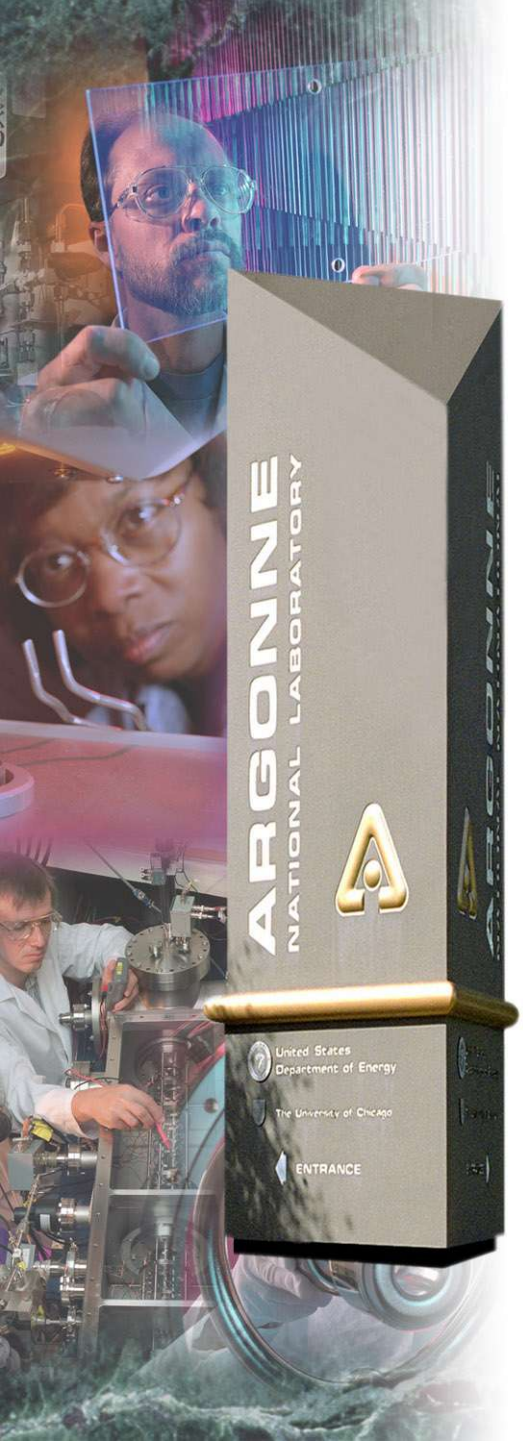

Accelerator Possibilities for Enhanced Time-Resolved Imaging at APS

Michael Borland
Operations Analysis Group
APS Operations Division
January 26, 2005

Office of Science
U.S. Department of Energy

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Outline

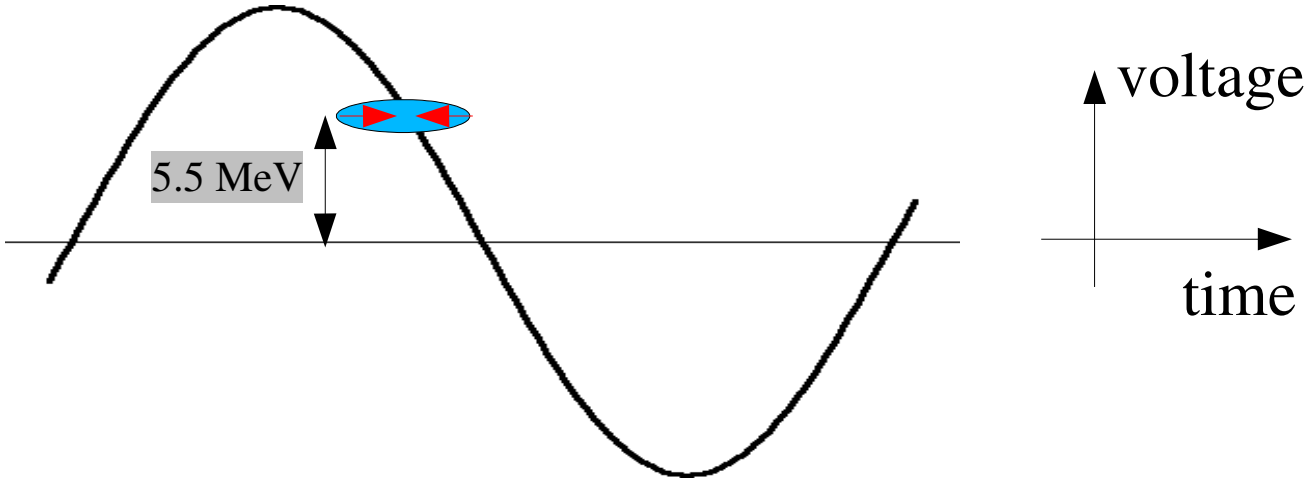
- Background
  - AP101: A review of relevant accelerator physics
- Review of types of improvements
  - What's the limitation now
  - What might be done about it
  - Benefits, costs, and trade-offs
  - Activities and plans
- Summary

AP101: Longitudinal Dynamics

Or, "Why can't the bunch be arbitrarily short?"

- Synchrotron radiation has two effects
  - Electrons lose on average ~5.5 MeV per turn
  - Different electrons lose slightly more/less due to quantum fluctuations
    - This leads to energy spread
    - Determined mostly by ring circumference, energy
- Energy spread leads to
  - Variation in go-round time ("momentum compaction")
  - Bunch length

AP101: Longitudinal Dynamics

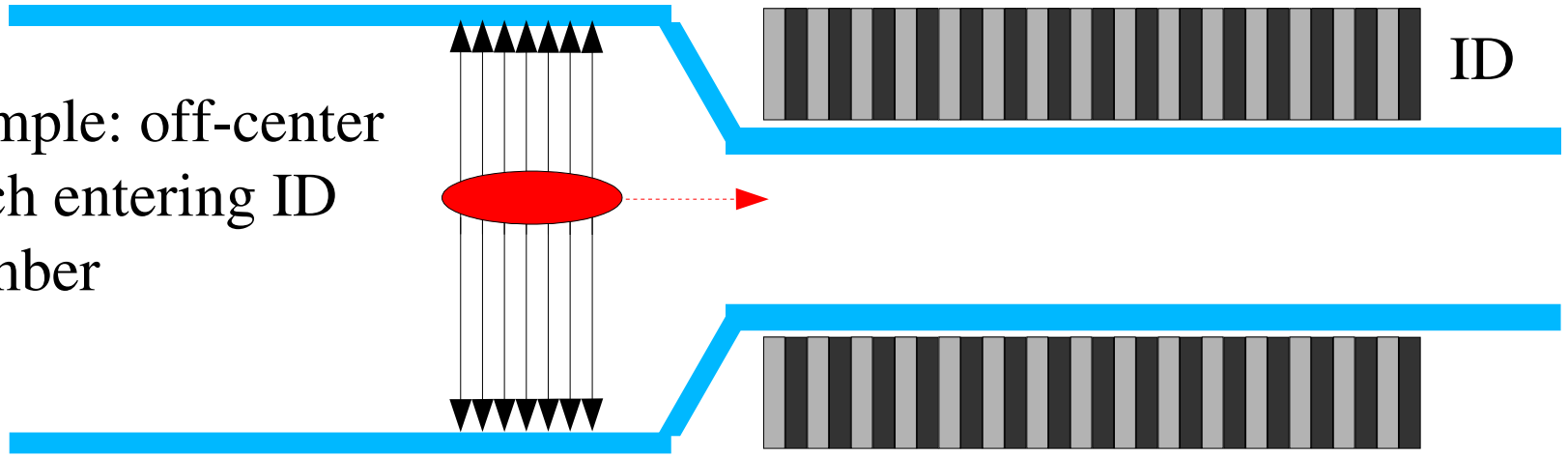


- High-power rf systems restore beam energy
- Provide focusing force that prevents bunch length from growing indefinitely
- Minimum possible bunch length is set by
  - Rf slope
  - Momentum compaction
  - Energy spread

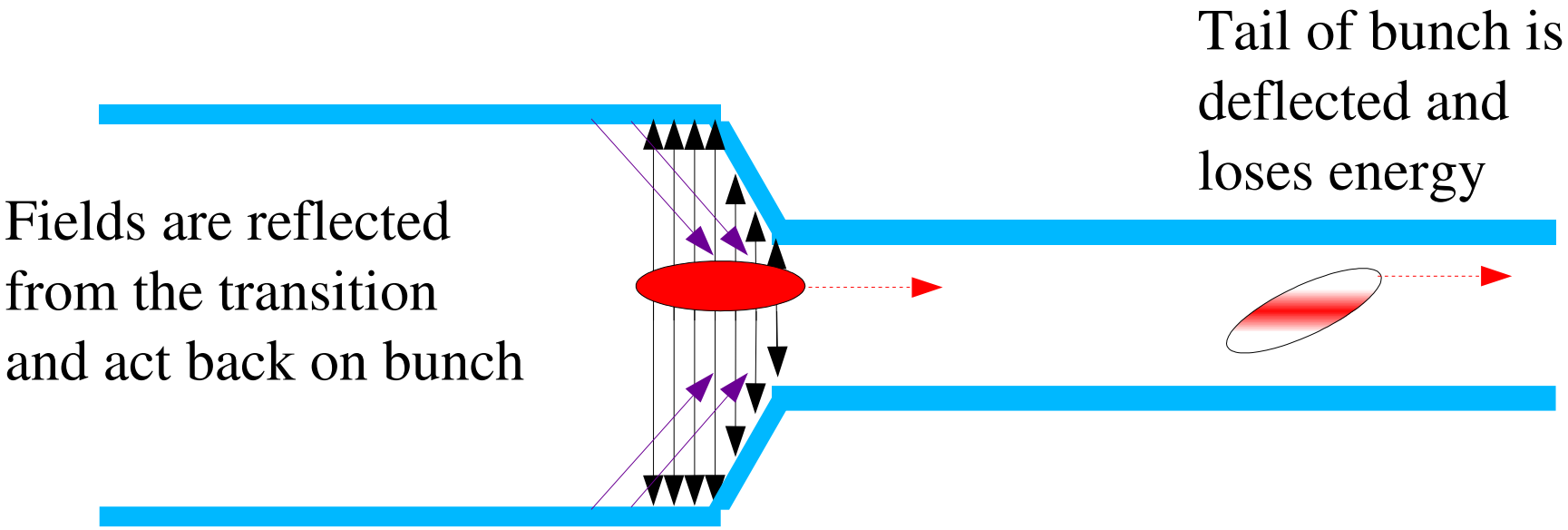
AP101: Short-Range Impedance

- "Impedance" concept describes electromagnetic interaction of electron bunch with the vacuum chamber
- This time-dependent interaction
  - Changes the energy of electrons
  - Gives transverse kicks to electrons

