

*ISS Recommendations for a Neutrino Factory  
Proton Driver*

Chris Prior

Accelerator Science & Technology Centre, ASTeC  
CCLRC Rutherford Appleton Laboratory

FFAG Workshop, KURRI, Japan, December 2006

# *Outline*

*Neutrino Factory*

*ISS Conclusions*

*Proton Drivers*

*Conclusions - Neutrino Factory*

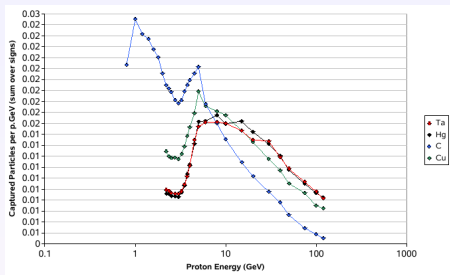
## *NF Demands on Proton Driver*

- Proton driver is first stage in an accelerator complex that is required to generate  $10^{21}$  muon decays per year
- Muon production rate is low
  - ⇒ large proton beam power  $\sim 4$  MW.
  - ⇒ pulse structure must be such that muon beam can be accelerated to final energy (25  $\rightarrow$  40  $\rightarrow$  50 GeV) before it decays.
- Choice of proton beam energy, repetition rate and pulse structure must refer to target and muon accelerator capabilities.
- Proton bunches must be compressed to a few ns (rms) but can consider proton bunch length trade-offs (cost of compression *versus* muon production).

## *Considerations for Proton Driver*

- The required production of  $10^{21}$  neutrinos per year
- Muon yields as a function of the proton energy
- Muon yields as a function of the target material
- Heating and stress levels for the target material
- Muon capture as a function of proton bunch extent
- Maximum duration of proton pulses on the target
- Peak beam loading levels in the  $\mu^{\pm}$  accelerators
- Bunch train stacking in the  $\mu^+$  and  $\mu^-$  decay rings

# Target



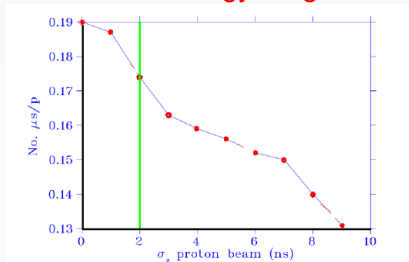
## Proton Beam Energy

- Liquid mercury jet or moving solid (tantalum?) target
- Analytical studies (MARS15 and GEANT4) explore energy for optimum pion/muon distribution/production.
- Needs confirming with HARP data.

## Bunch Length

- Find 1 ns proton bunches best but 2–3 ns acceptable;
- 12% fall-off in performance at 3 ns;
- Such short bunches are hard to achieve at low energy.

Recommend energy range 5–15 GeV



Compromise with 2 ns bunches

## *Proton Beam on Target*

### *Repetition Rate*

- Lower rate increases charge per bunch and makes bunch compression harder
- Higher rate increases RF wall power demand

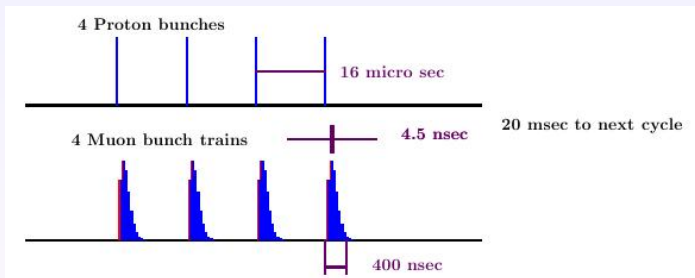
Choose 50 Hz

### *Bunch Train*

- Set to ease bunch compression difficulties
- Spacing between bunches  $\geq 400$  ns to allow use of Neuffer capture scheme

Choose 3 or 5 proton bunches per pulse

## Proton Driver Bunch Spacing



$\gtrsim 17 \mu\text{s}$  between bunches is a good compromise to:

- Avoid mercury cavitation and target density loss
- Help top up RF, correct field gradient droop and
- Reduce beam loading in downstream FFAG acceleration system

