ISS Muon Bunch Structure

Convenors: S Berg, BNL, and G H Rees, RAL

ISS 201 MHz Bunch Structure Options

(Separate comparison later for lower frequencies)

Single train of 80 μ^+ and 80 μ^- bunches/cycle?
Or, n trains of 80 μ^+ and 80 μ^- bunches/cycle?

Factor of 50/3 in $\mu^\pm$ currents proposed to date:
$n = 1$ at $F = 15$ Hz, $I/nF = 50/750$ (USA)
$n = 5$ at $F = 50$ Hz, $I/nF = 3/750$ (RAL)

What are the criteria for choosing n and F?

Factors involved in choice of n and F

	Preferred values
Target thermal shock effect:	high F and energy
Design of the proton driver:	n =3, 4 or 5 ; F = 50 Hz
Beam loading in $\mu^\pm$ stages:	high n, F and radius
Switch-on power for $\mu^\pm$ RF:	low F (P scales with F)
Design of μ^+, μ^- decay rings:	n (inj) <6 ; high F (RF)

Target Effects (SB & RB)

(SB) $\pi^\pm$ and $\mu^\pm$ yields: 10 GeV a good proton energy (except for a carbon target?)

(RB) Solid Targets: Thermal shocks reduced at higher F, & by 50 μs delays of n bunches.

Liquid Target: The total duration of the proton pulse/cycle must be < 60 μs.

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Proton Drivers for the Two Cases

(n, F(Hz), T(GeV))	=	(1, 15, 26)	(5, 50,10)
Protons per bunch	=	6.4×10^{13}	10^{13}
Booster bunch L_b	=	6.4 x L_b	L_b
Bunch A (eV sec)	=	6.4 x A	A (= 0.66)
Booster harmonic	=	1	6
Driver harmonics	=	~ 6, 36, 216	36, 216
Final bunch $\Delta p/p$	=	± 2.0%	± 0.8%
Bunch Δt (ns, rms)	=	< 3 ?	$2 \rightarrow 1$
Δt compression	=	problematic	adiabatic

Proton Driver Longitudinal Bunch Area

The bunch area to be compressed (in eV sec) is:

$$A = (8R\alpha/(ch))\ ((2\ V(I-\eta_{sc})E_o\gamma)\ /\ (h\eta\pi))^{½}$$

Choose low linac energy & booster radius for A < 0.7.

Choose 200 MeV linac & 63.777 m, booster radius.
Choose n = 5, h = 6, and 10^{13} protons per bunch.
(These allow room for the RF and ease extraction).
Choose h = 36 & 216, and 2 x radius for an NFFAG.

Proton Driver Longitudinal Space Charge

η_{sc} is the ratio of the longitudinal space charge forces to the focusing forces of RF system.

η_{sc} = 1 corresponds to an RF bucket collapse.
= 0.4 gives onset of a microwave instability.

η_{sc} = 0.21 for V = 93 kV at 0.20 GeV, and
= 0.39 for V = 476 kV at 3 GeV in booster.

η_{sc} = 0.11 for V = 469 kV at 3 GeV in NFFAG and
cancels the inductive wall fields at 10 GeV.
V =1.0, 2.5 MV (h=36, 216) at 10 GeV (1 ns rms).

Proton Driver Transverse Space Charge

Assume a 2-D elliptic beam density distribution.

$\Delta Q_v \;=\; - N\, r_p\, G\, F \,/\, [\, \pi\, \varepsilon_v\, (1 + a/b)\, \beta\, \gamma^2\, B_f \,]$

ε_v = normalised, 2σ vertical beam emittance

G = 1.2 and F = image force enhancement.

ε_v = 122 (π) mm mrad (2σ, normalised)

ΔQ_v = - 0.35 in booster after H^- injection

ΔQ_v = - 0.25 in driver at 3 GeV injection

ΔQ_v = - 0,14 at 10 GeV after compression.

