



Linear Collider Damping Rings

Andy Wolski

Lawrence Berkeley National Laboratory

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:
 - $3.6 \mu\text{m} \times 0.04 \mu\text{m}$ for NLC/JLC
 - $10 \mu\text{m} \times 0.03 \mu\text{m}$ for TESLA
 - Need to allow some budget for dilution
- Stability requirements of main linacs, beam delivery system and final focus are extremely demanding

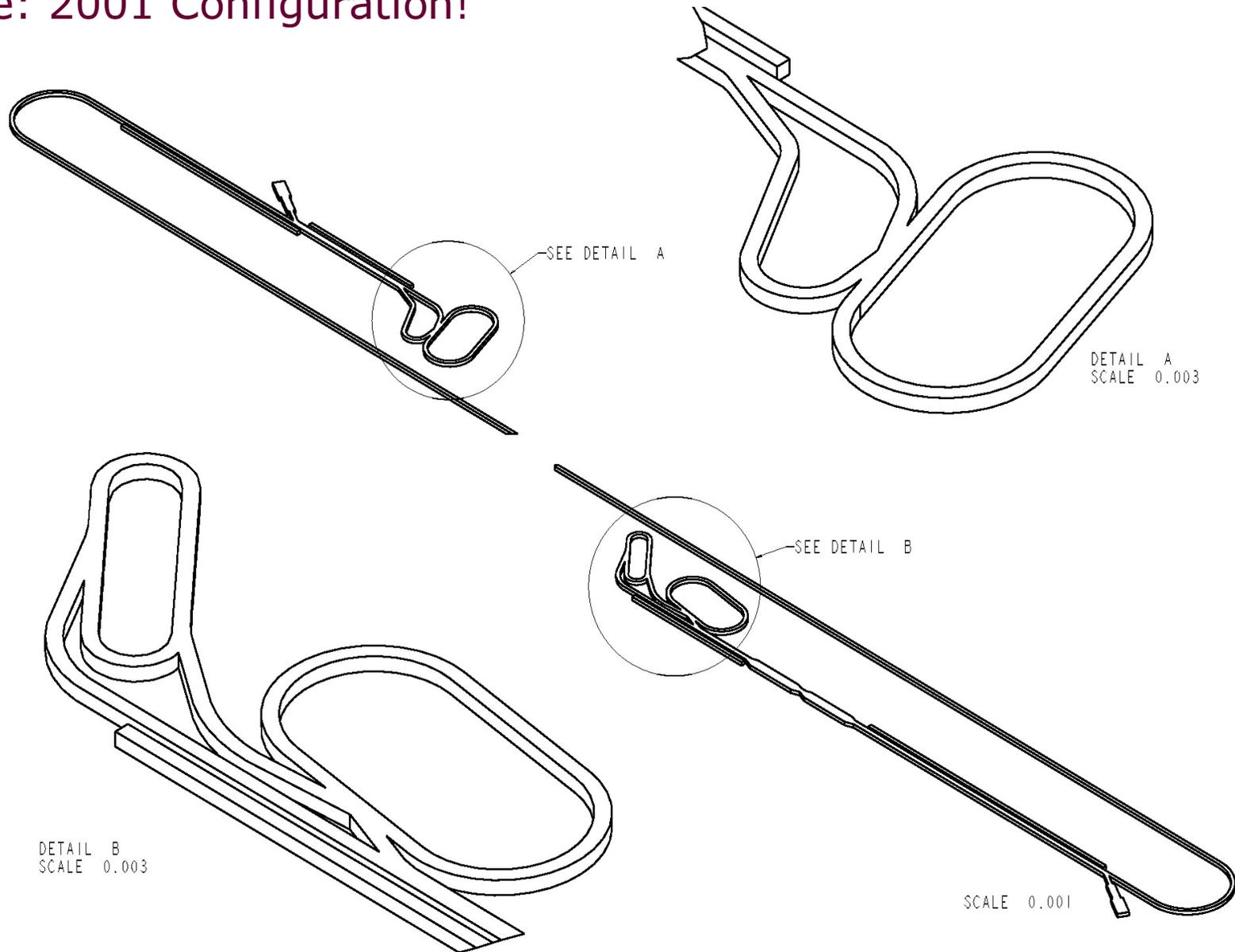
	NLC MDR	TESLA e ⁺
Injected $\gamma\varepsilon$	150 $\mu\text{m rad}$	10 000 $\mu\text{m rad}$
Extracted Horizontal $\gamma\varepsilon$	3 $\mu\text{m rad}$	8 $\mu\text{m rad}$
Extracted Vertical $\gamma\varepsilon$	0.02 $\mu\text{m rad}$	0.02 $\mu\text{m rad}$
Injected Energy Spread	1% full width	1% full 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*

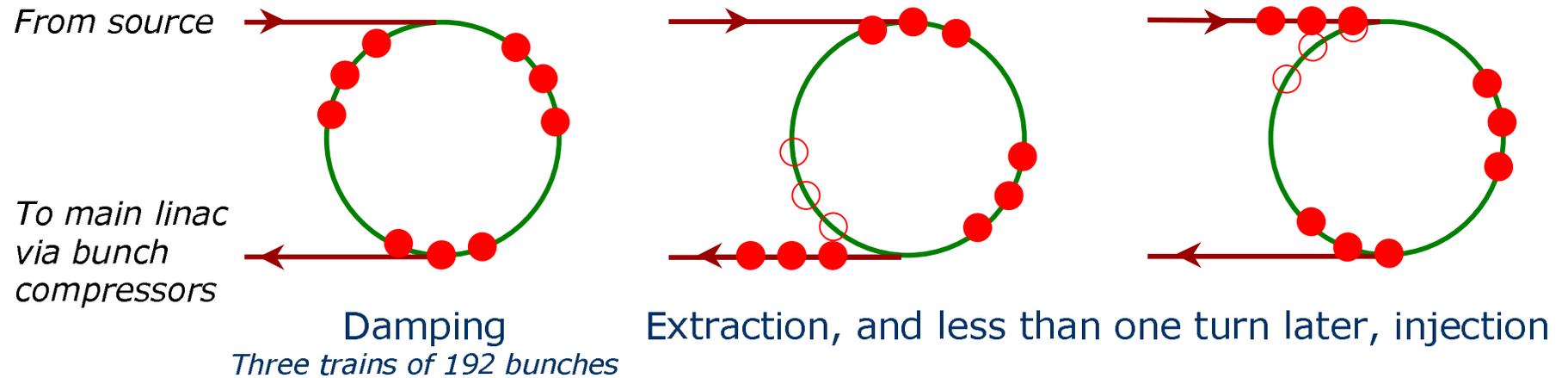
NLC Injector Systems Scheme

Note: 2001 Configuration!

