Booster Laser Notcher Proposal

David Johnson
Jinhao Ruan, Jamie Santucci, Vic Scarpine, Ray Tomlin

Presentation to PIP
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Motivation

- Proton Improvement Plan Intensity Goals
  - Ultimate goal: 2.2E17 protons delivered/hr @ 15 HZ by 2016
  - Assuming 90% acceleration eff. -> 1E9/200MHz bunch injected
- Notching in the Booster ring deposits the removed bunches in the gradient magnets. This represents on the order of 30% of Booster losses (few % of beam intensity).
- Ultimately one needs about 50-60 ns notch in the beam at extraction time for the extraction kicker rise time.
- In the 200 MHz beam structure this would correspond to ~10-12 200 MHz bunches every 2.2 us and for 10 turns this would be a total of about 60 to 80 bunches or about 1-2% of injected beam.
- Assuming 1E9/bunch this would be 1 to 1.2E11 /pulse but for simplicity lets assume 1E11 H- need to be neutralized per pulse. At 15 Hz -> 1.5E12/sec -> 100 watts of beam power to be removed.
- We would like to remove this loss from the ring and safely dispose of the notched ions.
- Techniques developed here are applicable in other projects such as laser stripping and laser chopping.

Laser Notching Experiment

- In 2001 Ray Tomlin reported on an experiment where he created a 25 ns notch in the H-beam in the H- 750 keV line utilizing a 200 mJ 5 ns laser pulse.

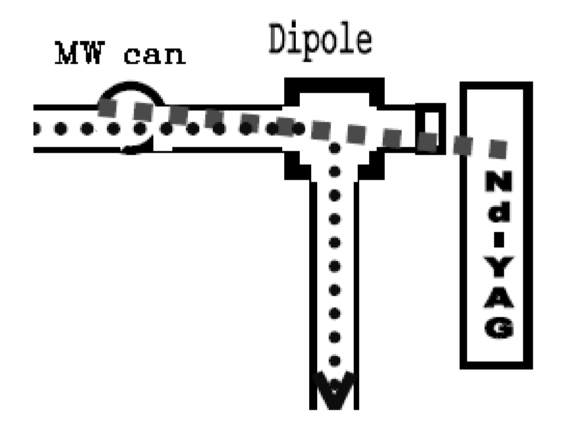


Figure 1

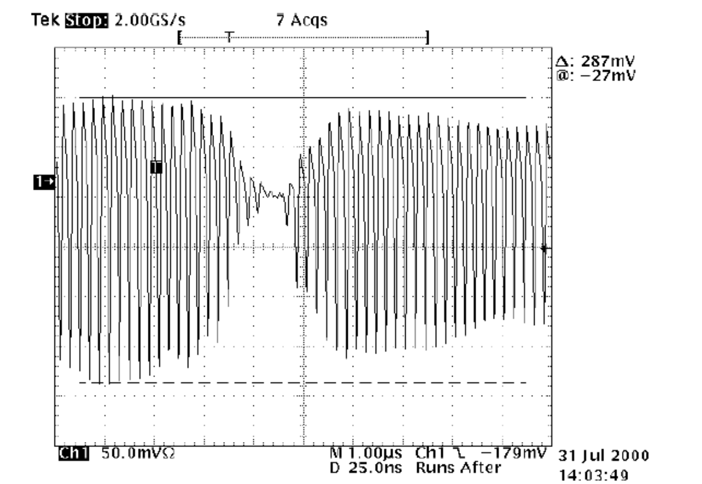
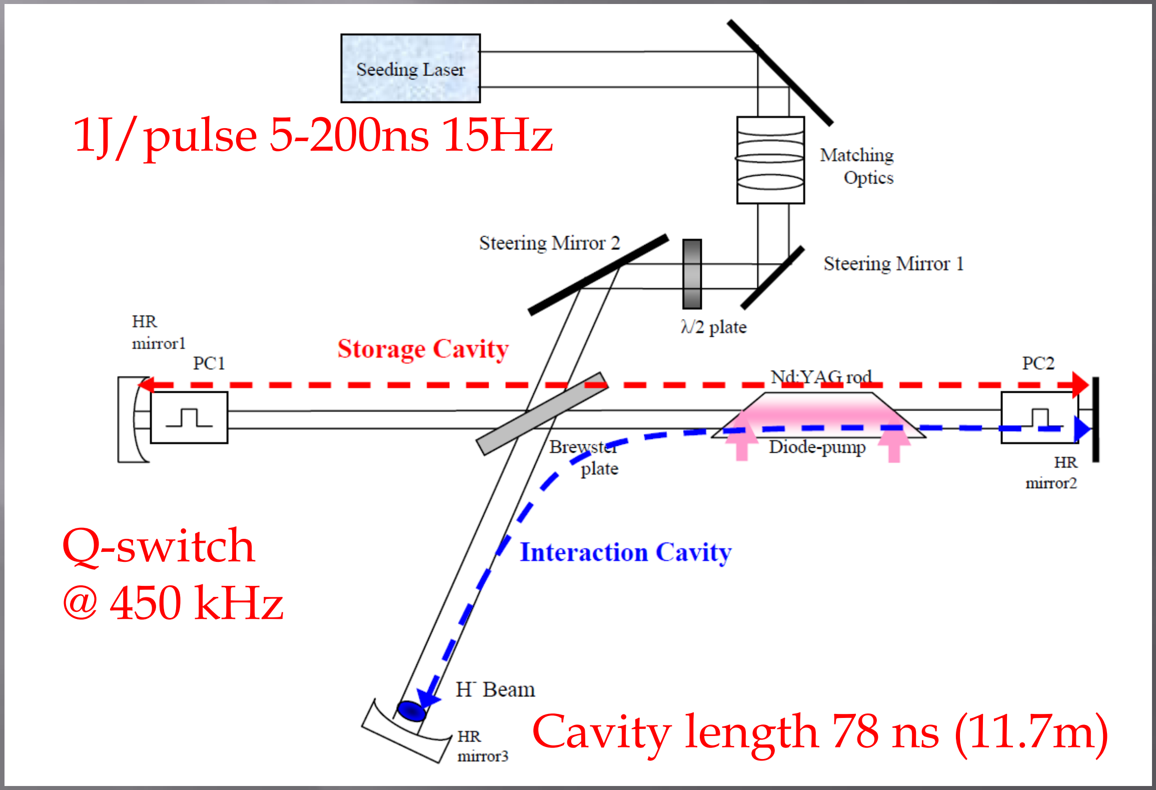


Figure 2: 200 MHz bunch signal from a BPM plate at the end of RF tank two in FNAL Linac shows a 99% notch. This is a 200 mJ, 5 ns pulse crossing at an angle.

