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# Initial Configuration Overview

Paul Derwent  
PXAF Collaboration Meeting  
21 Nov 08

# The role of the Initial Configuration Document

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## ■ What is its role?

- Projects have to work within context of DoE order 413.3a (a 54 page document)
  - Program and Project Management for the acquisition of Capital Assets
  - Critical Decision path
- Input to CD-0 “Approve Mission Need”
  - R&D and Conceptual Planning
  - “A Mission Need Statement is the translation of this gap into functional requirements that cannot be met through other than material means. It should describe the general parameters of the project, how it fits within the mission of the Program, and why it is critical to the overall accomplishment of the Department mission, including the benefits to be realized. **The mission need is independent of a particular solution, and should not be defined by equipment, facility, technological solution, or physical end-item.** This approach allows the Program the flexibility to explore a variety of solutions and not limit potential solutions.”
- but we also need a cost estimate!!!! so we need a configuration to cost

# Development of the configuration

## ■ Steering Group Report

- “a linear accelerator with the currently planned characteristics of the ILC combined with Fermilab’s existing Recycler Ring and Main Injector accelerator”
- “the same as or similar to those used in the ILC at a scale of about 1% of a full ILC linac”

## ■ 8 GeV H<sup>-</sup> linac

- 9 mA x 1 msec x 5 Hz  $\Rightarrow$   $5.6 \times 10^{13}$  particles per pulse
- Strip and accumulate 3 pulses in Recycler
- transfer to Main Injector

## ■ Emphasis on synergy with ILC:

- scale test
- industrialization
- $\Rightarrow$  9 mA x 1 msec x 5 Hz

## ■ Jan – May 08

- R&D plan to develop concepts towards CD-2

## ■ May 08 AAC

- “Project-X, based on a superconducting linac, is important but aside from synergy with ILC, hard to justify unless one thinks of the long-term goals of Project-X – what upgrade potential could be incorporated from the start that would demand a superconducting linac?”

## ➤ June 08 P5 Report

# The Intensity Frontier -- the P5 Report

## ■ P5 report: Fermilab's physics vision for this proton source has three main elements:

1. *A neutrino beam for long baseline neutrino oscillation experiments.* A new 2-megawatt proton source with proton energies between 50 and 120 GeV would produce intense neutrino beams, directed toward a large detector located in a distant underground laboratory.
2. *Kaon-and muon-based precision experiments exploiting 8 GeV protons from Fermilab's Recycler, running simultaneously with the neutrino program.* These could include a world-leading muon-to-electron conversion experiment and world-leading rare kaon decay experiments.
3. *A path toward a muon source for a possible future neutrino factory, and, potentially, a muon collider at the Energy Frontier.* This path requires that the new 8 GeV proton source have significant upgrade potential.

## ■ #1

These physics objectives define the mission need.

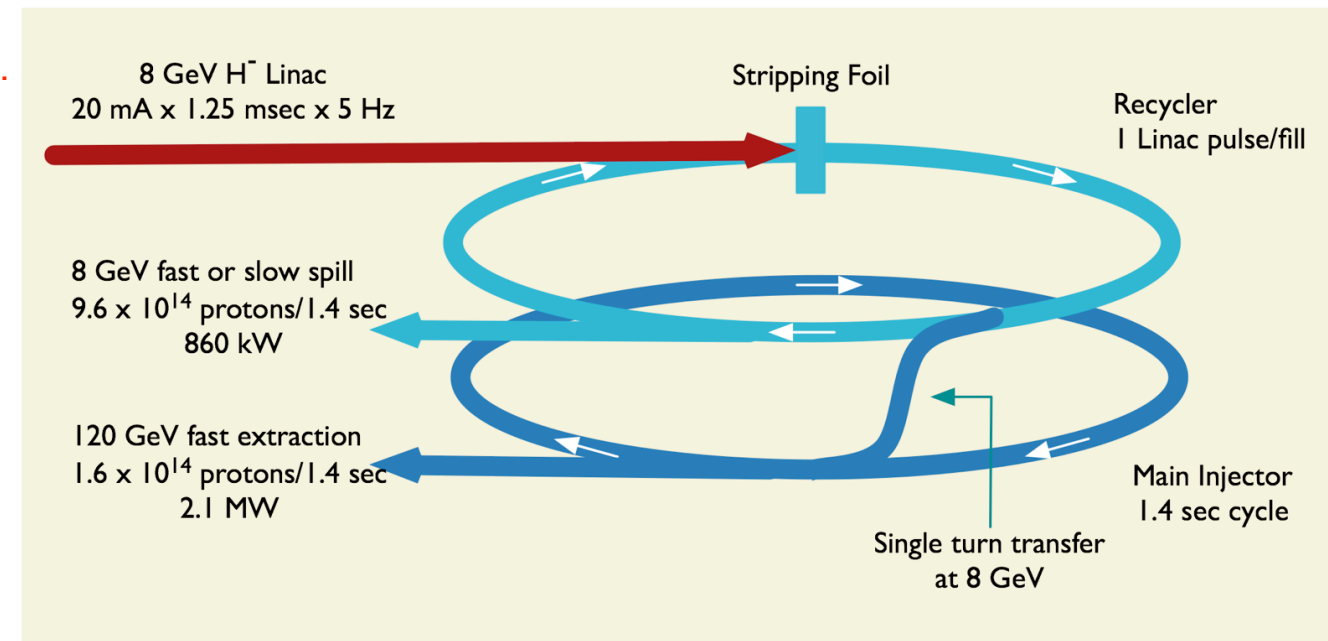
- 1.6e14 / 1.4 sec at 120 GeV: 2.1 MW
  - 20 mA, 1.25 msec, 5 Hz from 8 GeV H<sup>-</sup> linac
  - Strip in Recycler
  - Single Turn transfer to MI

## ■ #2

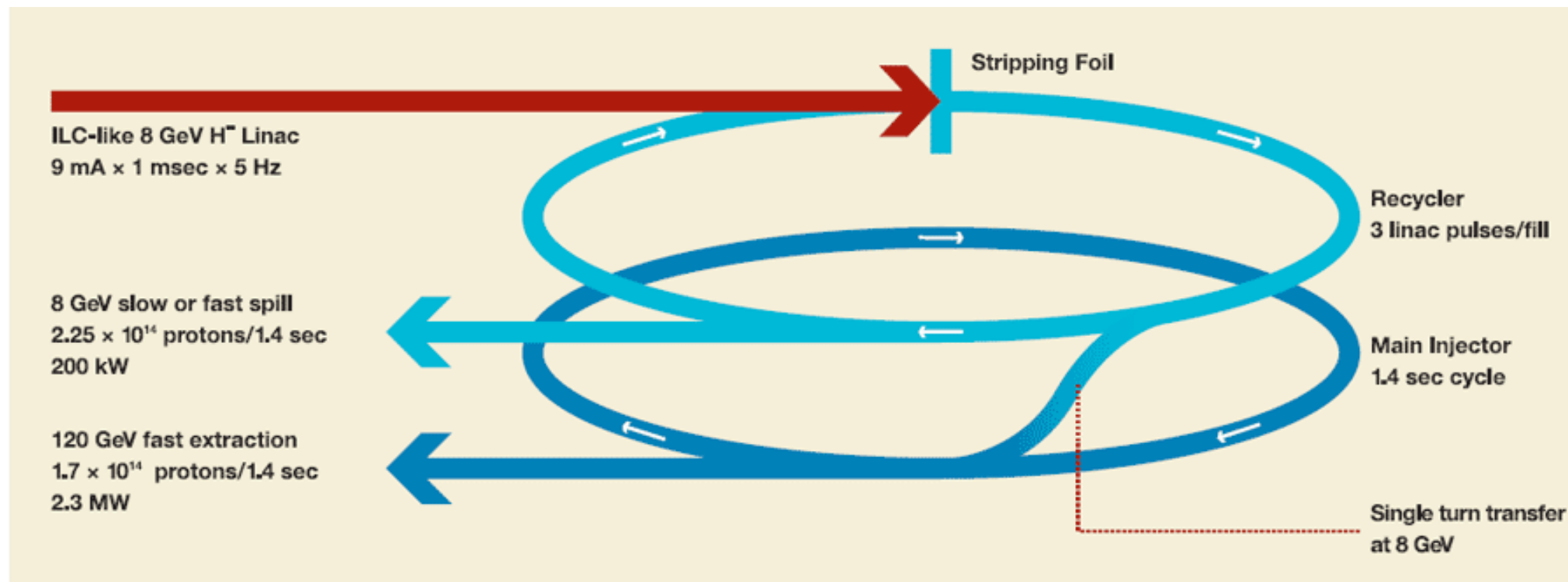
- 3 pings from Recycler to Accumulator
  - 7e13 / 1.4 (0.7) sec at 8 GeV: 70 (140) kW for mu2e
  - >3(6)× improvement over NOvA era beam power
- Investigate slow spill

## ■ #3

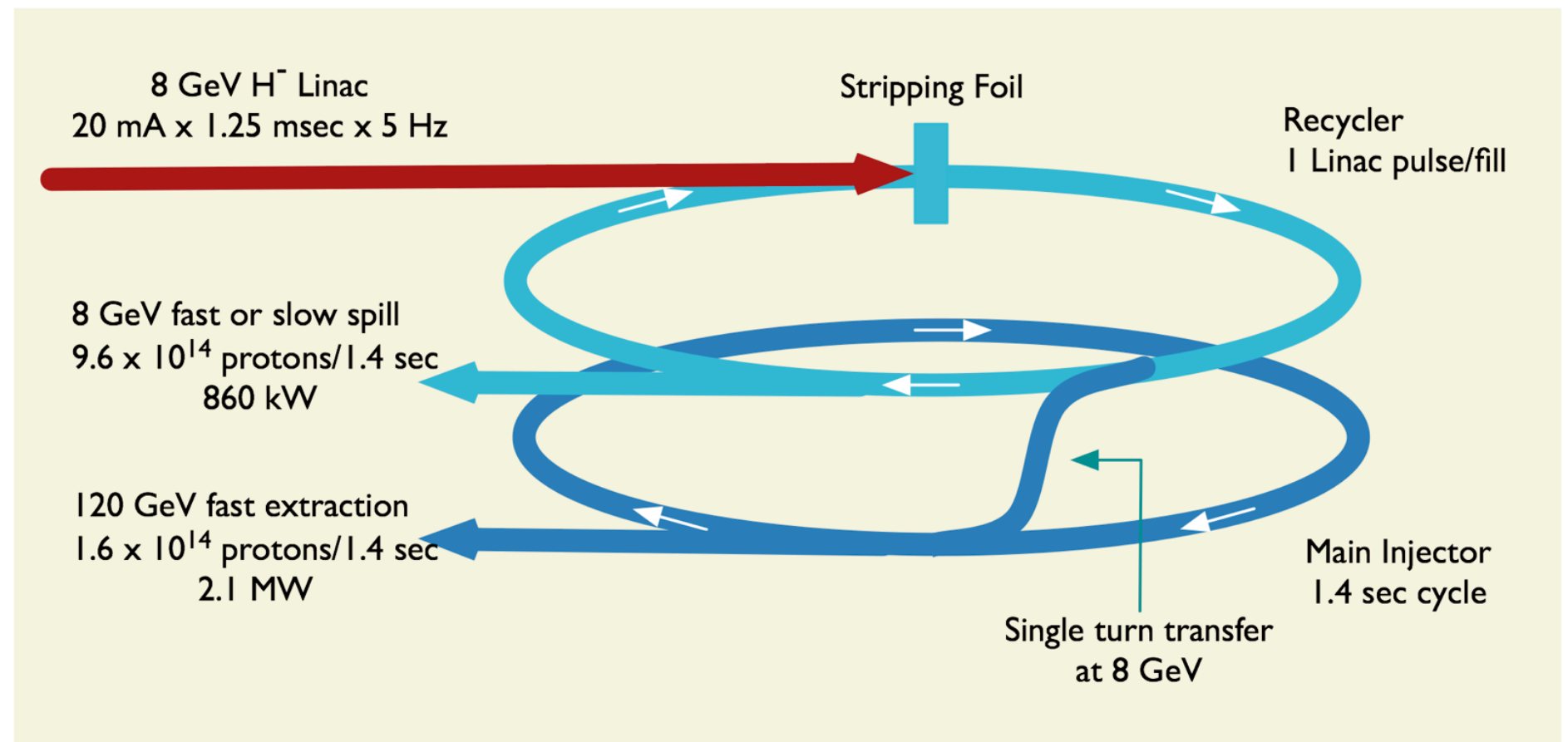
- upgrade path to 10 Hz, longer pulse length



