APS Storage Ring Injection Topics: Optimization and Top-up

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Outline

- APS operating modes
- Review of the APS injector
- Injection Optimization
  - Booster extraction jitter
  - SR vertical emittance
  - SR first-turn trajectory fitting, optimization
  - Transfer line optics
  - SR dynamic aperture
- Top-up
  - Safety
  - Problems and requirements
  - Performance at APS

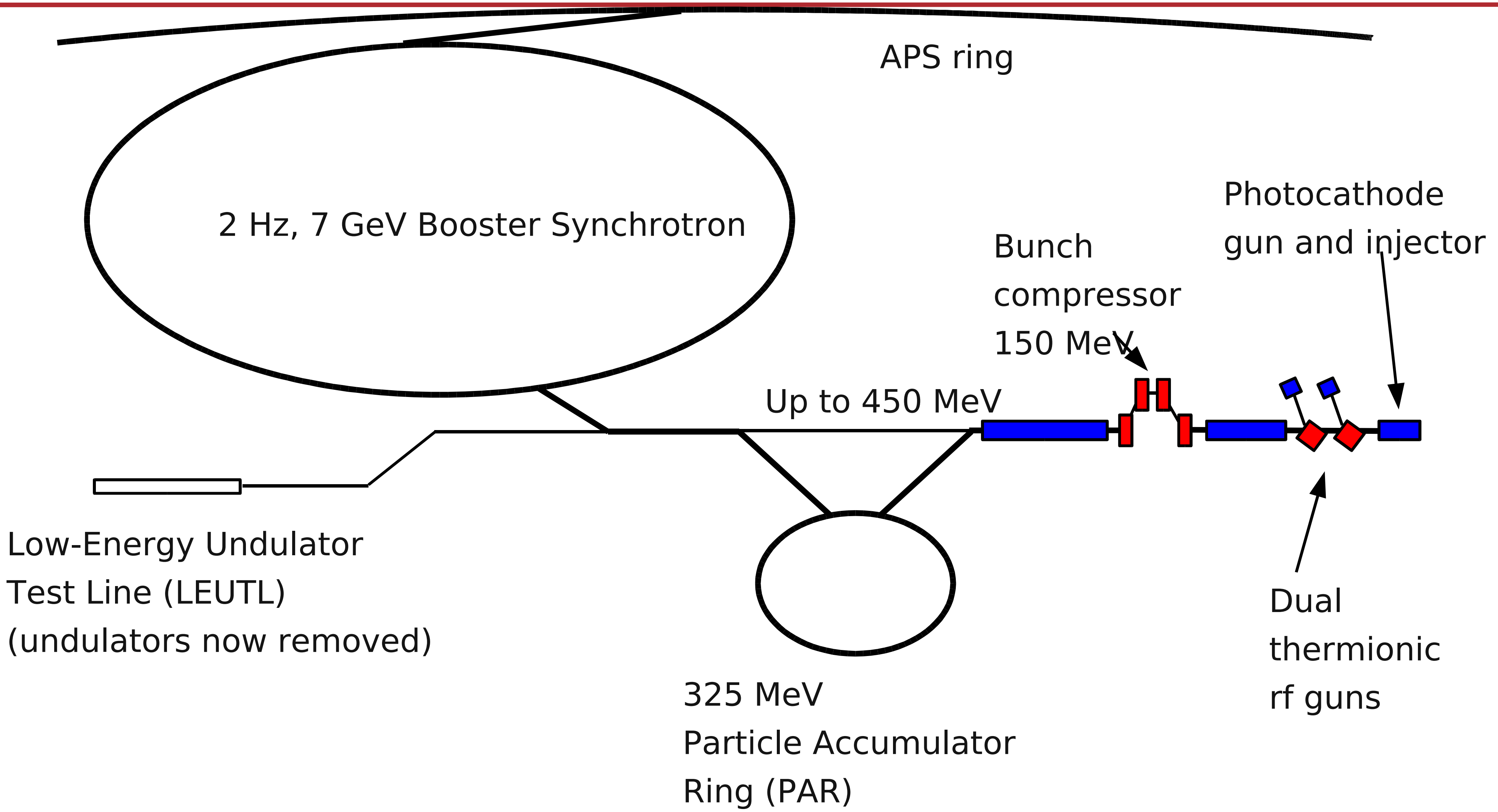
APS Operator Parameters

- Operating parameters and modes determine injector requirements
- Presently, always operate at 100 mA
  - Not all beamlines can withstand higher current
  - Accelerator designed for 300 mA
  - Have filled to 250 mA for machine studies
- All operating modes now use the low-emittance lattice
  - Raw emittance is 2.5 nm
  - Effective emittance is 3.1 nm
  - Original APS emittance was 7.7 nm
- Operating modes distinguished by fill pattern.

Fill Patterns

- 24 bunches, uniformly spaced
  - Supports time-resolved studies
  - Used ~60% of the time
  - Lifetime is 6 hours, so top-up is required
- 324 bunches, uniformly spaced, and 1296 bunches
  - Used ~20% of the time
  - Lifetime is 60 and 100 hours, top-up is not required
  - Refill every 12 hours
- Hybrid mode:
  - Supports time-resolved studies
  - Used ~20% of time
  - One 16 mA bunch and 56, 1.5 mA bunches
  - Lifetime of 16 mA bunch is ~2 hours, top-up required.

Overall Layout of APS Injectors



Motivation of Injection Optimization

- Reduce radiation damage in undulators
  - both Toushek scattered particles (80%) and injection loss particles (20%)
- Reduce charge required by injectors in top-up
- SR Trajectory and BTS Optics studies
- SR Dynamic aperture studies

Booster Extraction

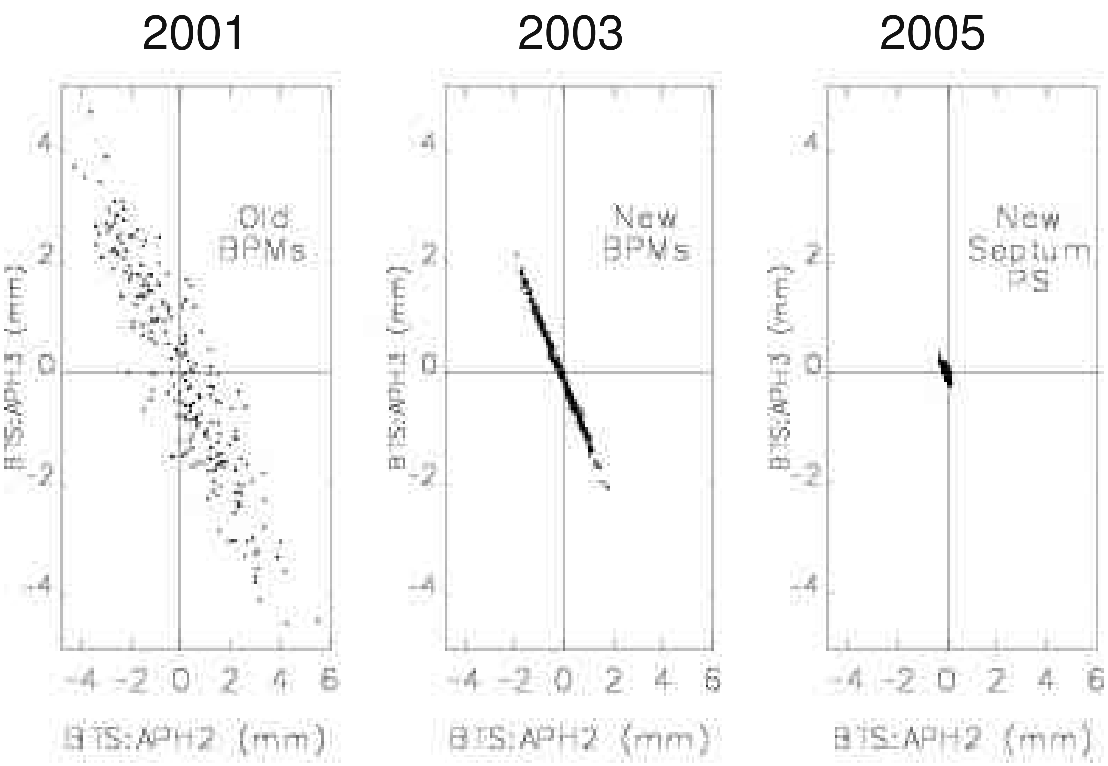
- Stable transfer line trajectory facilitates injection into SR
  - requirement is 1σ in hor. beam size (1.1 mm)
  - vertical trajectory has been very stable
- Sources of error
  - Septum jitter
  - Kicker jitter
  - Booster momentum jitter ($< \pm 0.04\%$)
  - Booster orbit jitter (~25 $\mu\mathrm{m}$)
- Septum power supplies were primary problem
  - Jitter is too small to be measured directly; need beam
  - ±0.15% (0.1 mrad) with original supplies
  - Also drift due to thermal effect on resistance of coils
    - *supply provides a fixed voltage pulse.*

Correction of Problems

- Principle components analysis was instrumental
  - Use SVD to separate signal from noise
  - Compare principle singular vectors to expected response of suspected noise sources
- Drifts corrected by two approaches
  - Adjust septum setpoint based on pulsing history
  - Perform slow feedback from transfer line BPMs
  - Needed higher resolution BPMs
    - *Old bpms had 0.5 mm rms noise.*
    - *New BPMs have 25 μm rms noise*
- Jitter reduced by recent upgrade of septum power supplies
  - Supply regulation reduced from 0.15% to 0.01%
  - Measured with beam and PCA
  - Same upgrade will be done to SR pulsed septums.

Booster Extraction

Pair of BPMs with largest correlation due to septum jitter over last two upgrades

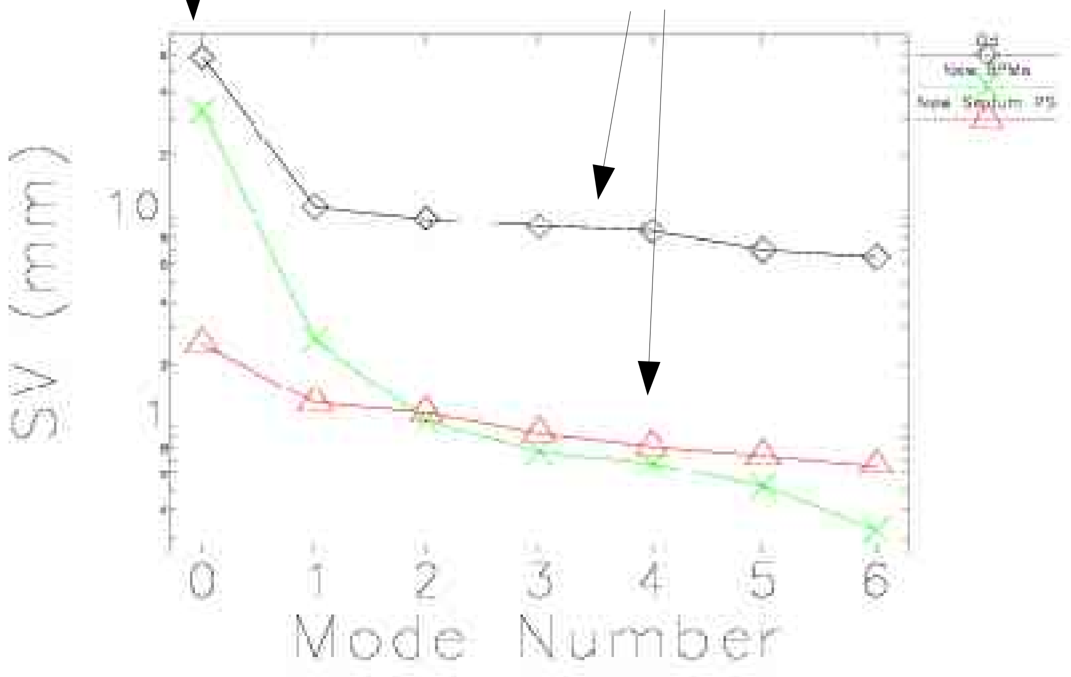


Booster Extraction

Spectrum of singular values

Proportional to jitter amplitude

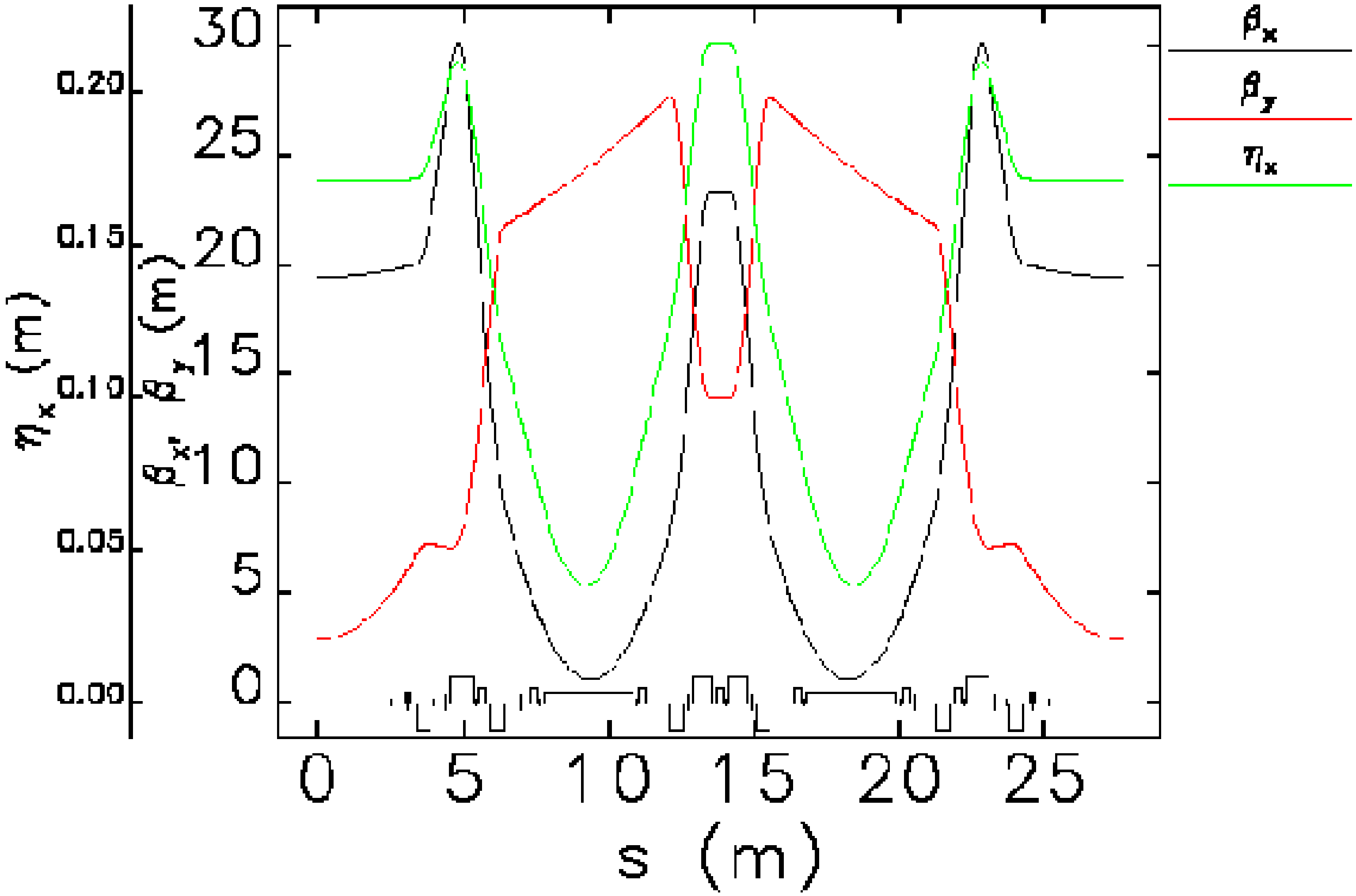
Proportional to bpm noise



APS Storage Ring

- DBA-style cell with 5-m straight sections
- Dispersion in straight section reduces emittance to 1/3 original value (8.0 nm-rad to 2.5 nm-rad)
- Effective emittance: 3.1 nm-rad (7GeV)
- $\nu_x = 36.2$, $\nu_y = 19.26$
- $\xi_x = +6$, $\xi_y = +6$, depends on bunch pattern