Example: off-center bunch entering ID chamber



AP101: Short-Range Impedance



- In APS, this generally results in
  - Bunch lengthening, then
  - Transverse instability, then
  - Energy spread growth
- We'll look at possible remedies later

AP101: Beam Lifetime

- Electrons can be lost if they scatter off of
  - Residual gas
  - Other electrons
- Electron/electron scattering (Touschek effect) is worse when electron density is higher
- Shorter lifetime is an unavoidable consequence of almost every enhancement, e.g.,
  - Lower emittance
  - Customized beta functions
  - Shorter bunch length
  - Higher single-bunch current

AP101: Remedies for Lifetime Decrease

- Use a higher-emittance lattice
  - Reverting to 8 nm would raise 7 hr lifetime to 20 hr[1]
  - Not a popular option
- Increase the vertical emittance
  - Not quite as unpopular
  - Limited benefit before it hurts injection efficiency
    - Could use pulsed skew quads to solve this
- Add harmonic rf system to increase the bunch length[2]
  - Quite expensive (~8M$)
  - Needs half a straight section
  - Few Users want longer bunches

[1]L. Emery

[2]M. Borland, OAG-TN-2005-003
Cost guess from data by G. Pile *et al.*

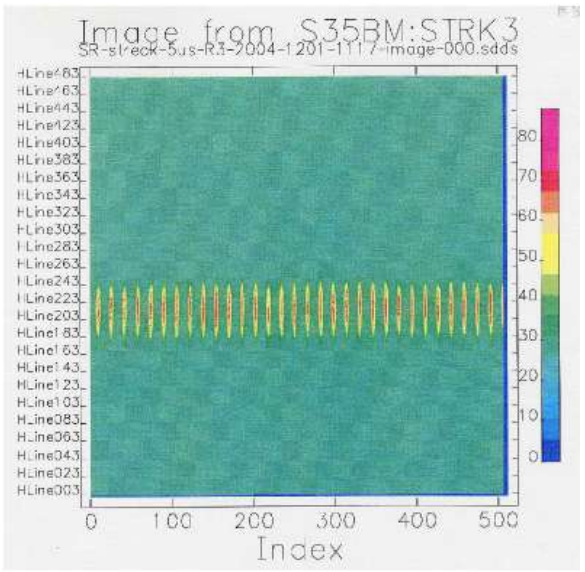
AP101: Remedies for Lifetime Decrease

- Strengthen sextupole magnets
  - FY2005 Project Proposal
  - Cost ~400k$
  - May give a factor of 2[1]
- Increase top-up current[2] in inverse proportion to lifetime
  - More charge per shot (not always easy)
  - Top-up more frequently (*very*, *very* easy)
- At some point we'll have to decide which choices are least onerous.

[1]V. Sajaev, ASD/APG/2004-16
[2]M. Borland *et al.*, OAG-TN-2004-001

Bunch Lengths for Different APS Fill Patterns

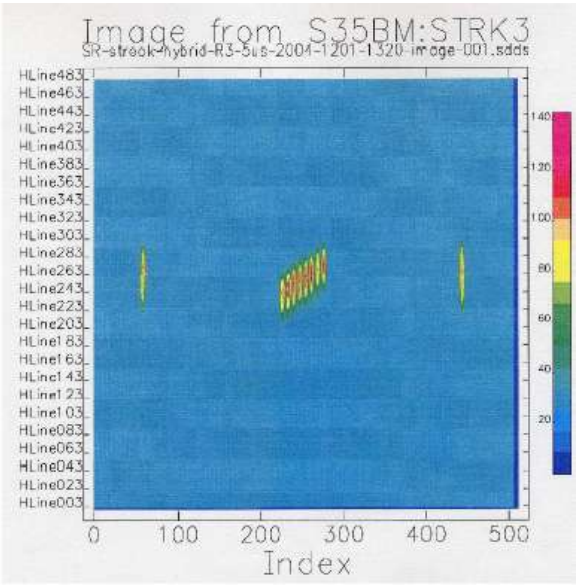
Data from Sector 35 Dual-Sweep Streak Camera



T_2 (1 ns range)

T_1 (5 µs range)

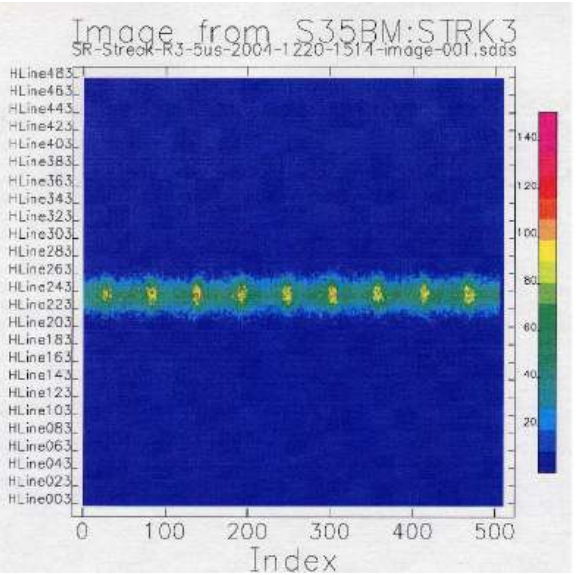
24-singlets



T_2 (1 ns range)

T_1 (5 µs range)

1+8*7



T_2 (1 ns range)

T_1 (5 µs range)

324-singlets

	24-singlets	Hybrid: 1+8*7	324-singlets
Bunch length (rms)	40 ps	Singlet: 50 ps Septuplet: 32 ps	25 ps

Courtesy of A. Lumpkin and B. Yang

Possible Improvements for Time-Resolved Imaging

1. Improved bunch purity
2. Higher single-bunch current
3. Shorter equilibrium bunch
4. Transient concepts
5. Zholents' transverse rf chirp concept

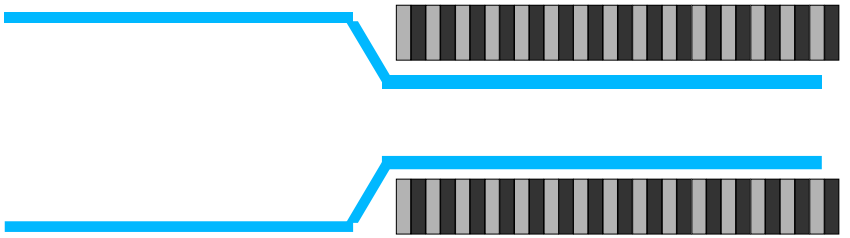
1: Bunch Purity

- APS accumulator ring (PAR) creates single bunches for the storage ring
- Performance as good as 10^{-6} seen, but sometimes can't maintain better than 10^{-3}
- A prototype PAR bunch cleaning system[+] used at end of last run and maintained 10^{-6}*
- FY2005 Project Proposal to build permanent system with target of better than 10^{-6}
- Also revisiting bunch cleaning in storage ring itself

[+]C-Y Yao et al., OAG-TN-2004-051
*A. Lumpkin

2: Single Bunch Current Limit

- Presently limited to 8~10 mA in a single bunch
- Raising limit would permit
  - More intense bunch for hybrid mode.
  - Few-bunch modes (e.g., 100mA in 6 bunches).
  - More current in 24 bunch mode (e.g., 200mA in 24)[1]
- Limit imposed by single-bunch transverse instability
- Related to characteristics of ID chambers
  - Small gap
  - Transition geometry
  - Material conductivity

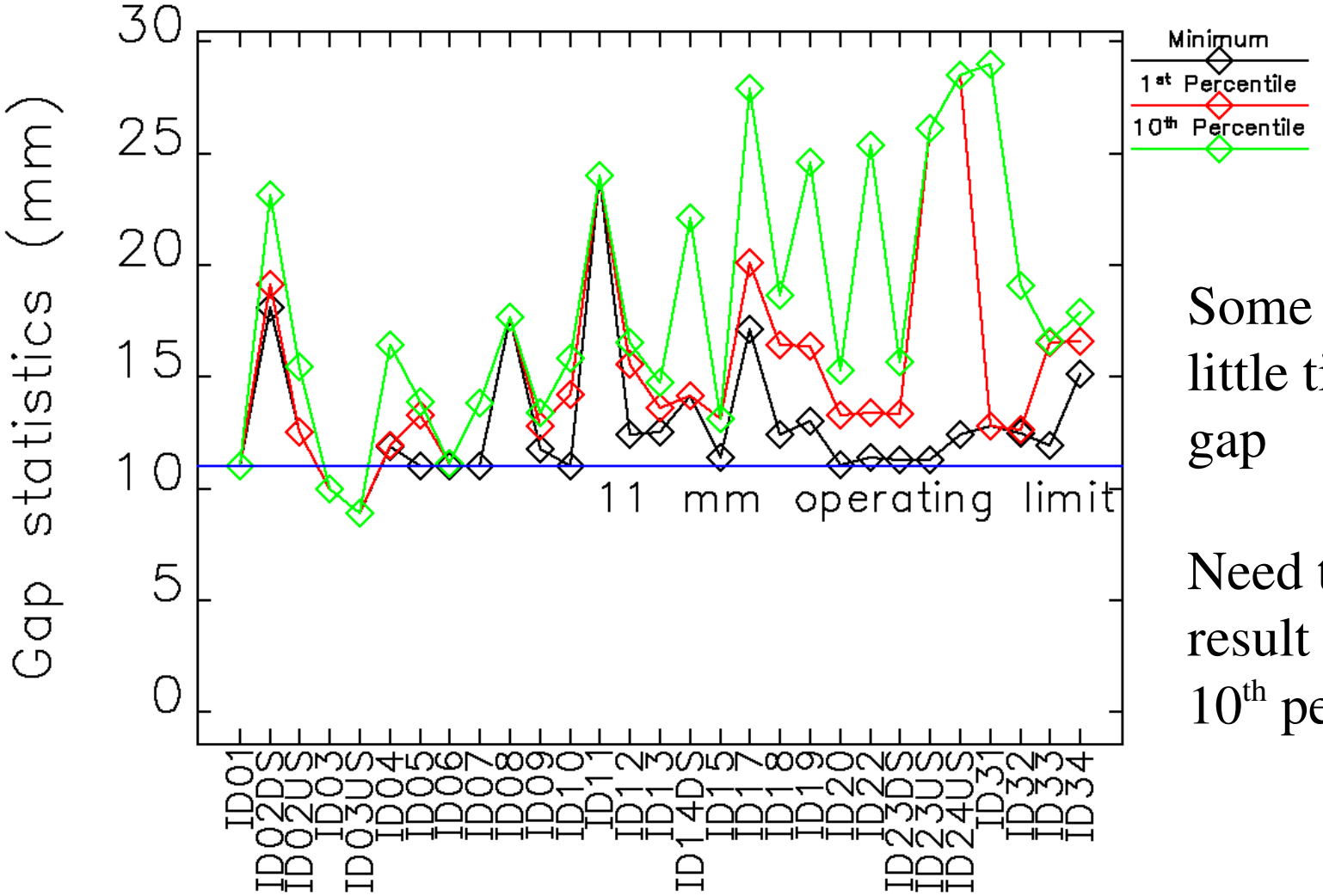


[1]J.M. Gibson

2: Possibilities for Raising the Limit

- Modify the ID chambers
  - Redesign transition or silver-coat chambers themselves
    - Not clear which will help most and by how much
    - Extensive simulation studies and more experiments needed
  - Increase chamber apertures
    - Reduced scan range
    - ID redesigns might be needed
    - Benefits also uncertain at this point

2: Possibilities for Raising the Limit



Some ID's spend very little time at minimum gap

Need to estimate result of limiting at, say, 10th percentile value.

