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Booster γ_T-Jump Systems for Transition-Crossing

J. Eldred

Accelerator Capabilities Enhancement (ACE) Workshop

Jan 30th 2023

Booster γ_T-Jump Systems

Booster historically had a γ_T –jump system:

- Booster orbit was not controlled (much improved).
- Timing of the jump was not precise enough (improved).
- Real-estate for the quadrupoles was needed (account for).

A new Q-jump or a resonant γ_T –jump system can be considered:

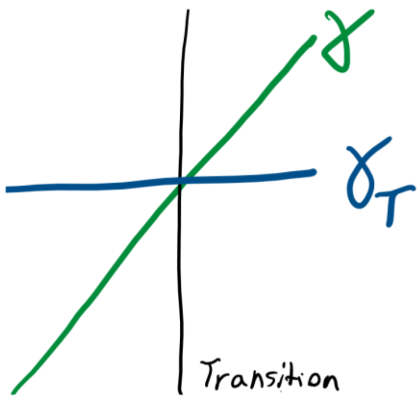
- **Q-jump** can change γ_T by 0.1-0.3 units with existing Booster QS correctors.
  - Changes γ_T linearly, side effect is a change in Qx tune.
  - System is being developed now as part of Booster improvement.
- **Resonant γ_T jump** can change γ_T by 0.4-0.7 units with new quads.
  - Changes γ_T quadratically, side effect is a change in max disperson.
  - Quad requirements similar to MI quad γ_T jump requirements.

Implementation details for both types of jump:

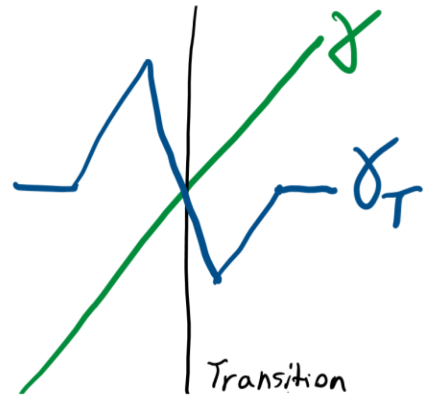
- Stabilize beam orbit near transition.
- Synchronize γ_T-jump with transition-crossing (freq.-based timing).
- Adjust RF transition parameters to account for γ_{T}-jump.

Illustration of γ_T Jumps near Transition

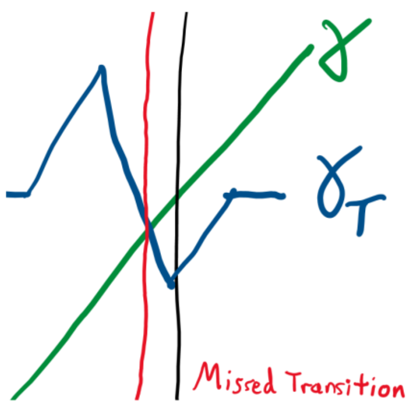
No Jump



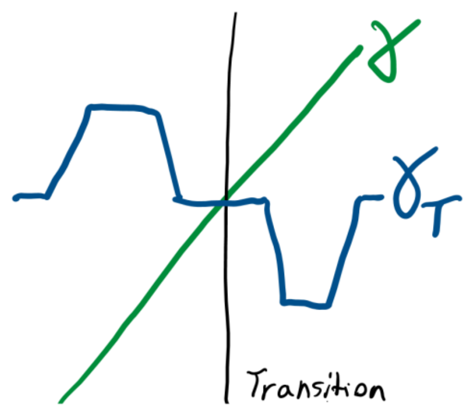
Well-timed Jump



Badly-timed Jump



Jump Tuning Range Study



Booster γ_T-Jump Systems

Chandra Bhat simulations in ESME,

Jean-Francois Ostiguy simulations in PyORBIT

This on-going simulation work requires:

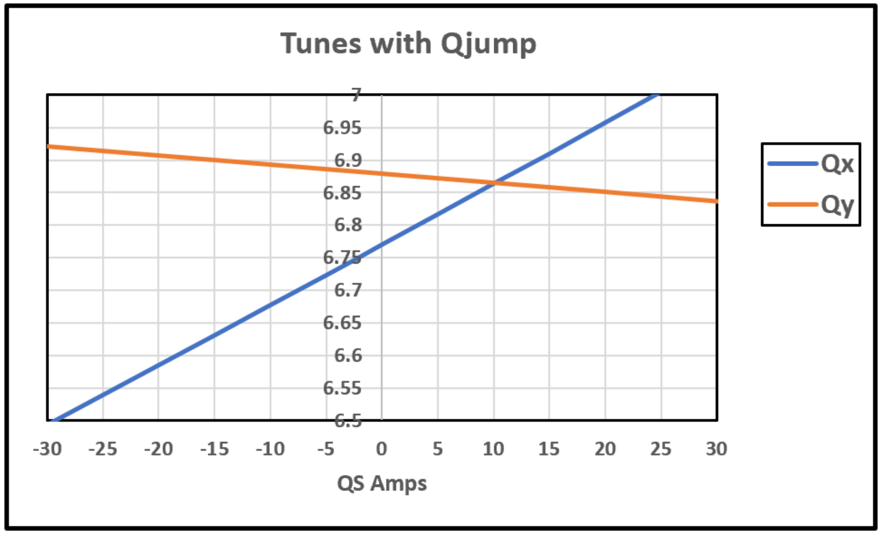
- voltage and phase-curves.
- linear and nonlinear phase-slip factors.
- accurate longitudinal particle distribution.
- RF feedback and damper systems.
- space-charge and impedance effects at transition.
- validating against existing Booster transition-crossing observations.
- quantifying impact of 20 Hz ramp, higher intensity.

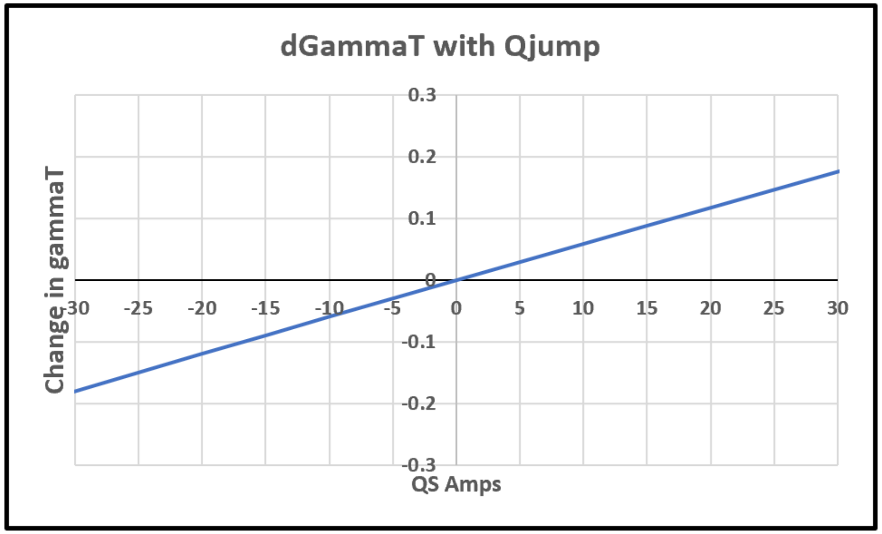
Likely benefits of Q-jump or a resonant γ_T –jump system for transition:

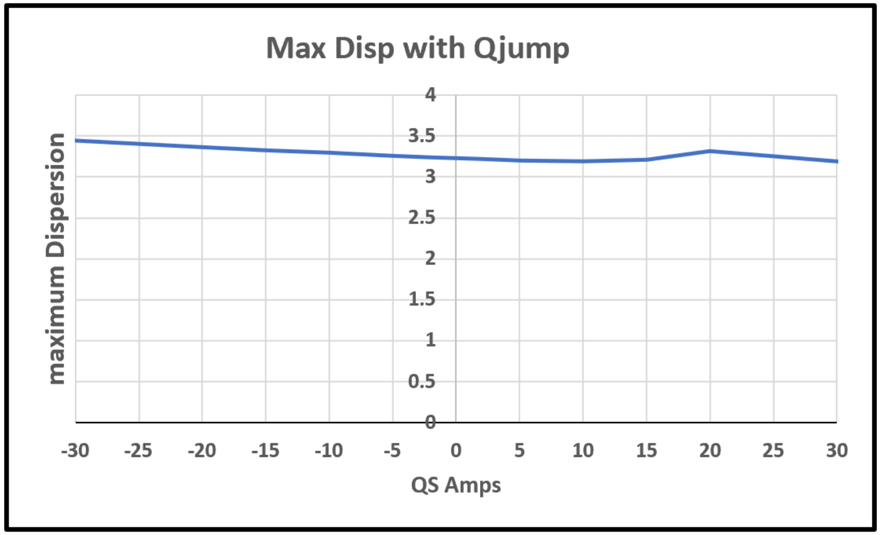
1) Reduce direct loss from RF bucket.
2) Reduce collective instabilities which occur at transition.
3) Reduce longitudinal emittance growth (exacerbates slip-stacking later).

Plan to implement Q-jump and go from there.

Q-Jump Transverse Effects – Tunes, γ_T, Dx







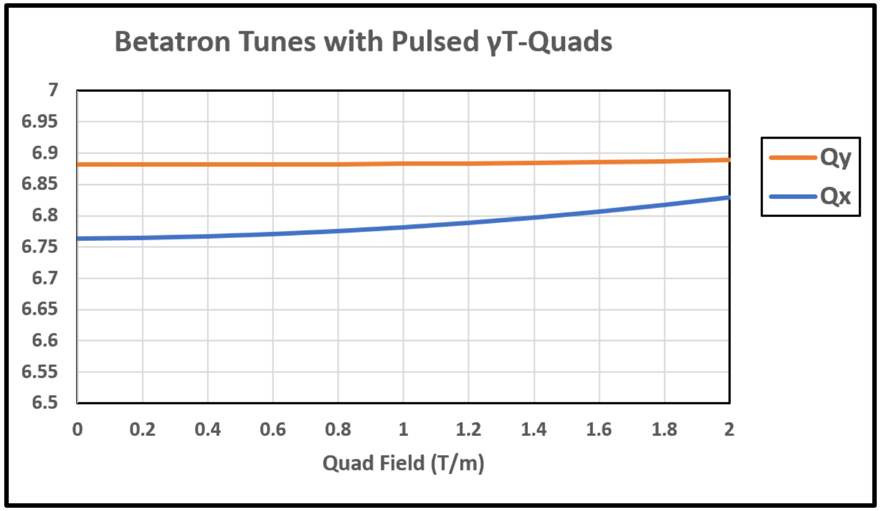
Studies show we can only operate with QS between about -15 and +10, resulting in a 0.1-0.2 γ_T, unit jump.

