Dynamic Aperture Experiences and Optimizations at CESR

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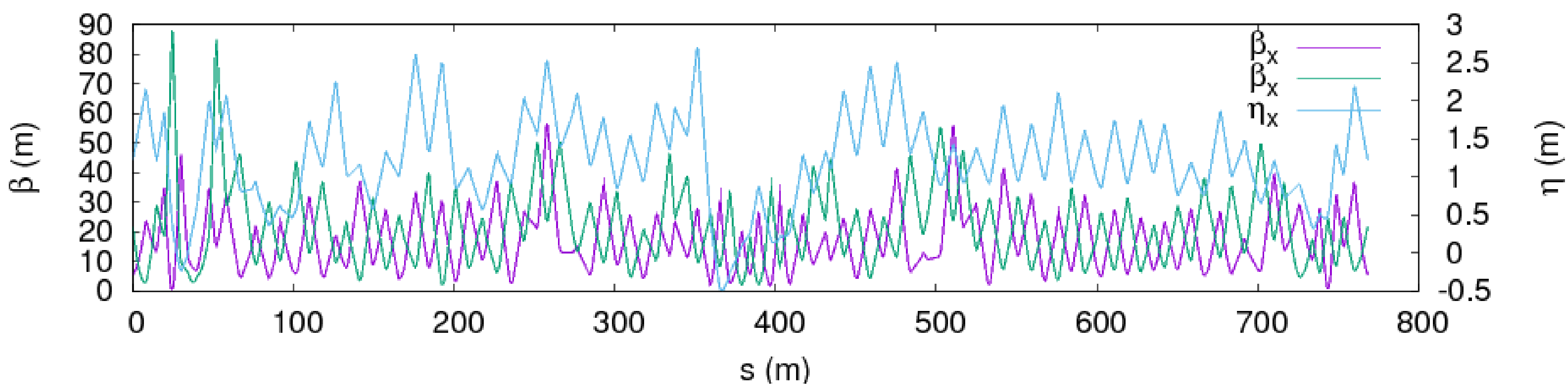
Outline

- Recent CCU installation project in CHESS.
  - Pretzel Orbits
  - Compact Cornell Undulator (CCU) nonlinearities
- 2018 Partial Machine Upgrade: CHESS-U
  - 100 nm → 30 nm emittance
  - Ten CCUs
- Early Stage Optical Stochastic Cooling project
  - Machine energy 6 GeV → 300 MeV

Some CESR Details

- 5.3 GeV dedicated light source, originally for e^+/e^- collisions.
- FODO Lattice
- 125 x 125 mA (e^+ & e^-)
- 768 m circumference
- Periodicity 1, no useful symmetry
- 77 Independently powered sextupoles
  - Some times ganged to be mirror symmetric to ~37 variables.

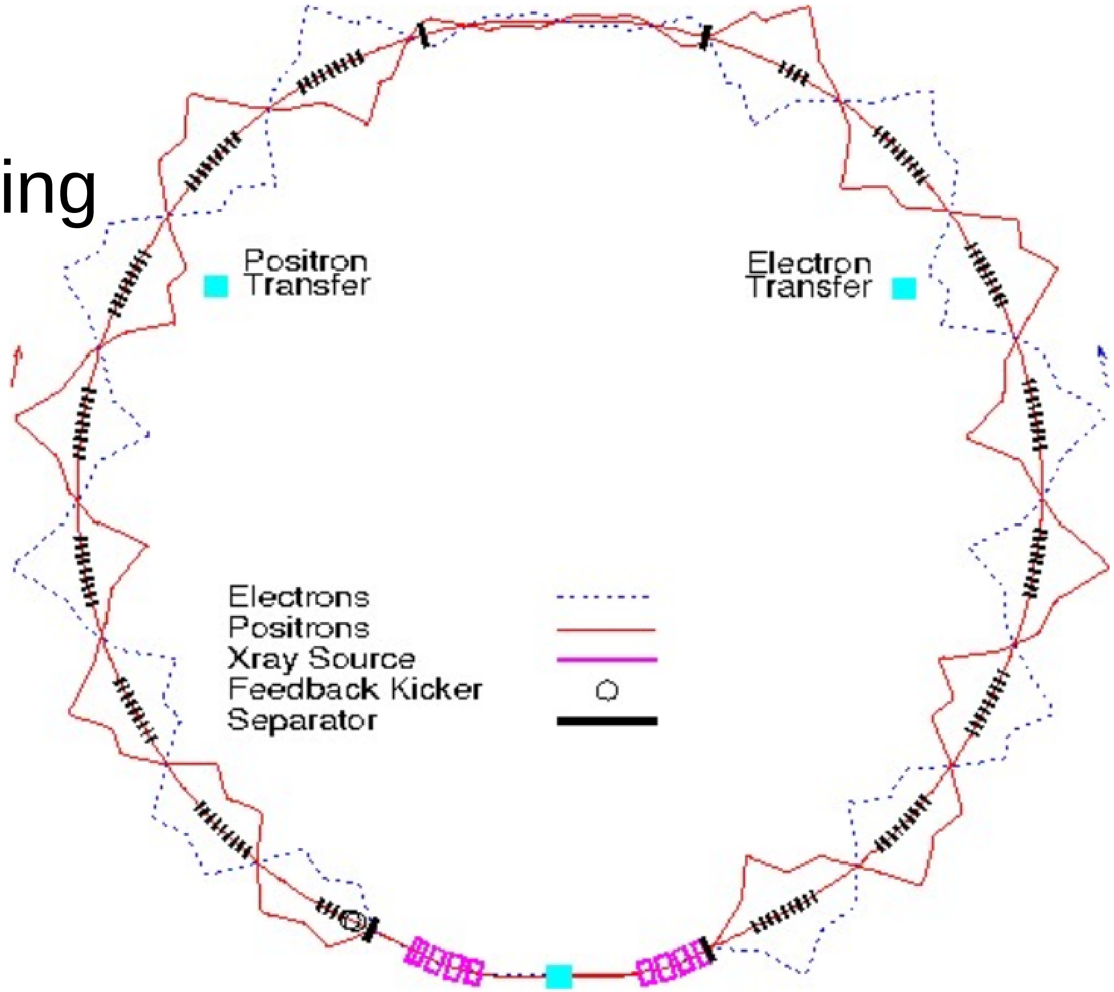


Nonlin in Current CHESS Cond.

- Pretzel orbits: two beams (e^+, e^-), different tunes.

- Tonality: Each beam has own off-axis trajectory through sextupoles
  - Two tunes, avg is working point.
  - Typical spread: $\Delta Q_{h,v} \sim 0.05$ fractional

- Each beam follows same trajectory through canted CCUs.



Nonlin in Current CHESS Cond.

- Nonlinear Optimization Goal:
  - DA on/off energy: Beam lifetime & Injection efficiency
- Objectives (analytic forms, linear in K_2):
  - $d\beta_{x,y}(i) / d\delta_p$
  - $d\beta_{x,y}(i) / d\bar{x}$
  - $d\beta_{x,y}(i) / dJ_{x,y}$
  - $dQ_{x,y} / d\delta_p$
  - $dQ_{x,y} / d\bar{x}$
  - $d\,Coupling(i) / dJ_{x,y}$
- Solved as over-constrained least squares problem
- For given weights, solution K_2 distribution is unique.

Nonlin in Current CHESS Cond.

