Single-bunch Instability Simulation in CesrTA

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IWLC2010

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CERN

Instability simulation code CMAD

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

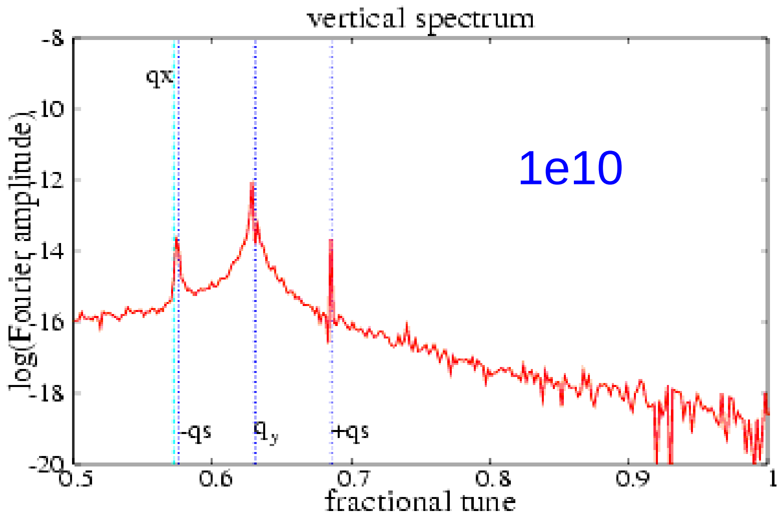
- full **ring lattice representation from MAD**
- interaction beam - cloud is computed at every element in the ring lattice: **933 "stations" in CesrTA**, 11,735 in ILC DR
- Parallel code needed! typically ~100 processors (NERSC)
- Particle in cell PIC code.
- 0.3 M macro-particles for beam.
- Self-consistent 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.

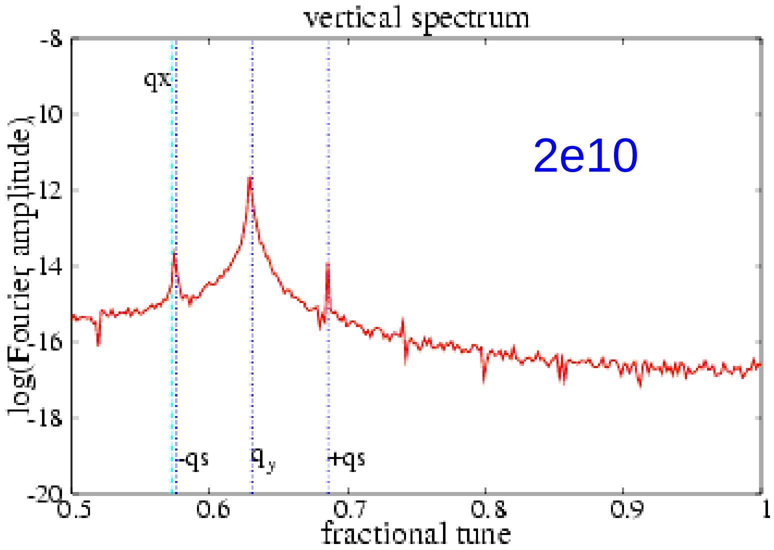
parameters – CesrTA

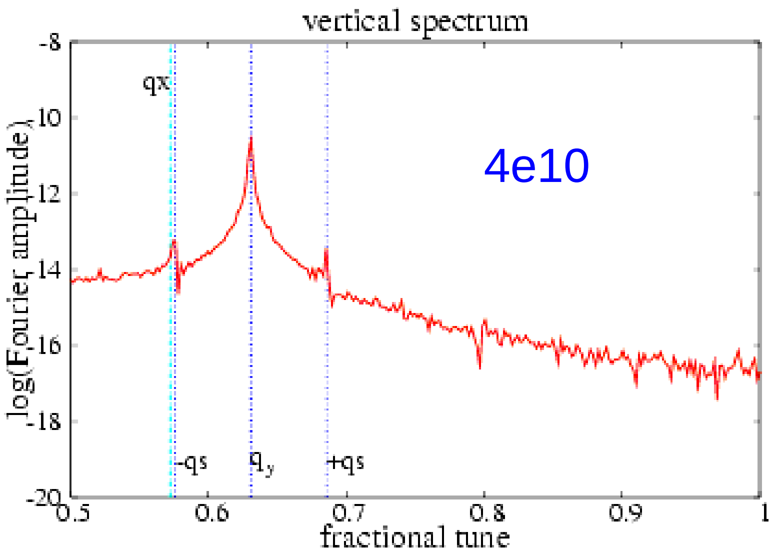
CesrTA simulations:

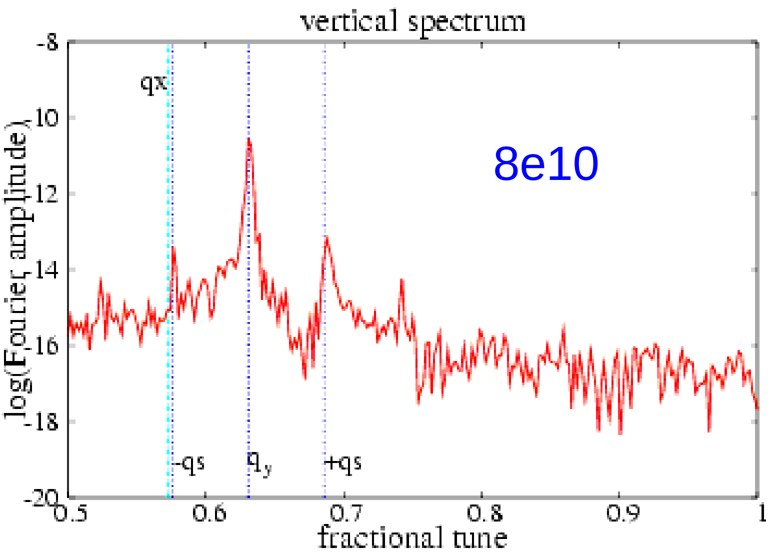
- Chromaticites 0.6 (x) and **2.3** (y)
- Cloud **uniformly distributed** over **all elements**
- **CesrTA lattice** file: cta_2085mev_20090516.**mad**
- Tune obtained from tracking without cloud -
  Qx = 0.5722   Qy = 0.6308 ν_s = 0.055
- Bunch Current = 1.0 mA (1.6e10 e+/bunch)
- Feedback OFF
- All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

