Overview of Electron Cloud Studies for the Future Linear Colliders

Mauro Pivi
NLC Division
SLAC

Napa Valley, California, April 2004

Builds on the experience of many colleagues and friends; I am particularly grateful to:

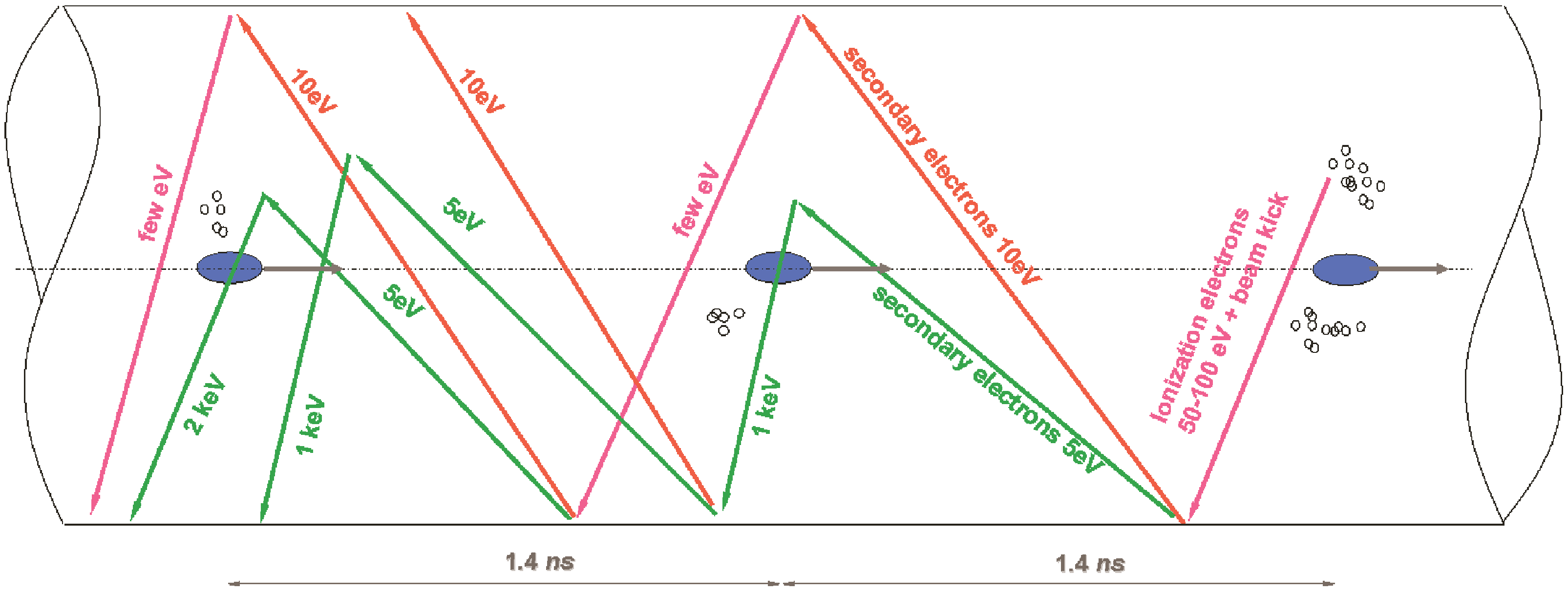
J. S. Berg, Y. Cai, A. Chao, **A. Feiz**, **M. Furman**, O. Gröbner,
K. Harkay, S. Heifets, N. Hilleret, **R. Kirby**,
J.M. Laurent, A. Novokhatski, **F. Le Pimpec**,
R. Macek, **K. Ohmi**, R. Rosenberg, **G. Rumolo**,
G. Stupakov, J. Seeman,
T. Raubenheimer, G. Vorlaufer, F. Zimmermann, **A. Wolski**,
and many other colleagues …

NLC and TESLA Positron Damping Rings

parameter	symbol	NLC MDR	TESLA
number of particles per bunch	N_p	0.75×10^{10}	2.0×10^{10}
bunch spacing	T, ns	1.4	20
Synchrotron tune		0.0118	0.0659
circumference	C, m	300	17000
bunch length rms	σ_z, mm	5.5	6
bunch size transverse	σ_x, σ_y μm	49, 6	400, 7
vacuum chamber str. sec. round	r_w, mm	20	50
vacuum chamber arc	r_w, mm	20	22
beam tube material	*matsurf.*	Aluminum, TiN	Aluminum
beam energy	E, GeV	1.98	5
average beta functions	$\beta_{x,y}$, m	10, 10	65, 35
Antechamber included		yes	not

simulation code as for NLC simulations: we assume that the ring consist of 36 identical, evenly-spaced BB dipole bending magnets of length 0.96m, 68 field free D3 drift sections of length 0.975m and 45 D2F inj. sections in between every pair of dipole. circumference= 299.792m

Main sources of primary electrons



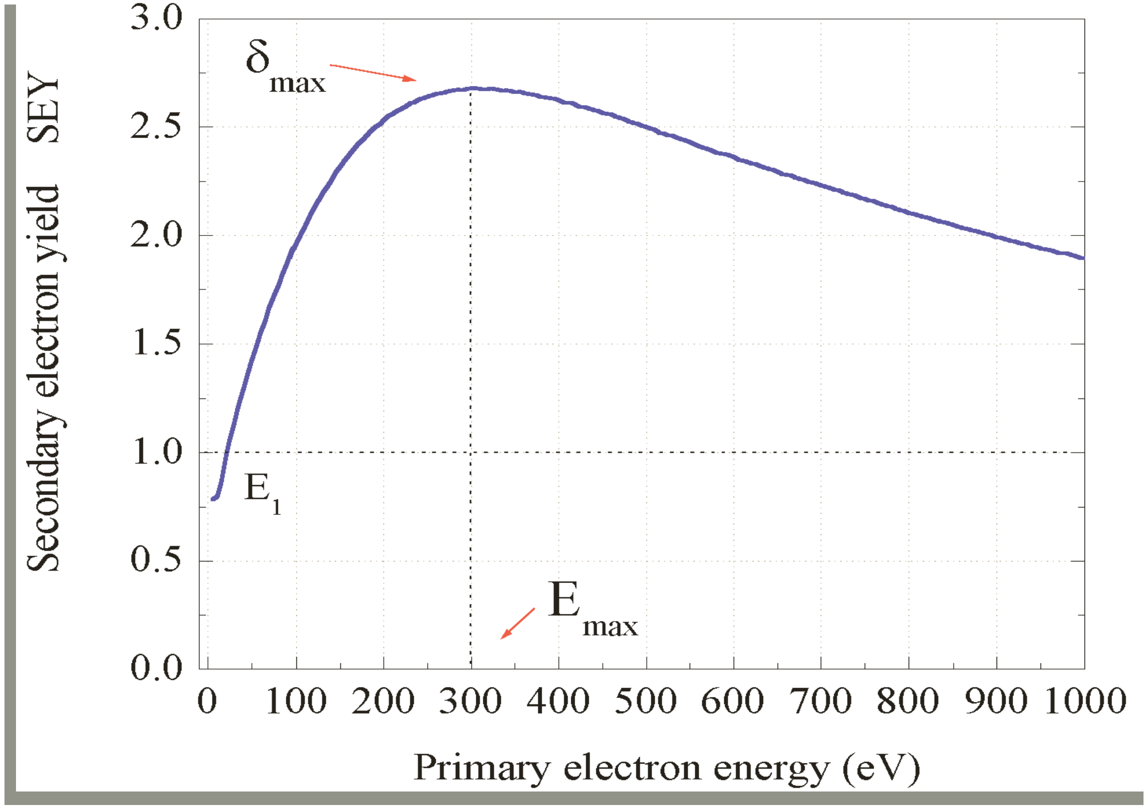
Picture:

The NLC positron MDR stores 3 trains, separated by 65 nsec with each train consisting of 192 bunches. Each bunch generates a small number of electrons by residual gas ionization which does not dissipate completely during the train-gap and may grow up to an equilibrium saturation limit due to space charge, secondary yield etc. Simulations starting with initial e^- density near the saturation limit

Concern for Luminosity in future hadron and linear colliders: TRC R2-3

Secondary electron yield (SEY or δ) for aluminum (courtesy R. Kirby, SLAC)

Aluminum etched



Electron reflectivity here δ(0) ~ 0.65. We have included a linear dependence of E_{max} with δ_{max}, typically during ph+el conditioning, $E_{max} = 310\ eV$ when δ_{max}=2.75, and E_{max} =170eV when $\delta_{max} = 1.1$.

