# Overview of Booster PIP II upgrades and plans

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PIP II Collaboration Meeting
03 June 2014

U.S. DEPARTMENT OF ENERGY

Fermilab

# PIP II Booster parameters

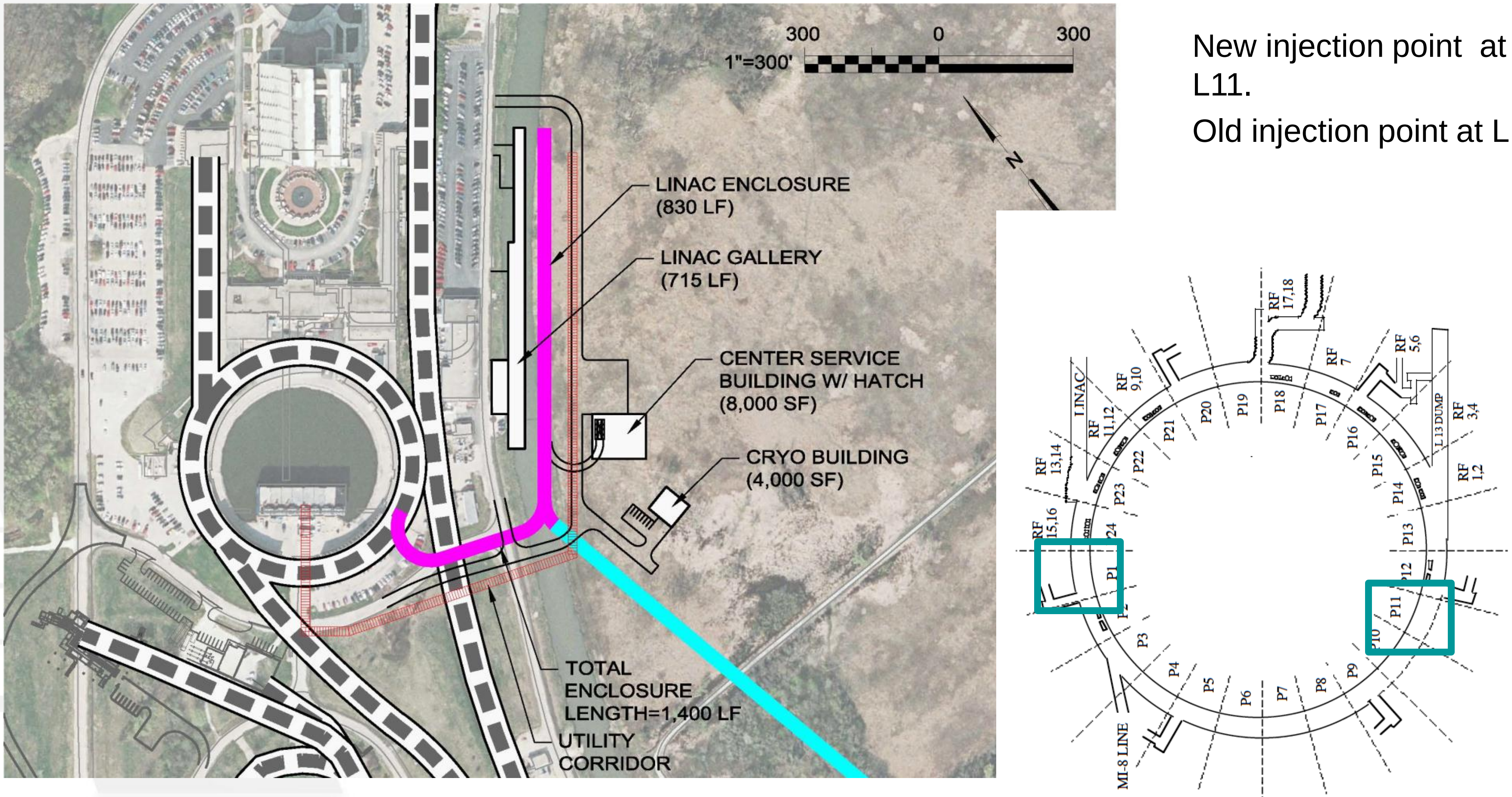
| Performance Parameter | Requirement | |
|---|---|---|
| Particle Species | Protons | |
| Input (H$^-$) Beam Energy (Kinetic) | 800 | MeV |
| Output Beam Energy (Kinetic) | 8.0 | GeV |
| Protons per Pulse (injected) | 7.0×10$^{12}$ | |
| Protons per Pulse (extracted) | 6.4×10$^{12}$ | |
| Beam Pulse Repetition Rate | 15 | Hz |
| RF Frequency (injection) | 44.7 | MHz |
| RF Frequency (extraction) | 52.8 | MHz |
| Injection Time | 0.6 | msec |
| Injection Turns | 315 | |
| Beam Emittance (6s, normalized; $e_x = e_y$) | 15 | p mm-mrad |
| Laslett Tune Shift at Injection (Gaussian) | -0.34 | |
| Delivered Longitudinal Emittance (97%) | 0.08 | eV-sec |
| Delivered Momentum Spread (97% full height) | 12.2 | MeV |
| Delivered Bunch Length (97% full length) | 8.2 | nsec |

50% higher flux than the planned PIP operations **which is expected to double present flux level**. (4.3e12 protons @15 Hz at the end of PIP I)

30% decrease in space charge tune shift @ 800 MeV.

