Challenges Associated with 8 GeV H- Transport and Injection for Fermilab Project-X

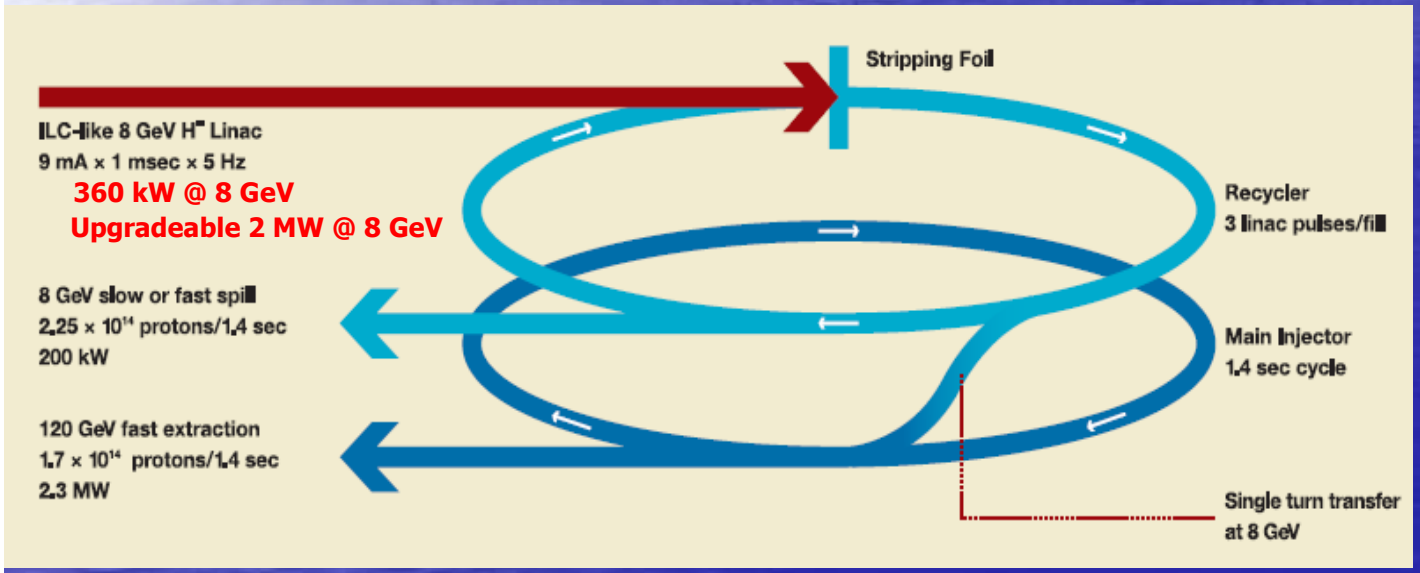
David Johnson
Accelerator Physics Center
Fermilab

HB2008
Loew's Vanderbilt Hotel ★ Nashville, Tennessee, USA ★ August 25-29, 2008

Project X Introduction

Project X is a high intensity proton facility conceived to support a world-leading program in neutrino and flavor physics over the next two decades at Fermilab. Project X is an integral part of the Fermilab Roadmap as described in the Fermilab Steering Group Report *

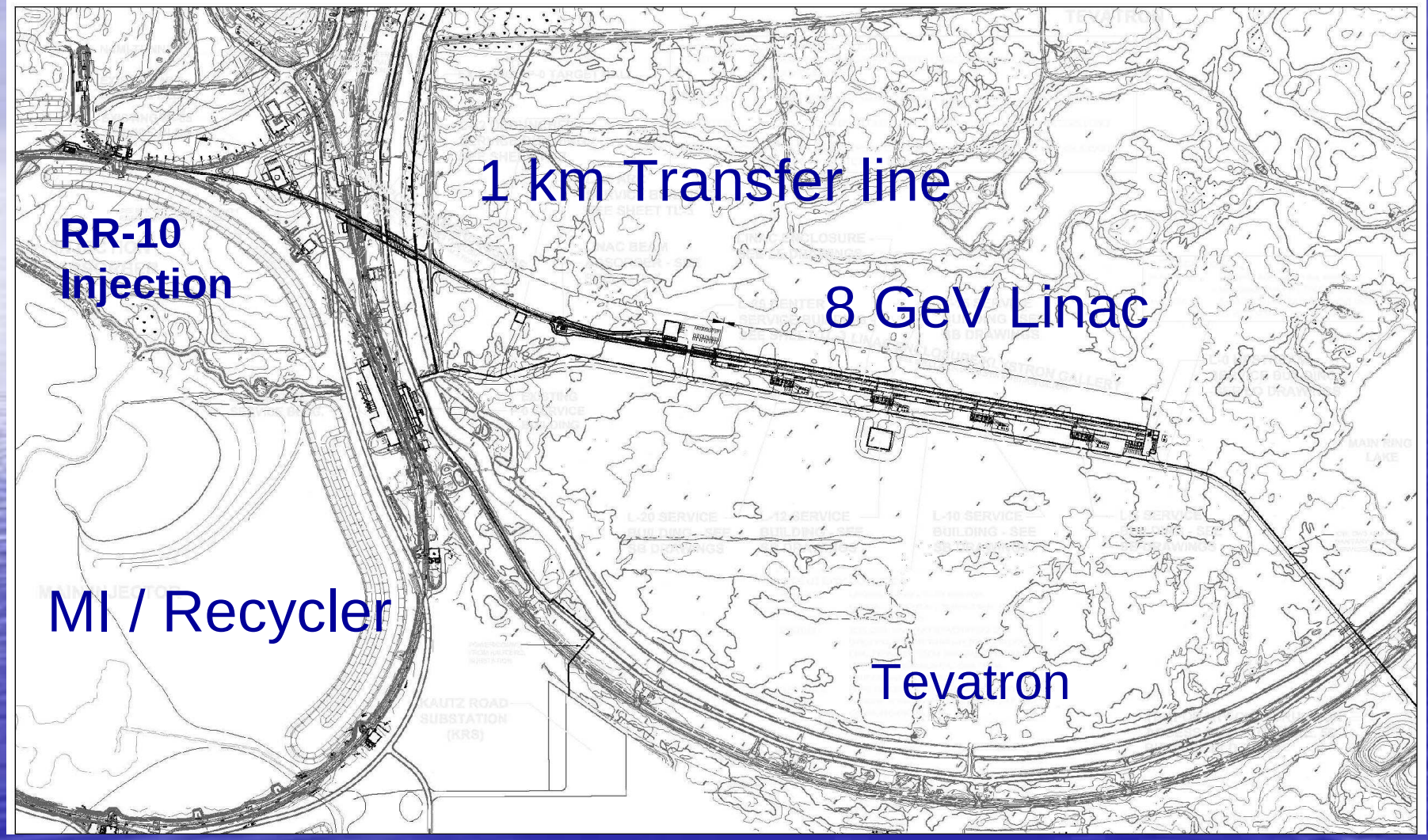
http://www.fnal.gov/pub/directorate/steering/index.shtml



325 Mhz front end
1.3 Ghz linac
8GeV H- transport
8GeV H- injection
Recycler (re)config
Recycler extraction
MI upgrades
Civil Construction
Utilities & Controls

*From Project X R&D plan

Project X Layout



Project X Components

- The base line specifications call for an 8 GeV H- linac capable of running at 5 Hz with a pulse length of 1 ms and an average beam current of 9 mA -> leads to a beam power of 360 kW out of the linac with 200 kW available for 8 GeV Physics program.
  - delivers 5.6E13/pulse at 72 kJoules/pulse -> 2.8E14/sec for 360 kW
- A transport line to cleanly transport the H- and prepare for injection into the Recycler
  - Average activation level on beam pipe < 20 mrem/hr (i.e. 0.05 w/meter)
    - Transport efficiency > 99.99%
- Modification of the Recycler lattice to permit multi-turn injection and accumulation over multiple linac cycles.
  - For neutrino program: MI cycle of 1.4 sec -> 3 linac pulses ->1.7E14 for 154 kW at 8 GeV and 2.3MW at 120 GeV (4 linac pulses left over i.e. 200 kW @ 8 GeV)
- Single turn Transfer to the Main Injector
- Extraction from the Recycler for an 8 GeV experimental program
- Modifications to Main Injector for high intensity acceleration
- Upgrade path for 2 MW beam power at 8 GeV (linac current, pulse length, rep rate) Although this is not in the base line design….