Machine Functions and Layout

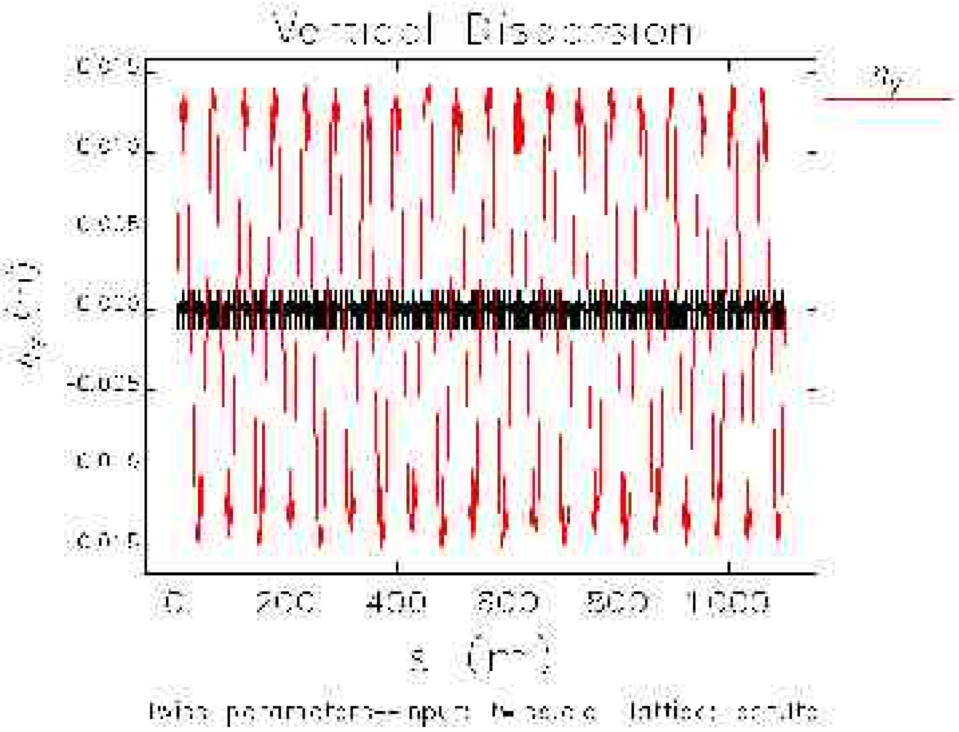


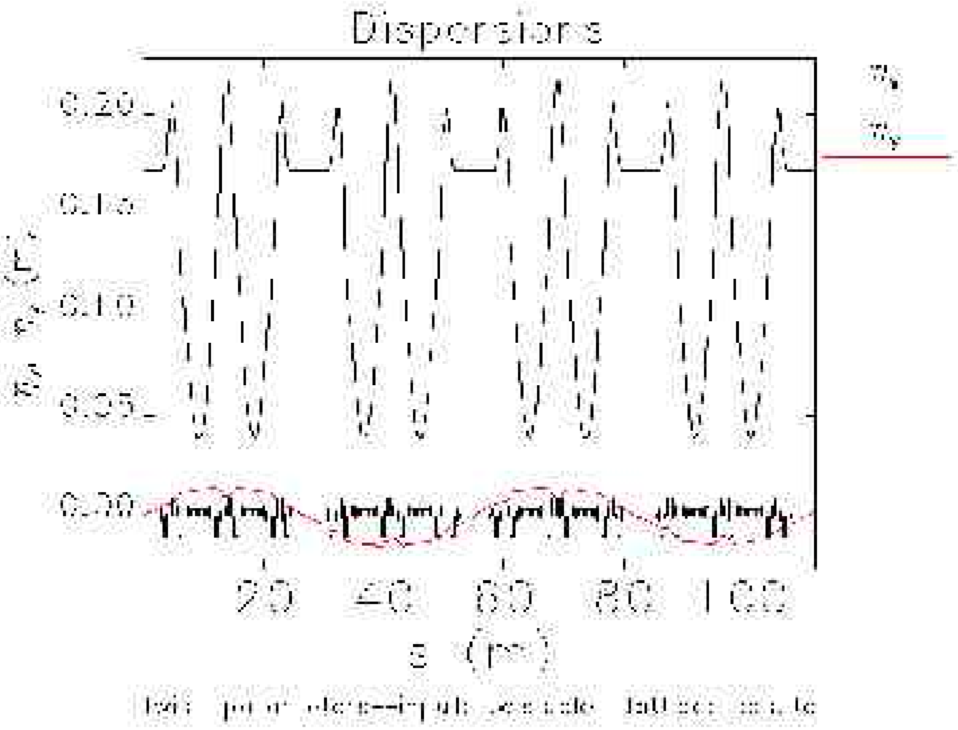
Twiss parameters for sector33

Vertical Emittance

- Vertical dispersion is added to increase lifetime to a certain goal
- First we minimize vertical dispersion and coupling for baseline solution
  - 19 skew quadrupoles as correctors
  - SVD correction of vertical dispersion
  - Coupling minimized with two harmonic knobs. Get 0.3%-0.5% emittance ratio
- Use skew quadrupole knobs in 0th harmonic to generate vertical dispersion wave
  - center of straight section: disperion zero, slope non-zero
  - Hopefully doesn't generate x-y coupling too much
  - Give range of 0.5% to 5% emittance ratio

Vertical Dispersion 0th Harmonic





Sextupole Magnets

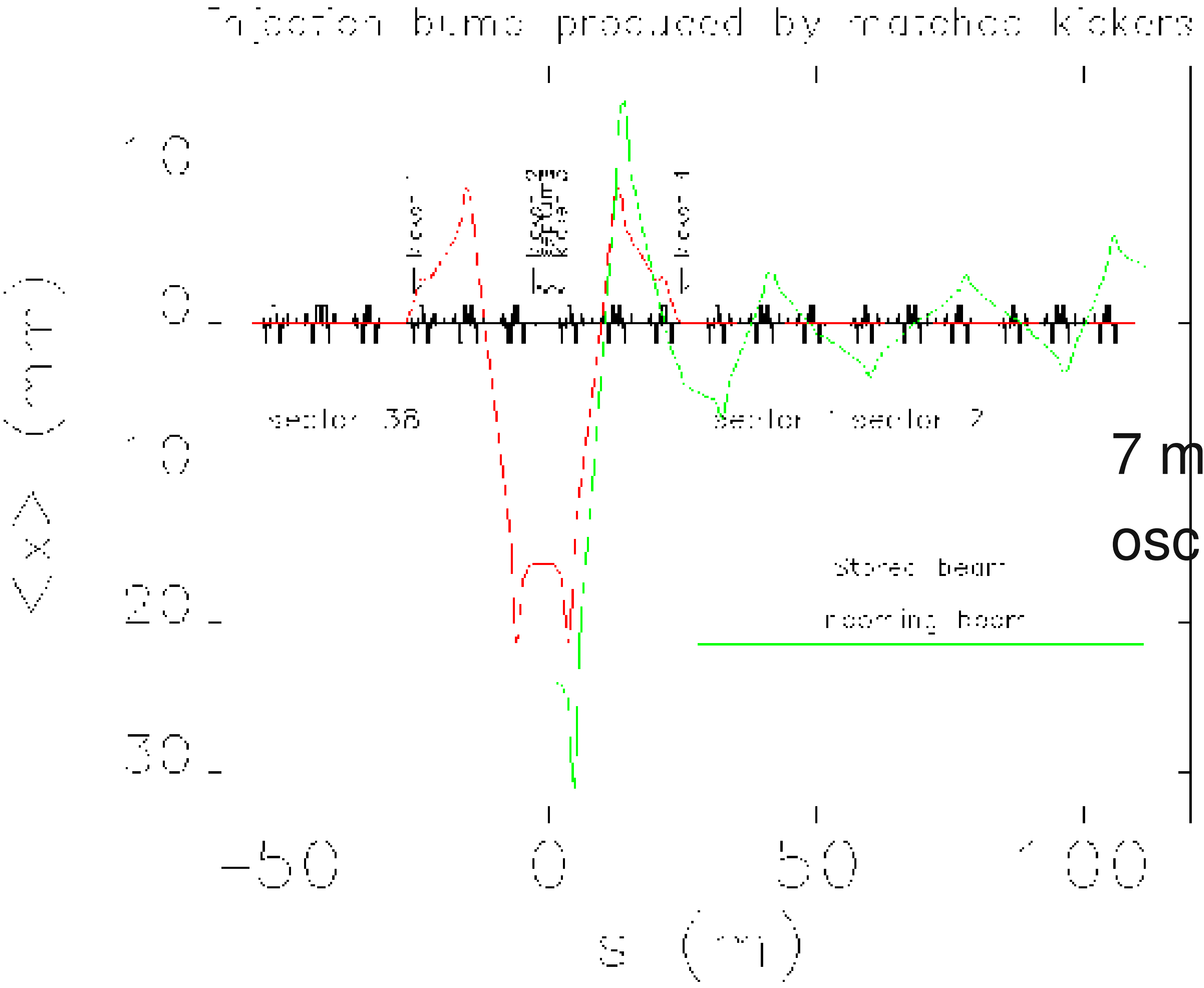
- Sextupole magnet strength have increased with changes to lattice optics over the years.
  - dynamic aperture 7-10 mm, depending on optics correction and coupling errors.
- Four families with 2-parameter freedom to optimize lifetime, dynamic aperture or injection bump.
- Individual PS's; allows lattice development with sectors of sextupoles turned off.

Limiting Storage Ring Apertures

- Main chamber: ±42 mm in x, ±21 mm in y
- Vertical apertures in straight sections
  - ±2.5 mm in two straight sections, four cells downstream of injection point
  - ±4.0 mm typically
- Horizontal apertures in straight sections:
  - -15 mm in two straight sections
  - -17 mm at injection septum
  - Much larger in positive direction (e.g. pumping slots)

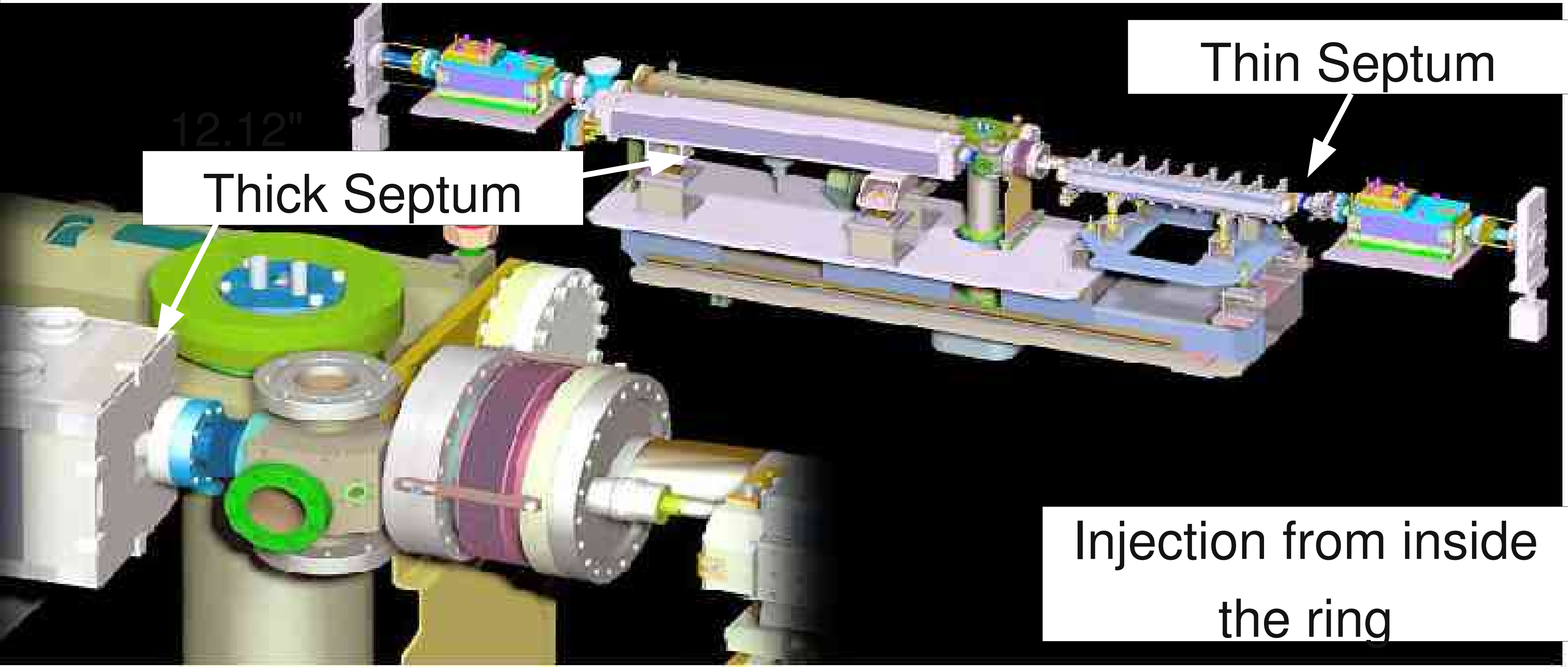
Injection System

- Four kickers located over two cells fire simultaneously
- ~1 mrad kicks produce -16 mm at injection point
- Booster beam launches into SR at about -23 mm
- Booster beam size is about 1.3 mm rms.
- Injection centroid oscillation for matched bump is about 7 mm, but some particles in distribution oscillate for much more, say 11 mm.



