MEBT Laser Notcher (Chopper) for Booster Loss Reduction

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- Alignment crew
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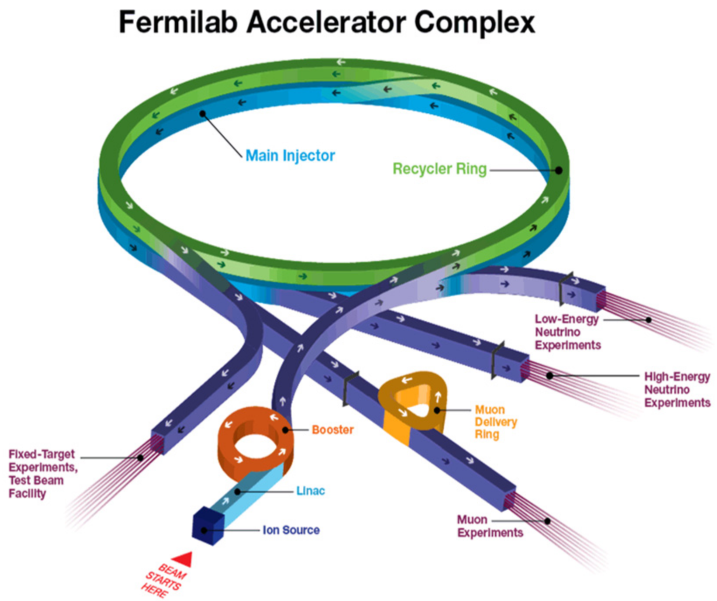
- Jay Doster & Dennis Lockwood Grumman
- Plus many others

Outline

- Introduction to Fermilab
- Introduction to Proton Source
- Laser Notcher System
- Booster Injection with Notches in Linac beam
- Operational Impact
- The un-expected
- Path forward
- Summary

Introduction to Fermilab Accelerators & a Little History



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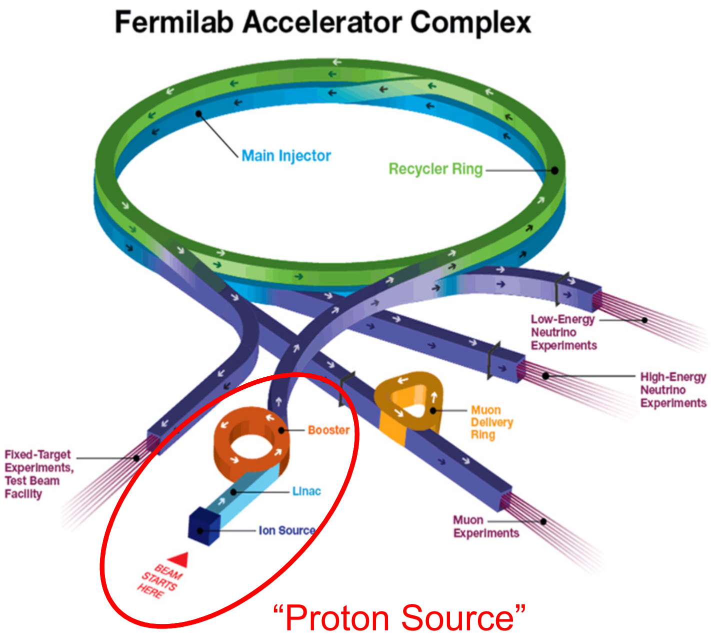

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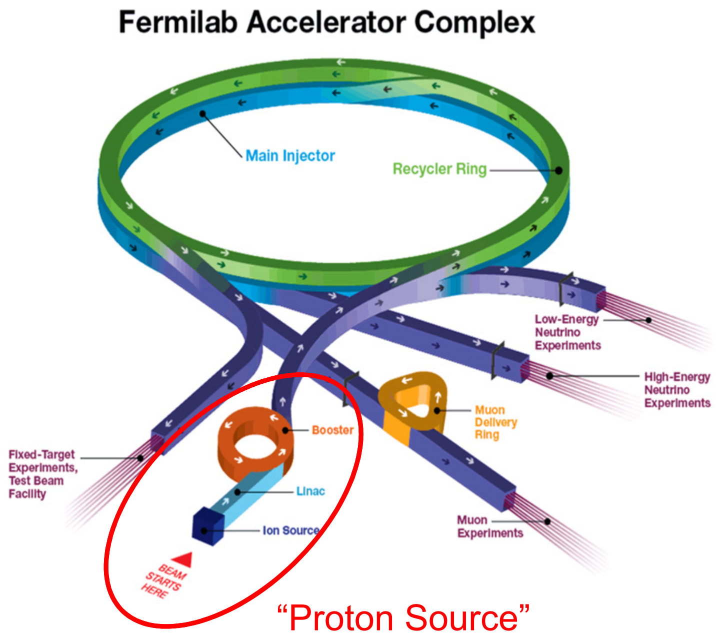
Transitioning from Energy to Intensity Frontier



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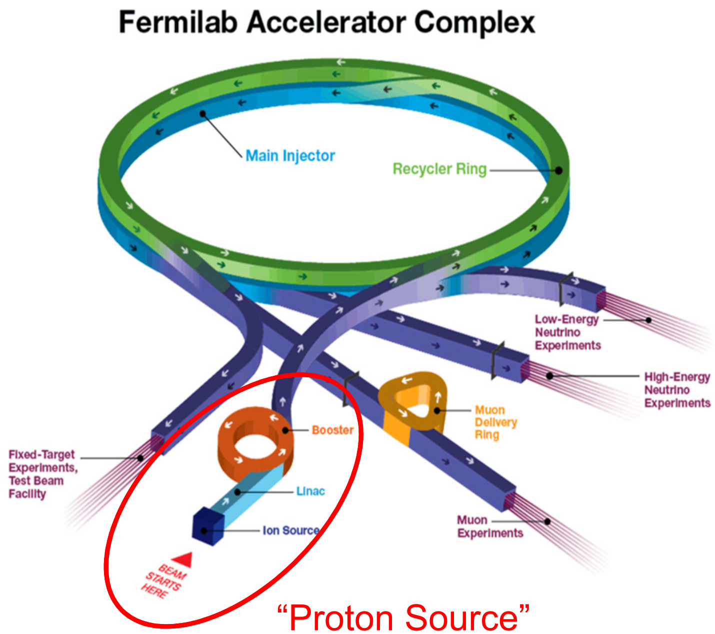

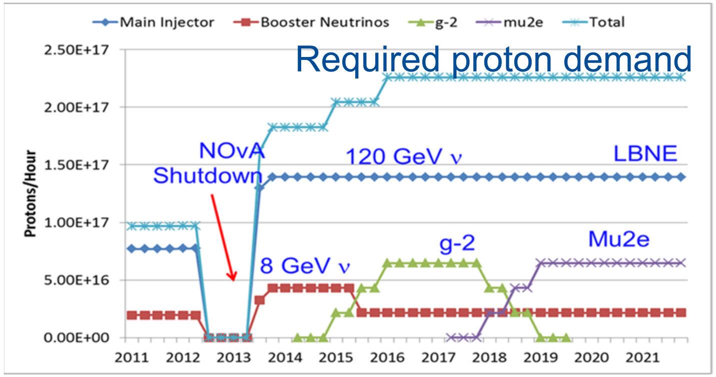

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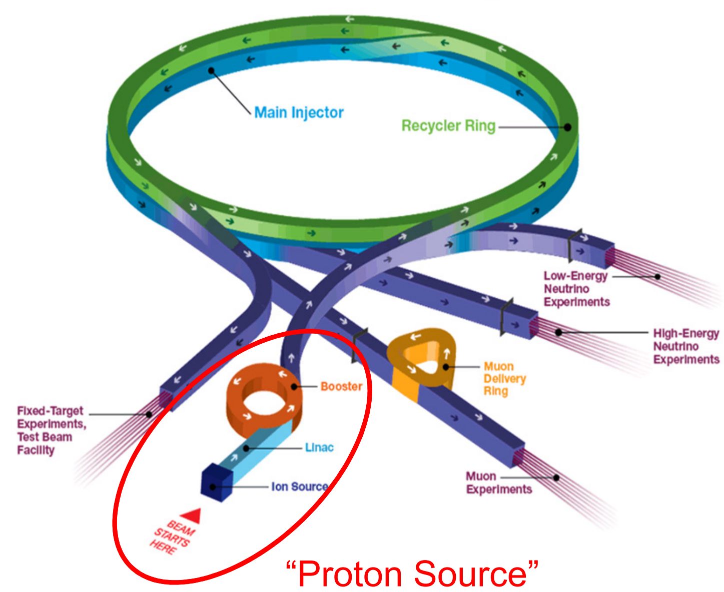
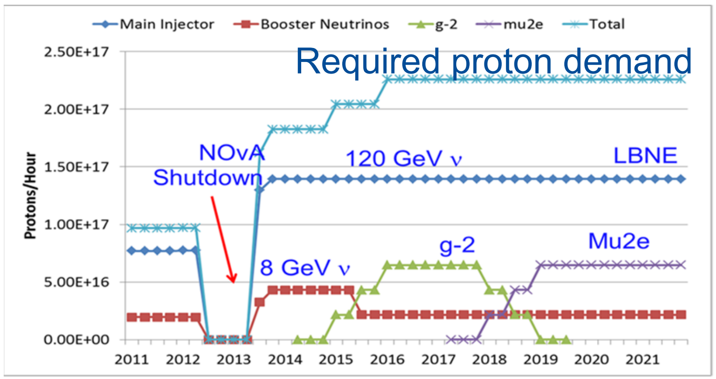
Transitioning from Energy to Intensity Frontier

First task replacing old Cockcroft-Walton with new RFQ inj. line

Fermilab Accelerator Complex





Fermilab

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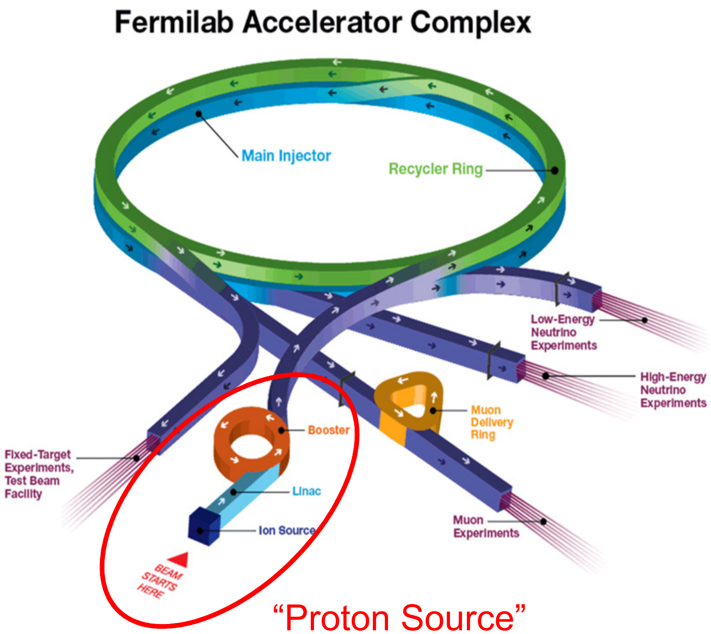
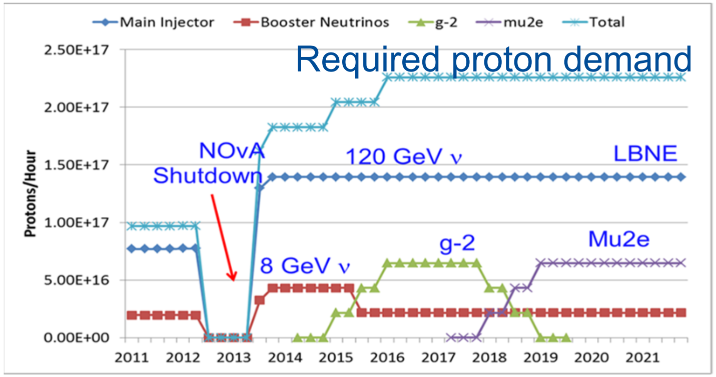


Transitioning from Energy to Intensity Frontier

First task replacing old Cockcroft-Walton with new RFQ inj. line

- Proton Improvement Plan (PIP) 2011
  - Double flux without increasing loss
    - From ~1.1E17 /hr to 2.25E17 /hr with loss < 1W/m
  - Up-time (availability) > 85%
  - Proton Source remain viable to 2025



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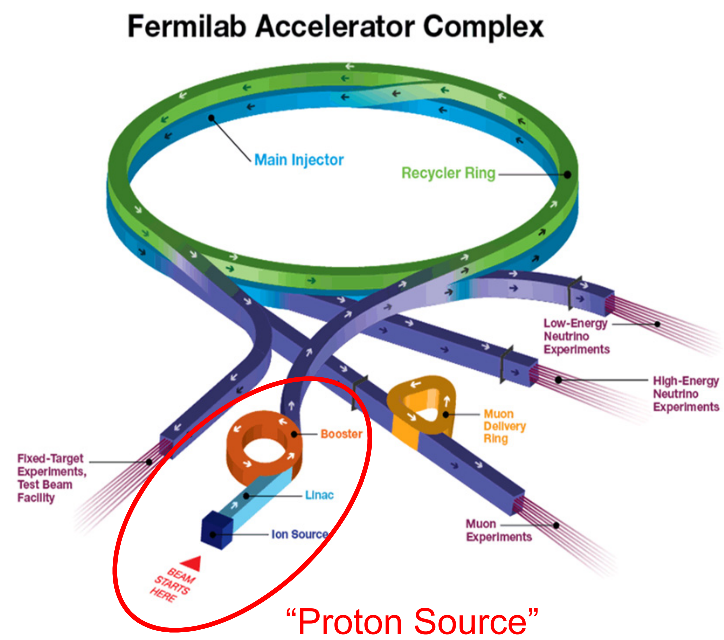

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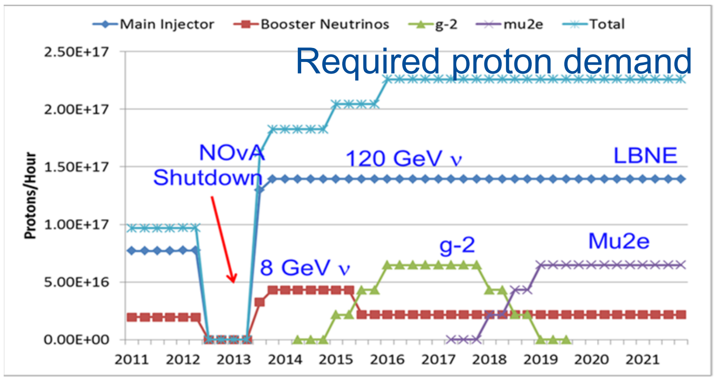
  - **Up-time (availability) > 85%**
  - **Proton Source remain viable to 2025**
- **Additional Accelerator Improvements (AIP)**
  - **Further increase throughput to 2.7E17/hr to support 900kW Neutrino running**
  - **Prepare for PIP-II to come on line in 2028**



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Introduction to Proton Source

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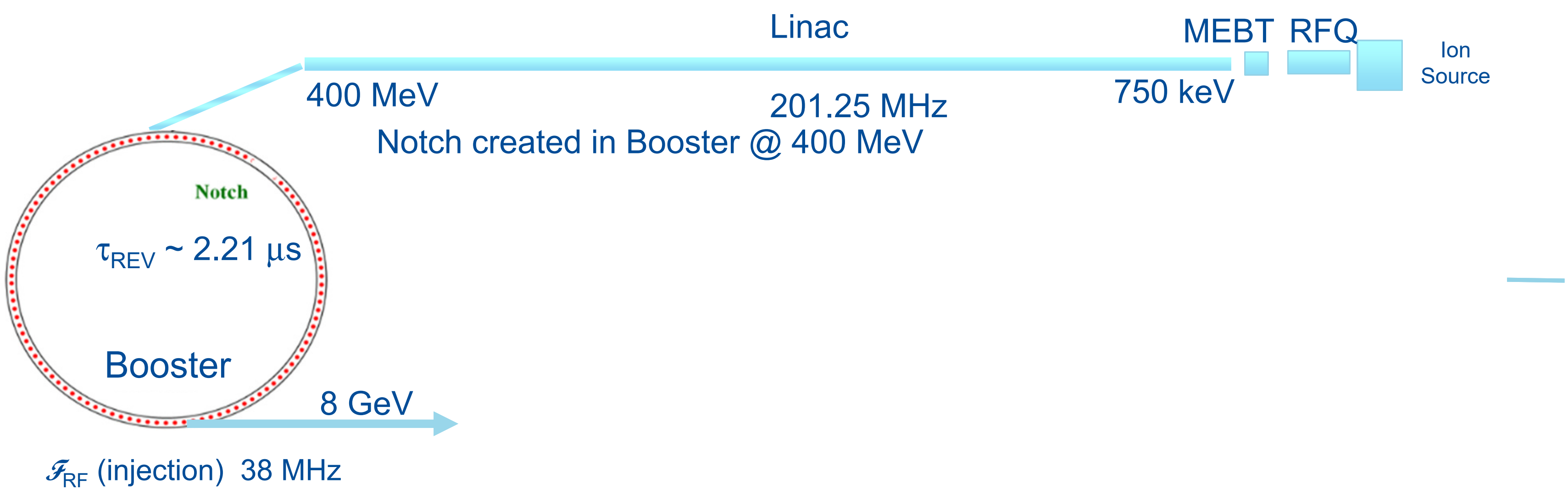

Introduction to Proton Source

Linac

MEBT RFQ

Ion Source

400 MeV

201.25 MHz

750 keV

Notch created in Booster @ 400 MeV

Notch

τ_{REV} ~ 2.21 µs

Booster

8 GeV

$\mathscr{F}_{RF}$ (injection) 38 MHz

Fermilab

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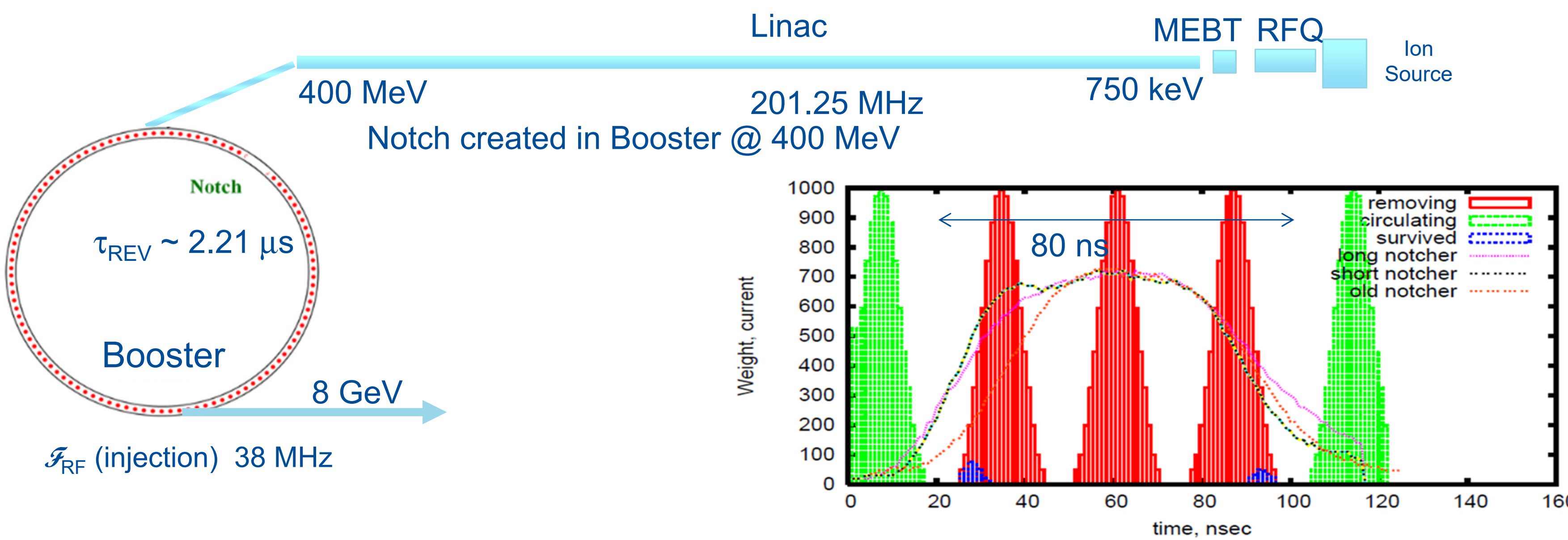

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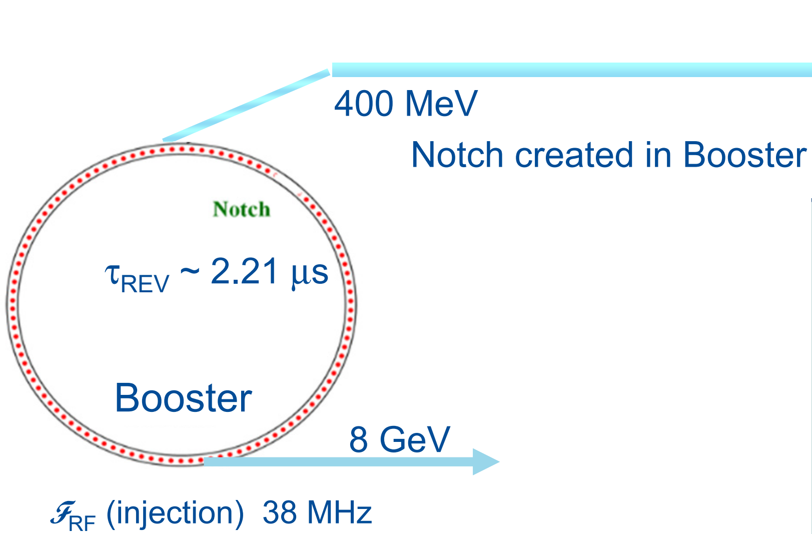

