Neutrino Factory – Facility Overview

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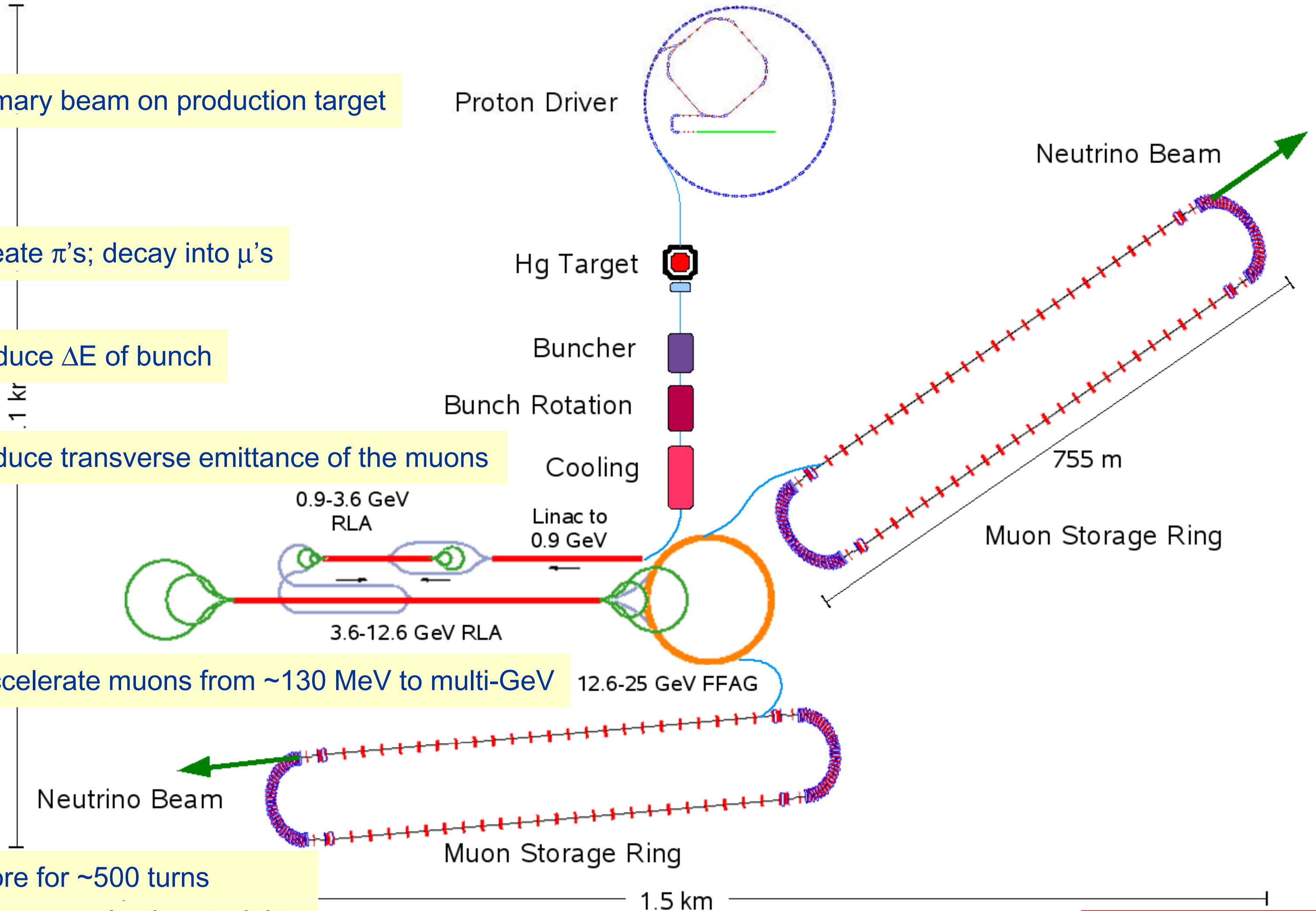
Motivation – Compelling Scientific Case

- Neutrino Factory – intense (10^{14} μ/sec), small divergence neutrino beams with well-understood systematics – attractive option aimed at precision measurements of parameters of the neutrino mixing matrix (θ_{13}, cos δ)
- Its performance and feasibility depend strongly on how efficiently a muon beam can be produced/collected, cooled and accelerated (to multi GeV energies).
- Recent technical progress (ISS design studies and prototype tests) encourages the hope that such facility can be built during the next decade.

Neutrino Factory – Facility Requirements

- 10^{21} muon decays per year
- Muon energies of 20 GeV, system upgradable to 50 GeV
- Pulses of ν and $\bar{\nu}$ separated by 100 ns at detectors roughly 3000 km and 7500 km away.

