Single-bunch Instability Simulation in CesrTA

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ECLOUD10 Workshop

October 8-12

Cornell University

Instability simulation code

CMAD (M Pivi SLAC, collab. K. Sonnad Cornell U.)

- full **ring lattice representation from MAD**
- interaction beam - cloud is computed at every element in the ring lattice: **933 "stations" in CesrTA**, 11,735 in ILC DR
- Parallel code, typically ~100 processors NERSC
- Particle in cell PIC code.
- 0.3 M macroparticles for beam.
- Self-consistent beam particle dynamics in 6D; electron cloud dynamics in 3D. Electric forces are 2D.
- Pinching of the electron cloud and the effect of the magnet fields are included.

Code benchmarking

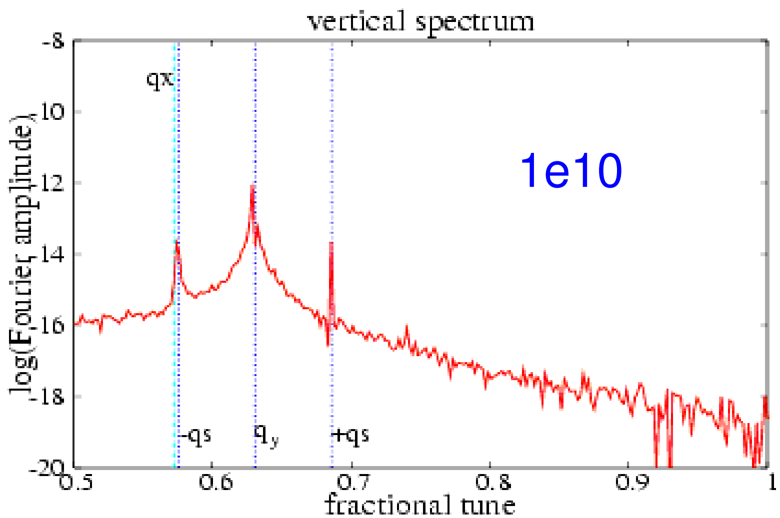
- For code benchmarking and testing refer to poster presented by Kiran …. (first poster outside)

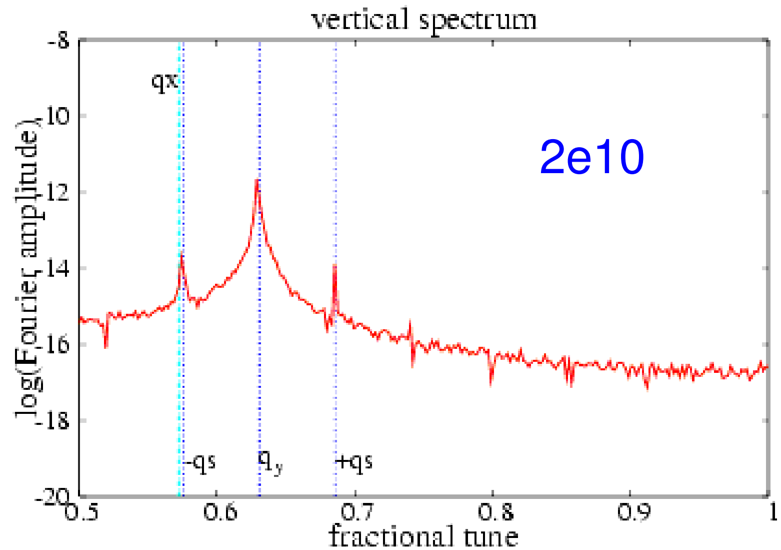
parameters – to match experiment

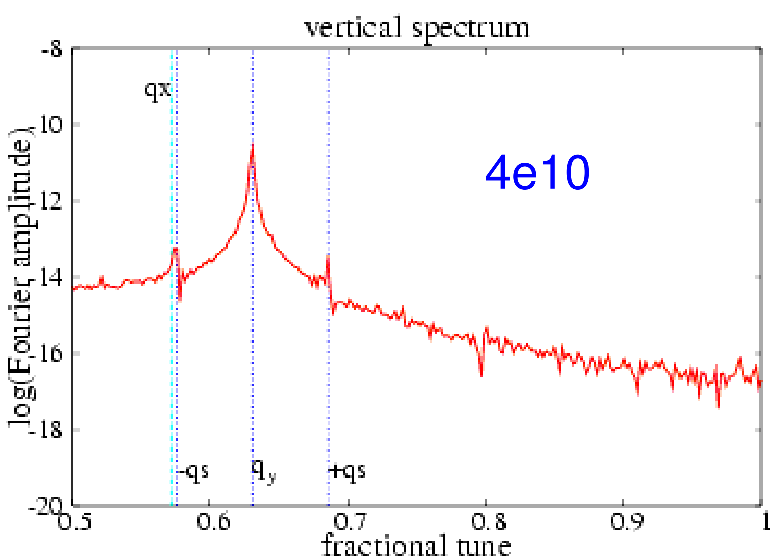
CesrTA simulations:

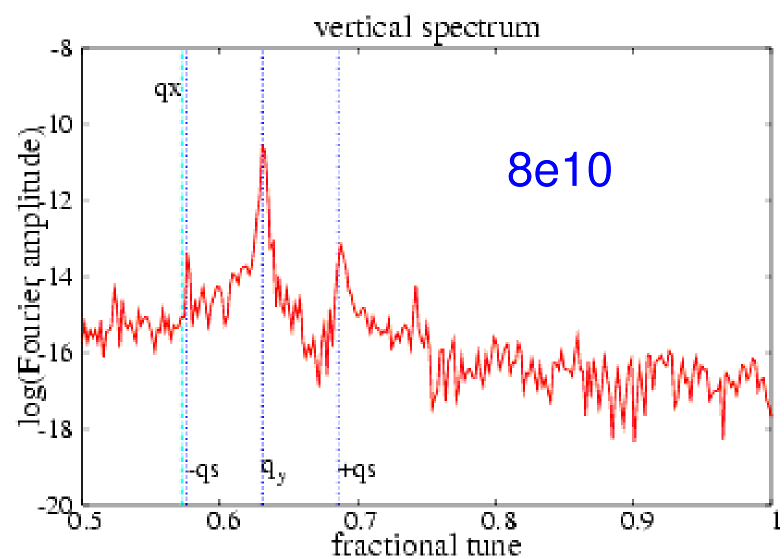
- Chromaticites 0.6 (x) and **2.3** (y)
- Cloud **uniformly distributed** over **all elements**
- **CesrTA lattice** file: cta_2085mev_20090516.**mad**
- Tune obtained from tracking without cloud -
  Qx = 0.5722 Qy = 0.6308 νs = 0.055
- Bunch Current = 1.0 mA (1.6e10 e+/bunch)
- Feedback OFF
- All cases were tracked for 512 turns – track longer in future

CesrTA lattice with cloud densities ~e10/m^3

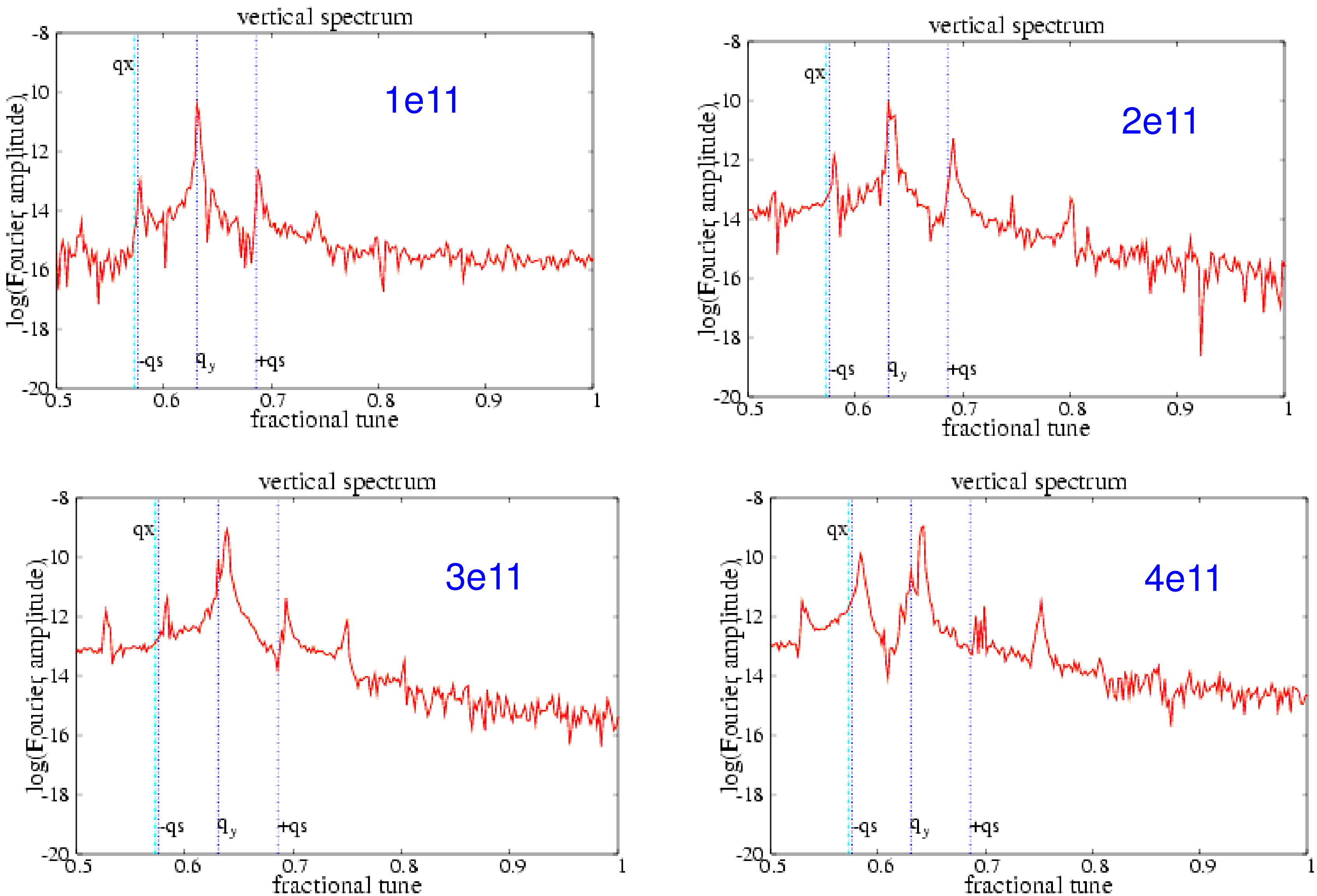




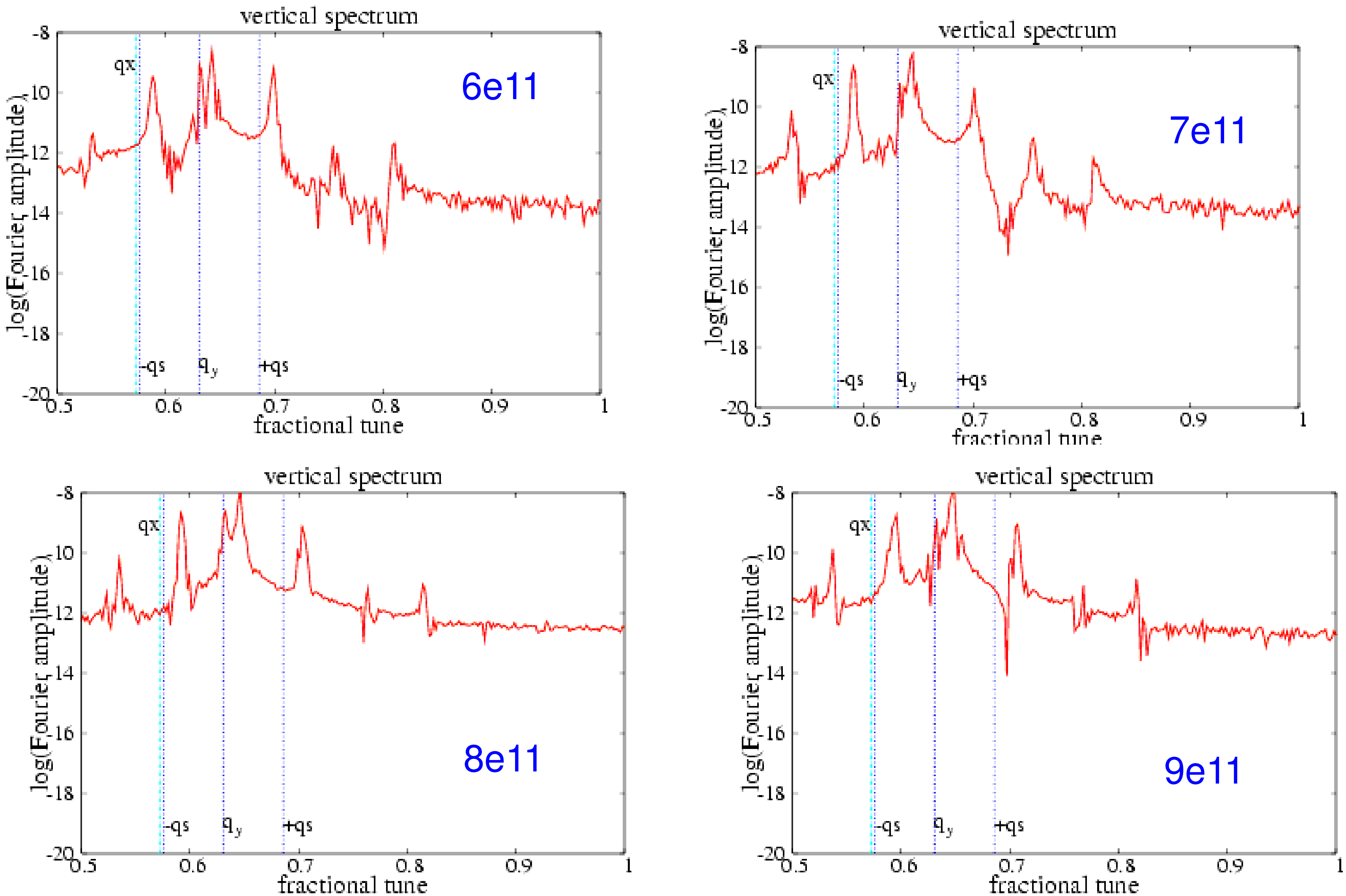




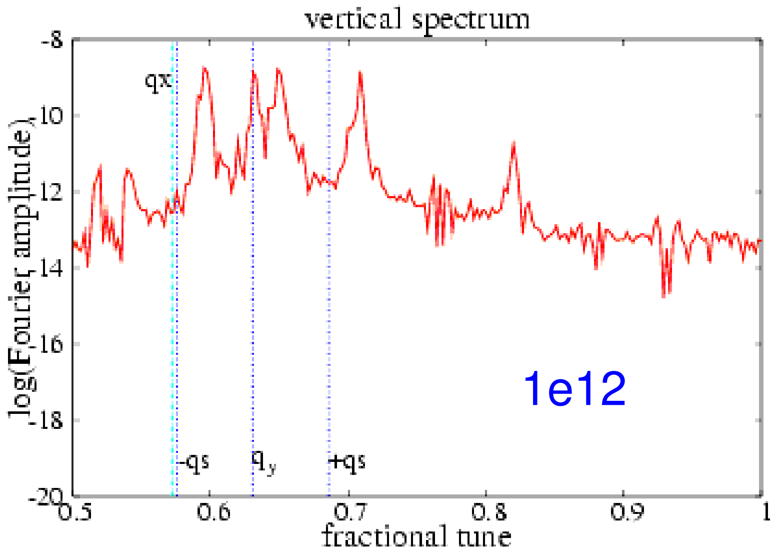
CesrTA lattice with cloud densities ~ e10/m^3

