Injection Design for Fermilab Project X

David Johnson, Z. Tang, C.Y.Tan

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Outline

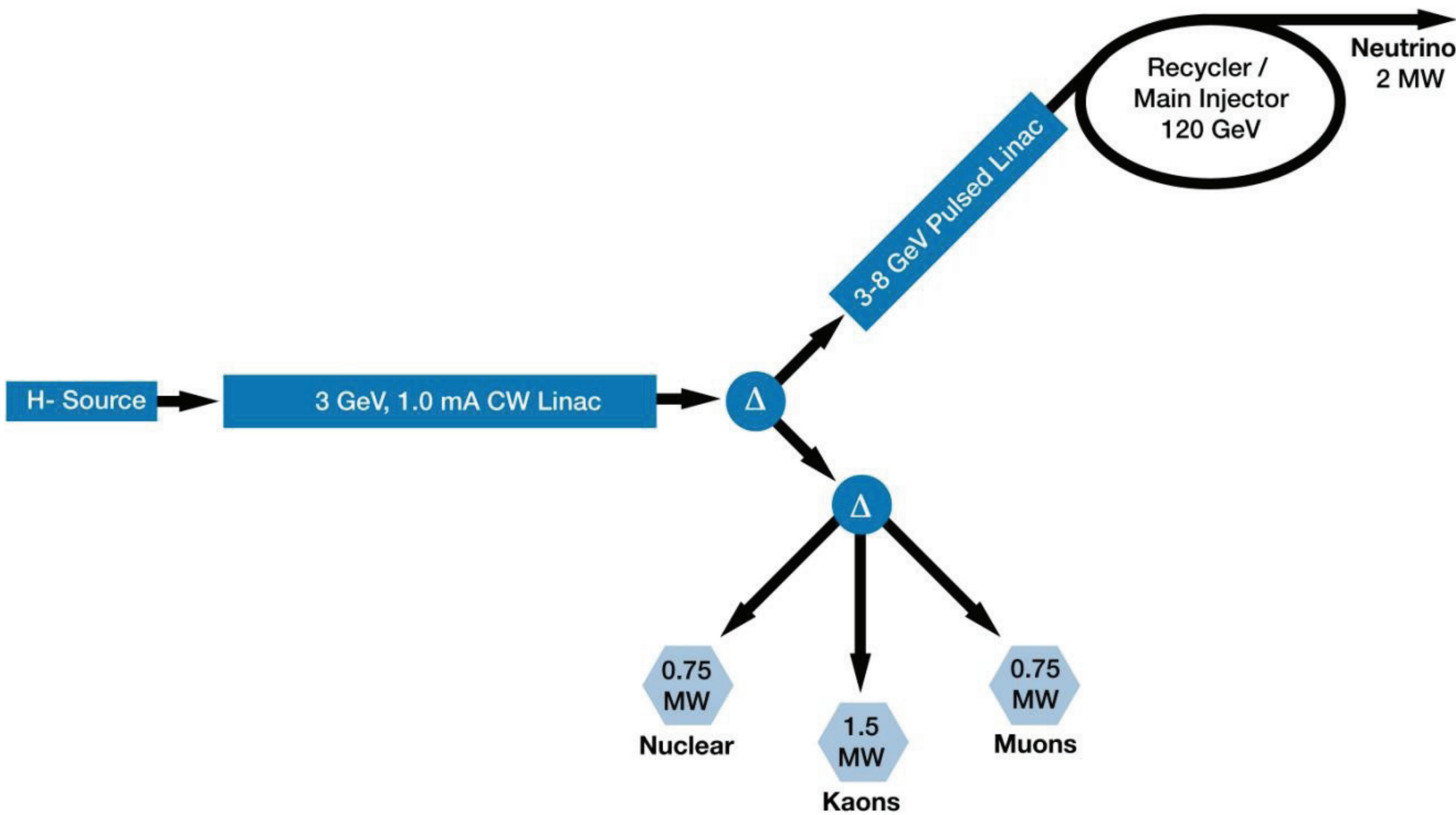
- Concept Evolution
- Reference Design
- Staged Approach
- Booster Injection
  - Current Conditions
  - 1 GeV injection
    - Configurations
    - Energy Matching
    - Transverse painting
    - Foil issues
- Summary

Concept Evolution

"a Little History"

