Proton Source for Muons Bunching and Phase Rotation

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October 2022

Outline

- **Proton Source – Front End for Muon Collider**
  - Baseline MAP version
    - 8 GeV proton beam from Linac
    - Accumulator and Compressor
  - Other configurations
    - Linac + RCS ?
    - Proton Driver scenarios CERN/RAL (2013)
    - JPARC example
  - Bunching and phase-energy rotation for muons

Acknowledgements & White Papers

Snowmass White papers related to DUNE/LBNF proton driver upgrades

"A Cost-Effective Upgrade Path for the Fermilab Accelerator Complex"
Sergei Nagaitsev and Valeri Lebedev

"An Upgrade Path for the Fermilab Accelerator Complex"
Rob Ainsworth, Joe Dey, Jeff Eldred, Roni Harnik, Jonathan Jarvis, Dave Johnson, Ioanis Kourbanis, David Neuffer, Eduard Pozdeyev, Mike Syphers, Sasha Valishev, Vyacheslav Yakovlev and Bob Zwaska

"Design Considerations for Fermilab Multi-MW Proton Facility"
Jeff Eldred, Sergei Nagaitsev, Vladimir Shiltsev, Mike Syphers, Sasha Valishev, and Bob Zwaska

"An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade"
Sergey Belomestnykh, Mattia Checchin, David Johnson, David Neuffer, Hasan Padamsee, Sam Posen, Eduard Pozdeyev, Vitaly Pronskikh, Nikolay Solyak, Vyacheslav Yakovlev

References

Design of accumulator and compressor rings for the Project-X based proton driver, Y. Alexahin , D. Neuffer FNAL, Batavia, IL 60510 U.S.A Proc. IPAC 12, TUPPC043 (2012)

Design of a 2.2 GeV Accumulator and Compressor for a ν Factory, B. Autin et al. CERN–PS/2000–011 (AE) (2000)

Proton driver scenarios at CERN and Rutherford Appleton Laboratory, JWG Thomson et al. PRSTAB 16, 054801 (2013)

H.K. Sayed et al., Optimization of the Capture Section of aStaged Neutrino Factory, THPHO11, NA-PAC 13. (2013)

H.K. Sayed et al., Impact of the Proton Bunch Length on the Performance of the Muon Front End, TUPBA10, NA-PAC 13. (2013)

"A Muon Source at JPARC parameters, TUPMY005, IPAC 16 (2016)

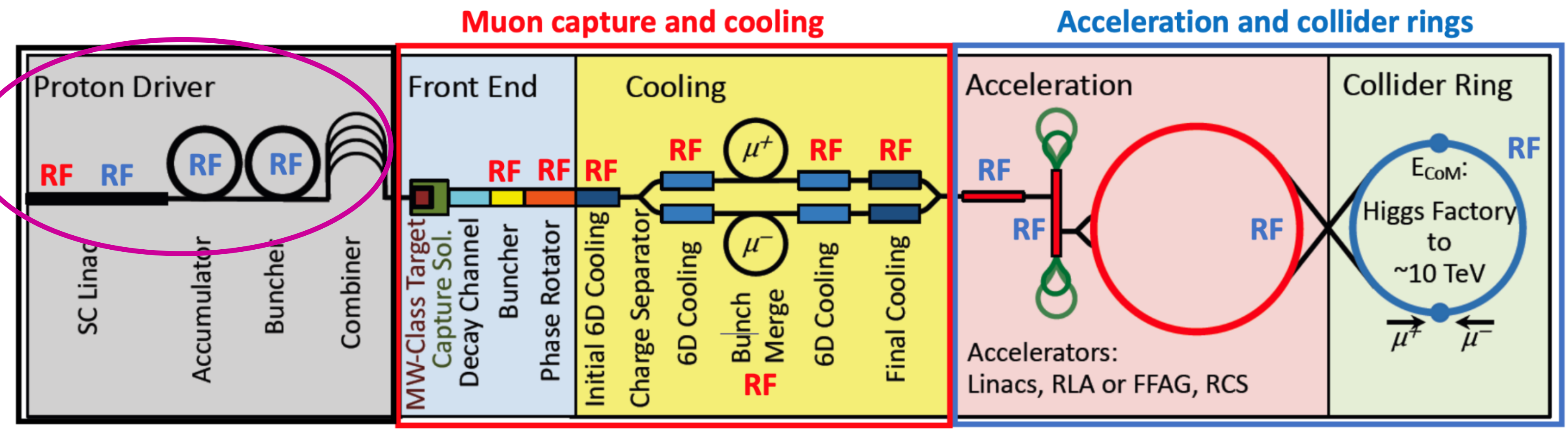
"High Frequency Bunching and ϕ-δE Rotation for a Muon Source" D. Neuffer and A. Van Ginneken, Proceedings of PAC 2001, Chicago IL, p. 2029 (2001).

Hisham Kamal Sayed and J. Scott Berg, "Optimized Capture Section for a Muon Accelerator Front End" PhysRevSTAB 17, 070102 (2014)

Compact muon production and collection scheme for high-energy physic experiments D. Stratakis and D. Neuffer 2014 *J. Phys. G: Nucl. Part. Phys.* 41 125002

High intensity muon beam source for neutrino beam experiments, Nucl. Inst. and Meth. A 794 (2015) 193–199 Hisham Kamal Sayed .

