the NLC MDR for on-momentum (left) and +1% off-momentum (right) particles. The red ellipse shows 15× the injected beam size.

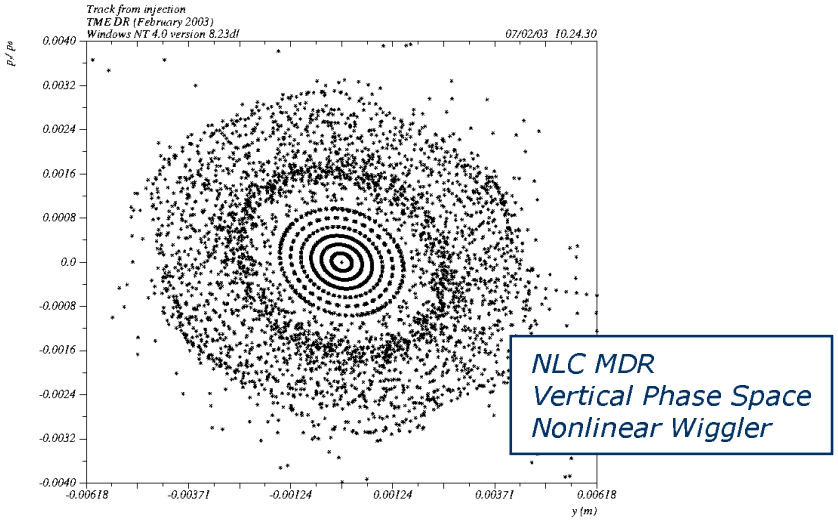
Dynamical Stability in Phase Space

- Track a bunch of particles with horizontal and vertical betatron motion
- Plot the phase space co-ordinates after each turn
- Dominant nonlinear effects are from sextupoles and wiggler