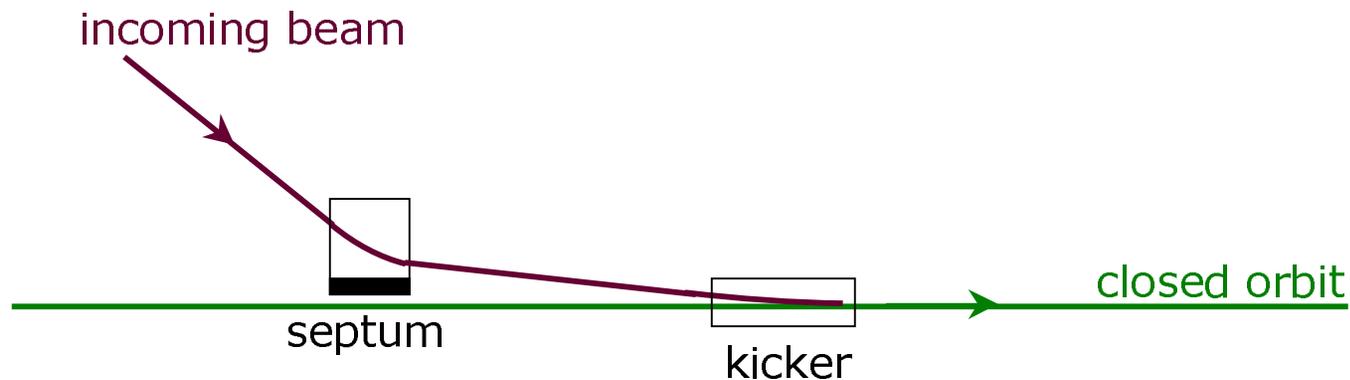


Damping Rings in NLC/JLC

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

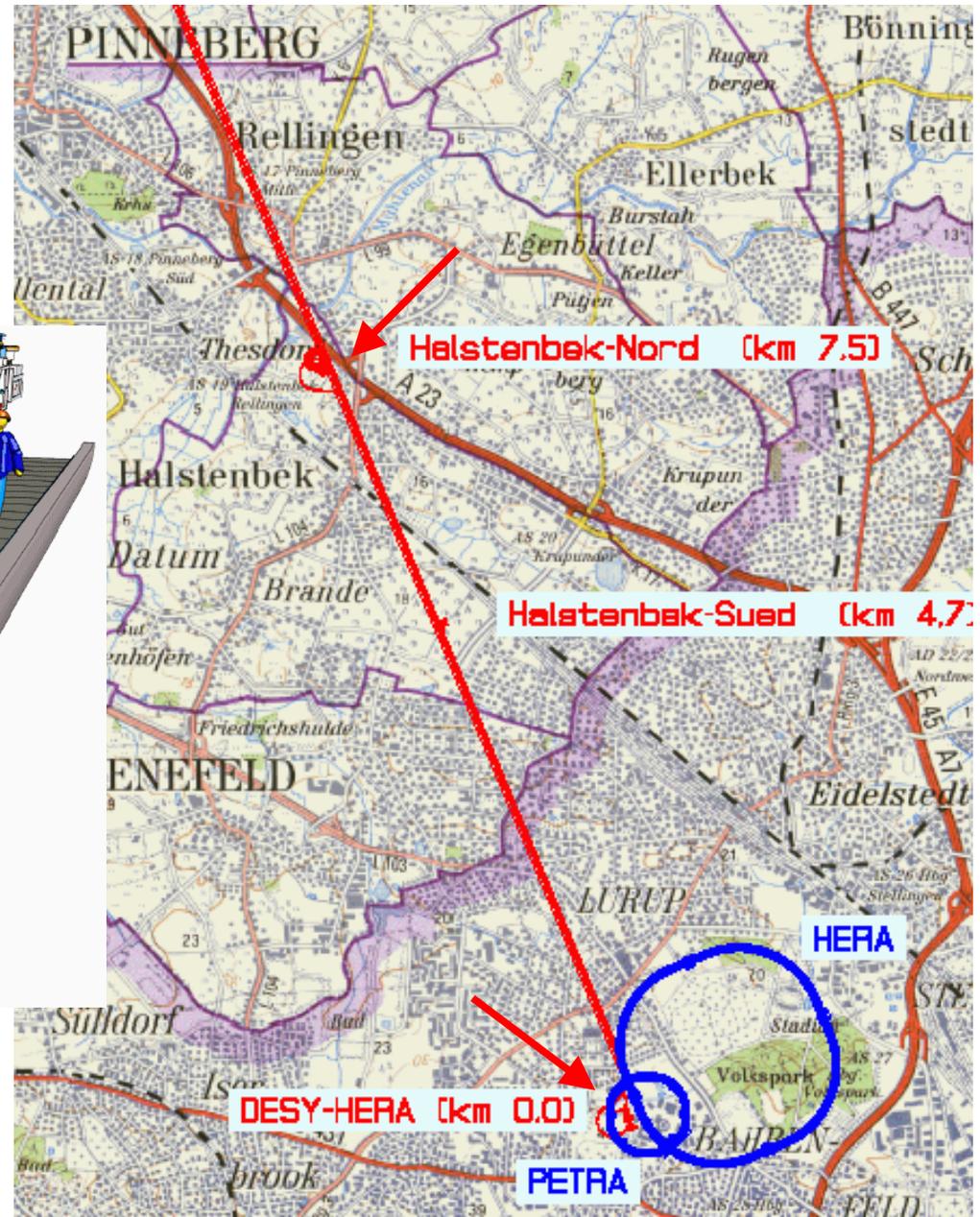
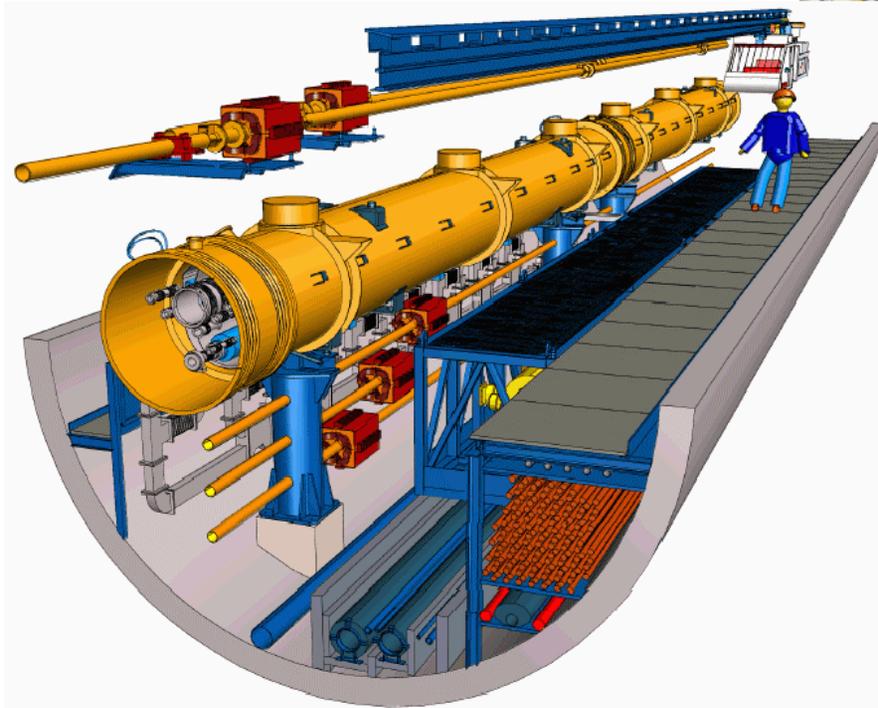


- On-axis injection needed, so current cannot be "stacked"