From L. Emery, OAG-TN-2005-004

2: Possibilities for Raising the Limit

- A fast (i.e., turn-by-turn) feedback system
  - Simulations indicate doubling of instability limit to 16mA[1]
  - Specification of one-bunch prototype system in progress[2]
    - May be ready to test this run
  - FY2005 Project Proposal targeting hybrid mode
    - Inexpensive (~150k$)
    - Puts us on the road to a full-blown system

[1]K. Harkay

[2]C.-Y. Yao *et al.*

2: Possibilities for Raising the Limit

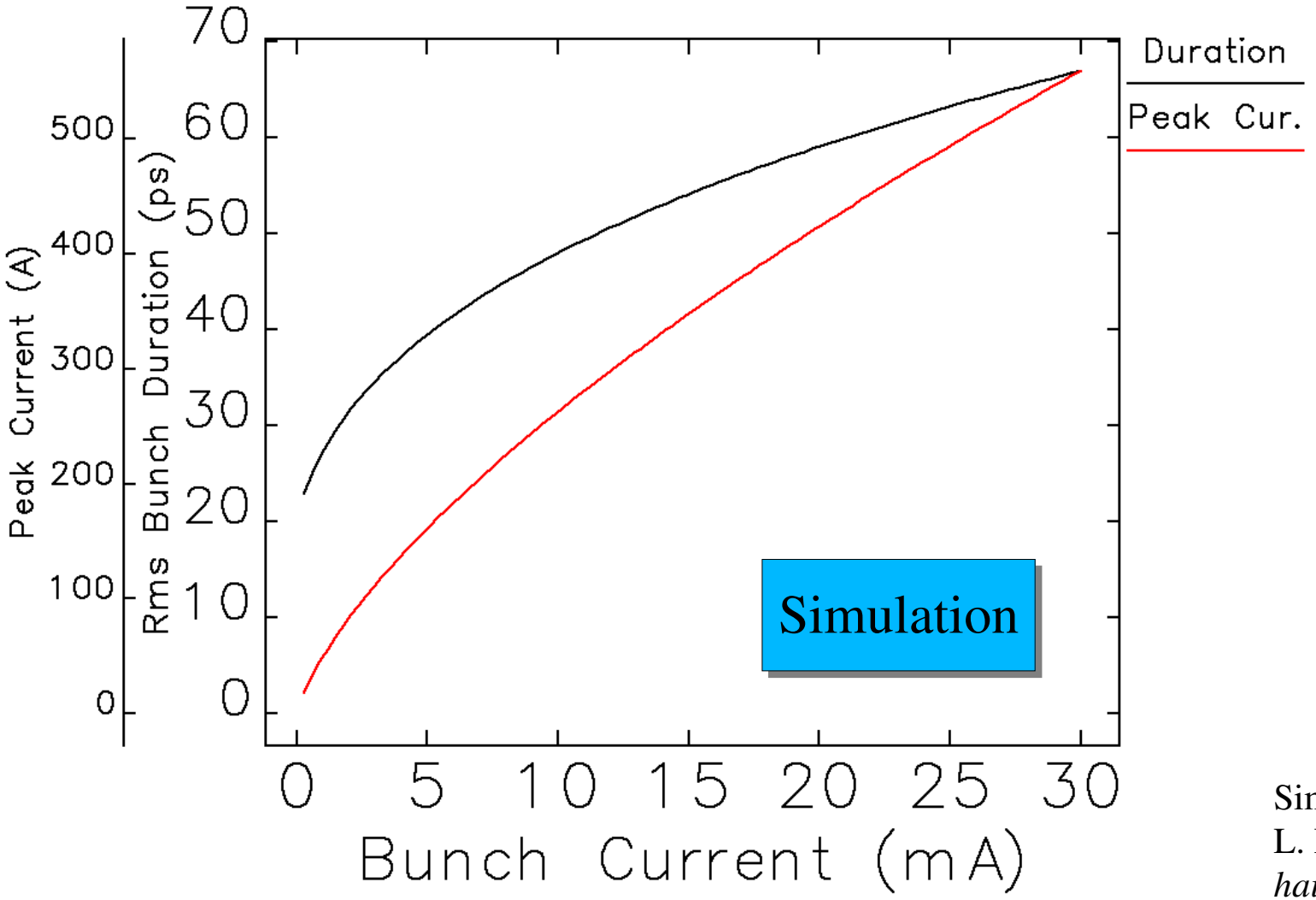
- Stronger sextupoles
  - Used to increase chromaticity and stabilize beam
  - Used to improve energy aperture and hence lifetime
  - Would let us go to higher single bunch current with good lifetime
  - FY2005 project proposal (~400k$) for stronger sextupoles

2: Possibilities for Raising the Limit

- These two projects can be used separately or together
  - Use feedback to stablize the beam to ~2x current
  - Use stronger sextupoles to get the lifetime back
- What might be seen if this works out?

2: Side Effects of Increased Charge

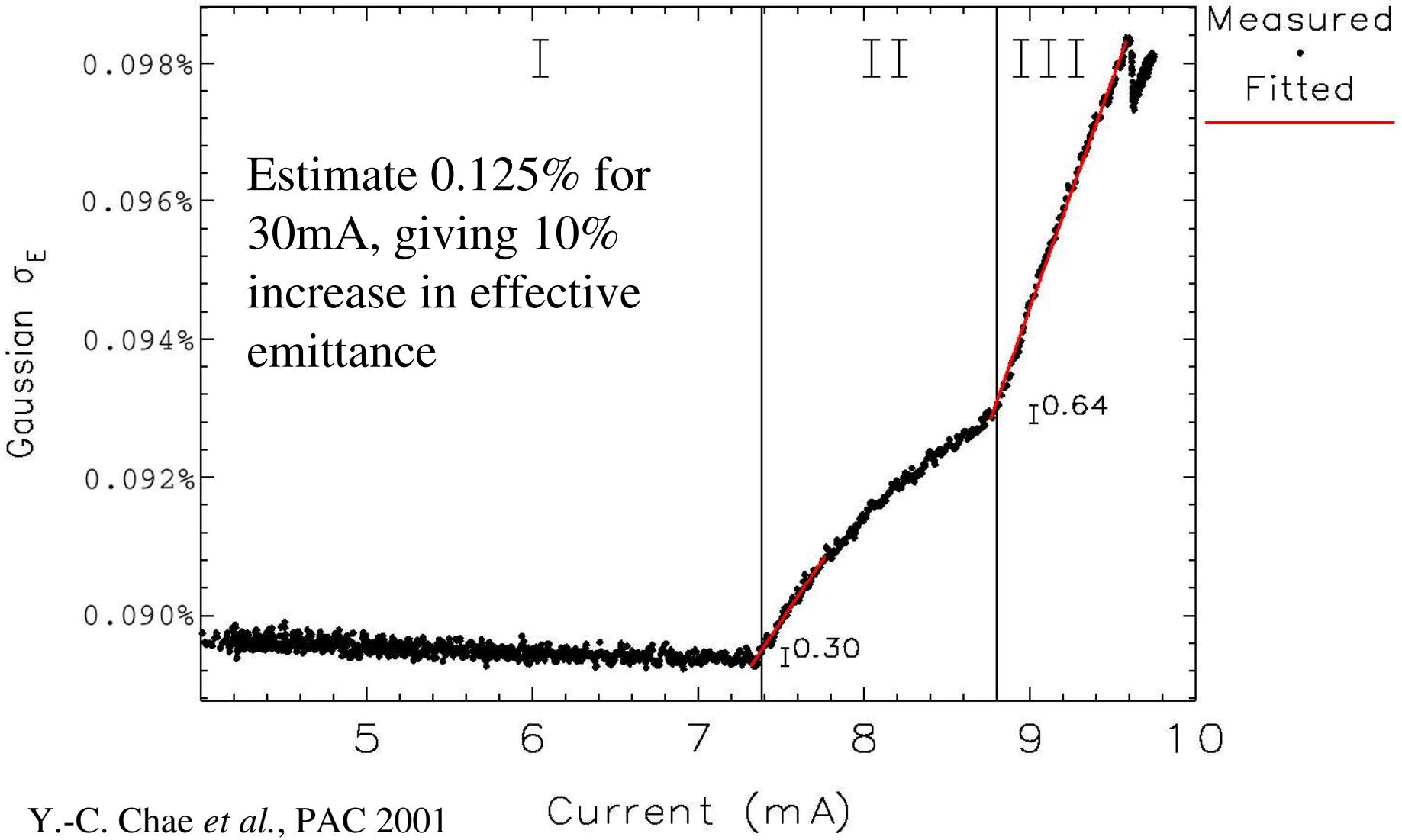
If impedance is not reduced, the bunch will lengthen.



Simulation with L. Emery's *haissinski* program.