- Project X grew out of the initial Proton Driver proposal… circa 2005
- Three Project X configurations have been developed, in response to limitations identified at each step:
  - Initial Configuration-1 (IC-1) circa 2008
    - 8 GeV pulsed linac + Recycler/MI
    - Fully capable of supporting neutrino mission
    - Limited capabilities for rare processes
  - Initial Configuration-2 (IC-2) circa 2010
    - 2 GeV CW linac + 2-8 GeV RCS + Recycler/MI
    - Fully capable of supporting neutrino mission
    - 2 GeV too low for rare processes (Kaons)
    - Ineffective platform for Neutrino Factory or Muon Collider
  - Reference Design circa 2011
    - 3 GeV CW linac + 3-8 pulsed linac + Recycler/MI
    - Ameliorates above deficiencies

Reference Design



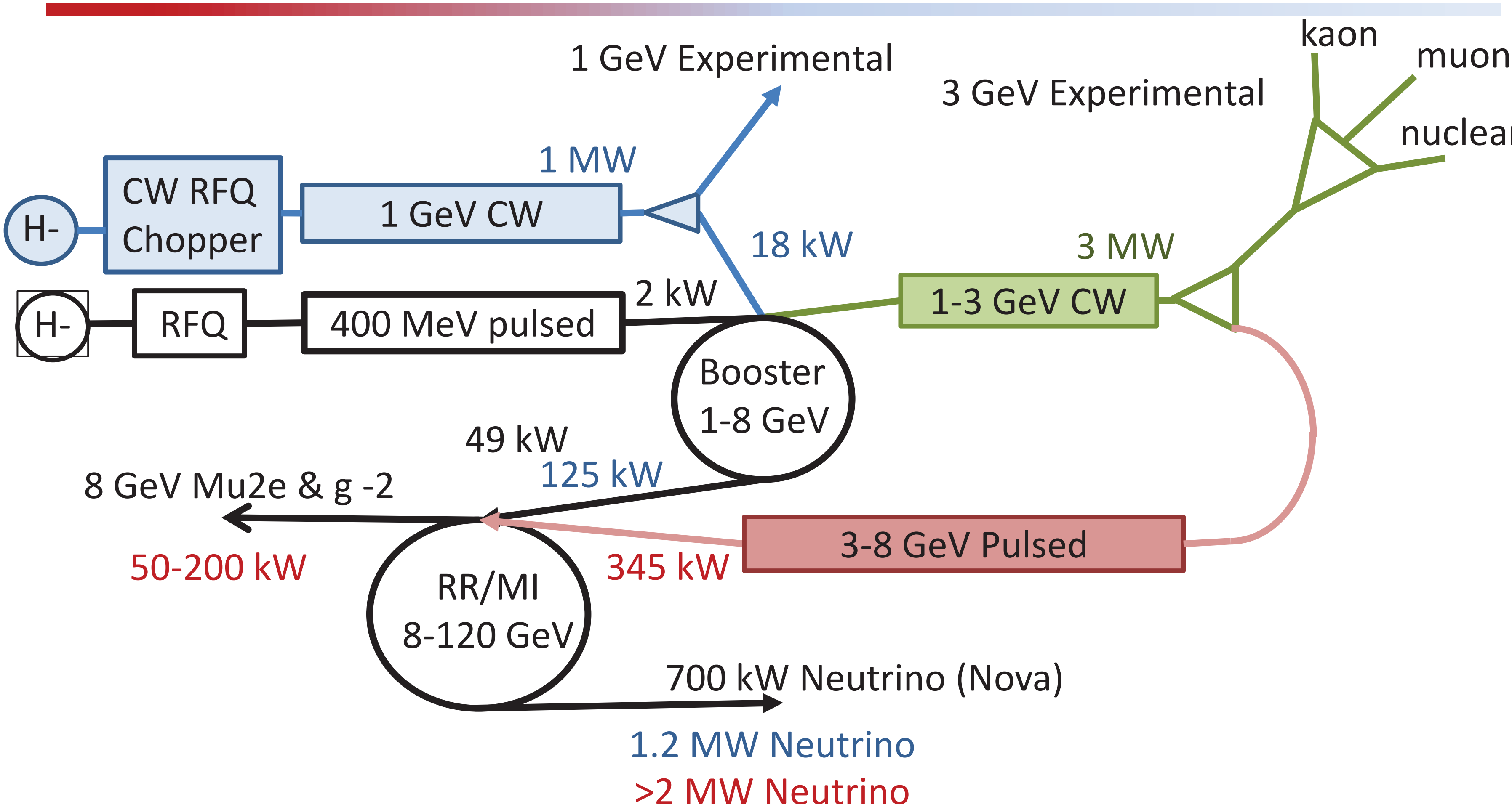
A Staged Approach

Circa Spring 2012

- In response to the DOE's request to investigate how we could stage Project X, a three phase approach has been proposed. This will gradually reach the goals of the Reference Design at the end of stage 3.
  - Stage 1: Construct a 1 GeV superconducting CW linac to inject into an upgraded Booster RCS.
