Detailed Electron Cloud Modeling Using CMAD

M. Pivi

PAC09

Vancouver, Canada

4-8 May 2009

Electron cloud in a nutshell

- Photons and beam residual gas ionization produce primary e-
- Number of electrons may increase/decrease due to surface Secondary Electron Yield (SEY) → number of secondary electrons per incident electron.
- Bunch spacing determines the survival of the electrons

Electron cloud in a nutshell

- Especially strong effect and possible consequences:
  - Single-bunch and Coupled-bunch instability
  - Emittance increase
  - Luminosity reduction
  - Vacuum pressure and excessive power deposition at walls (load on LHC cryogenic system)
- In summary: the electron cloud effect (ECE) is a consequence of the strong coupling between the beam and its environment:
  - many ingredients: beam energy, bunch charge and spacing, secondary emission yield, chamber size and geometry, chromaticity, photoelectric yield, photon reflectivity, …

The electron cloud has been observed / is expected at:

- PSR
- B-factories PEP-II, KEK-B
- DAΦNE
- CesrTA
- LHC complex, SPS, PS2
- Super-B
- Linear Collider (LC) Damping Rings (DR)

Simulation Efforts (LC)

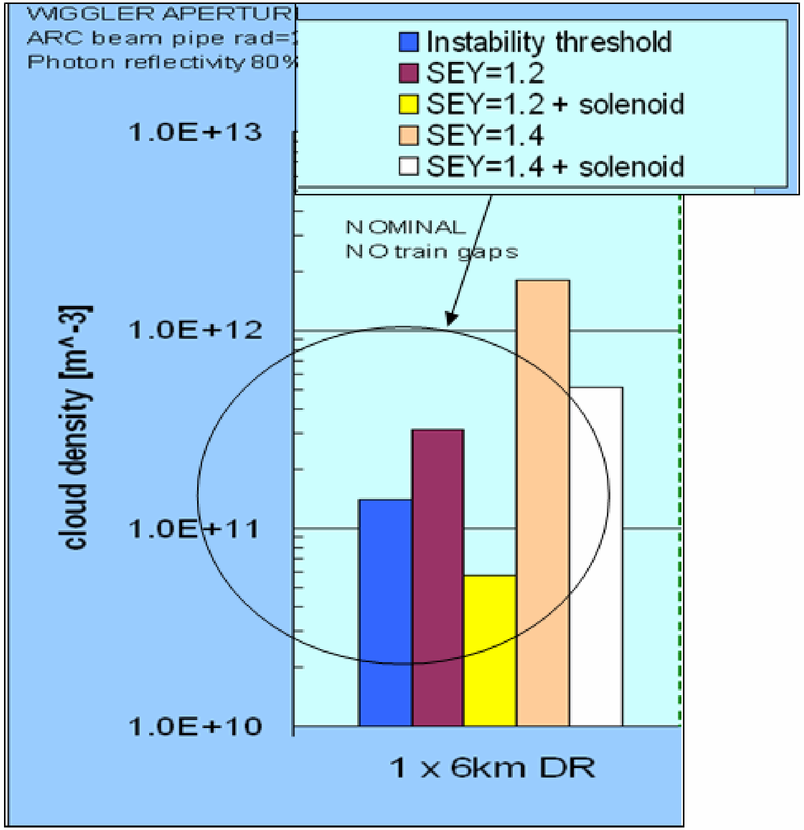
Color code:
Cloud Generation/Build-up code
Instability code

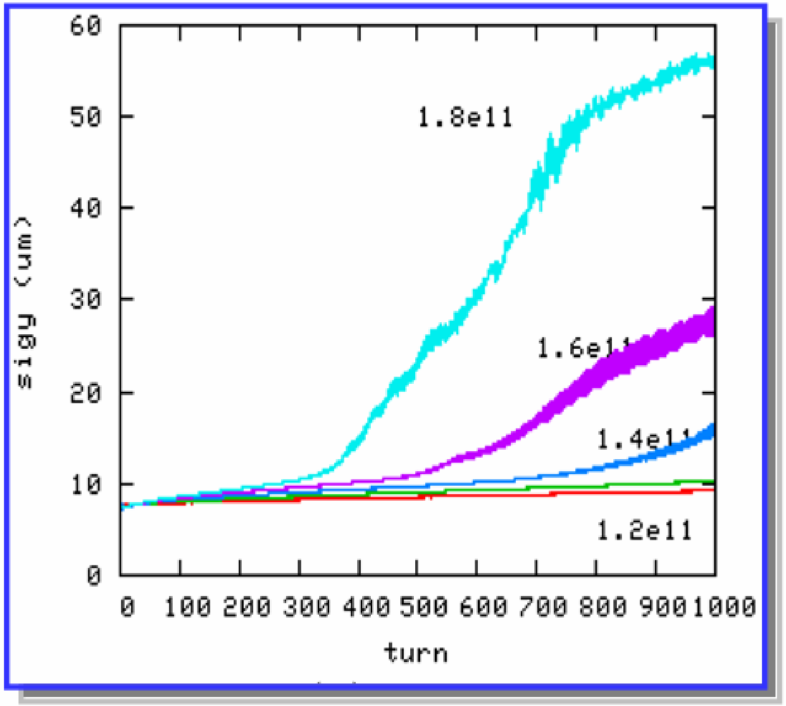
- KEK: PEI and PEHTS K. Ohmi
- LBNL: POSINST M. Furman, M. Pivi, J. Qiang, M. Venturini *et al.*, WARP/POSINST J. L. Vay et al.
- CERN: ECLOUD, FAKTOR2, HEAD-TAIL & (TAIL-HEAD) F. Zimmermann, G. Rumolo, D. Shulte, E. Benedetto, R. Thomas, W. Bruns
- SLAC: CMAD M. Pivi, CLOUD_LAND L. Wang, POSINST

Other used codes: ORBIT (SNS), QuickPIC (USC), COUD_MAD (SLAC), MICROMAP (GSI) ..

ILC DR simulations history: 2006

ILC DR "OCS2" 6.7km Ring design





ILC DR "OCS2". Vertical beam size increase with cloud density, PEHTS code.

Single-Bunch instability threshold (blue bar – see also picture on the right) and simulated ring averages cloud density according to SEY values assumed.

Single-bunch instability mechanisms

- Depending on cloud density beam instability:
  - **Beam break-up rise time τ shorter than synchrotron period: $\tau < T_s$**
  - **Transverse mode coupling instability: $\tau \sim T_s$**
  - **Head-Tail* slower growth rate: $\tau >> T_s$**

*Damping by synchrotron oscillation

See F. Zimmermann: *Review of Single Bunch Instabilities driven by El. cloud*

- Motivations for CMAD:
  - **Include real lattice and sampling the ring beta functions variation (ILC DR demanding …)**
  - **Parallel simulations to deal with many lattice elements and many turns (>1000)**
  - **Study incoherent emittance long-term growth below threshold: "real or numerical?"**
  - **2D forces**
  - **Cloud build-up (not there yet) and instability in the same code**
  - **Use for benchmark with other codes**

Simulation code

- Tracking the beam (x,x',y,y',z,δ) in a MAD lattice by 1^{st} order and 2^{nd} (2^{nd} order switch on/off) transport maps
- MAD8 or X "sectormap" and "optics" files as input
- Apply beam-cloud interaction point (IP) at each ring element
- Parallel bunch-slices based decomposition to achieve perfect load balance
- Beam and cloud represented by macroparticles
- Particle in cell PIC code 9-point charge deposition scheme

Simulation code

- 2D Beam-Cloud forces – FFT O(N log(N)) open space and conducting boundary
- 3D electron cloud dynamics Leap-Frog with Boris-rotation including magnetic fields
- Define at input a cloud density level [$0<\rho<1$] for each magnetic element type

Beam-cloud forces: electric field calculation

- Electric field computed near beam ~10-20 beam sigma
  - **Open space: use Green function method and Fast Fourier Transform FFT in a double gridded domain (*Hockney*)**

Solution of Poisson equation:

$$\phi(x,y) = \int dx'\, dy'\, G(x - x', y - y')\rho_c(x', y'),$$

with

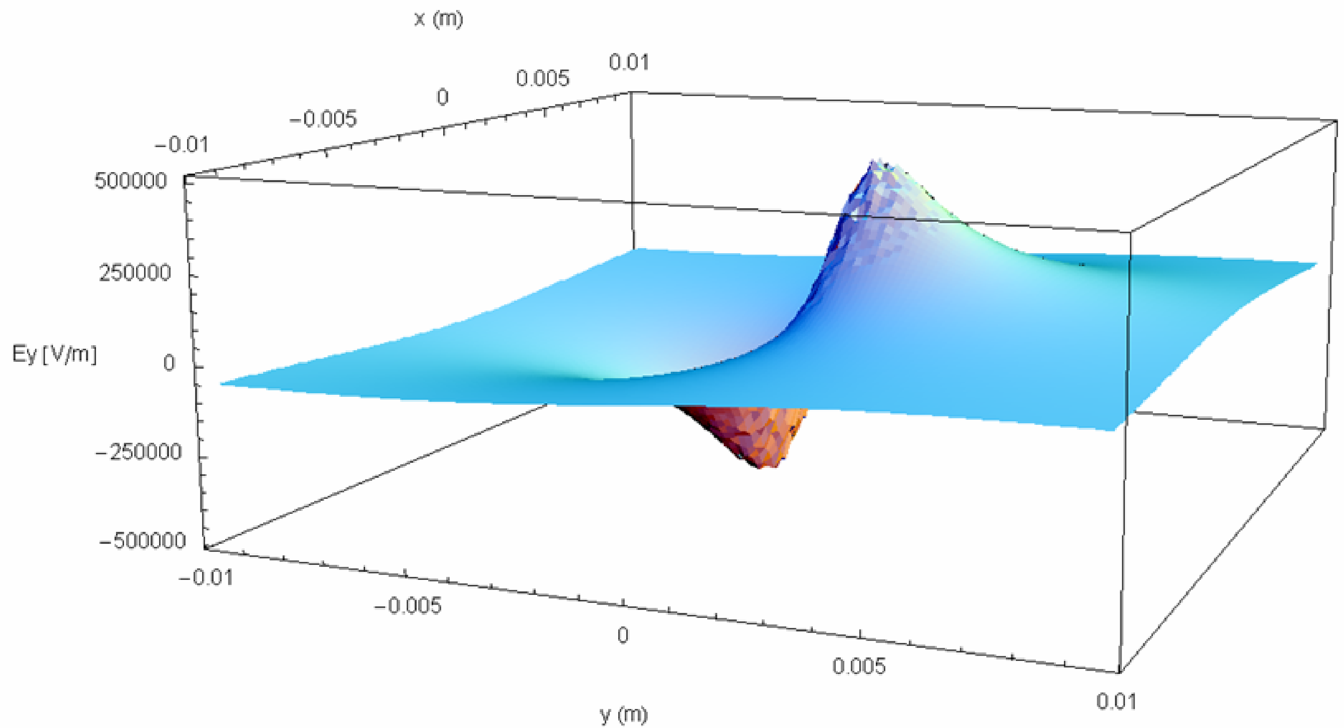
$$G(x - x', y - y') = -\frac{1}{2}\ln[(x - x')^2 + (y - y')^2].$$

