Overview of Advance Photon Source Multi-Bend Achromat Upgrade Proposal

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Low Emittance Ring Workshop
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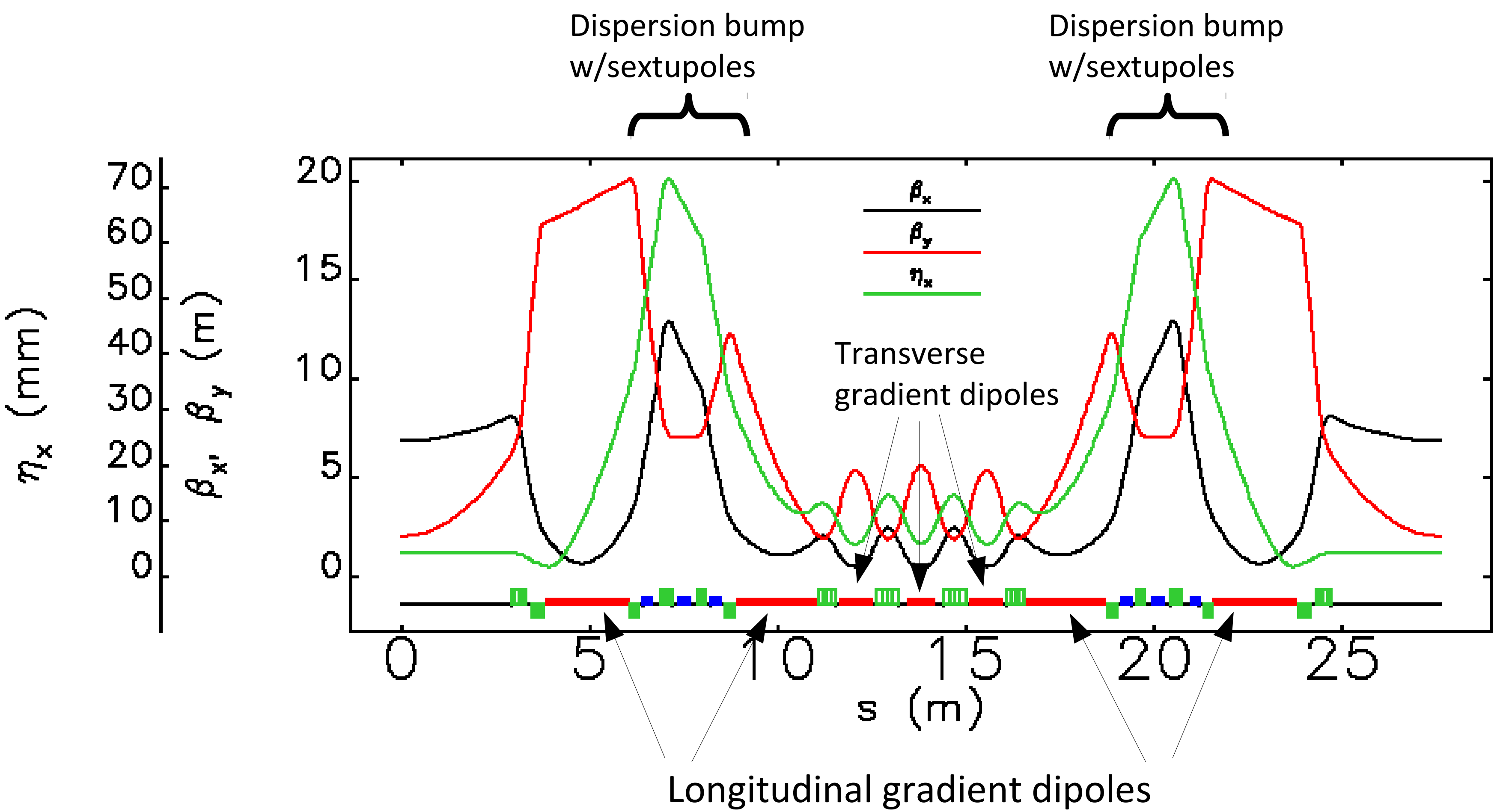
Outline

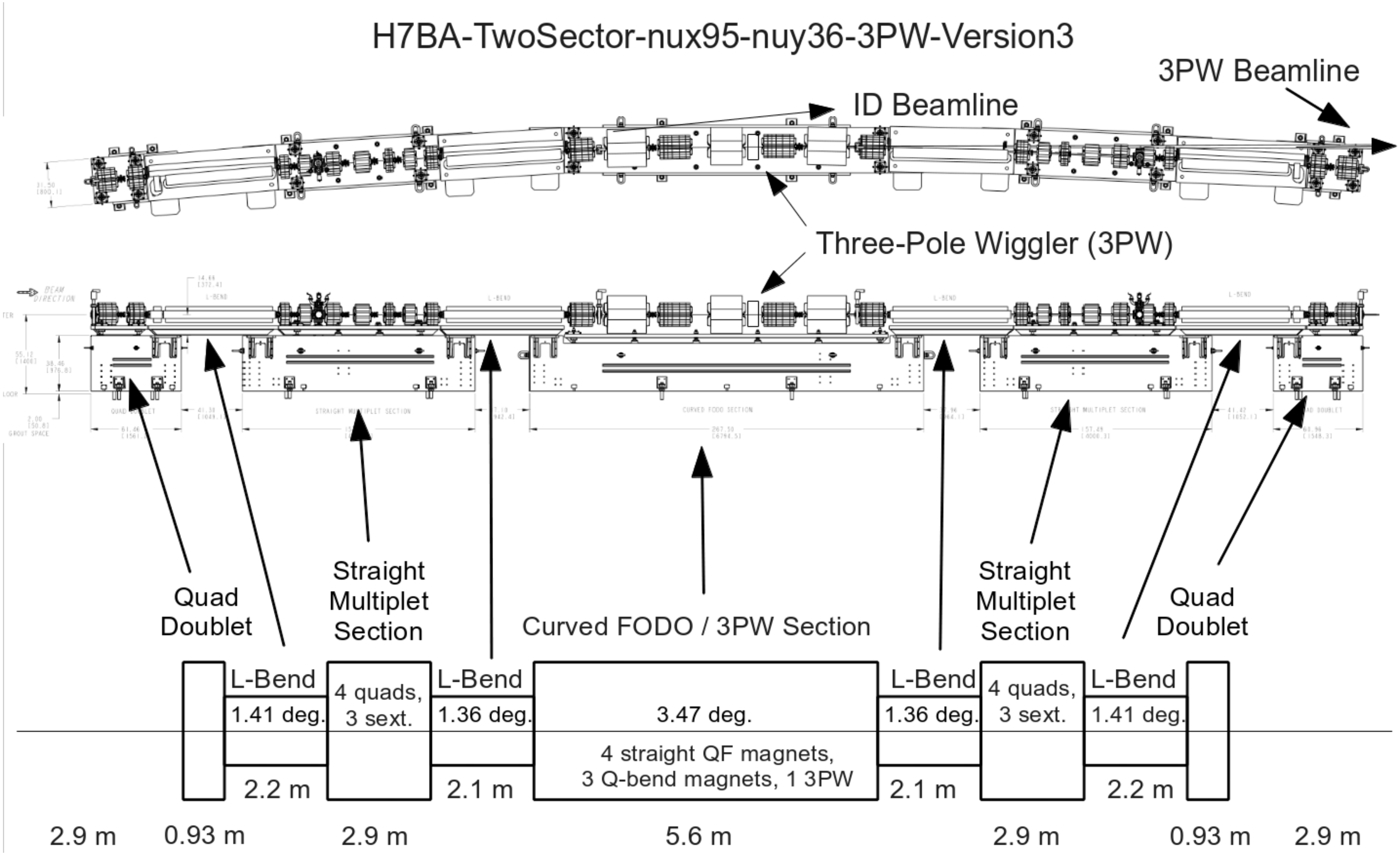
- Hybrid Multi-Bend Achromat Description
- Optimization of optics
- Tolerances
- Collective effects
- Higher harmonic cavities
- On-axis Injection
- Xray bpm diagnostics

