Proton Driver Considerations

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Muon Collider - Preparatory Meeting, CERN, 11th April 2019

- Requirements and Proton Driver Candidates
- Muon Flux per Proton Beam Power versus Proton Energy
- Proton Driver Proposals
  - CERN SPL with Accumulator and Compressor Rings
  - FNAL MAP with 8 GeV H^- Linac with Accumulator and Compressor Rings
  - RAL Scheme with 0.8 GeV H^- Linac followed by two RCSs
  - Based on ESS adding Accumulator and Compressor Rings
- Summary

No very recent papers on proton drivers found (Muon cooling & acceleration considered more challenging aspect for μ-collider?)

Requirements and Proton Driver Candidates for Neutrino Factories and Muon Colliders

- Typical requirements

Parameter	Value	Comments
Beam Power	1 to 4 MW	Higher beam power typically for MC
Beam Energy	a few GeV (say 2 to 12 GeV)	Muon flux normalized to beam power @2GeV?
Repetition Rate	15 to 50 Hz	Lower repetition typically for MC
Number of bunches	3 to 6	To be combined to one bunch for MC
Rms Bunch Length	2 to 3 ns	
Bunch spacing		Some limitations depending on target type

Number of useful muons per proton normalized to beam energy (valid for energy range – at least from 5 to 15 GeV)

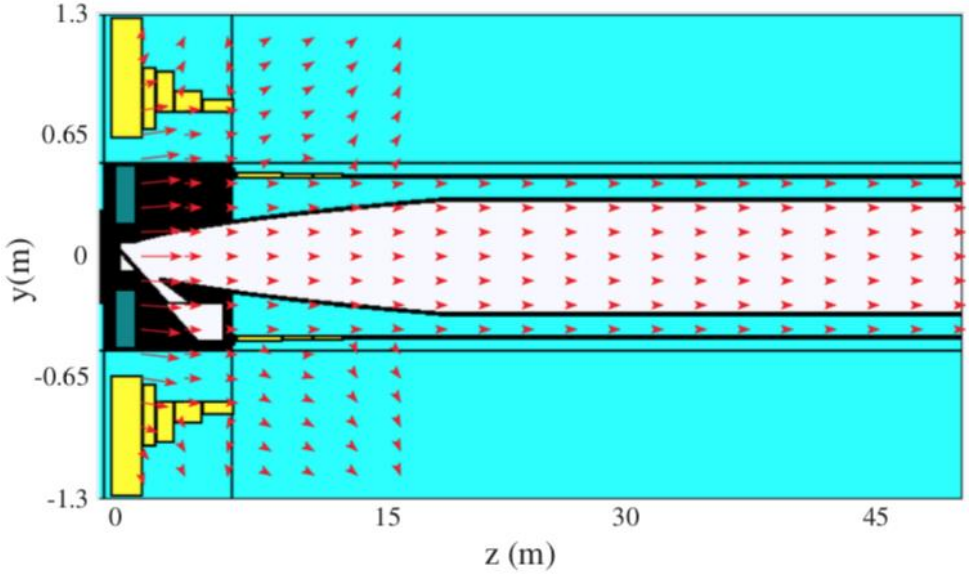
$$\frac{h}{E} = \frac{0.013}{\text{GeV}} = \frac{8.1\times10^{13}}{\text{MJ}} = \frac{8.1\times10^{13}\,s^{-1}}{\text{MW}} = \frac{10^{21}}{(12\,400\,000\ \text{s})\times\text{MW}}$$

- Candidates
  - Full Energy H^- Linac with accumulator and compressor ring
  - H^- Linac with Rapid Cycling Synchrotron(s) (possibly two in parallel)
  - H^- Linac with FFAGs
  - H^- Linac and a combination of RCS and FFAG …

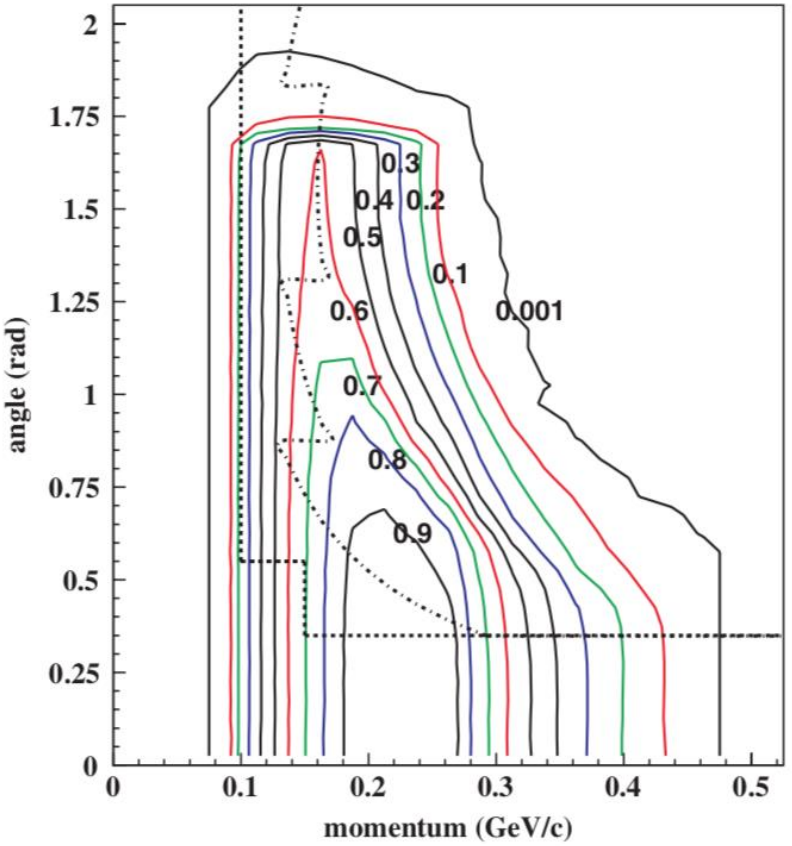
Muon Flux per Proton Beam Power versus Proton Energy