  - Stage 2: Add a 1 -3 GeV superconducting CW linac to provide up to 3 MW for a 3 GeV Experimental program
  - Stage 3: Add a 3-8 GeV superconducting 10 Hz pulsed linac to accumulate up to 1.5E14 protons and then use single turn injection into the Main Injector. This will provide up to 50-200 kW for an 8 GeV experimental program and > 2 MW for a 120 GeV Neutrino program.
  - A 4th Stage referred to "Beyond the Reference Design would be a 8 GeV power upgrade to 4 MW
- The PXIE program is the front-end technology development and verification for the first stage of Project X.

See: N. Solyak talk: WE03B03 PXIE at FNAL

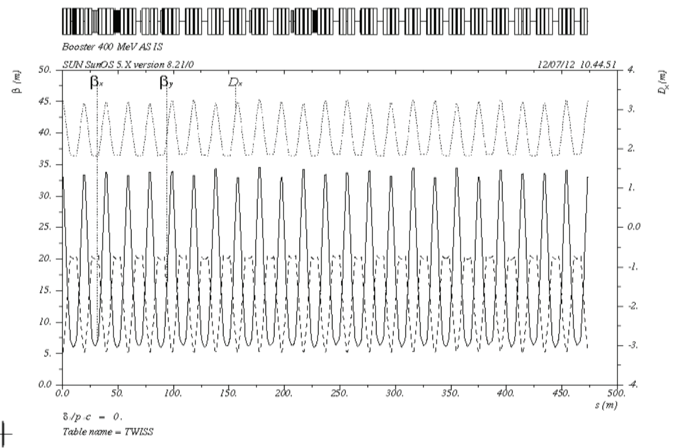
Staged Approach

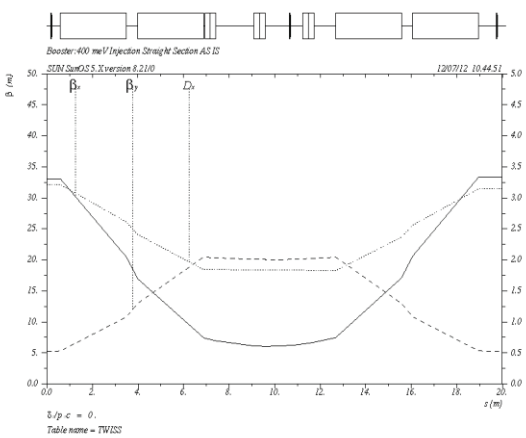


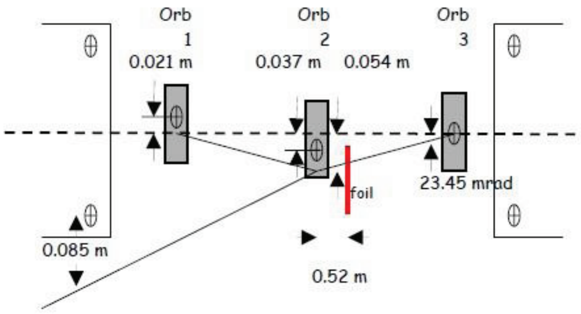
Current Booster

- 15 Hz resonant magnet system
- Inject 1-10 turns @2.2 us/turn
- 5E12 @7.5 Hz (upgrade to 15Hz now underway
- 2.4 kW injected beam power
- No phase space painting
- >380 ug/cm^2 foil -> 99.9% stripping efficiency
- New 3 magnet chicane (2005)
- No injection absorber
- Losses due to H0 & H- -> a few R on contact (2nd magnet)

24 FD0DF cell







See F. Garcia's talk this afternoon WG-D (TU03C02) on the current improvement plan.