## Comparison

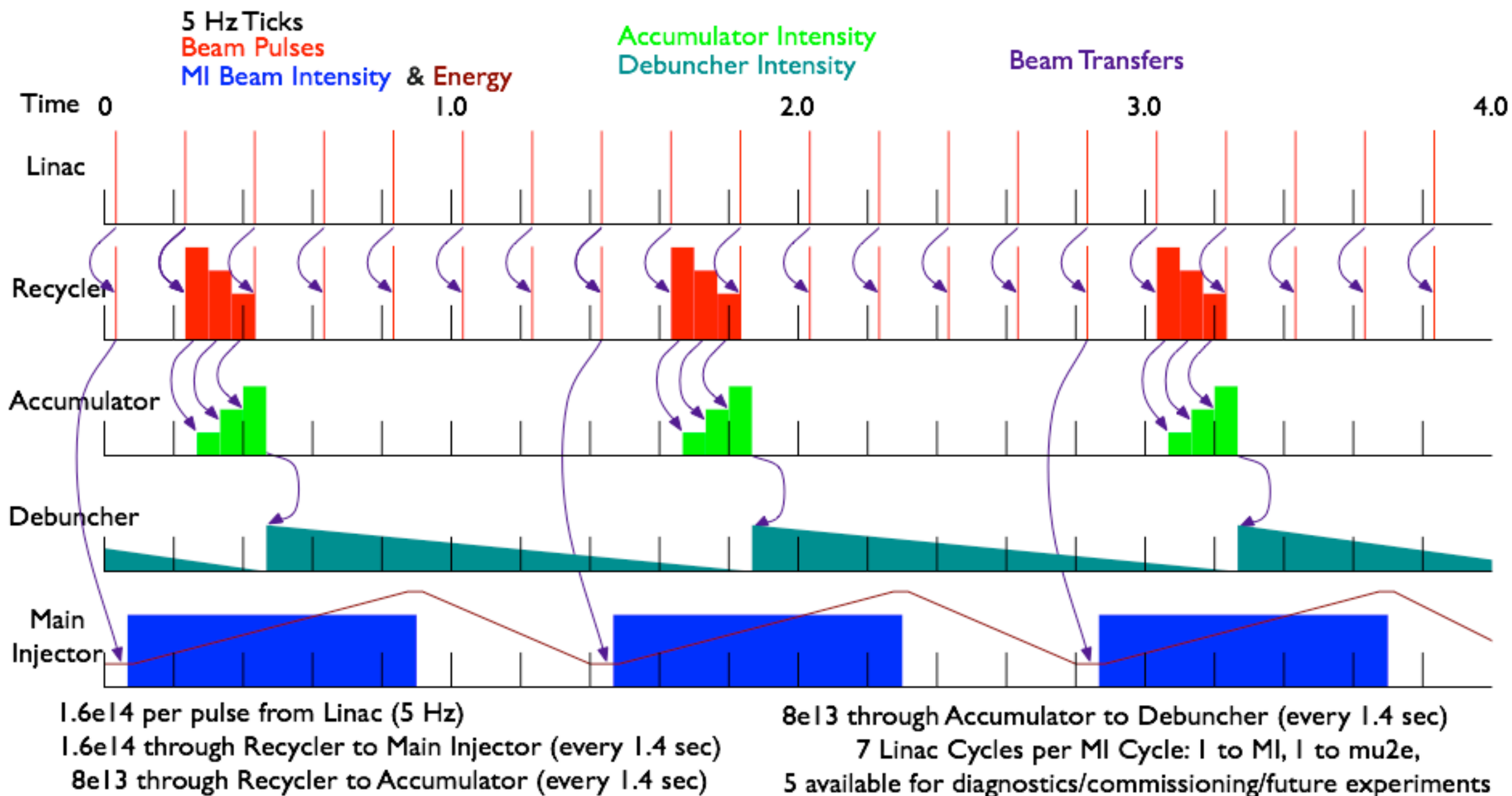


Steering Group  
Project X



Initial  
Configuration  
Document

# Operational Scenario



## Technical Goals

### Linac

Particle Type	H-
Beam Kinetic Energy	8 GeV
Particles per pulse	$1.6 \times 10^{14}$
Pulse Rate	5 Hz
Beam Power	1 MW
Average Pulse Beam Current	20 mA
Beam Pulse Length	1.25 msec

### Recycler

Particle Type	proton
Beam Kinetic Energy	8 GeV
Cycle Time	0.2 sec
Particles per cycle to MI	$1.6 \times 10^{14}$
Beam Power to MI	143 kW
Additional Beam Power available	857 kW

### Main Injector

Particle Type	proton
Beam Kinetic Energy (maximum)	120 GeV
Cycle Time	1.4 sec
Particles per cycle from MI	$1.6 \times 10^{14}$
Beam Power at 120 GeV	2.1 MW



# Initial Configuration Parameters

Req. No.	Description	Req.	Unit	Reference Requirements			
1.0	General						
1.1	120 GeV Beam Power	2.1	MW				
1.2	Total Linac Beam Power	1.0	MW				
1.3	Available (outside of MI) Linac Beam Power	0.9	MW				
1.4	Available (outside of MI) Duty Factor	86	%				
1.5	120 GeV Availability	75	%				
1.6	8 GeV Availability	80	%				
2.0	325 MHz Linac						
2.1	Average Beam Current	20	mA	1.2			
2.2	Pulse Length	1.25	msec	1.2			
2.3	Repetition rate	5	Hz	1.2			
2.4	325 MHz Availability	98	%	1.6			
2.5	Peak RF Current	31.9	mA	2.1	2.11	2.13	2.14
2.6	Final Energy	420	MeV	3.7			
2.7	Energy Variation (rms)	1	%	3.11			
2.8	Bunch Phase jitter (rms)	1	degree	3.12			
2.9	Linac Species	H-		4.1			
2.10	Transverse Emittance (95% normalized)	2.5	$\pi$ -mm-mrad	5.7	5.8		
2.11	Macro Bunch Duty Factor	67	%	5.10	5.12		
2.12	Macro Bunch Frequency	53	MHz	5.12			
2.13	Micro Pulse Length	10.4	microsec	5.13			
2.14	Micro Pulse Period	11.1	microsec	5.13			
3.0	1300 MHz Linac						
3.1	Average Gradient (ILC portion)	25	MV/meter				
3.2	Average Gradient (S-ILC portion)	23	MV/meter				
3.3	Average Beam Current	20	mA	1.2			
3.4	Pulse Length	1.25	msec	1.2			
3.5	Repetition rate	5	Hz	1.2			
3.6	1300 MHz Availability	88	%	1.6			
3.7	Initial Energy	420	MeV	2.6			
3.8	Length (approx.)	700	meters	3.1	3.13		
3.9	Peak RF Current	31.9	mA	3.3	3.15	3.17	3.18
3.10	Linac Species	H-		4.1			
3.11	Energy Variation (rms)	1	%	4.9			
3.12	Bunch Phase jitter (rms)	1	degree	4.9			
3.13	Final Energy	8	GeV	4.10			
3.14	Transverse Emittance (95% normalized)	2.5	$\pi$ -mm-mrad	5.7	5.8		
3.15	Macro Bunch Duty Factor	67	%	5.10	5.12		
3.16	Macro Bunch Frequency	53	MHz	5.12			
3.17	Micro Pulse Length	10.4	microsec	5.13			
3.18	Micro Pulse Period	11.1	microsec	5.13			



# Initial Configuration Parameters

4.0	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	+/- 0.75	%	3.11		
4.6	Minimum Transverse Aperture	25	$\pi$ -mm-mrad	3.14	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		
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	Not sure how this is defined...	
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	$\pi$ -mm-mrad	5.6		
5.8	r.m.s. normalized transverse emittance	13	$\pi$ -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	sec	6.1		
5.12	RF Frequency	53	MHz	6.2		
5.13	Abort Gap Length	700	nsec	6.3		
5.14	Peak Recycler Beam Current	2.36	A	6.5		
6.0	Main Injector					
6.1	120 GeV cycle Time	1.4	sec			
6.2	RF Frequency	53	MHz			
6.3	Abort Gap Length	700	nsec			
6.4	Acceleration Efficiency	99	%			
6.5	Main Injector Beam Current	2.36	A	1.1		
6.6	Final Energy	120	GeV	1.1		
6.7	120 GeV Beam Power	2.1	MW	1.1		
6.8	Availability	87	%	1.5		
6.9	Injection Energy	8	GeV	5.1		
6.10	Longitudinal emittance per Bunch	0.5	eV-Sec	6.2	6.11	
6.11	Space Charge Tune Shift	0.05		6.4		
6.12	95% normalized transverse emittance	25	$\pi$ -mm-mrad	6.11		
6.13	r.m.s. normalized transverse emittance	13	$\pi$ -mm-mrad	6.11		
6.14	Bunching factor	2		6.11		
7.0	8 GeV Extraction					
7.1	Fast Extraction Rate	15	Hz			
7.2	Fast Extraction Pulse Length	1.6	microsec			
7.3	Cycle Time	0.2	sec			

## Facility Scope

- An 8 GeV superconducting linac
  - 325 MHz section to 420 MeV
  - 1.3 GHz section 420 MeV to 8 GeV
- Beamline for transport to the Recycler
- Modifications to Recycler for H<sup>-</sup> injection and transfer to MI
- Modifications to the Main Injector to support acceleration and extraction of high intensity beams

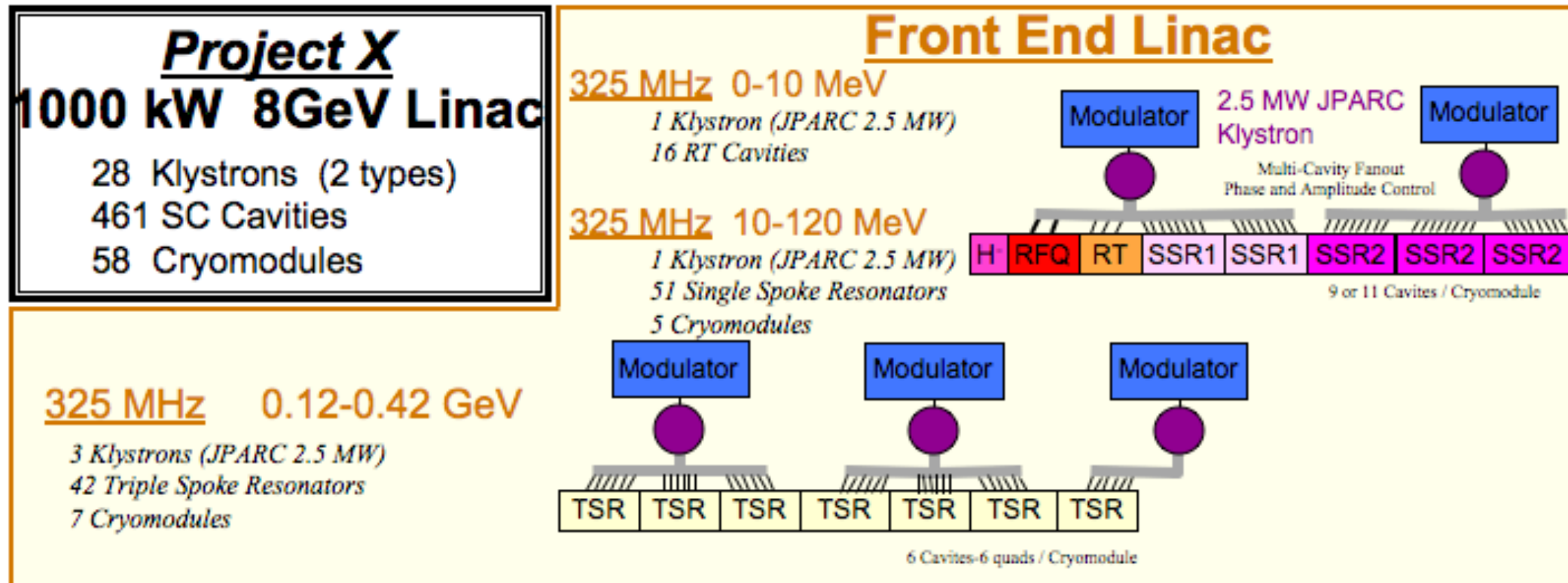
## Assumptions

- Existing linac and booster no longer operational
- Existing Tevatron no longer operational (cryo systems available)
- Existing test beam facility in Meson continues at low duty factor
- Existing antiproton source reconfigured and operating in support of mu2e
- A neutrino beamline directed towards DUSEL operating

## Interfaces

- DUSEL beamline: Main Injector extraction kicker
- mu2e : Recycler extraction kicker

# Linac Layout



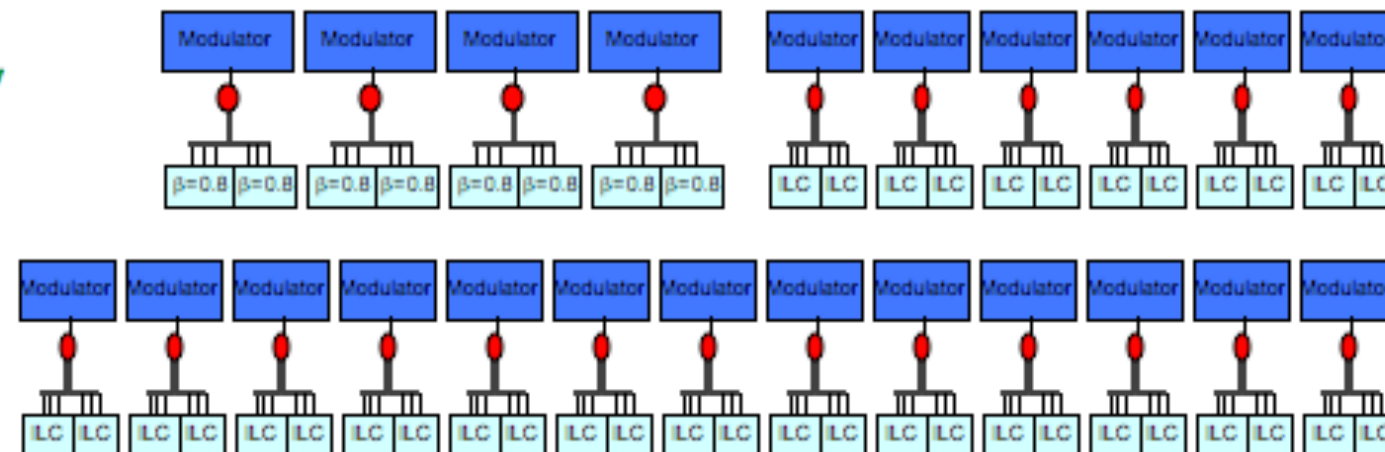
**1300 MHz 0.42-1.3 GeV**

*4 Klystrons (ILC 10 MW MBK)  
 64 Squeezed Cavities ( $\beta=0.81$ )  
 8 Cryomodules*