- Sextupole scheme is Lease Squares solution
- Additional criteria applied to pick weights

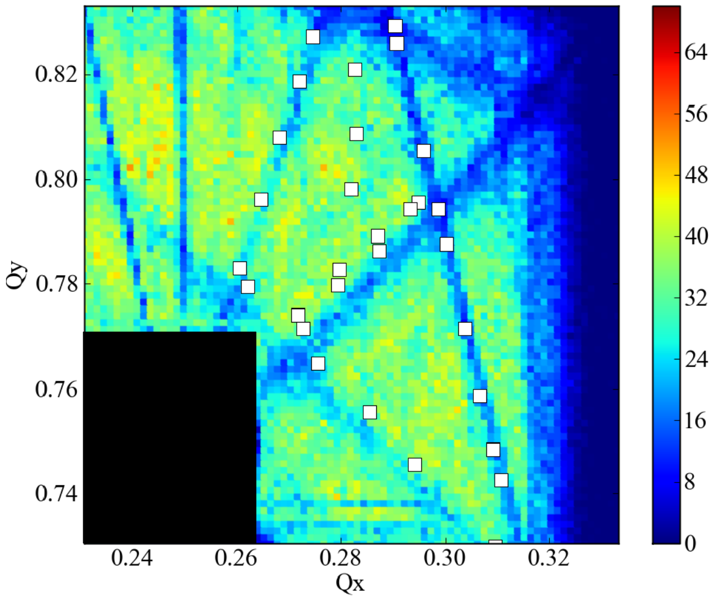
1) $\left| \left.\frac{d\beta_{x,y}(i)}{d\delta_p}\right|_{1st\ order} - \left.\frac{d\beta_{x,y}(i)}{d\delta_p}\right|_{exact} \right|$

2) Max K_2

3) Dynamic Aperture (tracking)

4) Determinant of 1-turn matrix, as determined by tracking.

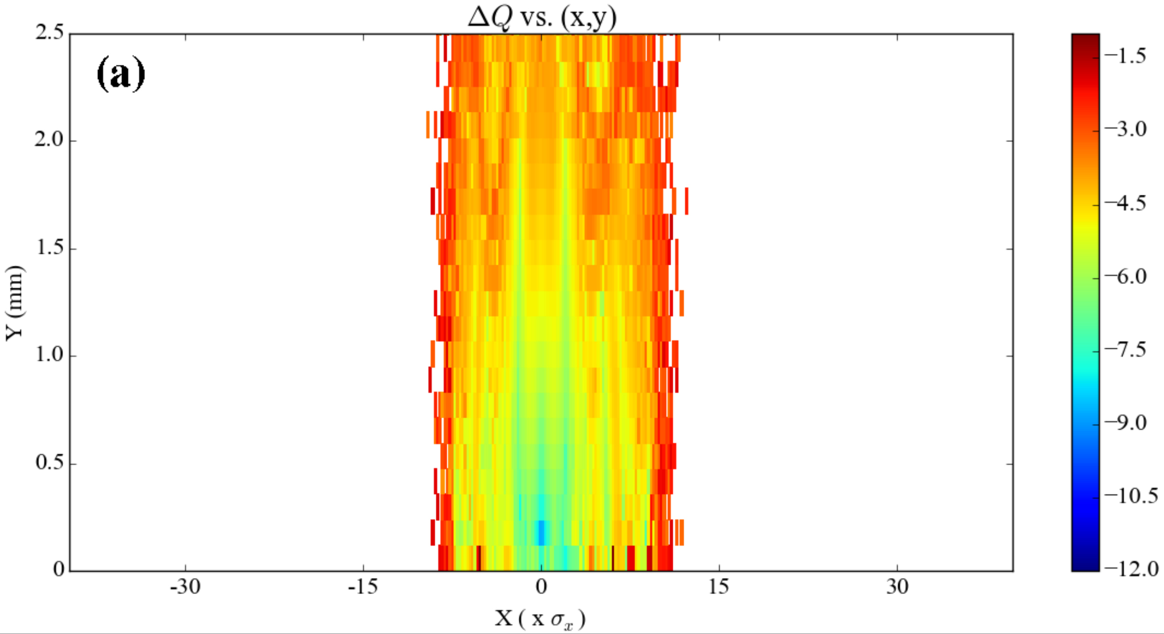
CHESS Results (1/2)



Study on CHESS after recent CCU installation

Injection Scan on Qx, Qy

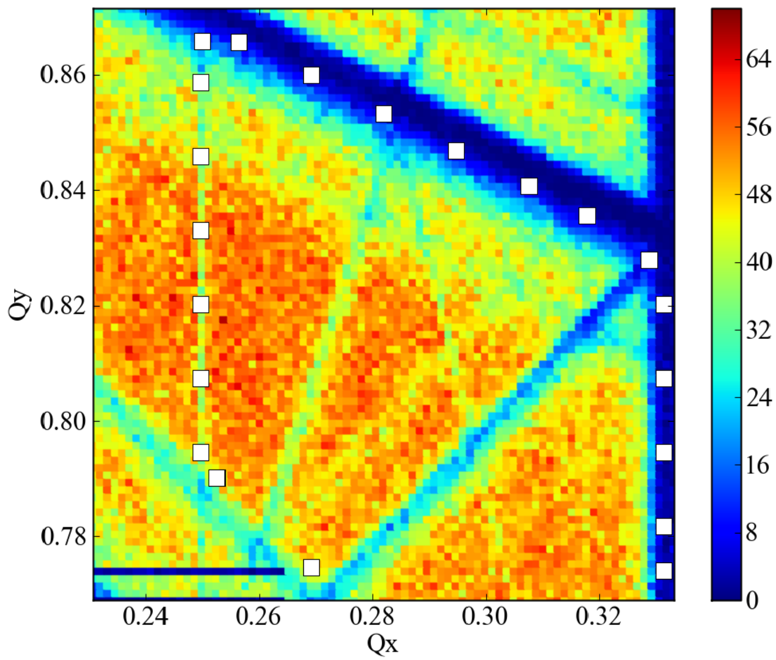
- Color scale is simulated injection efficiency.
- White squares are experimentally measured stability boundary.
  - Simulated efficiency was not so good.
  - Recall: Tonality (species tune split) ~0.05
  - Experiment shows resonances not present in simulation.



Tracking studies suggested the poor injection efficiency due to nonlinearities in the undulators.

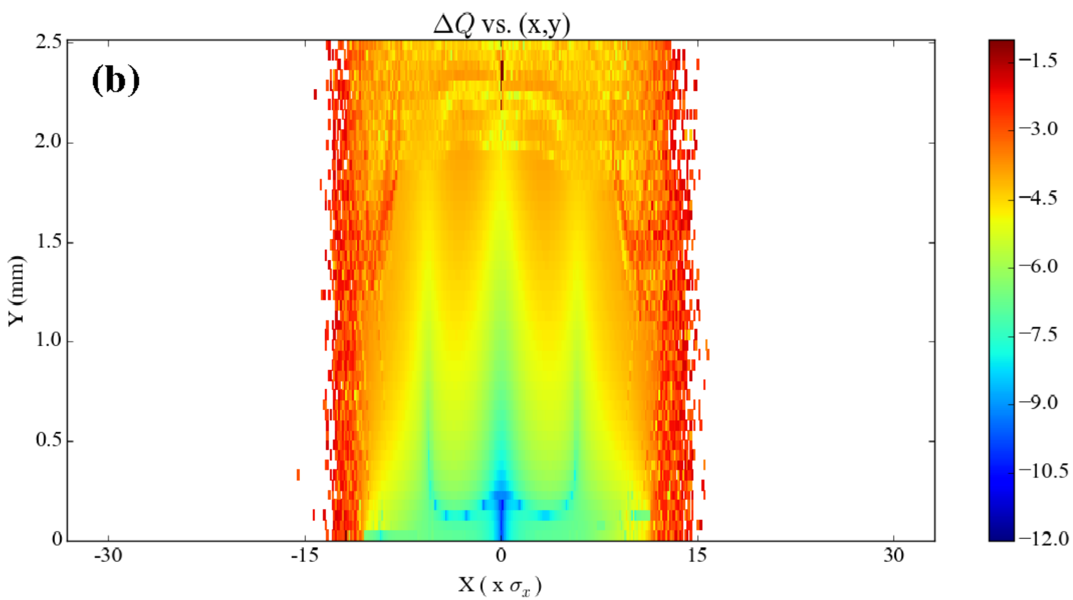
Solution: Add quadrupole near CCUs to allow lower H & V β-function.