1 GeV Booster Injection

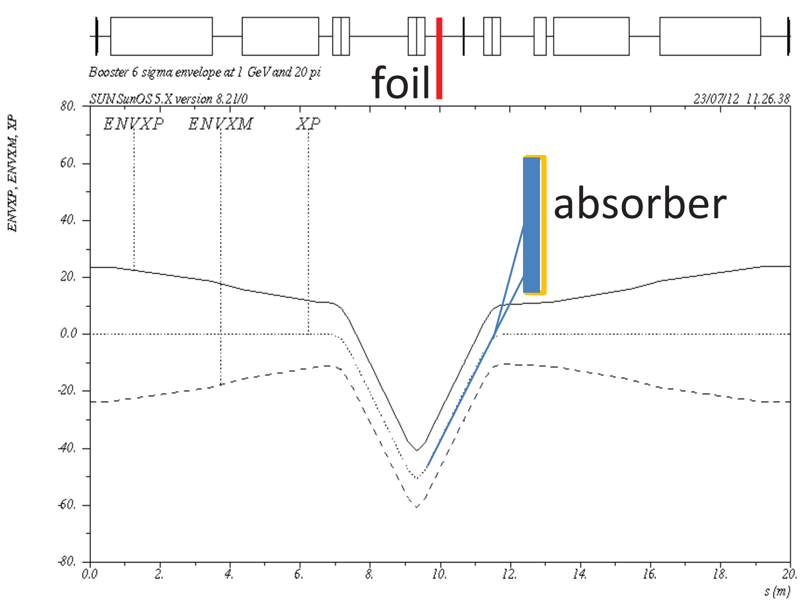
- Proton Intensity requirement 7.5e13 out of MI @120 GeV
- Booster provides12 pulses of 6.5E12/15Hz per MI cycle
- Assuming 95% efficiency inject 7E12/15Hz into Booster
  - If beam run on all cycles 18 kW injected and 125 kW extracted
- LINAC – 2.1MeV CW RFQ creates 162.5 MHz bunch train
- Bunch-by-bunch chopper in the MEBT
- Average current 1 mA (over 1 us) 3.8E7 H-/bunch (assuming all bunches are filled
- HE end of linac 650 MHz superconducting elliptical cavities
  - dE/E 0.025% (100% energy spread 0.25 MeV bunch length 3.8 ps
  - Transverse rms normalized emittance 0.25 p and 0.3 p-mm-mr (H&V)

Project X Modifications to Lattice

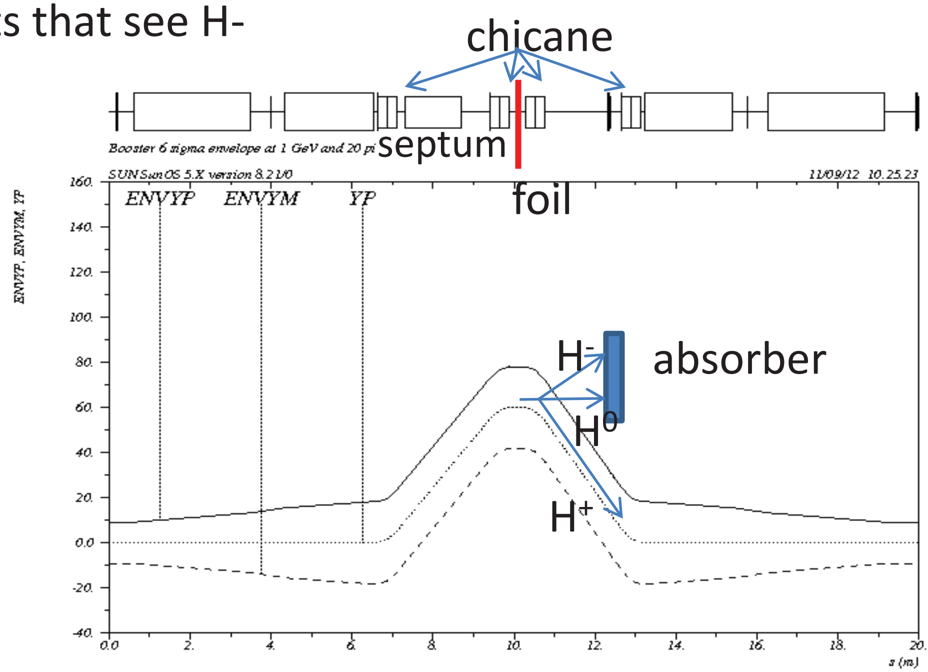
- Injection straight 6m between gradient magnets (no room to add an injection absorber -> increase in injection power X8)
  - Reduce "D" gradient magnets on either side by 25% (keep bc same)
  - Opens up straight by 12% (i.e. 0.72m)
  - Introduces small beta and dispersion error (<5%) that can easily be corrected
- Present chicane dipole design field 2.8 kG at 15 kA
  - Capable of 30 mr at 1 GeV
  - Lorentz stripping at 1 GeV and 2.8 kG -> loss rate ~10^{-8}/m
  - Could utilize existing magnets (with modifications to cross over buss)