MAP Proton Driver



Muon Collider Parameters

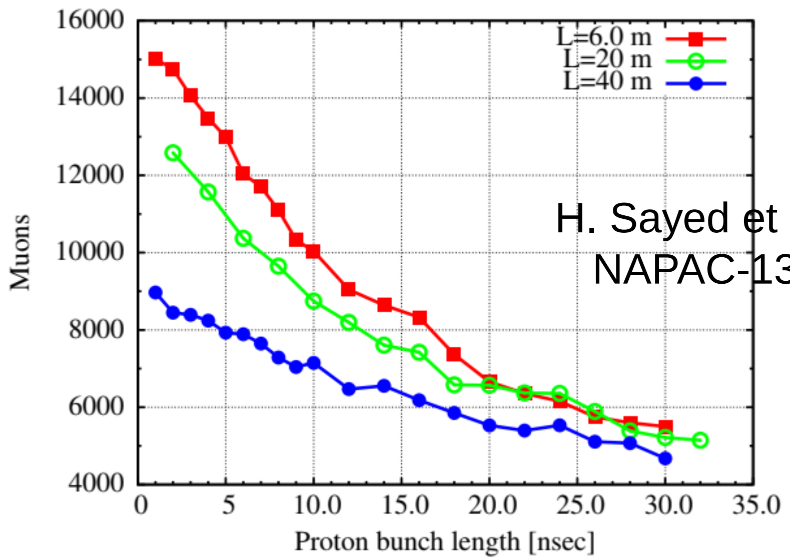
Parameter	*Units*	Higgs *Production Operation*	Multi-TeV		*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}cm^{-2}s$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B \rangle$	T	7	10.5	10.5
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63

ble 1: Tentative target parameters for a muon collider at different energies.

Proton Source Requirements

- **Want high intensity of protons in a short pulse to put on target**
  - Followed by Muon collection, cooling, acceleration
- **~2-400 MW – 10 Hz -> 5Hz**
  - 200 kJ / pulse -> 400 kJ
  - 1.6 10^{14}p → 3.1 10^{14} (8 GeV)
- **Bunch Length ~1-3 ns (rms)**
  - 0.3-1m rms
  - Lose a factor of 2 when L = 10 m