Simulation code features

POSINST

- 3D electron kinematics
- multi bunches on axis
- electron multiplication by SEY model

generation of the cloud

↓

HEAD-TAIL / CLOUD_MAD

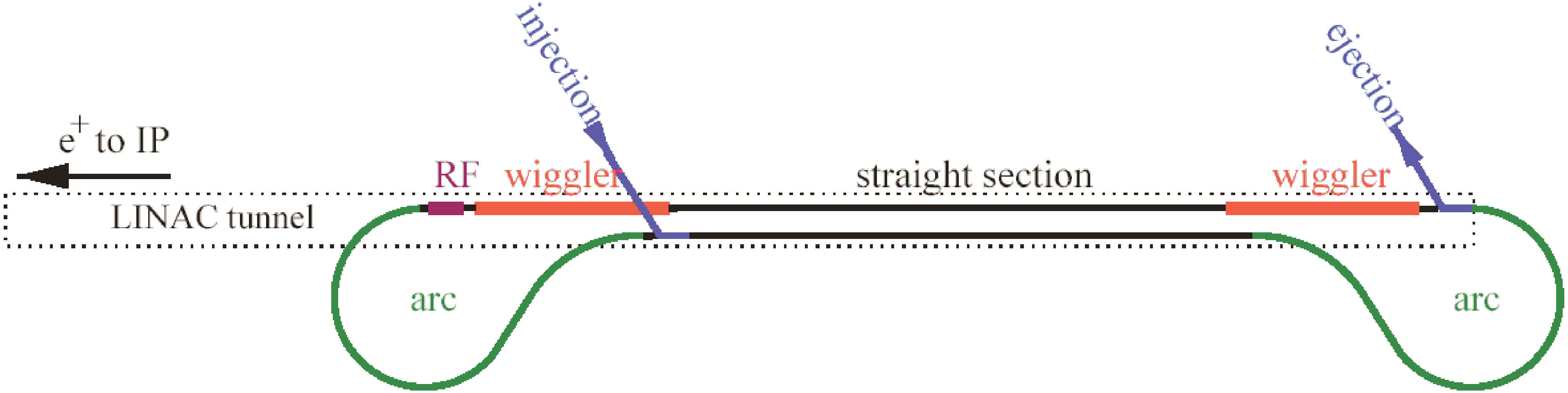
- 3D electrons and single-bunch particles dynamics
- constant number of electrons

single-bunch dynamic and instability

Electron Cloud in Linear Collider

1. Simulations: generation of the cloud (POSINST)
2. Simulations: single-bunch fast head-tail instability (HEAD-TAIL, PEHTS, QUICKPIC, CLOUD_MAD) and coupled-bunch instability (POSINST)
3. Possible remedies

Linear Collider Positron Damping Rings

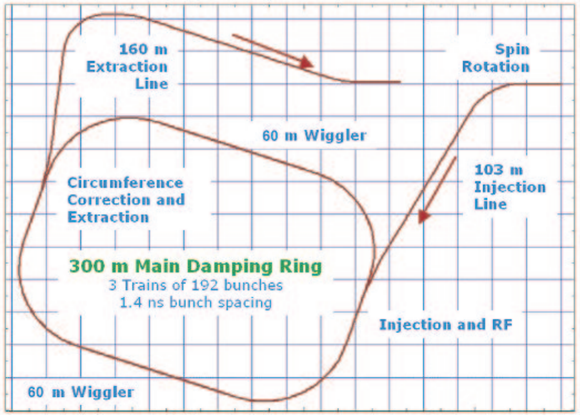


TESLA 17000m

Damping wigglers 500 m

arcs section 1900 m

Long straight sections 14500 m



NLC 300m

"POSINST" simulation codes features

Started '96 by M. Furman at LBNL, implemented since 2000 together with M. P. SLAC, (also contributions Y.Cai SLAC) single or multi-bunch passages, short or long bunches, and effective bunch profile the electron cloud is dynamically generated from:

- residual gas ionization
- secondary electron yield (SEY), detailed model included
- other possible sources: photoelectron emission LHC, proton losses in PSR and SNS

- field-free region, dipole sections, solenoid field, quadrupole, sextupole, wiggler, etc.
- bunch divided longitudinally into N_k kicks (typ. 251 for NLC)
- 3D electron kinematics
- purely transverse electron space-charge effects
- purely transverse beam-electron forces
- round or elliptical vacuum chamber geometry, with a possible antechamber
- perfect-conductor BCs (surface charges included)