and convolution of Fourier transforms

$$\tilde{\phi} = \tilde{G} \cdot \tilde{\rho}$$

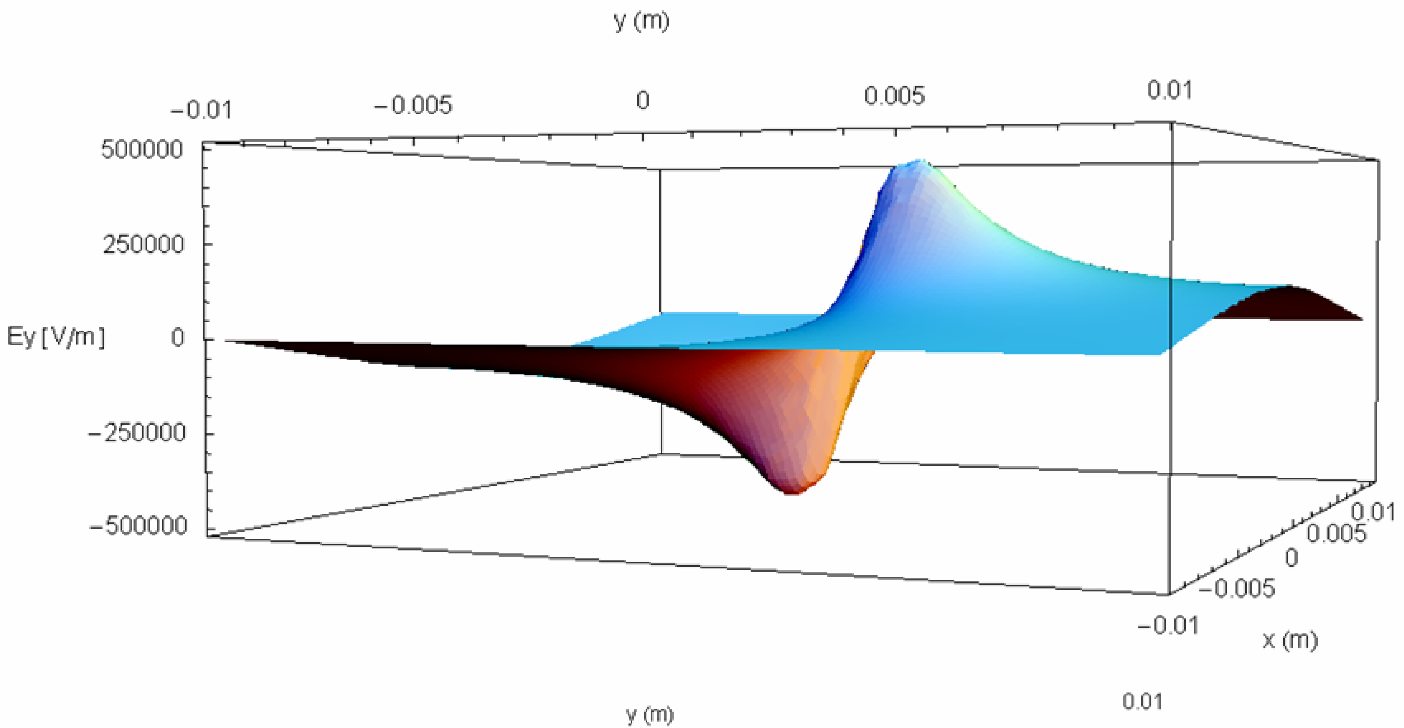
  - **or metallic conducting boundaries at grid domain edges, using FFT method**

Beam-cloud forces: electric field calculation



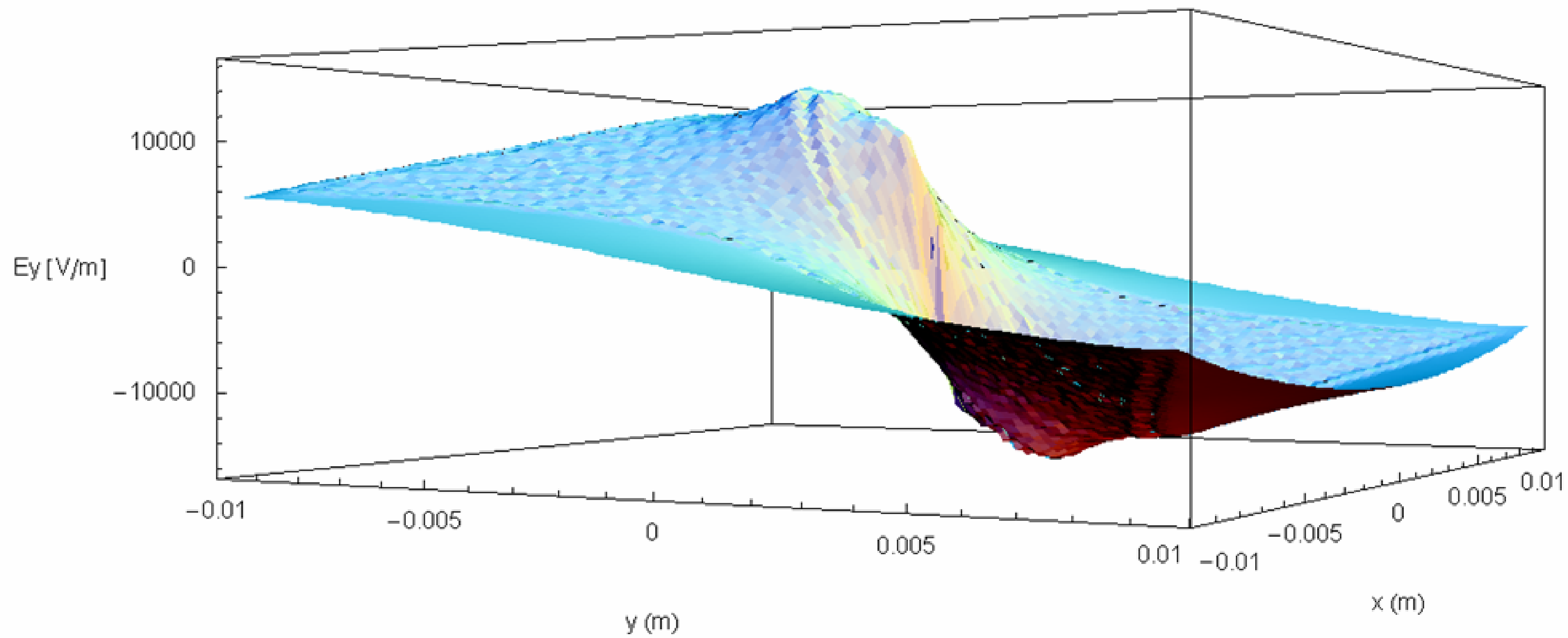
Open space: Beam Vertical electric field using 300000 macroparticles (middle of LHC beam)

Beam-cloud forces: electric field calculation



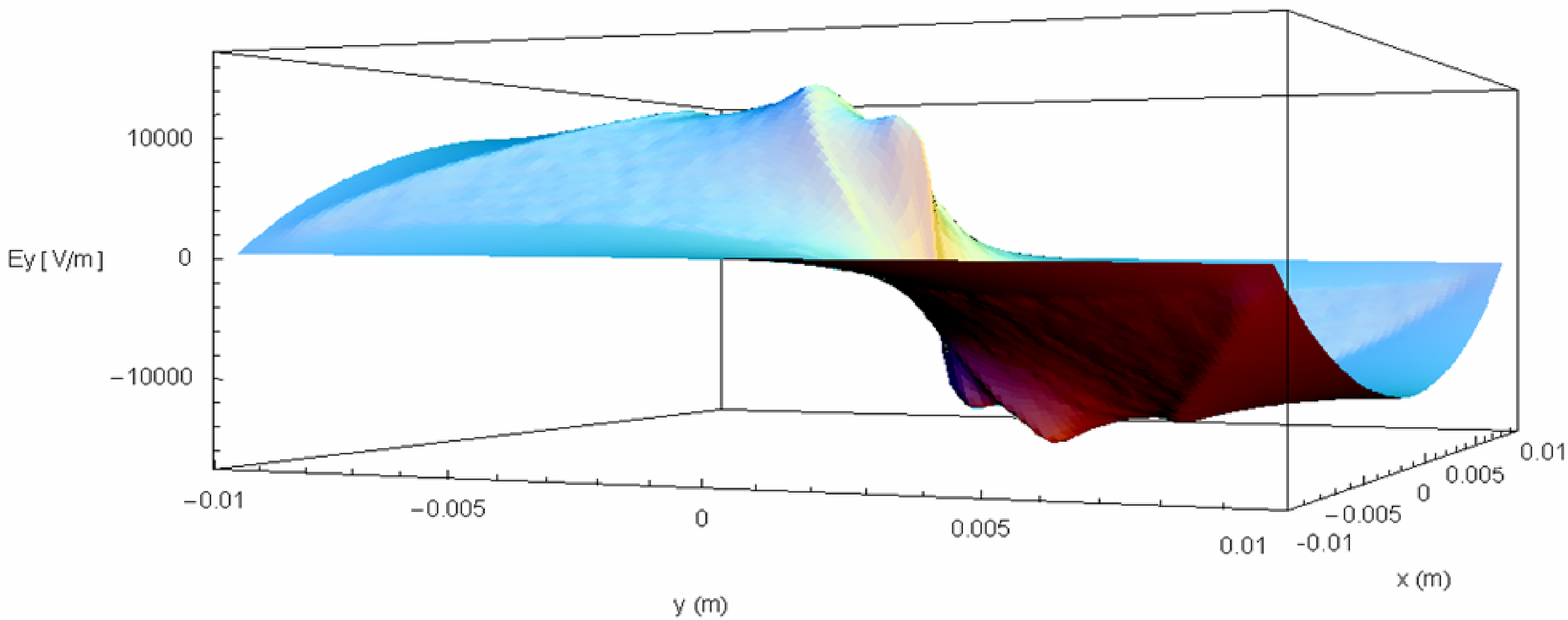
Conducting boundaries: Beam Vertical electric field (middle of LHC beam)