- Figures form PAC 2001 conference paper

Previous Laser Notching Proposal

- In 2005 Xi Yang, et. al. proposed to notch the linac beam in the 750 keV line at the Booster injection revolution frequency (FN-0767).



Required Laser Parameters

The fraction of electrons that are detached from the moving H- ions is:

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

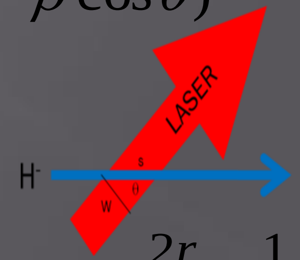
The photon flux (generated by the laser) in the lab frame [photons/cm2/sec]

$$f_{LAB} = \left(\frac{E_{laser}\lambda_{LAB}}{hc\tau_{laser}}\right)\left(\frac{1}{\pi r^2}\right)$$

The photon flux in the lab frame is transformed into the rest frame of moving ion as:

$$f_{cm} = \gamma f_{LAB}(1 - \beta \cos\theta)$$

The interaction (crossing) time is just the ion path length/ ion velocity



$$\tau_{crossing} = \frac{2r}{\sin\theta}\frac{1}{v_{H-}}$$

The neutralization factor for an ion crossing on axis of the laser beam may be written in terms of lab frame parameters

$$F_{neut} = (1 - e^{\frac{-E_{laser}\lambda_{LAB}\sigma(E)(2r)}{h\beta c^2 \tau_{laser}\pi r^2}\frac{\gamma(1-\beta\cos\theta)}{\sin\theta}})$$

Energy of the Ion Beam

- It is desirable to generate the notches at the lowest energy possible
  - to minimize the impact of the disposition of the neutralized ions (lower energy requires less shielding, if any),
- Lower ion energies have lower velocities and longer interaction times which reduces required laser energy
- Lower energies typically have larger beam sizes which increases the pulse energy due to the increased area of the laser beam.

Laser-Ion Geometry

- For near head-on collisions,
  - the path length of the ion through the laser can be increased, but the center-of-mass laser photon energy is <u>increased</u> with increasing beta.
- For near parallel collisions (laser-ion in same direction),
  - again the path length of the ion through the laser can be increased, but the center-of-mass laser photon energy is <u>reduced</u> with increasing beta.
- Both small angle orientations require more beam line space.
- Due to space considerations we assume that the laser interaction with the H- beam is near normal.
  - Center of mass energy is just gamma* Lab frame photon energy
  - The peak of the neutralization cross section for 400 MeV ions corresponds to 1 micron lab frame laser at near normal incidence.
  - The time structure of the H- beam that is neutralized (i.e. the length of the notch) is dependent on the laser pulse duration.