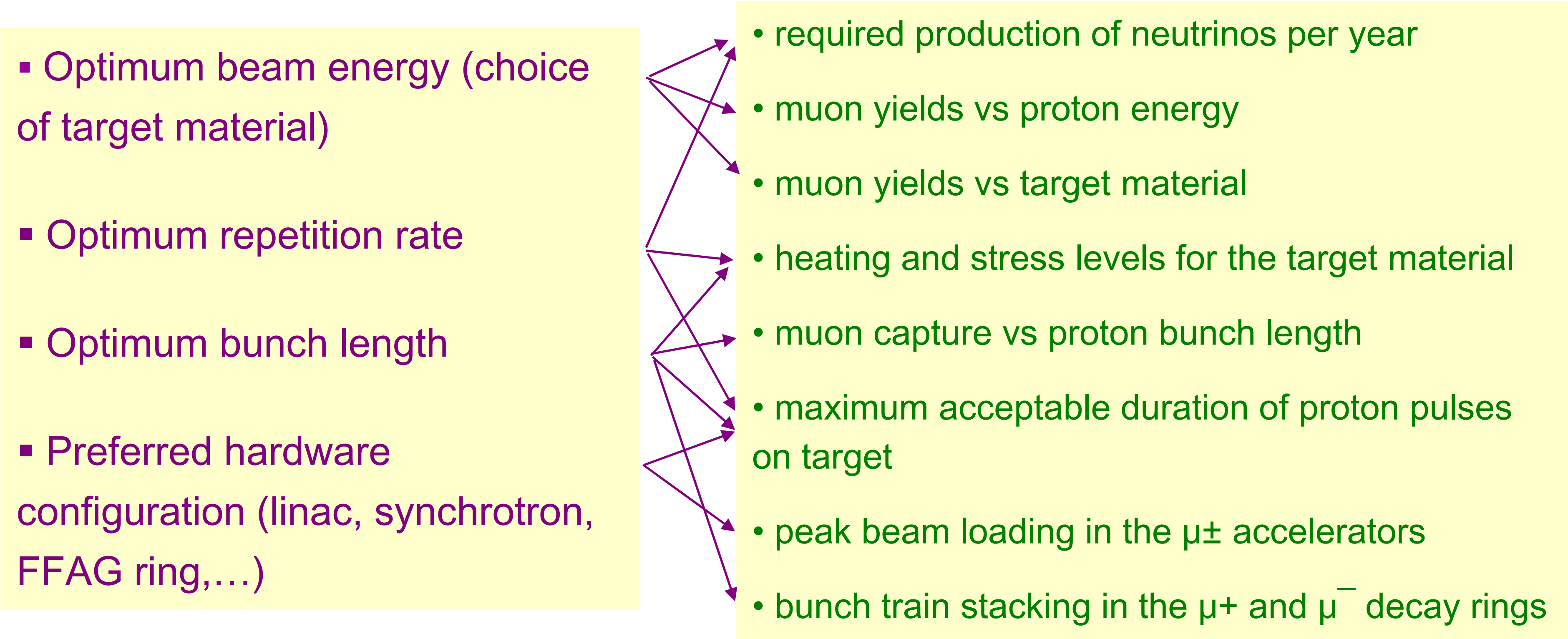
Neutrino Factory – ISS Design (25 GeV)



- primary beam on production target
- create π's; decay into μ's
- reduce ΔE of bunch
- reduce transverse emittance of the muons
- accelerate muons from ~130 MeV to multi-GeV
- store for ~500 turns
- Long ν production straights

C. Prior and S. Berg

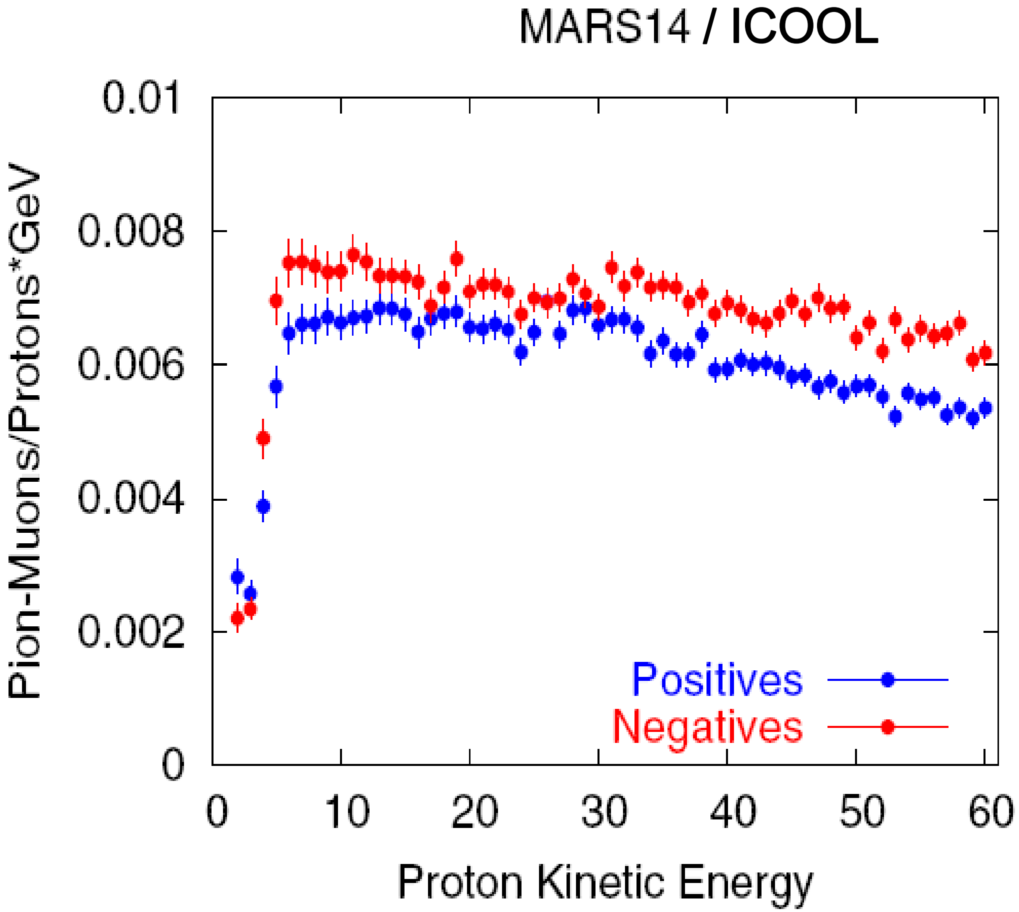
Proton Driver & Target – Issues/Influencing factors