Longitudinal emittance determined by Recycler slip stacking requirements.

# PIP-II New injection point into Booster




New injection point at L11.

Old injection point at L1

# Overview of required R&D

- New injection point at L11.
  - New injection girder.
  - Space charge mitigation: painting.
  - New stripping foil.
  - $H^0$ , H- absorber
- RF capture
  - capture scheme: paraphasing or direct injection into buckets
  - 2nd harmonic cavities (considered but probably unnecessary).
- Transition crossing
  - RF focusing method.
  - RF focus free method (flattening of RF amplitude)
    - 2nd or 3rd harmonic cavities. (can also be used in RF focusing method)
  - $\gamma t$ jump system
    - requires resurrection/rebuild of old system.

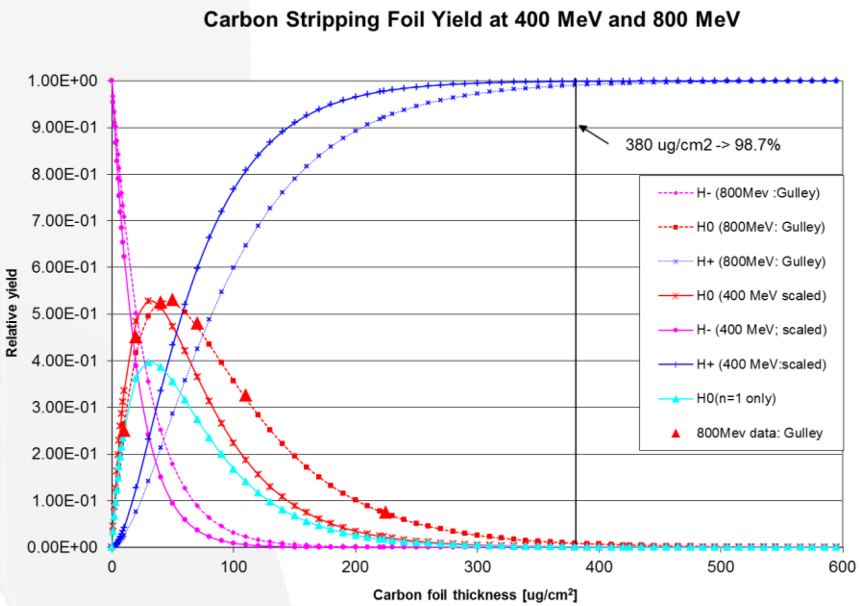
# Overview (cont'd)

- Damper upgrades and collimation system
  - longitudinal quadrupole damping when going through transition.
    - Will require voltage overhead in RF system
  - longitudinal coupled bunch mode damping at high field.
    - Will require an increase in RF power
  - Transverse dampers for coupled bunch modes.
    - Higher intensity may require more power for kickers.
  - Evaluation of present collimation system w.r.t. expected PIP II loss
- Beam quality at extraction
  - emittances determined by Recycler admittances.
    - 18 π mm mrad (6 σ normalized)
    - 0.08 eV s (97%)

# New injection girder

- Beam can enter either horizontally or vertically.
- A new 3 bump system that can take 800 MeV beam (2x stronger)
- Beam painting to mitigate space charge effects because of longer injection time (0.6 ms)
- Carbon foil for stripping (15 turns vs 315 turns)
  - Lifetime effects.
- New beam absorber for $H^0$ and $H^-$
  - Build inside a gradient magnet.
  - Design new stronger and shorter gradient magnets to make space for an absorber. (Preferred)

# PIP-II Foil



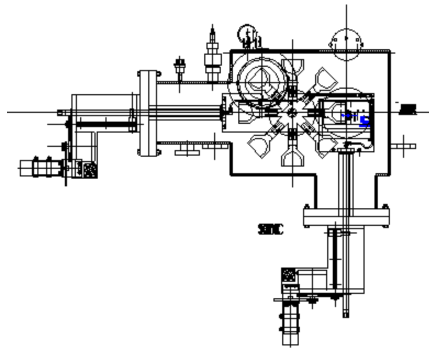

For a std. foil thickness 380 μg/cm$^2$ (1.15 μm)

400 MeV -> 99.9% efficiency to protons

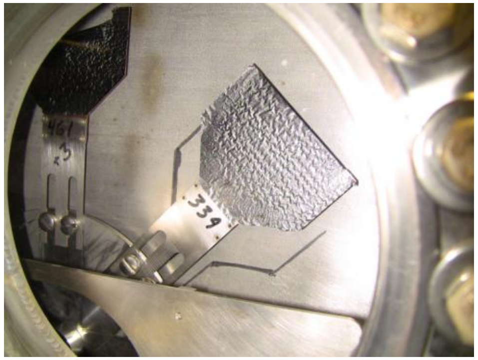
800 MeV -> 99.1% efficiency to protons

To match 400 MeV efficiency at 800 MeV foil thickness needs to increase to ~545 μg/cm$^2$

