Fermilab Booster Synchrotron – Historical Reflections

A Celebration of 50 Years and Beyond

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2020 Annual Users Meeting

10 August 2020

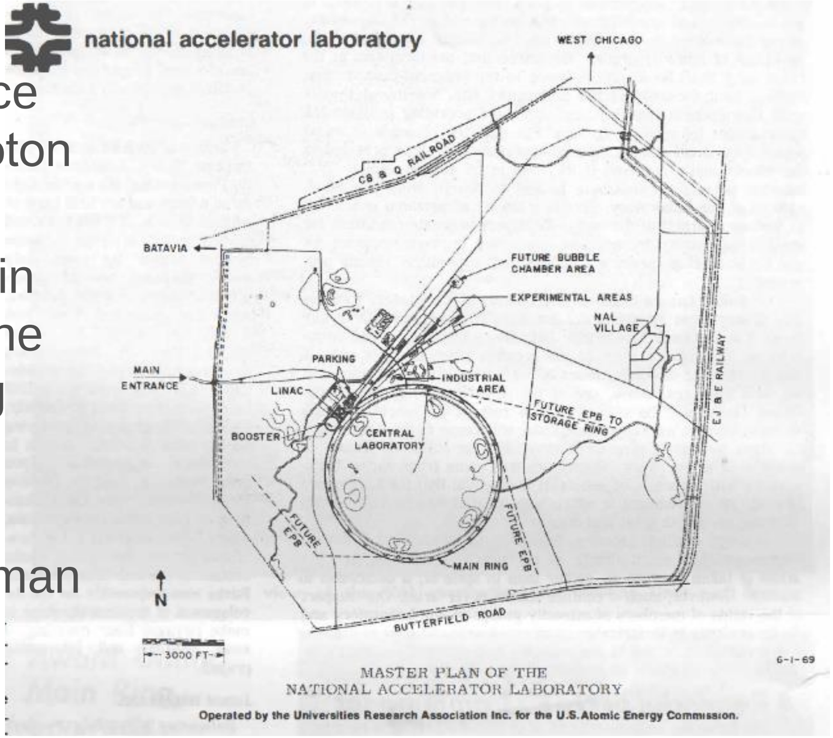
Topical outline

I will touch briefly on the following topics from a historical perspective

- The impetus to build National Accelerator Laboratory (NAL/Fermilab)
- Booster to be a critical piece to achieve a 200 GeV program
- The construction and commissioning of Booster
- The early years of Booster operation supporting fixed target HEP
- Booster support of Collider era and transition to Neutrino Program and further refinement
- Booster post Collider
- The future of Booster still viable
- Summary

National Accelerator Laboratory Beginnings

- 1963 -1966 - A developing plan for a high energy accelerator complex was taking shape. A place where a coordinated scientific effort could be coalesced for the country and the world. A place that showcased the world's highest energy proton synchrotron.
- 1967-1972 The building of the accelerator chain comprised of four accelerators would begin. The Pre-Accelerator, Linac, Booster and Main Ring Accelerator began to take shape.
- 1972-2020 - The next 48 yrs. Booster would continue to evolve as the ever willing "middle-man between the Linac and the Main Ring and eventually the Main Injector.



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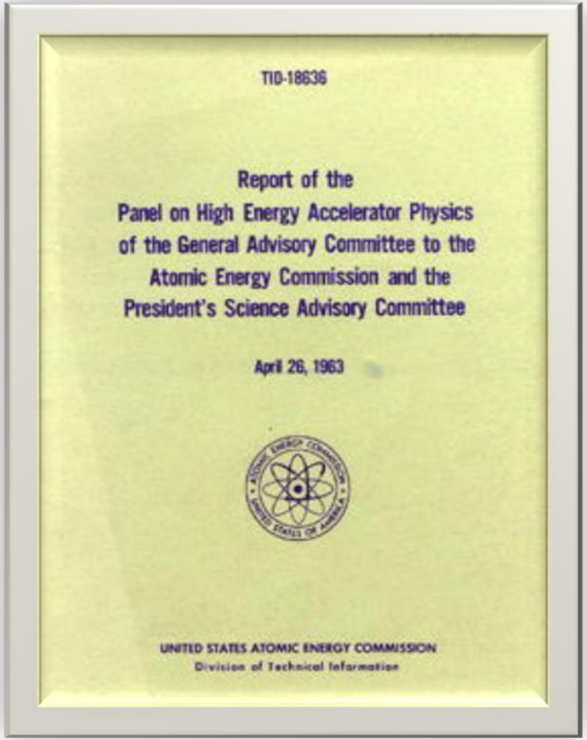
National Accelerator Laboratory – Meeting the need -1963- 1966

- In 1963 the proposal of National Accelerator Laboratory(NAL), a 200 GeV Accelerator, was promoted and headed by physicist Norman Ramsey chair of Presidents Science Advisory Committee.
- By 1965 the United States Joint Committee on Atomic Energy (JCAE) and the National Academy of Sciences (NAS) approved the NAL Project
- N. Ramsey would become president of the newly assembled University Research Association in 1966 which would manage NAL for the AEC.



National Accelerator Laboratory – Site selection 1966

- The AEC selected Weston, Illinois, in late 1966 as the location of National Accelerator Laboratory. There where 45 competing states.
- Over the next several years the 6800 acres of the town would become the grounds of NAL. Many of the farm structures where relocated and repurposed for lab needs.
- A director for the lab would be named soon.

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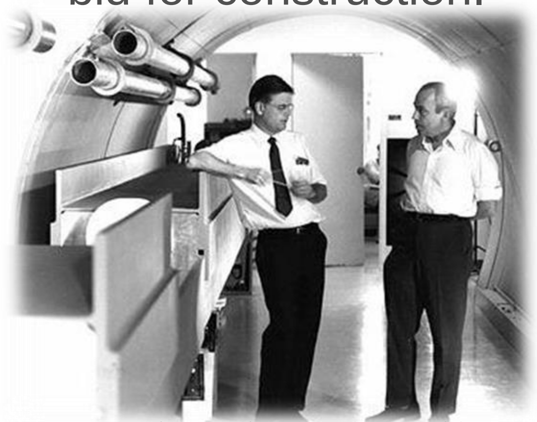
National Accelerator Laboratory – Taking shape - 1967

- Accomplished physicist, Robert Wilson, was director of Laboratory for Nuclear Studies at Cornell University at the time NAL was being proposed.
- Wilson accepted the role of director of NAL in February 1967.
- Many activities were now taking shape in 1967 with site preparations, and projects officially getting underway.
- Robert Wilson set up offices in nearby Oakbrook Illinois while the site office in the village was being prepared.
- Wilson and Edwin Goldwasser, Deputy Director, made NAL a unique Lab.
- DUSAF was the design and engineering joint venture company comprised of four entities that managed the design and engineering NAL. The Schless Construction Company, Inc., of Batavia, Illinois won bid for construction.