Uncertainties

•With the recent comments from the Fermilab Accelerator Advisory Committee*, a renewed interest in increased linac current and variations in SC linac cavity and cryo-module design have arisen. The impact of this is an uncertainty of which accelerator will be used for injection: directly into the MI or use the Recycler as an accumulator. This has a direct impact on the design of collimation systems, injection systems, the injection absorber, and ring modifications.

* "Synergy with ILC needs to be re-evaluated. There are limitations due to ILC adoption – may be detrimental if needed for a neutrino/muon facility later on --- that must be articulated: peak current, repetition rate, pulse length,….."

• This uncertainty requires us to approach the design as an exercise of risk analysis on the design choices of linac cavity design / Recycler vs MI injection.

Transport /Injection Design Challenges

- The number one challenge control and mitigation of uncontrolled beam loss due to:
  - Single particle loss mechanisms in the transport line:
    - Photodetachment of H- due to interaction with Black-body photons
    - Lorentz stripping of weakly bound electron
    - H- stripping by the residual gas in the beam pipe
  - Multi-particle beam loss
    - Controlled (halo & momentum collimation)
    - Un-controlled (alignment, aperture, orbit and lattice control)
- The other number one challenge are injection (foil) issues
  - Uncontrolled losses in the injection region due injected and circulating ion interaction with the stripping foil
  - Stripping Efficiency
  - Collection & disposal of waste beam (neutrals & H- missing foil)
  - Foil Lifetime
- Engineering Design issues
  - Absorbers, ring chicane & painting magnets (& ps), foil changer & e-catcher, cryo-shield, etc.

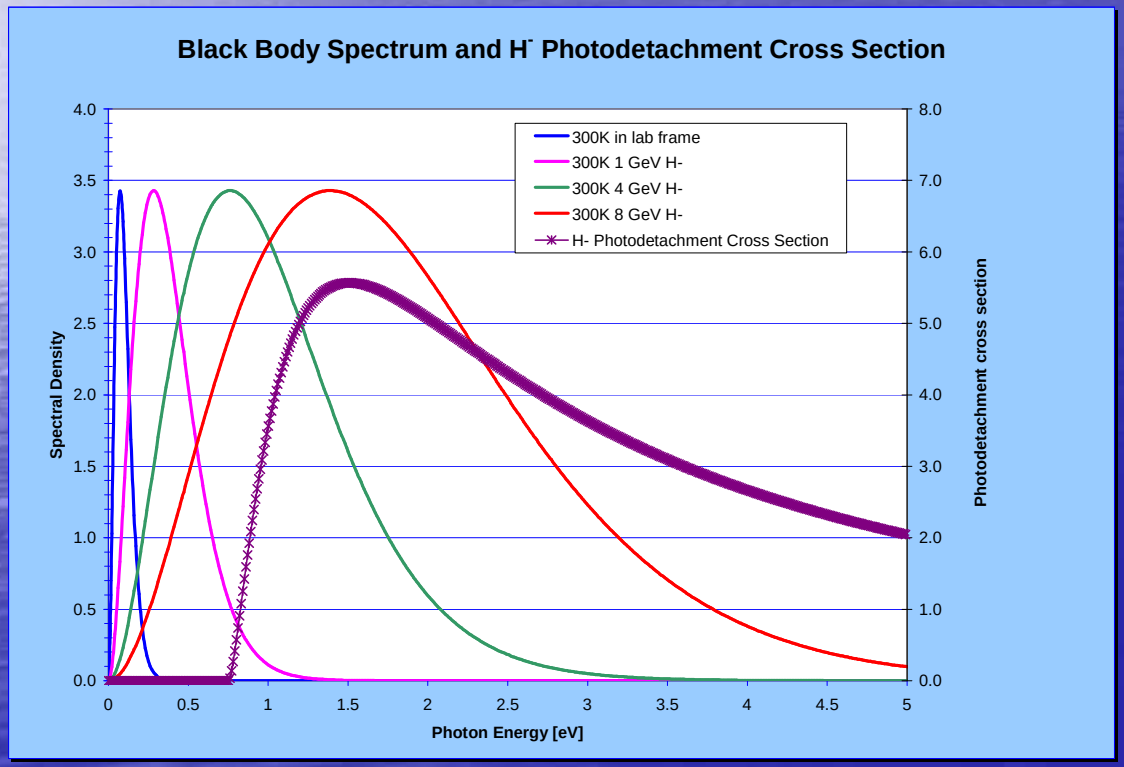
Current FY08 R & D Plan

- A Project X R&D plan* was established last January although no funds were available for significant implementation.
- With 2008 budget cuts restores and a private donation, activity on the R&D plan has resumed and CD0 planning has (re)started.
- Although we've been down this road before, we can/will build upon previous work done at other facilities (c.f. SNS, BNL, JPARC, TRIUMPH, LANL, etc.) as well as FNAL.
  - Create a viable Recycler injection straight section and transport line interface to the injection straight section and injection absorber. Integrate solutions with the new Recycler ring lattice.
  - Initialize simulations for transverse phase space painting.
  - Revise Proton Driver Injection absorber design for Project X beam parameters.
  - Evaluate the stripping efficiency, losses, impact on circulating beam, and technological feasibility of carbon foil stripping and laser stripping techniques for 98% to 99% stripping efficiency utilizing Project X beam parameters.
  - Begin Conceptual Design of transverse collimation absorbers

* Available on Project X web site: http://projectx.fnal.gov/

Black Body Stripping

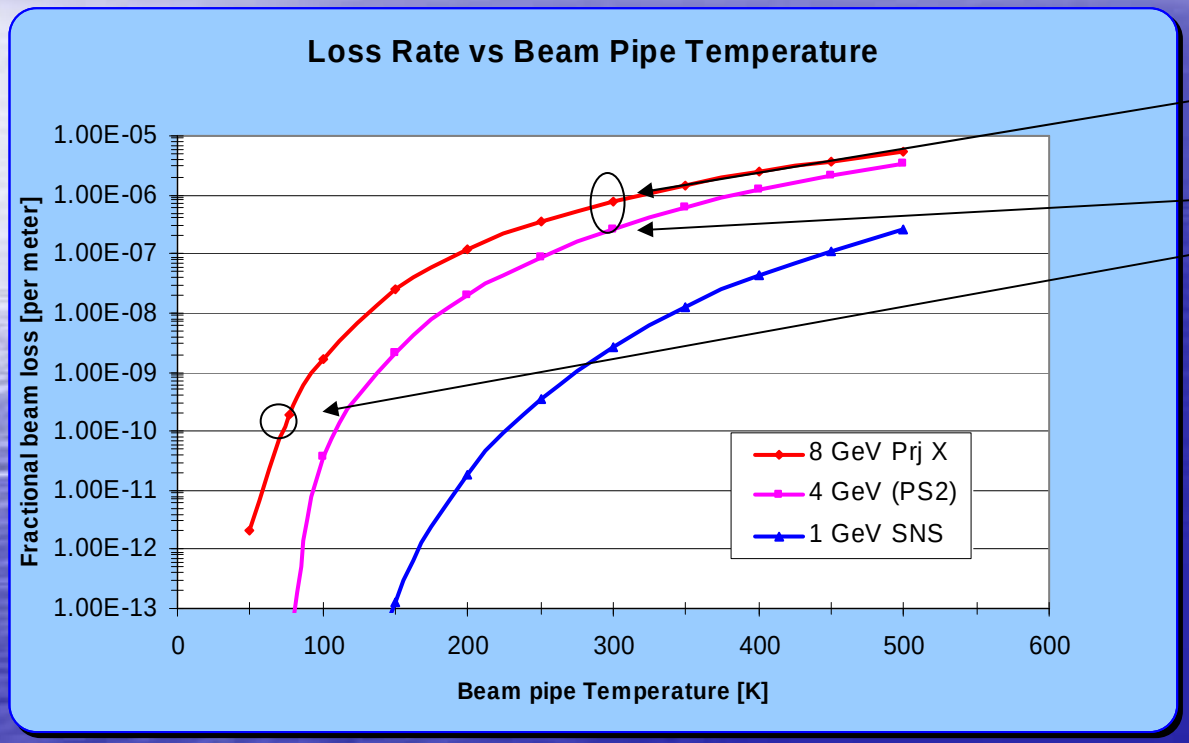
- The issue of potential photodetachment of H^- due to black body radiation was raised prior to 2004 Mini-workshop on H- transport and injection by C. Hill and H. Bryant and further discussed at the workshop (with potential mitigation options).
- Interior of the beam pipe emits blackbody radiation with a spectral energy density of thermal photons per unit volume