Beam-cloud forces: electric field calculation



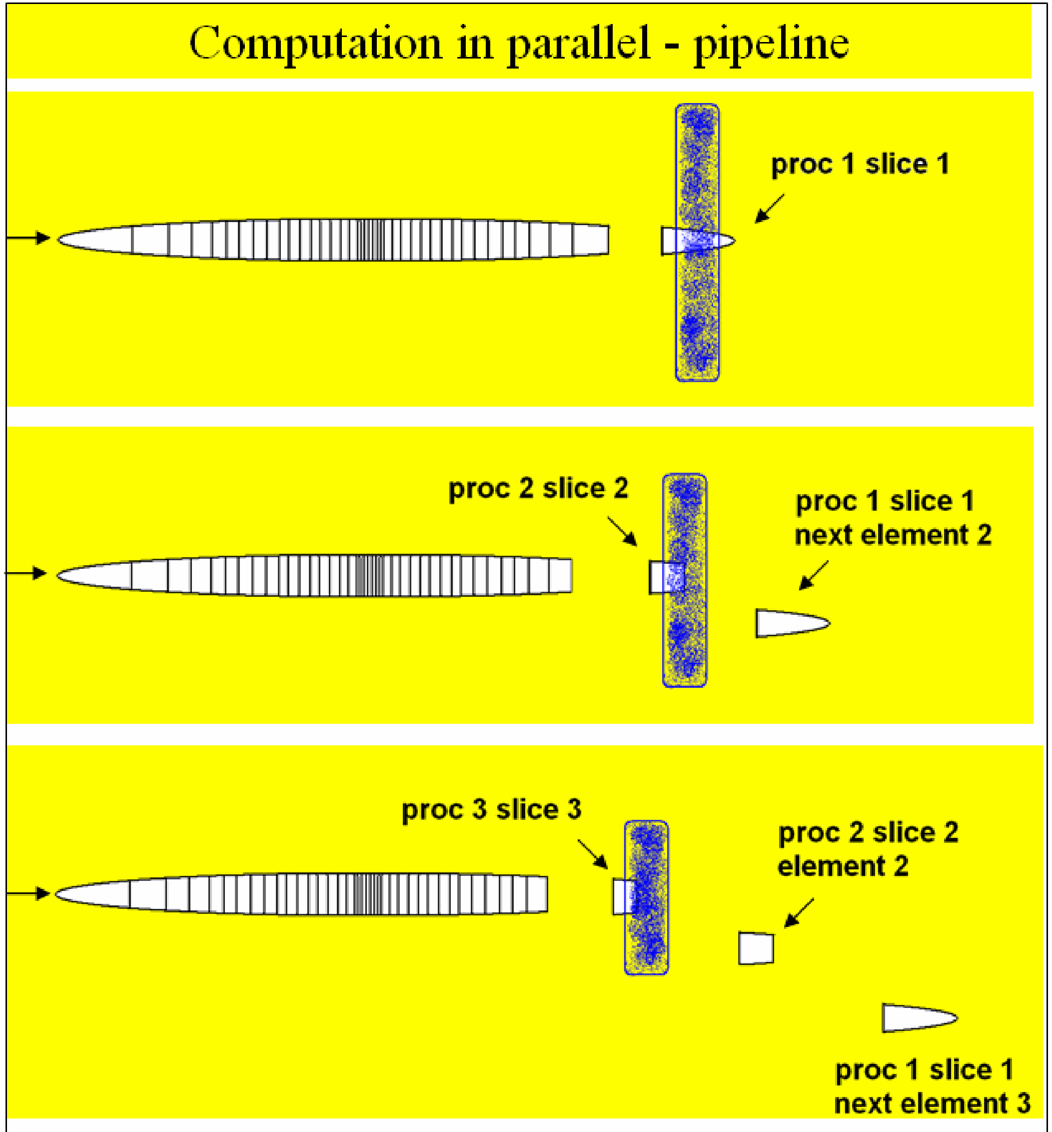
Open space: e- Cloud Vertical Electric field using 100000 macroelectrons (middle of LHC beam)

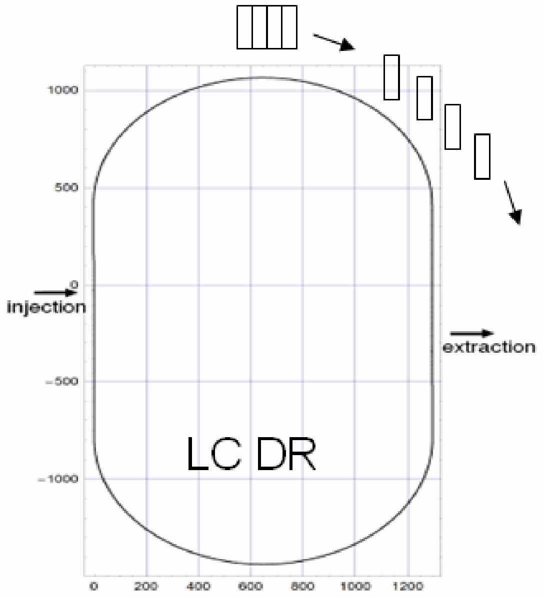
Beam-cloud forces: electric field calculation



Conducting boundaries: e- Cloud Vertical Electric field (middle of LHC beam)

Bunch-slice parallel decomposition

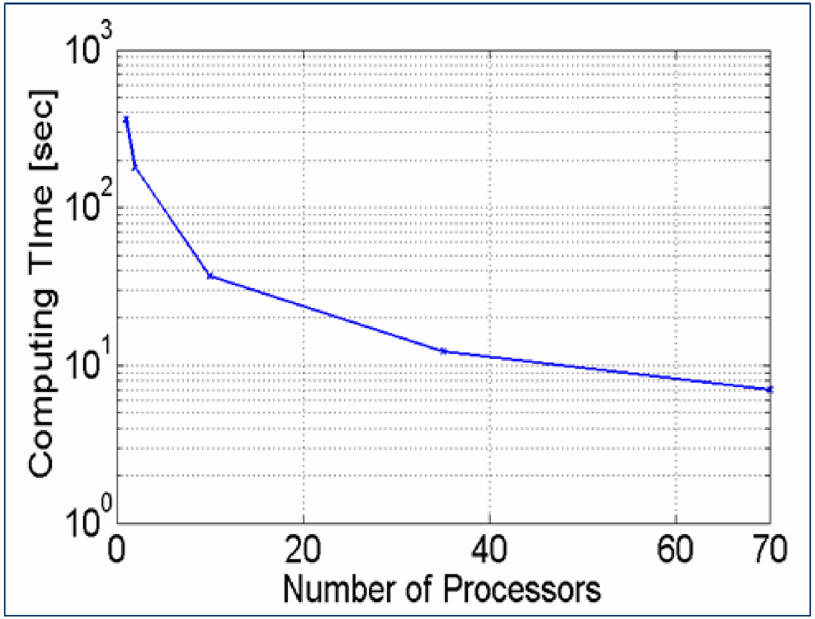


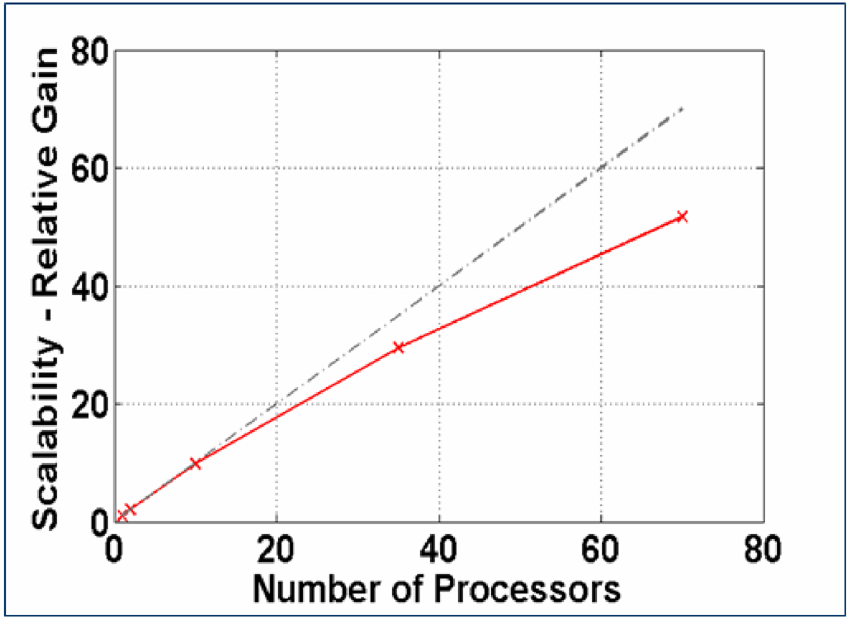


Each processor deals with the bunch-slice, then send cloud information to the next in the pipeline. The last processor print out the beam information. At each turn, 1 processor gathers all particles and give RF-kick.

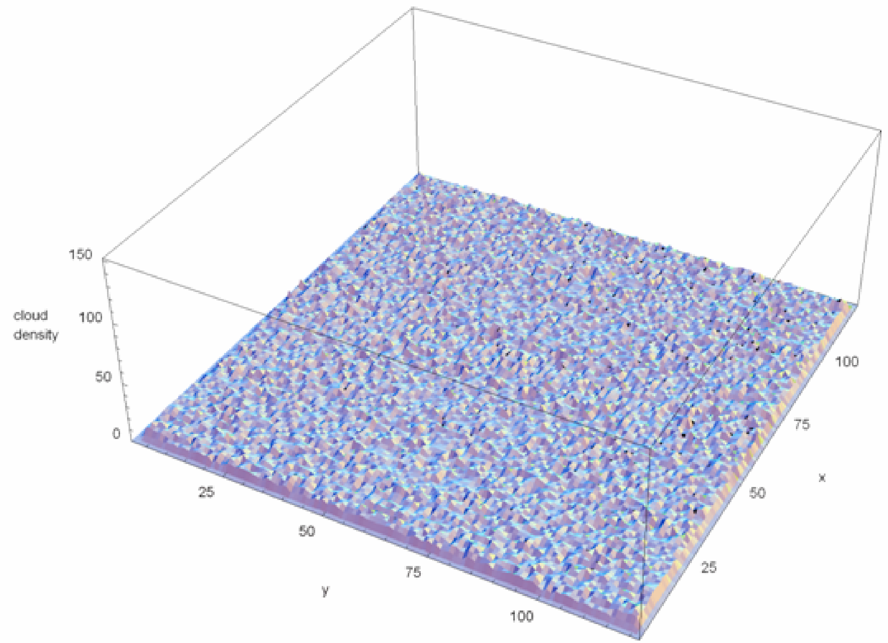
Scalability of parallel computation

- At the moment, the code can use a number of processors up to the number of bunch slices, typically ~70-100.
- Gain ~53 with 70 processors





Computing time (at NERSC) with number of processors, example for 1 LHC turn/100 elements, for simulation parameters: 70 bunch slices, 300,000 macroparticles, 100,000 macroelectrons, 122x122 grid size