From J. Strait et al "Towards the optimal energy of the proton driver for a neutrino factor and muon collider", PRSTAB 13, 111001

- Cross section for incident proton to generate useful muon at frontend exit based on
  - Pion production (differential) cross sections measured by HARP (evaluations from two sub-groups lead to two slightly different results) for Ta



  - Acceptance of front-end optimized for 16 GeV (higher than energy of most muon frontend proposals)

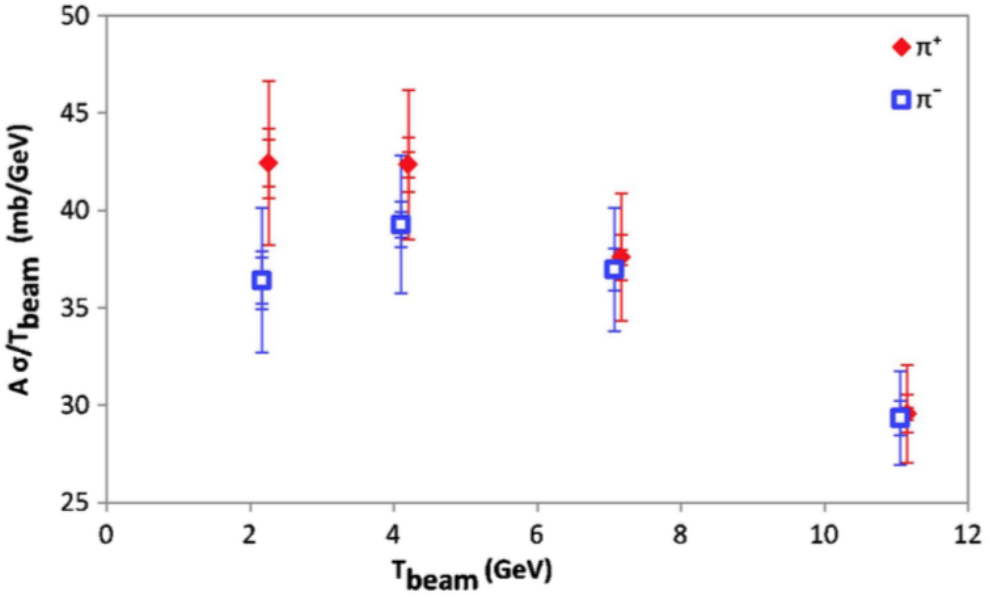


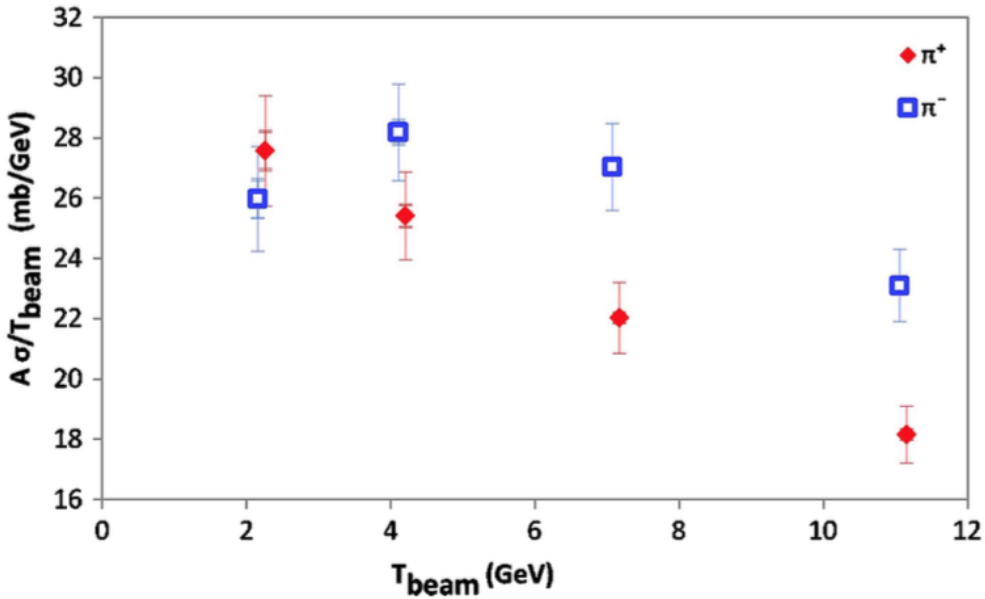
Front-end "acceptance": probability that a pion at the target leads to useful muon at the exit of the front-end