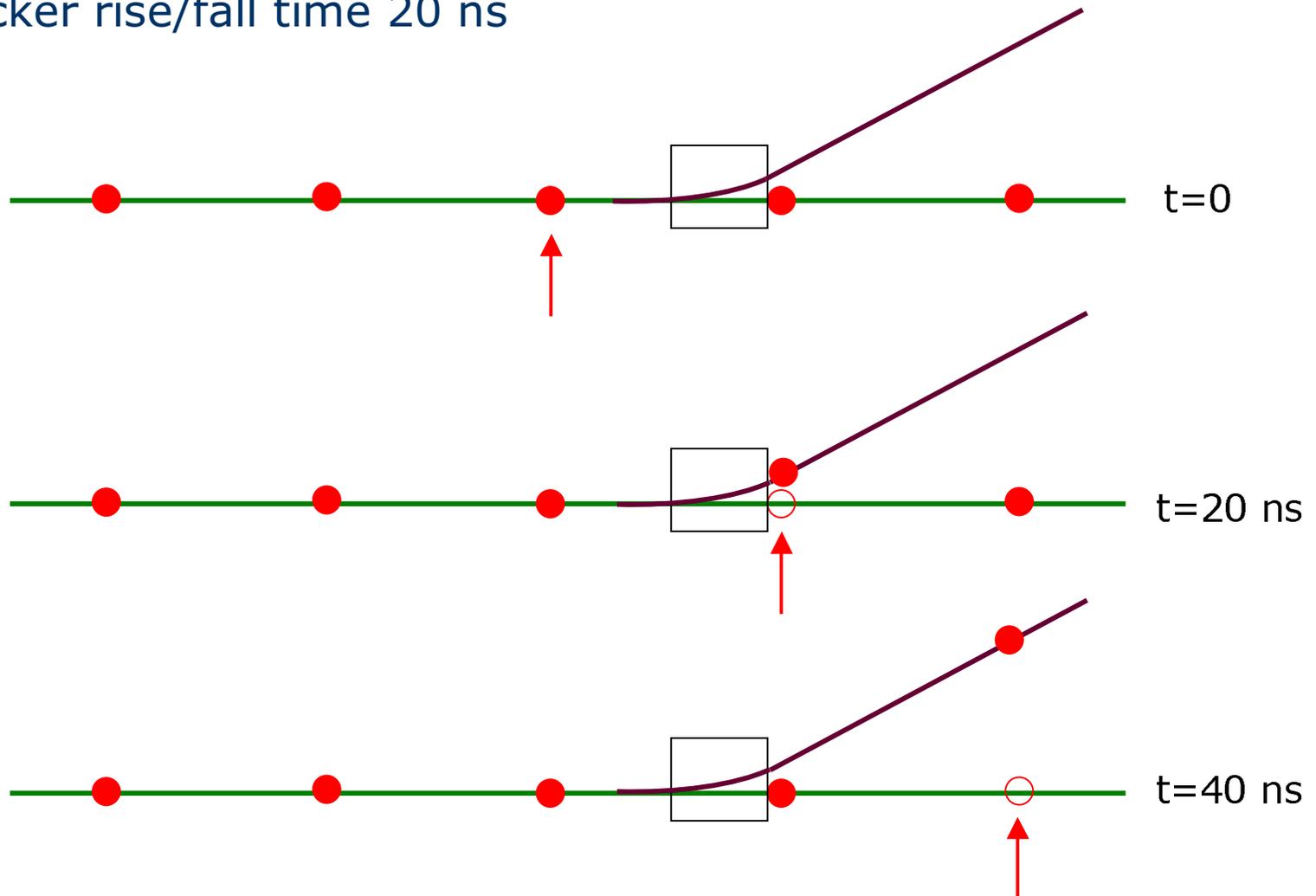
TESLA Damping Rings

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



Damping Rings in TESLA

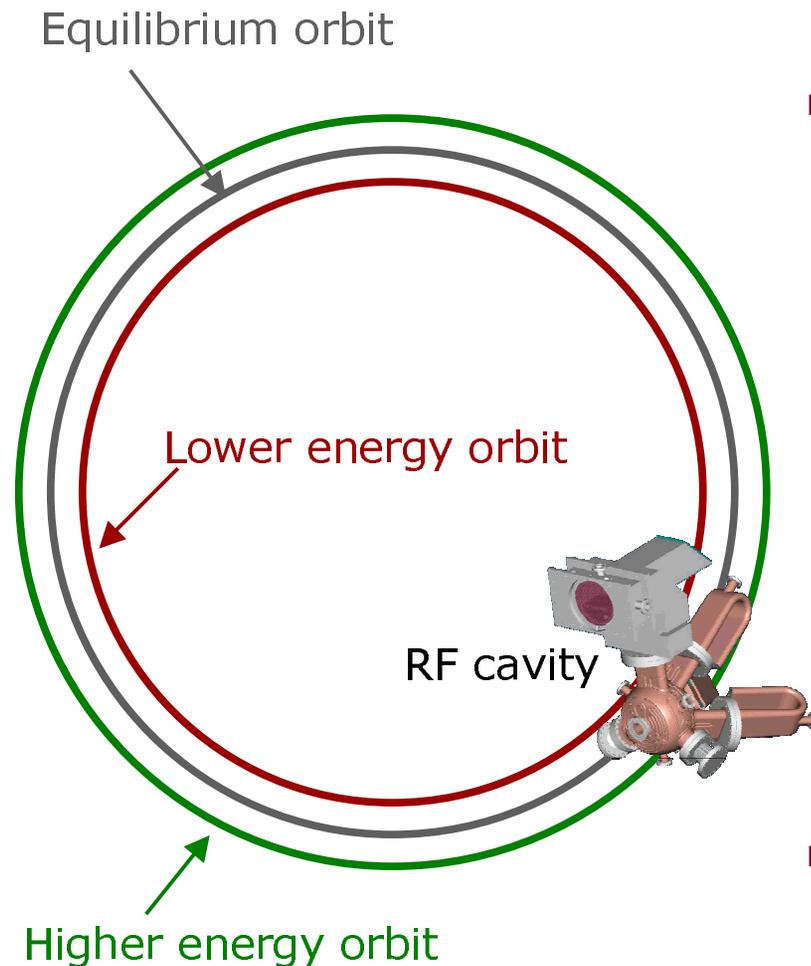
- Bunch trains of 2820 bunches with 330 ns spacing (280 km), must be compressed in the damping rings (17 km)
- Bunches injected/extracted individually
 - Kicker rise/fall time 20 ns



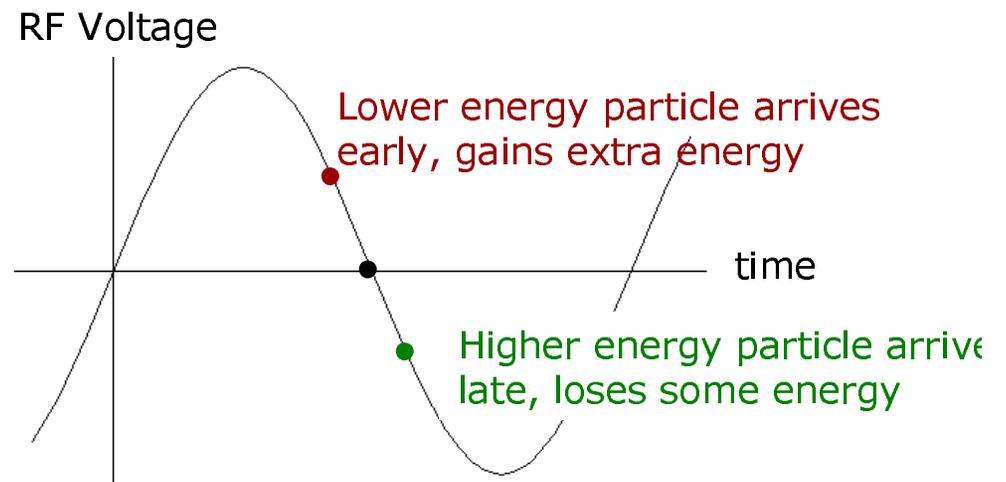
Radiation Damping

- 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



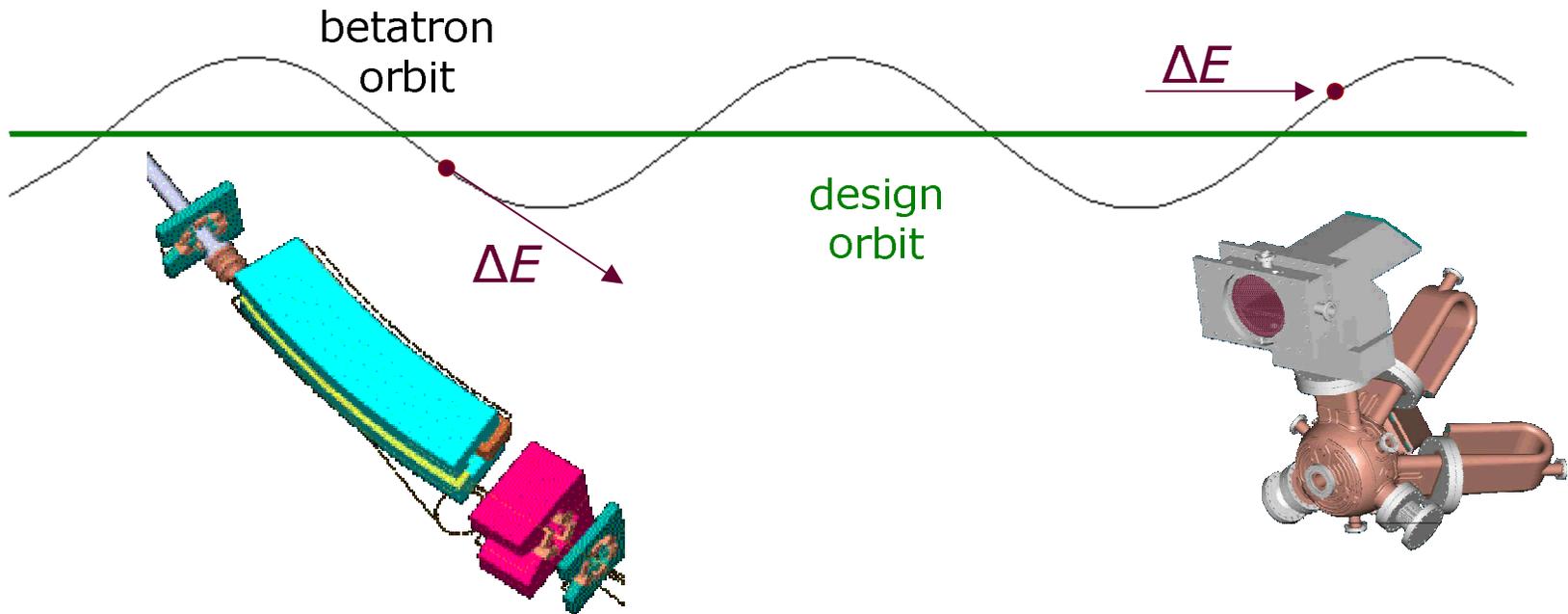
- Higher energy particles follow a longer orbit
- Particles perform synchrotron oscillations in the RF potential