CesrTA lattice with cloud densities ~e10/m^3

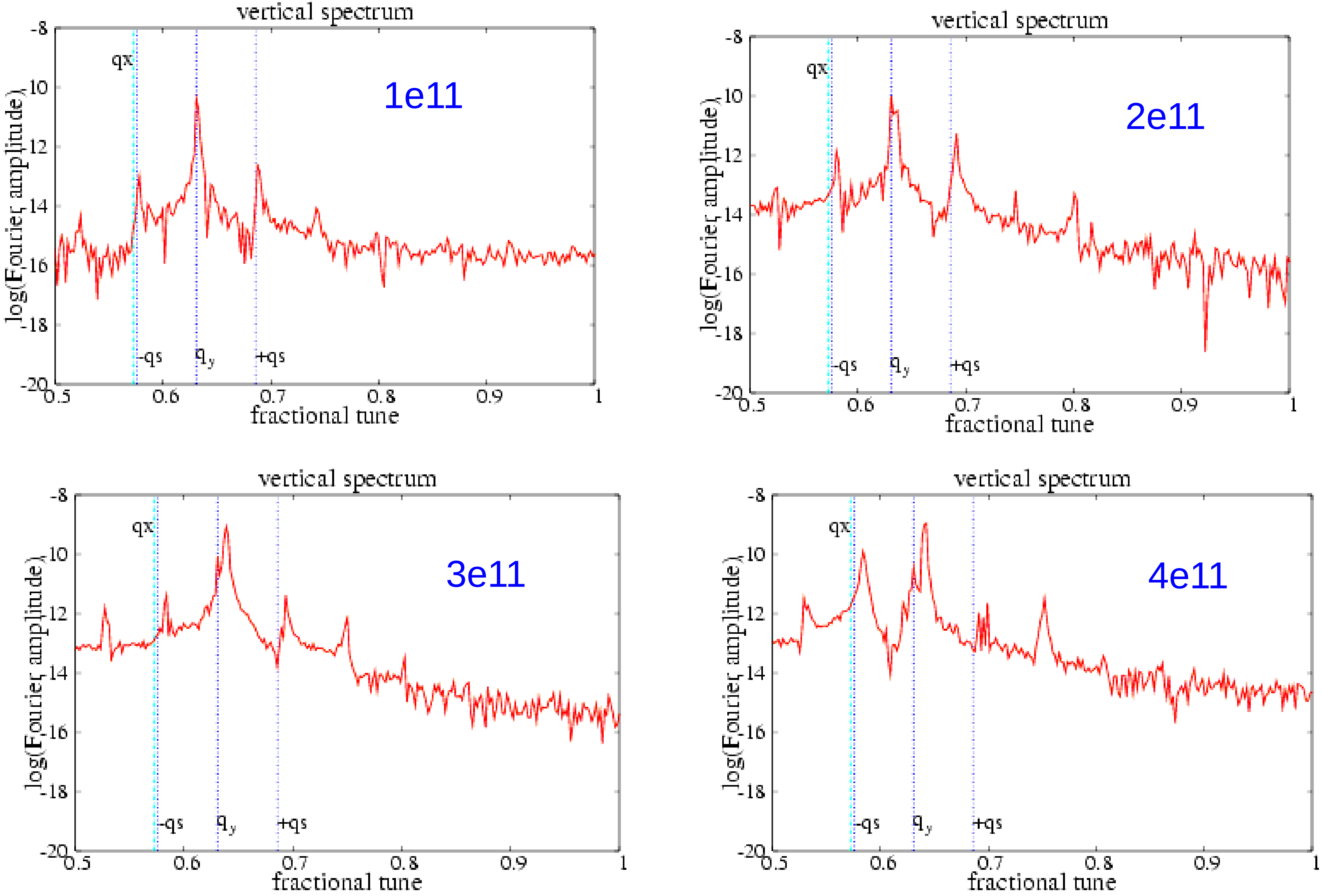




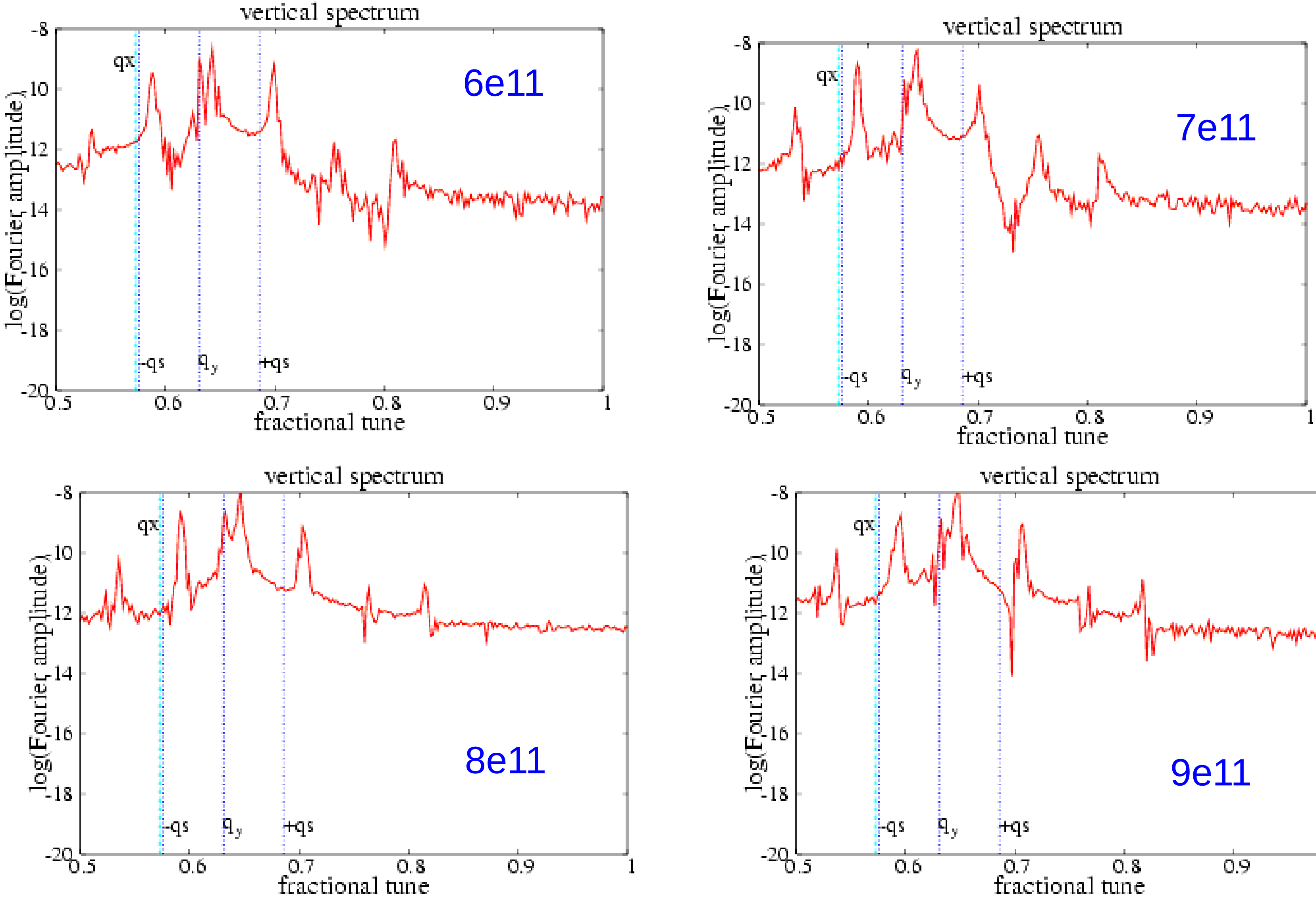




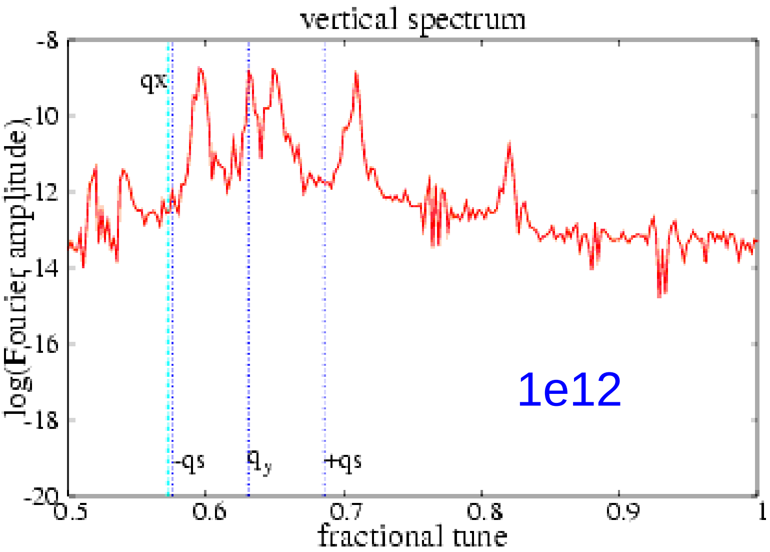
CesrTA lattice with cloud densities ~ e10/m^3

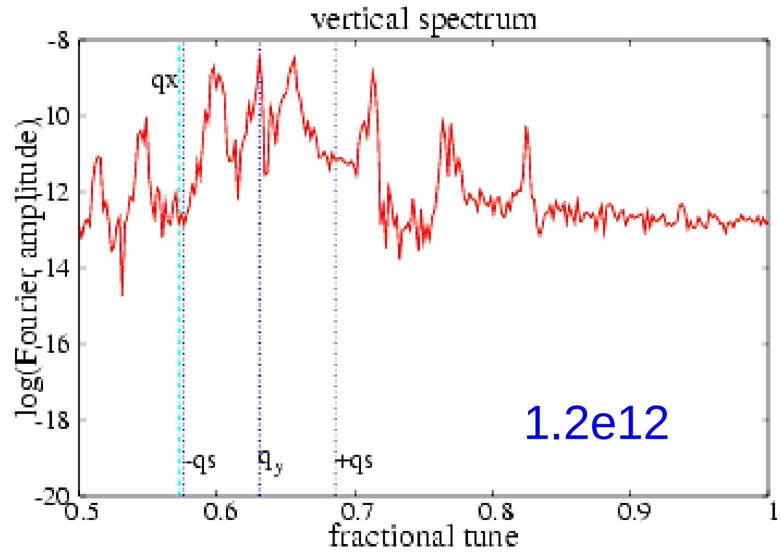


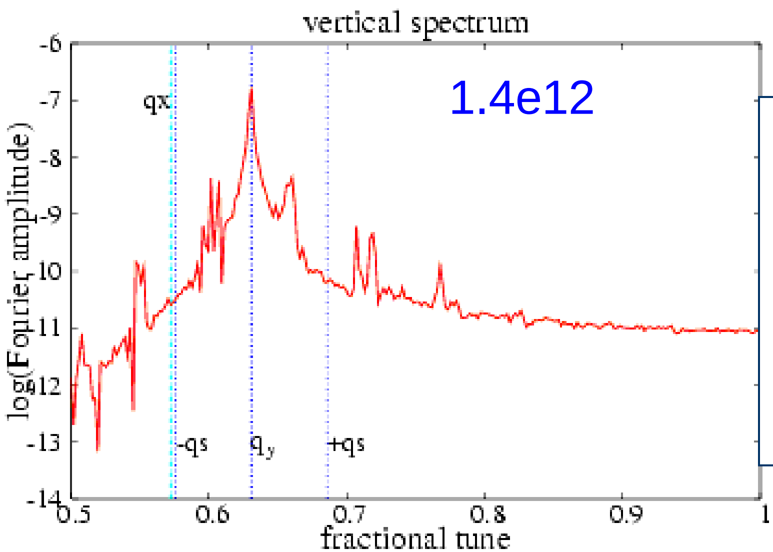
cloud density ~ e11/m³ (contd)