- Optimum beam energy (choice of target material)
- Optimum repetition rate
- Optimum bunch length
- Preferred hardware configuration (linac, synchrotron, FFAG ring,…)

- required production of neutrinos per year
- muon yields vs proton energy
- muon yields vs target material
- heating and stress levels for the target material
- muon capture vs proton bunch length
- maximum acceptable duration of proton pulses on target
- peak beam loading in the $\mu^\pm$ accelerators
- bunch train stacking in the μ^+ and μ^- decay rings

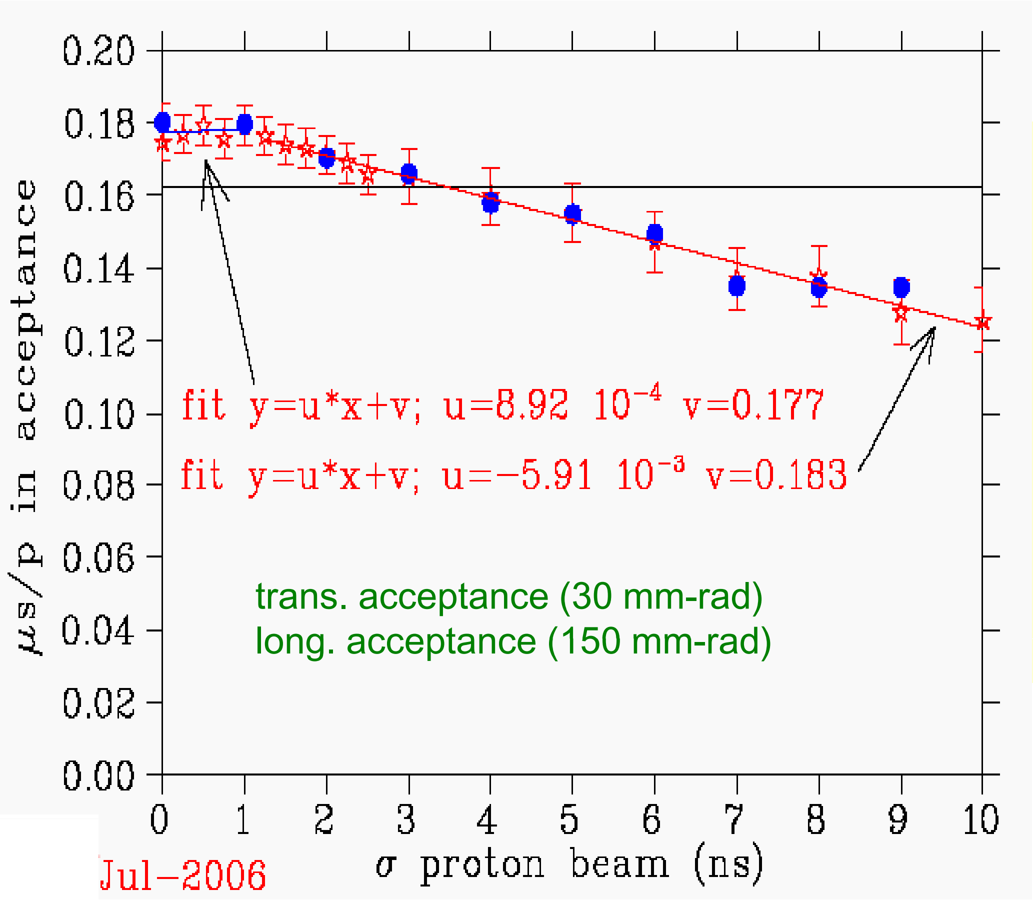
Proton Driver – Muon Production



- looked at accepted μ after cooling
  - transverse acceptance (30 mm-rad)
  - longitudinal acceptance (150 mm-rad)
- maximum yield for high-Z targets
- best efficiency for **E ~ 10 GeV**
- yield slightly higher for μ^-