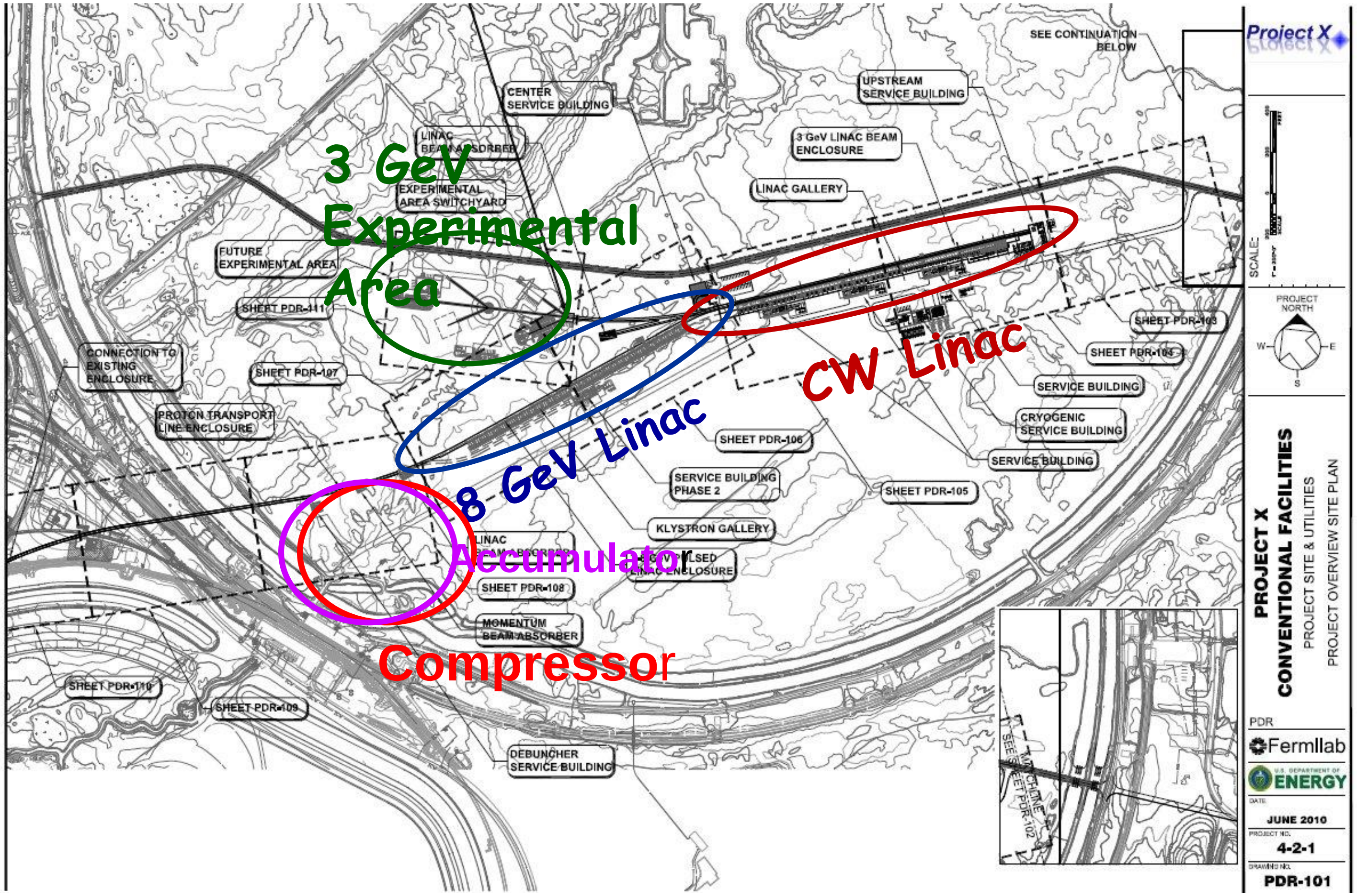
H. Sayed et al. NAPAC-13

Dependence of stored μ's on proton bunch length

and B-field taper length

~ non-adiabatic preferred

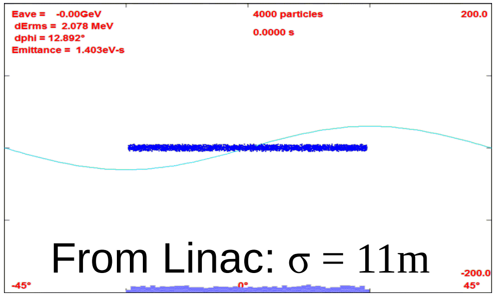
Baseline Project X Configuration



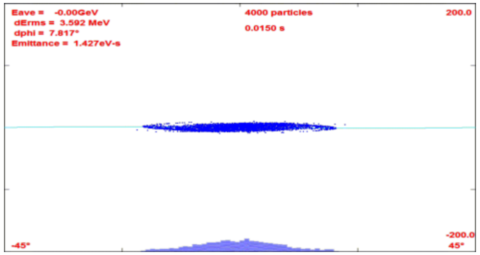
Need 15/60 Hz bunches

- Add Accumulator and Compressor Rings to Linac
  - ~8GeV rings
- Accumulator captures and bunches beam
  - 2×10^{14} p, h=4
  - 15 Hz → 4 MW
- Compressor: ¼ phase rotate to short bunch (combine onto target for MC)
- Challenges

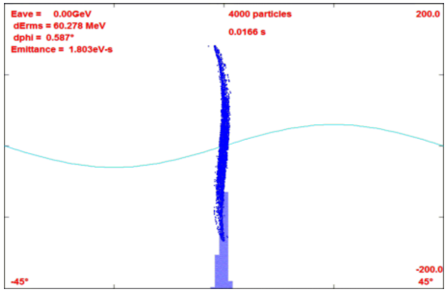
Parameter	Accumulator	Compressor
Circumference	300m	300m
Transition γ_t	4.0	11.3
Slip factor $\alpha_p = 1/\gamma_t 2 - 1/\gamma 2$	0.051	-0.0032
rf voltage V_{rf}	4.0kV	120kV
bunches (h)	4	4



From Linac: σ = 11m



Accumulator: σ = 6.5m



Compressor: σ = 0.5m

Lattice Design approaches

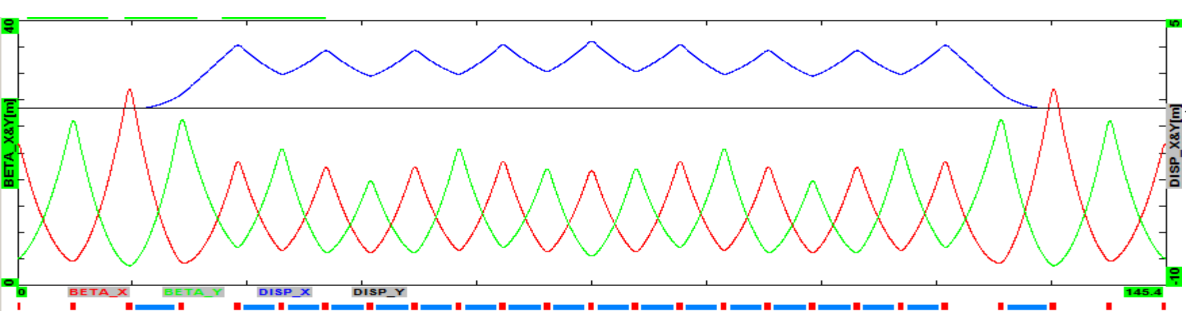
- **Requirements**
  - stability (better for $\eta<0$)
    - below transition
  - space charge
  - bunching
- **FODO lattice**
  - $\gamma_T \approx \nu_x$ (high tune for Cr)
- **Flexible Momentum Compaction**
  - α_p can be tuned
  - more flexible correction

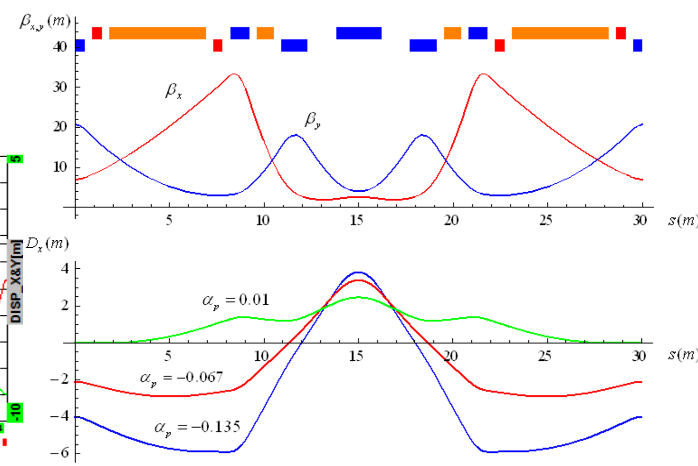
$$\eta = \alpha_p - \frac{1}{\gamma^2} = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2}$$