**1300 MHz 1.3-8.0 GeV**

*19 Klystrons (ILC 10 MW MBK)  
 304 ILC-identical Cavities  
 38 ILC-like Cryomodules*

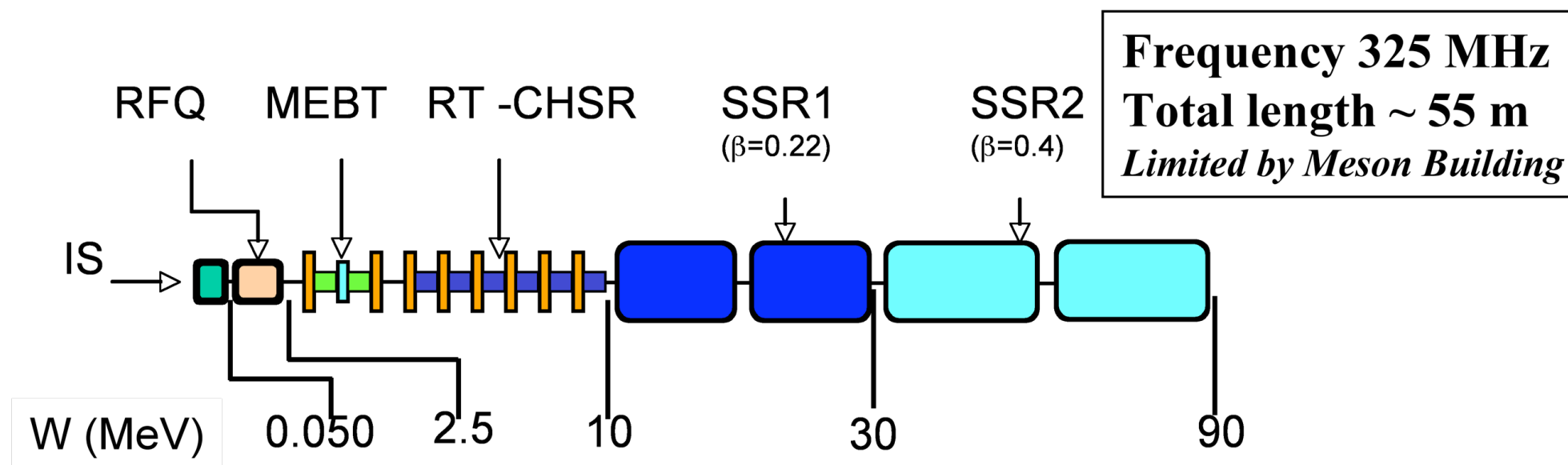
## 1300 MHz LINAC



## 325 MHz Linac

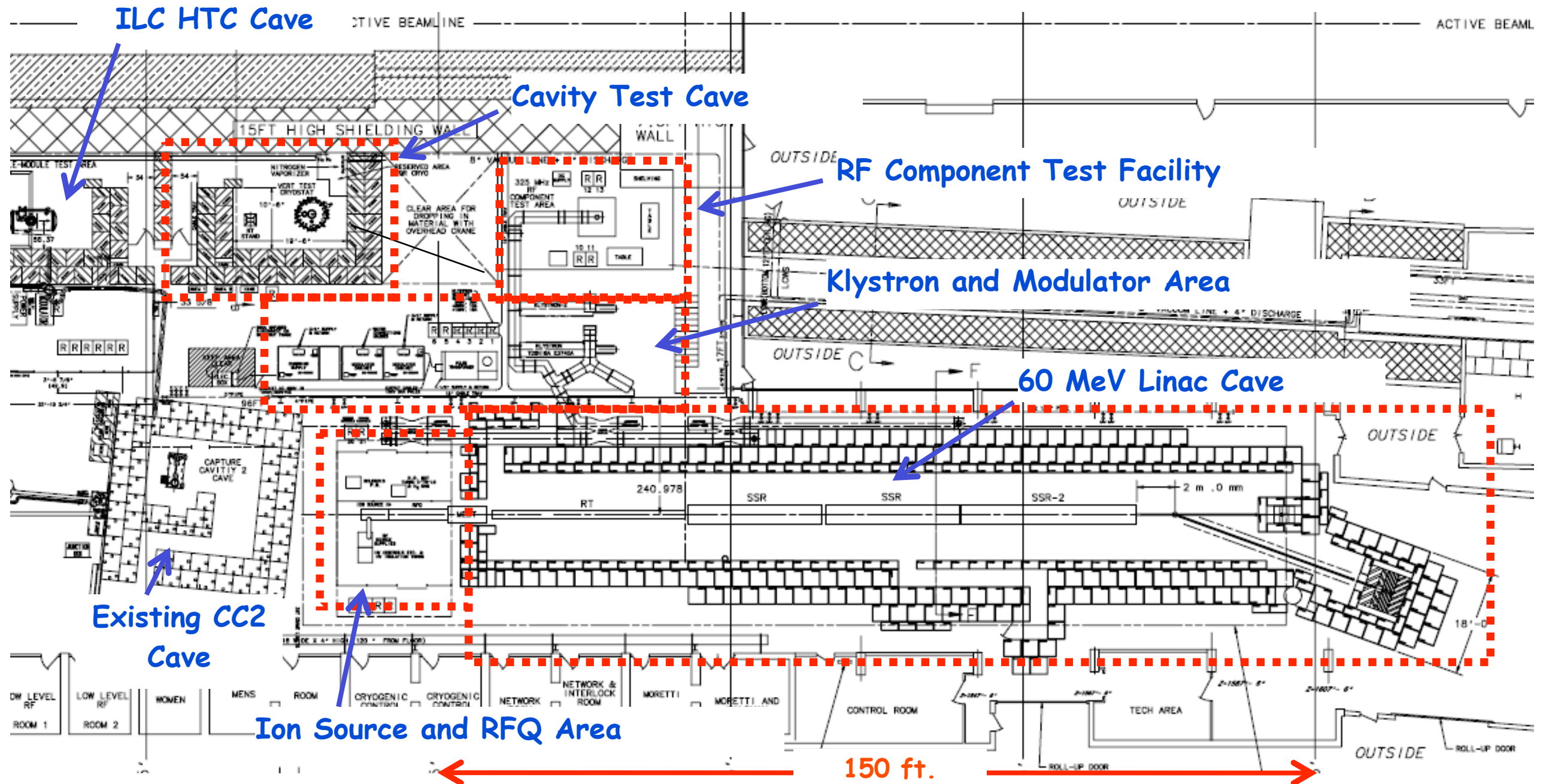
- builds off the HINS project:

- “to address accelerator physics and technology questions for a new concept, low-energy, high intensity, long pulse  $H^-$  superconducting linac”
  - Demonstrate beam acceleration using superconducting spoke type cavity structures starting at a beam energy of 10 MeV
  - Demonstrate the use of high power RF vector modulators to control multiple RF cavities driven by a single high power klystron for acceleration of a non-relativistic beam
  - Demonstrate beam halo and emittance growth control by the use of solenoid focussing optics up to 60 MeV
  - Demonstrate fast, 325 MHz bunch-by-bunch, beam chopper

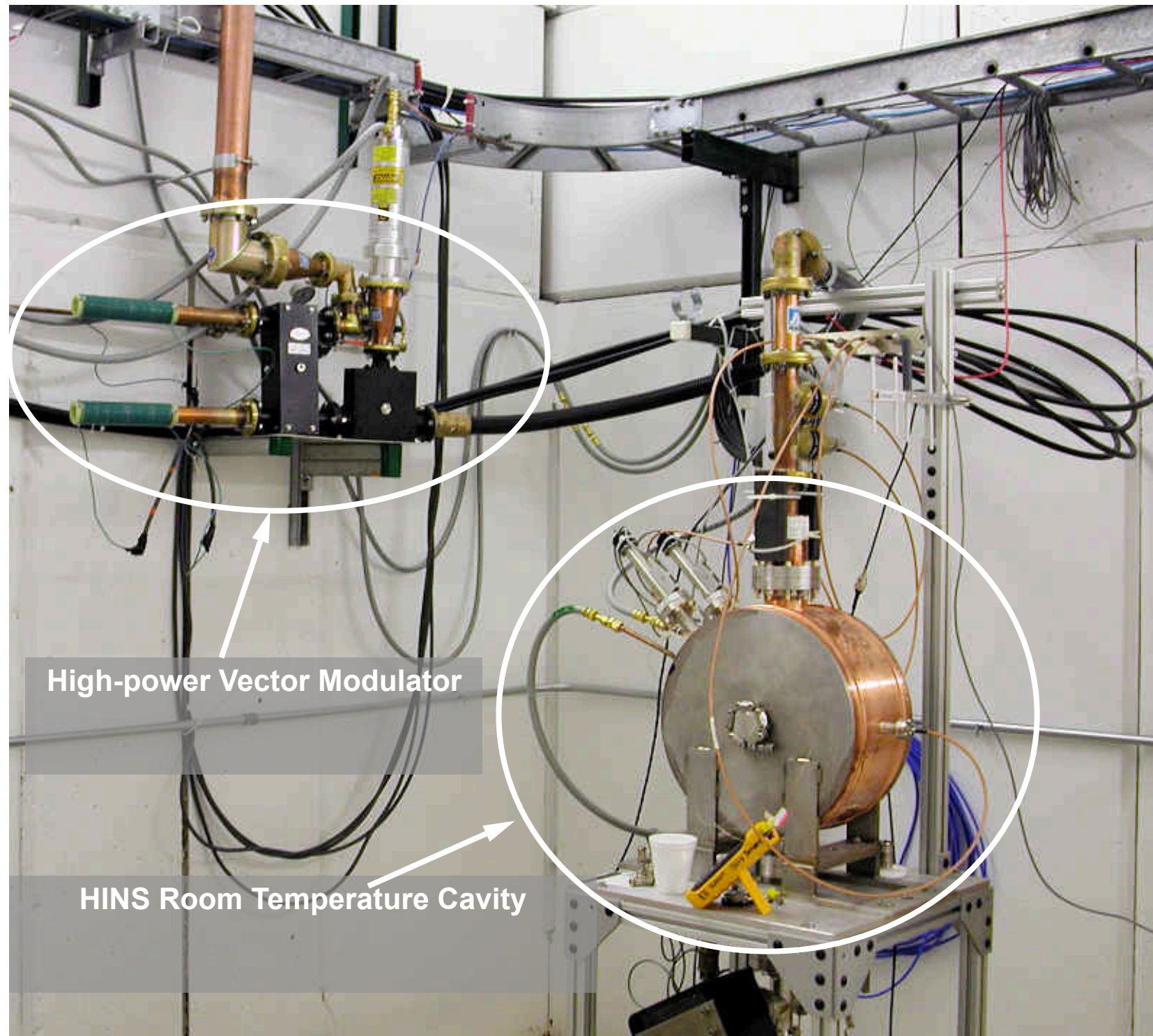




# HINS floor plan -- Meson Test Building



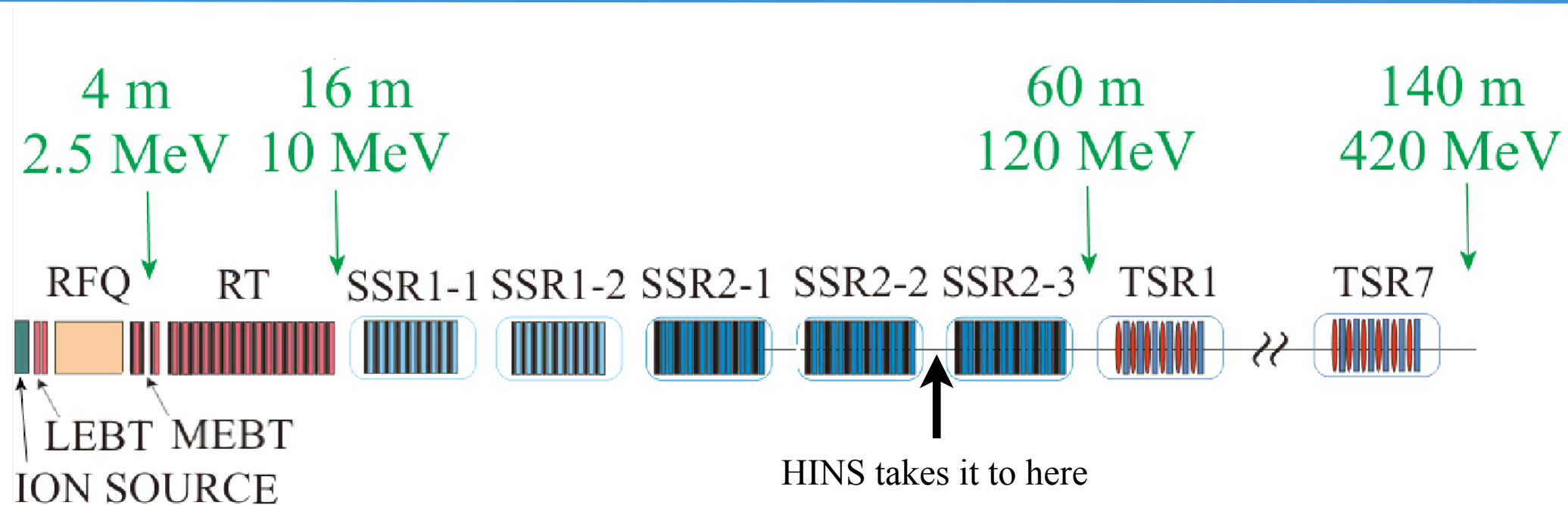
## HINS RT Cavity and Vector Modulator in Cavity Test Cave