H. Kirk

Proton driver – Muon acceptance

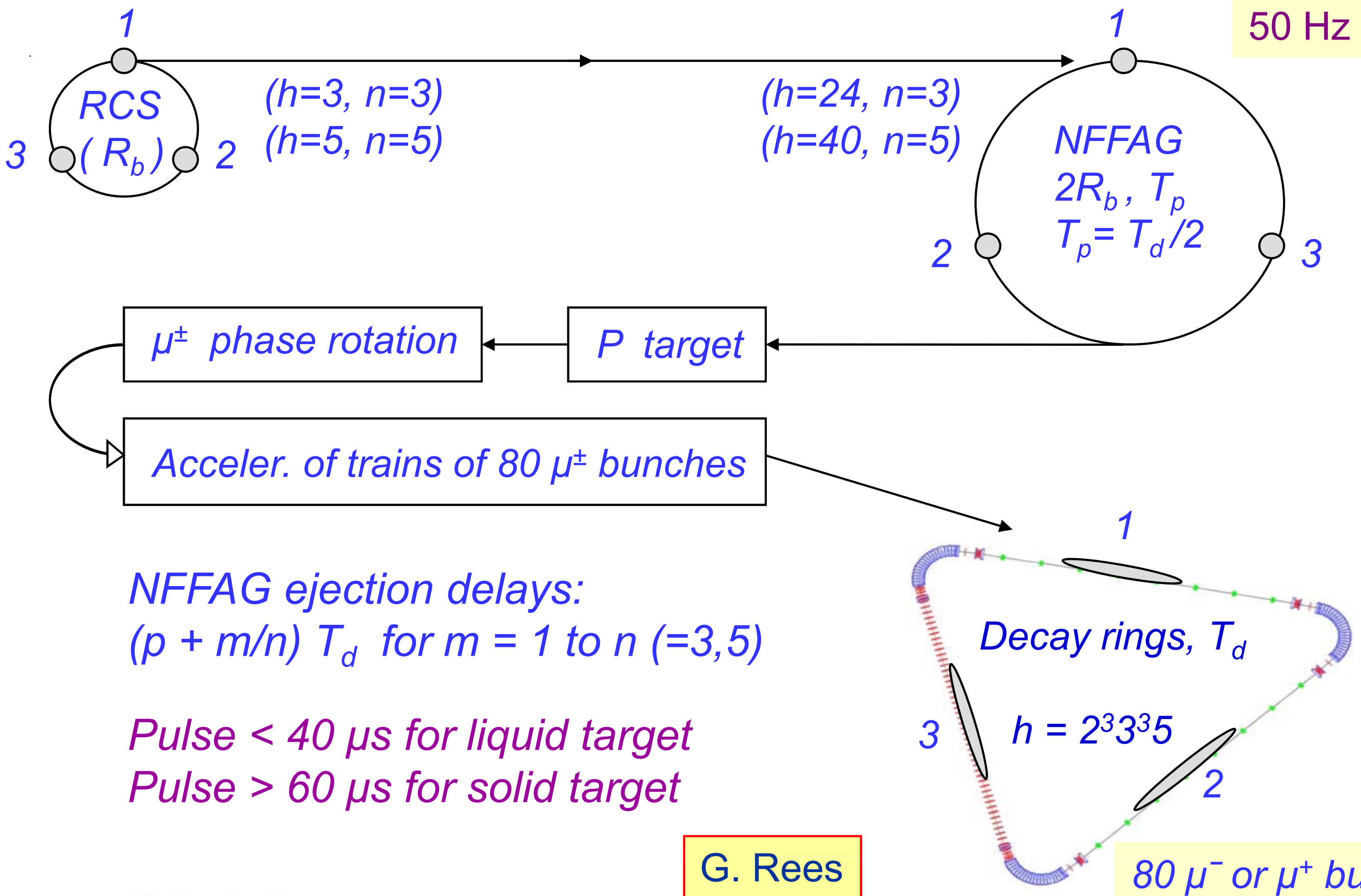


- looked at accepted μ after cooling
- varied time spread of initial production
- need short proton pulse on target (**3 nsec**)
- significant constraint put on final proton driver pulse length (**40 μsec**)

J. Gallardo

Proton and Muon Bunch Train Patterns

50 Hz cycle



NFFAG ejection delays:
$(p + m/n)\ T_d$ for $m = 1$ to n (=3,5)