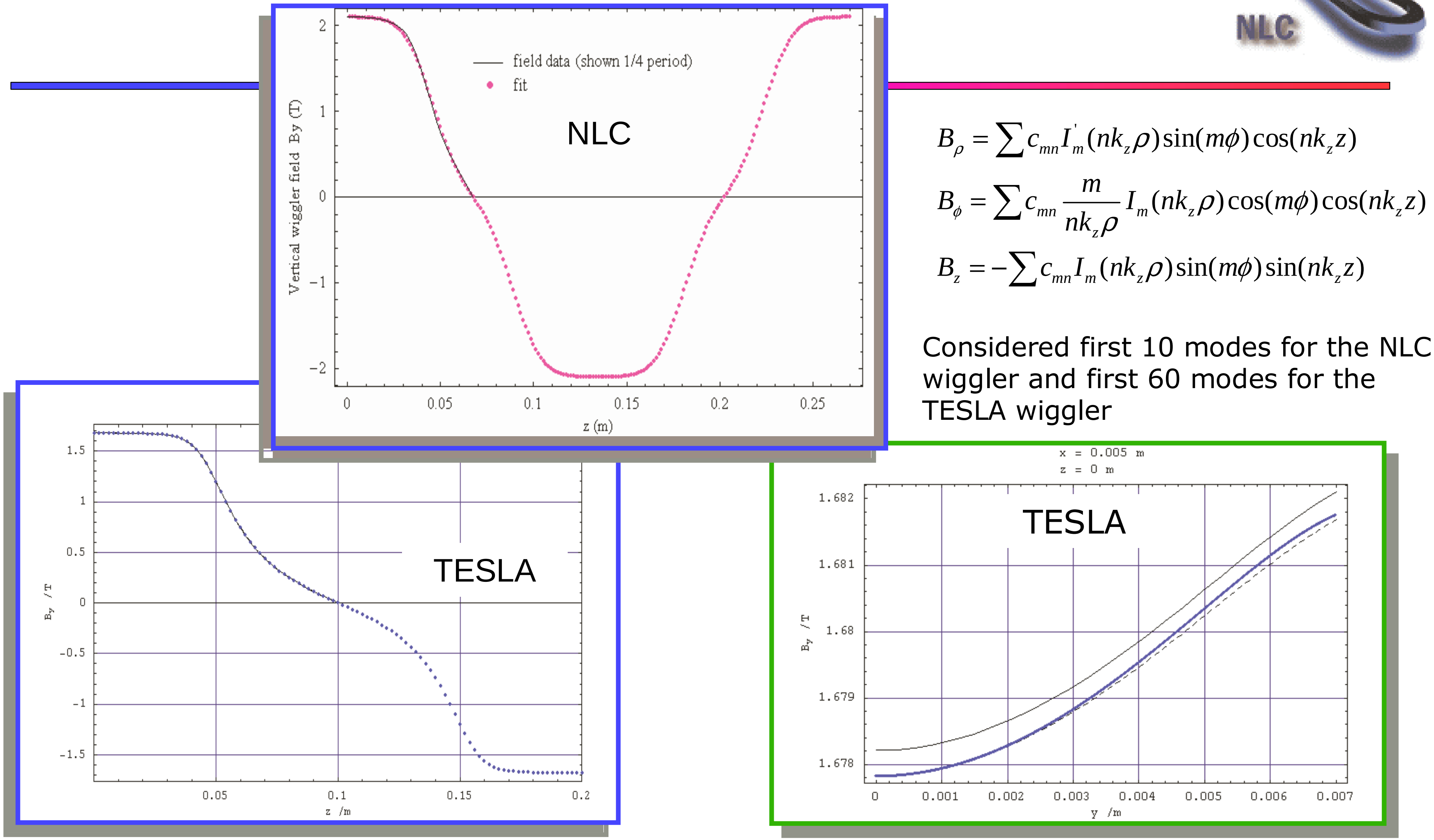
Wiggler Field Model

$$B_\rho = \sum c_{mn} I'_m(nk_z\rho)\sin(m\phi)\cos(nk_z z)$$

$$B_\phi = \sum c_{mn} \frac{m}{nk_z\rho} I_m(nk_z\rho)\cos(m\phi)\cos(nk_z z)$$

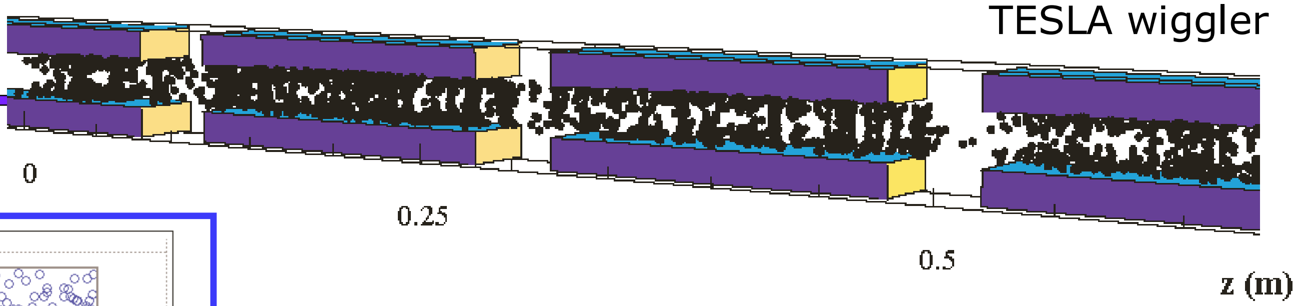
$$B_z = -\sum c_{mn} I_m(nk_z\rho)\sin(m\phi)\sin(nk_z z)$$

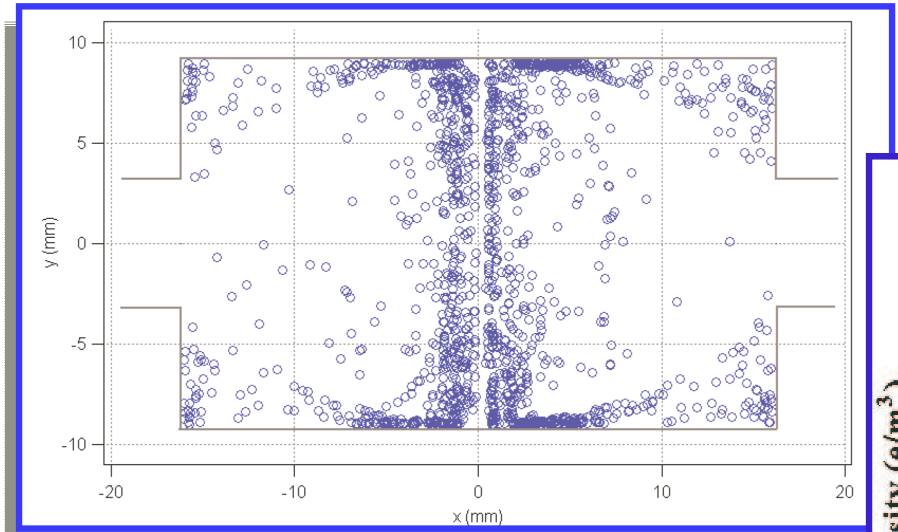
Considered first 10 modes for the NLC wiggler and first 60 modes for the TESLA wiggler



Sample field model for the NLC and TESLA damping wigglers. The wiggler vacuum chamber design includes an antechamber on both sides. The solid line shows the field data, the dotted line show the fit included in the posinst code (M. Woodley and A. Wolski from LCC-0113, CBP Tech Note-276).

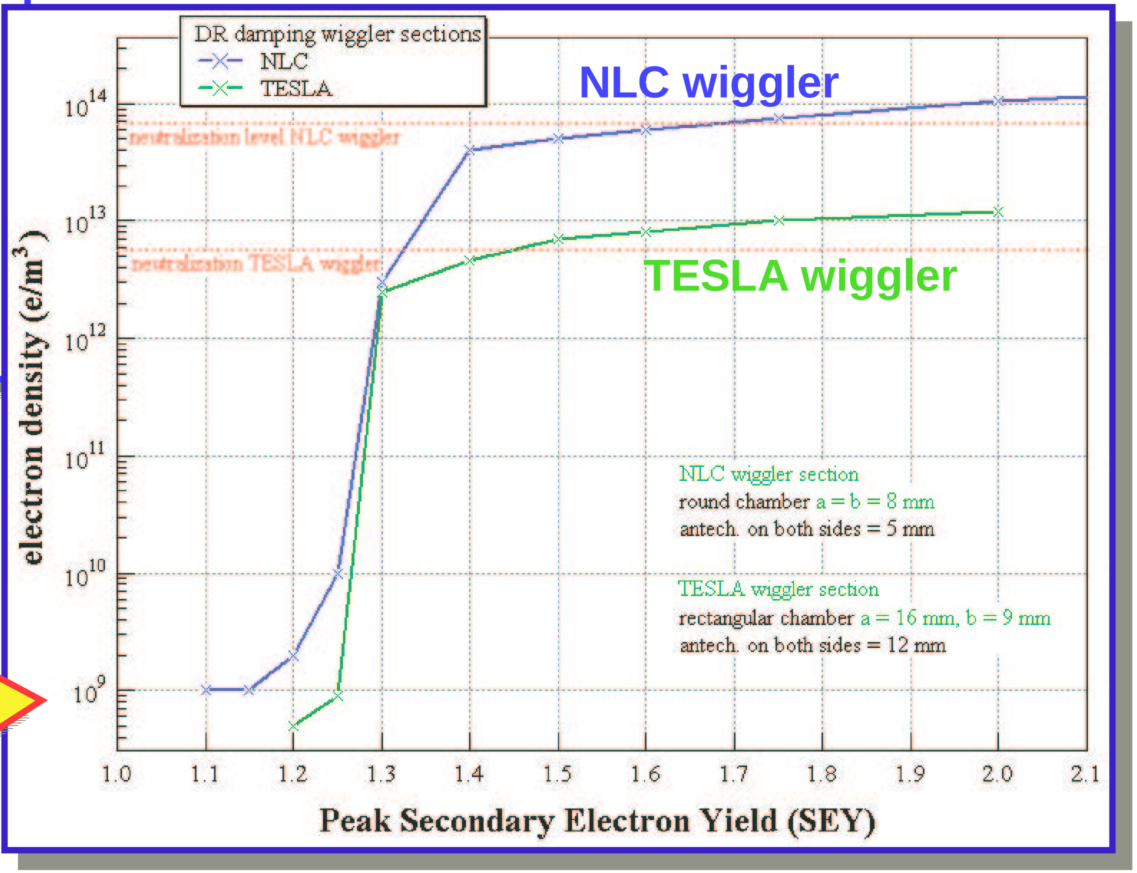
Electron distribution in wigglers





Snapshot of the transverse x-y phase space electron distribution in the TESLA wiggler