Robert Wilson   Edwin Goldwasser

Main Ring Model Oakbrook offices

NAL site taking shape

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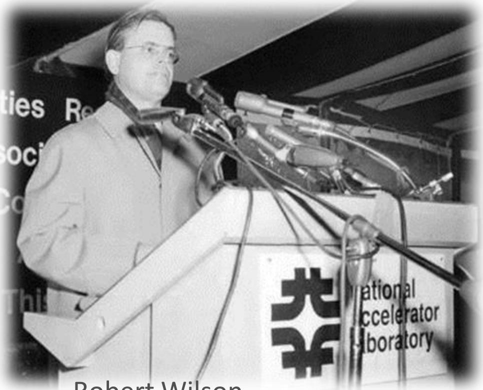
National Accelerator Laboratory- Breaking new ground 1968

- Linac groundbreaking took place on a cold Dec. 1st, 1968.
- Booster construction would begin soon but without much ceremony.
- Together Robert Wilson, Edwin Goldwasser and Norman Ramsey would be instrumental in the success of this new venture along with many creative and talented individuals that made it possible.



Robert Wilson

Norman Ramsey
URA President

Robert R. Wilson and Glenn T. Seaborg (Chair, AEC)

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National Accelerator Laboratory – 1968-69

- Between 1967-1969 support and infrastructure in the National Accelerator Laboratory (NAL) village was taking shape.
- September of 1968 marked the official opening of the village.
- Linac groundbreaking would take place Dec 1, 1968, followed by the Booster in the spring of 1969

A late Summer, 1969, aerial view focuses on the northeast section of the NAL Village. Across from parking lot is "The Director's Complex" of homes converted into offices for the immediate staff of Dr. Robert R. Wilson. Also, there is the Curia for NAL seminars. Beam Transfer, Booster, Linac and Main Ring laboratory buildings are designated.

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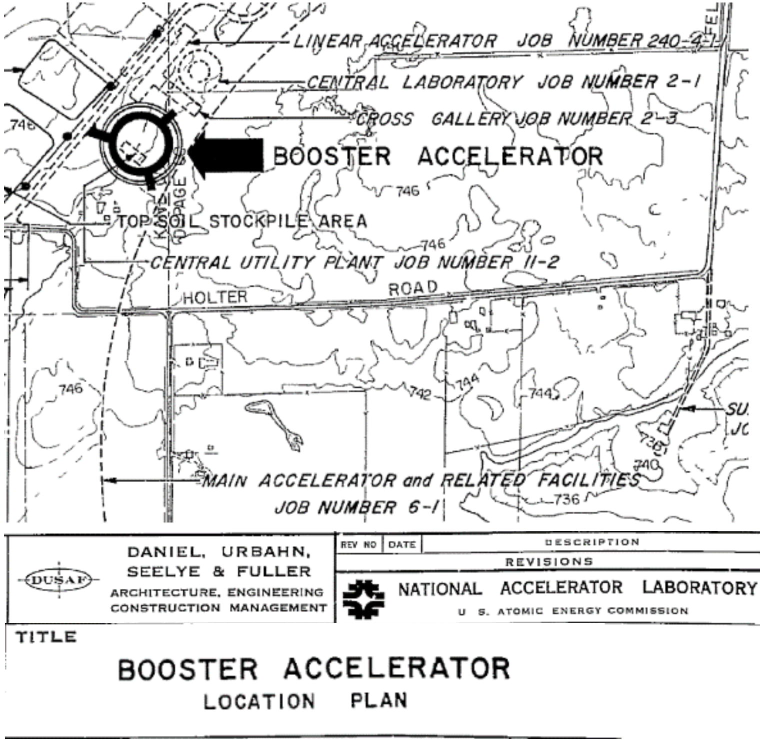
Why the Booster would need to be built

- In order to reach 200 GeV, the complex could not practically deliver protons to the Main Ring with a Pre-accelerator and Linac alone as it would be impractically long.
- The Booster ring would be a manageable size and relatively inexpensive. It was built with some similar features as the Cornell electron synchrotron which Wilson was familiar with.
- In March of 1969 Booster construction had begun



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- The Booster ring would be a manageable size and relatively cost effective. It was built with some similar features as the Cornell electron synchrotron which Wilson was familiar with, combined function magnets.
- In March of 1969 Booster construction had begun
- The tunnel would be completed by February 1970.

The Booster Construction begins – March 1969

- The Booster is about 492 ft. in diameter, 15Hz rapid cycling synchrotron.
- A 10ft wide by 8ft high tunnel enclosure ~15ft below grade contains the accelerator.