10 GeV, 50 Hz, 4 MW Proton Drivers

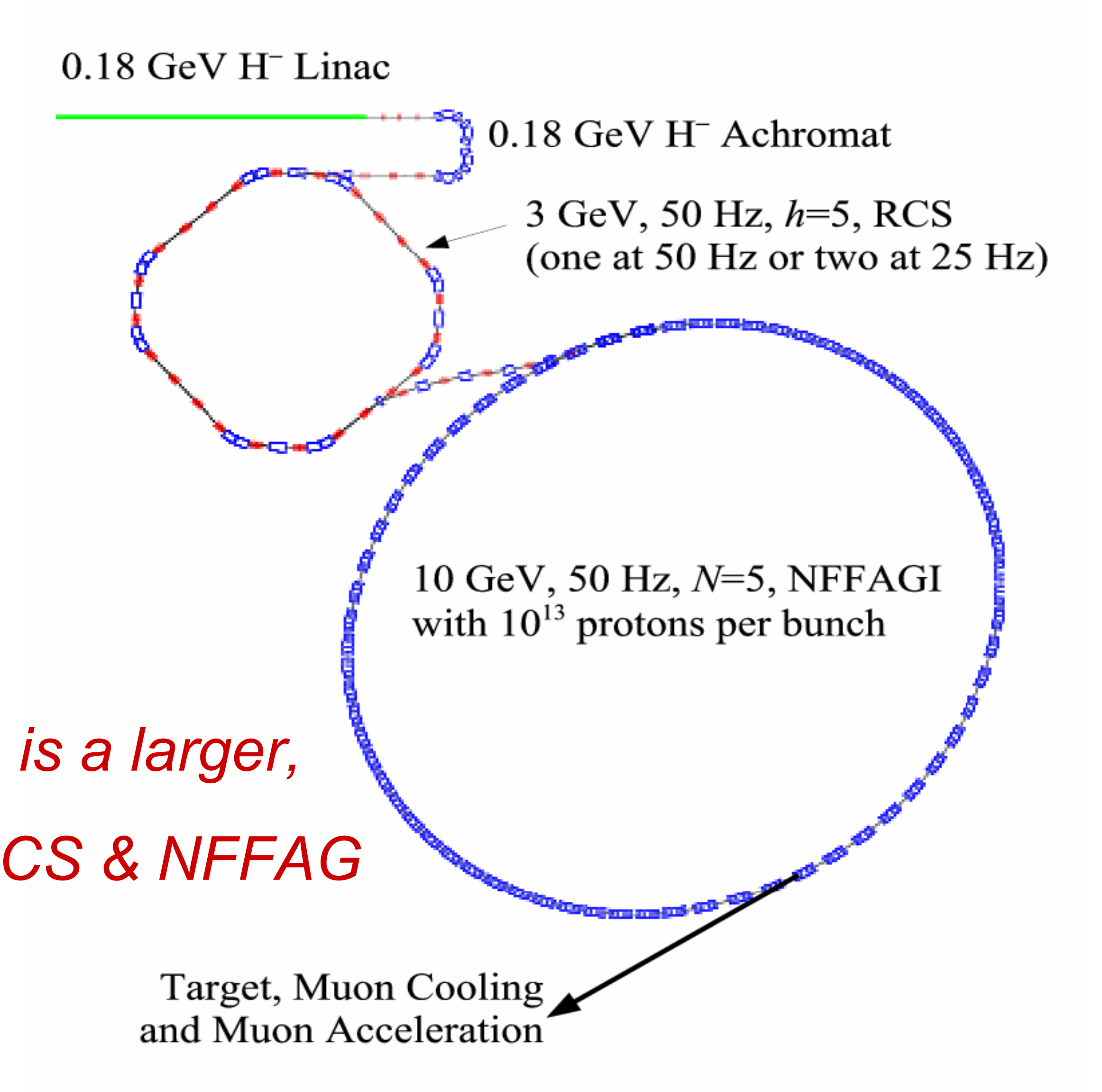
180 MeV H^- linac + 50 Hz boosters + 2, 25 Hz RCS
180 MeV H^- linac + 50 Hz booster + 50 Hz NFFAG(I)
A H^- linac feeding a chain of 50 Hz FFAGs in series

For 1, a slower RCS needs more difficult boosters.
For 2, electron models are needed for both options
For 3, injection of H^- into the first FFAG is difficult.

Typical number of bunches are n = 4, 5, …….or 1

8 GeV, 50 Hz, H^- linac + accumulator + compressor?

NFFAGI Proton Driver

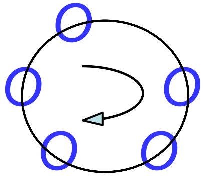


Alternative is a larger,

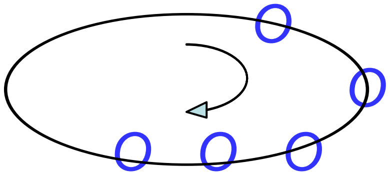
h=6,n=5 RCS & NFFAG

Proton and Muon, 50 Hz Bunch Trains

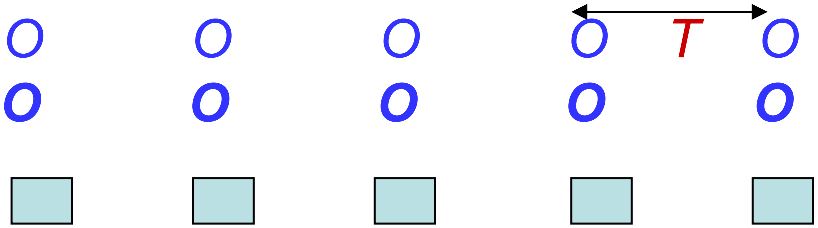
Proton booster (n=5, h=6)