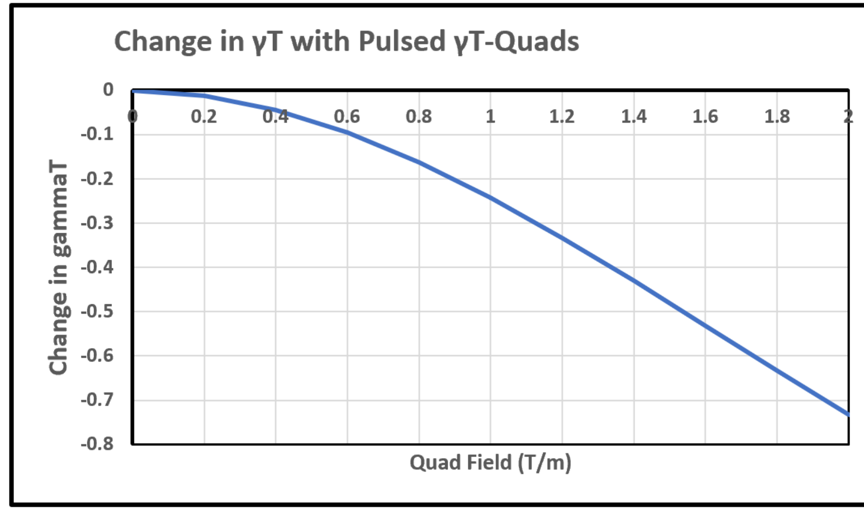
Still working on longitudinal aspects for operationalizing Q-jump system.

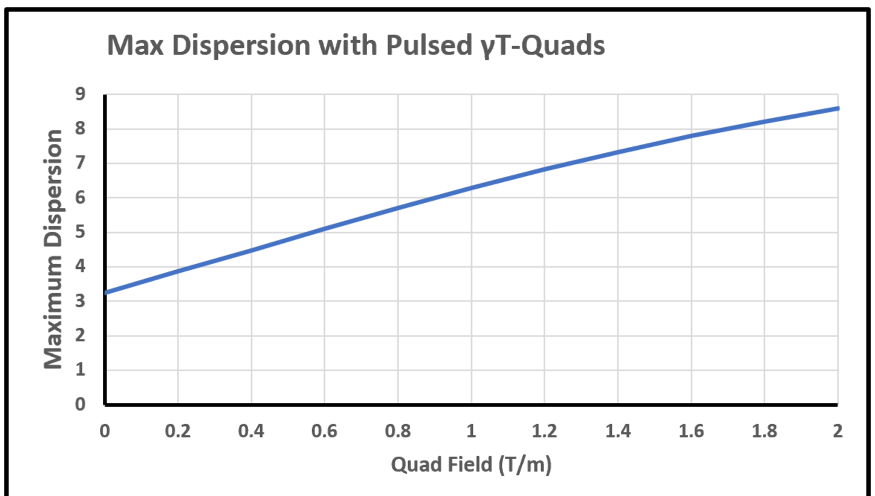
Larger jump requires resonant γ_T jump.

Fermilab

Resonant γ_T Jump Transverse Effects – Tunes, γ_T, Dx







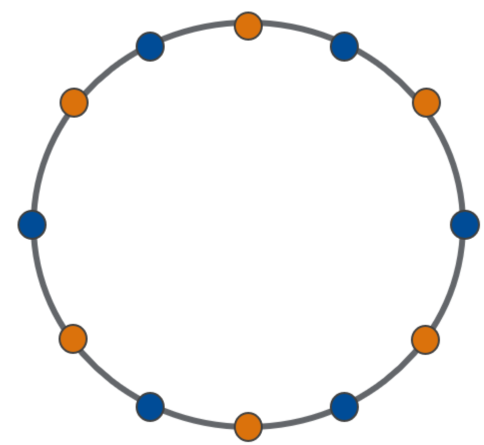
Aperture-scans near transition-crossing will be carried out to verify that the lattice can accommodate this dispersion (and to optimize the location).

Fermilab

Locations for γ_T jump System

24cm in every Booster short-straight section.

Uses 12 of 24 Booster short-straight sections:



Field strength and aperture requirements for Booster γ_T quads similar to MI γ_T quads. Although Booster location requires shorter quads.

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PAR Lattice Design
and Transverse dynamics

J. Eldred

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Acknowledgements

Presenting some work by:

John Johnstone developed the PAR lattice design I will present.

Ben Simons is an NIU PhD student working on the analysis of apertures and nonlinear resonances for PAR.

Other contriburions to this presentation:

Dave Johnson is leading PIP-II injection design.

Cheng-yang Tan provided 3D renderings and also coordinates efforts as head of Proton Source.

Bill Pellico leading PAR design effort.

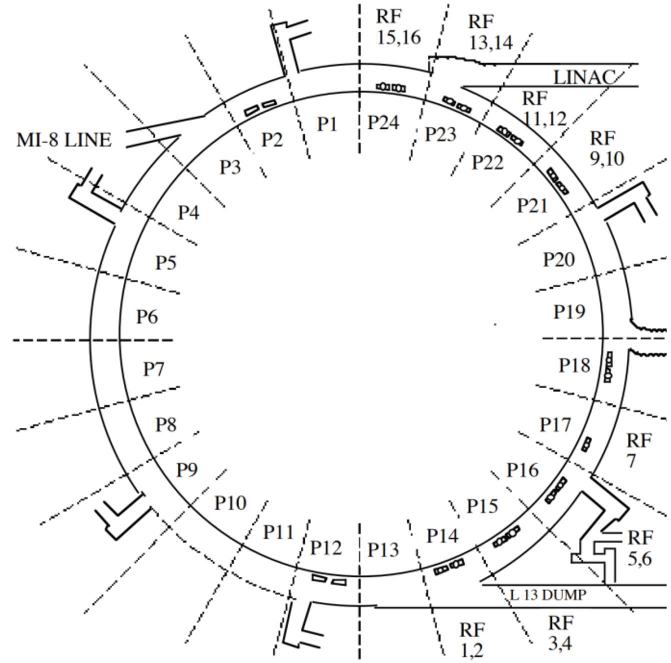
PSR & Booster

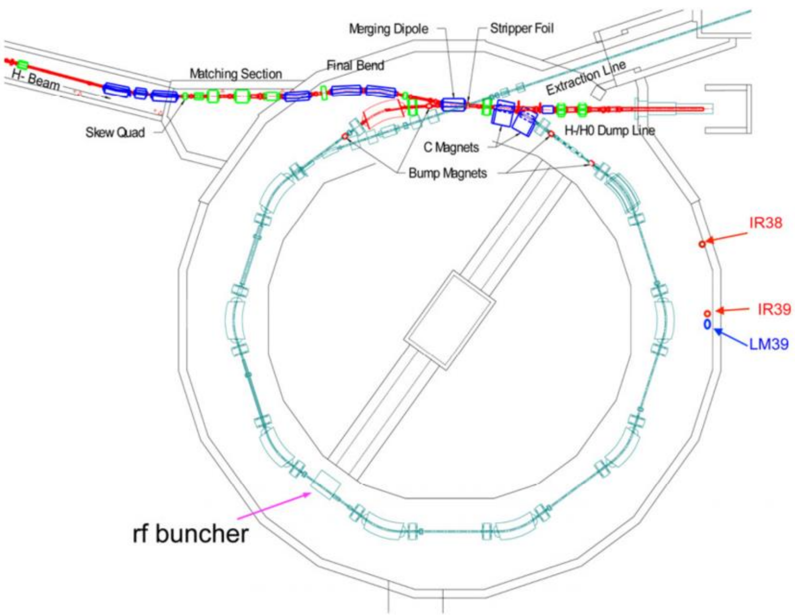
1970: Fermilab Booster

PIP-II Booster 17 kW inj, 160 kW extr.

24-sides, originally 5.7m dipole-to-dipole

to be modified to 6.7m dipole-to-dipole





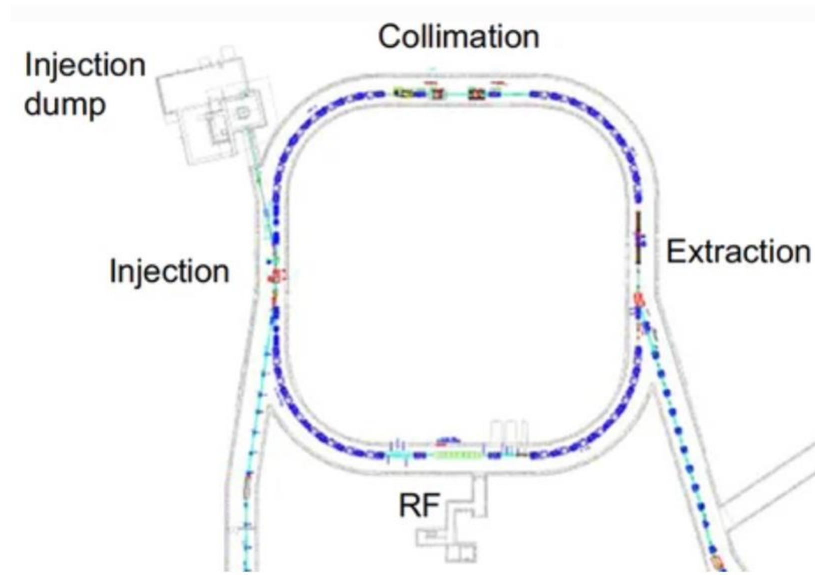
1985: Los Alamos PSR

currently 100 kW

10-sides, ~6m dipole-to-dipole

(first dipole bend is modified to large aperture)

SNS & J-PARC

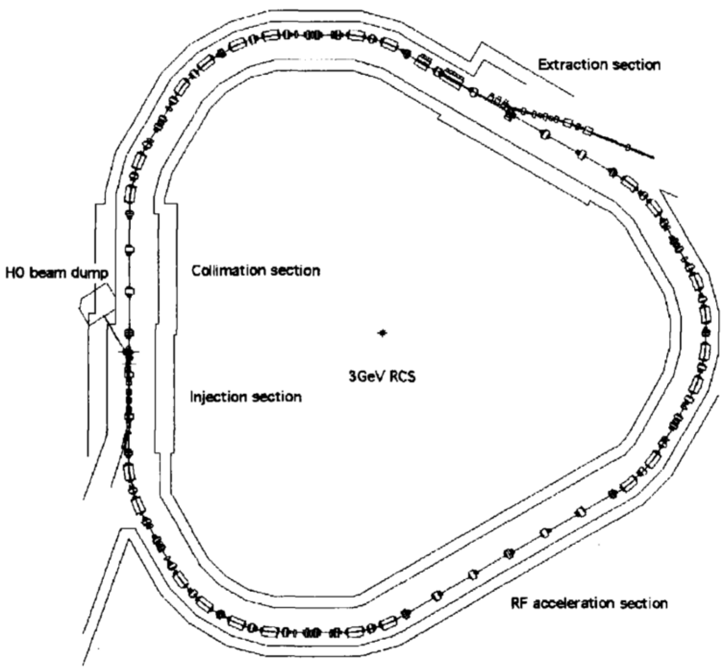


2006: Oak Ridge SNS

currently 1.4 MW

4-sides, 30m dipole-to-dipole

11m uninterrupted injection straight



2007: J-PARC RCS

currently 110 kW inj, 800 kW extr.