$$\alpha_p = \int D_x d\theta = \int D_x \frac{B}{B\rho} ds$$

$$eI_{peak}\left|\frac{Z_n}{n}\right| \le 2\pi|\eta|\beta\ pc\left(\frac{\sigma_p}{p}\right)^2 F$$

$$\Delta\nu_{SC} = \frac{3N_p r_p}{2\varepsilon_{N,95\%}\beta\gamma^2 B}$$





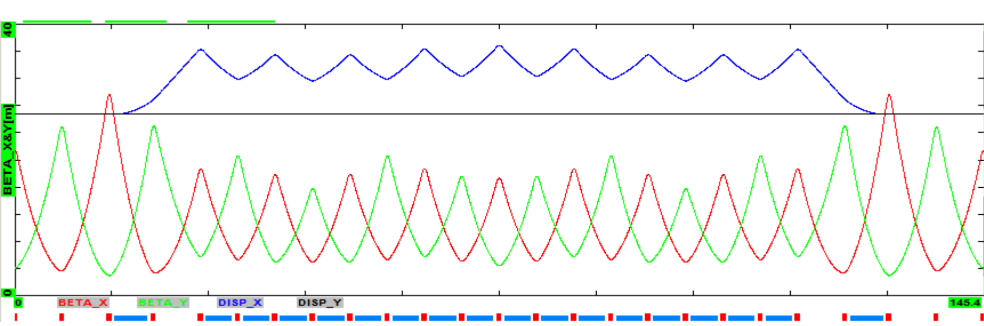
Accumulator, Compressor FODO lattices

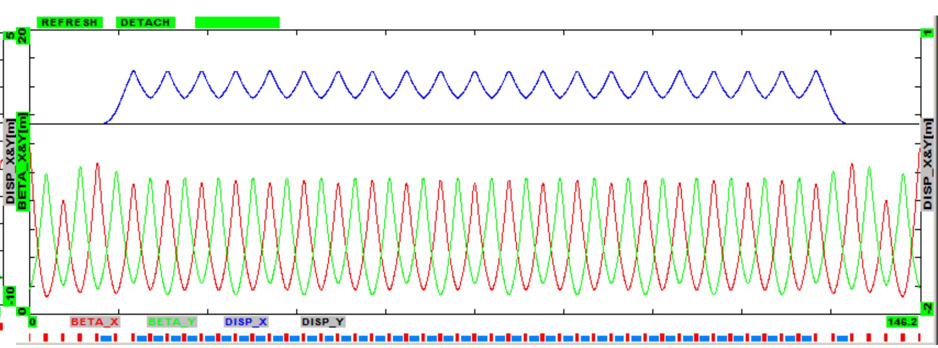
Parameter	Symbol	Accumulator	Compressor	Unit
Circumference	C	292	292	m
FODO cells	$L, N_{C,} \varphi$	11.2, 20, 72	5.6, 42, 90	m
Dipole params	L, B	4.0, 1.25	1.6, 1.4	m, T
Quad params	L, B′	0.8, 8.0	0.6, 27	m,T/m
β_{max},η_{max}	β_{max},η_{max}	18.0, 3.5	9.3, 0.56	m
transitions	α_p, γ_t	0.038, 4.52	-0.03, 11.1	
tunes	ν_x, ν_y	5.44, 5.30	13.45,12.72	
rf voltage	V_{rf}, f_{rf}	4kV, 4MHz	240 kV	

Simple FODO lattices (72º/90)

- large dispersion
- linear lattice
- missing magnet dispersion suppressor

Cell layout- OPTIM

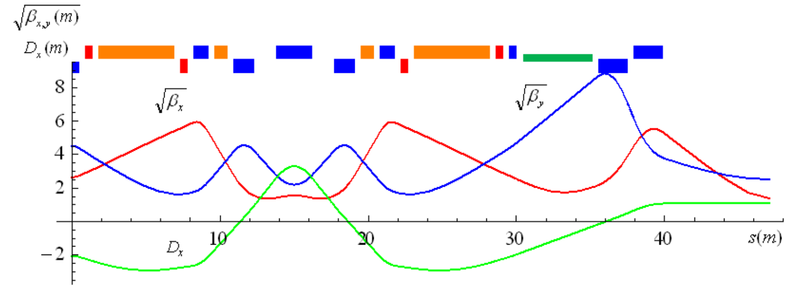


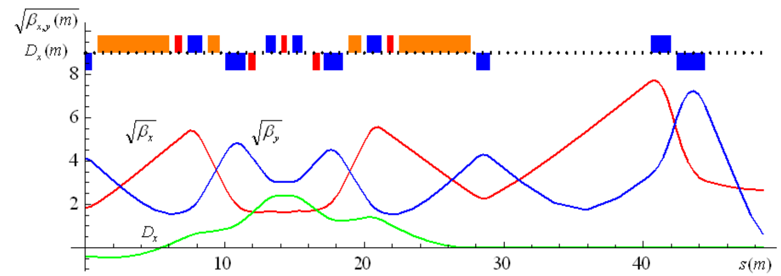


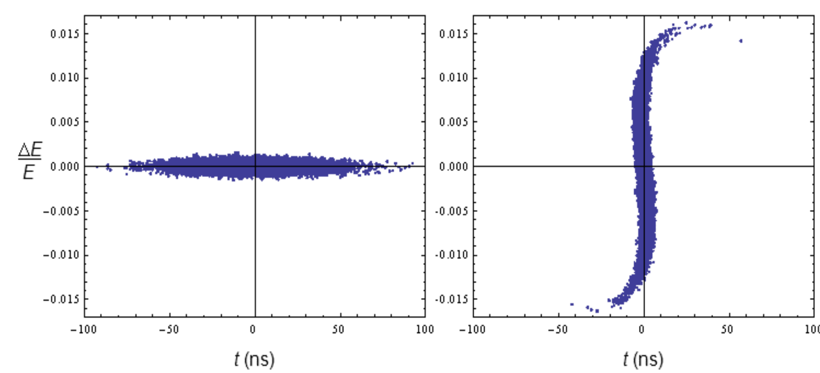
Accumulator and Compressor Ring Parameters