CHESS Results (2/2)



Results after installing additional quadrupole to lower beta in CCU pair.

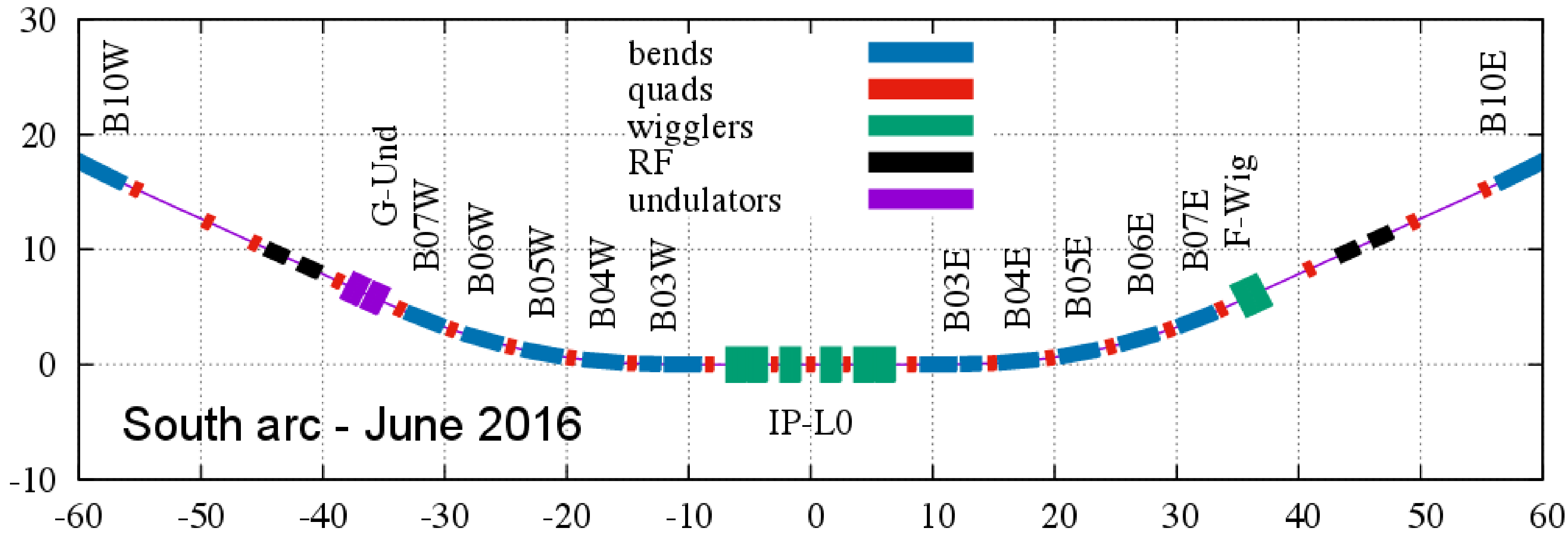
Resuls:
1) Larger stable region of tune plane.
2) Better injection efficiency.



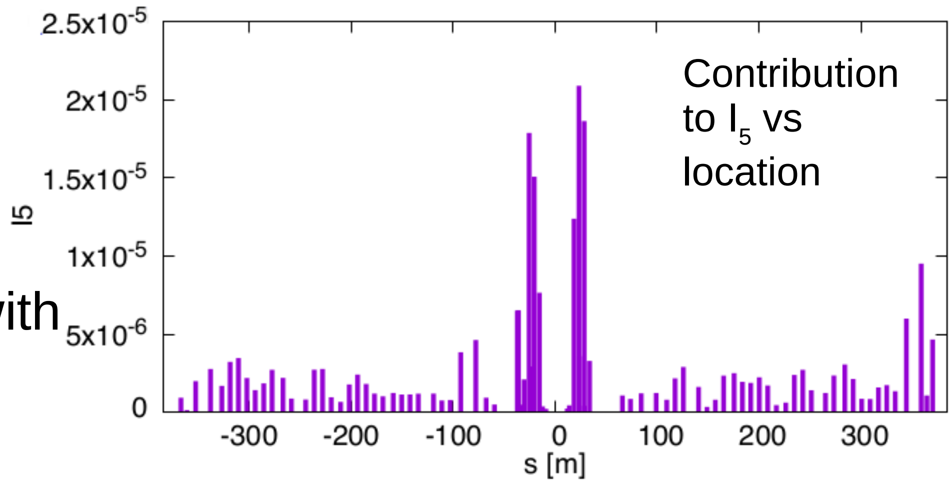
$\beta_{x,und}$ 28.1 m → 7.7 m

$\beta_{y,und}$ 6.8 m → 3.2 m

CHESS-U Overview

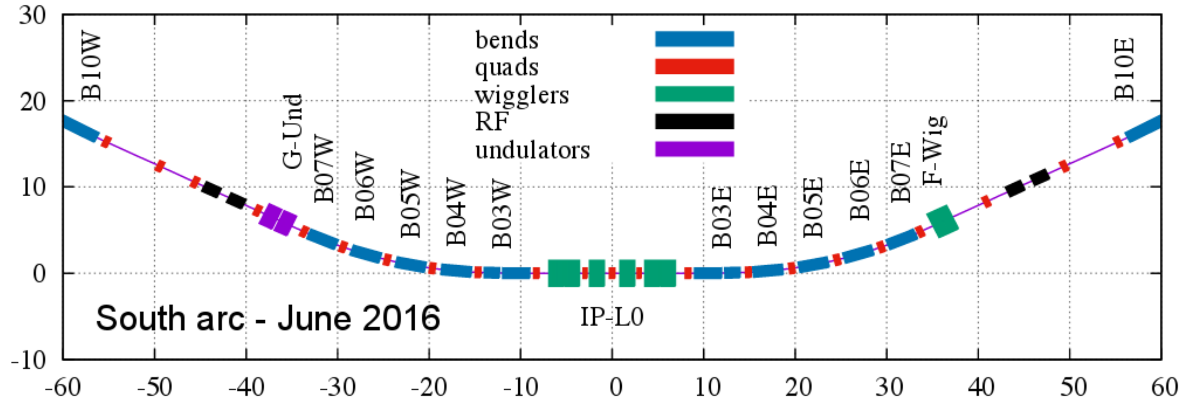


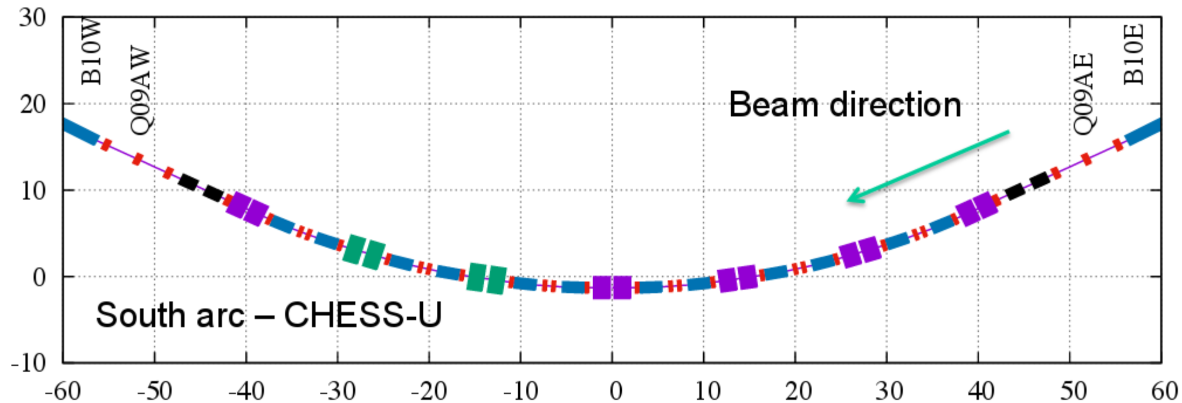
- Colliding beams had required hard bends near detector region.
  - Hard bends dominated emittance generation in CESR.
- CHESS-U (mostly) about replacing these with DBA's.
- Funded and procurement started: In Operation by end of 2018.