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

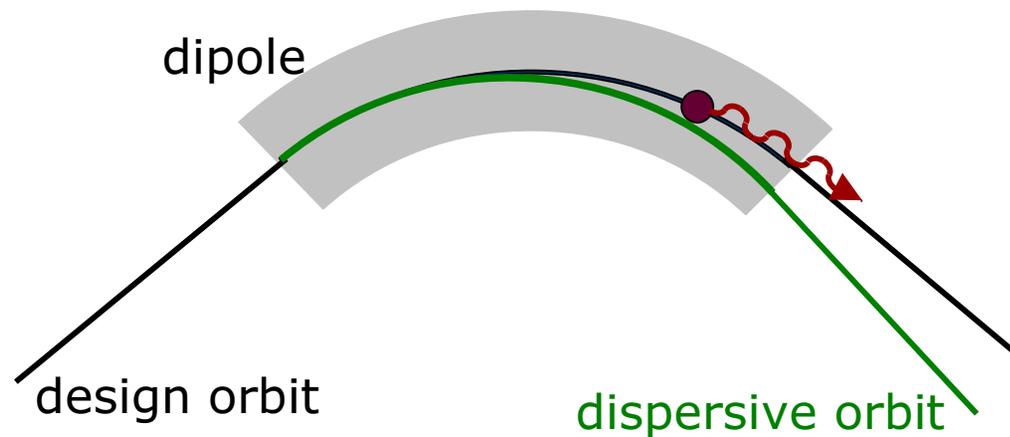
Transverse Oscillations and Damping

- Synchrotron radiation emitted in narrow cone (of width $\sim 1/\gamma$) 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 ($\hbar \rightarrow 0$) 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:

$$\frac{d\gamma\epsilon}{dt} = \gamma\epsilon_{\text{inj}}e^{-2t/\tau} + \gamma\epsilon_{\text{equ}}(1 - e^{-2t/\tau})$$

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

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

- 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:

$$\gamma\epsilon_0 = C_q\gamma^3\frac{I_5}{\mathcal{J}_x I_2}$$

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

Key Parameters

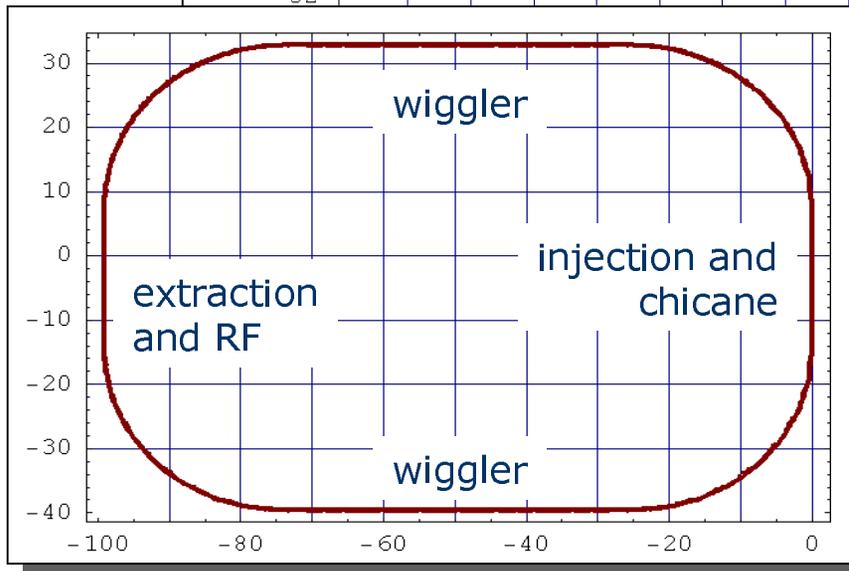
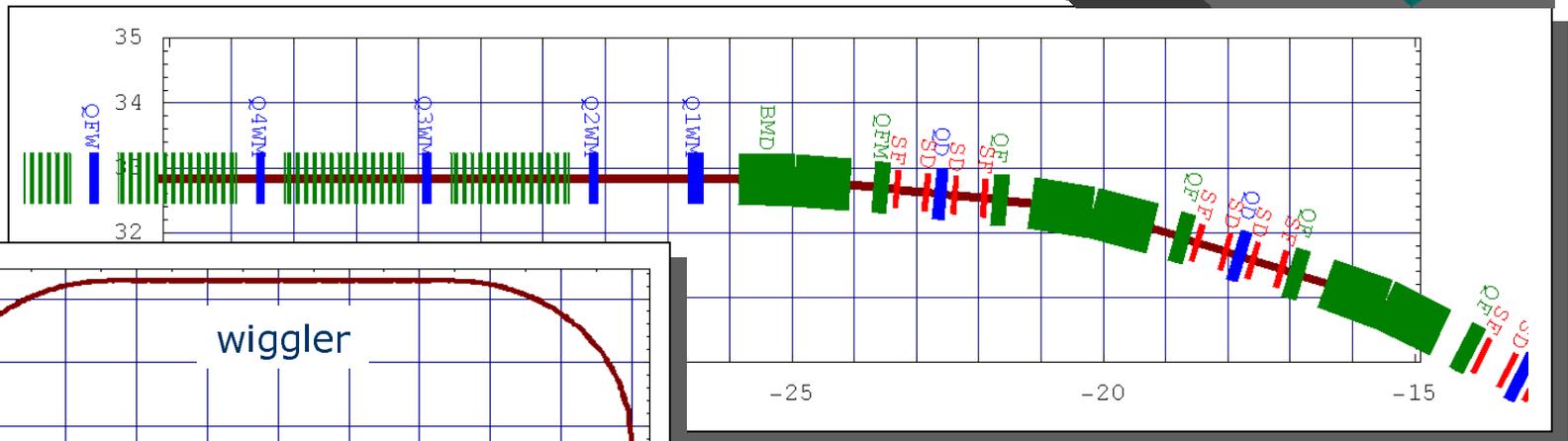
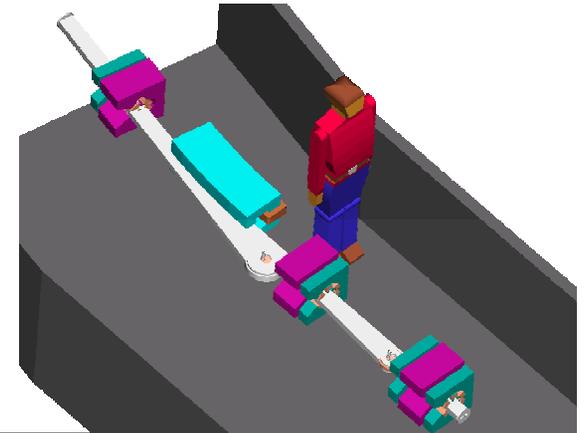
- **Damping time**
 - Requirement determined by specified injected and extracted emittance and machine rep rate
 - Scales as ρCE^{-3}
 - Circumference should be as short as possible...
 - ...but limited by **train structure and kicker parameters**
 - Higher energy is better
- **Natural emittance**
 - 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...