current foil holder



current foil



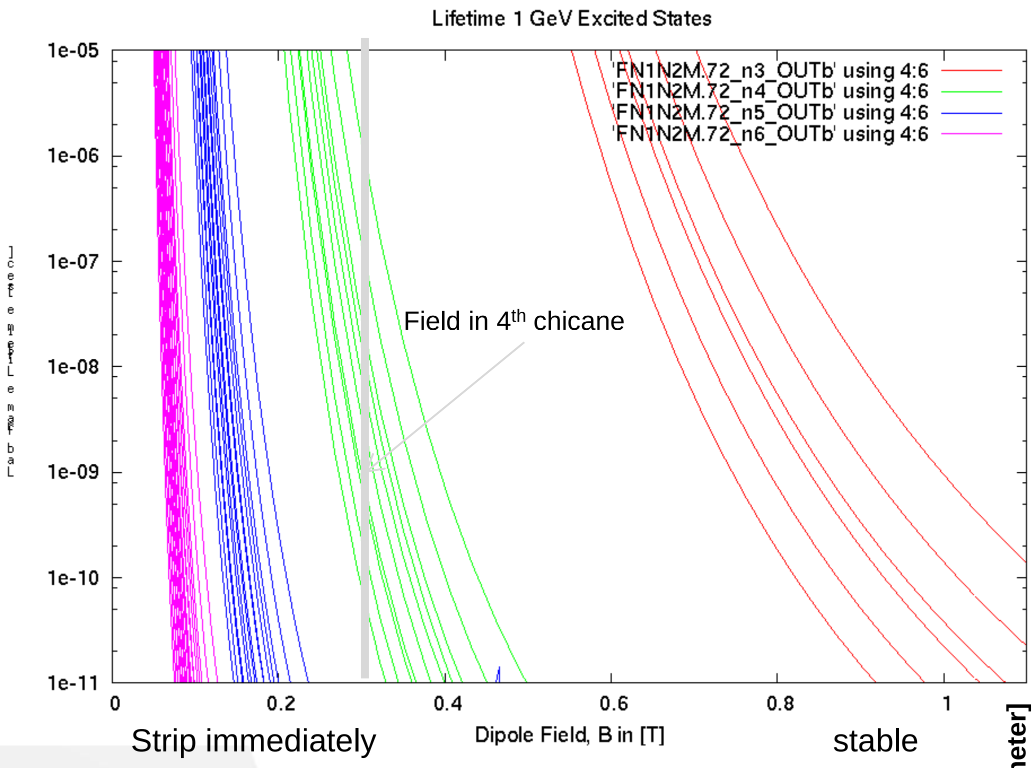
At 800 MeV with 7E12 injected at 15 Hz

Injection power increases to ~ 13 kW.

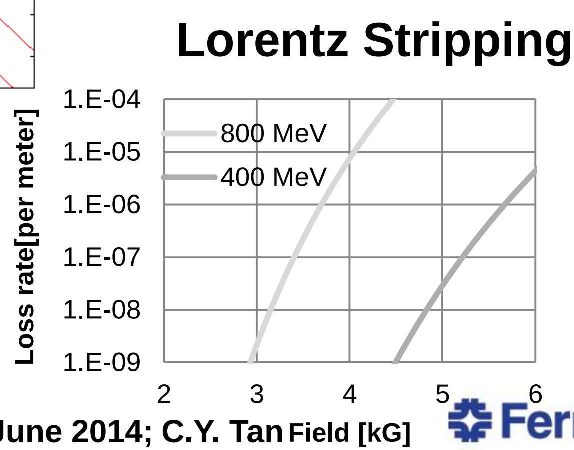
For a 2% loss -> 260 Watts on downstream gradient magnet.

-> **<u>Need to provide injection absorber</u>**

# Stripping efficiencies at 800 MeV




| 800MeV 545 μg/cm$^2$ | |
|---|---|
| State | Fraction |
| H+ | 0.999 |
| H- | 7.00E-09 |
| n=1,2 | 8.70E-04 |
| n=3 | 6.50E-05 |
| n > 3 | 6.50E-05 |
| total | 1 |