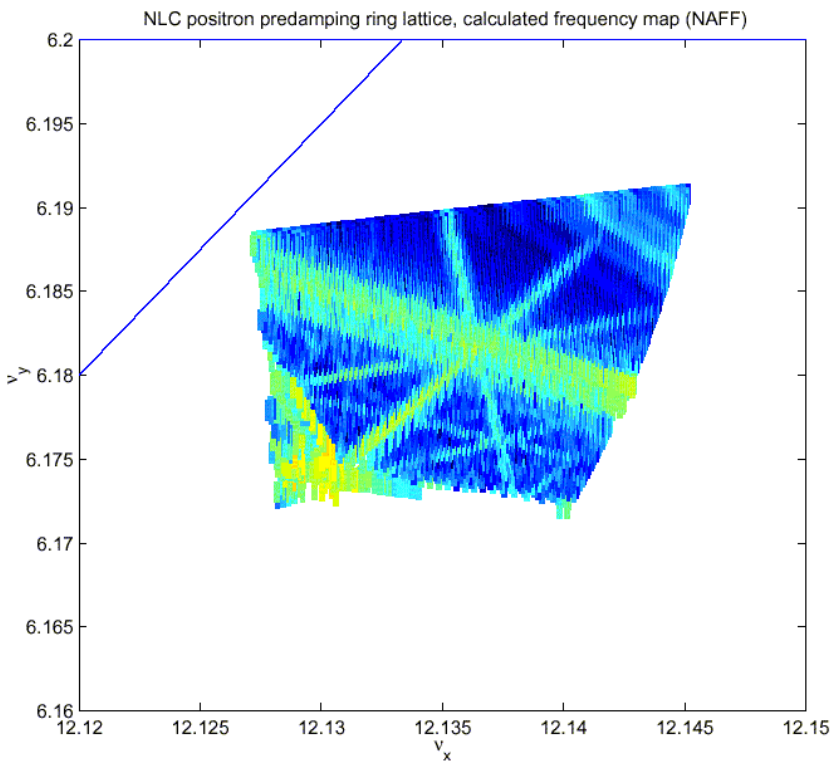


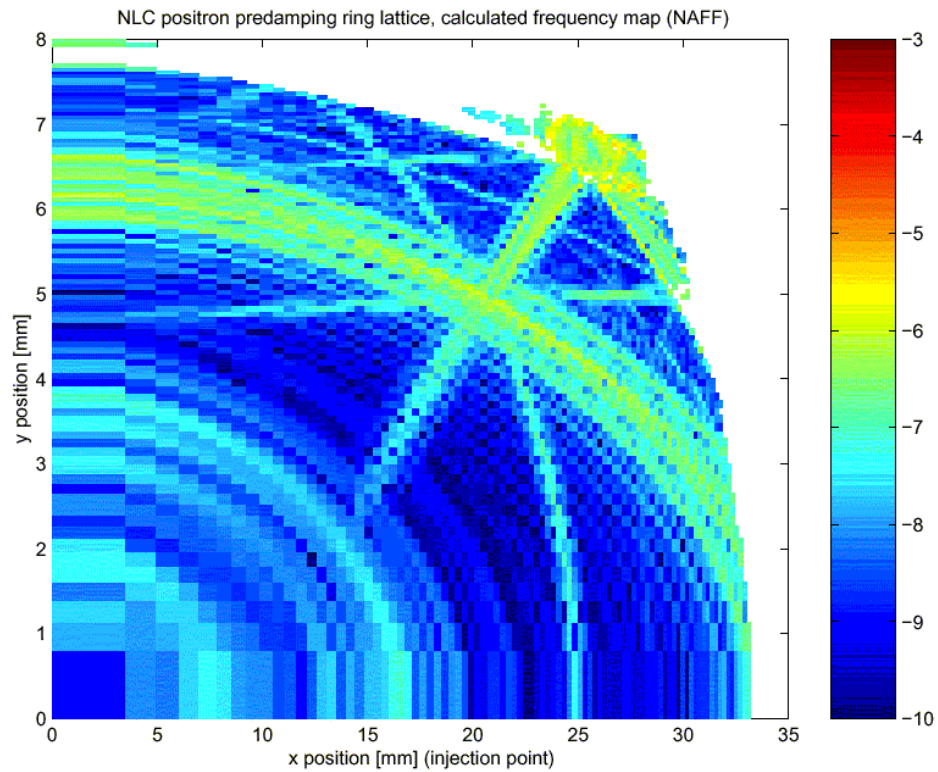




Optimizing the Acceptance

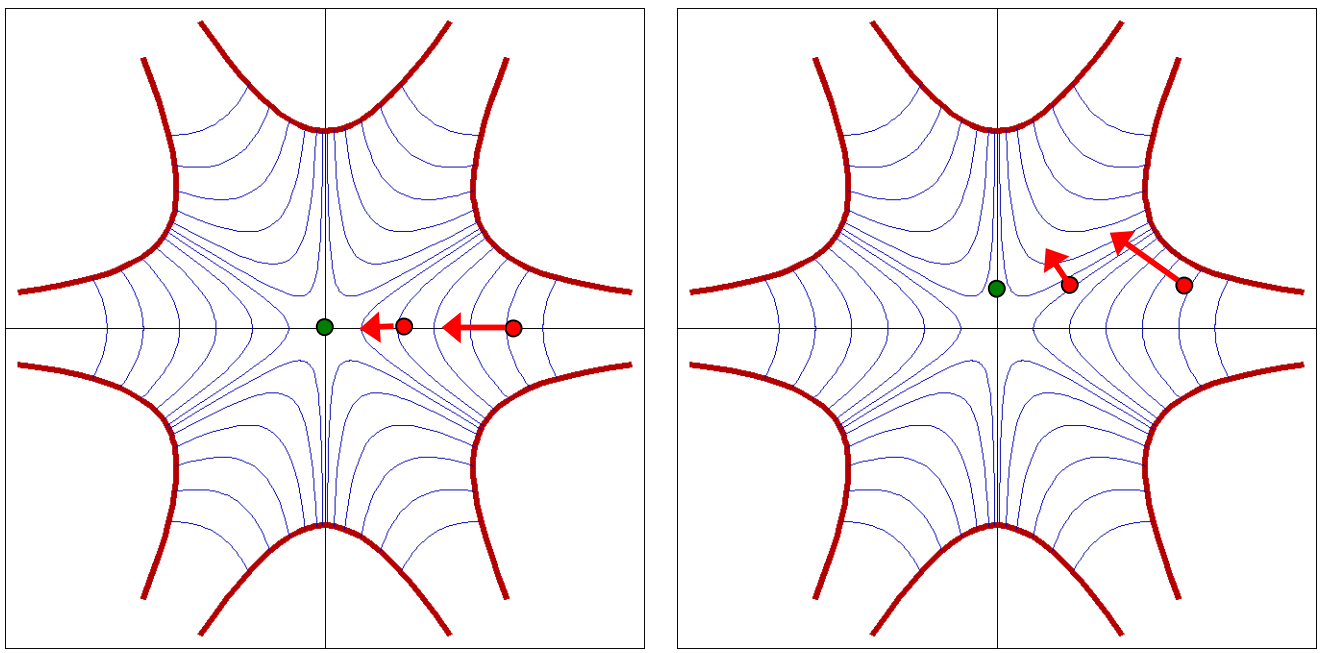
- Frequency map analysis shows the diffusion of particles in tune space
  - Perform numerical analysis of the Fourier frequencies to determine betatron tunes as a function of amplitude to high precision
  - Indicate rate of change of tune using a color chart in tune space and in co-ordinate space
- Dangerous resonance lines can be identified, and the lattice design adjusted to avoid them
  - Used at ALS to give significant improvement in beam lifetime





