Introduction to NUMAX

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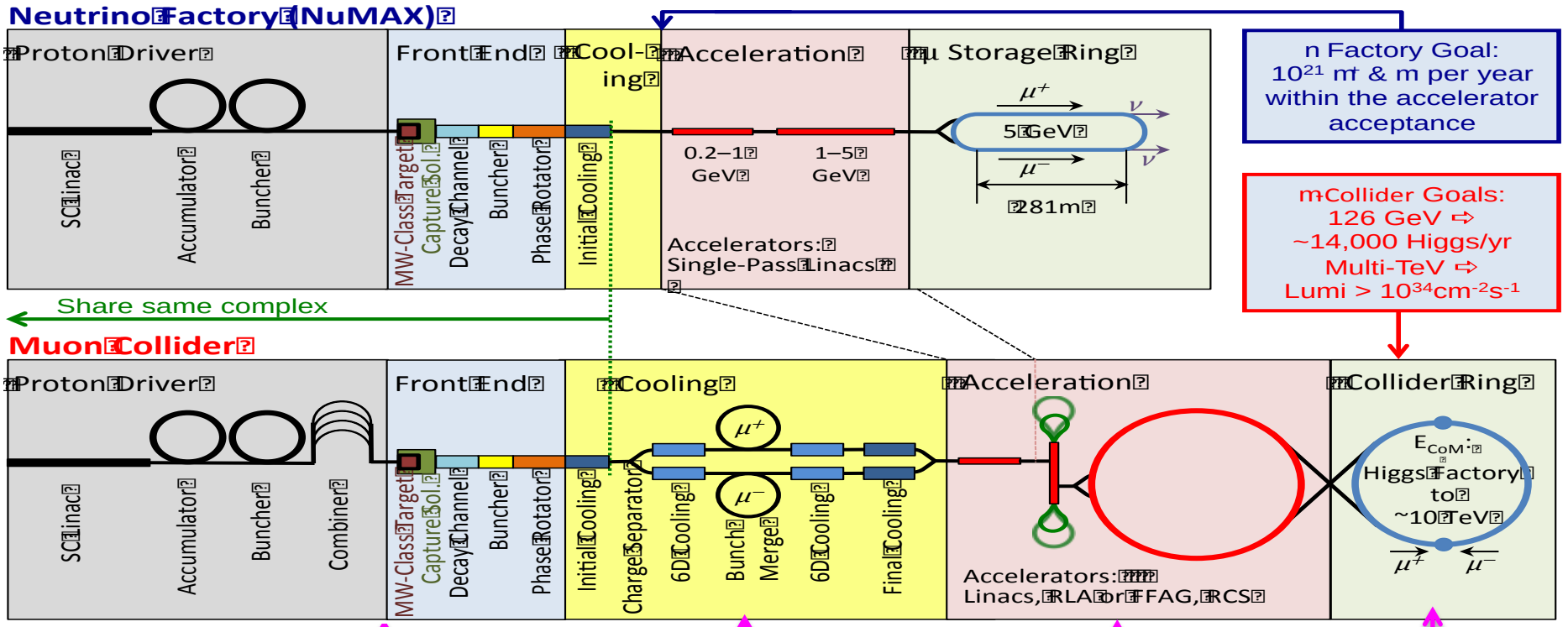
OUTLINE

- Overview
  - Staged Scenario Plan
  - Compatible with FNAL
    - succession of proton sources …
    - PIP 1 → PIP 2 → ???
- Sequence of neutrino sources
  - LBN(E)F
  - NuSTORM
  - NuMAX
  - Neutrino Factory