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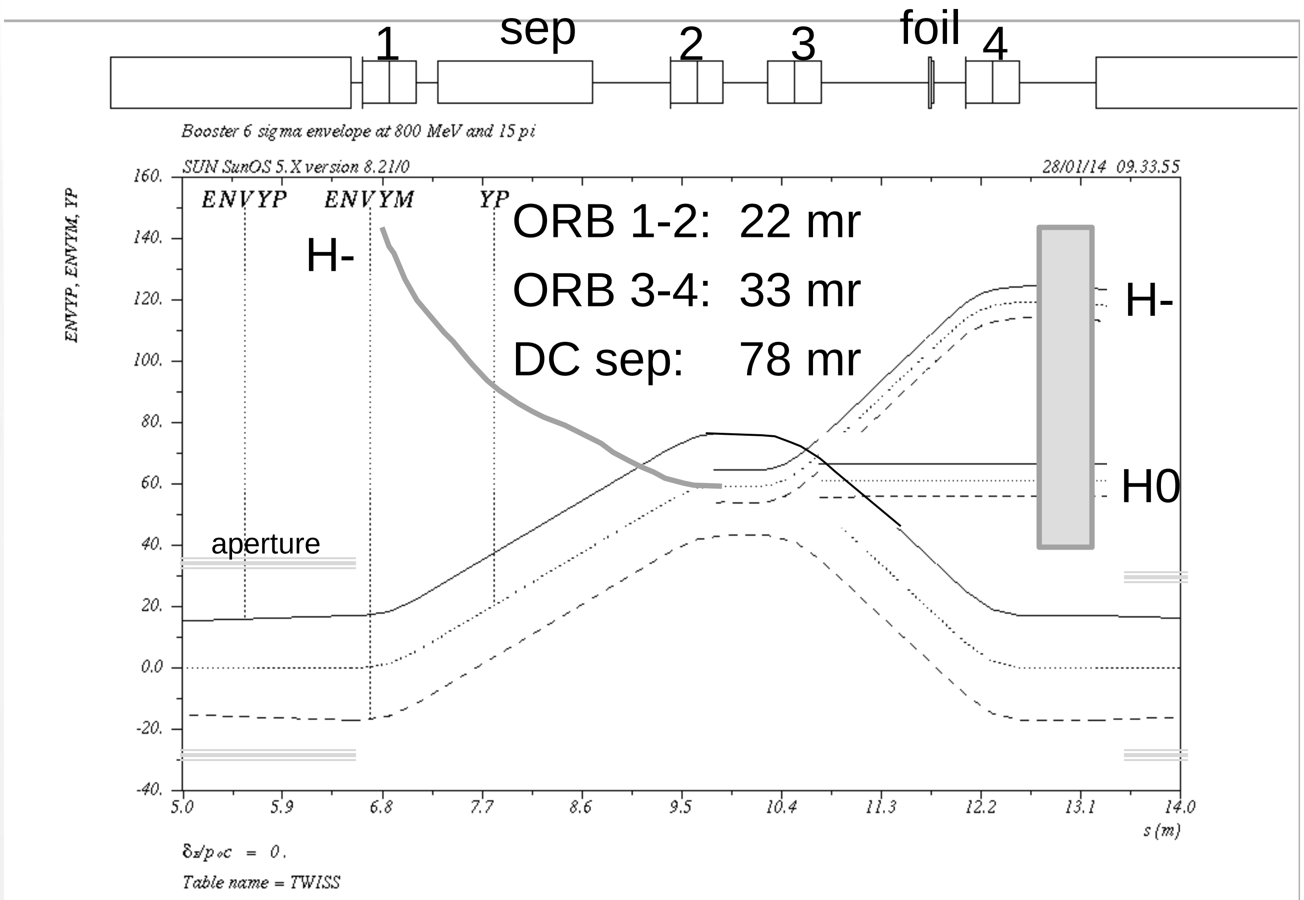
# Vertical Injection Concept





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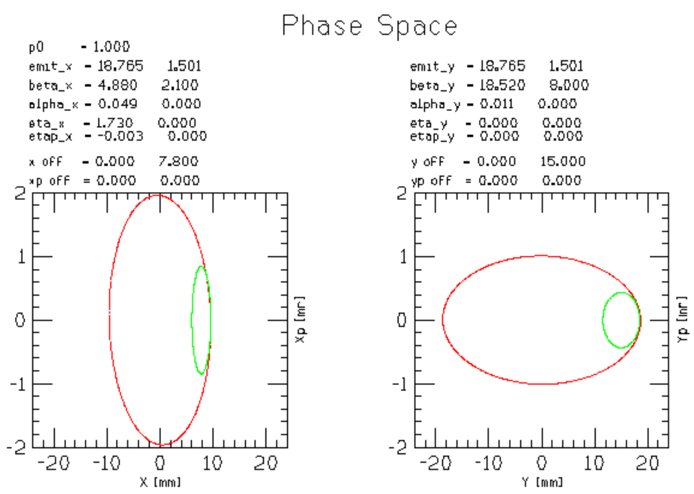
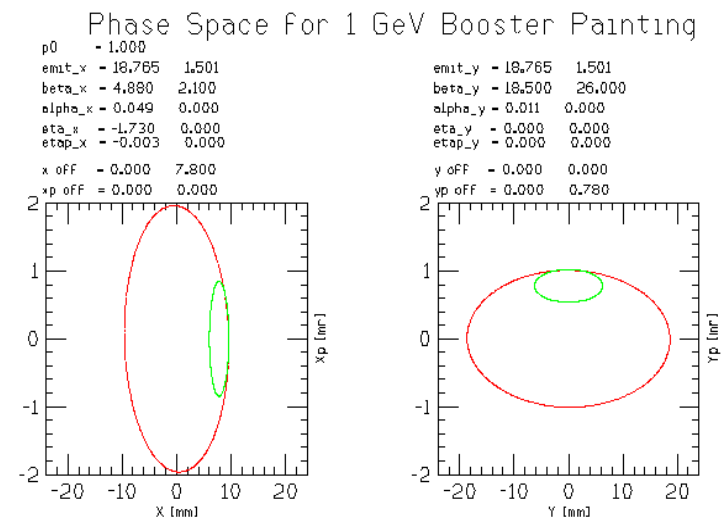
# Injection painting for space charge mitigation




Green: injected beam.

Red: phase space after painting.

Note: ellipses were calculated for 1GeV injection.

Beam line matching conditions for two painting scenarios. Left paint in both planes in the ring (SNS) and right paint horizontal in ring and steer (angle mismatch) from beam line (JPARC).