Injection configuration

- Three or four bump chicane
- Horizontal or vertical injection
- Want to limit field in injection magnets that see H-



Horizontal Injection



Vertical Injection

Micro Bunch Placement

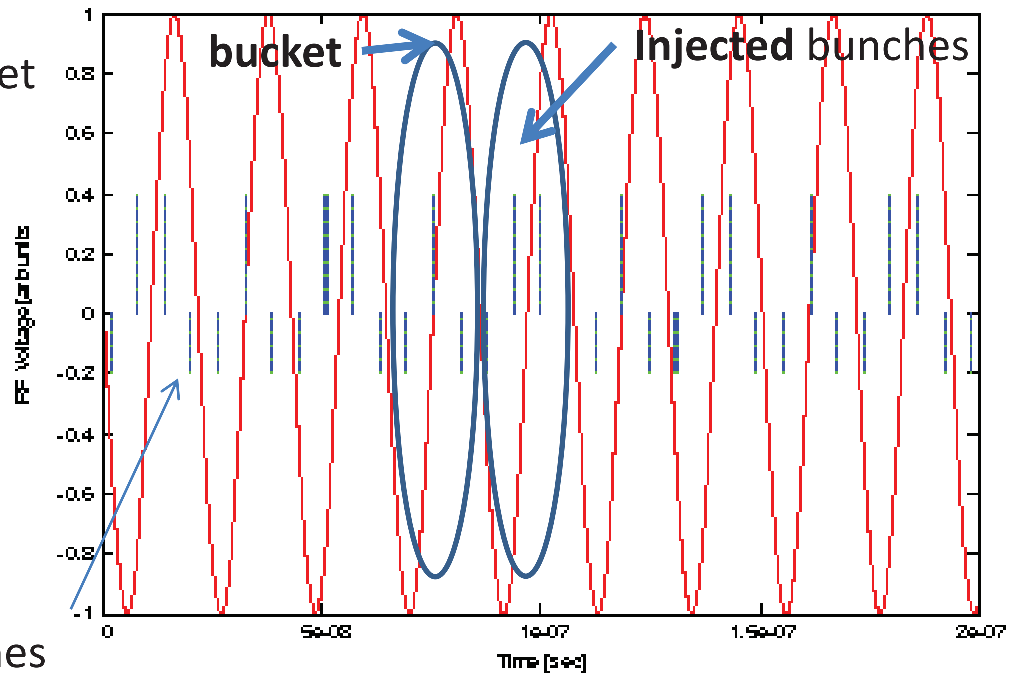
*Booster harmonic number is 84 *At 1 GeV f_{RF} =46.46 MHz *Ratio R = f_{bunch}/f_{RF} = 3.49

*Get no phase slippage between buckets on single turn *Alternate bucket filled with 1 or 2 bunches

•On multiple turns bunch injected at same phase in Booster bucket (no good- not uniform distribution)

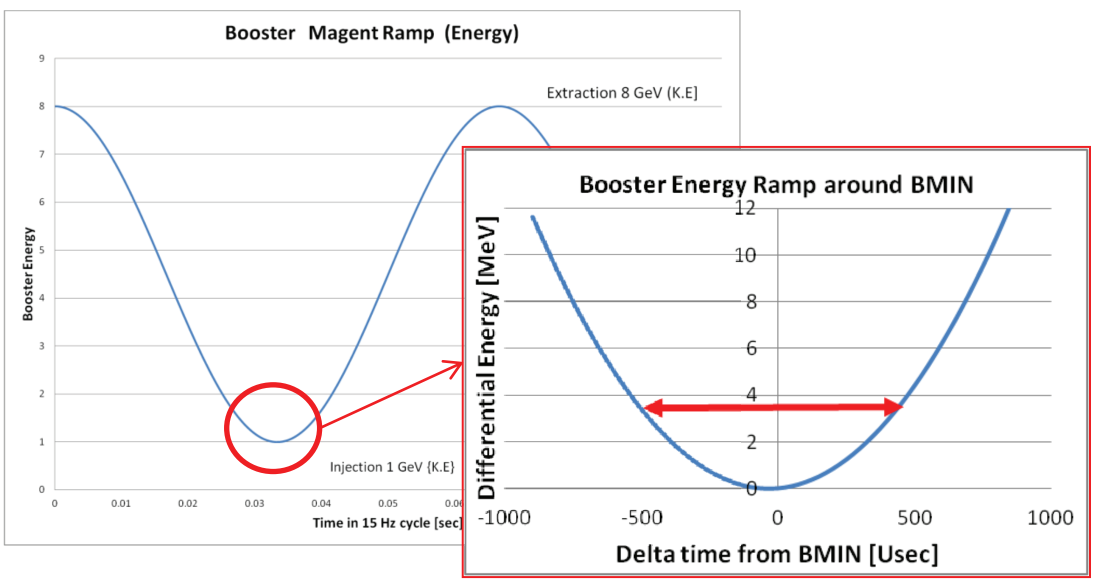
*Need to program a turn-by-turn phase shift -> longitudinal painting in phase

