LANSCE 800 MeV H^- Transport and Injection

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H^- Injection Mini-Workshop,

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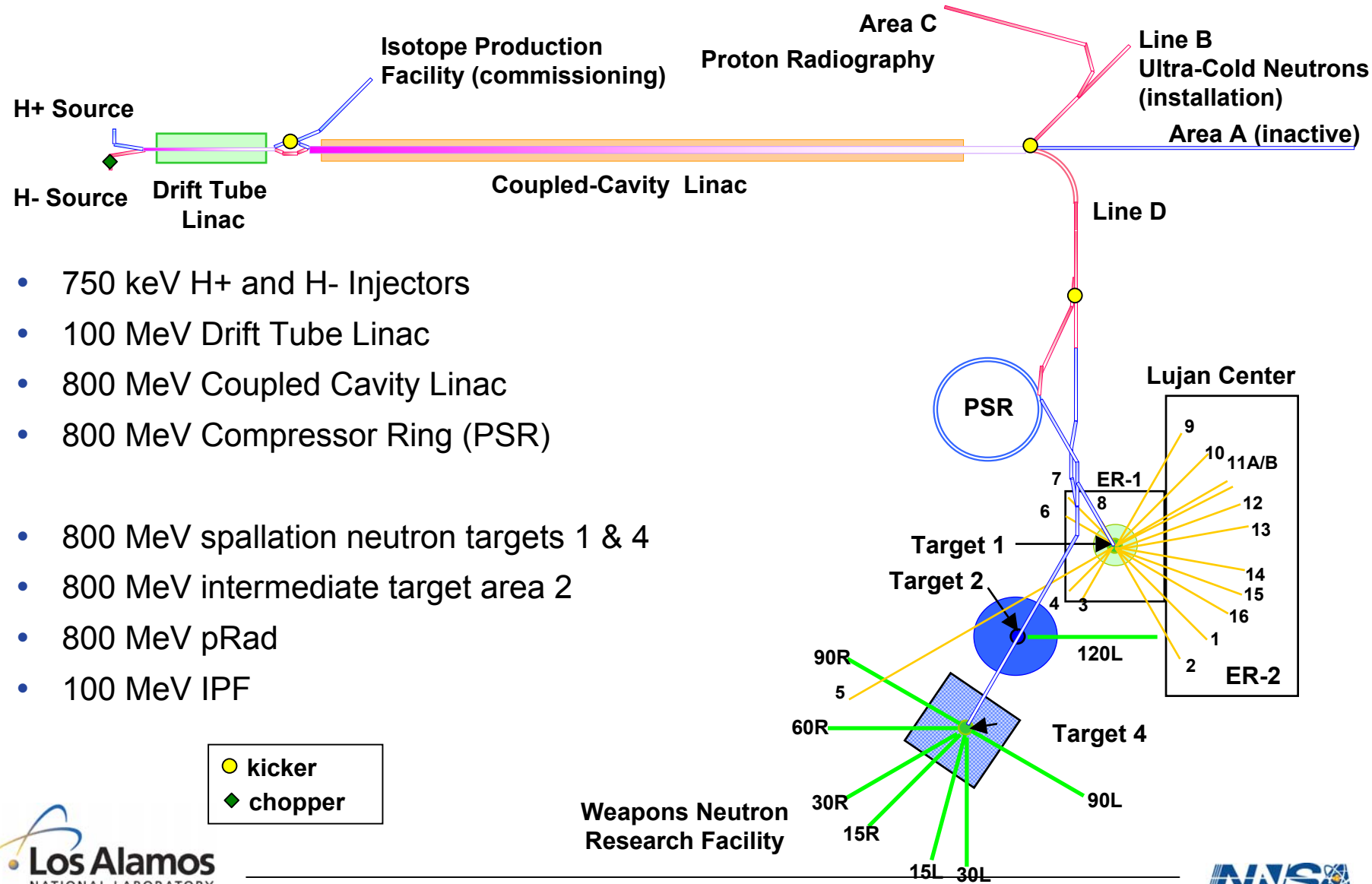
Outline

- LANSCE Overview
- 800 MeV H^- Beam from the LINAC
- H^+ Beam from PSR
- From Ring Injection Kicker to Stripper Foil
- Ring Injection
- Beam Dump
- Summary

LANSCE Overview



- 750 keV H+ and H- Injectors
- 100 MeV Drift Tube Linac
- 800 MeV Coupled Cavity Linac
- 800 MeV Compressor Ring (PSR)

- 800 MeV spallation neutron targets 1 & 4
- 800 MeV intermediate target area 2
- 800 MeV pRad
- 100 MeV IPF

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H^- Beam from the LINAC

- R. Macek found that measured profiles (transverse and longitudinal) of H^- Beam from the LINAC can be fit to a combination of a *narrow* and a *wide* Gaussian.
- Simultaneous least-squares fit of measured profiles (including wire scanner in 89^o bend - high dispersion) includes beam transport equations from linac to each wire scanner.
- D. Fitzgerald applied method to thirteen data sets taken during 1989-1998 and two sets taken in 2003.

H^- Beam from the LINAC

- The wide-beam Gaussians occupied on average 62% of the profiles and the emittance area for the wide beam was about 4 times that of the narrow beam.
- Apart from area, wide and narrow ellipses are quite similar, with overlap factors > 80%.
  $\Rightarrow$ Beams transport in same fashion!
- No systematic offset between centroids of wide and narrow beam.
- Some variation outside statistics was observed, likely due to variation in linac performance.

H^- Beam from the LINAC

- From Fitzgerald's compilation:.