Dashed lines: regions with availability of muon production cross sections measured by HARP

Muon Flux per Proton Beam Power versus Proton Energy

- Result: cross section for generation of useful muon normalized to energy
  - Typical value σ/E = 30 mb/GeV, but significant differences depending on which pion cross section result is used, some variations with energy



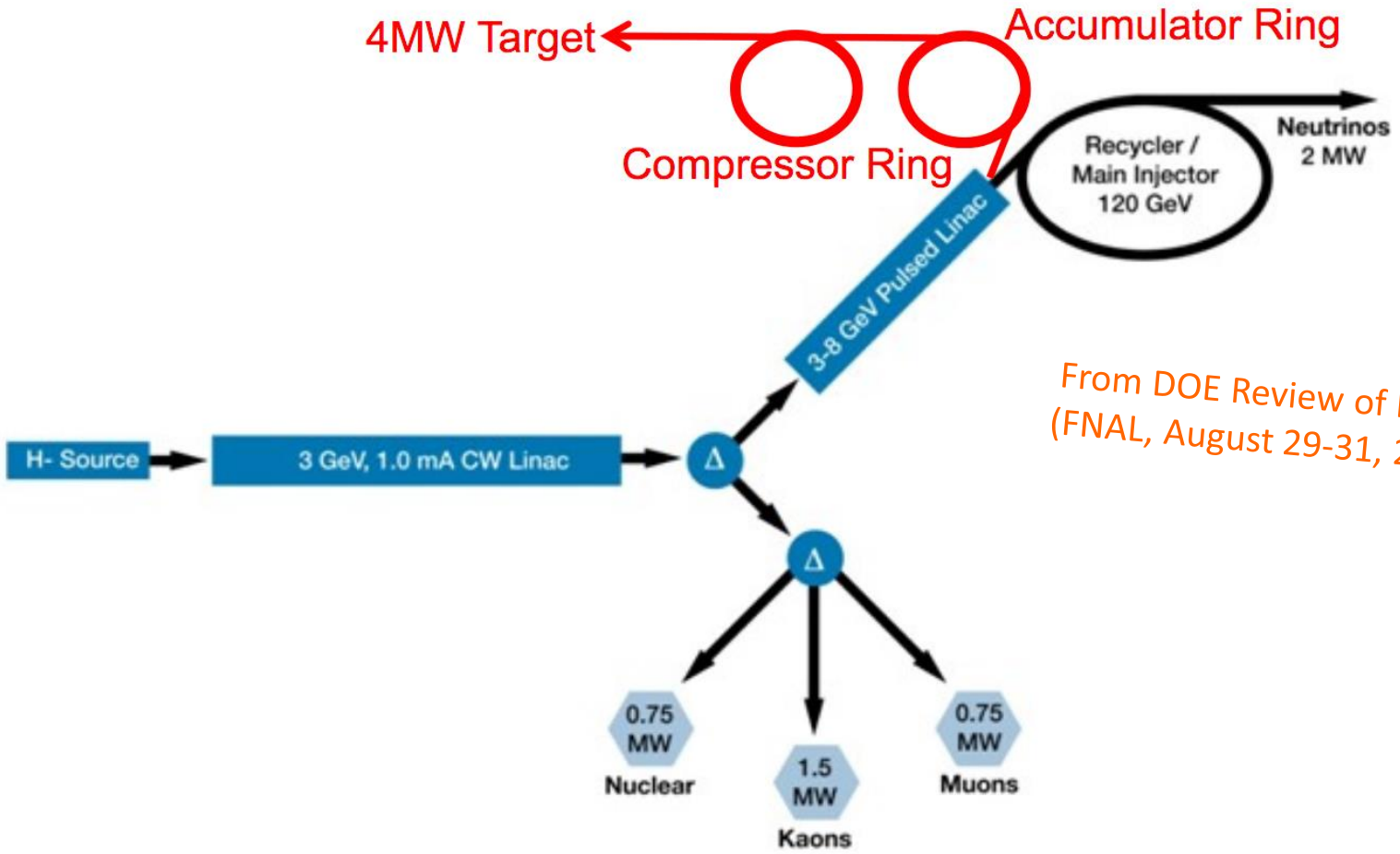


  - Yield given by $\frac{h}{E} = \frac{s}{E} n l$ with n the number of nuclei per volume and l the target length
  - For mercury (pion production cross sections close to Ta) with A = 200.6, ρ = 13.5 G/cm^3 and thus n = 4.1 10^{28} m^{-3}, the length l to find $h/E = 0.013$ is given by