Pulse < 40 μs for liquid target
Pulse > 60 μs for solid target

80 μ^- or μ^+ bunches

G. Rees

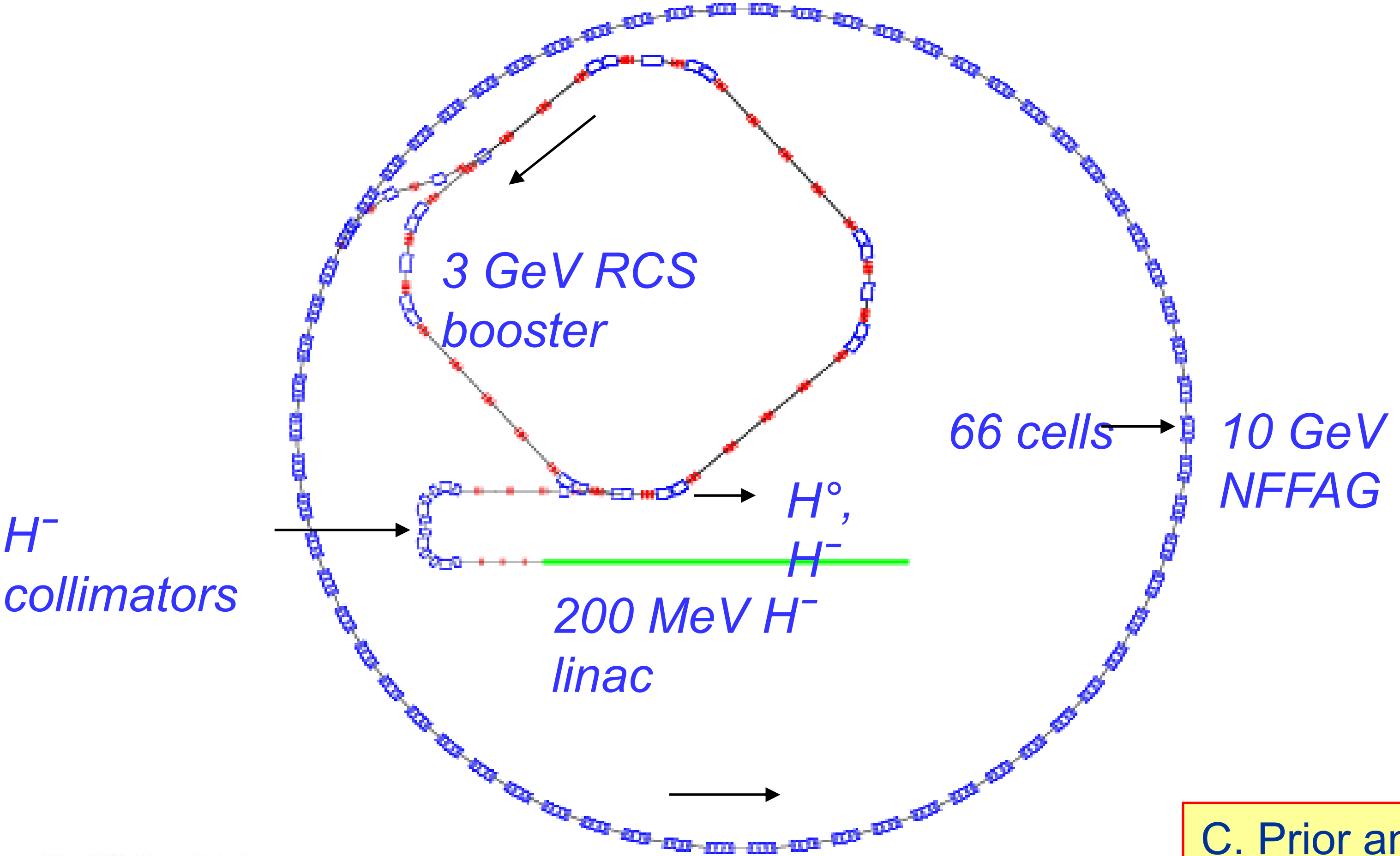
Proton driver – ISS Specifications*

Average beam power (MW)	4
Pulse repetition frequency (Hz)	50
Proton energy (GeV)	10 ± 5
Proton rms bunch length (ns)	2 ± 1
Number of proton bunches	3 or 5
Sequential extraction delay (μs)	≥ 17
Pulse duration, liquid-Hg target (μs)	≤ 40
Pulse duration, solid target (μs)	≤ 70

* baseline target choice is the **liquid-Hg jet** – a solid target could be accommodated with some changes in design parameters.

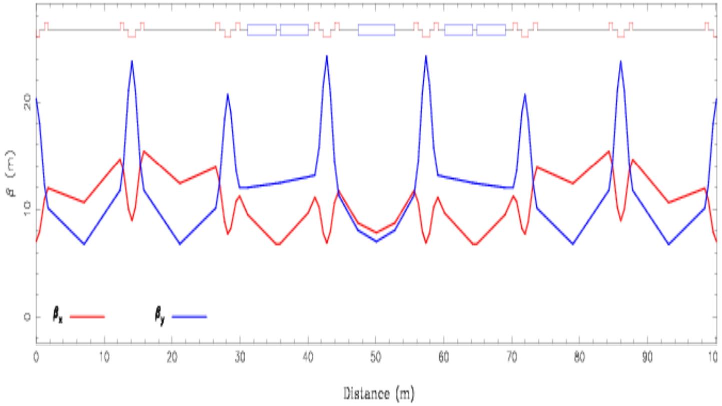
Proton Driver – Leading Option

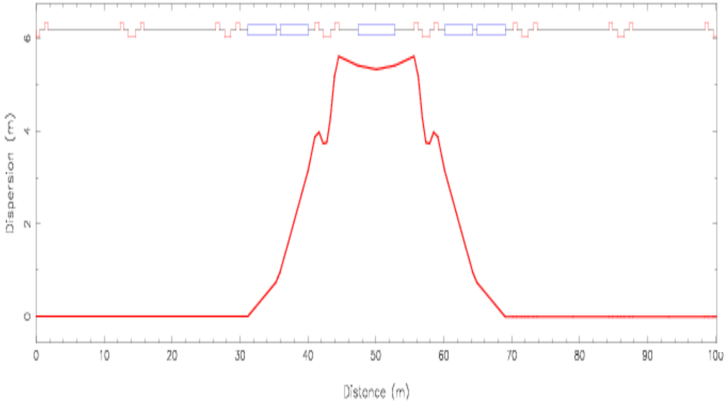
H⁻ linac with a 50 Hz RCS booster and a 50 Hz NFFAG driver ring