Table 1. Average Beam Emittance Parameters in X-Plane (1989-1998 Data)

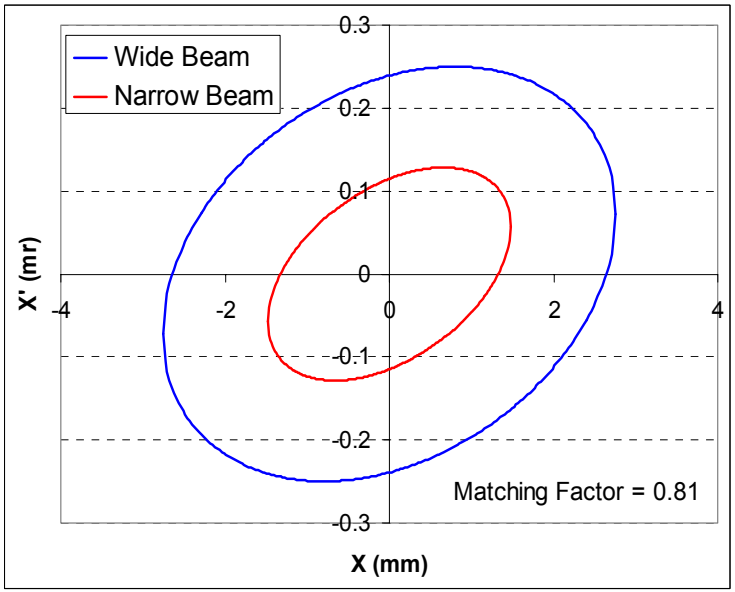
	X Wide Beam			X Narrow Beam		
Param.	**Value**	**Error**	**Std. Dev.**	**Value**	**Error**	**Std. Dev.**
x (mm)	2.8	0.3	0.3	1.5	0.4	0.3
r_{12}	0.27	0.08	0.22	0.37	0.35	0.24
x' (mr)	0.26	0.01	0.05	0.14	0.02	0.02
ε_x (π mm-mr)	0.68	0.08	0.11	0.18	0.10	0.05
α_x	-0.30	0.13	0.26	-0.50	0.70	0.54
β_x	11.5	2.5	2.6	12.9	11.4	4.5
γ_x	0.104	0.016	0.026	0.115	0.102	0.048
$\Delta p/p$ (%)	0.061	0.008	0.024	0.035	0.010	0.013
Matching Factor	0.86	–	0.03	0.80	–	0.06
F_W	62.2%	–	8.8%	37.8%	–	8.8%

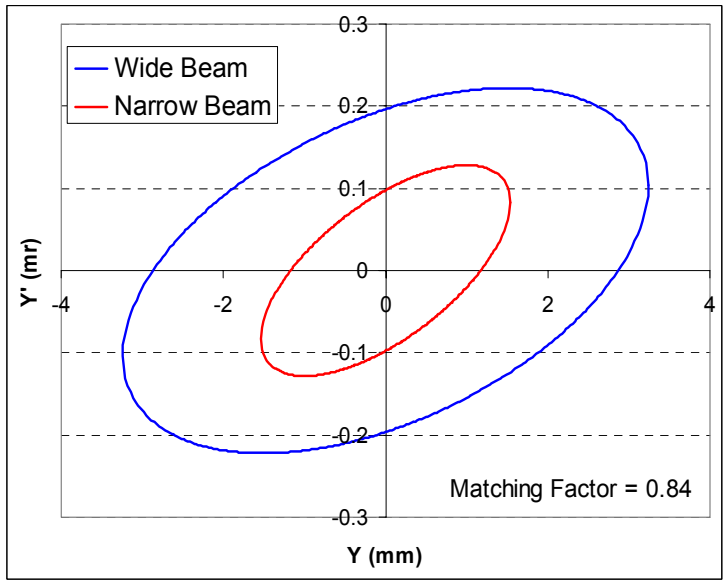
Table 2. Average Beam Emittance Parameters in Y-Plane (1989-1998 Data)

	Y Wide Beam			Y Narrow Beam		
Param.	**Value**	**Error**	**Std. Dev.**	**Value**	**Error**	**Std. Dev.**
y (mm)	3.2	0.1	0.3	1.5	0.2	0.2
r_{34}	0.45	0.09	0.16	0.64	0.26	0.10
y' (mr)	0.23	0.01	0.03	0.13	0.02	0.03
ε_y (π mm-mr)	0.65	0.06	0.11	0.16	0.02	0.06
α_y	-0.53	0.11	0.21	-0.85	0.16	0.21
β_y	16.5	1.9	3.0	15.7	4.6	2.3
γ_y	0.082	0.011	0.014	0.113	0.036	0.022
Matching Factor	0.89	–	0.03	0.89	–	0.02

H^- Beam from the LINAC

- Beam ellipses based on average values:



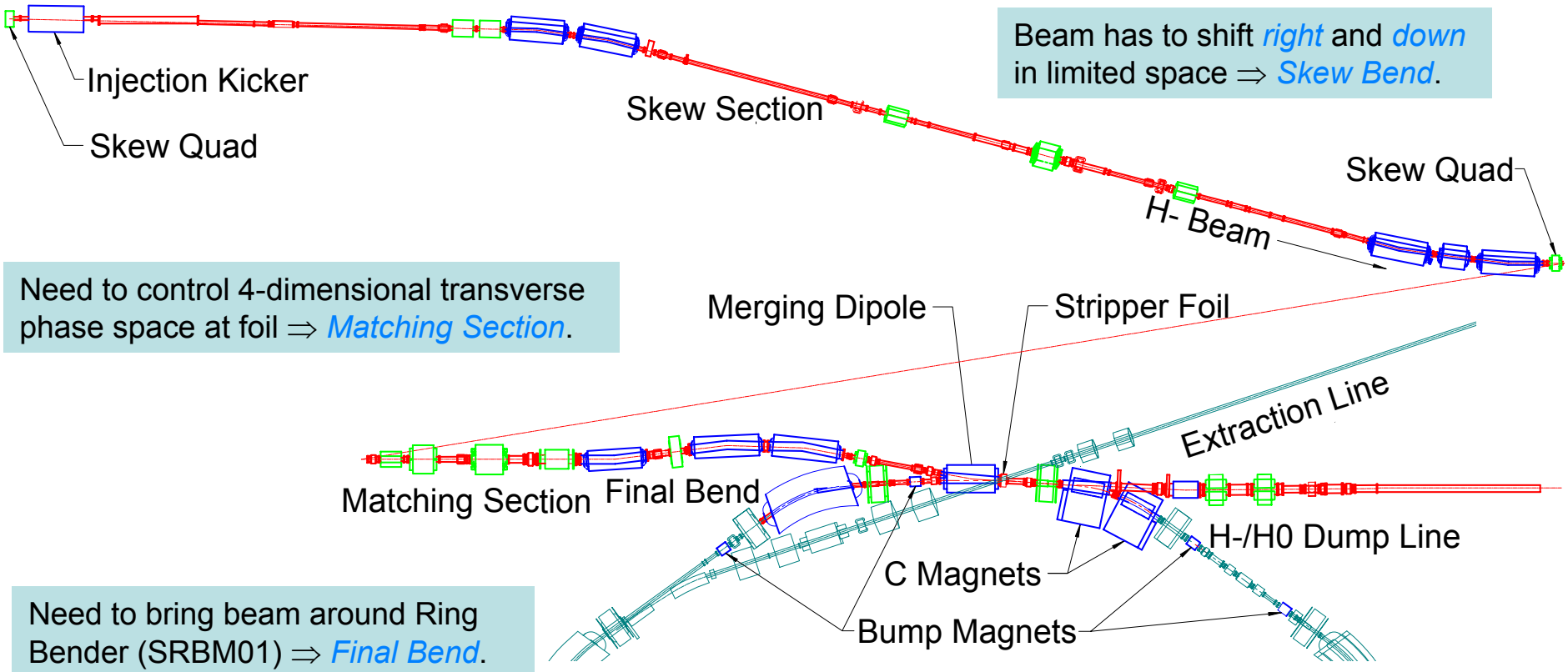


H^+ Beam from PSR

- PSR forms 6-700 μs long pulses from LINAC into short (~300 ns) intense proton pulses of up to 6.25 μC or $4 \cdot 10^{13}$ protons per pulse (i.e. 125 μA @ 20 Hz).
- To minimize losses injected beam is matched to ring acceptance. Only possible with *H^- injection*!
- For a different use (PSR to WNR) small emittance is required. ⇒ need small (close to on-axis) injection offsets.

  ⇒ need to be able to adjust injection for different beam sizes.

Ring Injection Kicker (RIKI) to PSR



Beam has to shift *right* and *down* in limited space ⇒ *Skew Bend*.

Need to control 4-dimensional transverse phase space at foil ⇒ *Matching Section*.

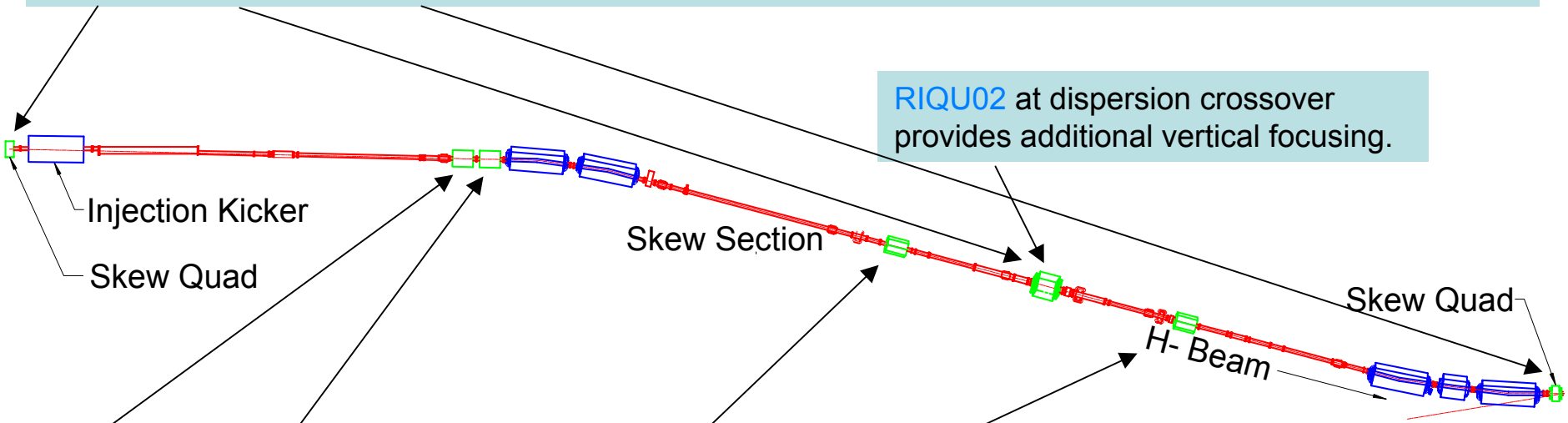
Need to bring beam around Ring Bender (SRBM01) ⇒ *Final Bend*.

Paint (vertical) phase space ⇒ *Bump Magnets*.

Dump Line needs to accommodate H^0 **and** H^- beams, as well as on-axis and off-axis beams ⇒ *C-Magnets*

Ring Injection Kicker (RIKI) to PSR - Skew Bend

LDQS01, RIQU02 and RIQS01 adjust transfer matrix elements to avoid coupling downstream of skew bend.