$$l = \frac{h/E}{n\,(s/E)} = 8 \text{ cm}$$

Proton Driver Proposals

FNAL MAP with 8 GeV H- Linac with Accumulator and Compressor Rings

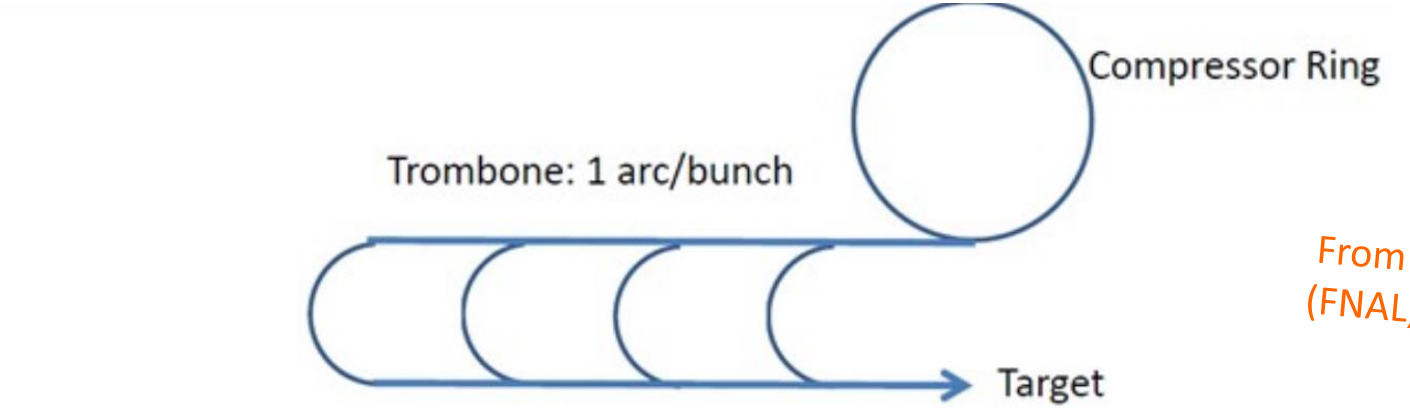


From DOE Review of MAP (FNAL, August 29-31, 2012)

- Based
  - Facility serivng several users
  - Accumulator and compressor rings added for muon collider
  - H^- beam current increased to 5 mA

Proton Driver Proposals

FNAL MAP with 8 GeV H- Linac with Accumulator and Compressor Rings



Muon Collider Proton Driver Trombone Schematic

(not to scale; bunches arrive simultaneously on target)

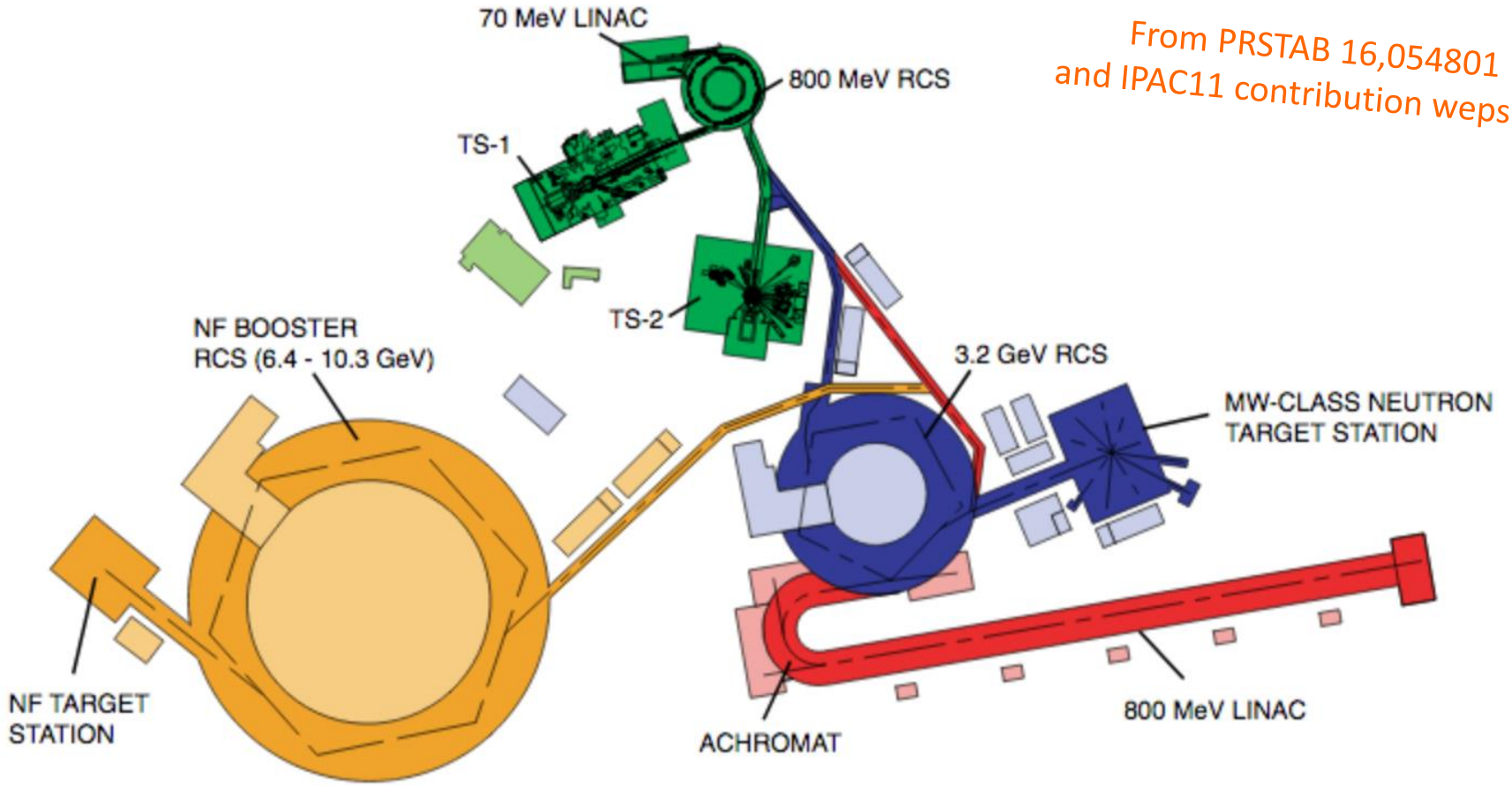
From DOE Review of MAP (FNAL, August 29-31, 2012)

