MC/NF Proton Driver

D. Kelliher (ISIS/RAL/STFC) with thanks to C. Prior.

26/1/2024, Proton Complex Monthly meeting

Based on slides first presented on 24/11/2023, UK Muons Beams Collaboration 2023

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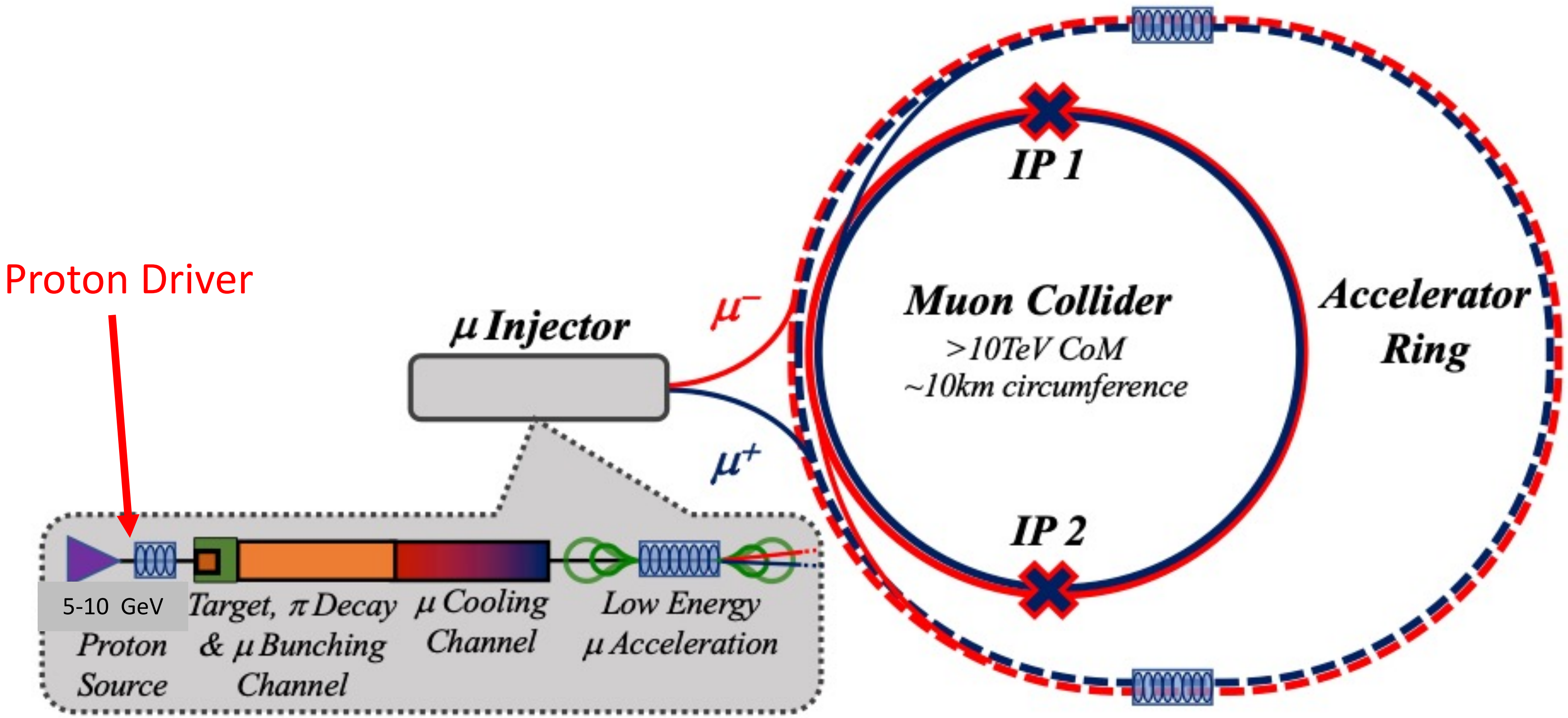
Muon collider schematic



Schematic: C. Carli, FFA'22 workshop

Proton driver parameters

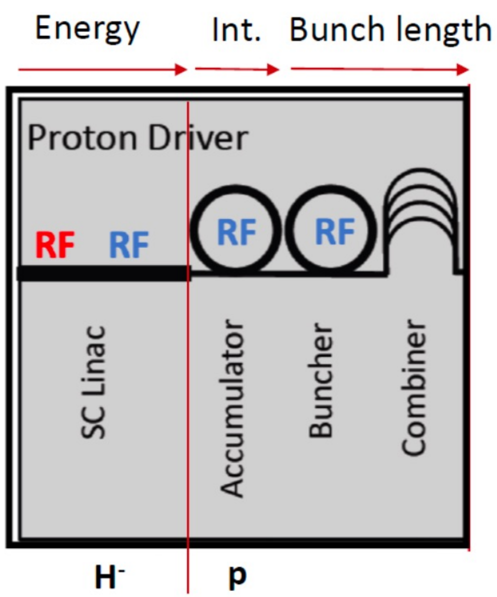


Table 3.1: Tentative Parameters for the H$^-$ Linac.