3-sides, 46m dipole-to-dipole

8m uninterrupted injection straight

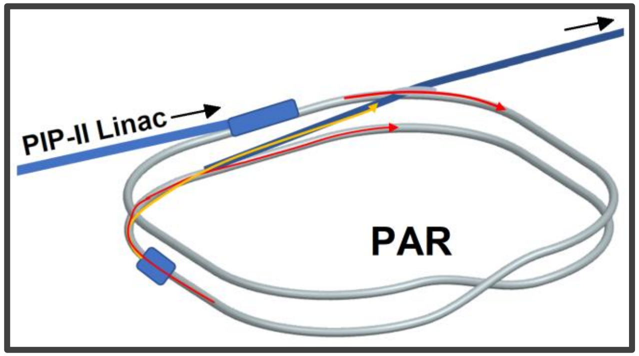
Proposed Fermilab PAR

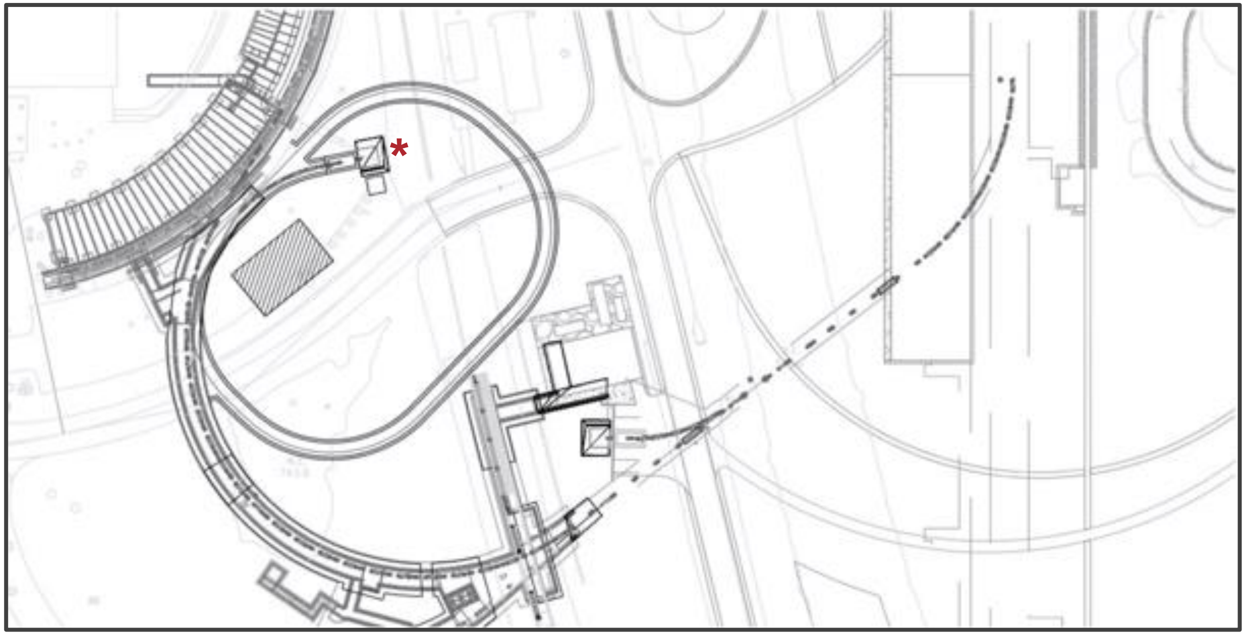
Fermilab PAR

at least 100 kW

racetrack, 28m dipole-to-dipole

10m uninterrupted injection straight



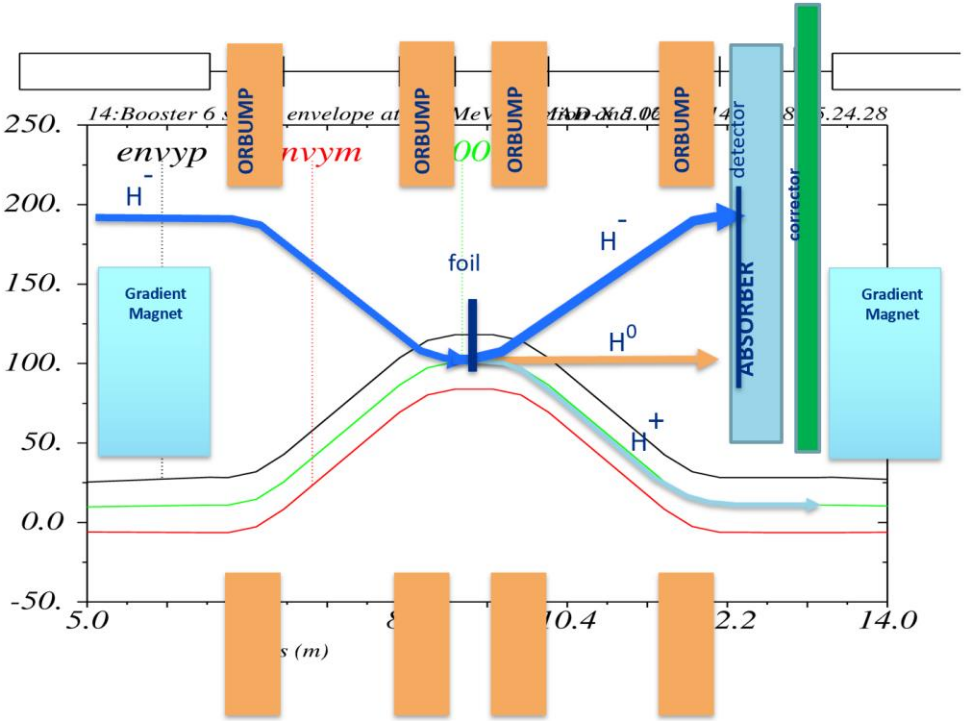


*injection dump will be straight-ahead not the interior of the ring.

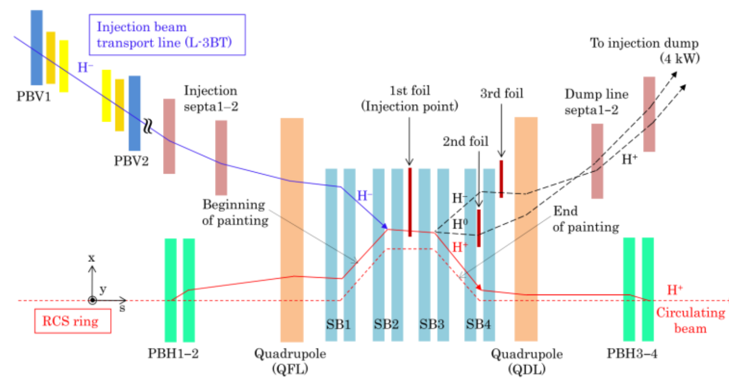
PAR is consistent with modern design strategy for powerful linacs.

Improvements vs. PIP-II Booster Injection Section

PIP-II Booster Injection Chicane (D. Johnson Dec 2020)



J-PARC RCS Injection Chicane



PIP-II Booster has 7.5 m for 800 MeV H$^-$ beam which is a tight fit.

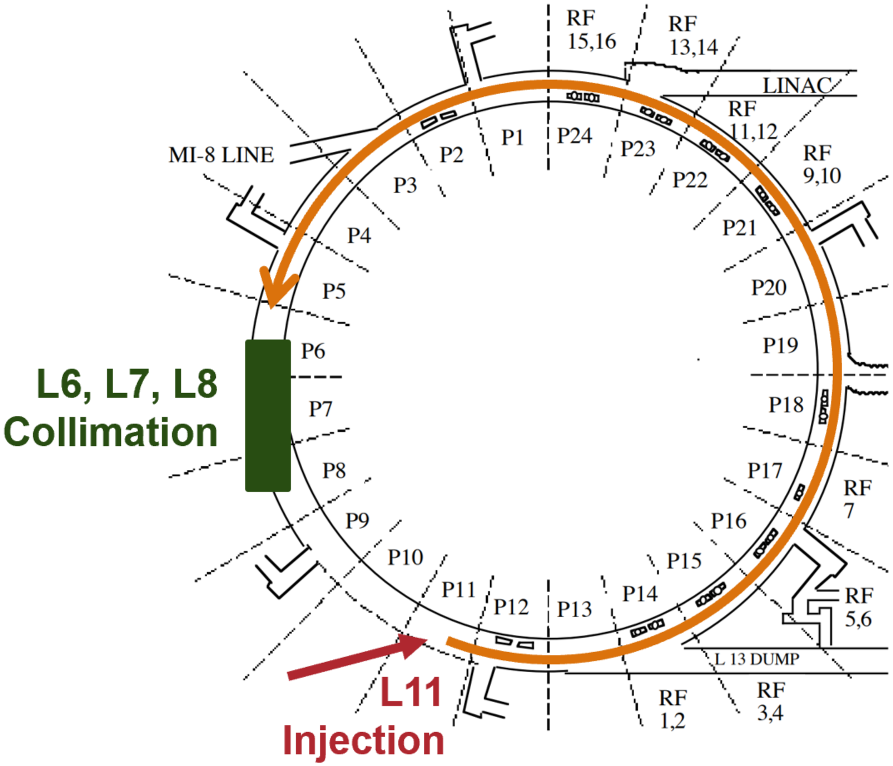
unstripped H$^-$ go to inline absorber (although BTL collimators try to mitigate).

SNS & J-PARC instead extract the H$^-$ particles to an external absorber.

