Initial Baseline Selection Process

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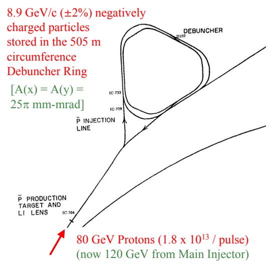
Historical context: After ~30 years we are on the verge of having initial designs of all key accelerator systems for muon-based neutrino factories and colliders @ Fermilab



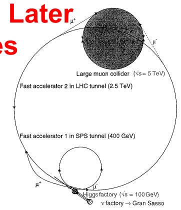
1980: A muon storage ring for neutrino oscillation experiments (Cline & Neuffer)

1986 (Madison WI): AAC Symposium: Multi-TeV Muon Colliders (Neuffer)

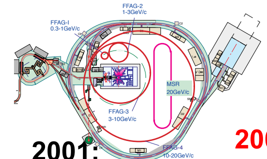
1991 (Napa,CA): First workshop on muon colliders

Snowmass'96

1997: Muon Collider Collab formed. Later becomes NFMCC

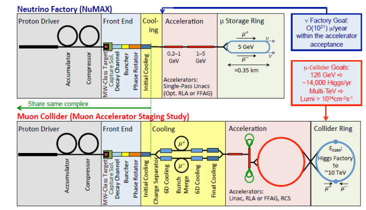


CERN studies 1999



2001: Japanese NuFac Design Study 1

2006: MCTF @ FNAL



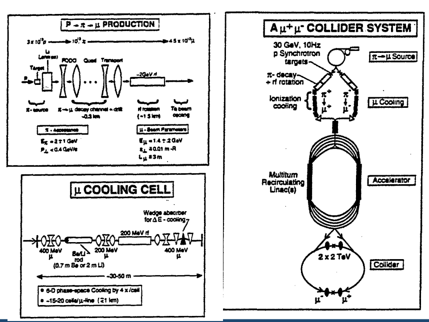
2011 IDS-NF Interim Design Report

1980 — **1990** — **2000** — **2010** — MAP IBS

1979: Colliding muon beams at 90 GeV (Neuffer)

1982: Skrinsky & Parkhomchuk: Ionization cooling

1994 (Sausalito,CA): 2nd workshop on muon colliders: A Practical HE-HL mu-mu collider (Palmer/Neuffer/Gallardo)



1997: Workshop on physics at 1st muon collider and FE of a muon collider

2001: US NuFac Design Study 1

Snowmass 2001: The Program in Muon and Neutrino Physics: Super Beams, Cold Muon Beams, Neutrino Factory and the Muon Collider

2002: US NuFac Design Study 2

2005-2006: ISS

2007: IDS-NF initiated

2011: US muon R&D consolidated into a single entity, MAP

Snowmass 2013: Enabling Intensity & Energy Frontier Science w/ a Muon Acc. Facility in the U.S.

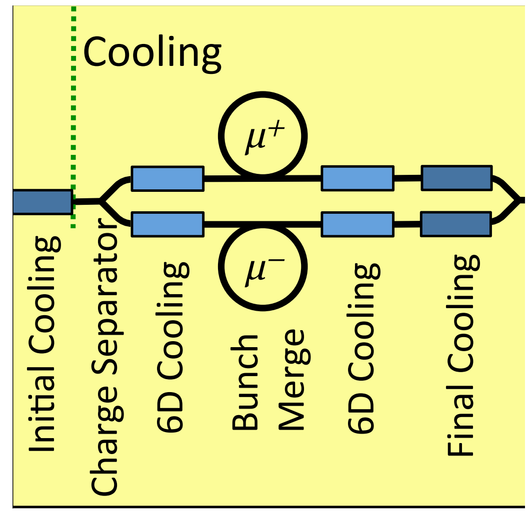
end of FY16

Initial Baseline Selection (IBS) Overview

- A site-specific set of designs for staged facilities at Fermilab
  – NuSTORM, NUMAX, Higgs Factory, Multi-TeV colliders
- To be completed by end of FY16
- Designs based on available knowledge *at the time*
  – Choose our initial baselines, then study in more detail and optimize in MAP FP-II
- Designs have evolved due to opportunities identified by MASS
  – better staging, reduced cost

IBS Overview, cont.

- D&S WBS contains 7 *Areas Systems*:
  - 2.1 Proton Driver; 2.2 Front End; 2.3 Cooling; 2.4 Acceleration; 2.5 Collider Rings; 2.6 Collider MDI; 2.7 Decay Rings
- IBS process includes a schedule and resources for
  - Concept specification
  - Lattice files & performance evaluation
  - Lattice file sign-off
  - Global optimization (where appropriate)
  - Interface parameters
  - Technology specification
  - Technology sign-off
  - IBS review (+ initial review in some cases)