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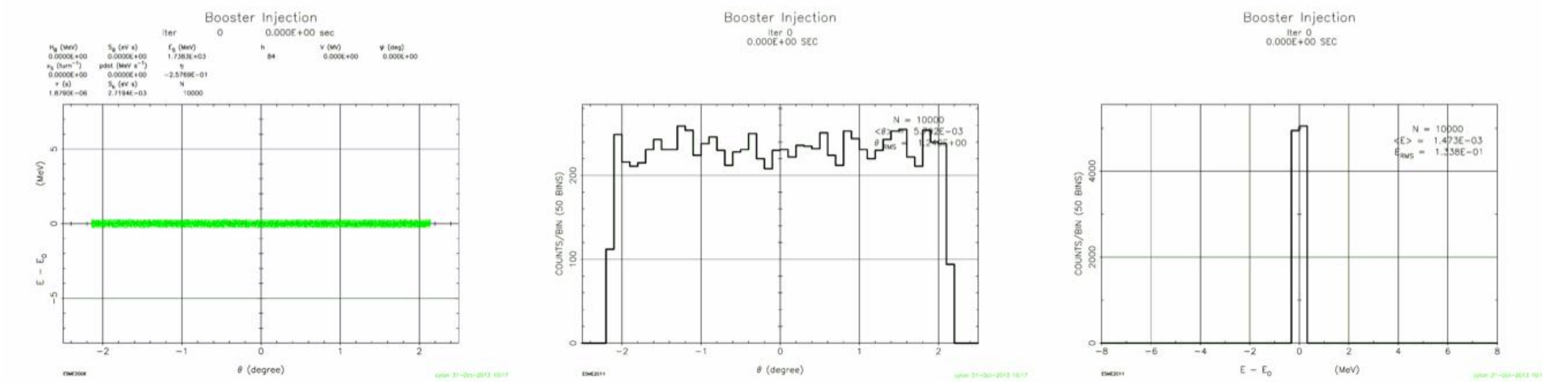
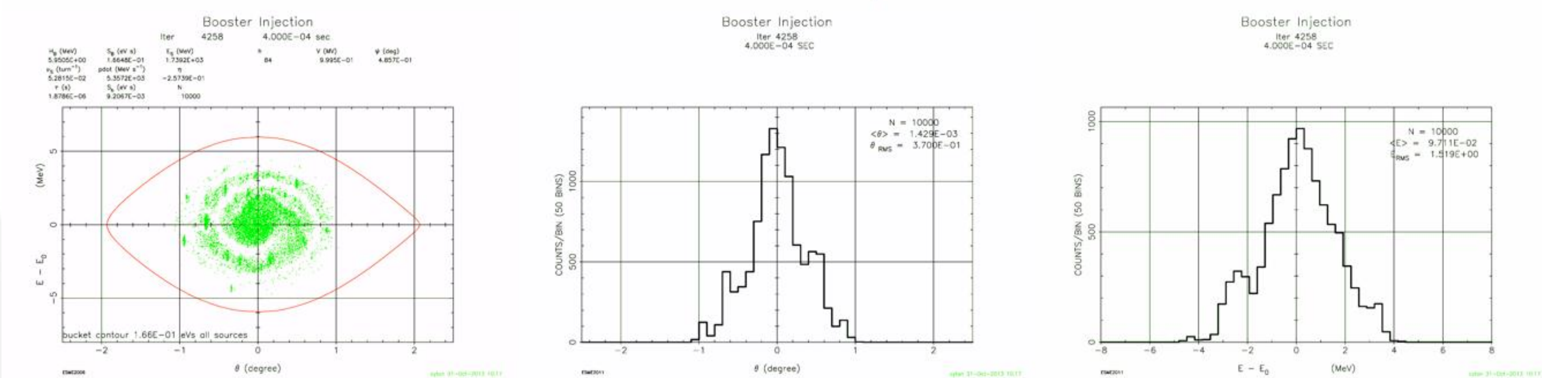
# Capture (adiabatic at 800 MeV)

## At injection



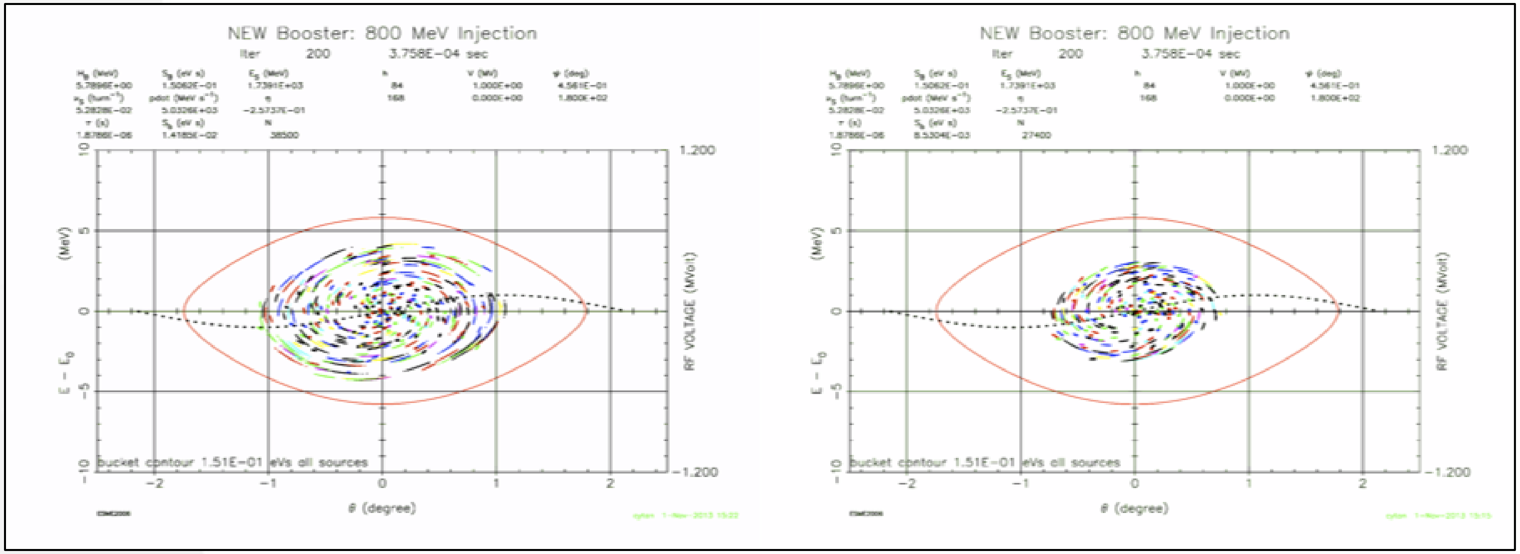

## After adiabatic capture




0.6 ms injection time.