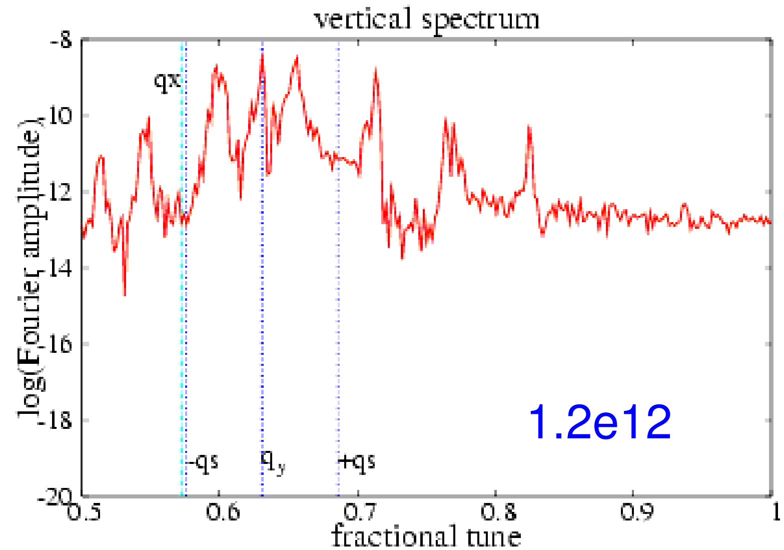


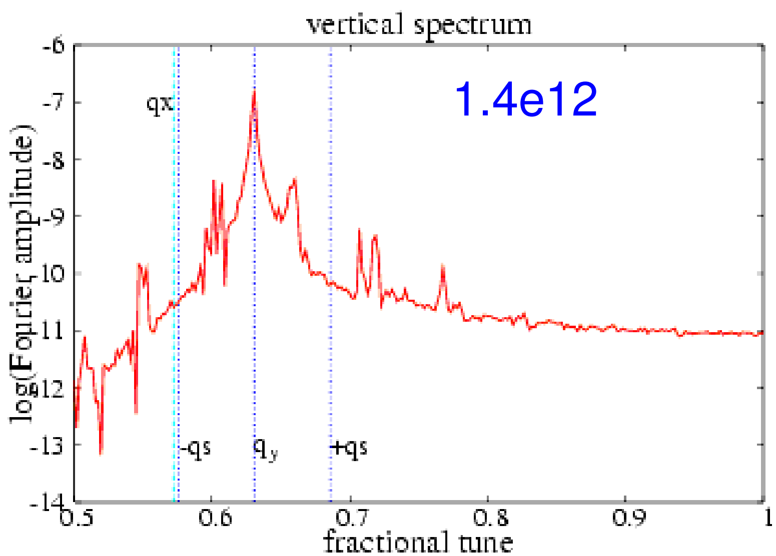
cloud density ~ e11/m^3 (contd)

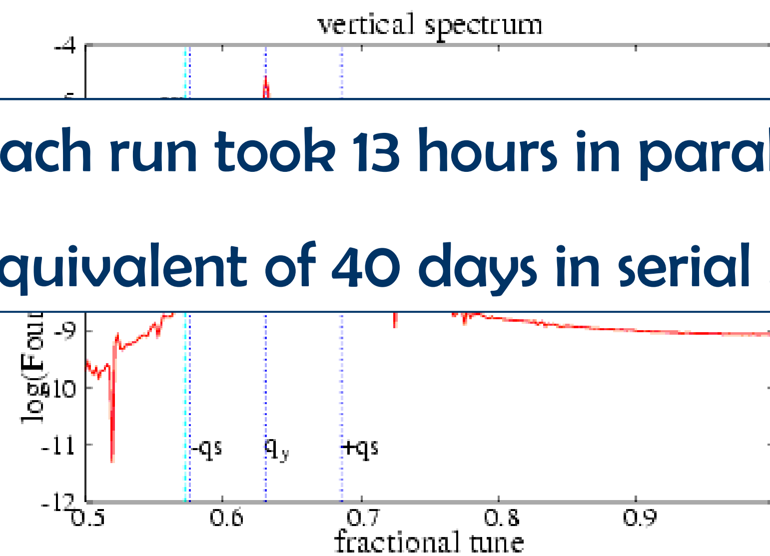


cloud densities ~ e12/m^3



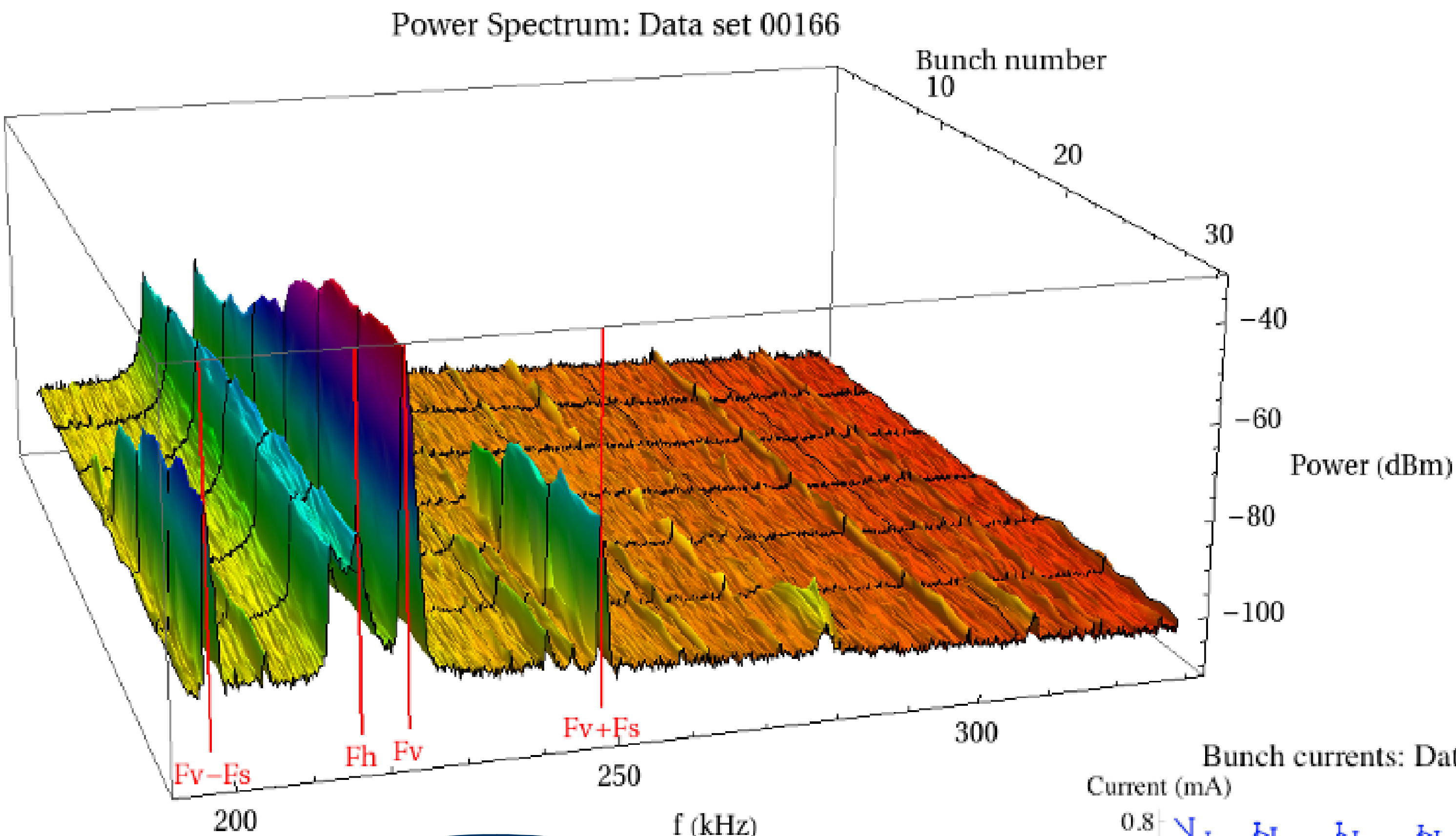


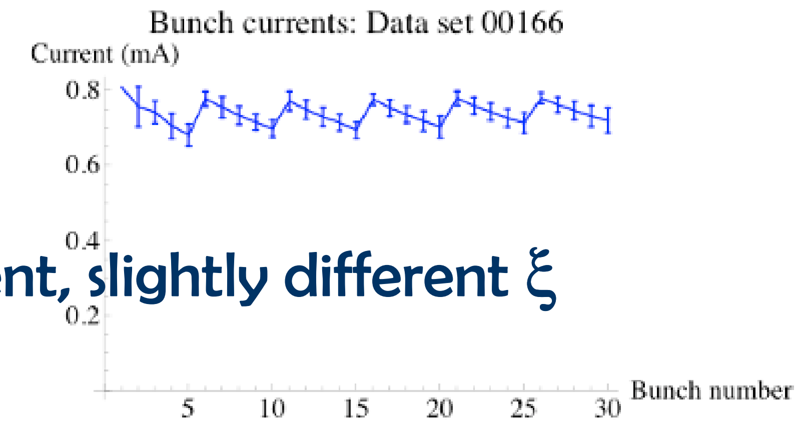




Each run took 13 hours in parallel equivalent of 40 days in serial ...

G. Dugan: Bunch-by-bunch power spectrum Run 166



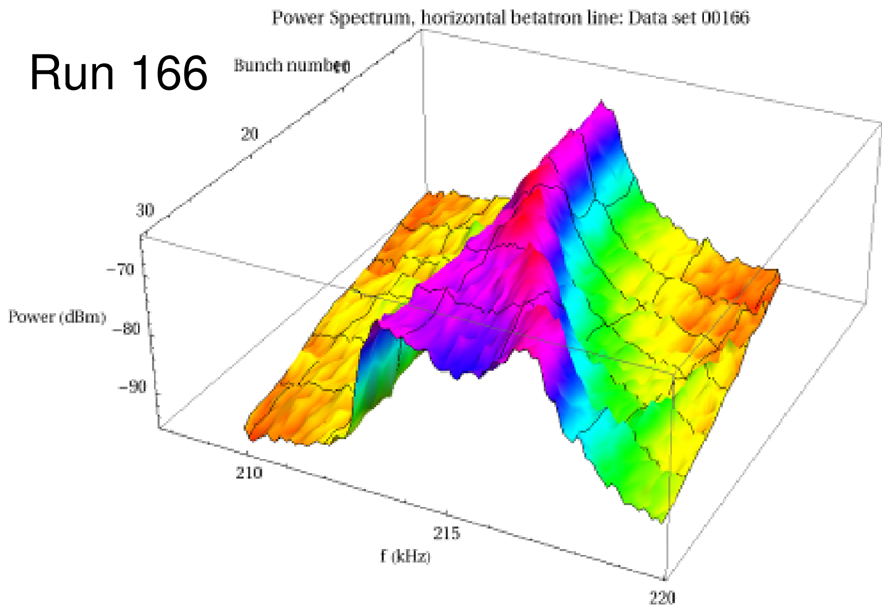


(H,V) chrom = (1.33,1.155)
Avg current/bunch 0.74 mA.

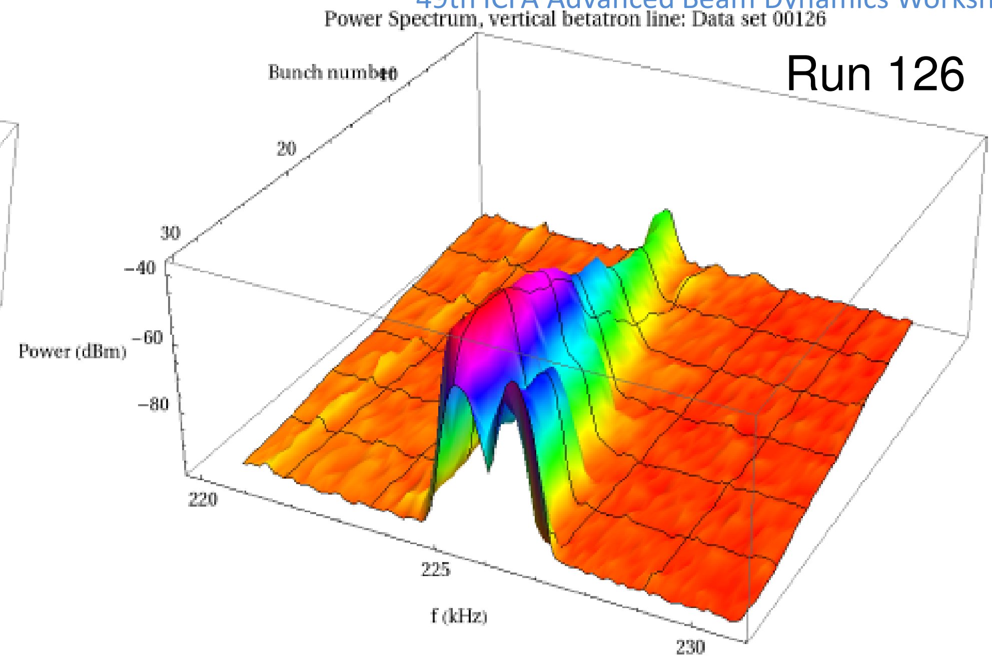
25% less current, slightly different ξ

Detailed features of horizontal and vertical lines

Run 166



Run 126

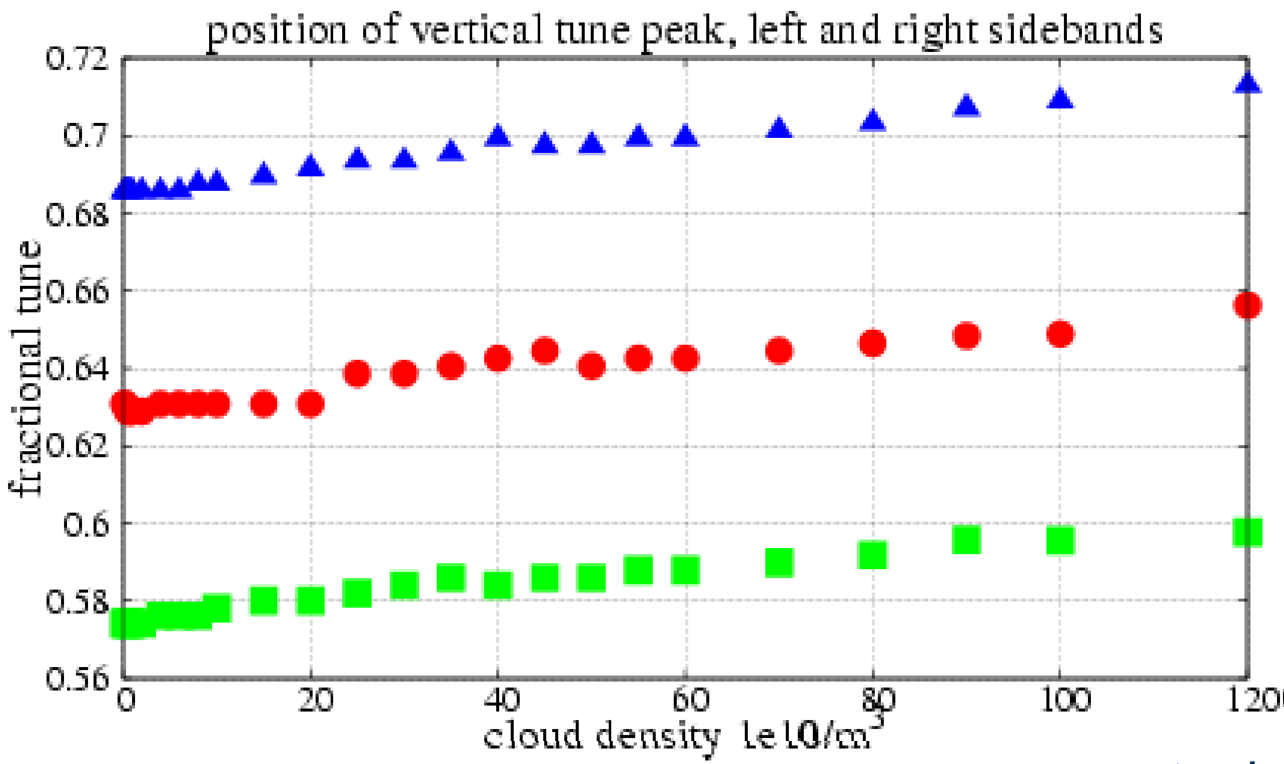


Lower frequency (~3 kHz) shoulder in the horizontal tune spectrum is attributable to known dependence of horizontal tune on the multibunch mode.