- IBS Timeline: Cooling

2	3		Cooling (NF and MC)	Concept Specification	Lattice/Layout & Performace Eval	Lattice Sign-off		Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications
			Initial Cooling (NuMAX+ Cooling Schem	4/1/14	7/3/14	8/1/14		8/29/14	12/30/14	1/30/15	4/24/15			
			Charge Separation	10/1/14	1/2/15	2/2/15		3/2/15	7/1/15	7/30/15	10/23/15			
			6D Cooling	10/1/13	1/2/14	1/31/14		2/28/14	9/3/14	10/1/14	2/27/15	**3/27/15**	**3/28/16**	**4/25/16**
			Bunch Merge	10/1/14	1/2/15	2/2/15		3/2/15	7/1/15	7/30/15	10/23/15			
			Final Cooling	1/2/15	4/3/15	5/1/15		6/1/15	10/1/15	10/29/15	2/1/16			
			Cool-Accel Interface Parameters	*1/2/15*				*6/1/15*						***4/25/16***

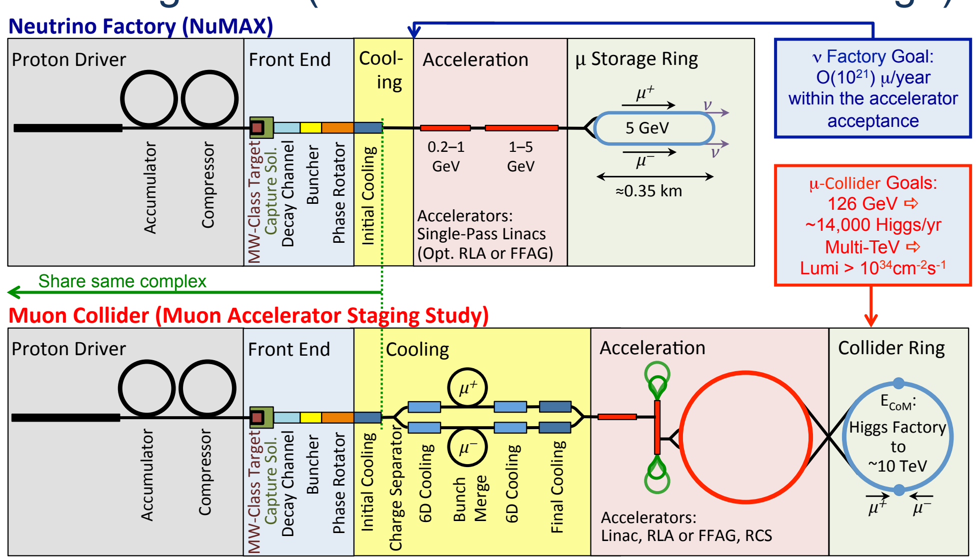
IBS Status

- IBS schedule and organization have been finalized for all 7 Area Systems
- Aligned with MAP master plan
- Marks a significant change in thrust
  - transition from "let's explore these concepts" to "based on what we have learned, let's produce the best credible designs we can at this time"
- Change in thrust evident in Cooling D&S
  - 6D cooling approaches narrowed down to 2
  - Criteria developed for 6D selection process
  - First start-to-end 6D channel designs delivered in Jan 2013

More about this in the Cooling session Thursday AM

Design Status

- Staging concepts: NuSTORM➔NuMAX➔Higgs➔multi-TeV colliders
- Maturing concepts for
  - proton driver, front end, cooling channel, fast acceleration, decay & collider rings
  - protection of components & IR from backgrounds
  - discrimination of background within collider detector
- Moving forward, MASS has identified the opportunity for better staging and lower cost if we can accelerate muons w/ single-pass linacs to 5 GeV
  - includes a dual use linac: 3-6.75 GeV protons, 1.25-5 GeV μ
  - requires Initial Cooling in 6D (instead of 4D as for FY13 design)



MAP Computational Tools

- Cooling channel design
  - G4Beamline
  - ICOOL
  - Warp
- Energy depostion
  - MARS
- RF simulation
  - ACE3P
- Beam Dynamics:
  - G4Beamline, Warp, MAD-X/PTC, Optim,...

- Other codes:
  - Scripts for parameter scans
  - Codes for parallel design optimization
- High performance computing is having a big impact on MAP D&S
  - million-particle runs in minutes
  - Huge performance gains: 35000x in G4Beamline example