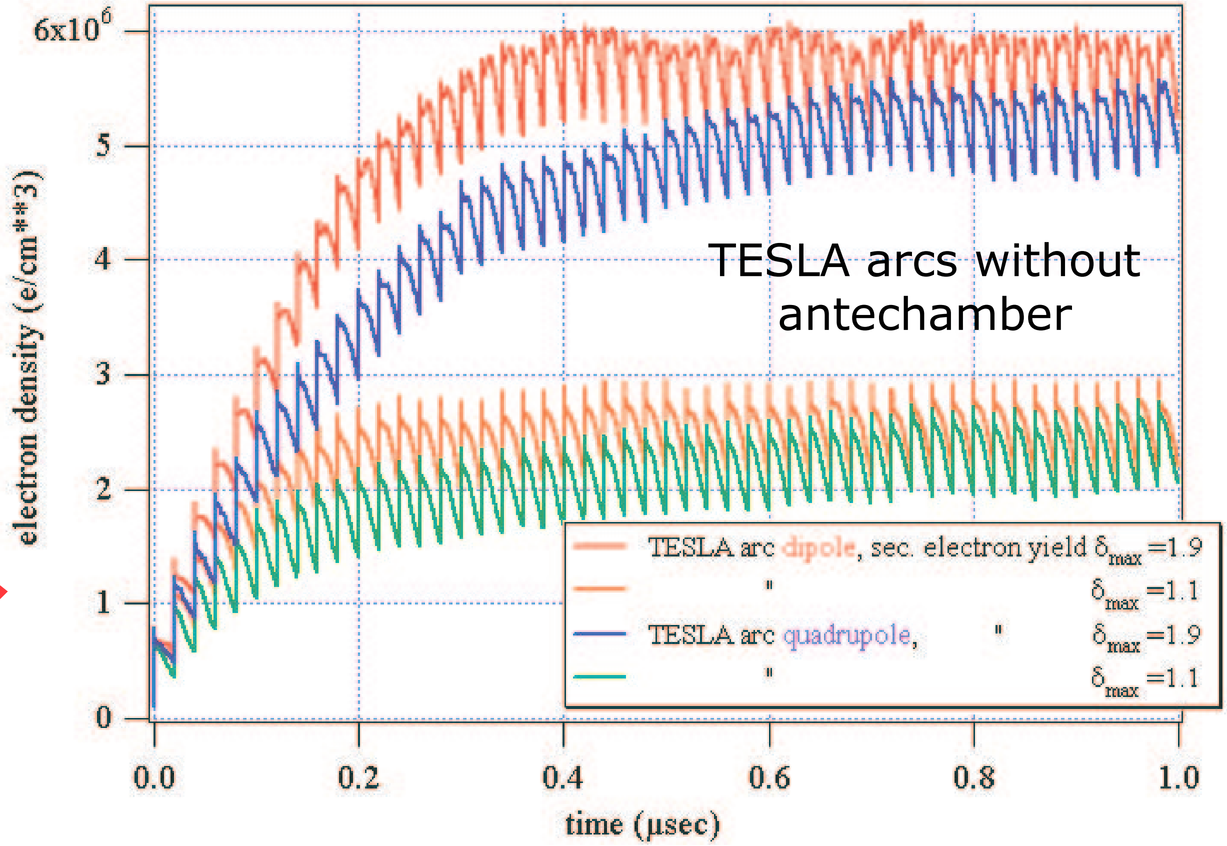
- **Equilibrium density in the NLC and TESLA damping wiggler sections. Threshold occurs at peak SEY~1.2÷1.3**



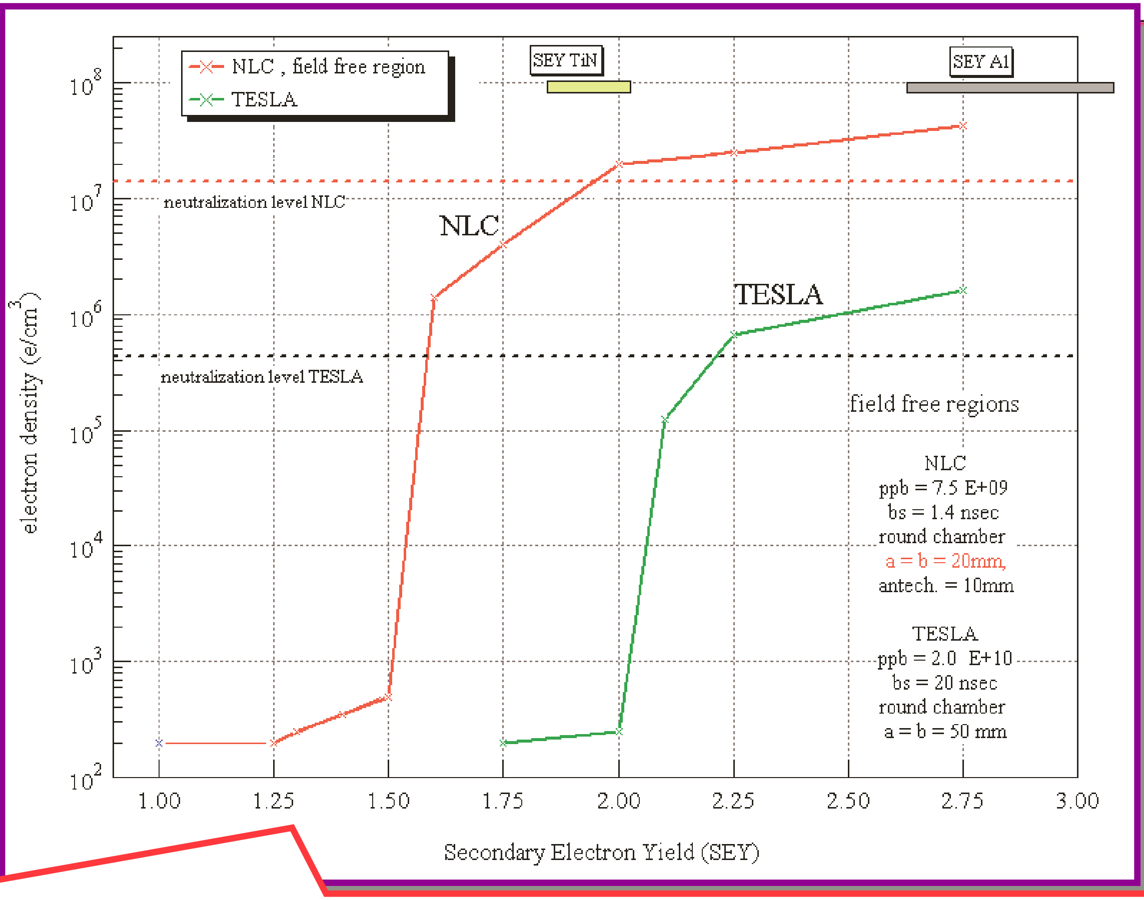
Electron Distribution in the Arcs

- Similarly, threshold in the NLC dipole is for δ_{max}~1.3 ÷1.4 and in arc quadrupole (3D model including fringe fields) δ_{max}~1.2 ÷1.25.
- Note: In quadrupole field regions electron trapping mechanism occurs (mirror effect), electrons are trapped for long time.

- TELSA DR arcs actually without antechamber. Cloud present indipendent of the SEY.
- IF include antechamber design, computed threshold in TESLA dipole (SR OFF) is for δ_{max}~1.4÷1.5.



NLC Field Free and TESLA long Straight Sections



- Threshold for the development of the electron-cloud for NLC field free and TESLA long straight sections

Bunch intensity threshold is 30% below nominal in NLC field free (SR OFF).

Low Emittance Transport Lines:
from the Damping Ring to the Interaction Point

- In the positron transport lines to the IP, electron cloud generation is only expected to be an issue for the normal conducting colliders GLC/NLC where the bunches are closely spaced, 1.4 ns, and not for TESLA where the bunch spacing is 337 ns.

- In the GLC/NLC transport lines, the peak electron cloud density is a strong function of the vacuum chamber radius as well as the SEY.

  By decreasing the SEY to 1.5 or increasing slightly the vacuum chamber radius, the peak cloud density can be reduced to acceptably low values. However, the effects of photoelectrons must still be taken into account.

Conclusions so far on the cloud generation

Electron cloud:

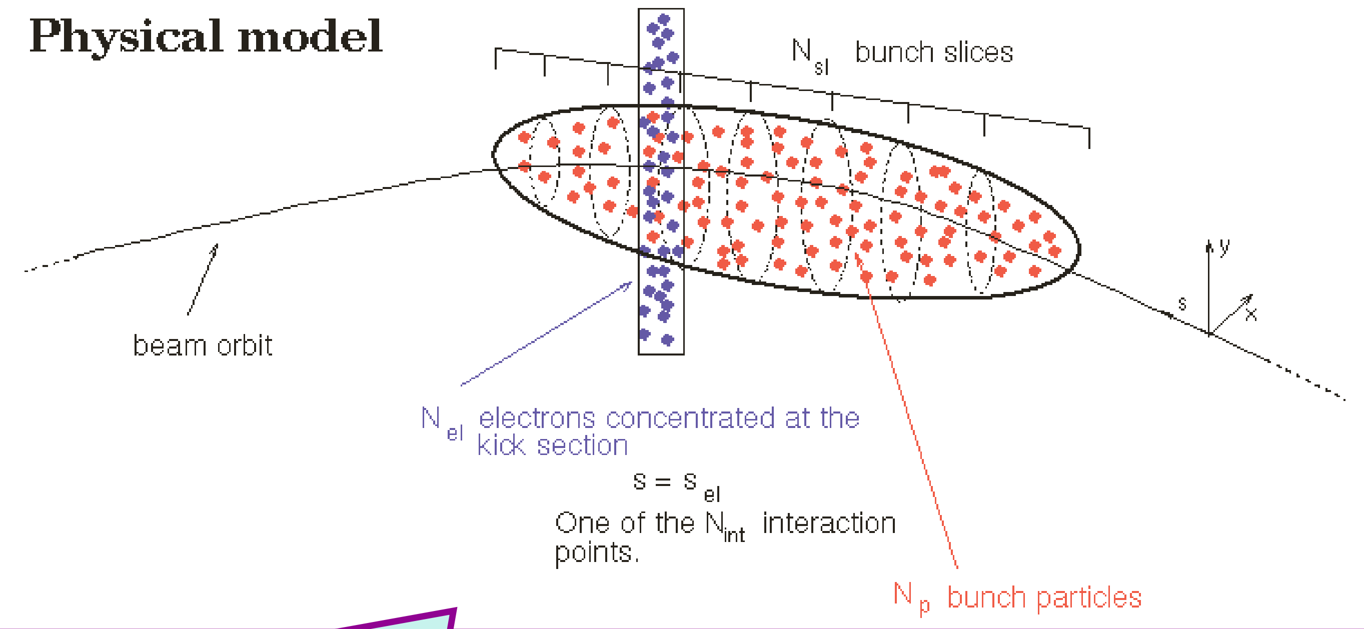
1) NLC Ramping Ring and low emittance transport lines to the IP

2) TESLA damping ring: arcs and wigglers (not in long straight sections provided SEY<2.0)

Electron Cloud in Linear Collider

1. Simulations: generation of the cloud (POSINST)
2. Simulations: single-bunch fast head-tail instability (HEAD-TAIL, PEHTS, QUICKPIC, CLOUD_MAD) and coupled-bunch instability (POSINST)
3. Possible remedies

HEAD-TAIL and PEHTS codes description



G. Rumolo at CERN and K. Ohmi at KEK, single bunch interacting with an electron cloud. The electron-cloud density is given, the number of electrons is constant, the electron-cloud is re-initialized at each interaction. PIC calculation, FFT open space.

Used also code developed at SLAC, see talk from Y. Cai. Dynamical slices approach to simulate bunch particles.

HEAD-TAIL and PEHTS codes description

- Cloud and bunch modeled as ensemble of macroparticles. Bunch is also divided in N_{sl} slices.
  - typ. 100.000 e^- and 300.000 e^+
  - typ. N_{sl} =70 bunch slices
- Kick approximation assuming electrons induce a small perturbation (difference with QUICKPIC)
  - cloud localized at $n=0,1,\ldots N_{int}$ positions along the ring. Used $n=1$ to 10.
- Momentum compaction, chromaticity, (space-charge, beam-beam, amplitude detuning) applied on a turn-by-turn basis. Impedance represented by the broad-band resonator model as a wake function kick at each turn, *not included in these sim.*

$$\frac{d^2\underline{x}_{p,i}(s)}{ds^2}+\underline{\underline{K}}(s)\underline{x}_{p,i}(s)=\frac{e}{\gamma m_p c^2}\sum_{n=0}^{N_{\text{int}}-1}\underline{E}_e[\underline{x}_{p,i}(s);\,f_e(x,y,t)]\,\delta(s-ns_{el})$$

$$\frac{d^2\underline{x}_{e,j}(s)}{dt^2}=-\frac{e}{m_e}\left(\underline{E}_p[\underline{x}_{e,j};\,f_{p,SL}(x,y)]+\frac{d\underline{x}_{e,j}}{dt}\times\underline{B}_{ext}\right)$$

Interaction between bunch particles and cloud electrons

Transverse phase space coordinates of the generic bunch macrop. are transformed over one turn:

$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix}=\boldsymbol{M}_1(\delta p)\boldsymbol{M}_2(I_x,I_y)\left[\boldsymbol{M}_{sc}(z)\begin{pmatrix} x_n-\overline{x}(z) \\ x'_n+\Delta x'_{EC,Z}-\overline{x}'(z) \end{pmatrix}+\begin{pmatrix} \overline{x}(z) \\ \overline{x}'(z) \end{pmatrix}\right]$$

Strong and regular head-tail

- Wakefields generated by betatron oscillations of the head of the bunch can drive oscillations in the tail. With high beam current this can lead to instability. In a two macroparticle model:

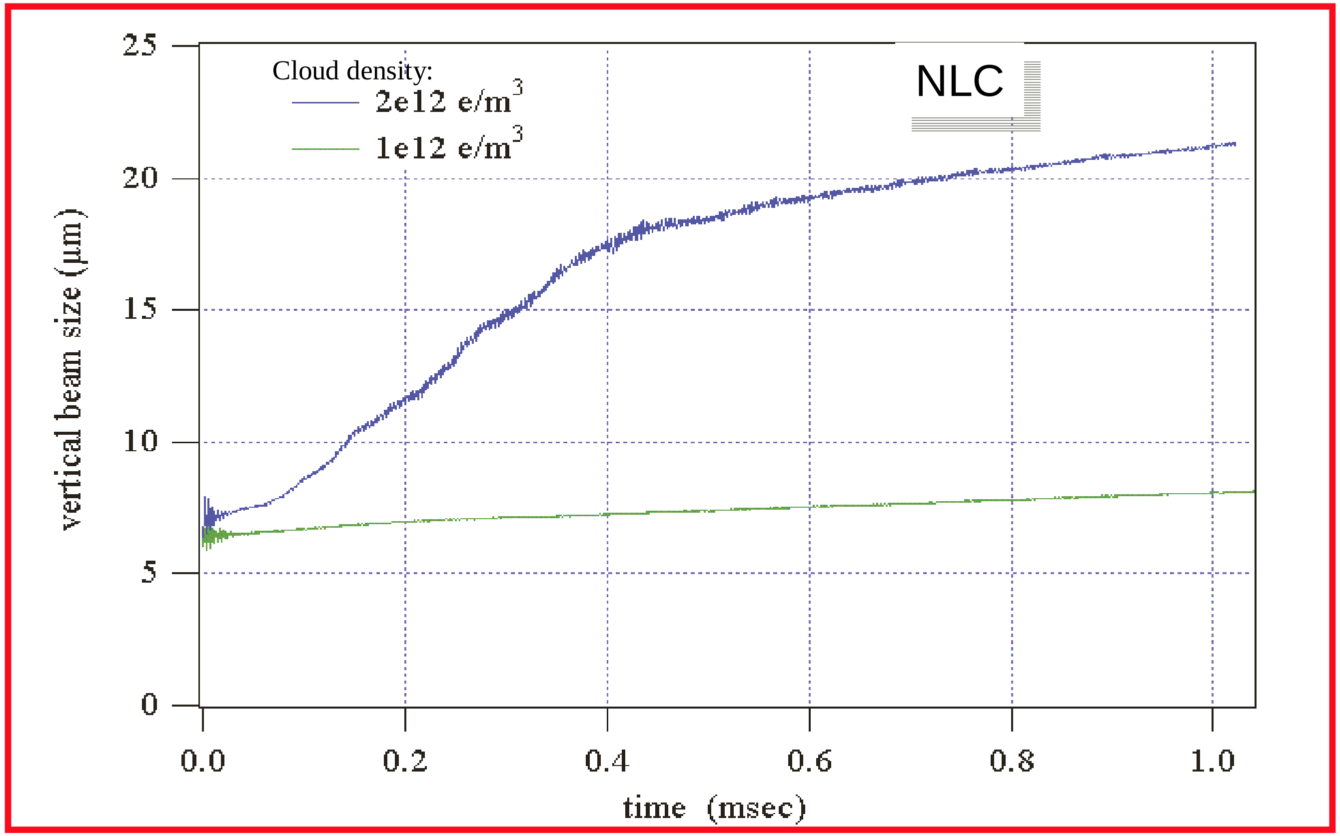
$$I_0 < \frac{4\pi \, {}^{E}\!/_{e} \, \omega_0 Q_\beta Q_s}{c\left|\mathrm{Im}\, Z_\perp\right|}$$