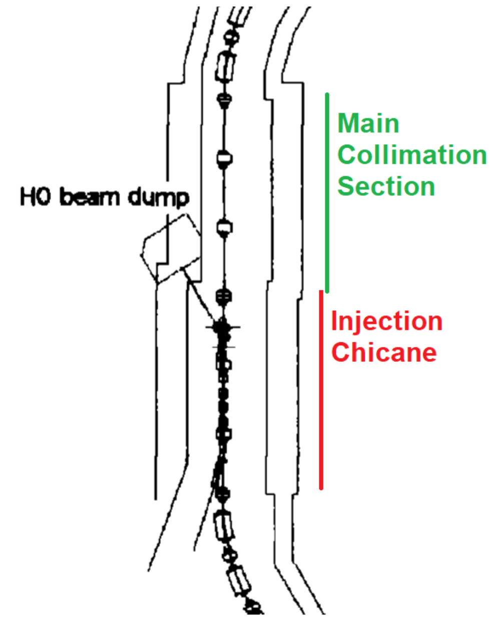
PAR would have at least 10m uninterrupted straight, another ~9m before dipole

Improvements vs. PIP-II Booster Injection Section

PIP-II Booster Injection & Collimation



J-PARC RCS Injection & Collimation



PIP-II Booster beam into L11 must circulate around ring before collimation.

SNS has collimation 1/4 around ring (after first bend section).

J-PARC has collimation immediately following injection.

PAR would also have collimation immediately following injection.

Modern Lattice Features

10m uninterrupted injection straight

- ability to safely extract unstripped H- particles.
- injection chicane suitable for higher energy beams (at least 1 GeV.)

28m dipole-to-dipole injection straight with **~π/2 phase-advance**

- real estate for collimation downstream of injection.

No combined function magnets or extreme edge-focusing dipoles.

- reduces field-errors, improves tuning, prevents electron cloud instability.

Dispersion-free straights

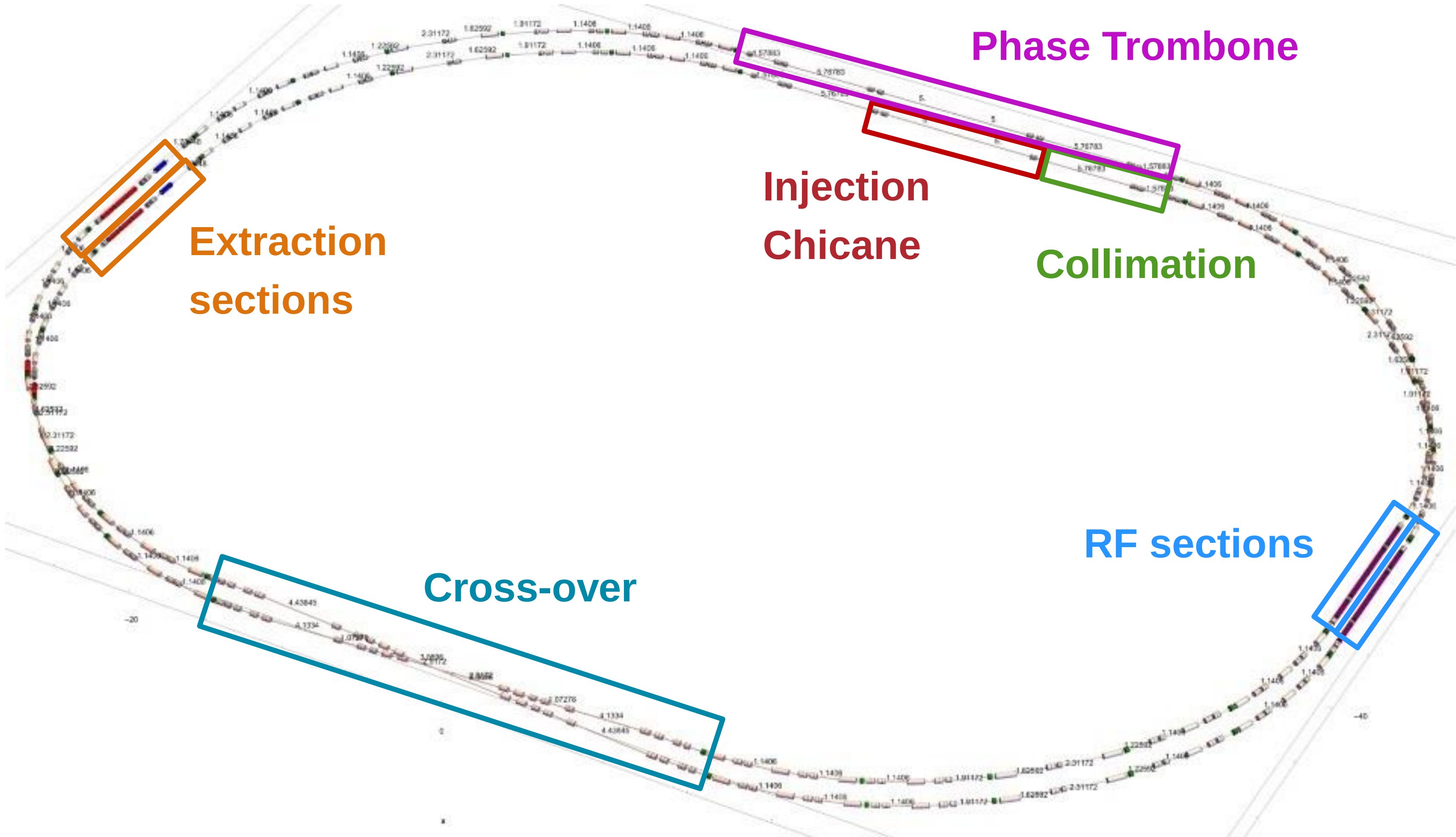
- no beam loss due to syncho-beta coupling resonances.
- ability to separate longitudinal and transverse degrees of freedom.

Two extraction straights, with ππ/2 between kicker and septum.

Real estate for RF, correctors and diagnostics.

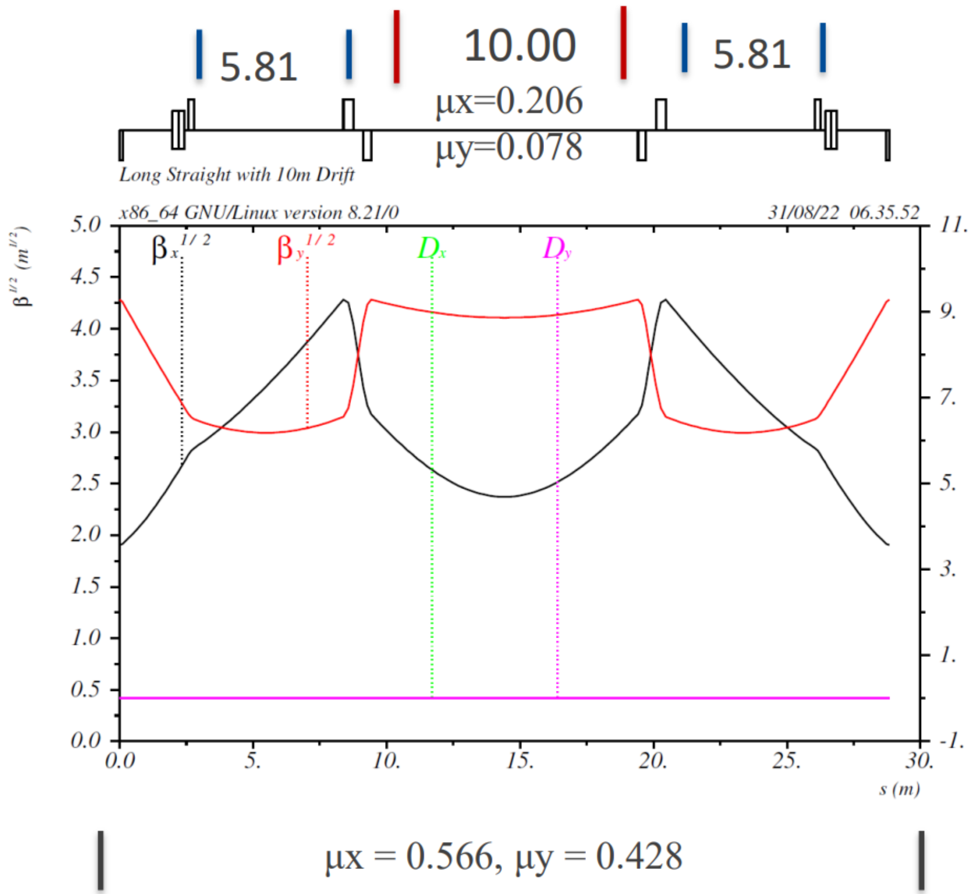
Sextupole π-pairs for mitigation of third-order resonances.

PAR Locations



CY Tan

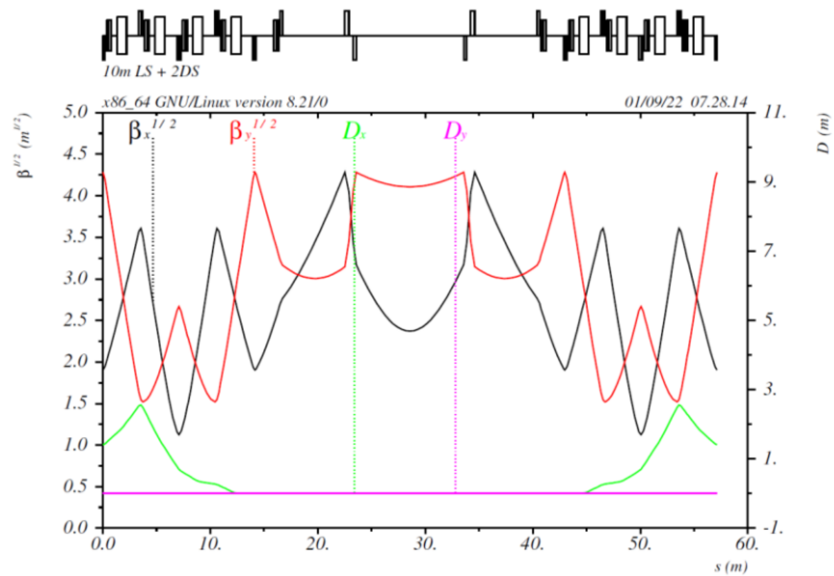
Long Injection Straight



10m uninterrupted straight section for injection chicane allows extraction of unstripped H^-