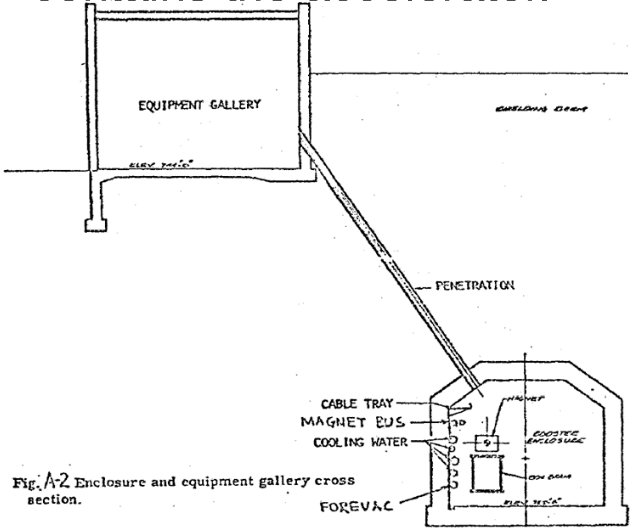
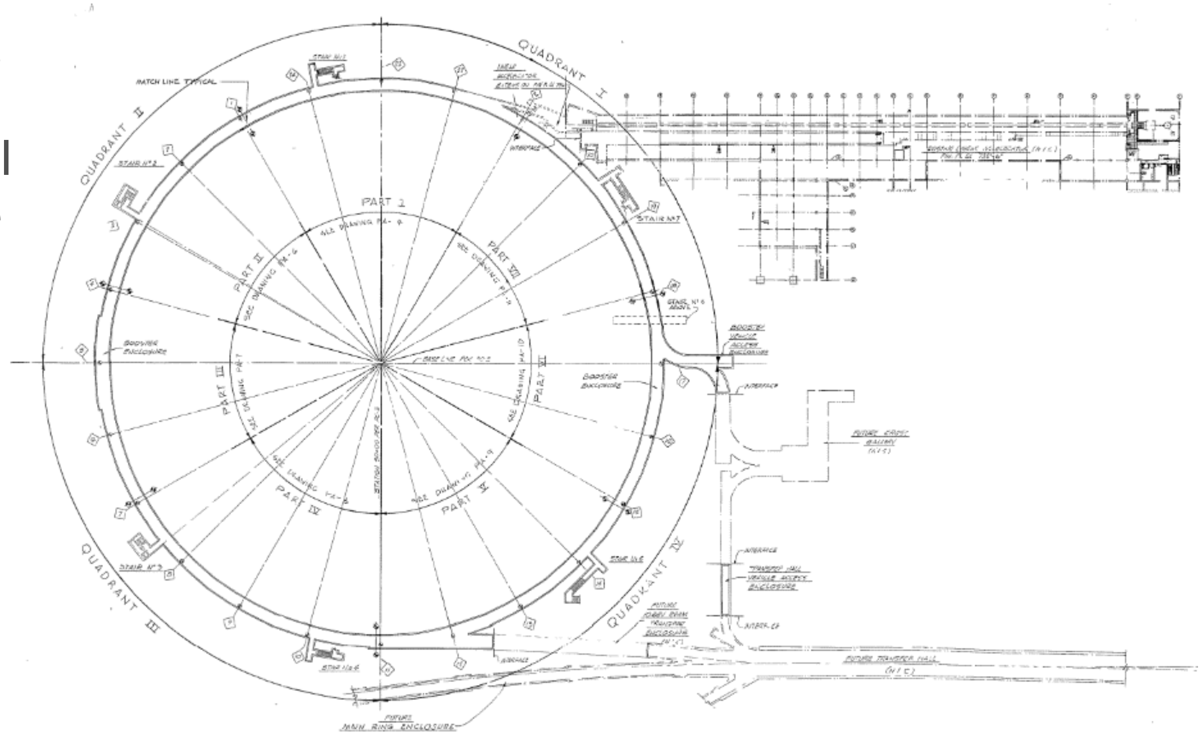


Fig. A-2 Enclosure and equipment gallery cross section.



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FNAL Booster Parameters (Legacy)

- Circumference = 2PI x 75.47 meters
- Injection energy = 200MeV/400 Mev (kinetic)
- Extraction energy = 8 Gev (kinetic)
- Cycle time = 1/15 sec, Ramp time
- Harmonic number, h = 84
- Transition gamma = 5.45
- RF Rep Rate = 3Hz/15Hz
- Injection Frequency = 30.06/37.77 MHz
- Extraction Frequency = 52.81 MHz
- Maximum RF voltage = 0.86 MV/.990MV
- Longitudinal emittance (extraction, 95%) = 0.1 eV sec
- Horizontal Beta Max = 33.7 meters
- Vertical Beta max = 20.5 meters
- Maximum dispersion = 3.2 meters
- Tune vx = vy = 6.7
- Transverse emittance(normalized at extraction, 95%) = (12-15) PI mm mrad
- Bend magnet length = 2.9 meters
- Standard cell length = 19.76 meters
- Bend magnets per cell = 4
- Bend magnets total = 96
- Typical bunch intensity = 3e10/5.1e10
- Phase advance per cell = 96 degs
- Cell type = FOFDOOD (DOODFOF)

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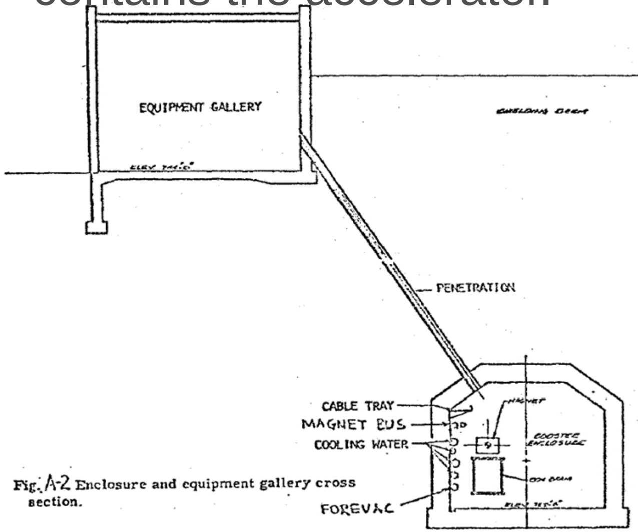
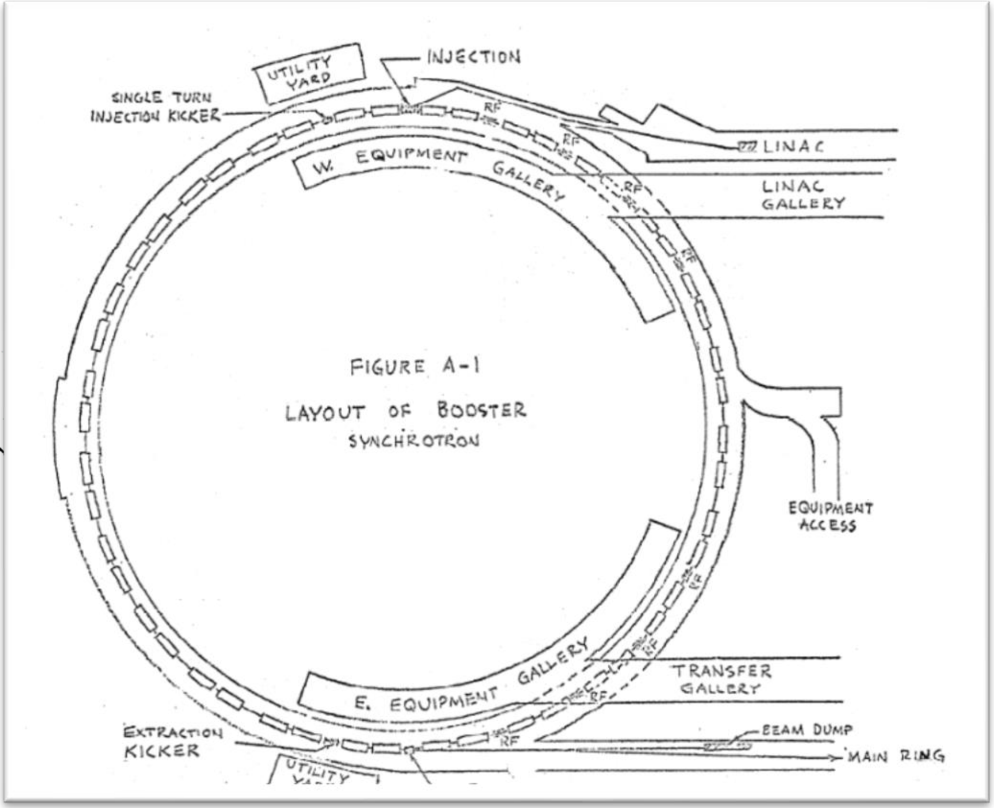