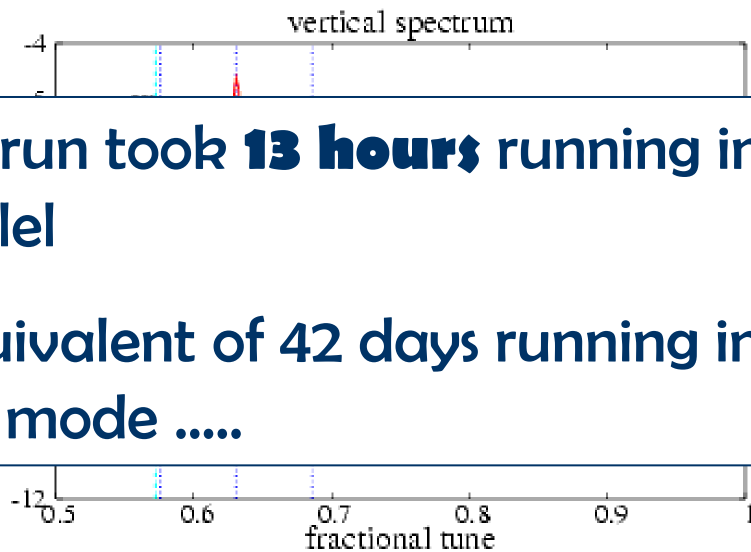


cloud densities ~ e12/m^3





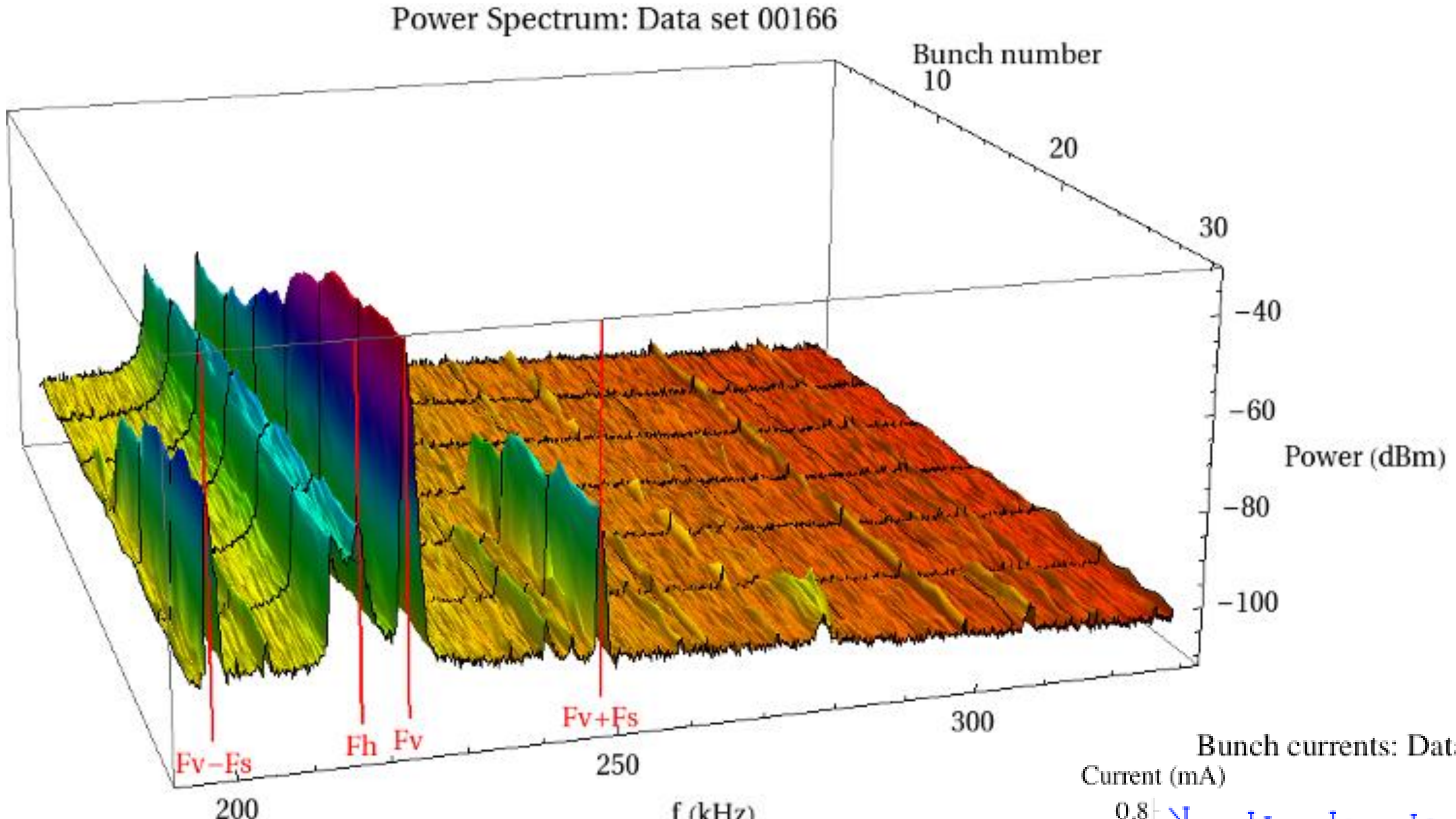


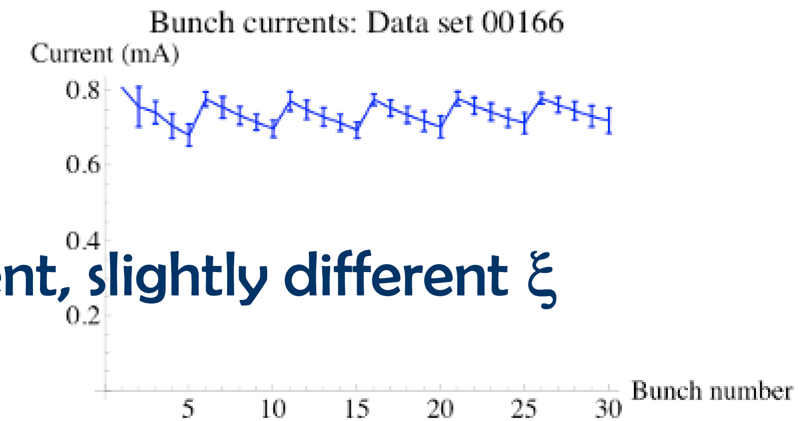


Each run took **13 hours** running in parallel

... equivalent of 42 days running in serial mode .....

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



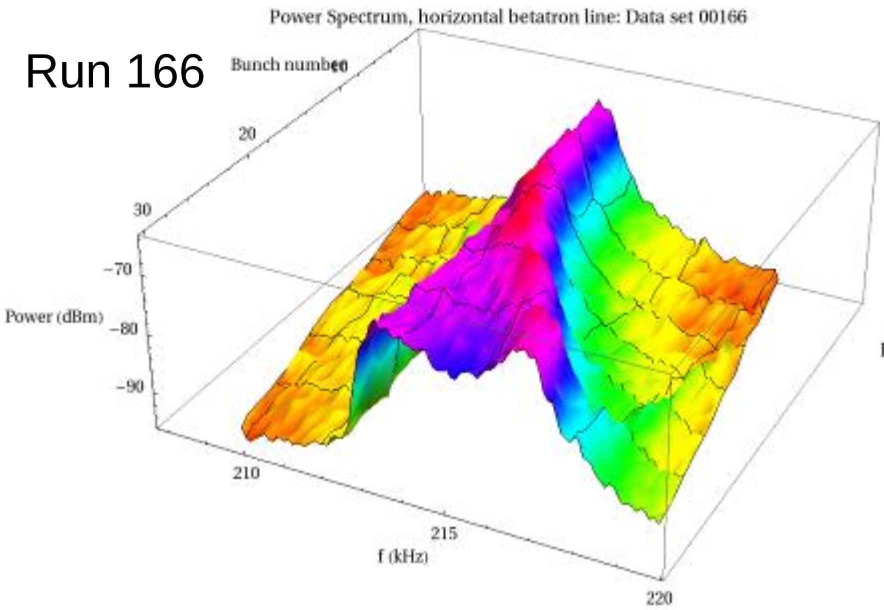


(H,V) chrom = (1.33,1.155)
Avg current/bunch 0.74 mA.

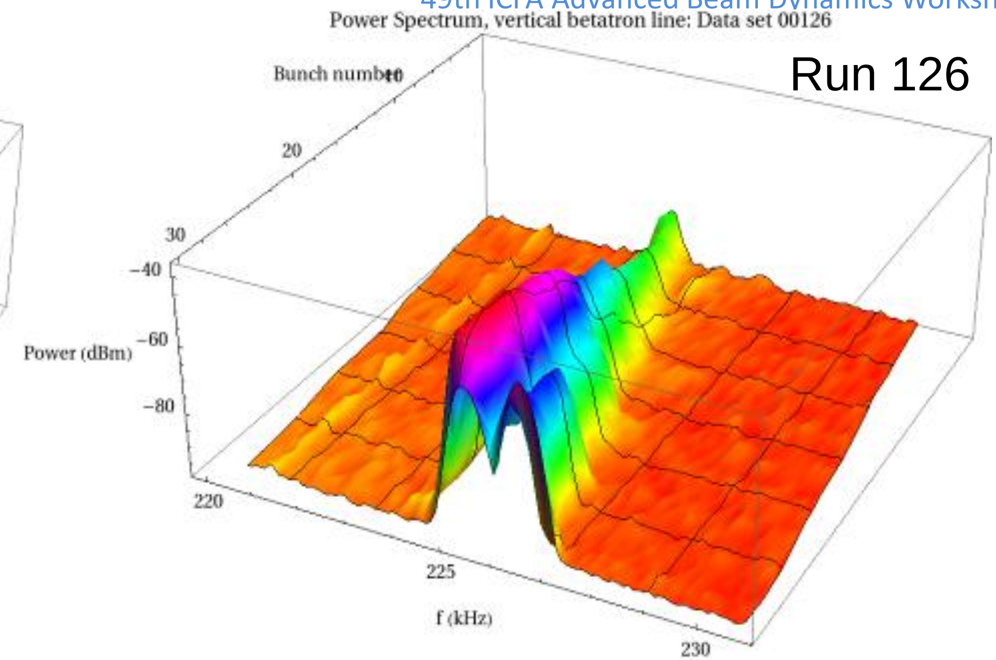
25% less current, slightly different ξ

Detailed features of horizontal and vertical lines

Run 166



Run 126

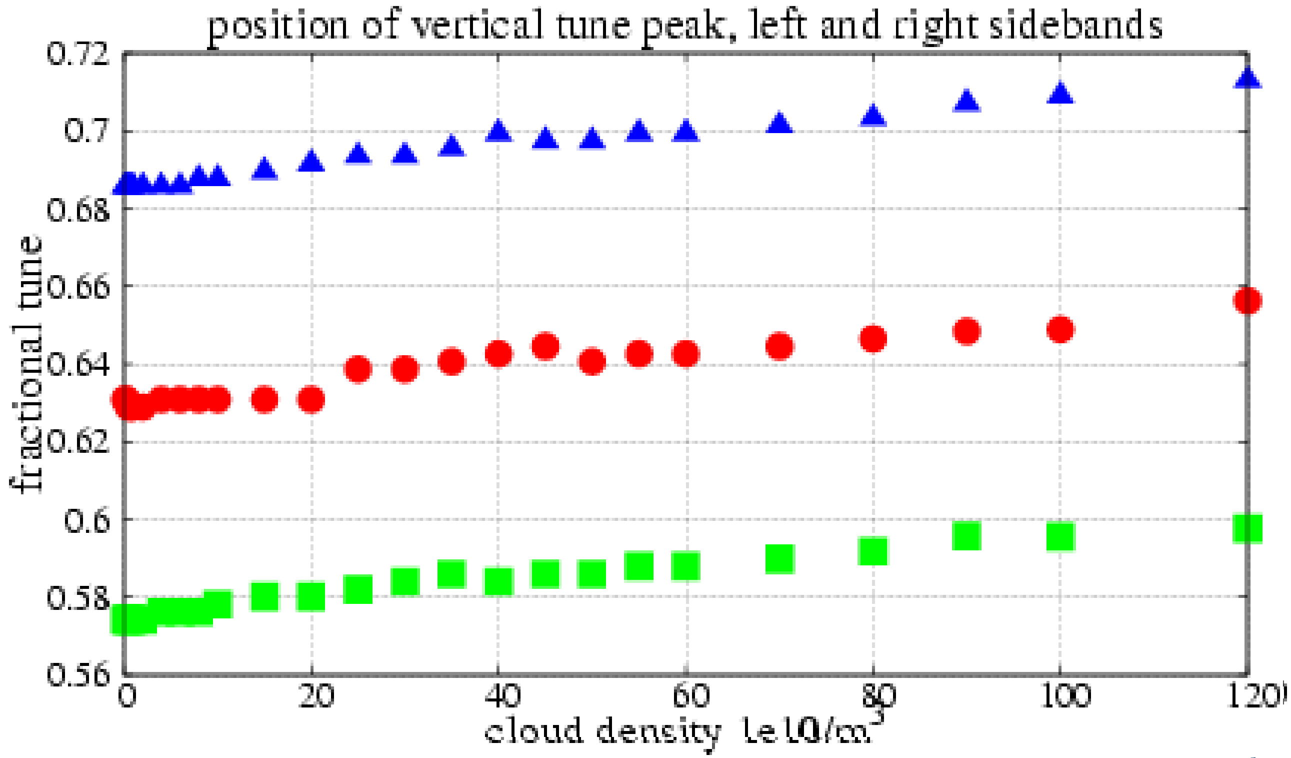


Lower frequency (~3 kHz) shoulder in the horizontal tune spectrum is attributable to known dependence of horizontal tune on the multibunch mode.