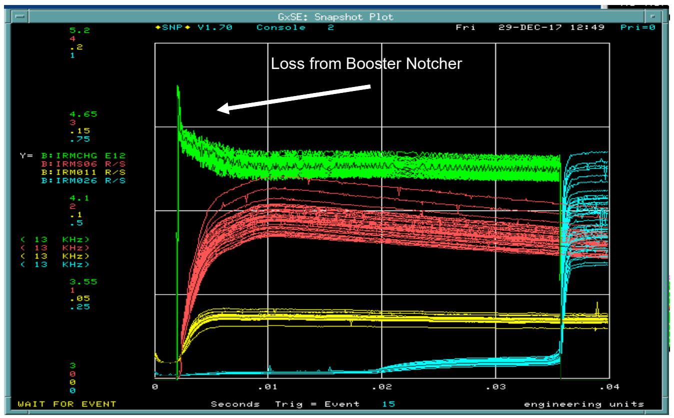

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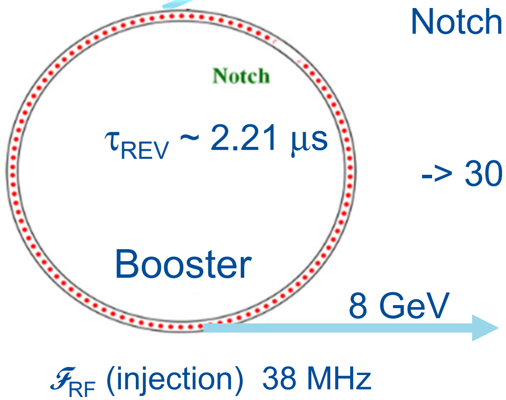
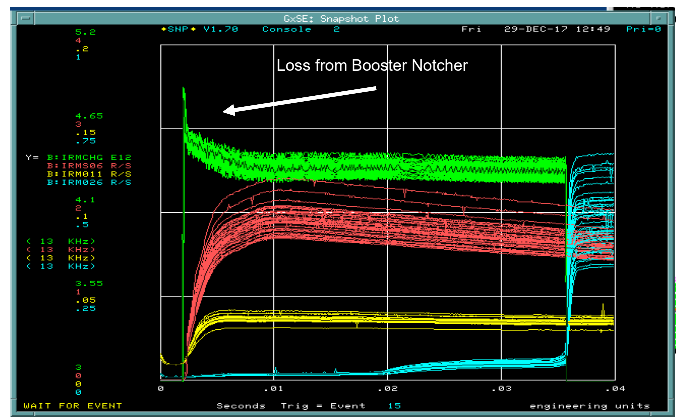


-> 30% total power loss



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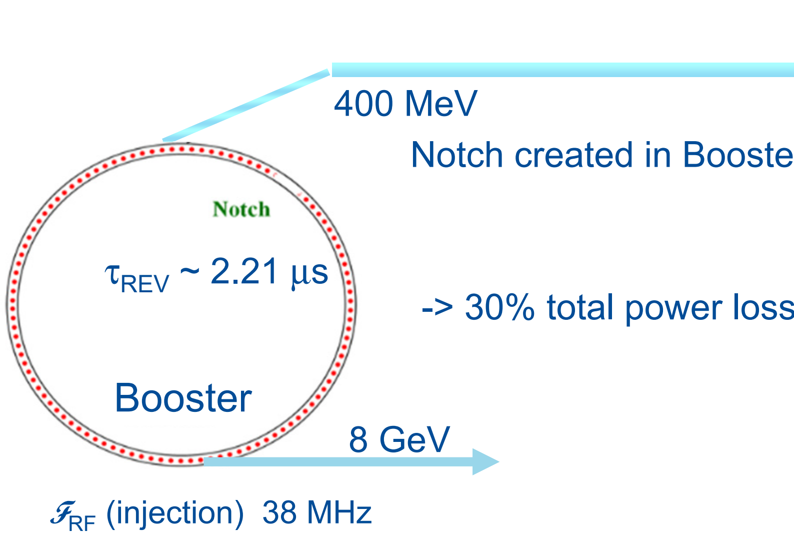

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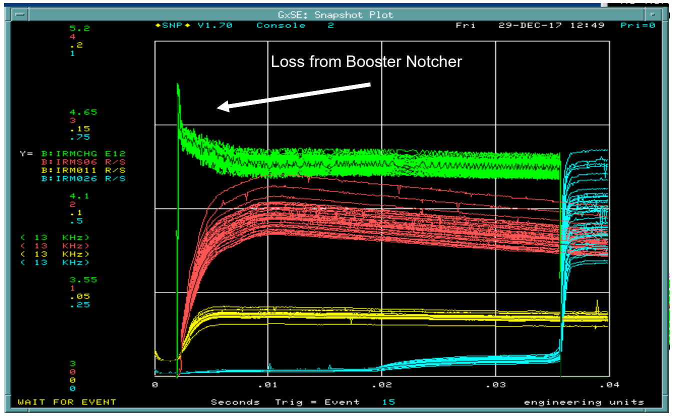

-> Move this process out of the Booster tunnel

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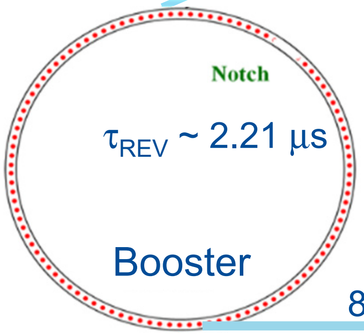

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8 GeV

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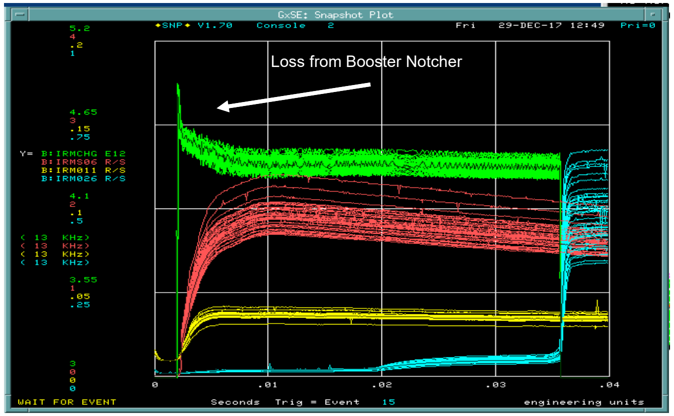

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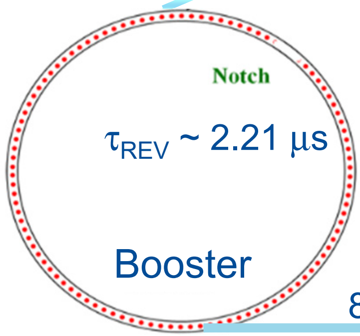

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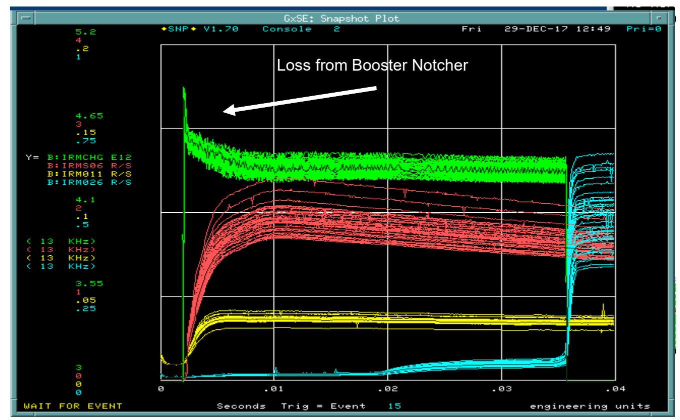

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LINAC PULSE

~35.5 us (~ 16 Booster turns)

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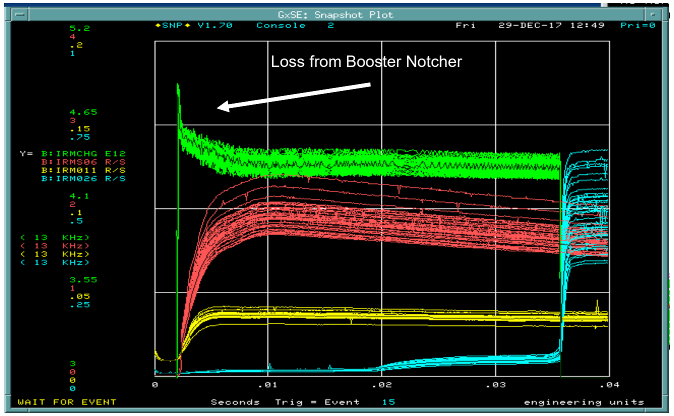

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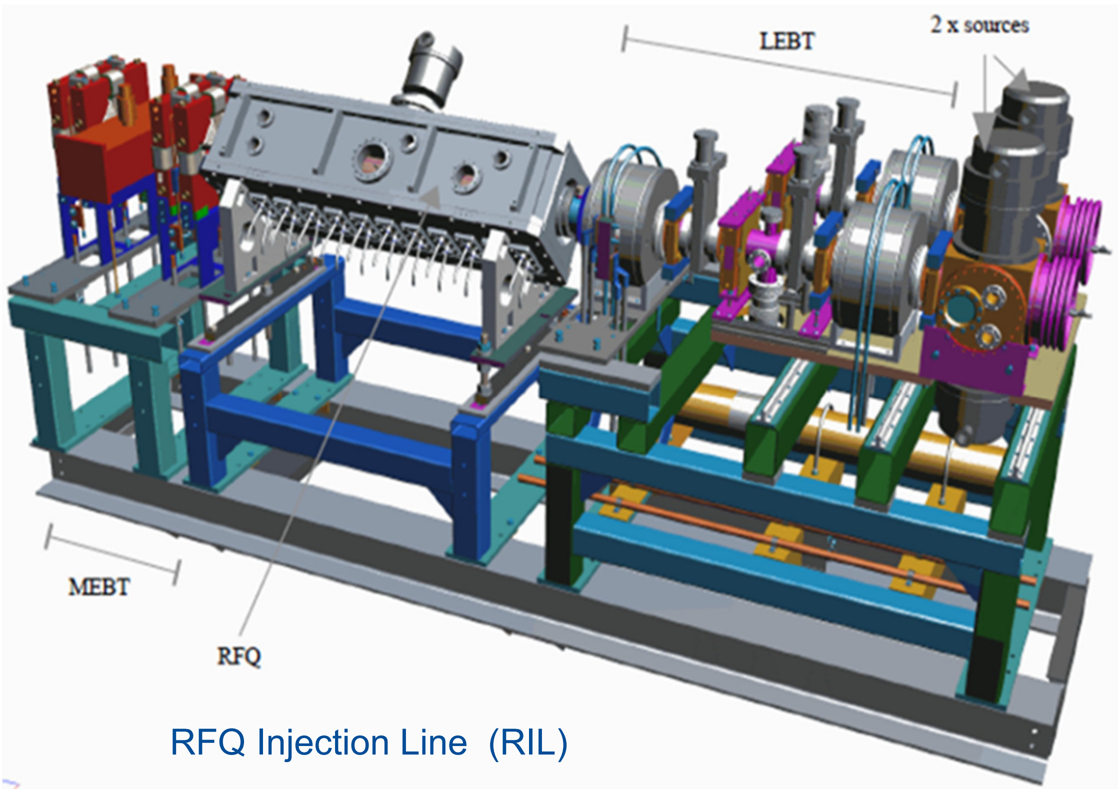
Introduction to Proton Source: the New Linac RFQ Injection Line (space constraints)



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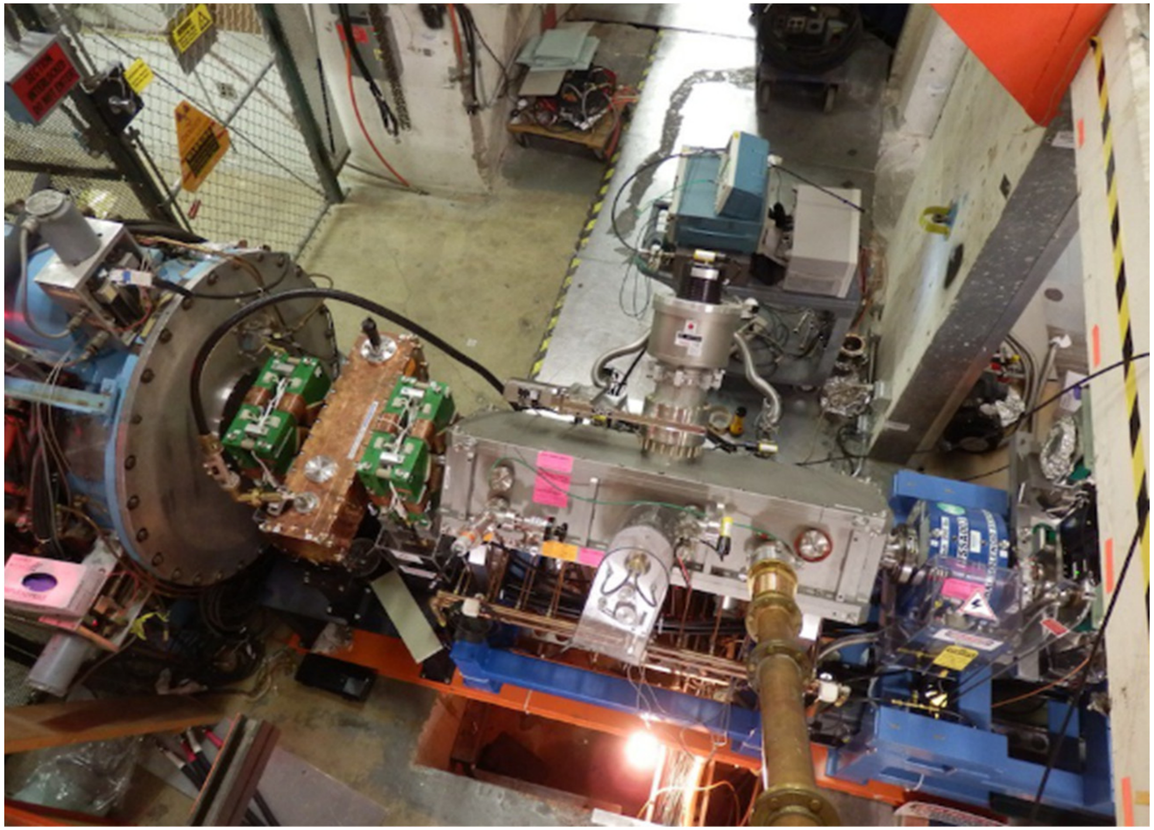

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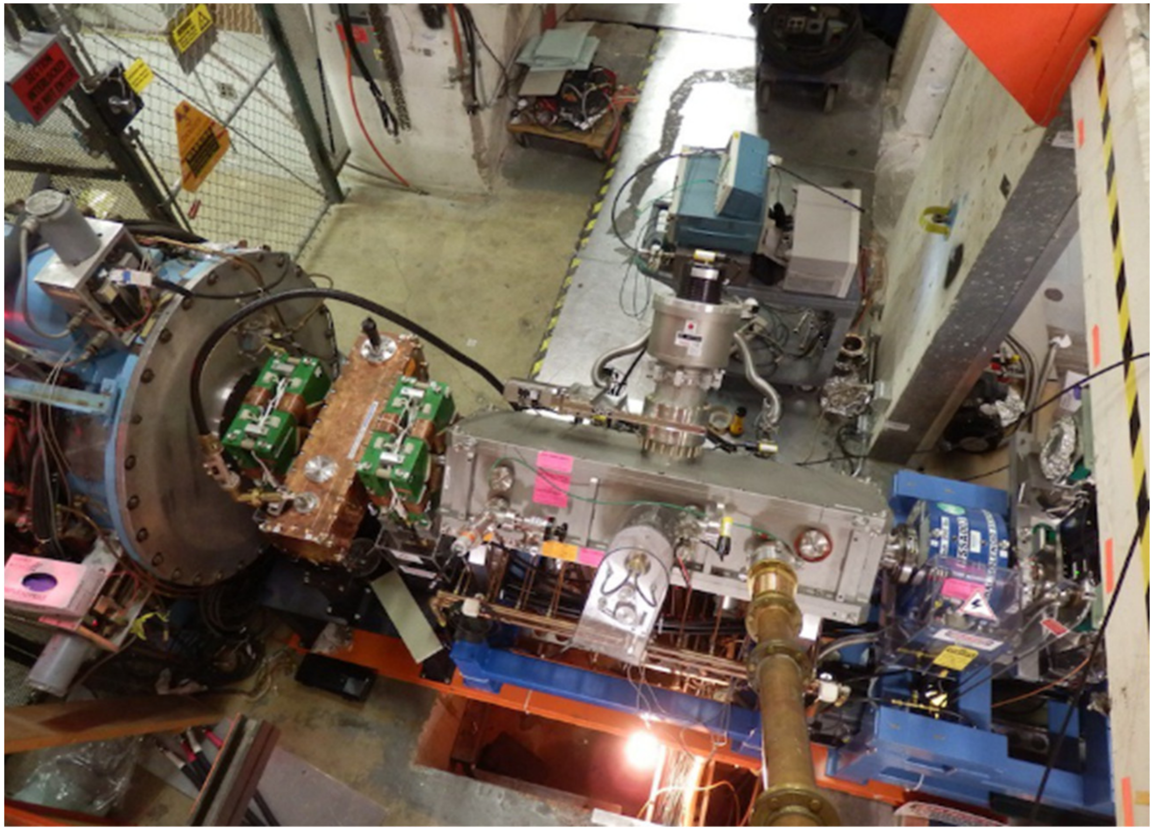

Standard E&M kicker
->Not enough space

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Standard E&M kicker
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A R&D project was included in PIP to develop a laser system to create the required notches in the linac pulse and could fit into the very tight space constraints.

Technique: Photoneutralization

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$$F_1 = {N}/{N_0} = (1 - e^{-f_{CM} * \sigma(E) * \tau_{\text{crossing}}})$$

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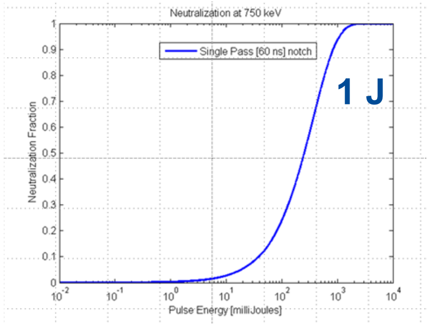

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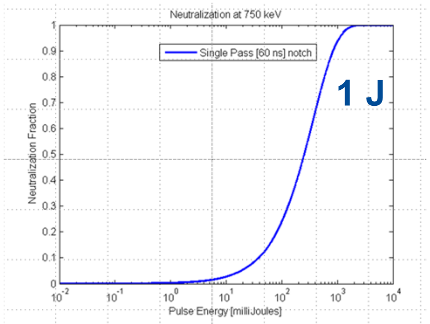

- ➢ Match laser pulses to bunch parameters

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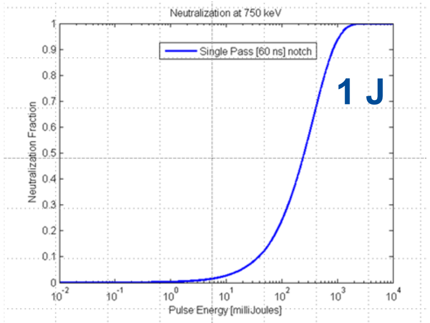

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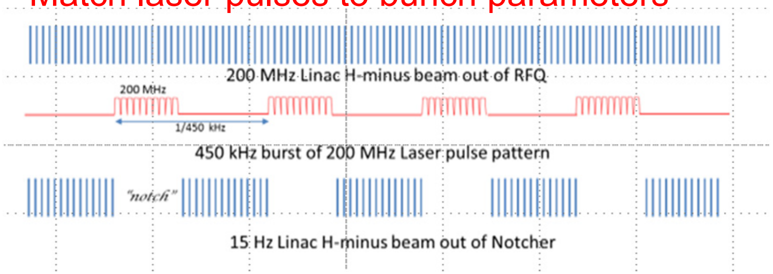

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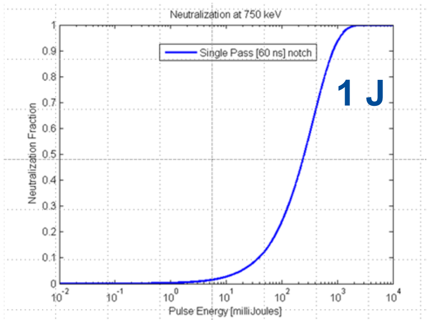

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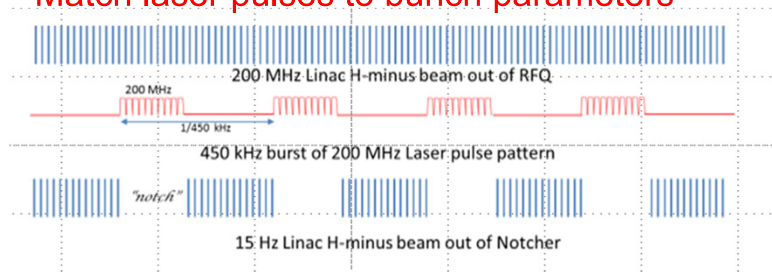