0.4 ms adiabatic ramp to full voltage (1 MV)

# PIP-II Capture (bucket to bucket injection)




Chopping 180 deg                Chopping 120 deg

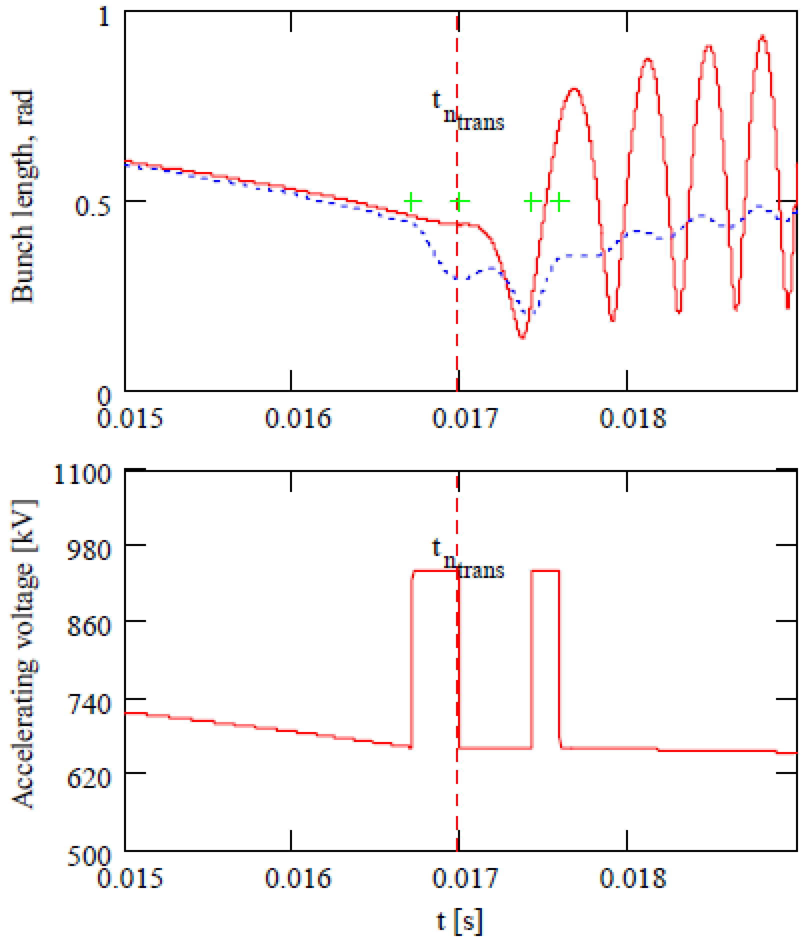
0.6 ms injection time.

Chopping is required to get the correct bunch pattern into the bucket.

2 mA for 0.6 ms gives 7.5e12 particles.

May need flattened front porch for injection

# Transition crossing




Transition crossing at 4.2 GeV

More RF for focusing during transition.

~25% more RF implies 3 – 4 more RF cavities using present design. (22 – 23 cavities)

Example shown here is the compensation of the effect of space charge that is defocusing before transition & focusing after transition.