Parameters	Linac Symbol	Unit	Value
Final energy	E_{Linac}	GeV	5.0
Repetition rate	-	Hz	$\geq$5
Max. pulse length	-	ms	2.0
Max. pulse current	I_{Linac}	mA	40.0
Norm. rms emittance	ε_{Linac}	mm.mrad	2.5
Power	P	MW	2.0 (4.0*)
RF frequency	f_{RF}	MHz	352 and 704

* Possible future upgrade. Higher powers will be included in the study once a baseline solution is available.

Table 3.2: Tentative parameters for the compressor.

Parameters	Symbol	Unit	Option 1	Option 2
Energy	E_{Ring}	GeV	5	10
Circumference	C	m	between 300 and 900	
Protons on target	n_p	-	5×10^{14}	2.5×10^{14}
Final rms bunch length	σ_z	ns	2	
Geo. rms. emittance	$\varepsilon_{x,y}$	π mm mrad	> 5	
Number of turns for phase rotation	N_{rot}	-	50	

- Tentative parameters for H- linac, accumulator and compressor rings submitted (EU milestone document, Nov 2023).
- **Accumulator ring (AR)** to generate bunch intensity and time structure.
- **Compressor ring (CR)** reduces bunch length to ~ns level.

The challenge of the proton driver is to produce high intensity (2 MW) short bunches (2ns rms) at low rep rate (5Hz)

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SPL as driver for Neutrino Factory

- 5 GeV H- from SPL operating at 50 Hz
- 6 bunches, 120µs duration, injected into AR and then into the CR
- **Zero phase slip** in AR to maintain bunch separation during accumulation (no RF needed in this case).
- CR features **negative bends** to minimise dispersion while maintaining high phase slip (rotation rate $\propto \sqrt{\eta}$) .

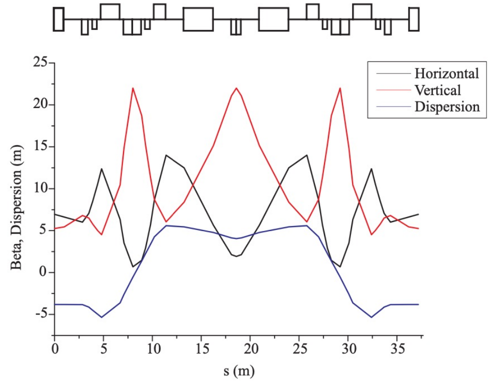
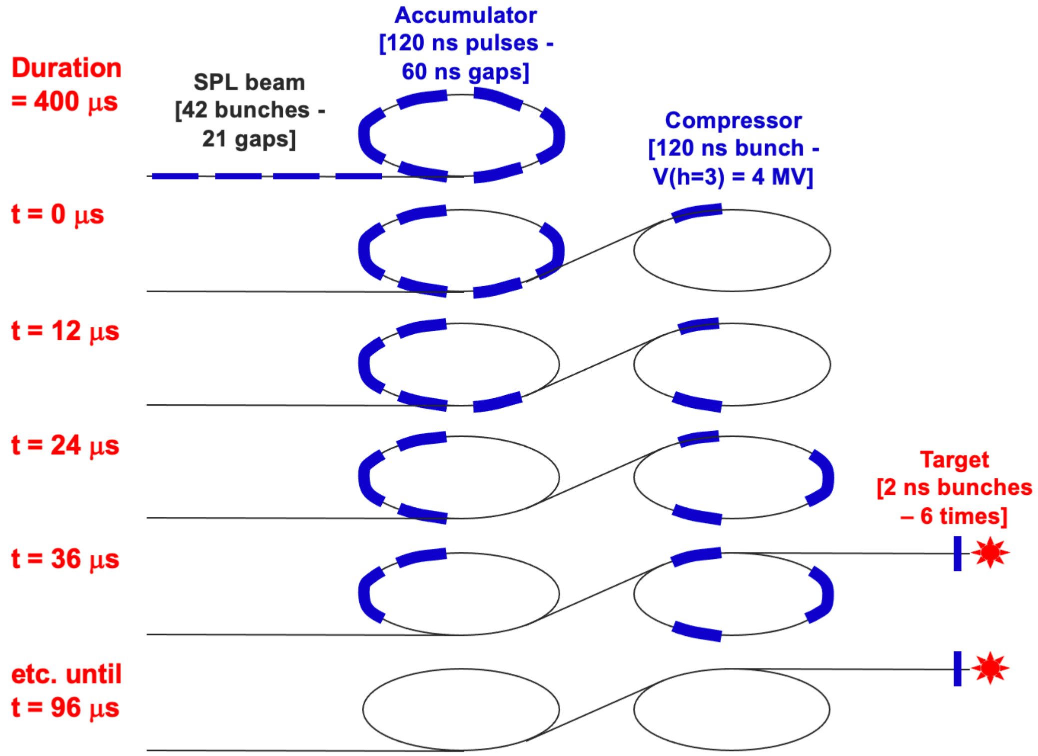


Figure 10: Arc cell with positive and negative bending magnets. Spaces of 1.85 m are retained at the both ends of superconducting magnets. They are necessary for coil-ends, connections, etc.

$$\eta \sim \alpha_c \text{ and } \alpha_c = \frac{1}{C}\int_0^C \frac{D(s)}{\rho(s)} ds$$



Alteratively, introduce phase slip to mitigate instabilities, barrier RF for bunch separation.

