Electron Cloud Effects in Linear Collider Damping Rings

Andy Wolski

Lawrence Berkeley National Laboratory

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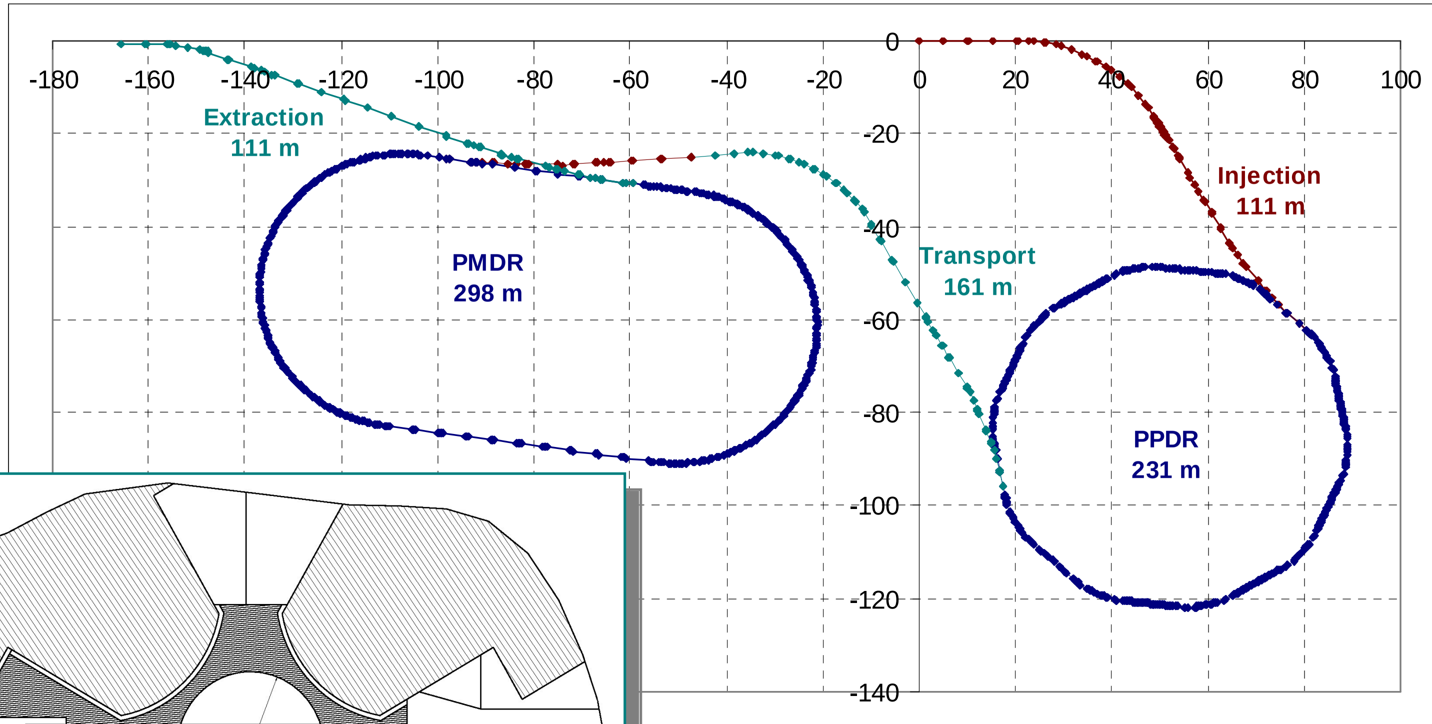
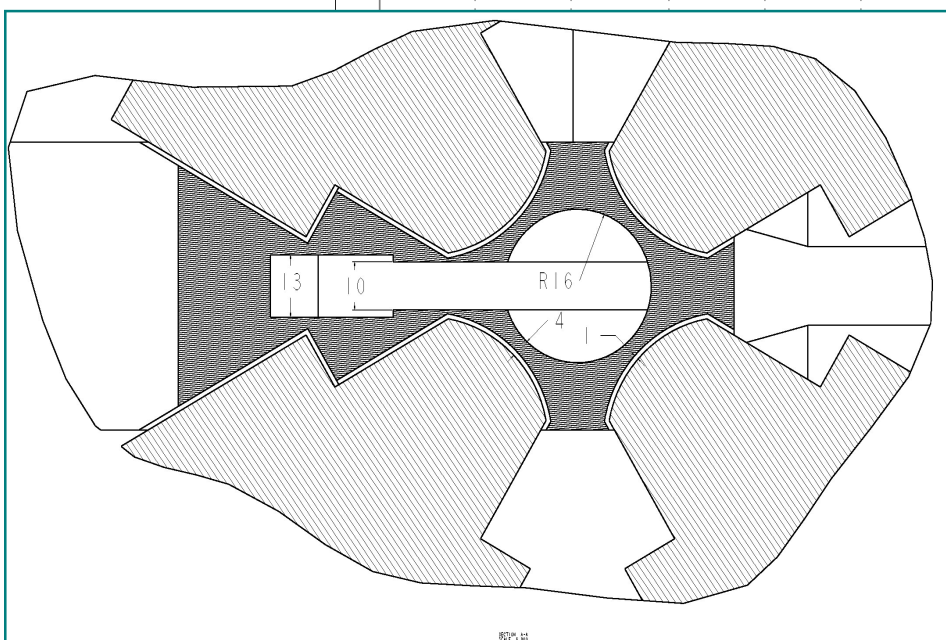
- Outline of Damping Rings and Parameters
- Preview of simulations
- Analytical estimates