7 mm oscillation

Injection Girder 3D Drawing

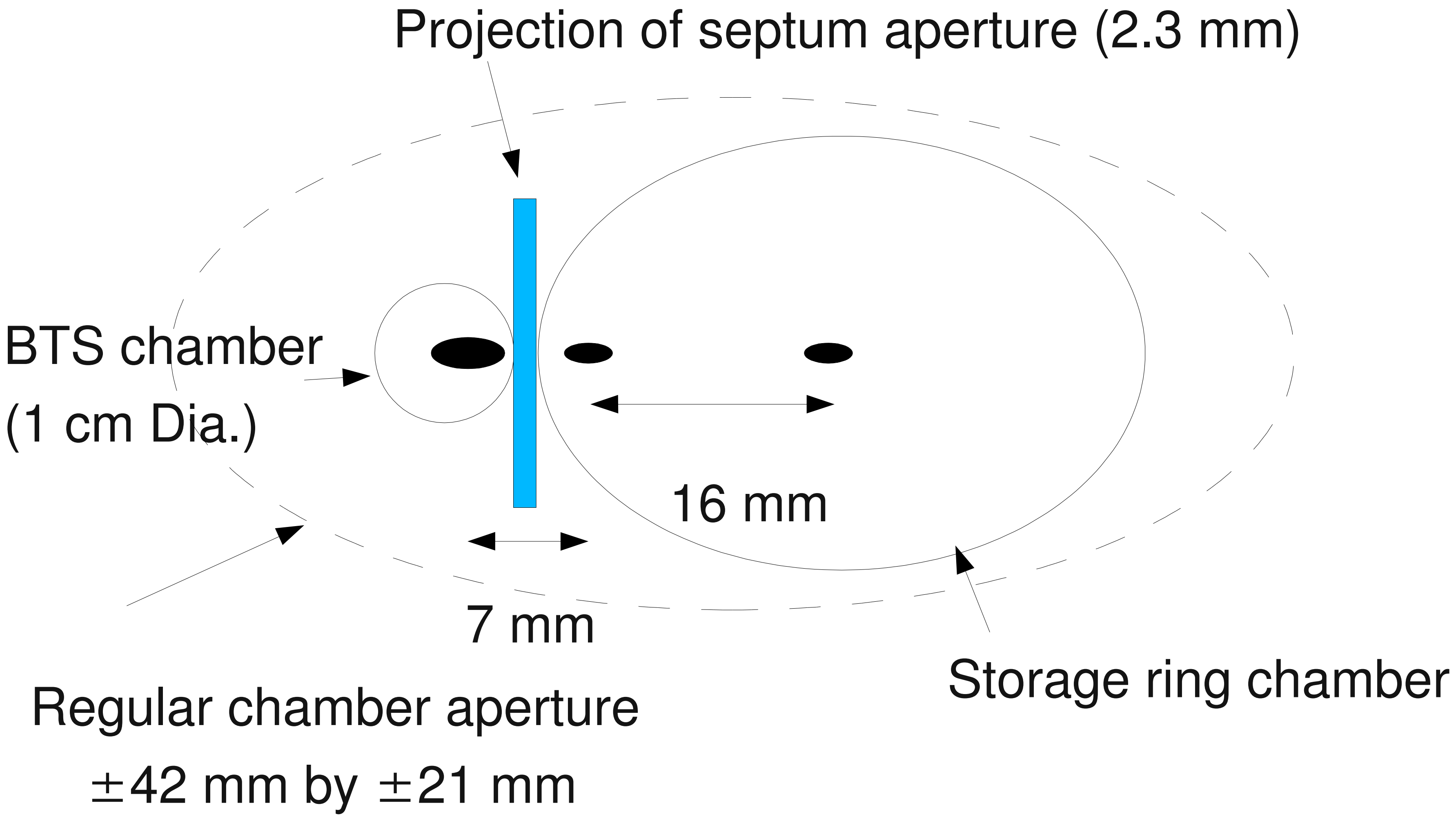


Thin Septum

Thick Septum

Injection from inside the ring

Injection Vacuum Chamber Aperture



Projection of septum aperture (2.3 mm)

BTS chamber
(1 cm Dia.)

16 mm

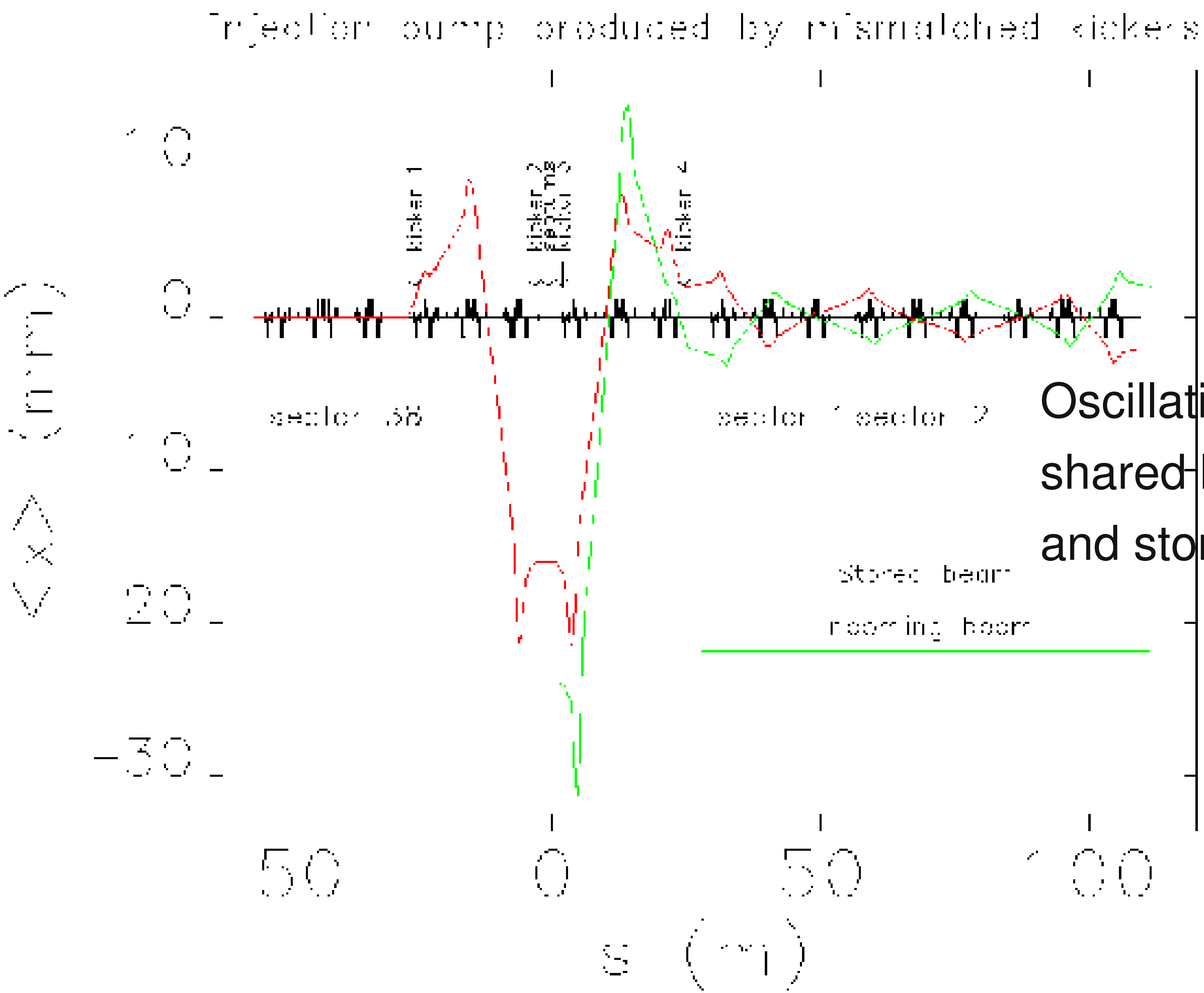
7 mm

Storage ring chamber

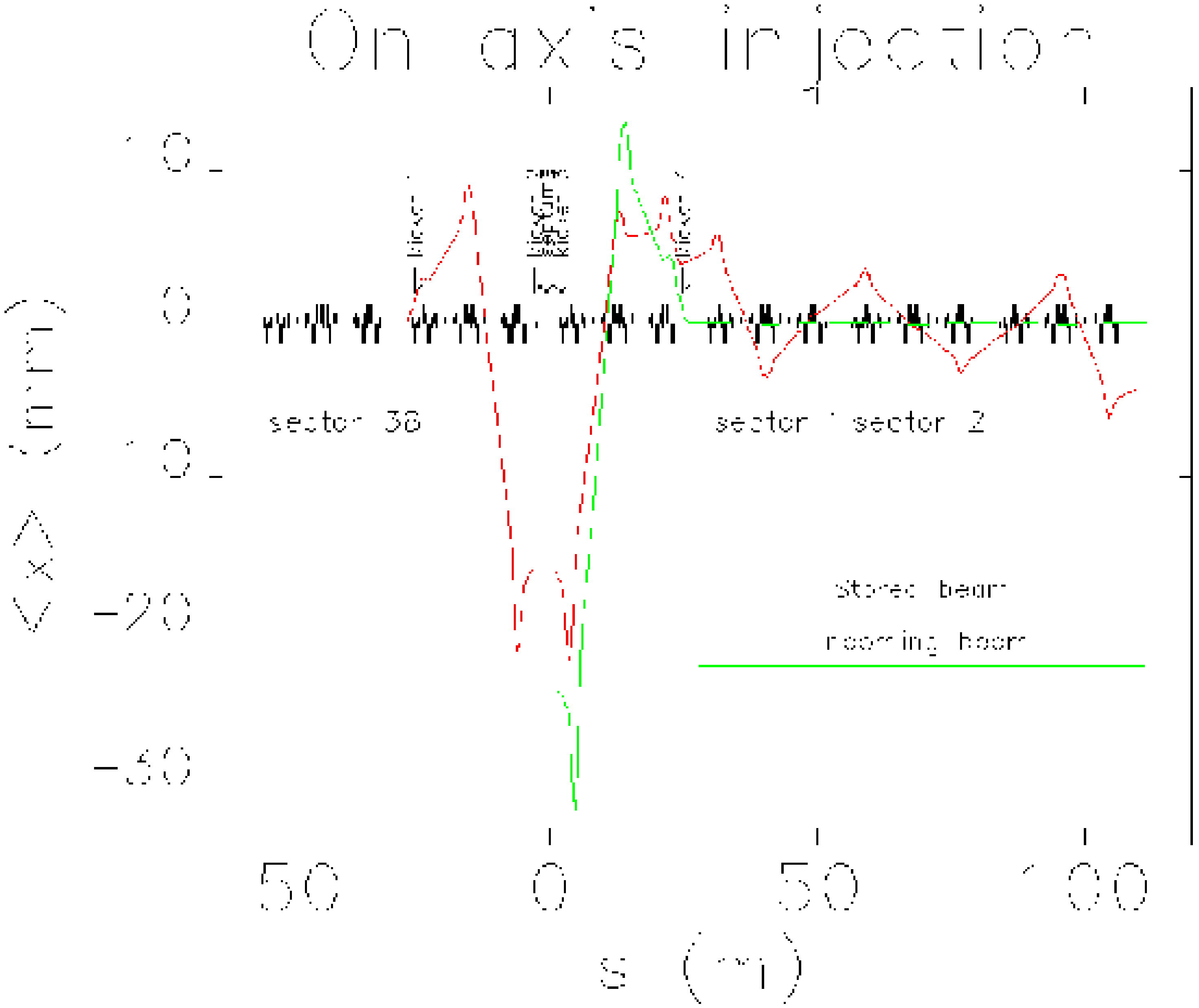
Regular chamber aperture
±42 mm by ±21 mm

Mismatched Kicker Bump

- Increasing the kick angle of last two kickers:
  - lowers injected beam oscillation
  - creates stored beam oscillation
- At large enough kick, one gets on-axis injection, such as in a booster.
- Optimum aperture conditions exists somewhere between matched bump and on-axis condition.



Oscillation amplitude shared between injection and stored beam



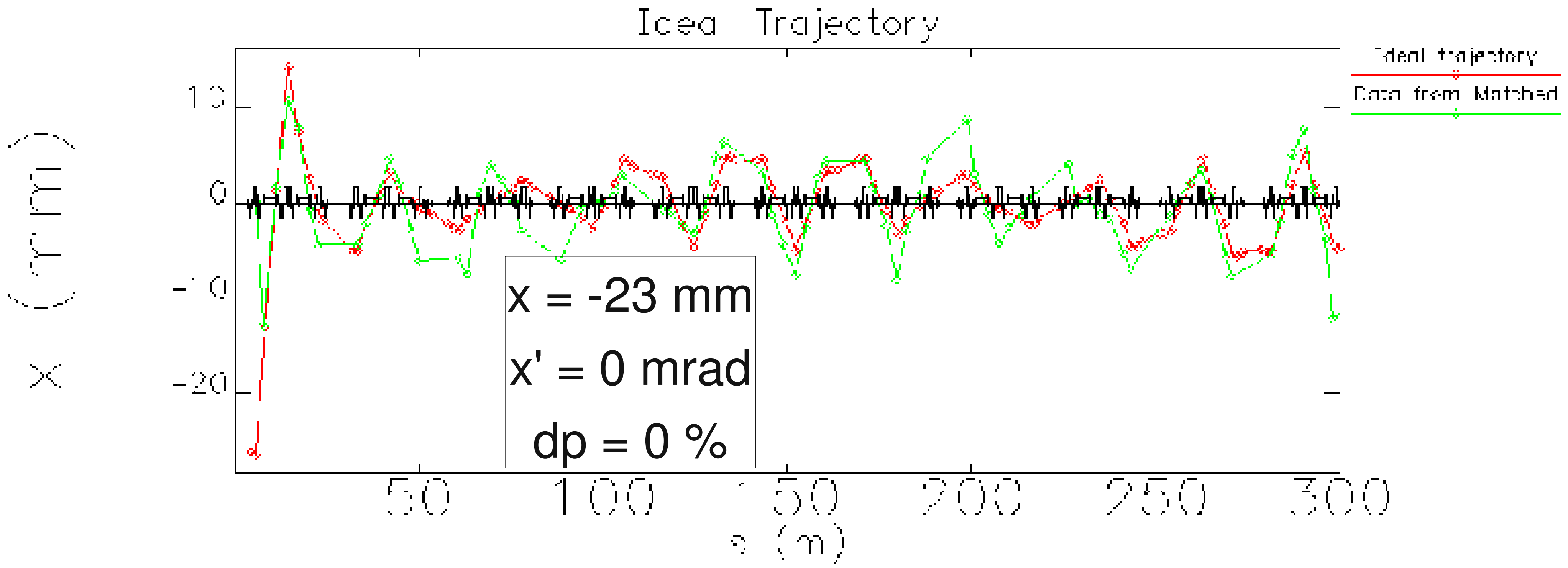
Stored beam is kicked

Modeling the First-Turn Trajectory

- Collect data from turn-by-turn BPMs for:
  - On-axis, matched bump, optimized bump
- Injection efficiency had been optimized with horizontal steering in BTS and horizontally deflecting septums using EPICS tool `sddsoptimize`
- Match the initial condition x, x', dp in a model that correspond closest with measurement using simplex minimization