- Different version of accumulator & compressor rings designed by different people
  - Accumulator with moderate RF voltage and far from transition
  - Compressor with large (120 kV) RF voltage close to transition to generate short bunches
- Combiner after extraction out of compressor ring
  - Combination of four bunches extracted from compressor to one bunch on target
    - Different path lengths such that bunches arrive simultaneously
    - Different incidence angles for different bunches
  - (Scheme useful to adopt any neutrino factory proton driver to muon collider)

Proton Driver Proposals

RAL Scheme with 0.8 GeV H- Linac followed by two RCSs

From PRSTAB 16,054801
and IPAC11 contribution weps105



- Proposal combining a spallation source (2 to 3.3 MW) and a 4 MW neutrino factory proton driver (could be adapted for muon collider by adding bunch merging section)
- Linac followed (for neutrino factor proton driver) by two Rapid Cycling Synchrotrons (RCS)

Proton Driver Proposals

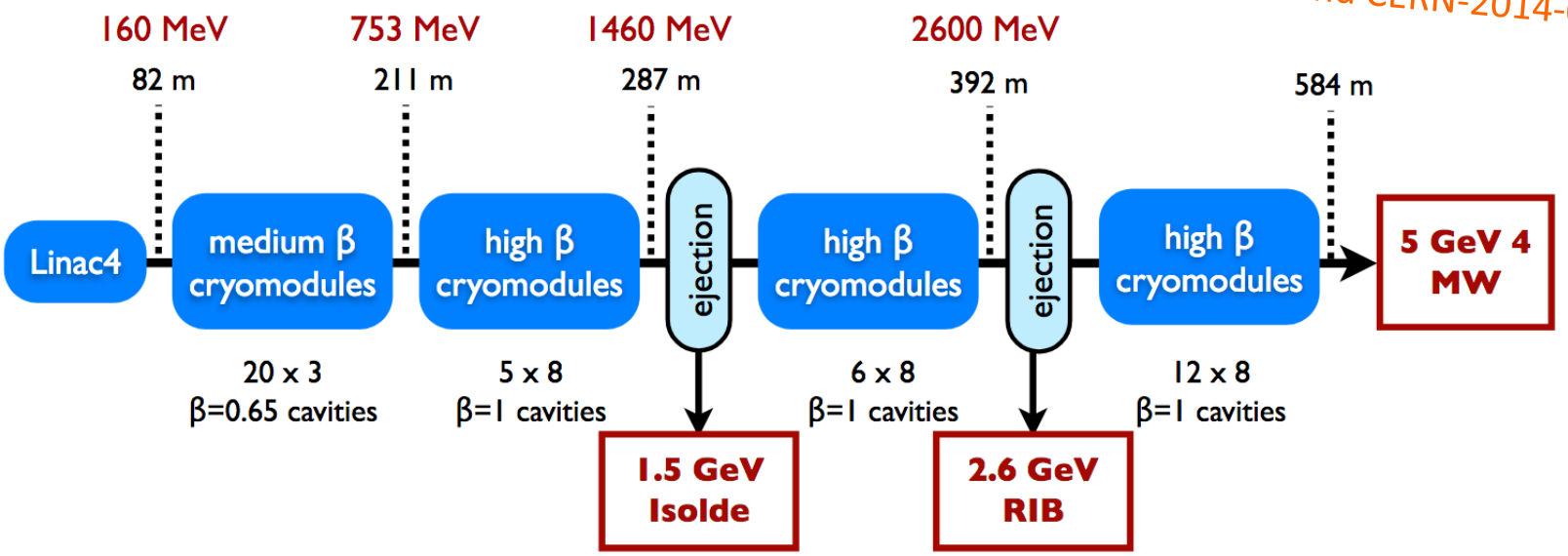
RAL Scheme with 0.8 GeV H- Linac followed by two RCSs