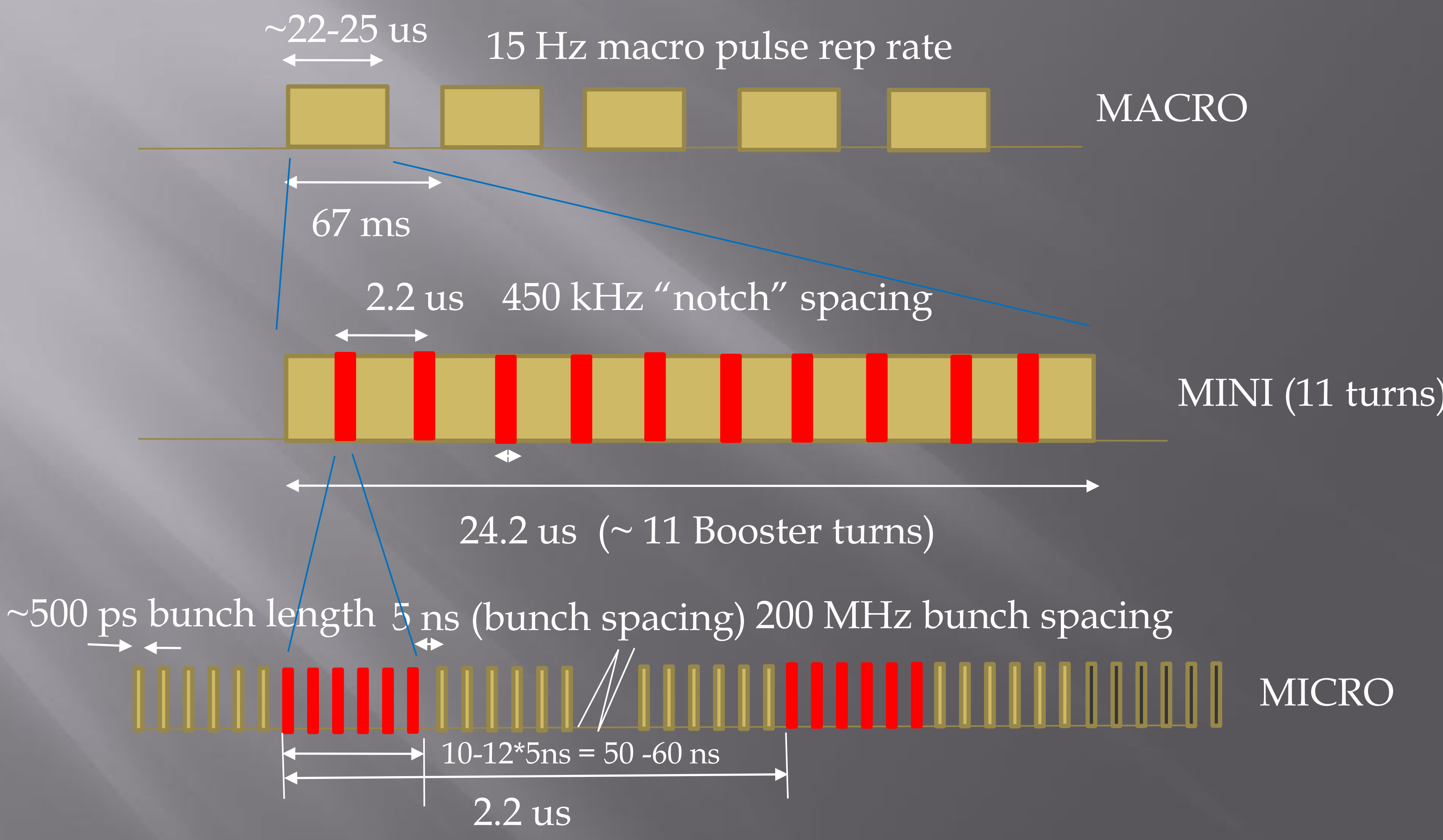
Laser Pulse Length

- For notching the linac beam,
  - the laser pulse length can either be matched to the bunch length (at 200 MHz) or
  - the notch length (at 450 kHz).
  - For notching at low energy before the RFQ, the pulse length should be approximately the required notch length for a single pass interaction.
  - For highly bunched beam, for example at 400 MeV, the bunch length occupies only 10% of the RF bucket, i.e. 0.5 ns/5 ns.
  - At the low energy end of the linac (750 keV) before the beam is completely bunched, it occupies up to +/-90 degrees of the 200 MHz bucket which means that the pulse length increases from ~0.5 ns upward to 2.5 ns (at 200 MHz).
  - Bottom line is that for bunched beam tailoring the pulse length to match the bunch length is most efficient.

Ion Beam Transverse Size

- The ion beam dimension perpendicular to the ion beam direction should be minimized.
- For a given neutralization, the required laser pulse energy is inversely proportional to transverse ion dimension.
- For the cases described here it is assumed that the laser will be oriented horizontally, so the laser must match vertical ion beam dimension

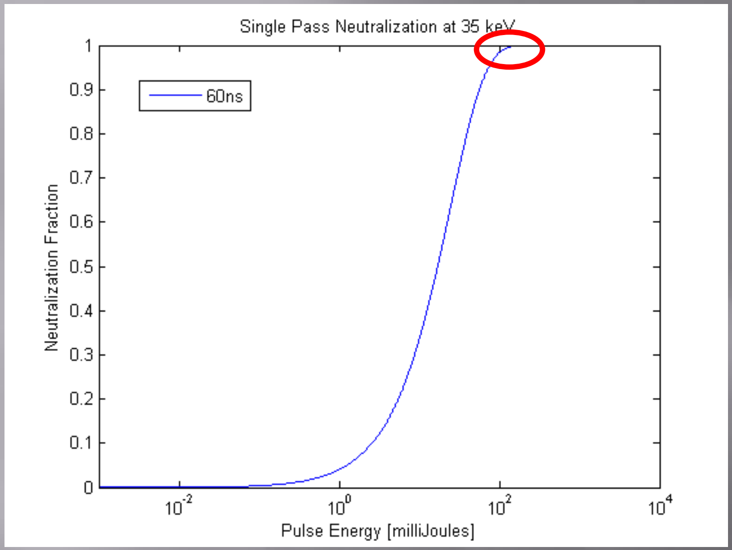
Linac Beam Bunch Structure

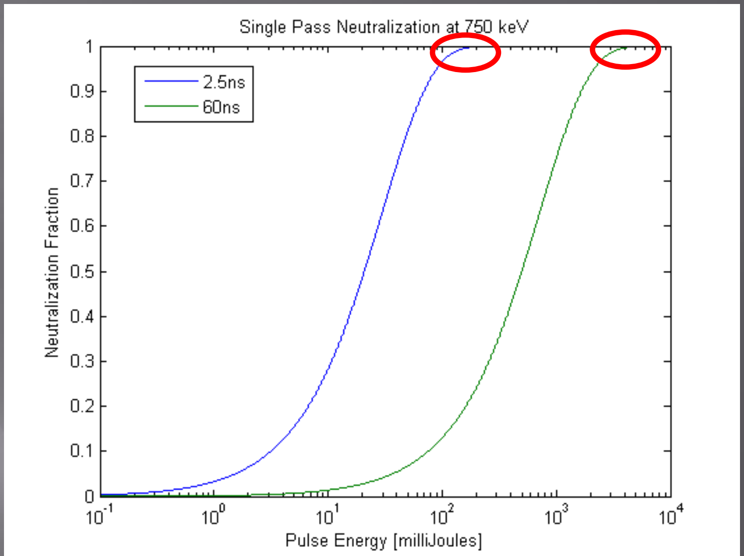


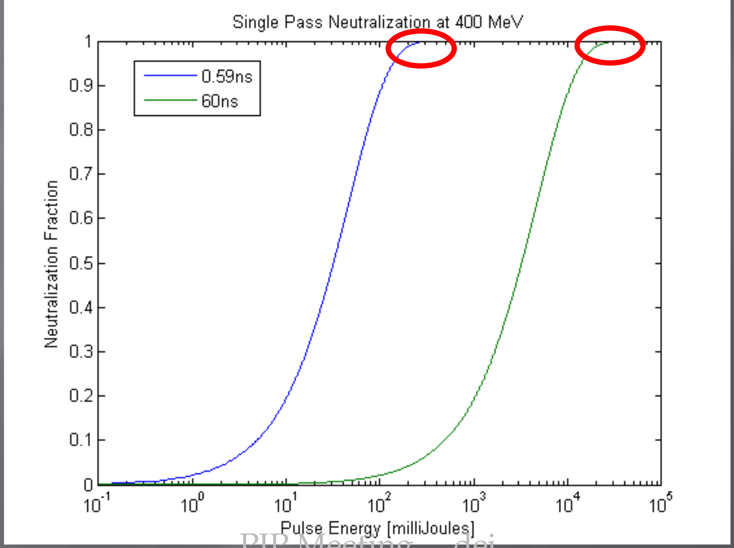
Potential Notching Energies

- Before the RFQ at 35 keV
  - DC beam
  - Laser pulse length ~ 60 ns
- After RFQ and before or at the start of Tank 1 at 750 keV
  - Quasi bunched with beam out to +/-90 degrees
  - Laser pulse length either 2.5 ns or 60 ns
- At 400 MeV just before MV2
  - Fully bunched with a bunch length of ~500-600 ps
  - Could use either 600 ps or 60 ns laser pulse length