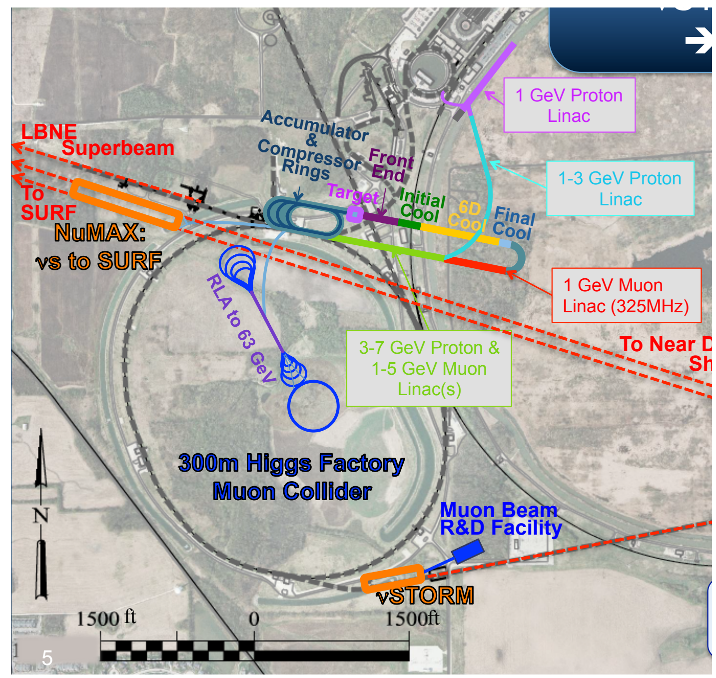
MAP D&S Organization

- D&S WBS contains 7 Areas Systems:
  - 2.1 Proton Driver
  - 2.2 Front End
  - 2.3 Cooling
  - 2.4 Acceleration
  - 2.5 Collider Rings
  - 2.6 Collider Machine-Detector Interface (MDI)
  - 2.7 Decay Rings

Proton Driver (PD)

- Evolution from Project-X to PIP-II, and opportunities identified by MASS, have helped guide PD plans:
  - Early emphasis was 4 MW @ 8 GeV for muon collider
  - FY13 focused on quicker path to initial PD via 1 MW @ 3 GeV
  - Moving forward, preferred initial option is 1 MW @ 6.75 GeV
    - includes dual-use linac ➔ less expensive route to NuMAX

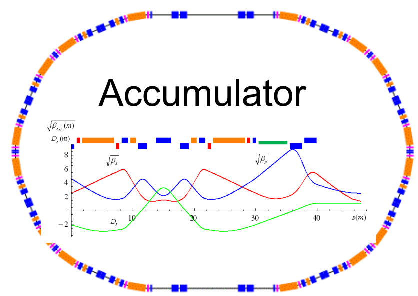
- Recent accomplishments:
  - PD concept specification
  - Interfaced w/ MASS on dual-use linac to produce 6.75 GeV H- beam
  - Developed a work plan for executing the IBS process

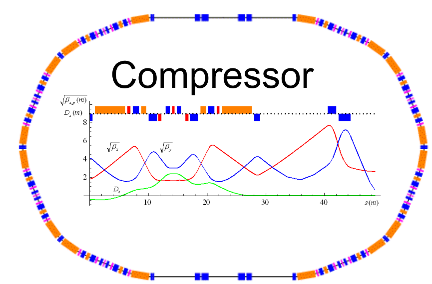


Proton Driver, cont.

- MAP PD builds on PIP-II foundation
  - PD D&S team works with PIP team to assure upgrade path
    - linacs to reach higher energy ➔ more power on target
    - accumulator & compressor rings ➔ modify beam structure

      4 MW @ 8 GeV will be revisited for initial 1 MW @ 6.75 GeV
    - Target focus system





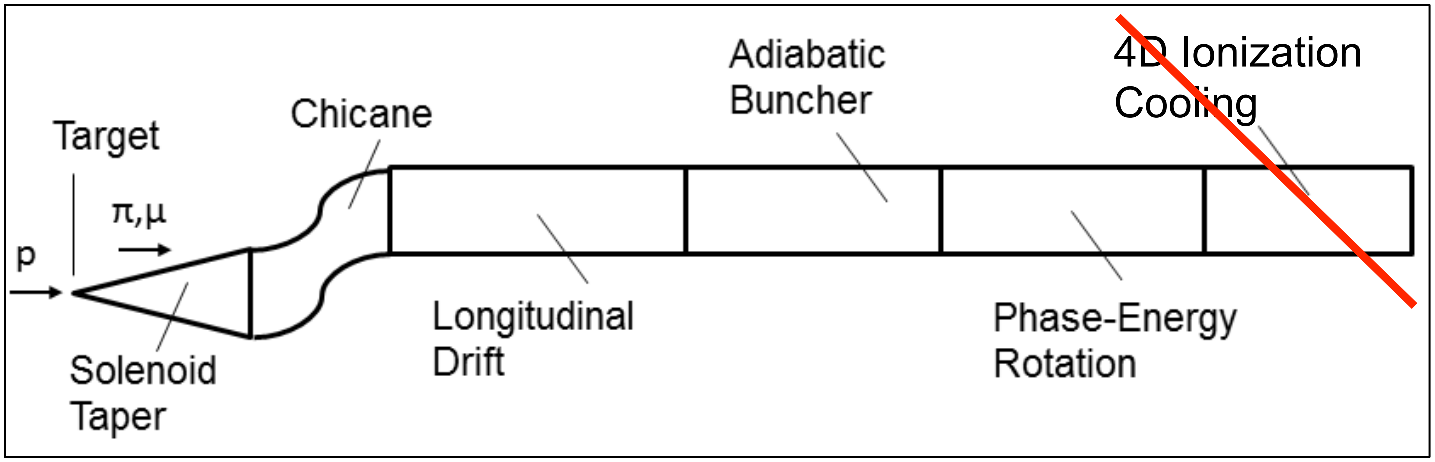
- FY14 IBS milestones:
  - Linac concept spec
  - Accumulator/Compressor concept spec & lattice files
  - Target focus concept spec