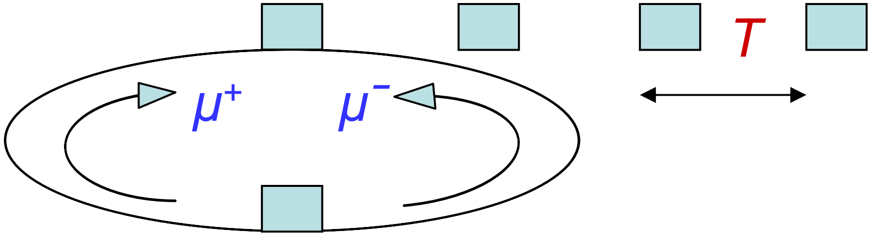
Proton driver (n=5, h=36)



Proton bunches at target
Pion bunches after target
Muon, 400 ns bunch trains

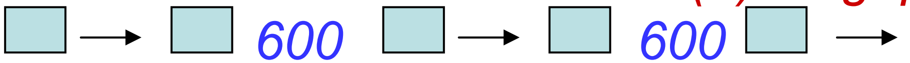


(n-1)T< 60 μs (liquid target)
T > 60 μs (for solid targets)
20 GeV μ^+ & μ^- accelerator



20/50 GeV μ^+ decay ring
C>1500 m circumference
20/50 GeV μ^- decay ring

400 ns bunch trains & 600(+) ns gaps



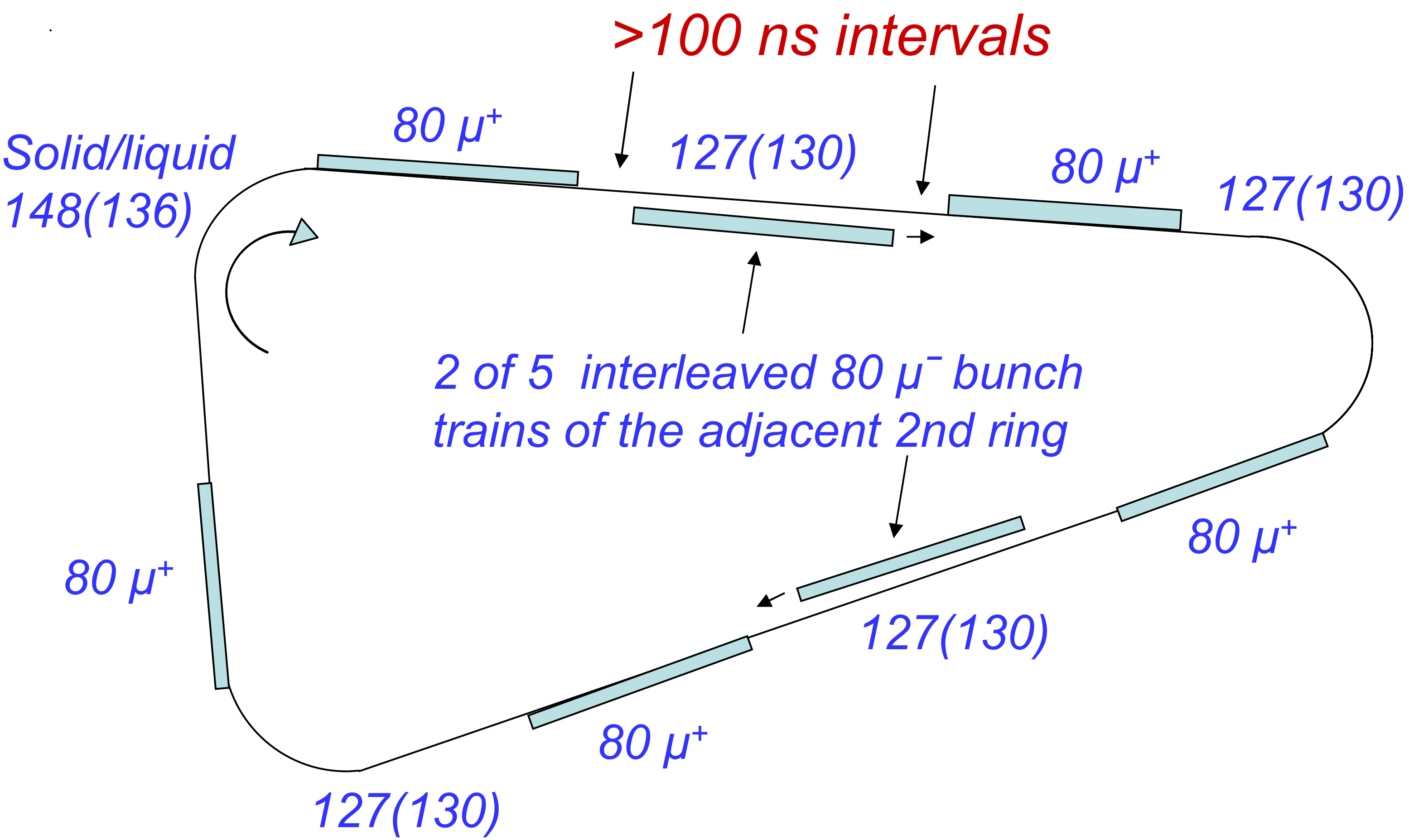
Box-car Stacking for Decay Rings

Driver has protons, while muons are to be stacked.
So, a revised method of box-car stacking is needed.

Sequential delays for proton bunches ~ 30 - 70 μs,
and an unchanging delay through the muon stages.

Times insufficient to adjust 201.25 MHz RF phases.
Make 201.25 MHz a harmonic of driver at 10 GeV.

n = 5, Muon Bunch Pattern in Decay Rings



80 full and 127 (or 130) empty RF buckets

Ring RF Harmonic Numbers

Rings	Beta	Circ (m)	h	RF (MHz)	N_b /Ring
50 GeV μ Decay	**0.9999977**	**1573.0691**	1056	201.250	**5x80**
20 GeV μ Decay	**0.9999861**	**1573.0509**	1056	201.250	**5x80**
20 GeV μ± Acc	**0.9999861**	**1135.0991**	762	201.250	**10x80**
? GeV μ± Acc				201.250	**10x80**
? GeV μ± Acc				201.250	**10x80**
3-10 GeV P Driver	**0.9963143**	**801.44744**	36	**13.079-13.417**	**5**
			216	**80.500**	**5**
			540	201.250	**5**
0.18-3 GeV Booster	**0.9712057**	**400.72372**	6	**2.5413-4.3595**	**5**

Box-car Transfer of μ^+ & μ^- to Decay Rings

