Proton Beam Inter-Bunch Extinction and Extinction Monitoring for the Mu2e Experiment

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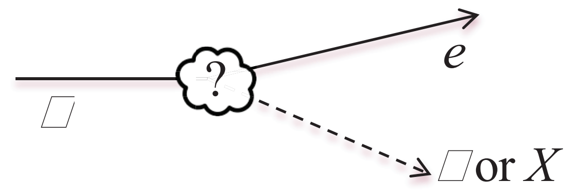
HB2012, Beijing, China

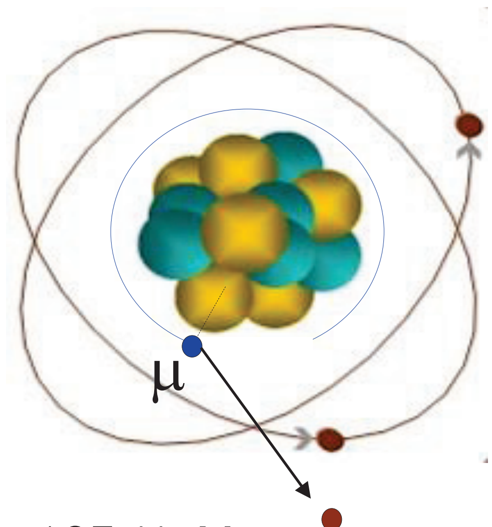
Acknowledgments

- Representing the Mu2e Collaboration
  - 24 Institutions
  - ~120 Collaborators
- This talk has direct contributions from
  - Alexander Drozhdin, FNAL
  - Andrei Gaponenko, FNAL
  - Carol Johnstone, FNAL
  - Vladimir Kashikhin, FNAL
  - Peter Kasper, FNAL
  - Sasha Makrarov, FNAL
  - Bill Molzon, UCI
  - Igor Rakhno, FNAL
  - Zhengyun You, UCI

The Physics of Mu2e: μ+N → e+N

- Nearly all models beyond the Standard Model predict the interaction:





105 MeV e^-

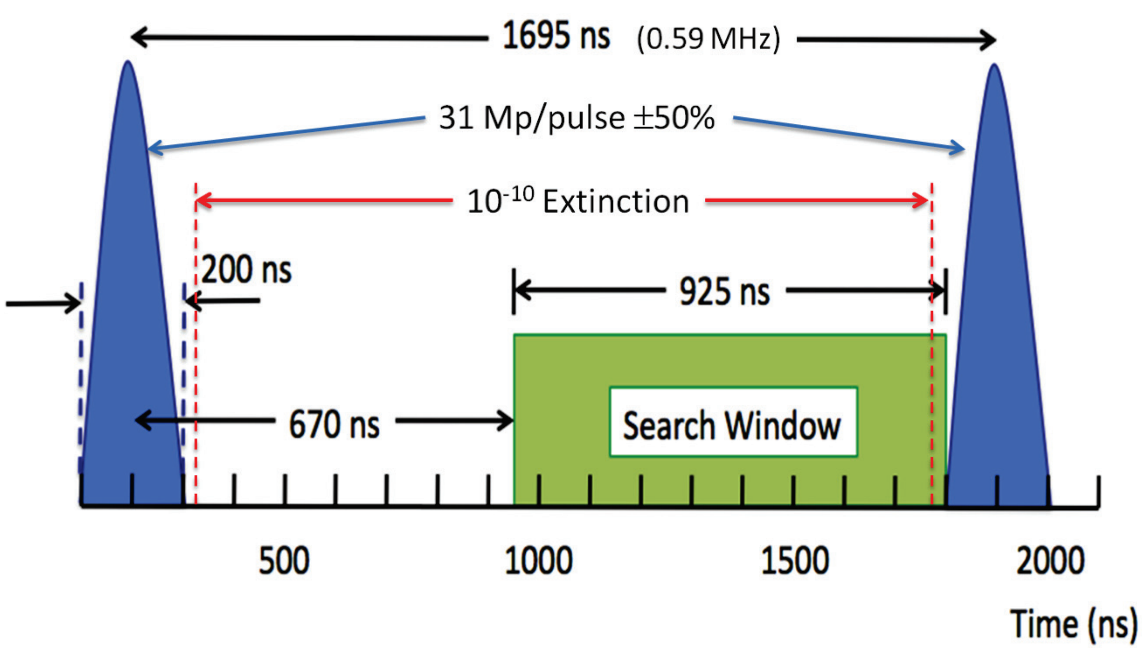
- If captured on the nucleus, a muon will have an enhanced probability of exchanging a virtual neutral particle
  - Could be a γ or heavy boson.
  - Two body decay➔mono-energetic electron!
- Similar to $\mu \rightarrow e\gamma$, with important advantages:
  - No combinatorial background
  - Because the virtual particle can be a photon *or* heavy neutral boson, this reaction is sensitive to a broader range of BSM physics
- Goal: measure

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

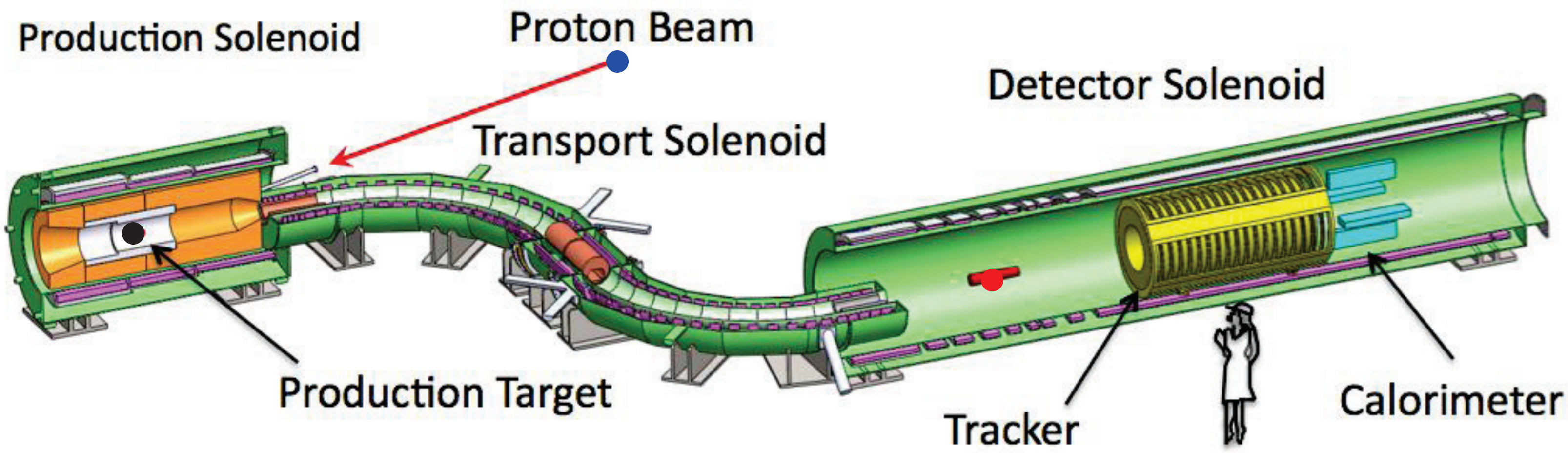
with a single event sensitivity of $<10^{-16}$