Vertical Emittance

- In a perfect lattice, the vertical emittance is limited only by the opening angle of the synchrotron radiation
  - Gives approximately 10% of the specified equilibrium vertical emittance for both TESLA and NLC
- Magnet alignment errors generate vertical emittance
  - Vertical quadrupole misalignments steer the beam, and generate vertical dispersion
  - Quadrupole rotations and vertical sextupole misalignments generate betatron and dispersion coupling



- Particle on closed orbit
- Particle with horizontal amplitude

Vertical kick depends on horizontal amplitude

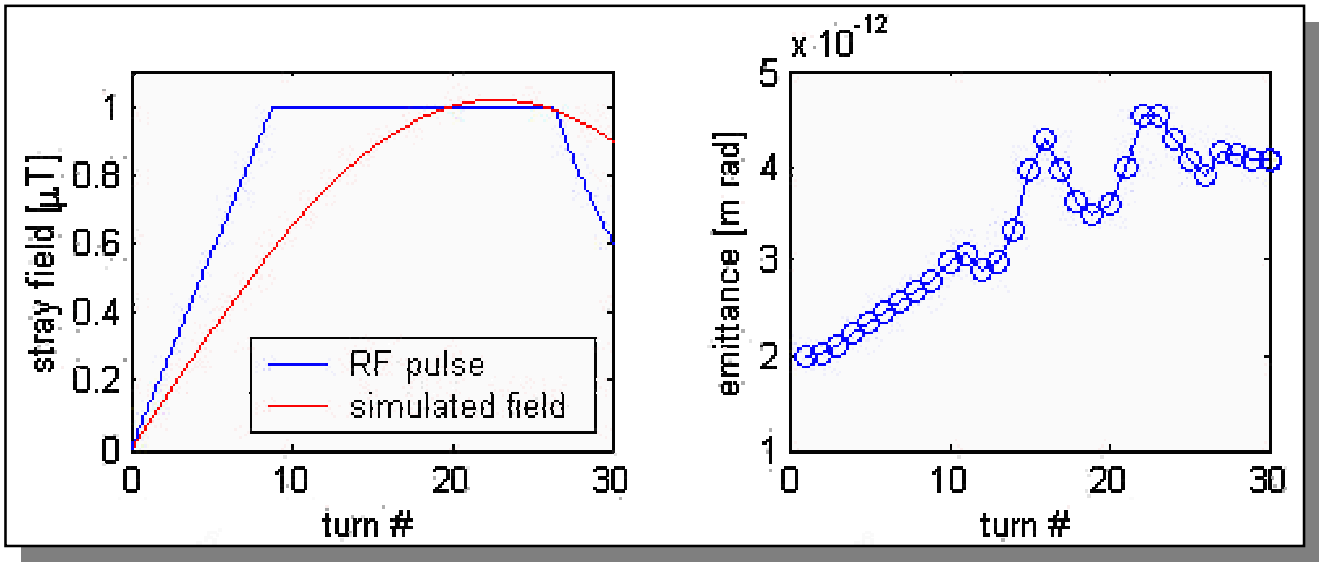
Vertical Emittance: Alignment Sensitivity

- Vertical emittance resulting from magnet misalignments depends on lattice design and on how the errors are correlated
- With some assumptions, it is possible to use simple expressions to estimate the sensitivity of the vertical emittance to various misalignments in a given lattice
- Sensitivities of NLC MDR are comparable to those in modern third generation light sources
  - We can benefit from their experience