2: Side Effects of Increased Charge

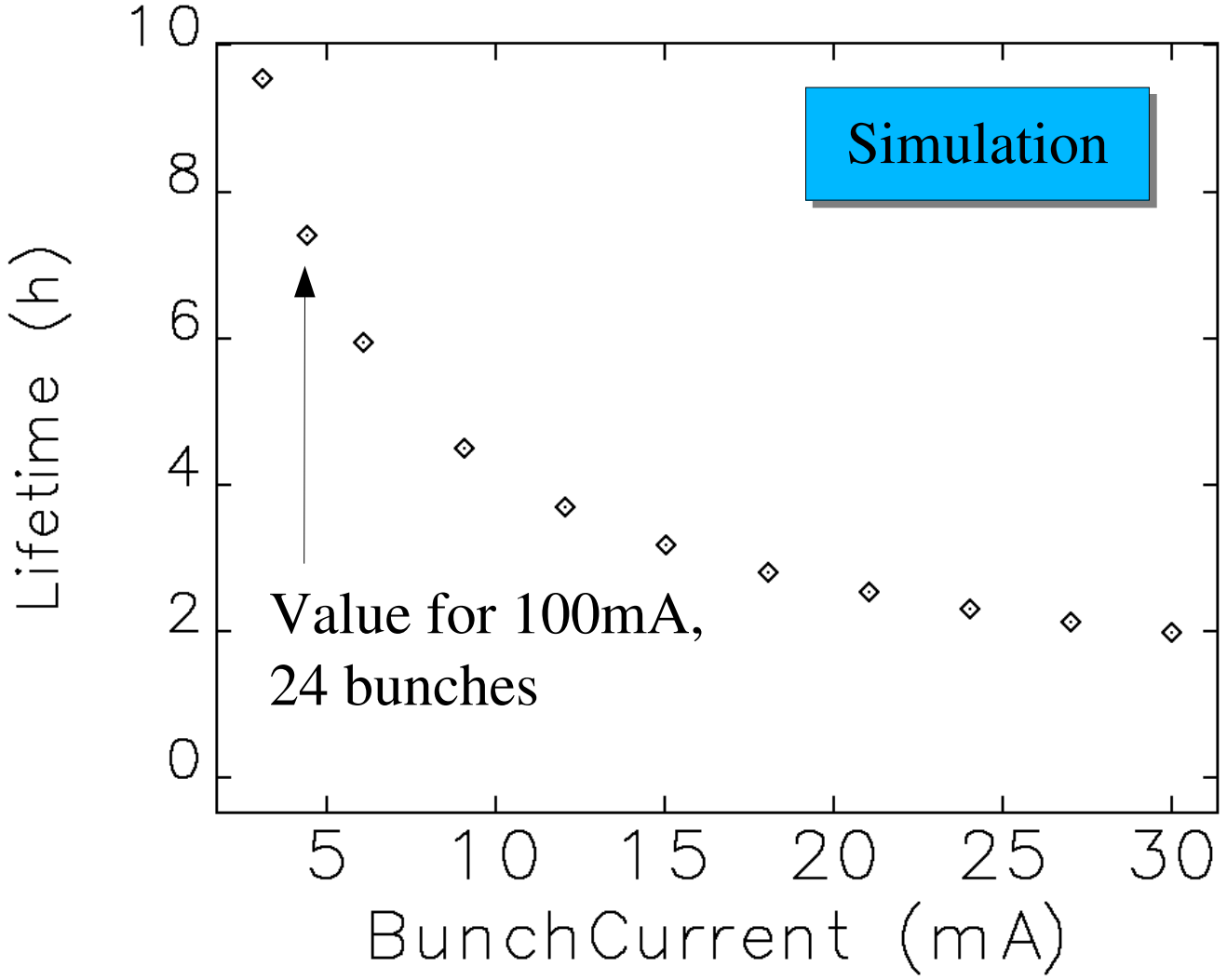
Energy spread will increase, increasing the effective emittance.



Y.-C. Chae *et al.*, PAC 2001

2: Side Effects of Increased Charge

Lifetime still goes down, even with the increased bunch length.



Stronger sextupoles may double the lifetime

Faster top-up can handle very short lifetimes

Simulation with M. Borland's *beamLifetimeCalc* program.

3: Limitations on Decreasing Bunch Length

- As just seen, bunch naturally gets longer as single-bunch current increases
- By itself, a longer bunch is beneficial
  - Increases lifetime (or limits decrease)
  - Delays onset of instabilities
- If we have other ways to manage those issues, what could we do?

3: Possibilities for Decreasing Bunch Length

1. Reduce the longitudinal machine impedance

- Modify ID chambers
  - Better transitions and/or conductivity
  - Larger gaps where possible
- Will also increase single bunch limit
- Again, extensive simulation required
- Best possible result is uninspiring:
  - 20 ps rms (present zero-current bunch length)

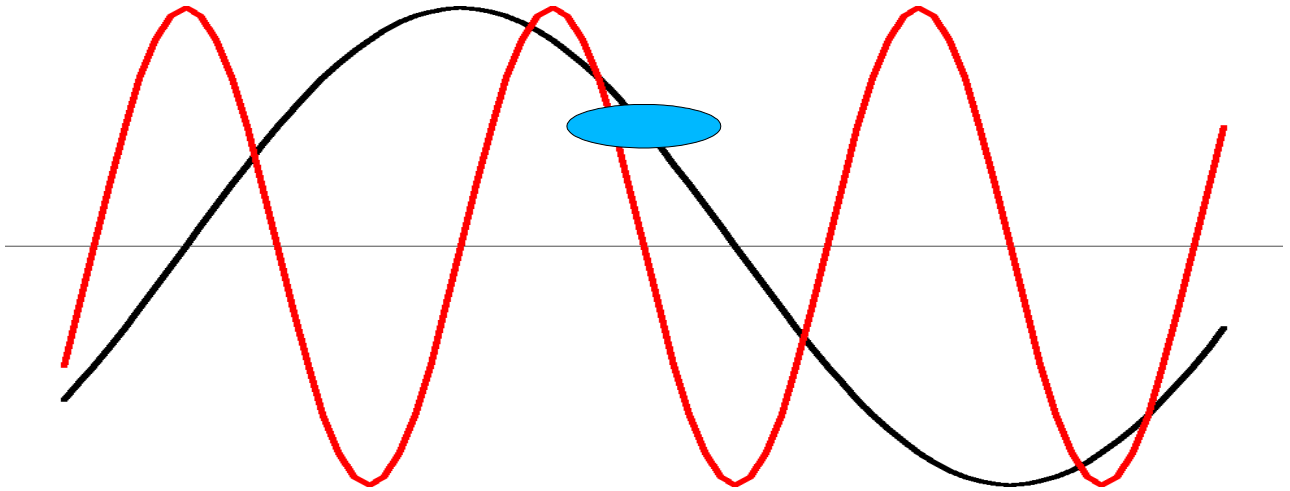
3: Possibilities for Decreasing Bunch Length

2. Change the accelerator lattice ("zero alpha")[1]

- Emittance gets large (e.g., 10x larger)
- Instabilities get worse, so stored current will be very small
  - Working to estimate just how small
  - An experimental test is planned this run
- BESSY II reports sub-ps, 1uA bunches[2]
- Could be used for some experiments during machine studies time

[1]V. Sajaev, ASD/APG/2005-02
[2]J. Feikes et al., EPAC 2004, p. 1954.

3: Possibilities for Decreasing Bunch Length



3. Add a higher-harmonic rf system

- Increases restoring force that opposes bunch lengthening
- 50% decrease requires a ~12M$ superconducting rf system
- Probably requires at least a full straight section
- Extensive study needed to look at instability issues

M. Borland, OAG-TN-2005-003

Cost guess from data by G. Pile *et al.*

3: Possibilities for Decreasing Bunch Length

- Decreasing the equilibrium bunch length is difficult
  - New ID chambers: expensive, can't go below 20 ps rms
  - Harmonic rf system: expensive even for 50% decrease
  - Zero alpha lattice: cheap, but current likely very low
- Non-equilibrium manipulations may work...

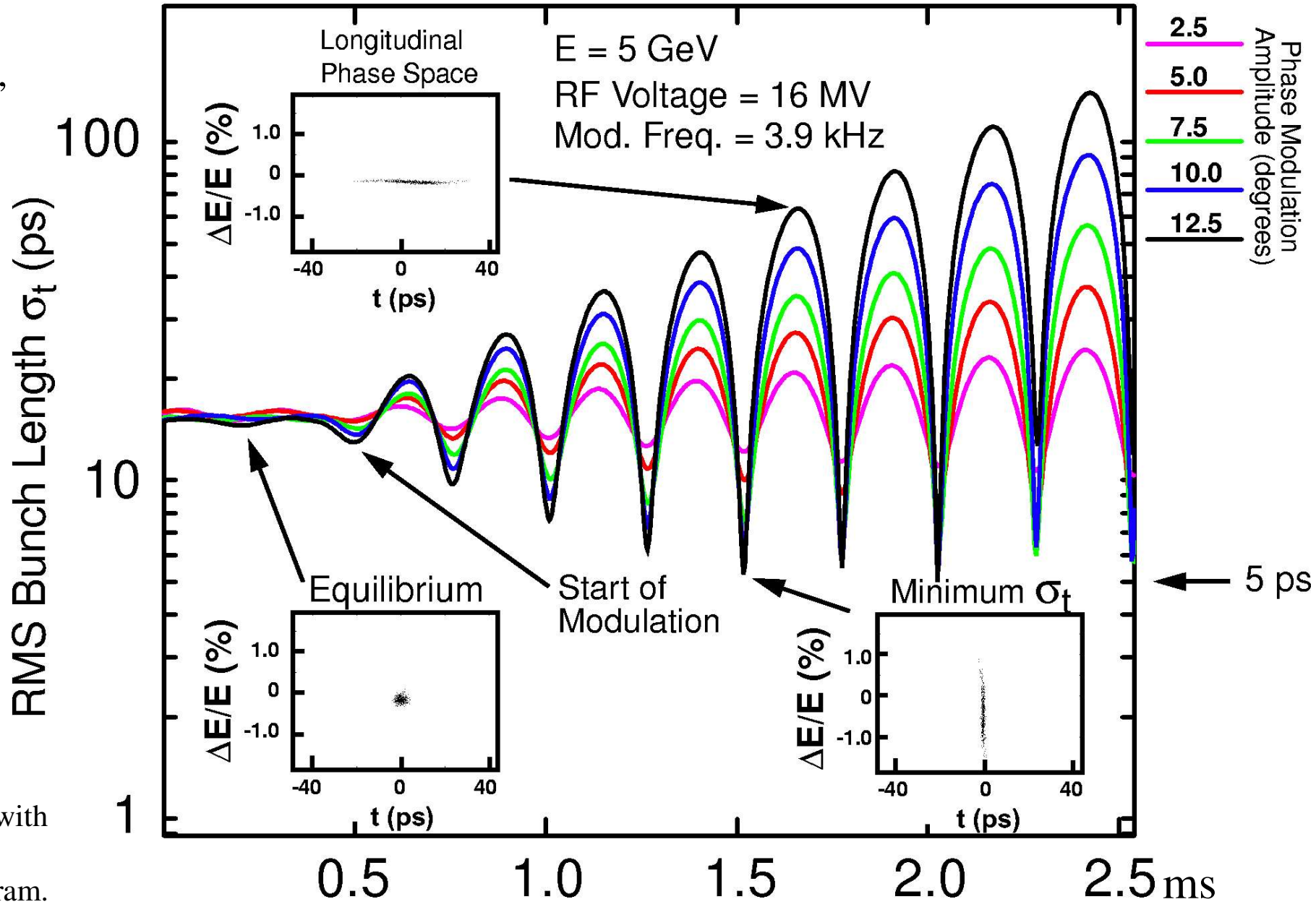
4: Transient Rf Modulation[1]

- Involves phase modulation of storage ring rf systems
- ~8 ps rms bunch length might be possible, however
  - Assumes 6 GeV operation
  - Blow up in energy spread and effective emittance
  - Duty factor limited to ~100 Hz by damping time
    - Further tricks might fix these, however
  - ~5 ps rms possible at 5 GeV
- Requires little or no new accelerator hardware
- Would affect all bunches

[1]G. Decker

4: Transient Rf Modulation Simulation

Courtesy
G. Decker,
N. Sereno



Simulations with
M. Borland's
elegant program.