Experimental Technique and Extinction

- A proton beam will be used to create muons, which will be transported and captured on an Aluminum target.
- Most backgrounds are prompt with respect to the parent protons, so a pulsed beam will be used.
  - Detection window will be after backgrounds have died away
- Out of time protons would limit sensitivity and must be suppressed at the 10^{-10} level (“Extinction”)

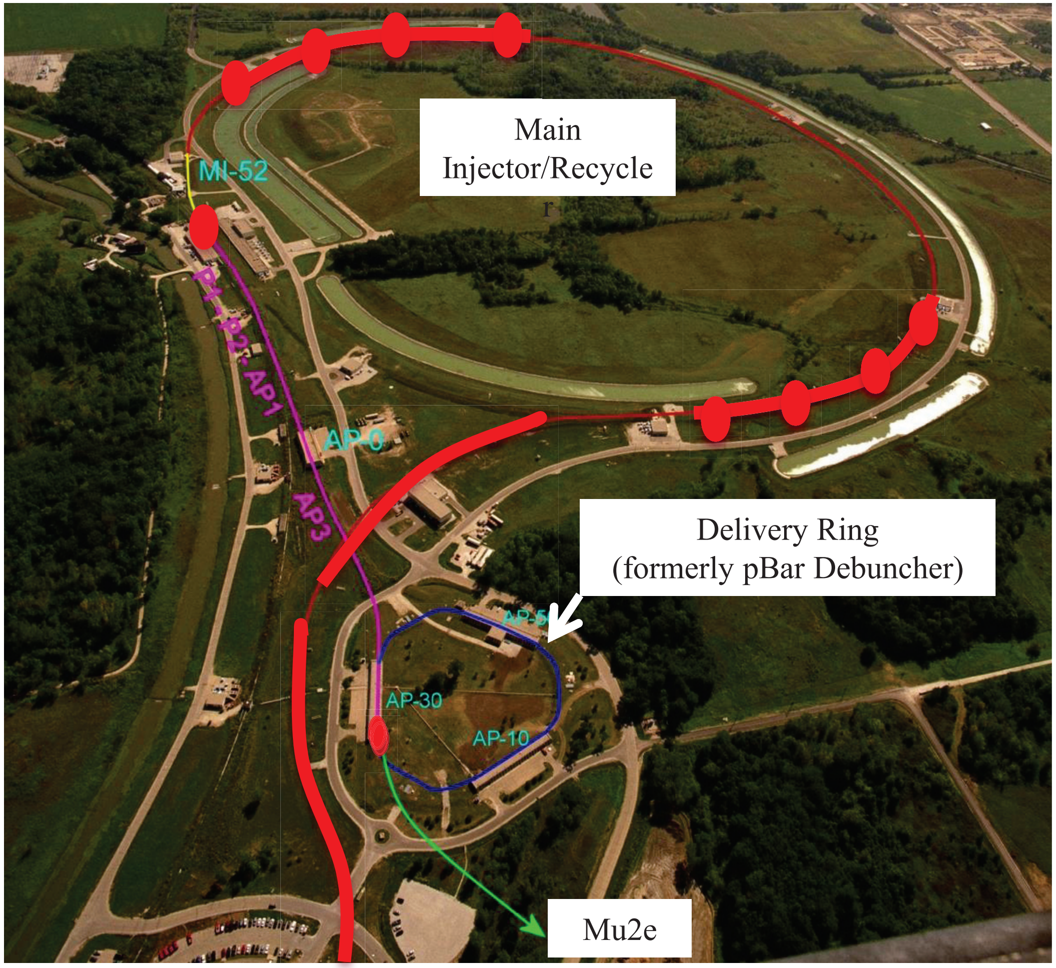


Muon Beam Line and Mu2e Detector



- Production Target
  - Proton beam strikes target, producing mostly pions
- Production Solenoid
  - Contains backwards pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - Capture muons on Aluminum target and wait for them to decay
  - Detector blind to ordinary (Michel) decays, with $E \leq \frac{1}{2} m_{\mu} c^2$
  - Optimized for $E \sim m_{\mu} c^2$

Overview: Proton Delivery at Fermilab



Booster

- One Booster batch (4×10^{12} protons) is injected into the Recycler.
- It is divided into 4 bunches of 10^{12} each
- These are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As a bunch circulates, it is resonantly extracted to produce the desired beam structure.
  - Bunches of $\sim 3 \times 10^7$ protons each
  - Separated by 1.7 μsec