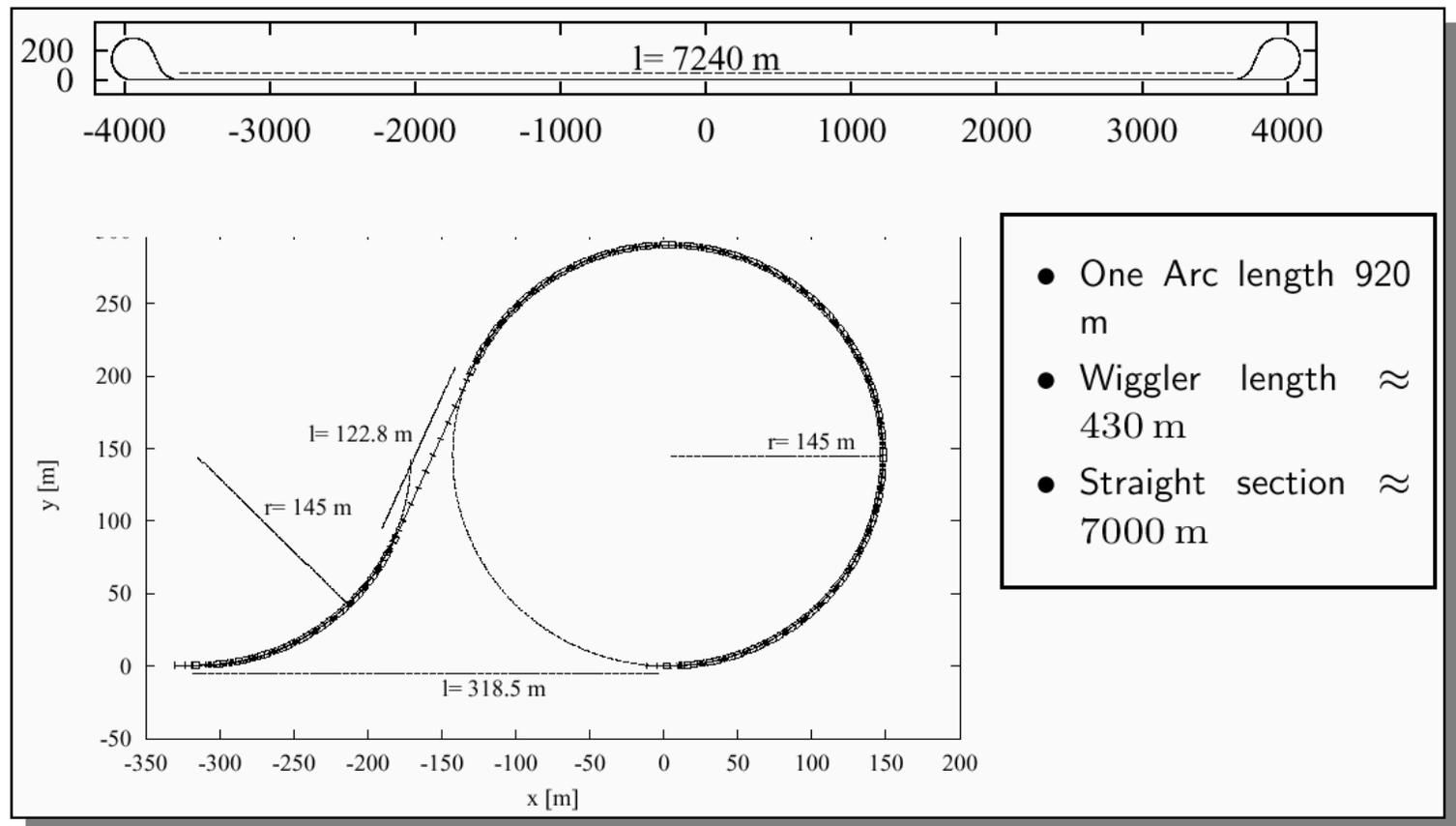
The NLC Main Damping Ring

- 1.98 GeV beam energy
- 36 arc cells
- 300 m circumference
 - 3 bunch trains, 192 bunches \times 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

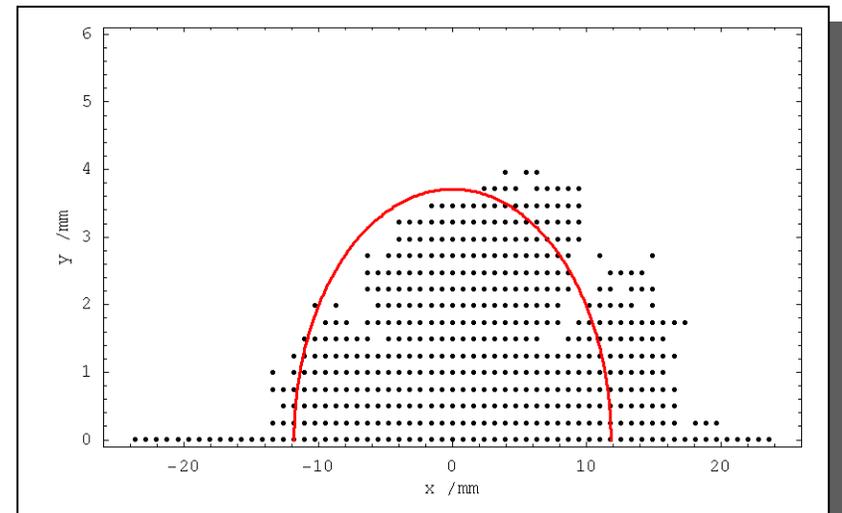
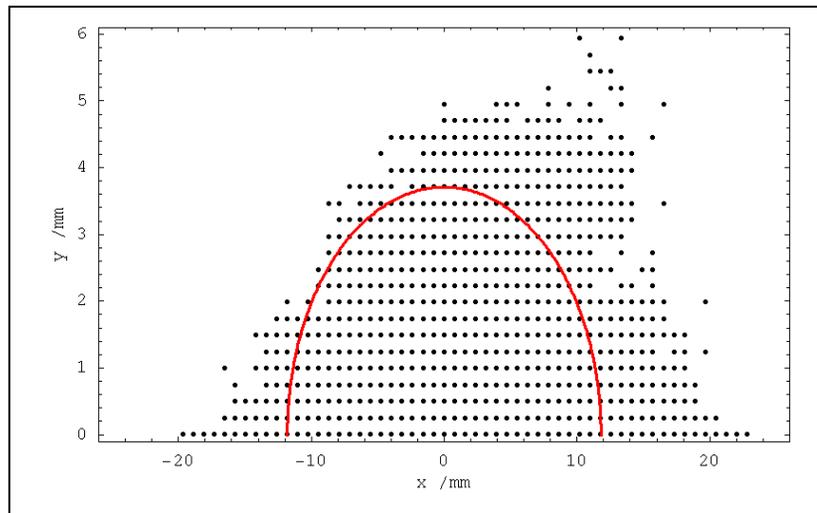


Design Issues

- **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

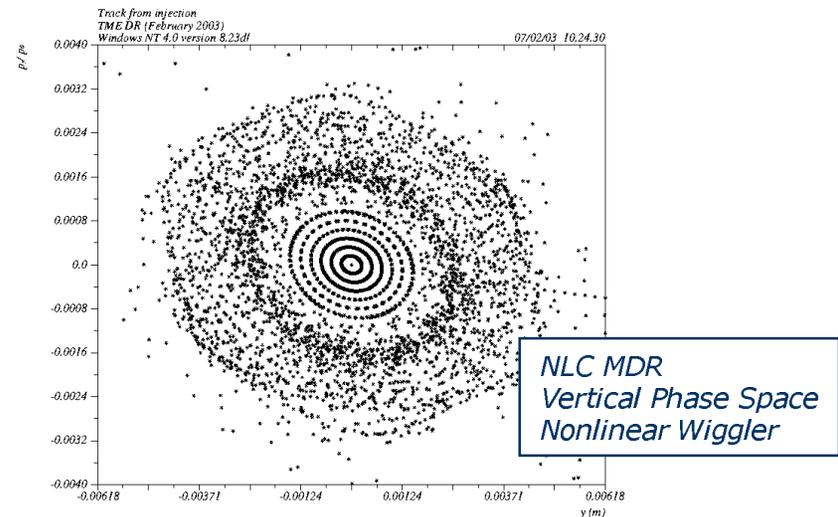
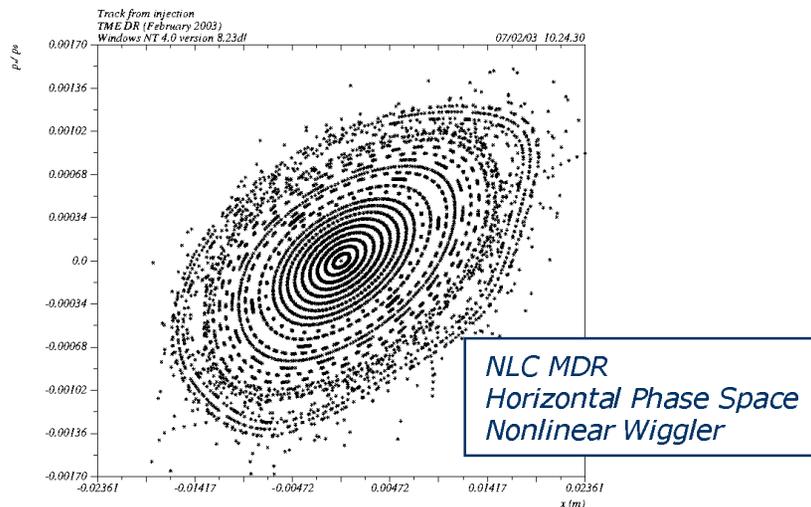
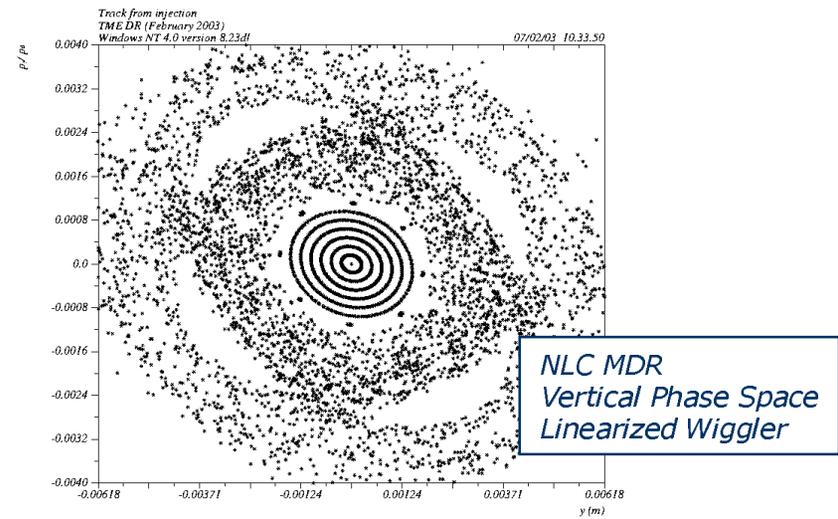
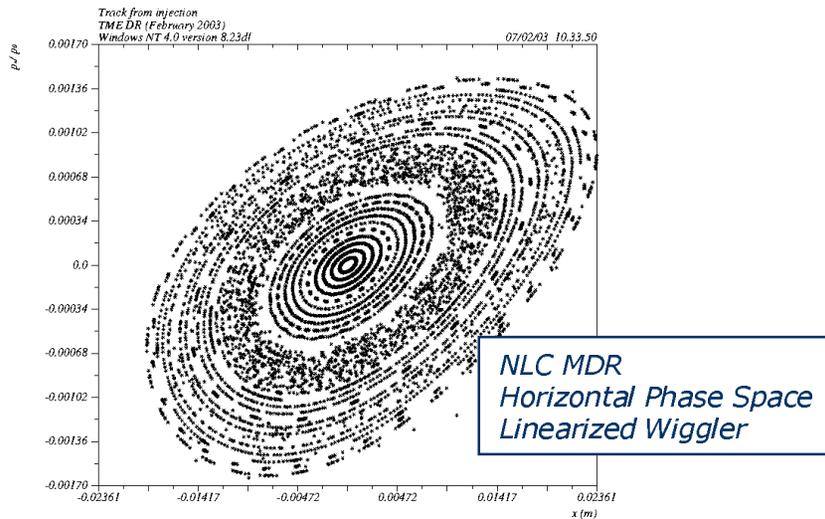
- **Dynamic aperture is limited by nonlinear magnetic fields**
 - Sextupoles are needed to correct the chromaticity, and stabilize the dynamics for off-energy particles
 - Wigglers have intrinsic nonlinear fields
 - Dipoles and quadrupoles have (small) systematic and random nonlinear components
- **An 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.