150
cloud
density
100
50
0
25
50
y
75
100
x
100
75
50
25

Review of recent codes benchmarking

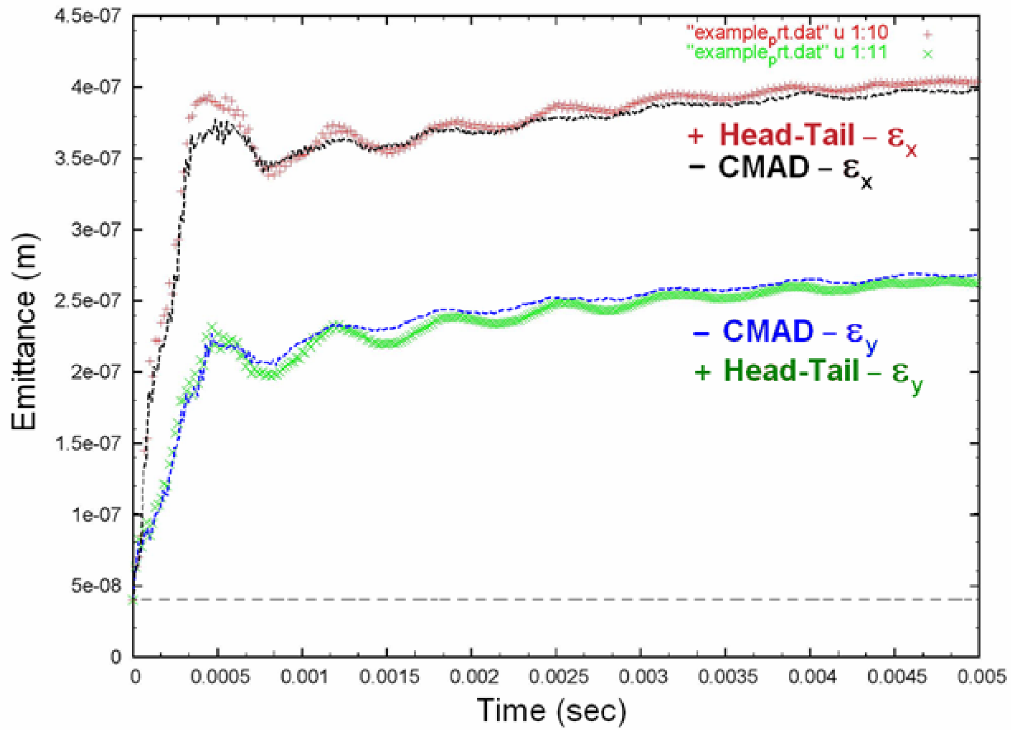
- Compare with Head-Tail (CERN) and WARP (LBNL)
  http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/modelinst.htm

  (CERN page)
- Head-Tail has been benchmarked with other codes, ex . PEHTS (KEK), with good results.

Review of recent codes benchmarking

- Compare with Head-Tail (CERN) and WARP (LBNL)
  http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/modelinst.htm

(CERN page)

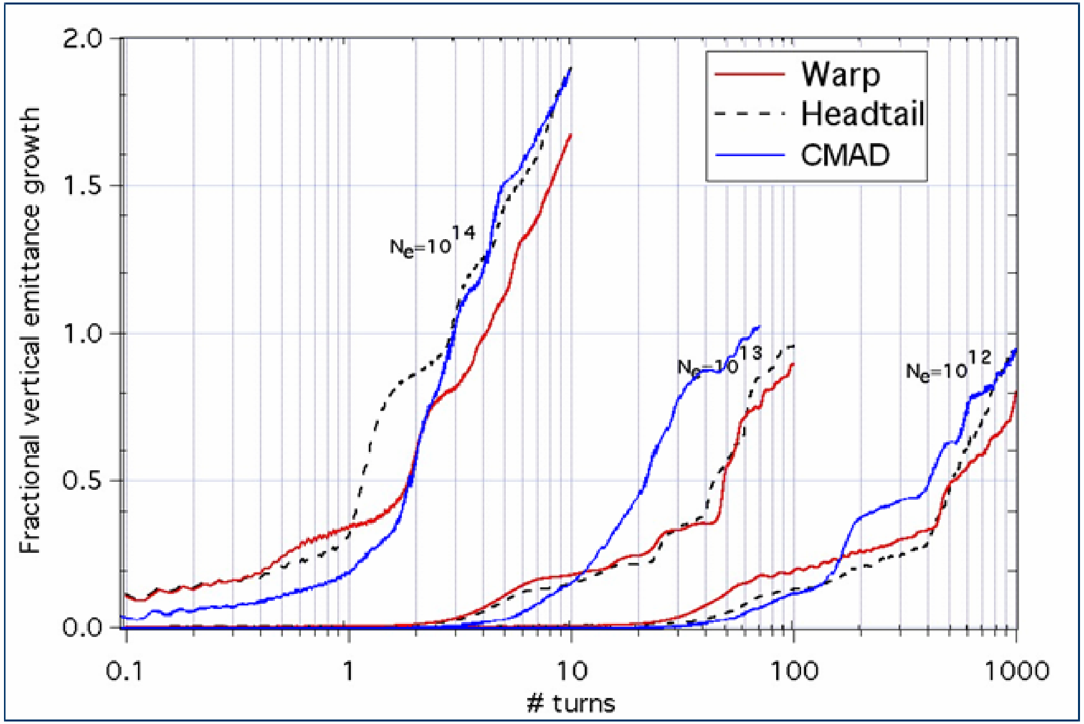


1 beam-cloud IP/turn, SPS with cloud density 1e12m^3. "New 2006 simulations results"

Codes benchmarking

- Compare with Head-Tail (CERN) and WARP (LBNL)
  http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/modelinst.htm

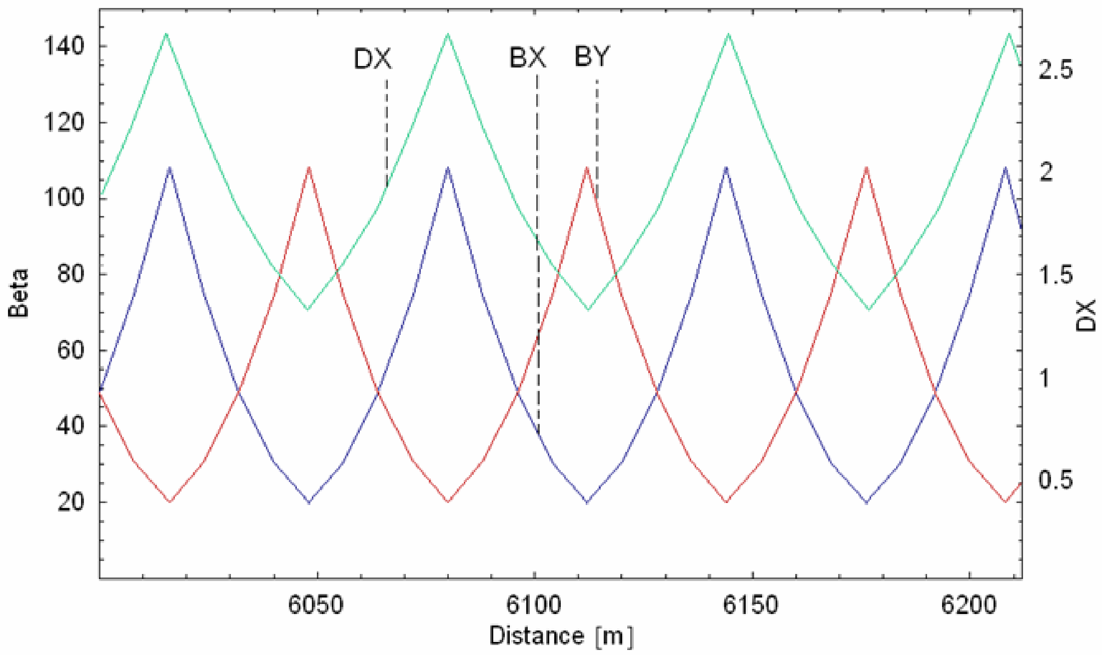
  (CERN page)



Upt to 100 beam-cloud IP/turn. LHC with cloud density 1e12 to 1e14m^-3. 2008 simulations results. Constant beta function. Magnetic free region.

Codes benchamrking
SPS simplified lattice

MADX input SPS simplified lattice beam-cloud IP kicks in ~250 dipoles. Synchrotron tune 5.92e-3. Qx'=Qy'=0.

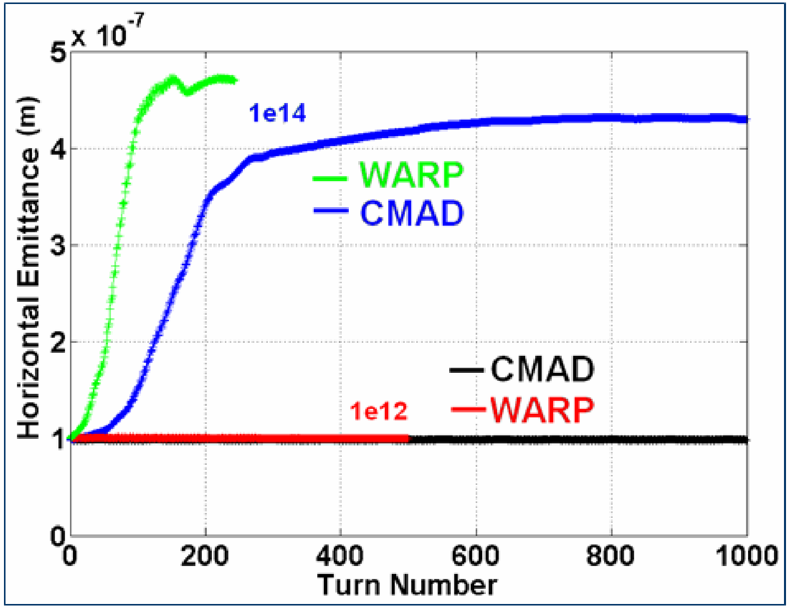


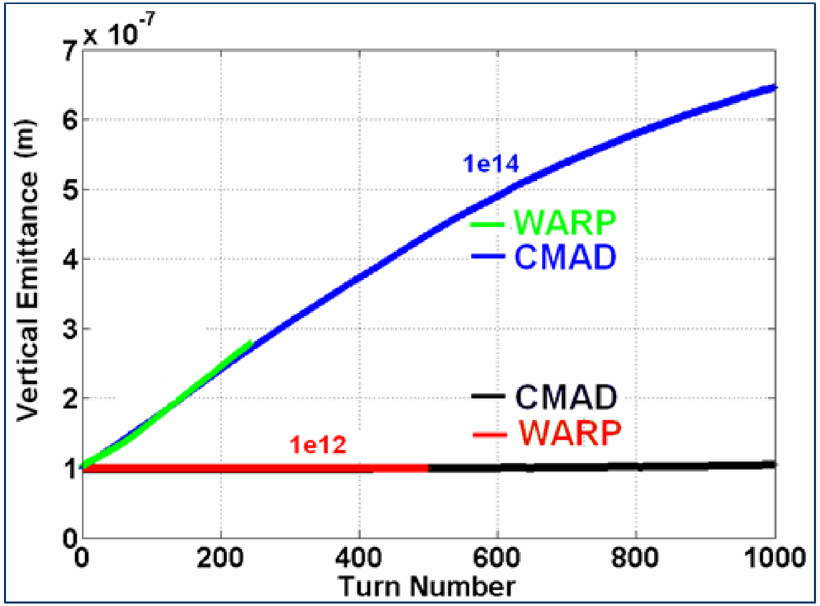
Energy (GeV)	26
Bunch population	1.15e11
Synchrotron tune	0.00592
Emittance (m)	1e-7
σz	0.24
dp	0.003887
α	1.63539
Qx', Qy'	0

Benchmarking proposed by F. Zimmermann; Simplified lattice by R. Thomas.