2	1		Proton Driver	Concept Specification	Lattice/Layout & Performace Eval	Lattice Sign-off		Interface Parameter Sign-off	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications
			Linac Specification (PIP-MAP Joint TF)	1/7/14				4/2/14						
			Accumulator & Compressor Rings	3/5/14	6/9/14	7/8/14		8/5/14	11/26/14	12/30/14	3/27/15		8/7/15	9/4/15
			Target Focus System	6/26/14	10/20/14	11/17/14		12/17/14	3/18/15	4/15/15	7/10/15			
			PD-FE Interface Parameters	*6/26/14*				*12/17/14*						*9/4/15*

Front End (FE)

FE key subsystems:

– Target, capture solenoid, chicane, decay channel, buncher/phase rotator



Significant progress in FY13:

– IDS-NF FE lattice completed and provided for RDR

– Buncher/Rotator matched to 325 MHz

– Preliminary design of a chicane for the new 325 MHz FE system

– Implemented global optimization algorithms

– Benefit of Initial Cooling (6D) identified by MASS

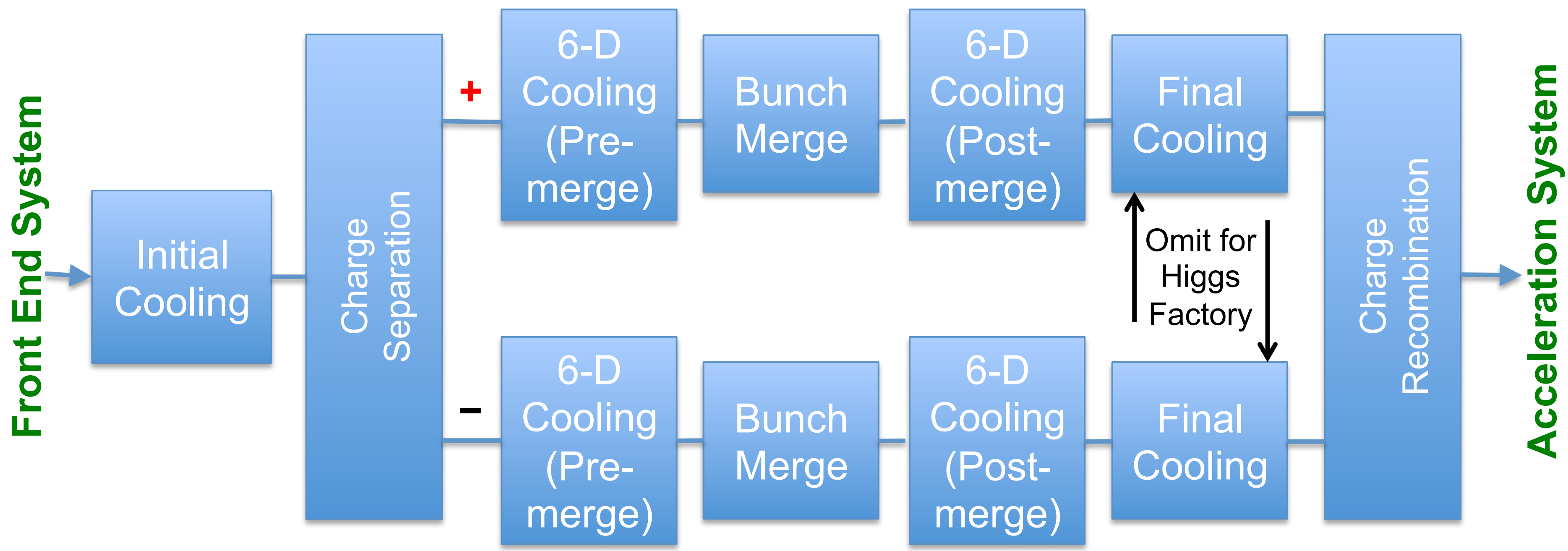
Front End, cont.

- Plans for FY14:
  - Evaluate new target parameters
  - Complete optimization of decay channel/drift/chicane @ 325
  - Buncher/rotator w/ fewer frequencies, realistic coils, windows/apertures
- FY14 IBS milestones:
  - Target module: concept spec & lattice files
  - Capture solenoid: concept spec & lattices files
  - Proton dump: concept spec & layout files
  - Chicane, decay channel, buncher/rotator: concept spec