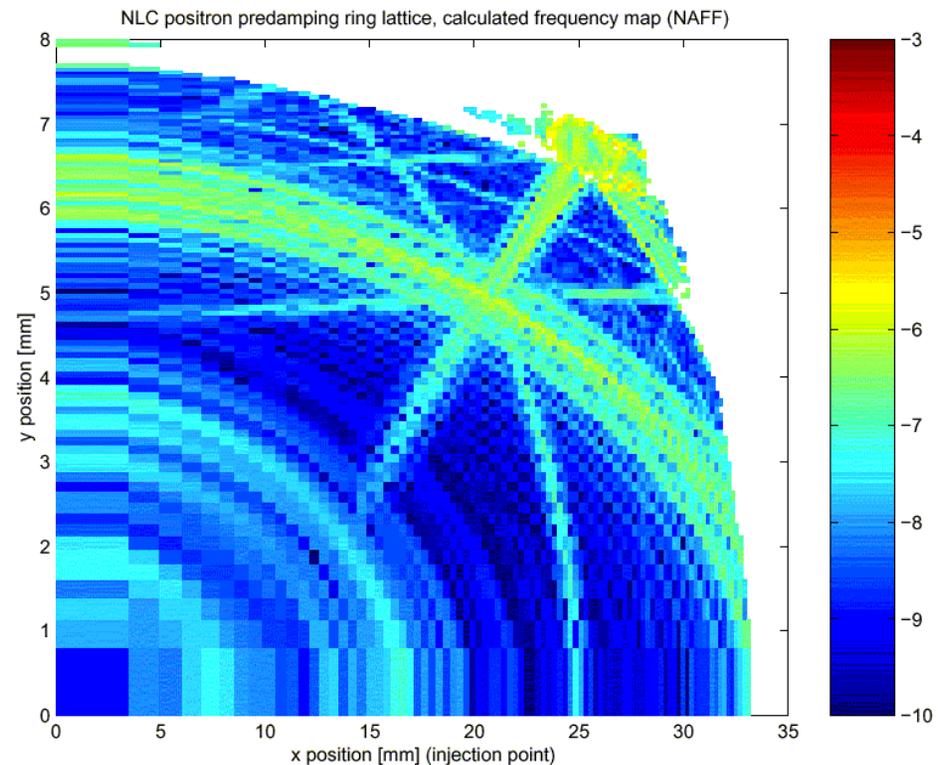
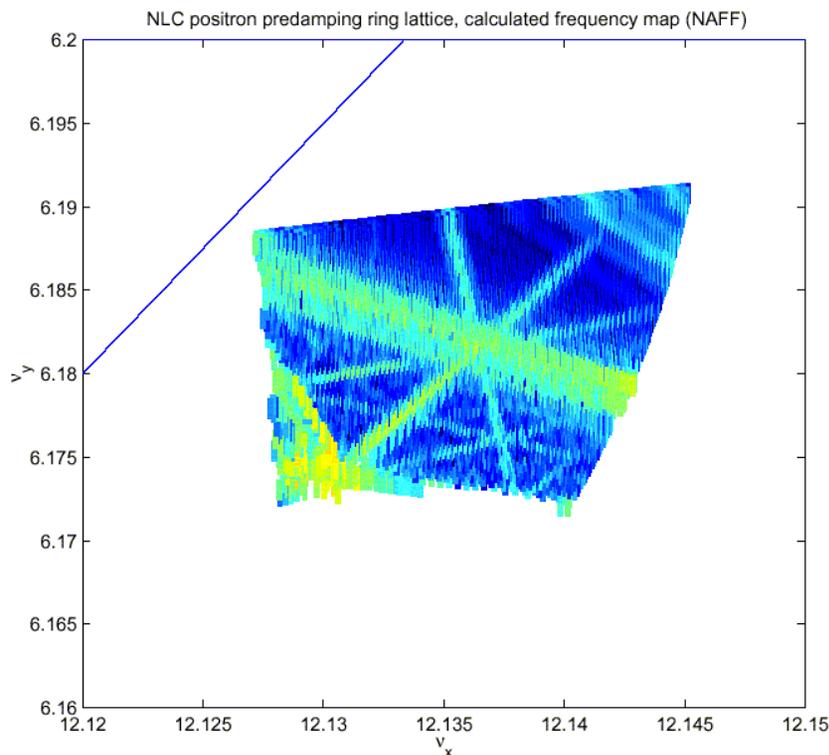
Dynamical Stability in Phase Space

- 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



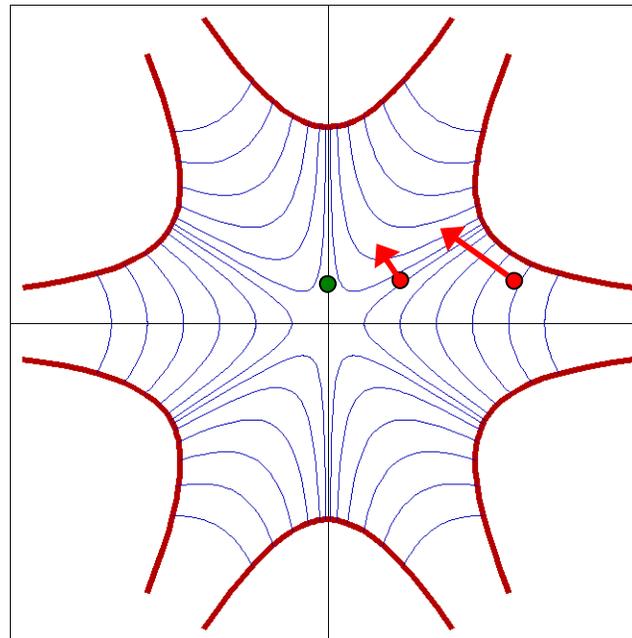
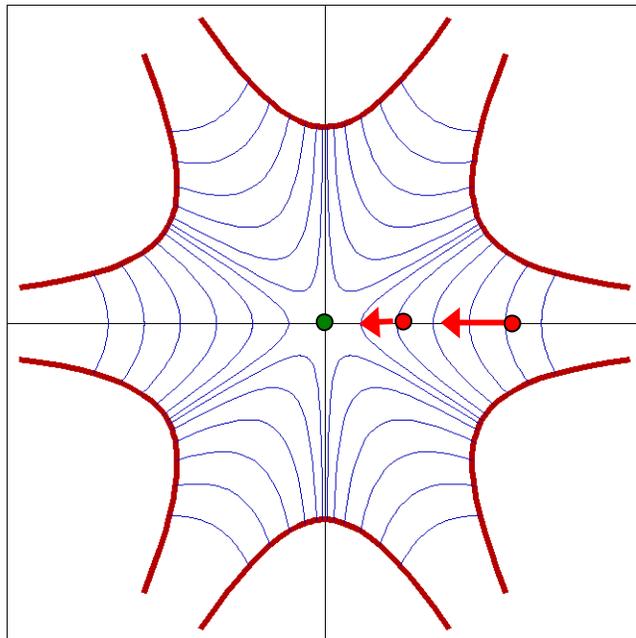
Optimizing the Acceptance