Bifurcation of the vertical tune spectrum (peak at ~ 1.5 kHz higher frequency) , which starts to develop at the same bunch number as the head-tail lines, is not understood.

G. Dugan ECLOUD10

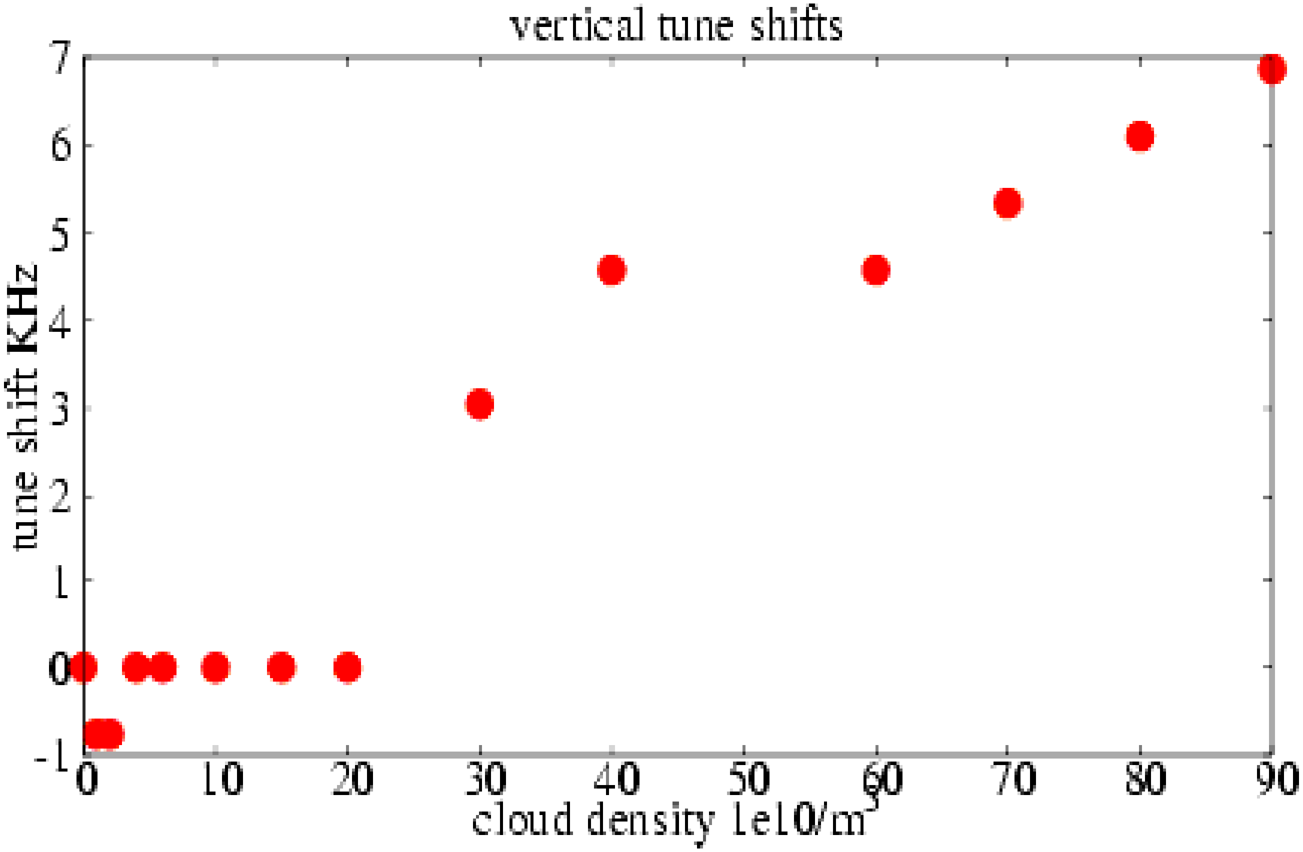
summary of peaks and sidebands



note: when the betatron peak was split, the shifted peak was chosen.

Simulated sidebands keep distance constant as measurements, suggesting no mode coupling

vertical tune shifts in KHz

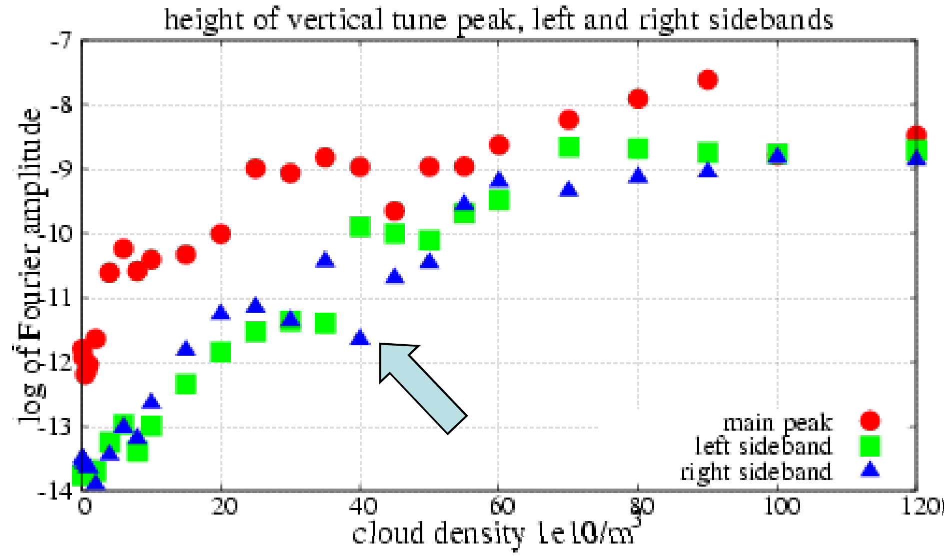


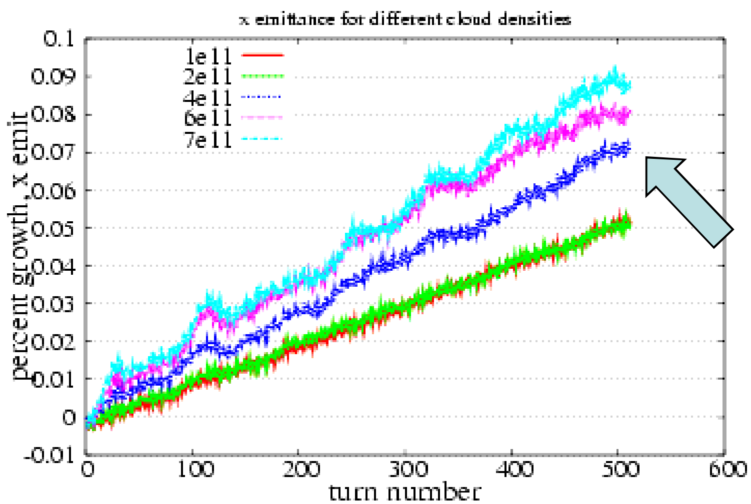
Simulated Tune shift above is larger then in experiments.

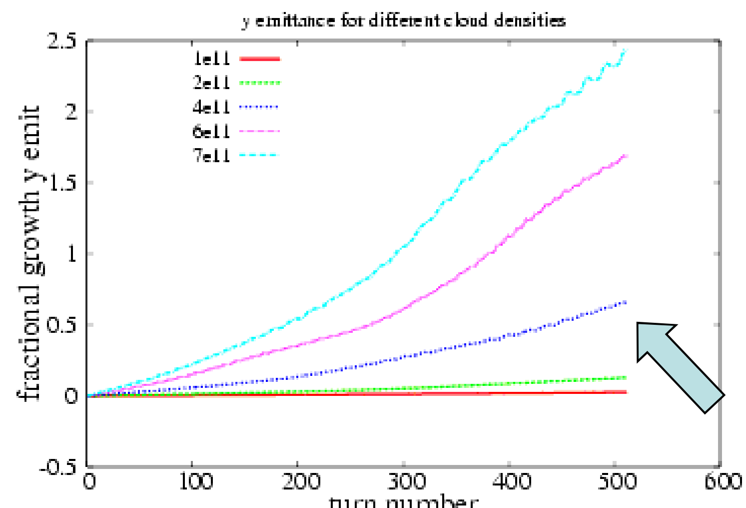
Next: Load cloud densities and distributions based on element type – especially for dipoles and quads

summary of peaks and sidebands

Height of tune peaks: "transition" effect at ~4e11/m³

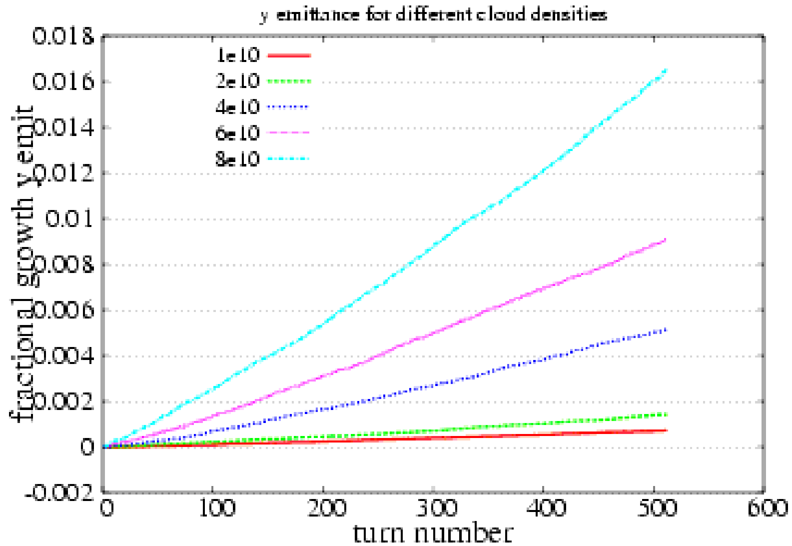


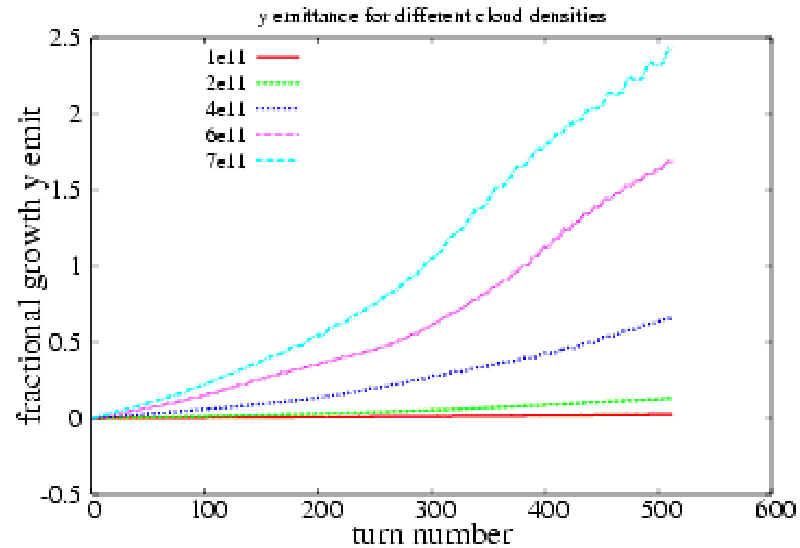




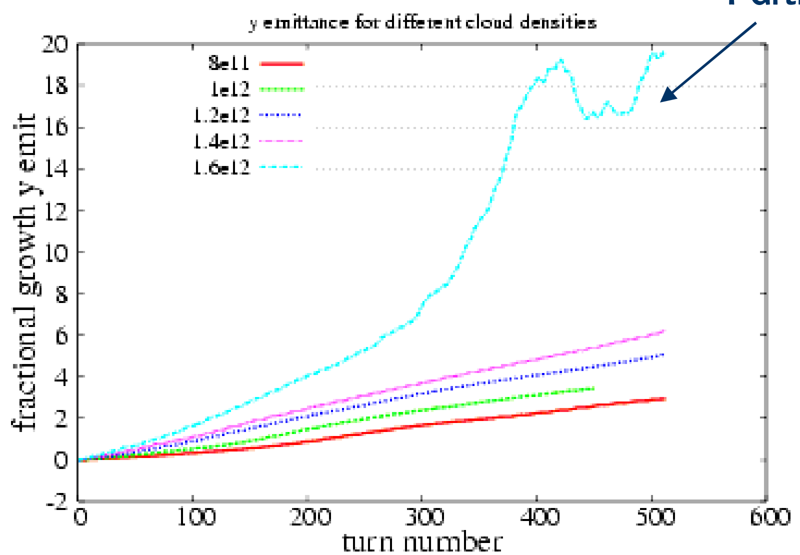
Horizontal and Vertical emittance, "transition" at ~4e11/m³

Vertical Emittance Growths





Particle losses



Steady linear emittance growth below the threshold

$1.6e12/m^3$ onset of instability, **consistent with experimental data** and PEHTS

K. Ohmi: Parameters

Table 1: Basic parameters of existing positron rings and ILC damping ring

		KEKB	PEP-II	Cesr-TA/5	Cesr-TA/2	ILC-DR	SuperKEKB
Circumference	L(m)	3,016	2,200	768	768	6,414	3016
Energy	E	3.5	3.1	5.0	2.1	5.0	4.0
Bunch population	$N_+(10^{10})$	8	8	2	2	2	9
Beam current	I_+ (A)	1.7	3.0	-	-	0.4	3.6
Emittance	ε_x(nm)	18	48	40	2.6	0.5	2
Momentum compaction	$\alpha(10^{-4})$	3.4		62.0	67.6	4.2	3.5
Bunch length	σ_z(mm)	6	12	15.7	12.2	6	6
RMS energy spread	$\sigma_E/E(10^{-3})$	0.73		0.94	0.80	1.28	0.8
Synchrotron tune	ν_s	0.025	0.025	0.0454	0.055	0.067	0.0256
Damping time	τ_x	40	40		56.4	26	43

Table 2: Threshold of the ILC damping ring and other rings

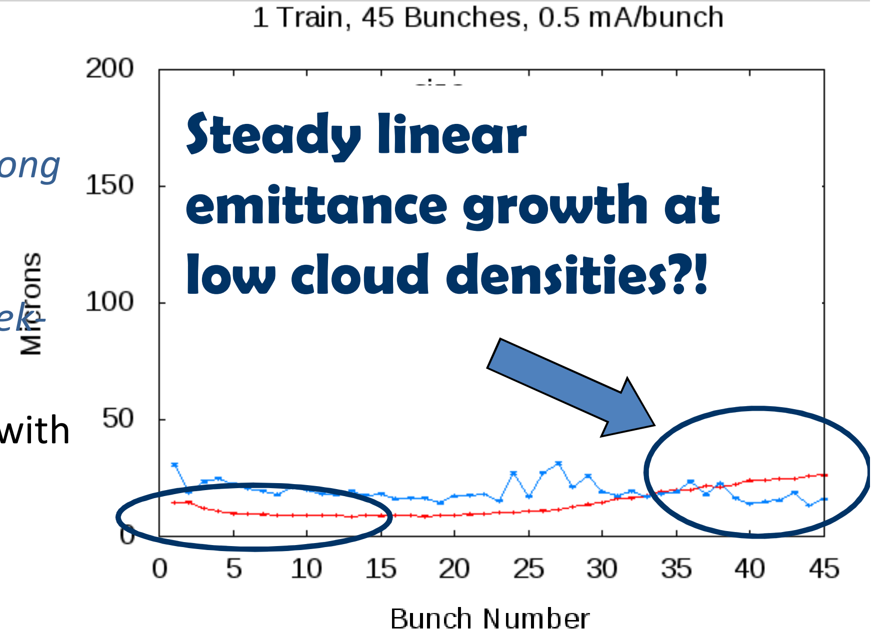
		KEKB[1]	KEKB[2]	PEP-II	CesrTA-5	CesrTA-2	ILC-DR	SuperKEKB
Bunch population	$N_+(10^{10})$	3	8	8	2	2	2	9
Beam current	I_+ (A)	0.5	1.7	3.0	-	-	0.4	3.6
Bunch spacing	ℓ_{sp}(ns)	8	7	4	4	4	6	4
Electron frequency	$\omega_e/2\pi$(GHz)	28	40	15	9.6	43	100	189
Phase angle	$\omega_e\sigma_z/c$	3.6	5.9	3.7	3.2	11.0	12.6	23.8
Threshold	ρ_e (10^{12} m^{-3})	0.63	0.38	0.77	7.40	1.70	0.19	0.27
Tune shift at ρ_e	$\Delta\nu_{x+y}$	0.0078	0.0047	0.0078	0.0164	0.009	0.011	0.003

High $\omega_e\sigma_z/c$ characterizes low emittance ring.