2	2		Front End (incl. Target)	Concept Specification	Lattice/Layout & Performace Eval	Lattice Sign-off	Global Optimization of Internal Systems	Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications (Dependent on results from previous system)
			Target Module	6/2/14	9/2/14	10/1/14	6/23/15	7/22/15	3/2/15	4/1/15	7/22/15		1/5/16	2/3/16
			Capture Solenoid	6/2/14	9/2/14	10/1/14		7/22/15	3/2/15	4/1/15	7/22/15			
			Proton Dump	6/2/14	9/2/14	10/1/14		7/22/15	3/2/15	4/1/15	7/22/15			
			Chicane	10/1/14	1/2/15	2/2/15		7/22/15	7/1/15	7/31/15	11/2/15			
			Pion Decay Channel	10/1/14	1/2/15	2/2/15		7/22/15	7/1/15	7/31/15	11/2/15			
			Buncher/Phase Rotator	10/1/14	1/2/15	2/2/15		7/22/15	7/1/15	7/31/15	11/2/15			
			FE-Cool Interface Parameters	*10/1/14*				*7/22/15*						***2/3/16***

Cooling

- Muon beam from FE has very large emittance
- Cooling subsystem reduces it to levels needed for NuMAX, HF collider, and HE collider



Cooling

- Most unique and critical subsystem in a muon facility
  - If we can't cool, there won't be a muon collider
  - If we can cool, and if other issues can be overcome (e.g. detector backgrounds, cost), then muon accelerators are the future for the nation and the world
    - Muons are the only practical path to domestic Energy Frontier facility
      - a natural progression from a muon-based Intensity Frontier program
    - Some day the international community will build the largest collider ring practical. When we have exhausted proton studies, next obvious thing will be to fill it with muons

Significant progress in Cooling in FY13

- Guggenheim (previous leading contender for vacuum) replaced by rectilinear channel (simplifies engineering; more realistic for last stage)
- Main 6D cooling system narrowed to two concepts:
  - vacuum rectilinear cooling channel (VCC) and HPRF helical cooling channel (HCC)
- 6D cooling selection criteria drafted
- First lattices & start-to-end simulations of 6D Cooling by VCC and HCC teams delivered in Jan 2014
- MASS identified opportunity afforded by initial 6D cooling instead of (IDS-NF) 4D cooling

Cooling IBS timeline

- FY14 thrust:
  - Optimization of start-to-end 6D Cooling lattices

– FY14 IBS milestones:
  - Initial Cooling: Concept spec, lattice files, interface params
  - Charge separator: Concept spec
  - 6D Cooling: Concept spec, lattice files, interface params, technology spec

2	3		Cooling (NF and MC)	Concept Specification	Lattice/Layout & Performace Eval	Lattice Sign-off		Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications
			Initial Cooling (NuMAX+ Cooling Schem	4/1/14	7/3/14	8/1/14		8/29/14	12/30/14	1/30/15	4/24/15			
			Charge Separation	10/1/14	1/2/15	2/2/15		3/2/15	7/1/15	7/30/15	10/23/15			
			6D Cooling	10/1/13	1/2/14	1/31/14		2/28/14	9/3/14	10/1/14	2/27/15	**3/27/15**	**3/28/16**	**4/25/16**
			Bunch Merge	10/1/14	1/2/15	2/2/15		3/2/15	7/1/15	7/30/15	10/23/15			
			Final Cooling	1/2/15	4/3/15	5/1/15		6/1/15	10/1/15	10/29/15	2/1/16			
			Cool-Accel Interface Parameters	*1/2/15*				*6/1/15*						***4/25/16***

Acceleration: Overview

- Comprises D&S of acceleration chains for NuMAX, HF collider, HE colliders
- Issues:
  - Fast acceleration, cost & power, large emittance beams
- Accelerator types:
  - RF linacs, induction linacs, RLAs, fast ramping synchrotrons, hybrid synchrotrons
- Technologies:
  - high gradient SRF cavities, kickers, very fast ramping magnets, power supplies for the latter two, high field SC magnets
- Challenging systems:
  - Switchyards, kickers for injection/extraction, pulsed magnets

Acceleration, cont.

- FY13 highlights:
  - Finalized lattices for IDS-NF (10 GeV)
  - NuMAX acceleration (5 GeV)
    - RLA+linac concept, dual-use linac concept
  - Study of rapid cycling dipoles
  - First look at Higgs factory acceleration
- FY14 IBS milestones:
  - NuMAX initial acceleration: concept, lattice, interface, technology specs
  - NuMAX to 5 GeV: concept, lattice, interface
  - 5-63 GeV acceleration: concet, lattice, interface, technology specs
  - 63-750, 750-1500, 1500-3000, > 3000 GeV: concept specs