	ALS	APS	SLS	ATF	NLC MDR	TESLA DR
Energy [GeV]	1.9	7	2.4	1.3	1.98	5
Circumference [m]	200	1000	288	140	300	17,000
$\gamma\varepsilon_x$ [μm]	24	34	23	2.8	3	8
$\gamma\varepsilon_y$ [nm]	60	140	70	28	19	14
Sextupole vertical [μm]	47	74	71	87	53	11
Quadrupole roll [μrad]	298	240	374	1475	511	38
Quadrupole jitter [nm]	102	280	230	320	264	76

Stray Field Effects in TESLA

- Klystrons pulse during damping cycle
- Stray magnetic fields (~μT) penetrate the vacuum chamber and distort the orbit
  - Shielding techniques less effective for very weak fields
- Orbit distortion leads to emittance growth before extraction
- Correction is possible, but may not be easy
  - Up to 2% of klystrons will be off (randomly)
  - Stray fields will come from other (less systematic?) sources



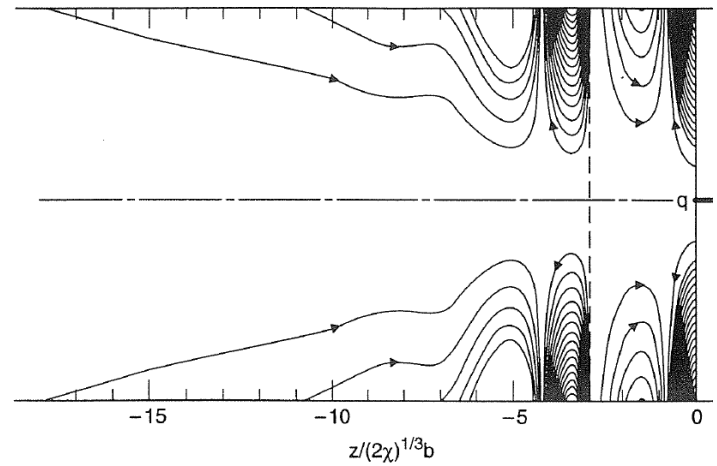
Emittance growth from stray fields in the TESLA damping ring.
(W. Decking, DESY. TESLA Collaboration Meeting, January 2003.)

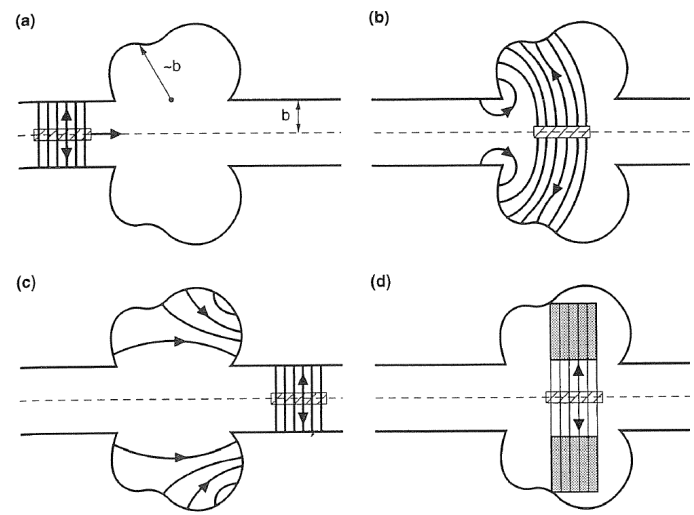
Collective Effects

- Operational performance is potentially limited by a wide variety of interactions between the particles
  - Results can be emittance growth, current limits…
- "Classical" collective effects and instabilities
  - Generally well understood, but not always easy to deal with
    - Space charge
    - Resistive wall impedance
    - Broad band impedance (microwave instability)
    - Potential well distortion
    - Trapped modes in vacuum chamber cavities
    - Higher-order modes in the RF cavities
- Other effects
  - Need further work, at least in the regimes of interest for damping rings
    - Electron cloud instability (in positron rings)
    - Ion trapping and fast ion instability (electron rings)
    - Intra-beam scattering
- Effects are generally made less severe by raising the energy or reducing the bunch density (increasing the bunch length)