Ring Injection Kicker (RIKI) to PSR - Skew Bend

- Transverse Transfer Matrix of skew bend in upright coordinate system (C=cos(Θ), S=sin(Θ)):

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{bmatrix} = \begin{bmatrix} C & 0 & -S & 0 \\ 0 & C & 0 & -S \\ S & 0 & C & 0 \\ 0 & S & 0 & C \end{bmatrix} \cdot \begin{bmatrix} \tilde{R}_{11} & \tilde{R}_{12} & 0 & 0 \\ \tilde{R}_{21} & \tilde{R}_{22} & 0 & 0 \\ 0 & 0 & \tilde{R}_{33} & \tilde{R}_{34} \\ 0 & 0 & \tilde{R}_{43} & \tilde{R}_{44} \end{bmatrix} \cdot \begin{bmatrix} C & 0 & S & 0 \\ 0 & C & 0 & S \\ -S & 0 & C & 0 \\ 0 & -S & 0 & C \end{bmatrix}$$

$$= \begin{bmatrix} \tilde{R}_{11}C^2 + \tilde{R}_{33}S^2 & \tilde{R}_{12}C^2 + \tilde{R}_{34}S^2 & (\tilde{R}_{11} - \tilde{R}_{33})CS & (\tilde{R}_{12} - \tilde{R}_{34})CS \\ \tilde{R}_{11}C^2 + \tilde{R}_{33}S^2 & \tilde{R}_{22}C^2 + \tilde{R}_{44}S^2 & (\tilde{R}_{21} - \tilde{R}_{43})CS & (\tilde{R}_{22} - \tilde{R}_{44})CS \\ (\tilde{R}_{11} - \tilde{R}_{33})CS & (\tilde{R}_{12} - \tilde{R}_{34})CS & \tilde{R}_{11}S^2 + \tilde{R}_{33}C^2 & \tilde{R}_{12}S^2 + \tilde{R}_{34}C^2 \\ (\tilde{R}_{21} - \tilde{R}_{43})CS & (\tilde{R}_{22} - \tilde{R}_{44})CS & \tilde{R}_{11}C^2 + \tilde{R}_{33}S^2 & \tilde{R}_{22}S^2 + \tilde{R}_{44}C^2 \end{bmatrix} = \begin{bmatrix} \tilde{R}_{11} & \tilde{R}_{12} & 0 & 0 \\ \tilde{R}_{21} & \tilde{R}_{22} & 0 & 0 \\ 0 & 0 & \tilde{R}_{11} & \tilde{R}_{12} \\ 0 & 0 & \tilde{R}_{21} & \tilde{R}_{22} \end{bmatrix},$$

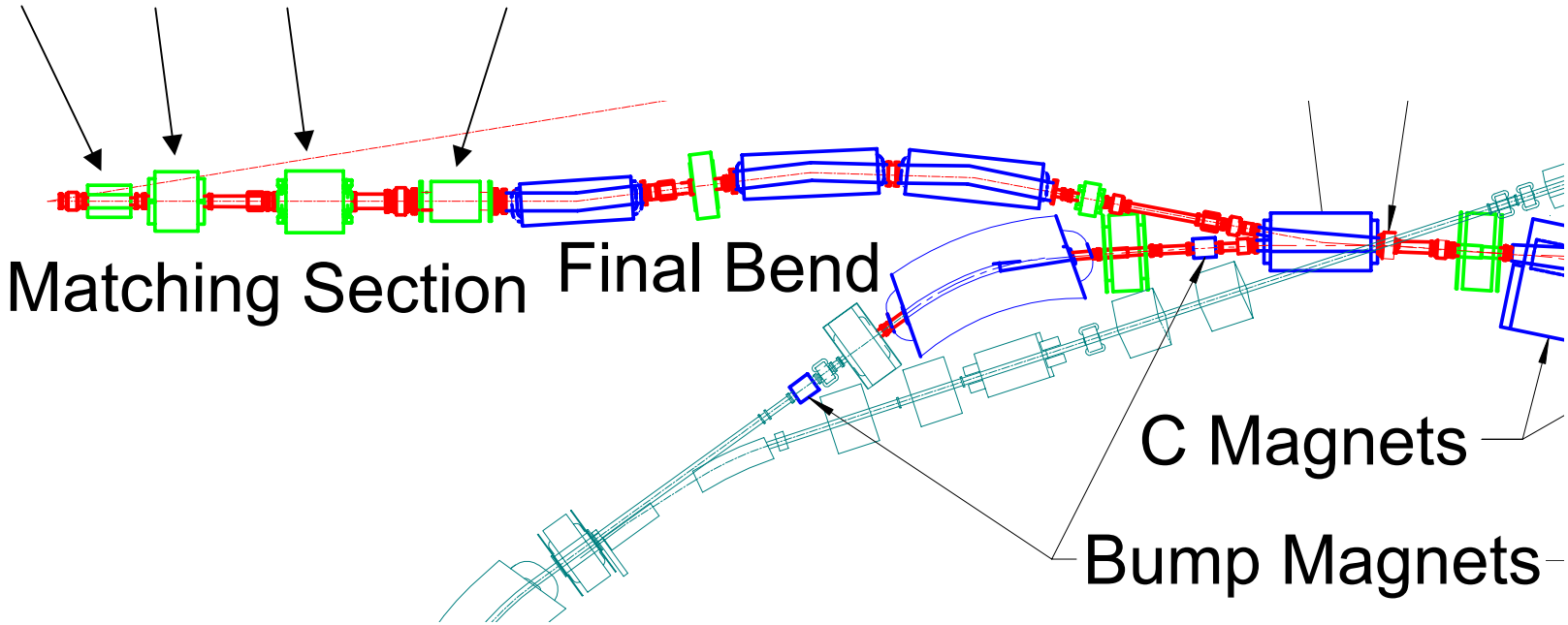
$$\text{if } \tilde{R}_{11} = \tilde{R}_{33},\ \tilde{R}_{12} = \tilde{R}_{34},\ \tilde{R}_{21} = \tilde{R}_{43} \text{ and (follows) } \tilde{R}_{22} = \tilde{R}_{44}.$$

  - Adjust LDQS01, RIQU02 and RIQS01 so that condition is always satisfied.