## *Summary of ISS Recommendations*

- An average beam power of 4 MW
- A pulse repetition frequency of 50 Hz
- A proton kinetic energy of  $10 \pm 5$  GeV
- An rms proton bunch duration of  $2 \pm 1$  ns
- A proton bunch number of either three or five
- A sequential extraction delay of  $\geq 17 \mu\text{s}$  per bunch
- A pulse duration of  $\leq 40 \mu\text{s}$  for a liquid mercury target
- A pulse duration of  $\leq 70 \mu\text{s}$  for a solid metallic target

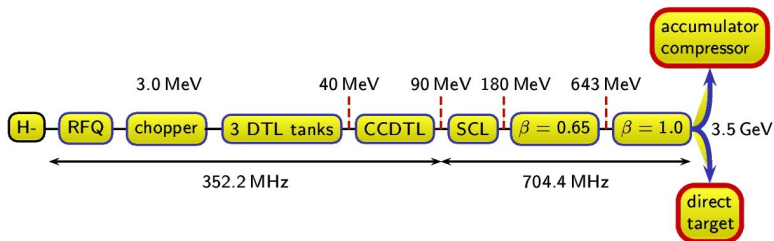
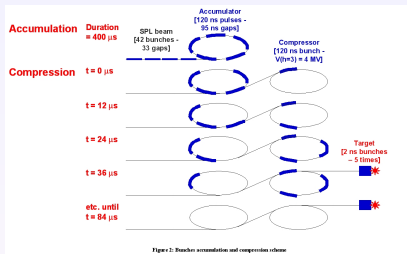
## *Proton Drivers*

### *Candidates*

- Consider which of the existing machines can be developed to meet NF requirements
- Analyse new designs.
- Compare merits of different structures – performance and cost.
  - *A  $H^-$  linac with pairs of 50 Hz booster and 25 Hz driver synchrotrons (RCS)*
  - *A  $H^-$  linac with a 50 Hz booster RCS and a 50 Hz NFFAG driver ring*
  - *A  $H^-$  linac with a chain of three non-isochronous FFAG rings in series*
  - *A  $H^-$  linac with two slower cycling synchrotrons and two holding rings*
  - *A full energy  $H^-$  linac with an accumulator and bunch compression ring(s)*

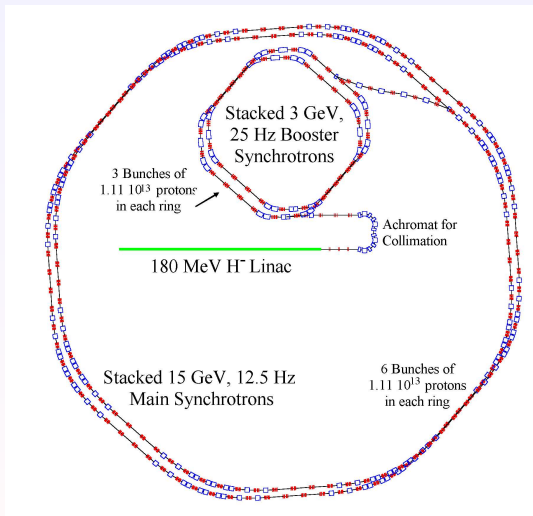
## Linac-based Proposals

- Fermilab 8 GeV Proton Linac (D. Neuffer talk?)
- CERN SPL
  - Phased construction: Linac4 to 160 MeV to feed PS Booster.
  - Add 366 m of SC RF to reach 3.5 GeV.
  - Then to 5 GeV for Neutrino Factory?