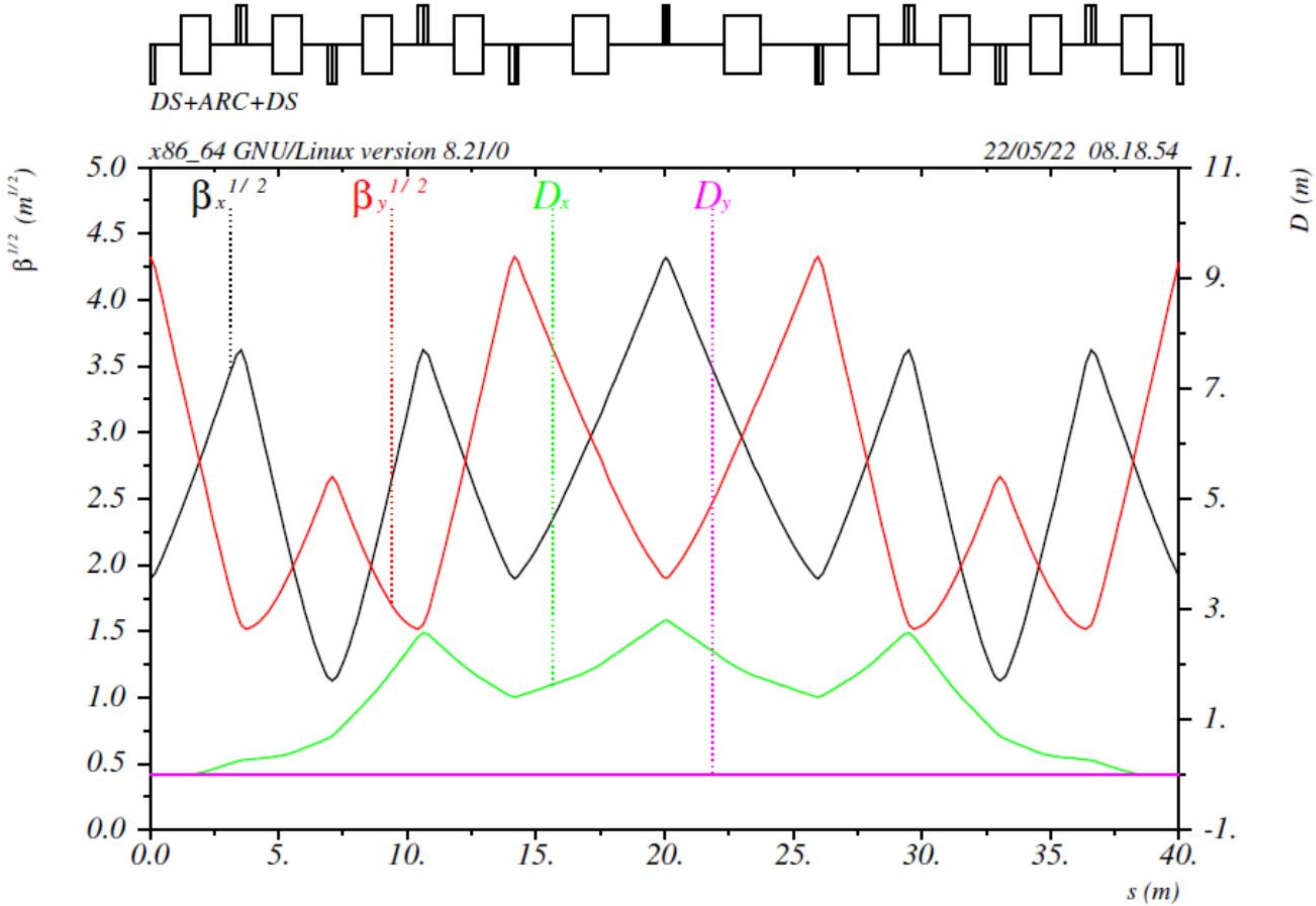
Following 5.8m allows collimation.

Also sufficient real estate for painting & corrector magnets.



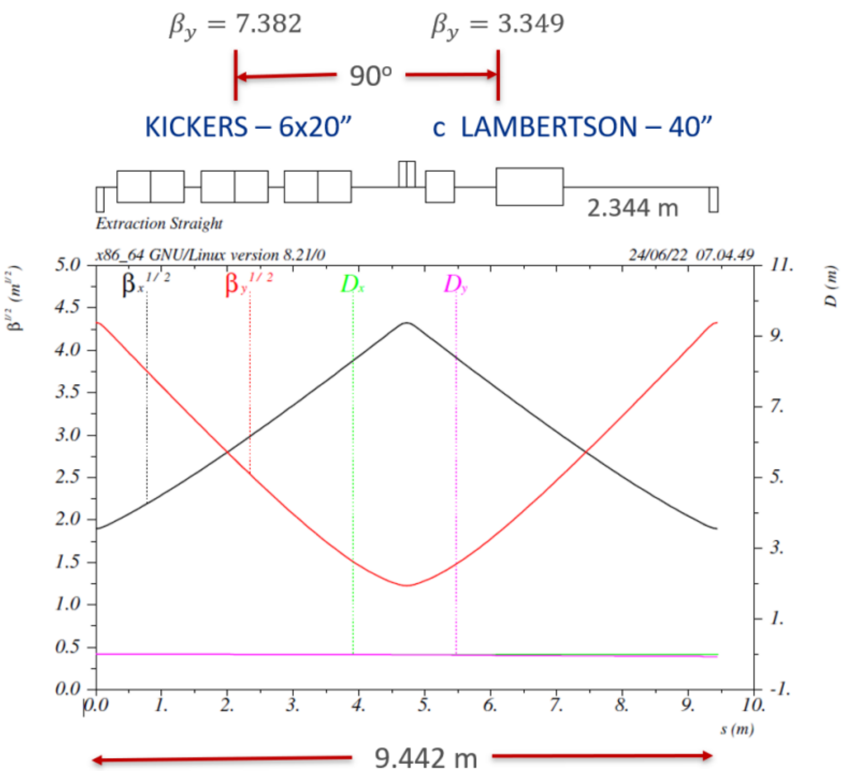
John Johnstone

Dispersion Suppressors + Arc Cell



John Johnstone

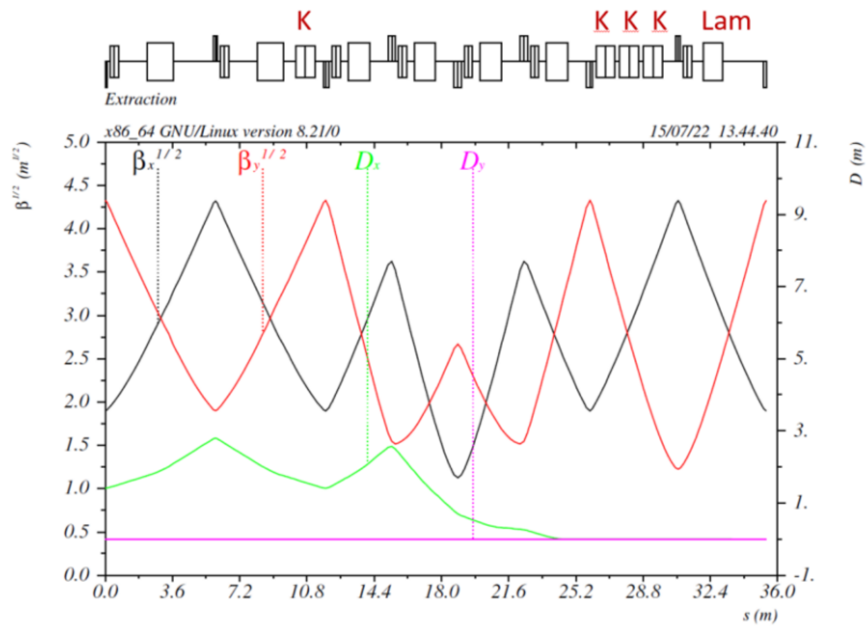
Short Straight for Extraction



π/2 phase advance from kicker to septa provides most efficient kick for extraction.

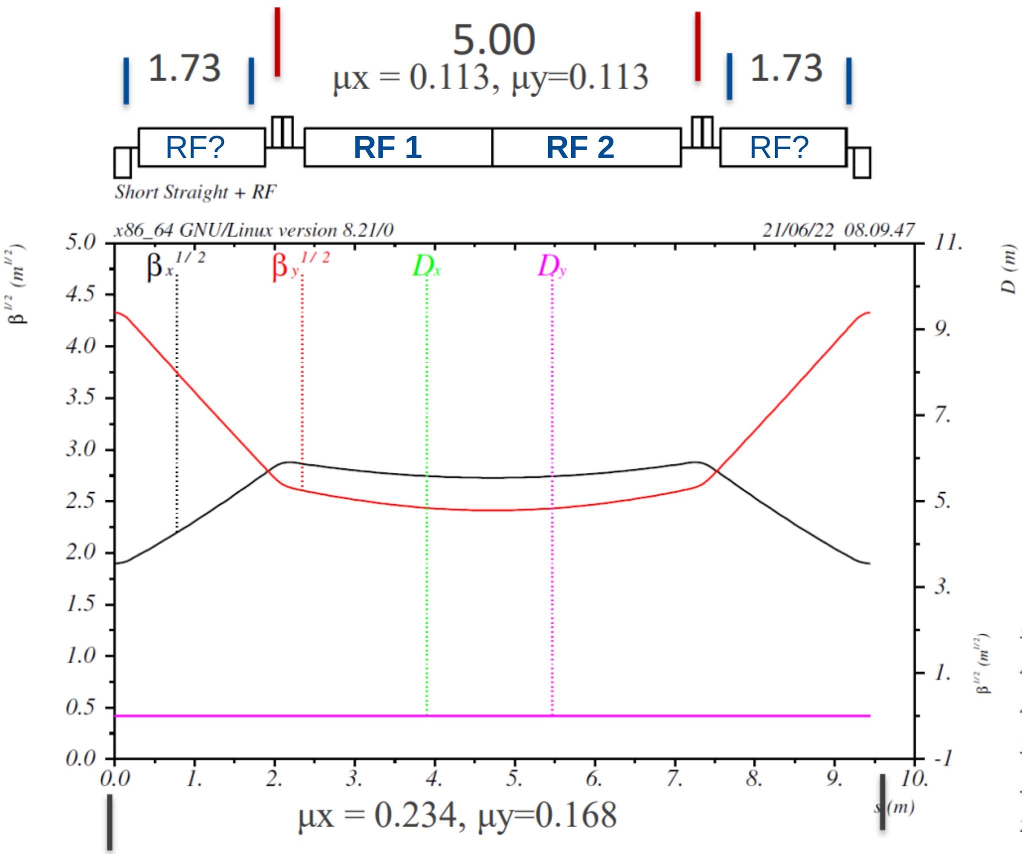
Space for fourth kicker if needed.

Option for two independent extractions.