# Beam Requirements

	Proton Driver Phase 1 Design	Proton Driver Phase 2 Design	HINS capability	Project X Base Design Nov 07	ICD Nov 08	
Particle	H-	H-	H+ then H-	H-	H-	
Nominal Bunch Frequency/ Spacing	325 3.1	325 3.1	325 3.1	325 3.1	325 3.1	MHz nsec
Particles per Pulse	15.6	15.6	37.5 *	5.6	15.6	E13
Pulse Length	3	1	3/1	1	1.25	msec
Average Pulse Current	8.3	25	~20	9	20	mA
Pulse Rep. Rate	2.5	10	2.5/10	5	5	Hz
Chopping -6% @ 89KHz and 33% @ 53MHz	37.5%	37.5%	0 - 37.5%	37.5%	37.5%	
Bunch Current	13.3	39.8	32	14.3	32	mA
Bunch Intensity	2.5 41	7.6 122	6.1 98	2.7 44	6.1 98	E8 pCoul





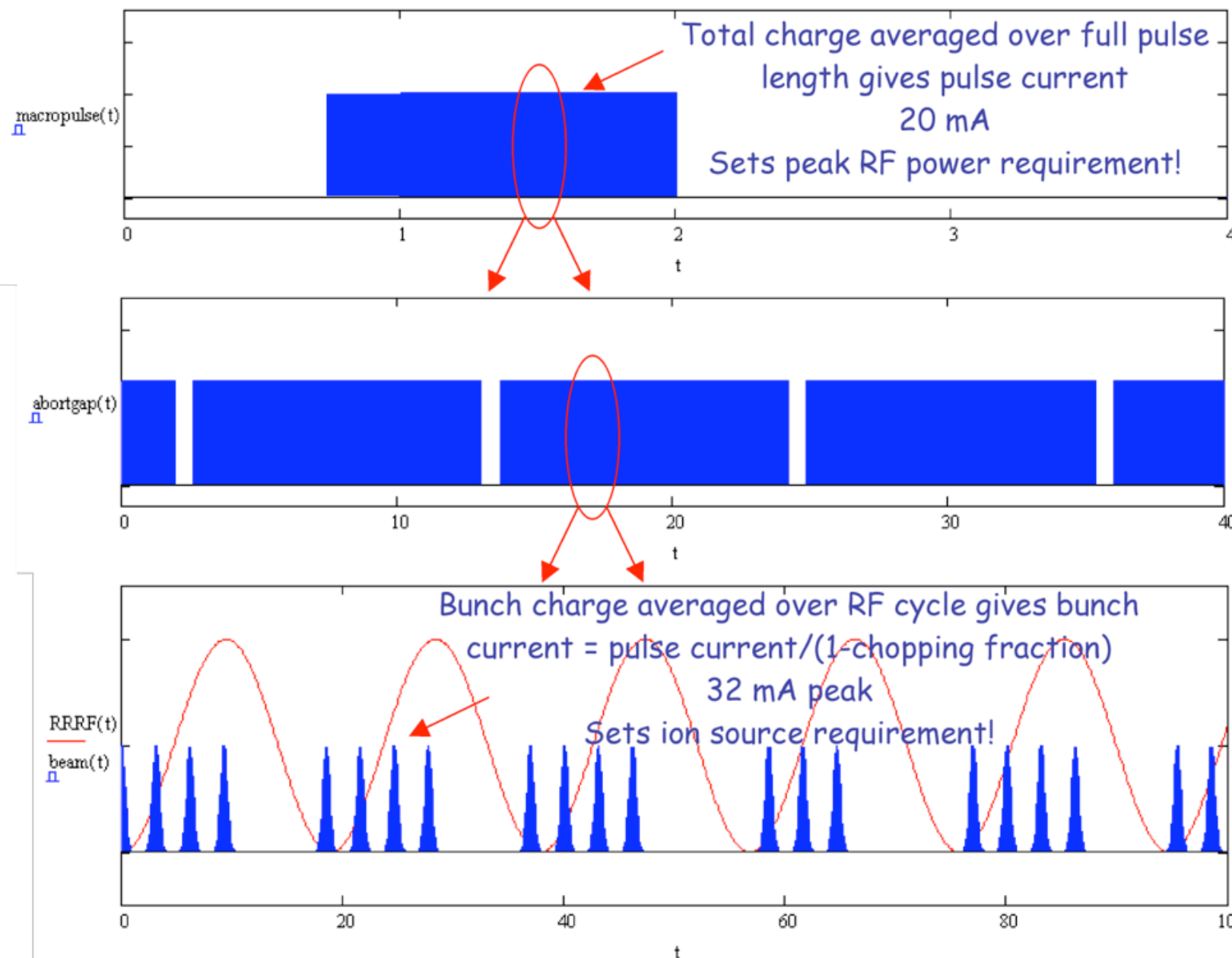
- 50 keV H<sup>-</sup> ion source
- 2.5 MeV RFQ
- Medium energy beam transport
  - 2 rebuncher RF cavities
  - 3 solenoids
  - beam chopper
- Room temperature cavities interspersed with SC solenoids to 10 MeV

- $\beta=0.22$  single-spoke resonator SC cavities to 30 MeV
- $\beta=0.4$  single-spoke resonator SC cavities to 120 MeV
- $\beta=0.6$  triple-spoke resonator SC cavities to 420 MeV
- Vector modulators throughout ... multiple cavities per klystron ... technical risk ...

## 325 MHz Linac Beam structure

### ■ Beam chopper has to match:

- 53 MHz structure for the Recycler/Main Injector
- 700 nsec gap every 11.1  $\mu$ sec for the Recycler / Main Injector kickers
- 75 nsec gap every 1.6  $\mu$ sec for the  $\mu$ 2e pulses (fast kickers)



1.25 msec Linac beam pulse  
4 msec full scale

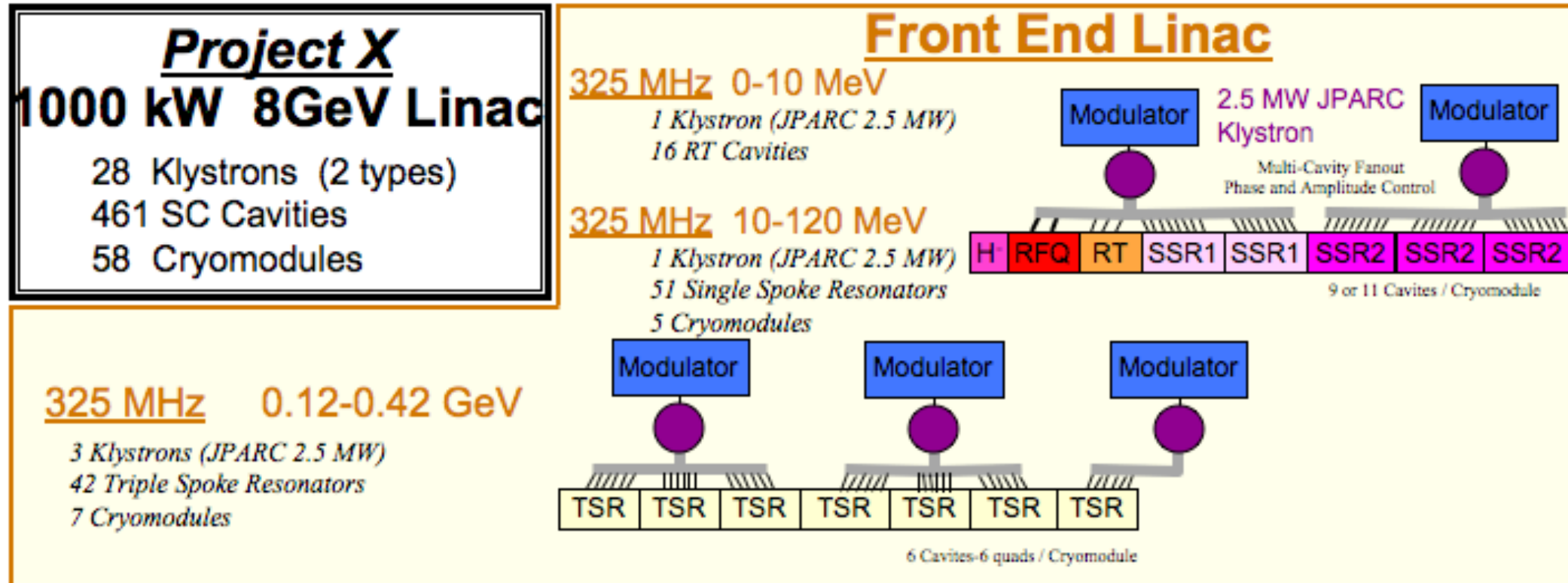
Linac beam chopped for  
700 nsec RR Abort Gap  
40  $\mu$ sec full scale

Linac 325 MHz beam  
chopped for RR RF  
multiple linac bunches per  
53 MHz RR RF cycle  
100 nsec full scale

- Use S-ILC for  $\beta=0.81$  section: 0.42 – 1.3 GeV
  - squeezed ILC cavity -- same frequency but shorter cavity length
  - needs to be developed for Project X
- Use ILC Type 4 Cryomodules as prototype for  $\beta=1$  section
  - use same cryomodule everywhere
  - 8 Cavities, 1 quad in all cryomodules:
    - CMs are interchangeable – 1 type of spare in  $\beta=1$  section
  - **25 MV/m**
  - 2 CM/klystron (instead of 3)
  - stand alone quads in regions where more focussing is needed (short cryo module without cavities)?
- Warm sections ~4 CMs (cryo junction boxes)
- Linac parameters:
  - RF: 25 MV/m, 1.5 ms pulse, 5 Hz
  - beam: 20 mA, 1.25 ms beam flat-top

- 10 MW multi beam klystron
  - 2 cryo modules per klystron
- Keep coupler power at 500 kW max.
  - Average power should be < 5 kW
- Longitudinal dynamics of the non-relativistic H- beam and possible cavities field variations over time (SNS experience) will require use of IQM modulators throughout the Linac.
  - Need of additional RF simulation/experience on cavities field uniformity to prove the ability to control the RF distribution through LLRF under beam-loading conditions in the in the HE part of the Linac.
- Bunch freq. is 325 MHz – lower voltage transient than ILC
  - Chopping at 52.8 MHz and kicker gaps (700 ns) every 11  $\mu$ s
  - Bunch – to – bunch charge variation is important

# Linac Layout



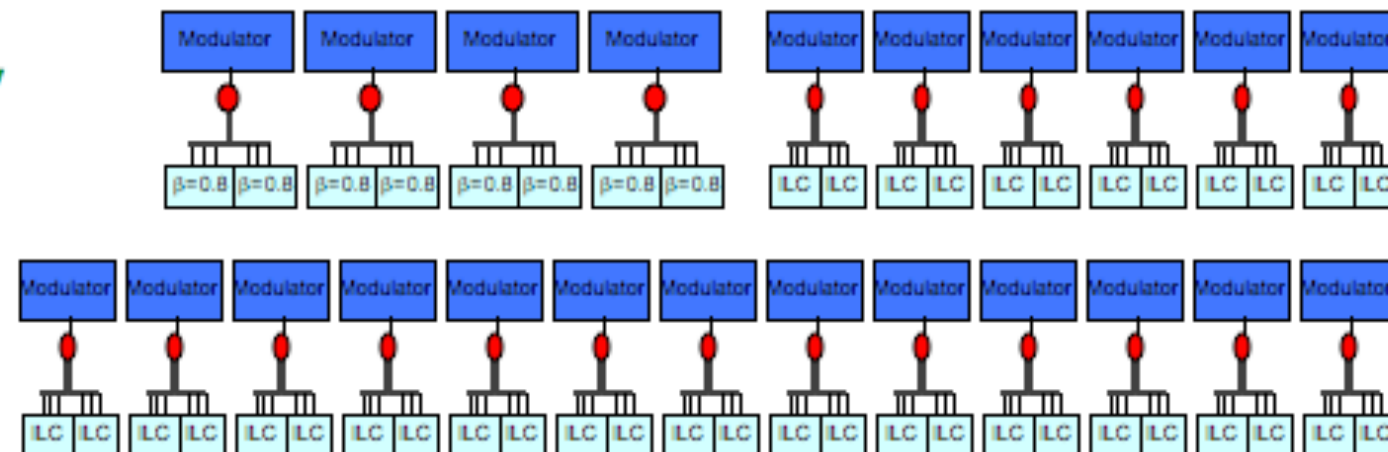
**1300 MHz 0.42-1.3 GeV**

*4 Klystrons (ILC 10 MW MBK)*  
*64 Squeezed Cavities ( $\beta=0.81$ )*  
*8 Cryomodules*