Codes benchamrking SPS simplified lattice

Tracking the beam in the linear lattice and beam-cloud kicks in dipoles only, assume e-cloud in field free regions is cured (no beam-cloud interaction in drift).

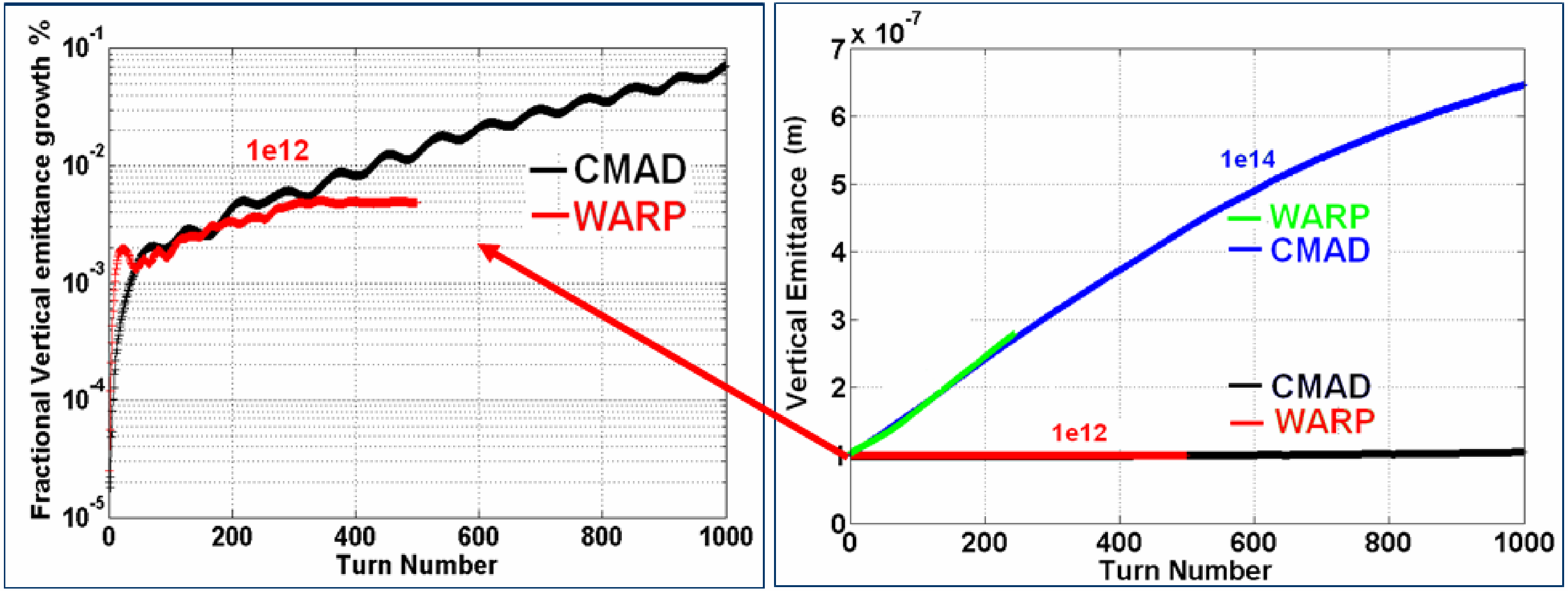




[CMAD run 3.5 hours at rate 13 sec/turn on Franklin/NERSC machine with 64 processors]

Codes benchamrking
SPS simplified lattice

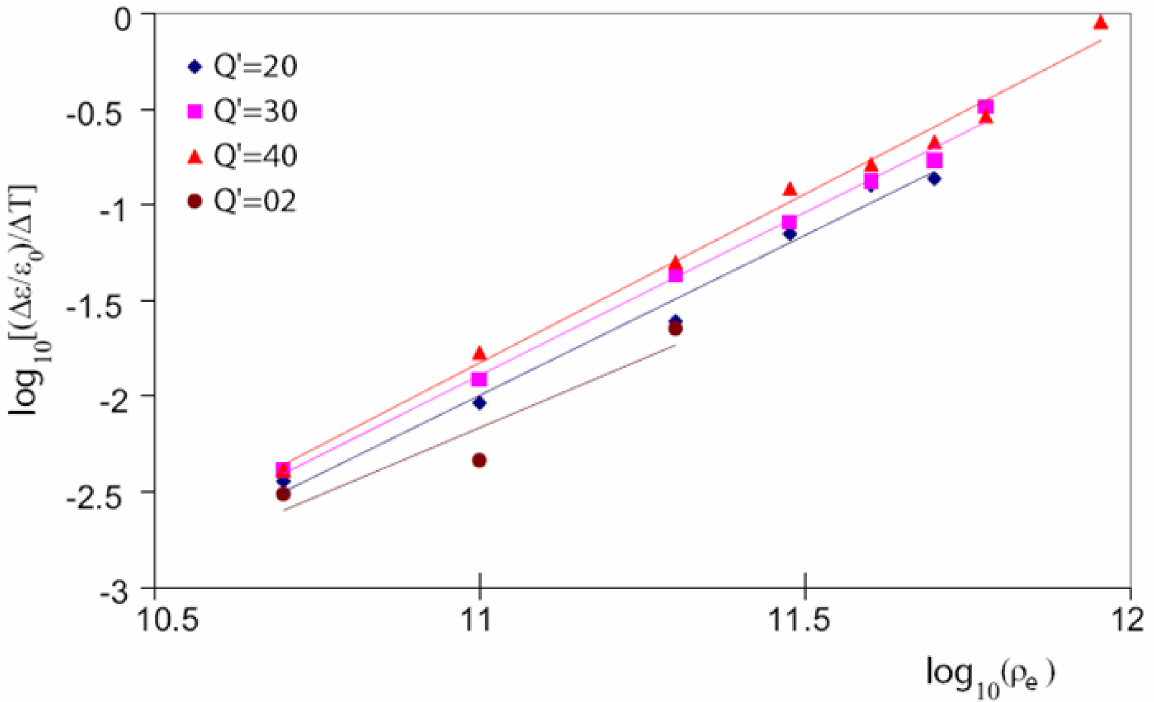
Tracking the beam in the linear lattice and beam-cloud kicks in dipoles only, assume e-cloud in field free regions is cured (no beam-cloud interaction in drift).



[CMAD run 3.5 hours at rate 13 sec/turn on Franklin/NERSC machine with 64 processors]

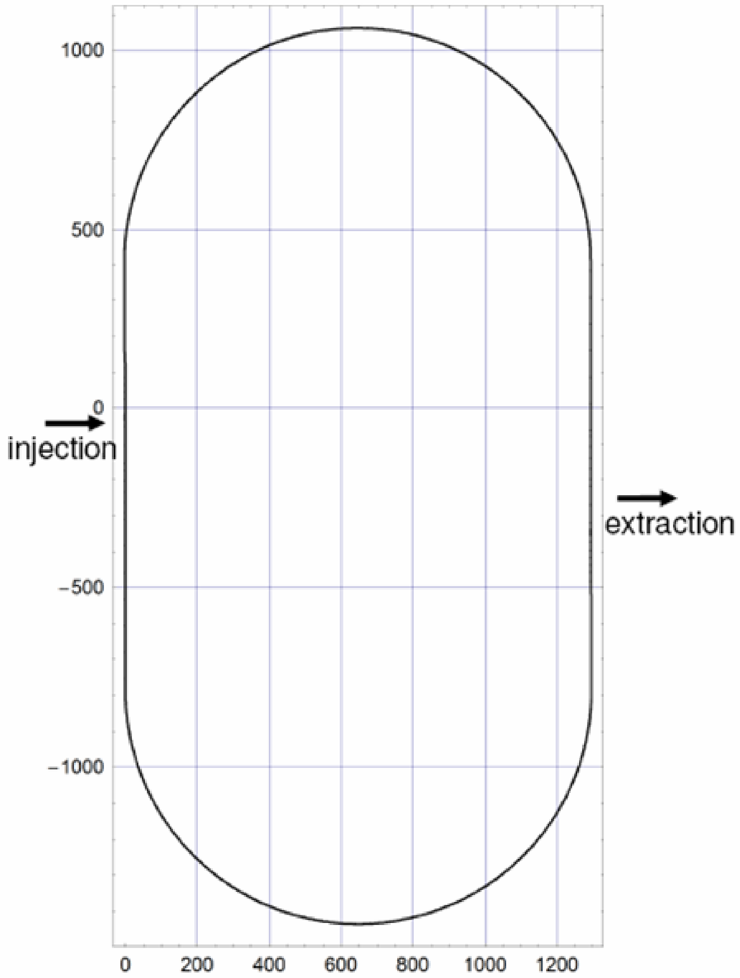
Slow emittance growth below threshold

Simulations indicate that below the instability threshold a slow (< synchrotron period) persistent emittance blow-up takes place



Emittance growth vs cloud density LHC at injection - from E. Benedetto (CERN thesis), G. Rumolo, F. Zimmermann

ILC DR Structure and layout



- Arcs consist of a total of 192 FODO cells
- Flexibility in tuning momentum compaction factor, given by phase advance per arc cell:
  - **72° phase advance: α_p=2.8×10^{-4}**
  - **90° phase advance: α_p=1.7×10^{-4}**
  - **100° phase advance: α_p=1.3×10^{-4}**
- No changes in dipole strengths needed for different working points.
- Racetrack structure has two similar straights containing:
  - **injection and extraction in opposite straights**
  - **phase trombones**
  - **circumference chicanes**
  - **rf cavities**
  - **"doglegs" to separate wiggler from rf and other systems**
  - **wiggler**

Major Parameter

Beam energy	5 GeV
Circumference	6476.440 m
RF frequency	650 MHz
Harmonic number	14042
Transverse damping time	21.0 ms
Natural rms bunch length	6.00 mm
Natural rms energy spread	1.27×10^{-3}