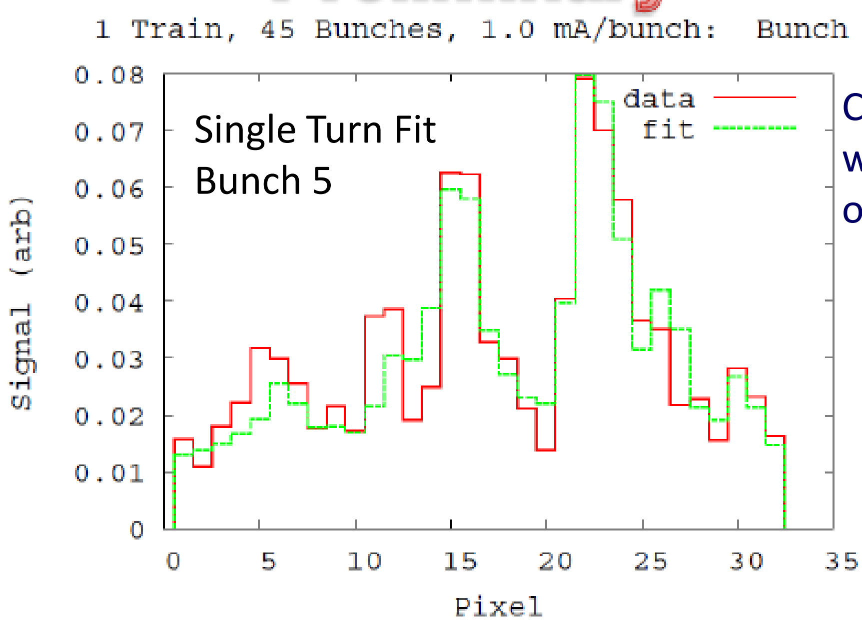
K. Ohmi ECLOUD10

Beam Size

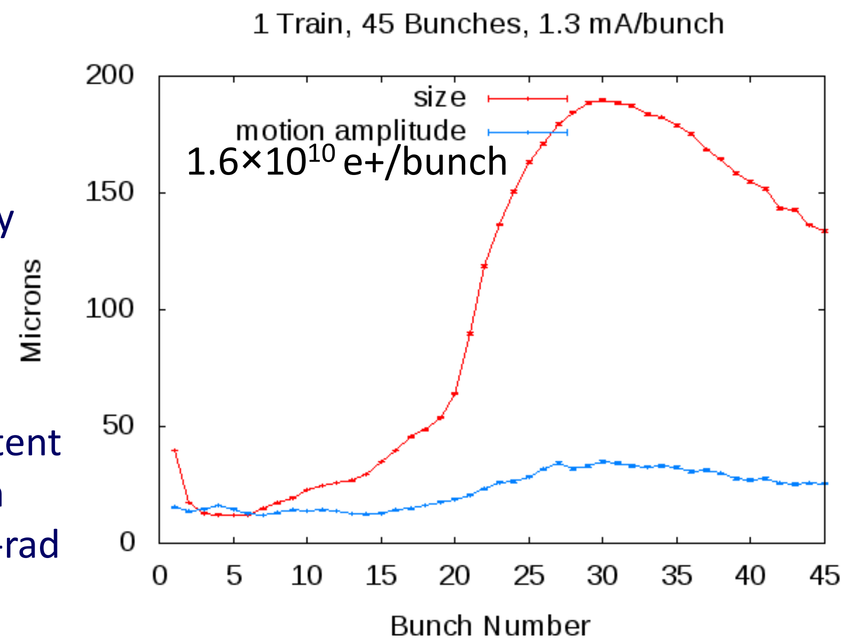
- Measure Bunch-by-Bunch Beam Size
  - Beam size enhanced at head and tail of train
    Source of blow-up at head appears to be due to a long lifetime component of the cloud (Dugan talk)
    Bunch lifetime of smallest bunches consistent with observed single bunch lifetimes during LET (Touschek-limited) consistent with relative bunch sizes.
  - Beam size measured around bunch 5 is consistent with $\varepsilon_y \sim 20$pm-rad (σ_y=11.0±0.2 μm, β_{source}=5.8m)



Preliminary

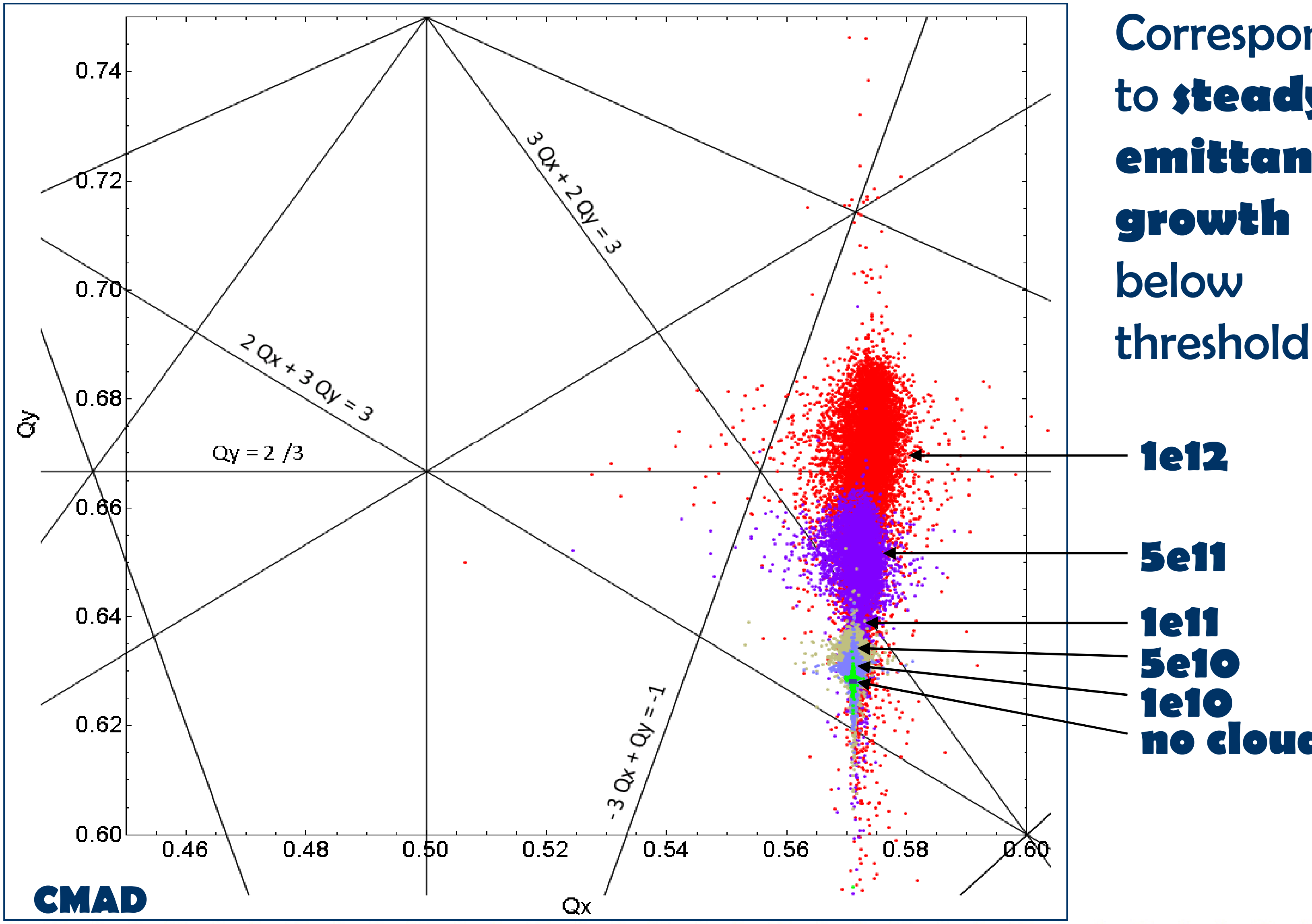


Consistent with onset of instability



Consistent with 20 pm-rad

Low cloud densities: Incoherent tune shift



Corresponds to **steady emittance growth** below threshold

Summary so far

CMAD beam tracking in real lattice with cloud stations at each element in the ring:

- Codes benchmarking satisfactory.
- Gerry Dugan "benchmarking between simulations and CesrTA cloud features data looks very good overall":
  - **Cloud density threshold agrees very well**
  - **Predicted two synchrotron sidebands as then in experiments**
  - **steady emittance growth at low cloud density as observed in CesTA**

Summary so far

- Work to systematically understand CesrTA experimental data in greater detail with code:
  - **tune shift higher then in experiments**
  - **Load cloud densities and distributions based on element type – especially for bends and quads**
  - **Close benchmark with machine of incoherent emittance growth**

- Main worry is now for the ILC Damping Ring and the steady incoherent emittance growth at very low cloud density
  - **Do we need SEY<<1 to completely suppress the cloud?**

movies

- Ecloud pinching
- ILC SR monitor

ILC Damping Ring Electron Cloud R&D effort

Mauro Pivi SLAC
on behalf of the DR Working Group

ECLOUD10 Workshop

October 8-12

Cornell University

Working Group Charges

Since 1 year, WG is meeting regularly and monthly via Webex

Charges are:

- Simulation of electron cloud build-up and instabilities (LBNL, INFN, SLAC, Cornell, KEK)
- Synchrotron Radiation simulations (ANL, Cornell)
- Mitigation evaluation and recommendation.
- Integration of CesrTA results into DR design

Working Group Main Deliverables

Recommendation for a reduced Damping Ring Circumference

Given March 2010

Recommendation for the baseline and alternate solutions for the electron cloud mitigation in various regions of the ILC Positron Damping Ring (DR).

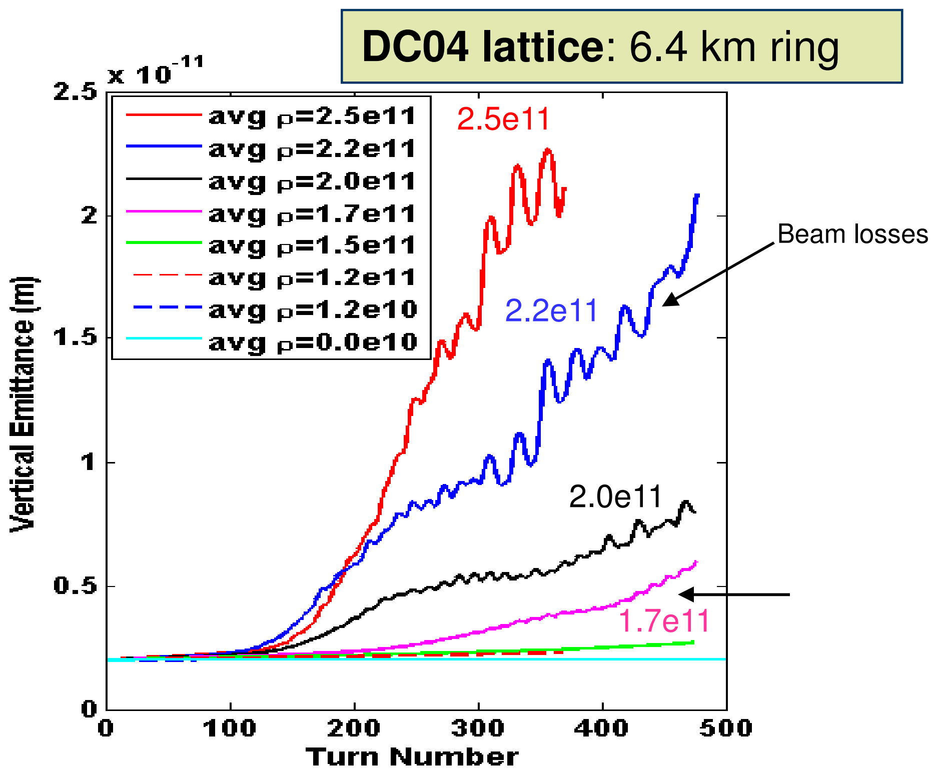
by end 2010

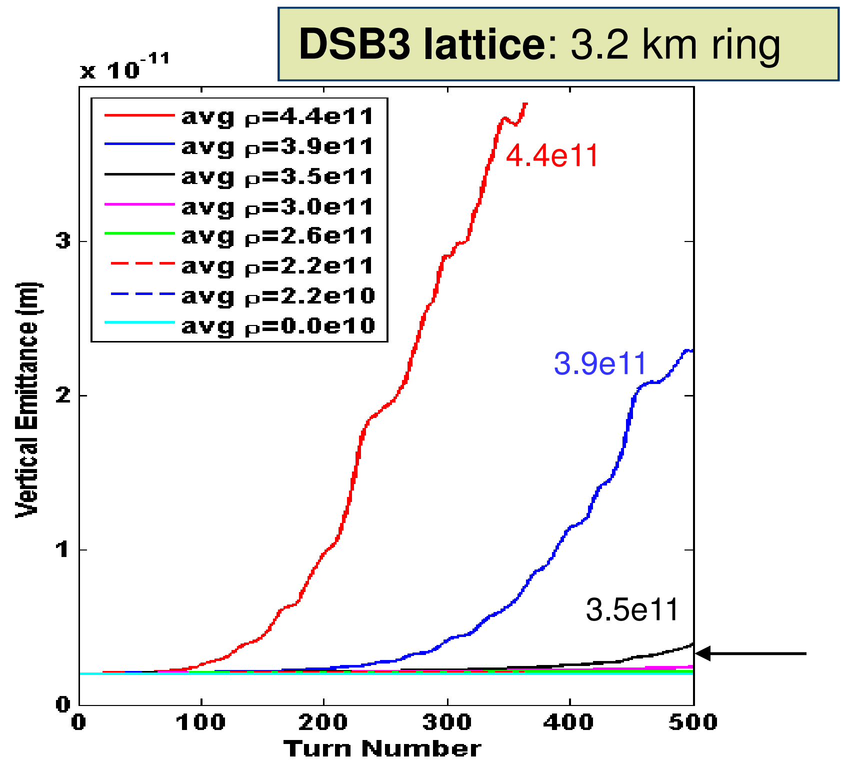
Characterization of electron cloud at different bunch spacing: 6ns (nominal) and 3ns (higher luminosity)

by end 2010

Beam instability simulations

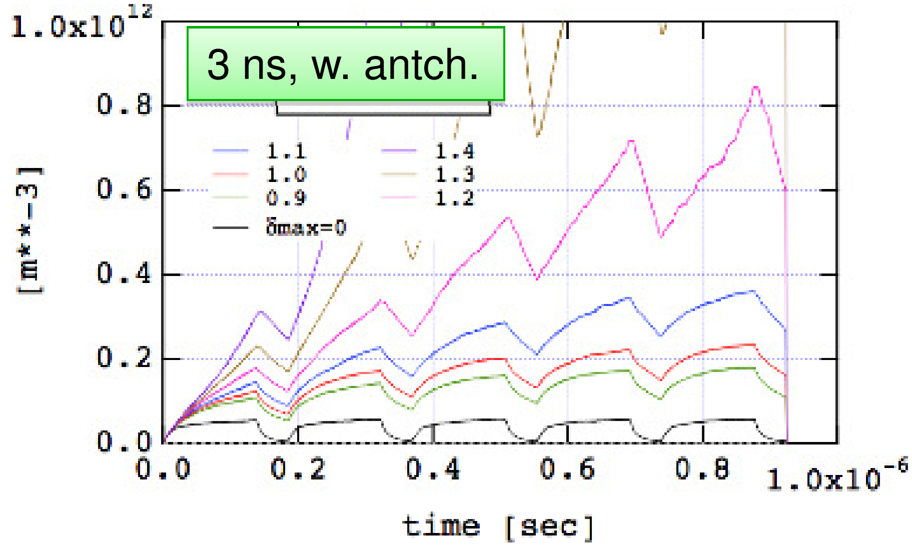
- CMAD tracking and beam instability parallel code (M.Pivi SLAC)
- Latest MAD files for Damping Ring: 6km “DCO4” and 3km “DSB3”
- Assumed solenoids (no cloud) in drift regions