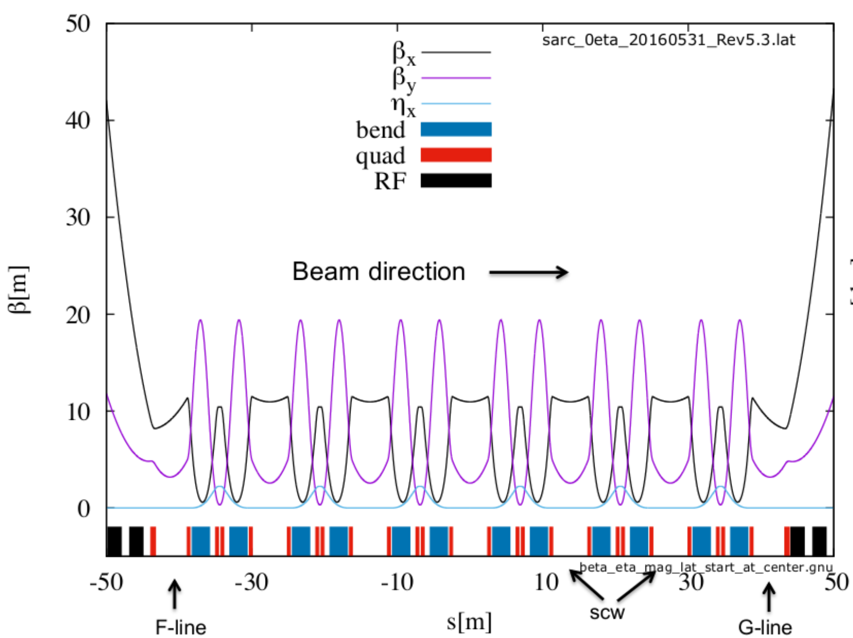


CHESS-U Overview

- Replace hard bends with DBAs
- 5.3 GeV → 6 GeV
- Emittance 100 nm → 30 nm
- Current 100 mA → 200 mA
- 2 CCUs → 10 CCUs
  - All CHESS-U beamlines will be undulators.







- Single beam oparation
  - Reconstruction of several beamlines.
- Online end of 2018.
- Design decision: no sextupoles in arc

CHESS-U: Important Factors

- Factors good for nonlinearities
  - Single species: no tonality
  - Large dispersion
    - $\langle\eta\rangle \sim 0.9$ m, $\eta_{max} \sim 2$ m
  - Low natural chromaticity
    - $\xi_{x,y} \approx 26.0$, $\xi_x/\nu_x = 1.6$, $\xi_y/\nu_y = 2.13$
  - Independently powered sextupoles (lots of variables)
- Factors bad for nonlinearities
  - No periodicity: all resonances are systematic
  - 10 narrow-gap undulators (4.5 mm beam aperture).
    - Strong nonlinearities & small aperture.
  - South arc has no sextupoles
    - Relatively low dispersion
  - Large compaction (0.0057) → low energy aperture (~0.5%)

CHESS-U Nonlin Optimization

- Three stage process:
  1) Begin with 2-family distribution.
     - Given $\xi_{x,y}$ uniquely determines K_2's
  2) Optimize determinant of the 1-turn matrix given by tracking (next slide!).
  3) Refine with minimization of 1^{st} order RDTs.

Transfer Matrix From Tracking

- Pick 5 initial coordinates $(x_i^{1\ldots5}, x'^{1\ldots5}_i, y_i^{1\ldots5}, y'^{1\ldots5}_i)$ at some δ_p and 4D-track for 1 turn to obtain $(x_o^{1\ldots5}, x'^{1\ldots5}_o, y_o^{1\ldots5}, y'^{1\ldots5}_o)$.

$$\mathbf{M}\begin{pmatrix} x_i^1 & x_i^2 & x_i^3 & x_i^4 & x_i^5 \\ x_i'^1 & x_i'^2 & x_i'^3 & x_i'^4 & x_i'^5 \\ y_i^1 & y_i^2 & y_i^3 & y_i^4 & y_i^5 \\ y_i'^1 & y_i'^2 & y_i'^3 & y_i'^4 & y_i'^5 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} x_o^1 & x_o^2 & x_o^3 & x_o^4 & x_o^5 \\ x_o'^1 & x_o'^2 & x_o'^3 & x_o'^4 & x_o'^5 \\ y_o^1 & y_o^2 & y_o^3 & y_o^4 & y_o^5 \\ y_o'^1 & y_o'^2 & y_o'^3 & y_o'^4 & y_o'^5 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

$$\mathbf{M}\mathbf{X}_{\text{in}} = \mathbf{X}_{\text{out}}$$

$$\mathbf{M} = \mathbf{X}_{\text{out}}\mathbf{X}_{\text{in}}^{-1}$$

$$\mathbf{M} = \begin{pmatrix} & & & & \bar{x} \\ & & & & \bar{x}' \\ & \underline{\text{M}}_{4\text{x}4} & & & \bar{y} \\ & & & & \bar{y}' \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$\bar{x}$, $\bar{x}'$, $\bar{y}$, $\bar{y}'$ is closed orbit

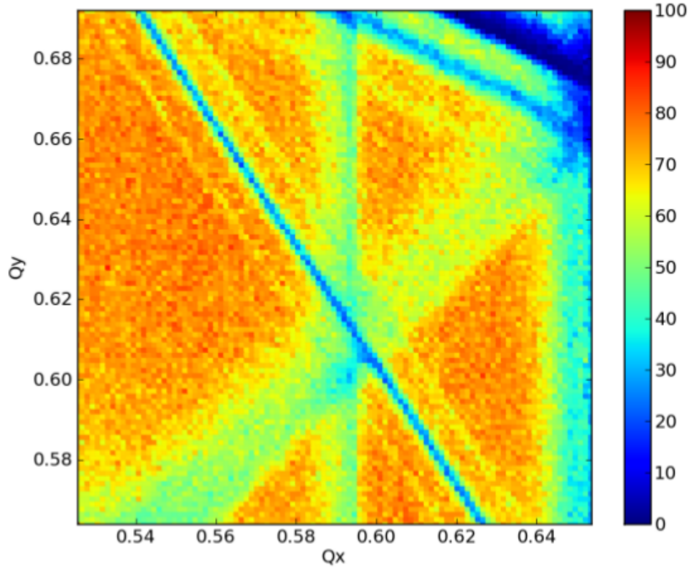
- Repeated at various δ_p.

- $\underline{\text{M}}_{4\text{x}4} = M_1 + N(Z_i) Z_i^{-1}$
- For small initial coordinates, $\text{M}_{4\text{x}4}$ is the linear map and $|\text{M}_{4\text{x}4}| = 1$
- Large coordinates probe nonlinearities and $|\text{M}_{4\text{x}4}|$ becomes a measure of the nonlinearity of large amplitude trajectories.
- Imperfect technique, but in experience has been useful.