Classical Instabilities

- Particles traveling through the vacuum chamber leave electromagnetic fields in their wake
- The fields depend on several factors
  - The charge distribution in the bunch
  - The vacuum chamber geometry
  - The material of the chamber
- The fields may be characterized by a wake field or an impedance
- The effect of the wake field is described by oscillation modes
  - Single bunch (short-range wake)
  - Multi-bunch (long-range wake)
- Frequencies and/or growth rates are found from perturbation theory
  - Growth rate greater than the radiation damping rate leads to an instability

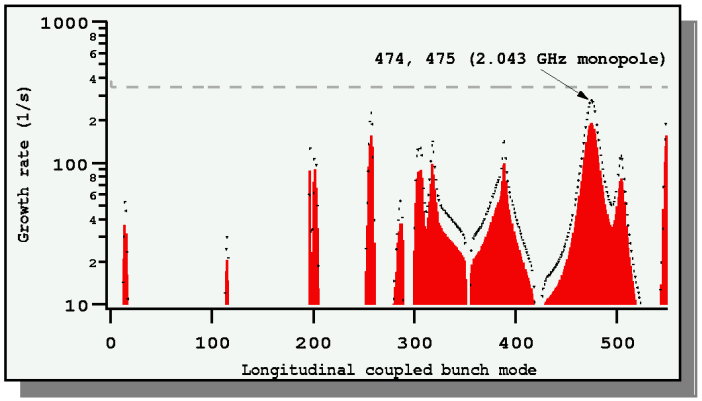


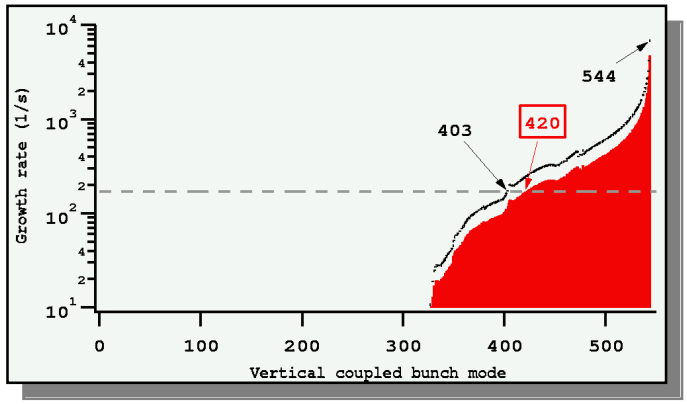


Top: Resistive wall wake fields
Bottom: Trapped modes in a cavity
From A. Chao, "Physics of Collective Beam Instabilities"

Classical Instabilities: Examples

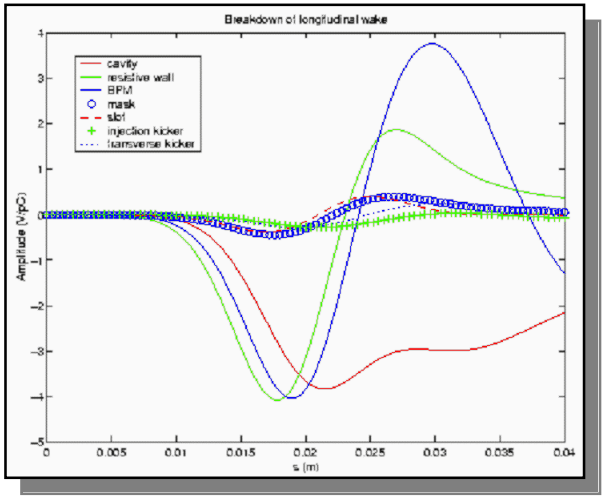
- For the NLC MDR, the resistive wall impedance drives coupled bunch instabilities that may need to be suppressed with a feedback system

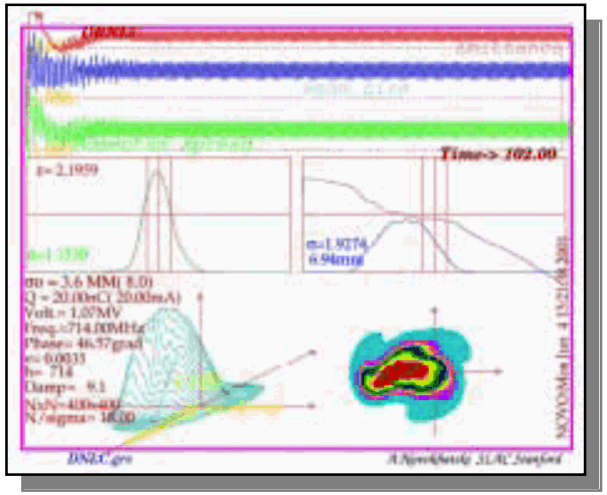




Longitudinal and vertical coupled-bunch growth rates driven by resistive wall and cavity highe order modes