Extinction Systems

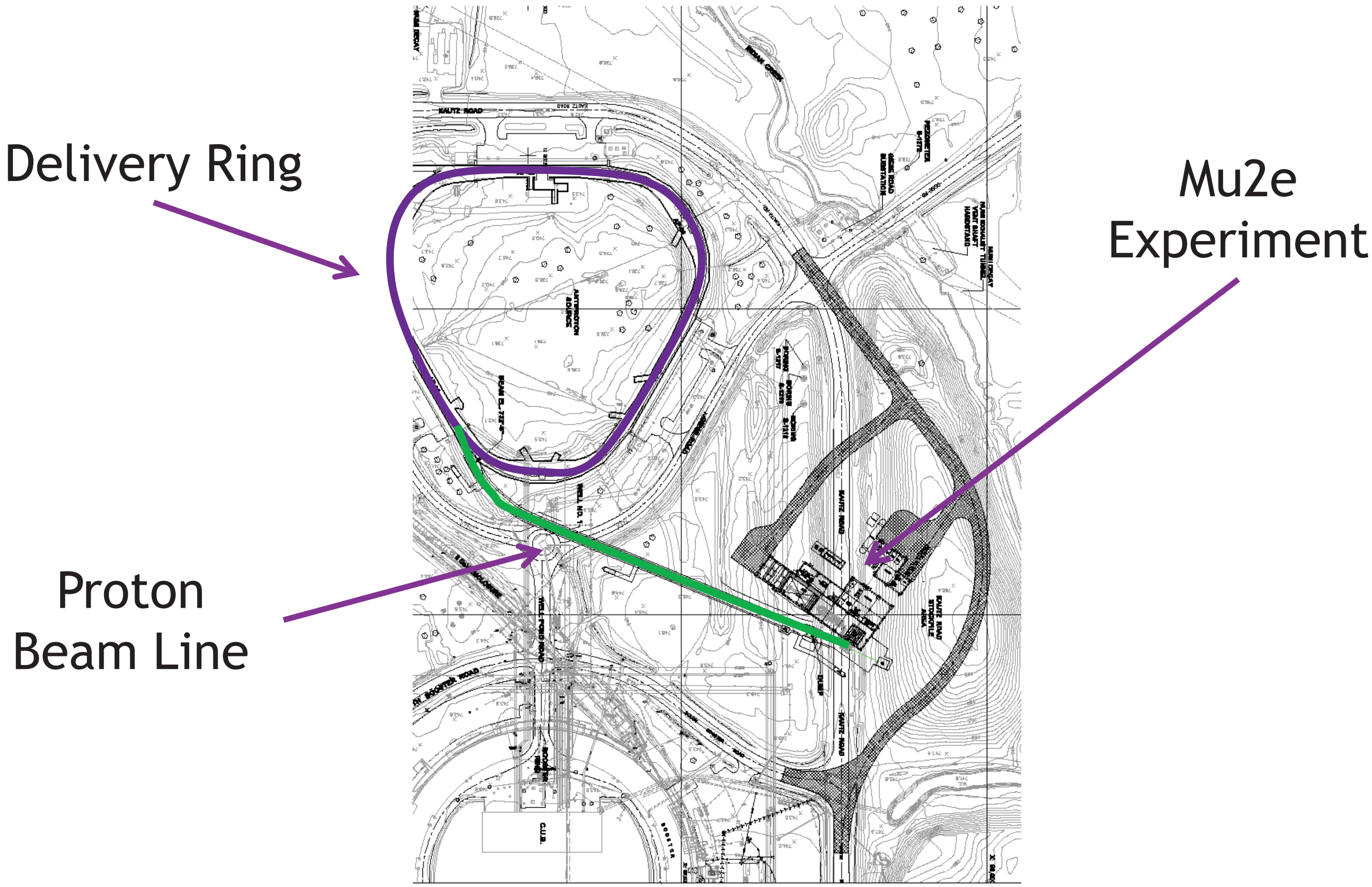
- Extinction will be achieved in two phases:
  - In ring
    - Beam delivery technique automatically gives good extinction < 10^{-5} going into the Delivery Ring
    - May degrade to 10^{-4} during the spill
  - In beam line
    - System of AC dipoles and collimators
    - Factor of 10^{-7} should be possible
- Monitoring
  - Need to show that 10^{-10} has been achieved

Delivery Ring

- Start with < 10^{-5} level of extinction going into the Delivery Ring, so the issue is how will it grow during the spill.
- Effects considered
  - RF noise
  - Intrabeam scattering
  - Beam loading
  - Beam-gas interaction
  - Scattering off of extraction septum
- Simulation still ongoing, but it looks like it should be possible to maintain a 10^{-5} level of extinction.

Extinction on the Proton Beam Line

- The proton delivery beam line will contain a system of resonant dipoles ("AC dipoles") and collimators to eliminate out of time beam



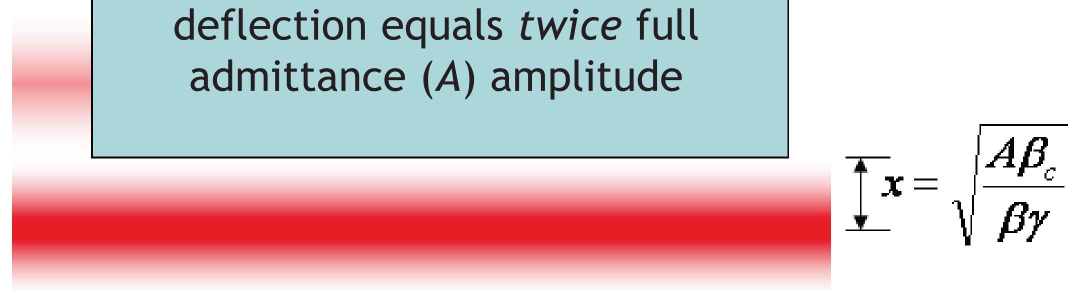
Generic Beamline Extinction Analysis

Assumptions:

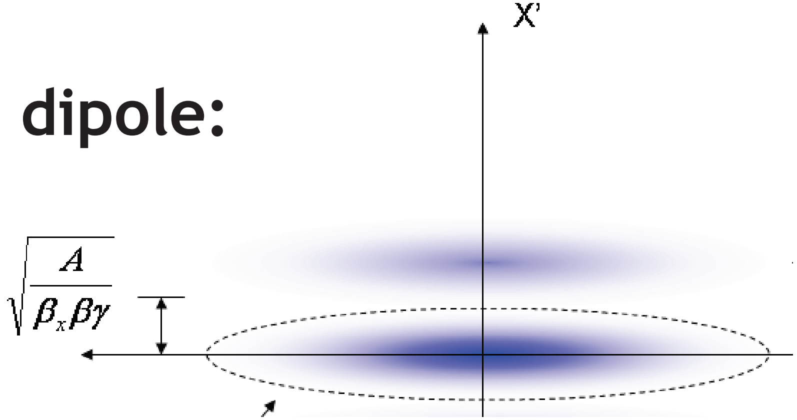
- Beam occupies entire admittance
- Beam line admittance is equal to the collimation channel's admittance
- Resonant dipole that deflects out-of-time beam into a collimation system

At collimator:

Beam fully extinguished when deflection equals *twice* full admittance (*A*) amplitude



At dipole:



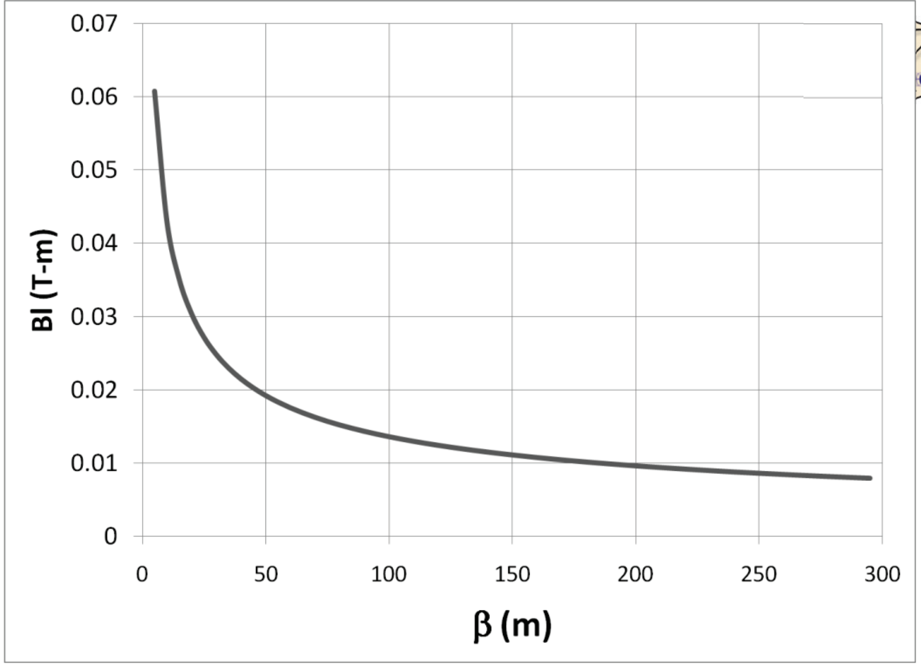
Angle to extinguish beam:

$$\Delta\theta = 2\sqrt{\frac{A}{\beta_x\beta\gamma}}$$

Magnet Considerations

Bend strength to extinguish:

$$(Bl) = 2(B\rho)\sqrt{\frac{A}{\beta_x \beta\gamma}}$$



Stored Energy:

$$U \propto B^2 Lwg = \frac{(BL)^2}{L} wg \propto \frac{1}{\sqrt{\beta_x L}}$$

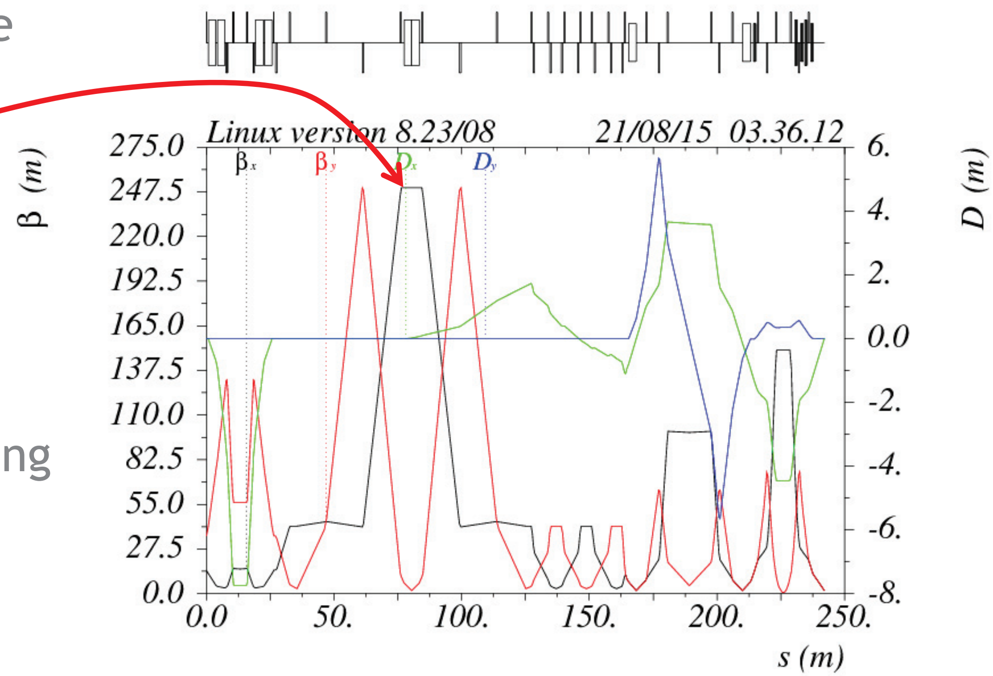
$(BL)^2 \propto \beta_x^{-1/2}$; $w \propto \beta_x^{1/2}$; $g \propto L^{1/2}$

⇒Large β_x, long weak magnets

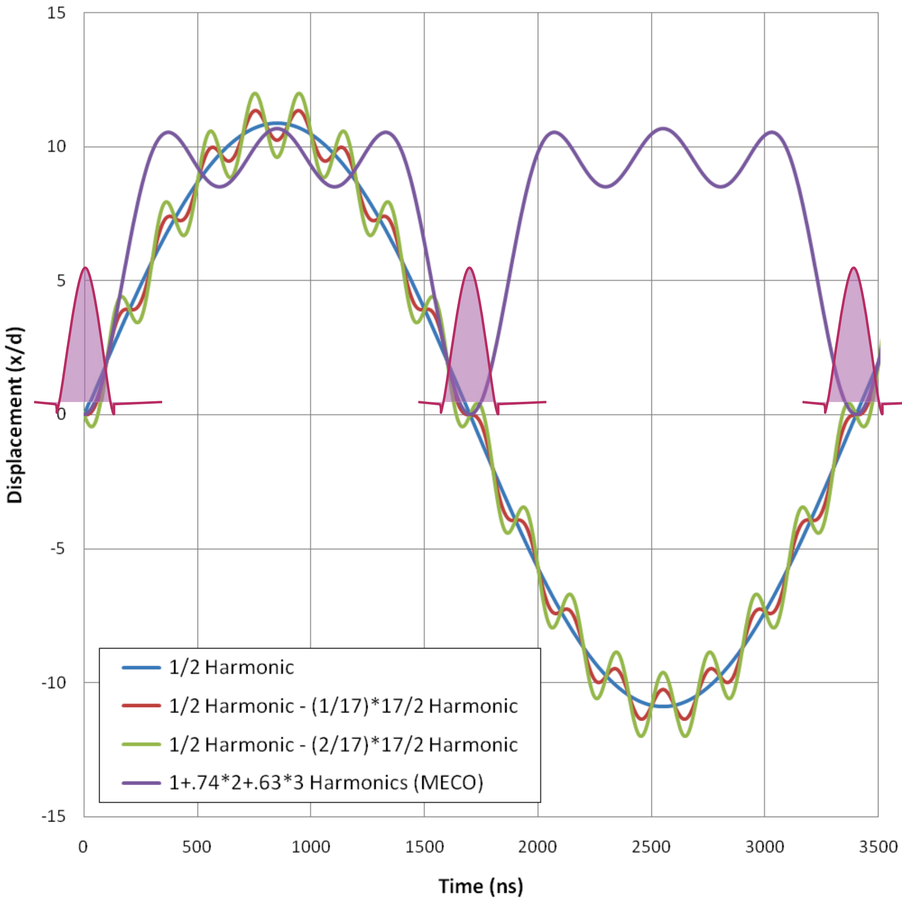
- Assume β_x=250m, L=6m
- Factor of 4 better than β_x=50m, L=2m