The 20 GeV decay rings, 20 GeV $\mu^\pm$ acc and P driver, of periods T_d , T_a , T_p , all have a harmonic at 201.25 MHz. The integers p (= 1,2,3 ,4), n and m are chosen so the proton bunch delays are a good approximation to:

$$(n \pm p/5)\ T_d \approx (m \pm 1/12)\ T_p$$

T_d , T_a , T_p = 5.2472044, 3.7863345, 2.6832296 μs, $(T_d/T_p) = 1.9555554$

Target	m	n	p	$(m \pm 1/12)$	$(n \pm p/5)\ (T_d/T_p)$	|Difference|
solid	23	12	-1	23 + 0.083333	23.075553	0.007780
liquid	5	3	-2	5 + 0.083333	5.084444	0.001111

For solid target: $(m + 1/12)\ Tp = n\ Td - 207\ Tb$ (RF period Tb)

For liquid target: $(m + 1/12)\ Tp = n\ Td - 423\ Tb$

Summary of Proton Driver for 201.25 MHz Muon Stages ($n = 4$ considered later)

Compression harder if $n < 5$, $F < 50$ Hz or $T < 10$ GeV.

The muon decay rings limit n to a maximum at $n = 5$.

Limit F to 50 Hz because of muon RF switch-on costs.

It does not appear necessary to increase $T > 10$ GeV.

Final bunch structure depends on accel.& target sites.

201.25 MHz Muon Stages

1. Initial Bunch Rotation Stage (Neuffer / Iwashita)
   Division into 80 bunches is needed to reduce the longitudinal bunch areas and later beam losses.

2. Transverse Cooling Stage (45 → 30 → ? (mm rad))
   Helps to reduce losses during muon acceleration.
   Lowers apertures in $\mu^\pm$ rings & transfer lines ($1/\sqrt{\varepsilon}$).
   Lowers μ / ν divergence ratio in decay rings ($1/\sqrt{\varepsilon}$).
   Eases downstream kickers (power scales as ε^2).

3. Linac + Ring Options: 1. RLAs, Dog-bone, DRLAs.
   2. Linear, Non-scaling, Near-Isochronous FFAGs.
   3. Non-linear, Not-scaling, Isochronous IFFAG(I)s.