- When this Doppler shifted spectrum of thermal photons overlaps the photodetachment cross section of moving H- ions, the photodetachment rate becomes non-negligible.

Black Body Stripping

Calculations of the photodetachment rate and fractional beam loss have been reported by Chris Hill (Fermilab) and H.C. Bryant (UNM) and replicated by J.-P. Carneiro for implementation in the beam dynamics code TRACK.



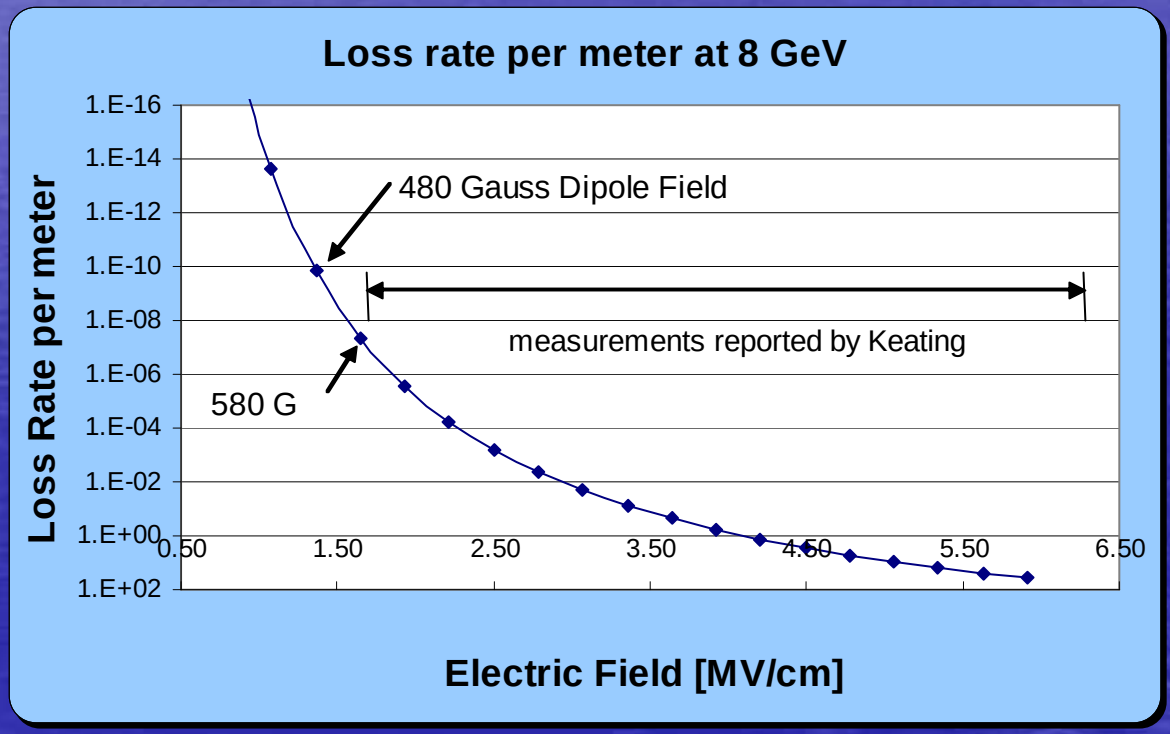
- Loss rate is 7.8×10^{-7}/meter which is 0.288 Watts/m
- Loss rate is 2.6×10^{-7}/meter
- Reducing the internal beam pipe temperature to 77°K with a beam shield lowers the loss rate at 8 GeV to 1.9×10^{-10}/meter or 7×10^{-5} Watts/m !

Lorentz Stripping

- A relativistic H- ion moving through a transverse magnetic field is subject to a rest frame electric field given by $E = \gamma(\beta c) B$.
- Lifetime in the rest frame* is a function of the electric field and can be espressed by $\tau = (A/E) \exp(B/E)$. The loss rate [per meter] is then $1/\gamma(\beta c)\tau$ *Scherk (1978)

- The coefficients A and B are fctn of electron affinity*
- Used the parameters for A and B obtained from fitting P1 parameterization of Keating (i.e.)
  - $A = 3.073 \times 10^{-6}$ s V/m
  - $B = 4.414 \times 10^{9}$ V/m

- By selecting dipole fields ~480G for main dipoles the loss rate is negligible.



Residual Gas Stripping Loss Summary

• The loss rate [per meter] of the H- by residual gas molecules is proportional to the molecular density and the ionization cross section $\alpha\ d_m \Sigma\sigma_i$ for i molecules.
•The cross section decreases with energy proportional to β^{-2}
•Vacuum levels are expected to by ~ 1E-8 in transport line leading to loss rate of a few E-8…

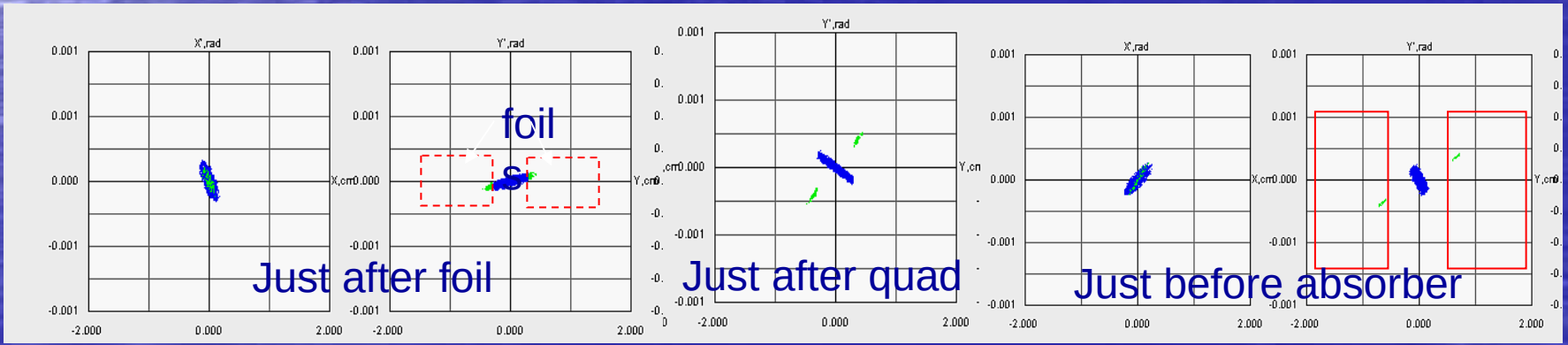
An average residual dose rate < 20 mrem/hr on beam pipe requires a beam loss rate of < 0.05 watt/meter*

loss mechanism	360 kW		360 kW with shield		2.1 MW with shield	
	[m^{-1}]	[w/m]	[m^{-1}]	[w/m]	[m^{-1}]	[w/m]
Black body (@300K)	8.00E-07	1.06E-01	1.90E-10	2.51E-05	1.90E-10	4.10E-04
Residual Gas (A150 10^{-8} torr)	1.30E-08	1.72E-03	1.30E-08	1.72E-03	1.30E-08	2.81E-02
Magnetic (500 G)	1.30E-10	1.72E-05	1.30E-10	1.72E-05	1.30E-10	2.81E-04
Total	8.13E-07	1.07E-01	1.33E-08	1.76E-03	1.33E-08	2.88E-02
		X2 >		X28<		X1.7<