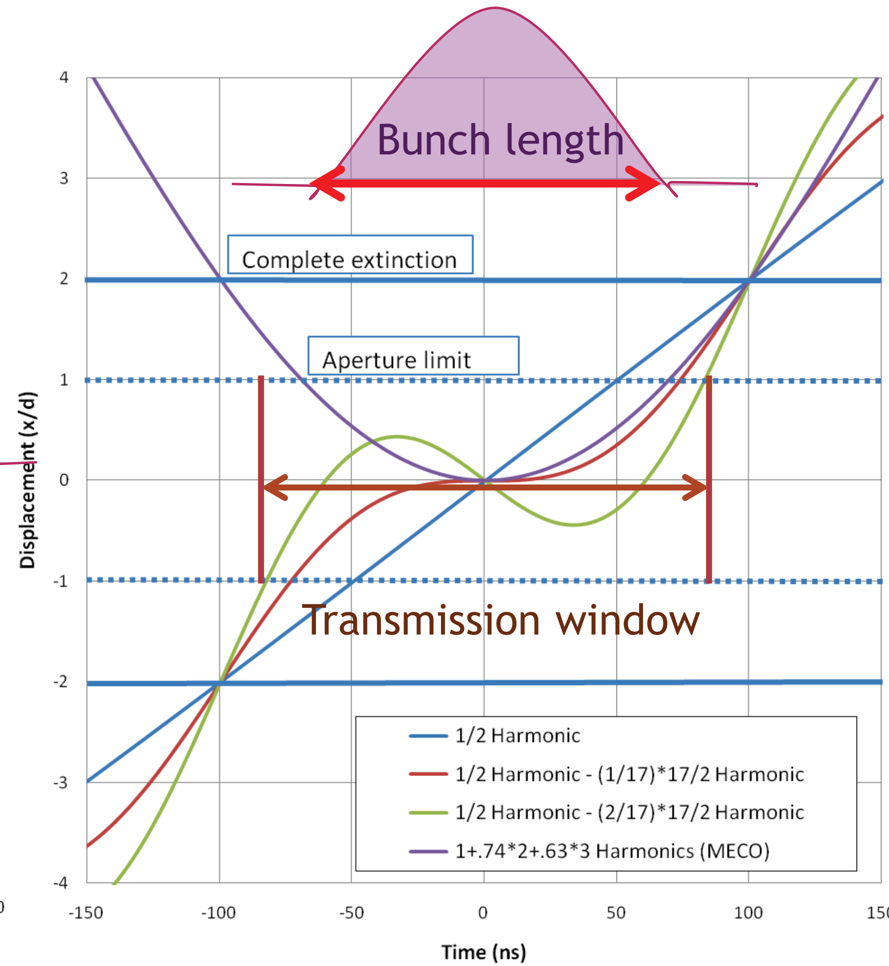
Features of the Extinction Beam Line

- Upstream of extinction dipole
  - Collimation to define beam line admittance to 50 π-mm-mr
- AC dipole region
  - Bend plane: β=250m
  - Non-bend plane: waist
- Extinction collimation
  - Minimize transmission of scraping particles
- Post-extinction
  - High dispersion region for momentum collimation.



Wave Forms Analyzed



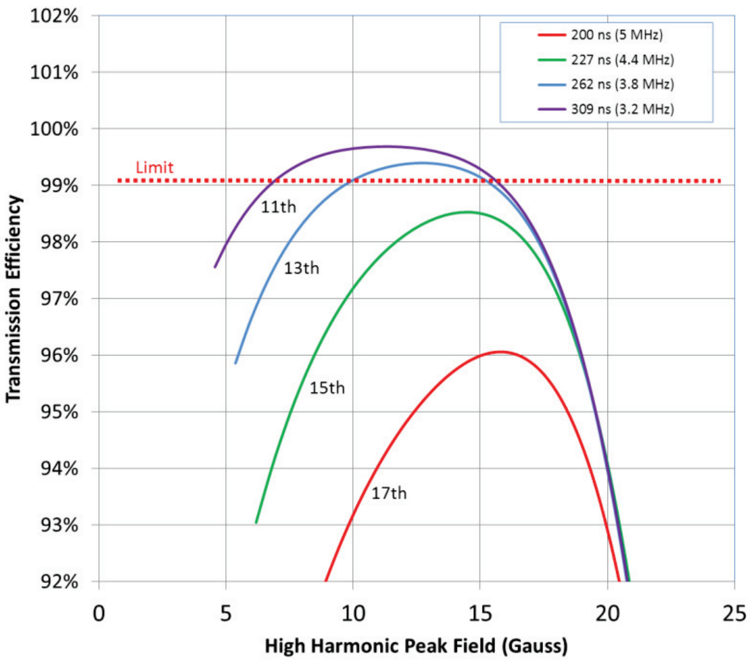


Of the options considered:

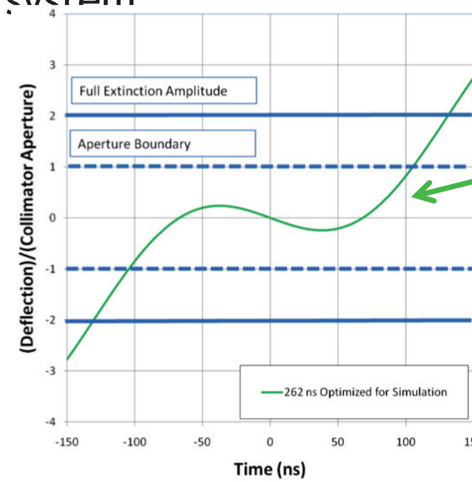
½ harmonic – (2/17) * 17/2 harmonic seems most promising

Wave Form Optimization

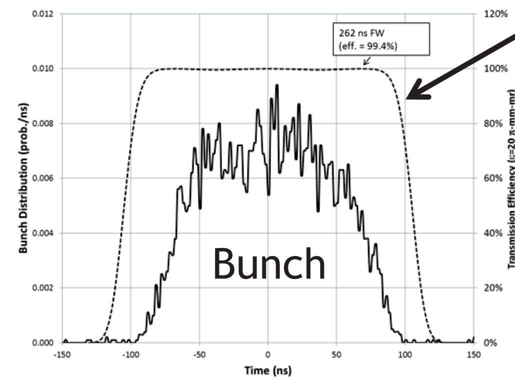
- Transmission efficiency was simulated with more realistic bunch shapes
  - Harmonic number and amplitude of high frequency component was varied



- This study produced in the final parameters for the two harmonic system



Beam motion in Collimator

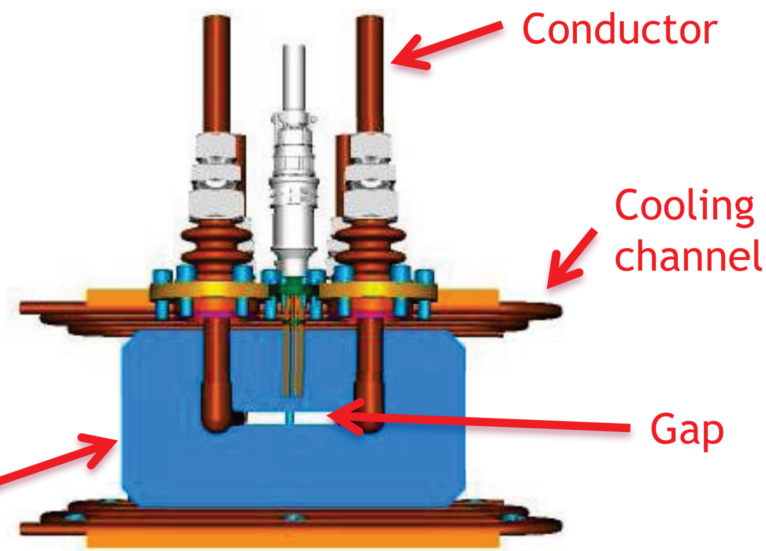


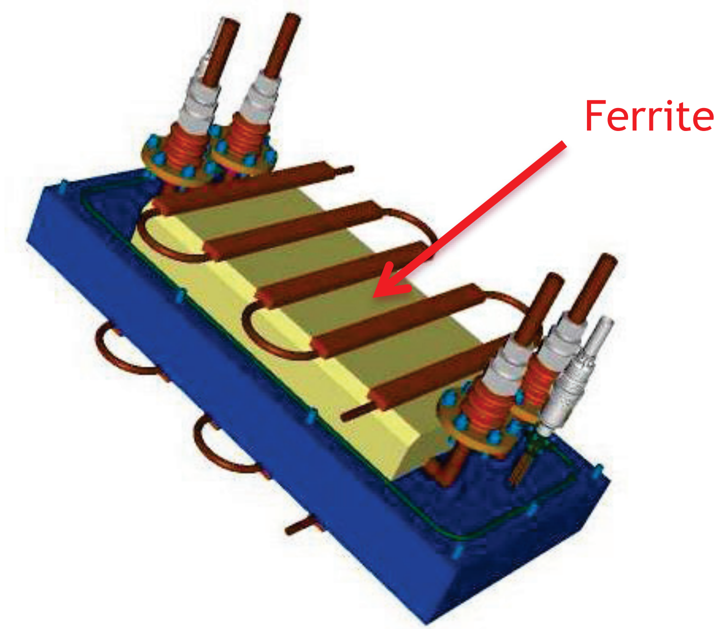
Transmission Window

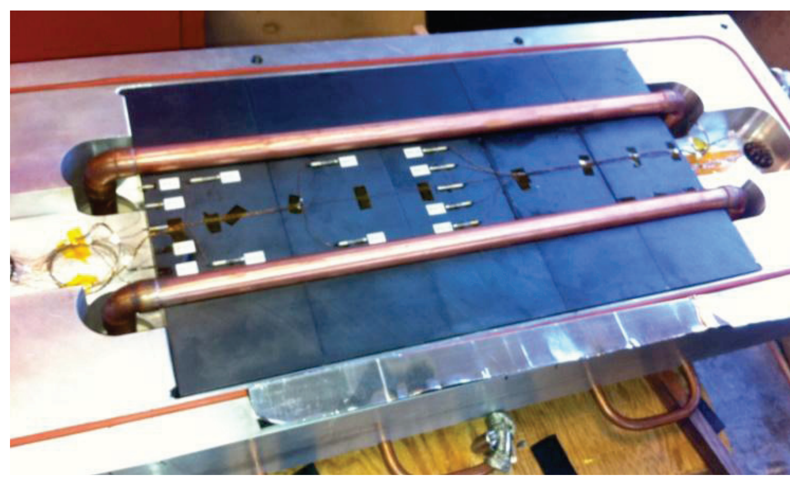
Component	Length	Frequency	Peak Field
Low Frequency	3 m	300 kHz	108 Gauss
High Frequency	3 m	3.8 MHz	13 Gauss

AC Dipole Prototype*

- 1 .5m prototype has built and tested
  - Successfully operated at both frequencies
- Plan is to build final system out of identical 1m segments