M. Aiba, CERN-AB-Note-2008-048, 2008

Bunch rotation

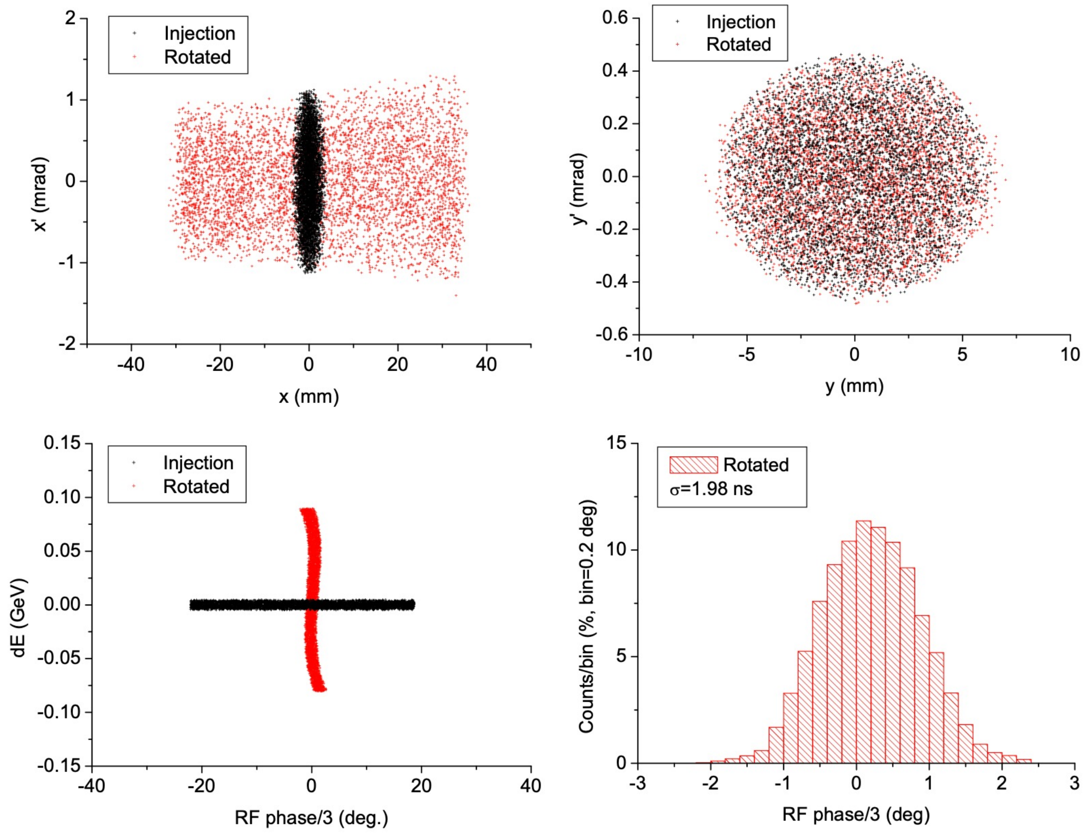
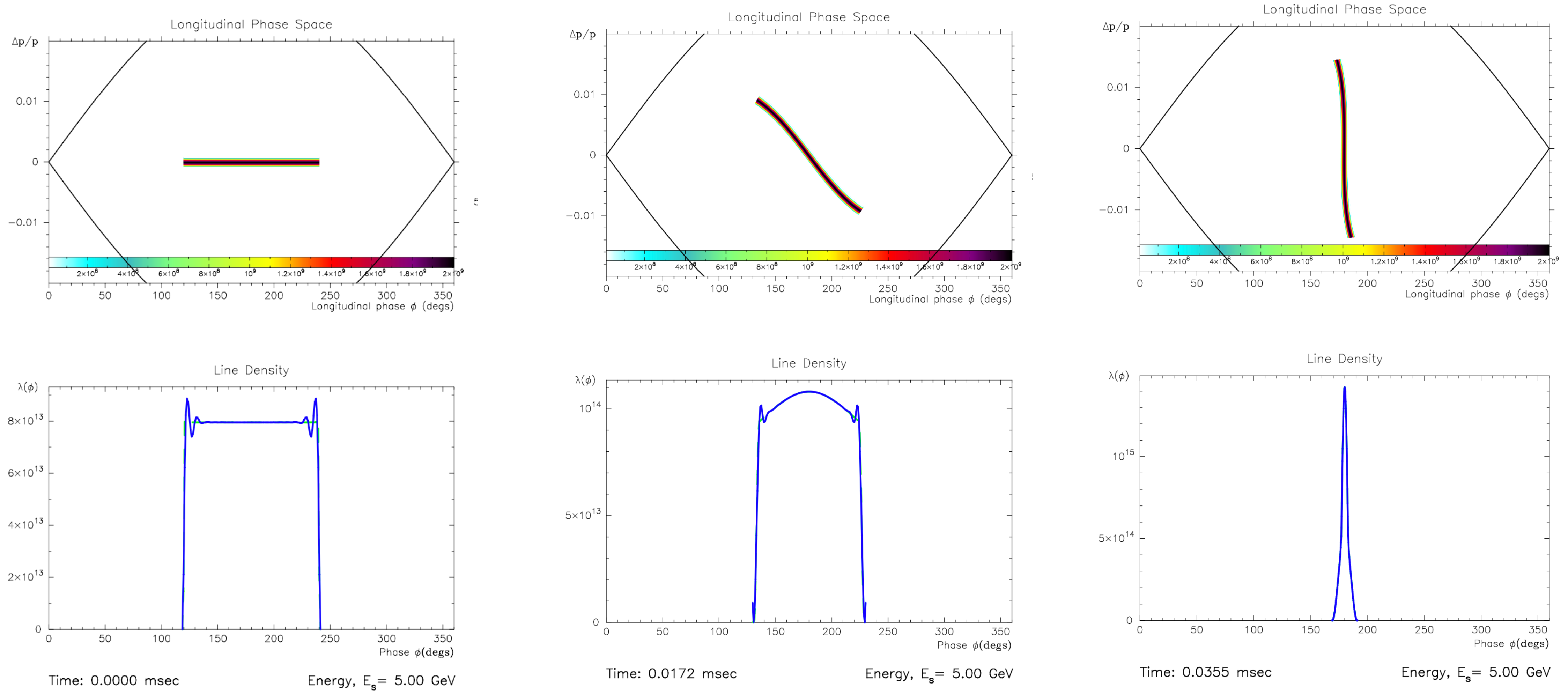