First-turn Trajectory Measurement

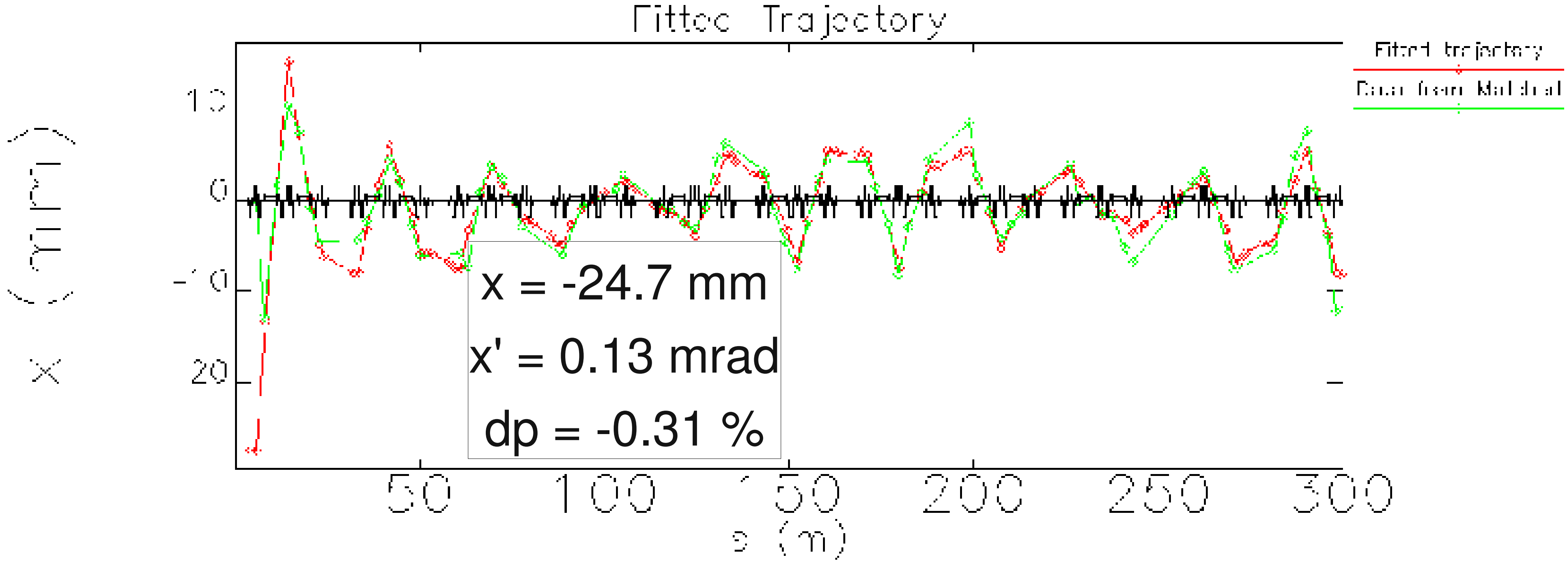
- Result for h-plane may guide us to problems with septum or injection area apertures
- Value for x should be around the design value of -23 mm



x = -23 mm

x' = 0 mrad

dp = 0 %



x = -24.7 mm

x' = 0.13 mrad

dp = -0.31 %

Comments on Fitting and Measurement

- Injection oscillation for matched bump condition is then ~8.6 mm with dp=-0.3%, apparently at or over the edge of the dynamic aperture.
- Model doesn't fit all parts of the oscillation
  - Should use a fitted ring model for optics
  - Should use bpm readback offset for small charge condition
- Momentum launching error is confirmed by BPM history over 2000 turns.

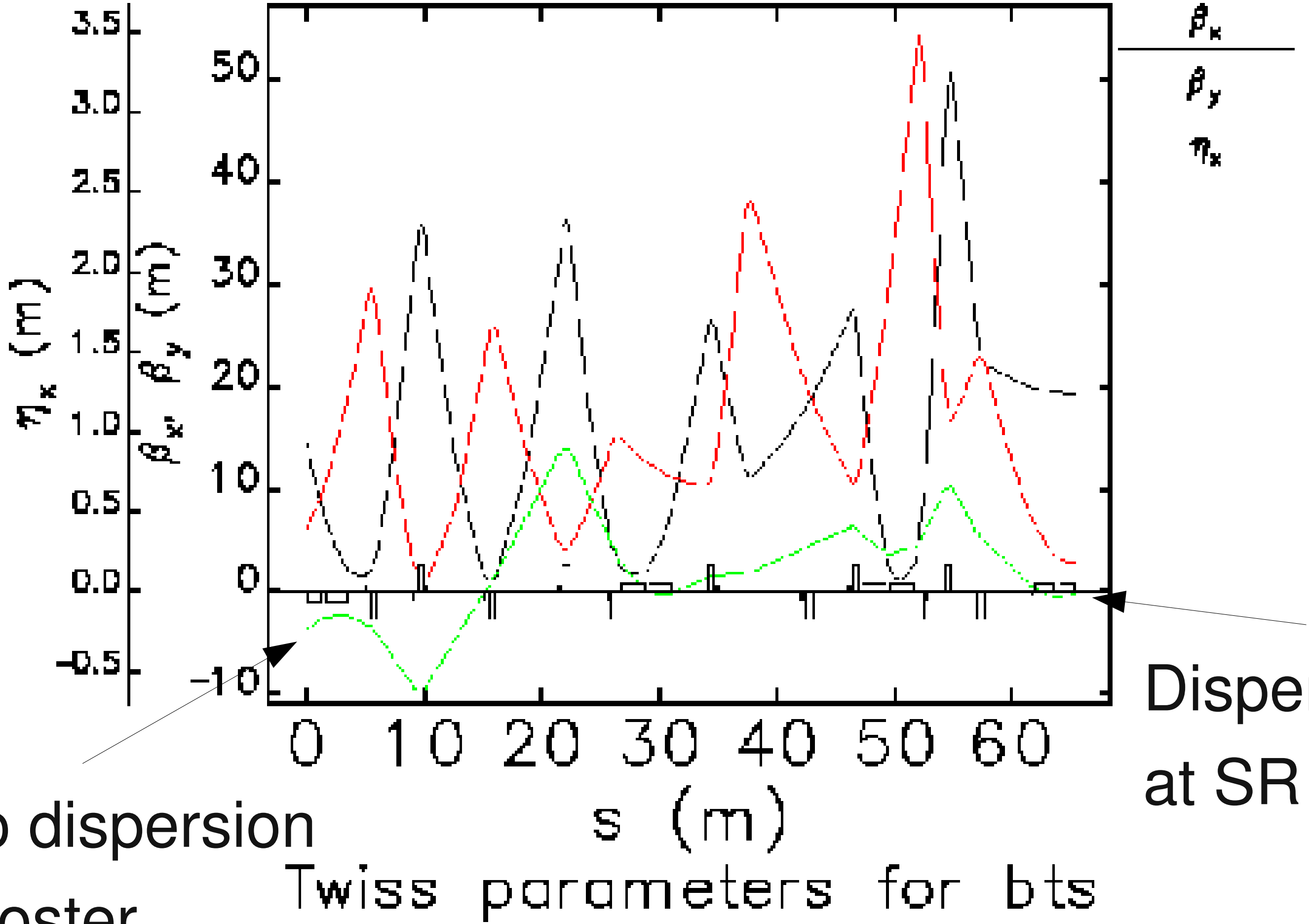
More Comments

- Negative momentum error is a good thing, as it reduces betatron oscillation (Y.-C. Chae)
  - works for injection from interior of ring, and positive dispersion at injection point.
- New injection area (Jan 2004) have been surveyed for exact aperture positions.
- Surveyed YAG crystal inserted between two septum can be used as BPM for BTS beam. (Not used yet)

Conclusion on SR Trajectory

- Comparison of measurements and model of injection process doesn't reveal a bad alignment.
- One could plan to setup longitudinal injection with say, dp = -0.5%, and reduce the betatron oscillation somewhat.

Nominal BTS Optics



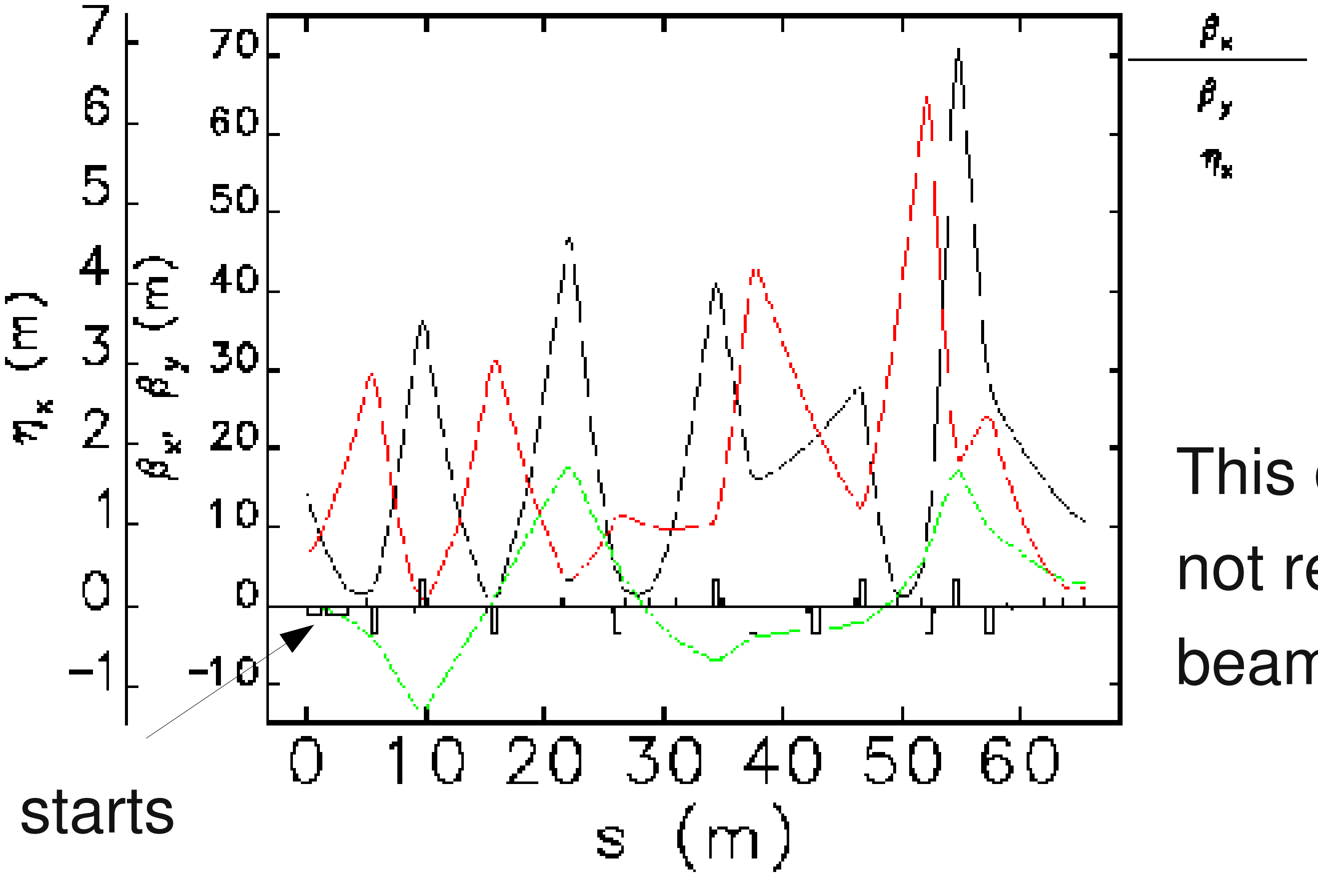
Dispersion zero at SR injection point

Non-zero dispersion out of booster

Dispersion Measurement

- Vary the timing of booster extraction along ramp
- Do not vary any magnets in BTS line
- Launching condition at booster extraction kicker does not vary, i.e. x=0, x'=0 for all timing steps
- Measured response of BTS bpms to timing change is a kind of “dispersion” that has initial value of 0 at kicker

BTS Optics Model for Dispersion Measurement

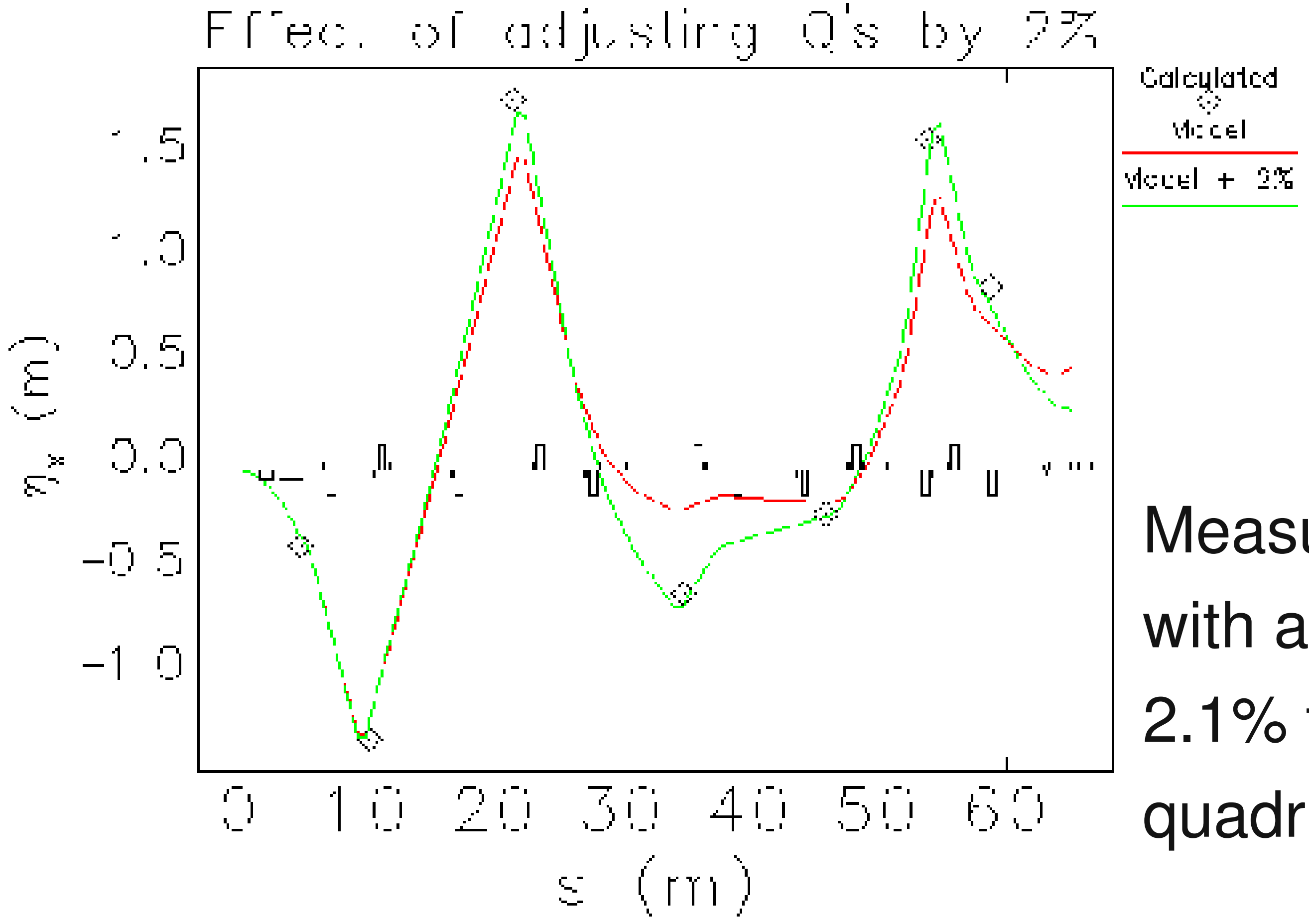


Twiss parameters for btsAdj2

This dispersion is not related to beam size

Dispersion starts out with zero value

Model Adjustment Based on Dispersion Measurement



Measurement agree with a model with 2.1% too strong quadrupoles

Comments on Optics Error

- After correcting the error, we got better injection efficiency.
- Identified a bpm displaced by ~2 m. Confirmed with on-line photographs during the run
- A corrector response measurement would give the same result, if tried
- Dispersion response is easier to analyze.