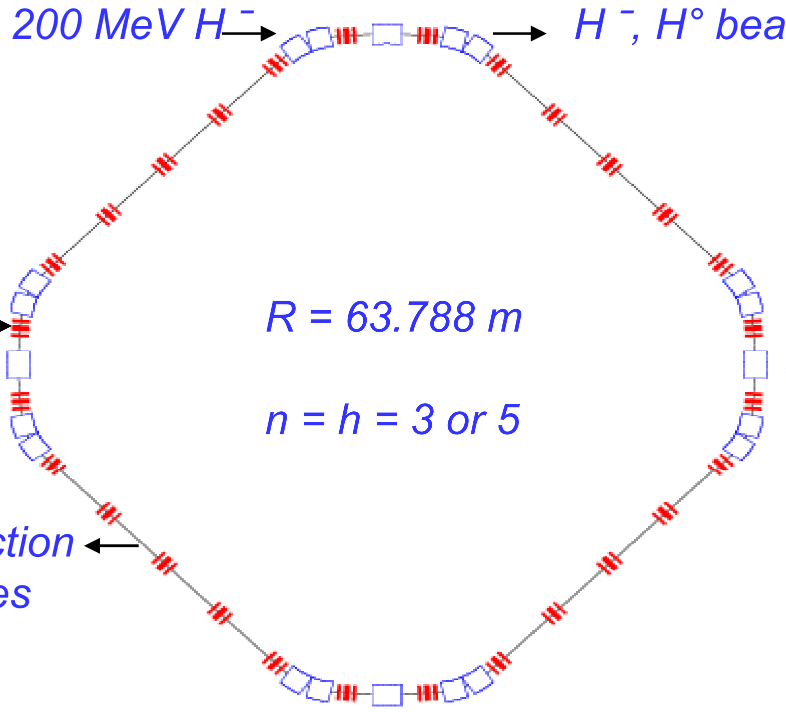


C. Prior and G. Rees

Schematic Layout of 3 GeV, RCS Booster







200 MeV H^- →

→ H^-, H° beam

triplet →

R = 63.788 m

n = h = 3 or 5

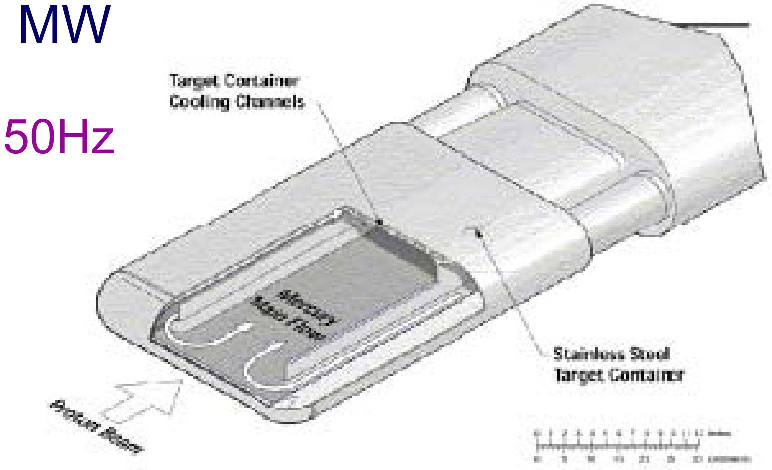
8° dipole

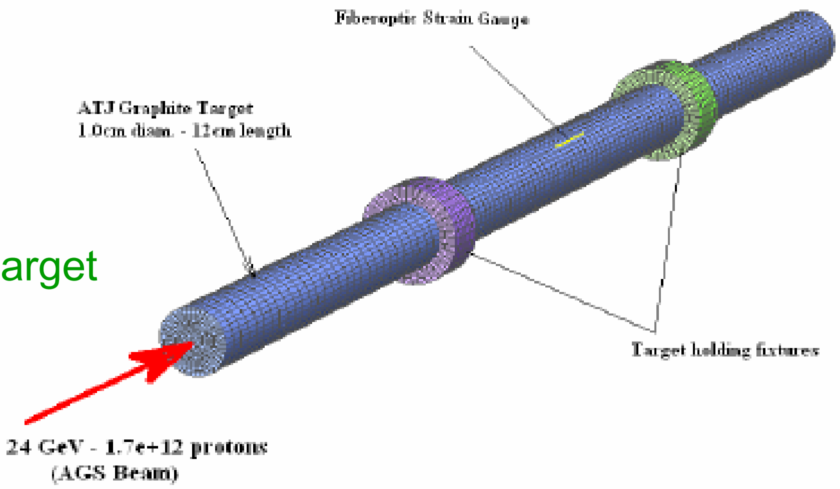
extraction cavities ←

G. Rees

Target for π production

- Typical beam: 10 GeV protons up to 4 MW
  - 1m long bunches up to 4×10^{13}/bunch, 50Hz
- Options:
  - Liquid Metal targets
    - SNS – type (confined flow)
    - MERIT – Hg jet in free space
  - Solid targets
    - C (graphite targets) (NUMI)
    - Solid metal (p-source) – rotating Cu-Ni target

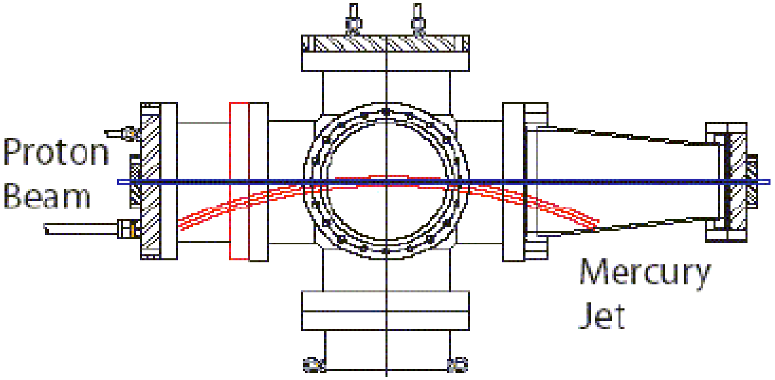


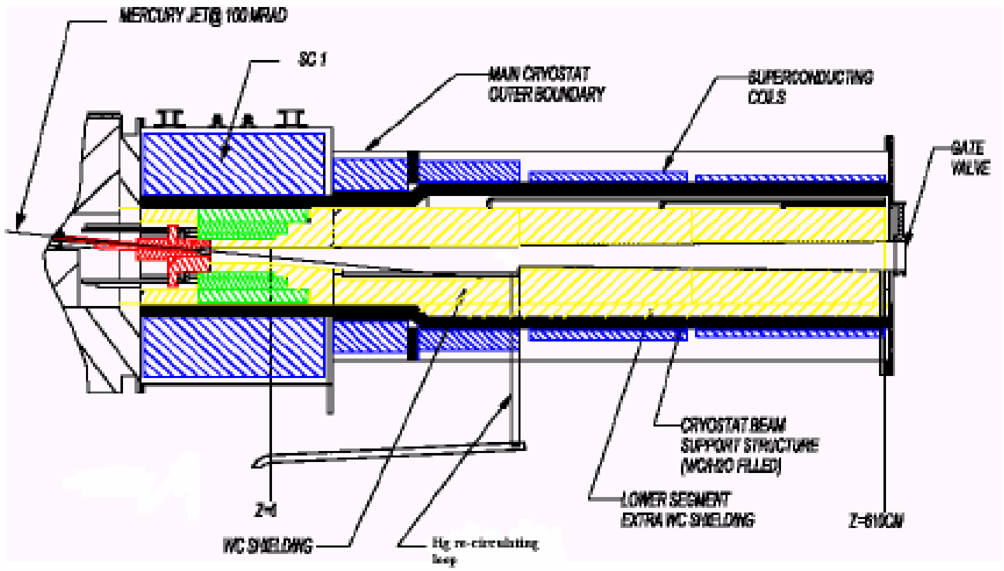


Liquid Target

- Contained liquid flow (~SNS)
  - Damage to containment vessel possible
  - Shock of short pulse
- Liquid Hg jet target
  - Jet is disrupted by beam