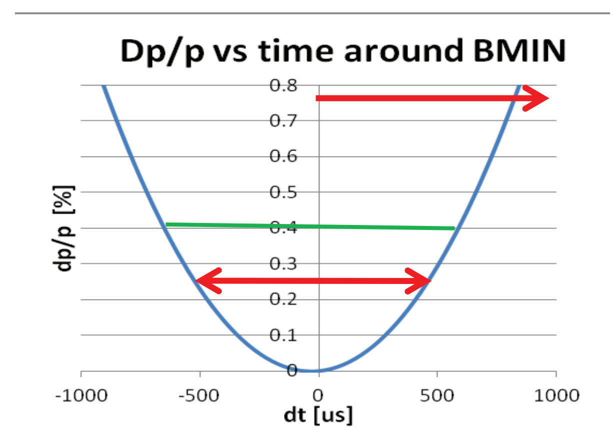
- requires 2 turns to get 3 bunches/bucket
- Increase number of turns or increase bunch intensity
- Even harmonic gives uneven bucket filling pattern
- Change harmonic number to odd
  - Cf 83 in Booster -> 581 in MI/RR



Project X Momentum Acceptance

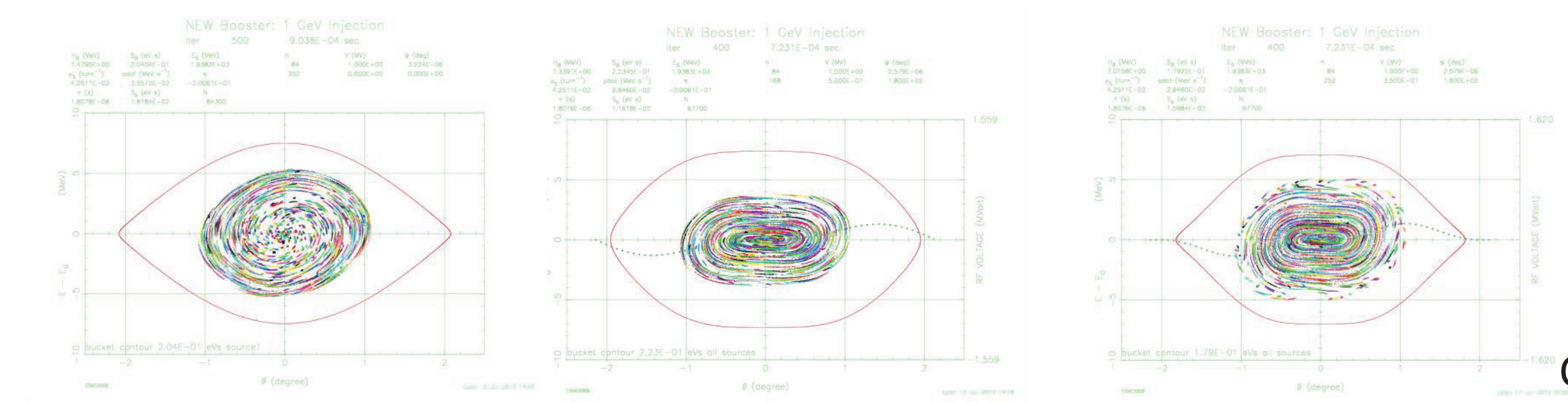
- Booster momentum acceptance has been measured to be +/- 0.15-0.2 % -> |0.4%|
- At 1 GeV revolution period 1.8 us require ~627 turn injection ~1.12 ms injection time
- 48 resonant RLC cells in series powered by 4 supplies – sinusoidal ramp profile
- Since 1 GeV injection time >> 400 MeV injection time we have several Options





Project X Energy Matching (2)