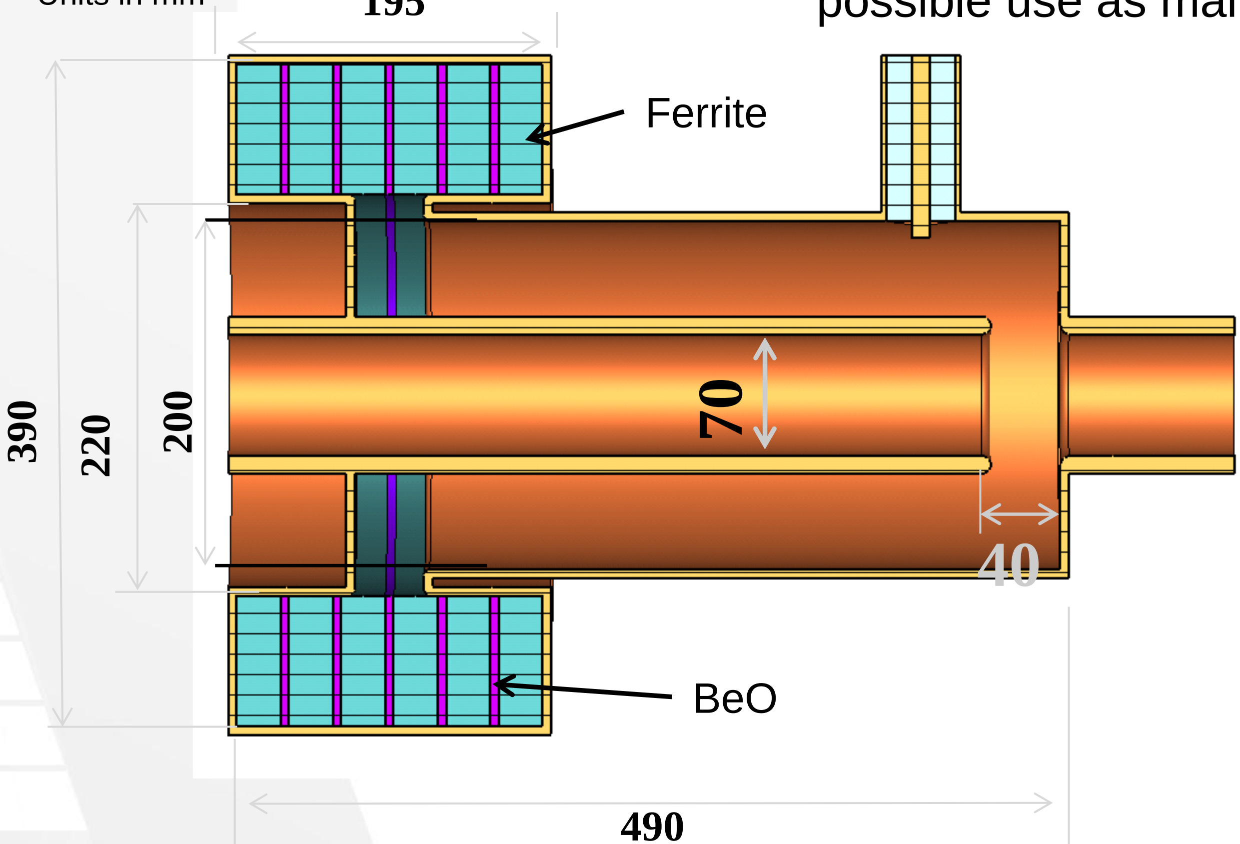
Increase RF voltage before transition

Increase RF voltage again to damp out quadrupole oscillation.

# Perpendicular biased cavities

Simulations of use at injection for PIP I and possible use as main RF cavity is underway.

Units in mm




| Name | Value | Description |
|---|---|---|
| Gap | 40 | |
| Gap_2 | 40 | |
| Imped | 1000 | |
| L | 405 | pp |
| Linner | L-Gap | |
| Linner_2 | 50 | |
| L_antenna | 105 | |
| L_ferr | 175 | |
| Mu | 3.7 | |
| Oe | 1600 | Magnetization |
| Rinner | 90/2 | |
| Router | 200/2 | |
| Router_2 | R_ferr_in-5 | |
| R_antenna | 5 | |
| R_ferr_in | 230/2 | |
| R_ferr_out | 380/2 | |

Designed by G. Romanov

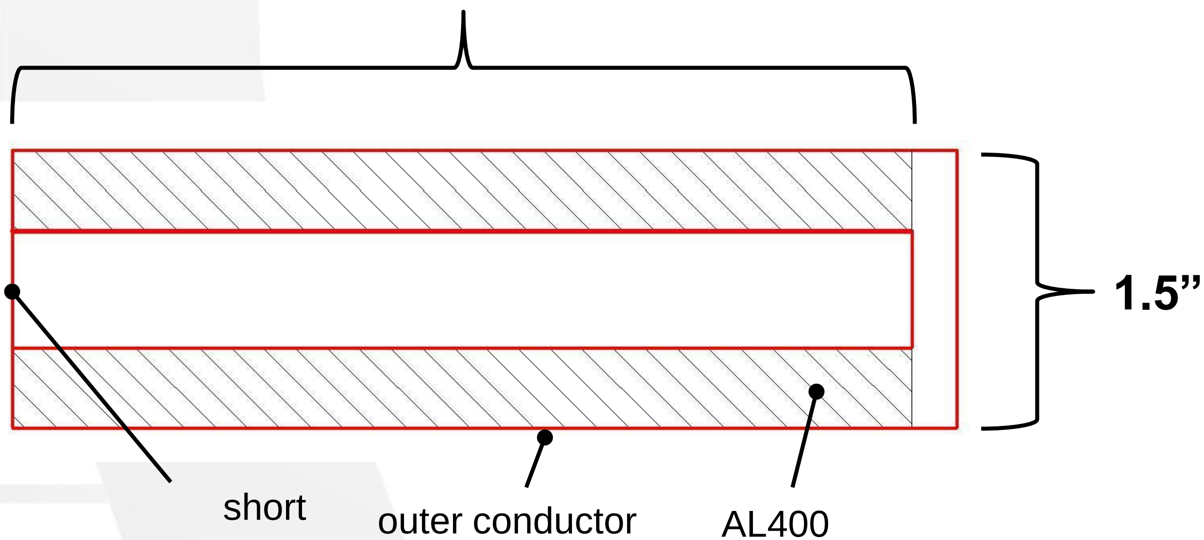
Example here: 2nd harmonic cavity

# What was done recently

- Measured $\mu$ and Q (tan $\delta$) *resonantly* with a **1.5" OD** sample of AL400: measure $f_{res}$, then with $c = f\,\lambda$