Thanks to: Miguel Furman, Mauro Pivi, Tor Raubenheimer, Sam Heifets

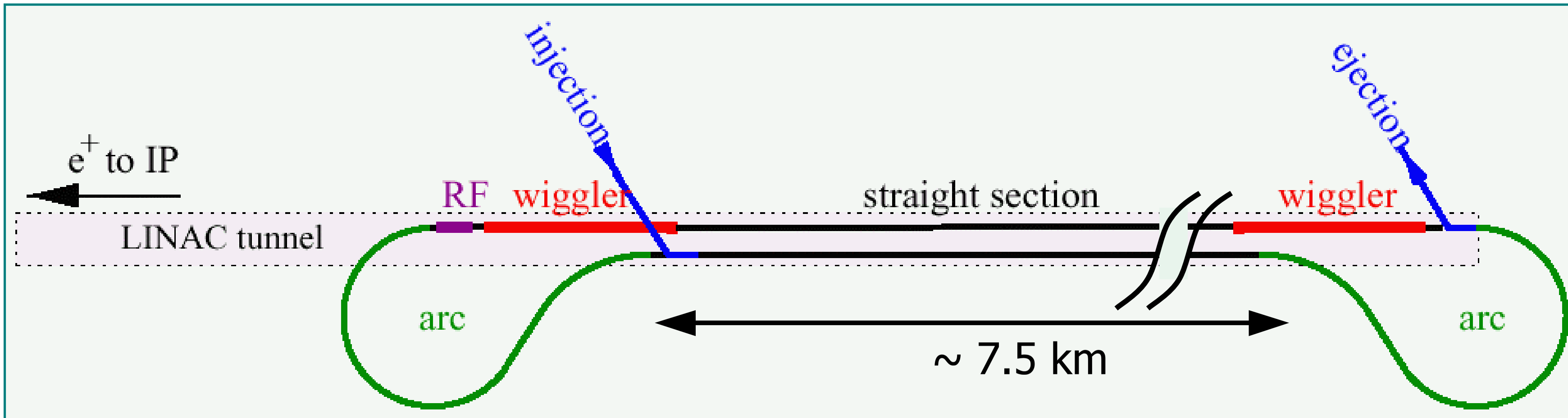
NLC: Two Damping Rings for Positrons

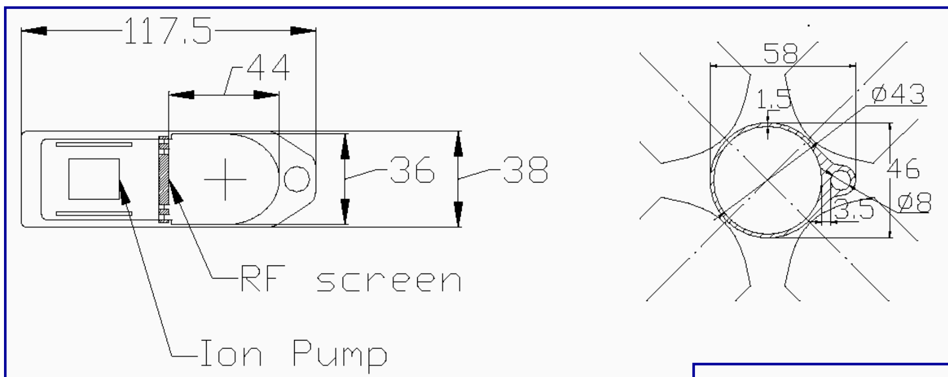




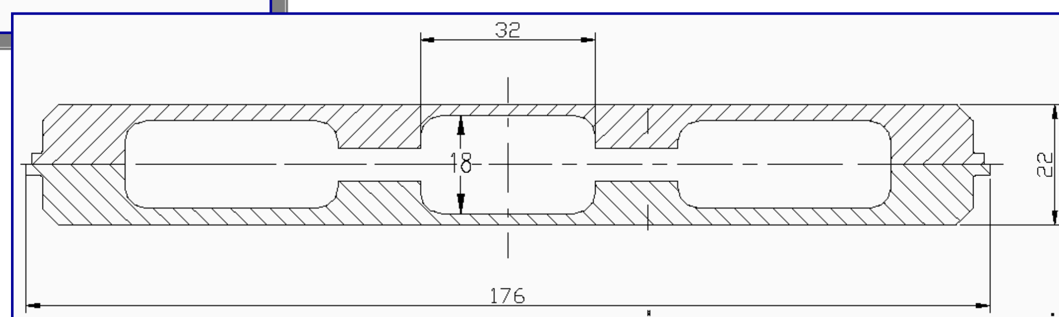
- 300 m circumference MDR
- Al vacuum chamber
- 16 mm radius (8 mm in wiggler)
- Antechamber
- 7.5×10^9 particles/bunch
- 1.4 ns between bunches
- 700 mA beam current

TESLA





- 17 km circumference
  - ~ 430 m wiggler
  - 2× 920 m arcs
- Aluminum vacuum chamber
- Antechamber in wiggler
- 2×10^{10} particles/bunch, 20 ns separation
- 160 mA beam current