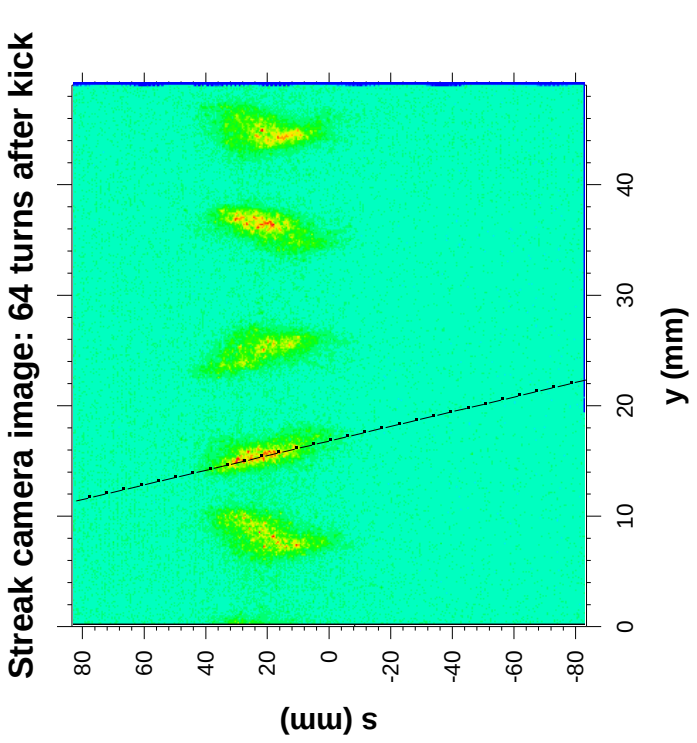
5: Guo's Kick Concept

- In this proposal, the bunch is kicked vertically and allowed to oscillate
- A correlation between time and vertical coordinates develops due to
  - Variation of oscillation frequency with energy offset ("chromaticity")
  - Time/energy oscillations due to rf system
- Correlation allows compression or spatial filtering to produce a shorter pulse
- Requires no new accelerator hardware
- Verified by simulation and experiment

5: Guo's Kick Concept

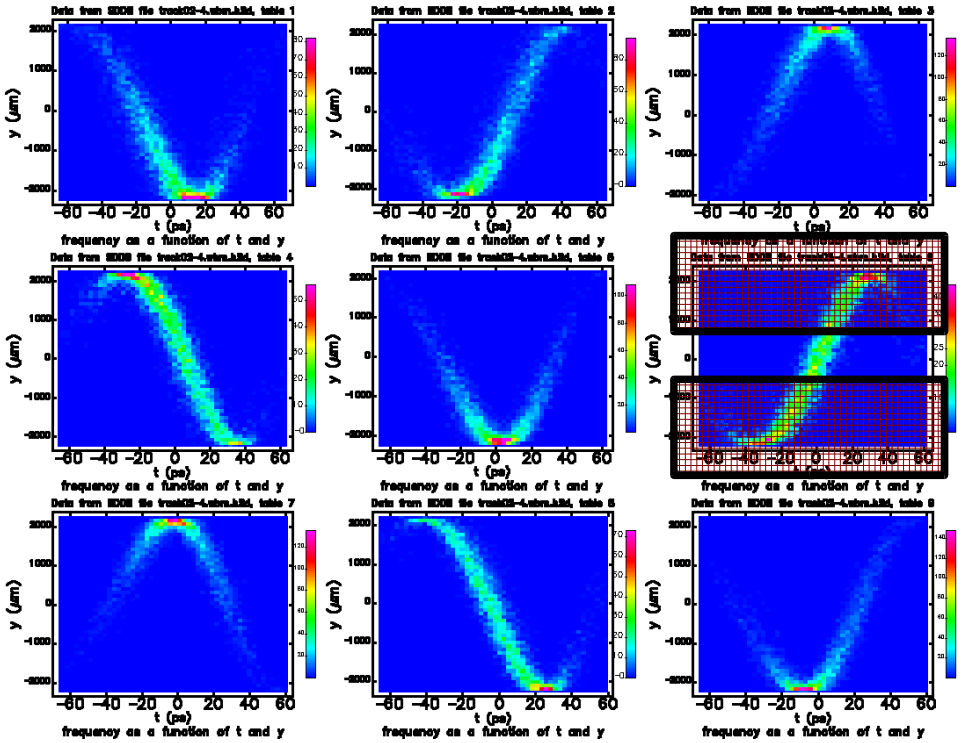
Kick induces correlation between time and vertical position coordinates after half a synchrotron oscillation period

Experimental data



Courtesy B. Yang

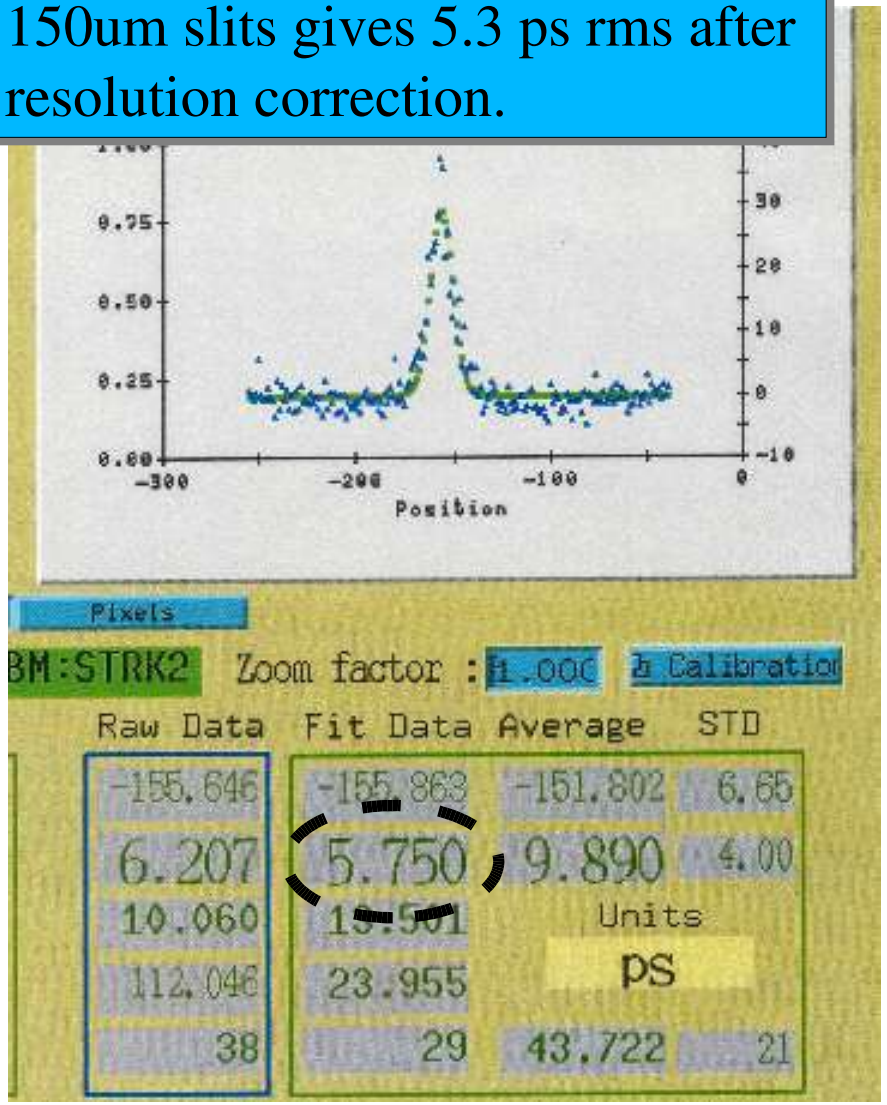
Simulation result



elegant simulation by M. Borland

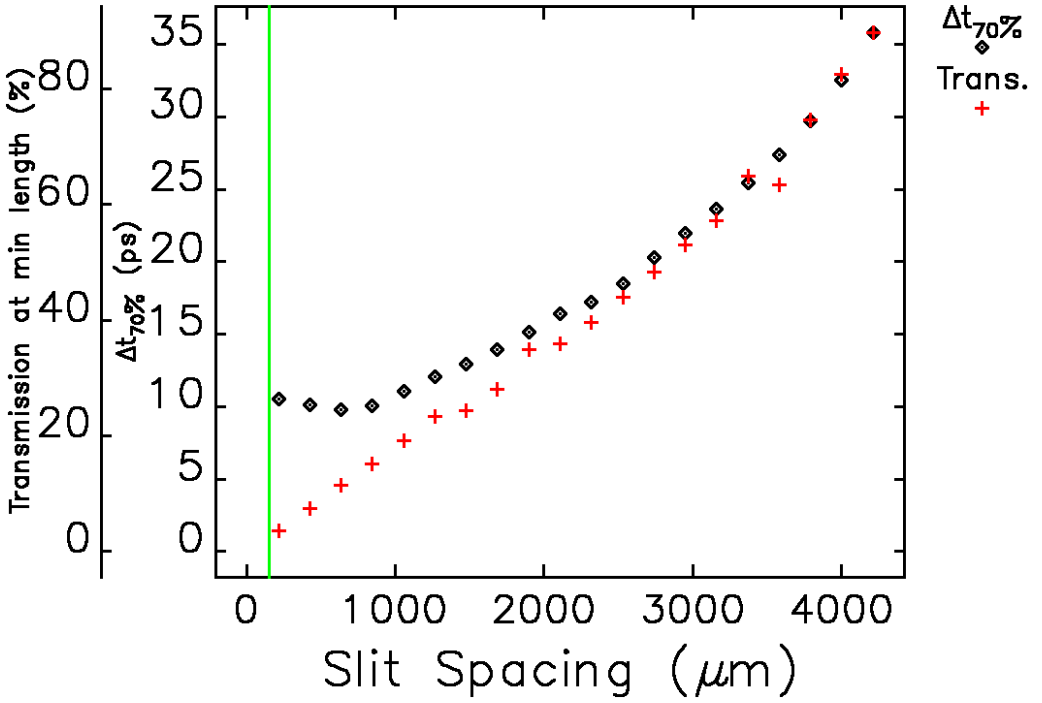
5: Guo's Kick Concept

Streak camera measurement with 150um slits gives 5.3 ps rms after resolution correction.