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

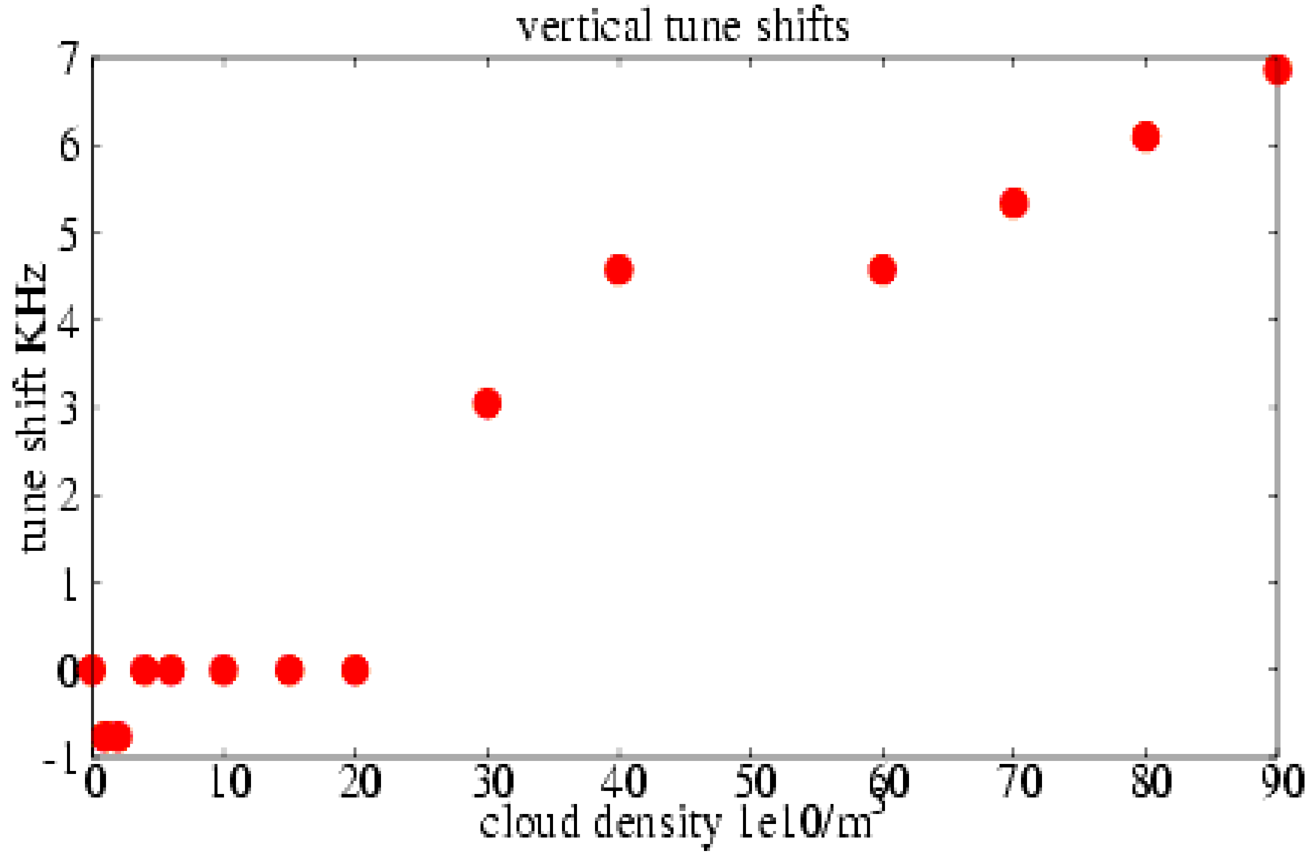
summary of peaks and sidebands



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

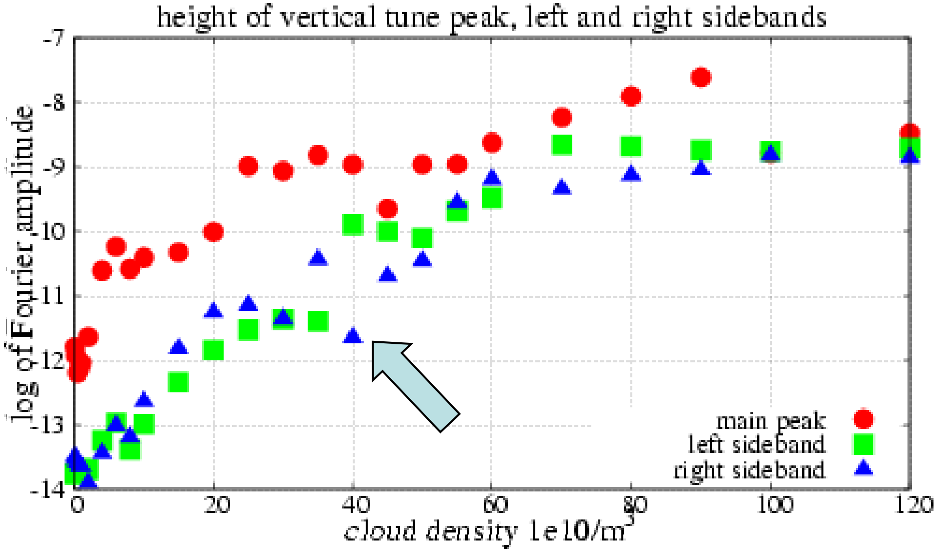


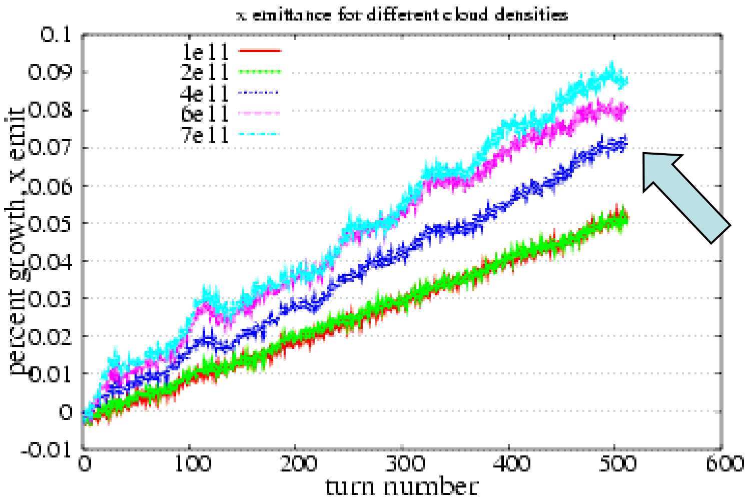
Simulated Tune shift above is larger then in experiments.

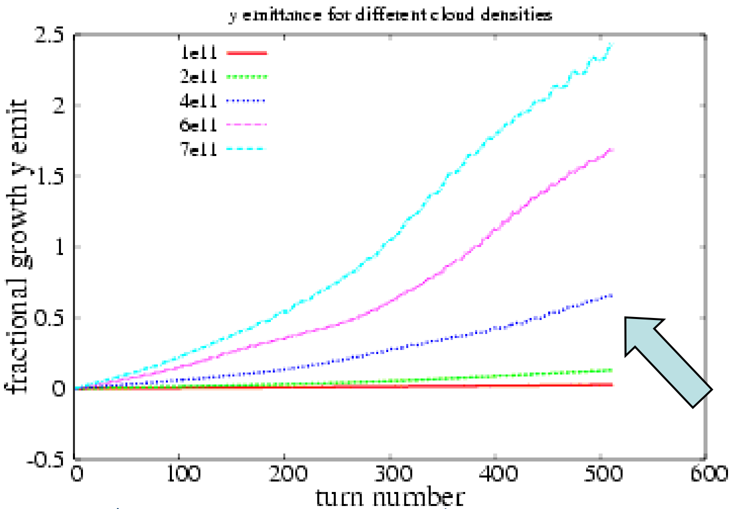
Next: Load cloud densities and distributions based on element type – especially for dipoles and quads