Transverse Collimation Scheme

T

- Challenges for transverse collimation are:
  - to design a system safely remove large amplitude halo (depend on linac current)
  - to design a movable foil and absorber capable of safely accepting a 1% beam loss on each foil/absorber assembly (baseline 3.6kW ultimate 20 kW)
  - Accurately predict beam phase space including halo at exit of linac
  - Anticipate fast transverse steering feedback system to keep beam position fixed at foil locations (if necessary)- SNS experience position move within macro pulse
- Similar to SNS: 2 step process-> foil in front of quad strips halo, quad defocuses resultant protons which drift to a movable jaw absorber
- Simulation using TRACK which tracks H-,H+,H0 simultaneously through multiple collimation systems (see example for 1 vertical location only)



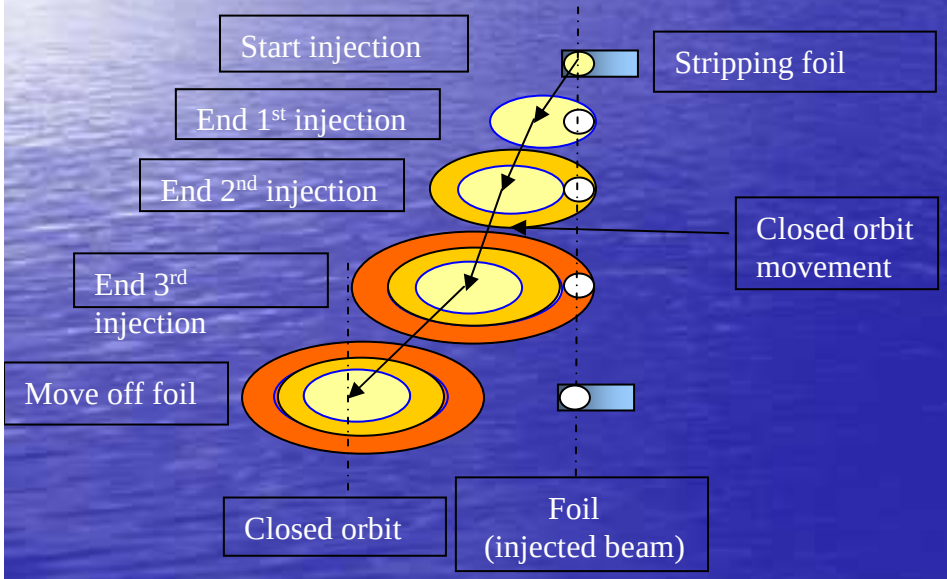
Injection Losses

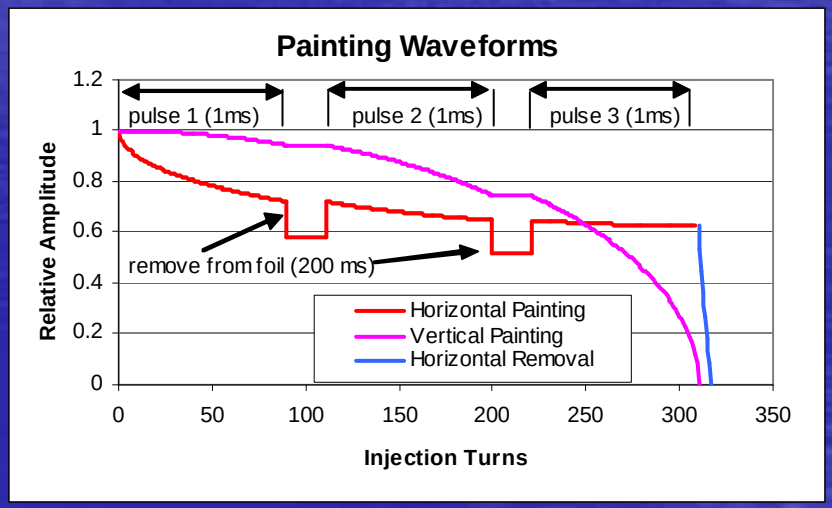
- First turn H- missing foil
  - Goal of less than 2 percent
  - determined by foil dimensions & depth of transverse collimation
- First turn H0 excited states stripping and falling outside the acceptance of the ring
  - Minimized by chicane design
- Multiple scattering in foil
  - Determined by foil thickness
- Energy straggling in foil
  - Contribute to longitudinal emittance dilution
- Nuclear interaction with foil producing hadronic shower
  - Initial estimates ~6E9 particles/sec
  - Reduce parasitic hits and foil thickness
- Stripped electrons
  - at 2.8E14 H-/sec contribute ~360 watts
- Circulating protons interacting with foil
  - Minimize injection time, foil orientation & cross section, and painting
- Single large angle Coulomb scattering
  - Estimate loss rate at 4E-4 or ~150 watts
- Many of these processes are included in the simulation code STRUCT (routines from MARS) and ORBIT. Those that are not will be added…

Design of Painting System
for Recycler Injection

Project X

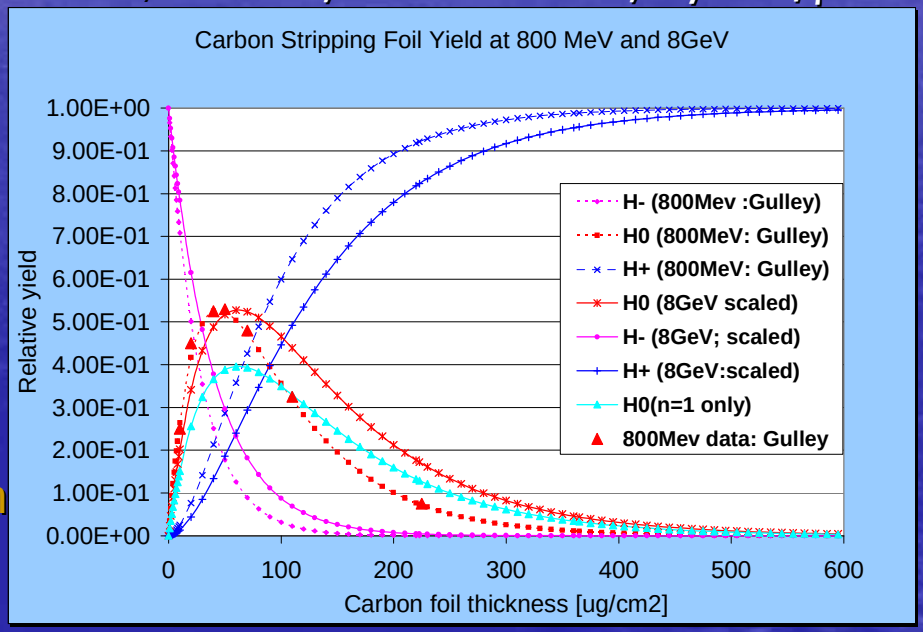
- Challenge is to design a painting system spanning multiple linac cycles which:
  - creates a uniform distribution
  - minimize interactions of circulating protons with foil
- Recycler used as an accumulator requires 3 linac cycles at 5 Hz with 5.6E13 injected per cycle (1 ms beam pulse).
- Painting algorithms and foil geometries will be investigated using simulations performed with STRUCT and ORBIT.