Courtesy B. Yang, K. Harkay

Simulation vs slit spacing

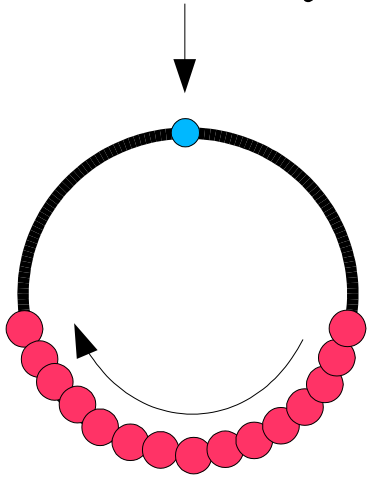


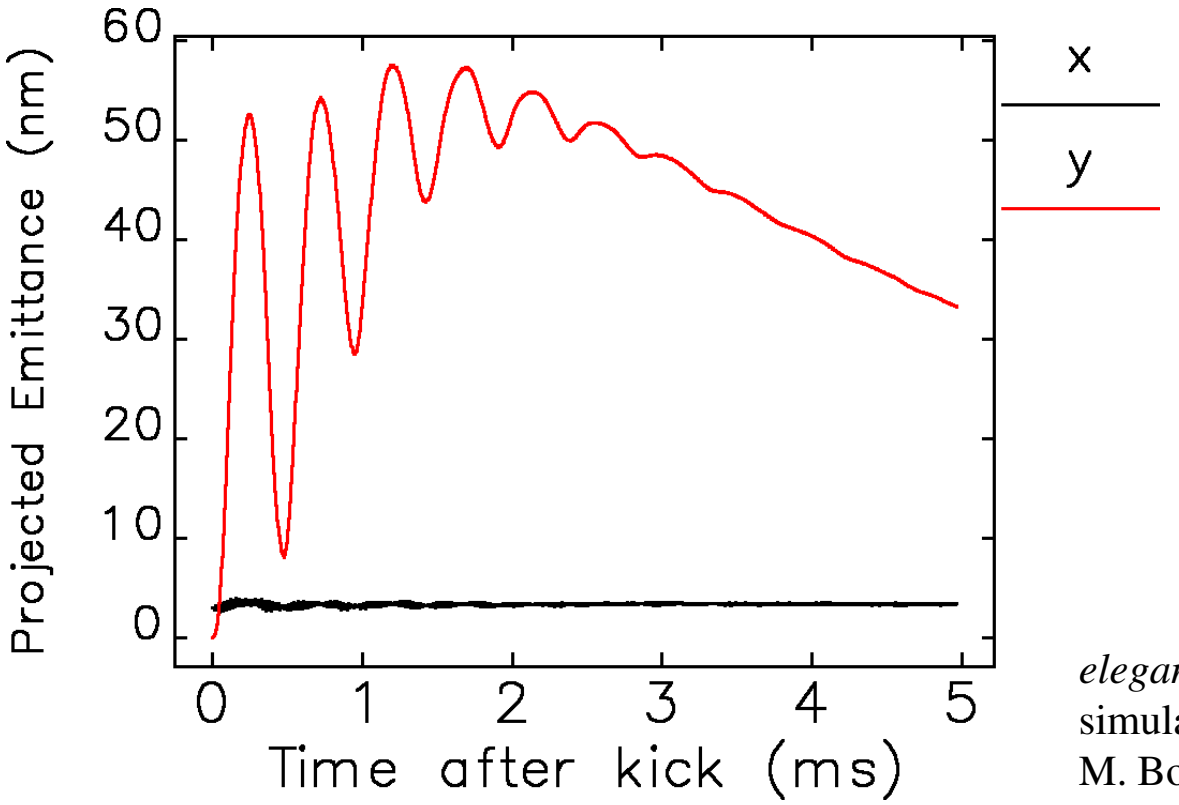
10ps for central 70% of charge equivalent to ~5ps rms

elegant simulation by M. Borland

5: Limitations and Problems

- Repetition rate limited to 40 Hz
- Works only for low intensity (~0.2 mA/bunch)
- Vertical emittance is blown up for ~30ms
- Consider special fill with one isolated bunch and faster kicker

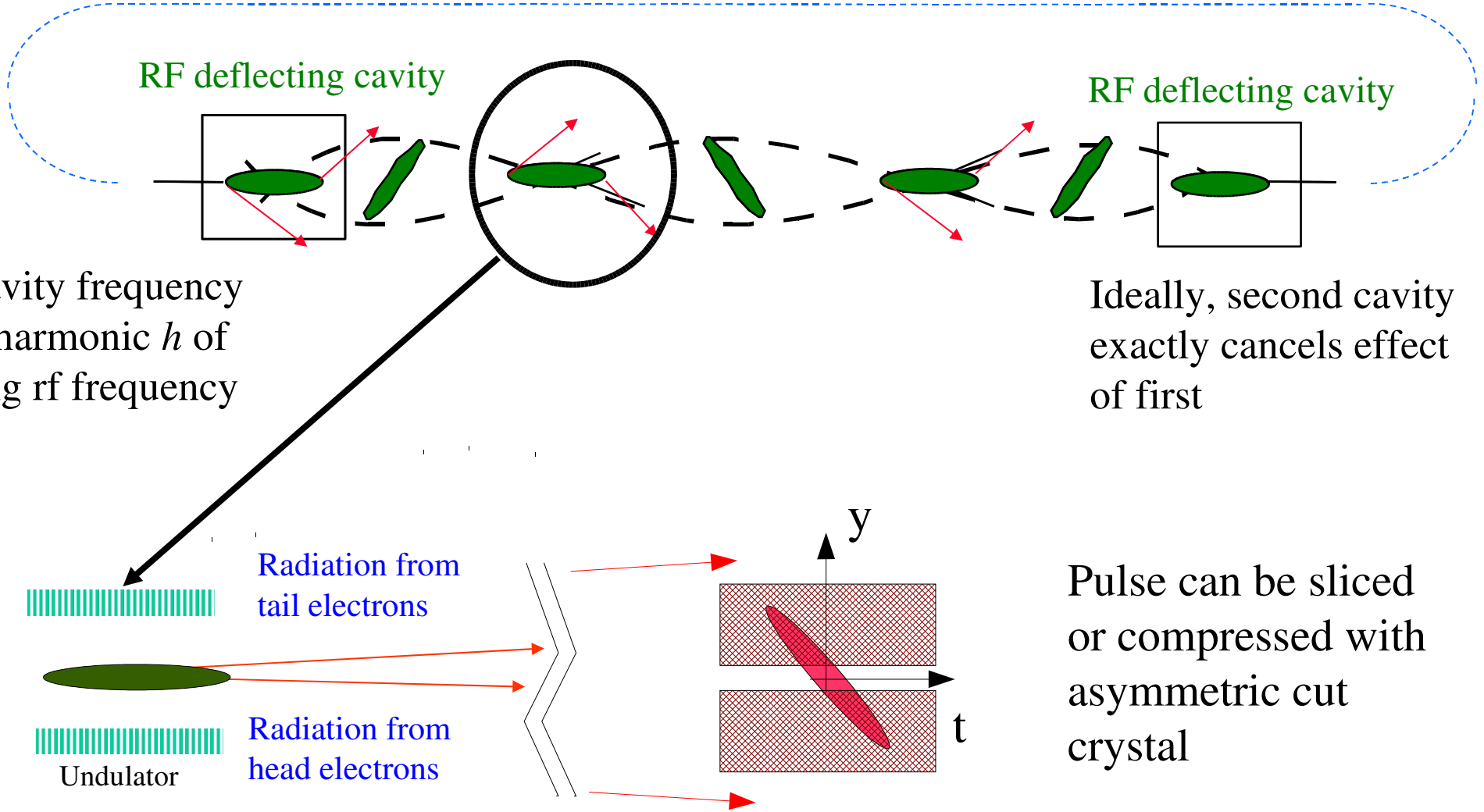




elegant simulation by M. Borland

6: Zholents' Transverse Rf Chirp Concept

(Adapted from A. Zholents' August 30, 2004 presentation at APS Strategic Planning Meeting.)



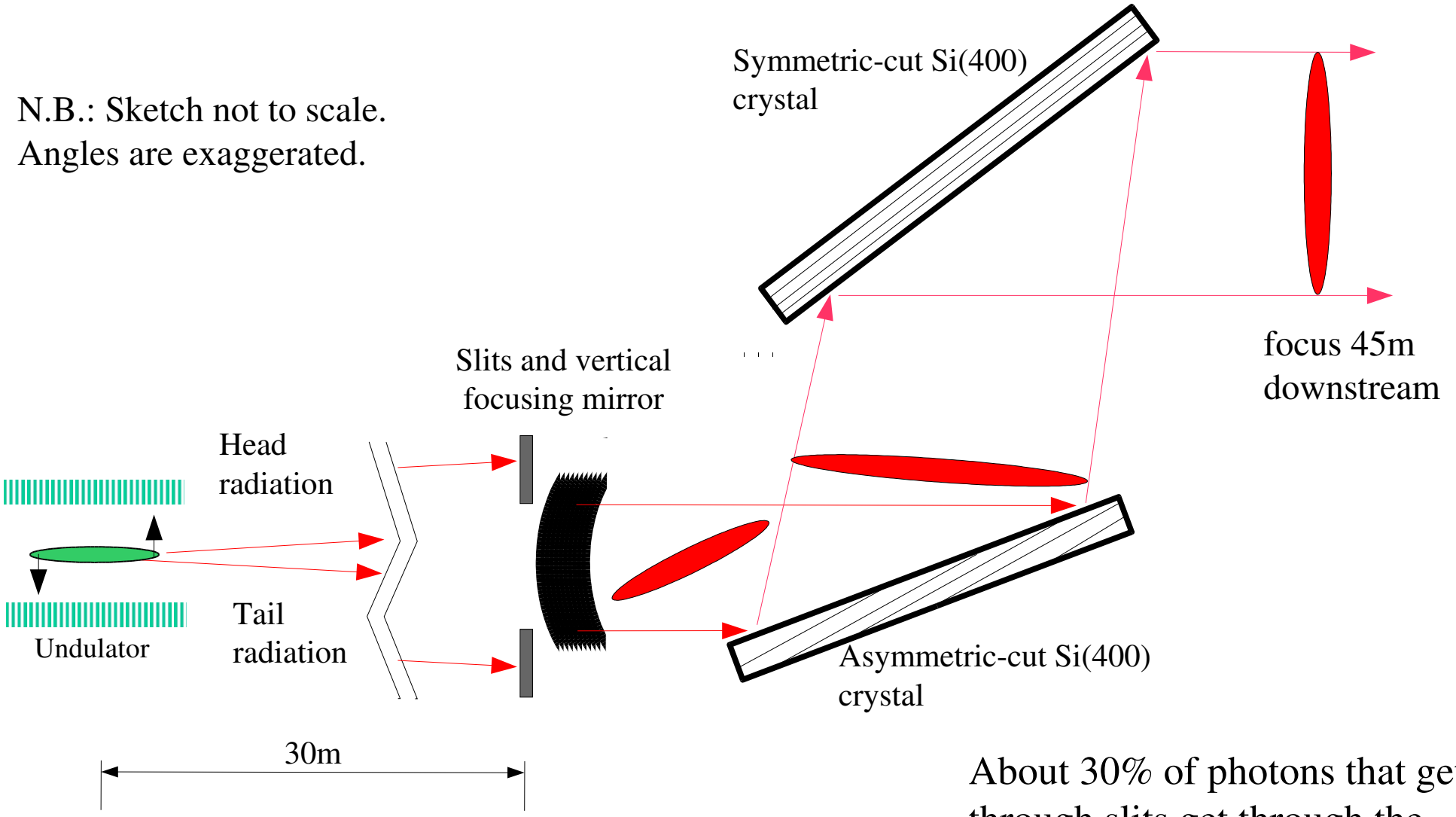
6: APS Feasibility Study

- We've made significant progress on a feasibility study, covering
  - Lattice options
  - Beam dynamics and tolerances
  - Instabilities
  - Lifetime limits
  - Compression and optimization
  - Undulator properties and compression
  - X-ray optics
  - Rf system

Participants include: M. Borland, Y-C Chae, R. Dejus, L. Emery, K. Harkay, D. Horan, R. Kustom, D. Mills, S. Milton, G. Pile, V. Sajaev, S. Shastri, G. Waldschmidt, M. White

6: APS Optics Concept for 10 kV

N.B.: Sketch not to scale.
Angles are exaggerated.