Ring Injection Kicker (RIKI) to PSR - Skew Bend

Ring Injection Kicker to PSR - Matching Section

RIQU03, RIQF04, RIQU04 and RIQF05 used to adjust 4-dim. transverse phase space at stripper foil.



Minimum of four quads required to set and adjust four transverse phase space parameters at foil.

Ring Injection Kicker to PSR - Matching Section

Magnets are so close together that their effective lengths are commensurate with their focal lengths.
⇒ *large gradient-length products* required.

To avoid *field-stripping* of H^- beam magnets have to be long.

Matching section can produce *nominal beam* at the foil, plus a range of other beams.

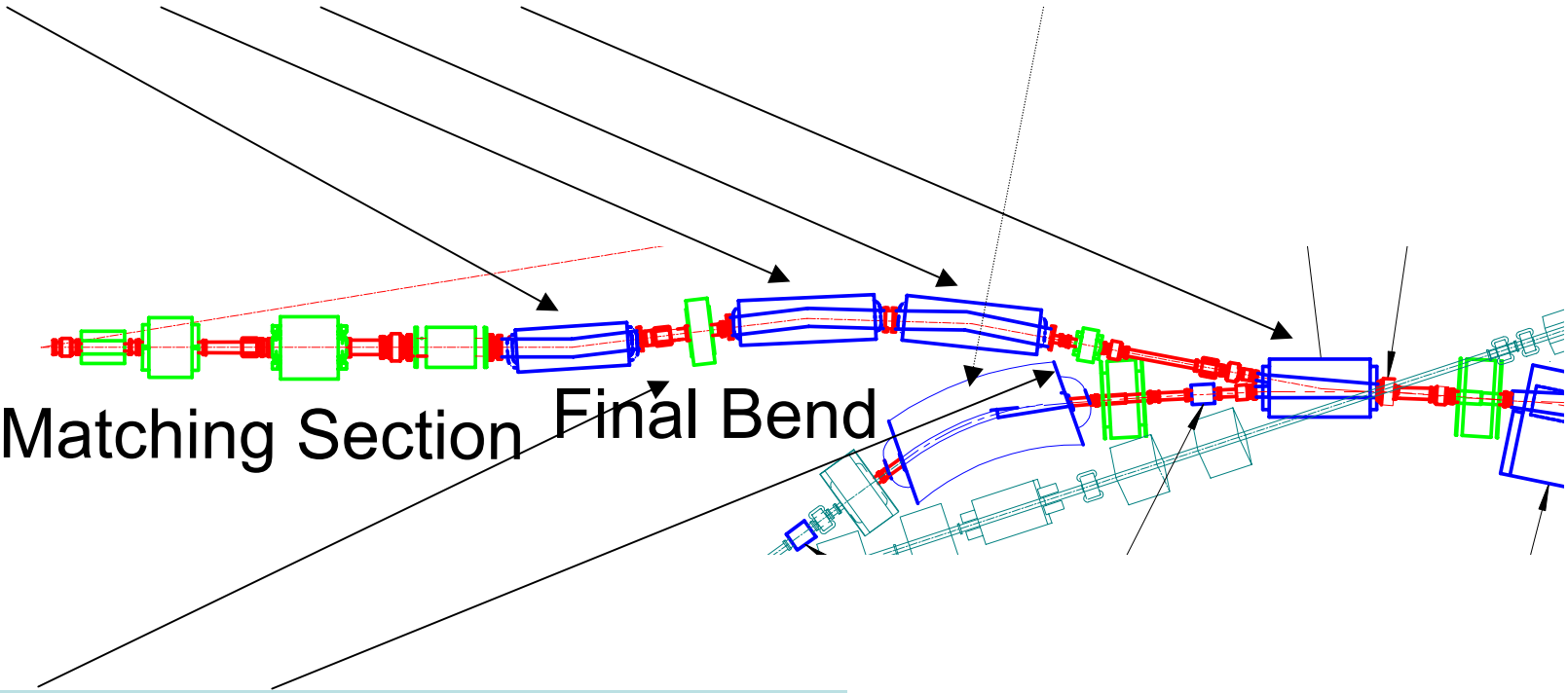
We have deviated from the *design tune* to a more "gentle" tune. ✦

Emittance station is essential (4 x-y wire scanners).

Ring Injection Kicker to PSR - Matching Section

Ring Injection Kicker to PSR - Final Bend

RIBM06, RIBM07, RIBM08 and RIBM09 form a chicane around SRBM01 and bring the beam to the foil.



RIQU05 and RIQF06 make the last bend *achromatic*.

Ring Injection Kicker to PSR - Final Bend

Geometry of Final Bend is largely fixed by geometric constraints.

Final Bend has to be *achromatic* to avoid horizontal emittance growth and centroid shifting due to energy fluctuations.

Fields have to be weak to avoid *field stripping*.

Final Bend steers the beam horizontally to nominal injection point. Also allows *on-axis injection*.

Merging Dipole (RIBM09) introduces permanent 6.8^{o} bend for circulating beam. $\Rightarrow$ Necessary to reduce bending strength of adjacent dipoles.