1st order RDT minimization

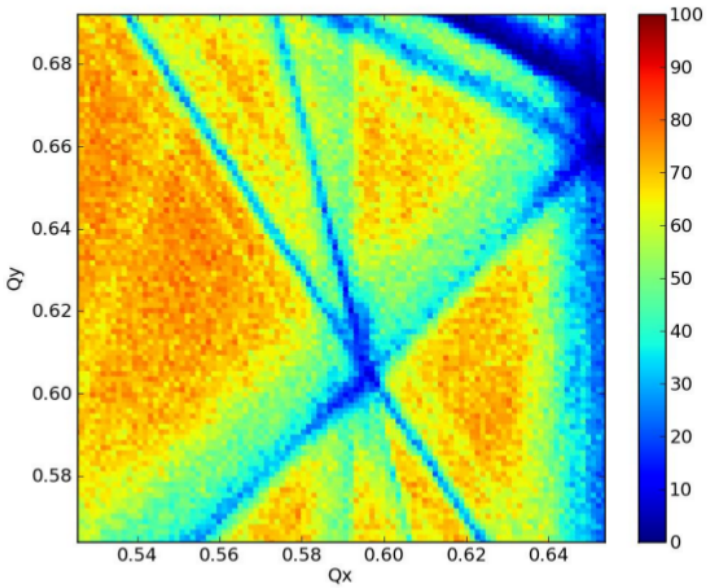
- After minimizing $|\underline{M}_{4x4}|-1$, then minimize 1st order RDTs.
  - Also chromatic β's & 2nd order η
  - Analytic forms for 1st order (in K_2) terms
  - Minimized in tao (Bmad) using either
    1) Levenberg-Marquardt (gradient descent)
    2) Differential Evolution (1-D evolutionary algorithm)

Injection Simulation



Top Plot: Simulated injection efficiency WITHOUT undulator fields (but with undulator apertures).

CHESS-U is single species … pretzel orbit tune difference is no longer an issue.

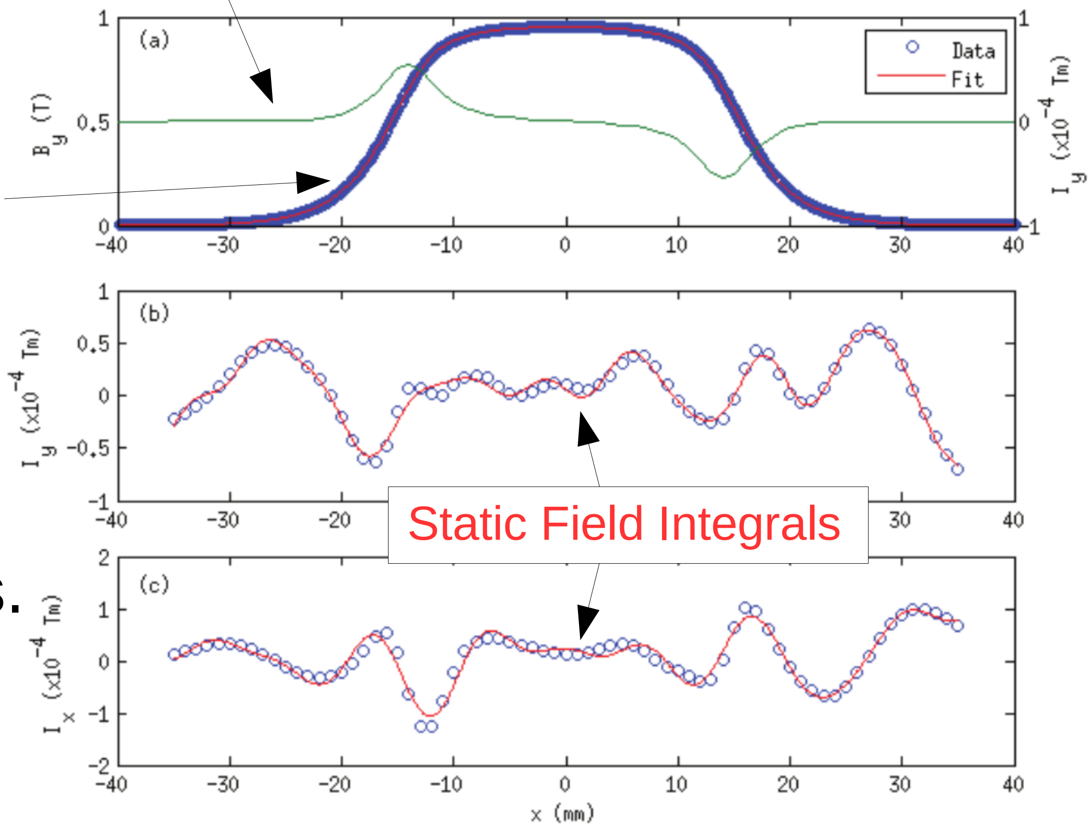


Bottom Plot: Simulated injection efficiency WITH undulator fields and apertures.

Impact of map-type undulator fields is important for accurate simulation.

Undulator Field Model

- CCUs are 1.5 m 104 pole w/ 0.93 T peak.
- Model components:
  - 27 term cos fit to B-field from Opera model.
    - Satisfies Maxell's Eqns.
  - Vibrating wire technique* obtains static field integrals.
    - Captures fringe fields and manufacturing imperfections.
    - Optics, tracking & normal form from Bmad or PTC.

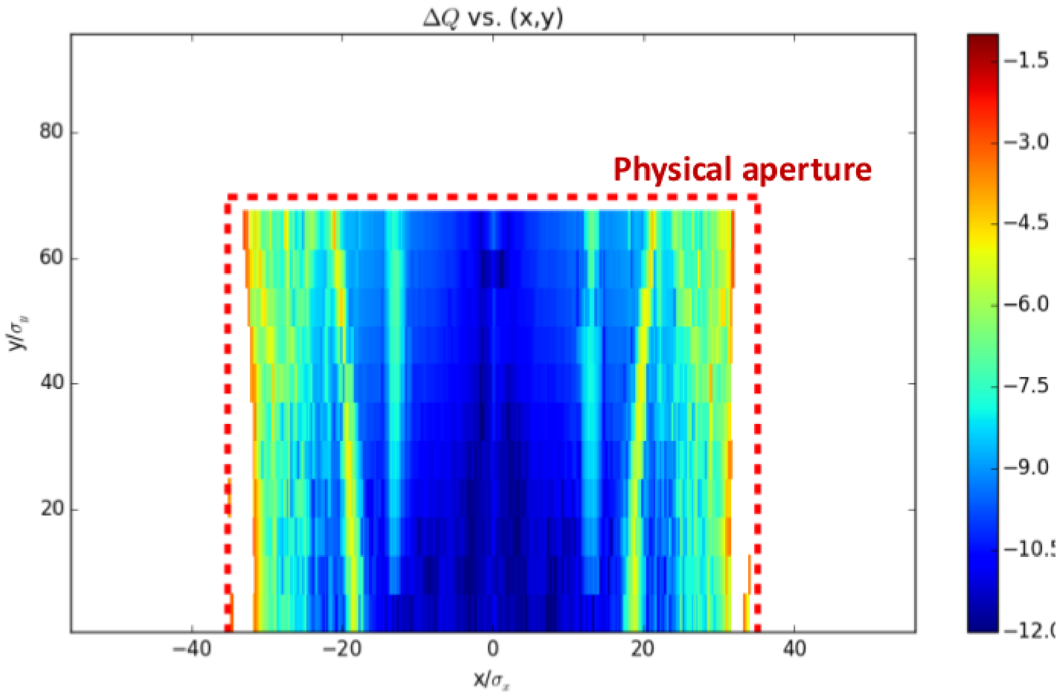


* Z. Wolf, "Undulaor field integral measurements," LCLS-TN-05-22, July, 2005.