summary of peaks and sidebands

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

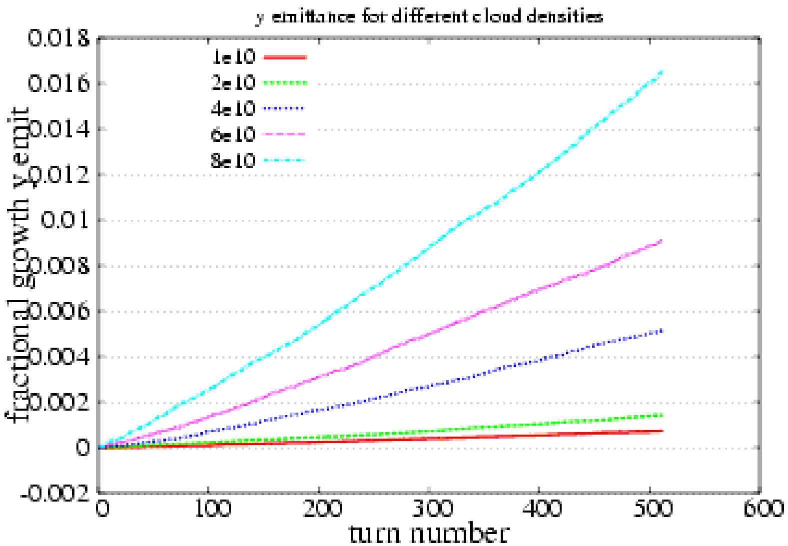


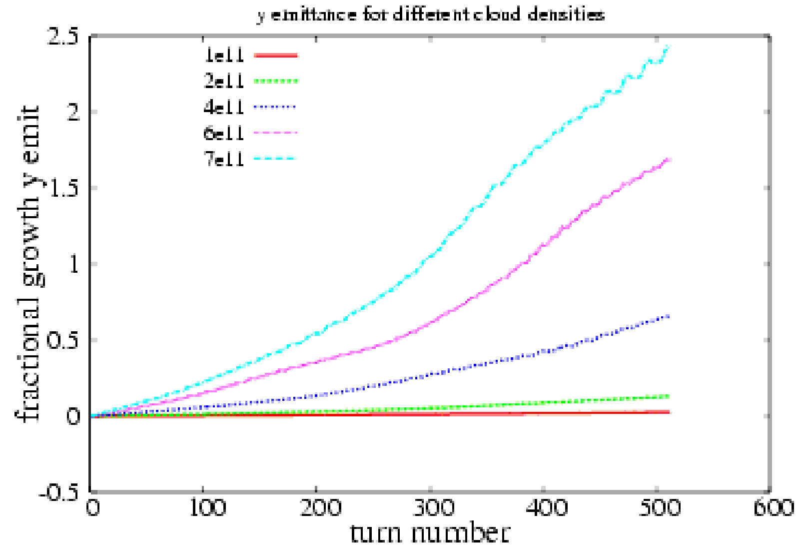




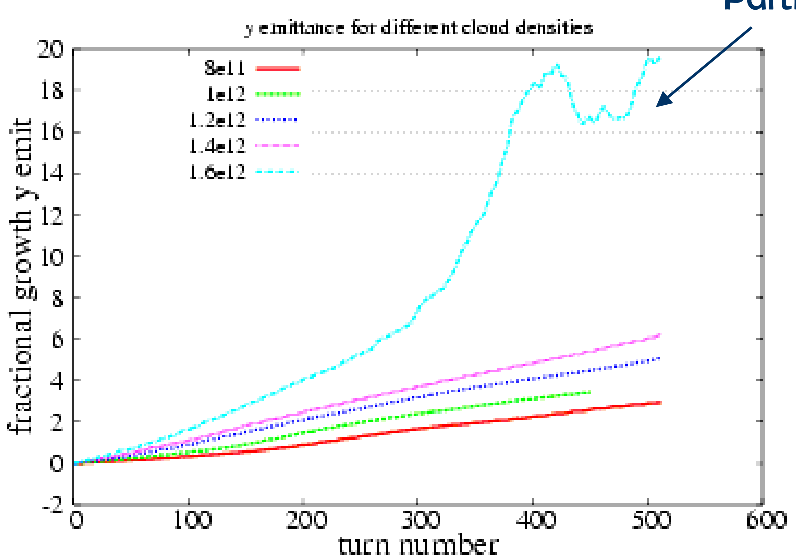
Horizontal and Vertical emittance, "transition" at ~4e11/m³

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

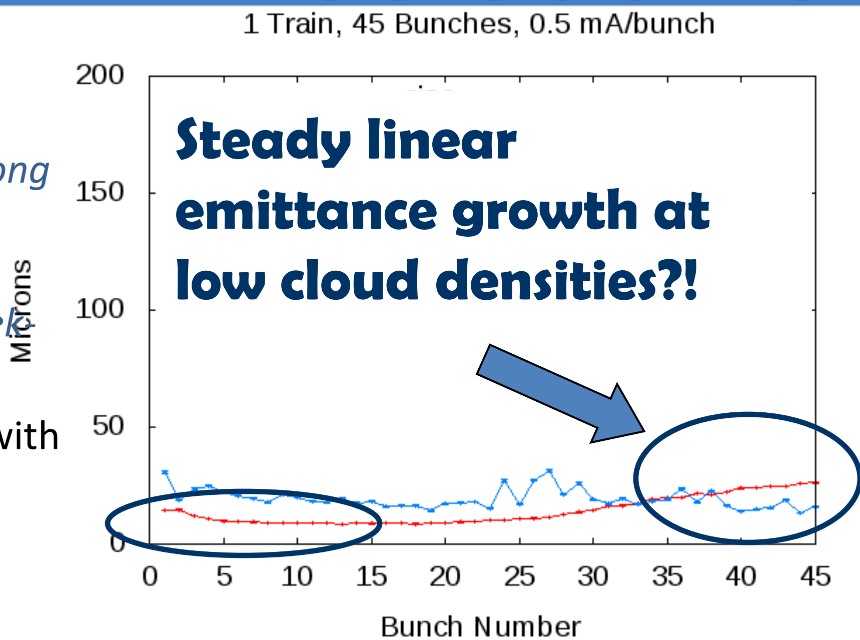
Table 2: Threshold of the ILC damping ring and other rings

		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

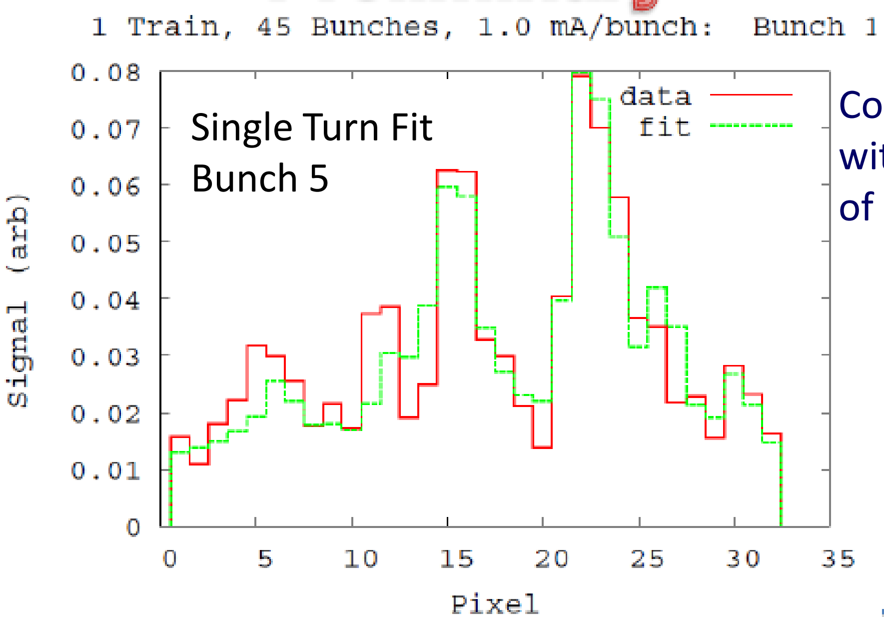
High $\omega_e\sigma_z/c$ characterizes low emittance ring.

Beam Size

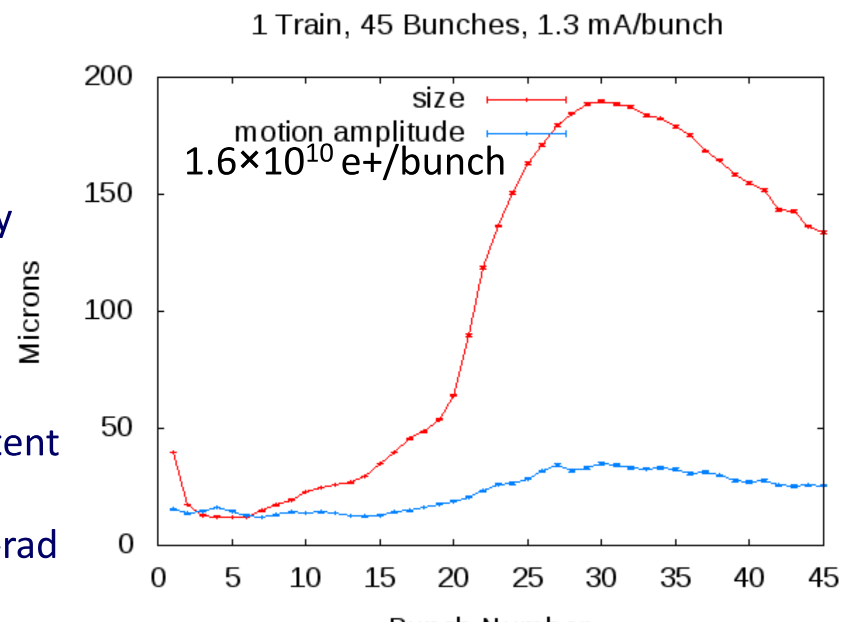
- Measure Bunch-by-Bunch Beam Size
  - Beam size enhanced at head and tail of train
    Source of blow-up at head appears to be due to a long lifetime component of the cloud (Dugan talk)
    Bunch lifetime of smallest bunches consistent with observed single bunch lifetimes during LET (Touschek-limited)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