2	4		Acceleration	Concept Specification	Lattice/Layout & Performace Eval	Lattice Sign-off		Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications (Dependent on results from previous system)
			Initial Acceleration (NuMAX Scheme)	10/1/13	3/31/14	4/28/14		5/27/14	9/26/14	10/24/14	1/27/15	3/31/15	6/17/16	7/18/16
			5 GeV Acceleration (NuMAX Scheme)	1/2/14	4/4/14	5/2/14		6/2/14	10/1/14	10/29/14	1/30/15			
			5-63 Acceleration (RLA initially)	10/1/13	3/31/14	4/28/14		5/27/14	9/26/14	10/24/14	1/27/15			
			Initial Acceleration (MC Final Cooling Sc	5/6/15	8/3/15	8/31/15		9/29/15	12/28/15	1/28/16	4/21/16			
			63-750 Acceleration	3/3/14	12/1/14	1/2/15		2/2/15	6/3/15	7/1/15	9/25/15			
			750-1500 Acceleration	3/3/14	1/2/15	2/2/15		3/2/15	7/1/15	7/30/15	10/23/15			
			1500-3000 (2500) Acceleration	3/3/14	2/2/15	3/2/15		3/30/15	7/30/15	8/27/15	11/20/15			
			Options for >3000 Acceleration	9/2/14	5/1/15	6/1/15		6/29/15	10/23/15	11/20/15	2/23/16			
			Accel-Ring Interface Parameters	*5/6/15*				*9/29/15*						*7/18/16*

Collider Rings

- D&S of rings for Higgs Factory and multi-TeV colliders
- Issues:
  - Lattice design and component design in presence of muon decays
  - HF involves extremely small energy spread and large muon beam emittance
  - Final-focus design w/ detector protection in mind
  - collective effects, multipole errors, fringe fields,...
- Emphasis in FY13 was on Higgs Factory
  - lattice design, correction of multipole errors and fringe fields, dynamic aperture, longitudinal dynamics, b-b, impedance
  - HF design used as input for preliminary engineering & MDI studies

Collider Rings, cont.

Overall collider design status:

- Preliminary designs in hand for HF,1.5 TeV, 3.0 TeV

Parameter	Baseline	Upgrade
Beam energy, GeV	63	63
Average luminosity, 10^{31}/cm^2/s	1.7	8.0
Collision energy spread, MeV	3	4
Circumference, m	300	300
Number of IPs	1	1
β^*, cm	3.3	1.7
Number of muons / bunch, 10^{12}	2	4
Number of bunches / beam	1	1
Beam energy spread, %	0.003	0.004
Normalized emittance, π·mm·rad	0.4	0.2
Longitudinal emittance, π·mm	1.0	1.5
R.m.s. bunch length, cm	5.6	6.3
R.m.s. beam size at IP, mm	0.15	0.075
Beam-beam parameter	0.005	0.02
Momentum compaction factor	0.079	0.079
Repetition rate	30	15
Proton driver power	4	4

High Energy MC parameters		
Collision energy, TeV	1.5	3.0
Repetition rate, Hz	15	12
Average luminosity / IP, 10^{34}/cm^2/s	1.25	4.4
Number of IPs	2	2
Circumference, km	2.5	4.5
β^*, cm	1	0.5
Momentum compaction factor, 10^{-5}	-1.3	-1
Normalized emittance, π·mm·mrad	25	25
Momentum spread, %	0.1	0.1
Bunch length, cm	1	0.5
Number of muons / bunch, 10^{12}	2	2
Number of bunches / beam	1	1
Beam-beam parameter / IP	0.09	0.09
RF voltage at 1.3 GHz, MV	12	150
Proton driver power	4	4

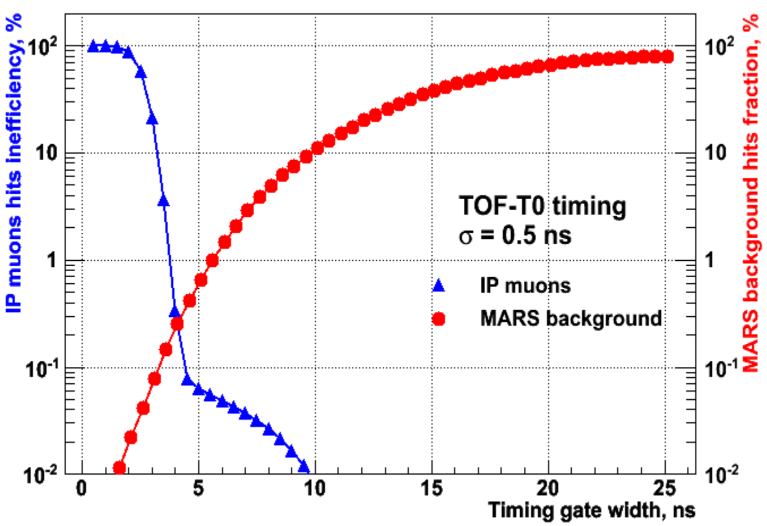
FY14 IBS milestones:

- HF: concept, lattice, interface, tech specs
- 1.5 TeV: concept, lattice, interface, tech specs
- 3 TeV: concept, lattice, interface
- > 5 TeV: concept

2	5		Collider Ring	Concept Specification	Lattice/Layout & Performance Eval	Lattice Sign-off		Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications (Dependent on results from previous system)
			Higgs Factory	10/1/13	3/31/14	4/28/14		5/27/14	9/26/14	10/24/14	1/27/15	3/2/15	3/16/16	4/13/16
			1.5 TeV (2 & 4 MW Source)	10/1/13	3/31/14	4/28/14		5/27/14	9/26/14	10/24/14	1/27/15			
			3 TeV (2 & 4 MW Source)	10/1/13	7/31/14	8/28/14		9/26/14	1/23/15	2/20/15	5/27/15			
			>5 TeV (<2 MW Source)	10/1/14	2/27/15	3/27/15		4/24/15	8/27/15	9/25/15	12/29/15			
			Ring-MDI Interface Parameters	*10/1/14*				*4/24/15*						*8/15/16*