FMC versions (Y. Alexahin)

Parameter	AR	CR
Circumference, m	308.23	308.23
Momentum compaction	-0.052	0.001
Slippage factor	-0.063	-0.01
RF frequency, MHz	3.87	3.87
RF voltage, kV	10	240
Synchrotron tune	$2.1\cdot10^{-4}$	$4.2\cdot10^{-4}$
Peak current, A	100	1040
Final r.m.s. bunch length, ns	29.2	3.2
Final r.m.s. energy spread	$5.2\cdot10^{-4}$	$6.9\cdot10^{-3}$
Threshold impedance, Ohm	20	$3 \rightarrow 53$
R.m.s. emittance, μm	5	5
Space charge tuneshift, h/v (Gaussian distribution)	0.02/0.02	0.14/0.16
Betatron tunes, h/v	7.94/6.91	6.76/8.44

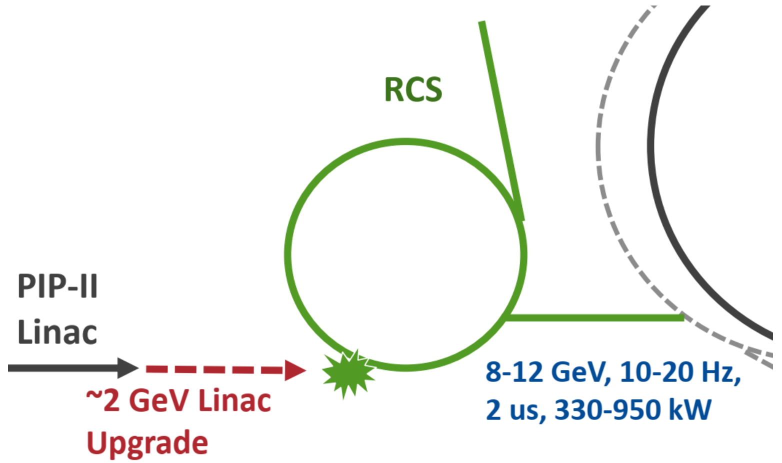


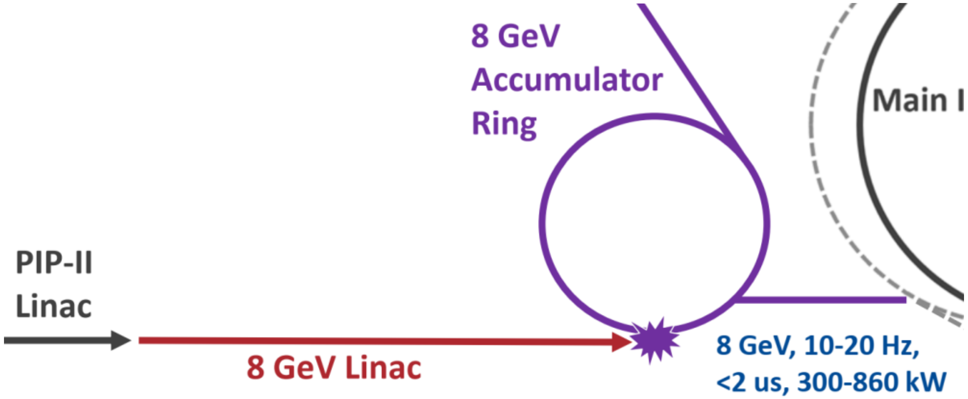




Proton Intensity Upgrade Scenarios

- Current Ideas on Fermilab next upgrade
  - 8 GeV RCS, C=~500-600
    - With 2 GeV Linac
  - 8 GeV Linac
    - With 8 GeV Accumulator Ring