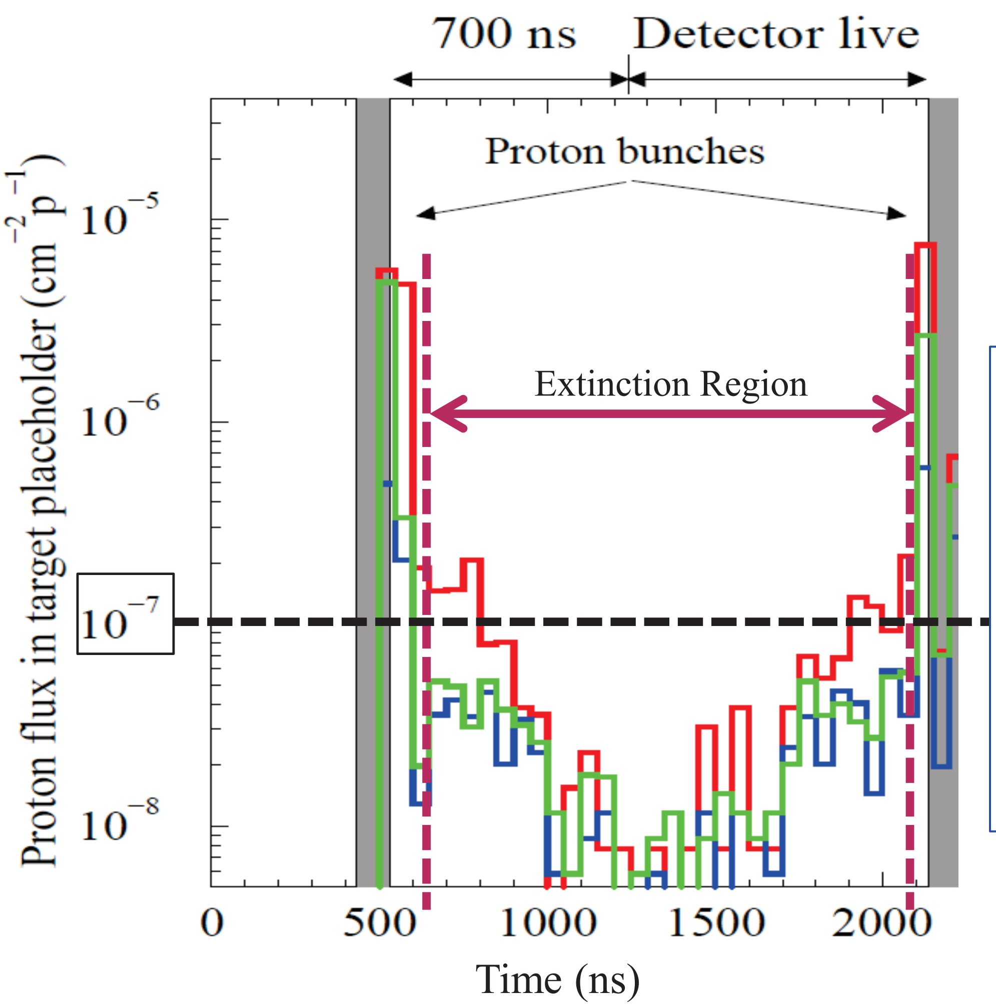




*Design by Sasha Makarov and Vladimir Kashikhin

Extinction Simulation

- The extinction beam line was simulated using STRUCT and MARS*



Extinction < 5×10^{-8} over range of interest for optimized collimators

This is multiplied by the Delivery Ring factor to produce a total extinction of **< 5×10^{-12}**

*I. Rakhno

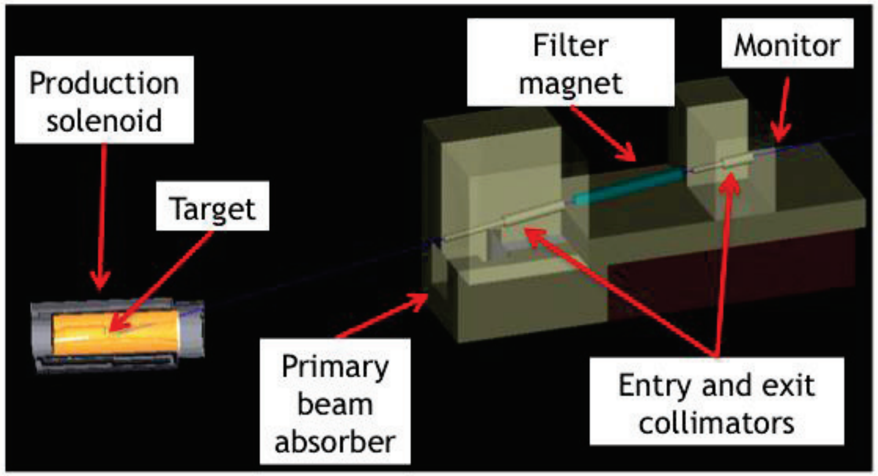
Monitor Requirements

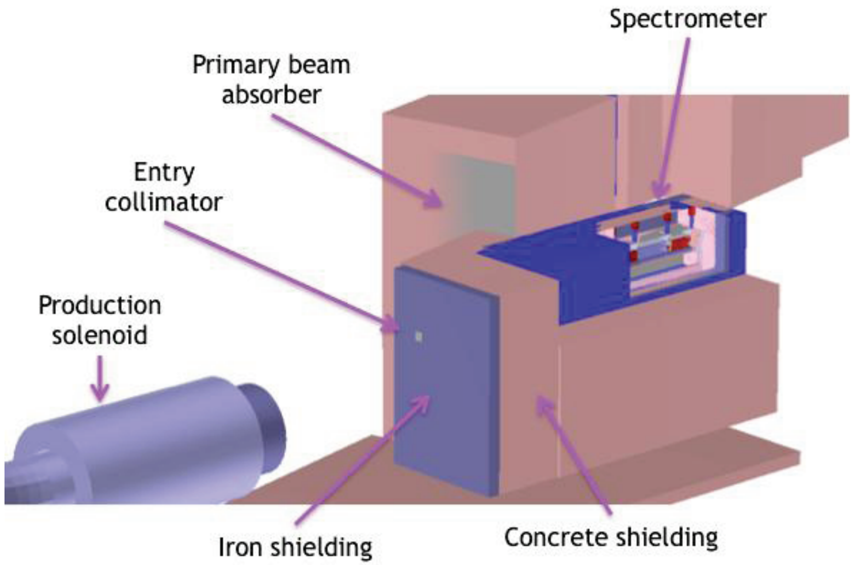
- Demonstrate 10^{-10} extinction
  - Assume ≈ 3 x 10^7 protons/bunch
  - Not possible measure 10^{-10} with a single bunch
    - ⇒ Integrate over many bunches
  - Integration time should be < ≈ 1 hour
- Only protons hitting the target can cause backgrounds
  - Monitoring beam itself will lead to a potentially large over estimate of the background to the experiment
  - ⇒ Monitor target interaction product and integrate a statistical profile of out of time beam.