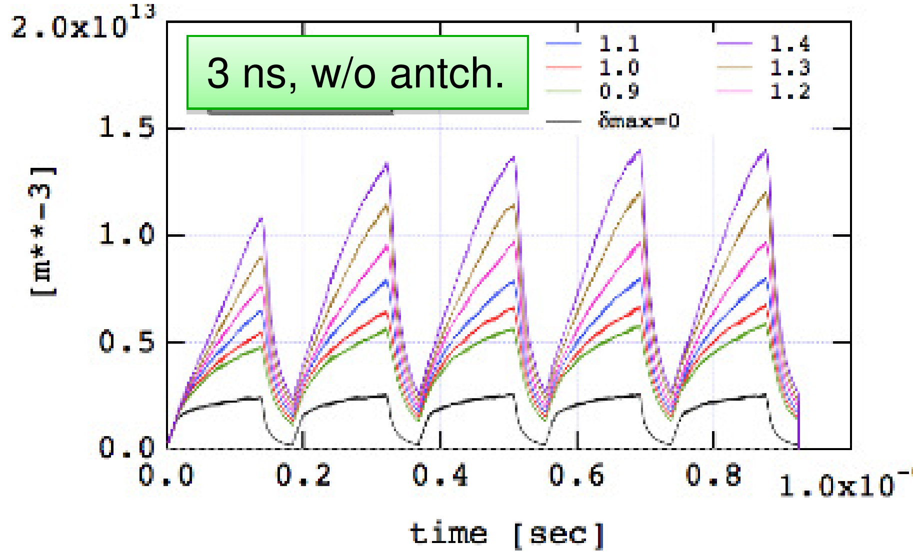


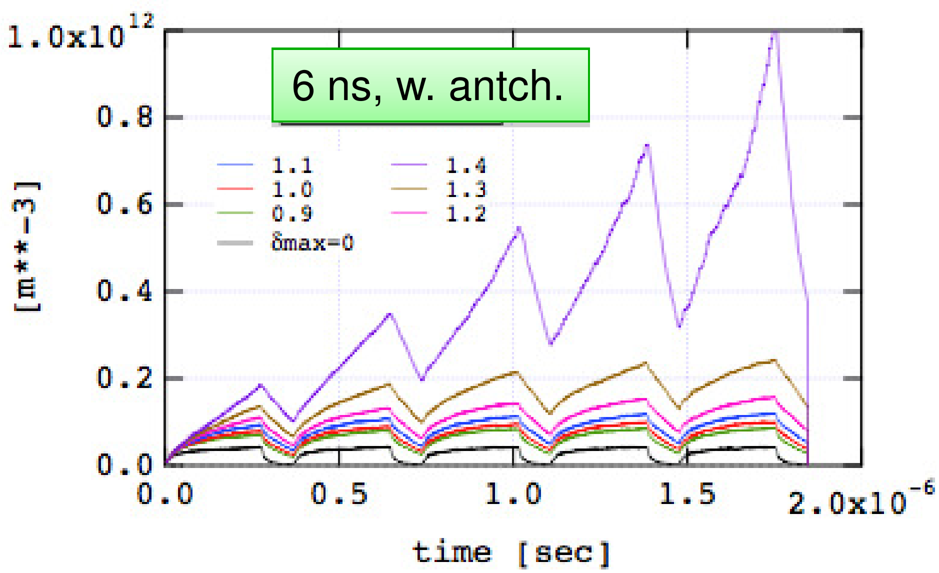


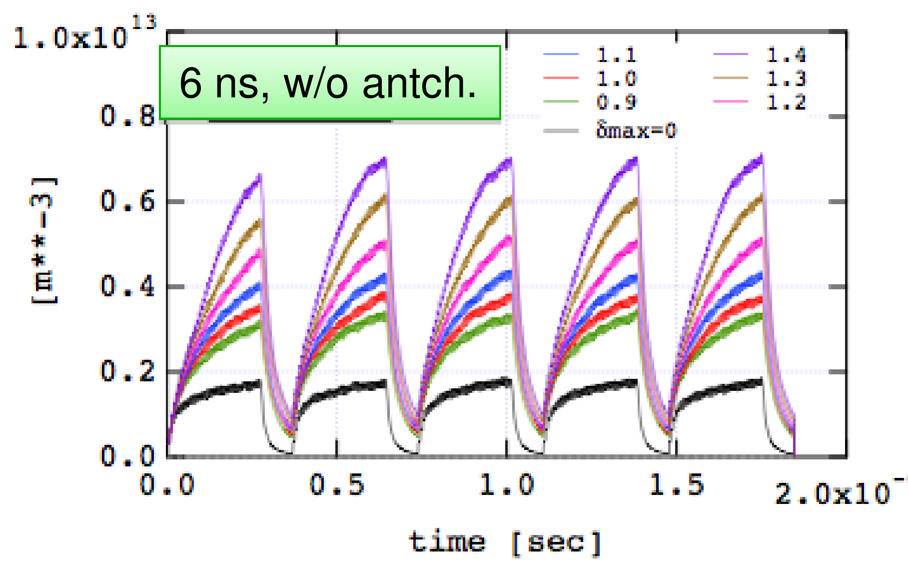
M. Pivi, SLAC

M. Furman LBNL: Bending magnet build-up, DSB3
space-averaged ecloud density



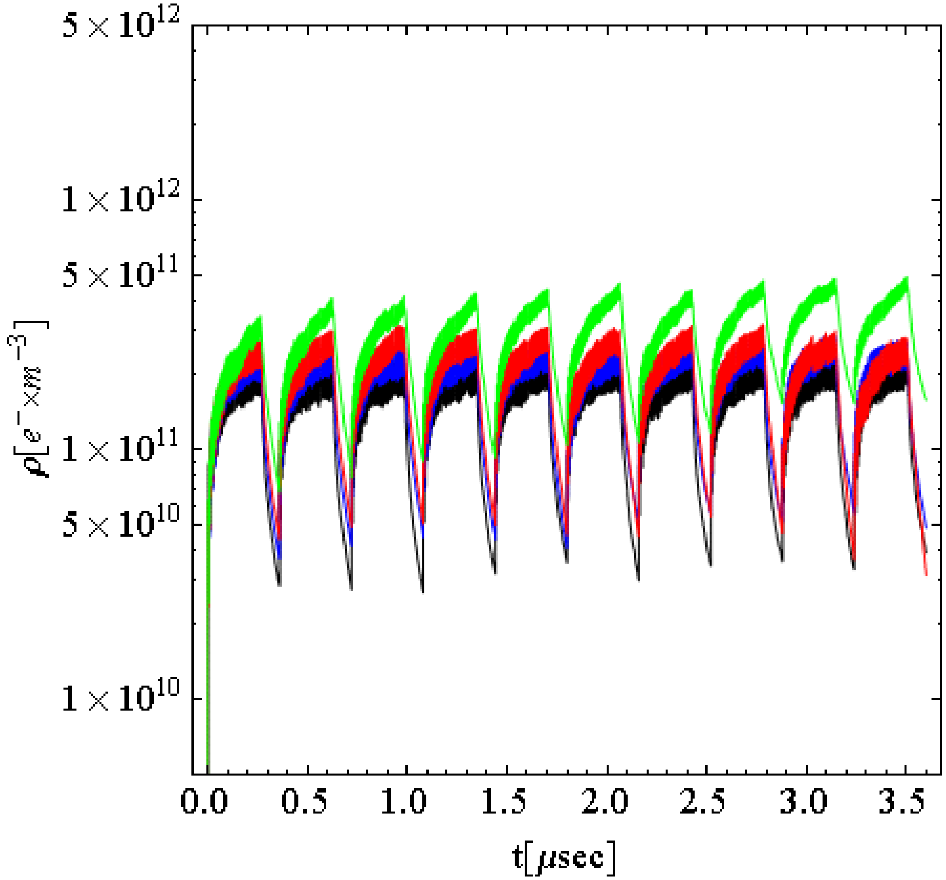




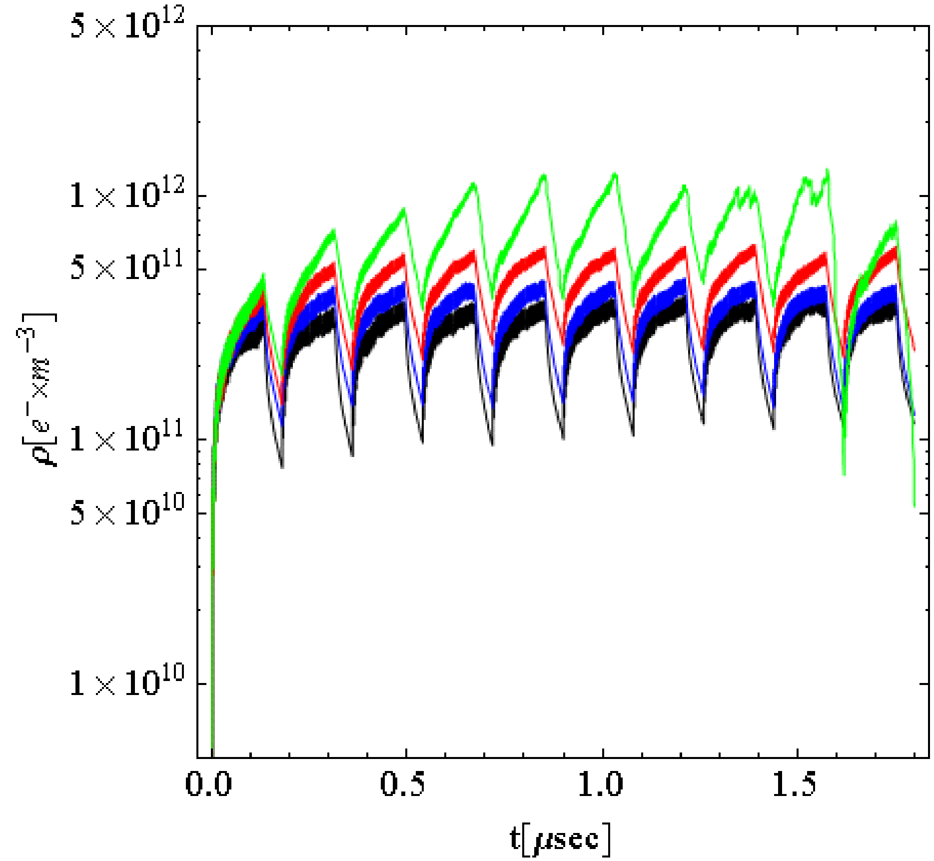


Theo Demma INFN: Average e-cloud density in ILC-DR DSB3 wiggler (η=90%,SEY=1.0;1.1;1.2;1.3)