Conclusion on BTS Characterization

- Obtained a good model of BTS optics
- Next step is to measure beam size at septum, and check with model
  - YAG crystal (for high resolution) between two septum is available but image is not calibrated yet.

Dynamic Aperture

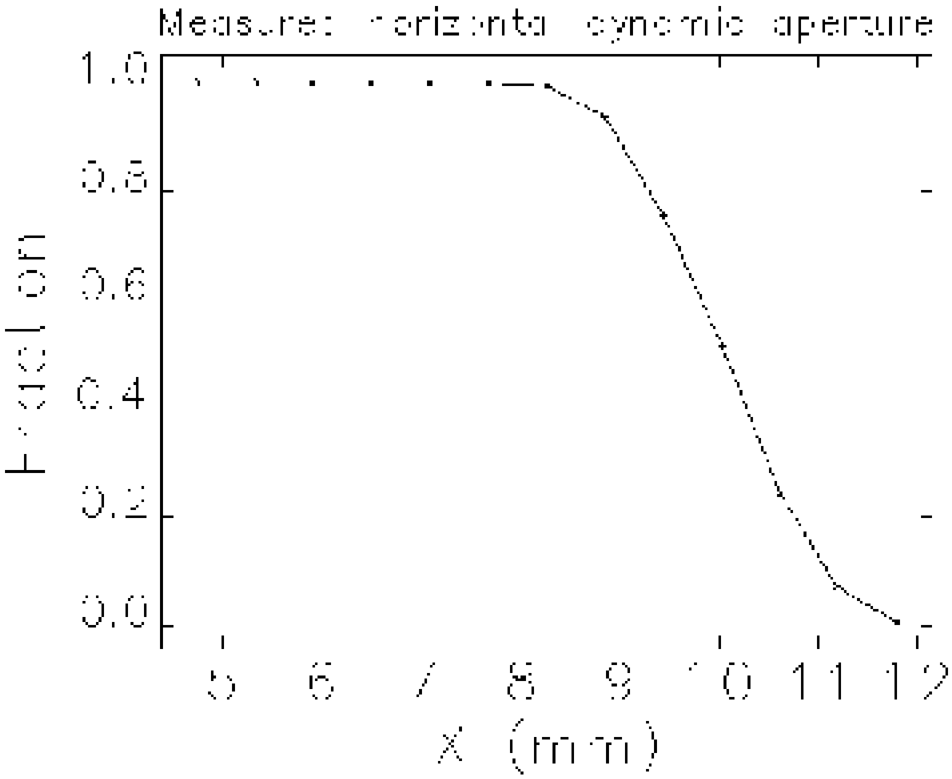
- Measurement, calculation
- Coupling, lifetime
- Sextupole familiies

Measurements

- We can only measure horizontal dynamic aperture. Vertical physical aperture is very small
- We use current monitor to measure the current left after the kick (cannot distinguish between fast and slow losses)
- We use single-turn beam history to calibrate the amplitude of the kick

Measurements

- Measured dynamic aperture (an amplitude of 50% loss) is 10 mm

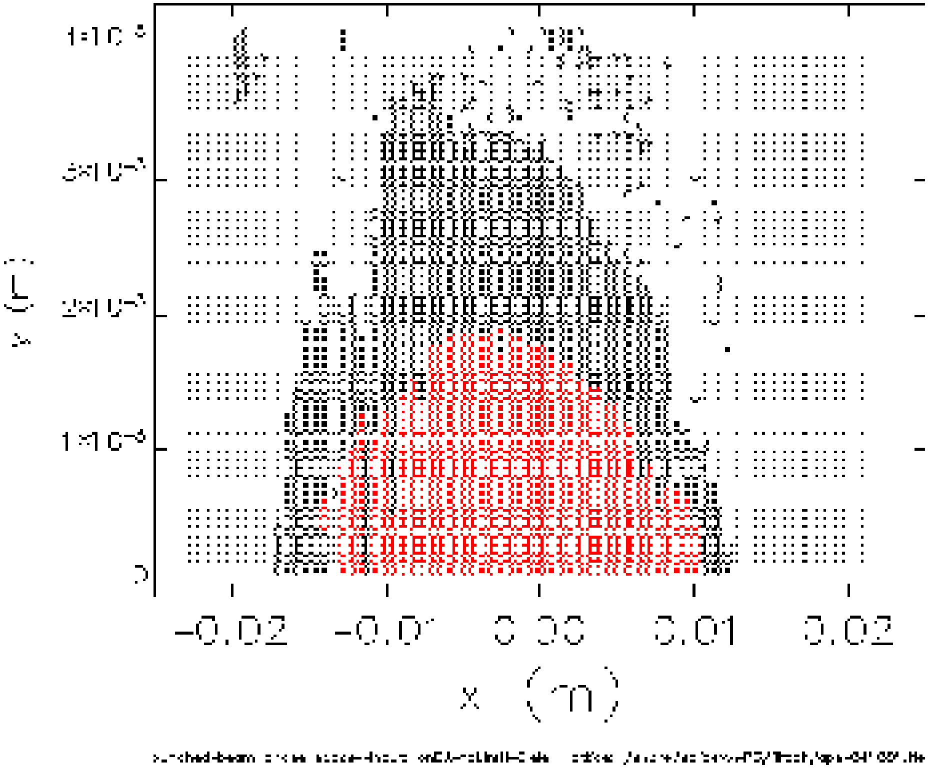


Calculations

- sdds-compliant `elegant`
- Calibrated model, i.e. quadrupole gradients that match the measured optics
- Use all aperture limitations
- Linux cluster, sdds toolkit and tcl-tk scripting. All this combined allows us to do fast and extensive calculations

Dynamic Aperture Calculation

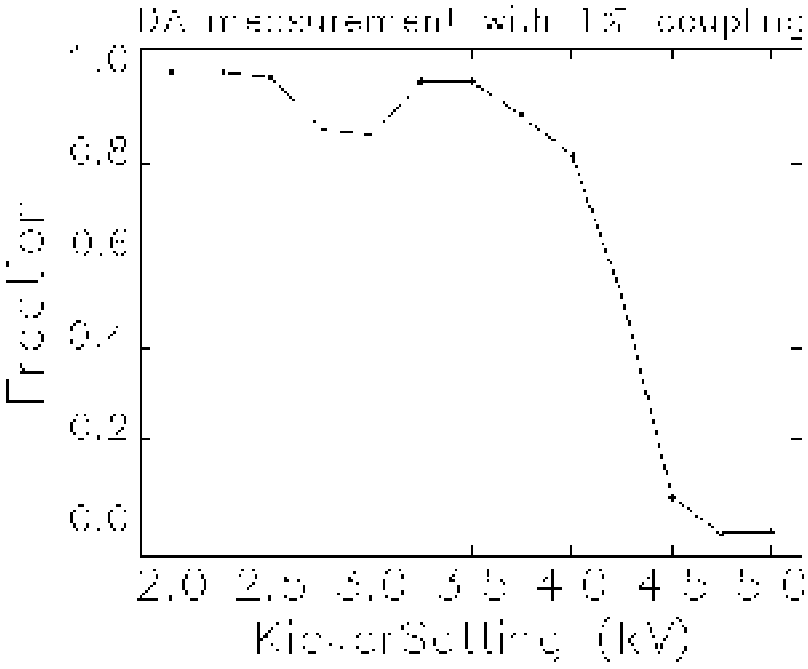
- Black dots are tracked particles
- Black symbols are surviving particles with no physical aperture
- Red symbols are surviving particles with physical aperture

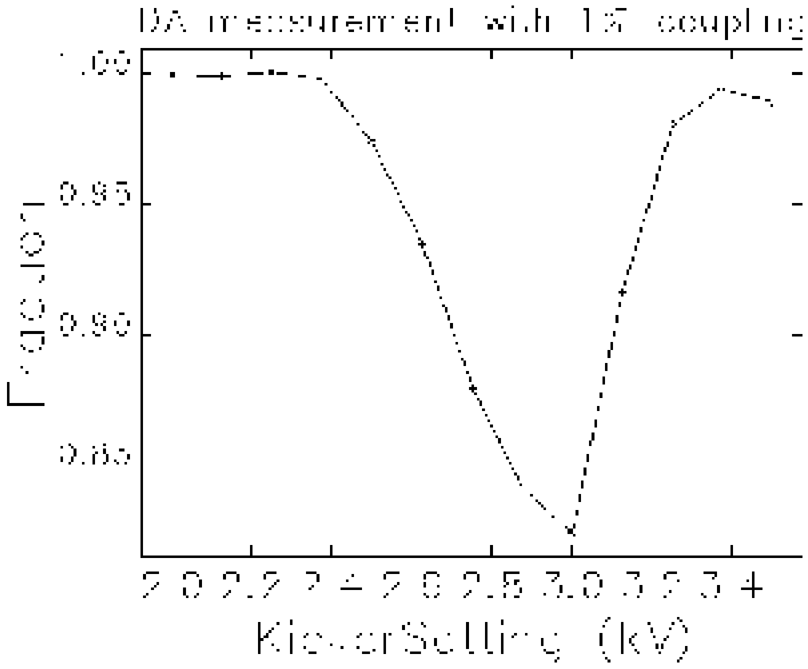


Calculated dynamic aperture is 10.5 mm

DA Measurement with Coupling

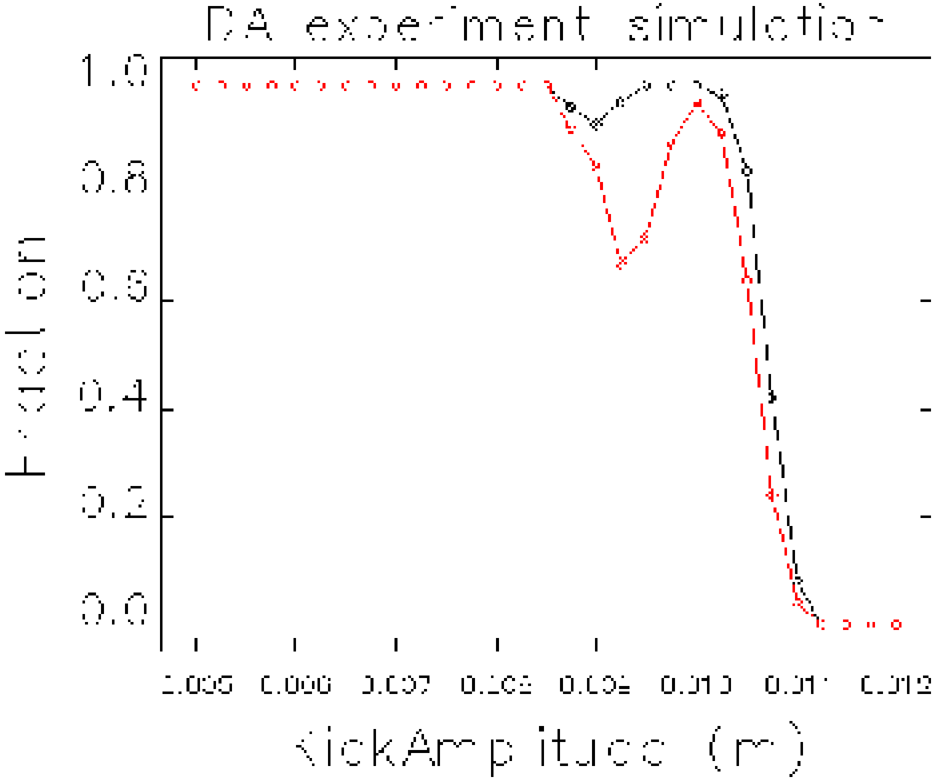
- Interesting dip observed during measurements with 1% coupling





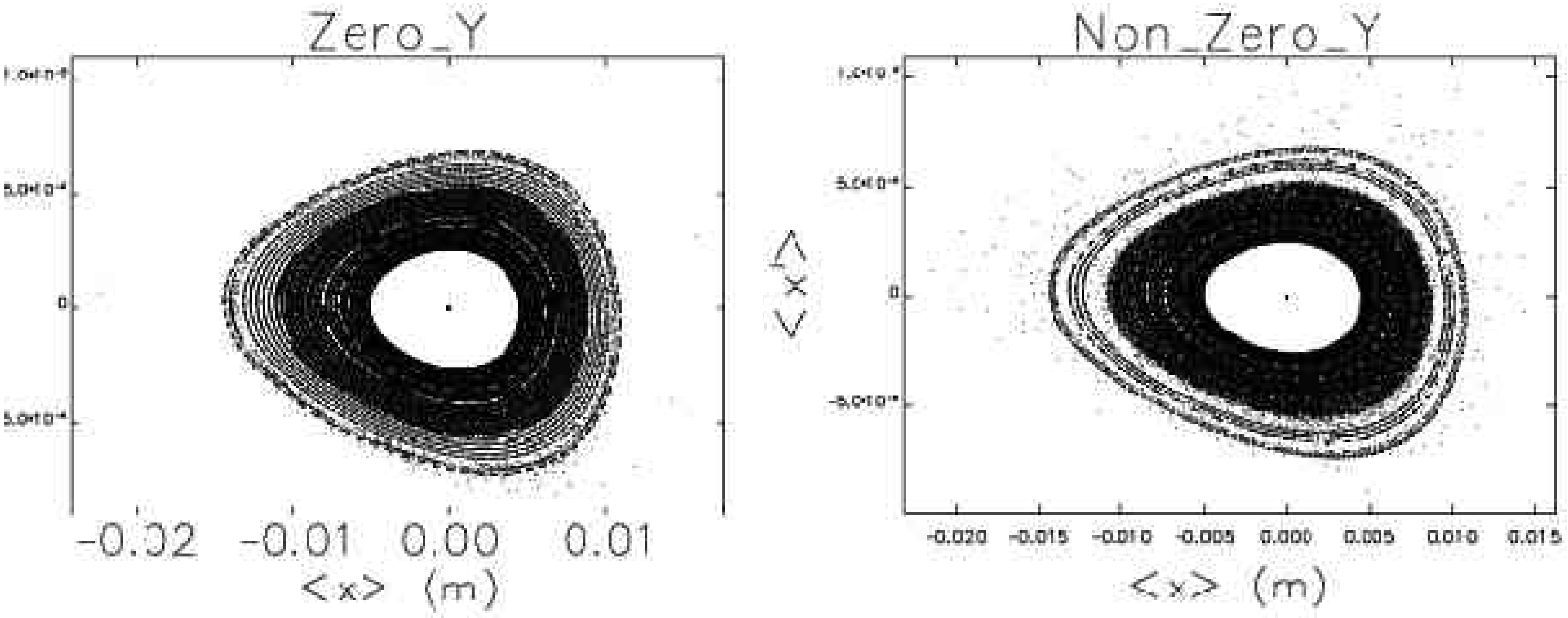
DA Experiment Simulation

- In order to understand this effect, we simulate the kick measurement
- We use 100 particles per bunch and track for 1000 turns