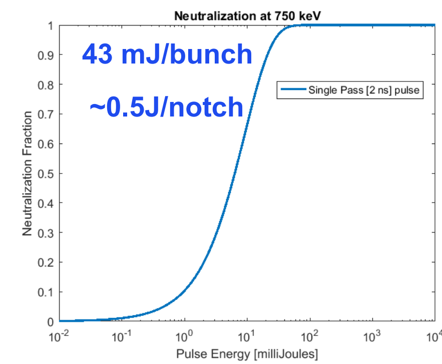

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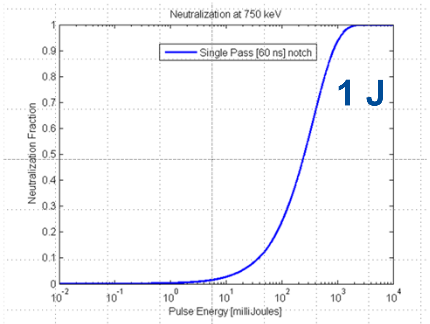

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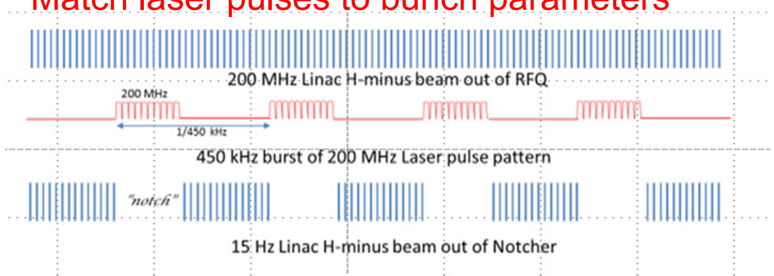

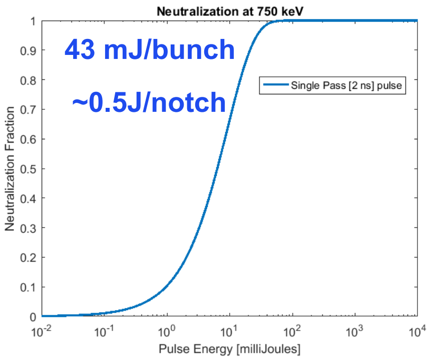

- Non-resonant optical cavity (we call a zig-zag cavity)

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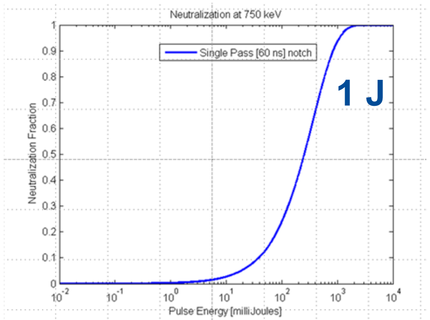

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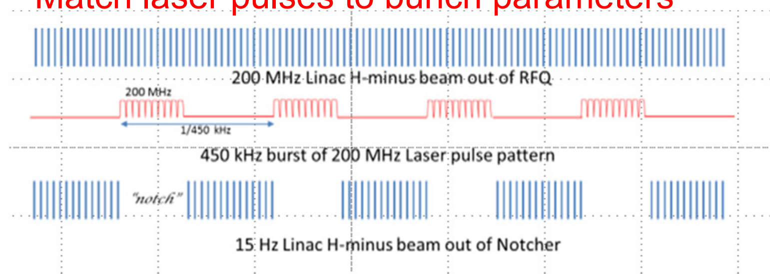

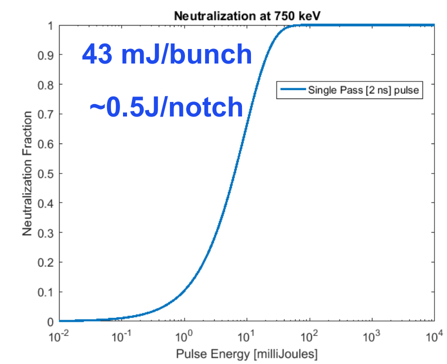

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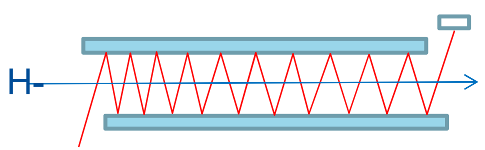

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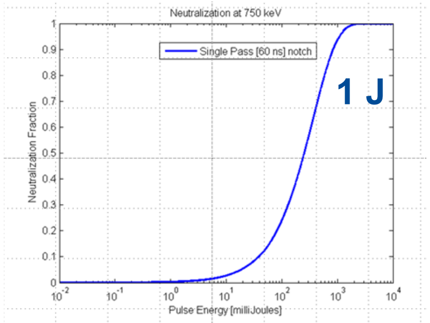

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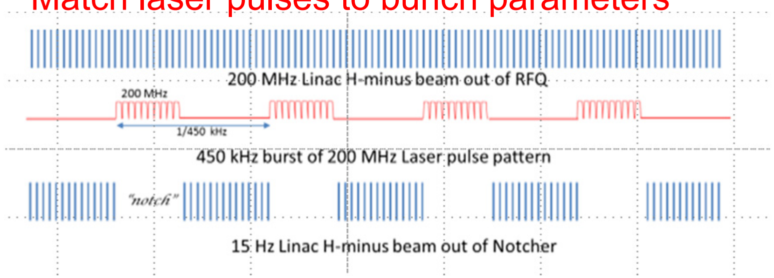

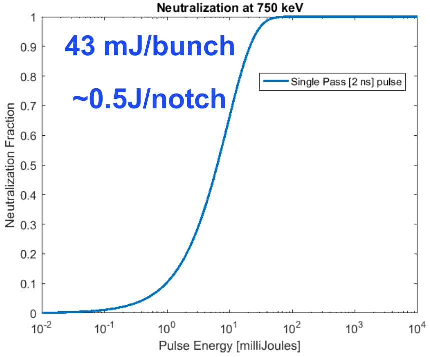

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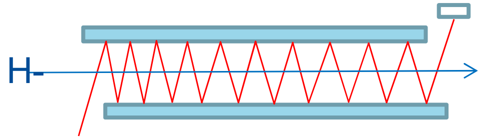

$$F_N = 1 - (1 - F_{neut})^N$$

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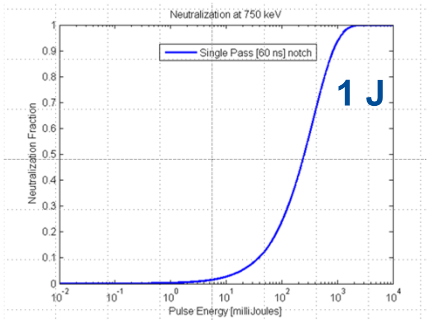

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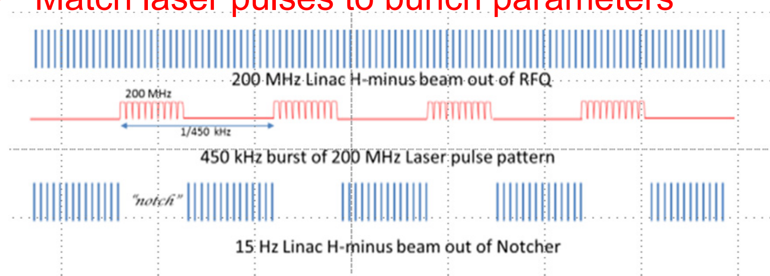

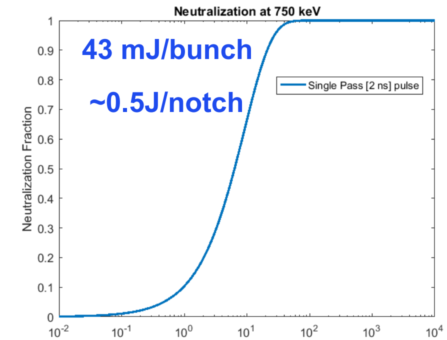

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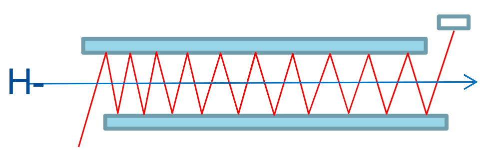

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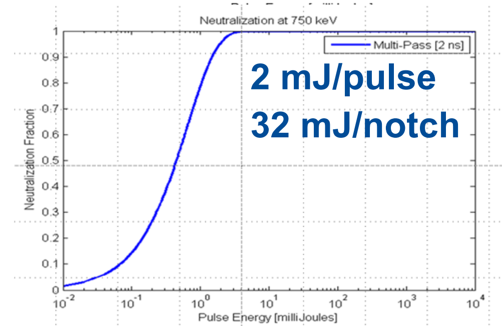

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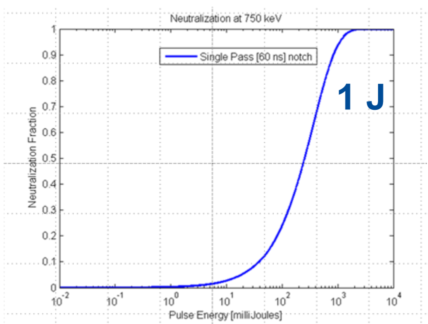
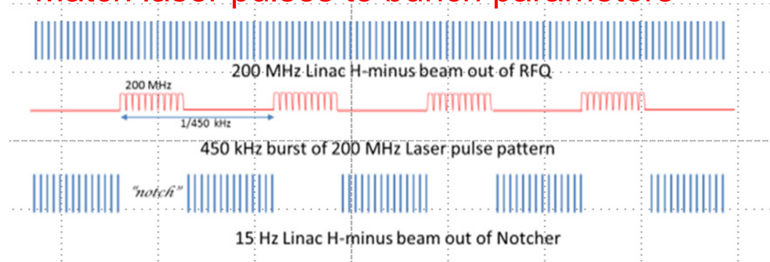
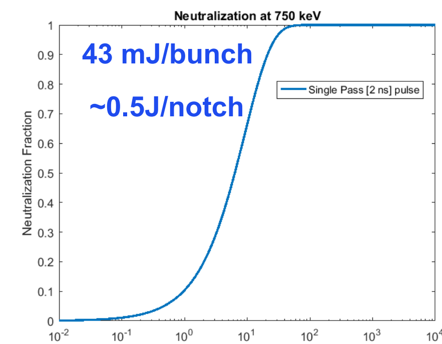
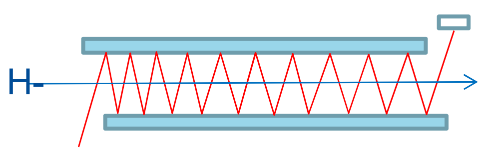


- Match laser pulses to bunch parameters

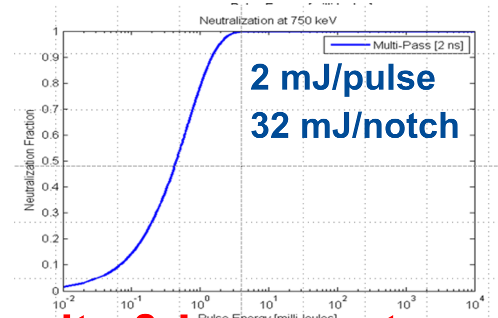




- Non-resonant optical cavity (we call a zig-zag cavity)

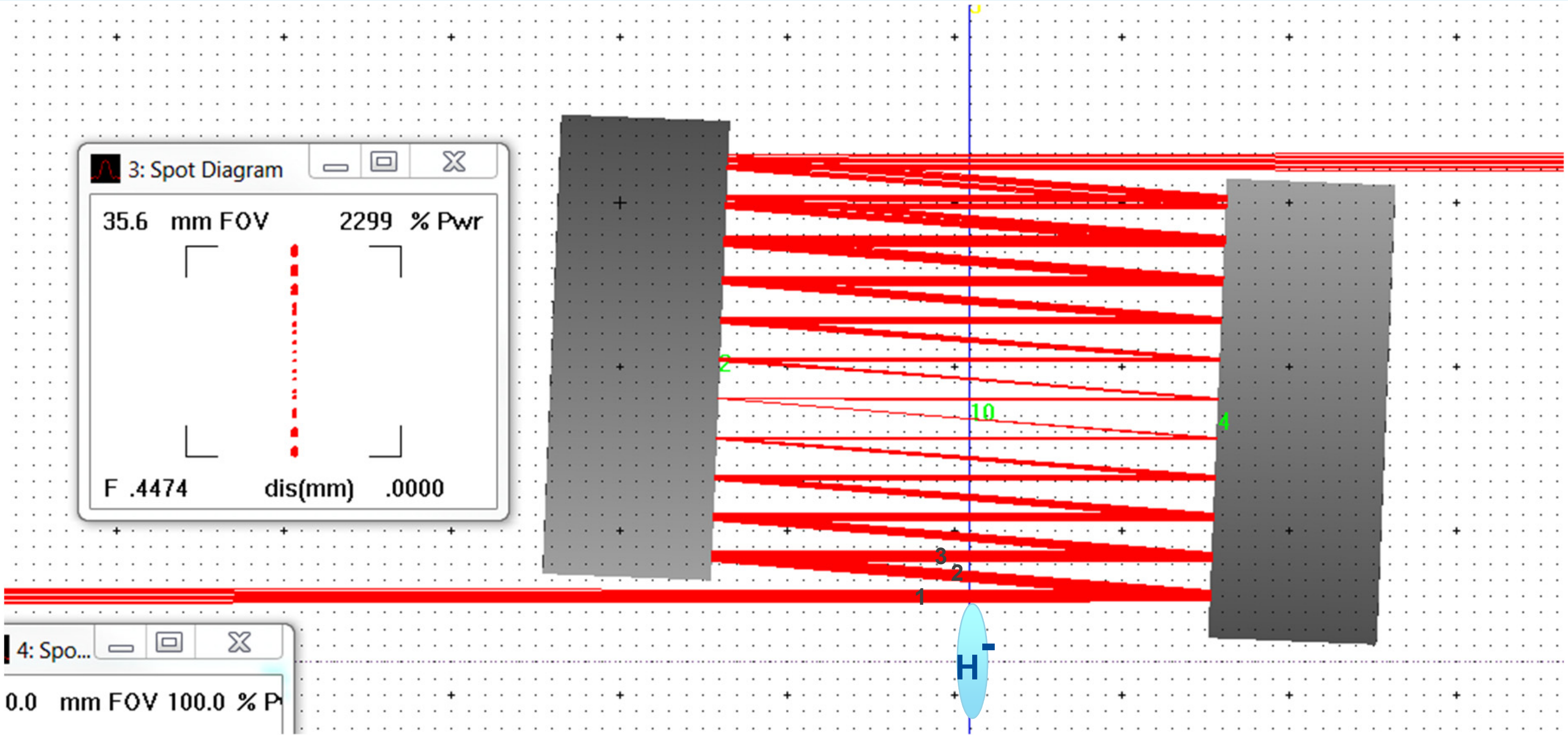


$$F_N = 1 - (1 - F_{neut})^N$$



- **We needed to develop 2 components: interaction cavity & laser system**

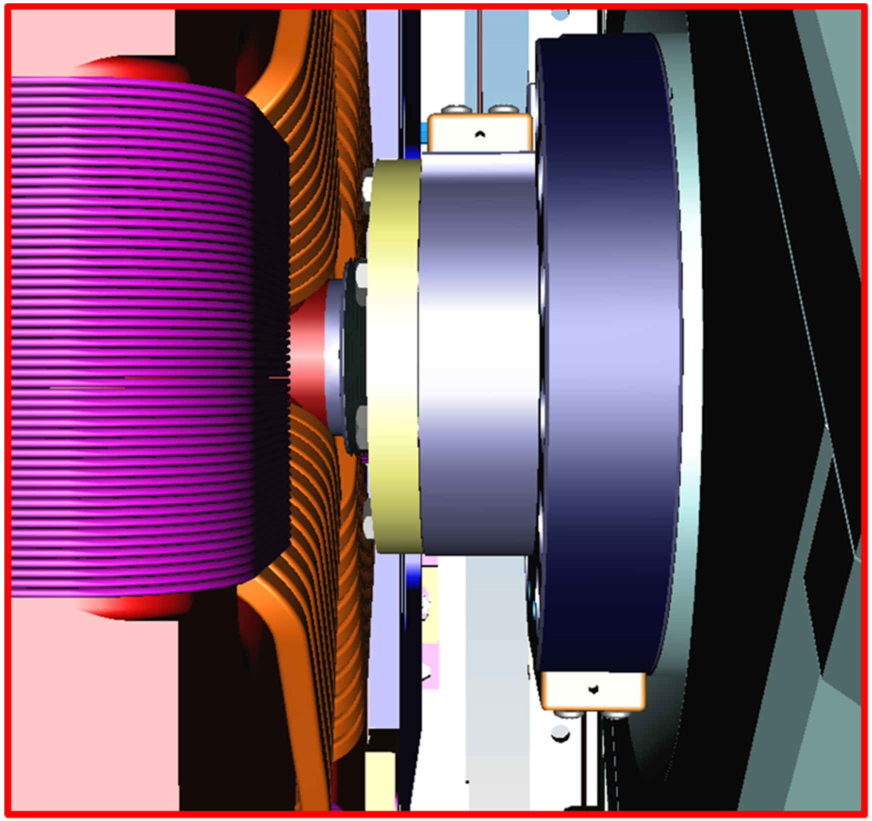
Interaction Cavity: Concept



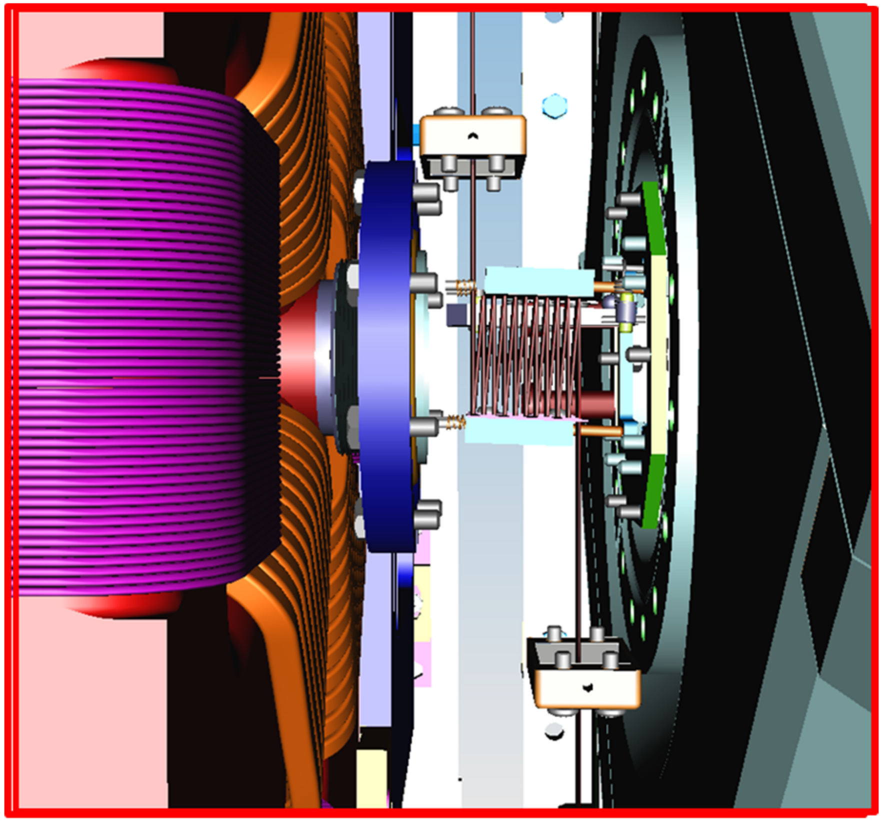
- Match velocities of laser propagation down the cavity with velocity of ion bunch.
- Laser pulse length match ion bunch length