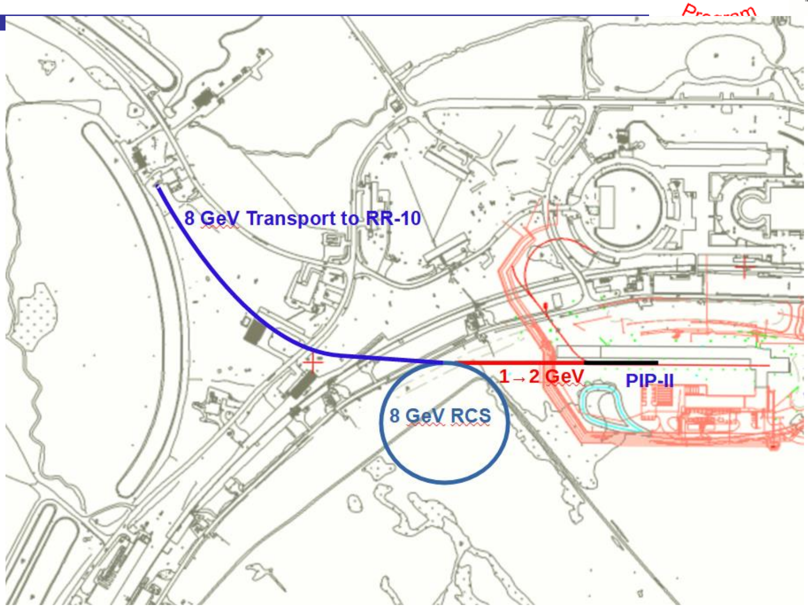




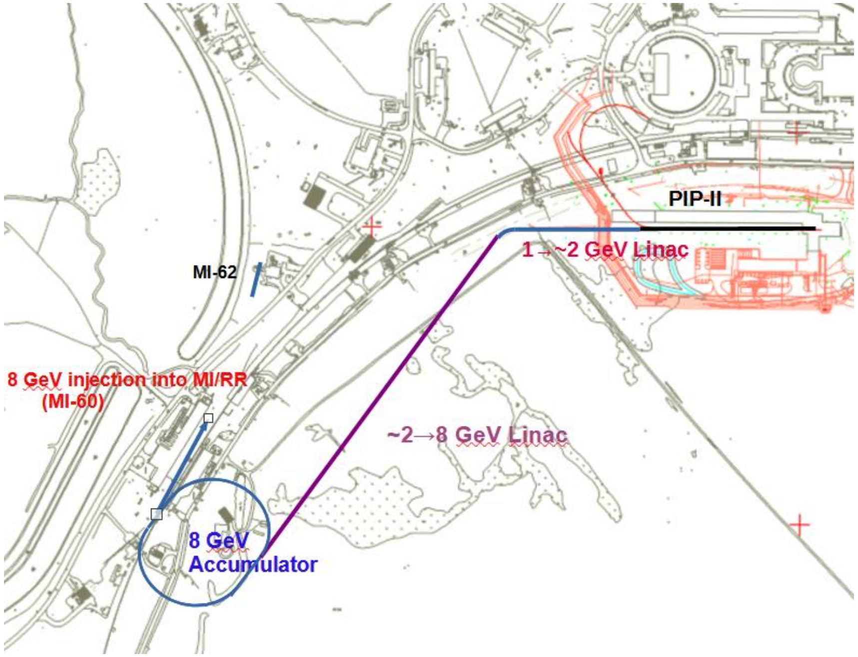
- Would need upgrade to Muon Collider parameters
  - Higher Intensity
  - Beam is in 53 MHz bunches
    - Matched to Main Injector
    - need to combine bunches

PIU → Adapt to Muon Collider

- **Overall 8 GeV power must be increased to ~ 2 MW**
  - 53 MHz bunch structure must be recombined to fit
  - Or RF Replaced with low-frequency rf

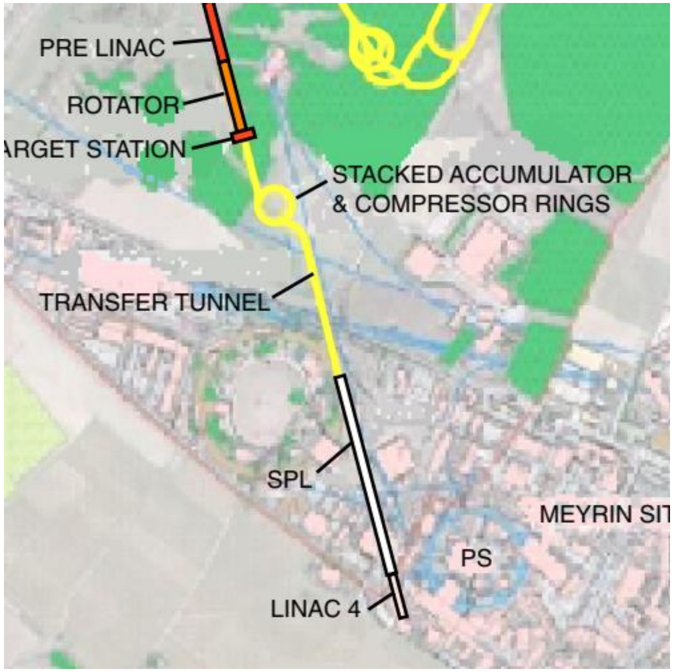


- **Accumulator/Compressor**
  - RCS or accumulator
    - 500-600 m circumference
  - Is a separate compressor ring needed ?



CERN/RAL Accumulator/Buncher

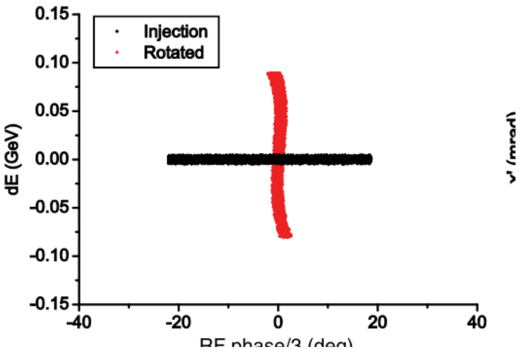
- **Early neutrino Factory Scenarios**
  - 2.2 GeV, 151m rings, 40 Mhz RF
  - RAL – 6 GeV FFAG
- **CERN Scenario (2015)**
  - E=5 GeV, C =185m→200m



  - CERN PS + ?
  - Has low – harmonic rf

TABLE II. Parameters of the accumulator and compressor rings for the CERN proton-driver scenario.