Hybrid 7BA Lattice Concept (originally from ESRF)



- Phase advance of Δφx=3π and Δφy=π between corresponding sextupoles chosen to cancel geometrical sextupole kicks
- Thick, interleaved sextupoles → cancellation isn't perfect

APS MBA Accelerator Implementation



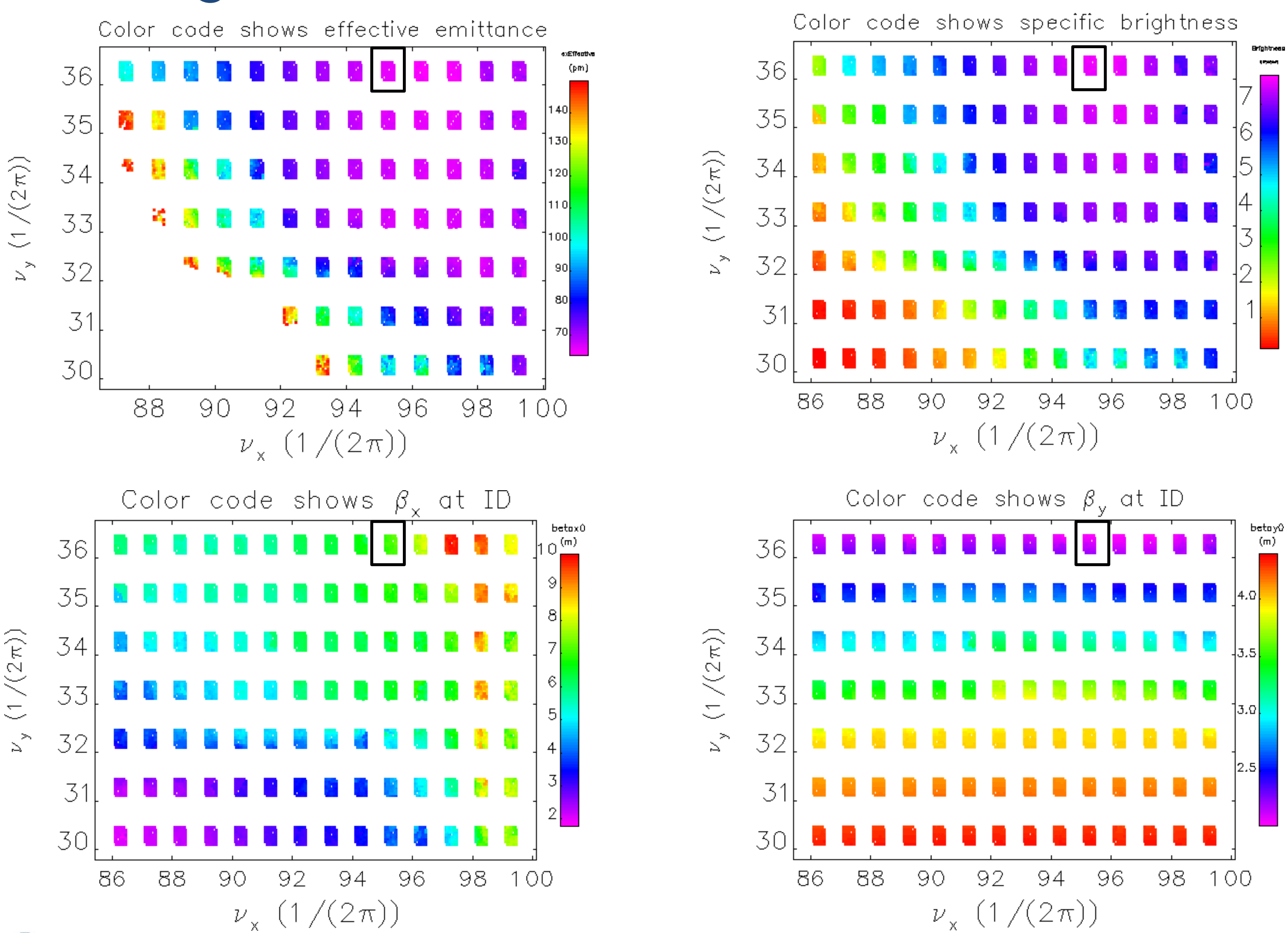
High-Level Machine Properties

	APS Now	MBA
Beam Energy	7 GeV	6 GeV
Beam Current	100 mA	200 mA
Single Bunch Current	> 16 mA	> 4.2 mA
Effective Emittance	3100 pm-rad	65 pm-rad
Sectors	40	40
Circumference	1104 m	1104 m
RF Frequency	352 MHz	352 MHz
Minimum Bunch Spacing	11.4 ns	11.4 ns
Energy Spread	0.096%	0.095%
Dipoles / Sector	2	7
Quads / Sector	10	16
Sext. / Sector	7	6
Fast Correctors / Sector	1 to 2 / plane	4 / plane

Optimization of Optics

- M=7 appears to be a good balance between difficulty and performance
- Beam energy 6 GeV based on early estimates of the difficulty of the magnets
- Accumulation vs swap-out injection
  - This lattice emphasizes swap-out
    - Weak bunches are replaced, not topped-up
    - Only requires on-axis injection
  - By reducing dynamic aperture requirements, swap-out should
    - Allow lower emittance to be achieved
    - Allow better optimizing momentum aperture
    - Relax tolerances
    - Reduce overall project risk
  - Swap-out permits use of helical and horizontal-gap IDs
  - APS injector appears capable of supporting swap-out
- Two-Stage Optimization
  - Choice of working point by direct scan of integers, starting from lattice provided by ESRF.
  - Tracking-based optimization of selected working point
- Redo optimization as needed when magnet locations are moved (vacuum group) or strengths limits are changed (remove steering coils from main magnets)

Working Point Scan[1]



1: M. Borland et al., NA-PAC13, 249-251.

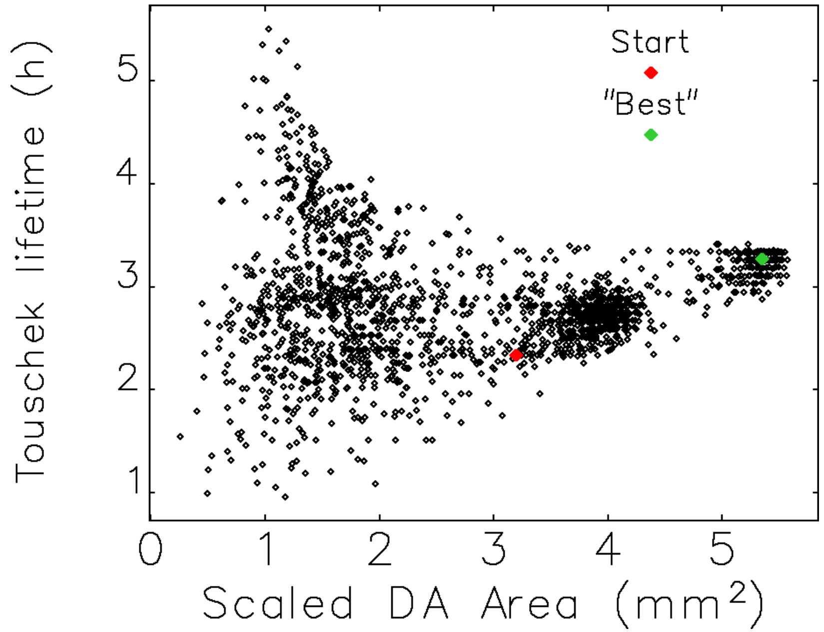
Tracking-Based Optimization[1]