- Match

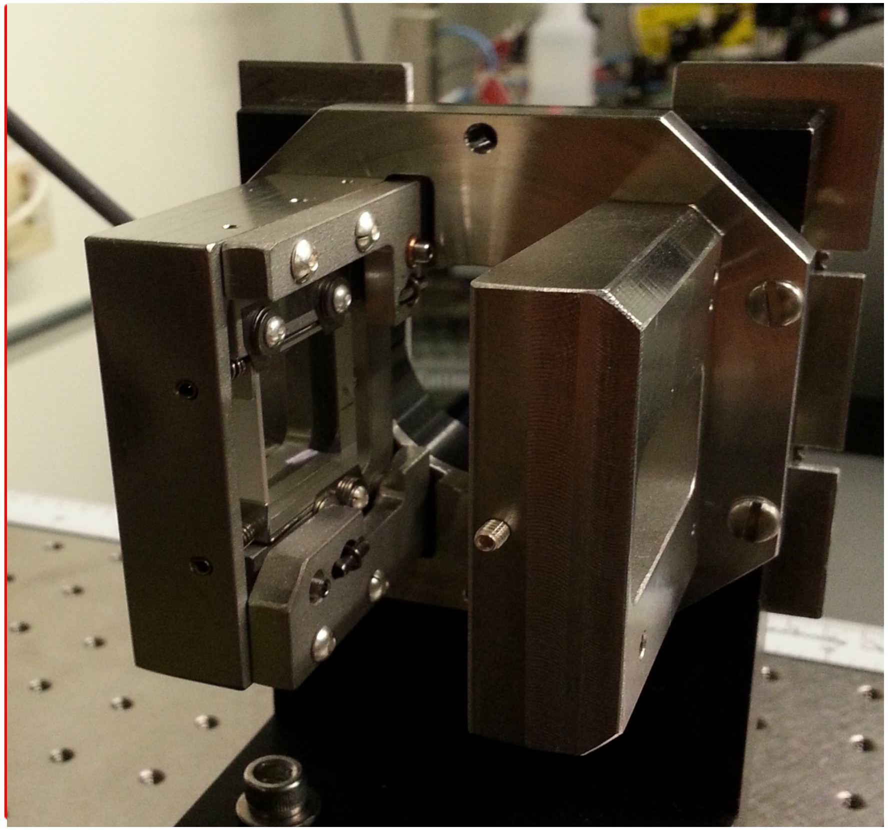
Interaction Cavity: Development



Interaction Cavity: Development



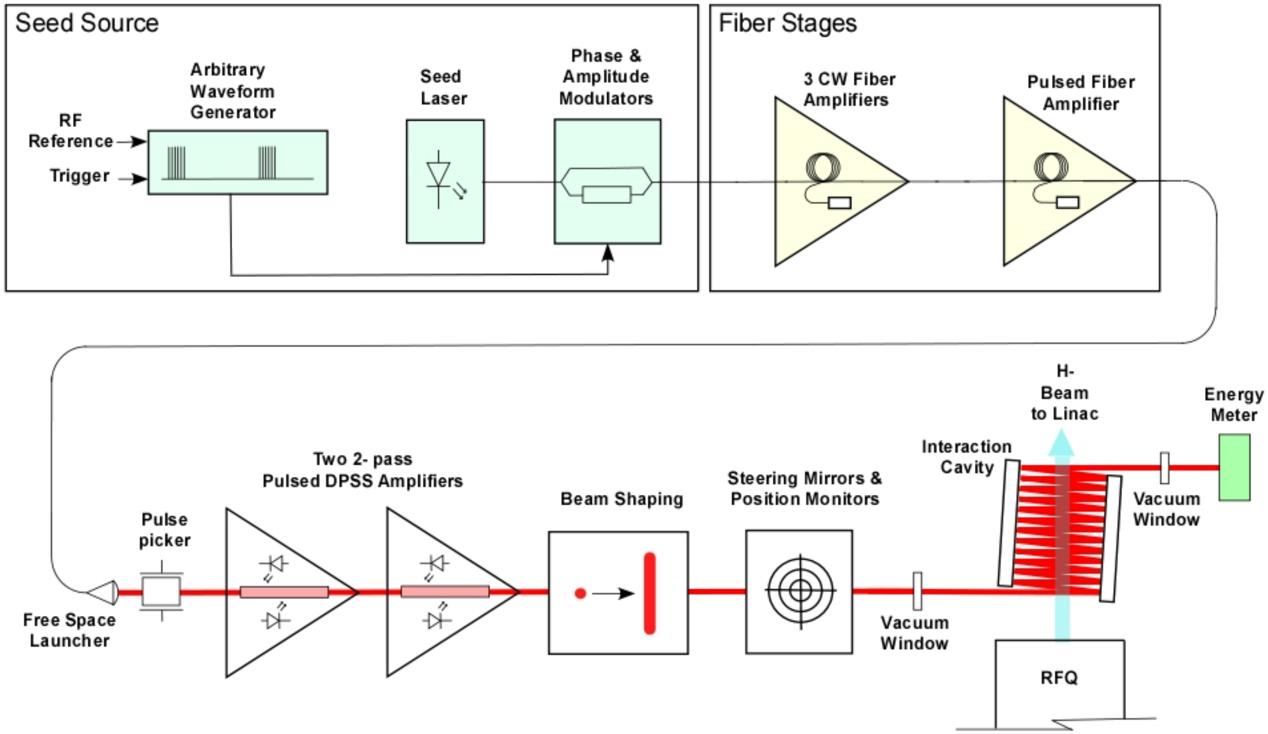
Interaction Cavity: Development



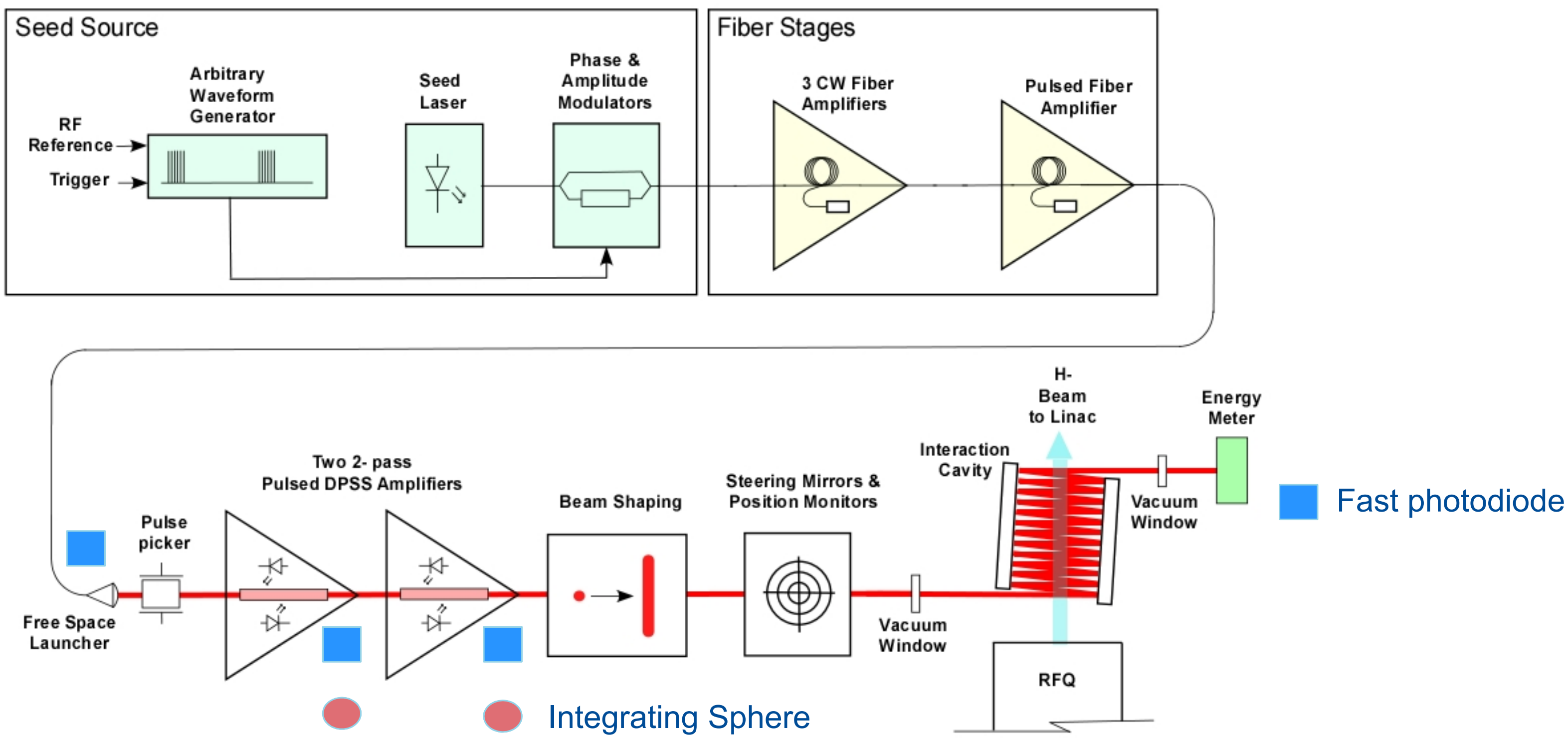
Interaction Cavity: Development

Laser System: Design

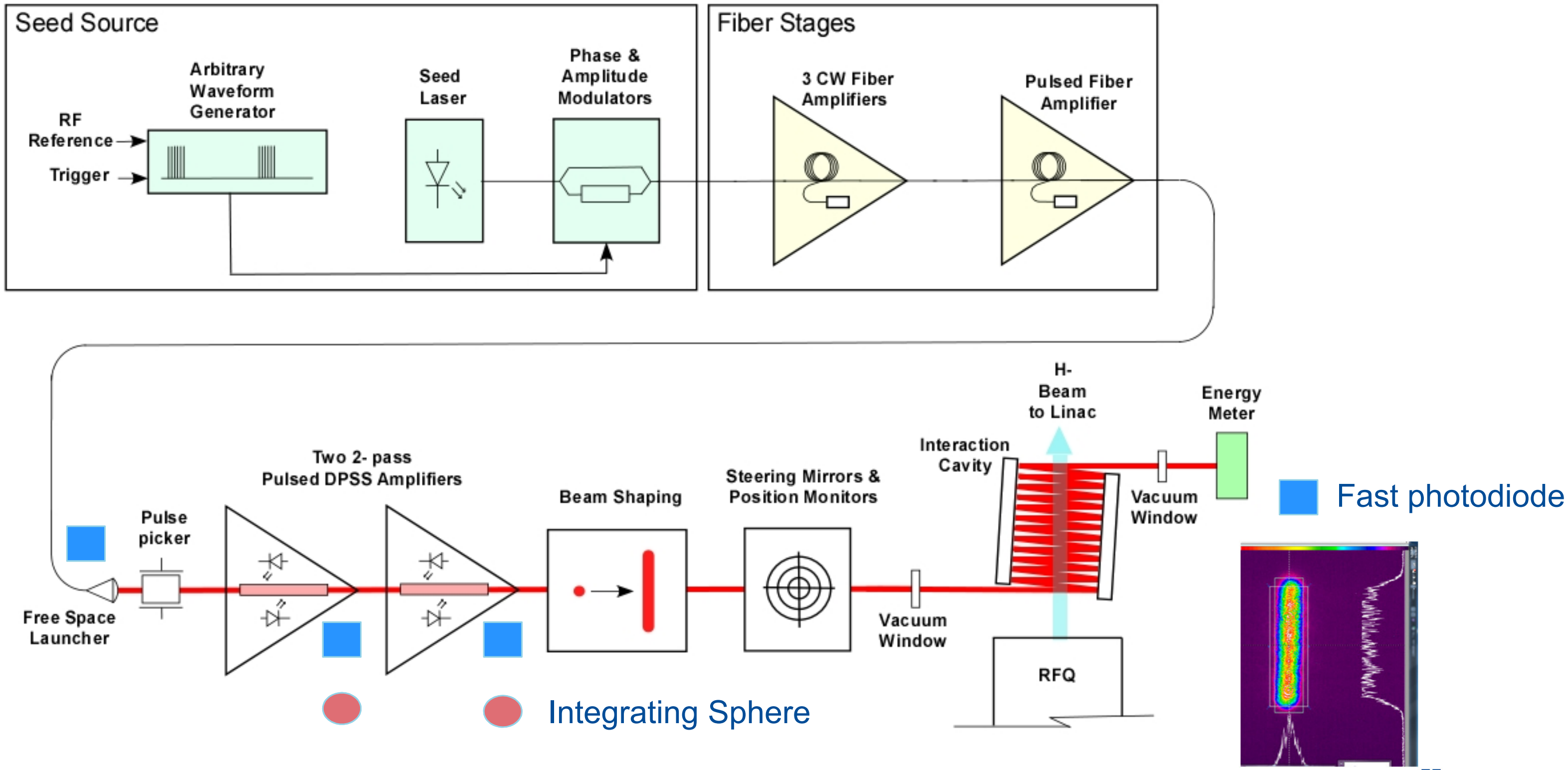
Laser System: Design



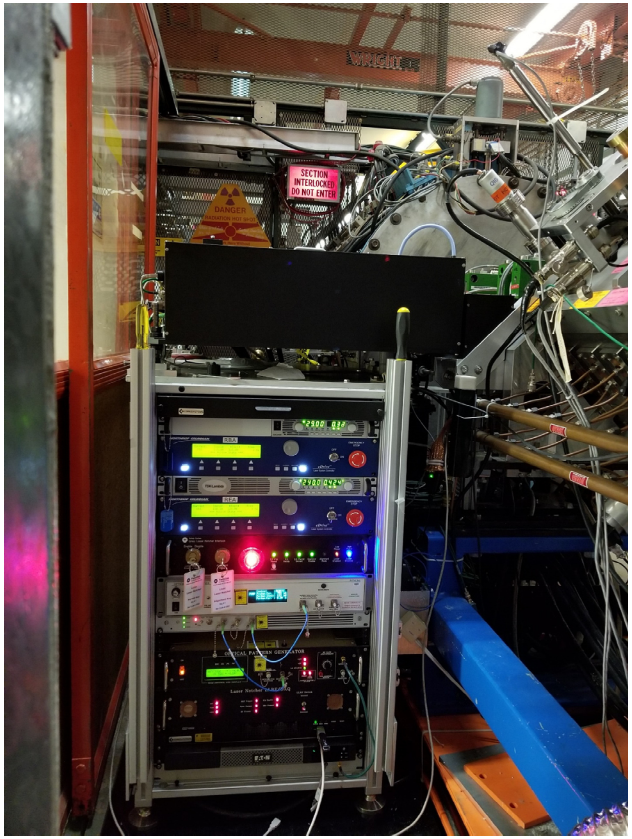
Laser System: Design

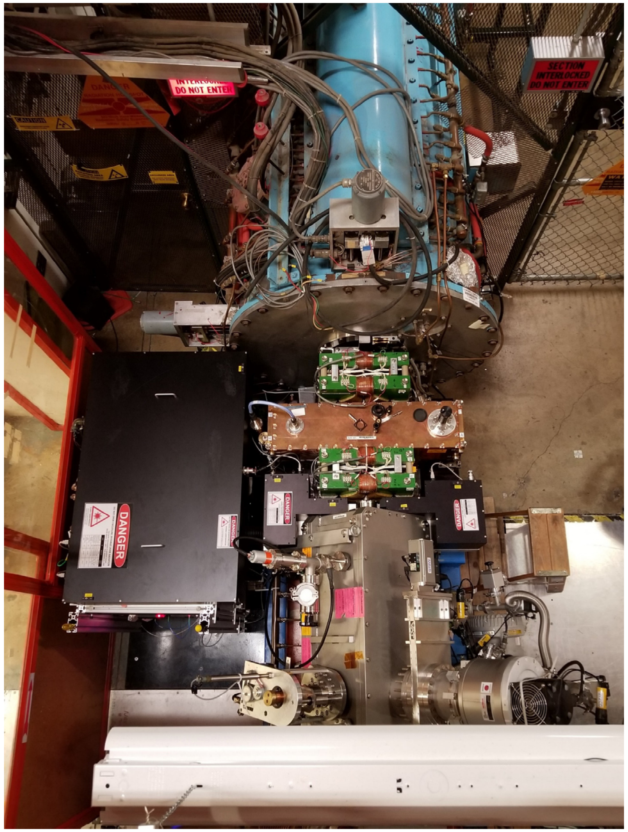


Laser System: Design

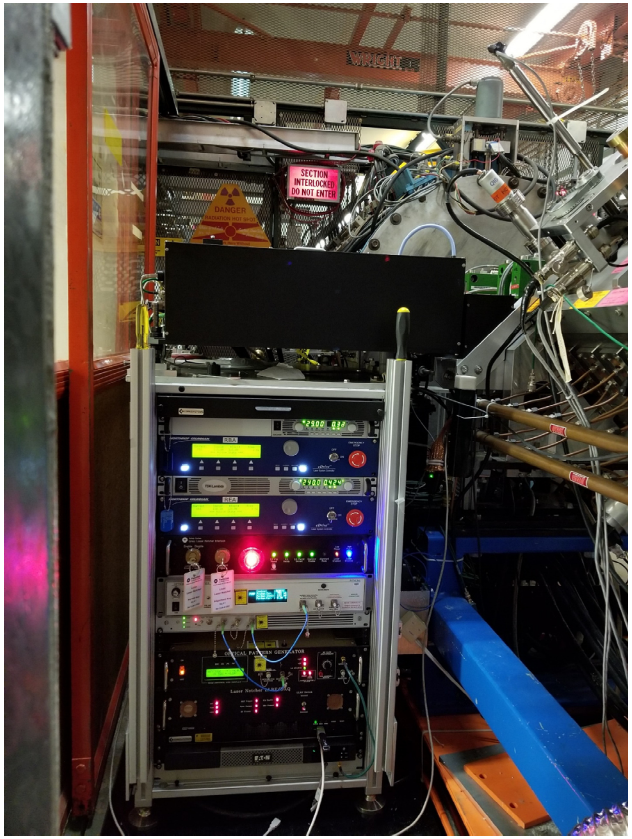


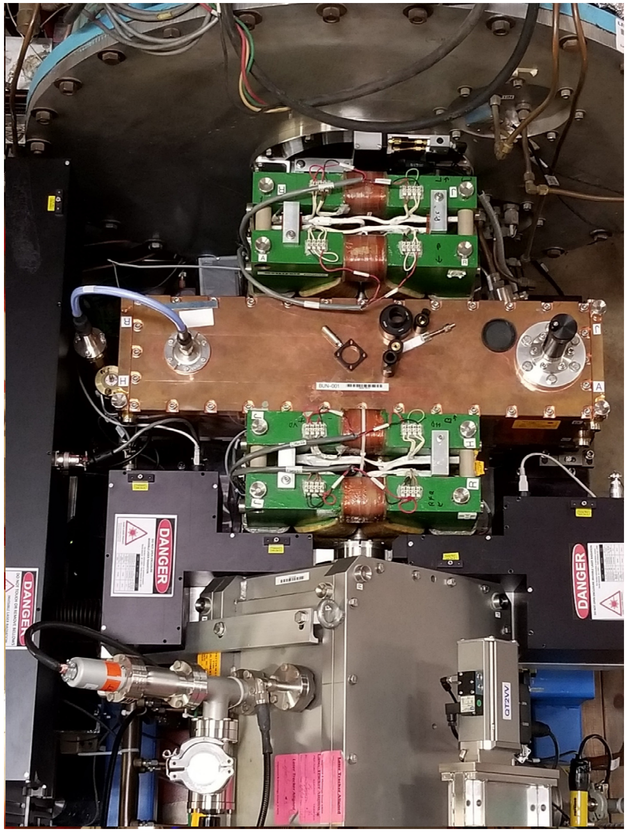
Operational Laser System Installed in Linac



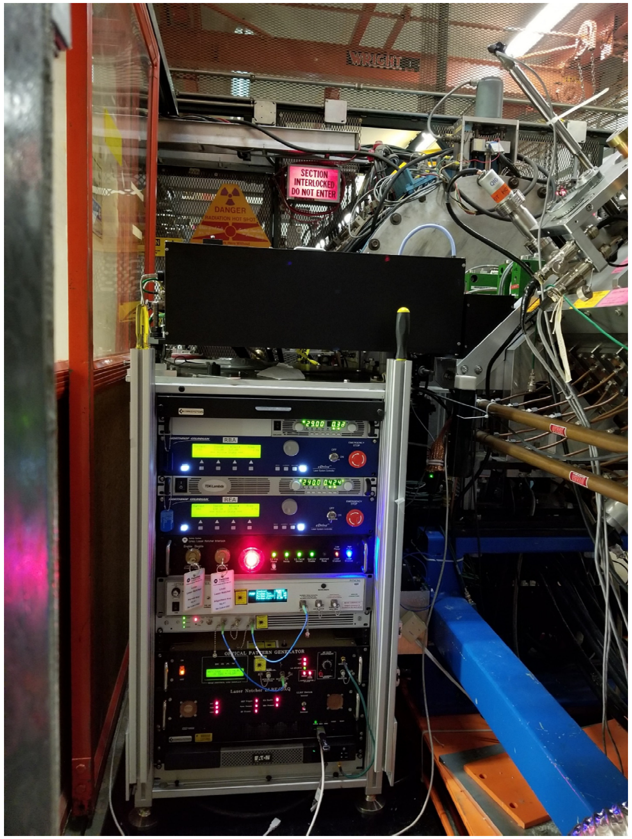


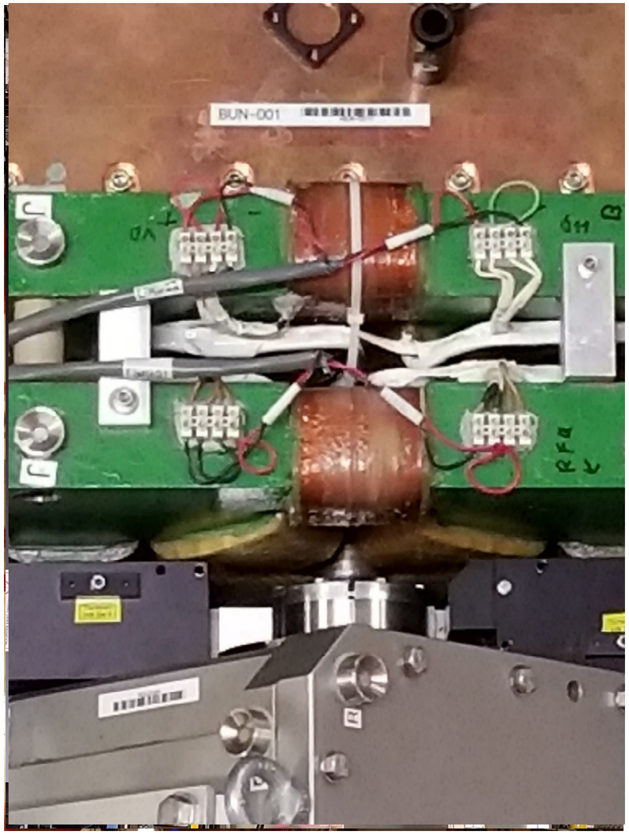
Operational Laser System Installed in Linac