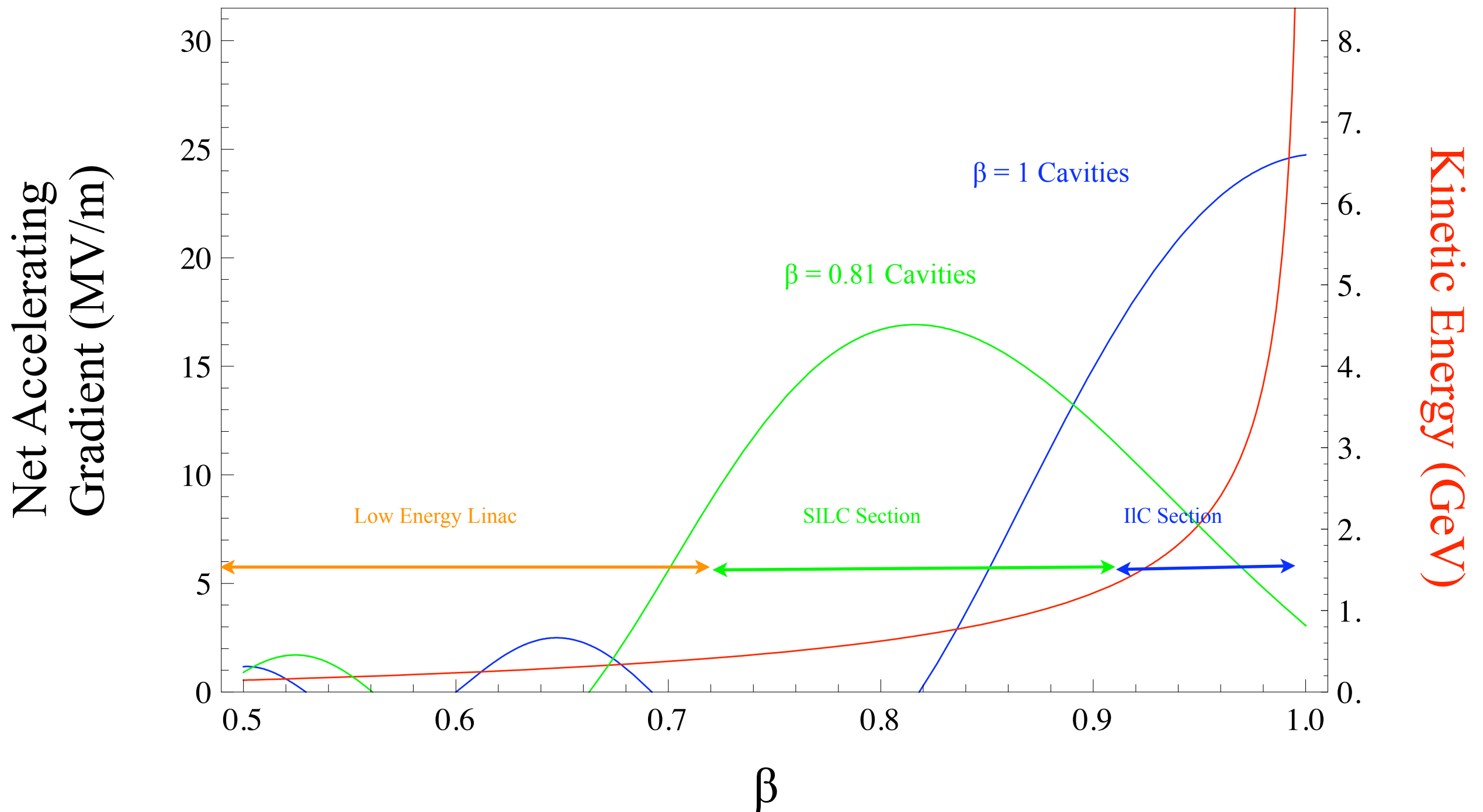
**1300 MHz 1.3-8.0 GeV**

*19 Klystrons (ILC 10 MW MBK)*  
*304 ILC-identical Cavities*  
*38 ILC-like Cryomodules*

## 1300 MHz LINAC



## Cavity response vs $\beta$



## Cavity and Klystron Counts

	Cavities	Cryomodules	Klystrons
SSR (2 types)	51	5	2 2.5 MW
TSR	42	7	3 2.5 MW
S-ILC	64	8	4 10 MW MultiBeam
ILC	304	38	19 10 MW MultiBeam
Total	461	58	28

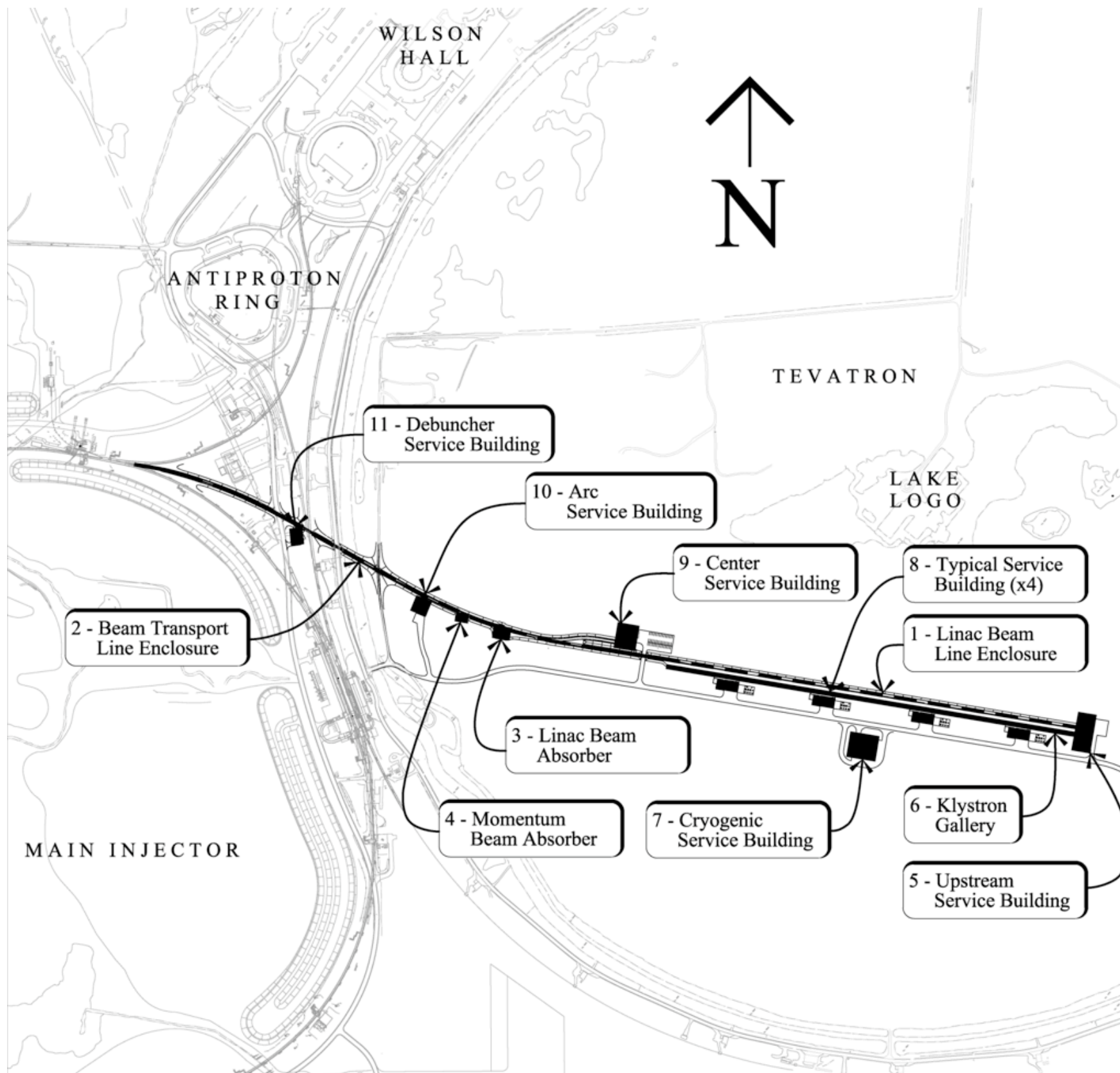


## Transfer line

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- from the output of the linac to the MI tunnel
  - ~1 km long
  - <500 G fields -- mitigate magnetic stripping of the H<sup>-</sup> electrons
  - liquid nitrogen cryogenic shield -- mitigate blackbody stripping of the H<sup>-</sup> electrons
- Acceptance matched to Recycler
  - 25  $\pi$  mm mr
  - $\pm 0.75\%$  momentum aperture
  - transverse collimation to capture large amplitude particles
  - momentum collimation to capture off momentum particles
  - passive phase rotator cavity to compensate for energy jitter
- Permanent magnets at 8 GeV (possible use of Main Ring or PEP-II HER magnets being investigated)
- losses less than <1 W/m  $\Rightarrow$  >99.9% transmission efficiency