Collider MDI

- Key areas:
  - MARS code development
  - MARS model of MDI and detector for HF and HE colliders
  - Design and optimization of magnet protection
  - Design and optimization of MDI
  - Background rejection in detector



Inefficiency of IP muon hits and surviving fraction of MARS background particle hits in the VXD and Tracker Si Detectors versus width of timing gate for hit time resolution of 0.5 ns

4-ns gate provides a factor of a few hundred background rejection while maintaining >99% efficiency for hits from IP muons.

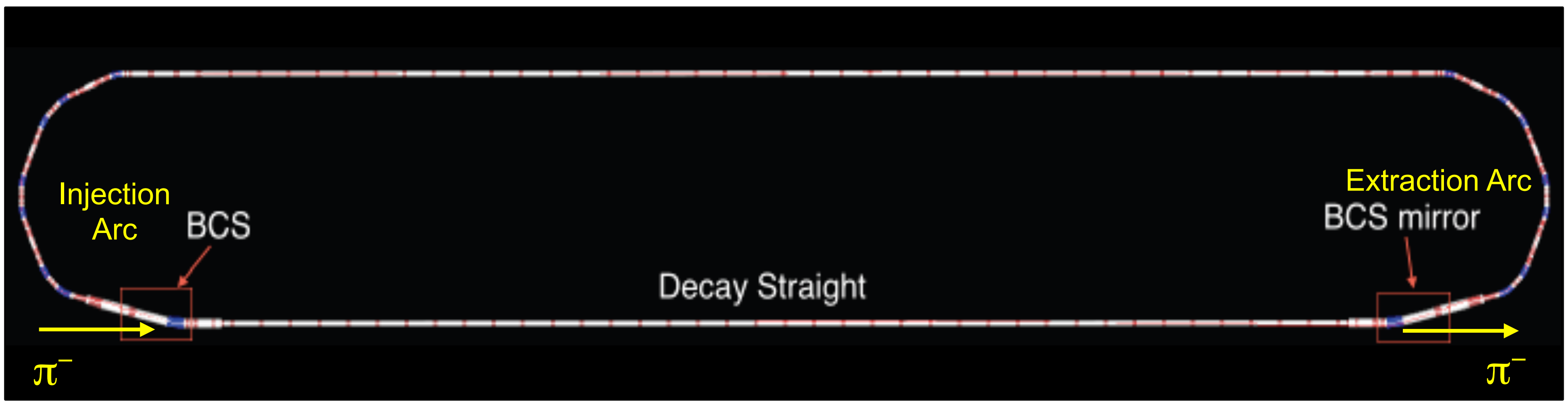
MDI, cont.

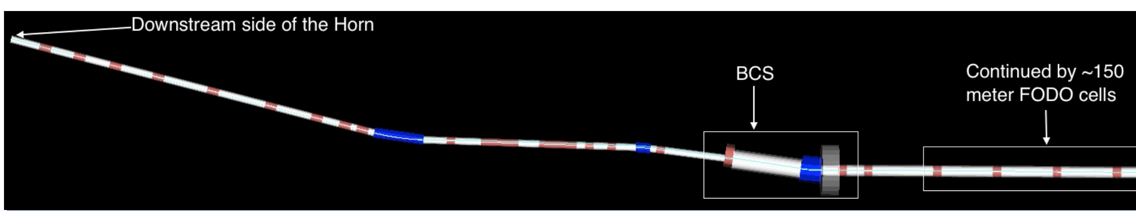
- FY13 highlights
  - Substantial enhancements to MARS15 modules related to HF and MC applications
  - Design of entire HF collider and detector model
  - D&S of SC magnet protection system allowing nearly 100-fold reduction of radiation loads on cold mass
  - Design and optimization of MDI components inside detector
  - Demonstrating of timing for background rejection for 1.5 TeV
- FY14 IBS milestones
  - HF MDI: concept specification
  - 1.5 TeV MDI: concept specification

2	6		Collider Machine-Detector Interface	Concept Specification	Lattice/Layout & Performace Eval	Lattice Sign-off		Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications
			Higgs Factory	8/6/14				12/1/14	12/1/14	1/2/15	2/2/15	3/2/15	3/16/16	4/13/16
			1.5 TeV (2 & 4 MW Source)	8/6/14				12/1/14	12/1/14	1/2/15	2/2/15			
			3 TeV (2 & 4 MW Source)	12/10/14				4/8/15	4/8/15	5/6/15	6/4/15			
			>5 TeV (<2 MW Source)	7/28/15				11/18/15	11/18/15	12/16/15	1/20/16			
			Ring-MDI Interface Parameters	*7/28/15*				*11/18/15*						***8/15/16***