Phase Space

- Horizontal phase space with zero Y amplitude (left) doesn't show anything special
- Horizontal phase space with small Y amplitude (right) shows unstable trajectories around X amplitude of 8 mm



Nonlinear Detuning

- Tracking shows that vertical nonlinear detuning with horizontal amplitude causes vertical tune to cross integer resonance $\nu_y=19$
- Due to fast decoherence, it is difficult to directly confirm this in experiment
- MIA-refined measurements were used by C.-X. Wang (ANL) to calculate the detuning using decoherence rate some time ago – they were in correspondence with simulations

Lifetime and Top-up

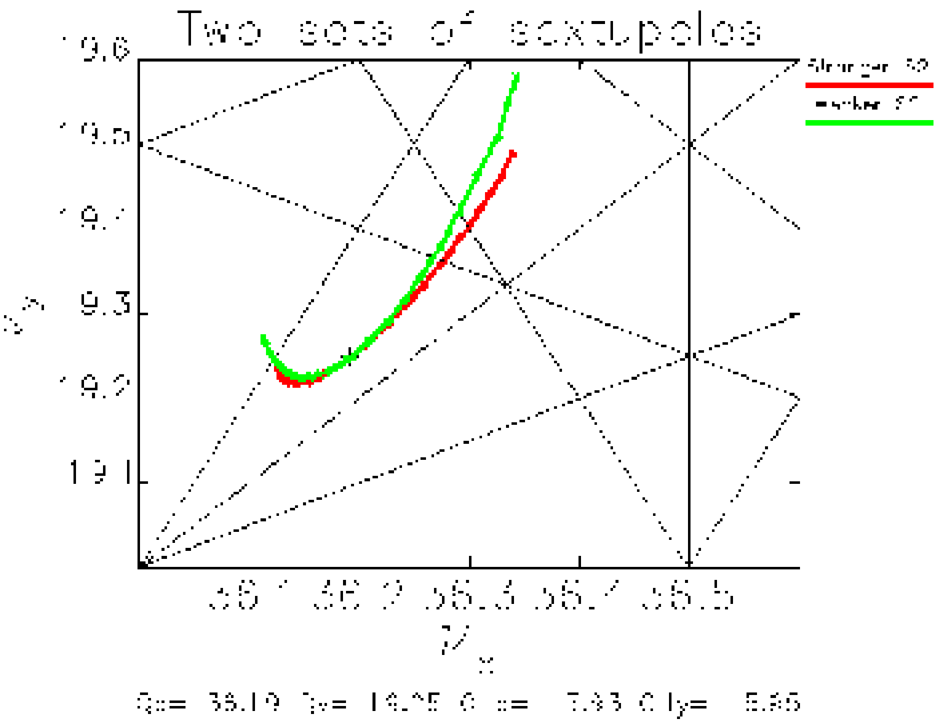
- Topup does not remove lifetime problem
- Minimum possible lifetime is defined by injection charge and topup interval
- For APS the maximum injection charge is 3 nQ and injection interval is 2 minutes – this gives the lifetime limit of about 5 hours
- To maintain lifetime of 6 hours in the low-emittance lattice at 100mA in 24 singlets, we had to run with 2.8% coupling for some time (pre-2004)

Redistributing Sextupole Family Strengths for Lifetime Increase

- APS has 4 families of sextupoles
- Strengths of sextupole families came from earlier high emittance lattice
- Experimental scan to increase lifetime was not successful
- Dynamic aperture optimization using tracking didn't give big benefit within limits of power supplies
- A new script to perform standardized nonlinear calculation for different lattices was written for different purpose. That script helped us to find a simple way to improve the lifetime

Lifetime Increase

- We found that with our present sextupole scheme the working point hits 19.5 at dp/p=0.016
- By increasing S2 family (S3 and S4 were used to keep chromaticity) we increased that to dp/p=0.019

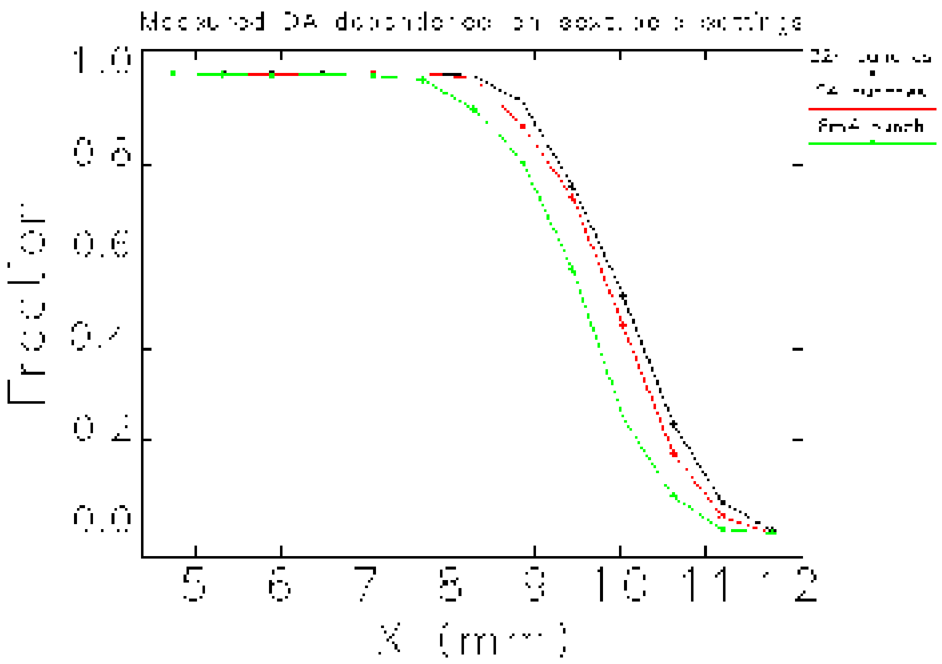


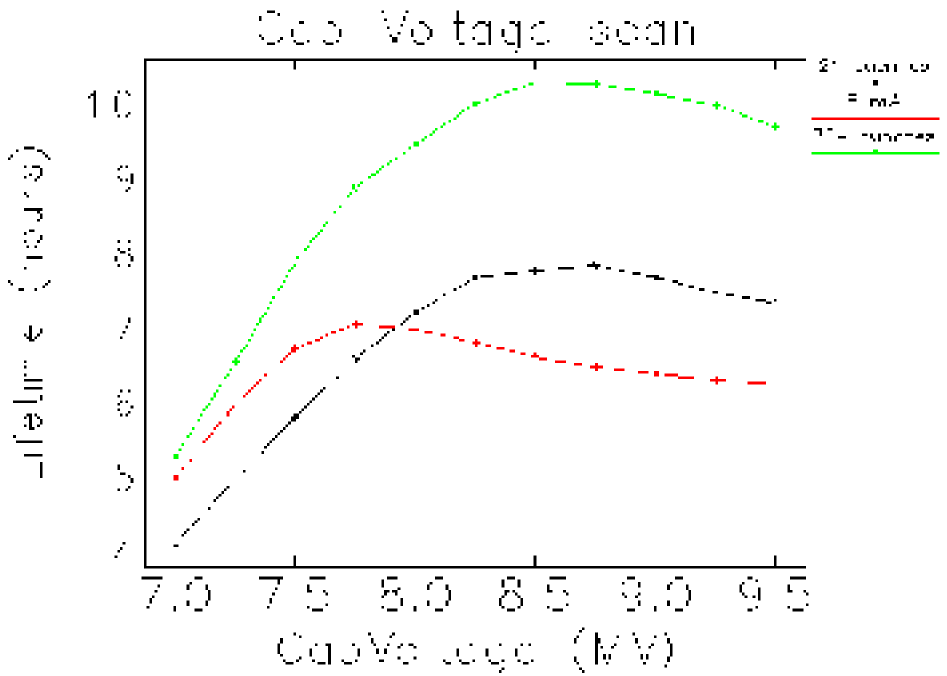
This change combined with small tune change and small optimization of RF voltage allowed us to lower our coupling to 1%

Chromaticity of Operating Modes

	Chrom X	Chrom Y	dp/p ν_y=19.5 limit
24 singlets	6.0	6.0	0.019
324 bunches	3.0	5.0	0.022
8 - 16 mA	9.5	9.0	0.016

Dynamic Aperture for Different Modes



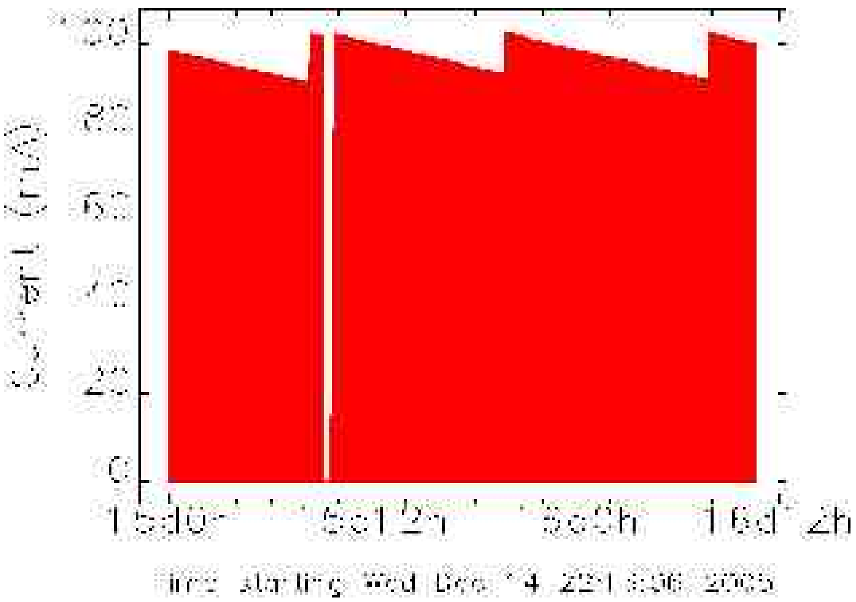


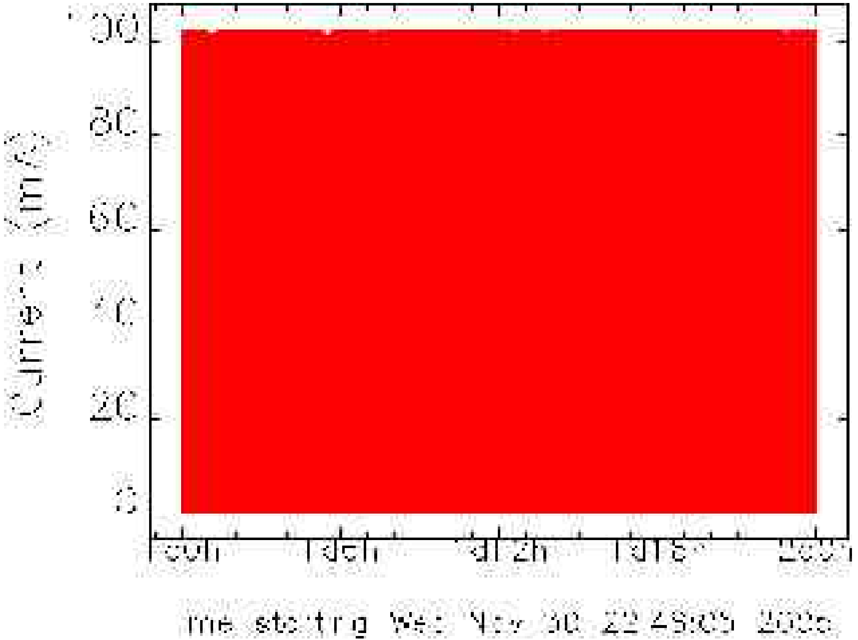
Conclusion for Dynamic Aperture

- In general, we have a good correspondence between dynamic aperture measurements and simulations
- Tracking with calibrated model and with real aperture limitations is important
- Fast calculations are useful, they allow us to quickly test many different ideas. Fast calculations are achieved by combining parallel processing with sdds toolkit and tcl/tk scripting

Top-Up

- Top-up is a recently-developed method of storage ring operation
  - Normally, stored beam decays and is replenished every 6 to 12 hours
  - In top-up, we replenish beam every few minutes.





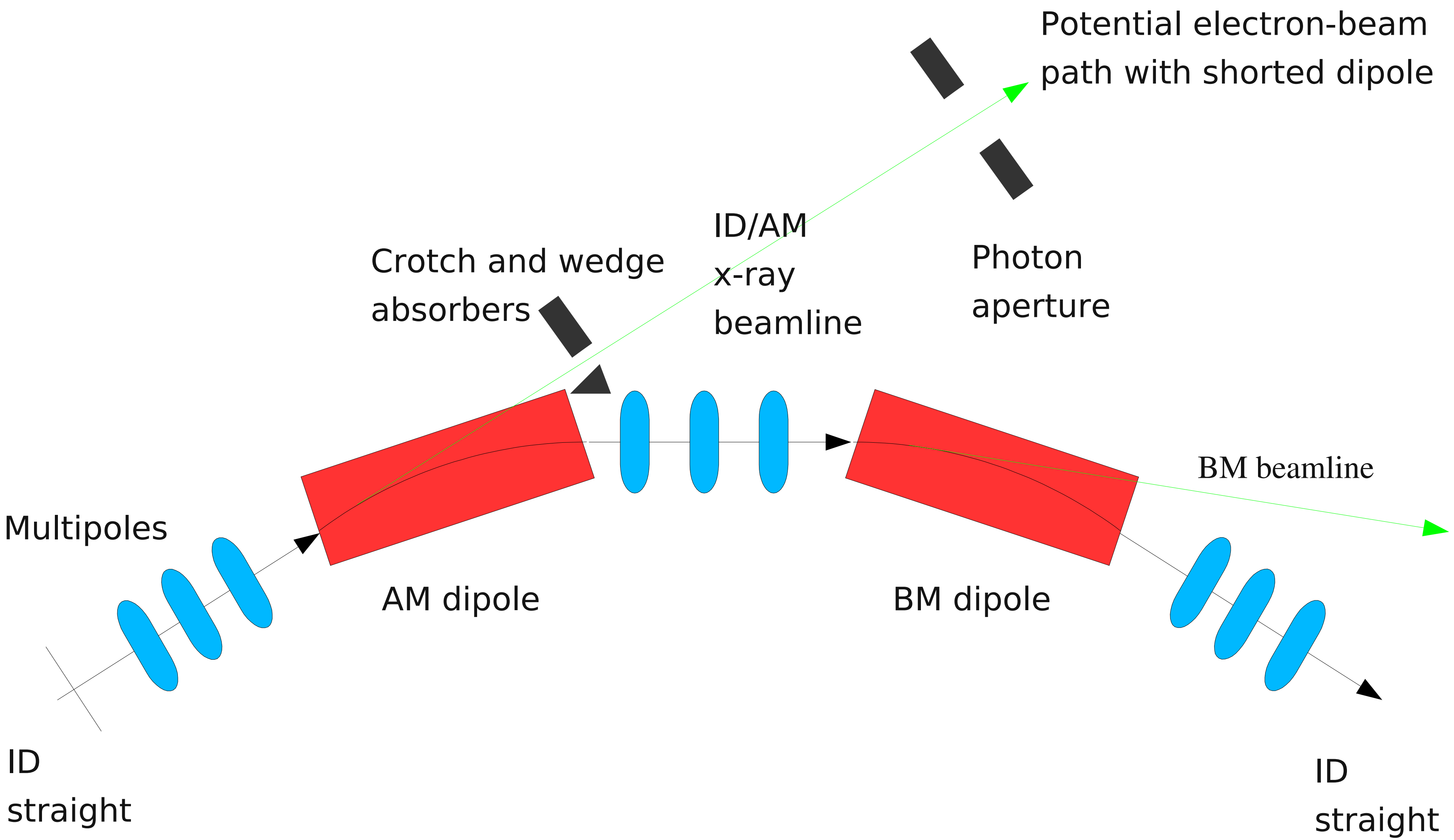
Top-Up Issues

- Safety concerns
- Safety interlock options
- Safety analysis for APS
- Regulation goals and limitations
- Injection transients
- Radiation concerns
- Automation
- Benefits and costs.