Images from TESLA TDR
Courtesy, DESY

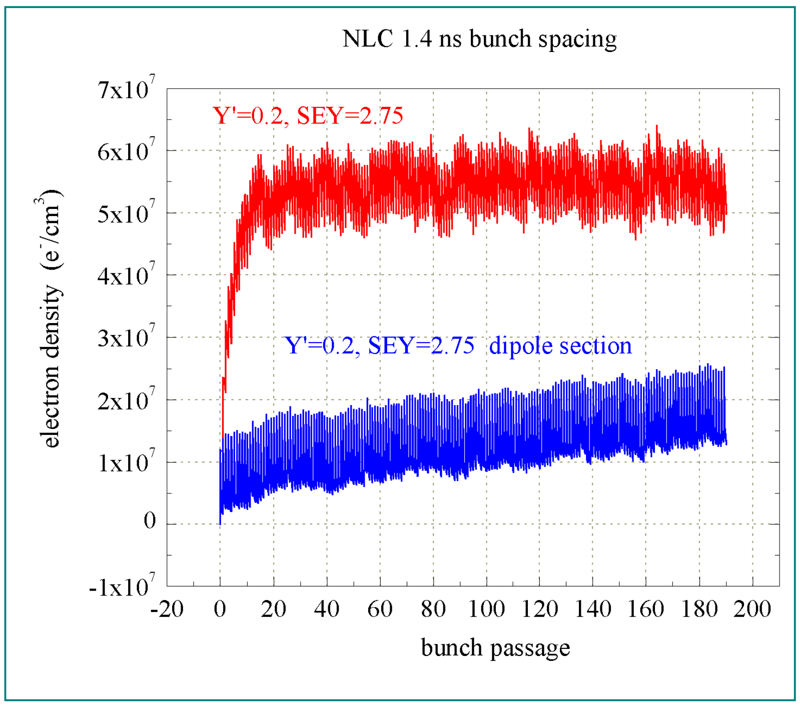
Linear Collider Damping Rings

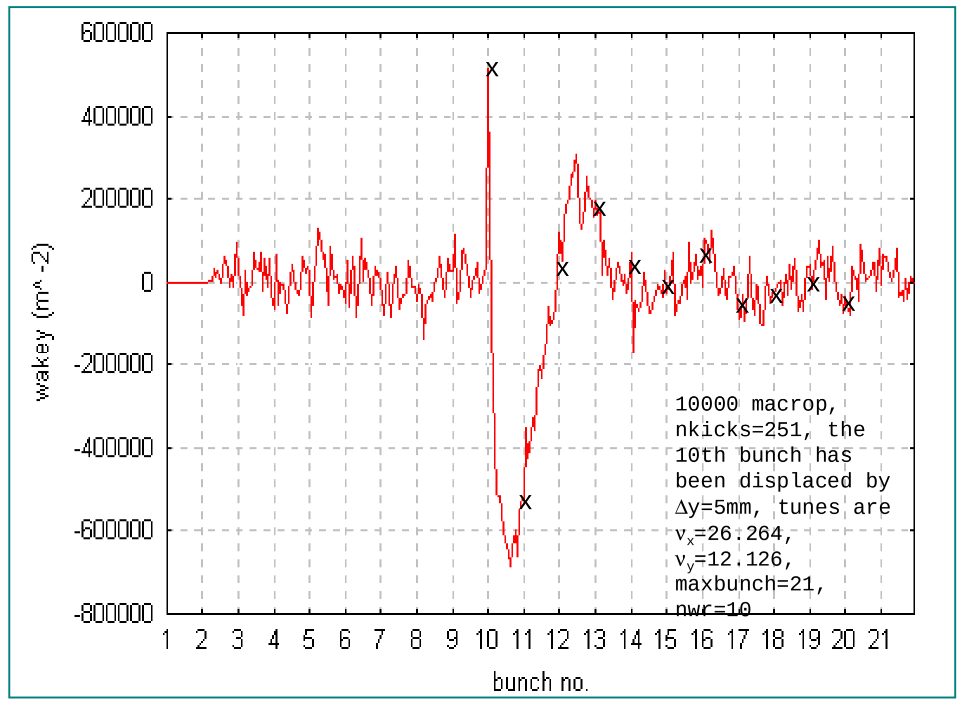
- Damping rings design driven by:
  - acceptance requirement
  - extracted emittance requirement
  - time structure of bunch train
- Parameter comparison:

	NLC MDR	NLC PPDR	TESLA	KEK-B LER	PEP-II LER	DAΦNE	HERA-e
Energy /GeV	1.98	1.98	5	3.5	3.1	0.51	12
Circumference /m	300	231	17 000	3 016	2 200	98	6 300
Bunch charge /10^{10}	0.75	0.75	2	3.3	9	5.4	3
Betatron tunes	27, 11	11, 5.5	76, 41	46, 46	20, 20	5, 5	50
Synchrotron tune	0.0035	0.011	0.066	0.015	0.03	0.01	50
RMS beam sizes /μm	200, 20	150, 230	60, 80	420, 60	1400, 200	1700, 95	110, 11
Bunch length /mm	3.6	5.2	6.0	4	13	25	5
Mom^{m} Compaction	0.3 10^{-3}	2 10^{-3}	0.1 10^{-3}	0.2 10^{-3}	1.3 10^{-3}	0.03	5 10^{-4}
Bunch separation /m	0.42	0.42	6.0	2.4	2.5	1.6	29
Beam pipe radius /mm	16	36	50	47	45/25	35	20/40

Simulations

- POSINST
  - M. Furman and M. Pivi (hear talks on Monday PM and Tuesday AM)
  - simulates build-up and dynamical behavior of electron cloud
  - can specify a range of vacuum chamber and beam properties as inputs
  - calculates long-range wake
- So far, only applied to NLC





Analytical Models

- Based on work by K. Ohmi, F. Zimmermann, E. Perevedentsev, and by S. Heifets
- Aim to calculate growth rates of single bunch and coupled bunch modes
- Simple models do not include full complexity of behavior:
  - cloud density given by the neutralization condition (or × some factor)
  - wake field corresponding to broad-band resonator, with different parameters for short-range and long-range wakes
  - standard theory applied to calculate growth rates
- Models seem to be in reasonable agreement with simulations (e.g. fitting parameters to long-range wake field)

Single Bunch

- Cloud concentrated *inside* the bunch
- Electrons perform simple harmonic motion in the field of the bunch
- Wake field given by (Ohmi, Zimmermann, Perevedentsev):