Fermilab Proton Sources

- "Existing" (w PIP-1)
  - 0.4 GeV Linac → 8 GeV Booster→ Main Injector
    - 0.4 to 0.7 MW with~120 GeV MI
  - 1 → 3 → 8 GeV "Project X" – no longer baseline
    - 1MW→3MW (3 GeV)→ ?? 8GeV → 2+MW at MI
  - PIP2 – 0.8 GeV pulsed linac
    - Linac: 0.014 MW → ?
    - **MI to 1.2 MW** ---? (LBNF expects 2.5 MW)
    - Booster: 8 GeV at ~0.12 MW
  - PIP2 is "upgradeable"
    - could go to cw ~1ma →0.8MW at 0.8GeV
      - Booster limits MI intensity
    - upgrade could follow old Project X scenario
  - Main Injector (60—120 GeV)
    - 0.4MW→ 0.7 → 1.2 MW ……..→ 2.5 MW (P5)

Muon Accelerator Concepts
Key issues and R&D to address feasibility



Key Challenges

- ~10^{13}-10^{14} μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

- MW proton driver
  MW class target
  NCRF in magnetic field
- Ionization cooling
  High field solenoids (30T)
  High Temp Superconductor
- Cost eff. low RF SC
  Fast pulsed magnet (1kHz)
- Detector/ machine interface

Muon Accelerator Staging Scenario (MASS) in the FNAL context

- **nuSTORM (neutrinos from STOred Muons):**
  - **short-baseline 10^{17} muon decays/year @ 3.8 GeV**
  - **sterile neutrinos and cross sections**
- **Neutrinos from Muon Accelerators at Project X (NuMAX) as first stage**
  - **Neutrino Factory with 10^{20} muon decays/year @ 5 GeV**
  - **Neutrino ring at 5 GeV pointing towards Sanford (10kT LAr detector) upgraded fr**
  - **use Phase 2 project X with 1MW@3 GeV as proton driver**
- **Upgrade to full luminosity NuMAX+: 10^{21} muon decays/year@5 GeV**
  - **Similar Physics performance as IDS-NF**
  - **Upgrade proton driver to 3MW (PX2) and later 4 MW@8GeV of PX4 Larger magnetized detector (34kT)?**
- **Follow with:**