From PRSTAB 16,054801
and IPAC11 contribution weps105

- Common to spallation and proton driver
  - 800 MeV H^- Linac and 3.2 GeV RCS running with 50 Hz
    (5 or 9 bunches, different versions for beam intensities and bunch sharing)
  - 2 MW to 3.3 MW on spallation target
- Only for NF proton driver
  - Second RCS “Neutrino Factory Booster” running with 50 Hz
  - Aim is 4 MW on target
  - Typically two or three bunches (machine partially filled)
  - maximum energy between ~4 GeV and 10 GeV
    (depending on number of bunches, intensity per bunch ..)
  - Bunch compression envisaged towards end of acceleration (possibly bunch rotation) in RCS

Proton Driver Proposals
CERN SPL with Accumulator and Compressor Rings

From PRSTAB 16,054801 and CERN-2014-007

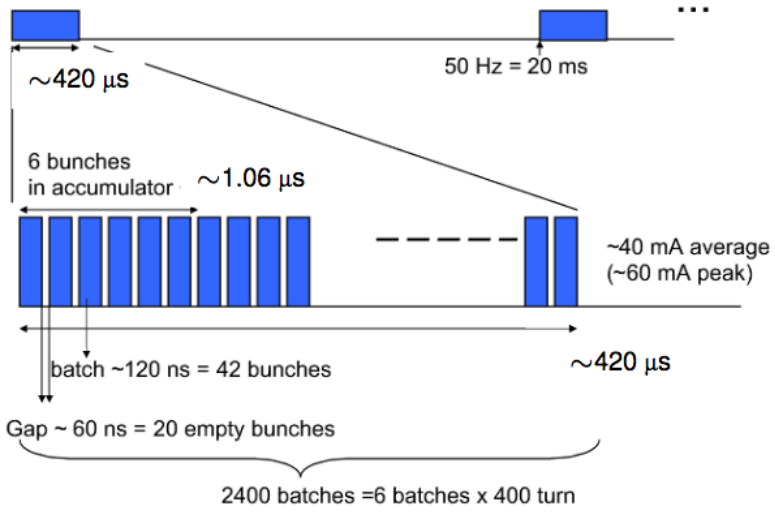


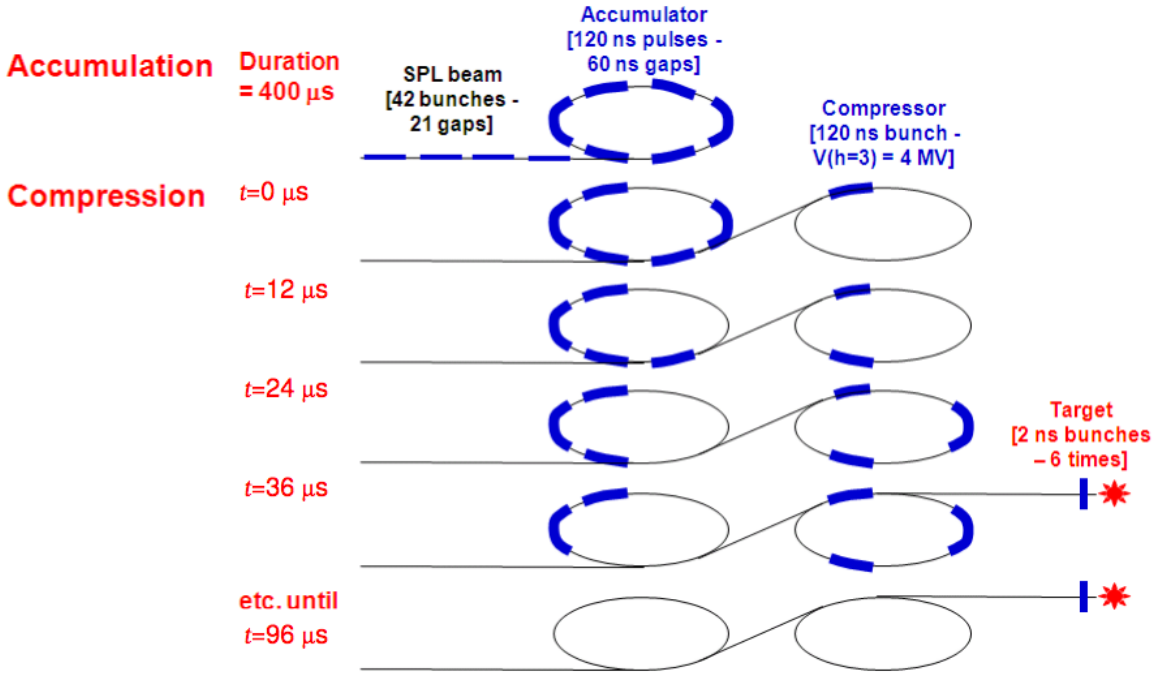
- Full energy 5 GeV H^- Linac SPL
  - 50 Hz repetition rate (baseline, but flexible design?)
  - Versions with 20 mA and 40 mA beam current (average after chopping)
  - Accumulator and compressor ring designed for neutrino factory (special extraction sequence)