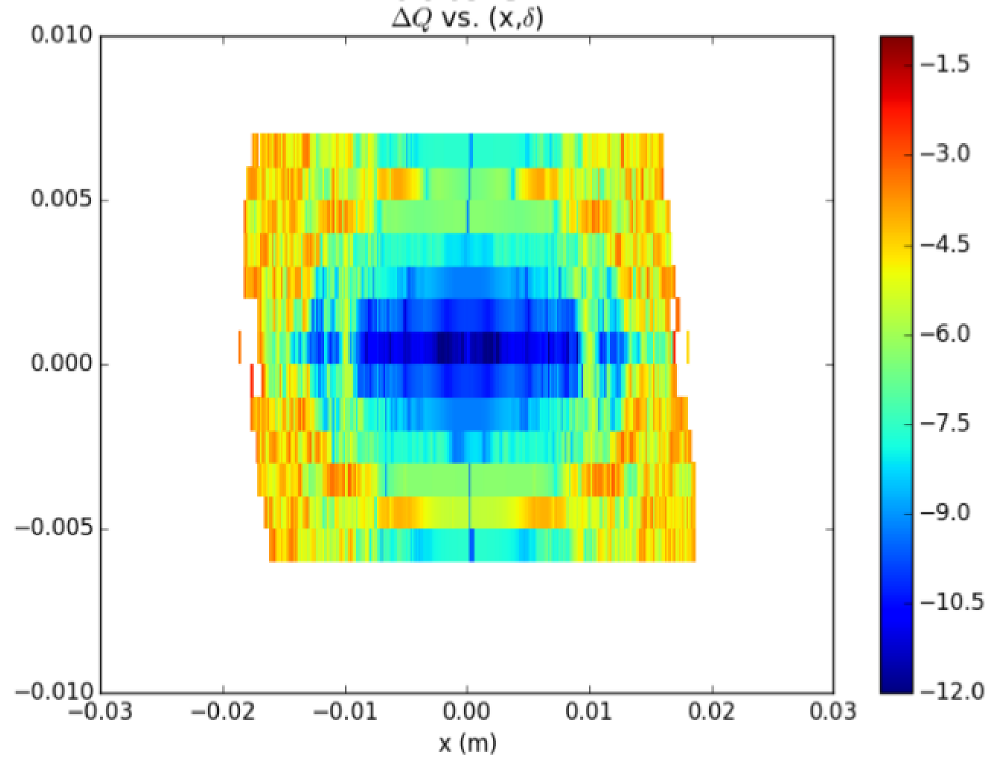
Freq. Map w/o CCUs

- CHESS-U with CCU aperture.
- Without CCU fields.

DA



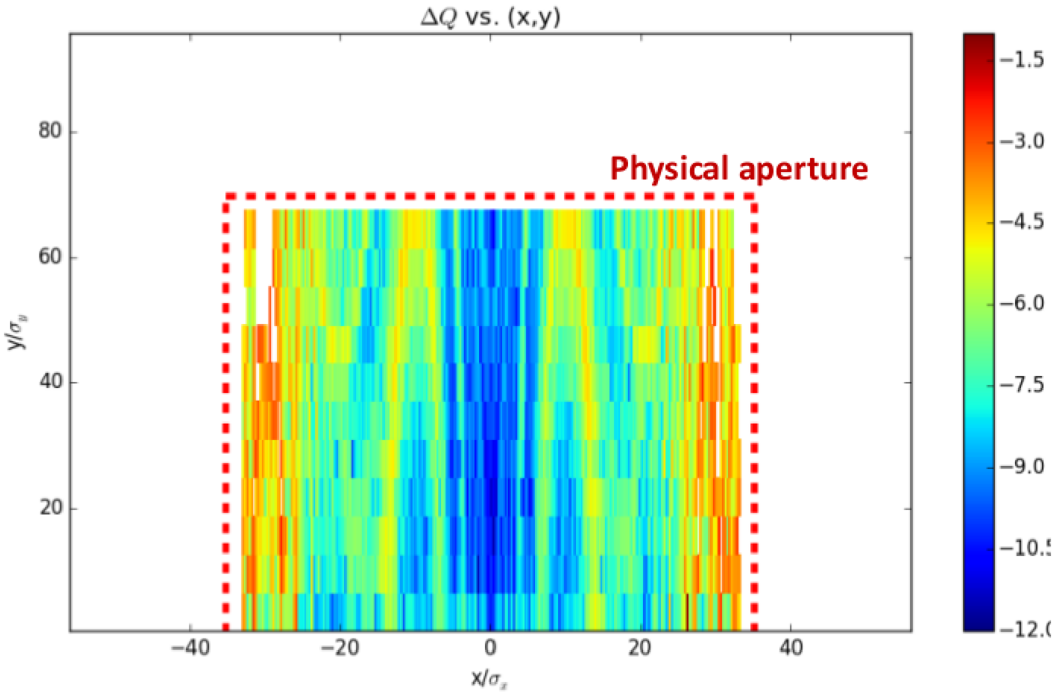
MA



Freq. Map w/ CCUs

- CHESS-U with CCU aperture.
- With CCU fields (Ten CCUs).