Foil Stripping Efficiency

- We need to be able to predict the efficiency of converting H^- into protons and H^0 excited states for incident 8 GeV H^- ions.
- The efficiency of converting H^- into protons and H^0 excited states have been measured at energies up 800 MeV [Stinsen (69), Webber (79), Mohagheghi (91) , Gulley (96), and Keating (98)]
- Scale the 800 MeV cross sections for $H^- \rightarrow H^+$, $H^- \rightarrow H^0$, and $H^0 \rightarrow H^+$, by $1/\beta^2$. [W.Chou, et.al. NIM A 590 (2008) 1-12]
- Capture to circulating beam -> H+ & H0(n>3) from chicane design
- Only H0(n=1,2) are sent to absorber (dependent on Chicane 3 field)
- Foil Stripping cross sections to be implemented in TRACK which will produce injection phase at foil of H^+,H^0,H^- which can track each species through the injection region and to absorber.
- Will also be used as input to ORBIT.

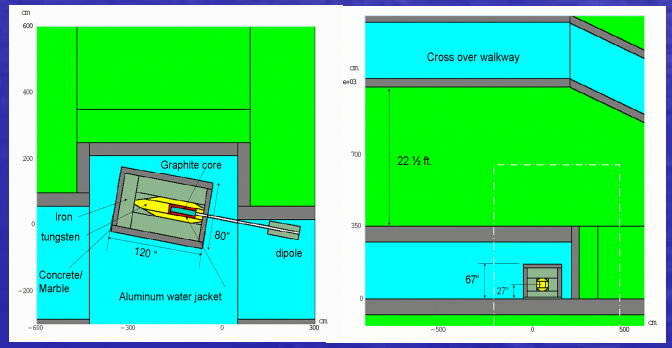


425 μg/cm² 98% 507 μg/cm² 99%

Waste Beam Disposal

- Must cleanly transport both H- and H0 excited states to injection absorber
- Absorber must handle both routine and accident conditions
  - Routine 10% of 360 kW
  - Accident 360 kW for x number of pulses)
- Shielding must meet all radiological standards
- Must be instrumented for hardware protection
- Internal vs External (a risk analysis)

INTERNAL	EXTRENAL
simple optics	complicate optics
no civil	civil const
$$ absorber	<$ absorber
residual shielding	separate enc
elevation of absorber (RR or MI)	



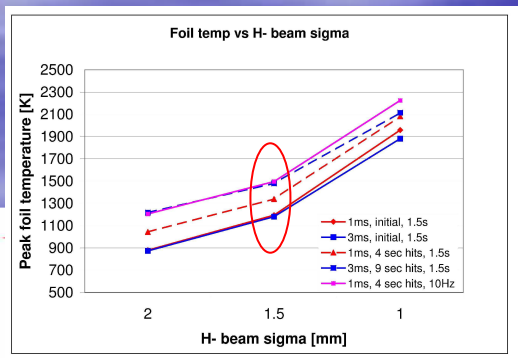
- Currently utilizing MARS and ANSYS to investigate absorber core geometries and thermal capacities

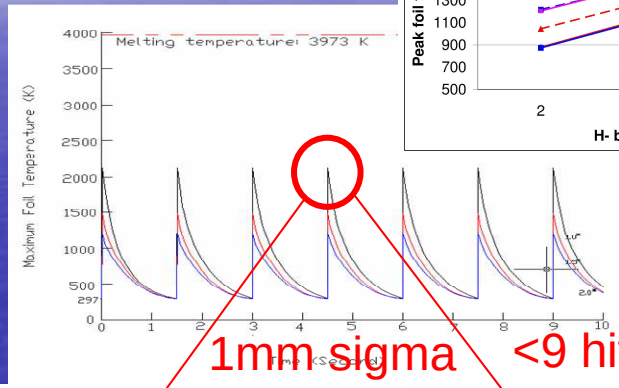
Stripping Foil Lifetime Issues

- Foil lifetimes are associated with peak temperature and thermal and mechanical stress due to periodic heating.
- There has been much progress with the manufacture and testing of new foils capable of withstanding the brutal punishment of high intensity/fast rep rate associated H- injection(c.f. SNS, JPARC, LANL)

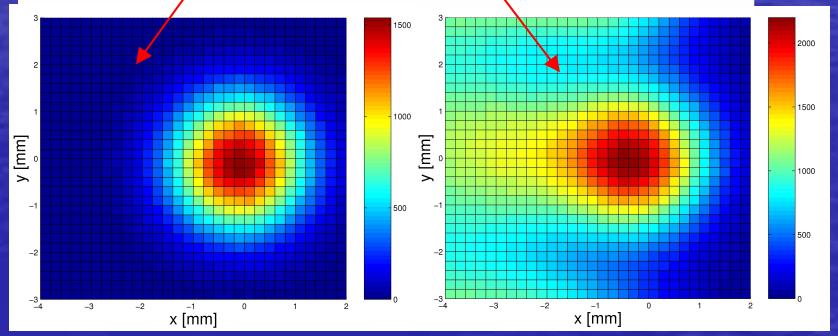
- Calculations done for Proton Driver by C.J Liaw and J. Beebe-Wang (BNL)
- Project X intensity down by factor of 3 (i.e.5.6E13/1 ms pulse)
- Spot size will determine foil size and trade-off on the number of secondary hits.

1.5E14/3ms @ 1.5s
9 secondary hits
3 beam sizes





1mm sigma <9 hits>



Peak Temperature determined primarily by injected beam

Contributions from…

- Howard Bryant (UNM) [Black Body]
- Jean-Paul Carnerio [TRACK]
- Alex Chen [ANSYS – Absorber]
- Wieren Chou
- Alexander Drozhdin [STRUCT painting]
- Chris Hill [Black Body]
- Steve Hays [Power Supplies]
- Dave Harding [Magnets/Technical]
- Jim Lackey [Foil issues]
- C.-J. Liaw (BNL) [CDR/Foil issues]
- Nikolai Mokhov [MARS]
- Tom Nichol [Cryo beam shield]
- Petr Ostroumov [TRACK]
- Tony Parker [Drafting support]
- Igor Rakhno [MARS absorber/coll]
- Deepak Raparia [PD CDR / injection]
- Zhijing Tang [ANSYS – absorber/coll]
- Kamran Vaziri [Shielding Requirements]
- Leonid Vorobiev [ORBIT painting]
- Joanne Beebe-Wang (BNL) [PD CDR Foil /painting issues]
- J. Wei (BNL) [PD CDR]
- Meiqin Xiao [Recycler lattice]
- Bob Zwaska [Laser stripping]
- Others….

Plus:

- Participants in Proton Driver Studies I and II (inside & outside FNAL)
- Participants in 2004 Mini-Workshop on H- Transport and Injection
- The many staff from labs and universities world wide who have contributed to the advancement of HB beam technologies….

Summary

•The design choice of beam parameters (linac current, pulse length, and rep rate) and potential upgrade paths will determine which accelerator will be used for the injection of H^-, hence the direction of future efforts.

•Simulation software TRACK,STRUCT,ORBIT,MAD, OPERA, etc. exists for transport, collimation, injection painting, waste disposal, injection losses, energy deposition, field maps, etc. Future modifications and optimizations are expected.

•Selection of transport line fields, vacuum, and beam shield mitigates issues for single particle loss.

•Continue foil development and testing.