L_{sep}=6 ns

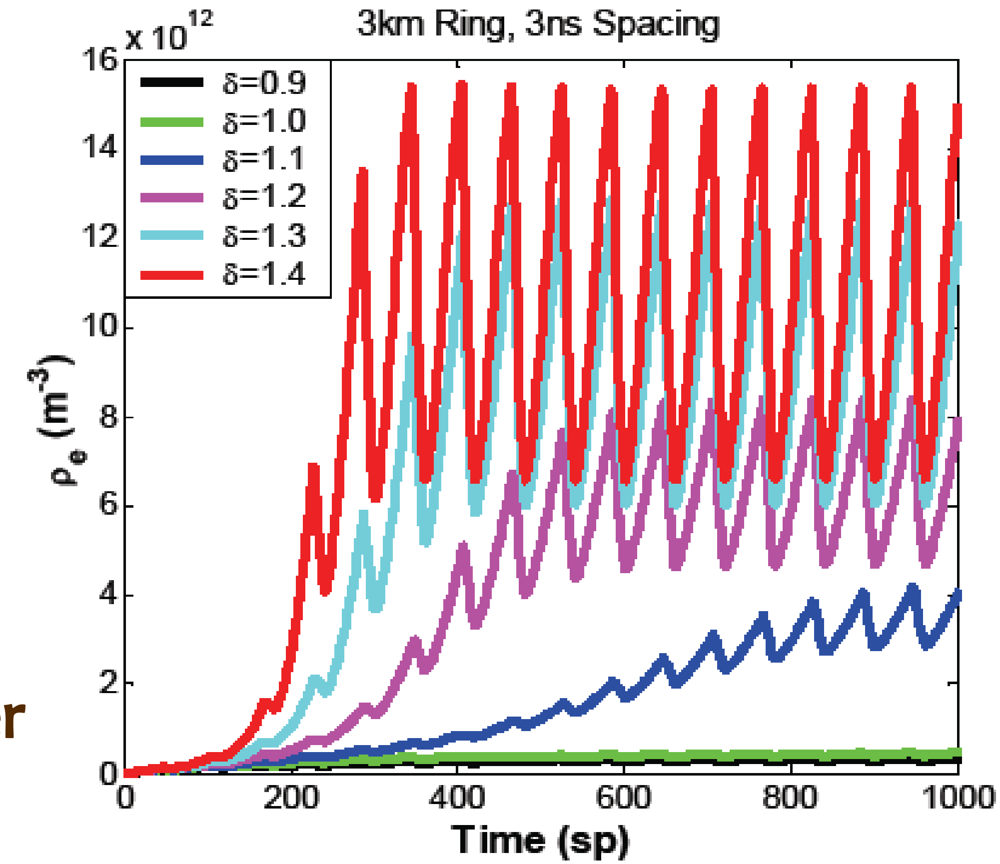


L_{sep}=3 ns



Lanfa Wang SLAC: ILC Quadrupole

Average density



3 ns spacing

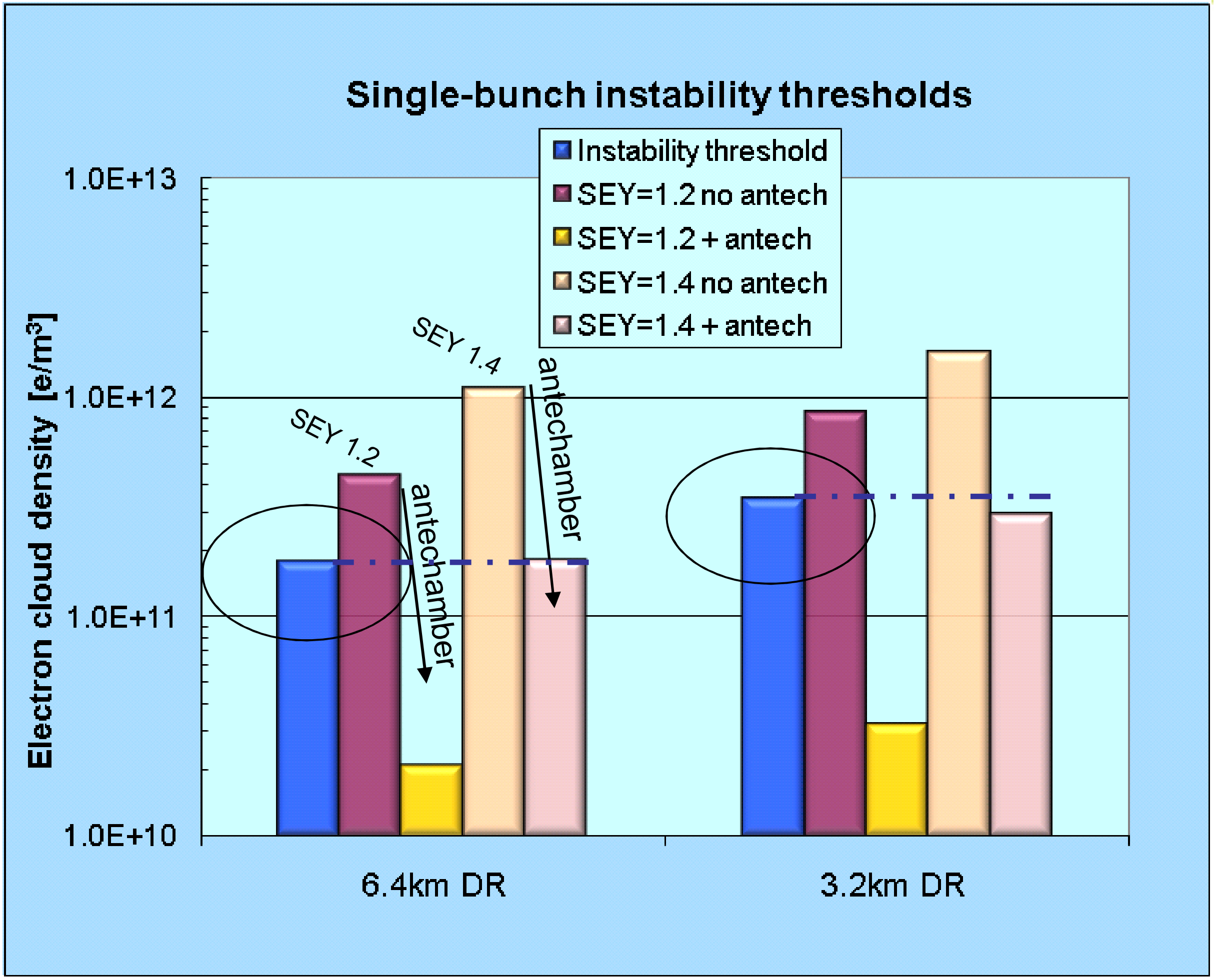
Need SEY~1 or better in quadrupoles with short bunch spacings

Need to understand antechamber role

Comparing bunch spacing: 6ns and 3ns

- Collecting last data from the simulations for the comparison
- Generally though, with 3ns bunch spacing the cloud density is **larger** by a factor 1.5 – 2 with respect to the 6ns bunch spacing.

Compare thresholds for 6 km and 3km DR



Simulation Campaign 2010: cloud density for different SEY compared with the instability thresholds.

Recommendation for Mitigations

GOAL: Select electron cloud mitigation for each of the damping ring regions: drift, quad, sext, bend, wigglers

Identify Criteria for mitigation evaluation:

1) Efficacy of mitigation

2) Costs

3) Risks

4) Impact on Machine Performances

Criteria includes a number of sub-criteria. For example “Costs” includes: Design, Manufacturing, Durability & Maintenance costs, see below

Evaluation of mitigation alternatives

Then identify electron cloud mitigation Alternatives for each region.

Example for BENDs in the DR arcs are:

1) TiN coating

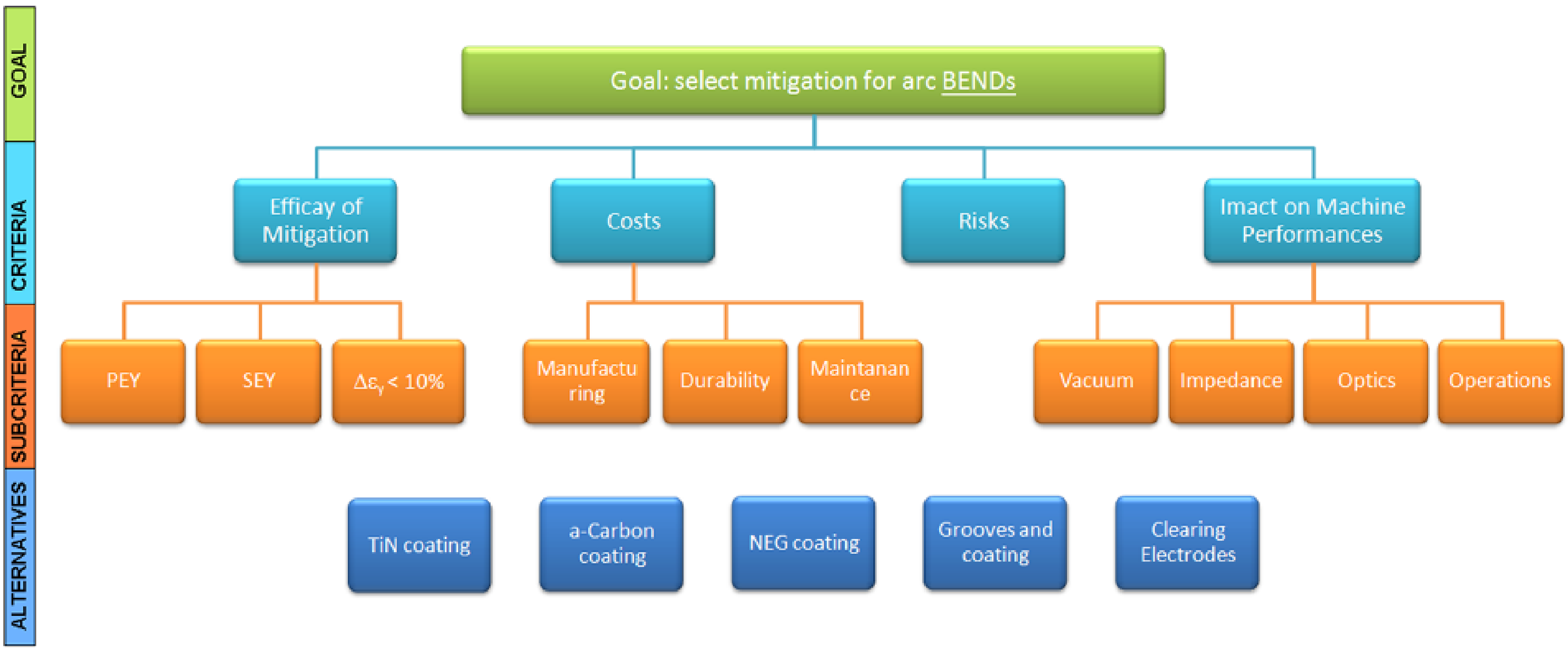
2) amorphous-Carbon coating

3) NEG coating

4) Grooves with coating

5) Clearing electrodes

Recommendation for mitigations in the damping ring.



At tomorrow satellite meeting, we will have a full day to go through and evaluate mitigations for the DR

Recommendation process

- assign a weighting factor to the criteria

Efficacy of mitigation	**0.523**
Costs	**0.095**
Risks	**0.168**
Impact on Machine	**0.214**

- rank the mitigations

	Efficacy of mitigation	Costs	Risks	Impact on Machine
TiN coating	2	0	0	0
C coating	2	0	0	0
NEG coating	1	0	0	1
Grooves & coating	3	-1	-1	-1
Clearing Electrodes	4	-1	-1	-1

Mitigations ranking

ILC DR Mitigation Alternatives ranking

ILC DR	Drift	Quad	Dipole	Wiggler	Notes
Antechamber	**n**	**-**	**-**	**-**	-
Solenoid Windings	**y**	**-**	**-**	**-**	-
Al	**n**	-	-	-	-
Cu	**n**	-	-	-	-
TiN coating on Al	**0.25**	-	-	-	-
Amorphous Carbon coating on Al	**0.23**	-	-	-	-
Diamond Like Carbon on Al	**n**	-	-	-	-
NEG coating on Al	**0.275**	-	-	-	-
Rectangular Grooves w/TiN on Al	**0.23**	-	-	-	-
Triangular Grooves w/TiN on Al	**n**	-	-	-	-
Clearing Electrode	**n**	-	-	-	-

Example: select mitigation in BENDs

The assumptions for each evaluation will be attached to an executive summary document in preparation:

- ## Efficacy of Mitigation

Measurements of the secondary electron yield of several coating and groove samples installed in situ in accelerator beam lines have been made. Typically the sample SEY is monitored before the installation in the beam line and after periods of beam conditioning. In field-free regions, TiN and a-Carbon thin film coatings show the measured secondary emission yield values just lower than unity after conditioning. NEG coating measured SEY values are slightly larger than unity after activation and conditioning. Rectangular grooves coated with TiN show SEY values well below unity and as low as 0.6.

TiN and a-Carbon coated chambers installed in a beam line, measured close values of electron cloud current which indicate close performances [CesrTA]. Experimental test chambers using inserts with coatings, triangular grooves coated with TiN or clearing electrodes was installed in bend magnet regions of an accelerator beam line [KEKB]. Grooves had shown a reduction of a factor ~10 with respect to just TiN coating, while clearing electrodes had shown a reduction of a factor ~10 with respect to grooves. Note that a second test in a different region showed a smaller beneficial effect of grooves with respect to TiN.

- ## Costs

The costs of coating chambers either with TiN, Carbon or NEG should be relatively close. Chambers with a groove profile require additional costs while clearing electrodes are the most expensive in terms of design, manufacturing and installation.

Durability of TiN is good as measured from stoichiometry ration from samples extracted from a vacuum chamber installed in a machine after 10 years of operation at high Ampere□hour values. NEG coating requires re-activation cycles with additional costs.

Select electron cloud mitigation in BENDs

- **Risks**

  Chambers with small depth grooves in the mm scale to fit into the dipole chamber aperture might be challenging to manufacture. Clearing electrodes and interconnections might also be a manufacturing challenge for the > 2m long DR magnets.

- **Impact on machine Performances**

  TiN coating has a low impact on machine performances with respect to vacuum, and impedance. Amorphous-carbon coating may impact vacuum by photo-desorption and outgassing with slightly larger presence of carbon oxides in high synchrotron radiation regions. NEG coating has pumping capability with a positive impact on vacuum performances but requires re-activation cycles after its saturation, which may imply additional maintenance periods.

  In bend magnets, chambers with a groove profile have a small impact on the beam impedance since grooves are only needed on the top and bottom portion of the chamber and for the limited length of the magnet. Thus, it has been computed that an increase in beam impedance by < 2% has to be account for grooves in the bend magnets [Lanfa simulations].

Next for the Damping Ring Working Group

- Benchmarking with CesrTA experimental data
- 3D synchrotron radiation simulations are underway
- Then … re-do build-up simulations with new SR data
- Study details of steady emittance growth at low cloud densities
- Integration of the CesrTA results into the DR design

Summary

- Comparison between 6ns and 3ns bunch spacing is almost completed.
- Need for antechamber designs either in 6km and 3km DR
- Satellite meeting to evaluate mitigations for the DR and give recommendation

Summary

- With respect to the baseline of 6km ring, the risk level for adopting a reduced 3km Damping Ring while maintaining the same bunch spacing is: Low.
- The acceptable surface Secondary Electron Yield (SEY) may strongly depend on issues not yet thoroughly investigated such as beam jitter and steady **incoherent emittance growth**. Refined estimations of the photoelectron production rate by simulations will better define the maximum acceptable SEY.

Risks Assessment

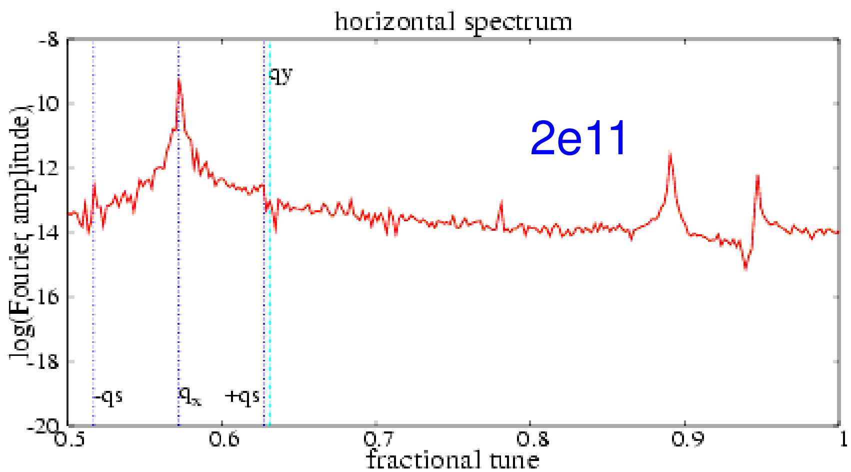
- Reducing the positron ring circumference to 3-km eliminates the back up option of 12 ns bunch spacing (safer e- cloud regime) and may reduce the luminosity margins.

- In the event that effective EC mitigations cannot be devised for a 3km damping ring, an option of last resort would be to add a second positron damping ring.

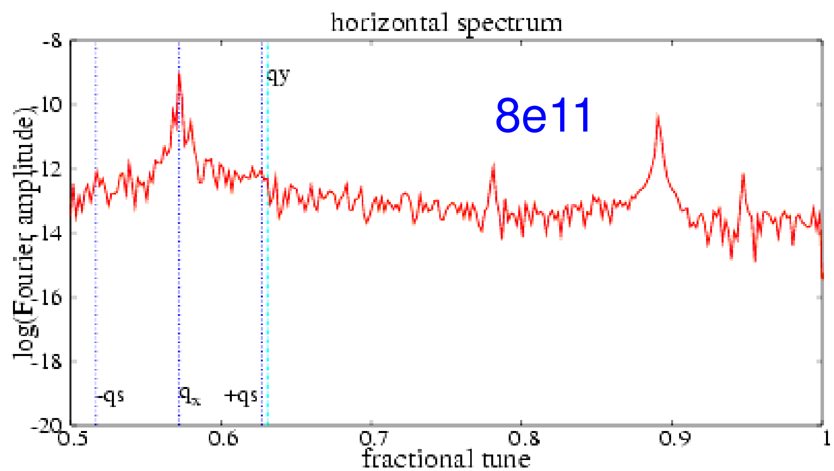
Thank you!