- In the absence of synchrotron oscillation or for Qs→0, the beam is always unstable, since the tail is continuously driven by the head, and the amplitude of oscillation will increase without limit.
- If one include the chromaticity (*ξ=ΔQ/Q/ Δp/p)* the growth rate of the head and tail oscillation mode is given by

$$\frac{1}{\tau} = \frac{\sigma_l \omega_0 I_0 \,\mathrm{Im}(Z_\perp)}{2\pi^2 \, {}^{E}\!/_{e} \, \eta\beta Q_\perp}\xi$$

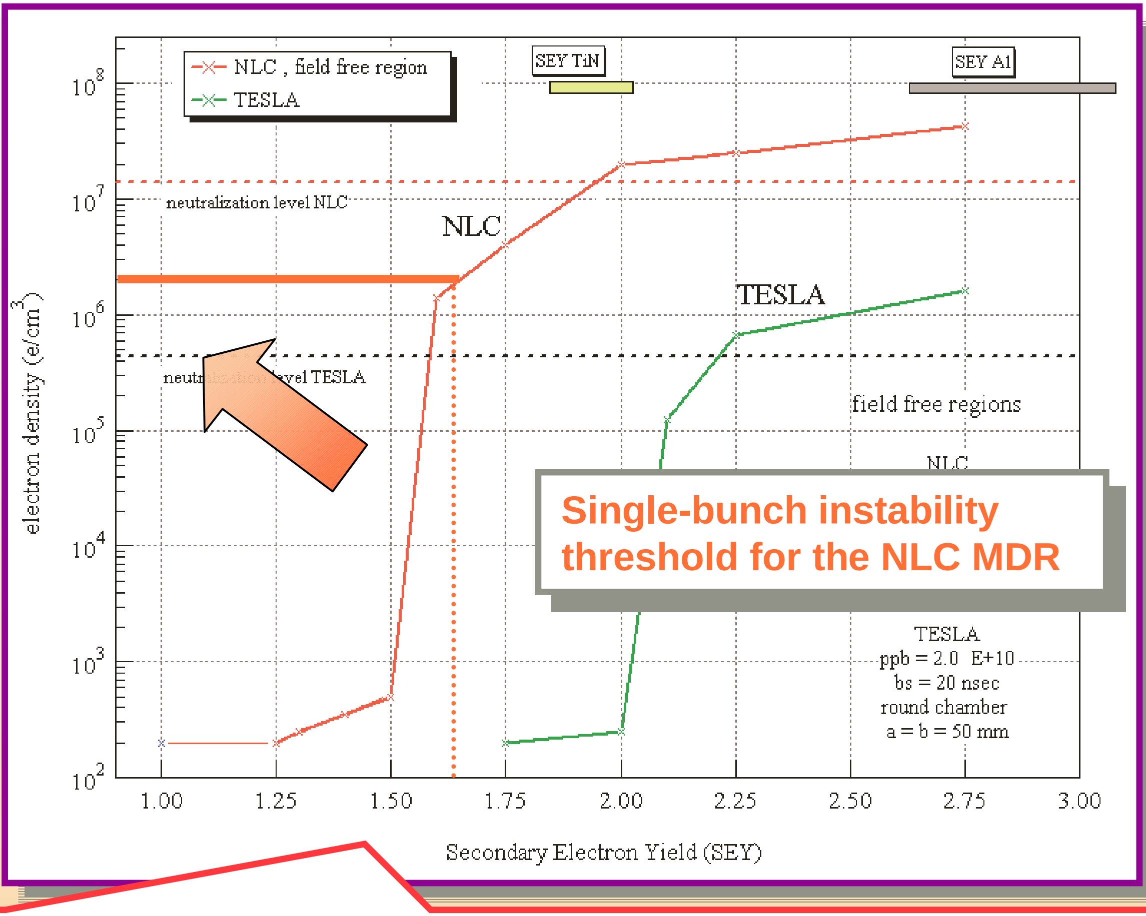
→ need to correct the natural (negative) chromaticity to zero.

Single-bunch instability: NLC



Simulation of single-bunch beam instability from electron cloud in GLC/NLC Damping Ring. Threshold confirmed by PEHTS code.

NLC field free and TESLA long Straight Sections

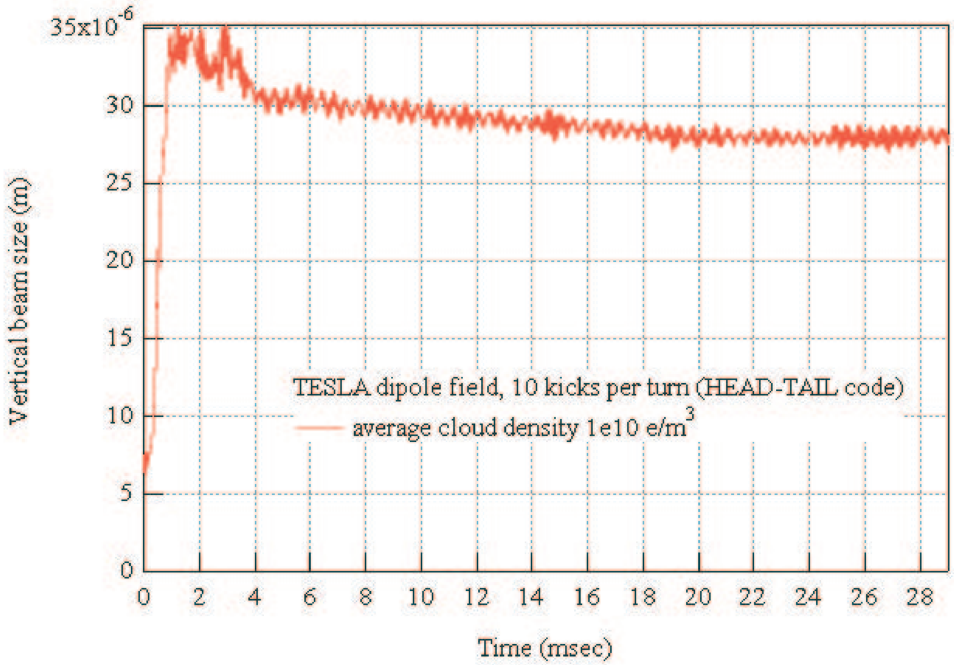


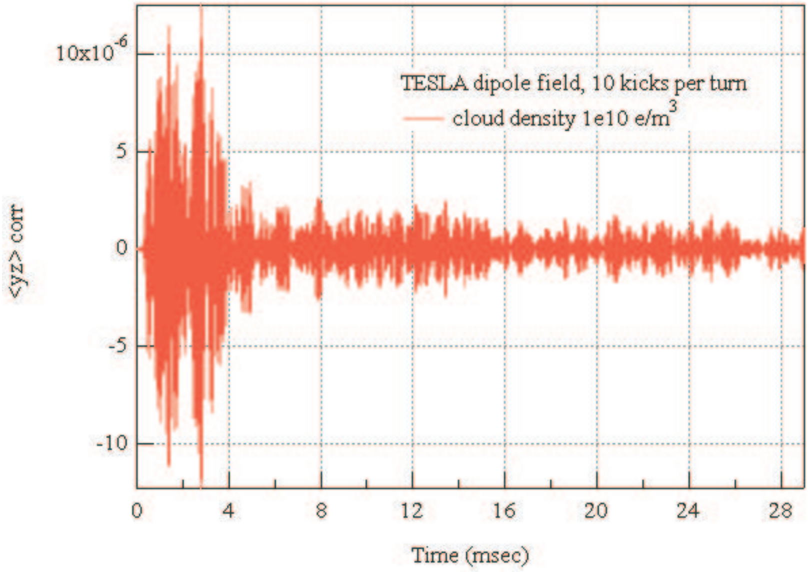
Single-bunch instability threshold for the NLC MDR

- Threshold for the development of the electron-cloud head-tail instability in the NLC field free region is at ~2E+12 e/m^3 occuring for a peak SEY δ_{max}~1.5÷1.6.

Single-bunch instability: TESLA

Multiple kicks per turn (10) and av. cloud density 1e10 e/m^3.
Note synchrotron tune = 0.0659, ring 17 km.