- 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

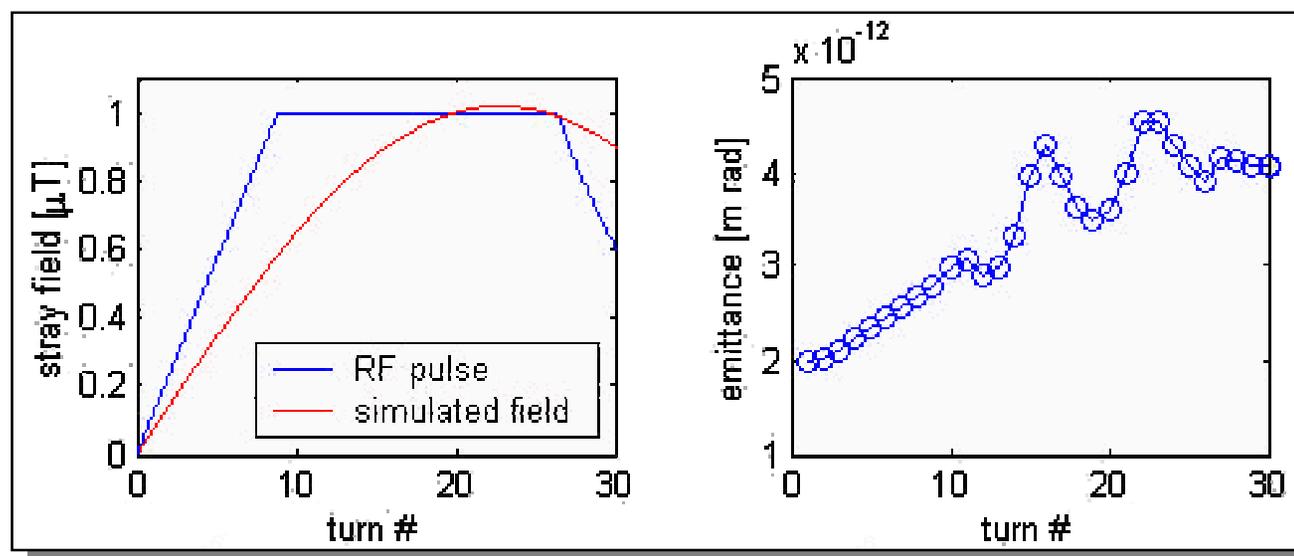
Vertical Emittance: Alignment Sensitivity

- 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
$\gamma\epsilon_x$ [μm]	24	34	23	2.8	3	8
$\gamma\epsilon_y$ [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 ($\sim\mu\text{T}$) 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



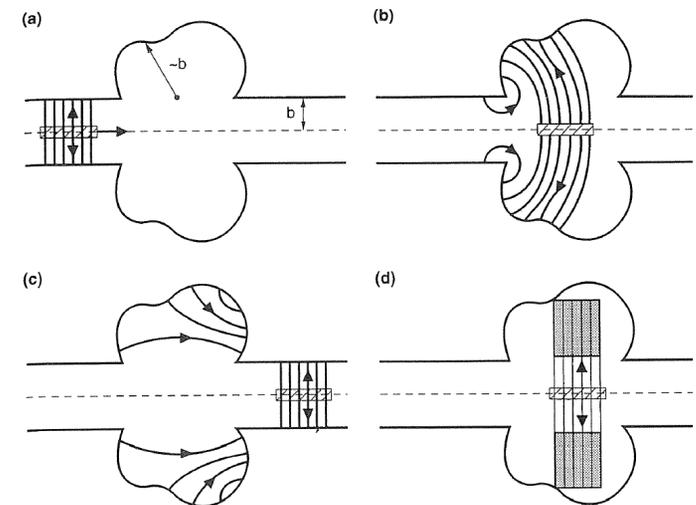
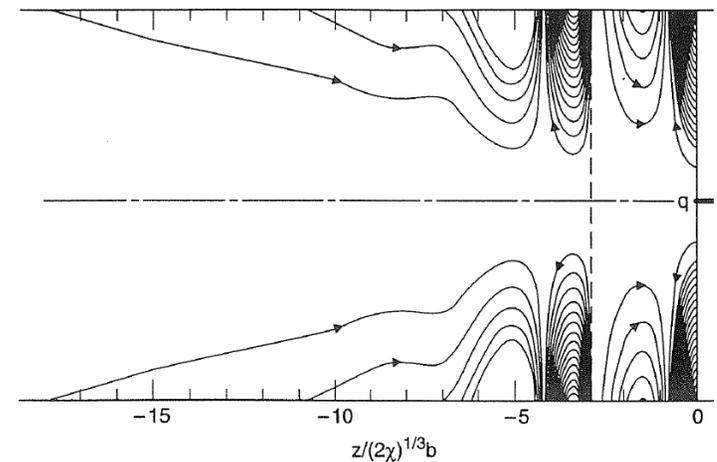
*Emittance growth from stray fields in the TESLA damping ring.
(W. Decking, DESY. TESLA Collaboration Meeting, January 2003.)*

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

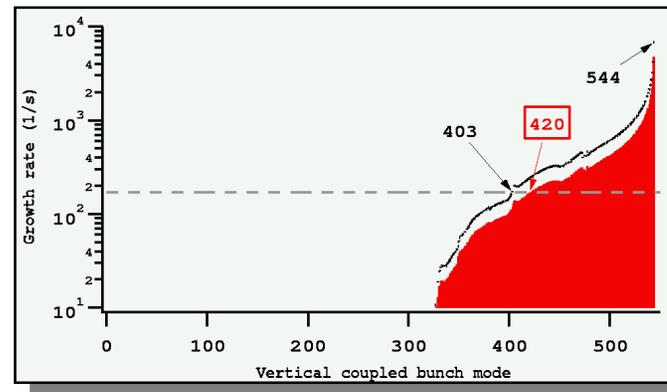
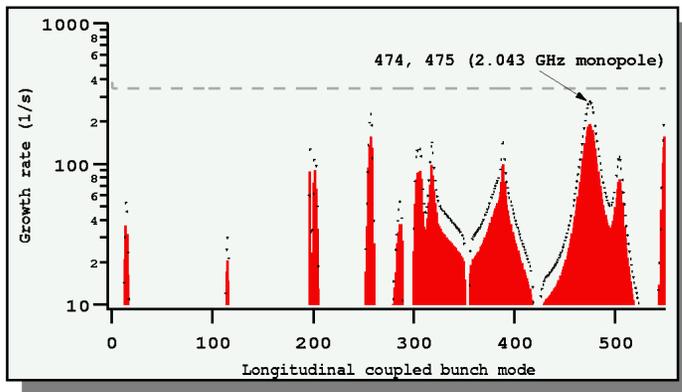
- Particles traveling through the vacuum chamber leave electromagnetic fields in their wake
- The fields depend on several factors
 - The charge distribution in the bunch
 - The vacuum chamber geometry
 - The material of the chamber
- The fields may be characterized by a wake field or an impedance
- 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"*

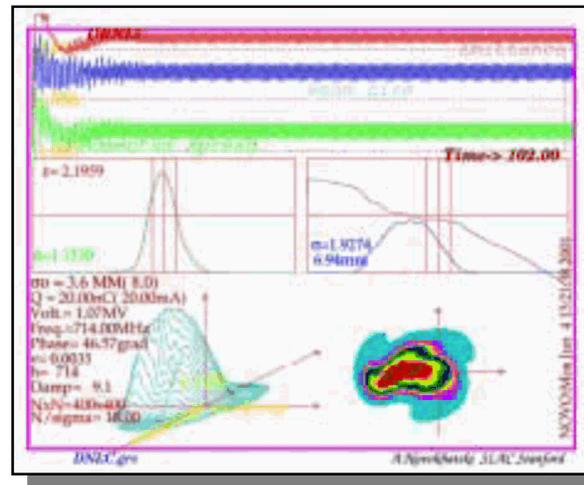
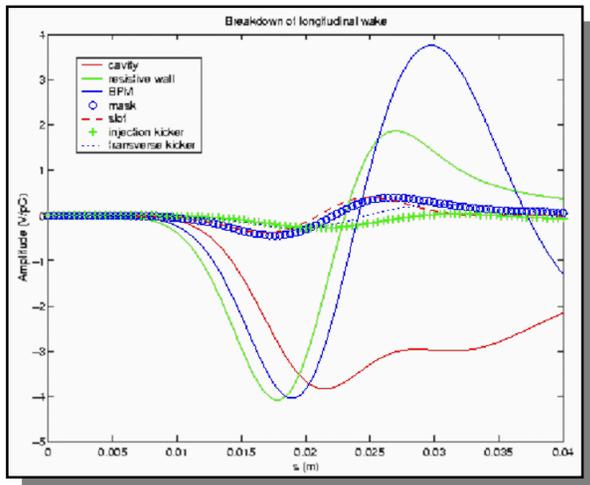
Classical Instabilities: Examples