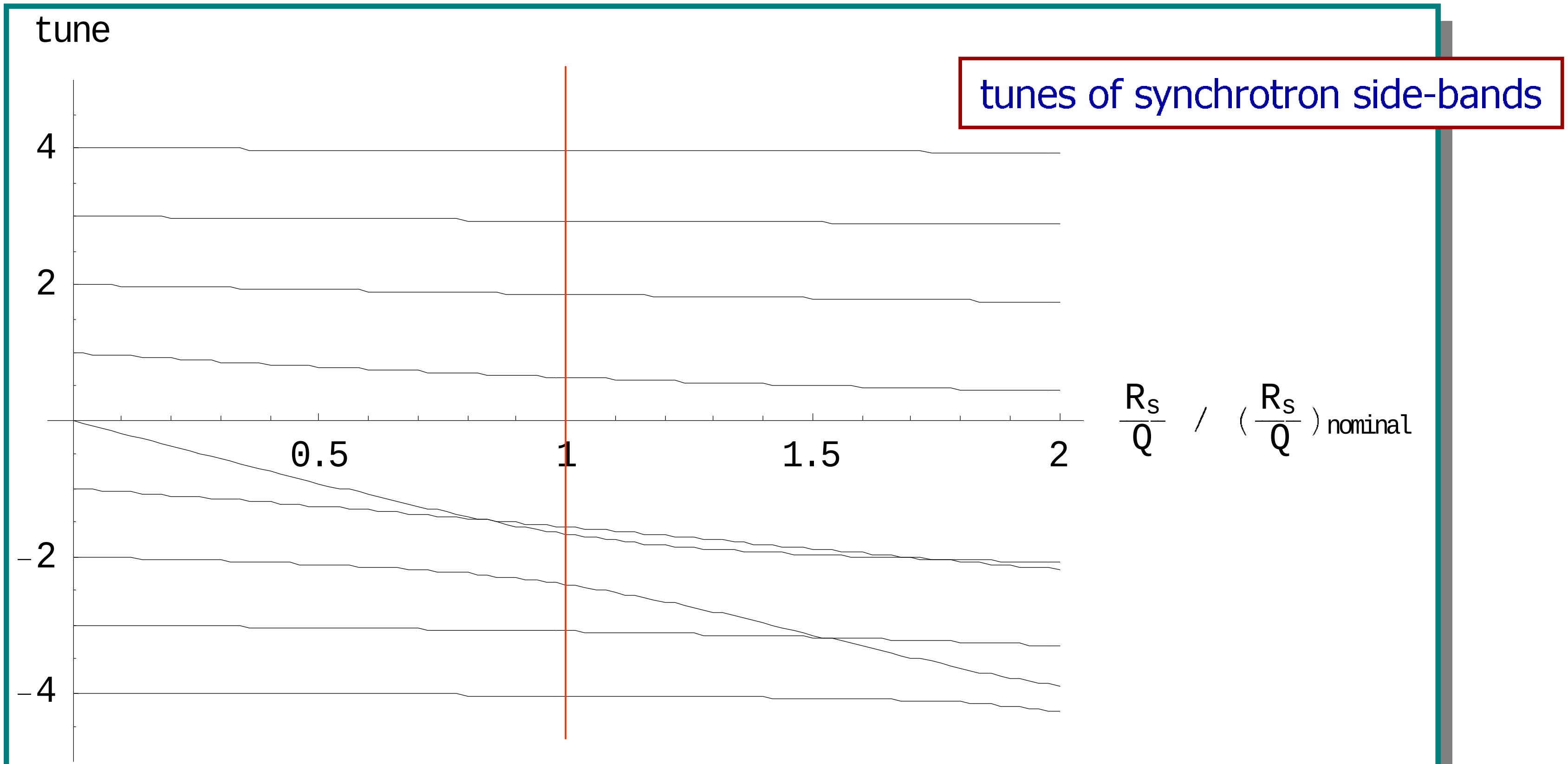
$$W_1(z) = \frac{cR_s}{Q} e^{-\frac{\omega_c z}{2cQ}} \sin\left(\frac{\omega_c}{c} z\right) \qquad \frac{cR_s}{Q} = \frac{\gamma \omega_b^2 \omega_c C}{\lambda_b r_e c^3}$$

  - results insensitive to precise value of Q; we take $Q = 5$

- Apply the standard azimuthal mode coupling theory (Chao, chapter 6)
  - assume a gaussian distribution in longitudinal phase space
  - consider only the lowest radial mode
  - find synchrotron side-band tunes as the eigenvalues of:

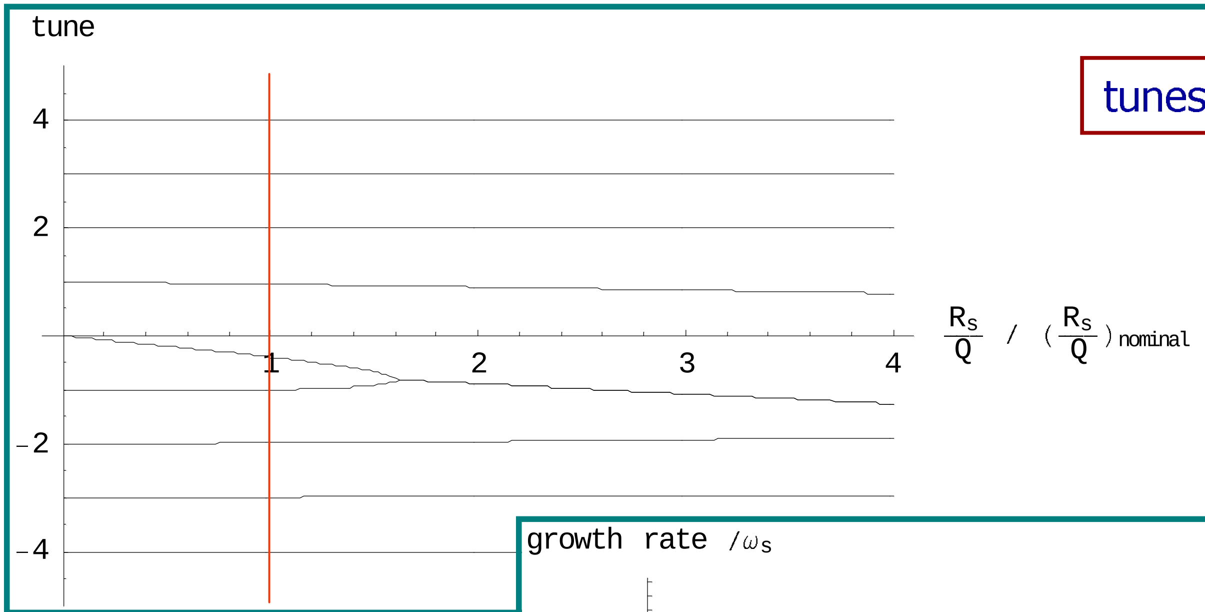
$$M_{ll'} = l\delta_{ll'} - \mathrm{i}\frac{N r_e c}{4\pi\gamma T_0 \omega_\beta \omega_s} \frac{\mathrm{i}^{l-l'}}{\sqrt{l!\,l'!}} \int_{-\infty}^{\infty} \mathrm{d}\omega Z_1(\omega) \left(\frac{\omega \sigma_z}{\sqrt{2}c}\right)^{l+l'} \exp\left(-\frac{\omega^2 \sigma_z^2}{c^2}\right)$$