Parameter	Value
Accumulator ring	
Circumference	185 m
No. of turns for accumulation	640
Working point (H/V)	7.37/5.77
Total bunch length	120 ns
rms momentum spread	0.863×10^{-3}
Compressor ring	
Circumference	200 m
No. of turns for compression	86
rf voltage	1.7 MV
Gamma transition	2.83
Working point	4.21/2.74



Has anyone done 200 kJ pulses ??

- JPARC MR
  - Large emittance beams
  - Low frequency RF
  - 30 GeV in MR
- Demonstrates that Proton Driver is Possible

Could be upgraded to μ proton driver

0.3 Hz → 1 Hz

Add Compressor ??

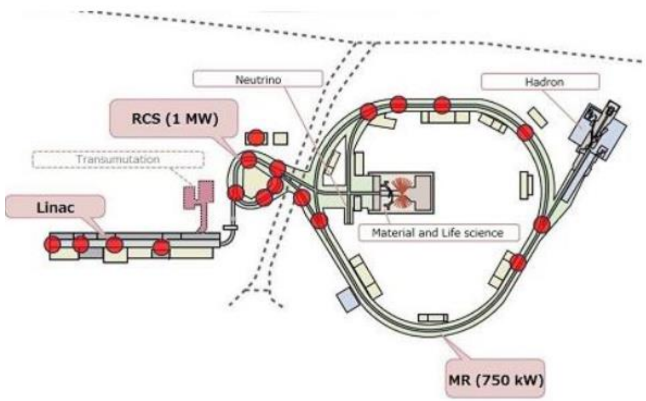


Table 2: Summary of proton drivers

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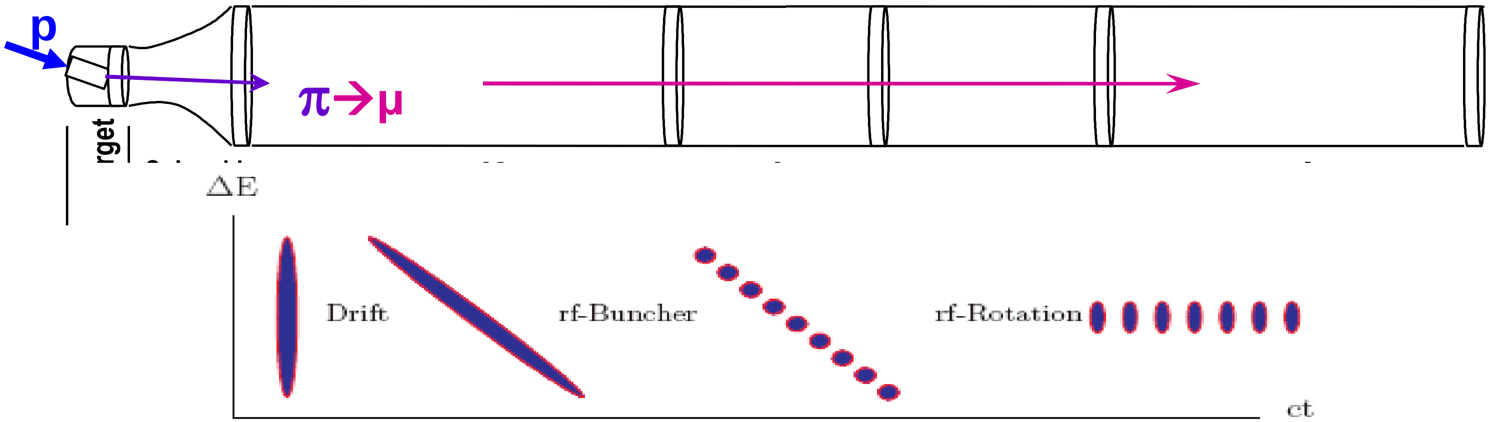
Parameter	MAP	JPARC RCS	JPARC MR
Injection E	8	0.4	3 GeV
Top Energy	8	3	30-50 GeV
Power	4MW	1MW	0.67-1.1 MW
Frequency	15	25	0.3 Hz
Emittance, 95%, N	30π	153π	153π mm-mrad
Admittance	50π	200π	300π
p/cycle	2.1×10^{14}	8.4×10^{13}	3.5×10^{14}
bunches	4→1	2	8
N/bunch	**5.2×10^{13}→ 2.1×10^{14}**	**4.2×10^{13}**	**4.2×10^{13}**
kJ/bunch	**67→268**	**20**	**200→320**
Circumference	308.2	348	1568m
Tune	7.94/6.91	6.7/6.3	22.3/22.3
γ_t	9.07	9.14	i31.7
Beam pipe R	5	12.5	6.5cm

IPAC16, TUPMY005

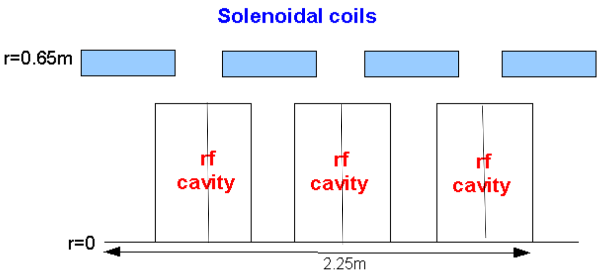
Buncher and Phase Rotation for Muons

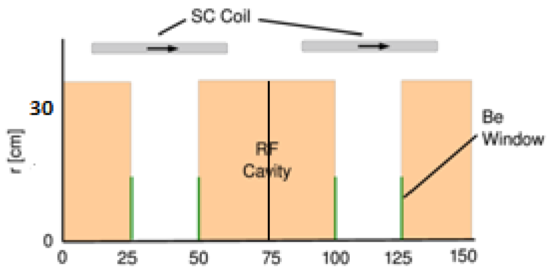


- **After bunching protons to short bunch on target**
  - Muons: short bunch to train of bunches for cooling
- **High Frequency buncher and phase rotation**
  - High frequency because we need high gradient
- **Works much better than expected**
  - Captures both μ^+ and μ^-