About 30% of photons that get through slits get through the compression optics.

After S. Shastri, APS

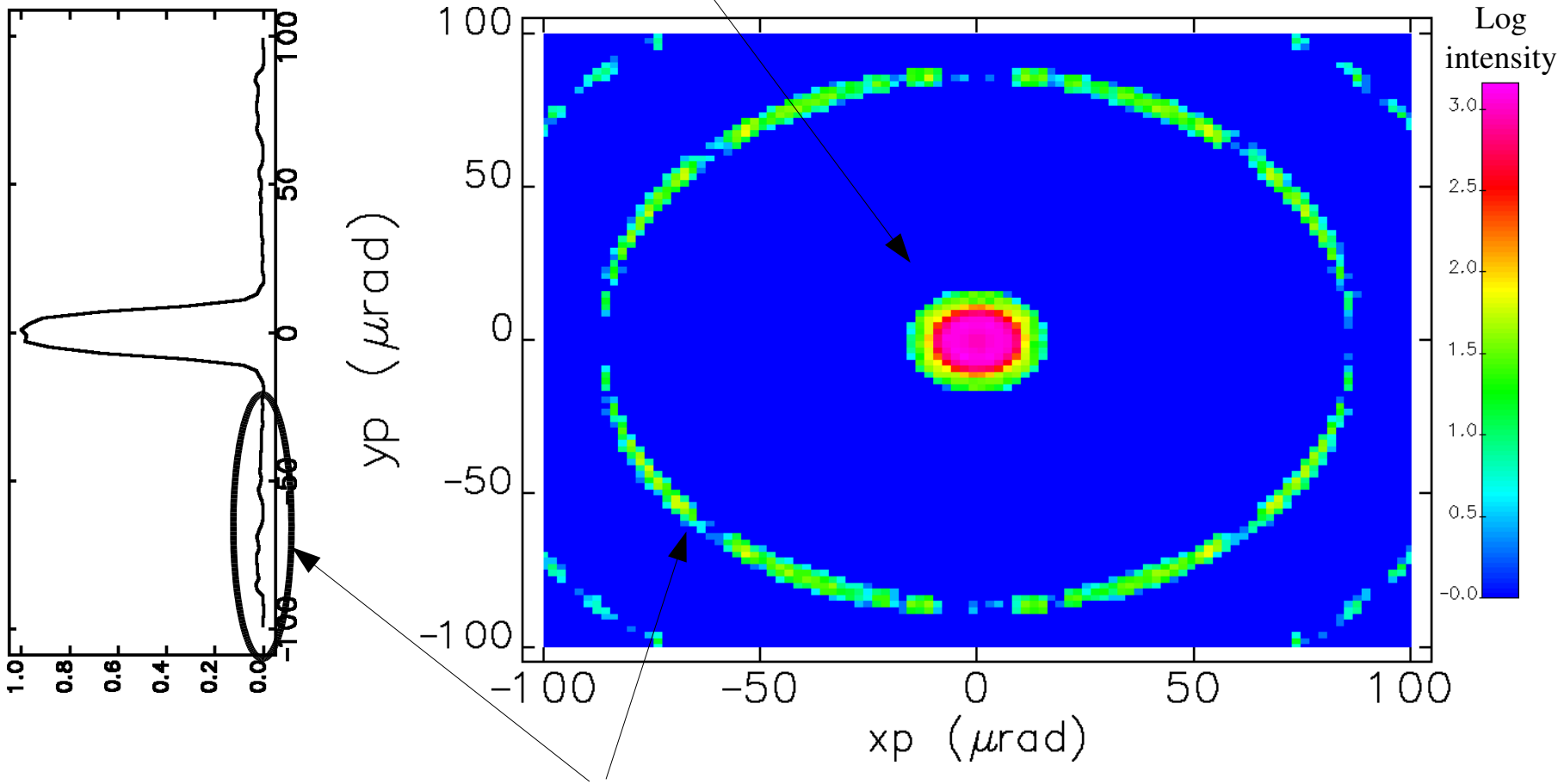
6: Compression Analysis

- We've found a number of issues with the original analysis
  - Radiation distribution not correct[1]
  - Didn't include rf nonlinearity and need for slits[2,3]
  - X-ray optics calculations not valid for APS parameters[4]
  - Didn't estimate loss of intensity due to compression optics[4]
- Zholents' parameters (4th harmonic, 2MV) give ~6 ps FWHM, not ~2 ps FWHM

[1]M. Borland, OAG-TN-2005-042; R. Dejus
[2]M. Borland, OAG-TN-2005-026, -031
[3]M. Borland, OAG-TN-2005-031
[4]S. Shastri

6: Undulator Radiation Pattern

Central cone opening angle ~5 urad rms



Third harmonic contributes a background, making compression somewhat harder

Calculation courtesy R. Dejus

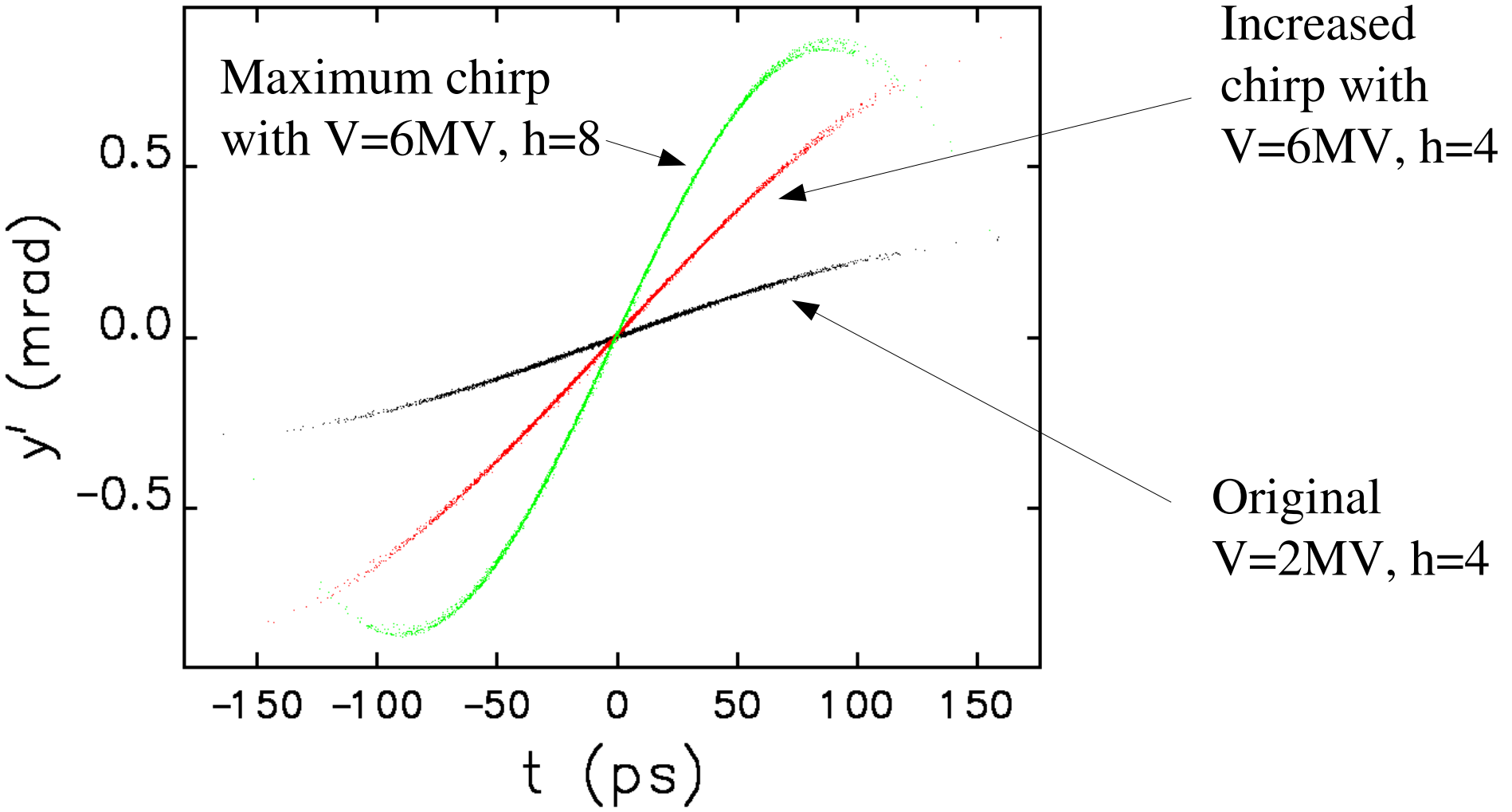
6: Achieving More Compression

- Reduce radiation opening angle
  - Use a longer ID
  - Use a shorter x-ray wavelength if possible
- Increase the chirp
  - Increase voltage
    - Lifetime limits us to ~7MV
  - Increase harmonic number
    - Power source availability up to h=8 (2.8 GHz)[1]
  - Makes emittance increase worse