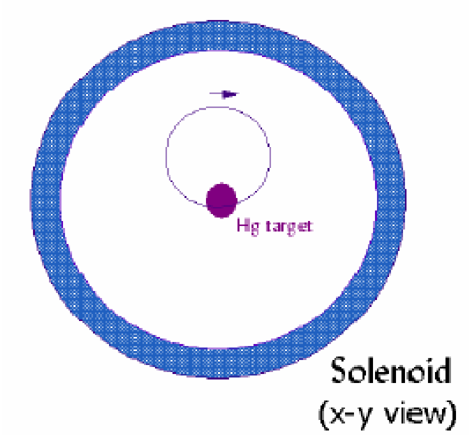
    $\delta T = 50\ \mu s$?
  - Need target material capture and recirculation system

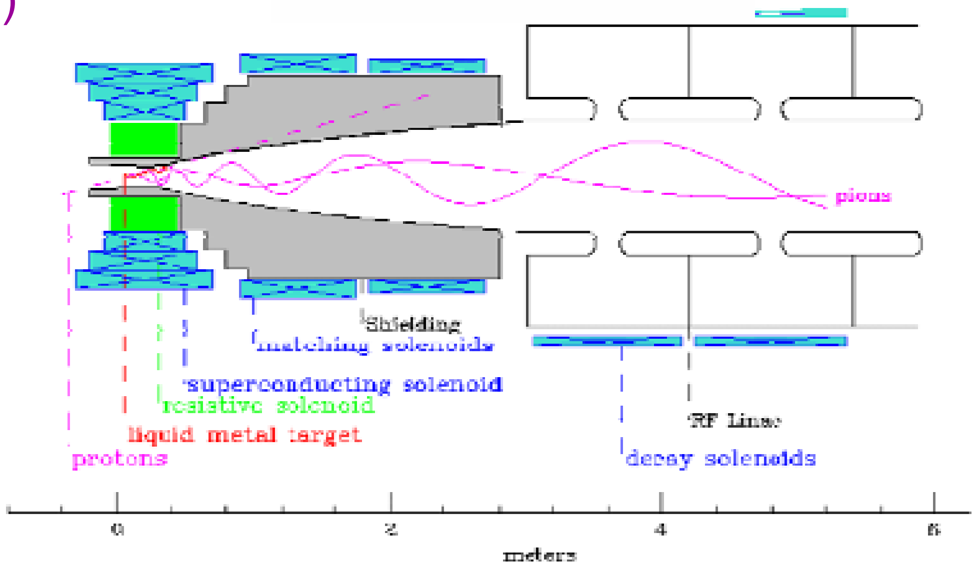




Solenoid Lens Capture and Transport

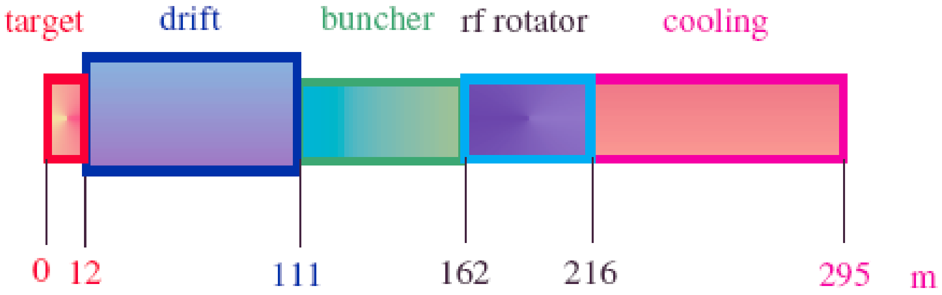
- Target immersed in high field solenoid
- Particles trapped in Larmor orbits
  - Produced with p = $p_{\parallel}$, $p_{\perp}$
  - Spiral with radius $r = p_{\perp}/(0.3\ B_{sol})$
  - Particles with $p_{\perp} < 0.3\ B_{sol}R_{sol}/2$ are trapped
  - $p_{\perp}$,max < 0.225 GeV/c for B=20T, R_{sol} = 0.075m
  - Focuses both charge species





ISS Front End based on Study 2a

- Collection of pions created in the target
- Formation of a muon beam (decay channel)
- Manipulate the transverse and longitudinal phase space of the muon beam so that they matches the accelerator acceptance
  - Neuffer's scheme for bunching and phase rotation
- Modest amount of transverse ionization cooling
  - simplified solenoid lattice
  - LiH absorbers on RF windows