# Site Layout



Paul Derwent Nov 2008 Collab Mtg

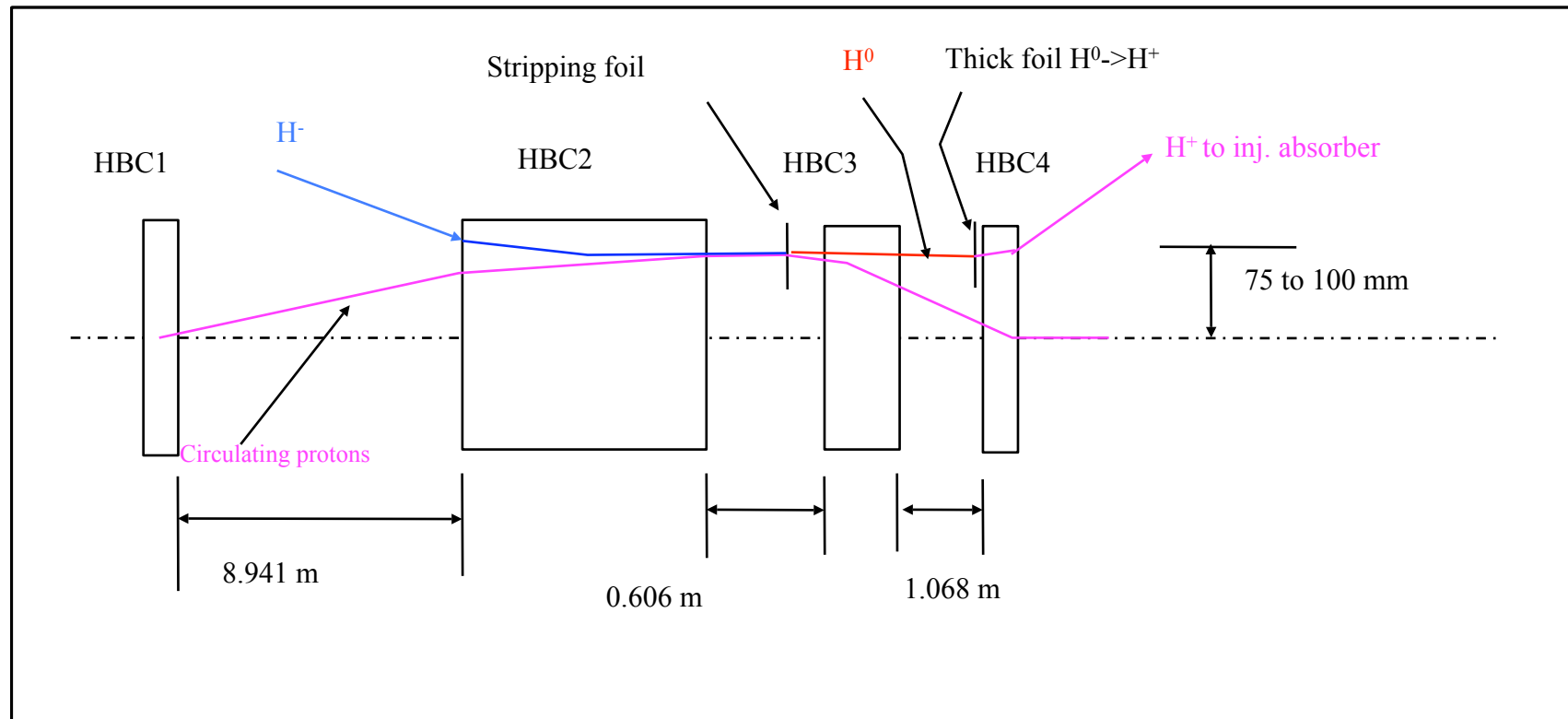
# Injection System

## ■ Multi turn Stripping System

- 1.25 msec = 110 turns in Recycler
- thin foil injection

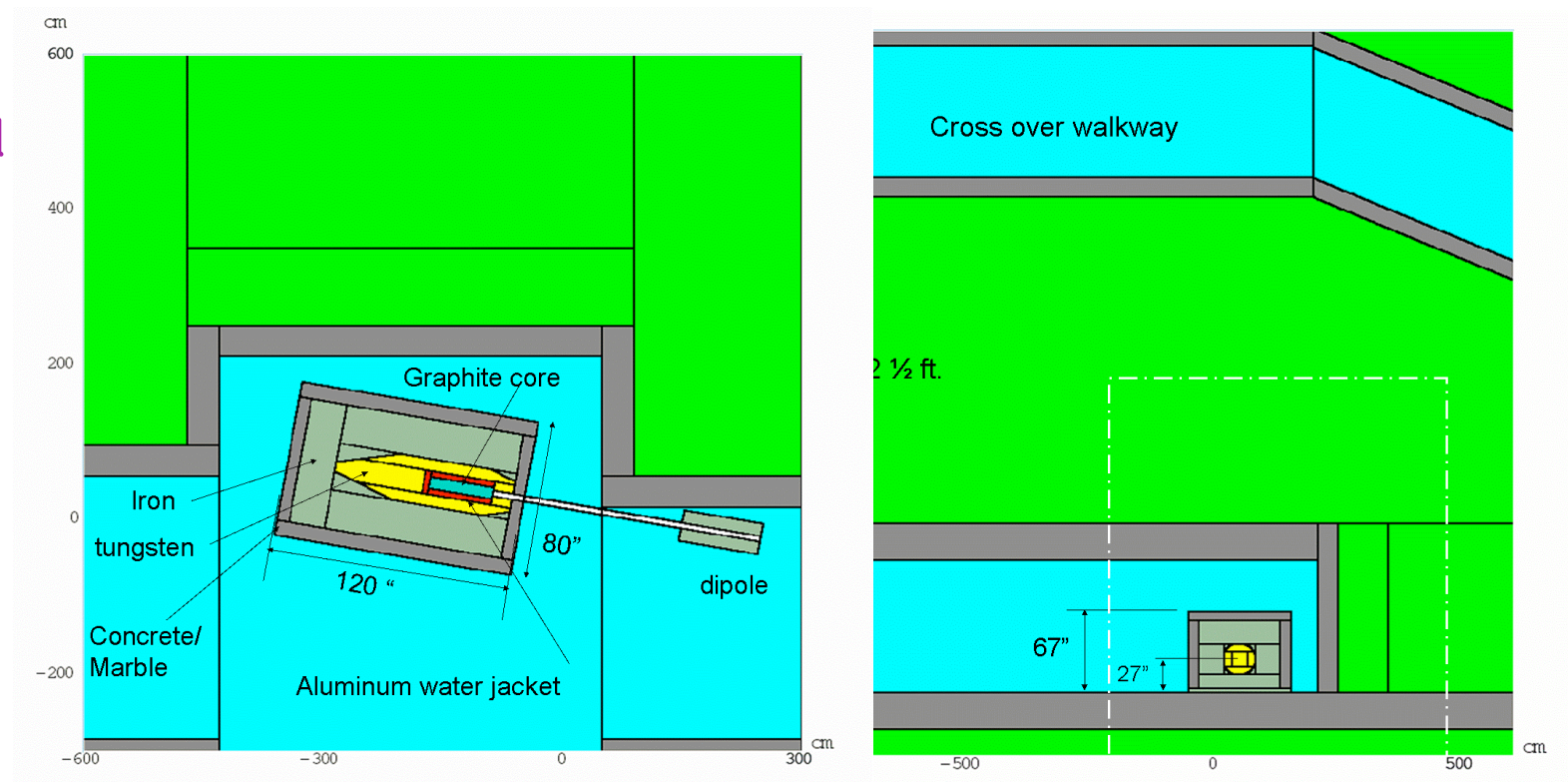
## ■ Transverse / Longitudinal painting ⇒ Kapchinsky - Vladimirsky distribution

- linear space charge force within beam radius
- RMS envelope radius =  $1/2$  beam radius
- minimize space charge tune shift in the Recycler and Main Injector



# Injection System

- elevation throughout matched to Main Injector elevation
  - adequate shielding
  - interferences with existing enclosures (TeV and AP1)
  - makes the line longer  $\Rightarrow$  vertical bend to reach Recycler elevation
- Beam absorber to catch  $H^-$  and  $H^0$ 
  - 2% stripping inefficiency  $\Rightarrow$  20 kW
  - design for 100kW
  - designed around MI tunnel



- Modified for NOvA by this time
  - proton ring with single turn transfer to MI
- Modifications to lattice for injection system
  - remove injection from MI 8 line!
- Add flexibility to lattice to handle tune shift, operating point, etc.
  - expect  $1.6e14$  with KV distribution to give  $\sim 0.05$  tune shift
- 53 MHz RF to capture injected beam
  - with 2nd harmonic RF ( $w/ V = 1/2 V_0$ )
  - make identical to MI system
- Fast extraction (1.6  $\mu$ sec length) for  $\mu 2e$ 
  - move NOvA injection kicker and supplies
- Electron cloud mitigation
  - coat the beam pipe?

- Single turn injection from Recycler
- ~3x intensity of NOvA era
- Upgrade RF system:
  - need more bucket area for acceleration
  - second harmonic RF also needed
  - 53 MHz design exists, 2nd harmonic does not
    - Very conservative design uses a lot of power to guarantee stability. Is this design optimal?
- Electron Cloud mitigation
  - TiN coating to decrease secondary emission yield
- First order matched  $\gamma_T$  jump (W. Chou et al. , PAC 1997)
  - 8 pulsed quad triplets
  - 2 units in 0.5 msec (16x faster than normal ramp)

## Cavity Characteristics

Q 4000  
R<sub>sh</sub> 100 k $\Omega$   
R/Q 25  $\Omega$   
f<sub>0</sub> 52.9577 MHz  
Range  $\pm 150$  kHz  
Material Cu coated stainless  
Voltage 300 kV

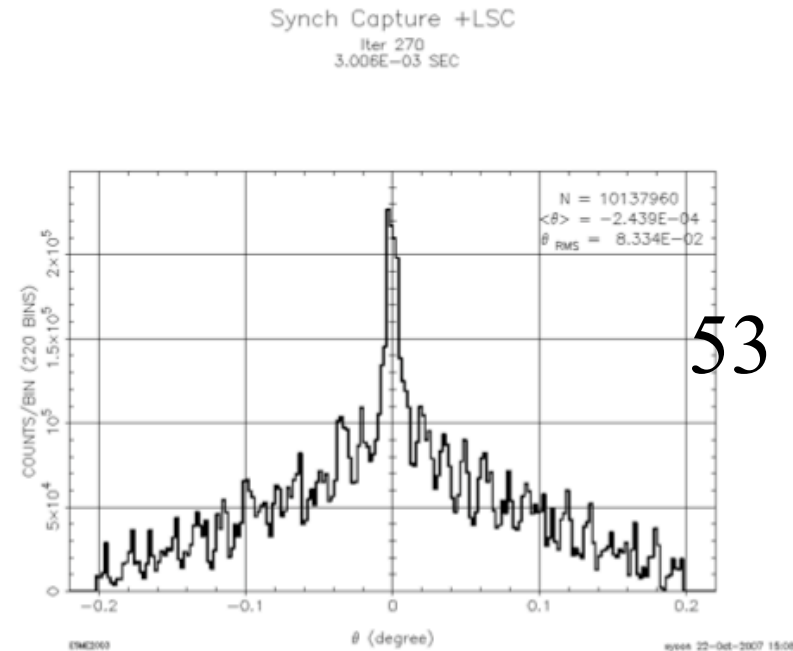
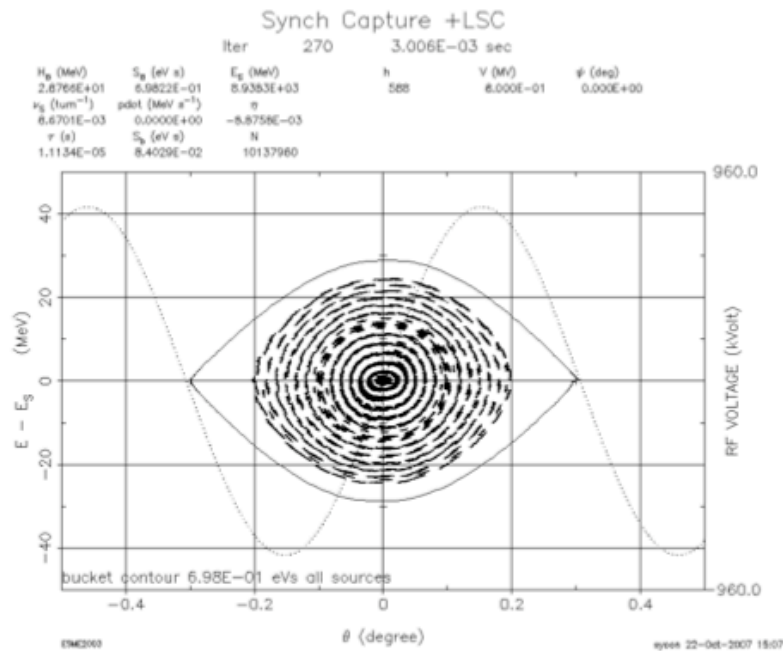
Proton Driver design, Mar 2005



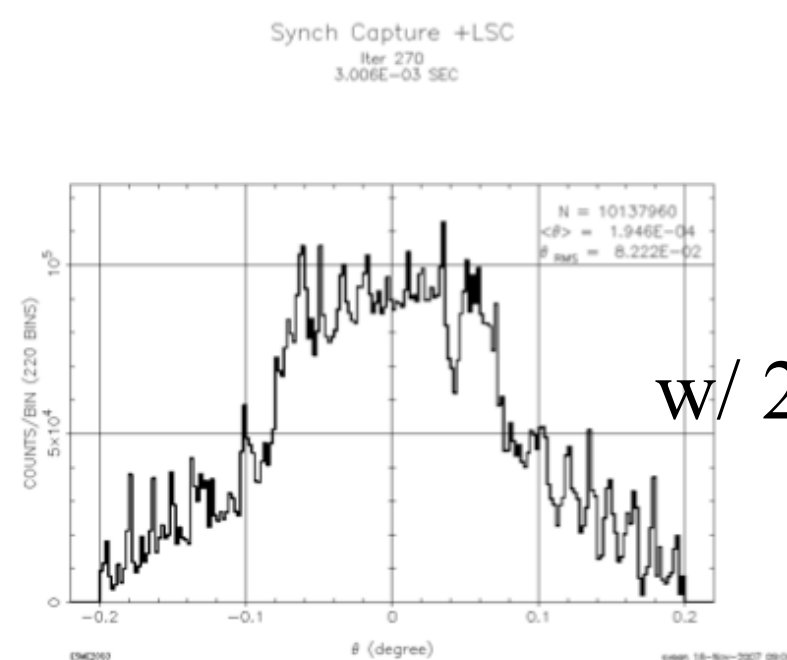
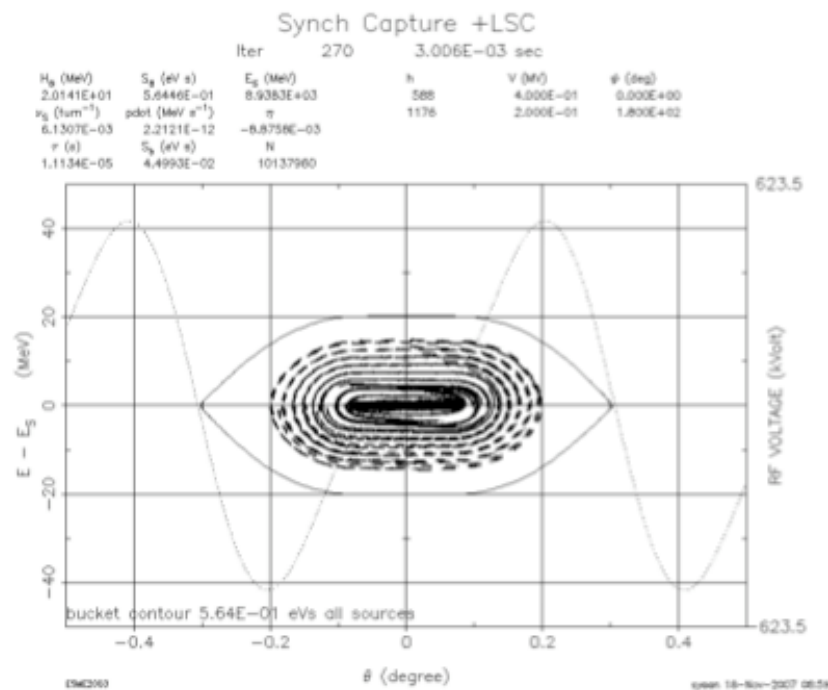
# RF Simulations