- multi-objective optimization to refine the solution, emphasizing
  - Maximum dynamic acceptance (DA) area (scaled with beta functions)
  - Maximum Touschek lifetime computed from local momentum acceptance (LMA)
    - LMA artificially capped where tune vs momentum crosses integer or half-integer
  - Minimum effective emittance
  - Desired chromaticities of +5 in both planes2
- The algorithm is (typically) allowed to vary
  - Tunes, restricted to fixed quadrant of the tune diagram
  - Target value for maximum dispersion in the bump
  - 10 sextupole strengths (out of 12 present in two sectors)
  - Target values of horizontal and vertical phase advance between sextupoles
- Each "function evaluation" typically involves
  - Matching to change tunes, phase advance, etc., while minimizing emittance
  - Adjustment of free sextupoles to obtain desired chromaticities
  - Tracking to determine "stable" range of chromatic tunes
  - Tracking with errors for dynamic acceptance
  - Tracking with errors for local momentum acceptance (first two sectors only)
  - Typically takes 40-60 minutes on 32 cores

1: See citations in M. Borland, IPAC12, 1035.
2: Y.-C. Chae

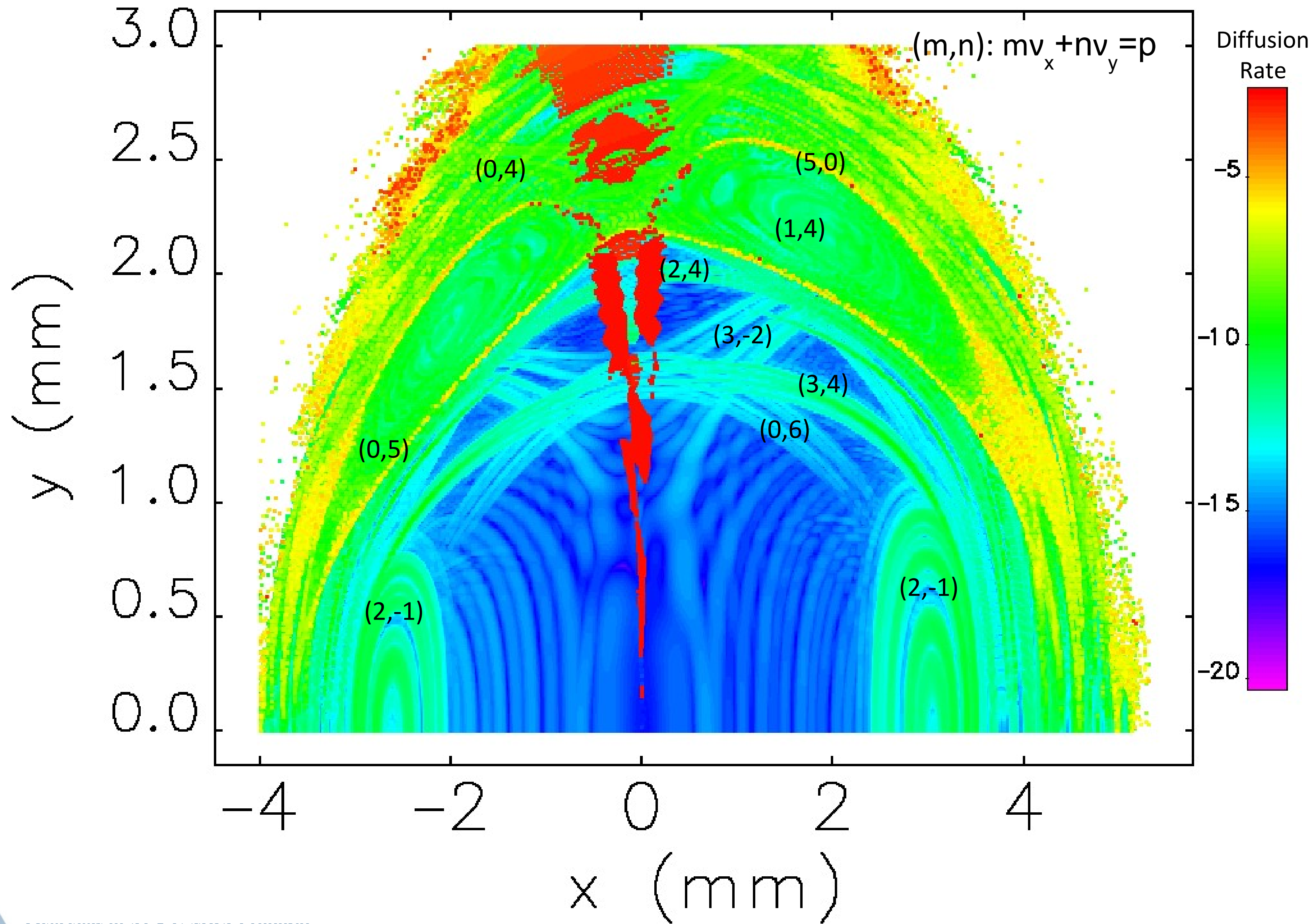
Tracking Details

- Parallel elegant used for tracking for tune vs momentum, DA, and LMA
- Symplectic integration for all magnetic elements
- Second-order matrix for drift spaces
- For DA and LMA
  - Apertures
    - 10 mm radius round aperture in arcs (13 mm bore radius for magnets)
    - 20 mm by 6mm ellipse in IDs
  - Errors (single ensemble) to give lattice function beats and coupling
  - Lumped radiation damping
  - Thin-lens rf cavity set for ±4% bucket height
  - Tracked 400 turns, sufficient for overlap of amplitudes