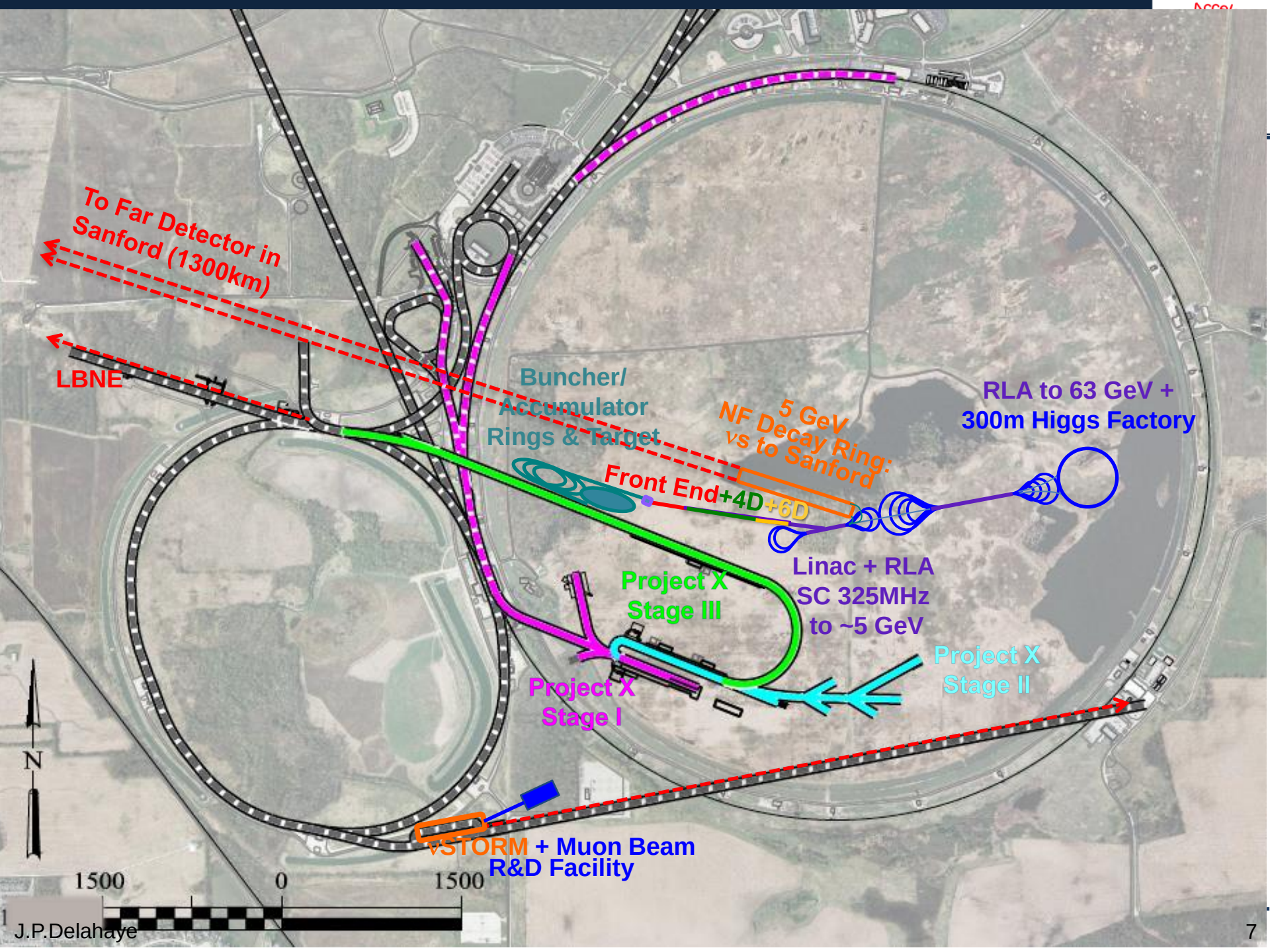
  Higgs Factory: 125 GeV collider

  Possible upgrade to a Top Factory

  Multi-TeV Collider: up to 10 TeV

NuMAX parameters (pre P5)