Phase advance per arc cell (approximate)	72°	90°	100°
Momentum compaction factor	2.80×10^{-4}	1.73×10^{-4}	1.29×10^{-4}
Normalised natural emittance	6.53 μm	4.70 μm	4.27 μm
RF voltage	31.6 MV	21.1 MV	17.2 MV
RF acceptance	2.35%	1.99%	1.72%
Synchrotron tune	0.061	0.038	0.028
Horizontal tune	64.750	75.200	80.450
Natural horizontal chromaticity	-76.5	-95.1	-106.9
Vertical tune	61.400	71.400	75.900
Natural vertical chromaticity	-75.6	-93.4	-103.5

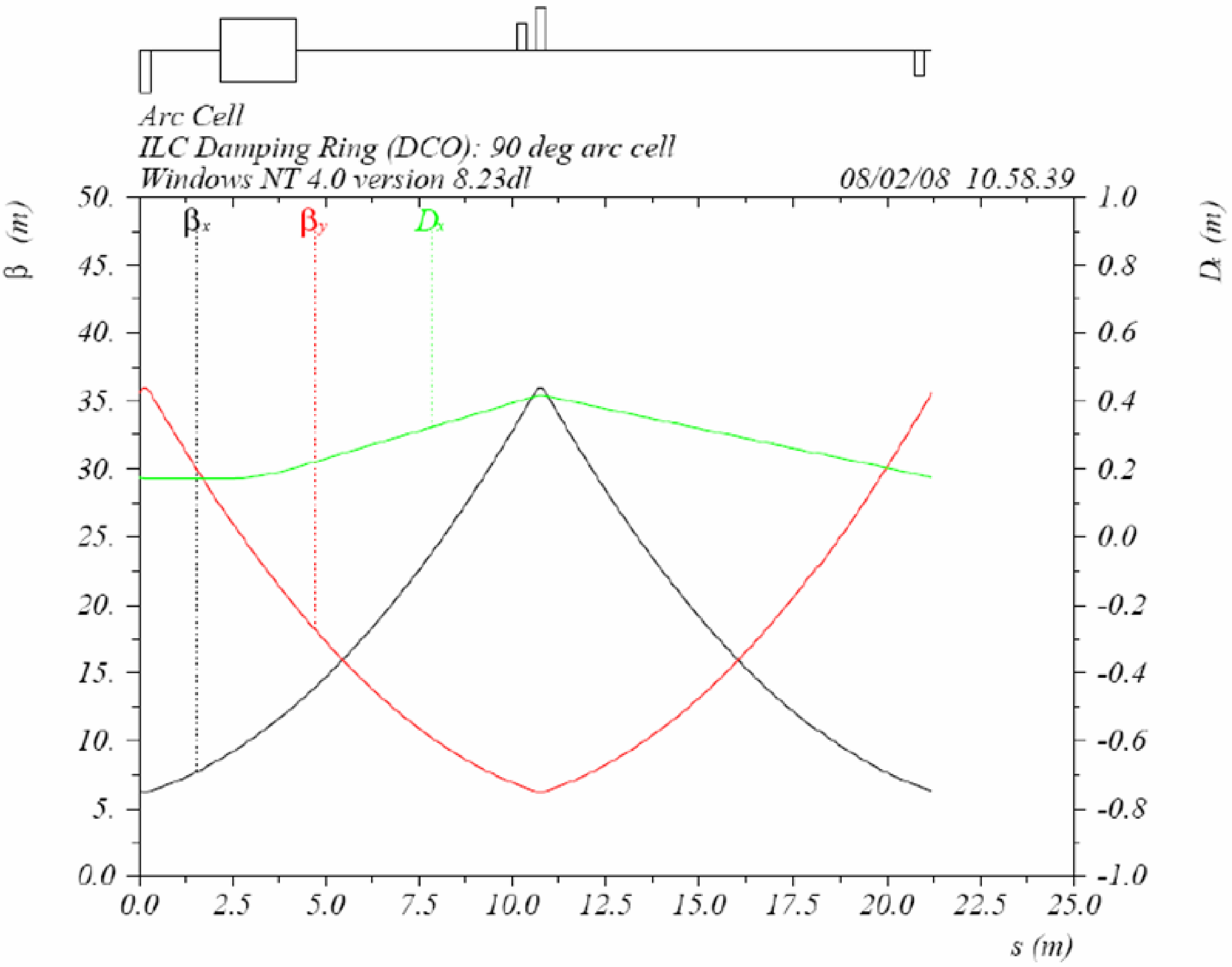
Magnet counts and Parameters

Arc dipole length	2.00 m
Arc dipole field	0.273 T
Number of arc dipoles	192 (1 per arc cell)
Total number of 2 m dipoles	200
Total number of 1 m dipoles (in chicanes)	48

Total number of quadrupoles	690
Maximum quadrupole gradient	12.0 T/m
Total number of sextupoles	384
Maximum sextupole gradient	215 T/m^2

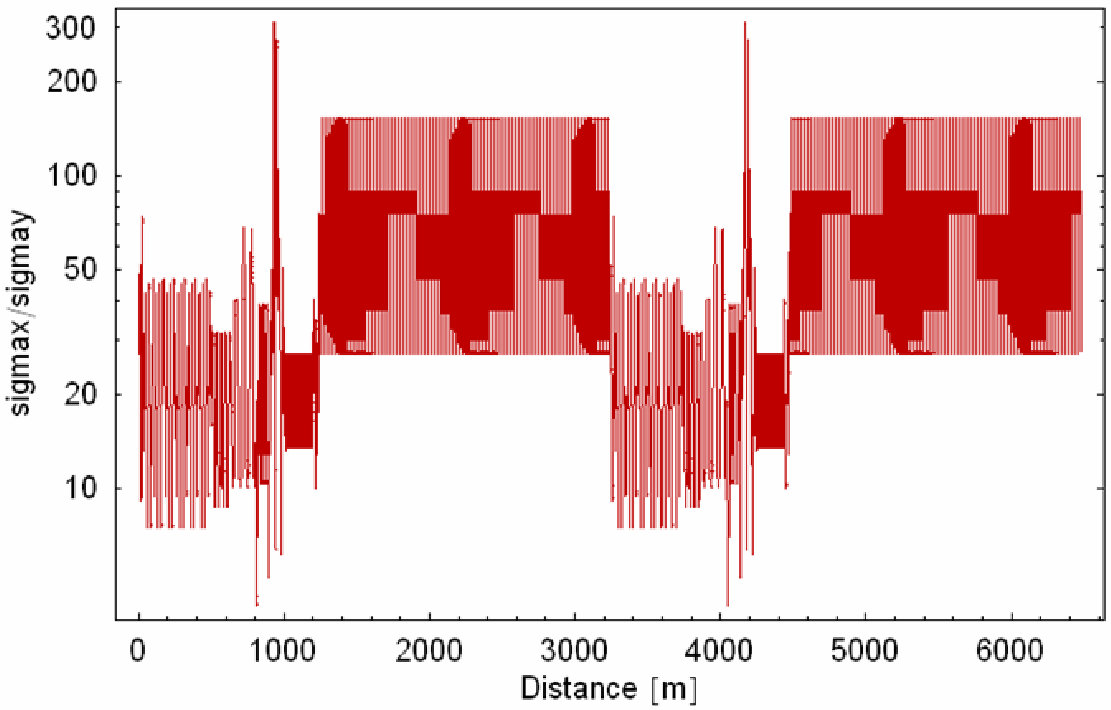
Wiggler peak field	1.6 T
Wiggler period	0.400 m
Wiggler unit length	2.45 m
Wiggler total length	215.6 m

Arc Cell



Arc Cell
ILC Damping Ring (DCO): 90 deg arc cell
Windows NT 4.0 version 8.23dl
08/02/08 10.58.39
β (m)
Dx (m)
s (m)
βx
βy
Dx
50.
45.
40.
35.
30.
25.
20.
15.
10.
5.
0.0
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0

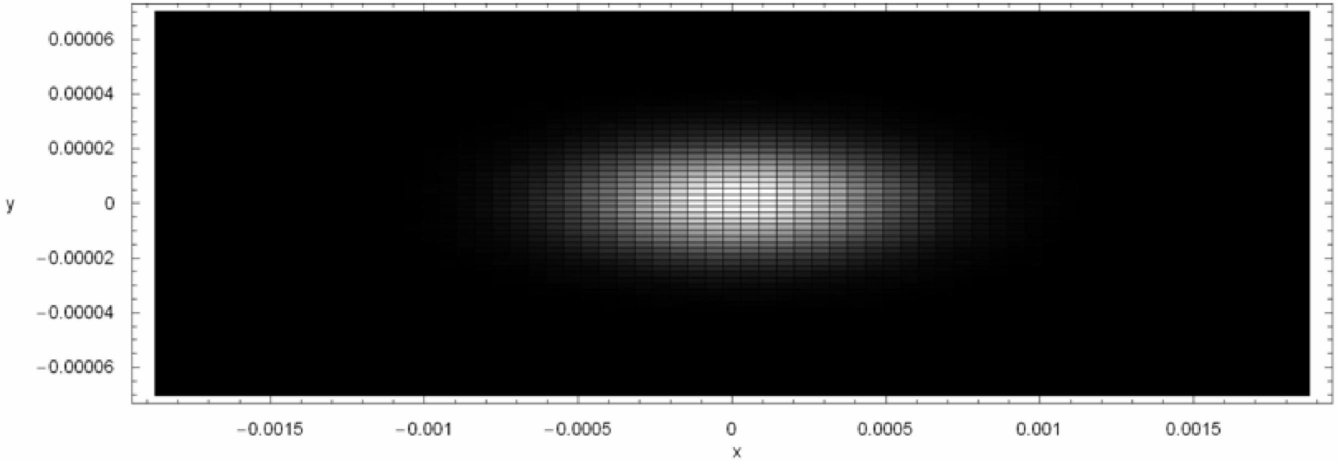
ILC DR flat beams



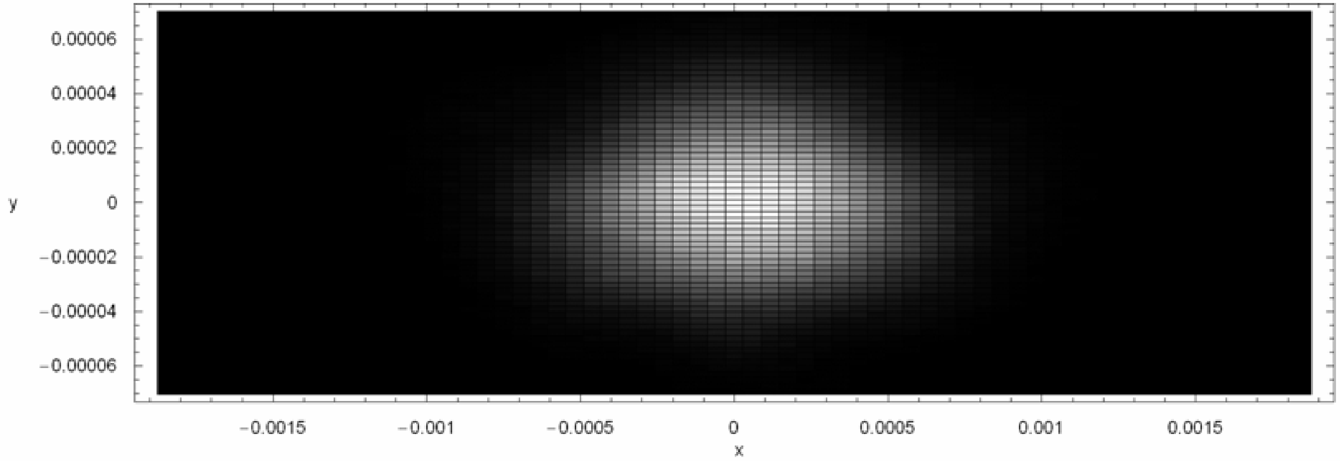
- To minimize the truncation errors in our simulation with flat beams [1], we select >> more mesh points in the horizontal direction compared to the vertical one so that at least grid size Hx ~ 10 Hy.
  - **Example in case of $\sigma x/\sigma y$ = 150:1, we use a transv. grid 300x20.**

[1] Y. Cai etal PRSTAB **4**, 011001 (2001).