John Johnstone

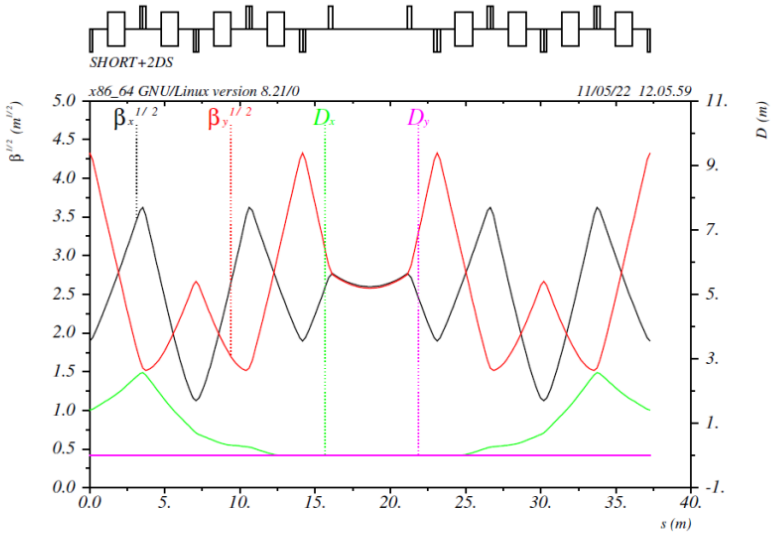
Short Straight for RF



Real estate for:

4 Booster-style RF cavities

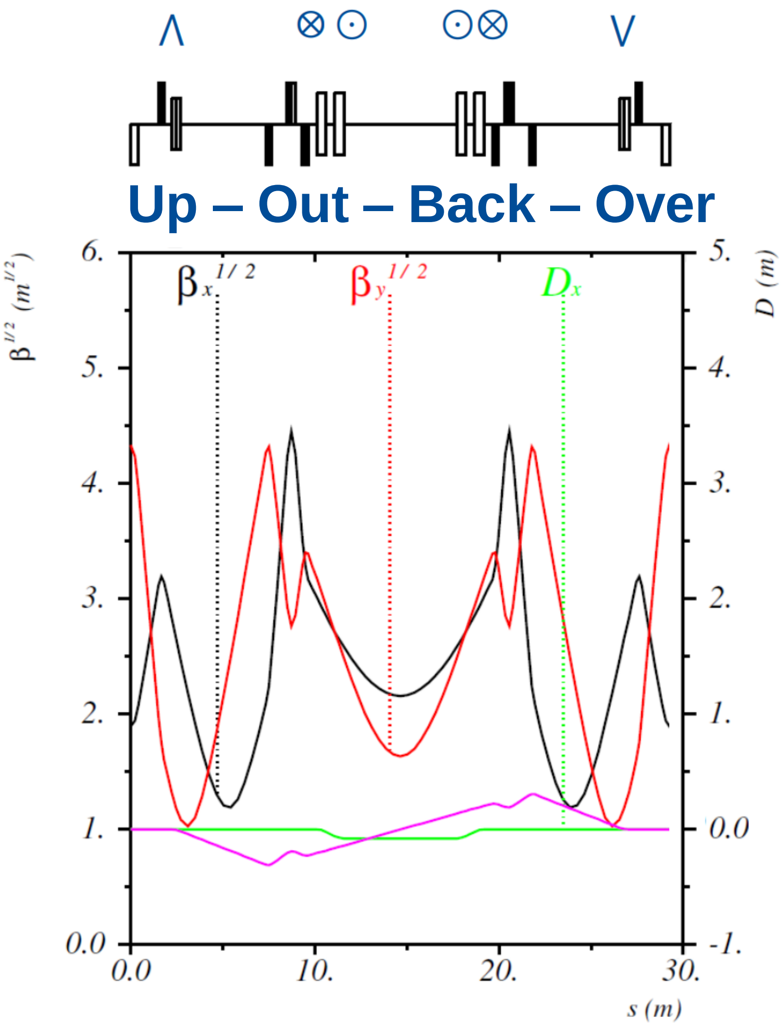
4 devices no more than 1.7m

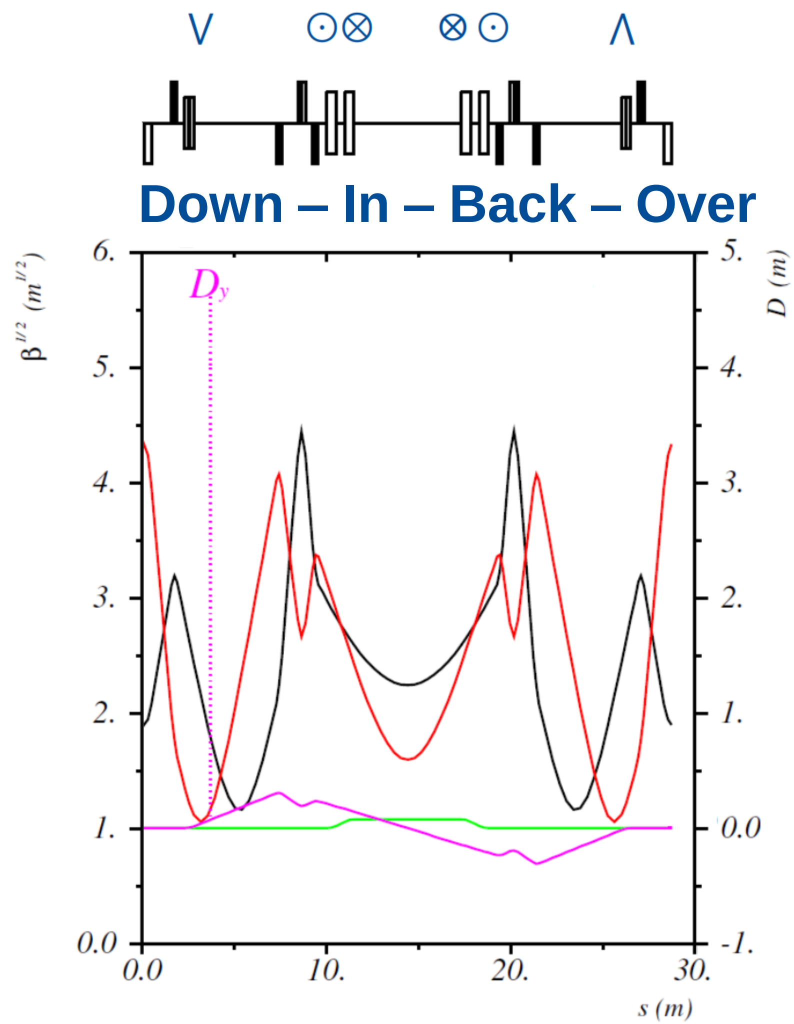


John Johnstone

Fermilab

Long Cross-over Straight (with 12" shift)



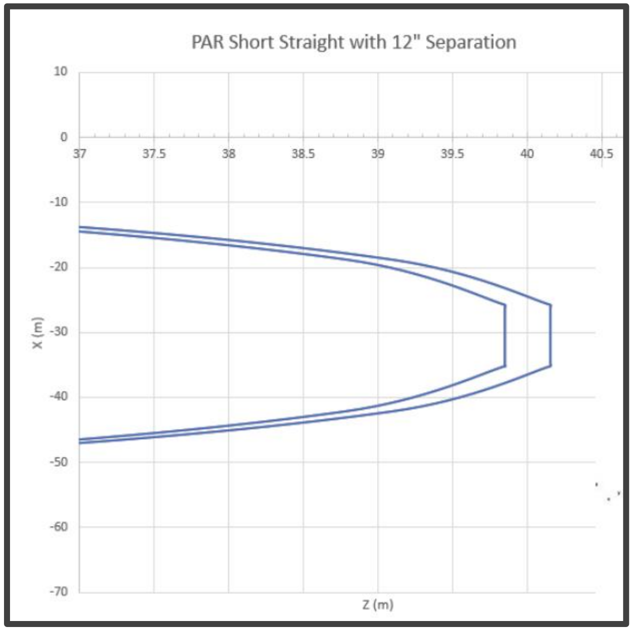


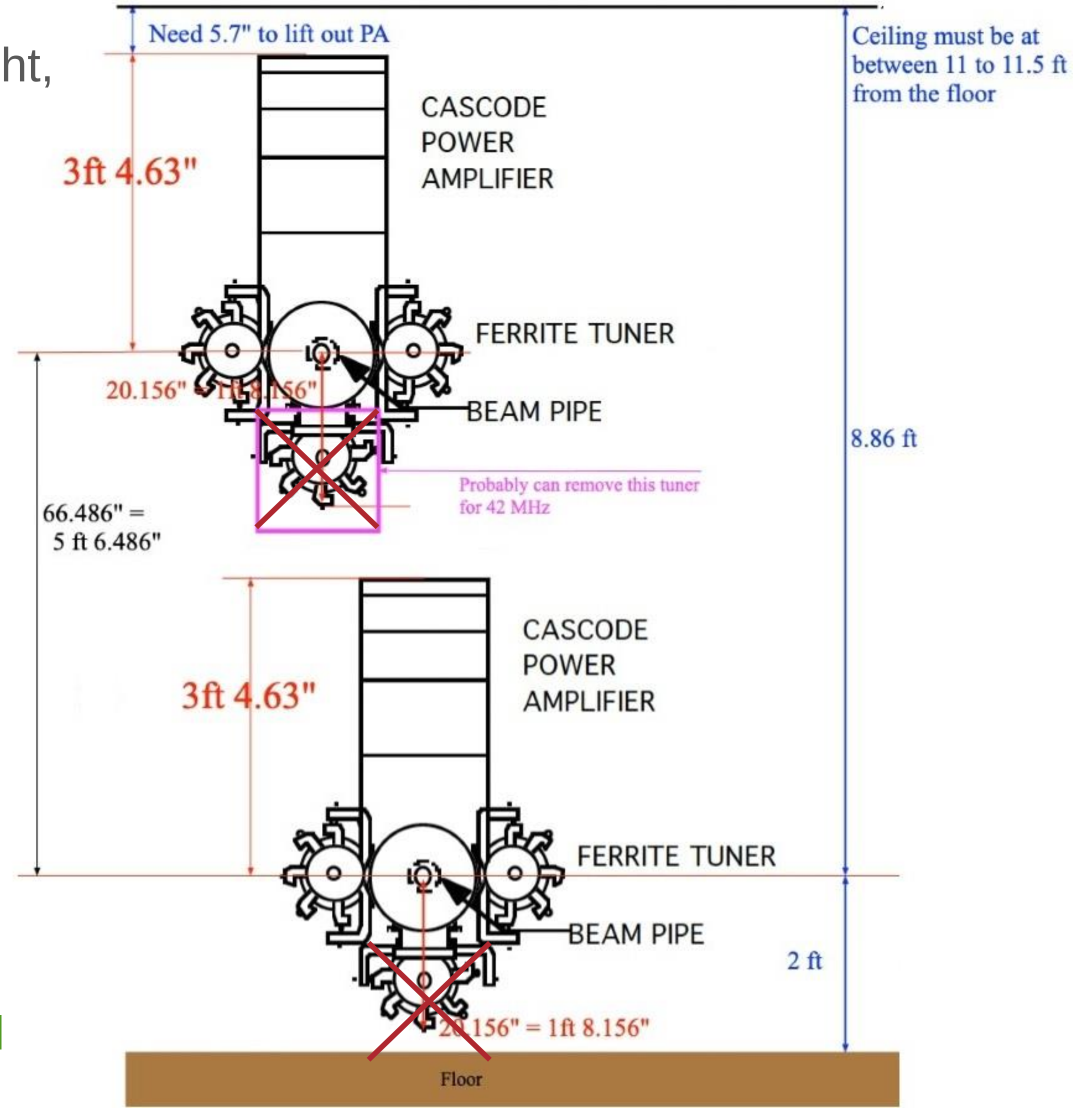
No shared beampipe required in cross-over region.