## ■ Phase mismatch between 325 MHz spacing from linac and 52.8 MHz in RR

➤ useful for longitudinal painting to reduce space charge tune shift



53 MHz only



w/ 2nd harmonic

(a) at the 270-th turn

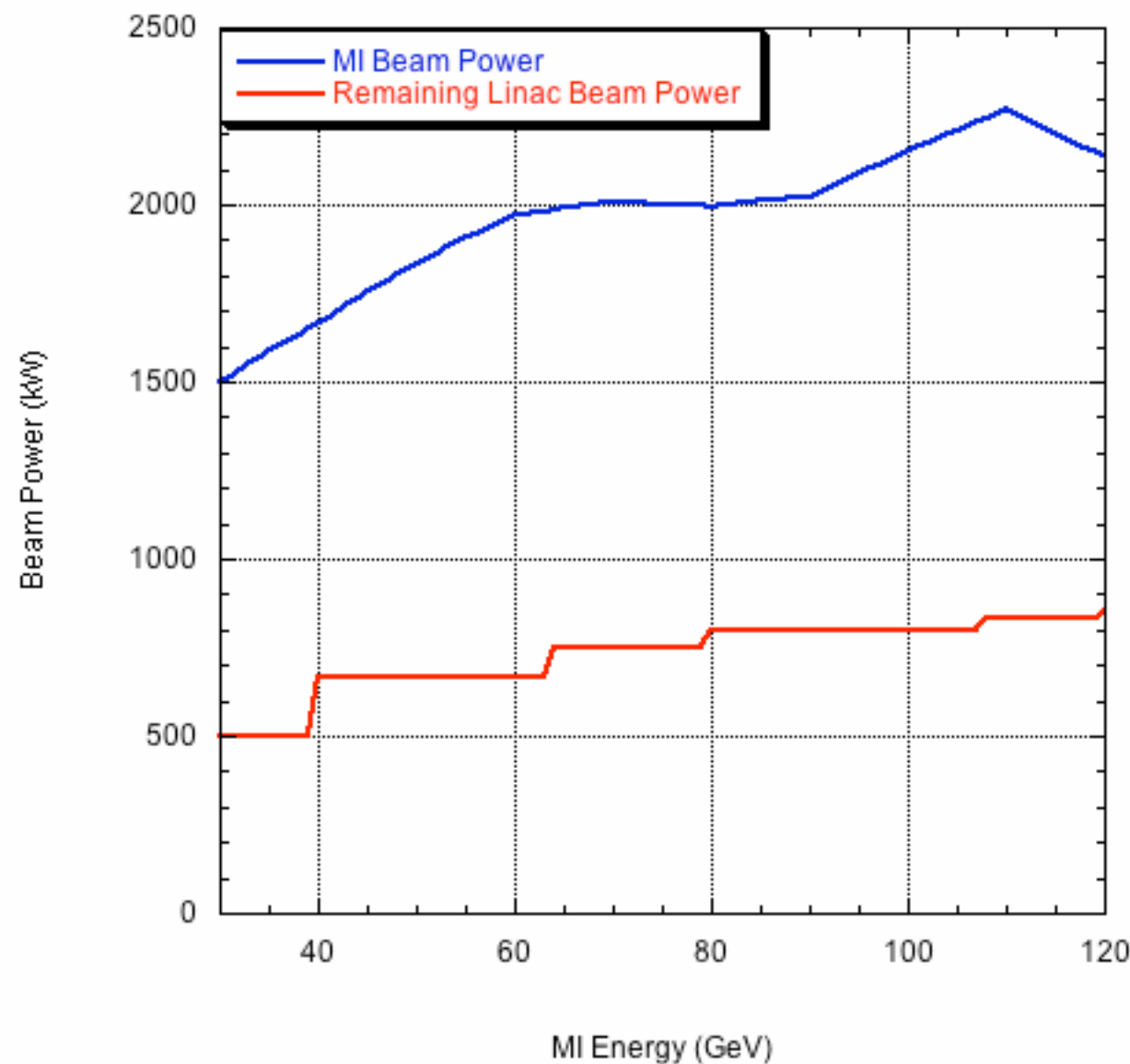
(a) at the 270-th turn

P.S. Yoon, D.E. Johnson, W. Chou  
Fermilab-TM-2398



## Main Injector Beam Power

- Optimum Energy for long baseline neutrino program?
  - deliver > 2 MW for extracted beam energies > 60 GeV (1.8 MW at 50 GeV)
    - varying the MI cycle time
    - holding beam in Recycler to match 5 Hz from linac with varying MI cycle time
  - deliver > 500 kW for 8 GeV beam



# Cryogenics

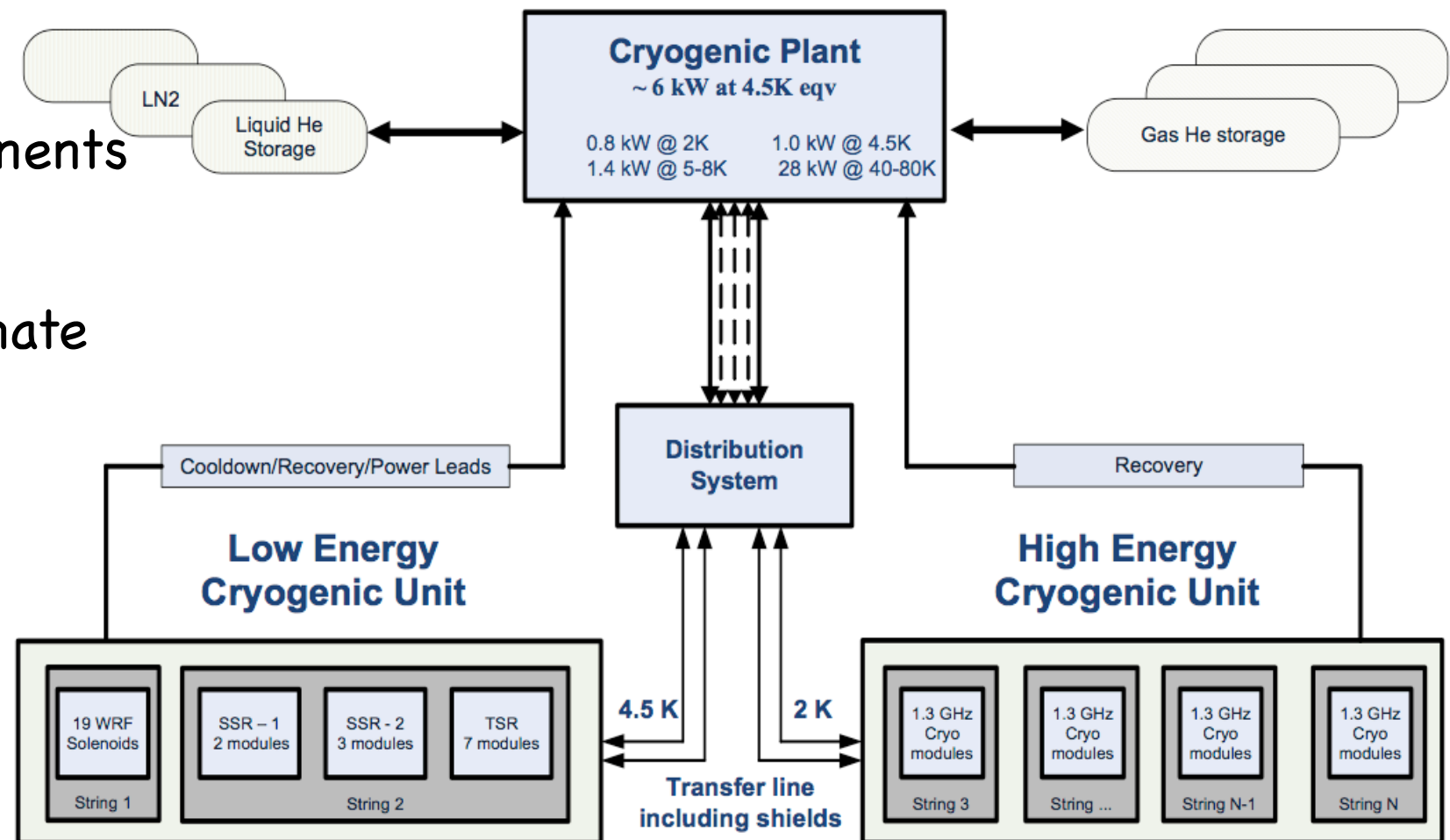
## ■ New Cryo plant

- 325 MHz linac: two phase liquid helium at 4.5 K
  - Static heat load (conduction/radiation) dominates dynamic heat load (RF power dissipation)
- 1.3 GHz linac: saturated He II at 2 K
  - Static and dynamic heat loads of same order
- Multiple strings in each unit

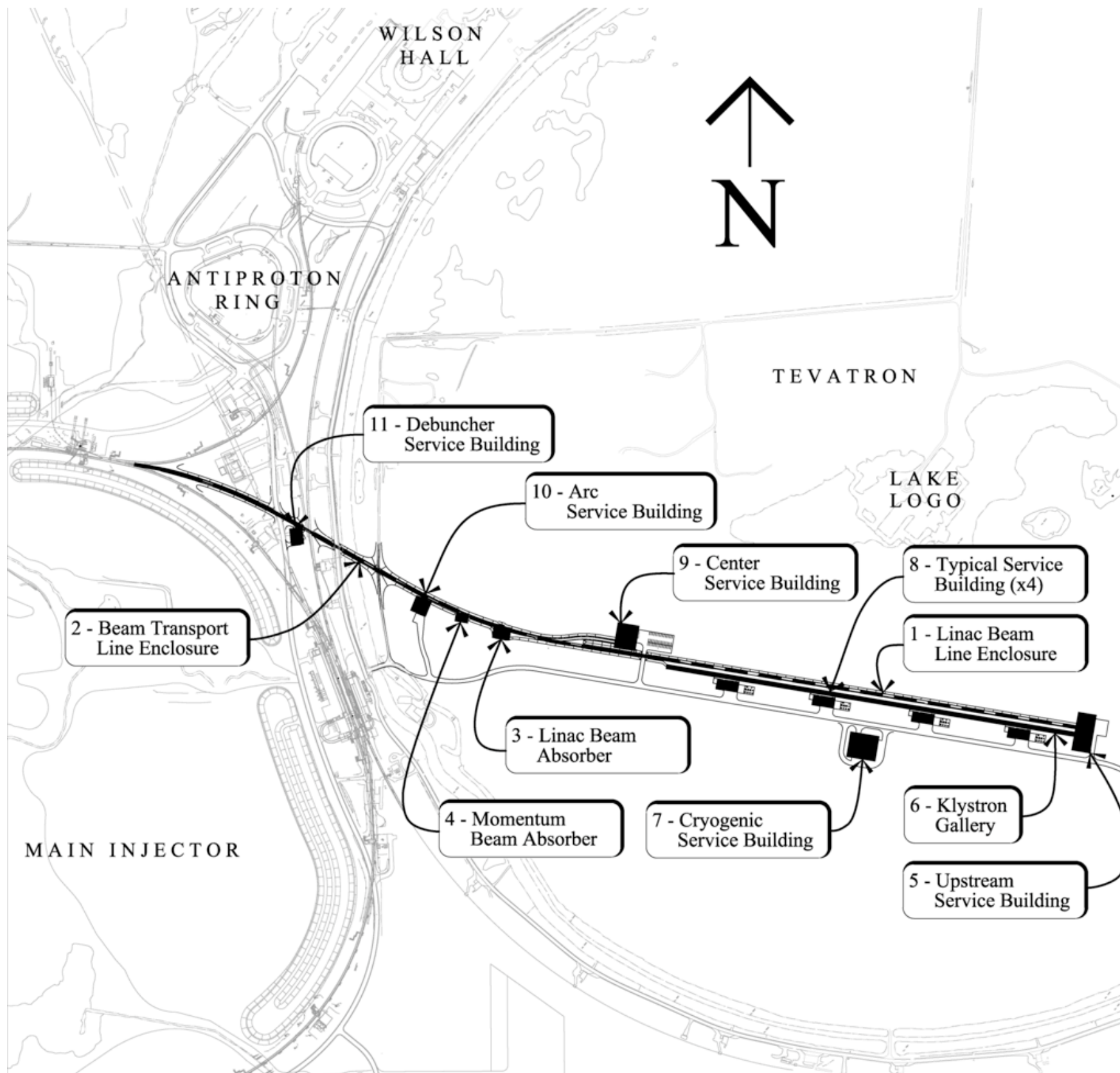
## ■ Re use Tev ancillary components

## ■ Preliminary heat load estimate

- 30% uncertainty
- 50% safety factor
- 6 kW at 4.5 K equivalent



## Site Layout - Conventional Facilities



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# Conventional Facilities

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## ■ 4 below grade construction:

- Linac enclosure
- Transfer line enclosure
- Linac dump
- Momentum dump (injection dump is in MI tunnel)
- Cut and cover
- single tunnel for beamline

## ■ 7 above grade construction:

- Upstream service building (ion source)
- Klystron gallery
- Cryo service building (plant)
- 4 additional service buildings