Statistical Filter + Detector Strategy

- Filter
  - Selects a sample of suitable secondaries and delivers them to the detector
  - Sets the per proton detector signal rate
  - Shields the detector from unwanted interaction products
- Detector
  - Measure “in-time” and “out-of-time” signal rates with equal or known relative efficiency
  - Must have LOW “out-of-time” backgrounds compared to signal rate

Precision Monitor Options





- Pixel Tracker
  - Located above and behind the proton absorber
  - Samples 3 to 4 GeV/c positive charged secondaries
  - Pixel detectors reconstruct and count straight tracks with a well defined direction in 25ns time bins
- Mini Spectrometer
  - Located beside the proton absorber
  - Samples ~ 1 GeV/c positive charged secondaries
  - Magnetic spectrometer with 4 scintillator stations measures dE/dx, time of flight, and momentum of identified particle tracks

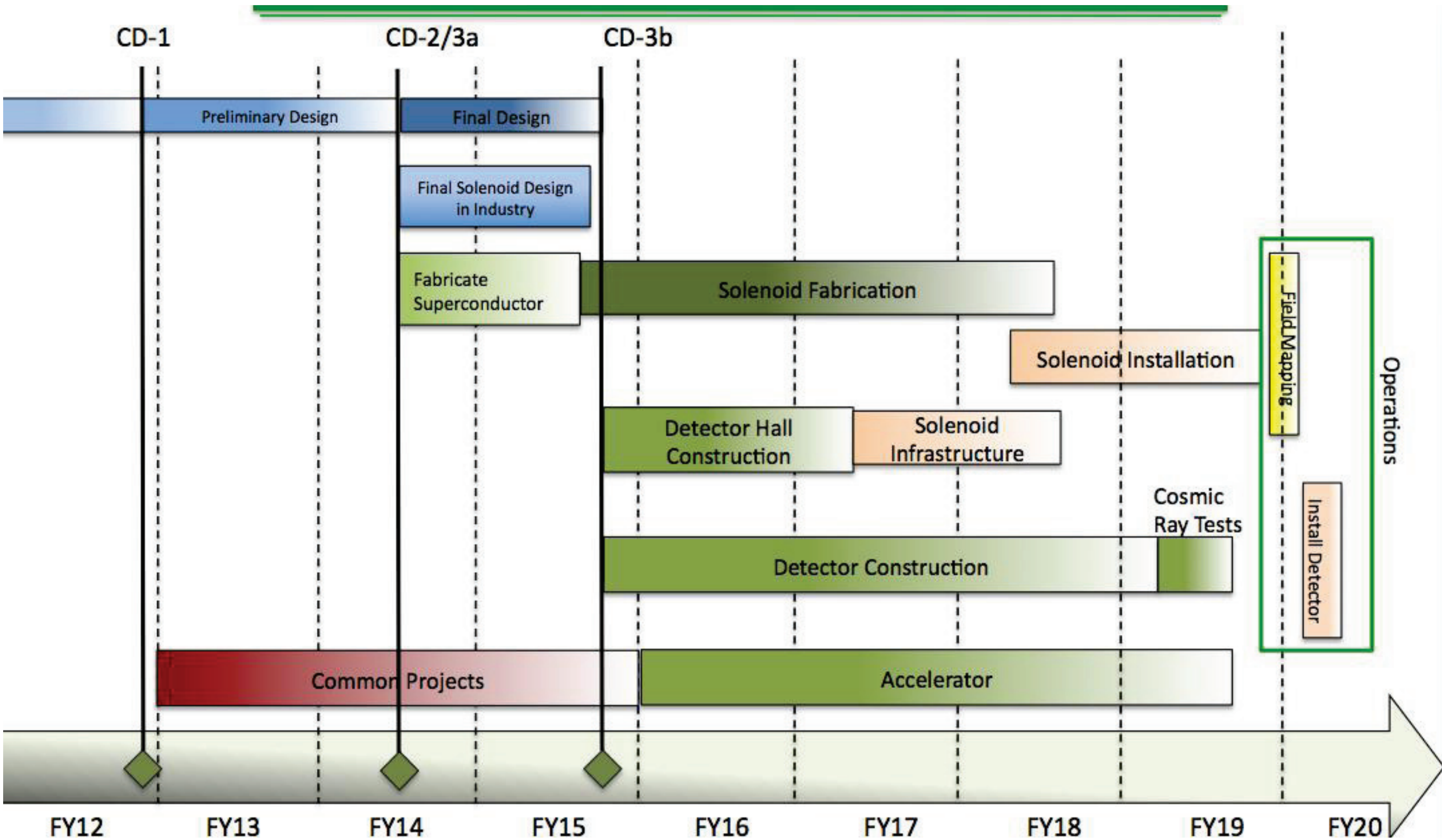
Requirements

- Signal Rate
  - Determined from beam intensity
    - 3 x 10^7 protons/bunch
    - Bunch rate: 0.6 MHz @ 33% duty factor
    - $\Rightarrow$ 2 x 10^{16} in-time p.o.t./hr
    - 10^{-10} extinction $\Rightarrow$ 2 x 10^6 out-of-time p.o.t./hr
  - To set a 90% C.L.
    - Need 2.3 expected out-of-time signal/hr
    - $\Rightarrow$ 1.2 x 10^{-6} signal events per p.o.t.
- Background
  - << 1 event/hr
- Both approaches seem to satisfy these requirements
  - Down selection committee formed.
  - Recommendation in November

What's Next

- In ring extinction
  - Complete calculations and simulations to determine the likely level of out of time beam.
  - Work in mitigation, such as in ring momentum collimation, if it's insufficient.
- Beam line extinction
  - Magnet design appears sound
  - Continue modeling effort to optimize collimation design.
- Monitoring
  - Down select between two precision monitor options
  - Develop fast monitor to measure extinction at the 10^{-5} level monitor beam coming out of the ring before the AC dipole
    - Hope to combine with precision intensity measurement for slow extraction feedback.

Mu2e Schedule



Conclusions

- Extinction and extinction monitoring are a critical part of the Mu2e schedule
- We have developed a plan for beam line extinction and have two apparently viable options for precision monitoring
- More analysis is required to determine what, if any, further mitigation will be required in Delivery Ring to achieve the required 10^{-5} level of extinction.