Why Are Light Source Safe?

- Photon beamlines of necessity diverge from the design electron beam path due to dipole magnets
- If a dipole shorts, field loss is gradual
  - Stored beam is lost before it “escapes” down a photon beamline
  - Only lose one store, not continuous beam
- Top-up or filling with shutters open is different:
  - Injected beam not on the stored beam orbit
  - Fast pulsed magnets are being used
  - Injected beam might have the wrong energy
  - Injection provides potentially continuous source of beam.

Schematic of Beamline Geometry



Potential electron-beam path with shorted dipole

ID/AM x-ray beamline

Crotch and wedge absorbers

Photon aperture

BM beamline

Multipoles

AM dipole

BM dipole

ID straight

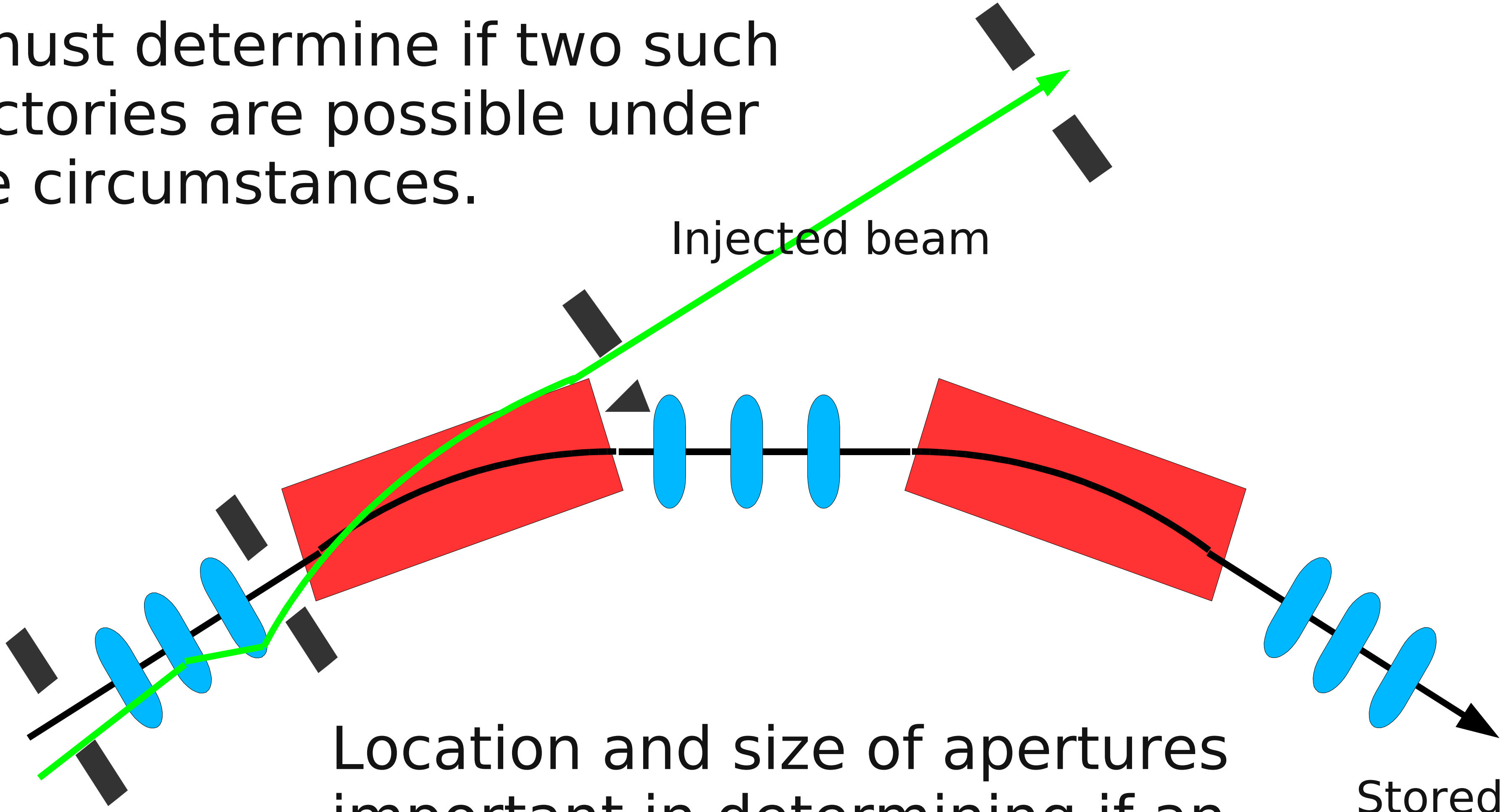
ID straight

APS Top-Up Safety Approach

- We considered it inadequate to rely on radiation monitors alone
  - They can't be placed everywhere
- We postulated that extraction of injected beam through a photon port is impossible if stored beam exists
  - If true, safety can be assured by an interlock that disables injection when there are shutters open but no stored beam
  - If false, then this approach is flawed and a “top-up accident” could occur.

Top-Up Accident

We must determine if two such trajectories are possible under some circumstances.



Location and size of apertures important in determining if an accident is possible.

Alternative Approaches to Top-up

- Place magnetic field sensors in the dipoles and interlock them to the injector
  - Advantage: very direct
  - Problems
    - *In principle, must have a sensor in every dipole*
    - *May be expensive and unreliable for large ring*
- Interlock the injector to the voltage and current from the dipole supply
  - Advantage: potentially very simple
  - Problems:
    - *Difficult to detect a partially shorted coil in a large ring*
    - *Possibility of spurious trips and downtime.*

Alternative Approaches to Top-up

- Place permanent magnets on each photon beamline to deflect electrons into an aperture
  - Advantage: very direct, passive
  - Problems:
    - *May be costly for large rings*
    - *Could be challenging if photon beam pipe is large in diameter*
    - *Must ensure that devices are not tampered with*
    - *Must periodically check field in each device*
- Don't worry, since an accident is very unlikely
  - US Department of Energy not likely to accept this!

More Details of APS Approach to Top-Up Safety

- Interlock is very simple and reliable
  - Two beam position monitors (BPMs) are used as detectors
  - An independent circuit monitors each BPM
  - Fail safe: if current is not detected, injection cannot occur with shutters open
- Ring apertures are important:
  - We maintain top-up-specific drawings showing apertures for all sector configurations
  - We verify the position of the chamber relative to all magnets using “go/no-go gauges” every shutdown (3 month interval)
  - We measure apertures in any photon beamline where a change is made
- A sign-off process is in place to ensure compliance
- Top-up tracking is complex and time-consuming.

Top-Up Safety Simulation Concept

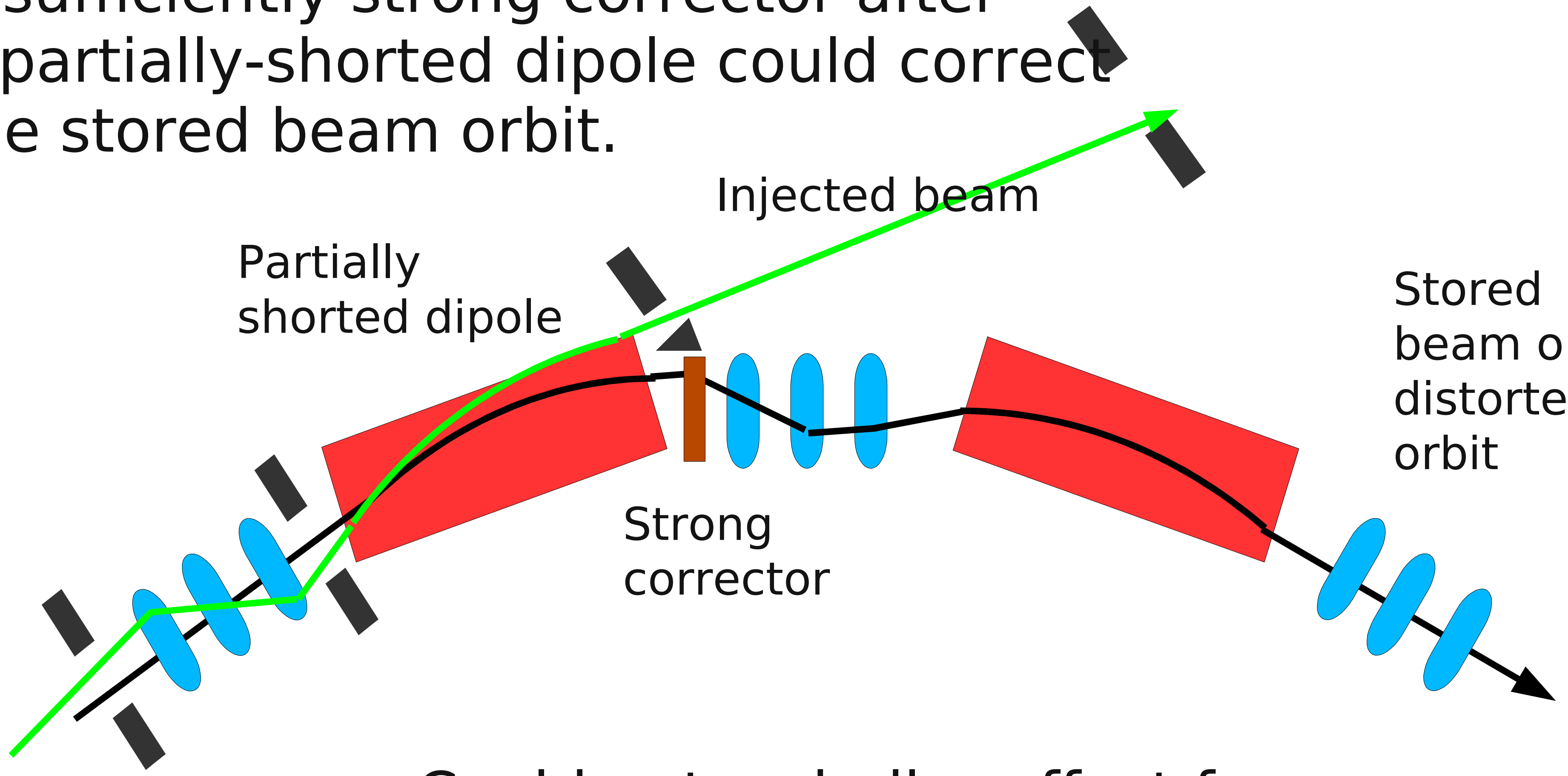
- At minimum, an accident requires a fully- or partially-shorted dipole in the location of a photon beamline
- For a fully-shorted dipole
  - injected beam will exit the photon port, but
  - stored beam very unlikely to survive.
- For an unshorted dipole
  - stored beam can survive, but
  - injected beam very unlikely to exit photon port.
- Is there some degree of shorting that simultaneously allows
  - stored beam and
  - injected beam down a photon port?
- Simulations are used to explore many possibilities.

Top-Up Safety Simulation Method

- We devised scenarios that had a good chance of causing an accident
- At minimum, a dipole is fully- or partially-shorted
- In addition, we look at effect of
  - Strong corrector magnet
  - Misaligned quadrupole or sextupole
- Two types of simulations are needed
  - Determine if closed orbit is inside the vacuum chamber
  - Determine if there is a path from the upstream ID straight section to the exit of the photon beamline.

Why Corrector Strength Matters

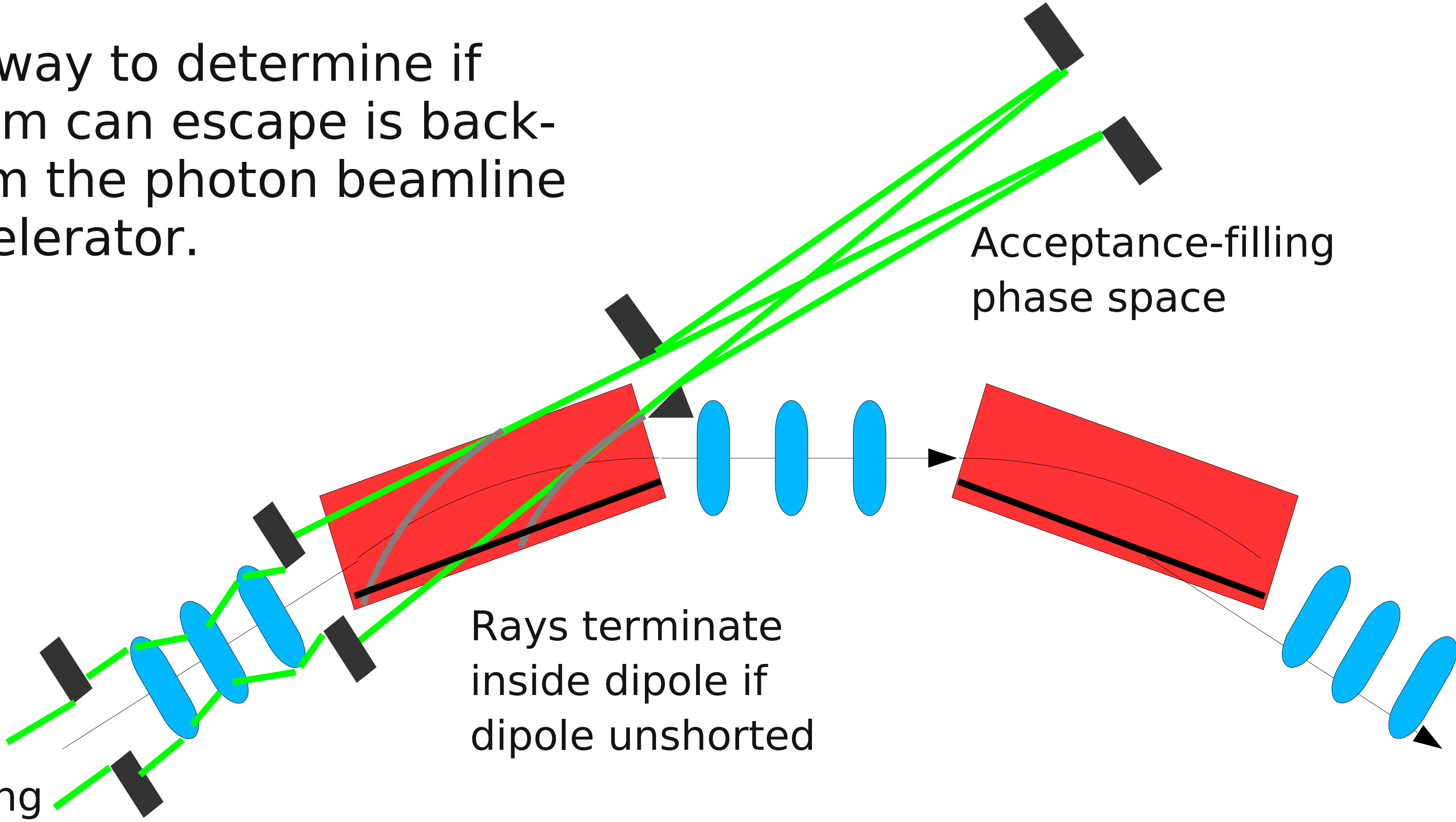
A sufficiently strong corrector after a partially-shorted dipole could correct the stored beam orbit.