Decay Rings

- Previous emphasis on IDS-NF and nuSTORM
  - IDS-NF ring design completed
  - preliminary design of nuSTORM 3.8 GeV decay ring
    - FODO ring and racetrack FFAG ring





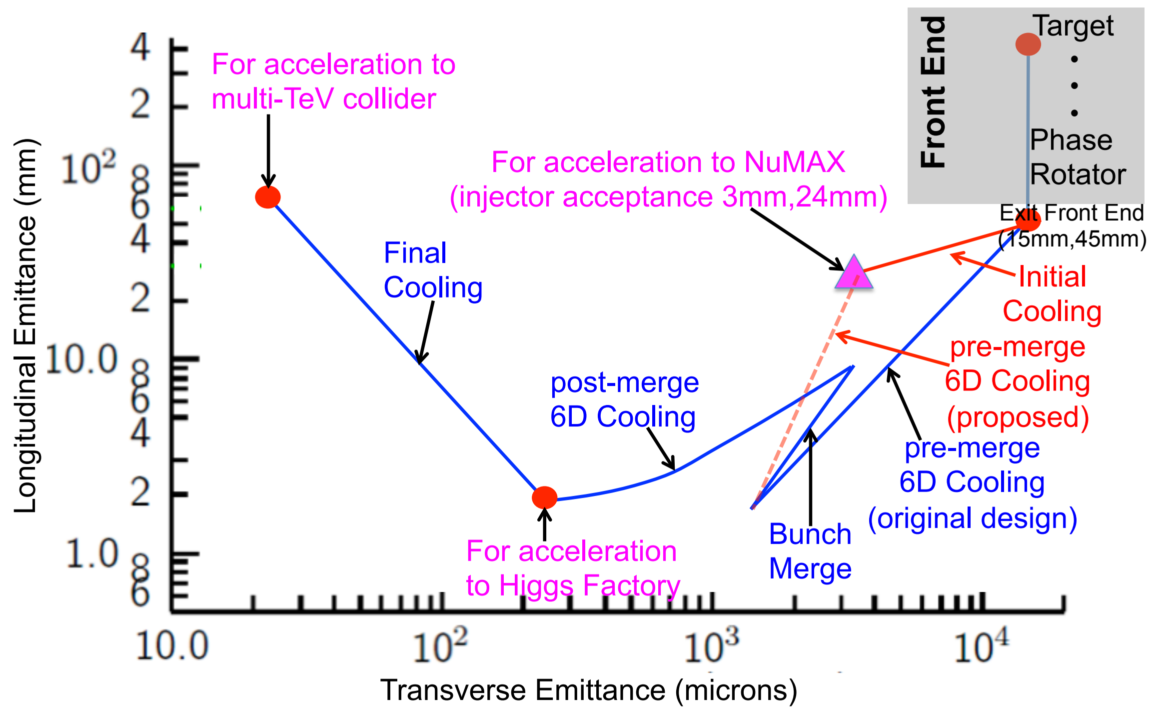
Decay Rings: Progress and Plans

- FY13 highlights:
  - Finalized lattice for IDS-NF decay ring
  - nuSTORM:
    - stochastic injection, chromaticity correction, injection timing, dynamic aperture
    - FODO and FFAG lattices
- FY14 thrusts:
  - NuMAX (scaled from IDS-NF);nuSTORM/NuMAX integration
- FY14 IBS milestones
  - NuMAX: concept specification, lattice

2	7		Neutrino Factory Decay ring	Concept Specification	Lattice/Layout & Performance Eval	Lattice Sign-off		Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications (Dependent on results from previous system)
			NuMAX Ring	10/1/13	6/9/14	7/8/14		8/5/14	12/5/14	1/8/15	4/3/15		**6/5/15**	**7/6/15**
			NuSTORM/NuMAX	1/29/15	6/19/15	7/20/15		8/17/15	12/17/15	1/21/16	4/14/16			
			NF Decay Ring Parameters	*10/1/13*				*8/5/14*						***8/15/16***

Moving Forward: FP-I

- Complete IBS on the schedule shown previously
- Explore opportunities identified by MASS:
  - Modifications to Cooling system could change the location of the minimum in the emittance diagram; might eliminate induction linacs, big $ savings
  - Possibility of 2 MW target instead of 4 MW. Consider use of solid targets, save $ and avoid environmental issues of Hg



Moving Forward: FP-II

- IBS process:
  - Study designs in more detail
  - Optimize the designs
  - Adjust as needed based on latest information
  - Maintain modest effort in approved alternatives, as appropriate
- Broader impact to MAP
  - By having more clearly specified initial designs, the IBS process will provide a foundation for better direction of R&D
  - Less generic R&D, more specific R&D
    - e.g. magnet prototypes

Summary

- IBS process in MAP is now fully underway
- Completion expected by end of FY16
- During remainder of FP-II, optimize the designs, take into account latest results from Technology Development and MICE
- Pursue opportunities identified by MASS for better staging and cost savings