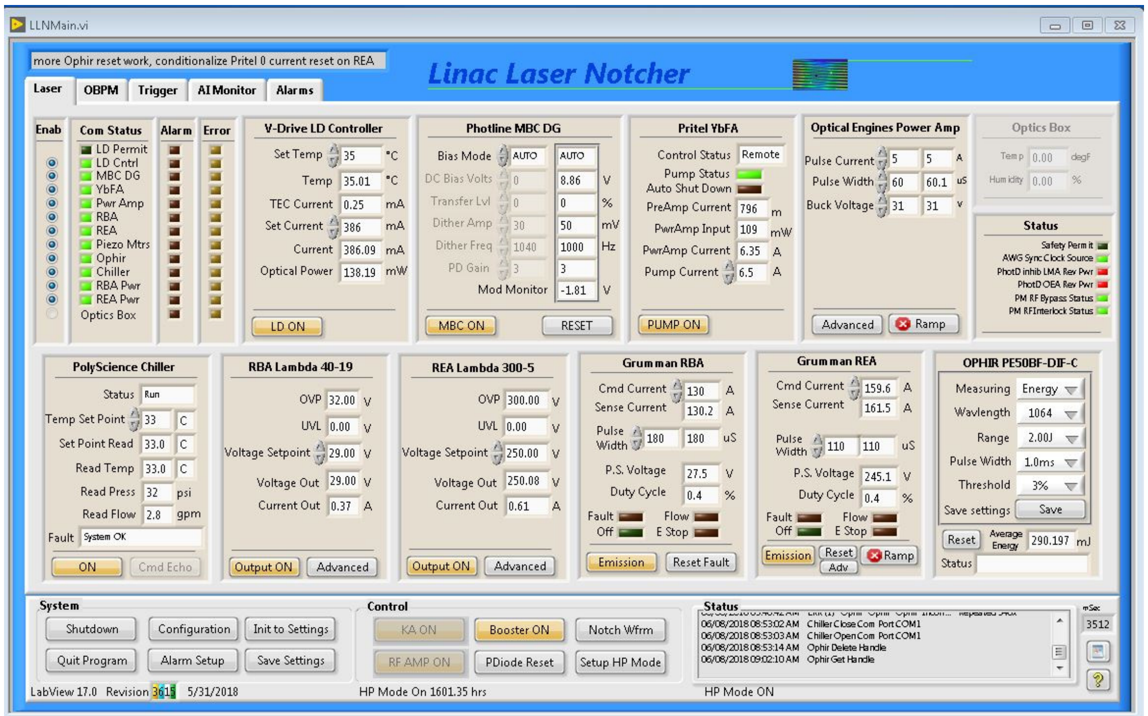


Operational Laser System Installed in Linac



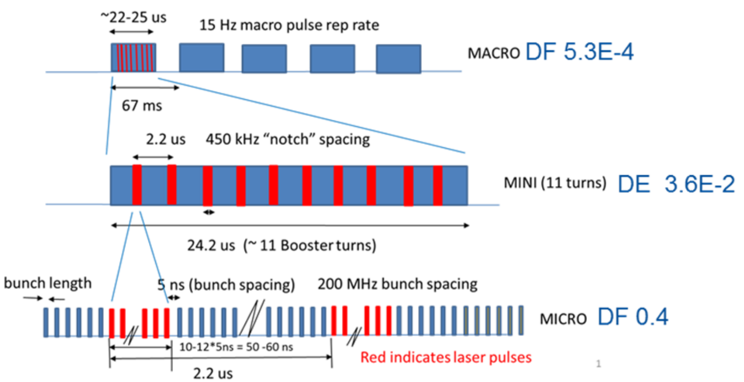


Laser System: Controls



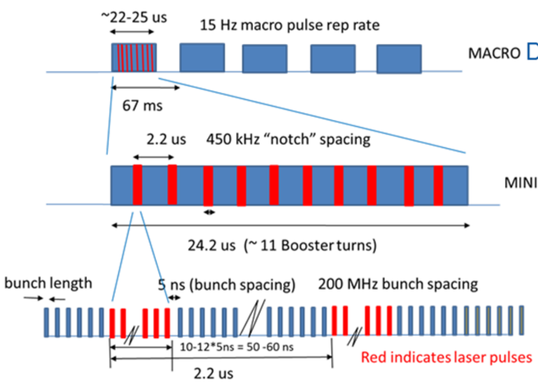
- Flexible que driven state machine
- GUI interface, ACNET communication, hardware monitoring, and state machine – ALL INDEPENDENT tasks
- Real time configurable alarms
- Robust setting, monitoring(configuration and communication) display and logging
  - Configurable mail reports
- Settable range constraints for all control inputs
- Very flexible waveform creation
- Main Operations interface through ACNET parameter page and JAVA web monitor page

Laser System: Arbitrary Waveform Generation

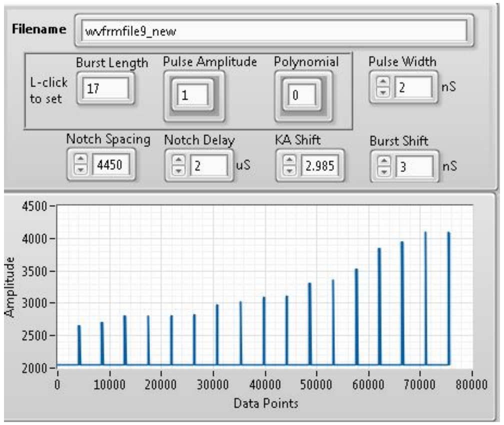


Total DF 7.7E-06

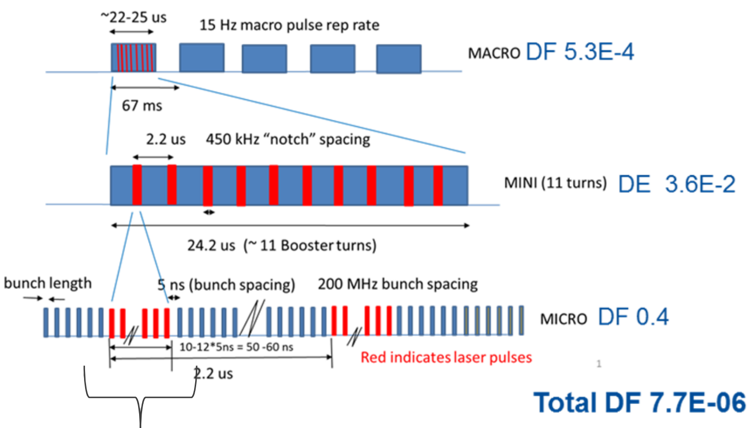
Laser System: Arbitrary Waveform Generation

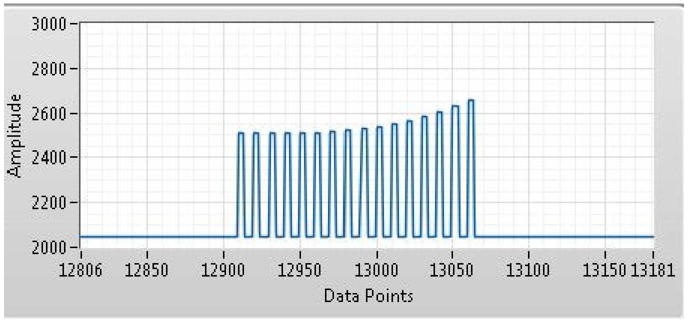


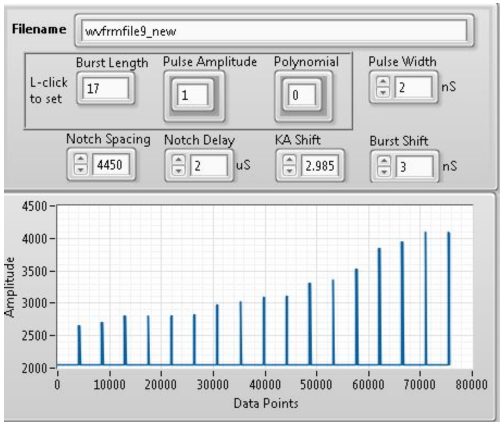
Total DF 7.7E-06



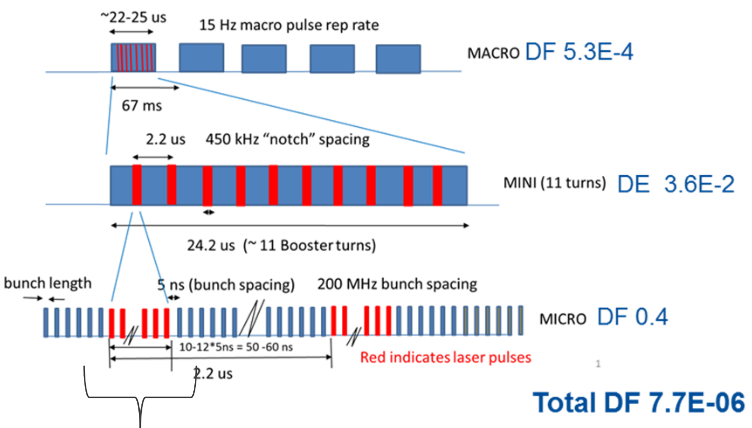
Laser System: Arbitrary Waveform Generation

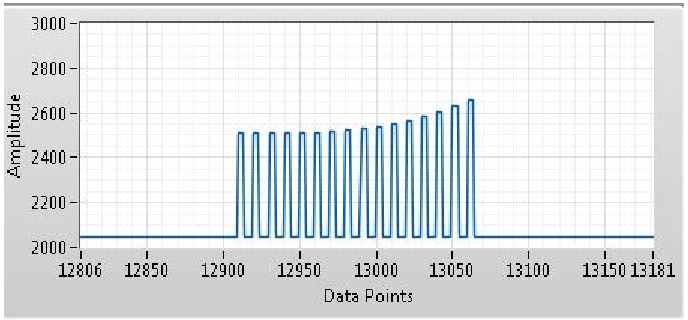


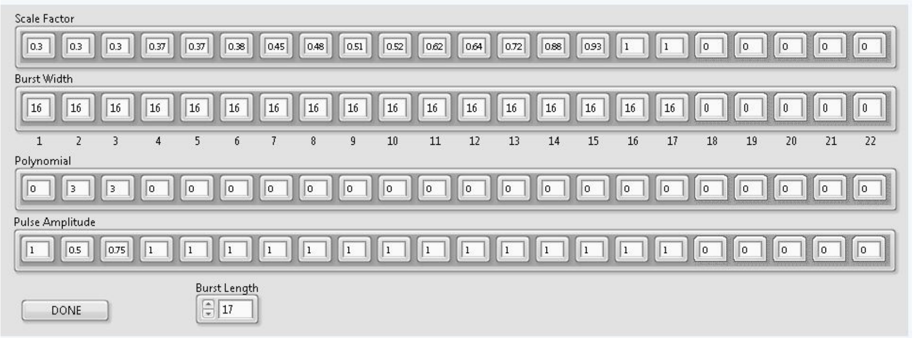


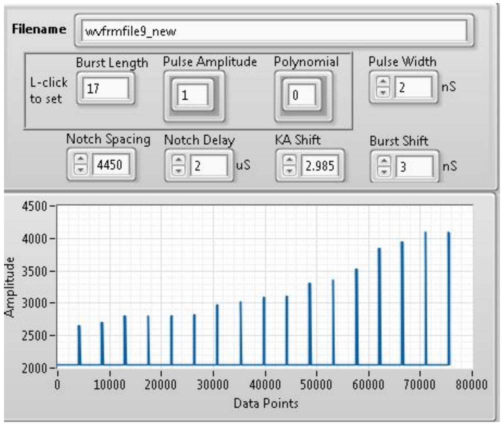


Laser System: Arbitrary Waveform Generation

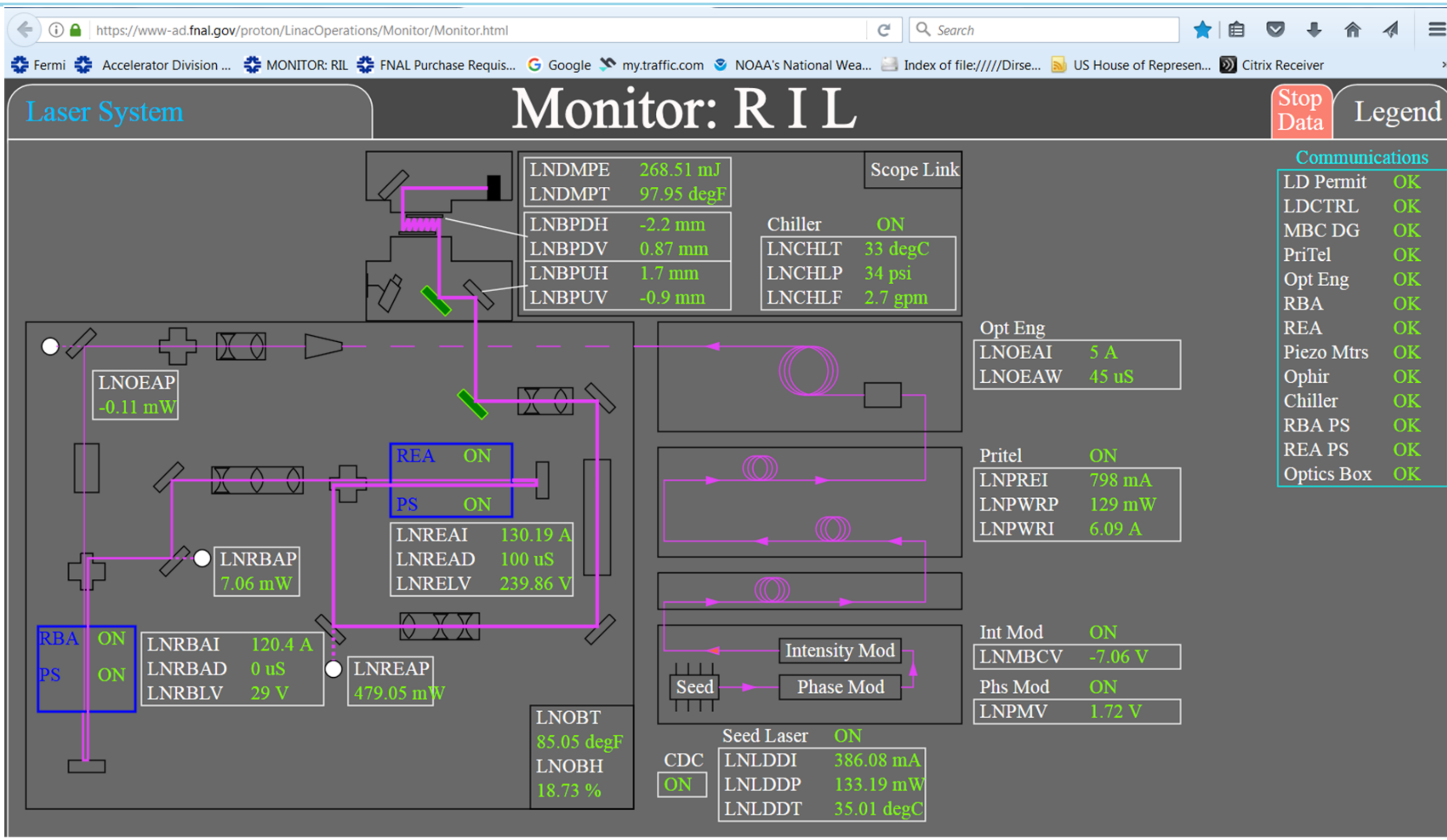






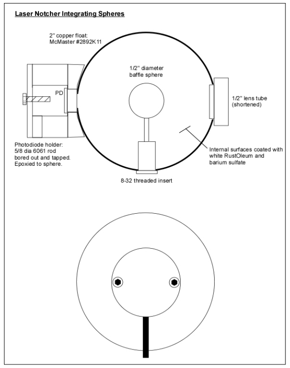


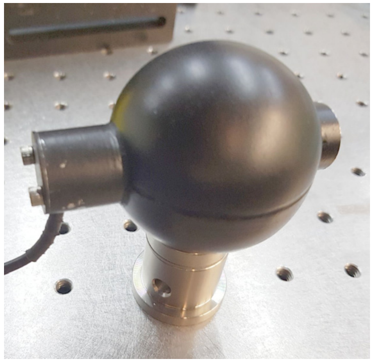
Laser System: Operational System Monitoring



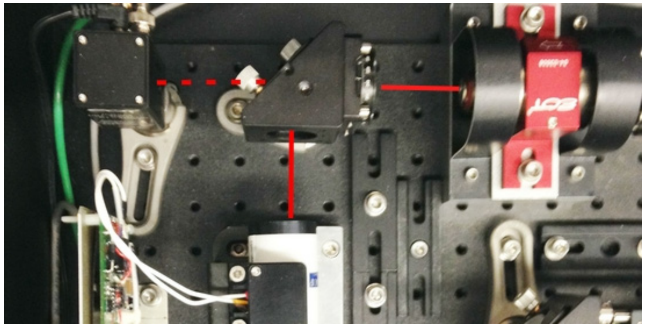
Laser System: Instrumentation in Optics Box

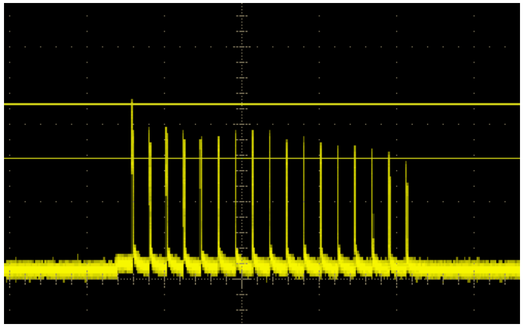
- Integrating Sphere (developed @ FNAL)



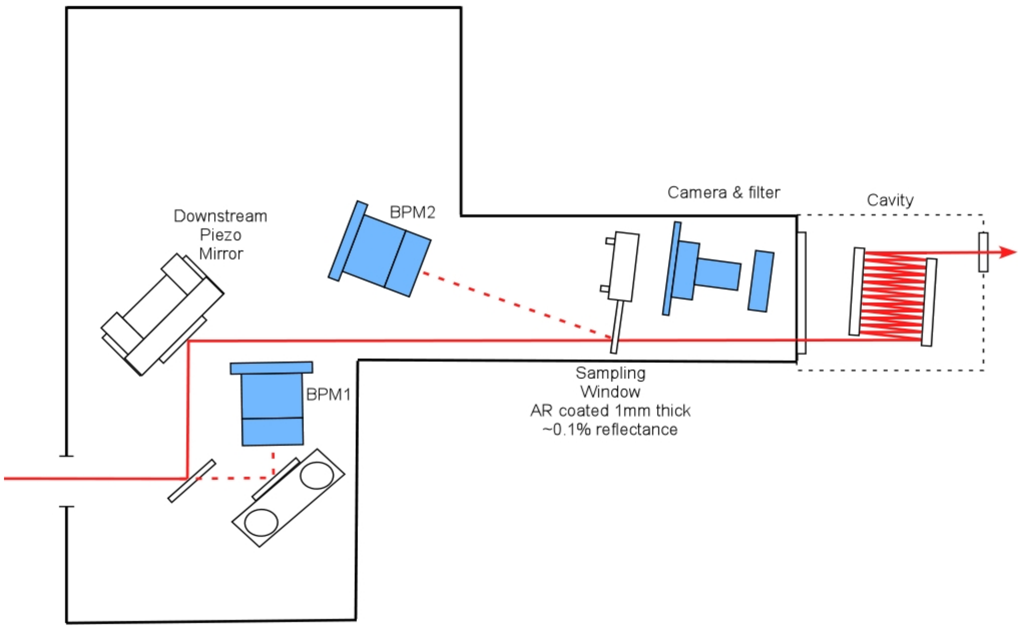


- Photodiode (commercial)