Figure 14: Phase rotation simulation.
The r.m.s. bunch length of 1.98 ns is achieved with tuning of rf voltage and initial longitudinal position (3.8 MV and -1.7 degree).

- Rotation in 36 turns.
- Results of 6D ORBIT simulations including space charge shown in figures.
- Bunch length reduced from 120ns to 2ns.
- Horizontal size spread by dispersion. This helps to reduce the space charge tune shift.

Longitudinal tracking study (no SC)



- Repeat study in longitudinal plane only (C. Prior). No space charge.
- Minimum rms bunch duration is 3.4ns.

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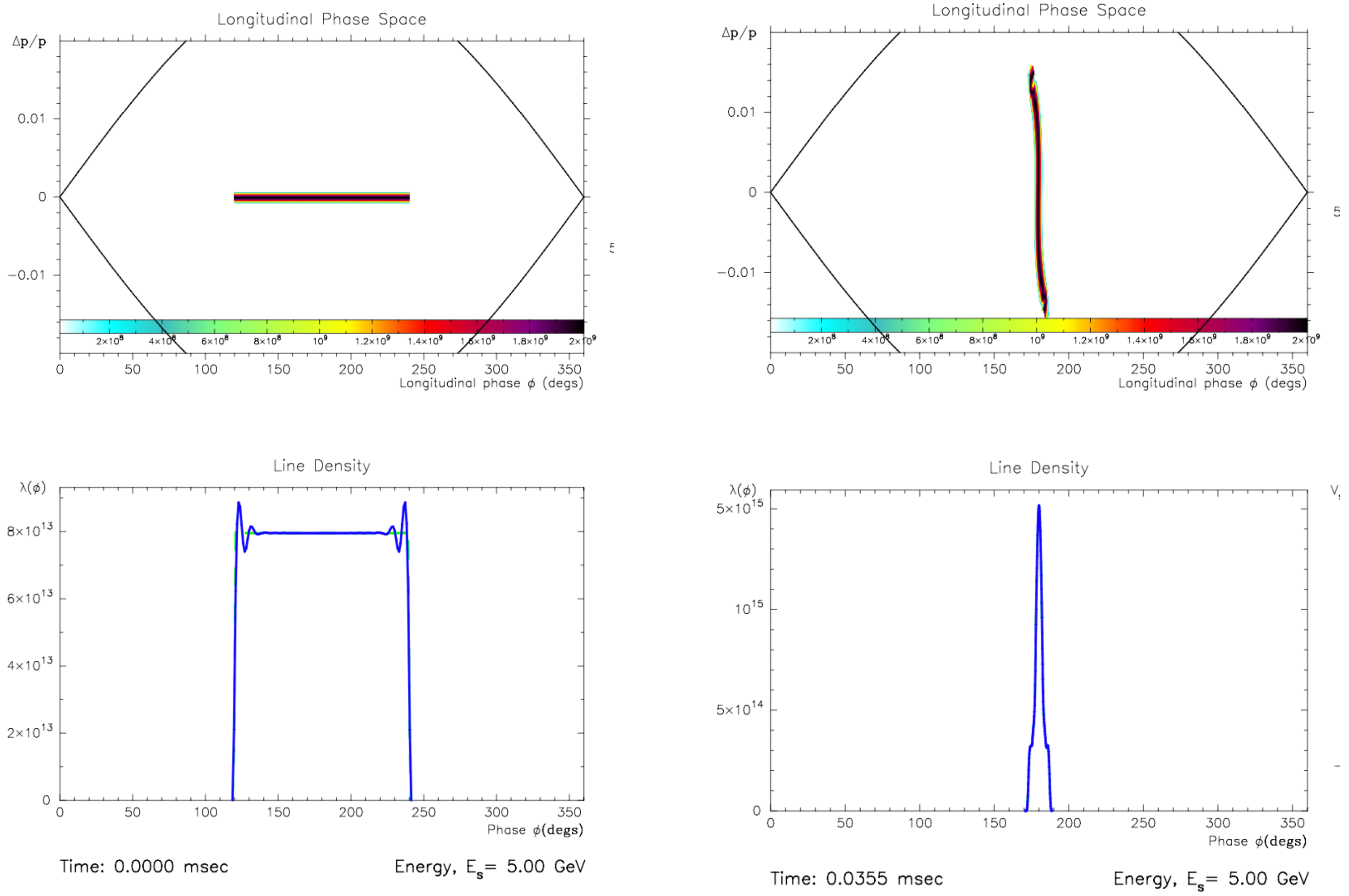
Longitudinal tracking study (with SC)