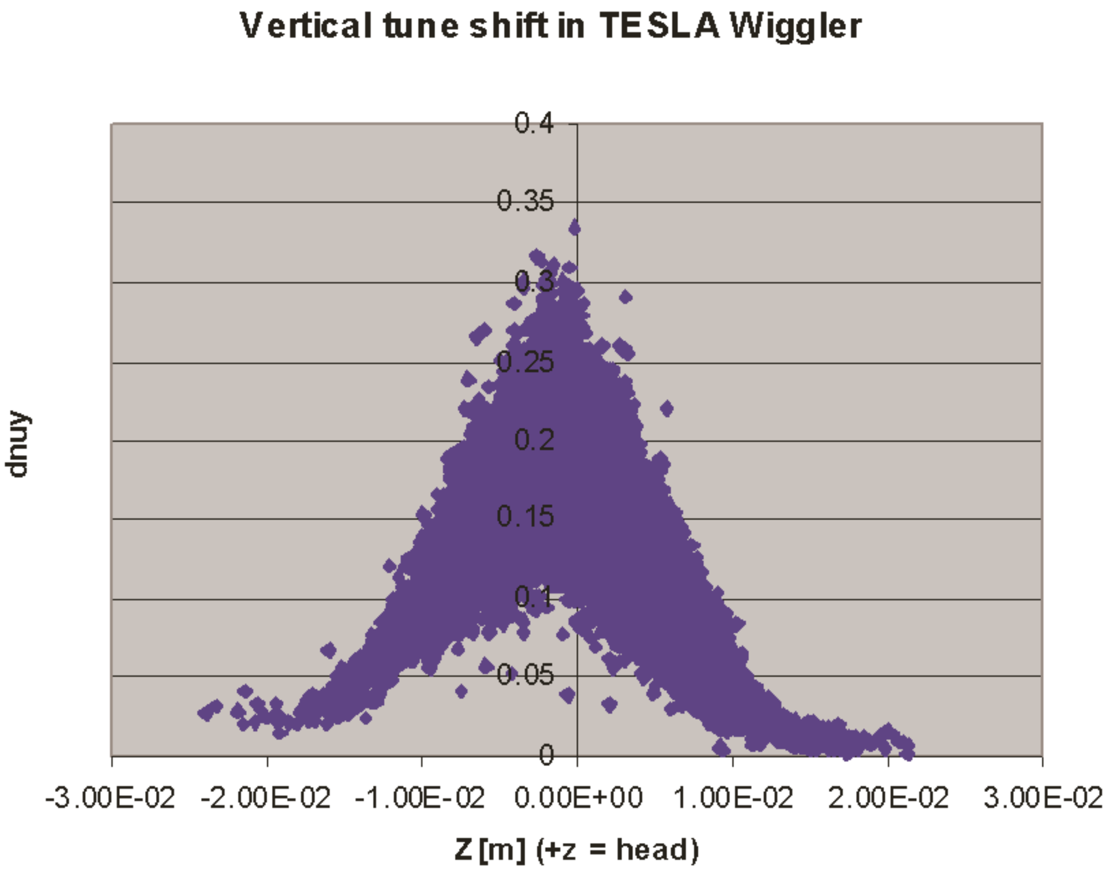
Beam size

<yz> correlation

Strong beam losses

We are increasing no. interaction points per turn with QUICKPIC

Incoherent tune shift in TESLA wiggler



Vertical tune shift after passing through the TESLA wiggler beam line which has 432 meters of wiggler in 520 meters of beam line. An electron cloud density of 6e12 e-/m^3 was assumed. No magnetic field was included.

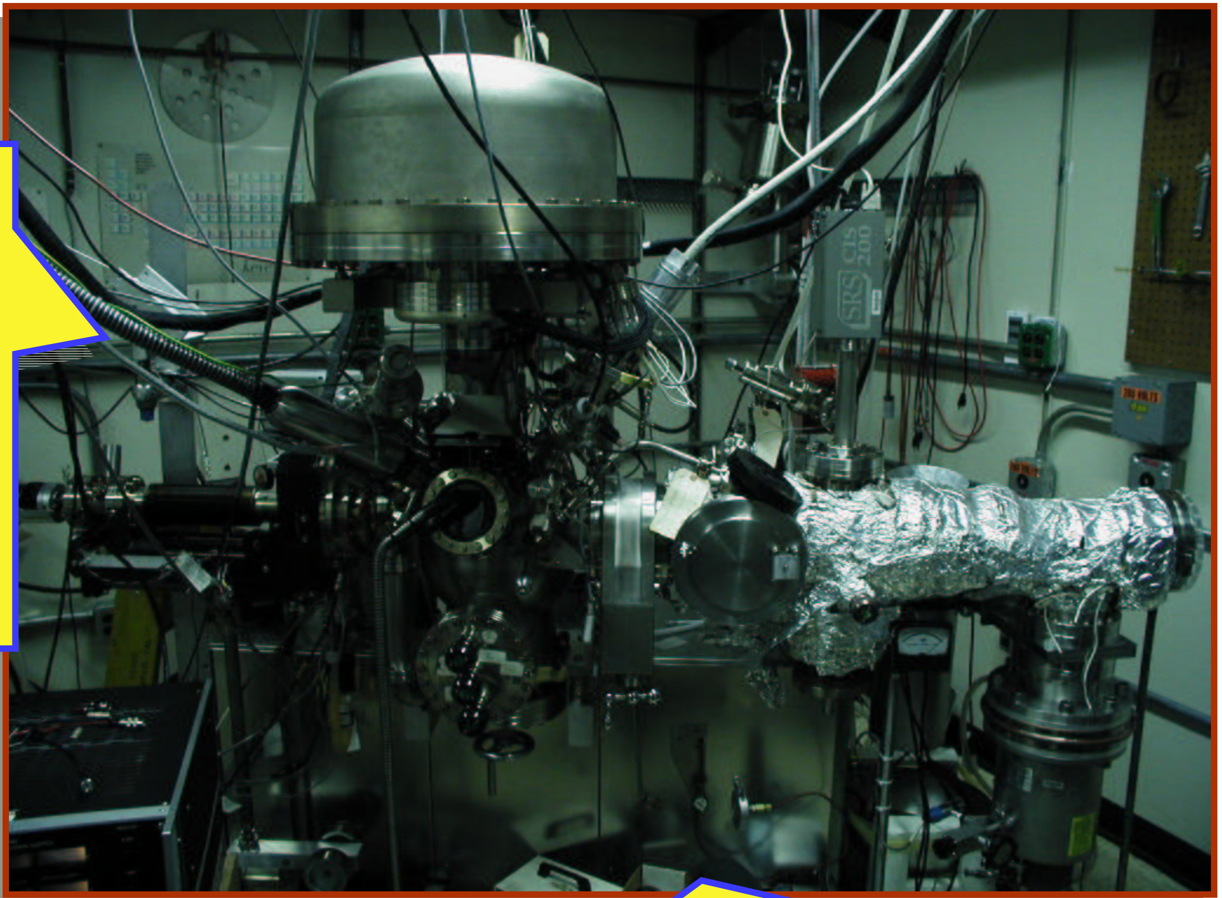
Electron Cloud in Linear Collider

1. Simulations: generation of the cloud (POSINST)
2. Simulations: single-bunch fast head-tail instability (HEAD-TAIL, PEHTS, QUICKPIC, CLOUD_MAD) and coupled-bunch instability (POSINST)
3. Possible remedies

Secondary Electron Yield Measurements and Surface Analysis at SLAC

Secondary Electron Yield (SEY) and secondary energy spectrum measurements. *In situ* Auger, XPS (surface characterization).