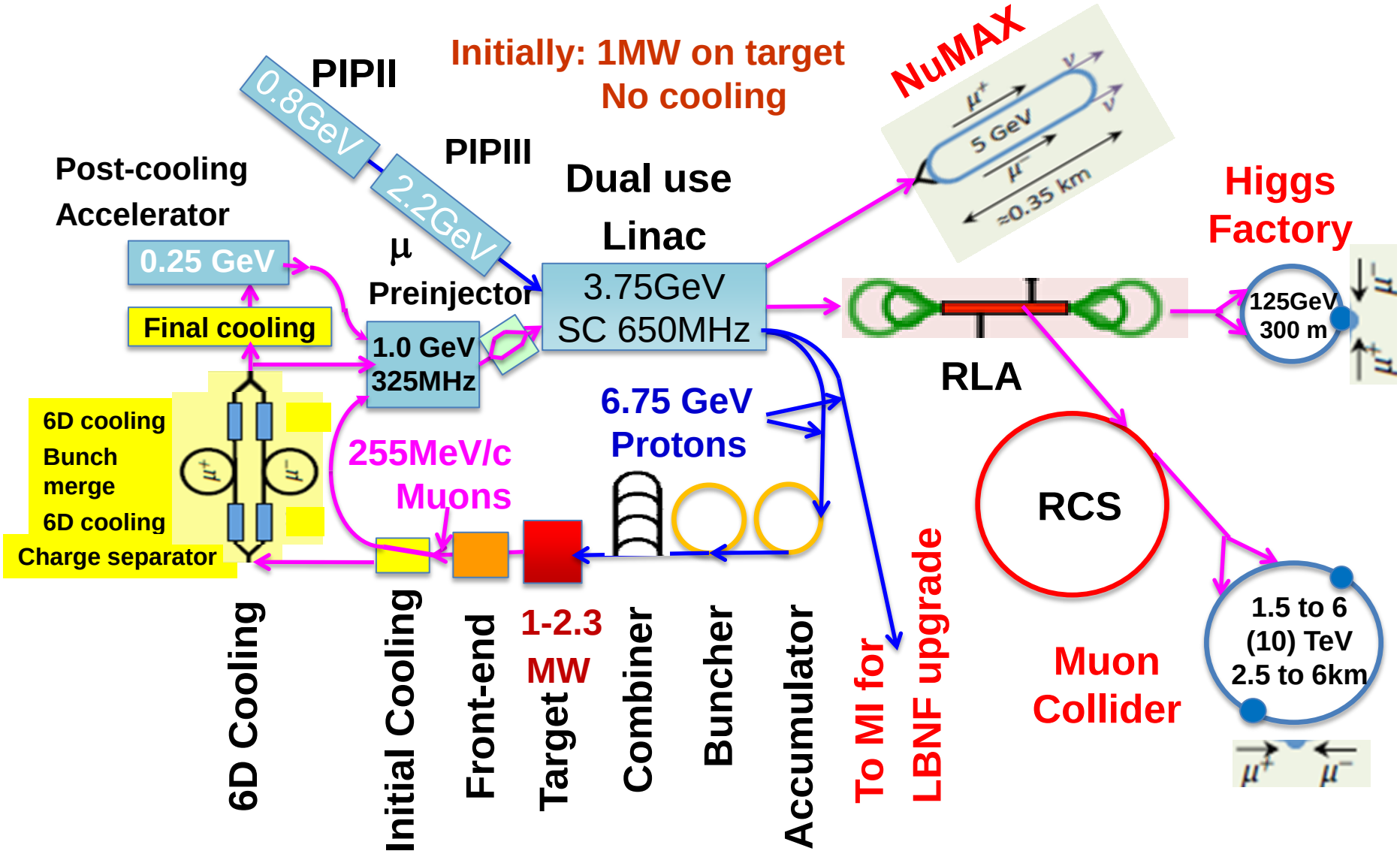
System	Parameters	Unit	nuSTOR	NuMAX	NuMAX+	IDS-NF
Performance	Stored μ^+ or μ^-/year		8×10^{17}	2×10^{21}	1.2×10^{21}	1×10^{21}
	ν_e or ν_μ to detectors/yr		3×10^{17}	8×10^{19}	5×10^{21}	5×10^{21}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND
	Distance from Ring	km	1.9	1300	1300	2000
	Mass	kT	1.3	30 / 10	100 / 30	100
	Magnetic Field	T	2	0.5-2	0.5-2	1-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	2.7	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	10
	Circumference (C)	m	480	600	600	1190
	Straight section	m	185	235	235	470
	Arc Length	m	50	65	65	125
Acceleration	Initial Momentum	GeV/c	-	0.22	0.22	0.22
	Single-pass Linac	GeV/pass	-	0.95	0.95	0.56
		MHz	-	325	325	201
	4.5-pass RLA RLA I	GeV/pass	-	0.85	0.85	0.45
		MHz	-	325	325	201
	RLA II	GeV/pass	-	-	-	1.6
		MHz	-	-	-	201
Cooling			No	No	4D	4D
Proton Source	Proton Beam Power	MW	0.2	1	3	4
	Proton Beam Energy	GeV	120	3	3	10
	Protons/year	1×10^{21}	0.1	41	125	25
	Repetition Frequency	Hz	0.75	70	70	50