Normalized to $\beta_x = \beta_y = 3$m

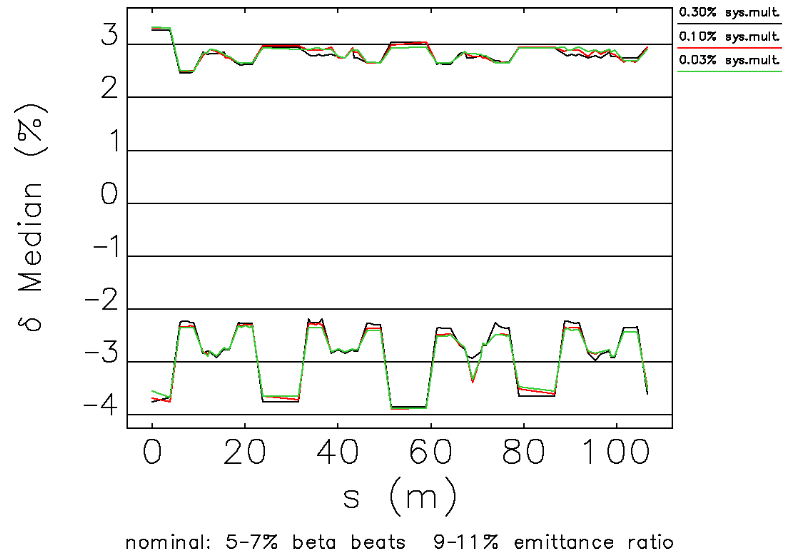
Nonlinear Dynamics---On Momentum

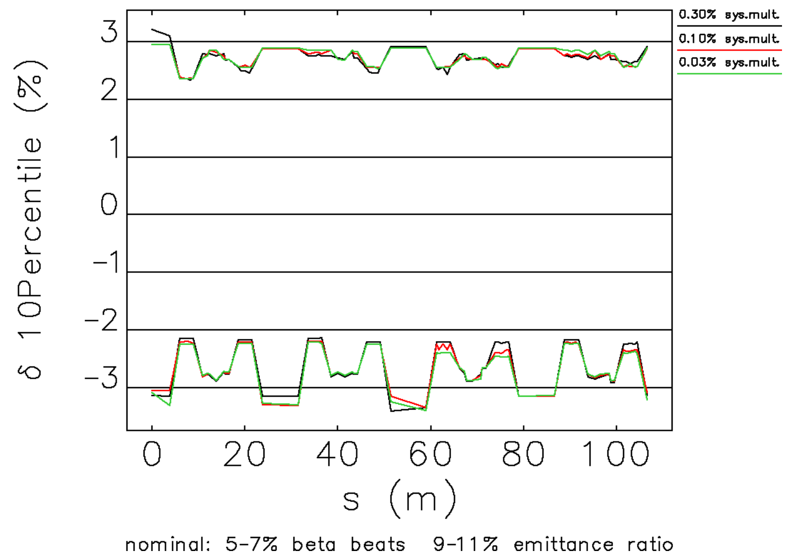


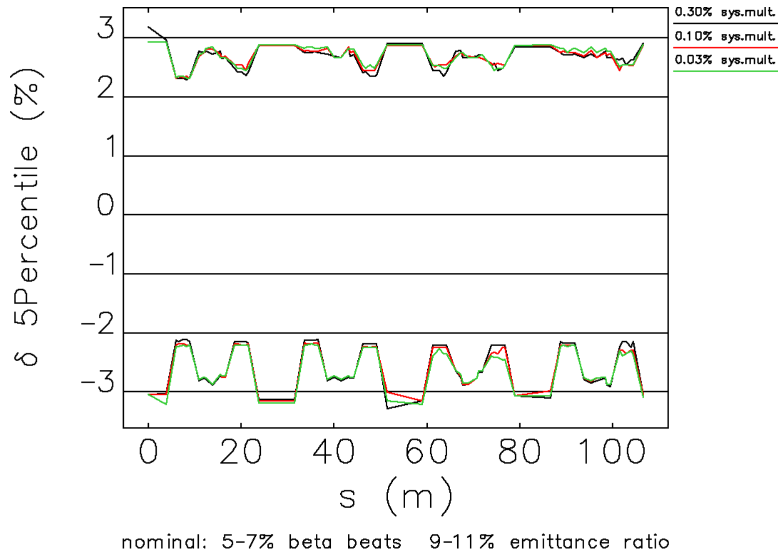
Ensemble Evaluation for Robustness

- Evaluated lattice with ~100 random error ensembles
  - Optics errors, including coupling
  - Systematic (i.e., allowed) multipole errors
  - Random multipole errors
- Proxy for orbit/optics correction
  - Add random tilts and strength errors, typically,
    - ±0.12% uniformly-distributed strength errors in gradients (quadrupoles and dipoles)
    - ±0.75 mrad uniformly-distributed tilt errors on quadrupoles and sextpoles
  - Compute lattice functions and emittances for ~12000 ensembles, employing only tune correction
  - Select ensembles providing given level of beta-beating and emittance ratio
    - E.g,. 5-7% beta-beating and 9-11% emittance ratio
    - These ensembles represent a selection of moderately-corrected lattices
- Systematic multipole errors
  - Set all harmonics to the same level as fraction of main harmonic at R=10 mm
  - Signs are all the same so effects add, to be conservative
  - Quadrupoles: include 12-, 20-, 28-, and 36-pole
  - Sextupoles: include 18-, 30-, and 40-pole
  - Dipoles: include sextupole through 18-pole

Local Momentum Acceptance







- Compute LMA for first 4 sectors only to save time
  - Haven't seen any surprises when doing entire ring
- Even 5th percentile results are relatively insensitive to level of systematic multipole errors
- Could probably tolerate errors at 0.3% level (per multipole at R=10 mm)

Lattice correction simulation

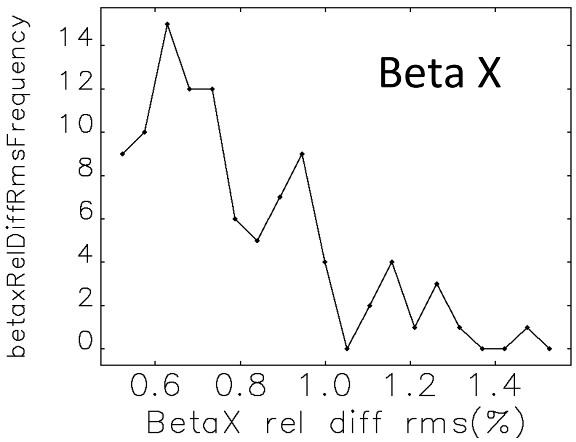
- Performed start-to-end simulation of orbit and lattice correction
- Want to include as many types of errors as possible
- The following errors were simulated:
  - Girder displacements – 100 μm rms
  - Displacement of elements on girders – 30 μm rms (focusing dipoles, quadrupoles, sextupoles)
  - BPM displacements – 500 μm rms
  - Quadrupole and focusing dipole gradient errors – 10^{-3} rms (relative)
  - Longitudinal-gradient dipole angle errors – 10^{-3} rms (relative)
  - Dipole, quadrupole, and sextupole rolls – 4×10^{-4} radians rms
- Maximum corrector strength used – 500 μrad per meter of length

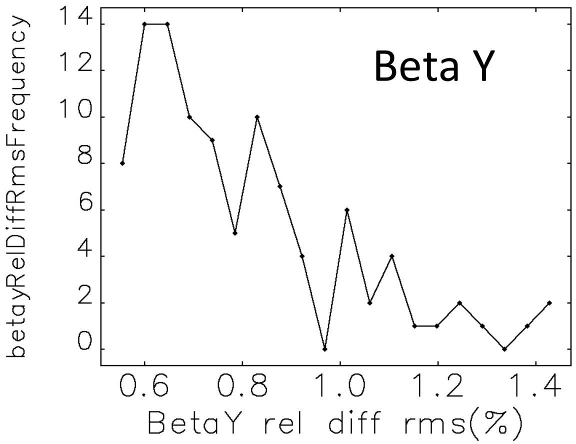
Automated Correction Procedure

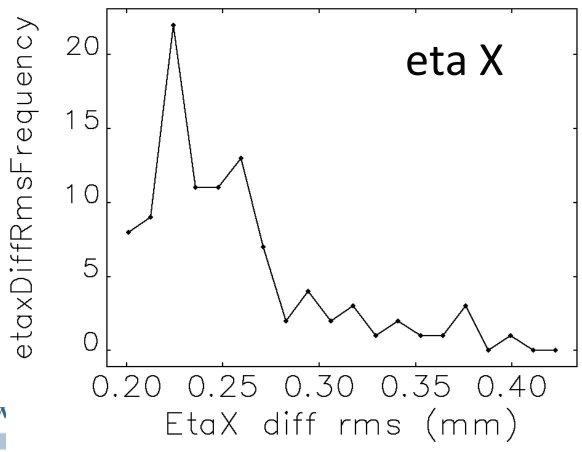
- Want to make procedure as realistic as possible
- The individual run consists of:
  - Error generation
  - Trajectory correction until closed orbit exists
  - Tune adjustment
  - Orbit correction with large BPM displacement errors (with tune adjustment between iterations)
  - Orbit correction with small BPM displacement errors (assuming BPM offset correction)
  - Beta function correction (using twiss file from the previous step)
    - 1% rms errors added to twiss file to simulate RM fit inaccuracy
  - Coupling correction (minimizing cross-plane response matrix)
    - 0.5 μm rms errors added to RM to simulate BPM noise
- This procedure mimics the real correction we would be performing
  - Except in real life we don't have twiss file after orbit correction – we perform response matrix measurement and fit
- Response Matrix fit is not simulated due to lack of time