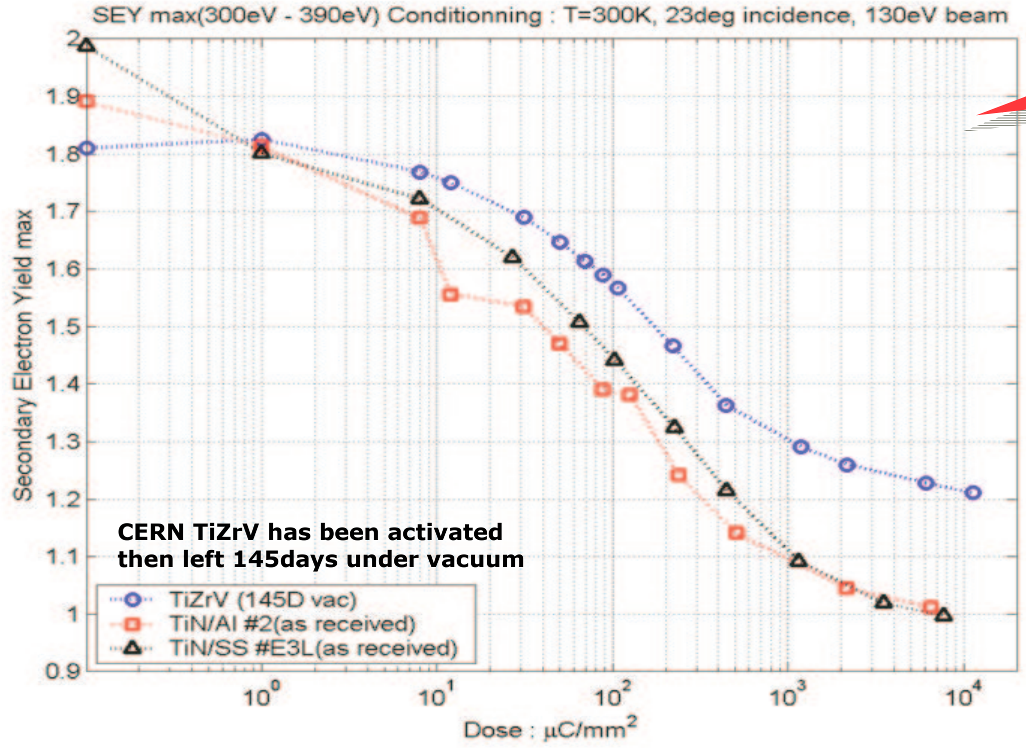
R. Kirby, F. Le Pimpec, M. P. at SLAC, A. Wolski, K. Kennedy, L. Koth at LBNL



Test promising remedies:

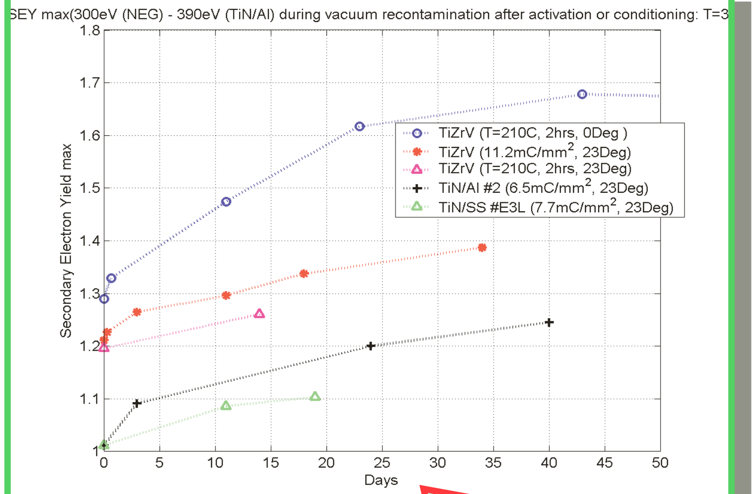
- TiN coating. Goal: reproducible results.
- TiZrV not evaporable getter NEG coatings (SAES, CERN, LBNL)
- Electron and ion conditioning

Electron conditioning for coatings material



CERN TiZrV has been activated then left 145days under vacuum

Electron conditioning



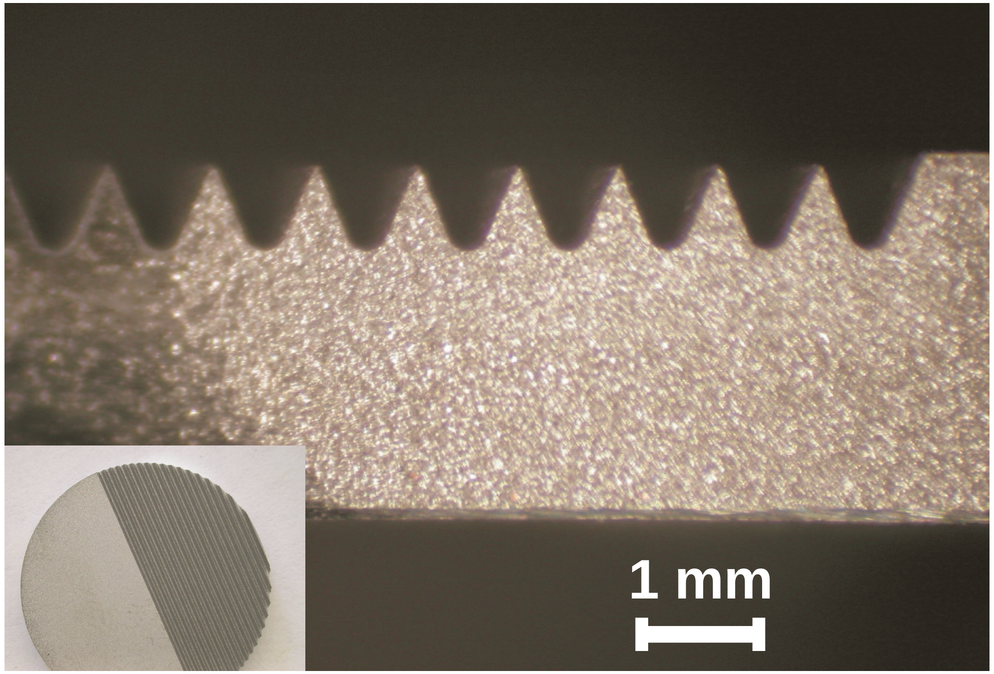
TiN and TiZrV surface recontamination under vacuum

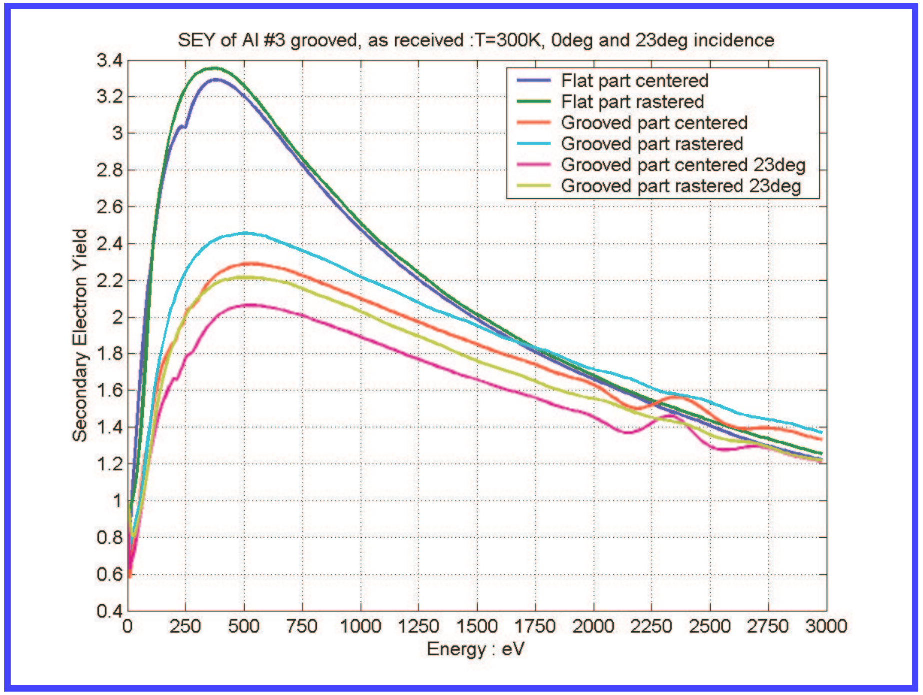
- Based on laboratory measurements, simulations estimates show that the required conditioning dose in NLC DR is achievable in few hours of beam operation during commissioning.
- Concerns about coatings durability and effective conditioning time in accelerator → PEP-II, KEKB, PSR …

Groove surface profile design

G. Stupakov (see also Krasnov, CERN LHC Proj Rep)

Artificially increasing surface roughness.





Special surface profile design. Al 6063.

Preliminary results.
Secondary Yield reduction ~35%

Preparing to measure copper sample with rectangular groove

Summary

- The electron-cloud effects through the Damping Rings to the Interaction Point have been evaluated
- Build up of the electron cloud will be prevented by treating the vacuum chambers
- Investigations of surface treatments include:
  - Measurement of the secondary electron yield of TiN and TiZrV NEG thin film coatings
  - Testing the effectiveness of electron or ion conditioning
  - Fabrication of specially grooved chamber surfaces
- A demonstration chamber will be installed in PEP-II