Single Pass Neutralization





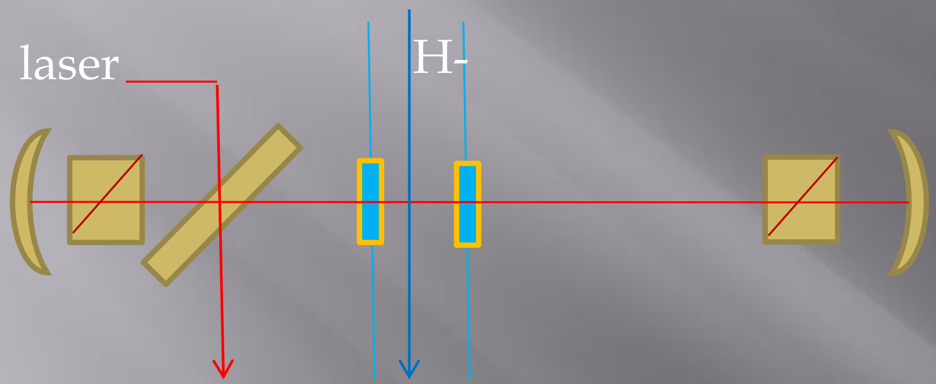


Summary of Laser Requirements

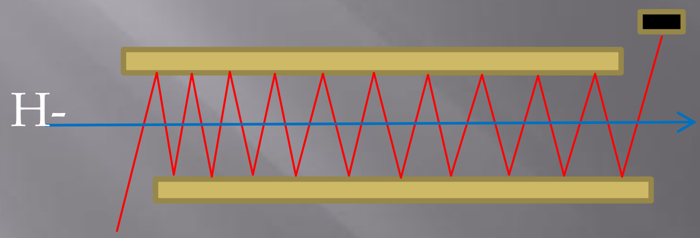
Ion Beam Energy	Pulse Energy	Laser Pulse Length	Laser Beam Size	Crossing Time	Cross Section $x10^{-17}$	Fraction Neutralized
35 keV	100 mJ	60 ns	3.1 mm	1.2 ns	3.8	98%
750 keV	140 mJ	2.5 ns	19.8 mm	1.65 ns	3.8	99%
750 keV	3000 mJ	60 ns	19.8 mm	1.65 ns	3.8	98%
400 MeV	120 mJ	0.59 ns	7.8 mm	0.36 ns	4.1	97%
400 MeV	12000 mJ	60 ns	7.8 mm	0.36 ns	4.1	97%

- To reduce the required pulse energies, we can increase the crossing (interaction) time by utilizing a cavity such that the laser beam interacts with the ion beam multiple times

Potential Cavity Geometries



Recirculation cavity



Linear cavity (zig-zag)

- Cavity length ~ laser pulse length
- Used to increase notch size by recirculating shorter laser pulse
- Requires Q-switch to switch laser pulse in/out of cavity
- Requires gain medium to compensate losses due to Q-switch, windows, etc.

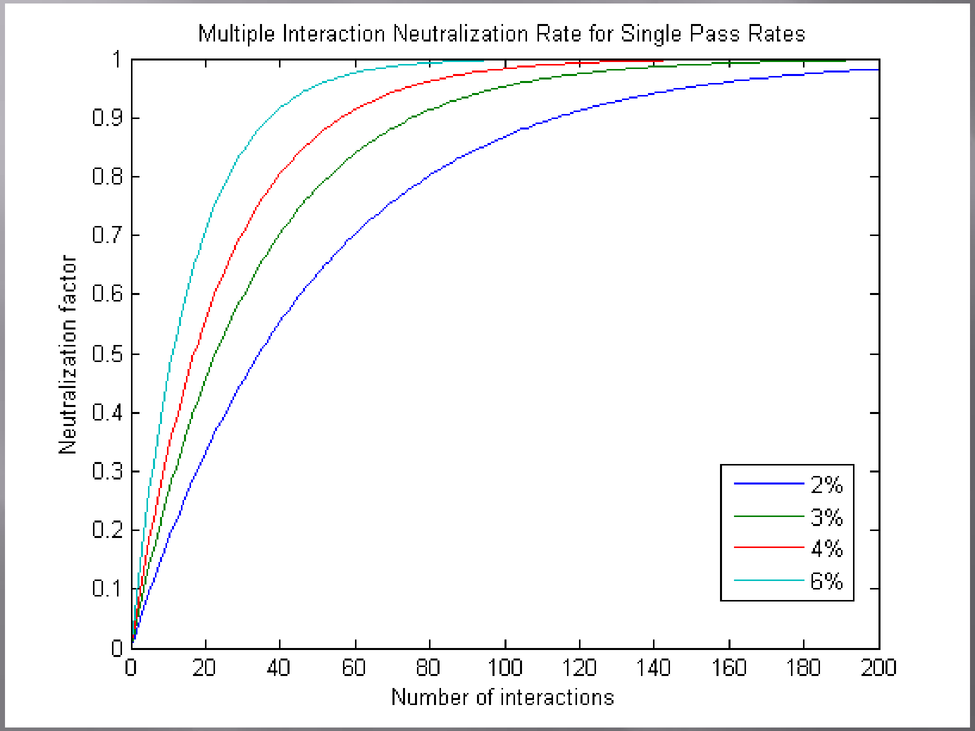
- Laser follows ion to interact many times (increase τ)
- Cavity length proportional to number of interactions
- Laser pulse length = notch length
- Cavity dimensions determined by ion velocity and spacing of interactions
- Reduces required laser pulse energy by number of interactions

Multiple Interaction Neutralization Factor

- If the laser passes through the H- beam N times, the fractional yield F_N of H^0 is related to the fractional yield F_1 of a single crossing by :

$$F_N = 1 - (1 - F_1)^N \quad \text{where} \quad F_1 = (1 - e^{-flux*\sigma*\tau})$$

R. Shafer , 1998 BIW



- Assume 100% reflectivity on mirrors
- Assume 200 µJ laser pulse on the input of the optical cavity
- Each curve represents single interaction neutralization factor, F_1.