Rf Buncher/Rotator requirements

- **Buncher -21m**
  - **37** cavities (**14** frequencies)
  - **13** power supplies **(~1—3MW)**
- **RF Rotator -24m**
  - **64** cavities (**16** frequencies)
  - 20 MV/m, 0.25m
  - ~**2 MW** (peak power) per cavity
- **Cooling System – 325 MHz**
  - 200 0.25m cavities (75m cooler), **25MV/m**
  - ~**4MW** /cavity





Front End section	Length	#rf cavities	frequencies	# of freq.	rf gradient	rf peak power requirements
Buncher	21m	42	484 to 365	14	0 to 16	0—1.34 MW/cavity
Rotator	24m	56	364to 326	16	20	~2.4 MW/cavity
Cooler	75m	200	325	1	25 MV/m	~3.7MW/cavity
Total df+bxr+rttr	~134m	93		30	~500MV	140MW
6-D cooler	126m	360	325 MHz	1	25 MV/m	~3.7 MW

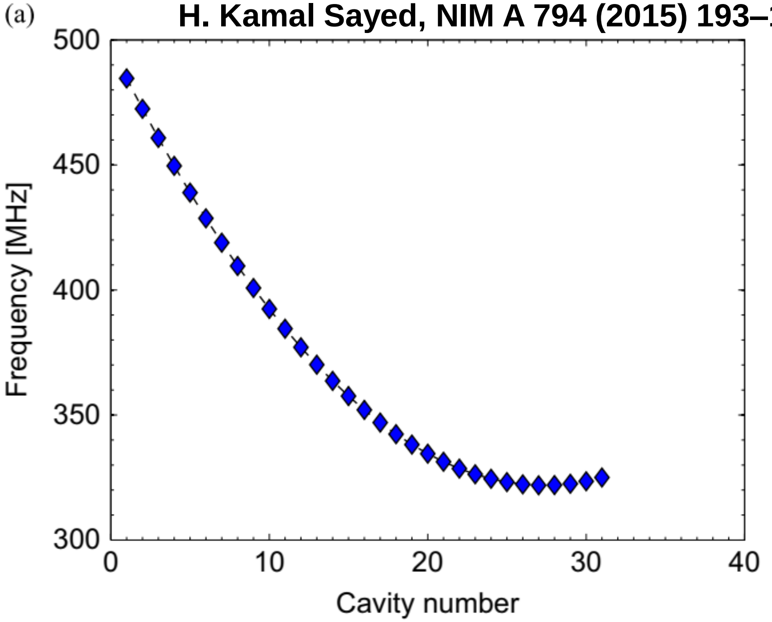
Optimization (H. Kamal Sayed)

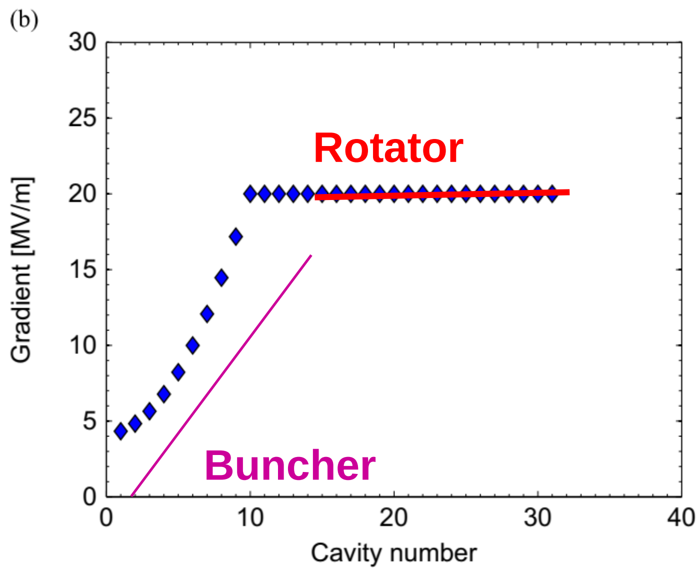
- **Buncher +Rotator-31 cavity sets**
  - Changed frequency, rf gradient

- **Optimized using NERSC supercomputer using evolutionary optimization algorithm, 100's of simulations**
  - Increase E_{rf} in Buncher
    - By ~4 MV/m
    - **Not very adiabatic**
  - Rf reaches 325 MHz faster …
    - Could use shorter system ?
    - Could start further downstream

- System could use more optimization

H. Kamal Sayed, NIM A 794 (2015) 193–199





Variations tried, or to try

- **Gas-filled or Vacuum-filled rf**
  - Gas-filled to prevent breakdown,   may not be needed
  - Both can be done
- **201.25 MHz front end**
  - Lower frequency → shorter bunch train
    - 21 → 12 bunches –easier to combine
    - ~1/2 number of cavities; larger apertures
  - Lower gradient for same performance (similar power)
- **Include some cooling in buncher/rotator or before HFOFO**
  - Combine cooling approaches.
- **Chicane after target to reduce downstream losses**
  - in Baseline design
- **Change magnetic fields**
  - 2T → 3T focusing increases mu's by ~15%

Thank you for your attention