Proton Driver Proposals

CERN SPL with Accumulator and Compressor Rings

From PRSTAB 16,054801 and CERN-2014-007





- Isochronous accumulator ring
  - No RF needed, longitudinal space charge impedance not an issue (energy change of head and tail of bunch acceptable)
  - Detailed simulations on bunch compression: final rms bunch length of 2 ns
- Compressor ring slightly shorter than accumulator to generate time structure for neutrino factory (irrelevant for muon collider)
- Some investigations on transvers and longitudinal impedances and instabilities
  - Scheme feasible at least for the short durations the beam stays in the rings

Proton Driver Proposals

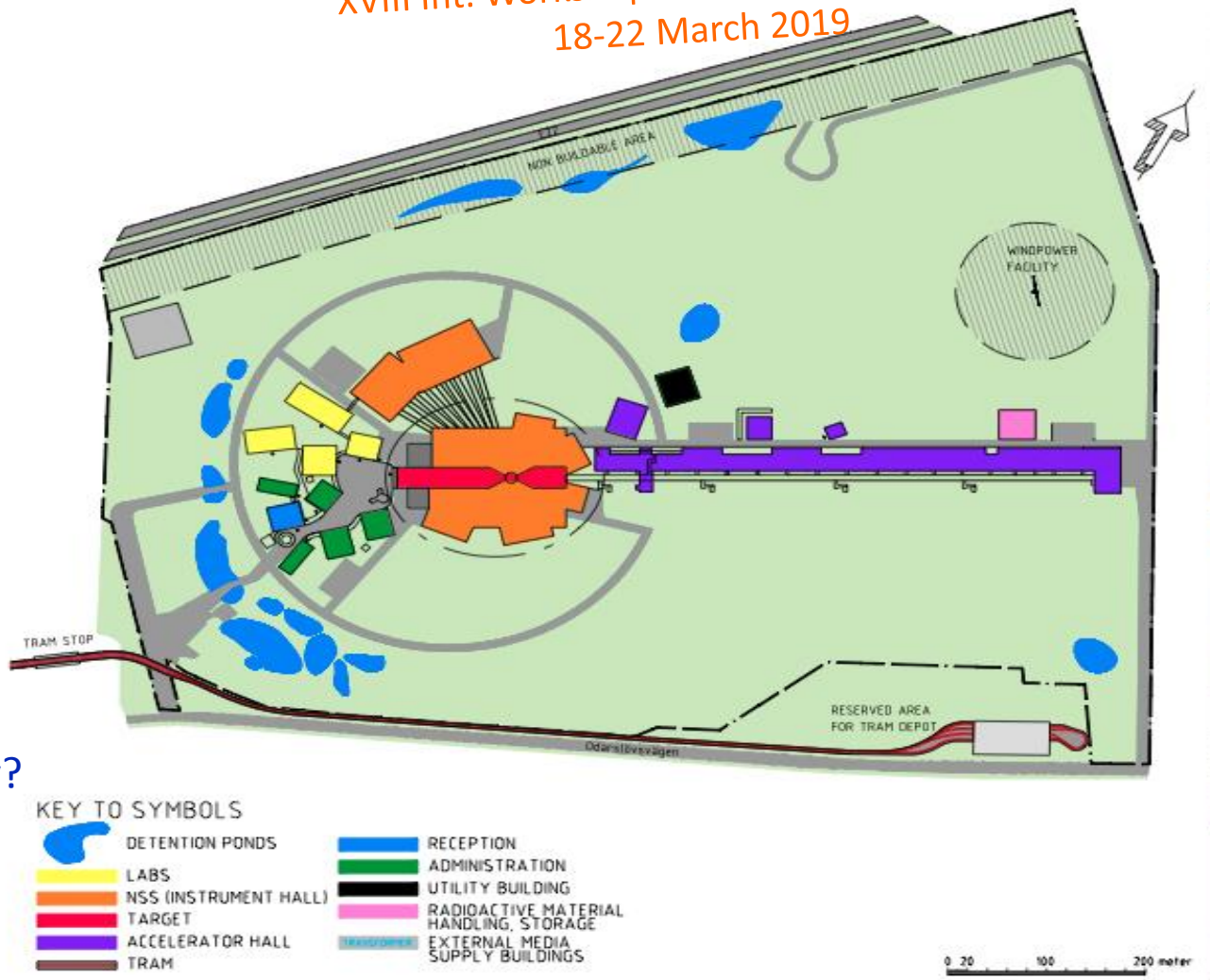
Based on ESS adding Accumulator and Compressor Rings

- Starting point: ESS only remaining option for a proton driver in Europe
- 1.1 10^{15} protons with 2 GeV per pulse and 14 Hz (increase to 28 Hz mentioned as option)