201.25 MHz Muon Acceleration

- *No allowance for emittance growth in acceleration*
  Beam loss collectors needed for high power levels.
  Long collimators for the counter-rotating $\mu^{\pm}$ beams.
  This infers long straights or insertions for the rings

- *Beam loading power for the rapid acceleration*
  This scales as 1/nFR, where R is the ring radius.
  Factor of ~ 50 higher for (1, 15Hz, low R) scheme.
  20 GeV ring: 1000 cf 20 units, for 2 MW couplers.

- *Injection and Extraction Fast Kicker Systems*
  Large systems needed for the two decay rings.
  Kickers for low R, FFAGs may not be feasible.

Aspects of 201.25 MHz Options

D/RLAs: *Kicker magnet systems not necessary.*
RF systems in zero dispersion straights.
Beam loss collectors in some of the arcs?

FFAGs: *Long.-transv. coupling at large amplitudes.*
Is there coherent trans. motion or ε growth?
How large does the final Δp/p become?

IFFAGIs: *Beam losses at Q_h = 1/3 cell resonances.*
New 9.5-20 GeV design avoids this feature.
Tracking studies haven't yet re-commenced.

μ^+ and μ^- Decay Rings

Separate rings are required to allow both fast injection and the time separations for the n (= 5) bunch trains.

For a single detector, racetrack rings are preferred.
For 2 detectors, two may be used, in own tunnels.

For two distant detectors, triangular, side by side rings in vertical or near vertical plane, have higher efficiency.

For detectors at 7500 & 3500 km, rings need to be in a near vertical plane & to have an apex angle of ~ 50°.

Features of Decay Rings

- The RF containing fields have to scale as $(\Delta p/p)^2$
- 3, 10 MV systems needed/ring for $\Delta p/p = \pm 1\%$
- Reactive beam loading compensation is needed

- 16, 50 kV PFN, 5 kA pulsers & 10 Ω feeders/ring
- 8, shorted, 3m, 10 Ω delay line, push pull kickers
- The kicker rise and fall times have to be < 600 ns

- Collimators in short straight of the isosceles Δ.
- Use of radiation hard quadrupoles is proposed

Effect of n = 4 in smaller Decay Rings

Benefits are smaller depth, cheaper tunnels for decay rings.

Efficiency of the two racetracks is reduced from 38 to 35%.
Efficiency of two, 50° apex rings is reduced from 48 to 43%.

Options (last is favoured) for changes needed to Proton Driver:
1. F = 62.5 Hz; RF costs up in both Proton Driver and $\mu^{\pm}$ rings.
2. T = 10 → 12.5 GeV (4 -12.5 or 3-8 and 8-12.5, GeV FFAGs).

3. N = 1.0 → 1.25 10^{13}/bunch; RF costs up in Driver & $\mu^{\pm}$ rings.
   Lower frequency, longer cavity, RF systems are required.

N = 1.66 10^{13}/bunch for n = 3 is also feasible (bunches longer).

Lower Frequency Muon RF Systems

Examples: Scaling FFAG schemes (KEK),
44/88 MHz RF systems (CERN).

KEK:

A low repetition rate, 3-50 GeV, Proton Synchrotron.
A chain of variable low frequency, scaling FFAGS.

RF systems compensate for cavity and beam power.

No transverse cooling & no separate bunch division.
Apertures are enhanced in scaling FFAG magnets.

Issues for Low Frequency Muon RF

RF systems & power costs are key considerations.
More space & switch-on power needed for cavities?

Issues little changed for the Proton Driver (n = 7?).
Keep F at 50 Hz to limit beam loading in $\mu^{\pm}$ rings.

How to provide transverse cooling at low frequency?
Possibility of NFFAGs or IFFAGs instead of FFAGs?

Bunch Structure Issues

1. *Change from 1 to ≤ 5 bunch trains per cycle?.*
2. *Use 50 Hz, 4 MW, 10 GeV Proton Driver, $n=5,4,3$?*
3. *Use proton bunch delays for low μ beam loading?*
4. *Compare low & high frequencies for muon stages.*
5. *Delay decision on $\mu^\pm$ acceleration for further R&D?*
6. *Use 201.25 MHz for $\mu^\pm$ rotation, cooling & acceln?*
7. *Create trains of 80 μ^+ & μ^- bunches while rotating.*
8. *Accelerate the bunch trains singly in the $\mu^\pm$ rings.*
9. *Provide transverse cooling to give $\varepsilon \leq 30$ mm rad?*
10. *Two rings (racetracks) needed for single detector.*
11. *Use two vert. Δ rings for best ξ for two detectors.*