•Continue investigation of Laser stripping

•Continue R&D effort to determine initial configuration

Project X Design Parameters
(back up slide)

Req. No.	Description	Req.	Unit	
1.0	**General**			
1.1	120 GeV Beam Power	2.3	MW	
1.2	8 GeV Beam Power	360	kW	->2.8E14 protons/sec
1.3	8 GeV Slow Spill Beam Power	200	kW	
1.4	8 GeV Slow Spill Duty Factor	55	%	
1.5	120 GeV Availability	75	%	
1.6	8 GeV Availability	80	%	
1.7	Upgradeable 8 GeV Beam Power for Civil, RF, & Cryo Systems	2	MW	->1.5E15 protons/sec

- **Baseline Linac running @ 5Hz and 9mA avg. current 1ms pulse length**
  delivers 5.6E13/pulse at 72 kJoules/pulse -> 2.8E14/sec for 360 kW
- **For neutrino program: MI cycle of 1.4 sec -> 3 linac pulses ->1.7E14 for 154 kW at 8 GeV and 2.3MW at 120 GeV (4 linac pulses left over i.e. 200 kW @ 8 GeV**
- **Upgrade paths**
  - **increase linac pulse length 1ms -> 3 ms**
  - **linac average current 9 mA -> 27 mA**
  - **linac rep rate 5 Hz, 10Hz, 15 Hz ???**

Transport Line Requirements

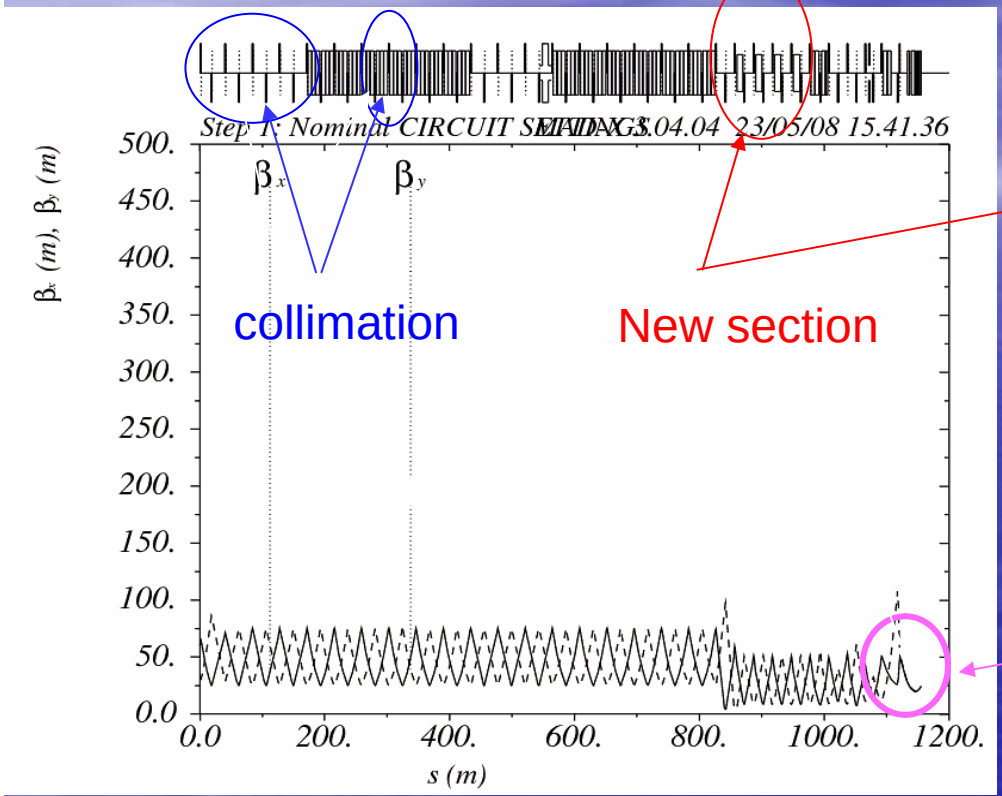
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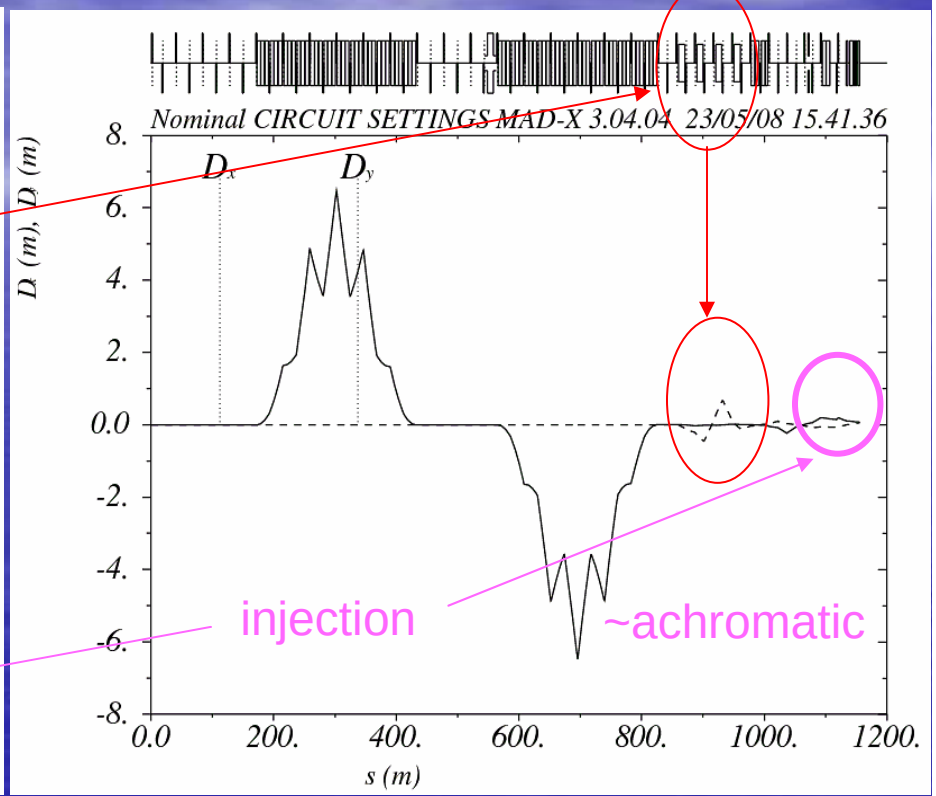
Req. No.	Description	Req.	Unit	Reference Requirements			
4.0	**8 GeV Transfer Line**						
4.1	Injection Stripping efficiency	98	%				
4.2	Length (approx.)	1000	meters				
4.3	Maximum average activation level	20	mrem/hr				
4.4	Availability	98	%	1.6			
4.5	Momentum Aperture	+/- 0.8	%	3.10			
4.6	Minimum Transverse Aperture	25	π-mm-mrad	3.13	4.3		
4.7	Maximum Dipole Field	0.05	T	4.1	4.3		
4.8	Transfer Efficiency	99.99	%	4.3			
4.9	Final Energy Variation	+/- 0.11	%	5.10			
4.10	Energy	8	GeV	5.1			

Req. No.	Description	Req.	Unit	Reference Requirements			
5.0	**Recycler**						
5.1	Energy	8	GeV				
5.2	Storage Efficiency	99.5	%				
5.3	Average Recycler Beam Current	0.6	A	1.2			
5.4	Availability	95	%	1.6			
5.5	Injection Rate	5	Hz	2.3			
5.6	Maximum Space Charge Tune Shift	0.05		5.2			
5.7	95% normalized transverse emittance	25	π-mm-mrad	5.6			
5.8	r.m.s. normalized transverse emittance	13	π-mm-mrad	5.6			
5.9	Bunching factor	2		5.6			
5.10	Longitudinal emittance per Bunch	0.5	eV-Sec	5.6	5.12		
5.11	Cycle Time	1.4	S	6.1			
5.12	RF Frequency	53	MHz	6.2			
5.13	Abort Gap Length	700	nS	6.3			
5.14	Peak Recycler Beam Current	2.4	A	6.5			