Fig. A-2 Enclosure and equipment gallery cross section.



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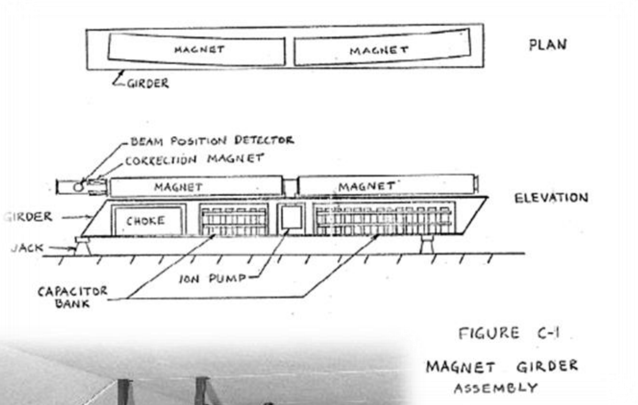
The Booster Construction begins – March 1969

- The Booster is about 492 ft. in diameter, 15Hz rapid cycling synchrotron
- A 10ft wide by 8ft high tunnel enclosure ~15ft below grade contains the accelerator.
- 48 magnet girders 25 ft long with two combined function magnets, 10ft. Long each, that focus and bend the beam. 96 magnets completing ring.
- 16 RF stations would take the 200MeV beam from Linac and accelerate to 8 GeV for the Main Ring.



2 Test girders in village with 4 magnets

The Booster Construction begins – March 1969

- Tunnel construction progressed well through 1969.

Pre-Accelerator, Linac and Booster, 1969

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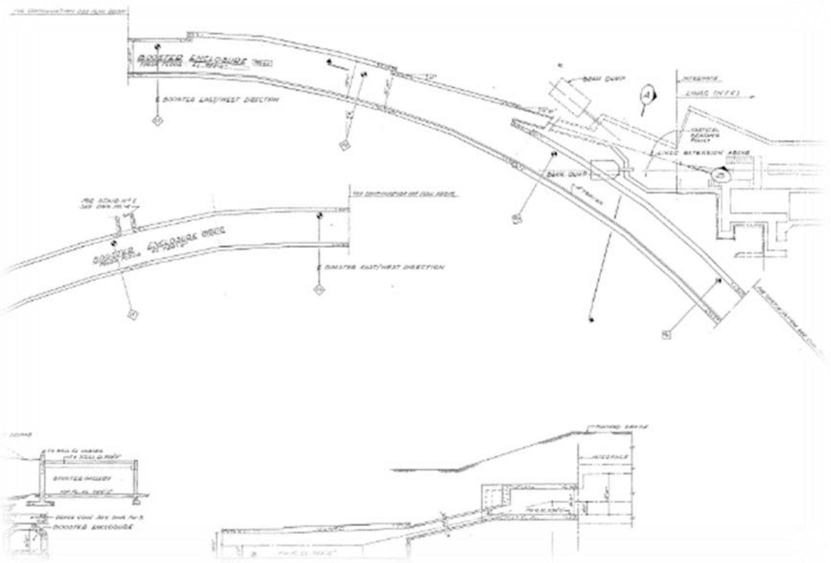
The Booster Construction begins – March 1969

- Tunnel construction progressed well through 1969.



Linac meeting Booster, 1969

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The Booster Construction begins – March 1969

- Tunnel construction progressed well through 1969.

Tunnel forming and sealing of exterior. 1969

Tunnel sections being formed 1969

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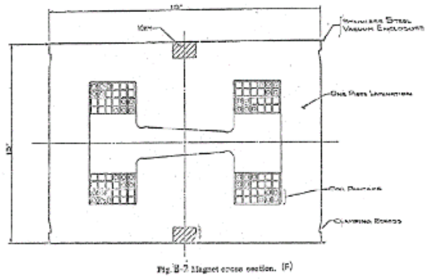
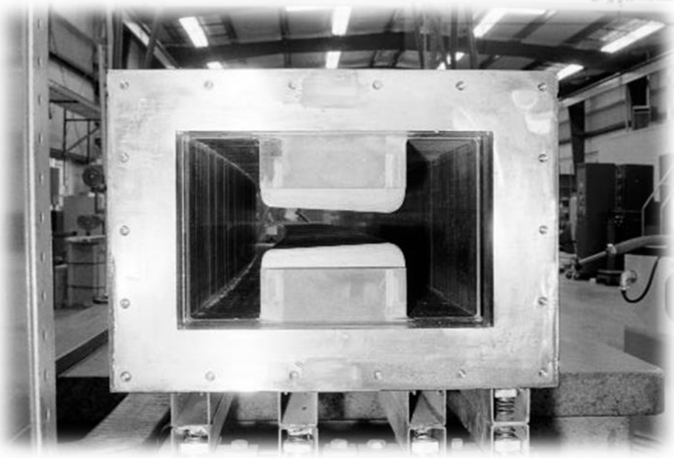
The Booster Components – assembling through 1969

- Building the Booster on site.
- The Combined function magnets and girders assemblies in the village
- As girders were completed, they would be installed.