Impact of Finite Reflectivity

For a given mirror reflectivity R, the laser fluence available for interaction at each of the M^{th} interactions is modified by R^M such that

$$flux_M = fluence * R^M / \tau_{laser}$$

where

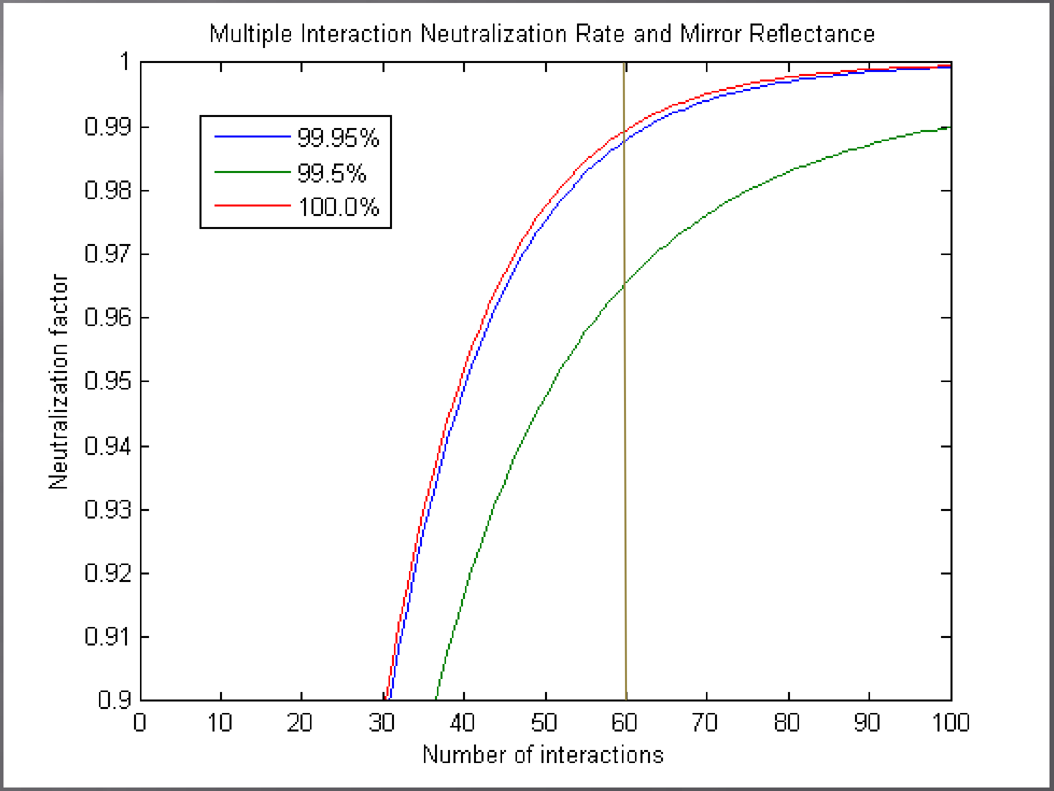
$$F_1 = (1 - e^{-flux_M * \sigma * \tau})$$

Then for N reflections

$$F_N = 1 - (1 - F_1)^N$$

Assume :

- 2 mJ laser pulse on the input of the optical cavity
- 600 ps laser pulse length
- 7.8 mm laser beam diameter