Back-up

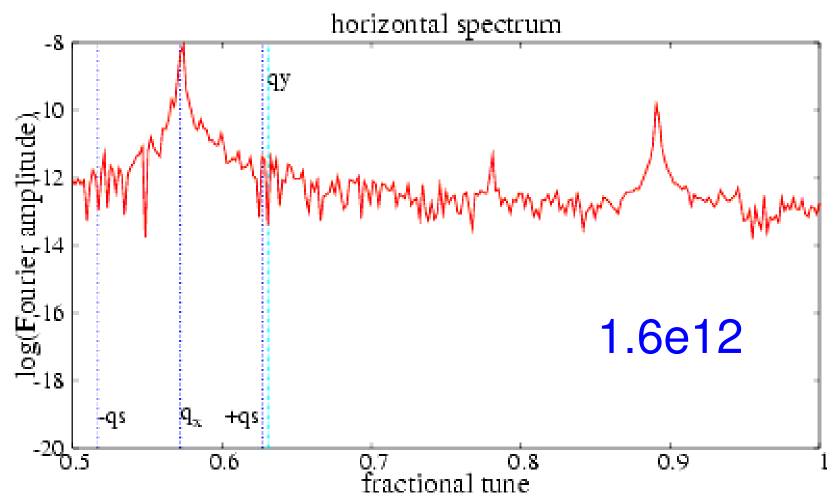
Single-bunch simulations - Horizontal Tune



Single-bunch simulations: Qx peak **doesn't split** neither shift.



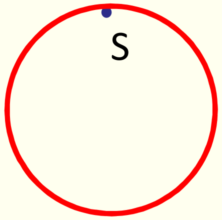
then, is the experimentally observed Qx peak line splitting due to **multi-bunch effect?** as Gerry suggestion ...



Intrabeam scattering: Monte Carlo tracking simulation

- The lattice is read from a MAD (X or 8) file containing the Twiss functions.

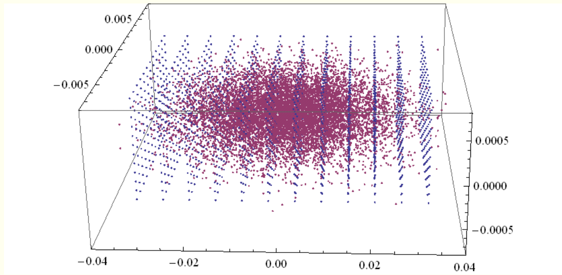
- A particular ring location is selected as an IBS Interaction Point (S).



- 6D macroparticles coordinates are extracted randomly from a **Gaussian** distribution generated at the chosen location S.

- The **IBS routine** *(Binary Collision Algorithm)* is called once per turn at S, recalculated at each turn using different random number seeds:

    - Beam macroparticles are grouped in cells
    - Macroparticles inside a cell are coupled
    - Momentum of particles is changed due to scattering

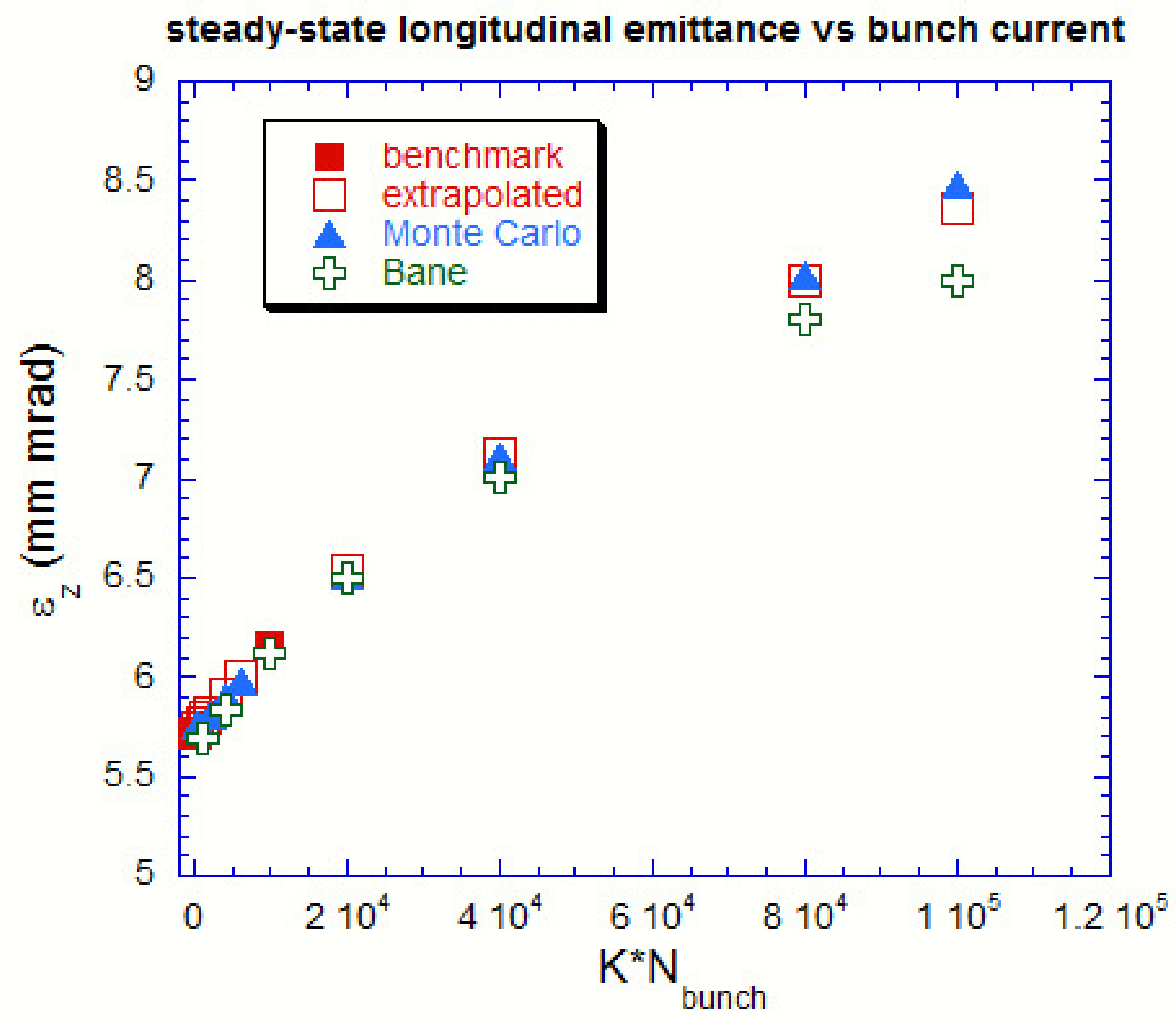


- **Radiation damping** and **quantum excitation** are evaluated at each turn at S

- Macroparticles are tracked through a 1-turn 6D R matrix starting from S for as many turns as needed

- Invariants of particles and corresponding growth rates are recalculated at S each turn

IBS: ε_z vs I



MacroParticleNumber=40000

NTurn=1000 (≈10 damping times)

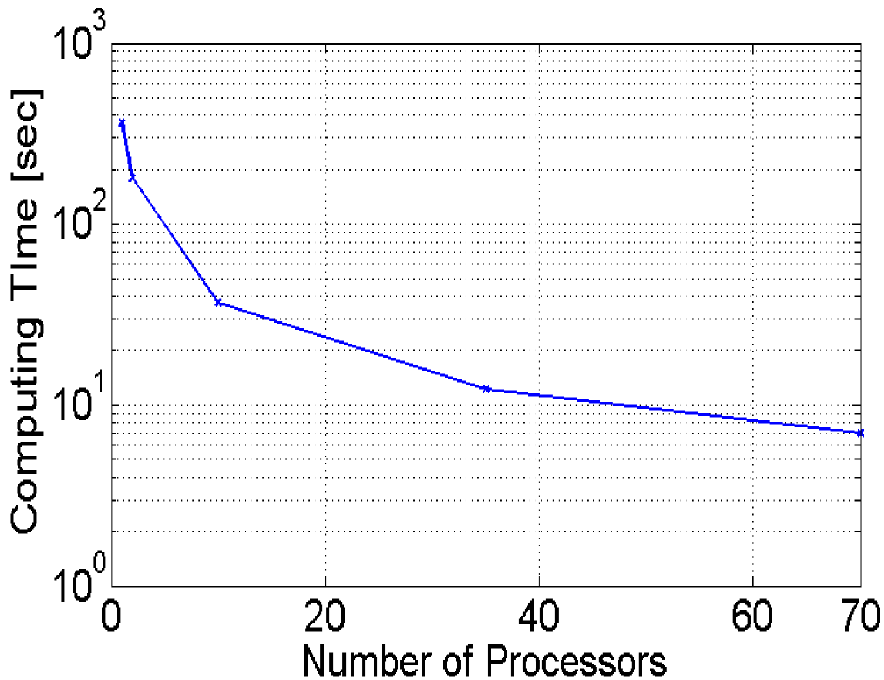
σ_z=12.0*10^{-3}
δp=4.8*10^{-4}

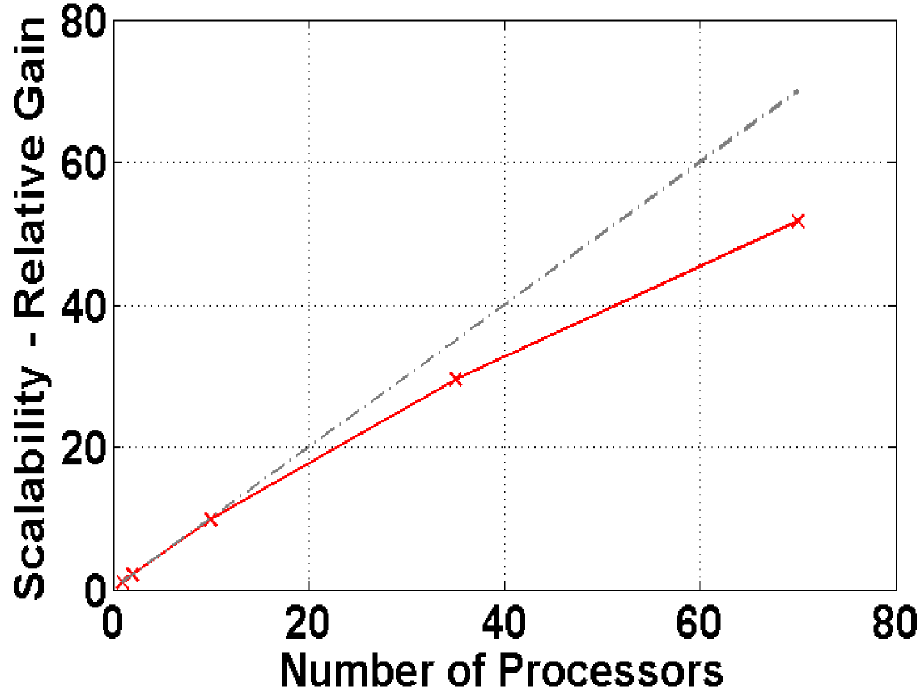
ε_x=(5.63*10^{-4})/γ
ε_y=(3.56*10^{-5})/γ

τ_x = 1000^{-1} * 42.028822 * 10^{-3}
τ_y = 1000^{-1} * 37.161307 * 10^{-3}
τ_s = 1000^{-1} * 17.563599 * 10^{-3}

Scalability of multi-processors computation

- CMAD uses a number of processors equal to the number of bunch slices, typically ~100.
- Very **high gain** in simulation speed.





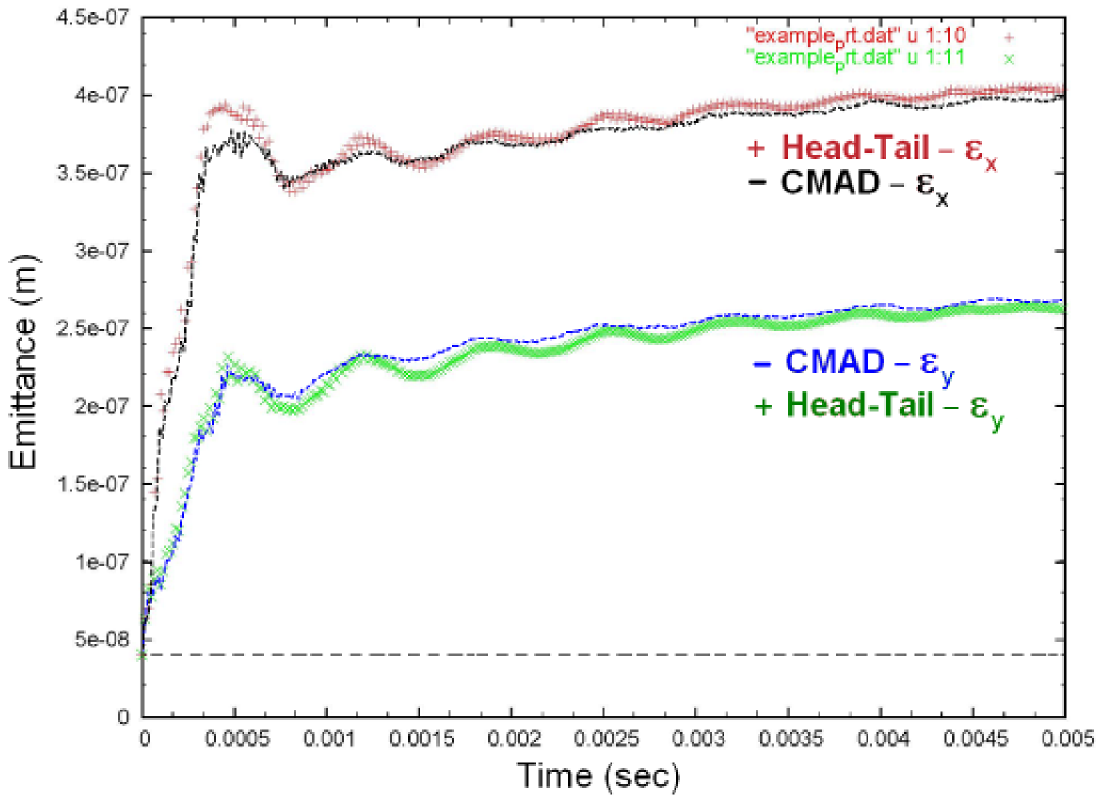
(Left) Time for computing 1 turn in LHC. (Right) Almost linear with number of processors.

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)

- Hea er codes,
  ex .



Benchmarking SPS example with 1 IP station/turn and cloud density 1e12m^3.