DA



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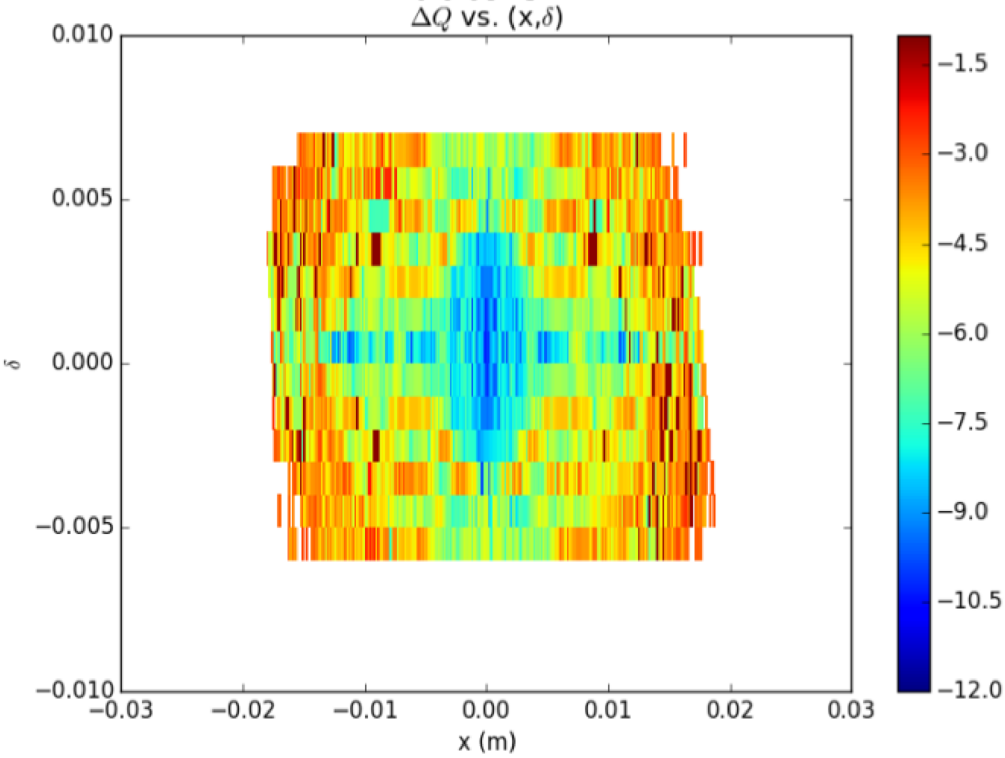
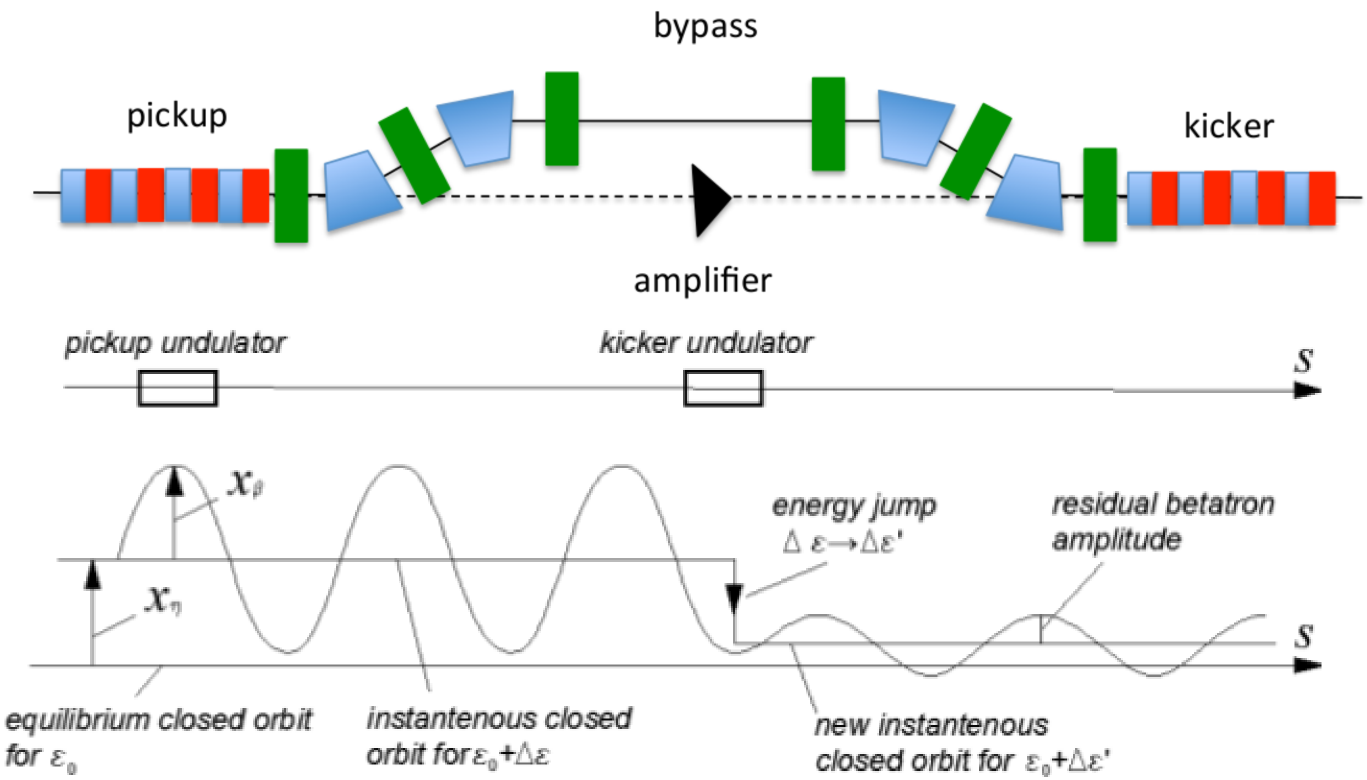


OSC Overview

- Optical Stochastic Cooling (OSC)
  - Undulator radiation is amplified and interacts with beam in 2nd undulator to decrease beam emittance on slice-by-slice basis.
  - Potential applications for hadron colliders.
  - 3 Year project funded 2017-2020.



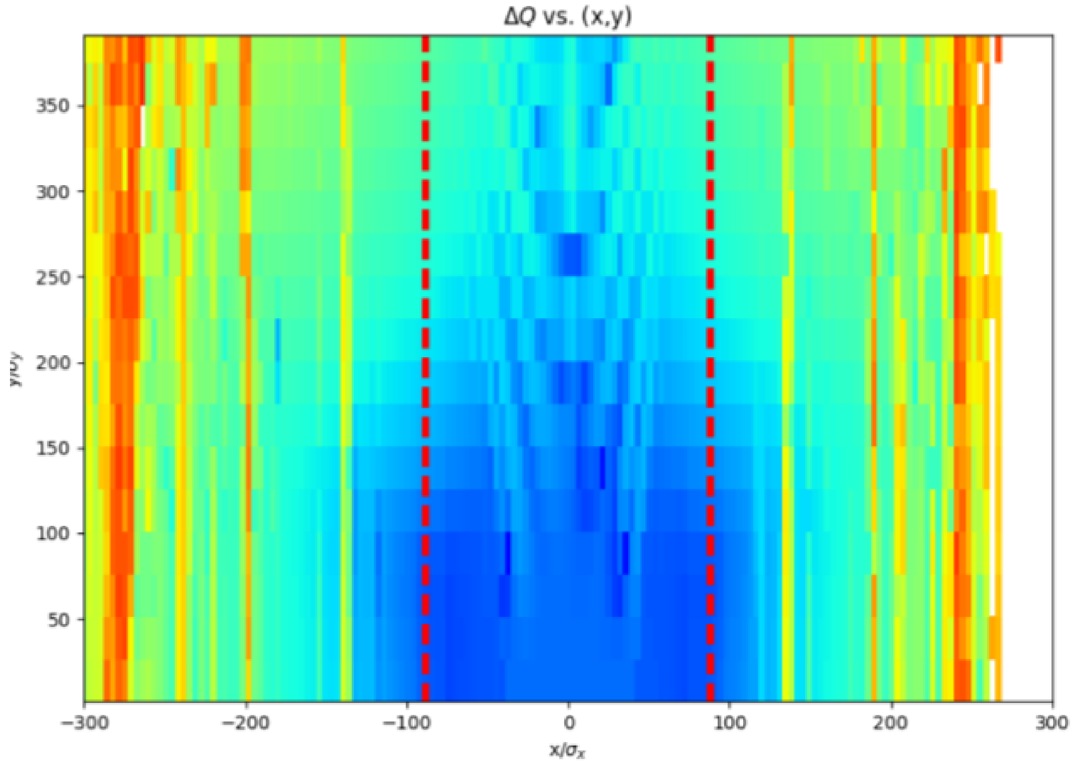
OSC Lattice

- Run CHESS-U at 300 MeV
  - 300 MeV is injector linac energy.
  - Synchrotron simply transports beam to CESR.
  - Damping time of a few seconds.
  - Ten CCU fixed-field undulators remain in place.
    - Relatively strong multipoles.
    - CCUs modeled using field map.
    - Need PTC (or the like) to calculate proper sextupole distribution to compensate CCU multipoles.