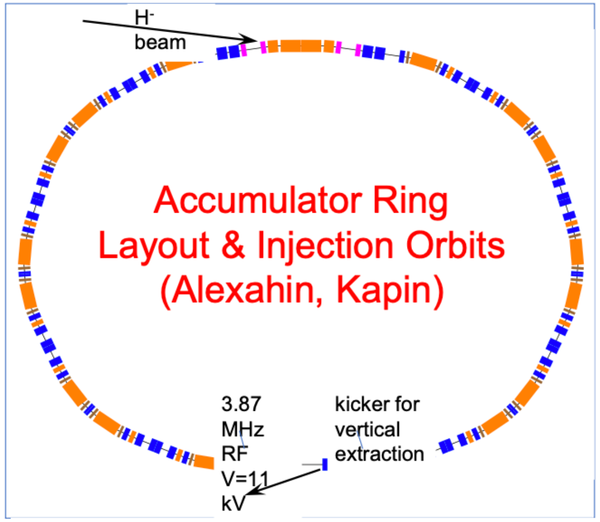
- SC included. Intensity 5e14/3 particles per bunch.
- Minimum rms bunch duration is 3.0ns (SC increases bucket size above transition).

FNAL design for proton driver

Table 1: FMC Accumulator and Compressor Parameters

Parameters	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	0.02/0.02	0.14/0.16
Betatron tunes, h/v	7.94/6.91	6.76/8.44

- Aim for high η in AR to suppress instabilities and low η in CR to reduce required voltage (unlike the SPL design!).
- Adiabatic compression in the AR to reduce rms bunch length to 30ns (RF voltage increases from 5kV to 10kV in 16ms).
- Flexible Momentum Compaction lattice to modify the dispersion while keeping phase advance fixed.



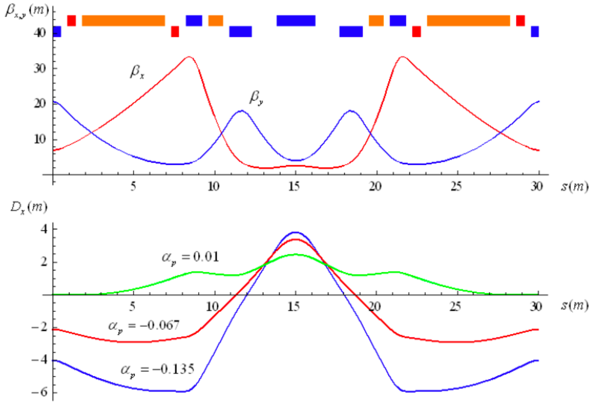


Figure 1. AR arc cell layout and optics functions. The rectangles at the top depict bends (orange), quads (blue) and sextupoles (red). α_p is varied by changing the central quad strength.