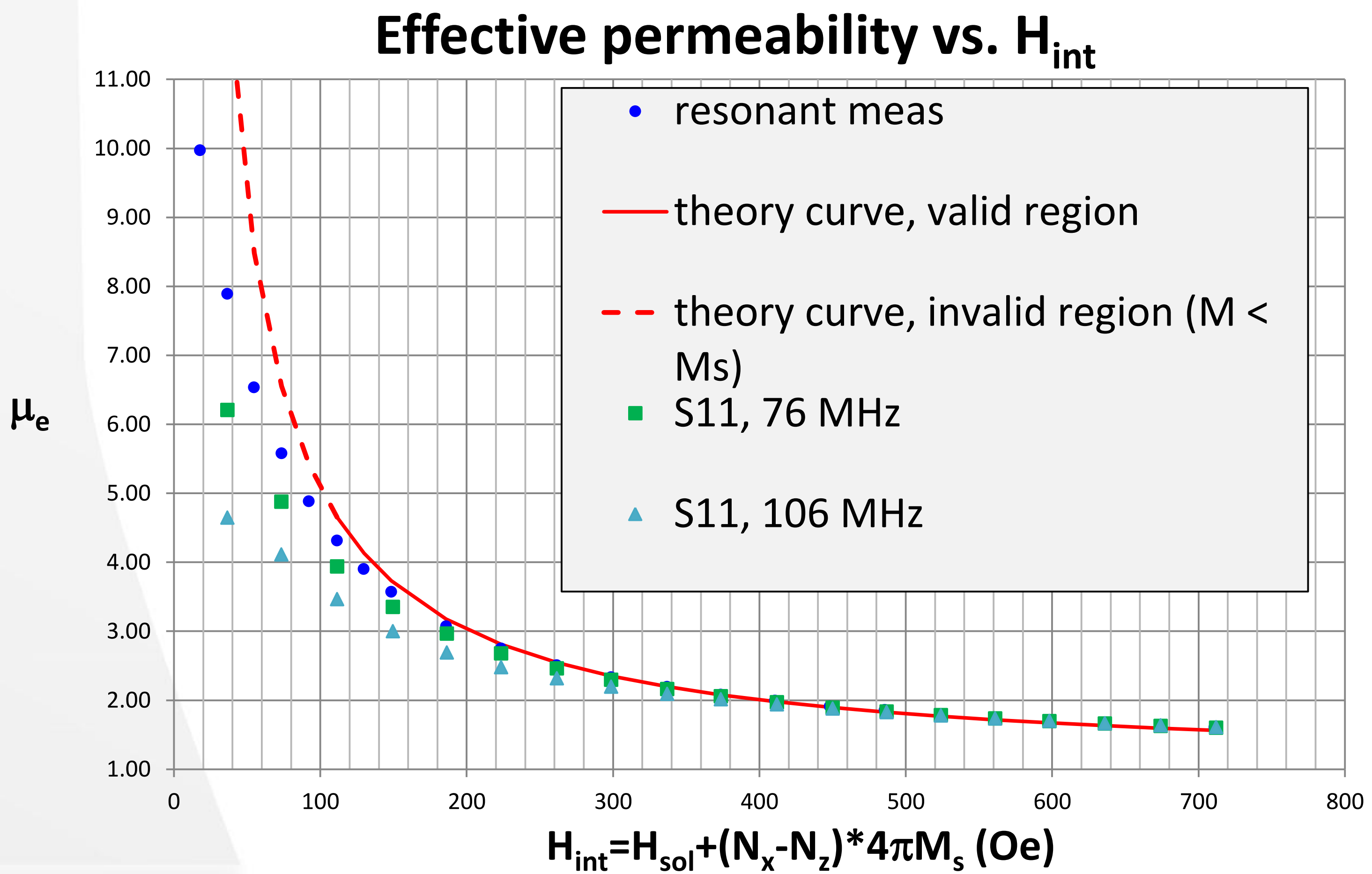
$$L = 5"$$

$$\lambda/4 = L * \sqrt{(\mu\varepsilon)}$$




Work done by D. Wildman and R. Madrak

# Old (S11) and New(Resonant) Measurements




Work done by D. Wildman and R. Madrak

# Dampers

- Longitudinal coupled bunch and quadrupole mode dampers
  - More RF volts is required whatever scheme is chosen.
    - E.g. Increase the number of RF cavities from 18 to 21 using present design will give ~150 kV.
    - Change from parallel biased cavities to perpendicular biased cavities could potentially increase volts/cavity from ~50 kV to ~60 kV and give 180 kV increase.
  - PIP I is working on improving present cavity design and perpendicular cavity design.
- Transverse and longitudinal dampers
  - PIP I upgrading analog dampers to digital dampers.

# Collimators

- PIP I plan is to reinvestigate present collimation operations and issues related to PIP I goals.
    - No upgrade of collimation is presently planned.

# Loss requirements

- Historically Booster losses is maintained <= 525 W ring wide.
- Independently set beam loss monitor trip points at each long and short straight sections.
- For PIP II
  - Keep ring wide activation at the present level would be recommended
  - Control loss points to be at collimators and beam dump
  - Notching in Linac will help reduce losses. Presently 3 bunches are kicked out => 95% efficient.
    - Ability to keep notch clean after multiple turns
    - Synchronization of Linac and Booster for extraction kickers and notch

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# Summary

- There is an R&D effort in place. Preliminary work has been started to find solutions to potential problems that we have identified:
  - New injection girder
  - RF capture
  - Transition
  - RF cavities
- Beam quality
  - Determined by keeping instabilities under control.
  - Constrained by Recycler requirements.