- 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 high order modes

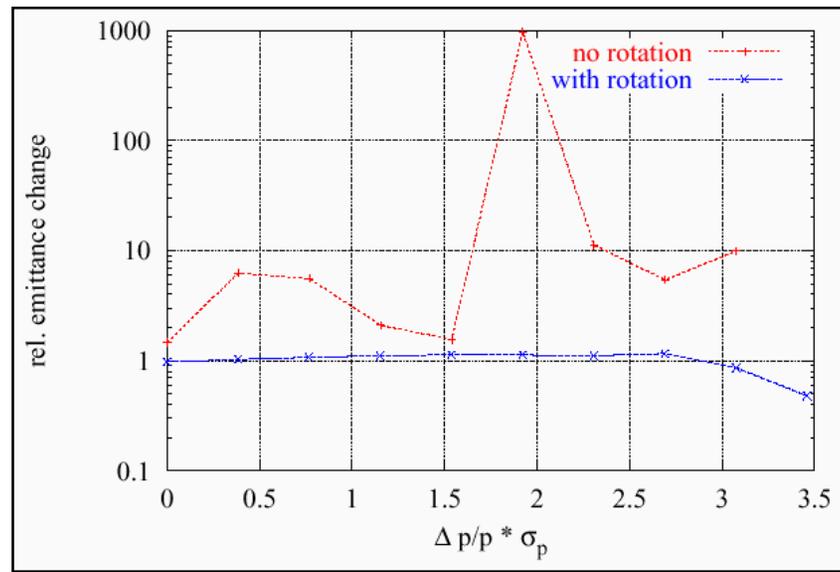
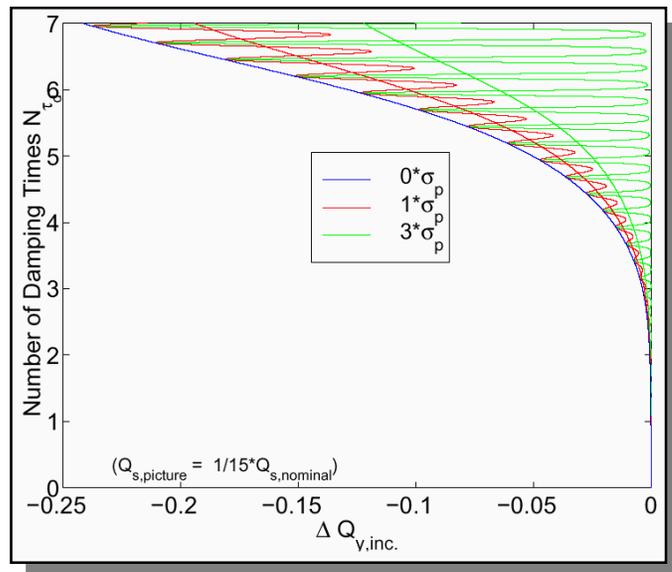
- Short range wake field can drive oscillations within a single bunch that leads to an increase in energy spread



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

Space Charge

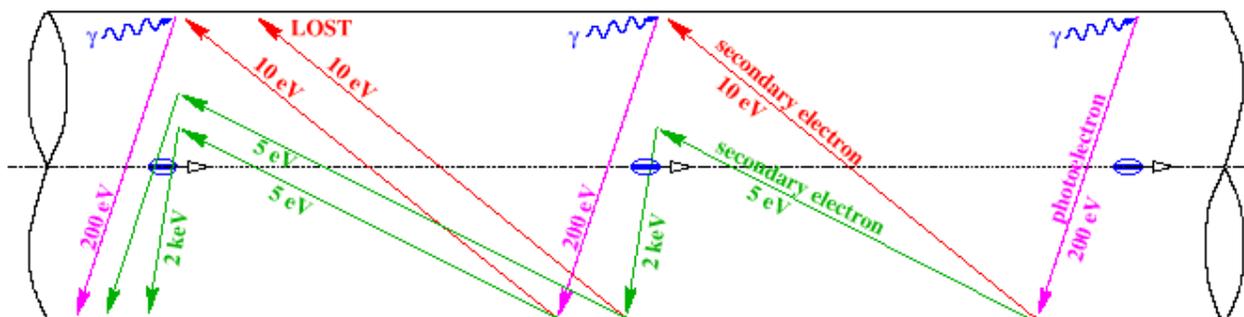
- Space charge force of the bunch provides transverse defocusing depending on the particle's position in the bunch
 - Leads to an incoherent tune spread
 - Particle dynamics can be very sensitive to the tune
- Space charge effects scale with the circumference, and inversely with the energy
 - Not a significant 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

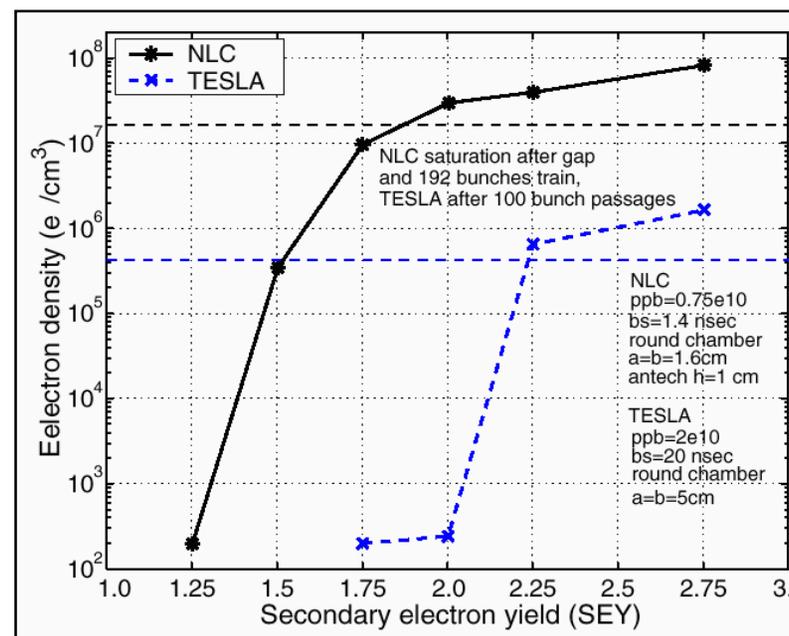
- Free electrons generated by a variety of processes
 - Photoemission from synchrotron radiation
 - Gas ionization
 - Secondary electrons from primary electrons impacting chamber



- 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...

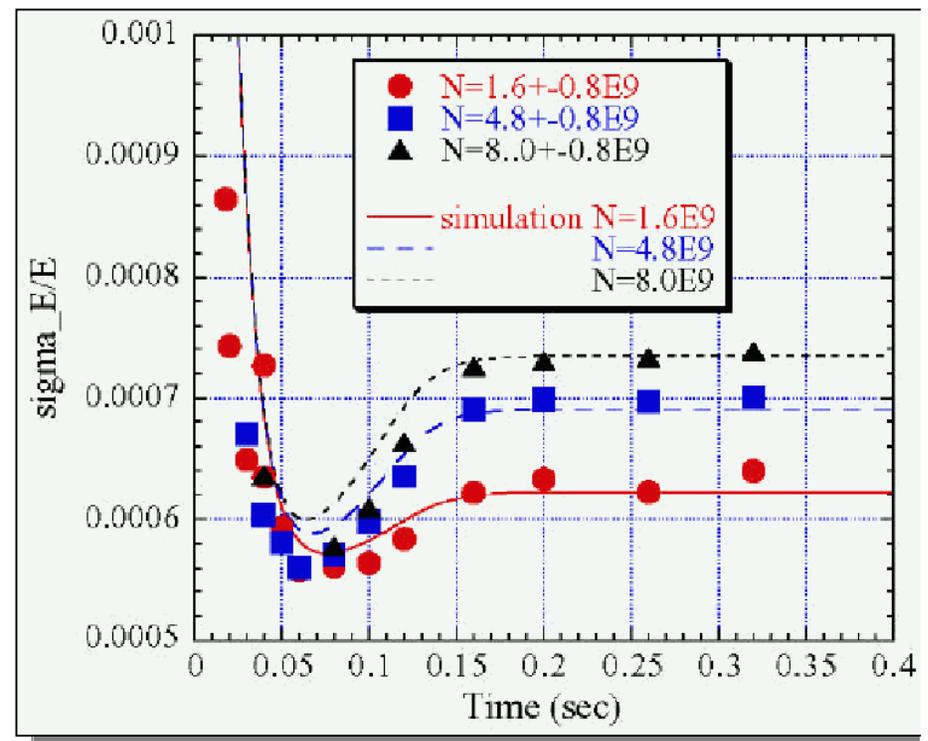


Simulation of electron cloud build-up as a function of chamber secondary yield in NLC MDR and TESLA damping rings

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/>