- Preliminary ESME simulations with a stationary bucket with fundamental harmonic [150 kV] + 2nd [75kV] and +3rd [50 kV]
- Inject for 1 ms then ramp RF to 1MV and harmonics to zero in 0.1ms
- Injected +/-180^o , +/-90^o and +/-60^o -> 30-40% survived for +/180^o inj.
- %survival to transition for +/-60^o : 1st 84% 1st+2nd 97% 1st+3rd 94%
- Bunch dE ~ +/- 4 MeV
- linac bunch 0.25 MeV & 0.14^o -> paint in both energy and phase



C.Y. TAN

Linac Booster Energy Match

OPTION 1: Modify the main magnet power supply system to create an injection front porch

- Preliminary simulations on 1 cell show feasibility
- Need to model entire ring
- Synchronous micro-bunch transfer into a stationary bucket

OPTION 2: Start injection 550 us before inject through BMIN and end inj 550 us after BMIN on the ramp (inject on the down/up ramp)

- Synchronous micro-bunch transfer
- Use stationary bucket and utilize energy swing to paint in energy/phase (requires orbit compensation due to dispersion)
- Linac energy follow Booster energy profile -> Accelerating bucket to keep orbit centered -> reduced longitudinal acceptance

Transverse painting

- Final 95% normalized painted emittance ε_R=20 π-mm-mr
- Average injected 95% normalized emittance ε_L=1.7 π-mm-mr
- Ratio $\varepsilon_L / \varepsilon_R$ = 0.085 (compared to SNS 0.01 and JPRAC 0.0185)
- Painting options:
  - Painting both dimensions in ring – SNS
  - Painting one dimension and steer in the other – JPARC
  - Correlated or anti-correlated
- Choice of painting scheme and bump motion important in determining number of hits.
- Horizontal beam size factor 2 smaller than vertical so the closed orbit is moved off slower leading to a greater number of foil hits.

Lattice Mismatch

J B-Wang,C. Prior SNS/BNL Note 080

Optimal positioning/orientation of injected beam in circulating beam ellipse.

$$\frac{\alpha_L}{\beta_L} = \frac{\alpha_R}{\beta_R} = -\frac{X_C^{'} - X_o^{'}}{X_C - X_o}$$

In our case α ~ 0 for both ring and line (upright ellipse)

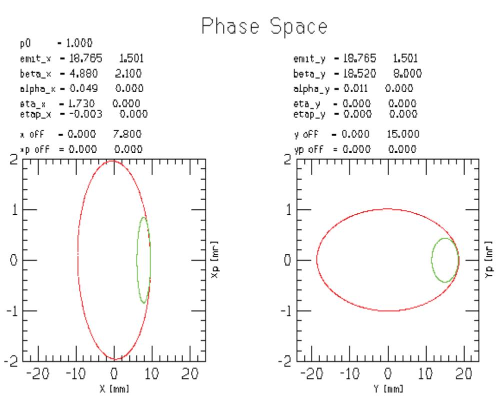
$$\frac{\beta_L}{\beta_R} \geq \left(\frac{\varepsilon_L}{\varepsilon_R}\right)^{1/3}$$

Injected beam proper aspect ratio (minimize hits)

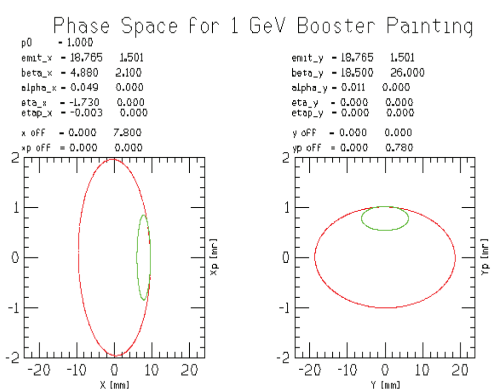
Determines values for transport line lattice functions

Booster Lattice at Foil

β_x	4.88m
α_x	0.049
β_y	18.52m
α_y	0.011
D_x	1.73
D'_x	-0.003



Paint x & y



Paint x & steer y

Foil heating

- With no painting the average number of hits per particle on the foil is just $N_t/2$
  - For N_p = 7.4E12/cycle and N_t ~ 600 Total foil hits ~ 2.2E15
- With painting and the foil the same size as the injected beam and assuming proper matching conditions the minimum number of hits can be estimated by

$$h_{\min} = \frac{1}{4} N_t \left(\frac{\varepsilon_L}{\varepsilon_R} \right)^{4/3}$$

