Accelerator Complex Studies Task Force (Booster Accumulator Ring Workshop 2020)

C.Y. Tan

15 Dec 2020

Task force charge

Fermi National Accelerator Laboratory

Memorandum

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Date: August 23, 2019
To: CY Tan
From: Michael A. Lindgren
Re: Accelerator Complex Studies Task Force Charge

Dear Tan,

To fully exploit the capabilities brought to the Fermilab Accelerator complex by the new PIP-II Linac and deliver the beam power that LBNF needs will require a deep understanding of the integrated complex. The long shutdown to install PIP-II is scheduled to begin in 2025, and careful study, decisions, and (presumably) actions are needed in the Booster and Recycler/Main Injector (AD Ring Complex) before the shutdown to ensure successful delivery of 1.2 MW beam to LBNF. Success hinges on understanding of the physics of high-intensity proton beams in the AD Ring Complex coming from PIP-II and the required infrastructure improvements to support the solutions and operational modes needed. With high-power targetry being an increasingly critical capability, short term Booster intensity increases to test new targets is needed before PIP-II. I am requesting that you lead a task force to undertake this work, with the following assumptions and points of common understanding in three areas, the Booster, Main Injector/Recycler, and infrastructure.

The physics requirements in the Booster are primarily driven by the 1.5x increase in beam intensity from the current of 4.5e12 ppb to 6.5e12 ppb in the PIP-II era. The increased beam intensity will require understanding the instability thresholds and mitigation of losses from injection, transition and extraction to keep total losses below 500 W. Besides the intensity increase, the mechanics of beam manipulation and acceleration will be drastically different from current operations. Examples are the 20-fold increase in injection time from 30 µs to 600 µs, upgrading from 15 Hz to 20 Hz operations, bucket to bucket transfers rather than paraphrased capture between the PIP-II Linac and the Booster, the relocation of the injection point from L1 to L11, and using a shorter pair of D magnets in the injection girder. All these changes will require focused and well-planned physics studies to understand the implications for changes in operations. In addition, vulnerabilities like operating the refurbished original RF cavities at 20 Hz with a higher DC bias will need to be understood as well.

Beam effects in Recycler will need to be understood as well. The larger beam separation for slip stacking in Recycler is assumed to require off-momentum injection from the Booster. The higher intensities will likely present challenges with electron clouds and other instabilities. Instability thresholds in both Recycler and MI also need to be investigated and understood. Higher beam intensity and longitudinal emittance will require the MI to have higher RF power and a Gamma-t jump. Beam from the Booster will likely continue to have both longitudinal and transverse tails that will require new collimators for the MI8 line.

Infrastructure upgrades to the AD Ring Complex include new systems for Booster that are required for bucket-to-bucket transfers between the PIP-II Linac and the Booster, gradient magnet power supply (GMPS) regulation for flat injection, and new Recycler slip-stacking controls. Furthermore, upgrades may be necessary to implement the solutions to physics issues. These solutions may require shuffling of equipment in the galleries, new enclosures and penetrations, increased ratings of breakers and transformers, etc. A new shielding assessment may be required for the AD Ring Complex because of changes made by the infrastructure improvements.

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As a first step, please define an organizational structure for the initiative and proposed membership, along with roles and responsibilities. Please coordinate closely with PIP-II and seek the participation of accelerator experts from inside and outside Fermilab. The PIP-II project beam studies group you are participating in plans to study some of the same issues, with greater emphasis on simulation. To maximize the overall impact, and to avoid duplication of effort, work with that group to align the study scope and timelines where they overlap, or where there is potential for confusion, and plan for timely information sharing, which will benefit both. The end point for this first step is a brief report on the organizational structure, with goals, participants, process followed, and agreement on delegated responsibilities between PIP-II and LBNF, AD-AST, and relevant AD Departments. The task force should then:

1. Develop a plan and timeline for studies in the three areas listed above, with:
    a. Well identified scope and a timeline that meets the current and future accelerator needs.
    b. Identified and achievable initial studies that provide near term planning benefits.
    c. Identification of longer-term R&D that could lead to paradigm shifting breakthroughs in how the complex operates.
    d. Clearly delineated roles and responsibilities between the two studies groups.
2. Include in the plan the following critical elements:
    a. Identification of the vulnerabilities of the AD Ring Complex and validation of the PIP-II implementation/upgrade plans for 1.2 MW, 20 Hz operations in:
        i. Booster
            1. Injection
            2. Transition Crossing
            3. Extraction
        ii. Recycler/MI
            1. Slip-stacking
            2. Transition crossing
            3. Beam instabilities
    b. Identification and determination of limits to the AD Ring Complex for high intensity operations, along with potential solutions for increasing those limits.
    c. Determination of the infrastructure vulnerabilities for 1.2 MW operations.
    d. An infrastructure plan needed to implement solutions.
3. Document all identified vulnerabilities and potential solutions in the Beams and PIP-II document databases.
4. For any needed activities identified that are not currently part of the AD and PIP-II plans, inform the AD and PIP-II management about the priority, impact, cost and scope of the activities.

Please deliver the first step to me by October 1, 2019, and the plan and timeline by December 31.

Mike Lindgren

cc: Mary Convery
Eduard Pozdeyev
Alexander Valishev
Jonathan Lewis
Dave Capista
Bob Zwaska

Mike L. formed an Accelerator Complex Studies task force to be ready for operations after PIPII Linac is handed over to AD.

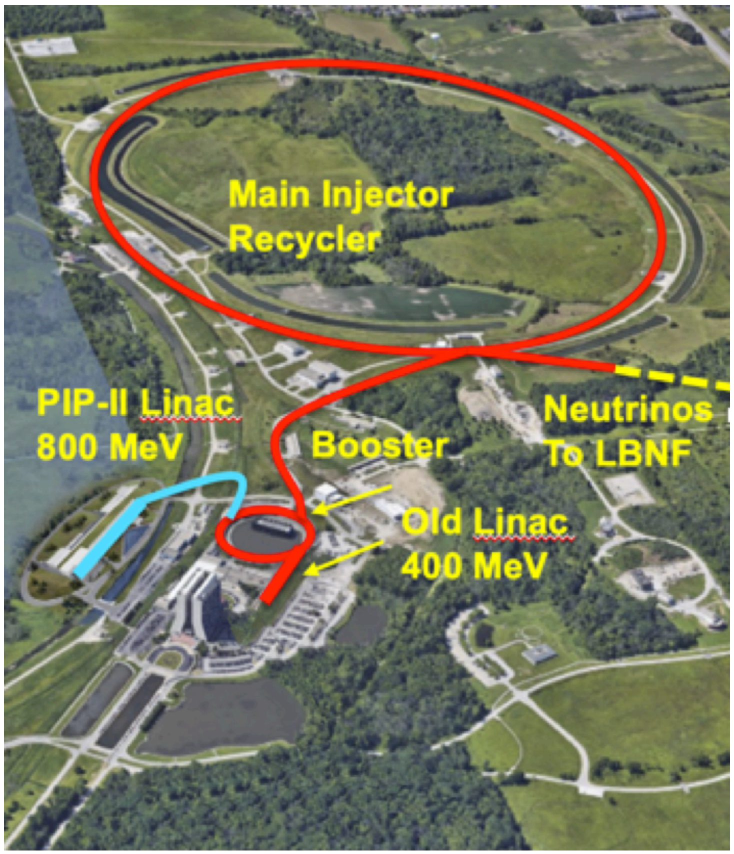
One charge of the TF is the "Identification of the vulnerabilities of the AD Ring Complex and validation of the PIP-II implementation/upgrade plans for 1.2 MW, 20 Hz operations …"

People (alphabetical order)

- Proton source
  - C. Bhat, S. Chaurize, E. Cullerton, J. Eldred, D. Johnson, J. Johnstone, V. Kapin, W. Pellico, B. Schupbach, K. Seiya, C.Y. Tan, K. Triplett
- Main Injector
  - P. Adamson, R. Ainsworth, D. Capista, K. Hazelwood, I. Kourbanis, D. Morris, M. Xiao
- EE support
  - R. Crawford, C. Jensen, H. Pfeffer
- Instrumentation
  - N. Eddy
- RF
  - B. Chase, J. Dey, J. Reid
- Accelerator physics support
  - V. Lebedev
- Target
  - N. Mokhov, V. Sidorov, I. Tropin
- ME
  - K. Duel, R. Ridgway
- PIPII
  - V. Grzelak (formerly RF), E. Pozdeyev

Apologies if names are left out

The Fermilab Accelerator Complex (present and PIPII)



Picture and annotation from E. Pozdeyev.