- Short range wake field can drive oscillations within a single bunch that leads to an increase in energy spread

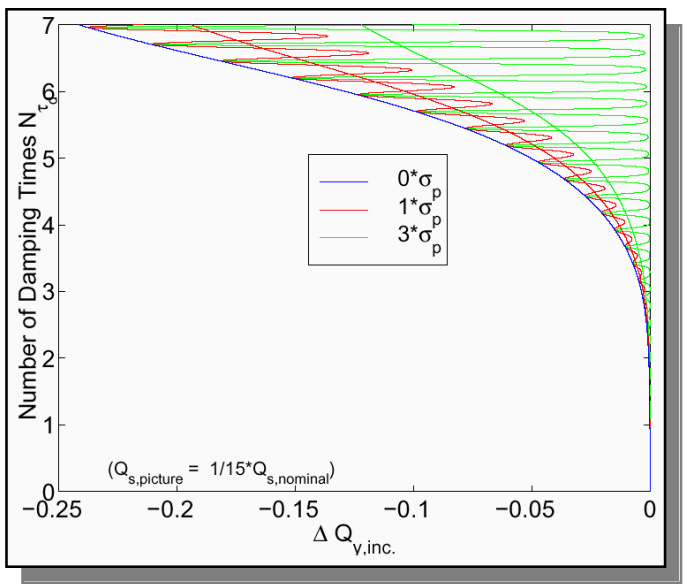


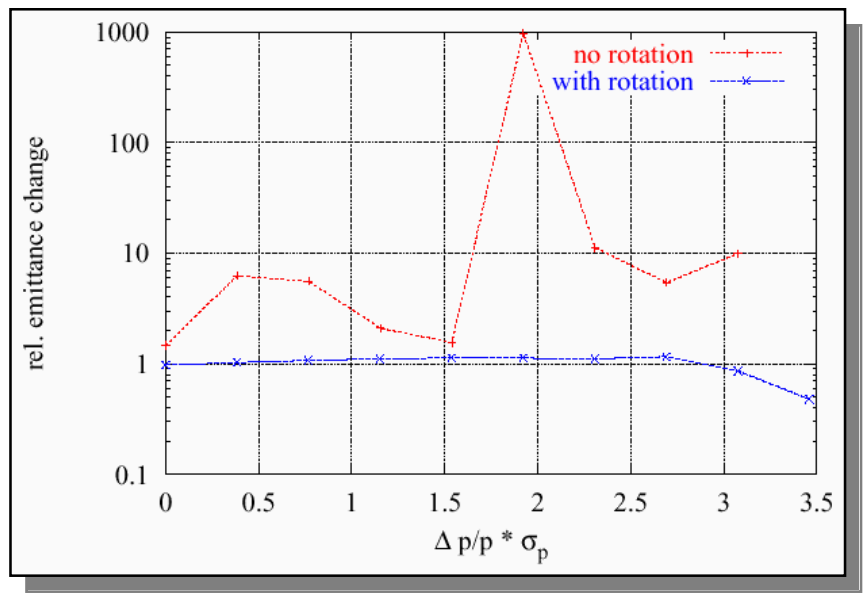


Longitudinal short range wake and simulation results from effect on charge distributi within a single bunch

Space Charge

- Space charge force of the bunch provides transverse defocusing depending on the particle's position in the bunch
  - Leads to an incoherent tune spread
  - Particle dynamics can be very sensitive to the tune
- Space charge effects scale with the circumference, and inversely with the energy
  - Not a significant problem for LEP: 26.7 km, 100 GeV
  - A big problem for TESLA: 17 km, 5 GeV
  - Proposed solution: local coupling in the straight sections