Ring Injection Kicker to PSR - Final Bend

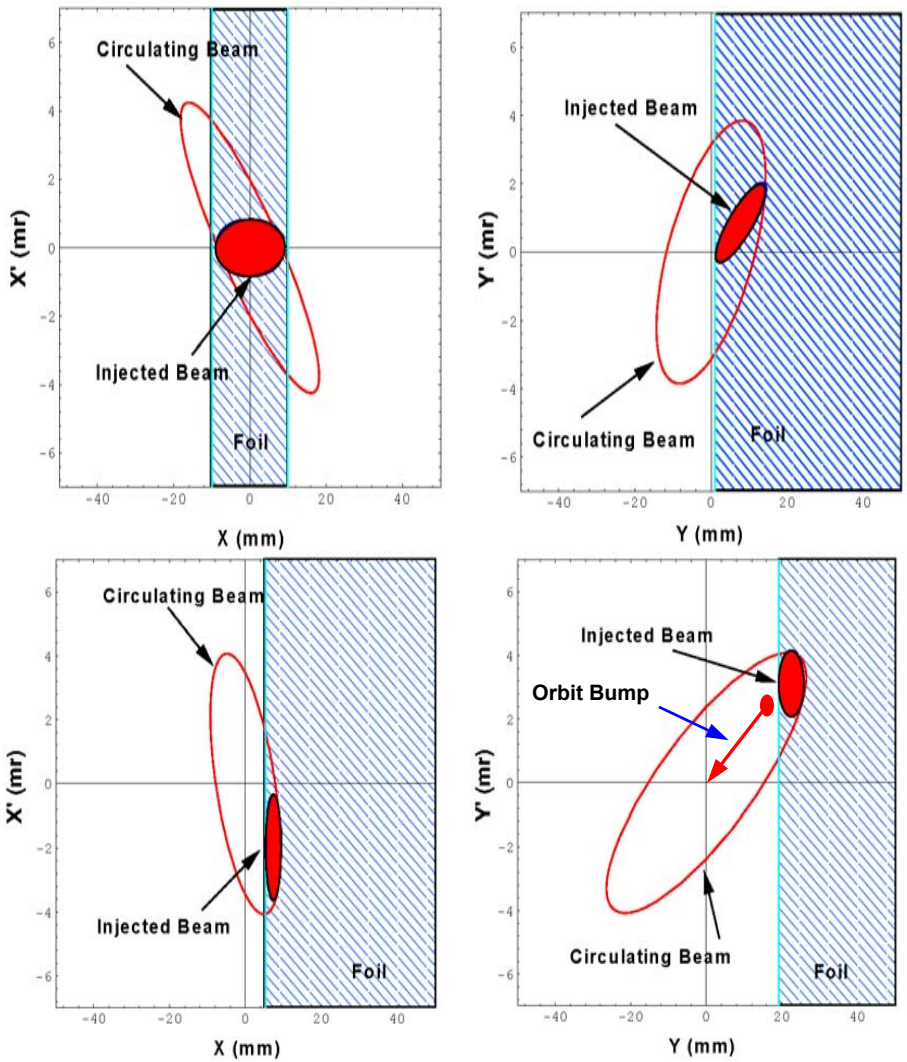
Ring Injection - H^- vs. H^0 Injection

H^0 Injection (before upgrade)

- Emittance growth of factor ~3 in bend plane of stripper magnet
- Large mismatch in the horizontal plane
- Cannot manipulate or tailor neutral beam for optimum filling (“painting”) of transverse phase space to keep the stored beam off the foil as much as possible

H^- Injection

- No emittance growth for injected beam
- Programmed vertical closed orbit bump to move stored beam off the foil
- Horizontal offset with painting by betatron oscillations
- Injected beam ellipses optimized for efficient painting and minimum foil hits



Ring Injection - H^- vs. H^0 Injection

- With H^- Injection the number of foil hits is reduced by roughly a factor 10, including a factor 2 due to the bump.
- To reduce *first-turn* losses the foil thickness has been increased from 200 μg/cm^2 to 400 μg/cm^2.
- Overall loss reduction by a factor of 4-5 allowed to increase the beam current to the Lujan Neutron Scattering Target from 50 μA to 100 μA at 20 Hz.
  - in 2004 we attained 125 μA.

Ring Injection - Design vs. Actual Injection Tune

- Matched Beam (likewise for y):

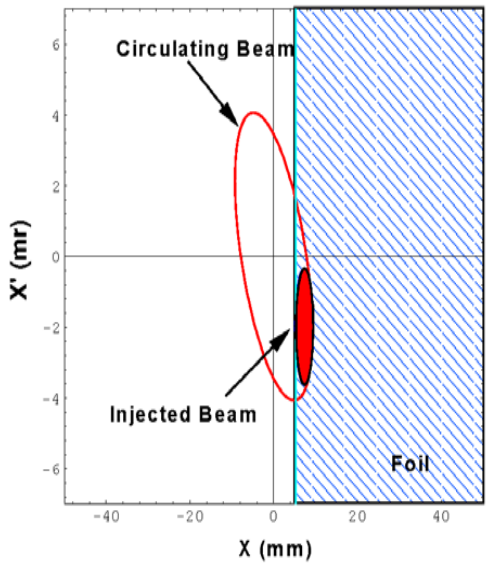
$$\beta_i = \beta_R \cdot \left(\frac{\varepsilon_i}{\varepsilon_R}\right)^{1/3}, \quad \alpha_i = \alpha_R \cdot \left(\frac{\varepsilon_i}{\varepsilon_R}\right)^{1/3}$$