NLC MDR Single Bunch Modes



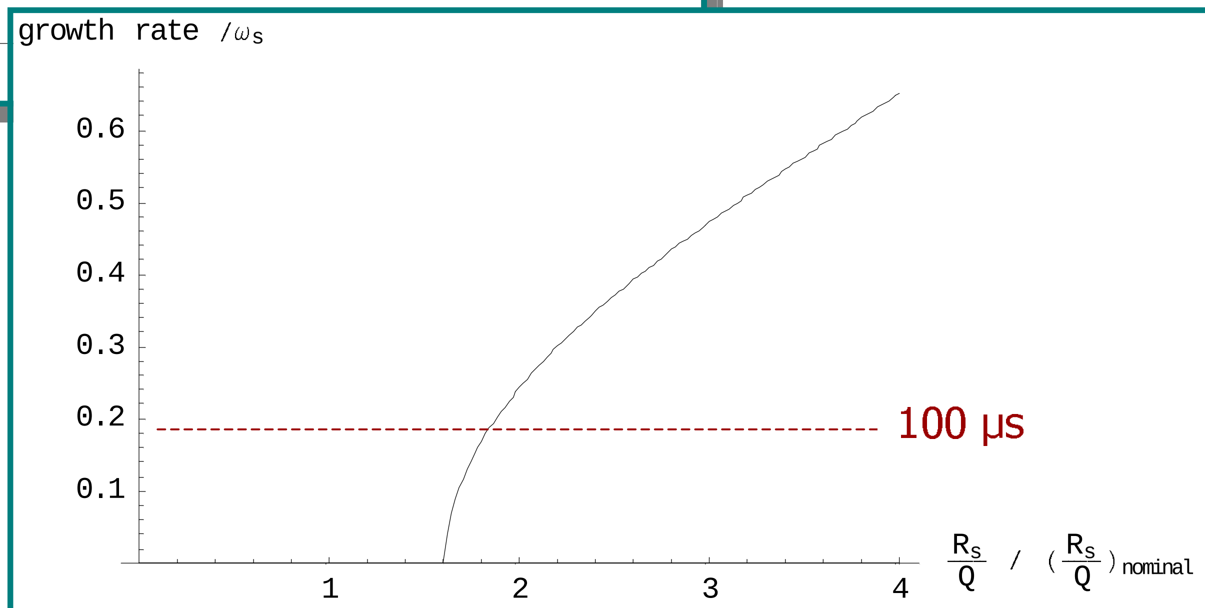
Results give only some indication of stability regime, and are not expected to give precise values for thresholds or growth rates.

TESLA Single Bunch Modes



tunes of synchrotron side-bands

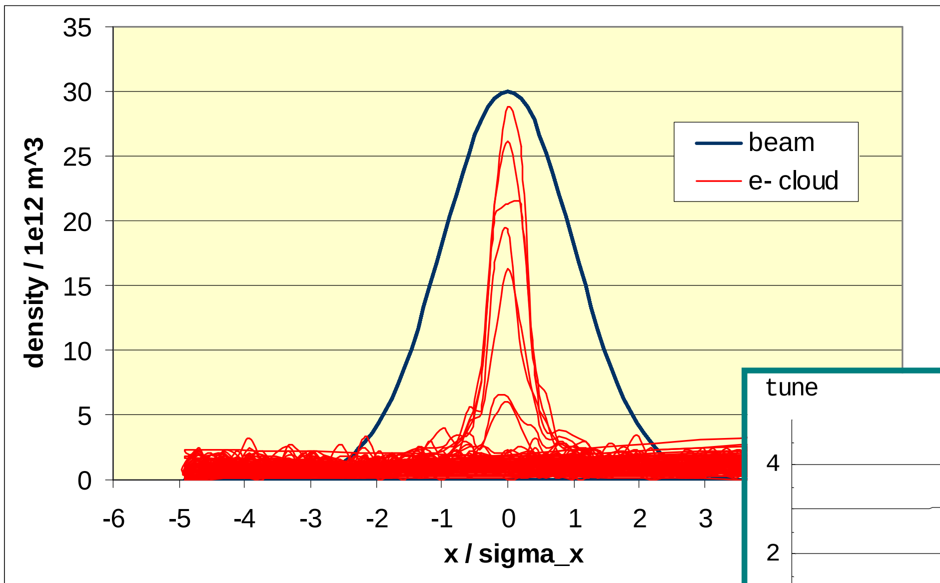
Fully coupled beam, 50 mm radius vacuum chamber

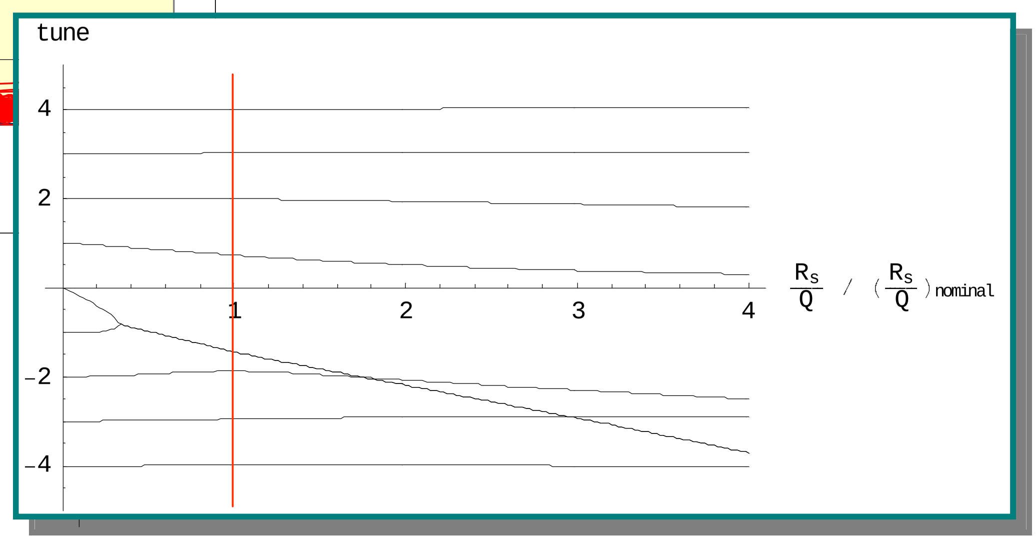


growth rates

Electron Cloud Density Increase

- Electrons can be focused by the positron beam, to give a much narrower distribution: density factor ~ 15 - 30
- Simulation for TESLA by T. Raubenheimer