The present complex > 750 kW to Nova experiment

Booster parameters (present):

1. 400 MeV injection, 8 GeV extraction
2. Injection time ~30 µs (15 turns, 2 us per turn)
3. Ramp rate 15 Hz
4. 4.5e12 protons per pulse
5. Future: 5e12 extraction, 900 kW operations

Booster parameters (PIPII, > 2026)

1. 800 MeV injection, 8 GeV extraction
2. Injection time ~500 µs (requires flat injection porch)
3. Ramp rate 20 Hz ← 33% higher rep rate!
4. 6.5e12 per pulse ← 50% more beam!
5. Goal: 1.2 MW to LBNF.

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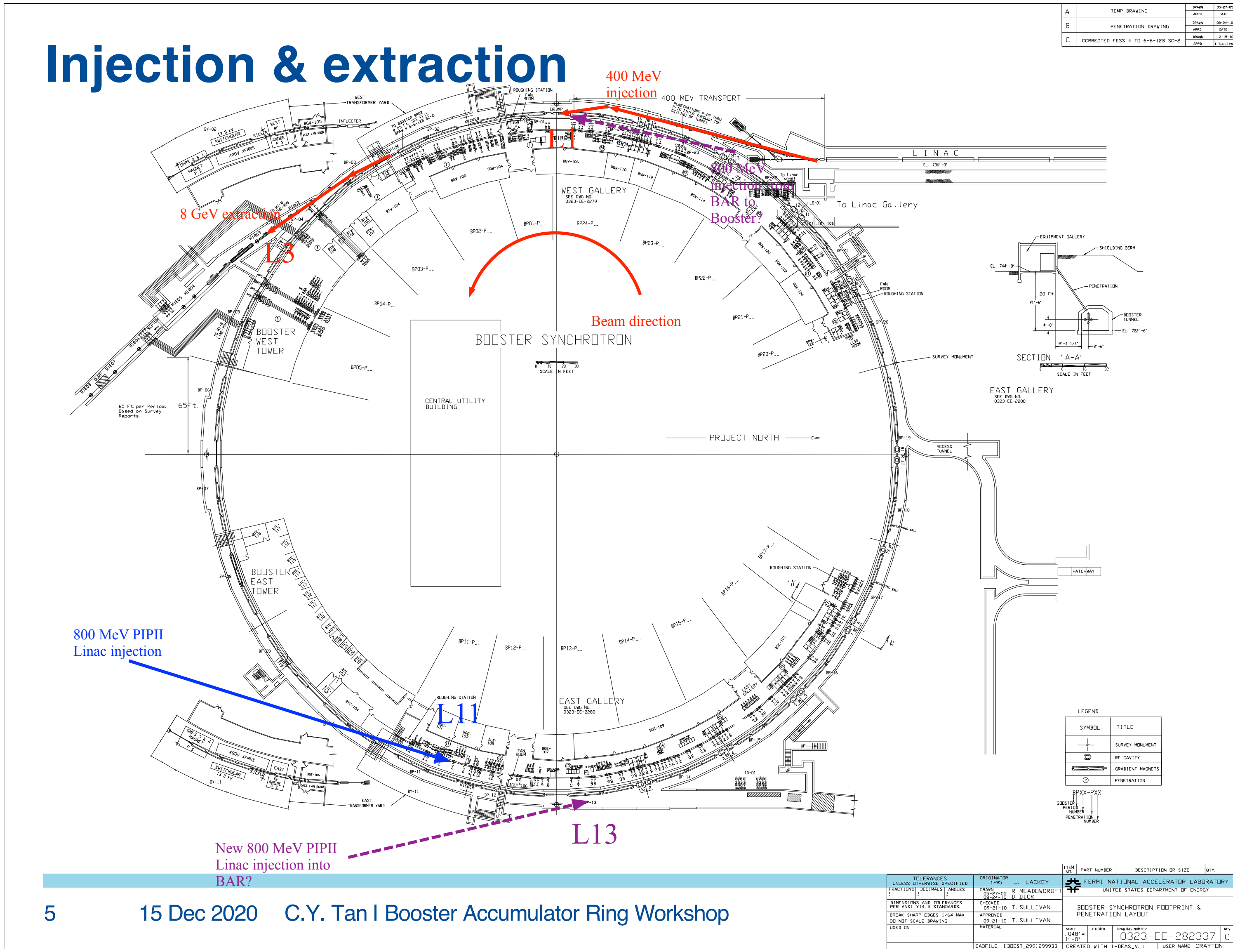
Injection & extraction