D. Raparia

- For parameters here: h_{min} ~ 6
- Booster circ. σx= 3mm and σy= 6mm , linac beam σx= .5 mm σy=1 mm
- Assume:
  - Hit distribution similar to circulating beam distribution
  - Use # hits/particle as 425 to give a total of 3.15E15 hits/ms (way over estimate)
  - Maximum hit density in the central sq. mm is ~10^{14} /mm^2/ms
  - Ignore cooling from delta electrons

Foil Heating ANSYS Model

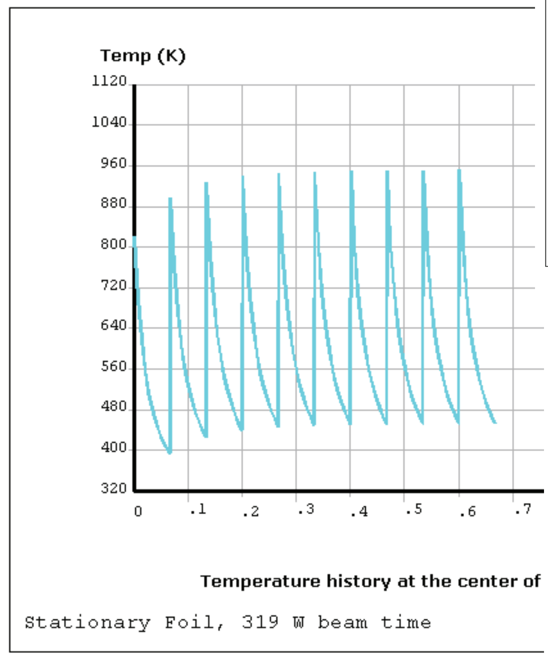
(Zhijing Tang FNAL)

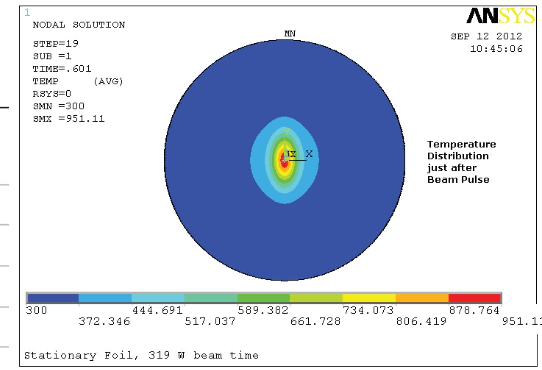
$$h\rho c\frac{dT}{dt} = h\nabla(k\nabla T) - 2s\varepsilon(T^4 - T_0^4) + \rho u h f(r) g(t)$$

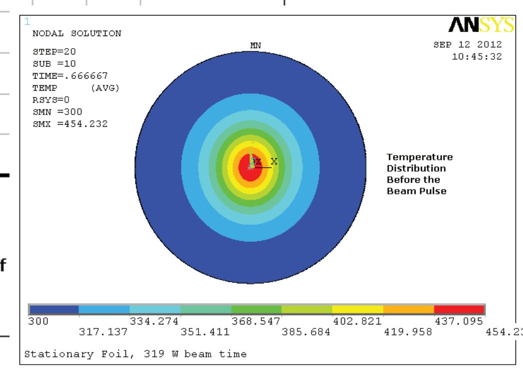
Assume :

- total hit on foil 3.15E15 in 1 ms (~1E14 in central mm^2)
- σx=3mm σy=6mm gaussian
- 15 Hz rep rate
- dE/dx = 1.94 MeV-cm^2/g
- Heating power 320W

Foil: ρ=2.2 g/cm^2
- k= 13.7 W/cm-K
- ε= 0.8
- *h*=1.5 um
- radius = 5 cm
- circ. Fixed @ 300K
- two surface radiate
- include thermal conduction







Summary

- We are beginning to look at siting issues for the linac and where we will inject into the Booster. (There are many ideas that need to be flushed out)
- It looks feasible for injection at 1 GeV (no show stoppers identified yet just $$) Need to start narrowing down options.
- Much more work needs to be done
  - Power supply simulations-
    - Can we make an injection front porch (if so how much $$ and is it needed)?
    - Can we use chicane dipoles/supplies for painting as well?
  - Transverse painting simulations (for several injection configurations)
    - Is there room for off-plane painting magnets in straight section or are we constrained to paint n’ steer ?
  - Longitudinal simulations to understand options
  - Magnet issues and designs
    - New gradient magnet, chicane dipoles, septum, etc.
  - Injection absorber design

Thank you for your attention

Questions ?

Example Power Staging Plan for the Research Program

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range is depends on MI injector slow-spill duty factor (df) for kaon program.