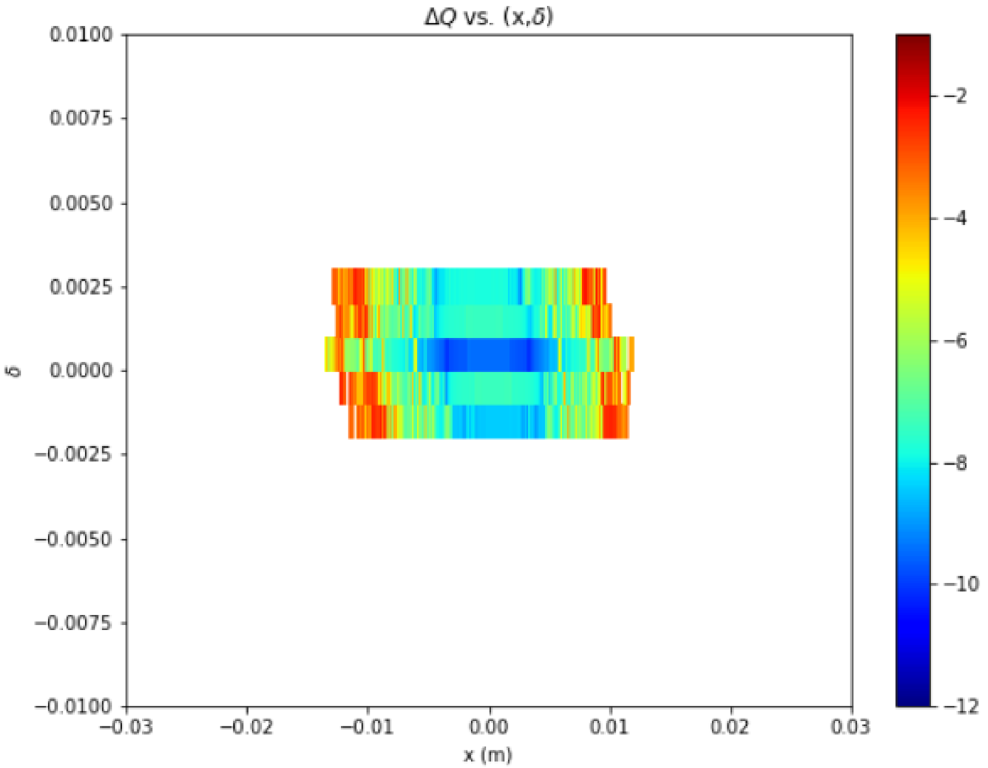
OSC Freq Map

- Frequency map of 500 MeV OSC lattice WITHOUT compact undulators.

dQ vs. x,y



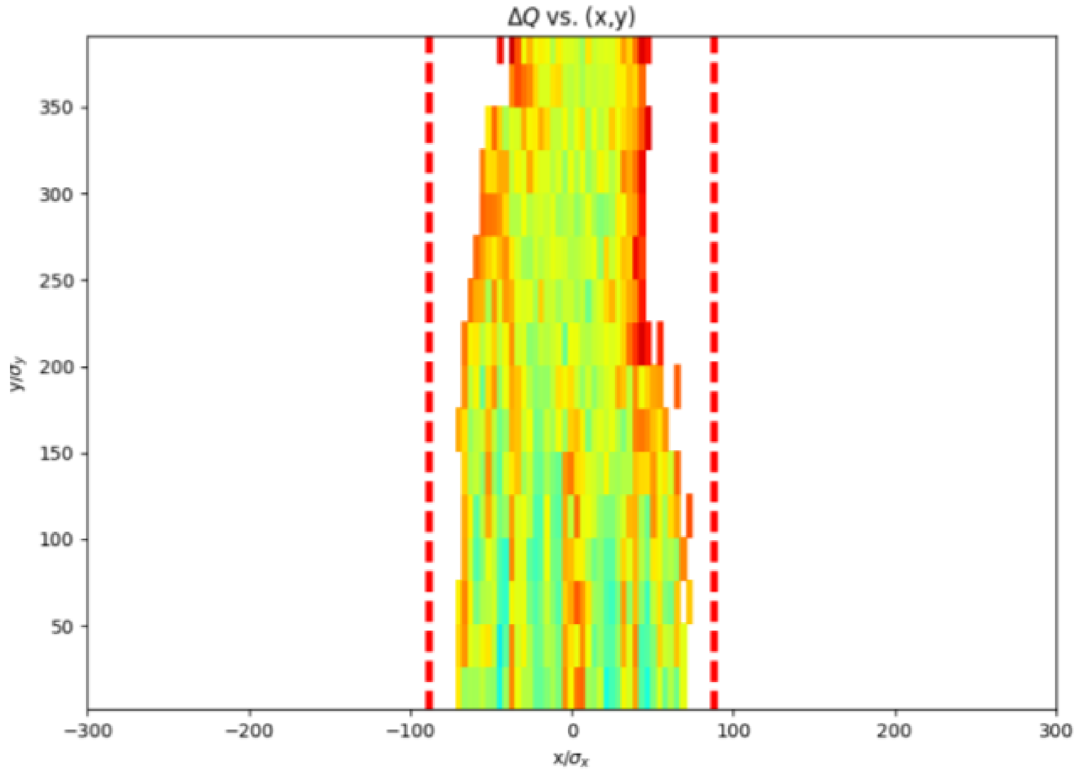
dQ vs. x,δ



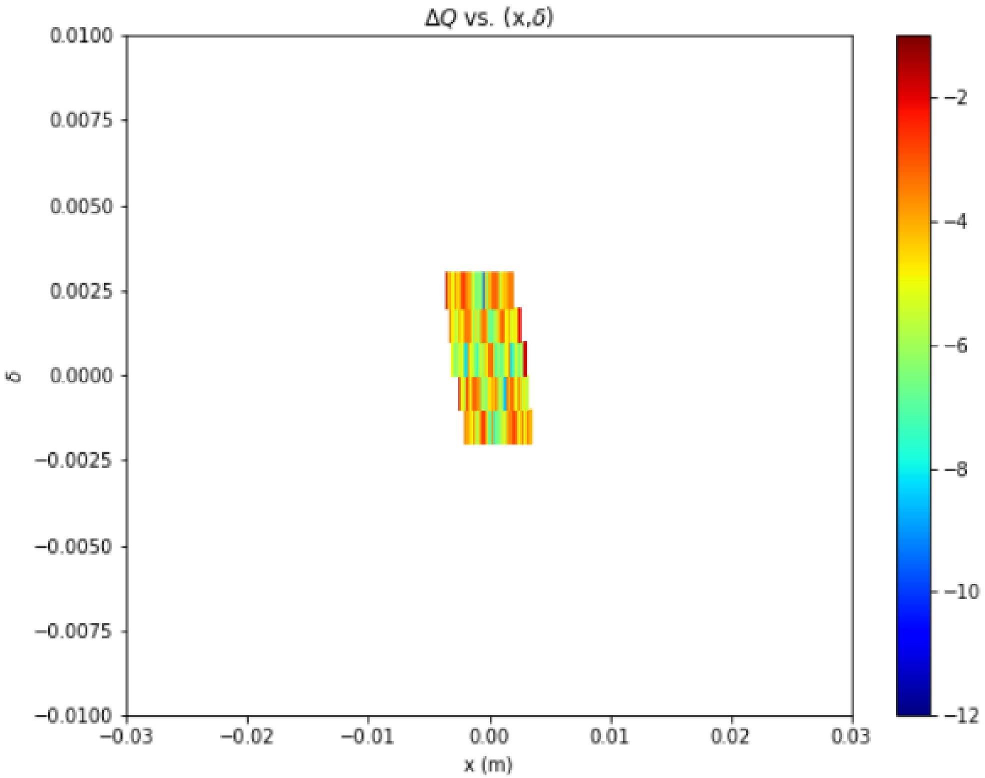
OSC Freq Map

- Frequency map of 300 MeV OSC lattice WITH CCUs.

dQ vs. x,y



dQ vs. x,δ



PTC & MAD-NG

- PTC can calculate Bengtsson-esque RDTs more exactly than summations over K_2 moments.
  - Works fine with field maps.
  - Driving terms obtained from normal form of map.
  - Build K_2 scheme to compensate undulator multipoles.
  - Unfortunately, prohibitively slow when integrating through field maps.
- **MAD-NG** would fix this (2018)
  - **Modern & computationally fast rewrite of TPSA, PTC, & MAD.**
  - Supported by CERN & Laurent Deniau.
  - MAD's TPSA & PTC interfaced with Bmad & Tao.

Conclusion

- CHESS was recently upgraded with CCUs, those fields are relevant to DA in simulation and machine studies.
- CHESS-U commissioned 2018.
  - Emittance from 100 nm to 30 nm.
  - Ten CCUs.
  - Nonlinearities of CCUs relevant for DA.
  - Field maps required for accurate modeling of DA.
- OSC brings unique challenge.
  - 6 GeV $\rightarrow$ 300 MeV
  - Relatively very strong fields from CCUs.