Further Single Bunch Considerations

- No synchrotron oscillations in the TESLA straight sections
  - instability resembles beam break-up

$$\mathrm{Y} = \frac{N r_e \beta_y C}{4\gamma}\frac{cR_s}{Q}$$

  - linear growth time of the order 3 μs (including density factor of 30)

- Focusing from electron cloud gives incoherent tune shifts
  - assume density factor 30 in TESLA straights, 15 elsewhere

	NLC MDR	TESLA Single Arc	TESLA Single Straight	TESLA Total
$\Delta\nu_x$	0.12	0.056	1.9	3.9
$\Delta\nu_y$	0.29	0.22	1.9	4.2

Coupled Bunch Modes

- Continue to consider density given by neutralization condition
- Cloud oscillates in field of averaged beam current
  - a reasonable approximation if oscillation period >> bunch separation
- Equation of motion: $$\ddot{y} = -\frac{k^2}{y} \qquad k^2 = \frac{2Nr_e c^2}{s_b}$$
  - y is transverse displacement of an electron with respect to the beam
  - cloud has oscillation frequency characterized by: $$\omega_c = \sqrt{\frac{\pi}{2}\frac{k}{a}}$$
  - we consider only electrons which are not "kicked to the wall" during the passage of a single bunch: $$a = \frac{2Nr_e s_b}{b}$$
  - decoherence comes from dependence of frequency on amplitude

Coupled Bunch Modes

- Use a broad-band resonator model:

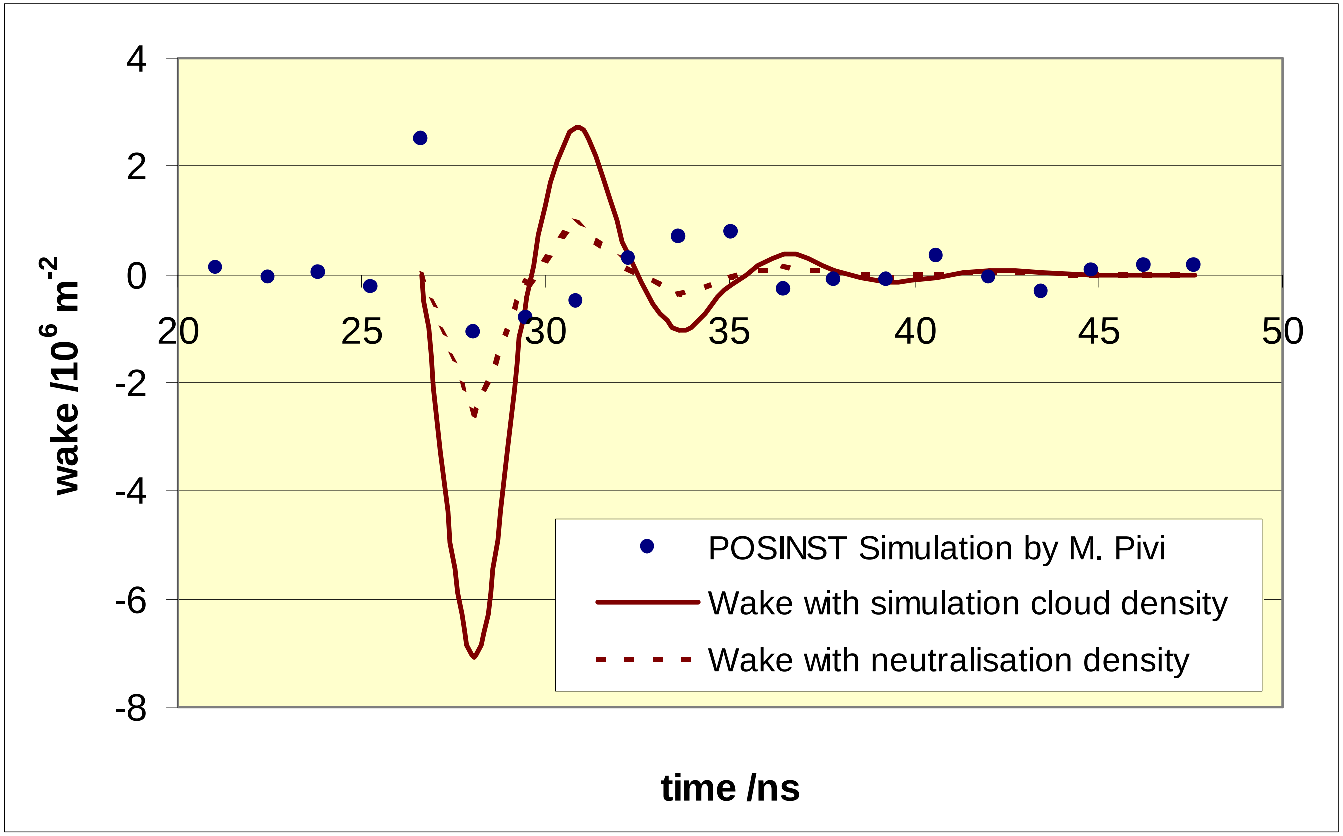
$$\frac{cR_s}{Q} = \frac{n_0 s_b}{N}\frac{\omega_c}{c}C \qquad \omega_c = \frac{bc}{2}\sqrt{\frac{\pi}{N r_e s_b^3}} \qquad Q \approx 5$$

- Calculate the mode frequencies from:

$$\Omega_\mu - \omega_\beta = \frac{N_b r_e c}{2\gamma\omega_\beta}\sum_{k=0}^{\infty} W_1(k s_b) \mathrm{e}^{2\pi i k(\mu+\nu_y)/M}$$