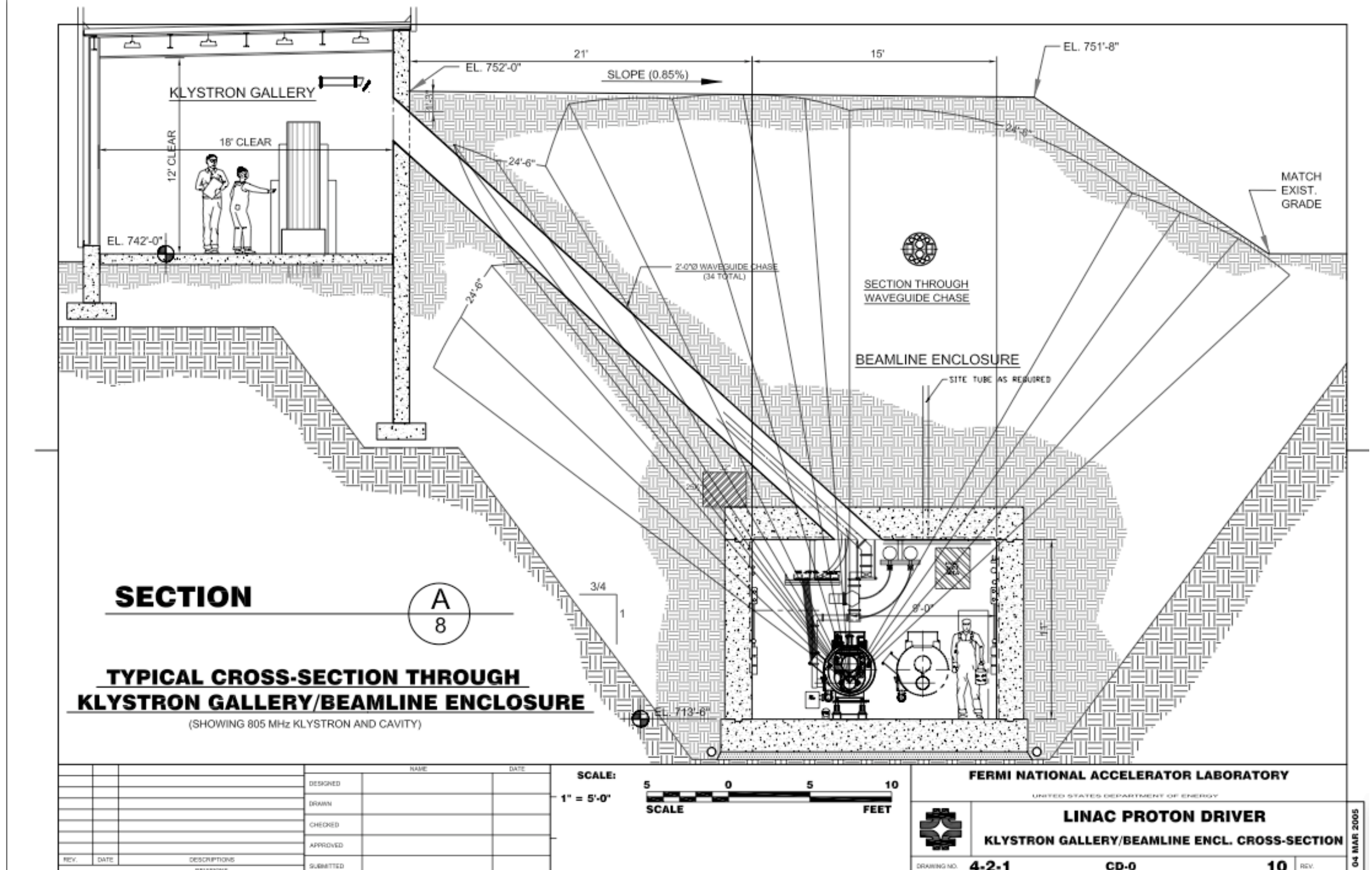
## ■ Site Prep:

- Drainage
- Roads
- Landscaping
- Wetlands mitigation (60 acres)
  - 3:1 for creation (\$50k/acre)
  - buy credits offsite?
- Space Replacement
  - 150000 square feet

## ■ Utilities

- Power
- Communications
- Water

# Cross Section of Linac Tunnel



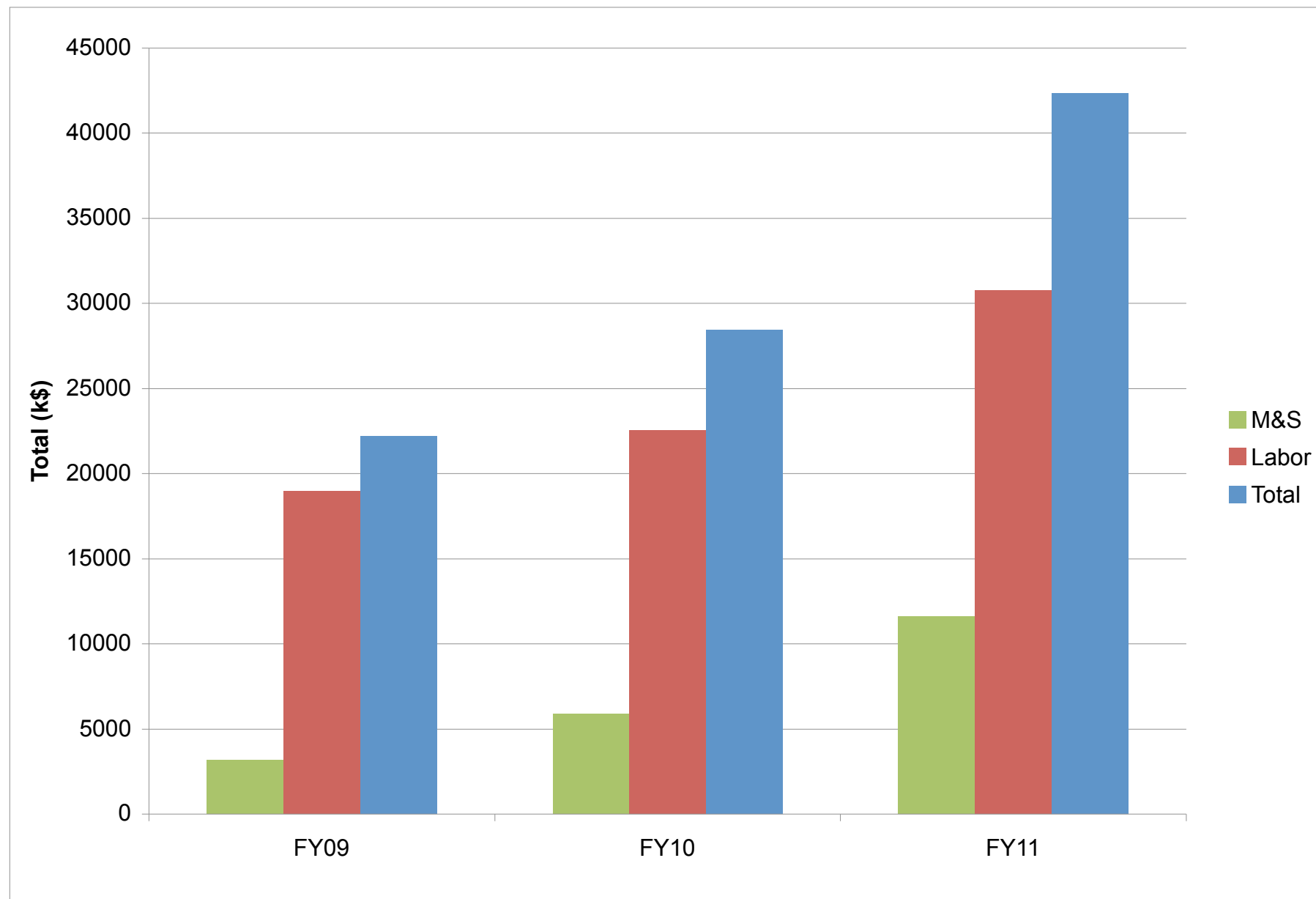
Paul Derwent Nov 2008 Collab Mtg



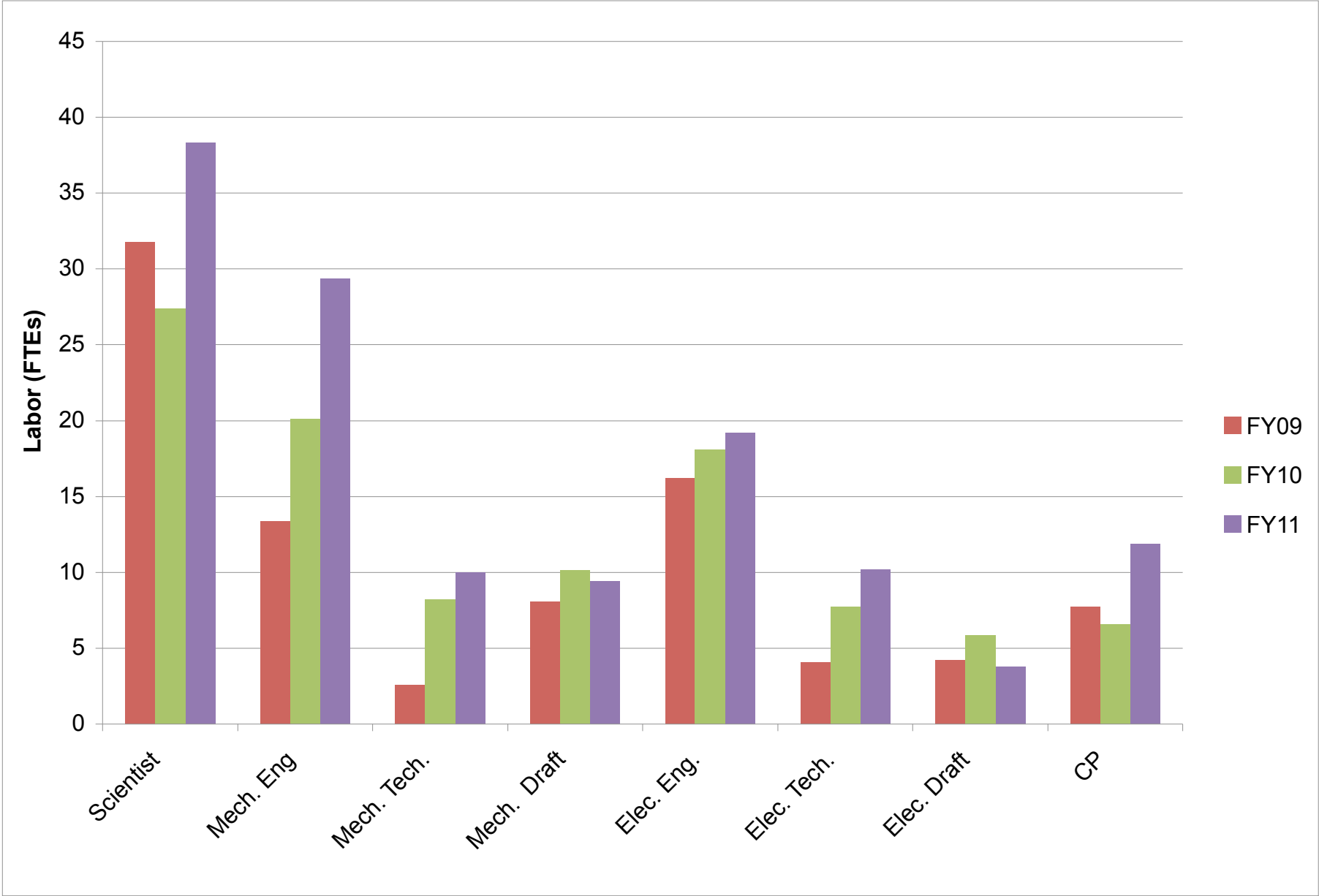
- Beam loss monitoring
- Beam Position monitoring
- Machine protection system
- develop new instrumentation
  - especially in SCRF sections
- Time Stamping
- 1 M devices and properties
- Machine protection system
- Evolving System
  - through NOvA era
  - support of HINS and NML efforts
  - Mix of EPICS and ACNET

- From CD-0 (“Approve Mission Need”) to CD-2 (“Approve Performance Baseline”)
- Jan 08 plan for Steering Group Configuration
  - 4 year plan starting in Spring 2008
  - most still valid!
  - Changes:
    - need to integrate HINS project into plan
    - need to integrate Cryo into plan
    - remove neutrino beamline and target hall (separate project)
- Schedule has gotten tighter: starting in Spring 2009
- Scale is \$100M, 100 FTE/year

## Cost vs Fiscal Year



# Labor Type vs Fiscal Year



## Summary

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- Developed an Initial Configuration Document to provide
  - >2 MW at 120 GeV
  - additional 8 GeV beam for other experiments
  - upgrade path to higher beam power
    - double the repetition rate (5 Hz  $\Rightarrow$  10 Hz)
    - double the pulse length (1.25 msec  $\Rightarrow$  2.5 msec)
    - conventional facilities, cryo plant, and utilities designed to accomodate these upgrades
  - 325 MHz and 1300 MHz superconducting rf linac
  - multi-turn injection to Recycler
  - Single turn transfer to Main Injector
  
- CD-0 Spring 2009  $\Rightarrow$  CD-1 Fall 2010  $\Rightarrow$  CD-2 Winter 2012