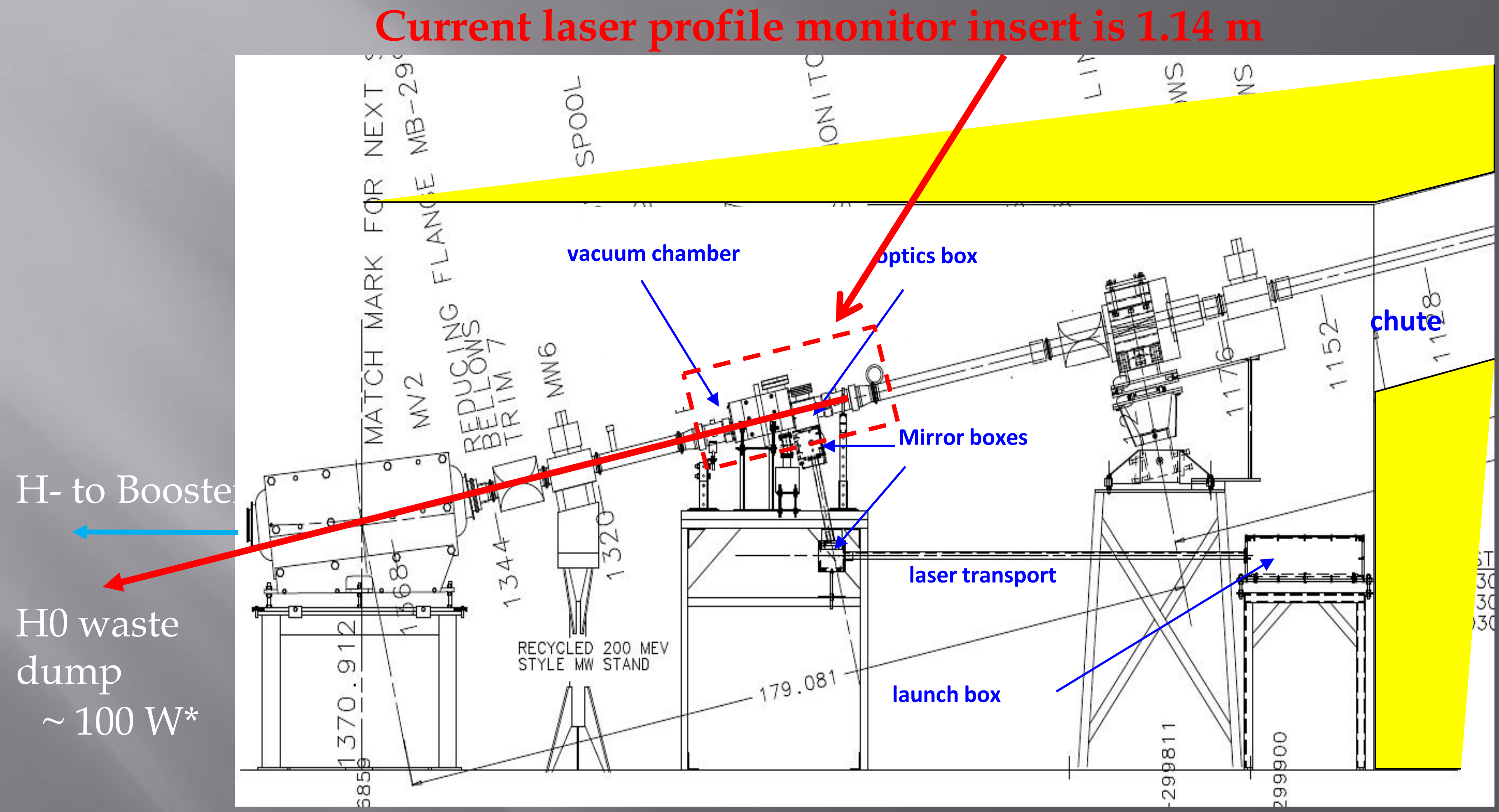


For near normal crossing cavity length ~ laser diameter*nbr crossing -> ~46 cm

Proposal for Booster Laser Notching

- If beam line space were available in the LEBT or MEBT where ion beam sizes were small, one could find potentially workable solutions, but these would require recirculation cavities, fast Q-switches and reasonably large pulse energies.
- At this point the most straight forward approach is to utilize the linear zig-zag cavity at 400 MeV with laser pulses to match the 200 MHz bunch structure.
- The following slides show the location, layout, and proposed laser system layout