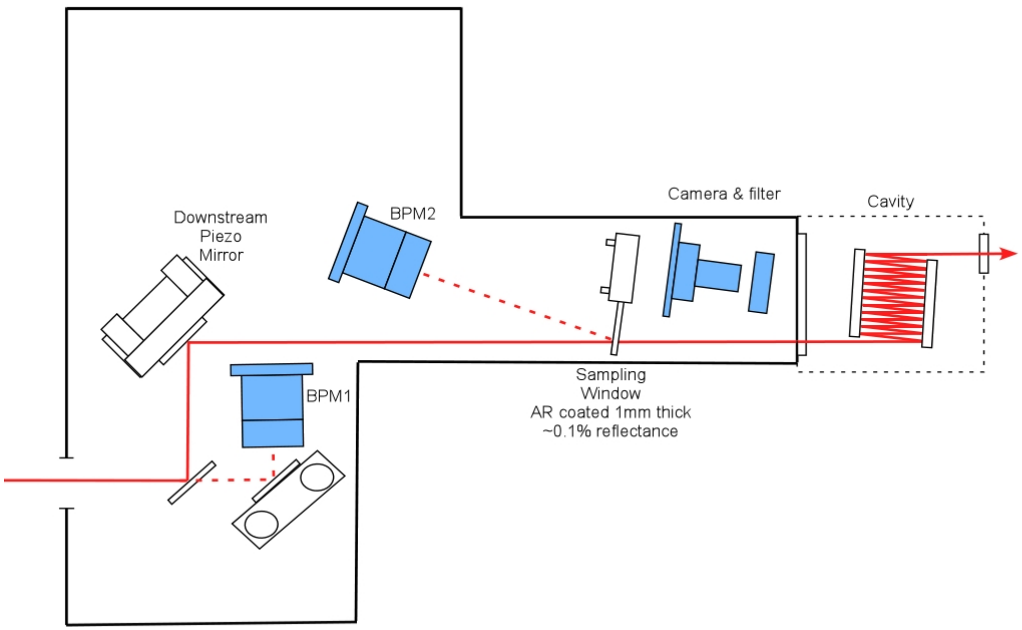


Laser System: Transport Enclosure

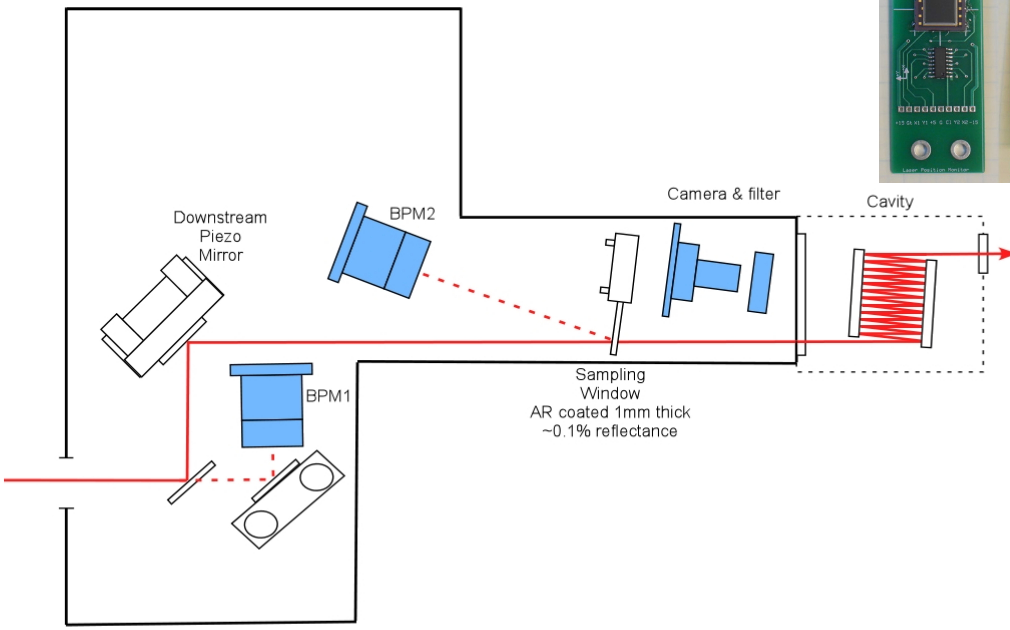


Laser System: Transport Enclosure

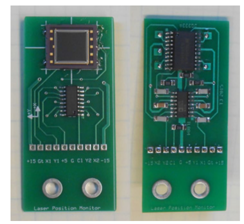
Optical BPM's (developed @FNAL)

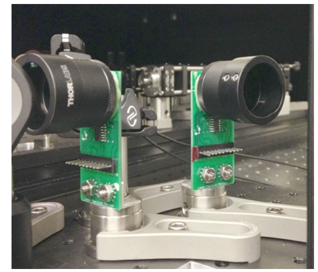


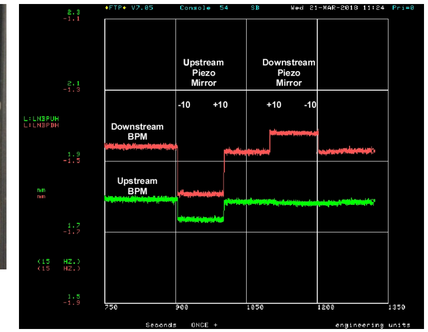
Laser System: Transport Enclosure



Optical BPM's (developed @FNAL)







Laser System: Transport Enclosure

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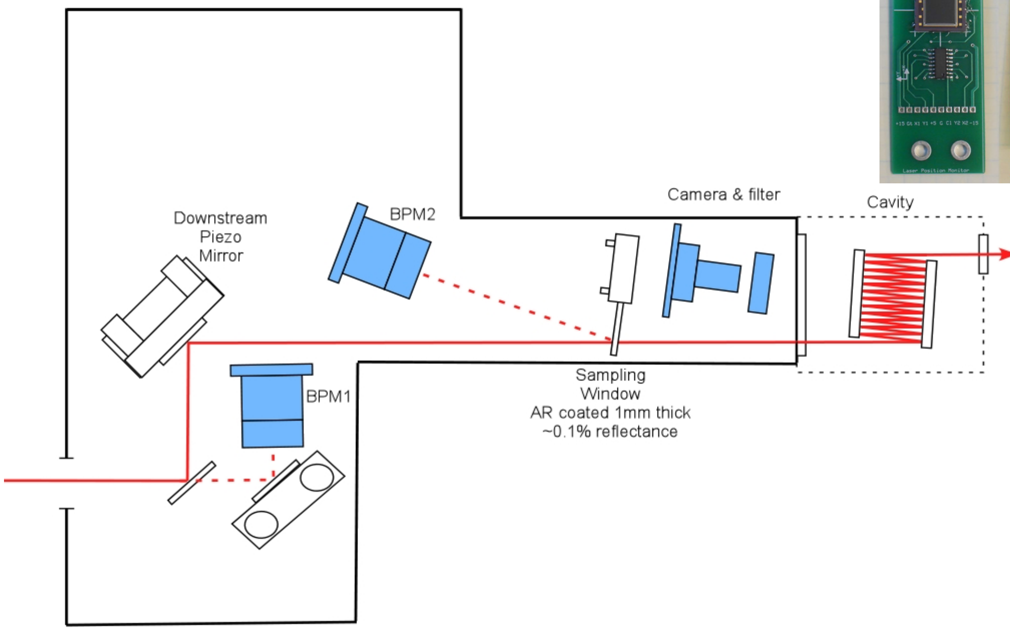
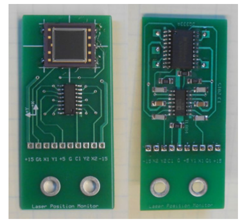
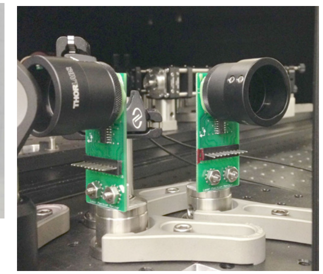
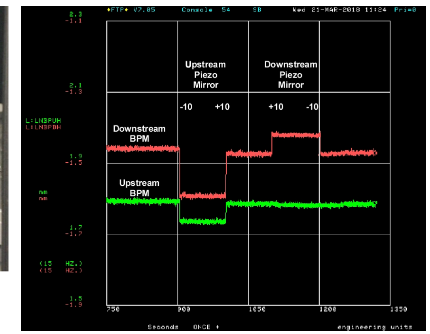




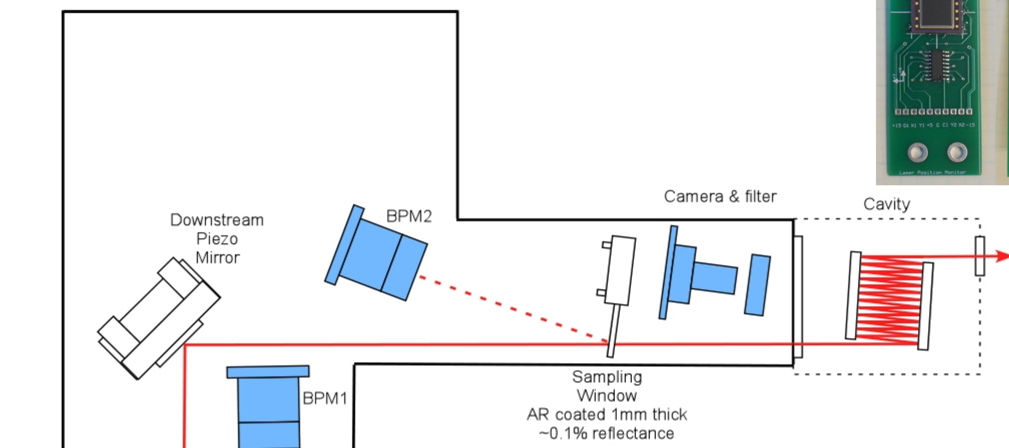


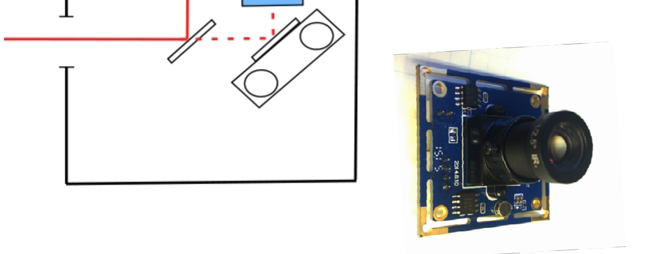


Video Camera

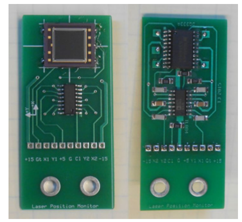
Fermilab

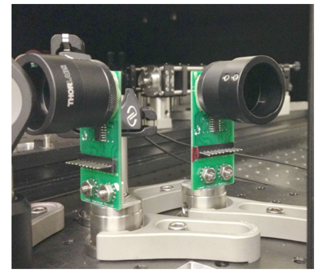
Laser System: Transport Enclosure

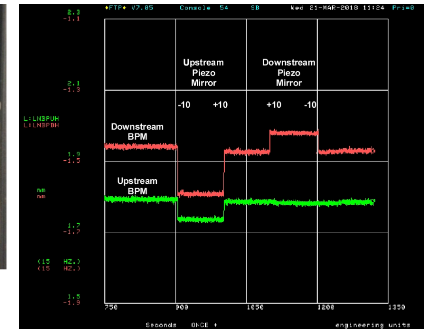


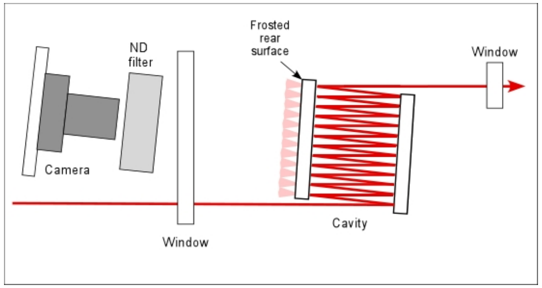


Optical BPM's (developed @FNAL)

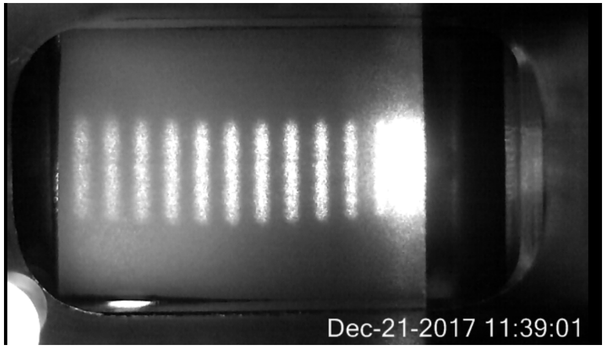






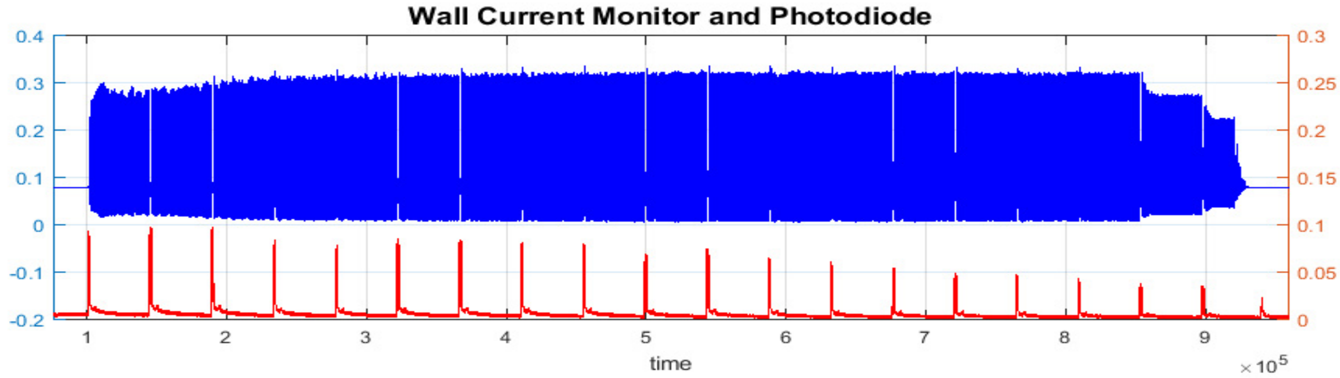


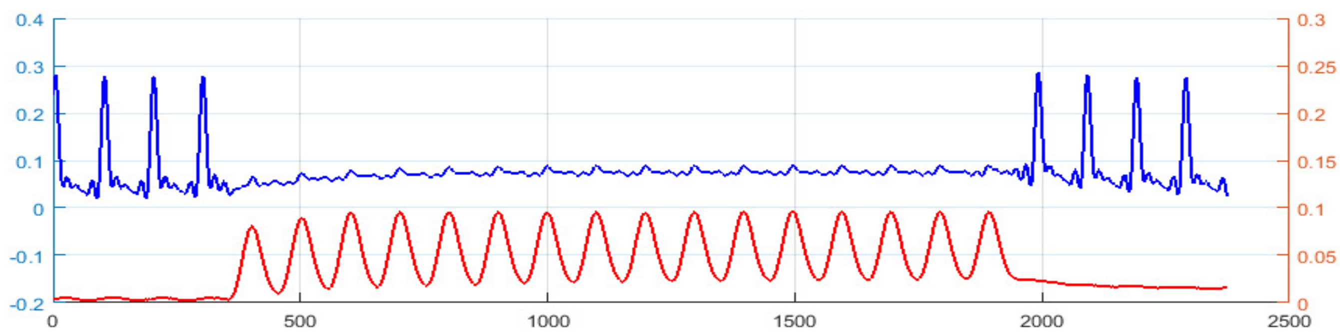
Video Camera



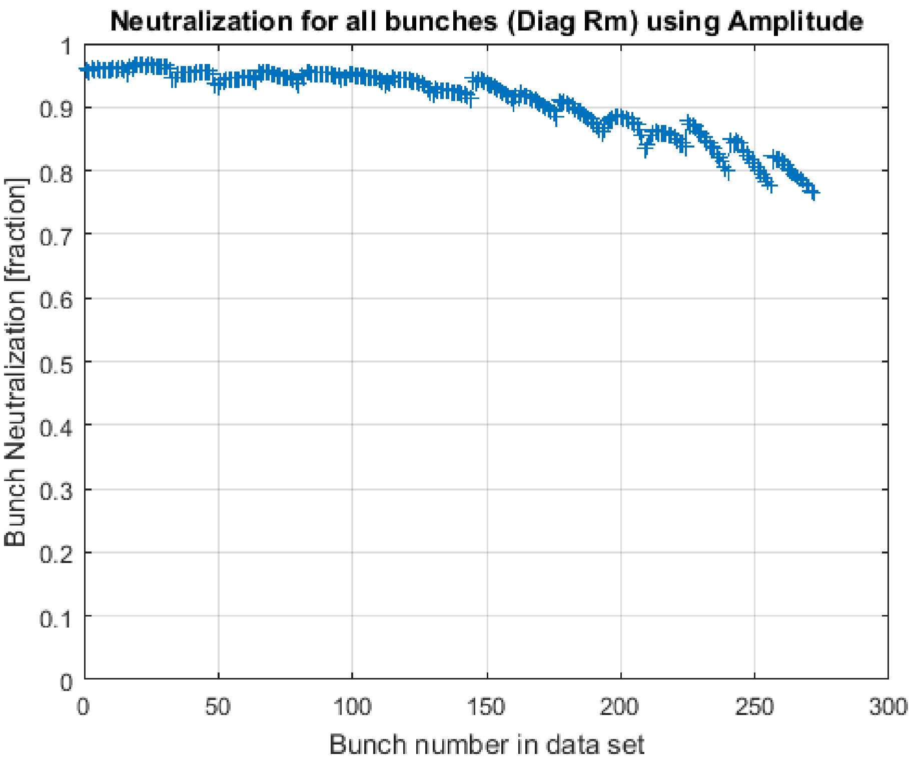
Fermilab

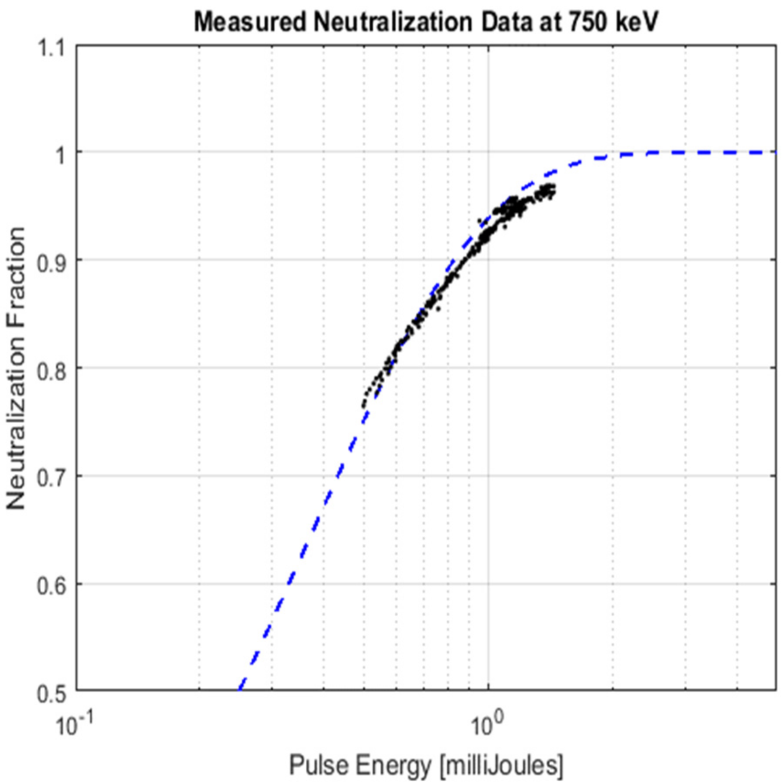
Laser System: Looking at the Notching Process Linac Signals



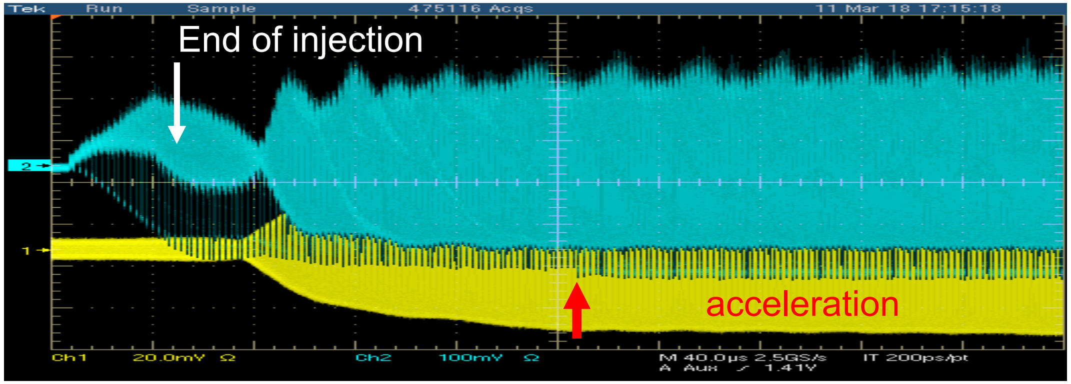


Laser System: Comparison with Neutralization Estimates





Notch survival in Booster



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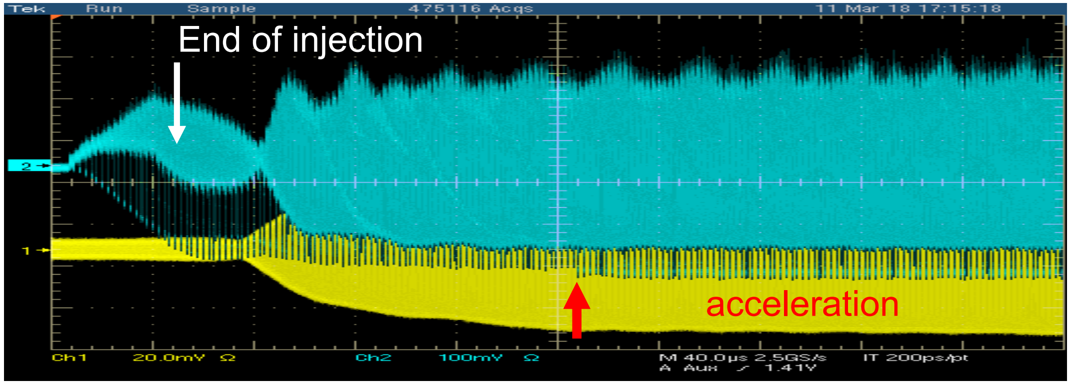