## *RCS-based Proton Drivers*

- AGS upgrades to 28 and 40 GeV
- J-PARC (3 and 50 GeV synchrotrons)
- Fermilab studies at 8 and 16 GeV
- RAL drivers at 5, 8, 15 and 30 GeV

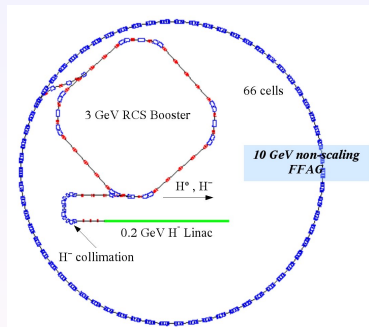


# FFAG-based Proton Drivers

*Ruggiero Model - see AGR talk*

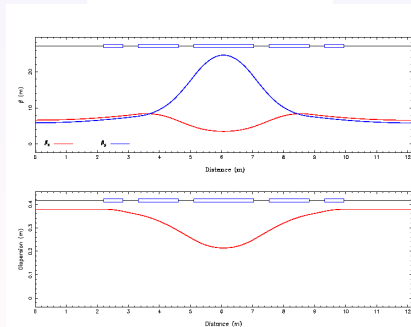
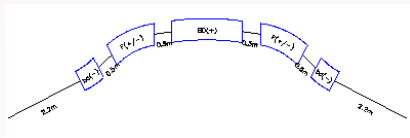
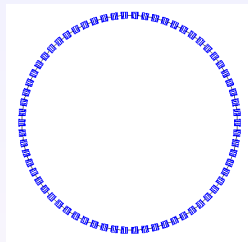
## *RAL Model*

- 50 Hz, 10 GeV, 4 MW proton driver
  - 200 MeV linac
  - 0.2–3 GeV RCS booster for efficient  $H^-$  injection
  - 3–10 GeV FFAG
  - FFAG circumference (802 m) is twice booster circumference (401 m)
  - Rotation period of protons at 10 GeV is half period of muons in decay ring
- Allows sequential delays of proton bunches on target
  - Allows muon bunch trains to pass one at a time through accelerating structures
  - e.g. 3 bunches, delay  $\sim 18\mu s$ , pulse duration on target  $\sim 37\mu s$ .



# RAL 3–10 GeV FFAG

- Non-linear, non-scaling, non-isochronous ring
- Can include insertions but omitted for the present
- 3 non-linear magnet types in 5-magnet cells (“pumpet”)
- Constant betatron tunes during acceleration



## *FFAG versus other options*

- High duty cycle, lower RF accelerating fields
- Adiabatic bunch compression; bunches may be held at top energy
- Metallic vacuum chambers c.f. ceramic with RF shields for RCS
- Single booster and driver rings and transfer lines - cost saving
- Low beam loss and compression easier than LAR

## Table of Proton Drivers

$\tau_p$  = pulse duration,  $N_b$  = number of bunches per pulse,  $\tau_b$  = final compressed bunch length.

Driver	Power (MW)	Type	Energy (GeV)	Frequency (Hz)	Protons per pulse ( $\times 10^{13}$ )	Pulse structure		
						$\tau_p$ ( $\mu$ s)	$N_b$	$\tau_b$ (ns)
BNL-AGS	1	Synch	28	2.5	9	720	24	3
	4	Synch	28	5	18	720	24	3
	4	Synch	40	5	12.5	720	24	3
FNAL	2	Synch	8	15	10	1.6	84	1
	2	Linac	8	10	15			
FNAL MI	2	Synch	120	0.67	15	10	530	2
CERN-SPL	4	LAR	2.2	50	23	3.2	140	1
	4	LAR	3.5	50	14	1.7	68	1
J-PARC	0.75	Synch	50	0.3	31	4.6	8	6
RAL	4	Synch	5	50	10	1.4	4	1
	4	Synch	6–8	50	8.3	1.6	6	1
	4	FFAG	10	50	5	2.3	5	1
	4	Synch	15	25	6.7	3.2	6	1
	4	Synch	30	8.33	10	3.2	8	1
RAL/CERN	4	Synch	30	8.33	10	3.2	8	1
KEK/Kyoto	1	FFAG	1	$10^4$	0.06	0.4	10	10
	1	FFAG	3	$3 \cdot 10^3$	0.06	0.5	10	10

## *Conclusions - Neutrino Factory*

- Proton energy: 5–15 GeV
- Proton driver bunch structure: 3 or 5 bunches spaced by  $\sim 16 \mu\text{s}$
- Proton bunch length:  $\sim 2 \text{ ns rms}$
- Repetition rate:  $\sim 50 \text{ Hz}$

Most promising choice looks to be FFAG