Booster radius is 75.47 m
Circumference: 474 m
(1/7 of MI)

The reason why PIPII Linac has a hook becomes clear: it's the beam direction!

Hook was first proposed by Pellico, Tan and Zwaska in 04 May 2010: https://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=601&filename=04May2010.pdf&version=2

How injection is different between PIP and PIPII

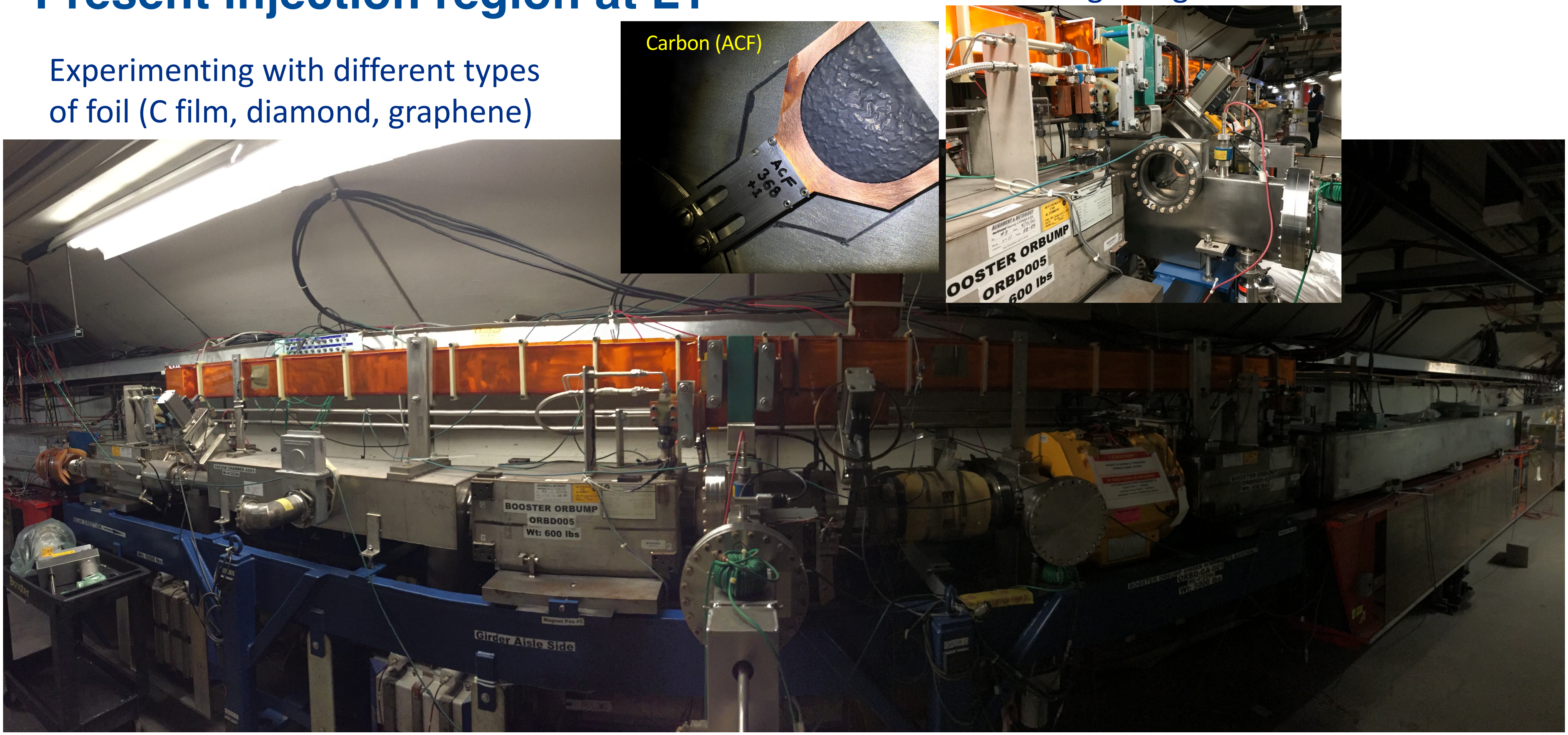
- Besides 400 MeV vs 800 MeV and 50% more beam , 33% higher rep rate, we have