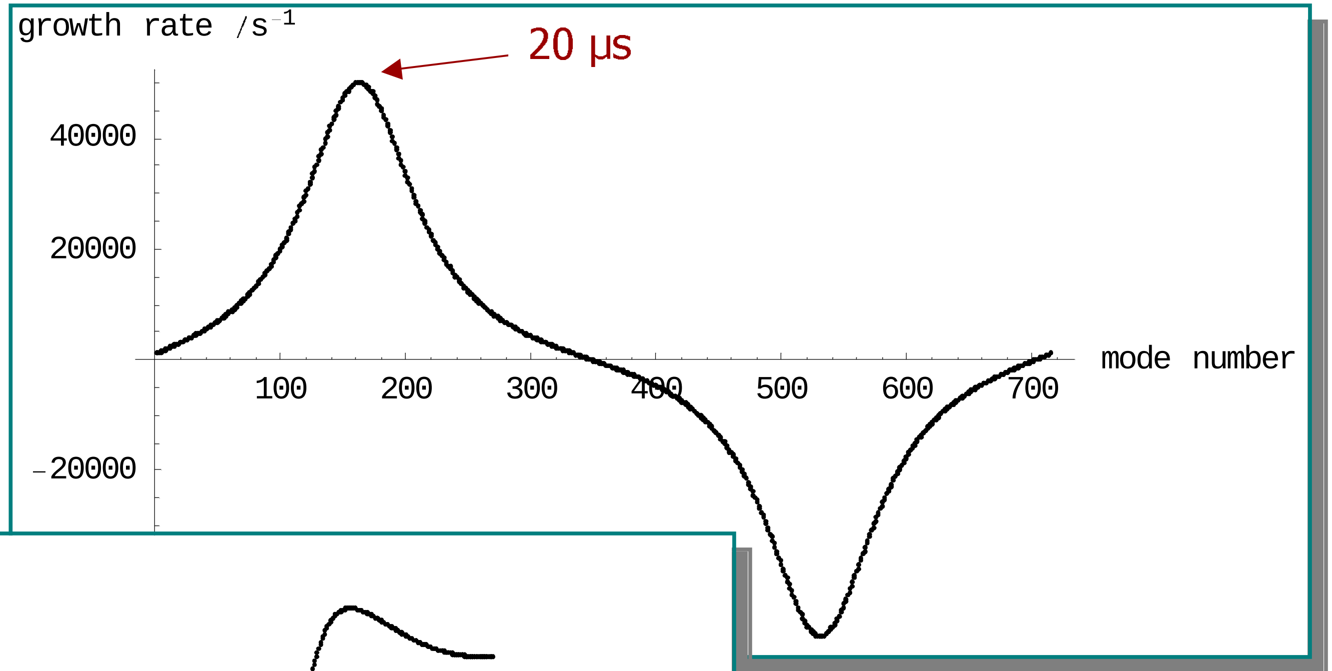
  - for simplicity, assume ring completely filled (gives pessimistic estimate)