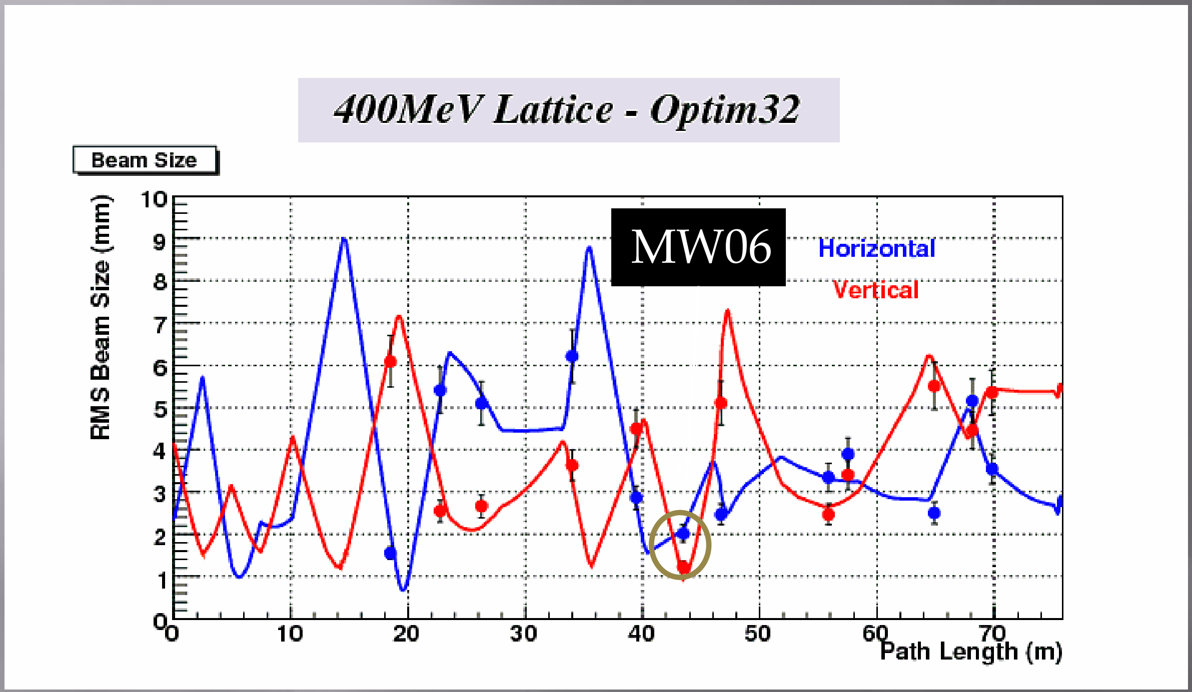
Location for Booster notcher

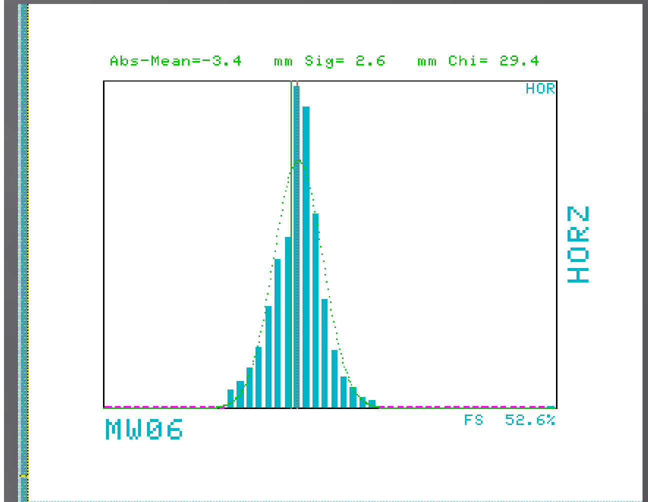


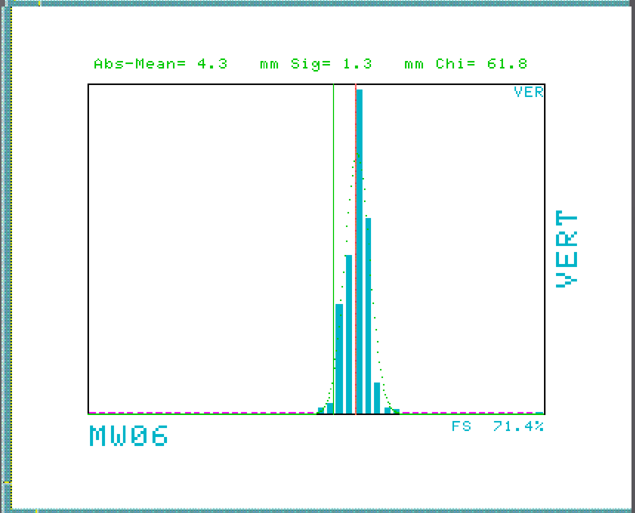
*MAX 10 bunches/notch *10 notch/inj*1E9/bunch = 1E11/pulse*15 Hz = 1.5E12 particles/sec-

Existing Laser wire insertion

400 Mev line beam size





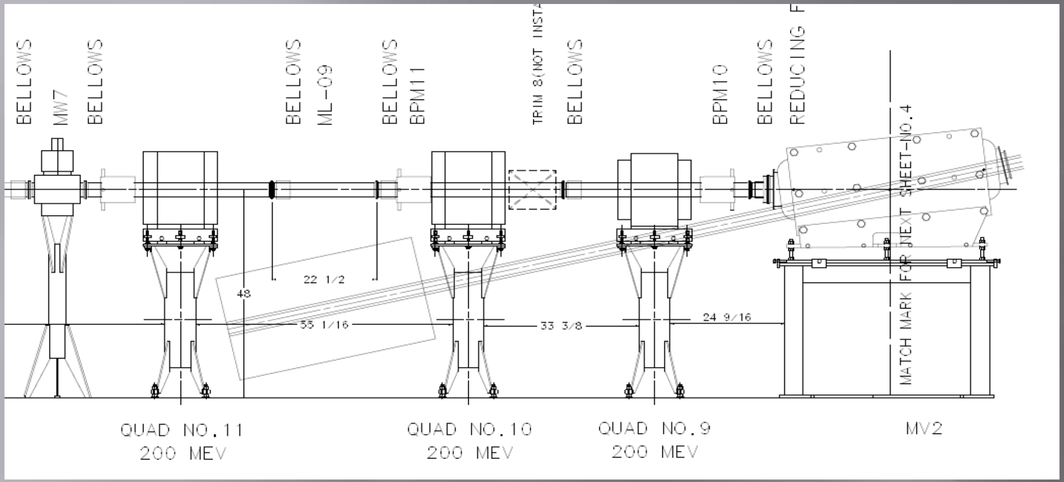


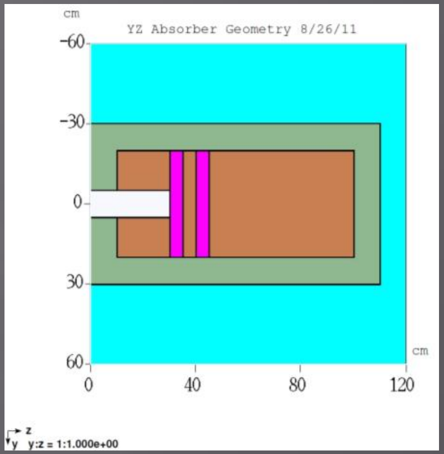
Laser beam size needs to enclose the smaller of the Booster beam dimensions i.e 6*1.3 ~ 7.8mm

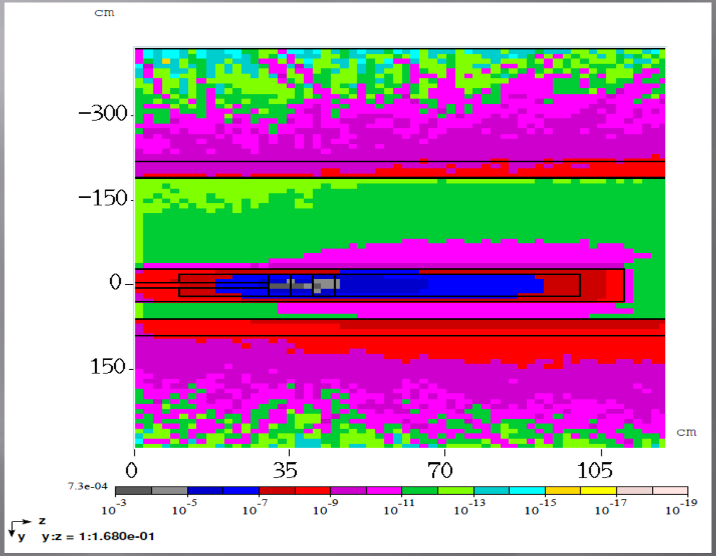
Can the linac vertical beam size at MW06 be reduced?

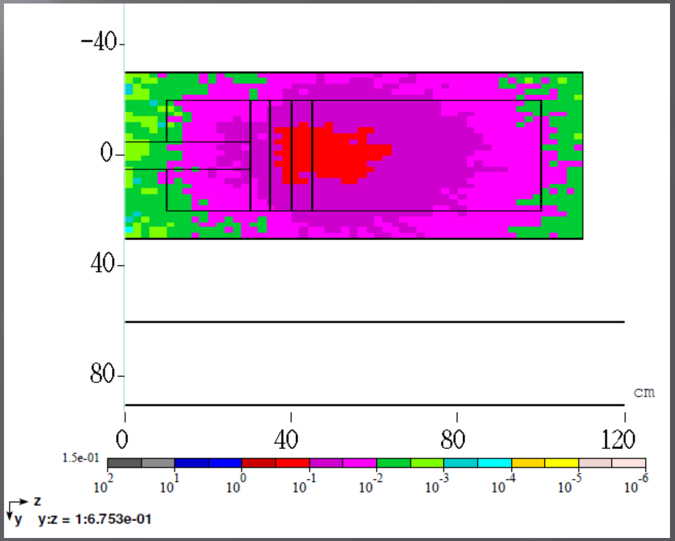
Is this optical model of the lattice accurate?