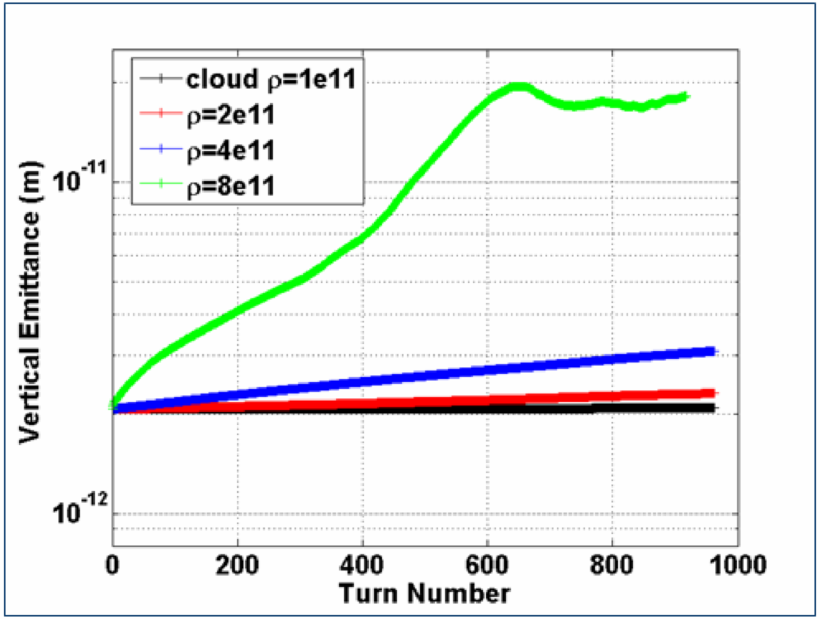
Simulations SR camera at injection

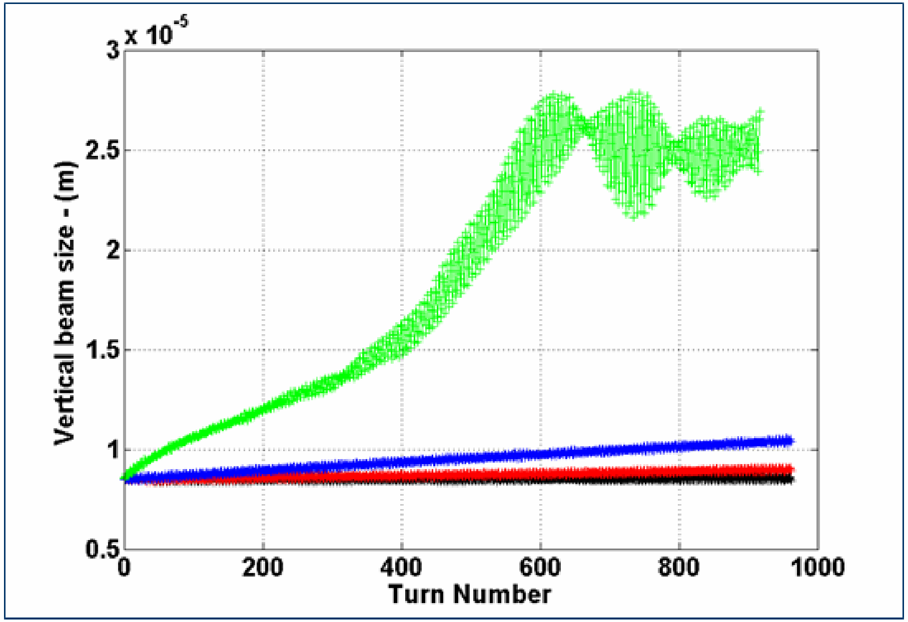


Simulations SR camera at injection



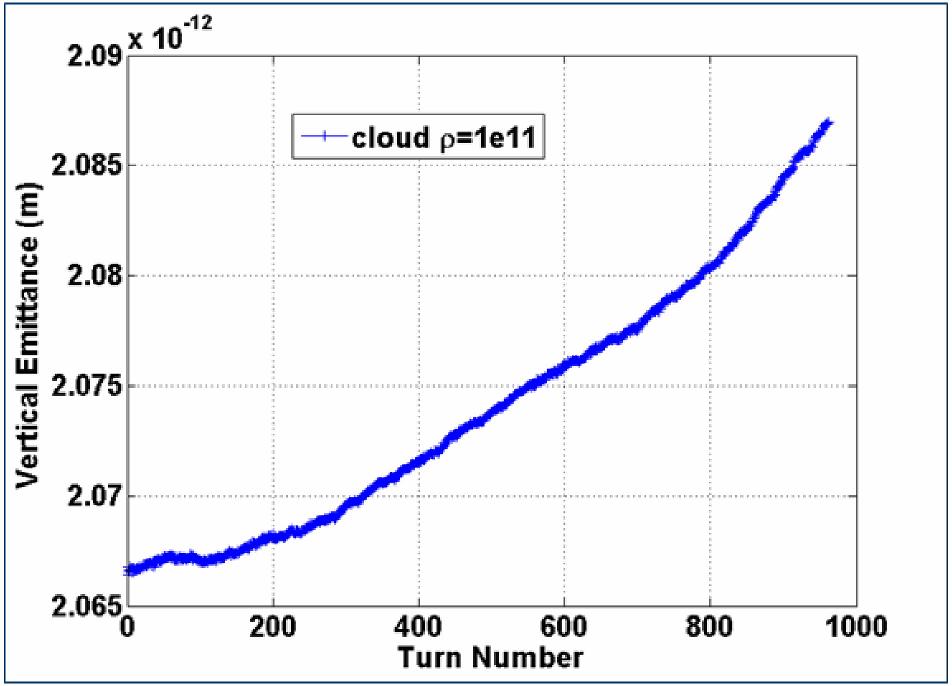
DR Simulations





- Tracking the beam and applying beam-cloud kicks everywhere except magnetic-free: assume e-cloud in field free Drift regions is mitigated. Note high synchrotron tune 0.038.
- Horizontal emittance small increase
- In the case 8e11, also beam losses of 40%

DR Simulations

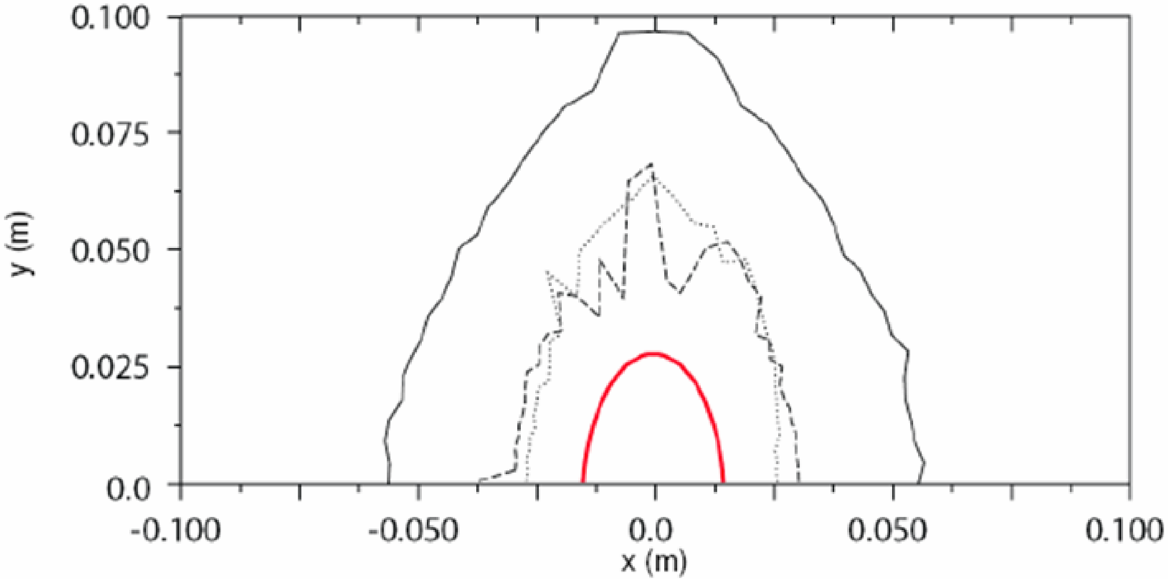


Incoherent emittance blow-up below threshold:

Next: include radiation damping and quantum excitations ...

Dynamic aperture

- Next to include in simulation: variation of the dynamic aperture with e- cloud density



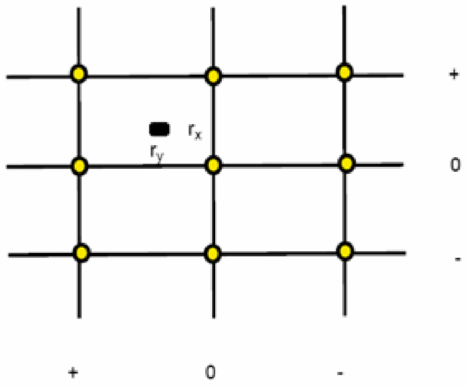
- 90° phase advance per arc cell.
- Red ellipse shows maximum particle coordinates for injected positron beam.
- Solid black line shows on-energy dynamic aperture.