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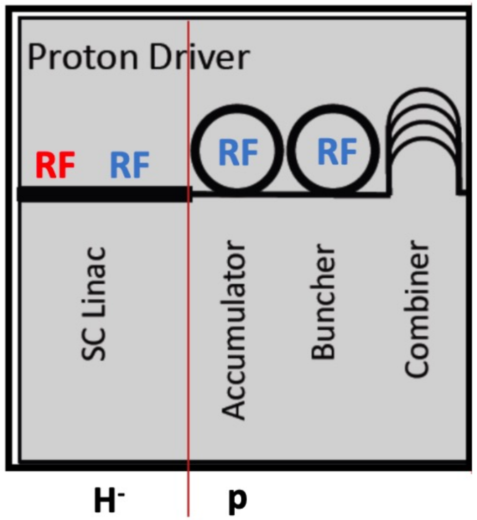
Y. Alexahin, L. Jenner, D. Neuffer, Proc. Of IPAC2012, TUPPC043 (2012)



- Beam Power: 2 MW
- Rep. rate: 10 Hz
- Beam spot size: ~ 5 mm (1σ)
- Bunch length: 2 ns = 0.6 m (rms)
- Beam Energy: 8 GeV
- Linac + 2 rings (initial design)
  - Combine 4 bunches on target

Compact AR/CR

- Recently compact AR & CR rings were proposed by S. Nagaitsev.
- Start by relating space charge tune shift and circumference:

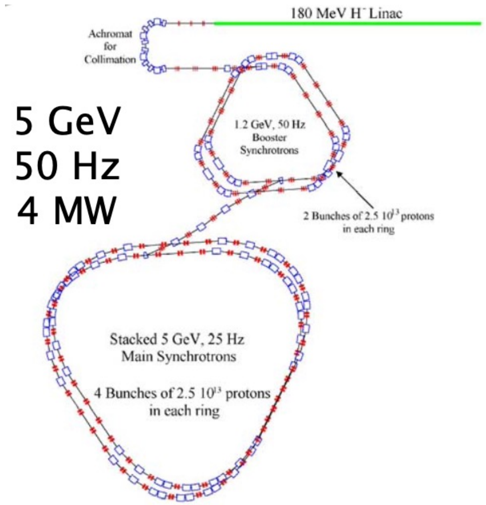
$$\delta\nu \approx -2 \times 10^{-7} \frac{C}{\varepsilon_{n,rms}}$$

- Assume $\varepsilon_{n,rms}$=100µm, then C = 100m to obtain δν=0.2.
- 3T magnets in compressor ring assuming 60% packing factor. Large aperture (~20 cm) SC magnets at h – 4 (~10 MHz).
- 20ns bunches extracted from AR.
- AR would have same radius as CR, or optionally 300m to allow NC magnets.

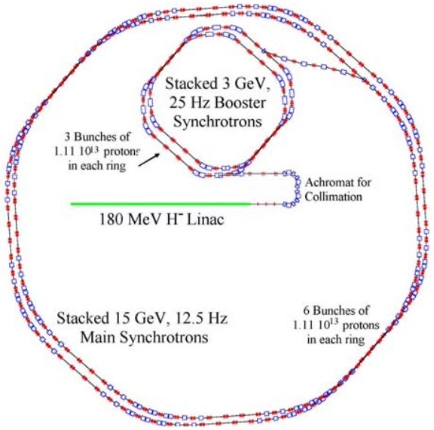
S. Nagaitsev, presented at "Fermilab ACE Science Workshop", 14th-15th June, 2023

Rings with acceleration

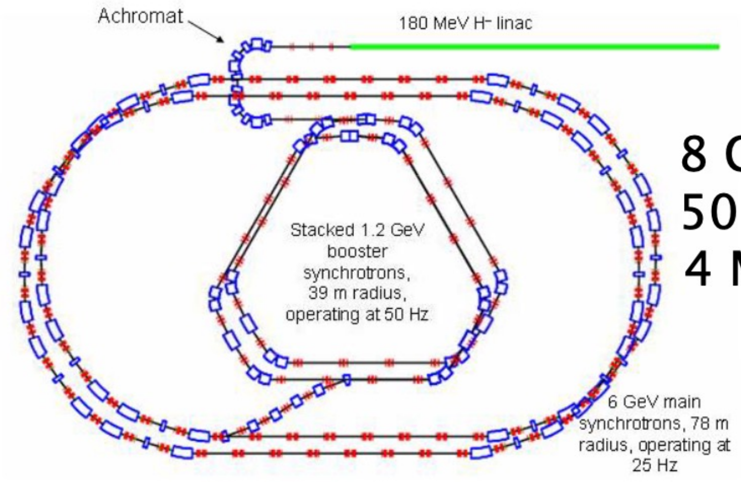
- In the case the linac is not full energy, RCS or FFA rings may be considered. Various combinations of such rings have been considered for the NF case.
- Scaling FFAs are fixed field machines with modest orbit excursion. The tunes are fixed .
- FFAs allow the beam to be stacked at the top energy before extraction, circumventing the space charge limit at injection.