John Johnstone

Shift Impact on Short-straight

12” longitudinal shift in the long-straight, 12” separation in short-straights.



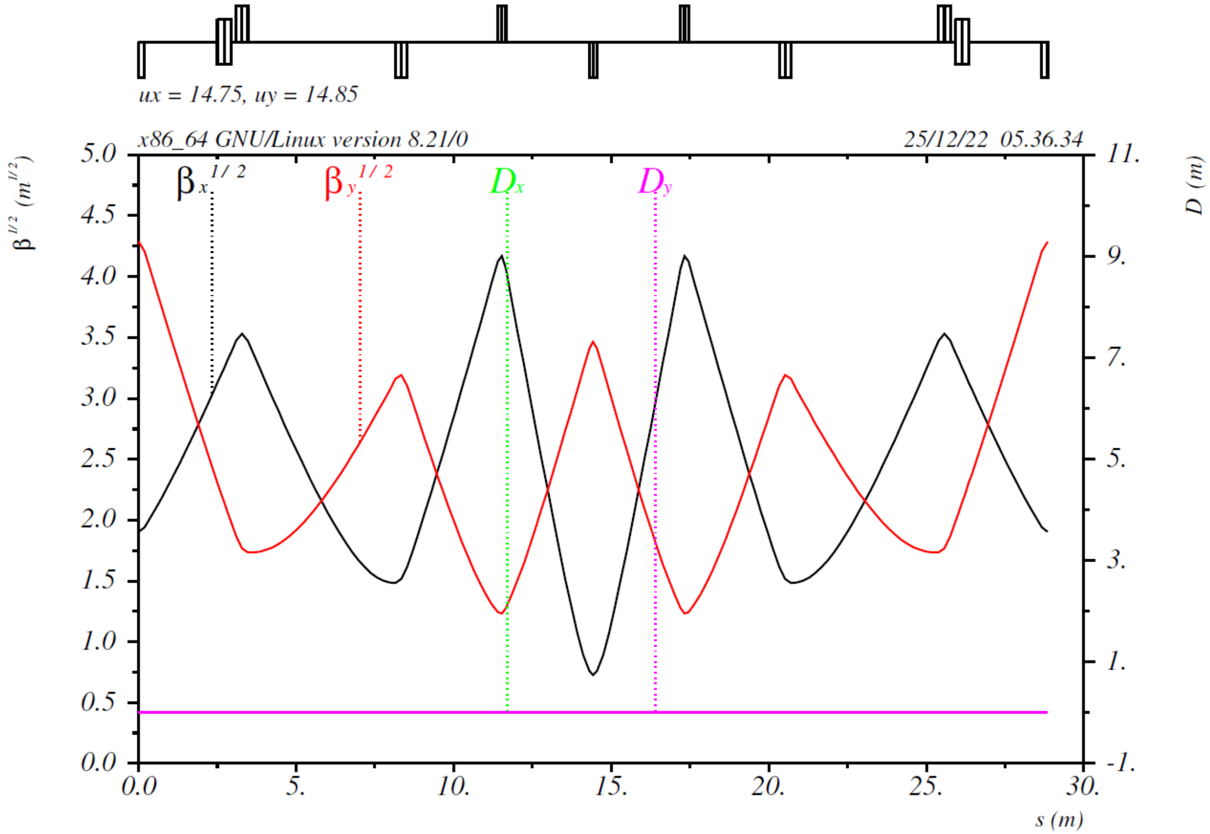


This helps create clearance for RF and in extraction regions.

Chandra’s talk will give more detail on main RF and DS-mode RF

Phase-Trombone Cell

John Johnstone



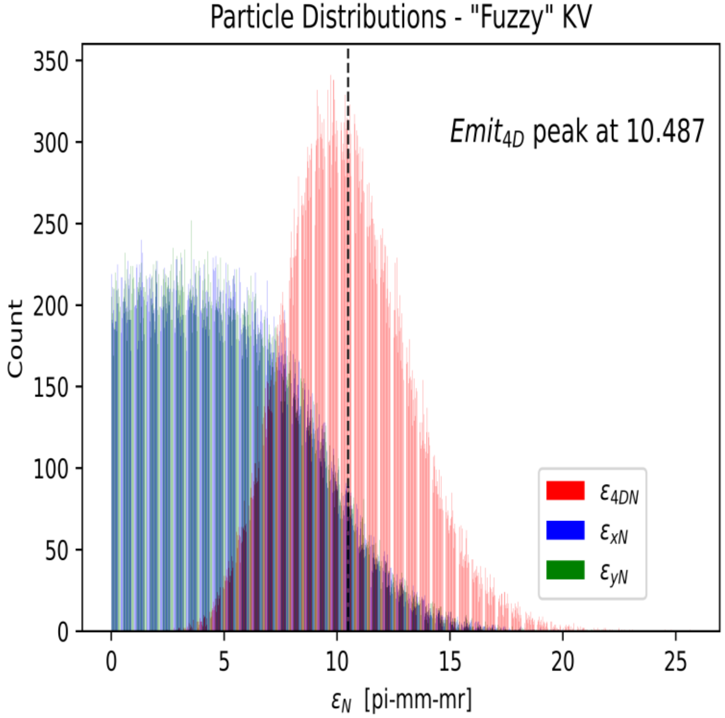
Seven quadrupoles allow tune to be changed +/- 75 degrees without impacting the beta functions at other location in the ring.

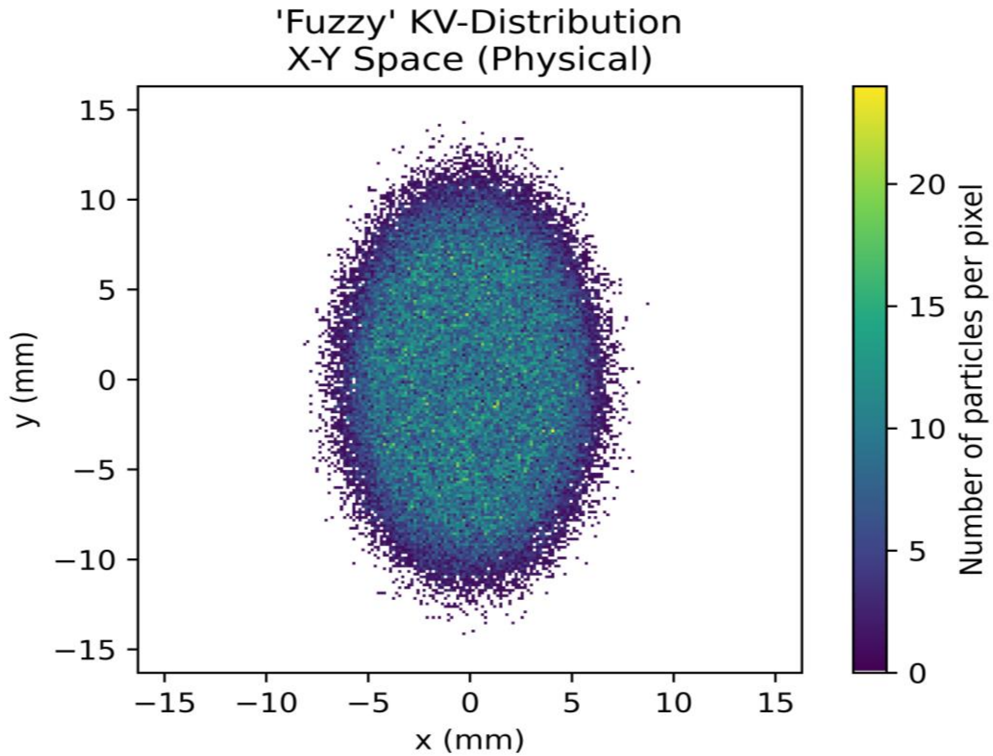
Fermilab Recycler currently operates with a phase-trombone.

Transverse Dynamics

Beam Distribution (after painted injection)

Ben Simons

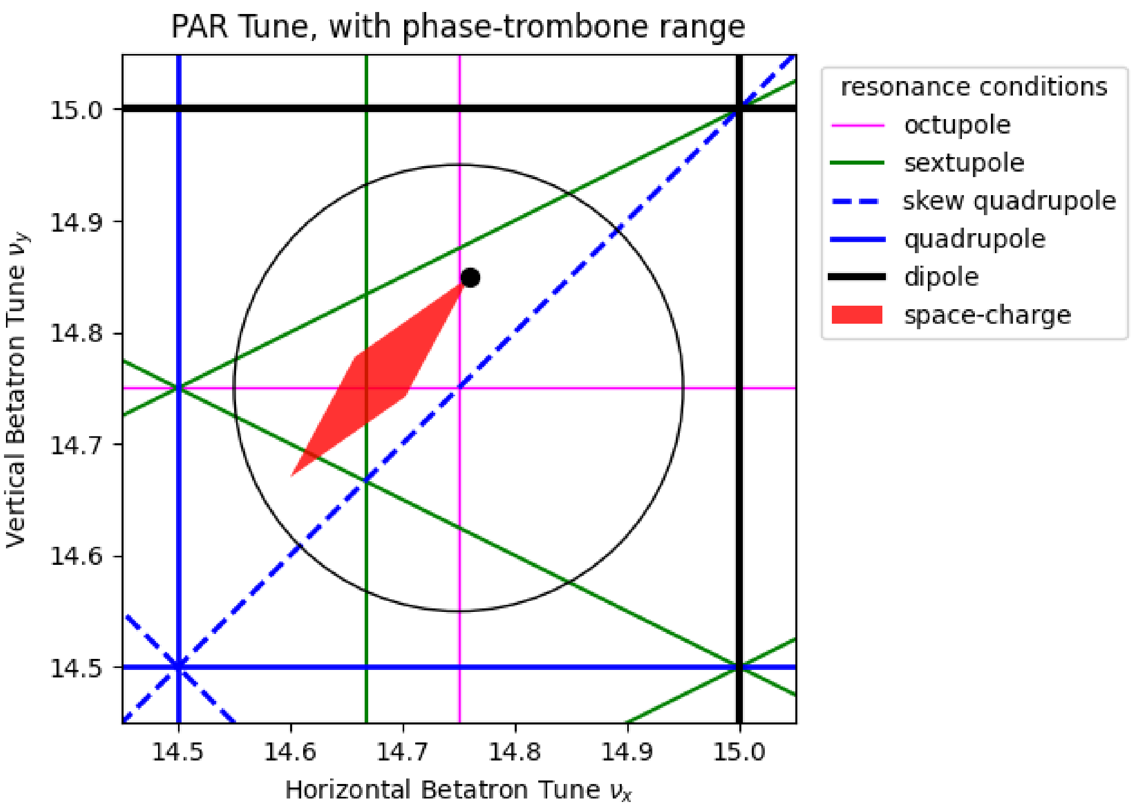




"Initial" beam distribution is well within +/- 40mm apertures (3.25" diameter)

- Nonlinear tracking simulations with full machine apertures is ongoing work.
- Dark Sector mode will be at least 50% larger.