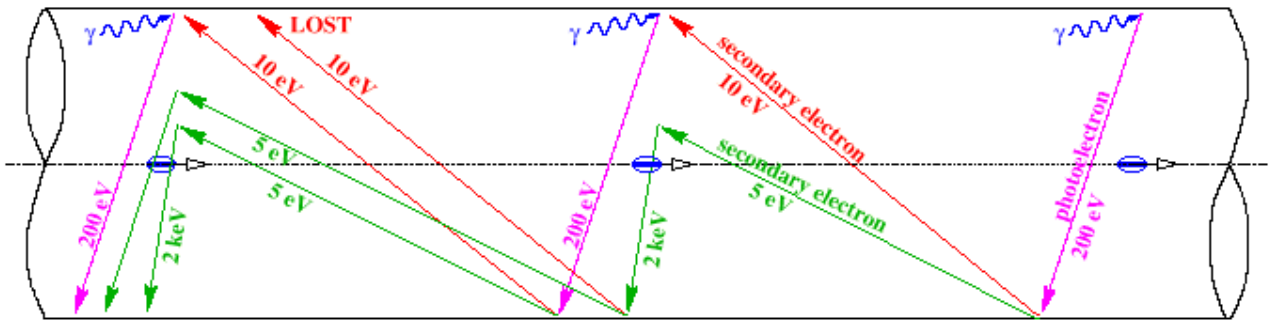




Space charge tune shift and resulting emittance growth in the TESLA damping rings (from W. Decking, DESY)

Electron Cloud Effect

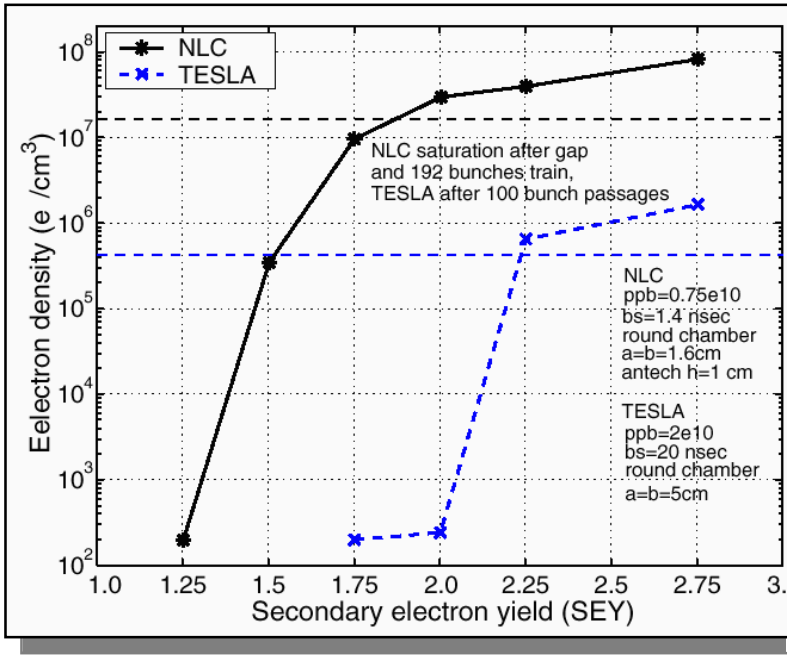
- Free electrons generated by a variety of processes
  - Photoemission from synchrotron radiation
  - Gas ionization
  - Secondary electrons from primary electrons impacting chamber



- Under certain conditions, electron density in the chamber can increase rapidly
  - Density tends to saturate at neutralization
  - Density of electrons is not uniform, and can be much larger close to the beam
- A dense electron cloud gives a strong coupling between single bunch and multi-bunch oscillation modes, leading to instabilities
- Observations at various positron and proton machines…