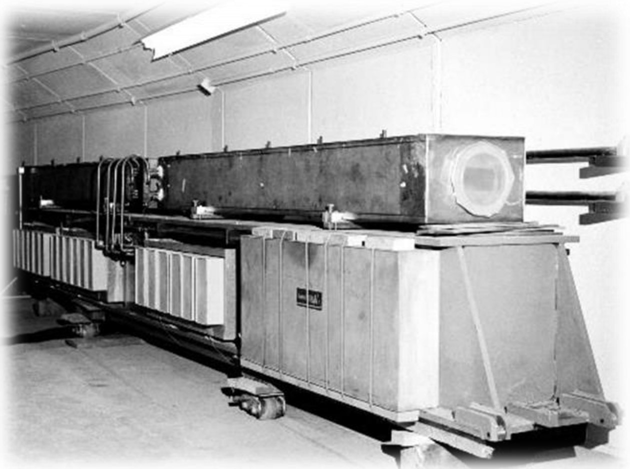
Girder component assembly



Gradient combined function magnet assembly

Booster enclosure completed on time – February 1969

- The first girder was lowered into Booster February 26th, 1969 once the construction was completed. Belding Engineering



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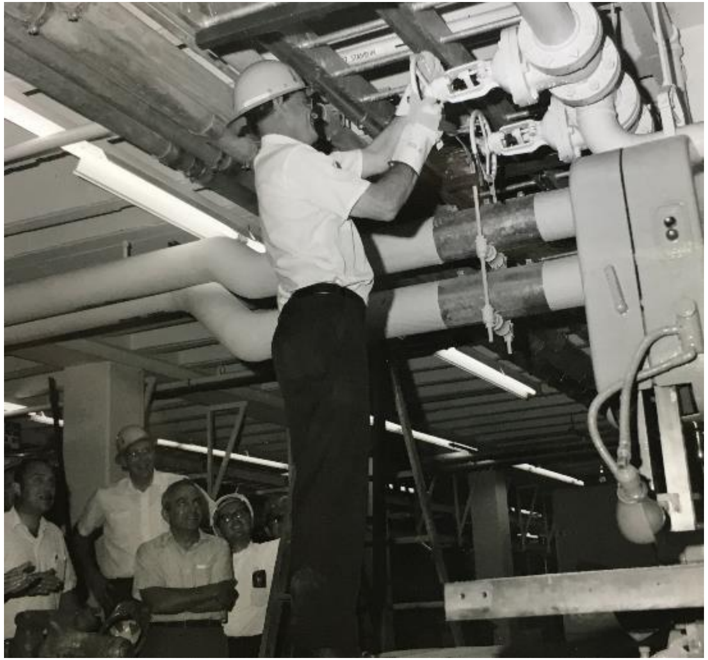
Booster Pond was filled – August 1970

- Booster cooling pond filling. August, 1970



Wilson with heavy arms after opening water valve for Booster Pond

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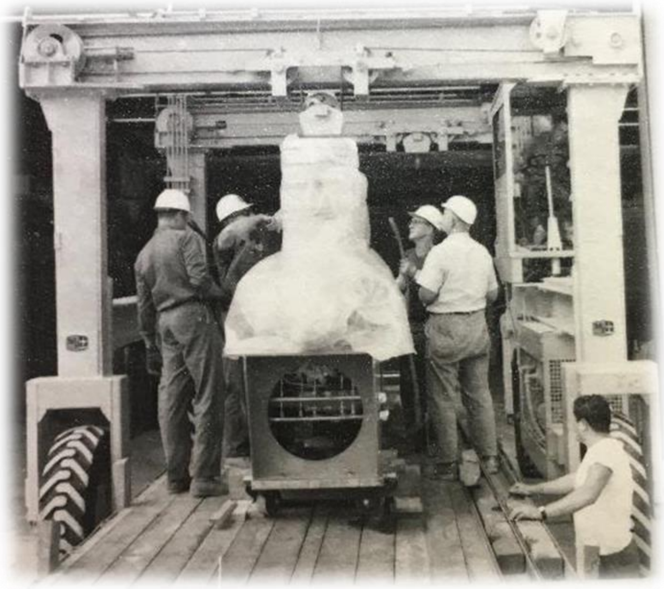
Booster Pond was filled – August 1970

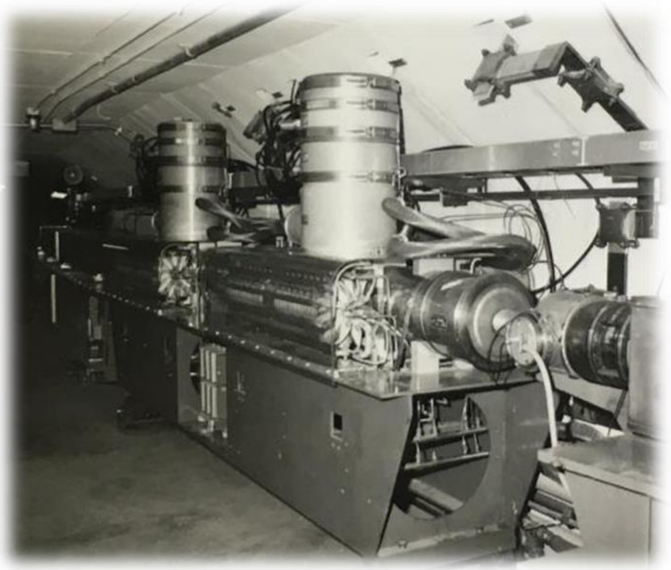
- Booster cooling pond becomes operational August 1970, now some of the girders can be power tested and cooled.