Preliminary

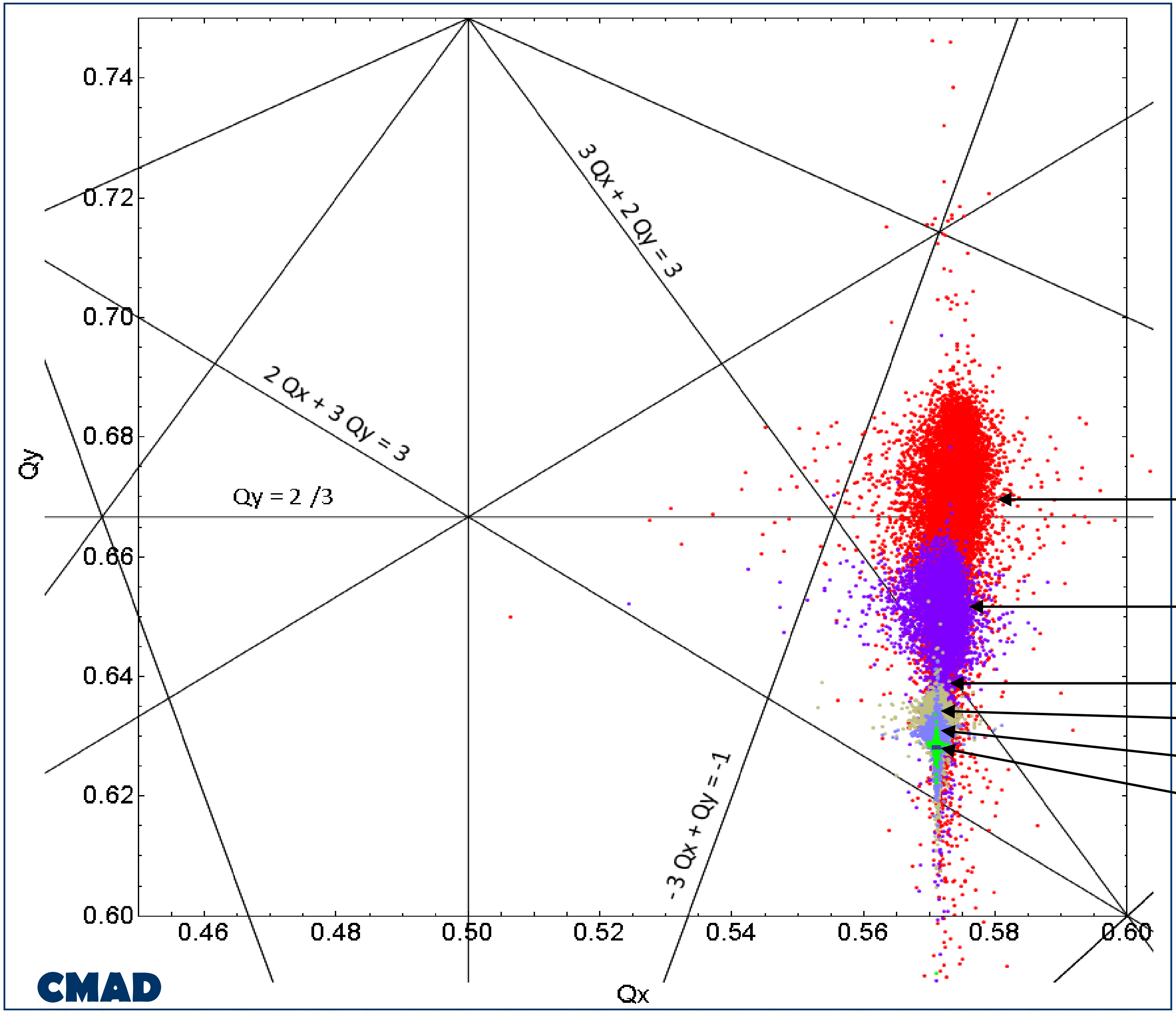


Consistent with onset of instability



Consistent with 20 pm-rad

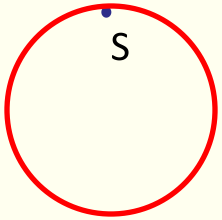
Low cloud densities: Incoherent tune shift



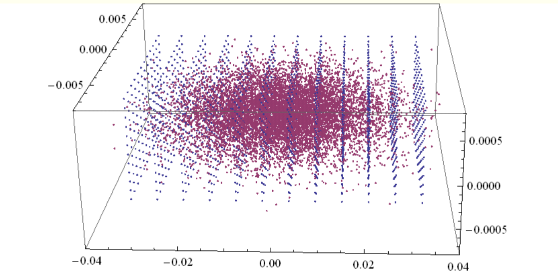
Corresponds to **steady emittance growth** below threshold

Next: Intrabeam scattering in CMAD, Monte Carlo tracking

- 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 growth rates are recalculated at S each turn

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?**

Recommendation for the ILC DR EC mitigations

Mauro Pivi SLAC

on behalf of the ILC DR Working Group

October 18-22

IWLC2010 - CERN

Working Group Charges

Since ~1 year, a DR Working Group (WG) has been set-up with Charges:

- Simulation of electron cloud build-up and instabilities (LBNL, INFN, SLAC, Cornell, KEK, ANL)
- Integration of CesrTA results into DR design
- Risk Assessment for Reducing the DR Circumference
- Risk Assessment for High Current (bs=3ns) operations
- Recommendation for electron cloud Mitigations

Working Group Main Deliverables

Recommendation for a reduced Damping Ring Circumference

DONE March 2010

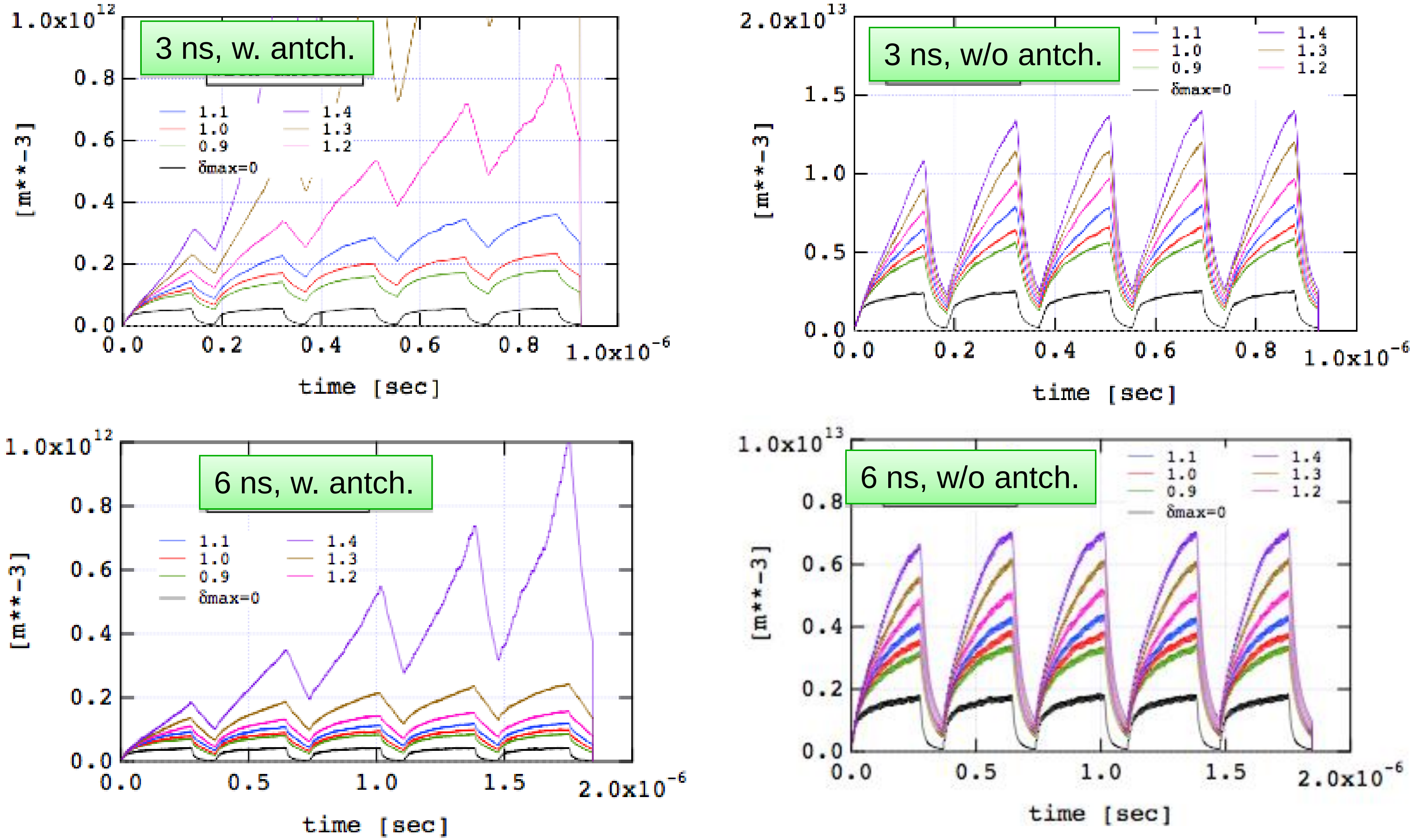
Recommendation for the baseline and alternate solutions for the electron cloud mitigation in various regions of the ILC Positron Damping Ring

by end 2010

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

by end 2010

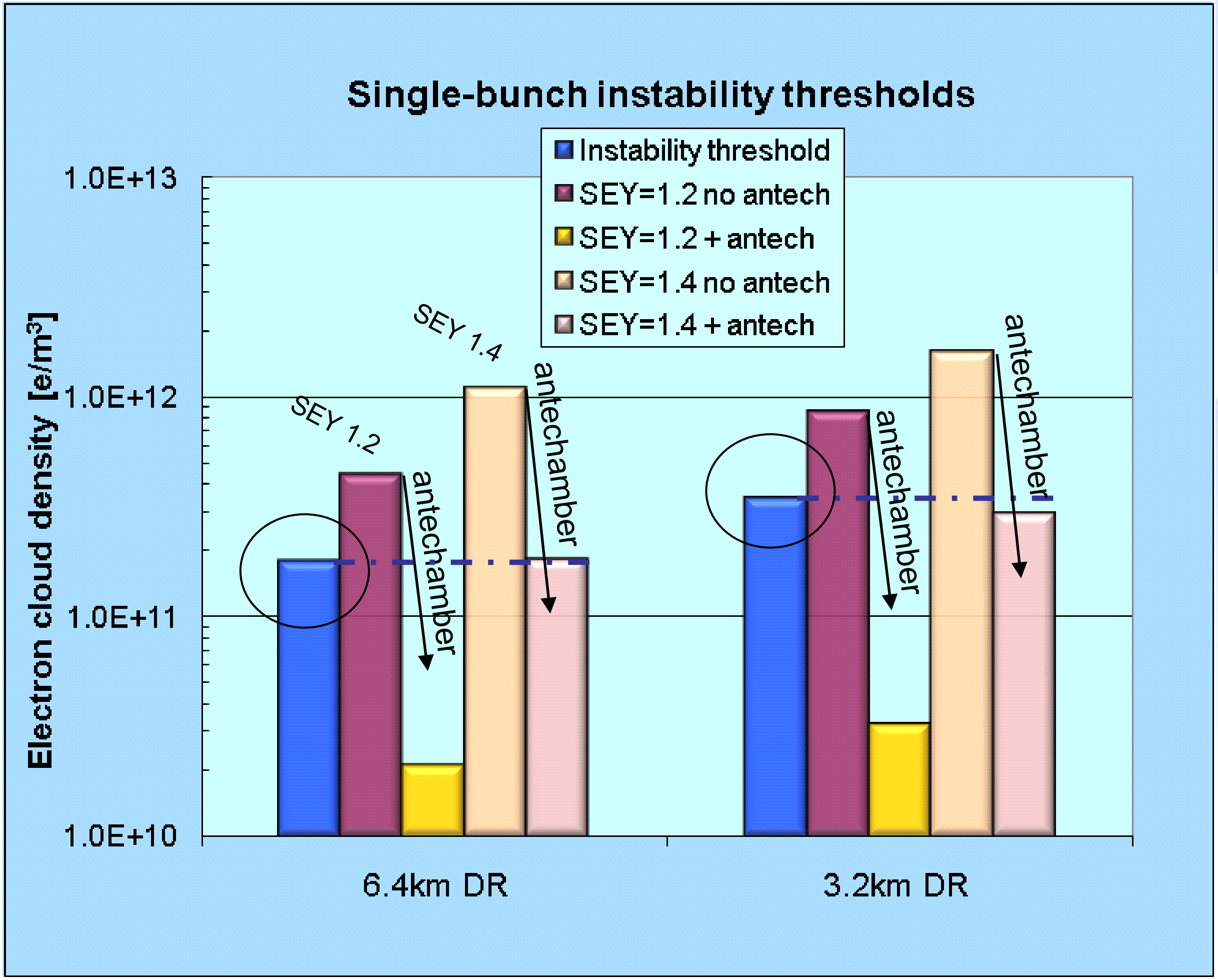
Bending magnet build-up, DSB3
space-averaged ecloud density