Comparison with Simulation

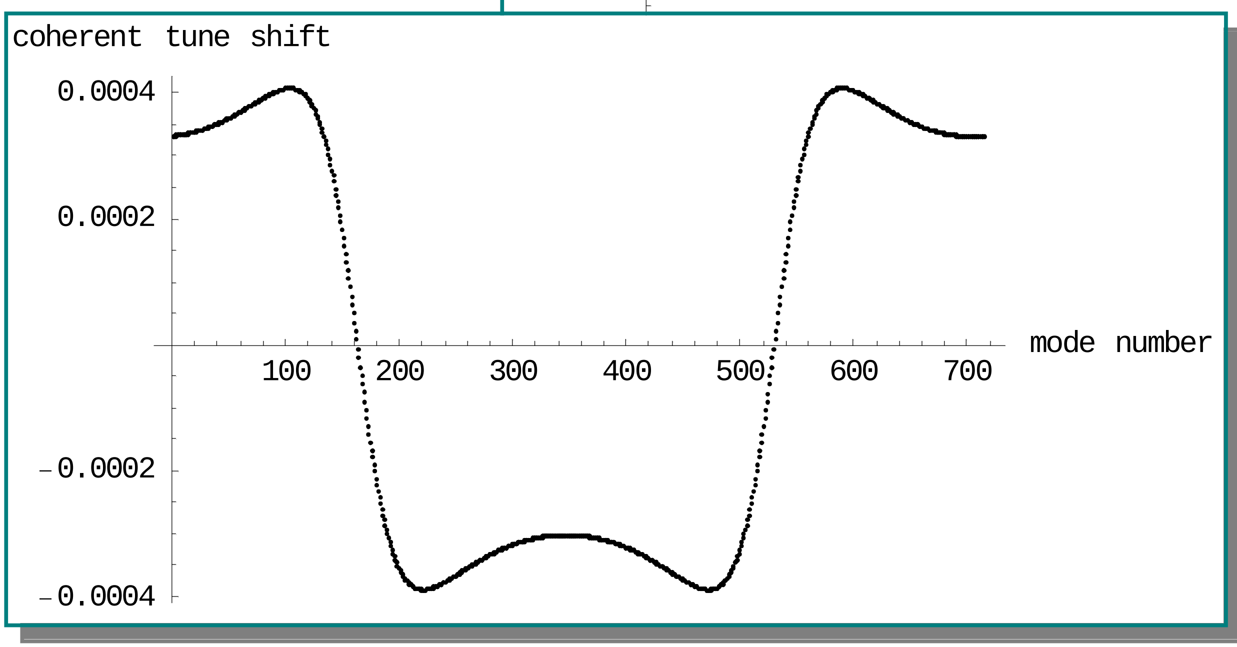


NLC MDR Coupled Bunch Modes

growth rates

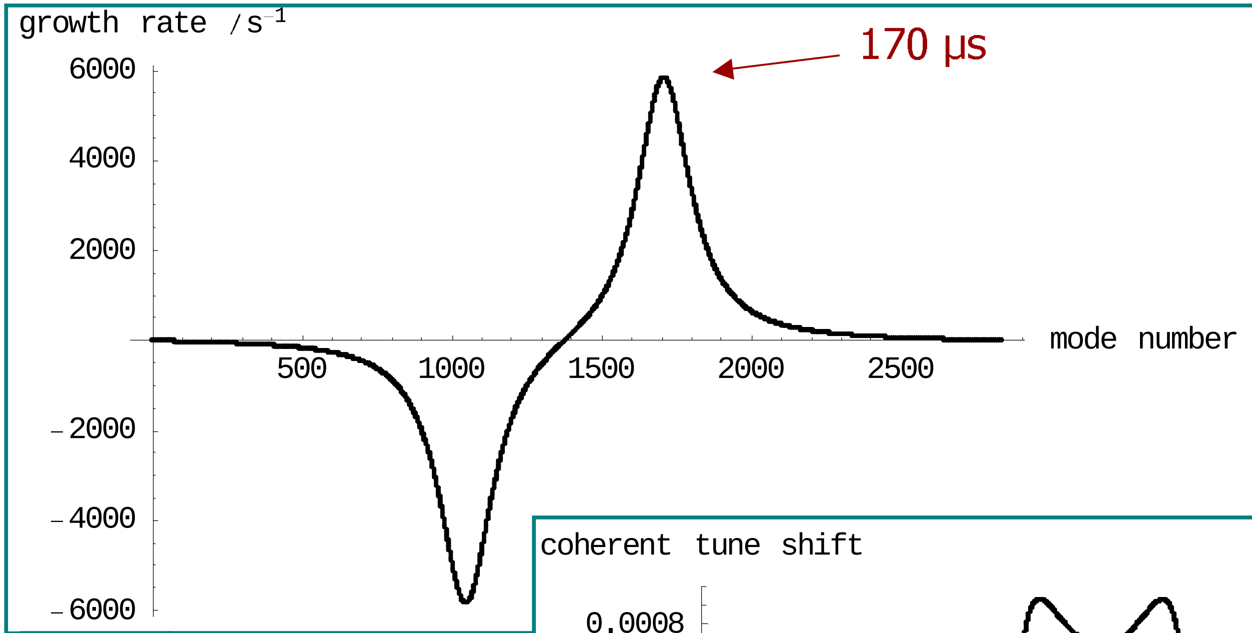


coherent tune shift



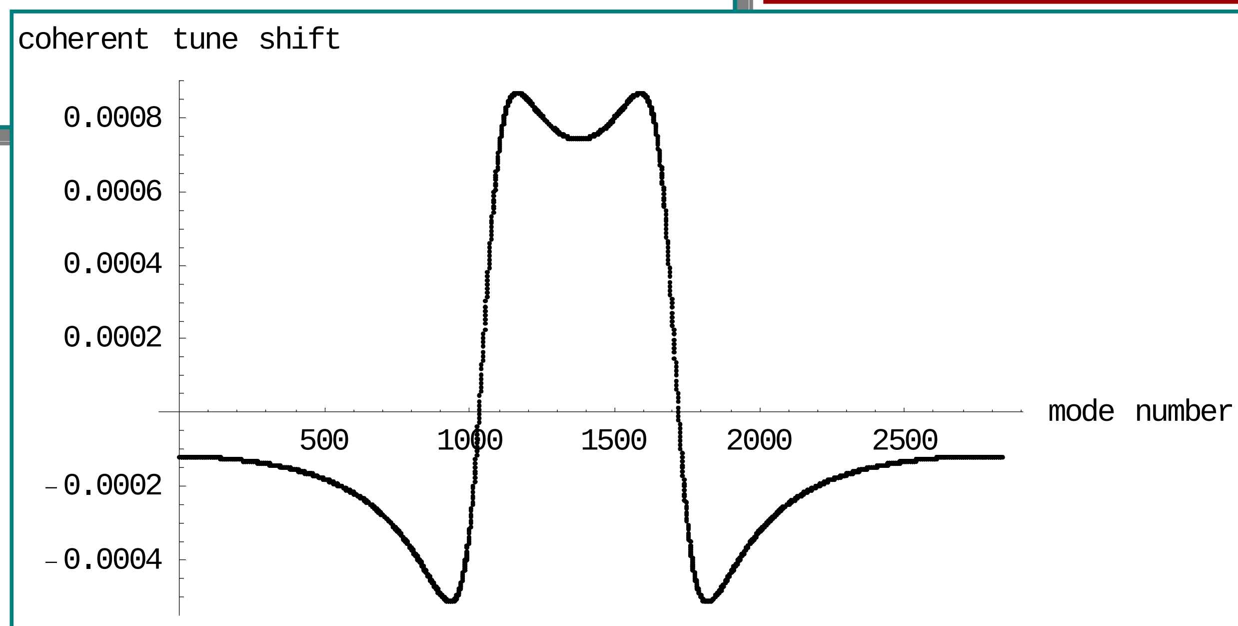
cloud oscillations/gap = 0.76

TESLA Coupled Bunch Modes



growth rates

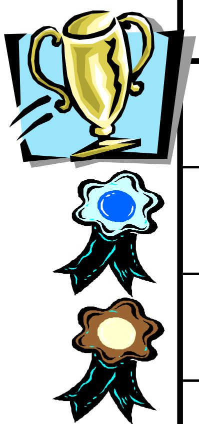
Fully coupled beam, 50 mm radius vacuum chamber



coherent tune shift

cloud oscillations/gap = 0.38

Machine Comparison



	Incoherent tune shift	Single bunch threshold / nominal	Coupled bunch growth time /μs
PEP II LER	0.16	0.6	16
NLC MDR	0.019	0.8	20
TESLA	0.114	0.5 - 5	30 - 170
KEK B LER	0.022	3	180
DAΦNE	0.0068	3	20
NLC PPDR	0.0025	10	370
HERA-e	0.0057	20	2000

Note:
No single-bunch density factor applied
TESLA beam break-up effect not included

Other Issues

- What is the real saturation level?
  - Need to include all sources, SEY, vacuum chamber geometry, beam structure… can only find by simulations
- Effects of magnetic fields
  - NLC rings are packed with dipoles and wigglers
  - Wiggler field has strong (~ 0.5 T) longitudinal component near the wall
- How well does the broad-band resonator model the wake field?
  - The real dynamics is certainly more complicated
- Need to investigate possible countermeasures
  - TiN or other coatings
    - effect on vacuum
  - Solenoid windings
    - difficult in NLC - there’s no room!