Wilson, Goldwasser and others do the first pond check

Last Booster girder is installed – December 1970

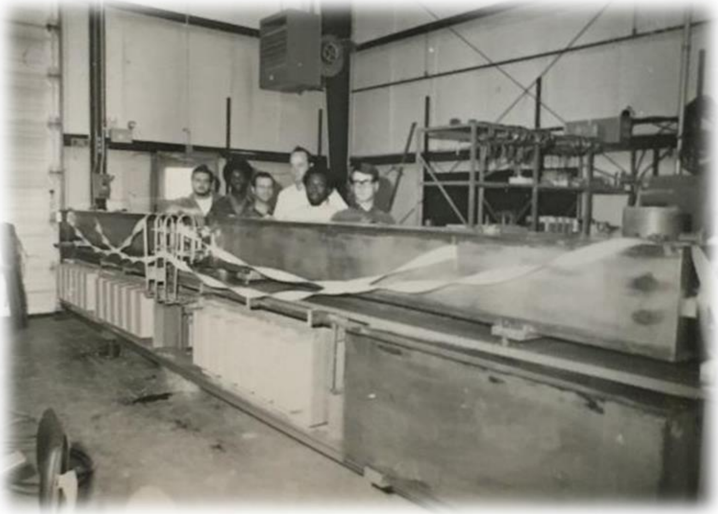
- Last of the RF stations going in.





Last Booster girder is installed – December 14, 1970

- Last girder shipped and lowered into Booster December 14[h], 1970. decorated with bows!



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Last Booster girder is installed – December 1970

- Booster girders where aligned and under vacuum by December 21st,1970.

Roy Billinge (Tie) Group Leader of the Booster group oversees last girder installation

James Humbert, Roy Billinge, Tom Topolski, Ed Stapleton

Ed Stapleton

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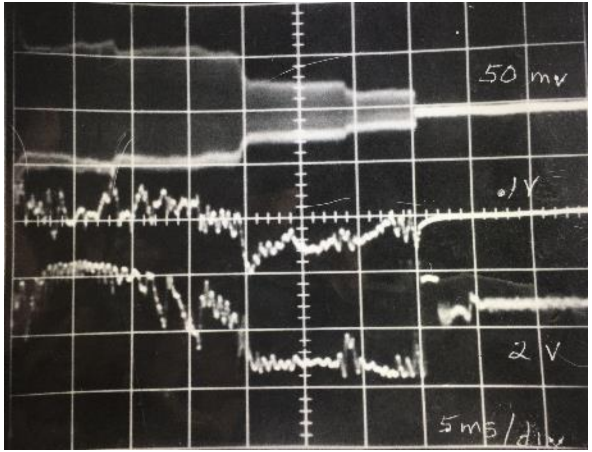
Getting Ready For Beam – January 1971

- RF systems, Magnet Power supplies and Kickers systems being checked out by early January,1971.
- Coasting Beam in Booster is seen January 23rd1971

Booster Accelerates beam to 8 GeV – May 1971

- All through April Booster systems where checked out and timed in. Low level beam feedback systems were tuned up. With incremental progress and repairs along the way it was a busy time.
- After much hard work, Boosters achieved 8 GeV beam by May 21st, 1971. It was at this point that all 16 RF stations were operational allowing beam to be accelerated to 8 GeV.

A. Mair and M. Kibilko monitor Booster beam



Booster Beam Signals

E. Hubbard, H. Gerzevske, H. Edwards

Booster Sends 8 GeV to Main Ring – August 1971- March 1972

- First turn beam in Main Ring was August 30, 1971

Wilson and Goldwasser in Main Control Room

- March 1st, 1972 Main Ring would achieve 200 GeV beam.

Booster being toured by Visiting Physicist - 1973

- Ed Hubbard (L) illustrates Booster Accelerator operation to Chinese physicists
- 14 physicists from the People's Republic of China, 1973 at NAL

- Lee Teng, NAL Accelerator Division (R), answering questions.

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Booster Synchrotron evolution – NAL now Fermilab

- After Main Ring achieved 200GeV, there where many more achievements and improvements to the complex.
- **In 1974 National Accelerator Laboratory would be dedicated to Enrico Fermi. The lab would now be known as Fermi National Accelerator Laboratory.**
- Booster would continue to improve. One significant change in 1976-78 was switching to H- ion injection into Booster.
  - H- ion acceleration in Linac allowed higher intensity Booster Multi-turn operation. This led to higher beam intensity to the Main Ring. By 1978 we were improving this mode of operation and not turning back to H+ Linac.
- By the 1980-1990 Booster was seeing improvements in Instrumentation and Controls and continuing to improve orbits and adding more RF stations.
- In 1984 the Booster built a new extraction line to support a studies beam line to send Protons to the Anti-proton source.

Booster Synchrotron evolution –

- Fixed Target was in full swing and the Tevatron was coming on stage in support of higher beam energy and retiring the Main Ring to operate in the 120 to 150 GeV domain.
- Collider operations would follow with Booster providing beam as needed.
- A big change came in 1993 when the Linac upgraded its last five drift tube RF tanks with side coupled Cavities capable of doubling the energy out of Linac from 200MeV to 400MeV. This changed required a new transfer line elements to be built and a new injection elements as well. This would help Booster improve it beam quality.

7 Klystron driven cavities to take Linac beam to 400 MeV

Linac Side Coupled 805Mhz Cavities being pulse tested but not yet installed.

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Booster Providing beam 8 GeV beam -

- In 1998-99 the Main Injector would make its debut. The Main Ring would only utilize a portion of the ring for fixed-target experiments acting as a transfer line from the Main Injector to Switchyard.
- 2002 MiniBooNE starts-up followed by NuMI 2005.
- More Booster beam throughput is required for these new experiments. Booster must now provide beam not just at 2 to 3 Hz but 7.5Hz and soon to approach 15Hz
- MiniBooNE alone will take up to 5Hz.
- After Proton Improvement Plan was established Booster was able to further support 8 GeV experiments. The BNB program begins in 2015 MicroBooNE (Booster Neutrino Beam, Annie, Icarus, SB-ND)

Booster Providing beam 8 GeV beam

- RF Cogging to reduce extraction loss
- 2003-04 would see new Booster collimators,
- 2007-09 Booster installed improved Correctors
- 2010 Proton Improvement Plan is implemented to address issues needed to keep the Proton source viable until new accelerators could replace the Proton Source as a whole. PIP was born.