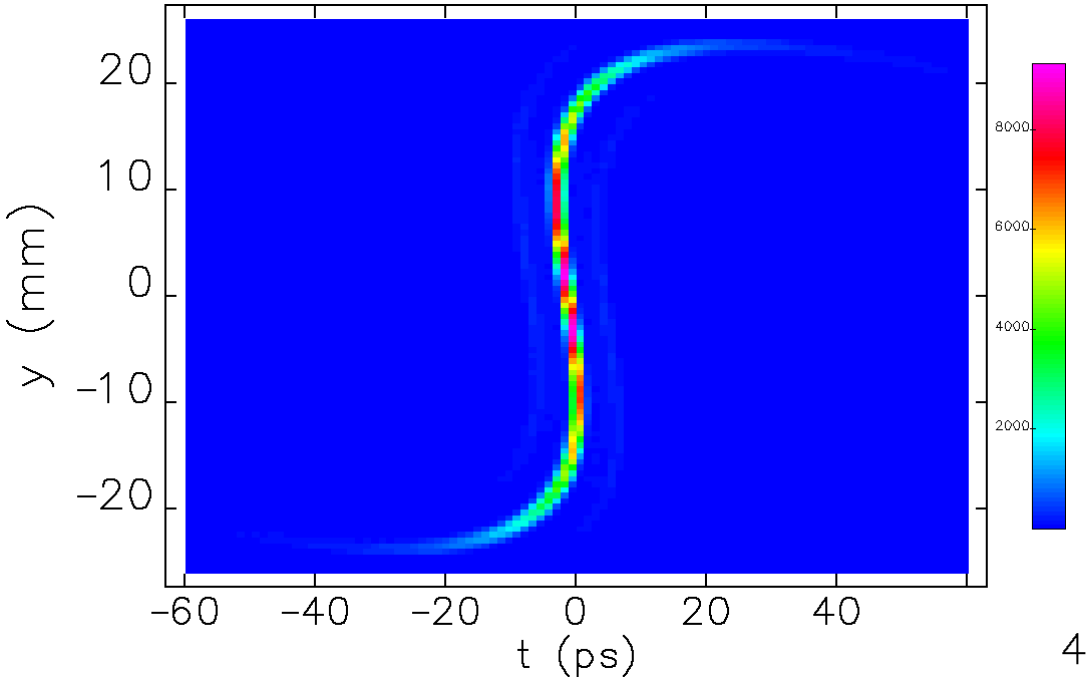
M. Borland, OAG-TN-2004-031, 035, 042

[1]D. Horan

6: Effect of Higher h, V

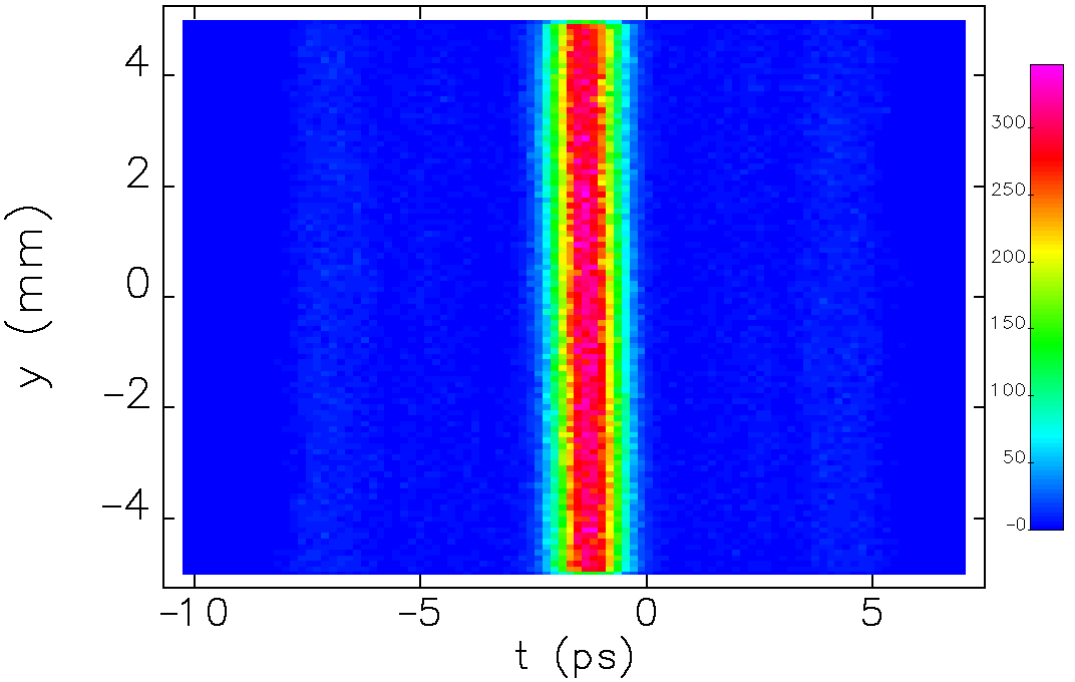


6: Compressed Pulse (h=8, V=6 MV)

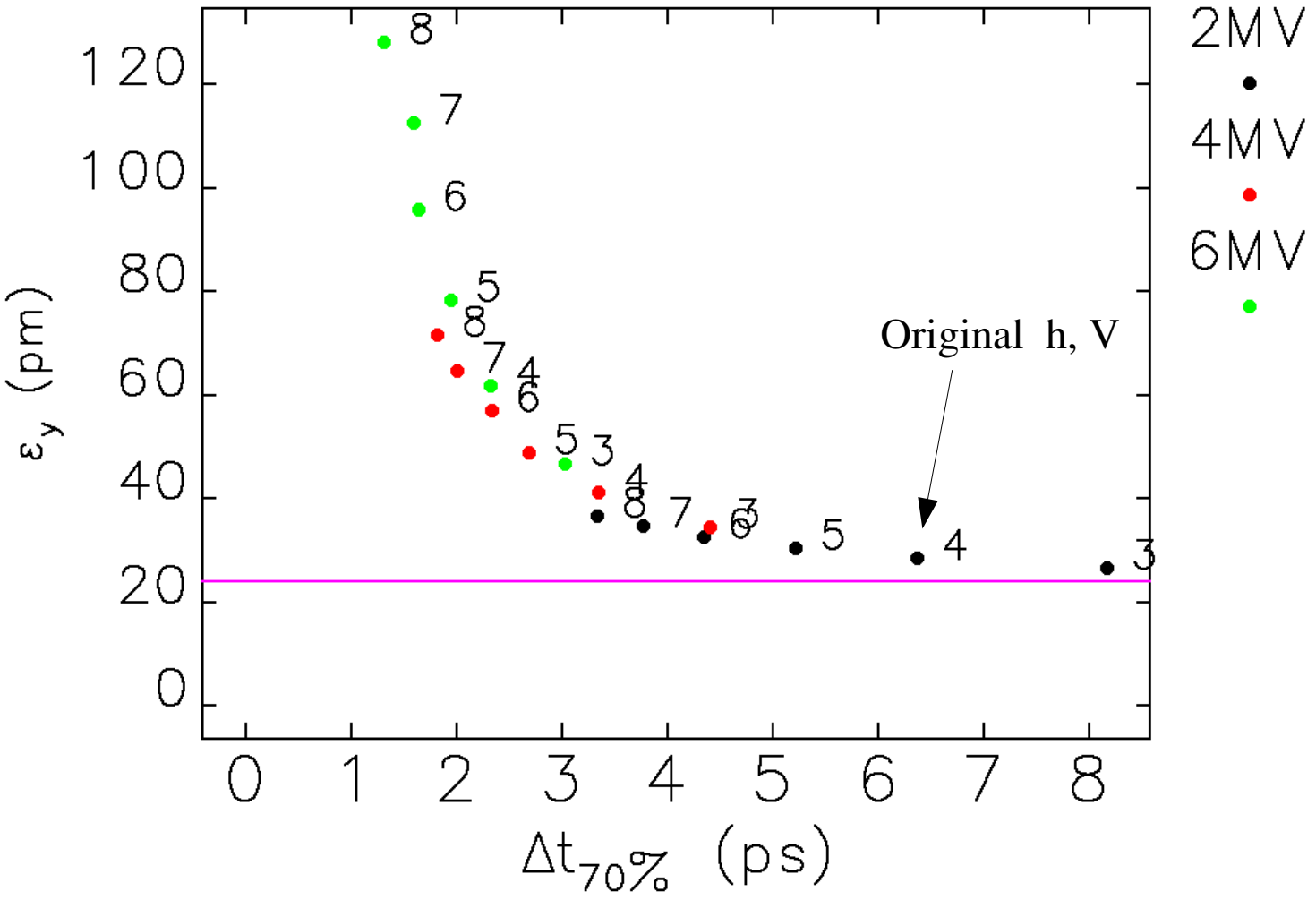


Without slits, rf curvature prevents complete compression

With slits, we lose intensity but get complete compression



6: Simulation Results for 10 kV, UA



Based on retaining 10% of photons, including slits and optics losses

Closing slits more helps very little due to broadness of ID radiation

elegant simulations by M. Borland

6: Causes of Increased Emittance

- If kick cancellation is not exact, vertical emittance will increase
- Many possible causes of imperfect cancellation
  - Lattice coupling between cavities
  - Roll of cavities about beam axis
  - Lattice errors
  - Rf phasing and voltage errors
  - Sextupole nonlinearity
  - Chromaticity and beam energy spread
  - Momentum compaction and beam energy spread

See M. Borland, OAG-TN-2004-026, OAG-TN-2004-027, OAG-TN-2004-054

6: Managing Vertical Emittance Effects

- Turn off interior sextupoles
  - Hurts lifetime, but necessary for V>2 MV
  - Included in the simulations already
- Can offset ~20 pm of increase by lowering the emittance ratio ahead of time[1]
- Use to improve injection efficiency and control lifetime:
  - Tune APS for lowest vertical coupling
    - Gives best injection efficiency
    - Cavities raise vertical emittance and hence lifetime

[1]V. Sajaev

Summary

- Improved bunch purity
  - FY2005 project proposal for PAR bunch cleaner
  - Anticipate improvement in near future
    - Virtual guarantee of high purity
    - Anticipate better than 10^{-6}
- More single bunch current
  - Two FY2005 project proposals address this
  - Prediction of 16 mA in hybrid mode with good lifetime

Summary

- Shorter equilibrium bunches
  - Difficult and expensive to make improvements
  - ~2-fold reduction in bunch length probably doesn't justify expense
  - Zero-alpha lattice may be interesting to some, but current is low
- Transient schemes
  - Two concepts under exploration
  - These require little new hardware
  - Guo's concept has already shown results
  - Repetition rate, beam disruption, intensity are issues

Summary

- Rf chirping
  - Extensive investigation performed, on-going
  - No show stoppers seen, but harder than expected
    - 1~2 ps FWHM
    - 10% intensity
    - ~100 pm vertical emittance (4 times present)
    - Short lifetime (~3 hours?)
  - Very expensive (~10M$[1])

[1]G. Pile, *et al.*

Conclusion

- Many possibilities for enhanced time-resolved imaging
- Some have significant cost and downsides that must be weighed against the benefits
- Much on-going activity on this subject
- Good reason to think we can significantly enhance the APS for time-resolved applications