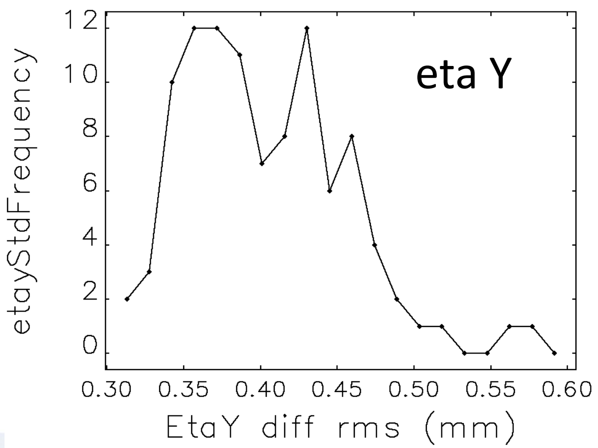
Lattice function errors

- Histograms of rms lattice function errors
  - Relative errors for beta functions
  - Absolute errors for dispersion
- Very good level of lattice correction is achieved







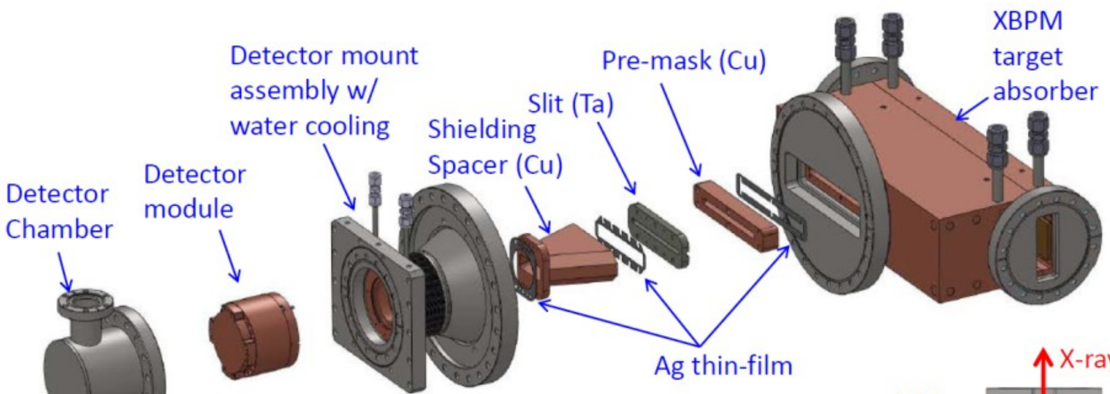


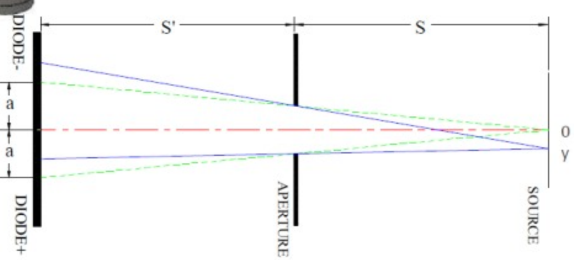
Tolerances for Orbit Stability

- Study was conducted to determine the allowed static and variable errors of MBA lattice magnets for specifying power supply stability, and also to determining whether some dipole families be connected in series or not.
- Tolerances assume good ability to do trajectory and orbit correction during commissioning
- Varying errors are categorized into four bands: very fast (>1kHz), fast (>0.1Hz), slow (<30min) and very slow (>30min)
- Results are checked by simulating commissioning steps with elegant code.

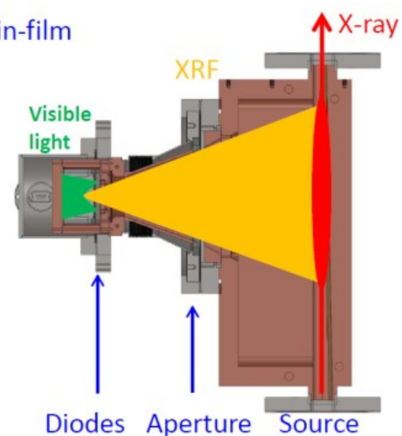
Fluorescence X-ray Bpms in Orbit Feedback

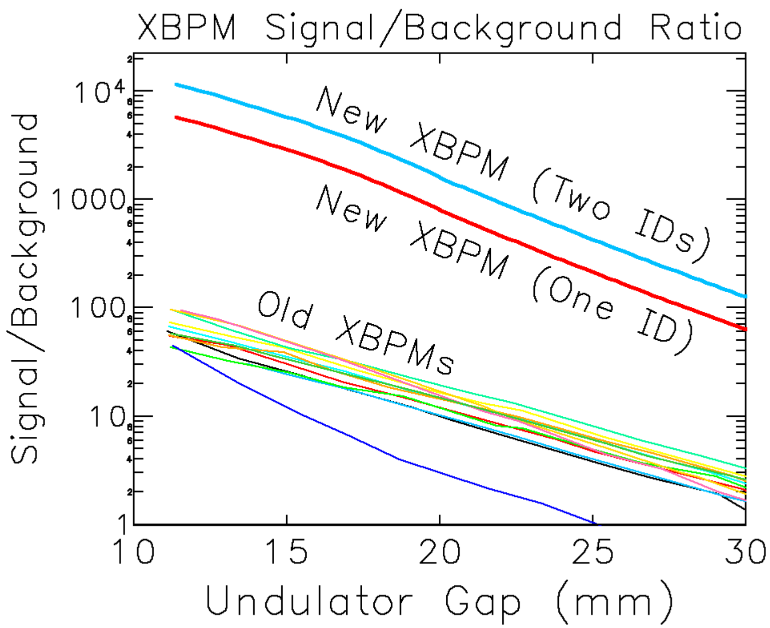
- Use of x-ray fluorescence (XRF) vs. photoemission dramatically reduces stray radiation background signals.
- Grazing incidence geometry allows use with high-power density from two in-line insertion devices (IDs) vs. only one with the old design.