PIP	PIPII	Challenges
Adiabatic capture of DC beam	Bucket to bucket transfer	New LLRF system.
Injection time ~20 to 30 us	550 us to 600 us	How to do flat injection? How flat? How to join up with ramp?
Injection at L1	Injection at L11	Activation, losses downstream. Apertures are at kickers and RF!
15 Hz ramp (33 ms with beam)	20 Hz ramp (25 ms with beam)	Change resonance. Lifetime of gradient magnets that are 50 years old!

Present injection region at L1

Experimenting with different types of foil (C film, diamond, graphene)

Long straight is 6 m



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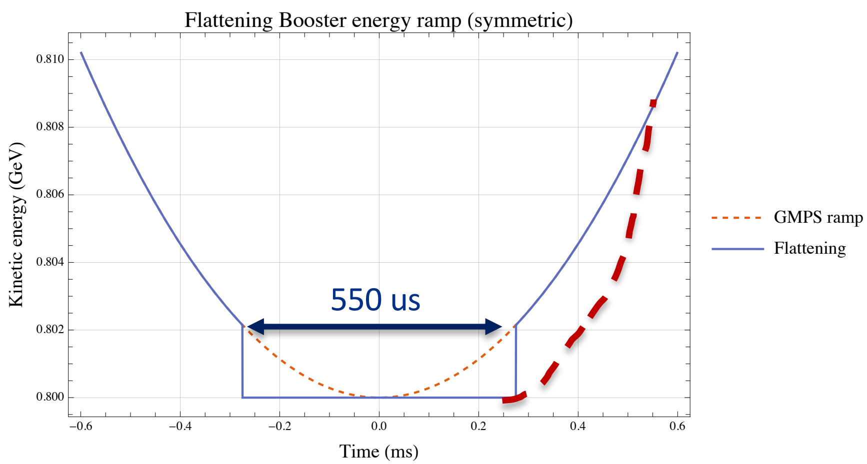
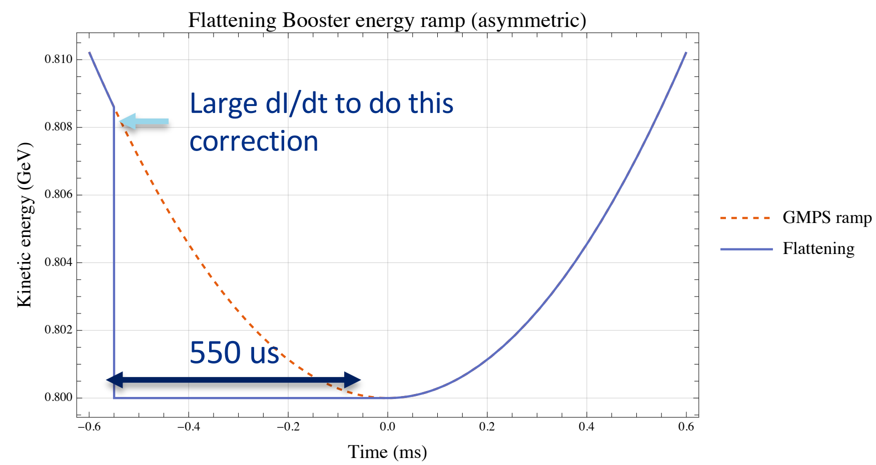
Critical problems that need to be solved