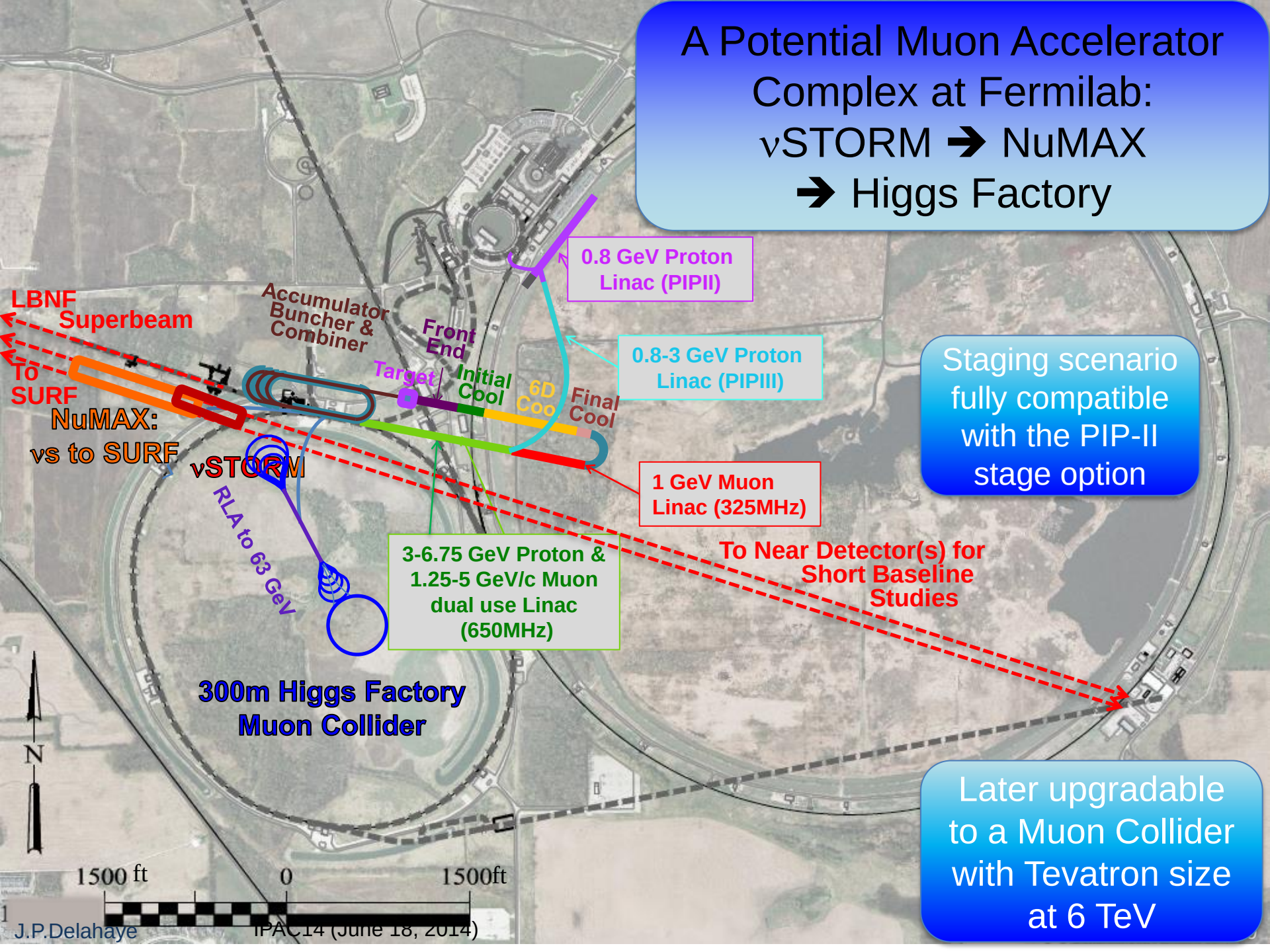

To Far Detector in Sanford (1300km)
LBNE
Buncher/ Accumulator Rings & Target
5 GeV NF Decay Ring: νs to Sanford
Front End+4D+6D
RLA to 63 GeV + 300m Higgs Factory
Linac + RLA SC 325MHz to ~5 GeV
Project X Stage III
Project X Stage I
Project X Stage II
νSTORM + Muon Beam R&D Facility
N
1500
0
1500