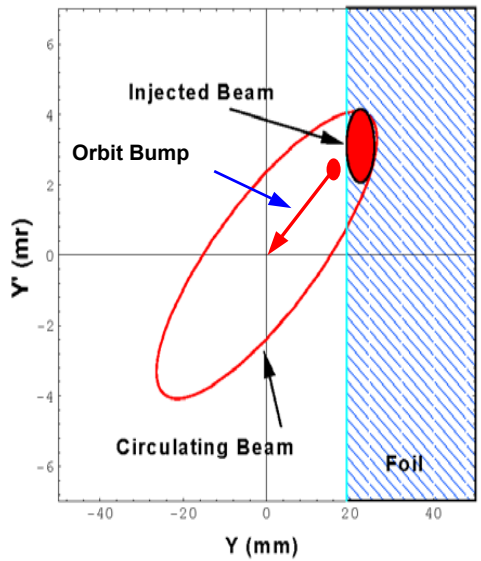
$$x_i = \sqrt{\varepsilon_R \beta_R} - \sqrt{\varepsilon_i \beta_i}, \quad x_i' = -\frac{\alpha_R}{\beta_R} x_i$$

$$x_f = \sqrt{\varepsilon_R \beta_R} - 2\sqrt{\varepsilon_i \beta_i}$$

$i = \text{injected beam}, \quad R = \text{Ring beam}$

$x_f = \text{foil edge}$

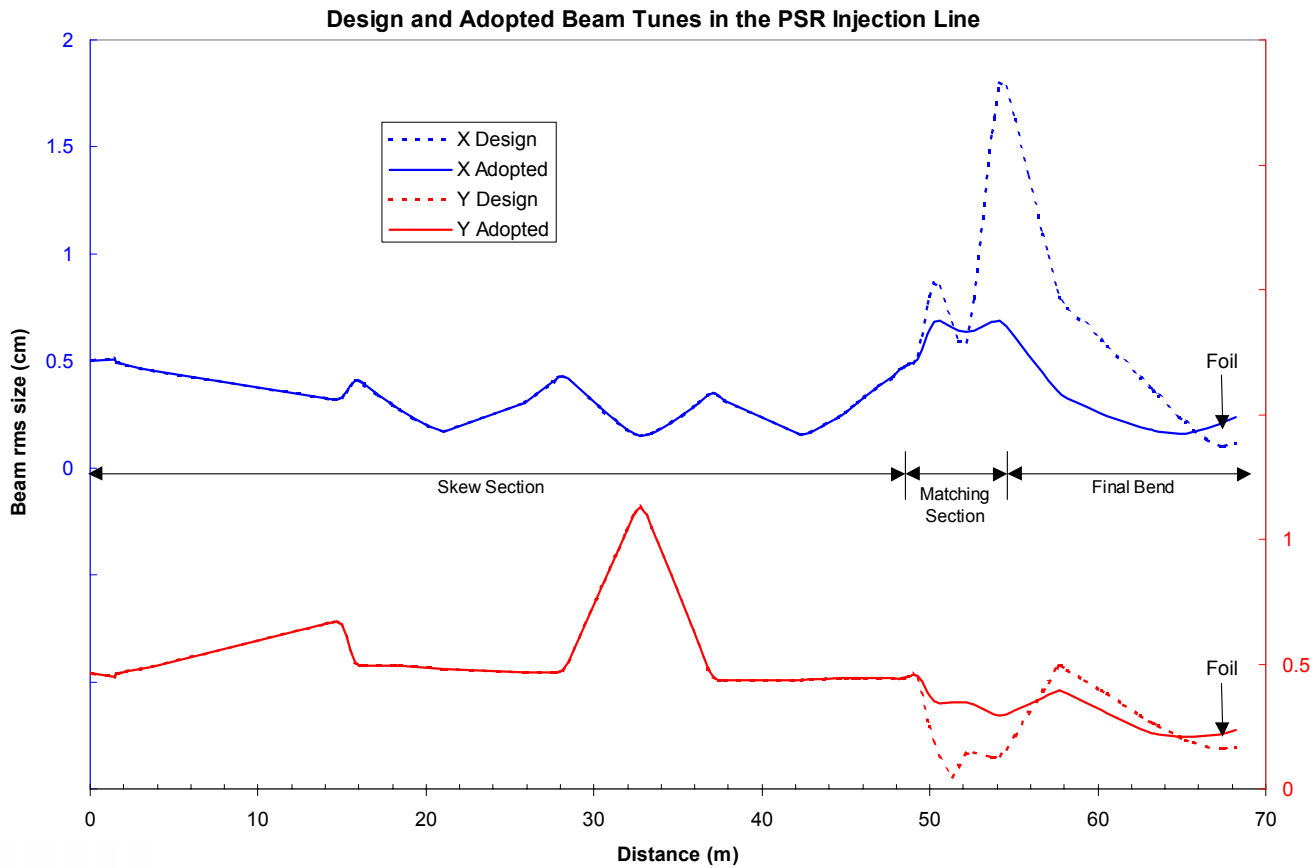




- Upright injected beam ($\alpha_i = 0$) is close enough.

Ring Injection - Design vs. Actual Injection Tune

- Design Tune proved too difficult to handle.

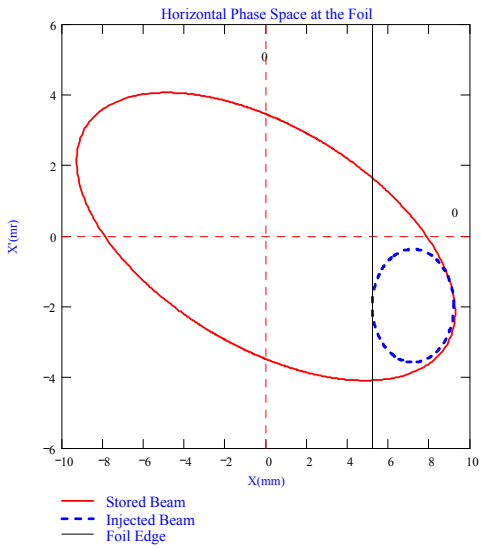


Ring Injection - Design vs. Actual Injection Tune

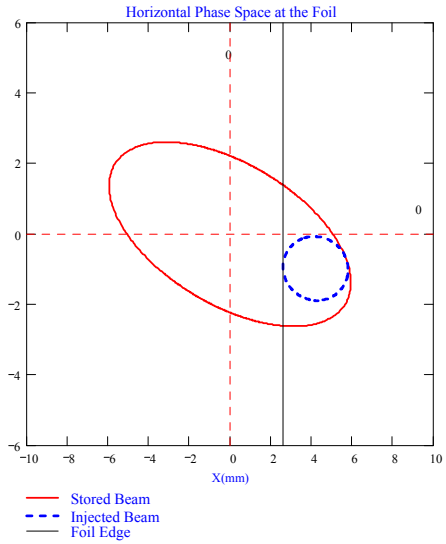
- Use a more “gentle” tune instead:

Example: Horizontal

Design



Actual



Parameter	Design Value	Measured Value
X_0 (mm)	7.2	4.2
X_0’ (mrad)	-2.0	-1.0
α_0	0.00	0.04
β_0 (m)	1.25	1.76
ε_0 (mm-mrad)	0.8	0.7
ε_p (mm-mrad)	32	18
“Fraction on foil”	0.16	0.33

Beam Dump Line

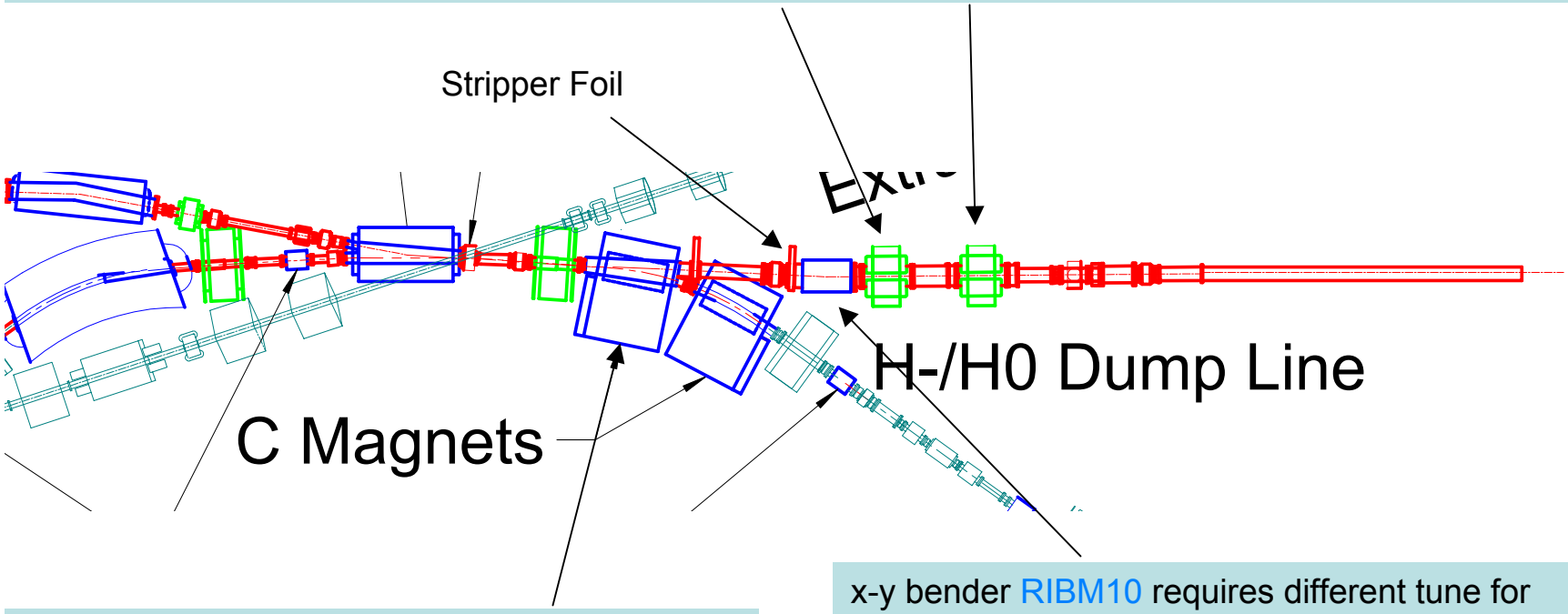
- Has to accommodate wide range of beam types:
  - H^0 (not completely stripped H^-)
  - H^- missing the foil
  - Nominally (i.e. off-axis) injected beam
  - On-axis (or close to) injected beam

  $\Rightarrow$ Need large horizontal acceptance.
- Merging Bend adds 6.8^o $\Rightarrow$ Dipole downstream of foil has reduced strength.
  - H^- field stripping efficiency reduced $\Rightarrow$ Larger horizontal emittance of H^- beam.

  $\Rightarrow$ Would need two quadrupoles immediately downstream of ring bender $\Rightarrow$ too congested.
- Replaced Bender (SRBM11) with two C Magnets.

Beam Dump Line

Because of smaller H^- beam emittance quads RIQF07 and RIQU06 can be placed downstream of bender.



H^- beam missing foil sees only first C magnet.
⇒ less effective length, can increase field to improve stripping.

x-y bender RIBM10 requires different tune for off-axis and on-axis beams.

Beam Dump Line

Summary

- Overall loss reduction by a factor of 4-5 allowed to increase the beam current to the Lujan Neutron Scattering Target from 50 μA to 100-125 μA at 20 Hz
- Constraints on injection line design from geometry (use of existing beam tunnels) and cost-effectiveness (use of existing magnets).
- Need for different types of beams (e.g. small emittance, on-axis injection) from ring requires large tuning range.
- Two species of beams to dump required redesign of dump line.
- At 800 MeV field stripping starting to become an issue.