$\Rightarrow$ 5 MW beam power

- Loss in muon yield with low proton energy (factor 2 or less)?
- Addition of accumulator and compressor rings
- Why not an RCS to increase energy? (would imply time structure different from scheme on next slide)

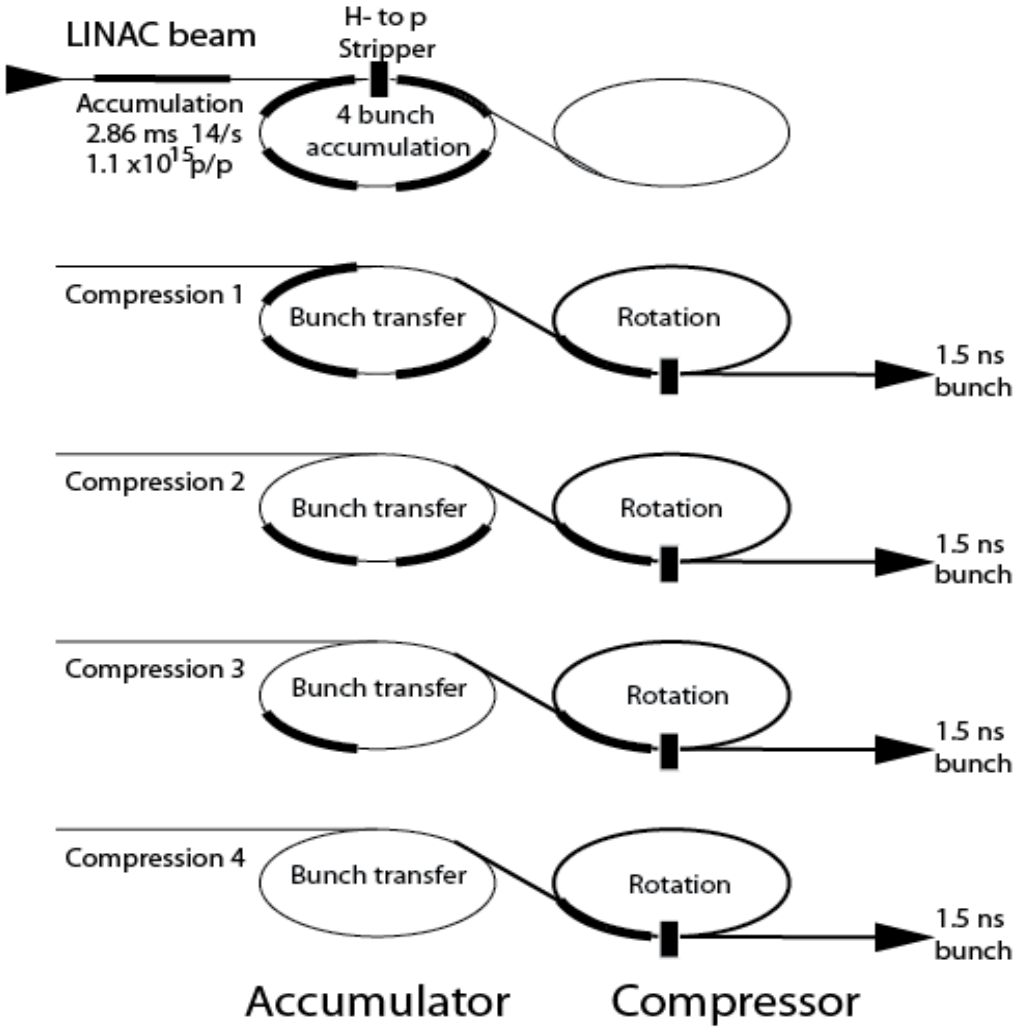
From a presentation by C. Rubbia at XVIII Int. Workshop on Neutrino Telescopes, 18-22 March 2019



Proton Driver Proposals

Based on ESS adding Accumulator and Compressor Rings

- Rings with ~35 m radius
- Accumulator ring filled with 14 Hz repetition rate
- Accumulator to compressor transfers with 4x14 Hz
  up to 54 ms



From a presentation by C. Rubbia at
XVIII Int. Workshop on Neutrino Telescopes,
18-22 March 2019

Summary, comments …

- Proton driver needed closer to existing facilities than other key ingredients of muon collider
  - … or rather less unknown territory?
  - Extrapolation from facilities as SNS, ESS, Project X …
  - Recent reports on muon colliders contain little information on proton drivers
- Different variants (full energy Linac with accumulator/compressor, different versions of Linacs combined with rings for acceleration) proposed
  - Optimum solution?
  - (feasibility, cost)?
- Topics for further studies
  - Instabilities and collective effects in particular for rings
  - Beam loss, collimation and machine activation (unwanted H^- stripping at high energies)
  - Optimum proton driver beam energy (muon yield, required power, cost, reliability ..), repetition rate (function of muon collider energy?)
  - H^- Injection into ring with high beam energies (foil, optimisation, feasibility of laser stripping? …)