Modify to match FNAL scenarios

- P5 Process forces modification
  - PIP 2 (0.8 GeV pulsed linac) endorsed (with “LBNF”)
    - NuSTORM too expensive for present
    - Neutrino Factory not needed (yet…)
- PIP2 needs upgrade(s) – to cw
  - MI injection requires > ~6.75 GeV protons
    - linac or synchrotron ?
- Stage II of Project X was 3 GeV Linac
  - PIP3 could be 3 GeV
- Dual Use Linac
  - could supply 6.75 GeV protons and 5 GeV muons

A cost effective and progressive installation in stages with increasing complexity




A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory
0.8 GeV Proton Linac (PIPII)
0.8-3 GeV Proton Linac (PIPIII)
Staging scenario fully compatible with the PIP-II stage option
LBNF Superbeam
To SURF
NuMAX: νs to SURF
νSTORM
Accumulator Buncher & Combiner
Front End
Target
Initial Cool
6D Coo
Final Cool
1 GeV Muon Linac (325MHz)
RLA to 63 GeV
3-6.75 GeV Proton & 1.25-5 GeV/c Muon dual use Linac (650MHz)
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Later upgradable to a Muon Collider with Tevatron size at 6 TeV
N
1500 ft
0
1500ft

Main parameters evolution (increasing complexity and challenge)

	NuMAX Commissioning	NuMAX	NuMAX+	Higgs Fact 125 GeV
Beam energy (GeV/c)	5	5	5	62.5
Cooling	No	Initial 6D	Initial 6D	6D no final
Proton beam power on target	1MW	1MW	2.75 MW	4 MW
Proton beam energy on target	6.75 GeV	6.75 GeV	6.75 GeV	6.75 GeV
Acceleration cycle rep rate(Hz)	60	60	60	15
μ / cycle at front end	$1.36\ 10^{12}$	$1.36\ 10^{12}$	$3.75\ 10^{12}$	$2.6\ 10^{13}$
Transmission efficiency (%)	15.3	56.7	56.7	15.4
μ / bunch in ring	$7.0\ 10^{9}$	$2.6\ 10^{10}$	$3.5\ 10^{10}$	$4\ 10^{12}$
Bunches in ring	30	30	60	1
ν towards detector/year(10^7s)	$4.9\ 10^{19}$	$1.8\ 10^{20}$	$5.0\ 10^{20}$	
Higgs per year (10^7 sec)				13500
Luminosity (10^{34} cm^{-2}s^{-1})				0.01

NuSTORM Options

1. Iterate design; adapt to another location
   - cross sections, steriles?, 1st μ storage ring for ν

2. Change ring location to match LBNEF
   - could use same extraction
   - Smaller, cheaper ring for near detector cross section measurements ?
   - Same ring used also for nu fact to SD ?

Fermilab future upgrade path ??

- **0.8 GeV PIP2** -- could upgrade to cw
  - Booster is bottleneck; must be replaced
- 3 GeV PIP3 is unlikely
- Booster to be replaced by 0.8 → 8 GeV synchrotron
  - power not yet certain; unlikely to be multi-MW
- **Main Injector** would be ~2.5MW at 60—120 GeV
  - could be more ???
  - Main Injector could supply new (renamed) NuSTORM
  - Could we add buncher ring to get short initial bunches for Neutrino Supersource / heavy-electron Collider?
  -

Summary

- NuSTORM Physics goals remain important
  - ν_e, ν_μ cross sections; sterile neutrino limits
- After LBNEF, more accuracy will be desired
  - ν_e, ν_μ precision beams → ”NuMAX”
- Use of multiMW beams upgraded from PIP-X could be a critical ingredient

BACK UPS

Staged Neutrino Factory and Muon Colliders Parameters

Neutrino Factory at intensity frontier

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^9		6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

Muon Collider at the energy frontier

		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top† Production/10^7sec		3,500*	13,500*	7,000†	60,000†	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4	4	4	4	4	4	1.6
Cooling			**6D no final**			**Full 6D**		