Comparing nominal and high luminosity configurations

- Collecting last simulation results for completing the comparison
- Generally, for the 3ns bunch spacing (high luminosity) the cloud density is expected to be **larger** by a factor 1.5 – 2 with respect to the 6ns bunch spacing (nominal).

Comparison of 6.4 and 3.2 km DR Options



Summer 2010 Evaluation

- Comparison of Single Bunch EC Instability Thresholds for:
  - 6.4km ring with 2600 bunches
  - 3.2km ring with 1300 bunches
  - ⇨ same average current
- Both ring configurations exhibit similar performance

⇨ 3.2km ring (*low current option*) is an **acceptable** baseline design choice

S. Guiducci, M. Palmer, M. Pivi, J. Urakawa on behalf of the ILC DR Electron Cloud Working Group

Recommendation for electron cloud Mitigations in the ILC DR

- The preliminary recommendations are the result of the Working Group discussions at Workshops and regular online Meetings.
- The Working Group met one full day on October 13, as a Satellite Meeting to the ECLOUD10 Workshop.
- Input from the Workshop participants is included
- The Workshop was devoted to hearing the results of detailed studies of a range of mitigation options.
- Studies were carried out over several years by ~50 researchers
- DR presently assumed to be the 3.2 km design.
- Detailed report later in 2011.
- The assessments of the different issues associated with each mitigation item, and the benefits or risks associated with the various options, were based on a systematic ranking scheme.

Recommendation for electron cloud Mitigations in the ILC DR

We should emphasize that although our systematic approach allows a "score table" for the various options for each item to be drawn up, our recommendations will be reached through structured discussion, and not by simply adding up the benefit and risk scores for the different options.

Recommendation for Mitigations

The **criteria** identified for the evaluation of mitigation are:

1) **Efficacy of mitigation**
2) **Costs**
3) **Risks**
4) **Impact on Machine Performances**

Efficacy of mitigation

- Photoelectric yield (PEY)
- Secondary emission yield (SEY)
- Ability to keep the vertical emittance growth below 10%

Costs

- Design and Manufacturing of mitigation
- Maintenance of mitigation
  - **Example: replacement of damaged power supplies for clearing electrodes**
- Operational costs
  - **Ex: Time for replacement of damaged power supplies for clearing electrodes**

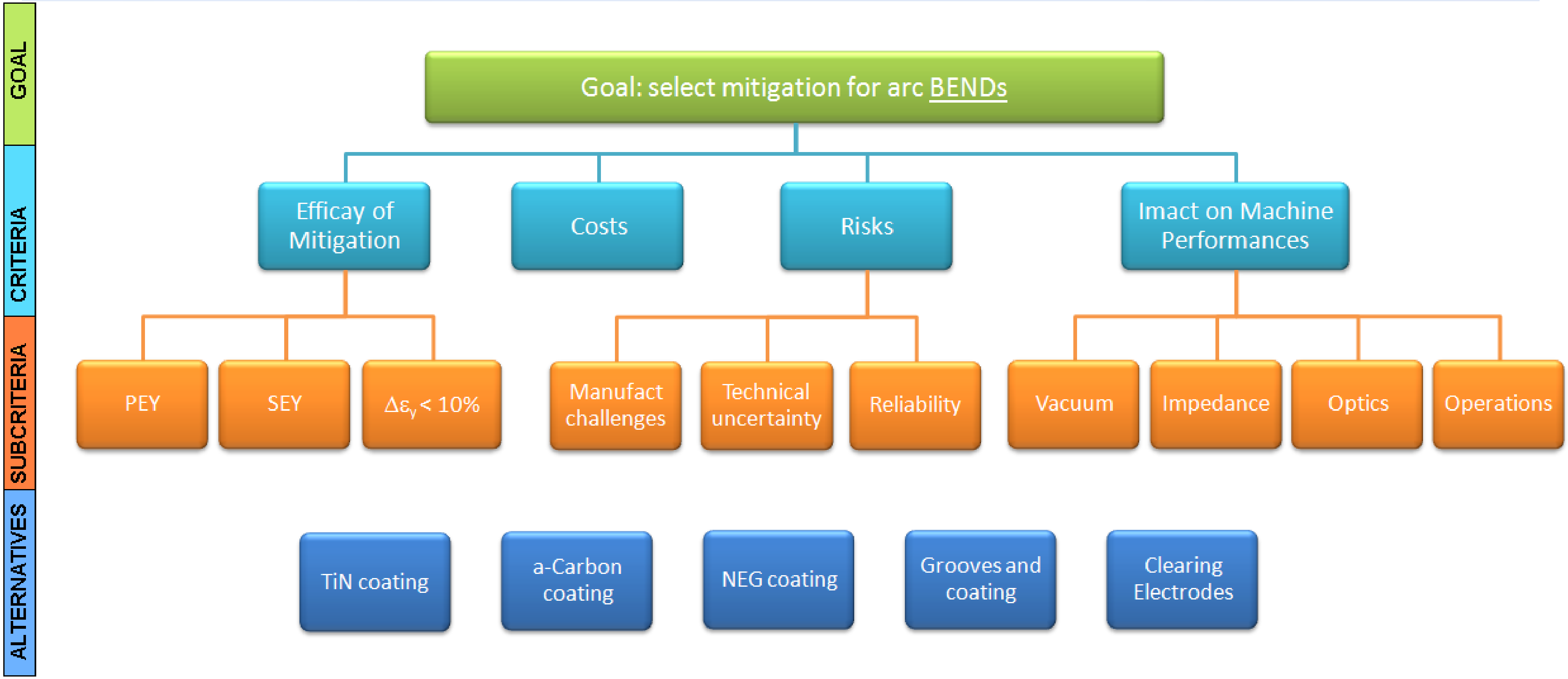
Risks

- Mitigation manufacturing challenges:
  - **Example: difficulty of manufacturing grooves of 1mm or less in a small aperture chamber**
  - **Ex: Difficulty of manufacturing of efficient clearing electrode in tight space or in presence of BPM buttons**
- Technical uncertainty
  - **Incomplete evidence of efficacy**
  - **Missing experimental evidences yet**
  - **Ex: a-Carbon coating not tested yet under high radiation power conditions for long time**
- Reliability
  - **Durability of mitigation**
  - **Ex: Damage of clearing electrode feed-through**
  - **Ex: Failure of clearing electrode power supplies**

Impact on Machine Performances

- Impact on vacuum performances
  - **Example: NEG pumping can have a positive effect**
  - **Ex: Larger grooves surface for pumping**
  - **Ex: Vacuum outgassing**
- Impact on machine impedance
  - **Ex: Impedance of grooves and of clearing electrodes**
- Impact on optics
  - **Ex: Generation of couplings with solenoids**
- Operational
  - **Ex: NEG re-activation after saturation**
  - **Ex: Availability**
  - **Ex: Time for replacement of damaged feed-trhough or power supplies**

Structured Evaluation of Mitigations for the Damping Ring



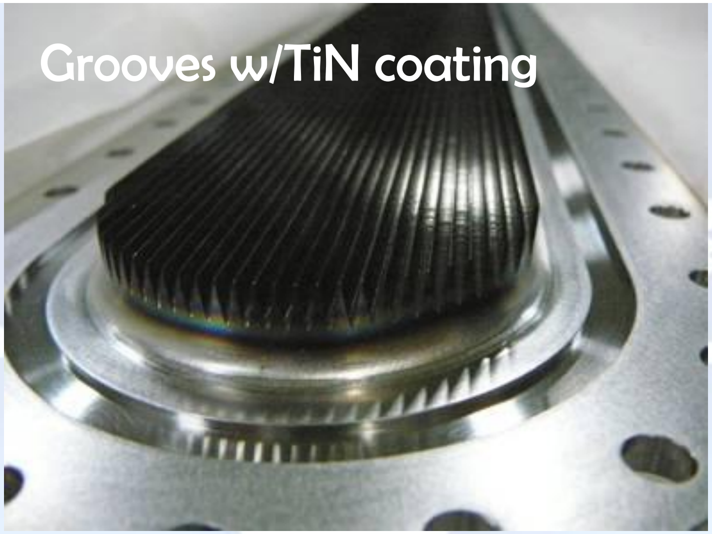
First step: Rating the Criteria

Assign a weighting factor to the criteria

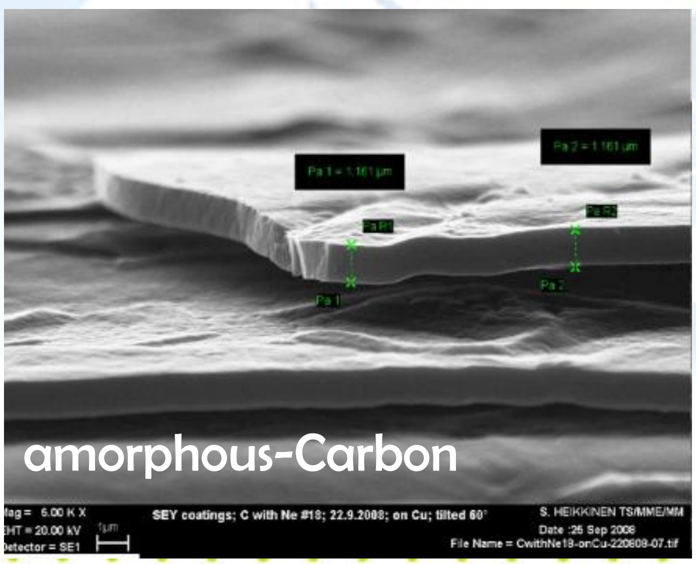
Criteria for the evaluation of mitigations: Working Group rating				
	Efficacy of Mitigation	**Costs**	**Risks**	**Impact on Machine**
Rating	**10**	**1**	**4**	**4**
Weight factor (normalized rating)	**0.53**	**0.05**	**0.21**	**0.21**