- Loss profile at injection at L11
  - This is a new location where the Linac is connected to Booster. Legacy location is at L1
    - What this means is that there are *no* collimators between L11 and the first RF cavity at L14. (solved by BAR)
    - Do we need to build new collimators or absorbers?
      - Will there be halo from injected beam at L11? No halo from beam missing foil if collimation in BTL works.
      - Problem is being worked on right now on excited H0 beam downstream of L11 being stripped by the magnetic fields. Where do these particles end up?
      - Preliminary calculations show that excited states of H0 will end up at the magnets or notcher kickers. Initial results shows that it may not be a problem because power is very low < 1 W. Lattice (solved by BAR)
    - Possibility that corrector package at L11 have to be removed to accommodate longer absorber.
      - Breaks lattice corrections, cogging and flat injection, bumps.
      - Local beta corrections developed.
      - Lattice corrections using a subset of the quads
- Flat injection (solved by BAR)
  - Flattening the injection port B-field for about ~600 us is crucial because otherwise the beam will move by > 5 mm (compared to 2 mm in PIP)
    - No more long injection, single turn injection with BAR.
  - B-field flattening with dipole correctors have been demonstrated for DC ramp, i.e. Booster at 400 MeV not ramping.
  - Dipoles have not demonstrated that it will be able to compensate at 20 Hz.
    - Higher voltages required is also a concern on the lifetime of the corrector package, eddy currents.
  - Matching to the slope of the ramping part of the ramp to the injection “flat” part can be a problem.

Symmetric or asymmetric?



How to turn off the dipoles to smoothly join with GMPS ramp?



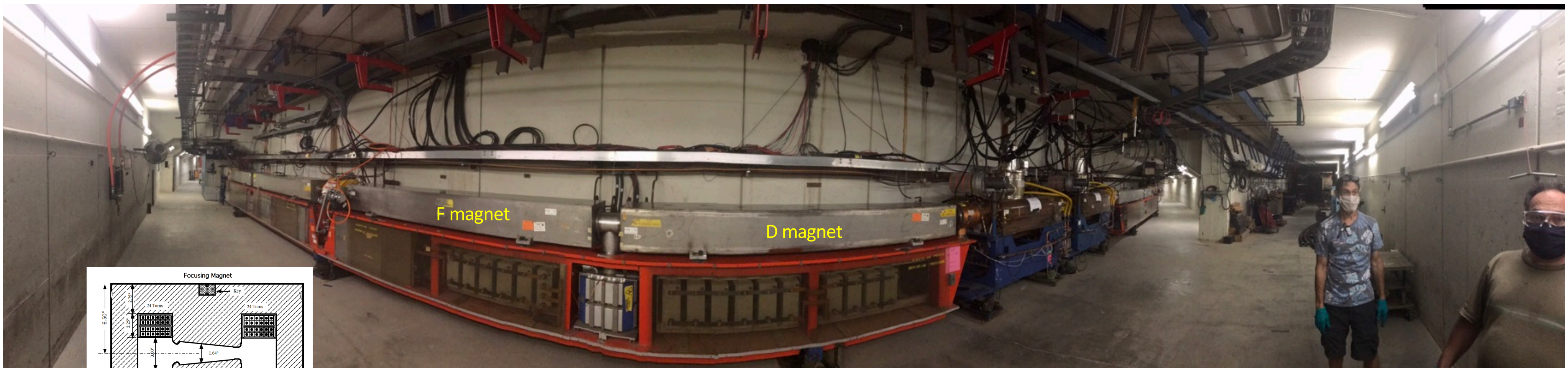
Naturally matches the GMPS ramp

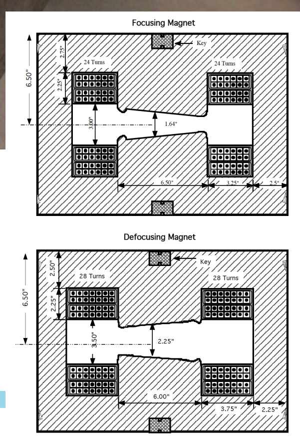
Here are two possible options and both have challenges that need to be solved. Probably longer than 550 us because of RF manipulations.