Principle of Pinhole camera

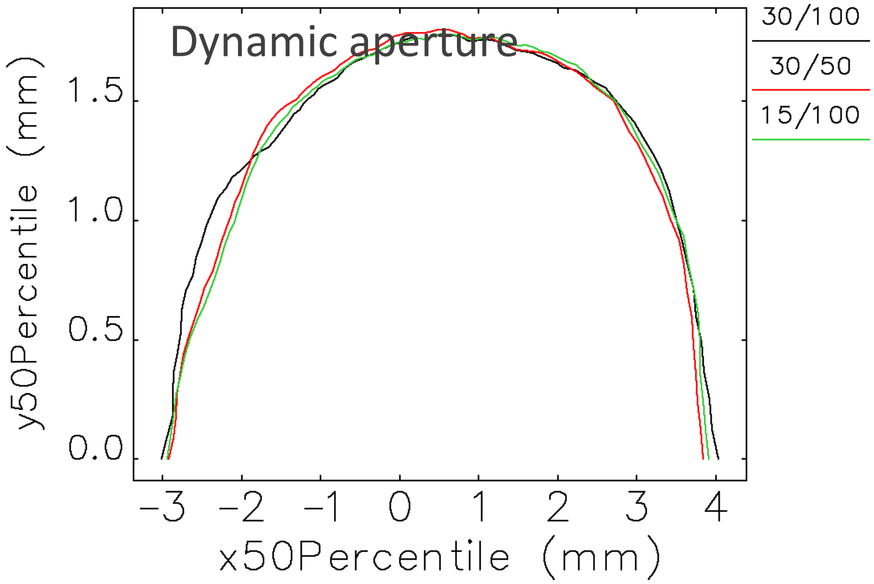


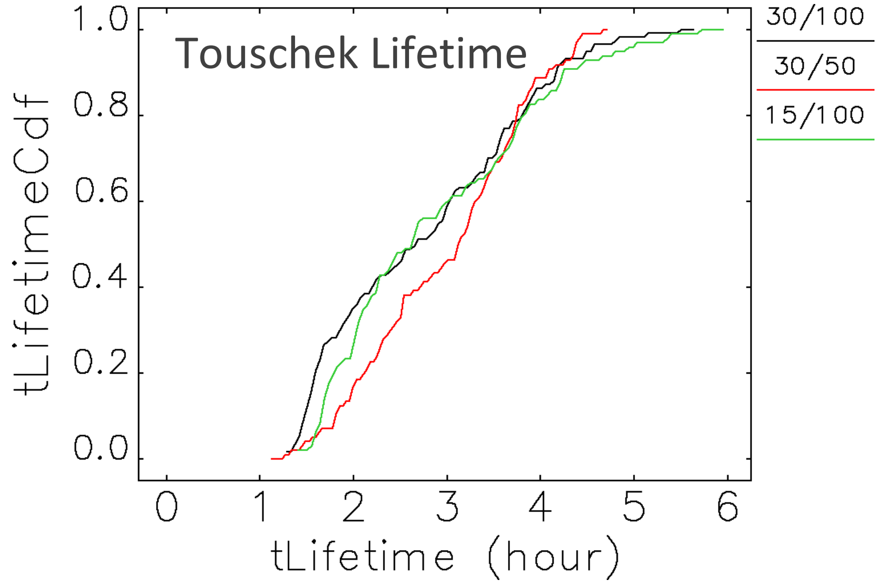


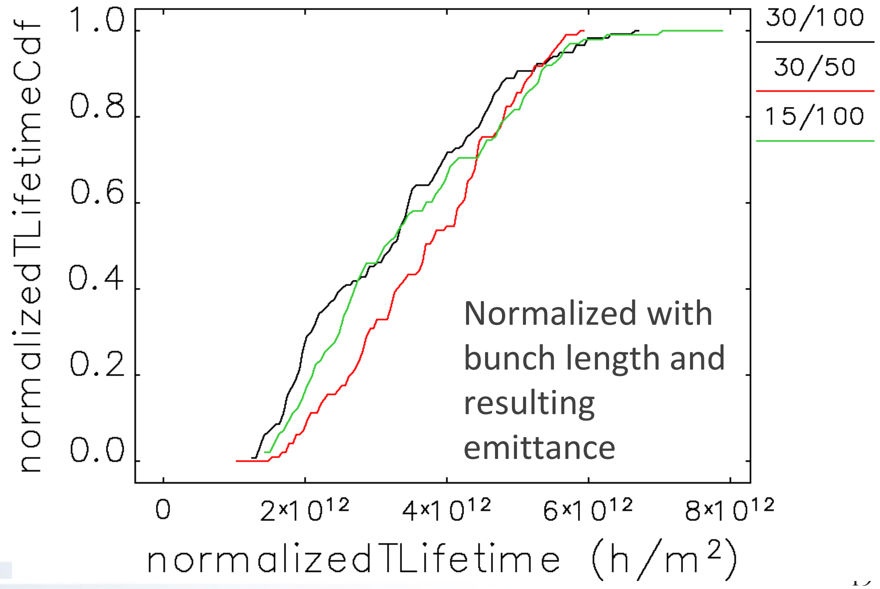
Magnet and Girder Alignment Tolerances Study

- Alignment specifications
  - Components on girders: 30 um rms
  - Girder-to-girder: 100 um rms
- These are achievable, but others have done better
- With 30/100 assumption, DA is good but lifetime is not as good as expected from mocked-up error sets
- Tried two additional error sets
  - Reduce on-girder errors to 15 um, leave between-girder errors at 100 um
  - Leave on-girder errors at 30 um, reduce between-girder errors to 50 um
- Looked at effects on
  - Residual orbit
  - Beta function variation
  - DA
  - LMA

Alignment tolerances study

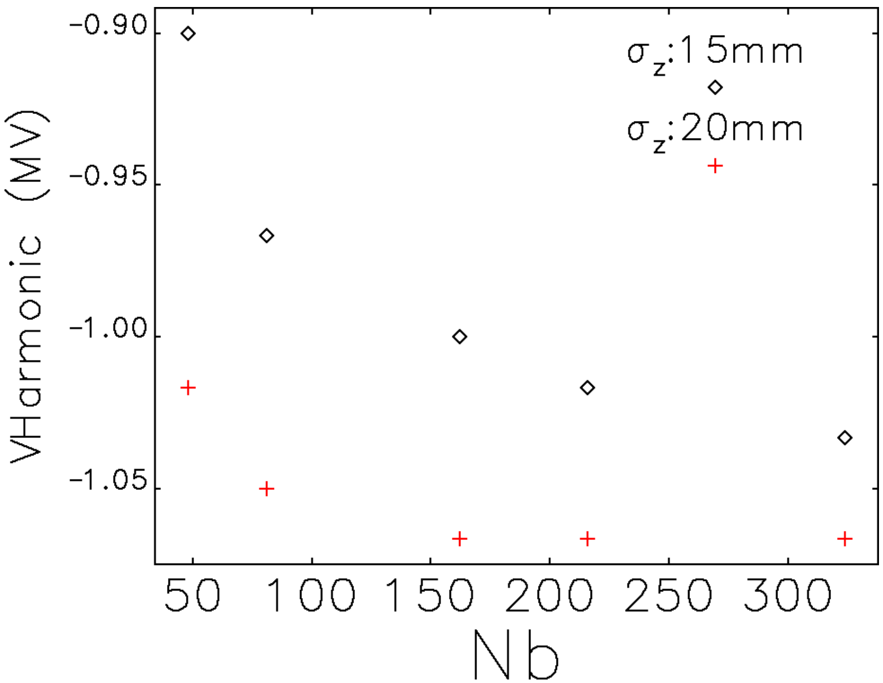






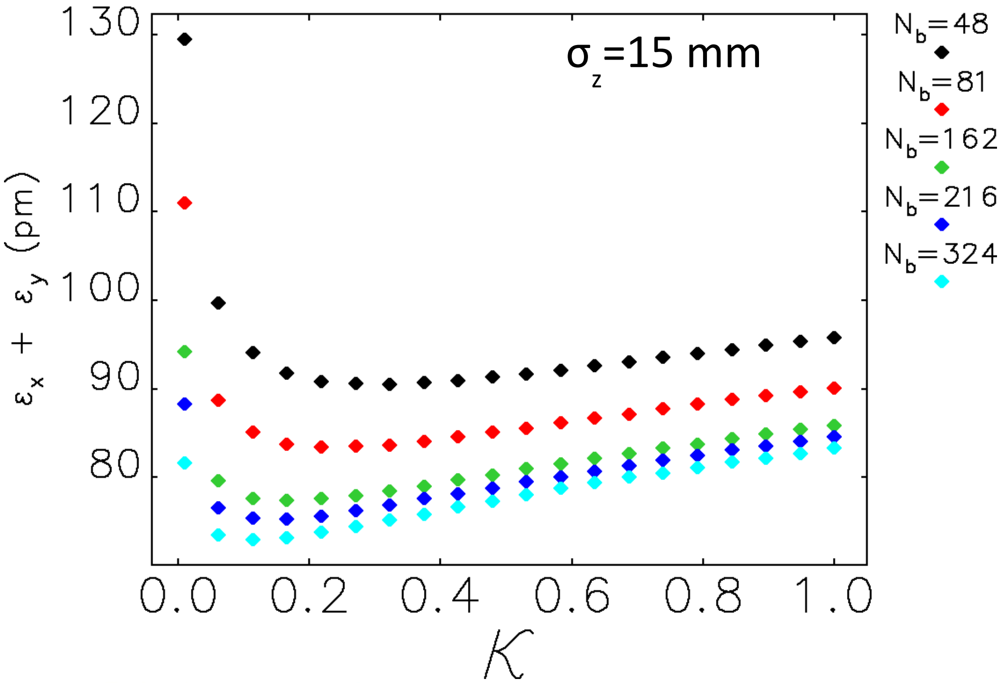
Bunch Lengthening

- IBS and Touschek scattering expected to be significant
- Zero-current bunch length without higher-harmonic cavity is ~4mm
- To get σ_z=15 mm we need about 1 MV of 3rd or 4th harmonic voltage
- Assume 200 mA total current
  - Assumed lowish |Z/n| of 0.1 Ohm[1]
  - Assumed 3rd harmonic cavity for this earlier calculation, though a 4th harmonic cavity is under design
- Lengthening helps with impedance effects as well (see later)