Mitigation alternatives

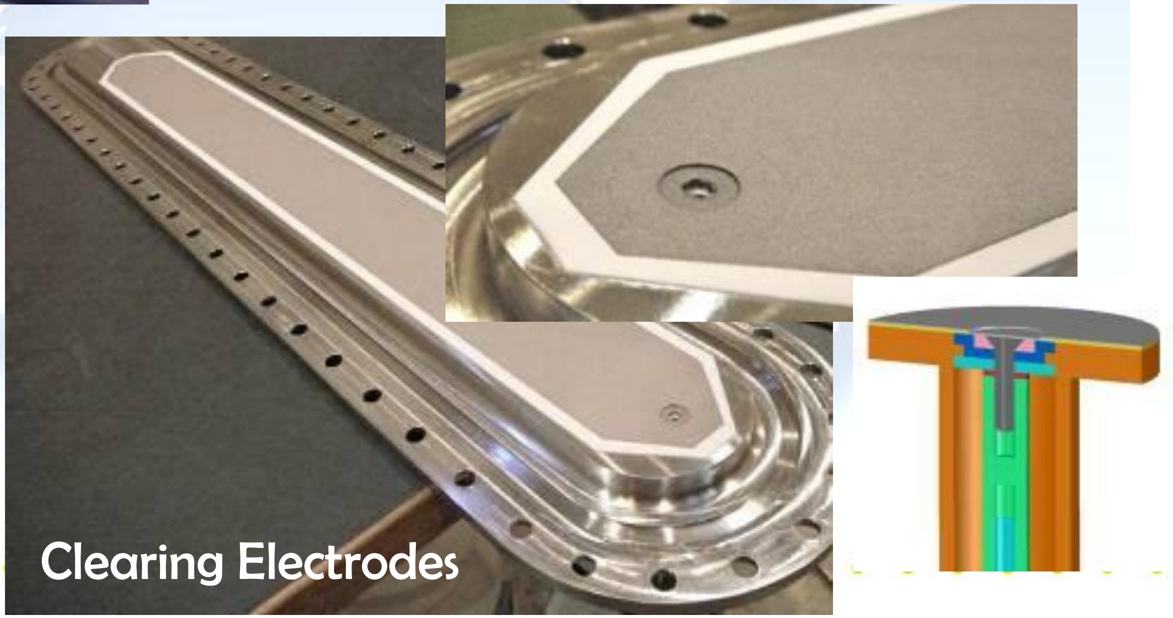
Solenoid windings



Grooves w/TiN coating



amorphous-Carbon



Clearing Electrodes

Coatings: TiN, a-Carbon, NEG

Evaluation of mitigation alternatives

The 2nd step is the WG evaluation of mitigation alternatives with respect to each criterion on a scale from +4 (Helpful or good) to -4 (detrimental or bad) for each of the DR regions.

Evaluation of mitigations in DRIFT regions: Working Group rating

	Efficacy (0.53)	Costs (0.05)	Risks (0.21)	Impact on machine (0.21)
Al	-4	1	1	0
TiN coating	2	0	1	0
C coating	2	0	-1	0
NEG coating	1	1	0	2
Grooves & coating	3	-1	0	-2

Evaluation of mitigation alternatives

The 2nd step is the WG evaluation of mitigation alternatives with respect to each criterion on a scale from +4 (Helpful or good) to -4 (detrimental or bad) for each of the DR regions.

Evaluation of mitigations in BEND magnets: Working Group rating				
	Efficacy (0.53)	**Costs (0.05)**	**Risks (0.21)**	**Impact on machine (0.21)**
Al (reference)	-4	1	1	0
TiN coating	1	0	1	0
C coating	1	0	-1	0
NEG coating	1	-1	0	1
Grooves & coating	3	-1	-1	-1
Clearing Electrodes	4	-3	-2	-2

Evaluation of mitigation alternatives

The 2nd step is the WG evaluation of mitigation alternatives with respect to each criterion on a scale from +4 (Helpful or good) to -4 (detrimental or bad) for each of the DR regions.

Evaluation of mitigations in WIGGLER region: Working Group rating				
	Efficacy (0.53)	**Costs (0.05)**	**Risks (0.21)**	**Impact on machine (0.21)**
Al (reference)	**-4**	**1**	**-1**	**0**
Cu	**0**	**0**	**1**	**0**
TiN coating	**1**	**0**	**-1**	**0**
C coating	**1**	**0**	**-2**	**0**
Grooves & coating	**3**	**-1**	**-1**	**-2**
Clearing Electrodes	**4**	**-2**	**-1**	**-1**

Evaluation of mitigation alternatives

The 2nd step is the WG evaluation of mitigation alternatives with respect to each criterion on a scale from +4 (Helpful or good) to -4 (detrimental or bad) for each of the DR regions.

Evaluation of mitigations in QUAD regions: Working Group rating				
	Efficacy (0.53)	**Costs (0.05)**	**Risks (0.21)**	**Impact on machine (0.21)**
Al (reference)	**-4**	**1**	**1**	**0**
TiN coating	**1**	**0**	**1**	**0**
C coating	**1**	**0**	**-1**	**0**
NEG coating	**0**	**-1**	**-1**	**0**
Grooves & coating	**3**	**-1**	**-2**	**-2**
Clearing Electrodes	**4**	**-3**	**-2**	**-3**

After normalizing the matrix and applying the criteria weighting factors, we obtain a ranking of the various options …

Recommendation for DR Drift Regions

Mitigation Recommendation, as extracted from the October 13 Meeting Executive Summary:

TiN is the recommended baseline mitigation for drift regions. TiN has good efficacy and the risks for its implementation are the lowest. Furthermore it has no significant impact on other aspects of the machine performance. **NEG coating** is recommended as the alternate mitigation. Although it has somewhat lower mitigation efficacy, it has the advantage of providing vacuum pumping in the long straight sections which can decrease the costs of distributed pumping. **In addition, solenoids** are recommended for inclusion in the baseline design as additional mitigation for the high beam current option ultimately desired for the 3.2km DR design.

Recommendation for Dipole Regions

Mitigation Recommendation

Grooves with TiN coating are the recommended baseline mitigation in dipoles. In this region, we want to have the greatest possible protection against the electron cloud and grooves have very good efficacy. **TiN coating** without grooves is specified as the alternative mitigation choice. Although **clearing electrodes** offer the best effectiveness, their use in the large number of bend magnets in the DR has potentially significant impact on the machine impedance as well as an inherent risk associated with the large number of active components required. At present, these drawbacks make clearing electrodes less attractive for the design. Further R&D may change this assessment.

Antechambers are included in the recommendation for the baseline mitigation design.

Recommendation for Wiggler Regions

Mitigation Recommendation

Clearing electrodes deposited *via* thermal spray on copper chambers is the recommended mitigation in the wiggler region. Clearing electrodes offer the best protection in the section that is most critical for electron cloud formation. The impedance and risk issues are less critical than in bends due to the smaller number of chambers involved.

We accept these impacts in order to obtain the best efficacy in this region. **Grooves with TiN coating** are recommended as the alternative mitigation.

Antechambers are required in the wiggler regions to remove synchrotron radiation power as well as to minimize the number of photoelectrons produced in wiggler fields.

Recommendation Quadrupole Regions

Mitigation Recommendation

TiN coating is the recommended mitigation in quadrupoles since it offers good efficacy against electron cloud with low risks and low impact on the machine performance.

There are concerns about long term build-up of electrons in the quadrupole field that would require extremely effective mitigation. This could be provided by clearing electrodes or grooves but more R&D will be required to validate either option.

Summary EC Working Group Baseline Mitigation Plan

Mitigation Evaluation conducted at satellite meeting of ECLOUD`10 (October 13, 2010, Cornell University)

EC Working Group Baseline Mitigation Recommendation				
	Drift*	**Dipole**	**Wiggler**	**Quadrupole***
Baseline Mitigation I	**TiN Coating**	**Grooves with TiN coating**	**Clearing Electrodes**	**TiN Coating**
Baseline Mitigation II	**Solenoid Windings**	**Antechamber**	**Antechamber**	
Alternate Mitigation	NEG Coating	TiN Coating	Grooves with TiN Coating	Clearing Electrodes or Grooves

*Drift and Quadrupole chambers in arc and wiggler regions will incorporate antechambers

- Preliminary CesrTA results and simulations suggest the presence of a steady *emittance growth* even below the instability threshold.
  - Further investigation required
  - May require reduction in acceptable cloud density ⇨ reduction in safety margin
- An aggressive mitigation plan is required to obtain optimum performance from the 3.2km positron damping ring and to pursue the high current option

S. Guiducci, M. Palmer, M. Pivi, J. Urakawa on behalf of the ILC DR Electron Cloud Working Group

Acceptable Electron Densities to Achieve the Design Emittance

- A concern for meeting the emittance specifications is a steady incoherent emittance growth at low electron cloud densities below the threshold for the head-tail instability.
- Recent simulations and CesrTA measurements suggest that this effect may be significant and are leading to a re-evaluation of the acceptable electron densities.
- While considerable work remains to precisely quantify this issue, initial results suggest that the acceptable cloud densities may need to be lowered by a factor of several.
- This further emphasizes the need to employ the most effective mitigation techniques, consistent with risk and cost constraints, possible in each region of the ring.

Summary

- Preliminary WG Recommendation for Mitigations of the Electron Cloud Effect in the ILC Damping Ring

- Recommendation for reducing Circumference:
  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.

Summary

- The acceptable surface Secondary Electron Yield (SEY) may strongly depend on issues under investigation such as the steady **incoherent emittance growth** below threshold and beam jitter. Refined estimations of the photoelectron production rate by simulations are underway and 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!