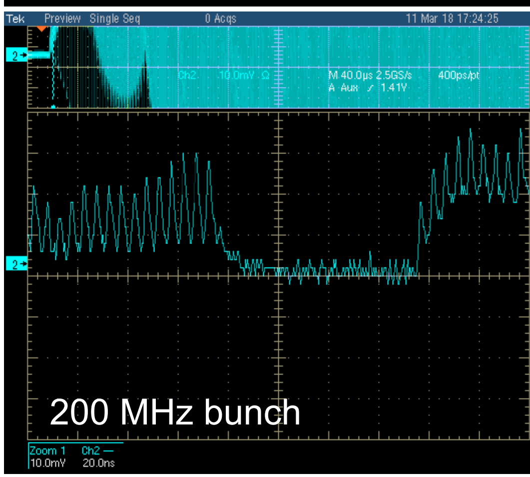

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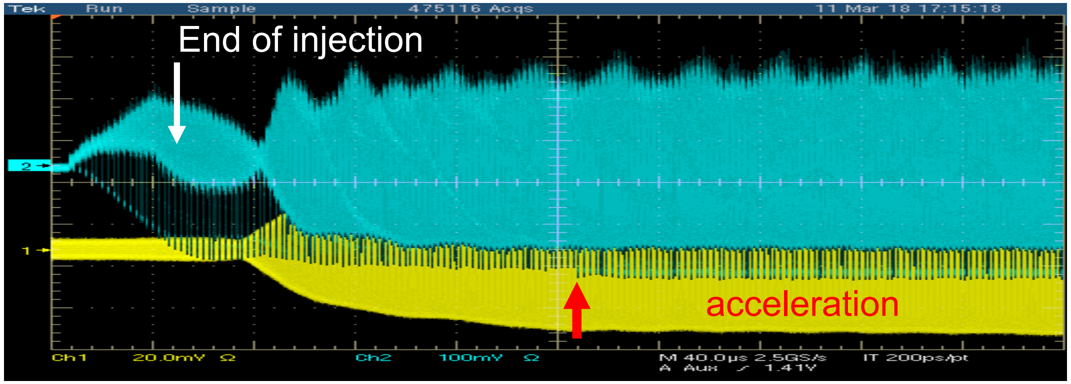
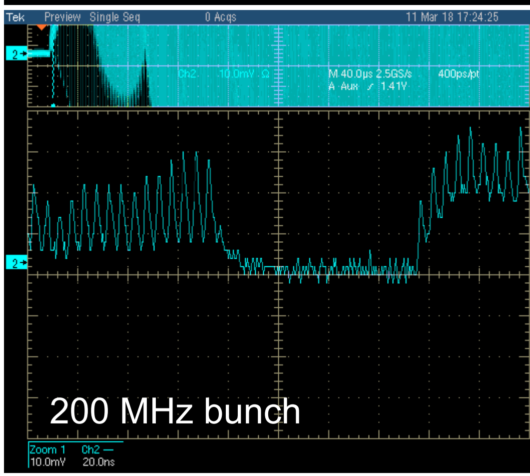
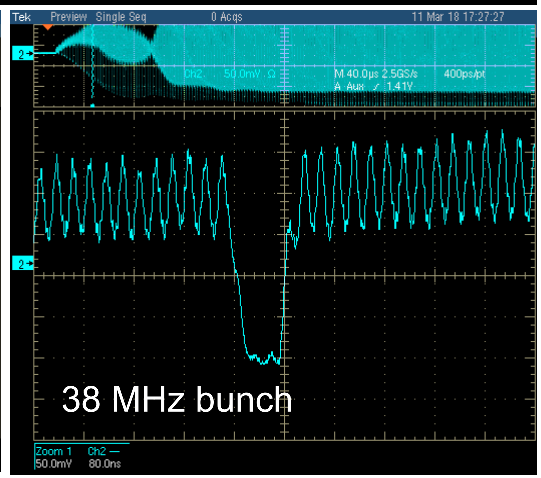
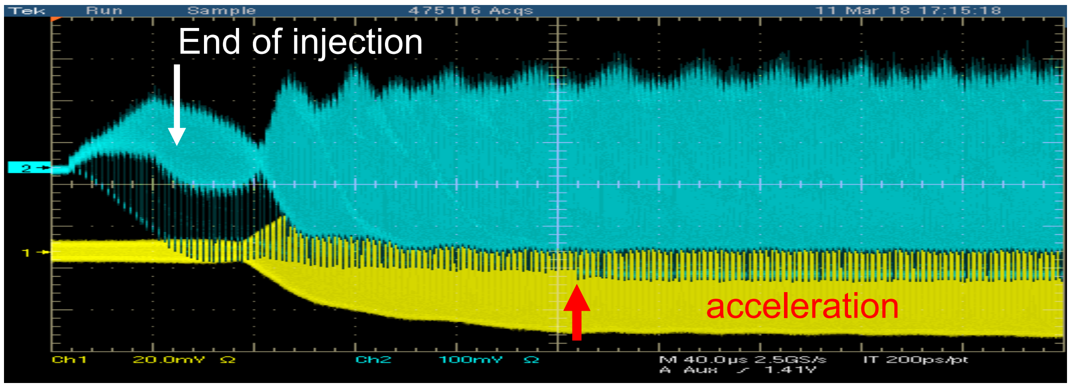
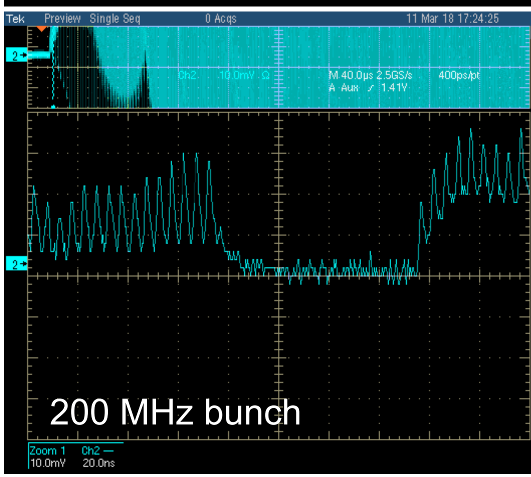


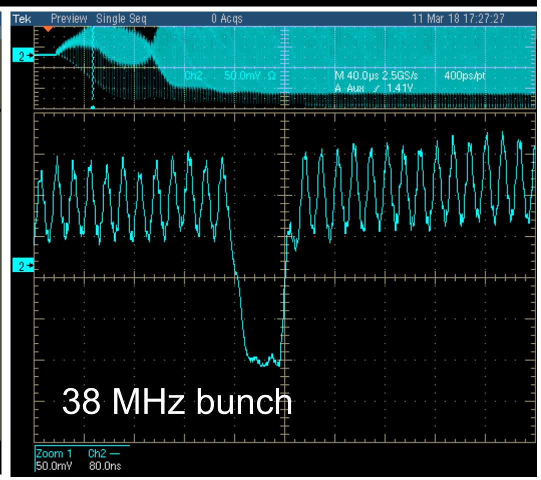


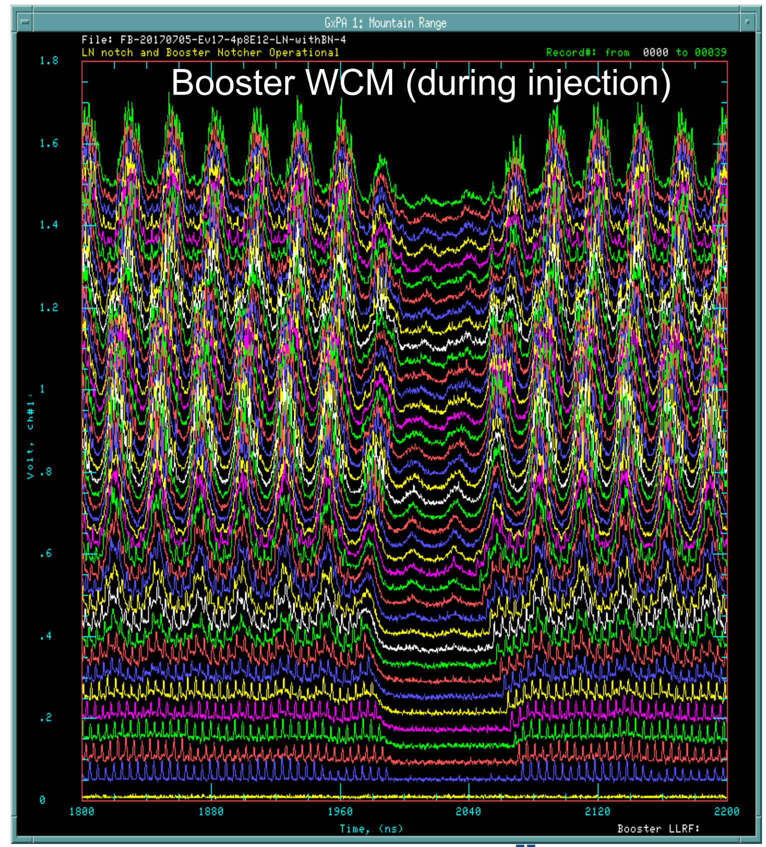


Notch survival in Booster

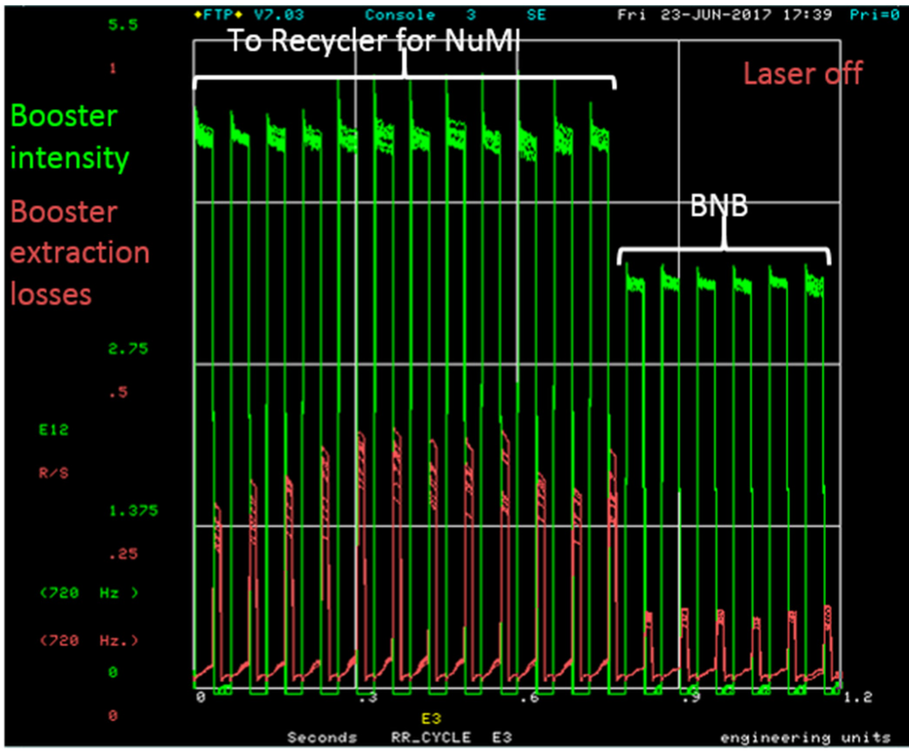


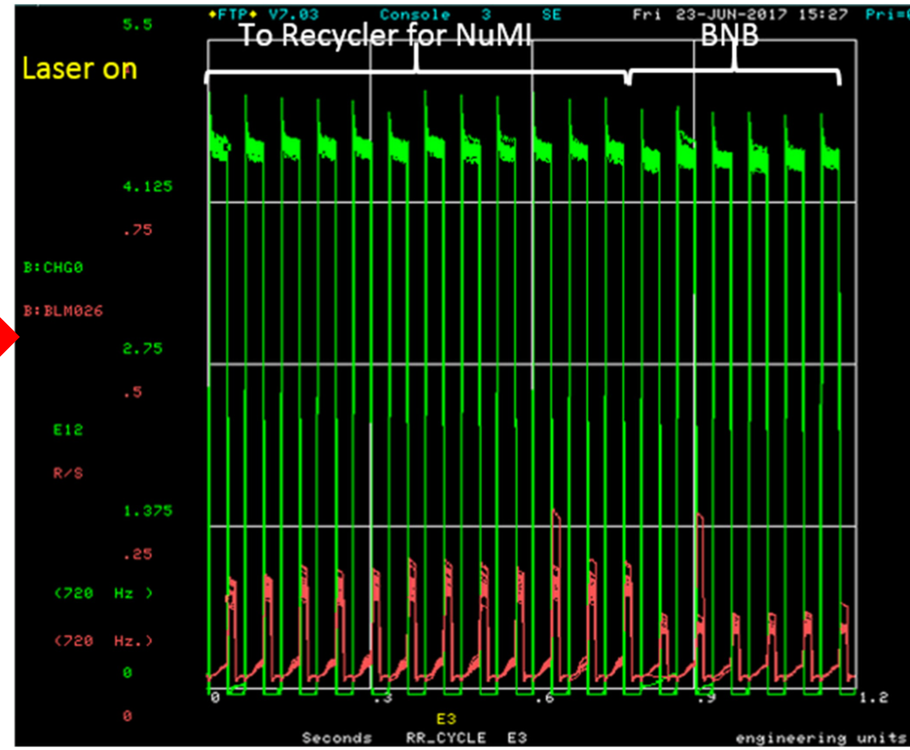






Impact of laser Notcher on Booster throughput





The un-expected

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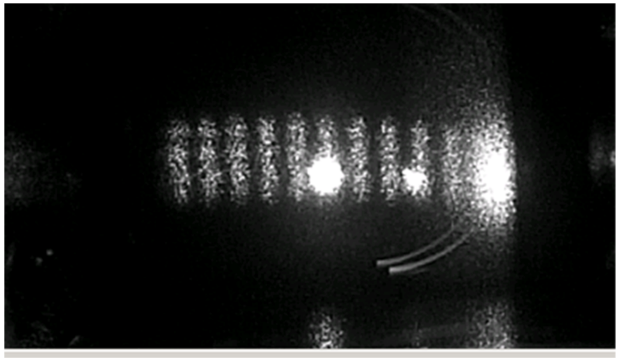

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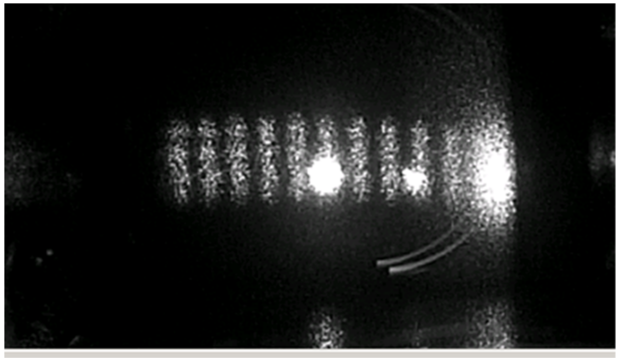

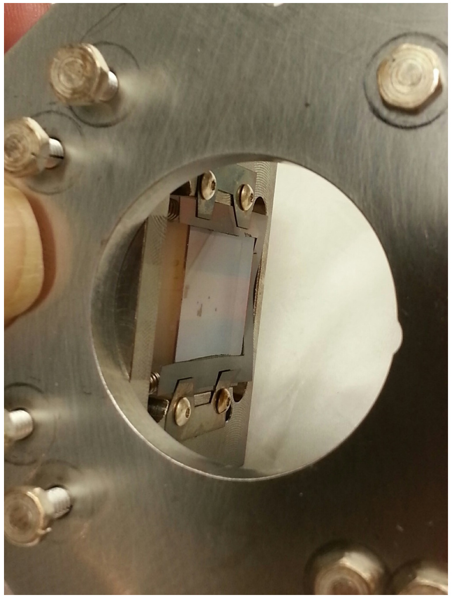

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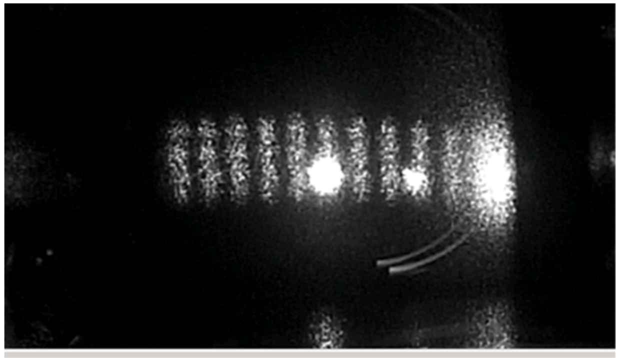

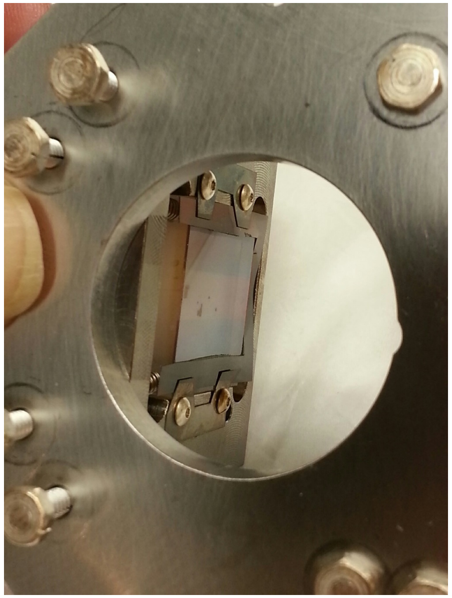

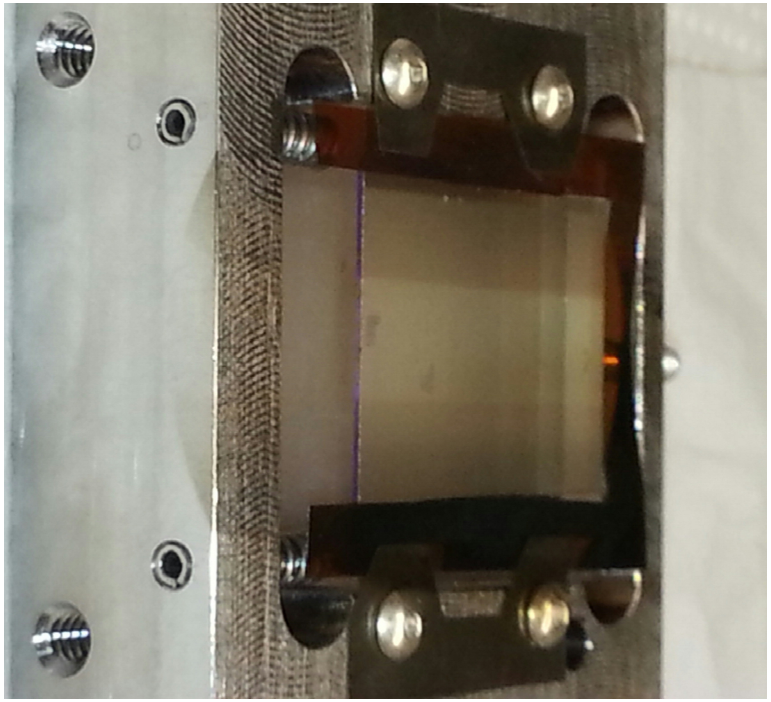

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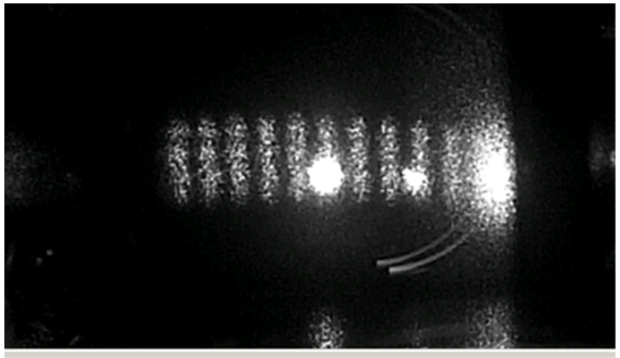

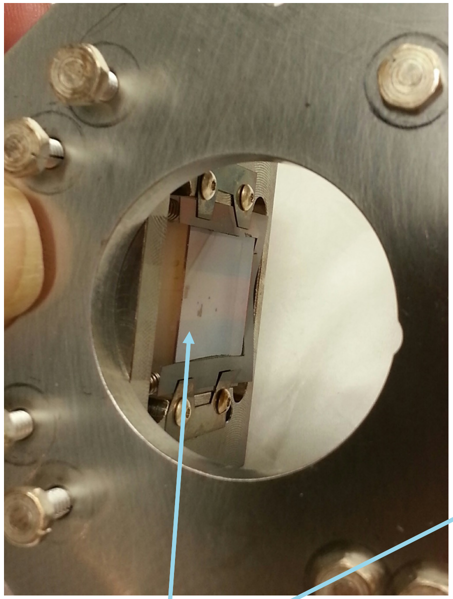

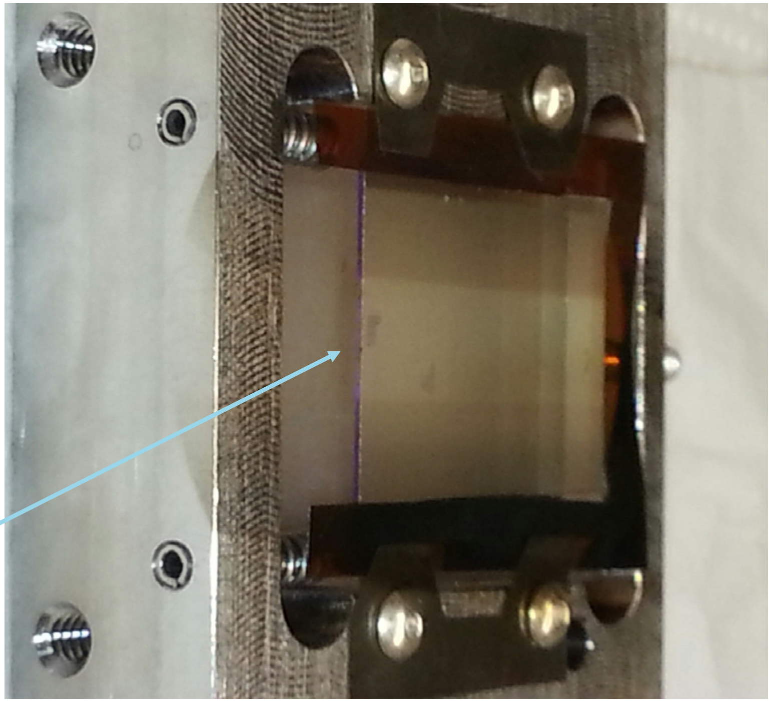

Let's take a closer look at these damage spots !