Intrabeam Scattering

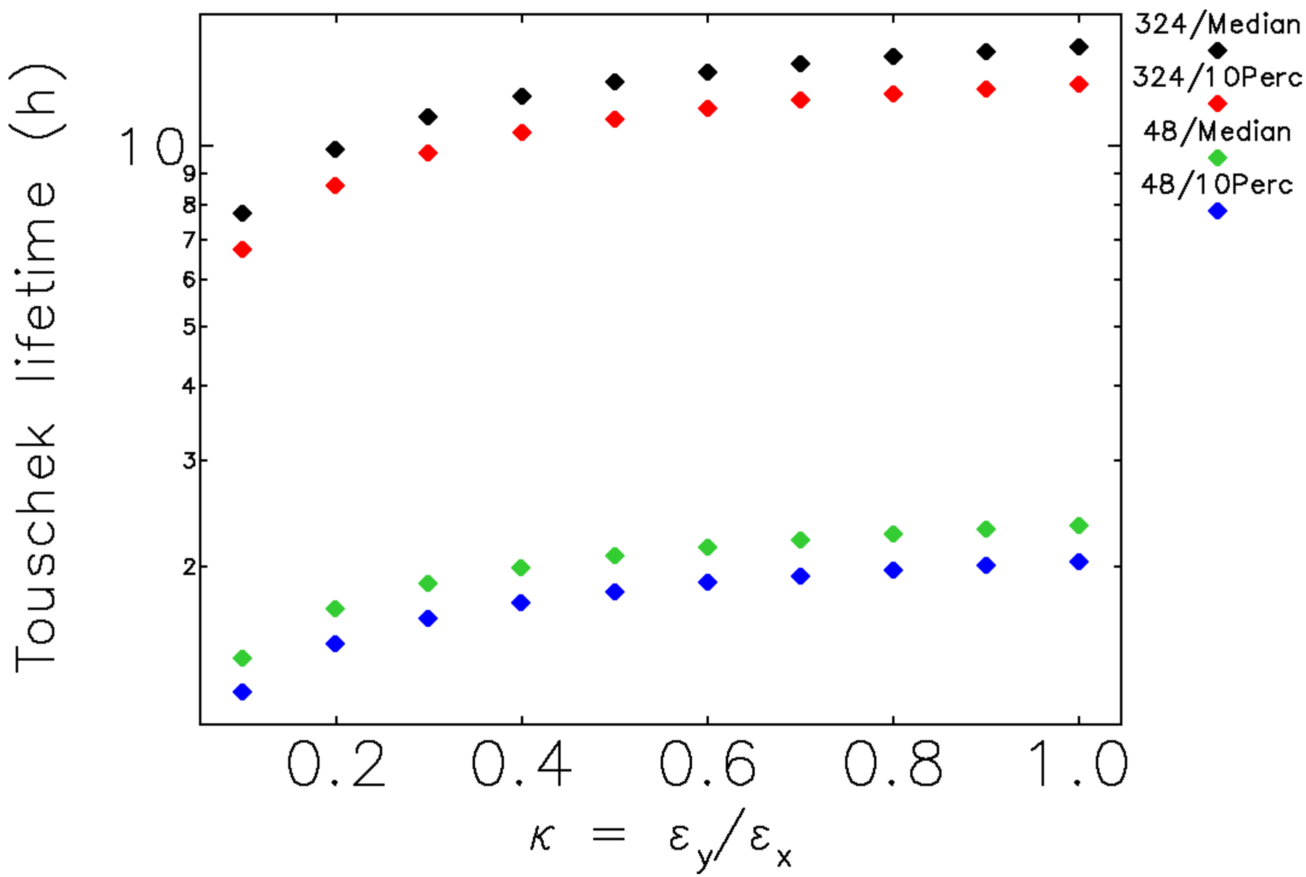
- Used ibsEmittance[1] to model intrabeam scattering
  - Assumed bunch length of 15 mm
- Uses Bjorken-Mtingwa formalism[2] to compute the IBS growth rates
  - Fixed ratio of bunch length to energy spread is assumed
  - Fixed ratio κ of vertical to horizontal emittance is assumed
- The effect on the "total" emittance is modest until ratio is taken below 5% percent



1: A. Xiao, L. Emery, M. Borland; A. Xiao, Linac08, 296-298.
2: J. D. Bjorken and S. K. Mtingwa, Part. Acc. 13 (1983) 115.

Touschek Lifetime

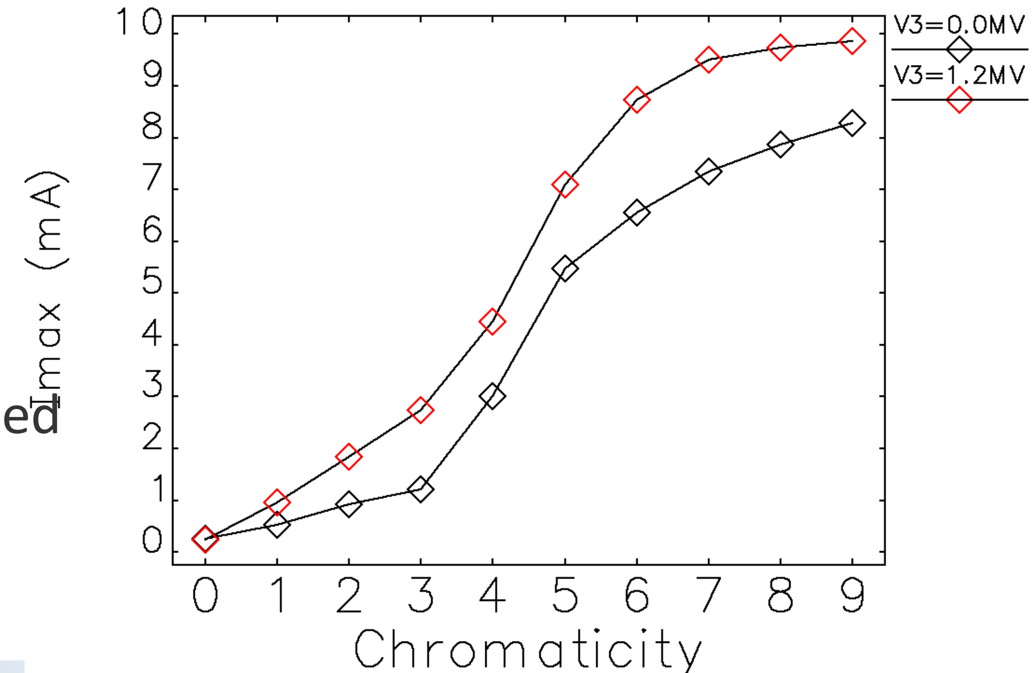
- Calculated from LMA results using touschekLifetime program[1]
  - Used results with 0.1% systematic multipoles
- Computed using bunch parameters from IBS simulations for σ_z=15 mm



1: A. Xiao, M. Borland, PAC07, 3453-3455.