5 GeV
50 Hz
4 MW



15 GeV
25 Hz
4 MW



8 GeV
50 Hz
4 MW

FFA for NF proton driver (G. Rees)

High intensity ~1014 protons

- Achieved with phase space painting in RCS booster

50 Hz rep rate

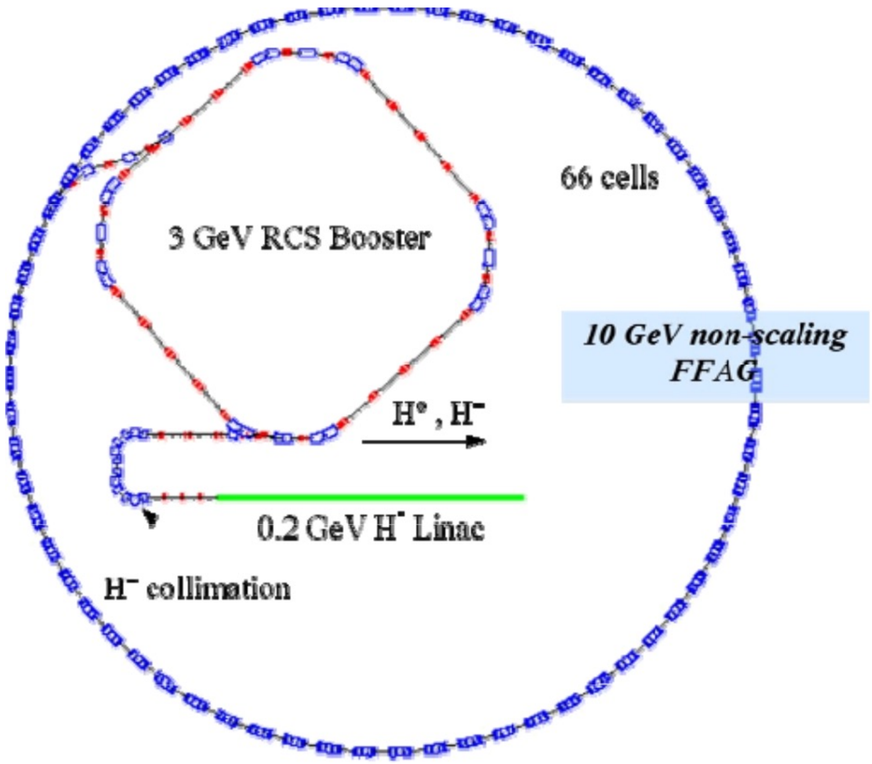
Booster circumference 400m

FFA circumference ~800m

Bunch area (h=3) 1.1 eV. Sec

ns bunch compression

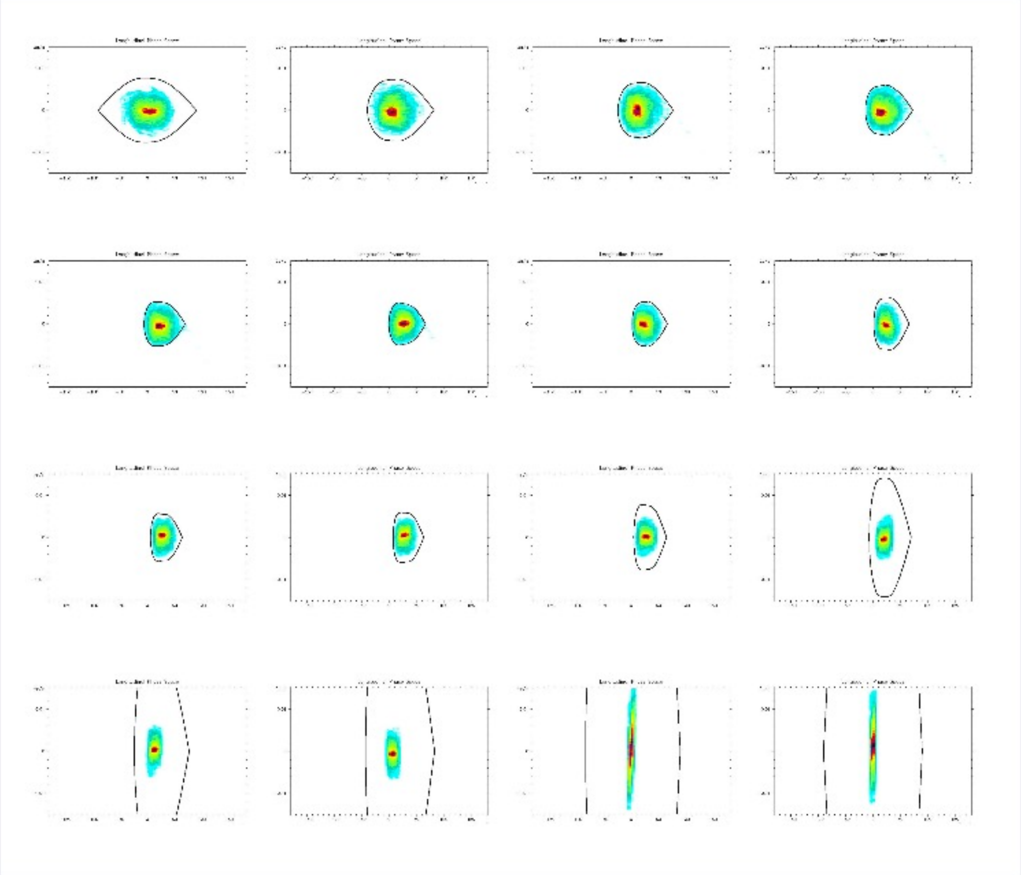
- Achieved in FFA ring
- 1.3 MV/turn for 3ns rms