The un-expected

>>>>Saga on-going <<<<

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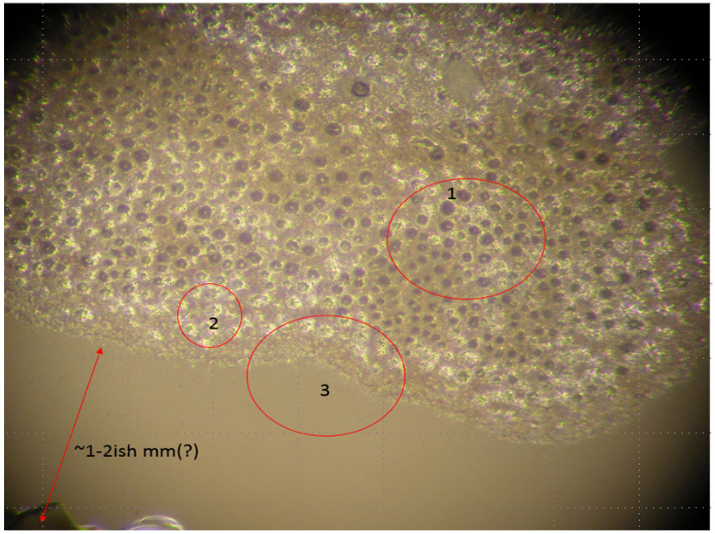

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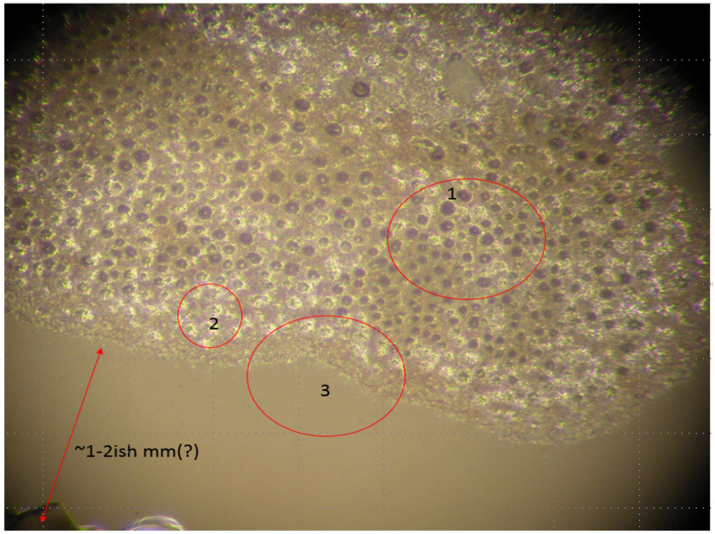

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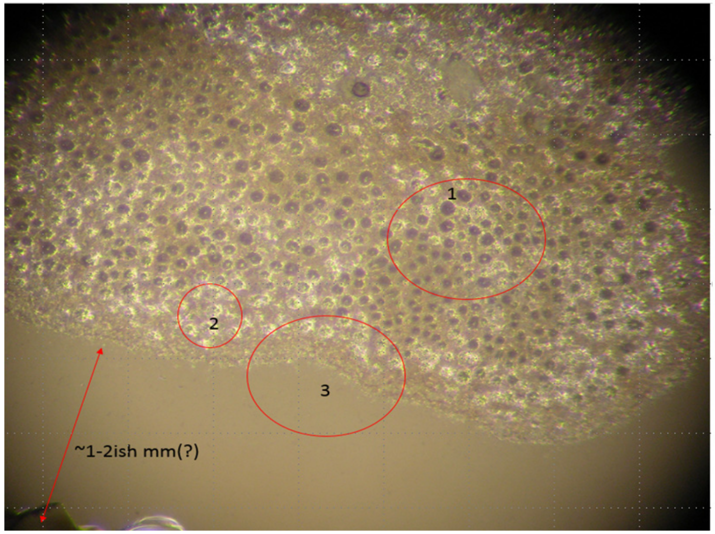

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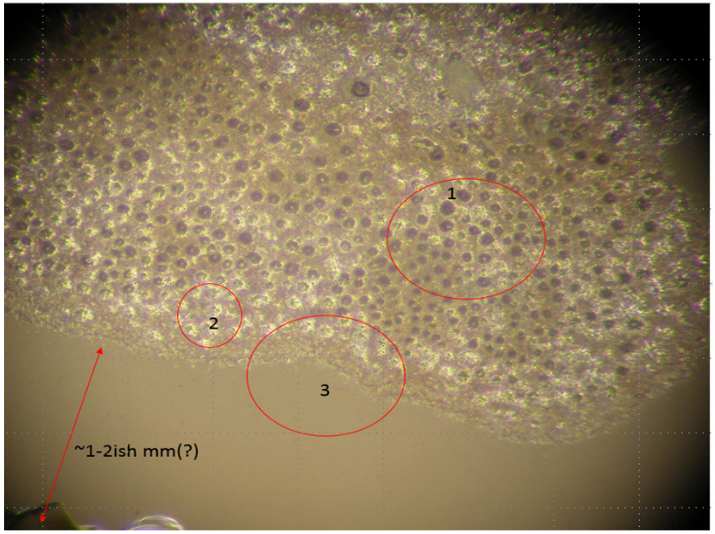

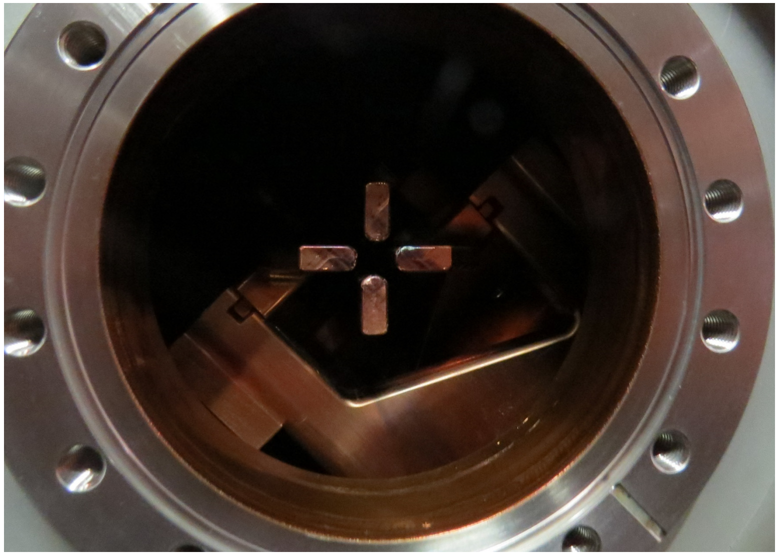

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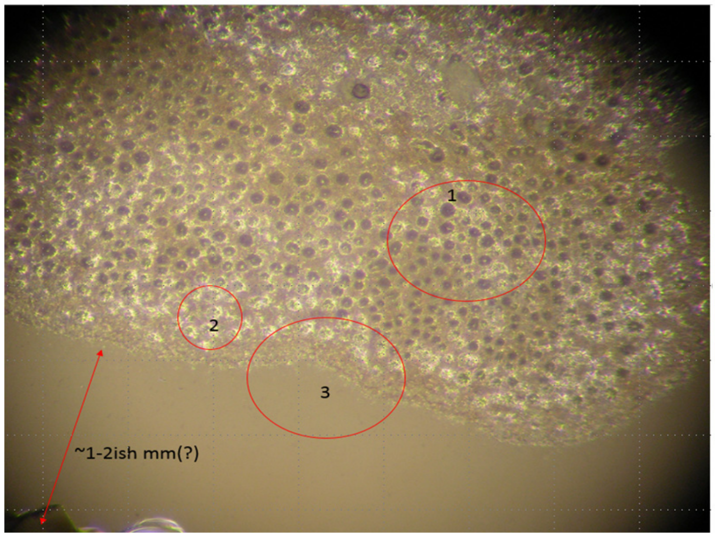

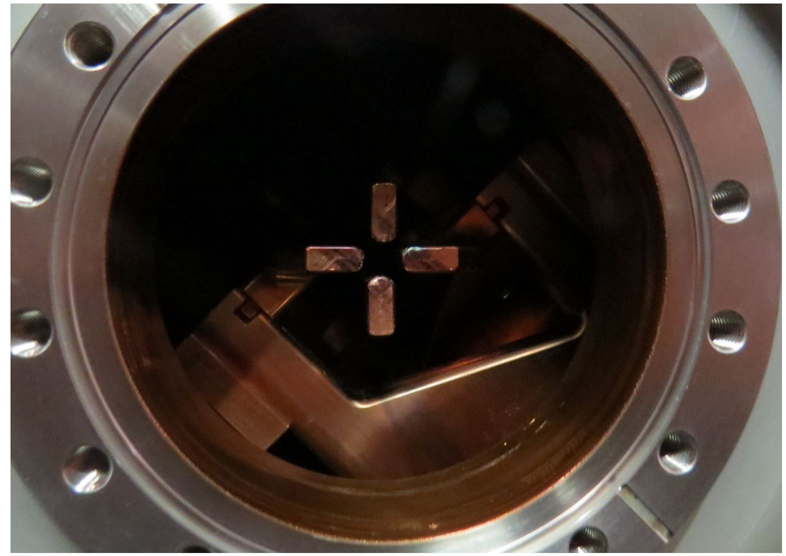

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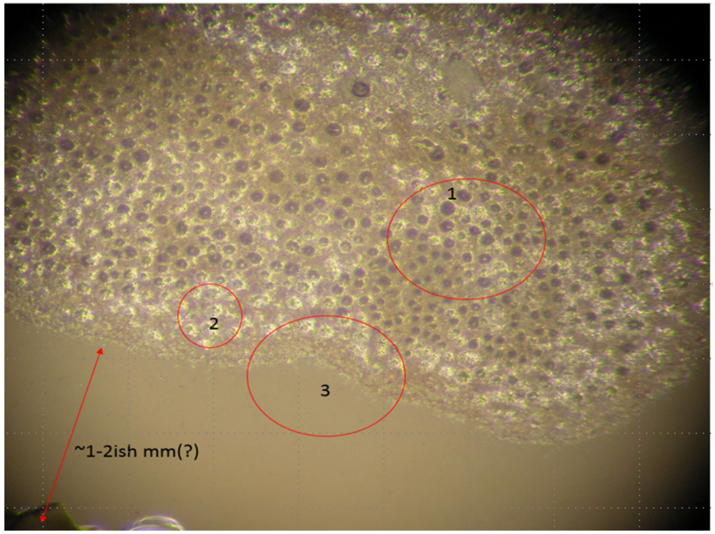

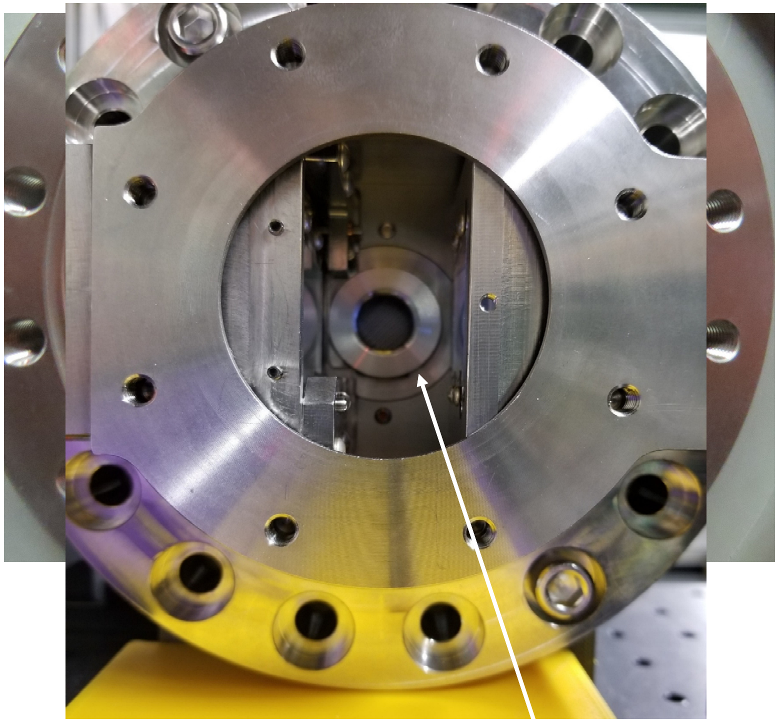

First try- a MASK

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Path Forward

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  - Creation of four beam sections in Booster for the g-2 experiment
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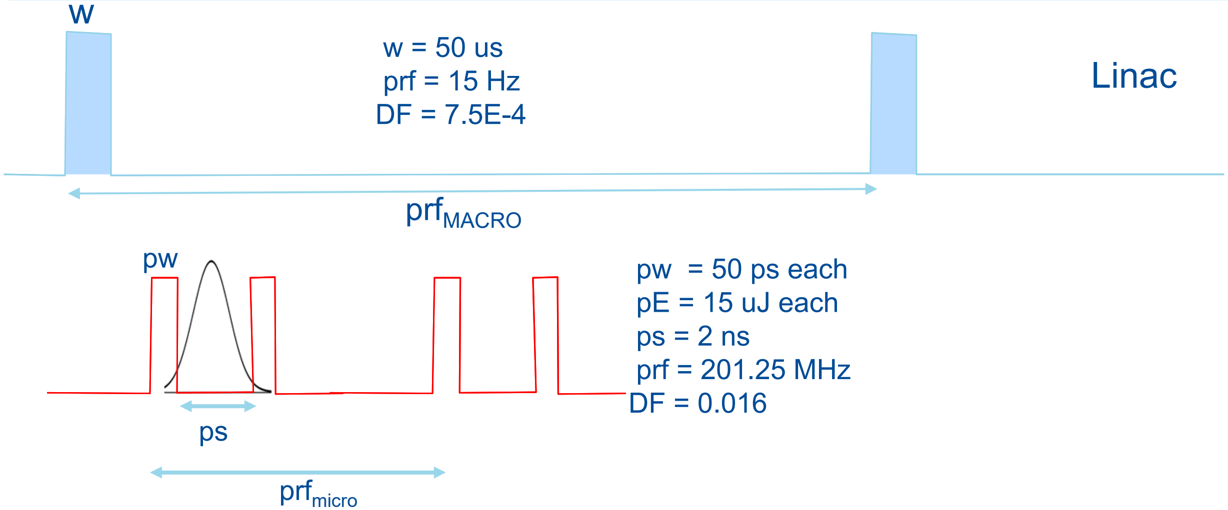
- Each may require a potential different final amplification stage, but can use the infrastructure and technology for the laser notcher.

Path Forward Continued

- We see two areas for further optimizing our amplifier system to be able to support higher duty factor applications
  - Further optimizing optical cavity to reduce required peak laser energy.
  - Move to a fiber only system which is capable of higher duty factors with larger average power and fast pumping
    - The state of art in pulsed fiber amplifiers is 300 kW peak power and 200 W average power.

Concept for Momentum collimation – shaving longitudinal phase



Split amplified pulse→ delay line → recombine temporally with adjustable spacing (ps)
Create head/tail out of single amplified laser pulse

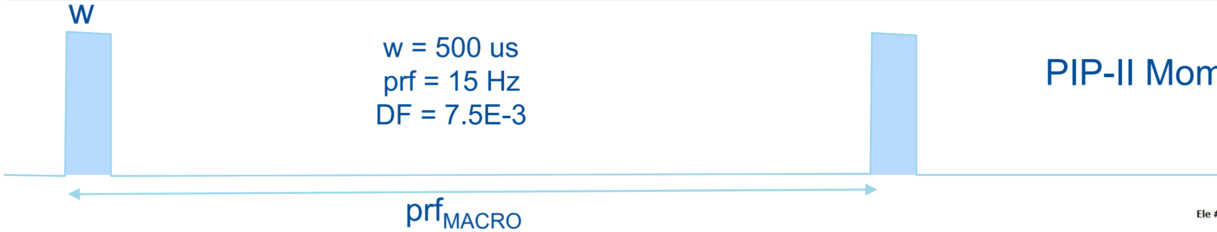
Spot size 1mm x 7.5mm
50 passes, 0.59 mm separation, 1.19mm at mirror
cavity length 2.9 cm, laser path 0.73 m,
neutralization 96% with 15 uJ pulse

Laser produces 201.25E6*50e-6 = 10,000 pulses /cycle
For 30 uJ/pulse*10,000 pulses = 0.3 J /pulse

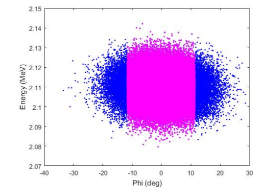
Peak Power = E/pulse/pulse width
=30 uJ/0.1 ns = 300 kW

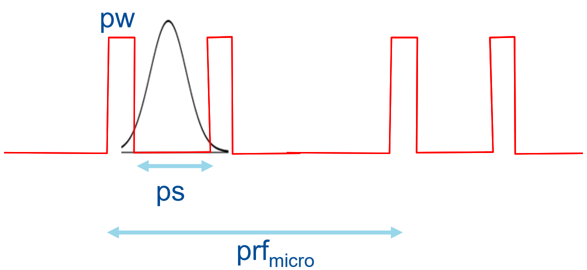
Average power = Peak power*DF
= 300 kW* 3E-5 = 9W

Path Forward: An Example: Momentum collimation

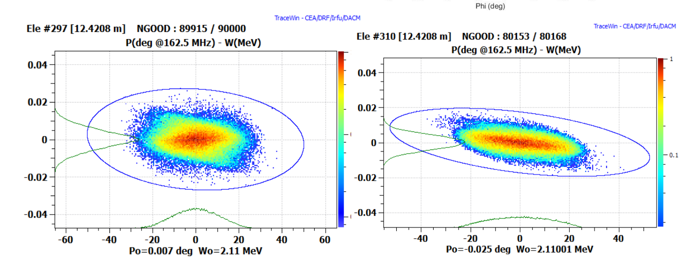


PIP-II Momentum collimation





pw = 100 ps
ps = 1 ns
prf = 162.5 MHz
DF = 0.016



Split amplified pulse→ delay line → recombine temporally with adjustable spacing (ps)
Create head/tail out of single amplified laser pulse

Spot size 1mm x 1.6mm
100 passes, 1.1 mm separation, cavity length 10.9 cm
Laser path 1.6m, neutralization 99.7% with 5 uJ pulse

Laser produces 162.5E6*500e-6 = 81,250 pulses /cycle
For 10 uJ/pulse*81,250 pulses = 0.8125 J /pulse

Peak Power = E/pulse/pulse width
=10 uJ/0.1 ns = 100 kW

Average power = Peak power*DF
= 100 kW* 1E-4 = 10W

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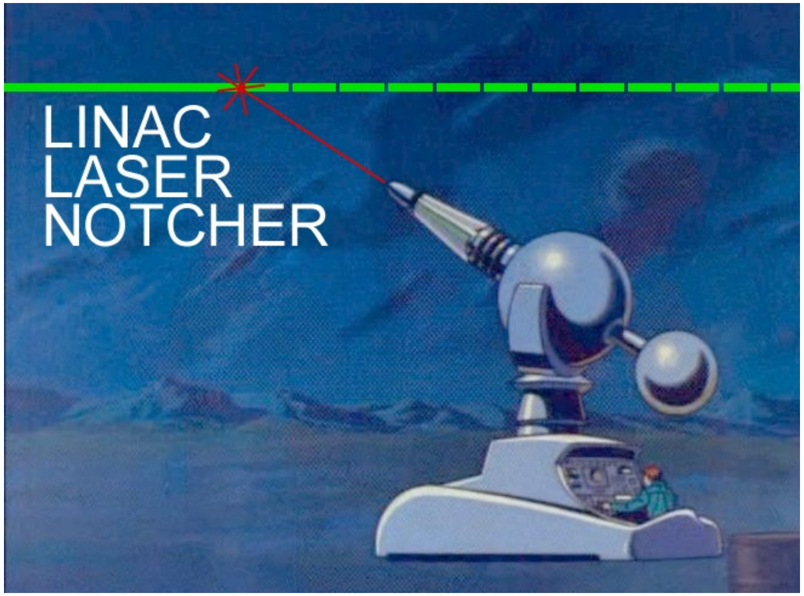
- We see this approach as contributing to the further growth in the utilizing of laser interactions with H- for a variety of applications.

Thank you for your attention



Questions ?