Codes benchmarking

- Compare with Head-Tail (CERN) and WARP (LBNL)
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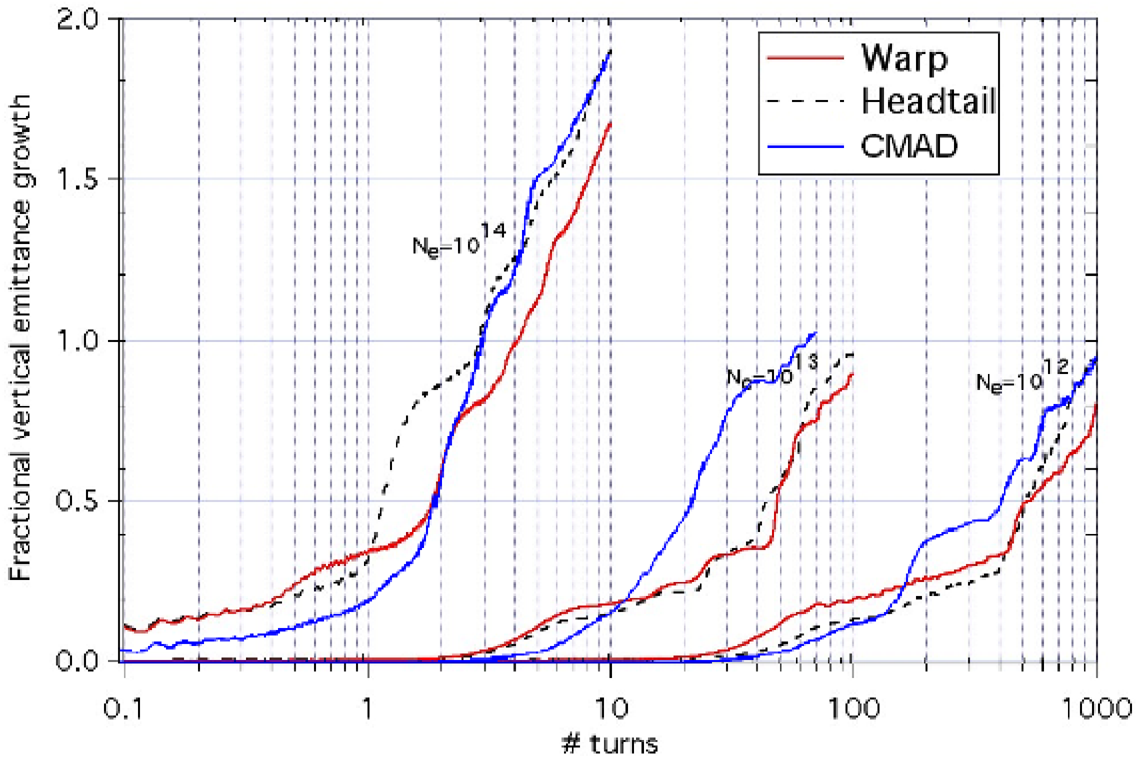
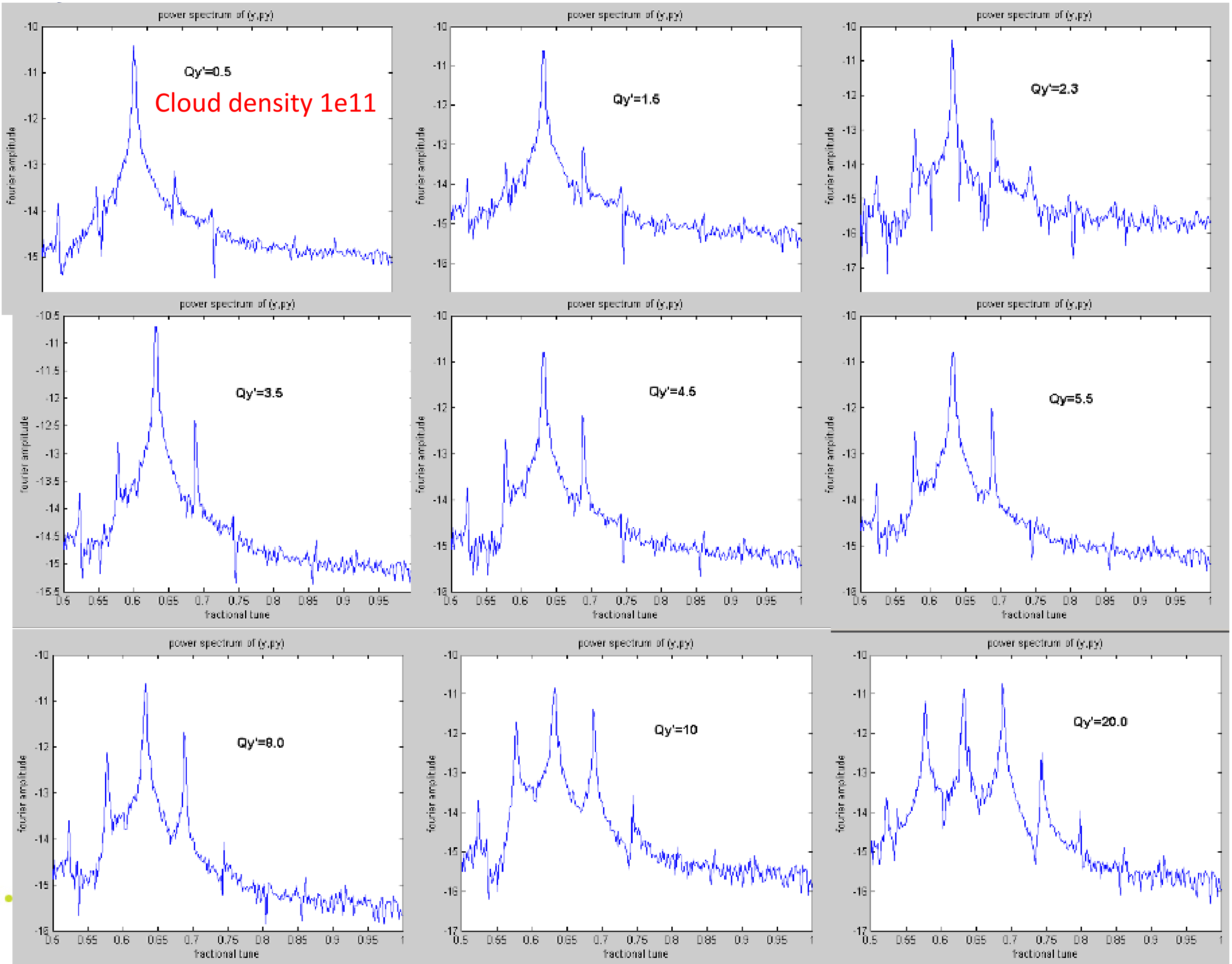
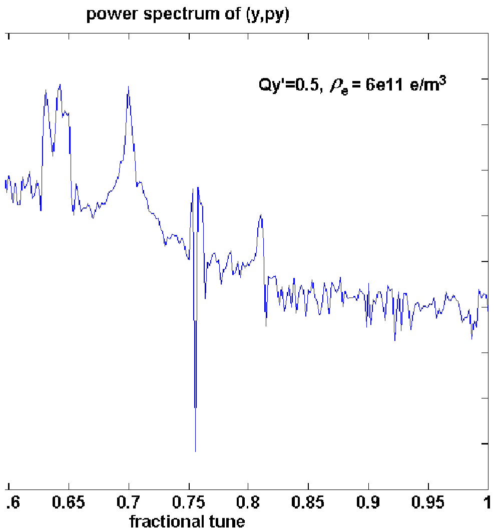
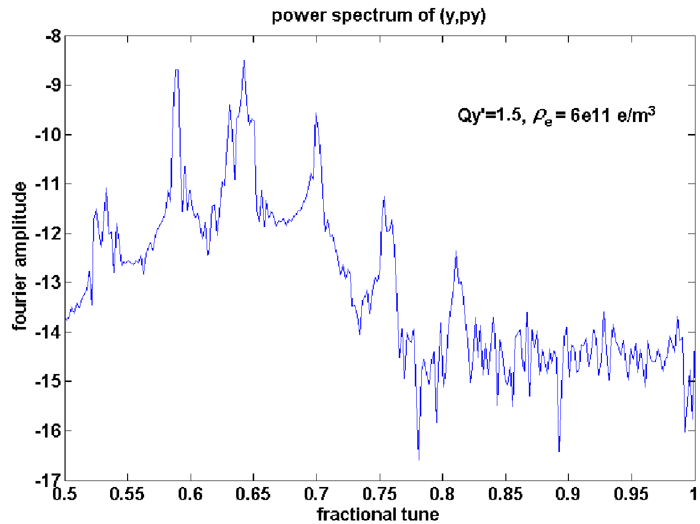


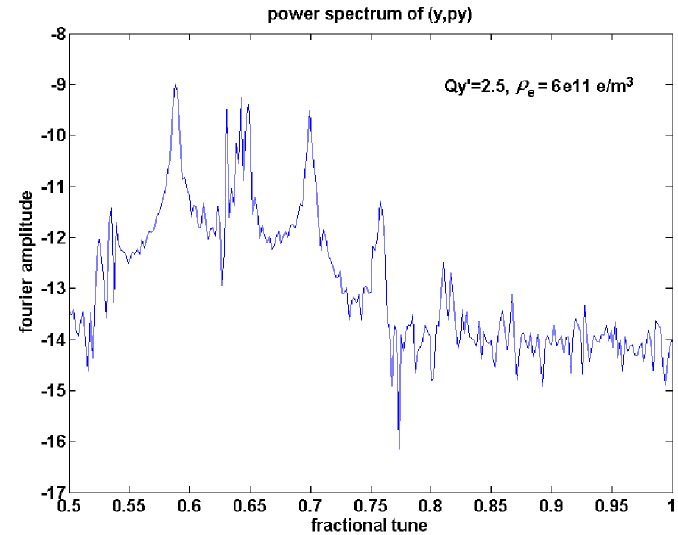
Benchmarking 100 IP stations/turn. LHC with cloud density 1e12 to 1e14m^-3. 2008 simulations results. Constant beta function. Magnetic free region.



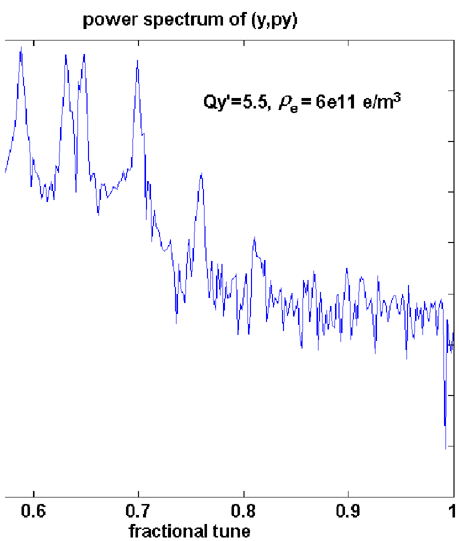
Cloud density 1e11
power spectrum of (y,py)
fourier amplitude
fractional tune
Qy'=0.5
Qy'=1.6
Qy'=2.3
Qy'=3.5
Qy'=4.5
Qy=5.5
Qy'=8.0
Qy'=10
Qy'=20.0

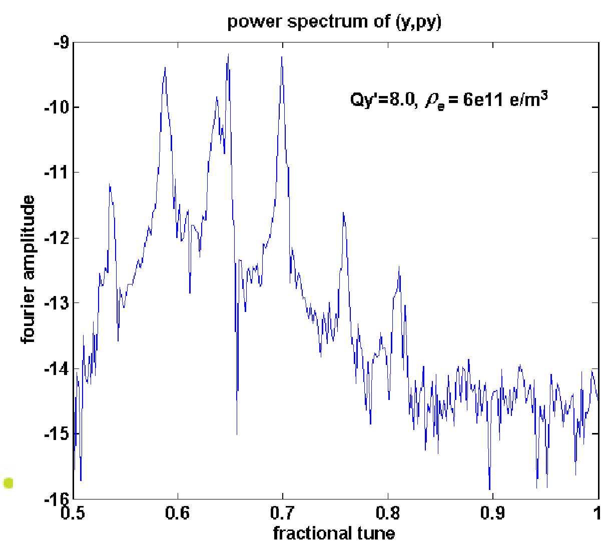


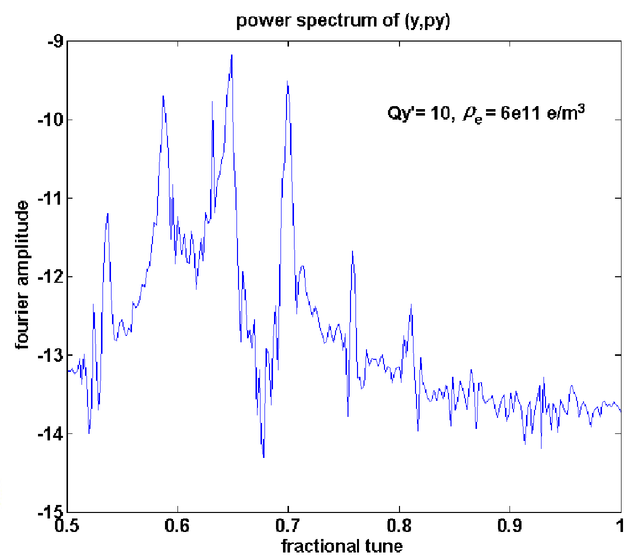




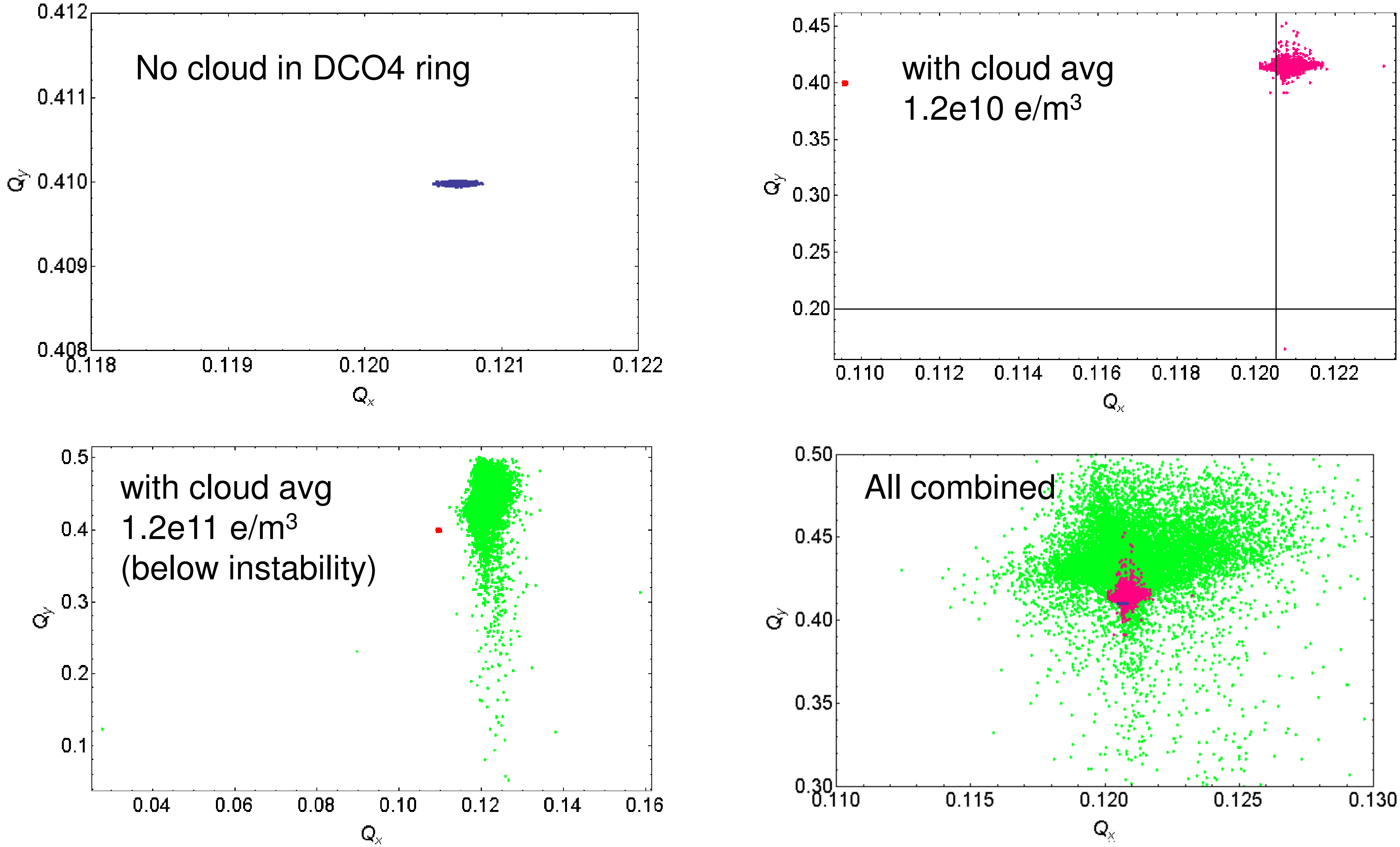
Cloud density 6e11







Incoherent tune shift in DCO4 DR



Plotting the tunes of selected particles in the beam

CMAD

M. Pivi, SLAC