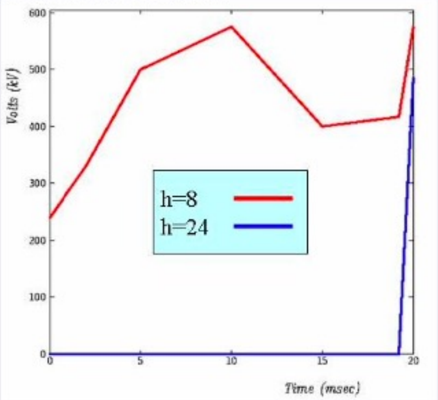
Slide: C. Prior (2007)

Bunch compression in RCS (C. Prior)

- Approach, but don't cross, γ_t during acceleration.
- As bucket becomes increasingly squeezed, bunch is compressed.
- Switch on high harmonic RF in the last few ms to compress further.



Final compression enhanced by addition by $h = 24$ voltage and achieved by converging on isochronous conditions.

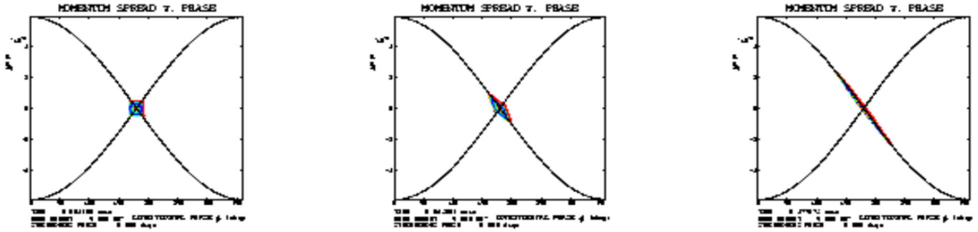


Use unstable fixed point (C. Prior)

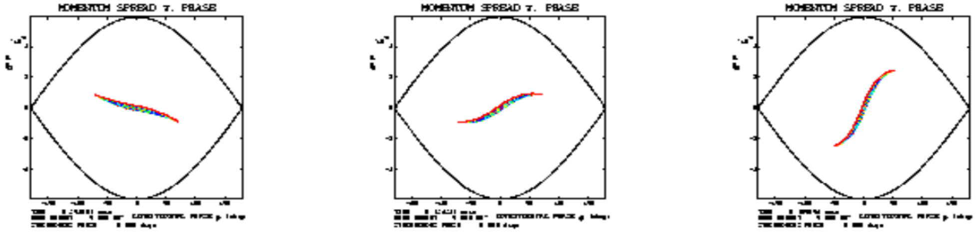
- Switch phase of RF to unstable fixed point to stretch bunch.
- Then switch back to stable fixed point so bunch rotates to upright position with minimum length.
- Distortion of bunch in non-linear voltage region.
- Separate compressor ring with with $\gamma > \gamma_t$ and zero RF voltage can result in improved bunch length.

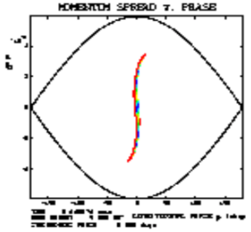
Neutrino Factory: Creation of Short Bunches I

Step 1. Bunch lengthening at unstable fixed point in RCS, $V = 2$MV, $h = 4$, $\gamma < \gamma_t$



Step 2. Phase change of 180° transfers bunch to centre of stable region, where synchrotron motion rotates it to upright (compressed) state. Final bunch length = 1.7 ns (rms).





Bunch length (nsec)	$(\pm)12.5 \rightarrow 48.3 \rightarrow 13.9$
rms	$5.59 \rightarrow 16.9 \rightarrow 1.66$
$\frac{\Delta p}{p}$	$\pm 5.0 \times 10^{-3}$ $\rightarrow \pm 2.48 \times 10^{-2}$ $\rightarrow \pm 3.45 \times 10^{-2}$
γ_t	10.375
Volts (MV)	2.0
Harm. no.	4

Conclusions

- Various solutions for the NF/MC proton driver have been proposed.
- The proton driver rings are high intensity, high energy machines – foil heating, instabilities and beam loss are issues to be studied in detail (is laser stripping an option?).
- In fixed energy compressor rings, bunch may be rapidly rotated in a large RF bucket (non-linearities at high amplitude introduce wiggles).
- In rings with acceleration, bunch may be compressed adiabatically ($\gamma \rightarrow \gamma_t$).