H0 Dump





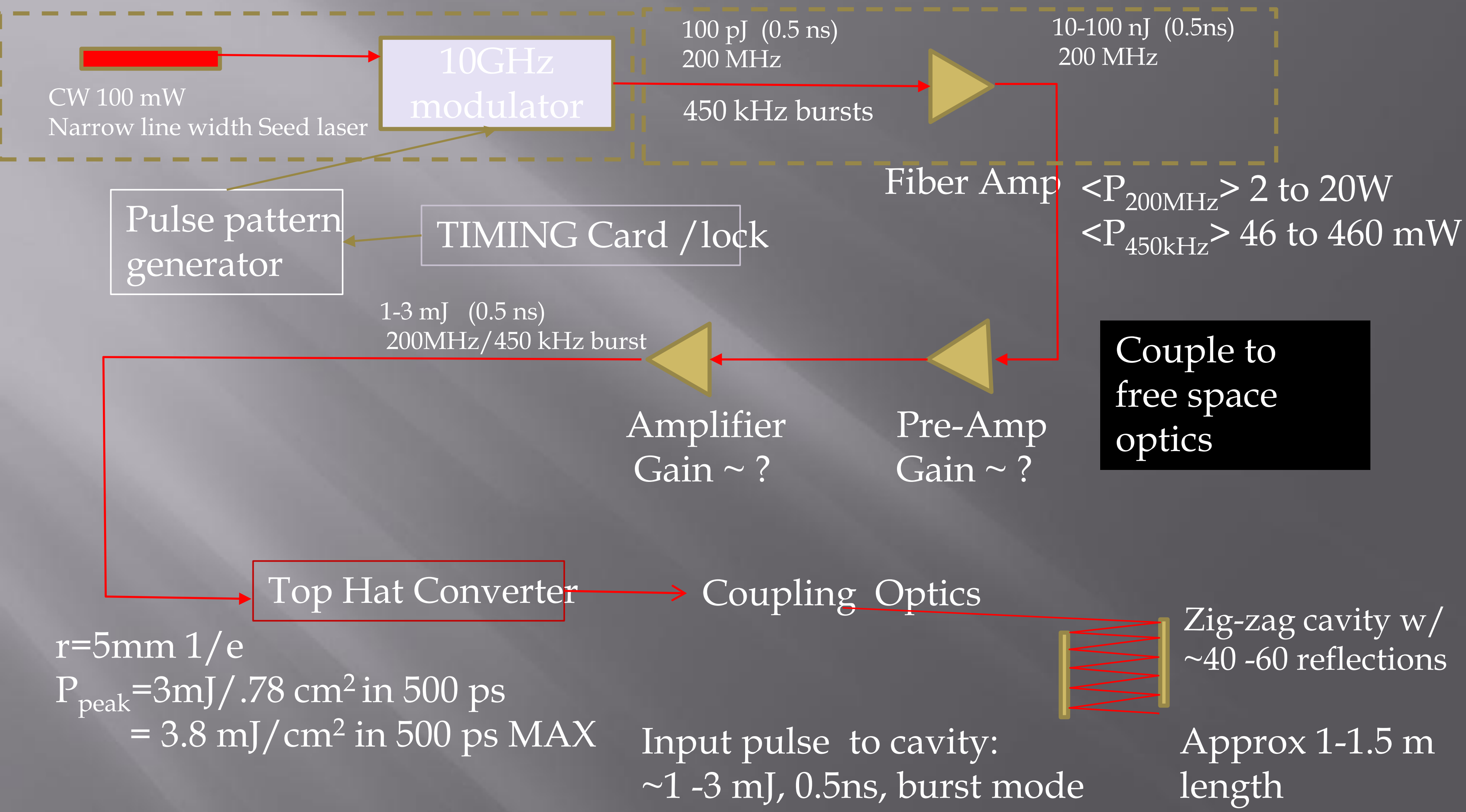




Max Star density 72.E-9 s/cm2/proton
22% limit for 1 flushing/yr

Peak contact dose 15 mrem/hr

BOOSTER NOTCHER CONCEPTUAL SYSTEM



Laser Notcher Components

- Seed laser (CW, ultra stable, narrow line width)
- Pulse Generator- initially commercial pulse generator
- Timing module – same design at laser wire
- Modulator – (c.f. 5 GHz Jenoptic modulator)
- Fiber pre-amp ~(20W)
- Matching to free space
- Main Amplifier
  - DPSS – Grumman proposal
  - Cryo DPSS - Snake Creek lasers
- Transport to tunnel – free space/fiber
- Top hat conversion
- Zig-zag interaction cavity (40-60 intractions)

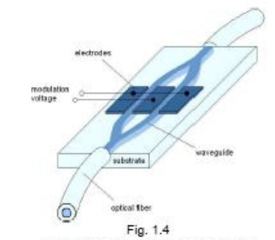
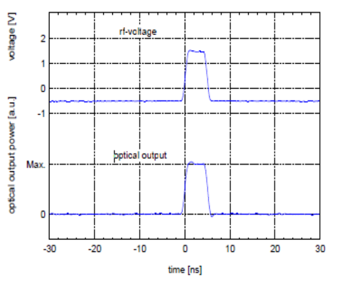


Fig. 1.4
Mach-Zehnder-amplitude modulator



40 dB extinction

Initial Plans

- Verify the combination of the CW seed and optical modulator will produce desired optical pulses with desired extinction
- Design optical zig-zag cavity and procure slab mirrors and mounts and set up prototype
- Beam line modifications planning
- Investigate fiber pre-amplifier options (many recent advances in high power fiber amplifiers)
- Investigate main free space amplifiers (potential designs from Grumman and Snake Creek Lasers)
- Investigate impact of radiation on diode pumps
- Determine transmission method (free space or fiber)
- Evaluate beam shaping techniques
- First experimental verification of technique in MUCOOL
- Plan 400 MeV line modifications (MV2, quad stands, dump)