Summary

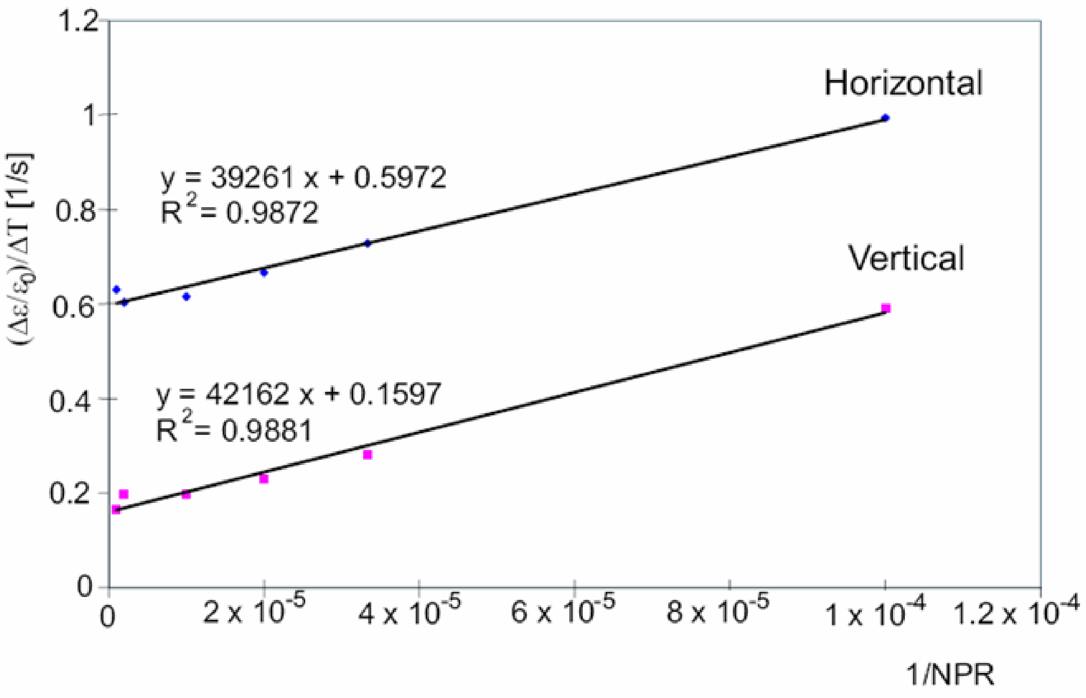
- Benchmarking for single-bunch instability codes looks from good to excellent.
- More confirmation of incoherent emittance blow-up below threshold
  - **Setting up for longer simulations at lower cloud density**
- Instability threshold for ILC DR new lattice is at cloud density about ~4-8e11 m^{-3}.
- Next: benchmarking CesrTA
- Next to include in simulations: dynamic aperture vs cloud density.

Special Thank to Frank Zimmermann;
K. Sonnad, J-L. Vay, T. Raubenheimer,

M. Furman, A. Kabel, G. Rumolo, NERSC
computing and consulting (!), K. Ohmi,
A. Wolski et many other colleagues...



+
r_x
r_y
0
-
+
0
-



Horizontal
y = 39261 x + 0.5972
R^2= 0.9872
Vertical
y = 42162 x + 0.1597
R^2= 0.9881
(Δε/ε0)/ΔT [1/s]
1/NPR
0
0.2
0.4
0.6
0.8
1
1.2
2 x 10^-5
4 x 10^-5
6 x 10^-5
8 x 10^-5
1 x 10^-4
1.2 x 10^-4

LC DR flat beam

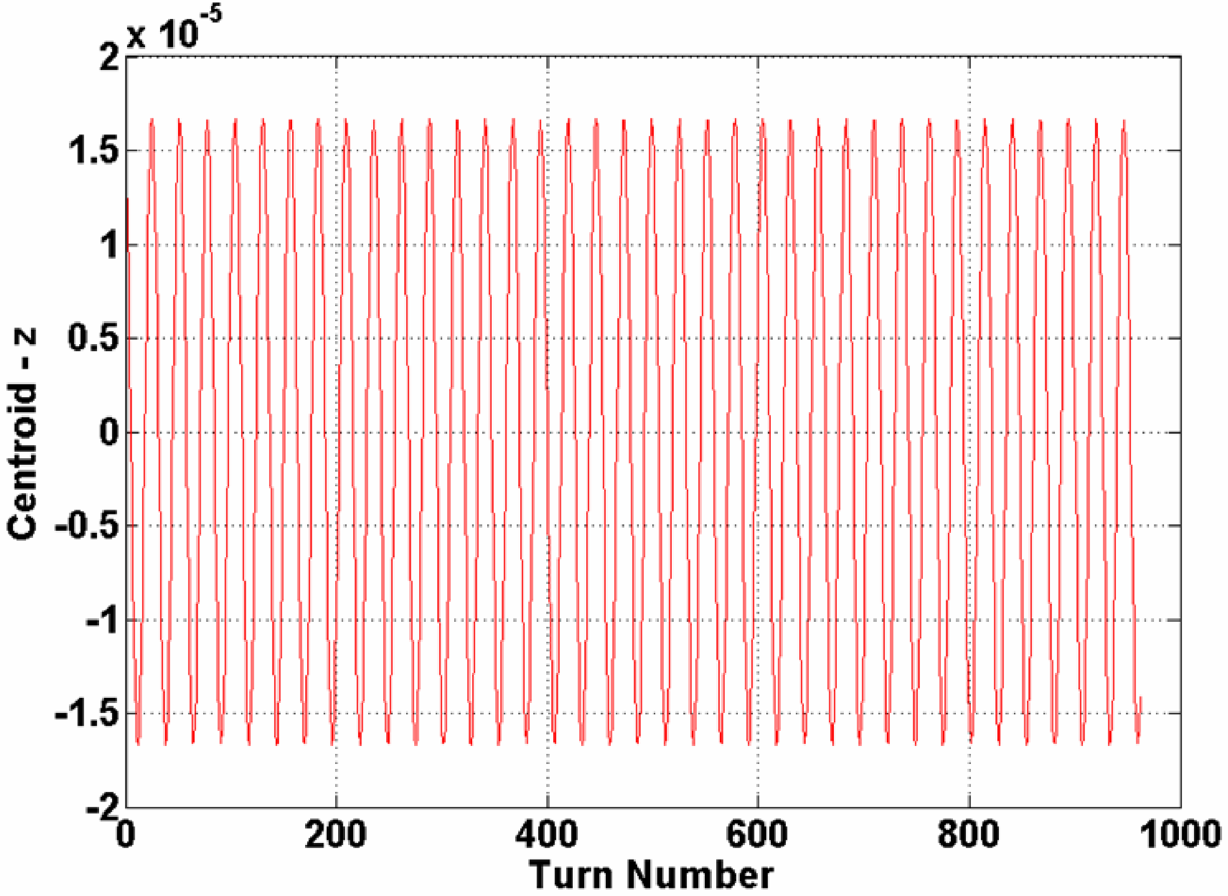
- In case of very flat beams, the discretized Poisson equation:

$$\frac{\phi_{i-1,j} + \phi_{i+1,j} - 2\phi_{i,j}}{H_x^2} + \frac{\phi_{i,j-1} + \phi_{i,j+1} - 2\phi_{i,j}}{H_y^2} = -2\pi\rho_{ci,j}$$

- The truncation errors are of the order of Hx^2 and Hy^2. If we use the same number of mesh points per σ in both directions, in case of very flat beams, the truncation errors in the Hx horizontal direction completely dominates [1].
- To minimize the errors in our simulation with flat beams, we select >> more mesh points in the horizontal direction compared to the vertical one so that at least Hx ~ 10 Hy.
  - **Example in case of $\sigma x/\sigma y$ = 150:1, we use 300x20 grid.**

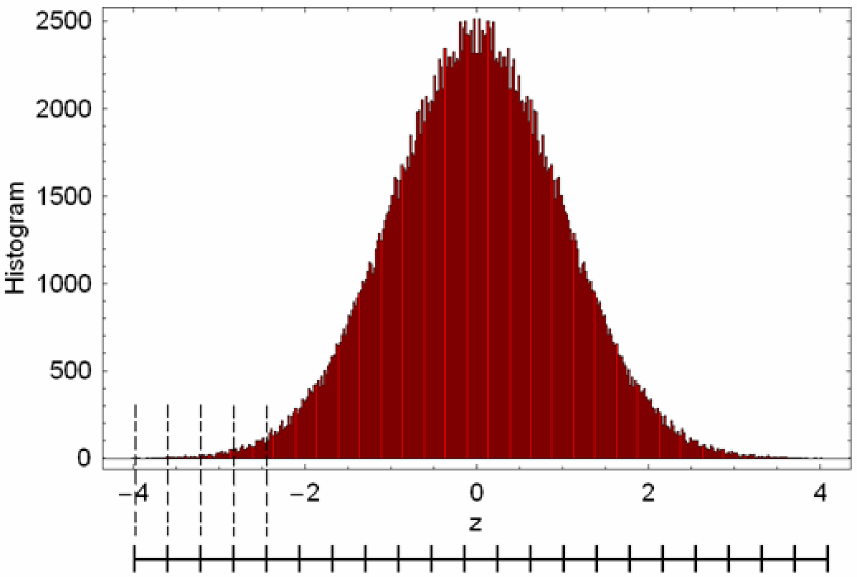
[1] Y. Cai etal PRSTAB **4**, 011001 (2001).

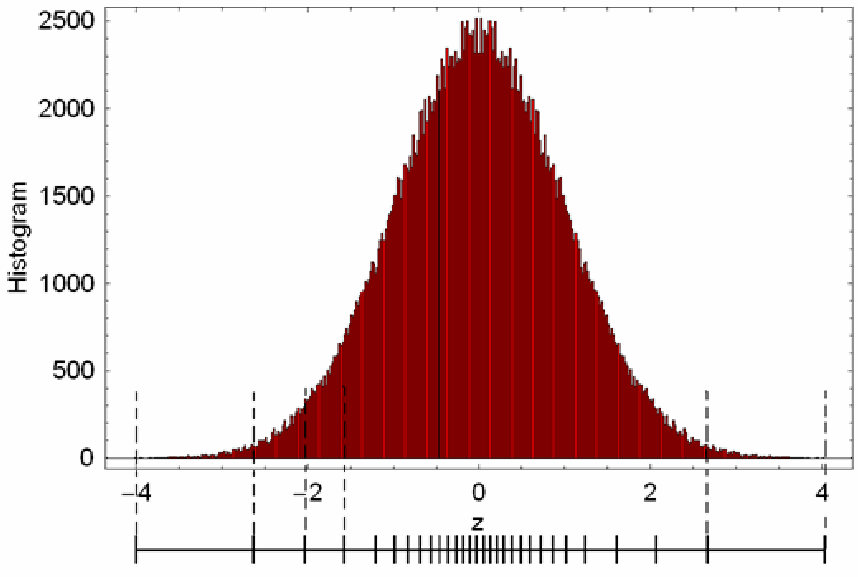
ILC DR synchrotron oscillations



Synchrotron tune 0.038

Slicing the beam





- Bunch sliced either uniformly in z, or with each slice containing same number of macroparticles, preferred for processors load balance. The methods should coincide in the limit slices>>1. Main difference with other codes, in the following simulations ..