Could get a similar effect from a displaced quadrupole or sextupole.

Back-tracking Concept

An efficient way to determine if injected beam can escape is back-tracking from the photon beamline into the accelerator.



Acceptance-filling phase space

Rays terminate inside dipole if dipole unshorted

Rays escaping sector for fully shorted dipole

Basic Formula for top-Up (Uniform Fill)

- Regulation of the average current is related to lifetime τ and injection interval T_i

$$\frac{\Delta I}{I_0} = \frac{T_i}{\tau}$$

- Charge per injection is related to current regulation and revolution time

$$Q = \Delta I \, T_r = \frac{I_0 T_i T_r}{\tau}$$

- If we top-up one bunch per injection, then for an N-bunch store, the fractional bunch-to-bunch current variation is

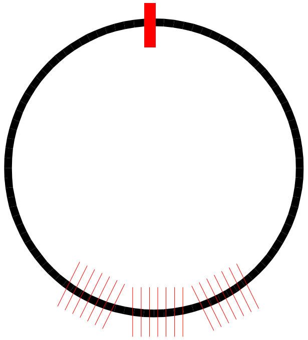
$$\frac{I_{b,max} - I_{b,min}}{I_0 / N} \approx N \frac{\Delta I}{I_0}$$

Examples

- Originally we thought about 0.01 % regulation at 100 mA
  - At this level, users could ignore current variation
  - Lifetime of 6 hours means injecting every 2 seconds
  - Injected charge would be 40 pC/shot, too small for our diagnostics
  - Users wouldn't accept this because of emittance disruption
- How about 0.1% regulation?
  - Inject every 20 seconds
  - 0.4 nC/shot is acceptable for diagnostics
- The bottom line
  - Users specified 2 minute interval as the minimum
  - Later, we we permitted to use 1 minute for special mode.

APS Top-Up Fill Patterns

- 24 bunch
  - 6 hour lifetime (or better)
  - 2 minute injection interval
  - 0.6% regulation
  - 2.2 nC/shot
  - 14% bunch-to-bunch variation
- Hybrid mode (16 mA bunch plus 56, 1.5mA bunches)
  - ~2 hour lifetime for 16 mA bunch
  - ~9 hour lifetime for other bunches
  - 60 second injection interval
  - 75% of top-up shots go to 16 mA bunch
  - 3 to 6% variation observed in 16 mA bunch
  - ~40% bunch-to-bunch variation among 56 bunches.

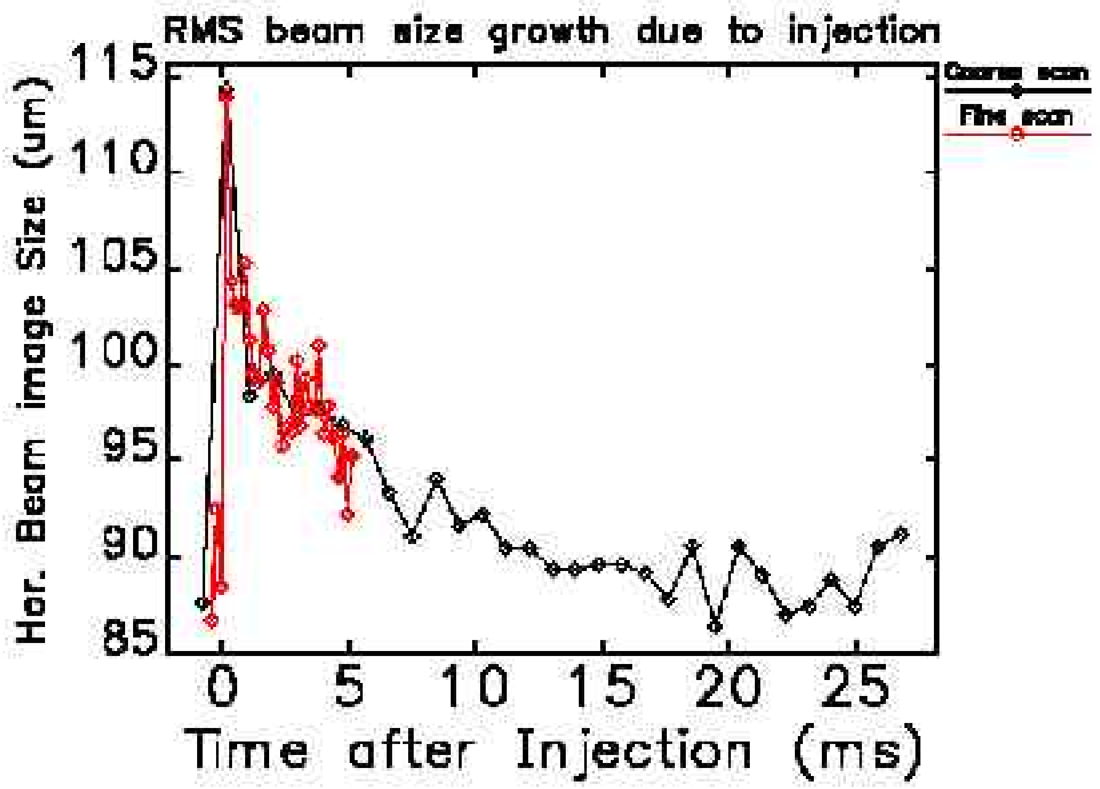


Injection Transients

- Emittance increase of stored beam due to
  - Betatron oscillation, which damps in 30 ms
  - Focusing perturbation due to sextupoles inside bump (minor)
  - Beam average is much less than that of bunch in injection bucket
- Perturbation of global orbit due to septum leakage field
  - If uncorrected, produces a ~200 $\mu\mathrm{m}$ orbit lasting about 25 ms
  - Corrected to level of normal beam motion (17 μm) under ambient conditions (i.e. orbit feedback turned off)
- Global electronic gating signal given to users to “blank” out experimental data
  - Apparently not used as the transient does not affect experiments.

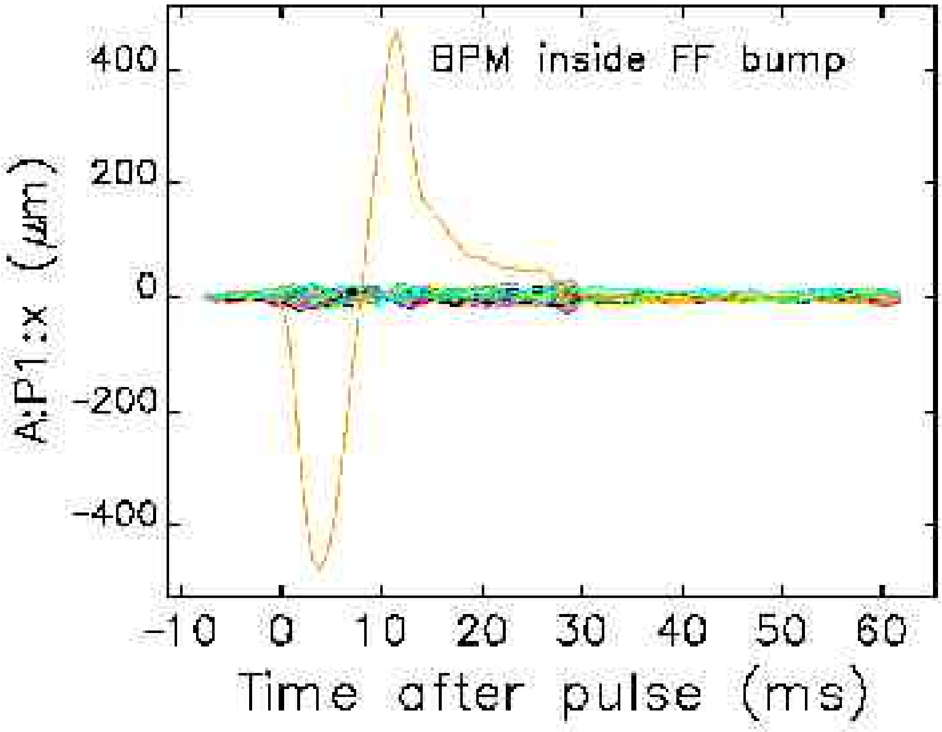
Emittance Transients

- Gated 10 turns of whole beam (24 bunches)
- BM X-ray pinhole camera
- Momentary 30% increase in average beam size.



Orbit Transients

- Use two fast correctors upstream of SR septum to form 3-bump
- Fast correctors are programmed with a waveform matching original perturbation multiplied by some coefficients
- Plot of bpms around the ring including one inside the 3-bump.



Radiation Issues

- Top-up is important because it lets us compensate for short lifetime
  - Low-emittance lattice
  - Unusual fill patterns
- Short lifetime necessitates more radiation
- Radiation outside shield wall may be elevated
  - We have radiation monitors in each sector
  - These may not respond even if we lost every top-up shot given the long interval
    - *Operators monitor injection efficiency*
    - *Surveys and use of TLDs has revealed no issues*
- Increased radiation damage to in-tunnel equipment is seen.

Radiation Damage

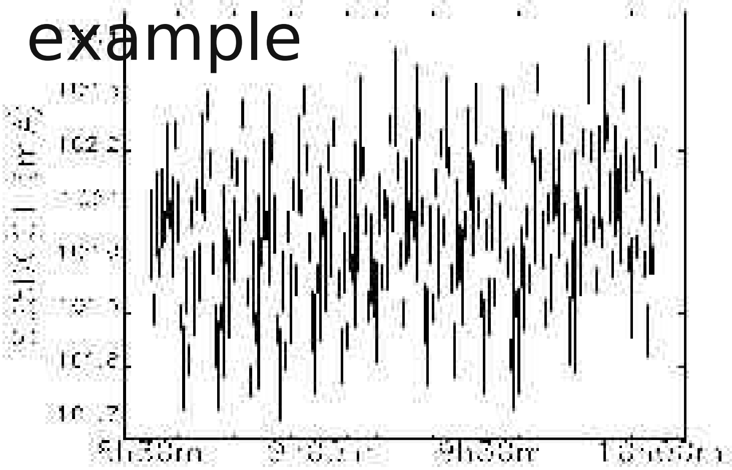
- Principal issue is damage to small-gap insertion devices
- These are close to the injection point
  - Damage took only a few weeks to manifest itself
  - Device tapering was required during the run to restore performance
  - Devices required frequent retuning (6 months)
- We discovered that most of the damage is Touschek-scattered particles
  - Small-gap chambers have ring's narrowest horizontal aperture
  - Can be remedied with properly positioned scrapers (underway)
- One small-gap device was removed (not needed)
- The other will be replaced with a more rad-hard material.

Automation

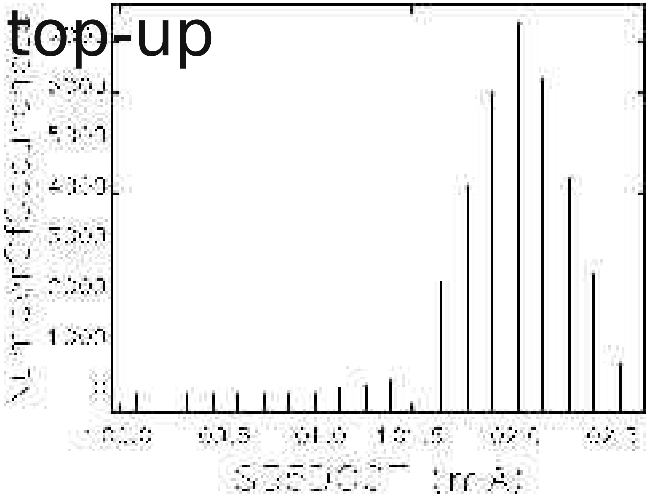
- Count-down timers in IOC with different offsets to trigger various processes in order: start injectors, start calculations, start checking of alarms
  - warm up booster pulsed septums
  - trigger booster extraction kicker at last possible moment
  - script determines which bunch to inject into
  - monitor status of SR injection kickers with alarm handler
  - automatically check PAR compression and cleaning status just before injecting
- Possible to inject more than one bunch at 2 Hz repetition, but users don't want that.

Top-Up Performance

detailed time-history example



4 days of continuous top-up



- Tune up injector to deliver more charge than needed
  - Ring current gradually increases, resulting in a skipped injection
  - Provides overhead in case of occasional problems
- Typically regulate ring current to better than ±0.5%
- Injector reliability and availability is very high:
  - 5000 hour user operation in FY2005
  - 98.8% availability for FY2005.

Benefits

- Users report much better x-ray stability
  - Heat-load on x-ray optics is nearly constant
  - Some users are unwilling to come during non-top-up periods
- Originally, we expected improved electron beam stability
  - This wasn't seen when we started running top-up
  - The monopulse receiver (Mp) bpms suffer from HOM around 352 MHz center filter frequency. The HOM spectrum depends on the bunch pattern non-uniformity which changes constantly during top-up
  - Three improvements since then:
    - *Added many narrowband (Nb) bpms near the light source points*
    - *The effect on the Mp bpms is much reduced by BPM “cogging”*
    - *Use of dipole ID source Xray bpms in DC orbit correction.*

Costs

- Injector is use most of the time
  - Lack of operator training time
    - *Training periods only every six weeks during 324- or 1296-bunch modes*
  - Limited time for injector machine physics, e.g.,
    - *Software development*
    - *CSR studies*
    - *LEUTL*
- Injector failures now may result in facility downtime
  - Beam decays rapidly if injector is unavailable
  - Previously, we could repair injector between fills.

Conclusion on Top-Up

- Top-up used for ~80% of APS operations
  - Safety method relies on two simple stored-current detectors
  - Extensive top-up tracking needed to validate this approach
  - X-ray stability is greatly improved.