Booster Collimators

New Booster Correctors

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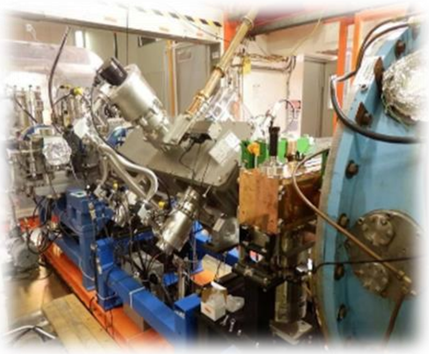
Fermilab Booster - PIP

- Pre-Acc
  - Replaced Cockcroft-Walton with modern RFQ system
- Linac
  - Replaced Linac 7651 tube in driver sys with solid state amplifiers
  - Replacing 7835 Modulator with Marx modulator
  - Upgraded Linac vacuum system and controls
  - Commissioned worlds first 200 MHz klystron – Proof of Principle
- Booster
  - RF Systems (nearly every part of drive system)
  - Added additional cavities – hot spares provide 20% overhead
    - From 18 to 22 stations
  - Upgraded Low Level System
  - BPM system – converting over to modern digital system
  - Vacuum pumps, LCW cooling and Power distribution systems
  - New Booster Cavities – higher voltage and wider apertures



54 cell Linac Marx Modulator

Fermilab Booster - PIP

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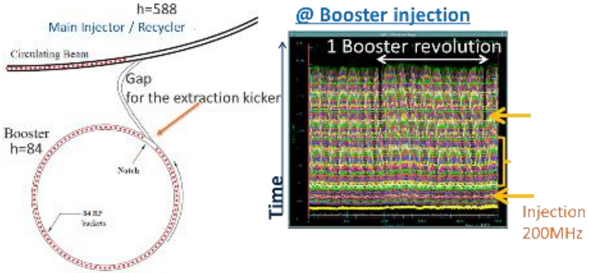
Booster – Cavity 21 & 22 installed at Long 20 Region

Refurbished Cavity and tuner assemblies.

Solid state driver in gallery connects to PA amp in tunnel. Improved PA lifetimes and

Longitudinal profile monitor @ Booster injection



81 bunches + 3 empty buckets

Notch(extraction kicker gap) – Booster extraction kicker –MI/RR injection kicker
Notch has to be created at LOW energy

K. Seiya (Fermilab Booster)

Fermilab Booster - PIP

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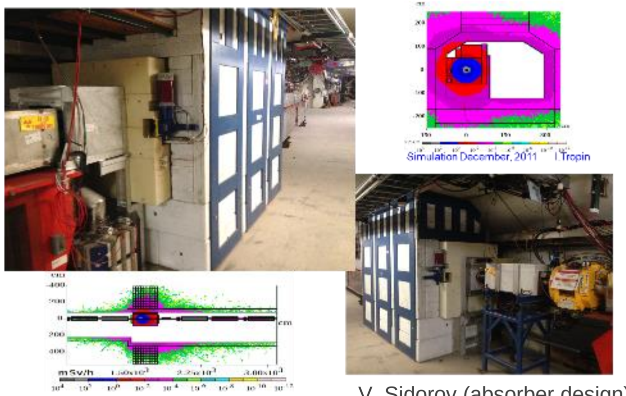
Faster Short notching Magnets

Horizontal Plane Beam Notching

Notch Absorber



V. Sidorov (absorber design)

W. Pellico- Fermilab

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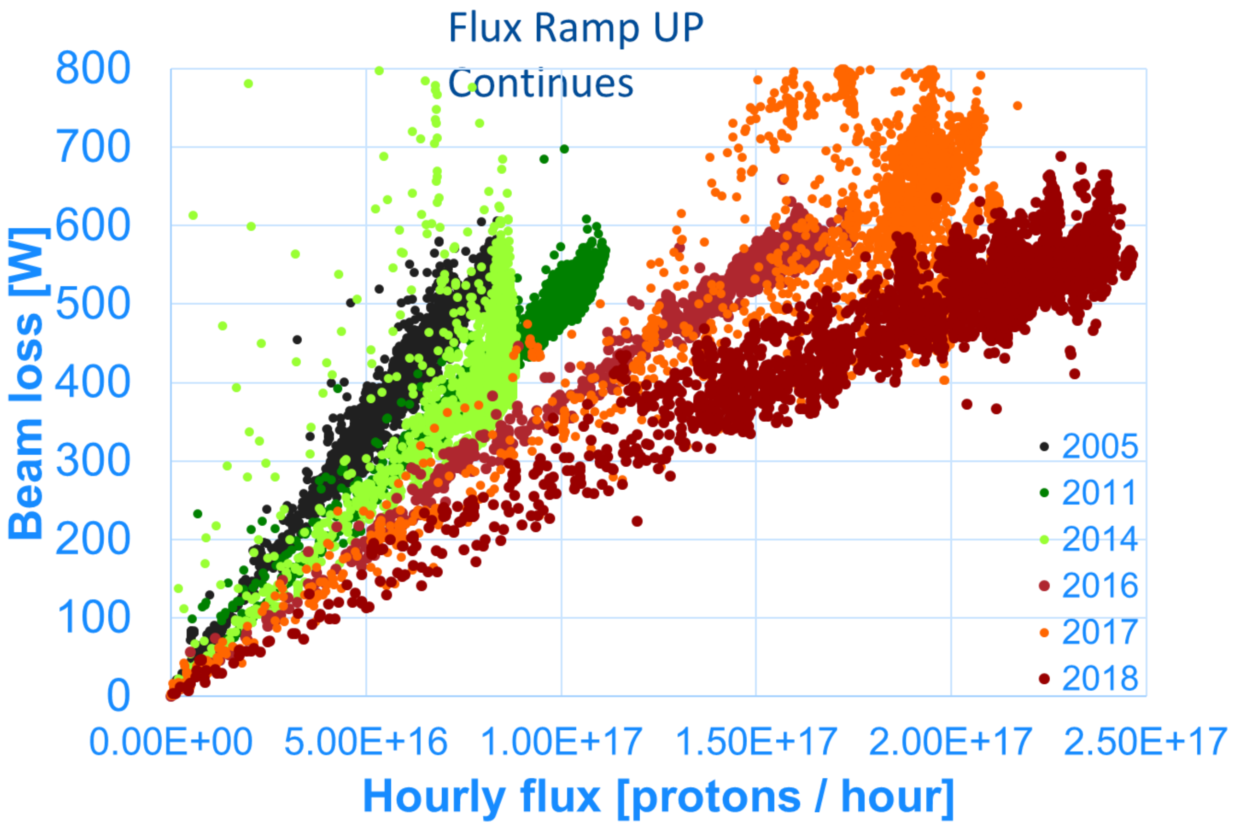
Fermilab Booster - PIP