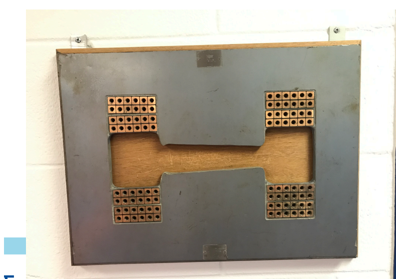
Critical problems that need to be solved (cont'd)

- Digital LLRF
  - Present analog/digital hybrid LLRF system is being upgraded.
  - It is necessary to have a new digital LLRF because of new handshaking protocols that are required between the PIPII Linac and Booster.
  - Major problems (solved by BAR)
    - Matching Booster injection porch energy to PIPII Linac energy?
      - Booster RF is "phase locked" (Note: not in the usual phase locked sense because Linac RF is not a harmonic of Booster RF) to PIPII Linac, so Booster *cannot* do any phase and radial feedback at this time.
        - Booster RF at 800 MeV is *not* a harmonic of PIPII Linac.
      - PIPII will "guarantee" energy within some specifications to be determined.
- Balance of Booster Gradient PS (partially solved by BAR)
  - With introduction of **2 different types of D magnets** (short D's at injection (not required with BAR) and tall D's at extraction), simulation is needed to show that there are no unintended resonances.
    - We probably still need the tall D's unless transverse emittances are smaller with BAR.
  - Waiting for D magnet design to get inductance specifications.
    - There is a preliminary calculation of the inductance.

Examples of magnets and RF at L13

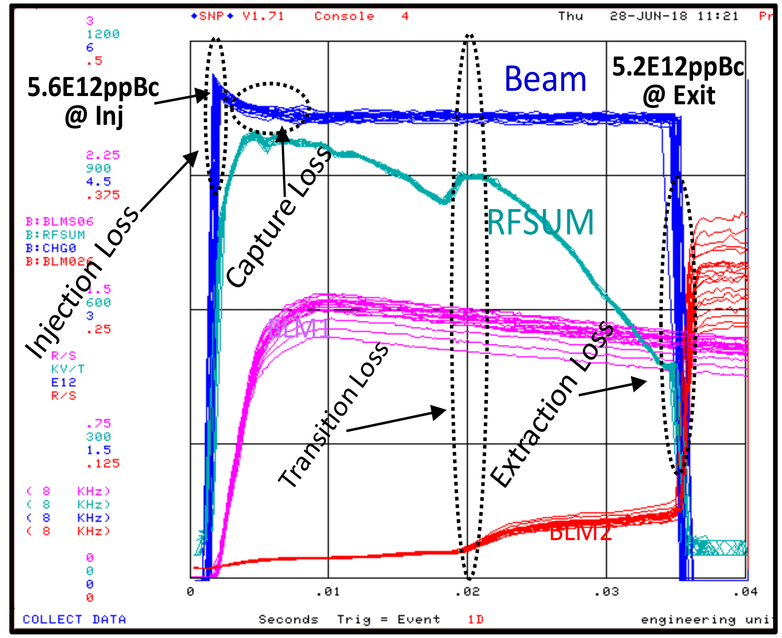






Critical problems that need to be solved (independent of BAR)

- Losses in Booster
  - During transition crossing (gamma = 5.45)
    - A subgroup has been formed to look into this problem.
      - Is it even possible to do a gamma-t jump with present quad correctors?
      - Orbit distortions from quad slews
      - Aperture limits due to dispersion
  - Extraction
    - Require larger aperture D-magnets.
      - Simulations require +/- 5 mm increase in vertical aperture.
- Beam loading compensation is required
  - Beam current increases by 50% from PIP to PIPII.
    - Calculations show beam will be Robinson unstable above 2 GeV.
    - Will start work testing in-house developed ARRIA board
  - Will need more volts from 1 MV to 1.2 MV
- There's other problems that are not listed here: Example water, magnet tests, 20 Hz etc.



Present: Beam in Booster for 33 ms.

PIPII: Beam in Booster for 25 ms

Conclusion

- Preparation for PIPII Linac era is underway
  - TF was created to make sure that AD is ready to accept beam from PIPII Linac
  - Many potential problems have been identified.
    - Work is ongoing to solve and address these problems before the first PIPII proton.
- It is important to note that whether BAR is built or not, there are other problems that still have to be worked on. But if BAR is built, the number of hard problems for Booster reaching 1.2 MW is reduced.