Transport line

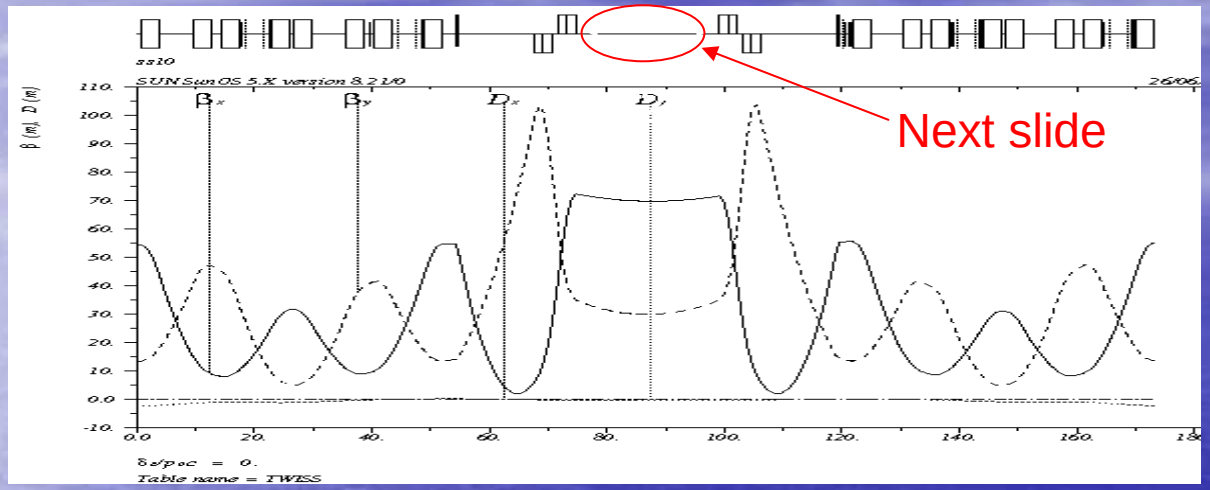
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- The upstream end of the transport line remains unchanged. The new vertical bend section moves transport line further under MI-65 (needs to be verified)
- Option II is to change elevation of entire beam line and linac
- Option III is to move dog leg elsewhere
- Solution will be greatly influenced by civil construction issues.

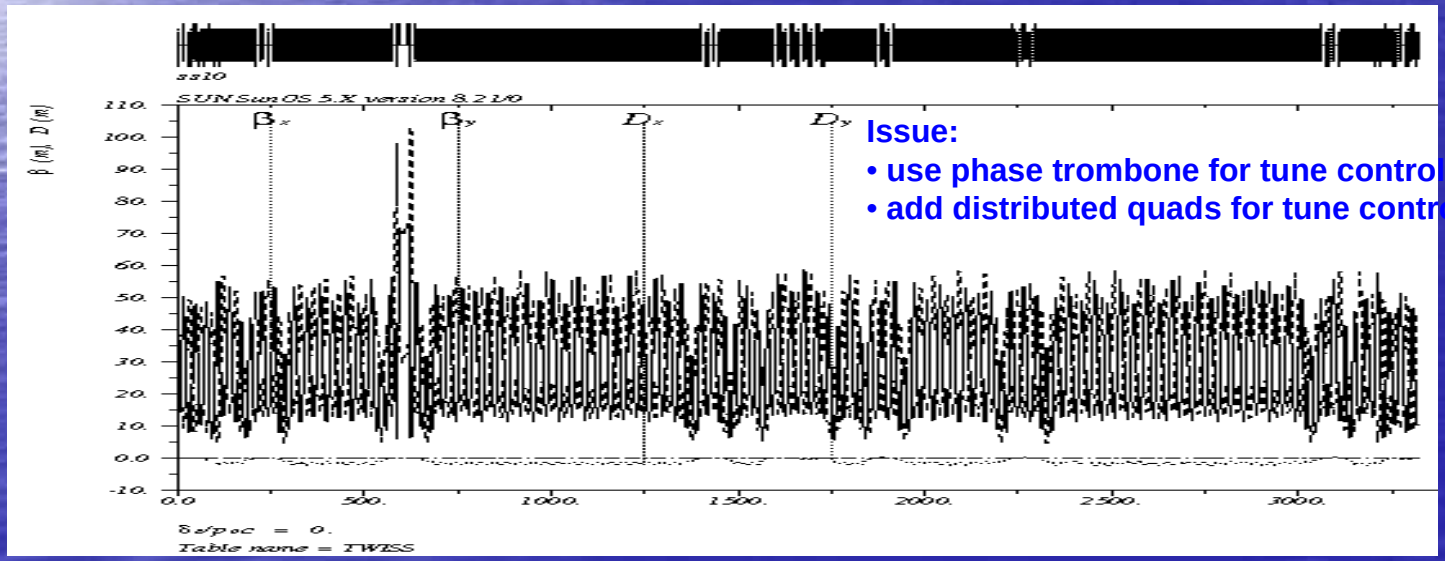
Initial Recycler Lattice Modifications
(back up slide)



βx~70

βy ~30

Dispersion “free”



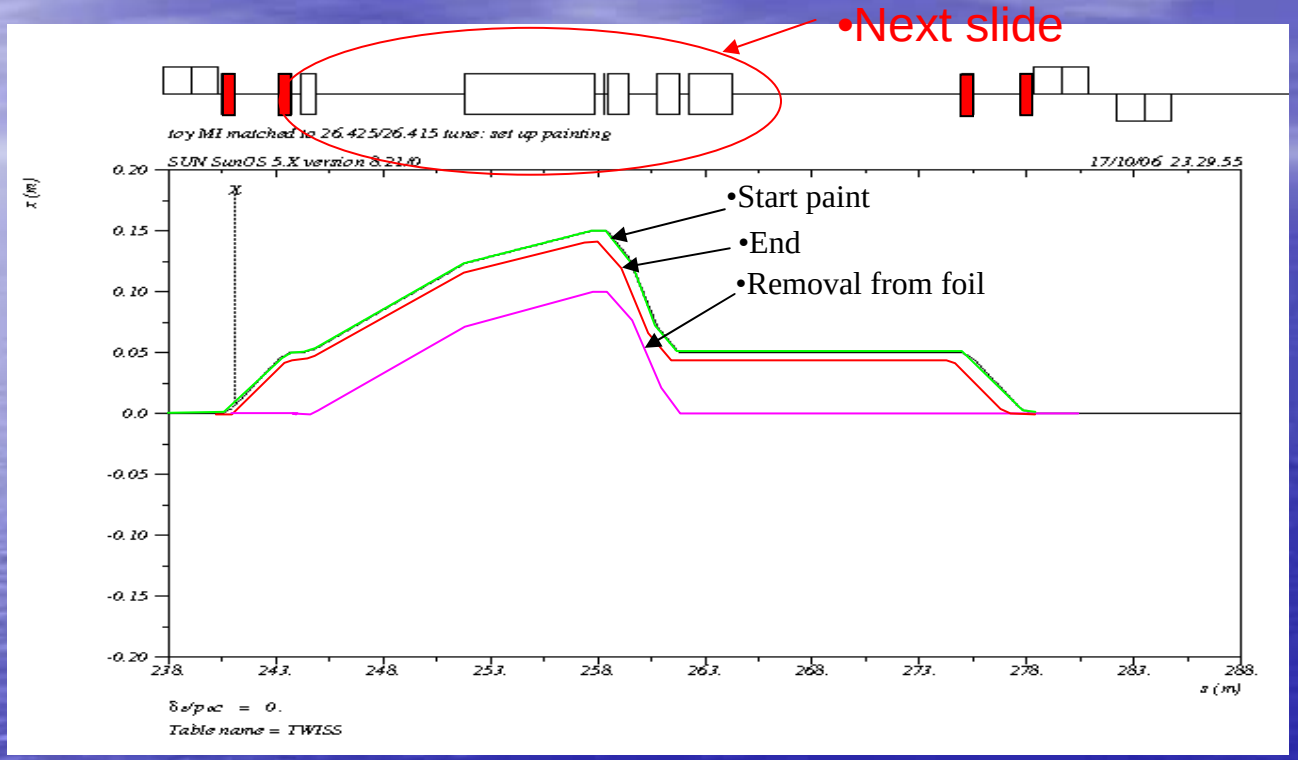
Qx=25.445

Qy=24.134

No tuning !