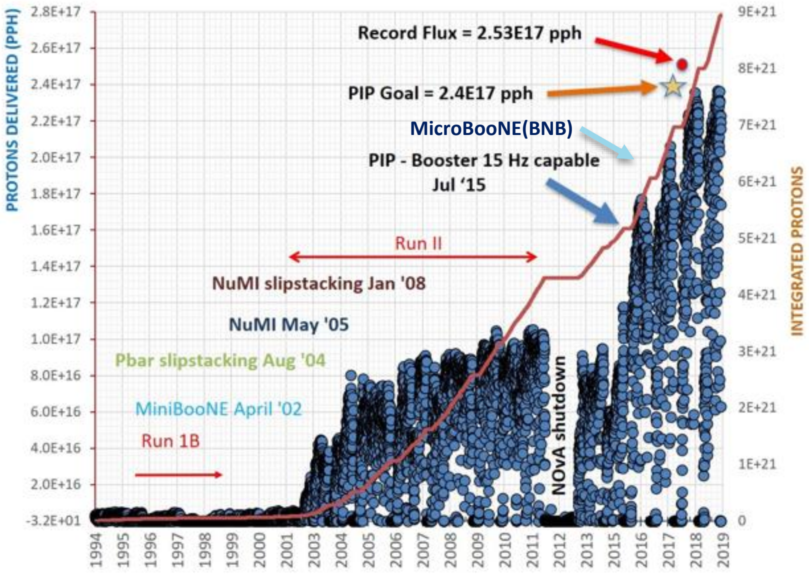
W. Pellico- Fermilab

Evolution of Booster Beam Flux to 2019

PIP campaign is $2.4 \bullet 10^{17}$ protons/hr (maintaining 2012 activation levels)

Intermediate "virtual" PIP-I+ (AIP) with a goal $2.7 \bullet 10^{17}$pph proposed in ~2017

PIP-II with the new SC linac (~2025) requires up to $4.8 \bullet 10^{17}$ pph in Booster.



Plot from W.Pellico, Beam-Docs-7601 (2019)

~2004 commissioning of **present** collimation system => ~ $2.0 \bullet 10^{16}$ pph

Increase in Booster intensity :

PIP (2017) ~x12
PIP1+ -> ~x14
PIP-II -> ~x24

Demand:
More effective control of beam losses via improved beam efficiency & collimation

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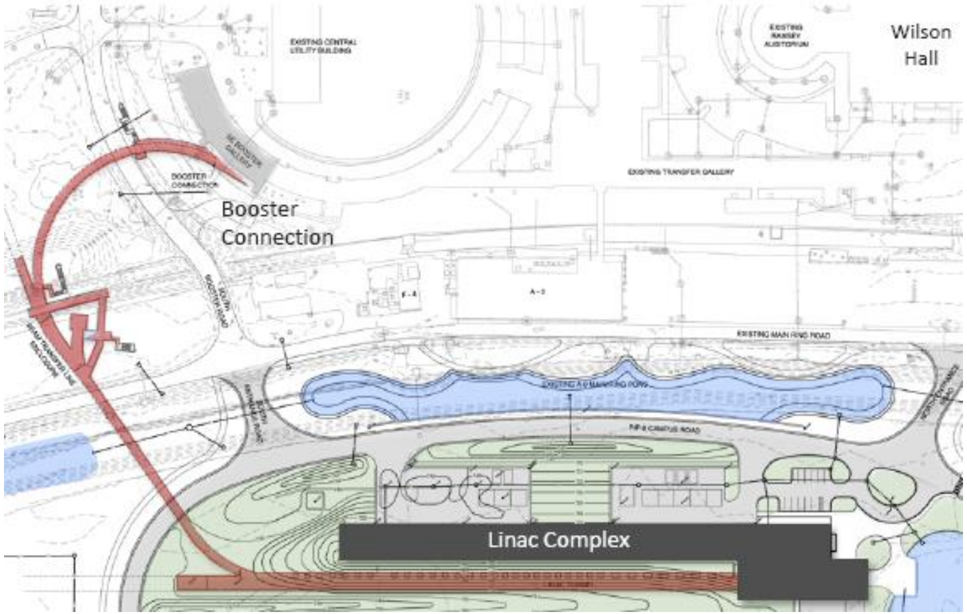
Future of Booster Operations – PIP-II

- The New SC 800MeV Linac:

Delivered H- Beam Energy	Current 400 Mev	PIP2 800 MeV
# of protons	4.7E12	6.7E12
Rep-rate	15Hz	20Hz
Avg Beam Current per turn	25mA	2mA
Injection Time	30 us	550 us



S. Dixon

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Summary

- Booster has met the increased proton demand from users of the Booster HEP experiments, to the users of Main Ring (in the past) and Main Injector (today) very reliably.
- The Fermilab user community has pushed the Laboratory to strive for greater performance to meet the needs of HEP community and Booster has met that challenge.
- The Booster has outlasted the original four accelerators by either being in operation still and having most of its core components intact.
- The Booster Group would like to thank the many groups at Fermilab that have helped build, maintain, control and monitor the Booster over the past 50 years!

Slide historical content acknowledgments

- NAL/Fermilab Village Crier volumes
- Fermi News Articles
- Fermilab On-line historical resources
- Creative Services Photo archive
- TM-405 E. Hubbard, FNAL

END