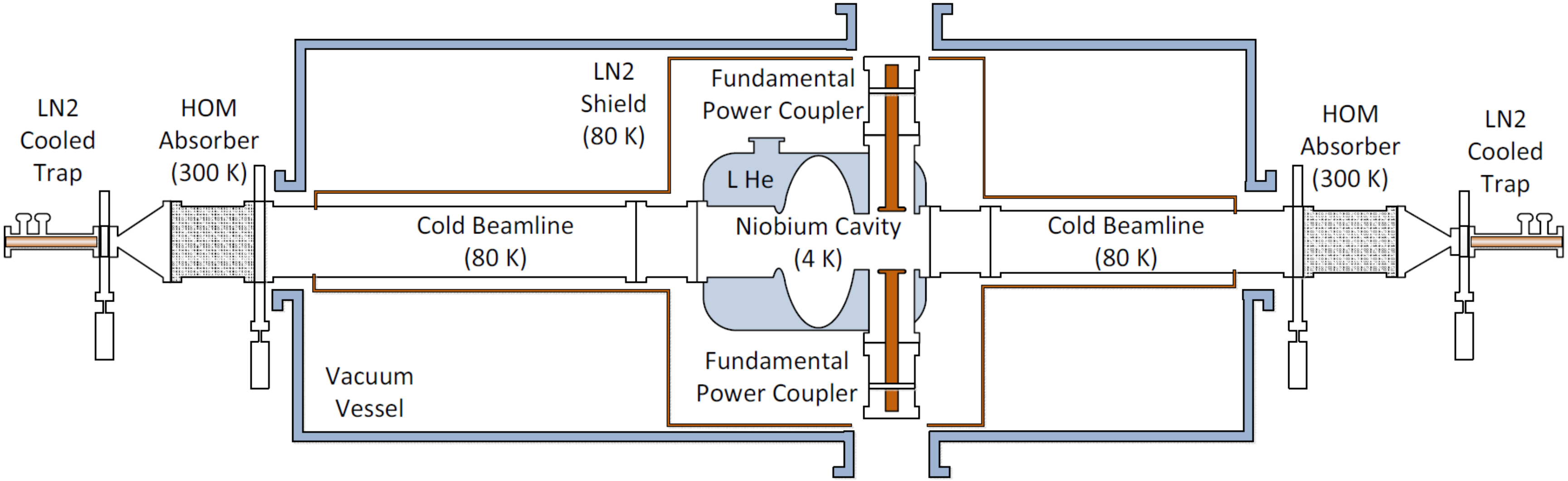
Impedance Issues

- Computed the ring impedance model consistent with the engineering design to date
- Established the impedance budget for 4.2 mA per bunch
  - Tracking simulation of injection limit due to impedance show that required chromaticity is 5
  - New design of vacuum components should comply with the budget
- Investigated the effect of a 3rd harmonic cavity
  - Higher single bunch current or lower chromaticity
  - Less IBS effect and longer lifetime
- Impedance effect of NEG coated surface is under an R&D plan.



Higher-Harmonic Cavity

- Higher harmonic cavity bunch lengthening system designed by ANL-PHY
- 4th harmonic
- Passive with fundamental coupler and tuner
- Operational goal is to maximize bunch length, which maximizes Landau damping of various instabilities

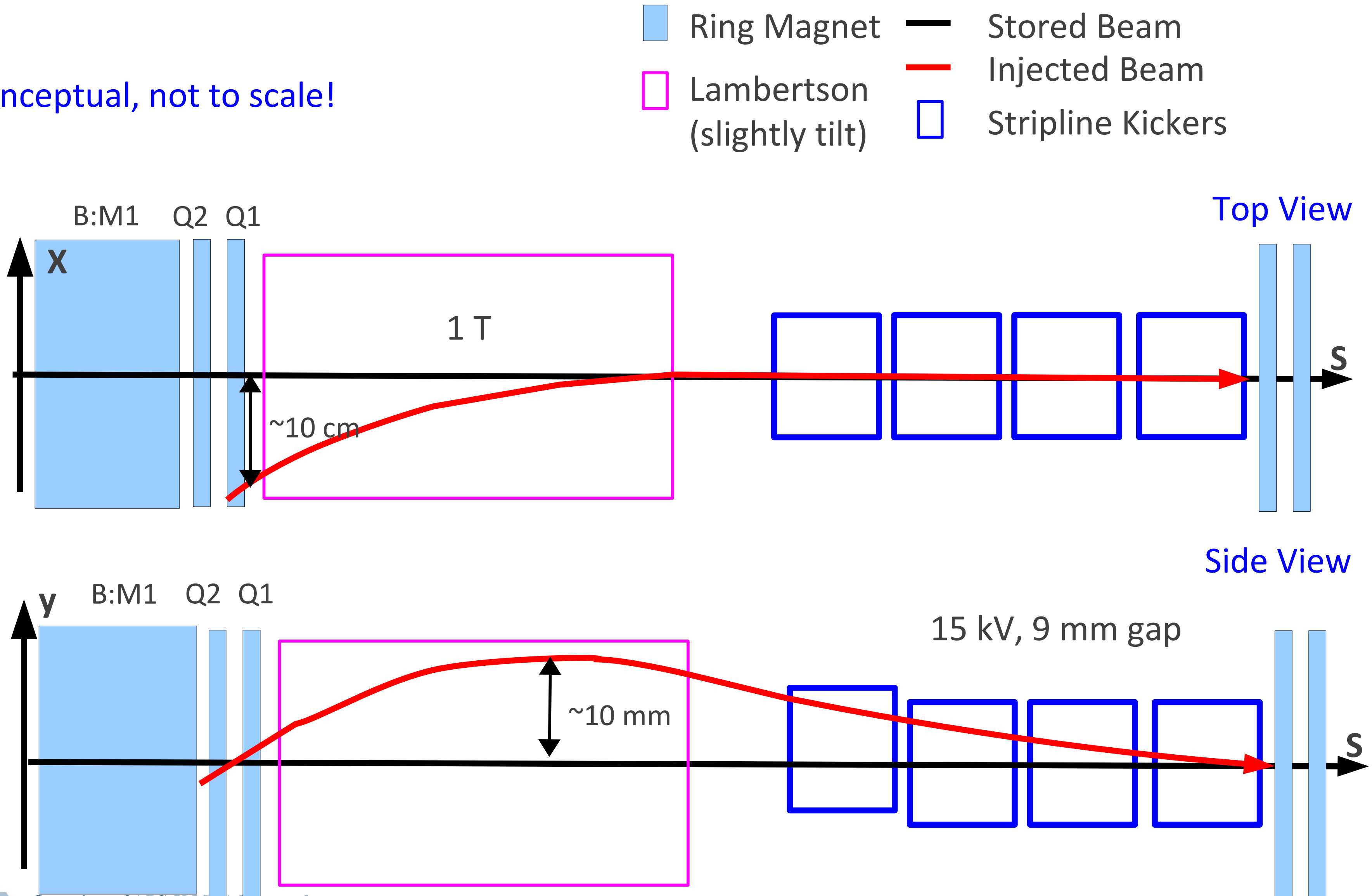


Swap-out Injection

- Vertical injection (and extraction)
- All injection elements in a single straight (5.8 m)
  - Less interference with optics evolution and future machine operation
  - No restriction on the optical design (phase advance)
- Fast injection kickers (< 20 ns) required for 324 bunch mode.
- High-charge (4 mA / bunch) injector operation required for 48-bunch mode.
- Insertion device apertures can be small in both horizontal and vertical planes.
- Systematic and random error analysis on kickers and septum has been done.

Vertical Injection Layout

conceptual, not to scale!



Summary

- A hybrid seven-bend achromat lattice for the APS tunnel has been developed, starting from ESRF's design
- Optimized linear optics, sextupoles using tracking-based MOGA
- Ensemble evaluation shows robust performance in spite of large assumed errors
  - Magnet field quality requirements are relaxed
  - 5-7% beta beats and 9-11% coupling not a problem
- Intrabeam scattering and Touscheck lifetime are acceptable assuming
  - Significant coupling of horizontal emittance into vertical
  - Bunch lengthening to 15 mm rms
- Several tolerance studies were done
- **4th DLSR Workshop 2014 - November 19-21, 2014 at Agonne National Laboratory**