PAR Tune Diagram



Space-charge footprint (sketch based on PIP-II Booster simulations).

- PAR avoids most dangerous quadrupole and dipole resonances.

Sextupole resonances is main focus of nonlinear correction.

Octupole, linear coupling, and skew-sextupole resonances will also be examined.

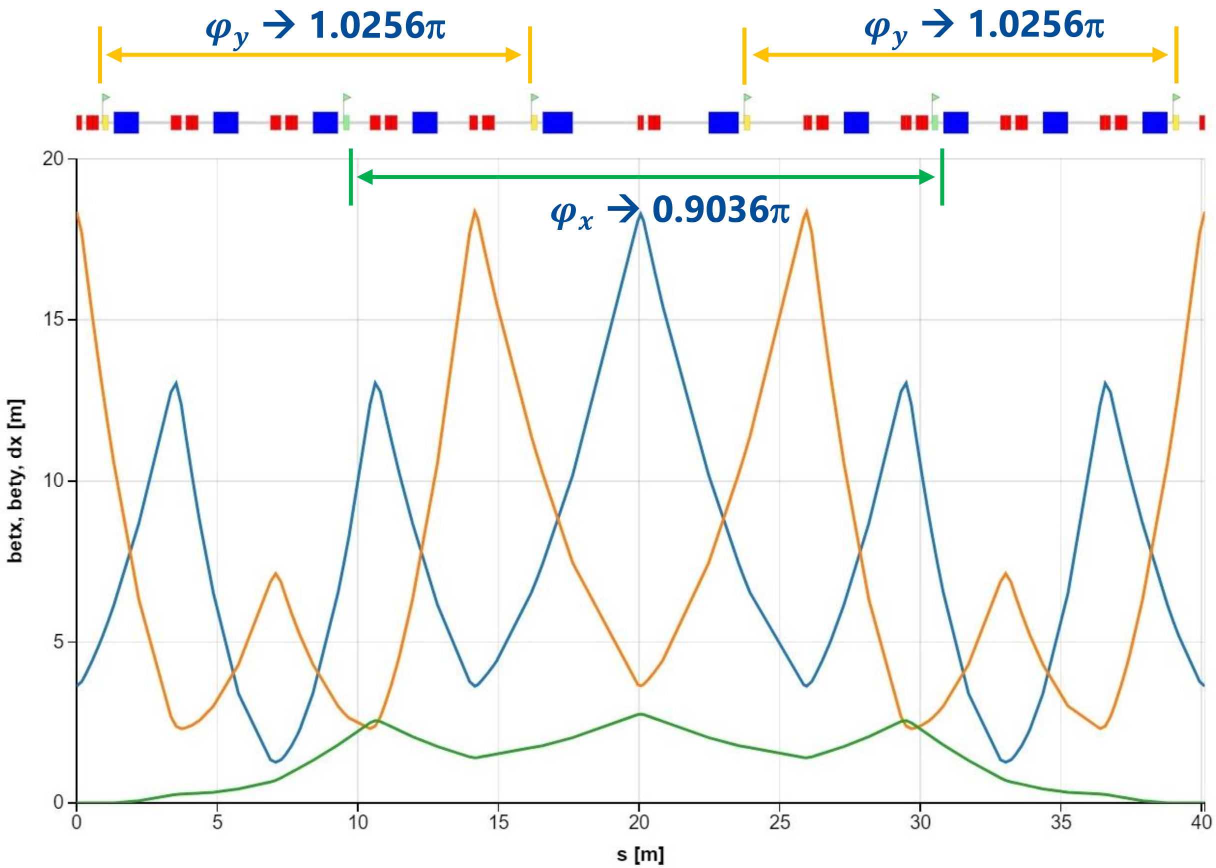
Sextupole Resonances

Ben Simons

2 Sextupoles for Horizontal Chromaticity

4 Sextupoles for Vertical Chromaticity

6 sextupoles x 8 arcs = 48 sextupoles, Organized in 2 families.



Currently the π-phase-advance and overall lattice symmetry suppresses the RDTs:

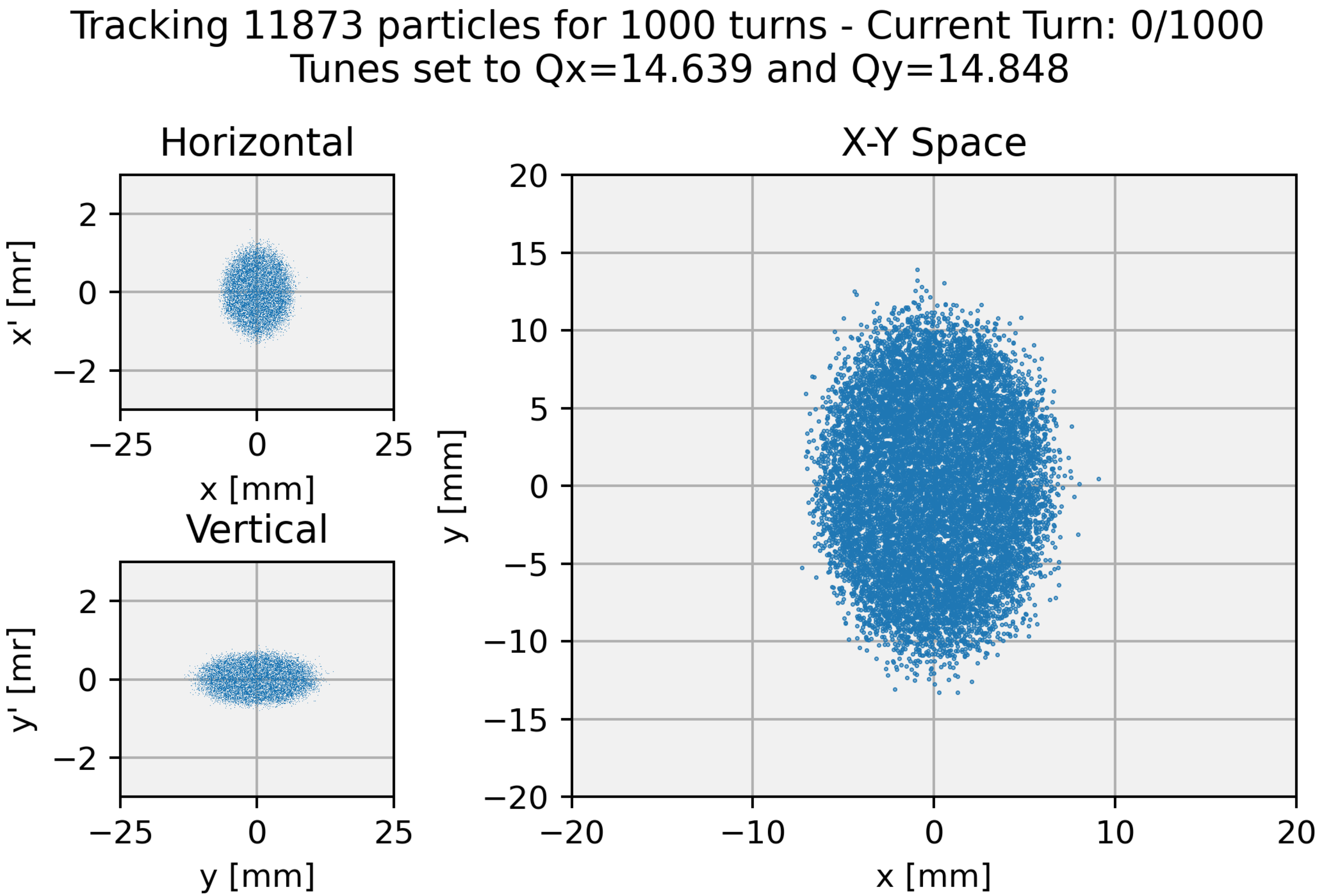
3Qx: 27% vs typical

Qx-2Qy: 6% vs typical

Qx+2Qy: 23% vs typical

Preliminary Tracking with Sextupoles is Stable

Ben Simons



Dark-Sector Mode Operation

Booster-mode operation is **6.5e12 intensity**, **20-Hz rep. rate.**

and **16 pi mm mrad 95% normalized emit.**

PIP2BD-mode operation can be **50-60 Hz**, and **24-32 pi mm mrad.**

- With the same space-charge (and also within foil scattering limits) PAR should be able to support 10-15e12 intensities.
- A further factor of x1.5 is possible with 1 GeV upgrade.

PIP2BD-mode operation will request shorter pulses (200-500ns full-width) using bunch-rotation, which may require using only 50-70% of that intensity

(i.e **5-10e12 at 0.8 GeV** or **7.5-15e12 at 1.0 GeV**).

- Simulation and analysis of bunch rotation case is ongoing.

Outlook

Preliminary considerations of transverse optics looks strong:

- Fits at BTL location with F-sector crossings.
- PAR greatly improves on PIP-II Booster injection optics.
- Siting and optics for RF, cross-over, collimation, extraction well-developed.
- PAR will encounter the same resonances as PIP-II era Booster.
    -- strategy for addressing sextupole resonances.
- PAR beam size generously fits within the larger aperture, with smaller max betas.

Tracking studies to investigate risks:

- Using additional sextupole correction circuits to avoid resonances.
- Finding the tolerances for dipole and quadrupole errors

Simulations to investigate upside potential:

- Booster will be limited by injection duration, PAR only limited by performance.
- How short and intense of a beam can be deliver to PIP2-BD program?
- Novel beam dynamics? self-consistent angular-momentum dominated beams
    - see 2022 SNS SpaceCharge workshop.