Eliminating the Electron Cloud

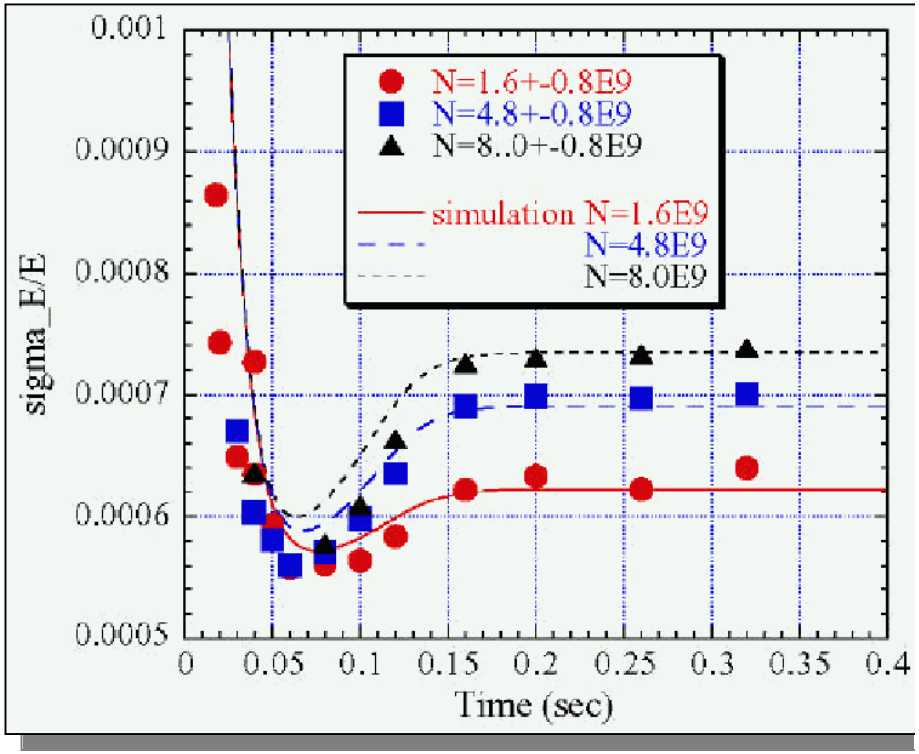
- Simulations of electron cloud build-up suggest that there will likely be a problem for the NLC/JLC positron damping rings, and maybe a problem for the TESLA positron damping ring
- Solenoids have been used successfully at the B-factories
  - Secondary electrons are trapped in the field close to the wall, and get reabsorbed before they are accelerated by the beam
  - Low solenoid field has little coupling effect
  - NLC/JLC damping rings are densely packed with magnets, leaving little room for solenoids
- Low secondary yield coatings are also a possibility
  - Titanium nitride coating will be used in SNS
  - Looks like an attractive solution for the damping rings, if it can be made to work…



Simulation of electron cloud build-up as a function of chamber secondary yield in NLC MDR and TESLA damping rings

Intra-Beam Scattering

- Particles within a bunch scatter off each other
- Higher transverse temperature gets transferred to the longitudinal motion
- If there is dispersion at the scattering point, longitudinal heating leads to transverse heating
  - Analogous to quantum excitation from synchrotron radiation
- Net result is 6 dimensional emittance growth
- Observations at ATF and ALS
  - Need quantitative studies to confirm the strength of the effect
  - Possible limitation for NLC/JLC, although there is some safety margin in the present designs



Measurements of growth in energy spread resulting from Intra-Beam Scattering in the KEK ATF

What is the present status?

- Present designs for NLC/JLC and TESLA look feasible, though they require some development
  - Lower emittance needed than has presently been demonstrated
- NLC/JLC designs are very similar to existing third generation synchrotron light sources
  - Comparable alignment tolerances to light sources
  - Components and systems are fairly conventional
  - Longer wiggler than usually found in storage rings
  - Dense lattice could present engineering challenges
- TESLA design has less experience base to draw upon
  - Extreme wiggler
  - Significantly tighter alignment tolerances
  - Some components (e.g. kickers) require R&D
  - "Special" problems
    - Space charge tune shift
    - Stray magnetic fields

What are the issues?

- Single particle effects
  - Acceptance
    - Transverse and longitudinal acceptances need to be improved
    - Wiggler effects need careful study (theory and experiment)
  - Emittance tuning
    - Specified vertical emittance has to be demonstrated in existing storage rings
  - Stray fields from the klystrons in the TESLA tunnel
- Collective effects
  - Electron cloud
    - Studies of low secondary yield coatings have been started
    - Need to investigate possibility of using solenoid
  - Fast ion instability
    - Observations have been made, but theory has not been quantitatively verified
    - May place demanding requirements on vacuum system
  - Vacuum chamber impedance is demanding
- Components and systems
  - Kicker R&D is needed

Further Information

- LBNL has responsibility for NLC Damping Rings, working closely with SLAC
  - http://awolski.lbl.gov
- KEK has designed damping rings for JLC, and operates the ATF
  - http://atfweb.kek.jp/
  - http://lcdev.kek.jp/RMdraft/
- DESY has developed TESLA Damping Rings
  - http://www.desy.de/~wdecking/dog/dogbone.html
- Recent Damping Ring Workshop at Daresbury Laboratory
  - http://www.astec.ac.uk/conf/dampingring/