Recycler Injection

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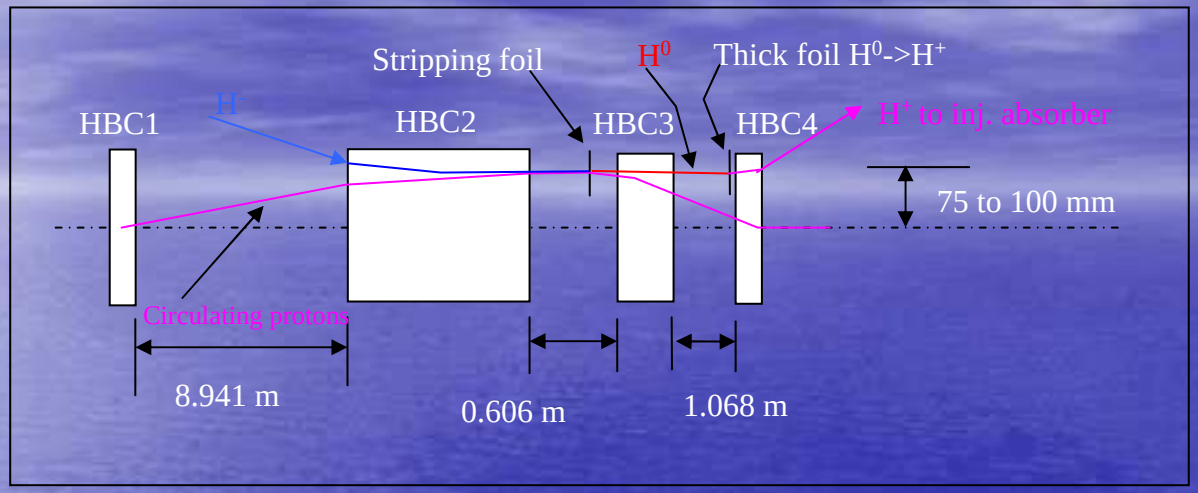
- Layout used for Proton Driver injection into Main Injector
- 150 mm offset dictated by MI geometrical constraints and missing MI magnets
- The DC chicane could become ramped bump

Injection Layout

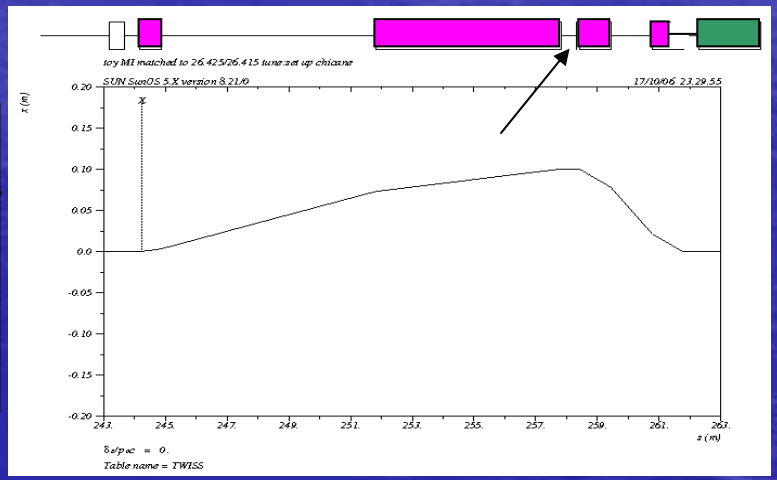
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Project X

- The



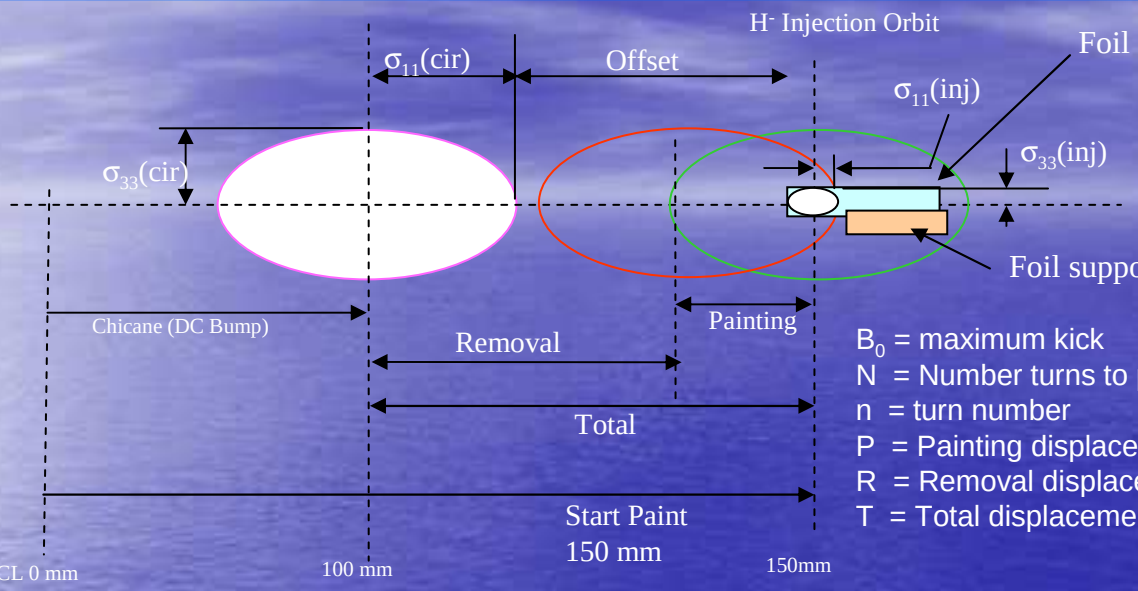
Magnet	Length [m]	Strength [kG]	Theta [mr]	H & V Aperture [in]
HBC1	0.7	+3.5669	+8.4211	6 x 2
HBC2	6.0	-0.4656	-9.4211	12 x 2 or 3?
HBC3	2.0	-5.5620	-37.5179	12 x 3 (?)
HBC4	1.0	+11.4206	+38.5179	12 x 3 (?)



Layout used for Proton Driver injection into Main Injector

Injection Painting

(back up slide)



B_0 = maximum kick
N = Number turns to paint
n = turn number
P = Painting displacement
R = Removal displacement
T = Total displacement

Maximum kick, B_0 [kG]	10.98
Painting Displacement, P [mm]	10.45
Removal Displacement, R [mm]	39.54
Offset [mm]	33.05

$$B = B_0\left[\frac{R}{T} - \frac{P}{T}\left(1 - \sqrt{\frac{2n}{N} - \left(\frac{n}{N}\right)^2}\right)\right]$$

$$y' = (\sigma_{44}^{cir} - \sigma_{44}^{inj})\left[\sqrt{\frac{2N-n}{N} - \left(\frac{N-n}{N}\right)^2}\right]$$

Current scheme is anti-correlated horizontal painting and vertical steering.
Suggested by KEK and implemented into STRUCT