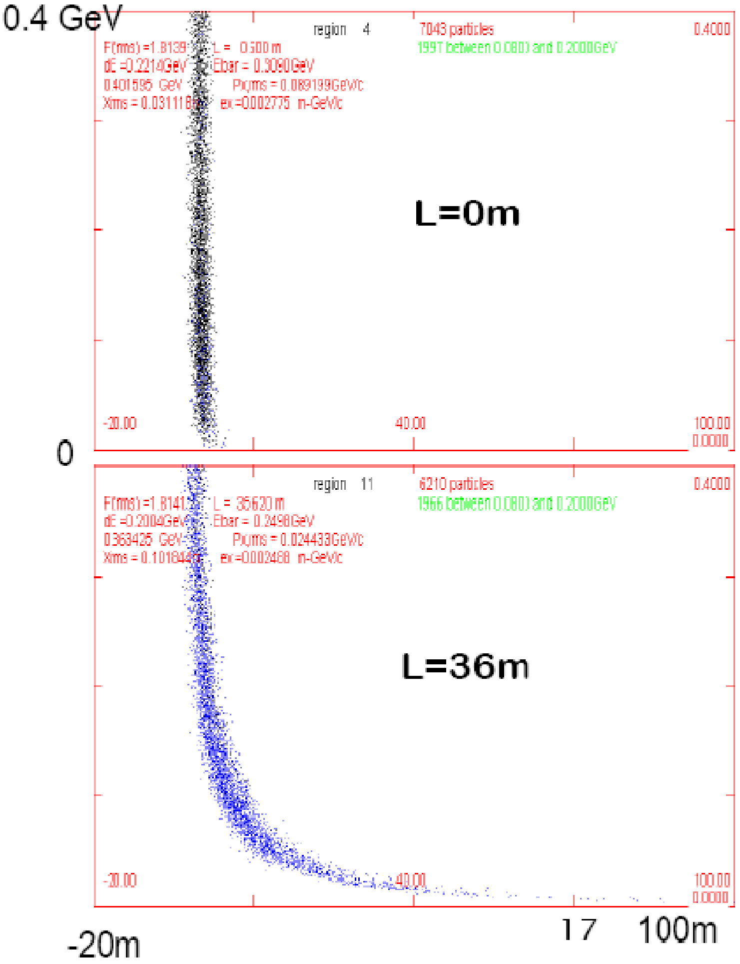
R. Fernow and R Palmer

π→μν decay in transport

- Capture relatively low-energy π → μ
  - 100 – 300 MeV/c
- Beam is initially short in length
  - Bunch on target is 1 to 3 ns rms length
- As Beam drifts down the energy-position (time) correlation develops:

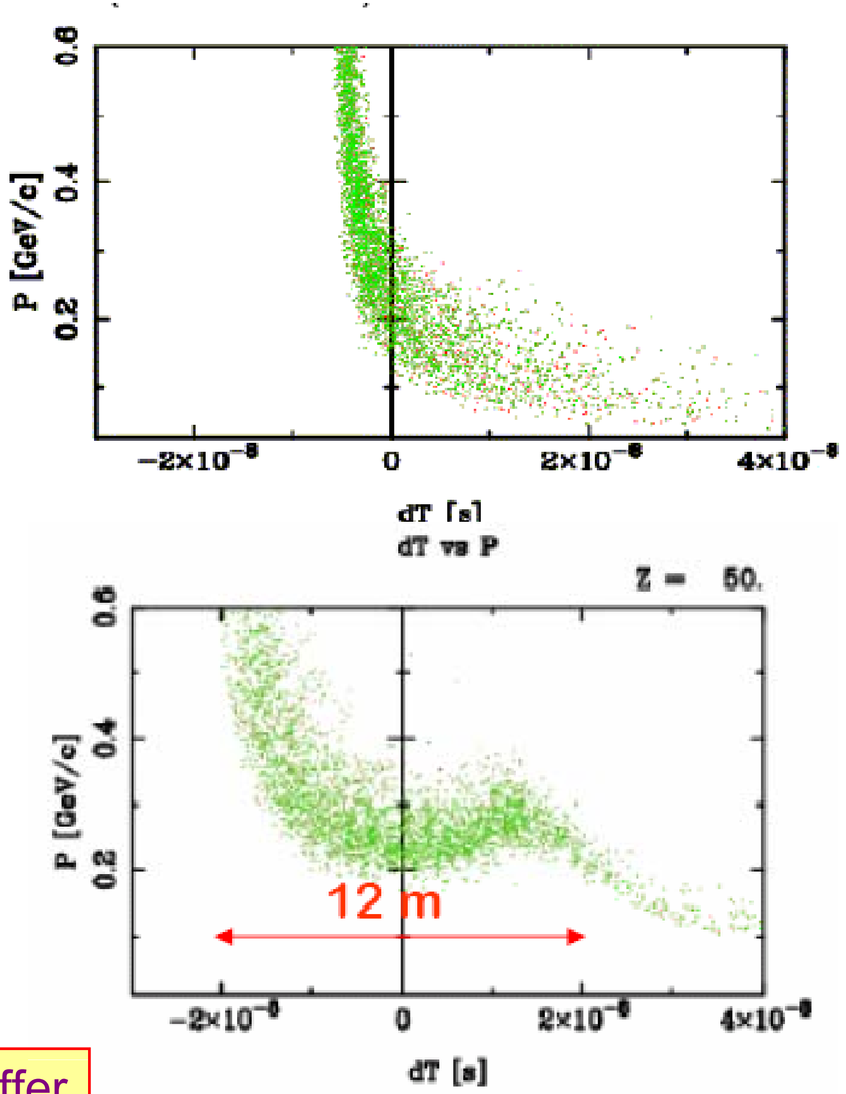
$$c\tau_{arrival} = \frac{L}{\beta}$$

D. Neuffer



$\varphi-\delta E$ Rotation

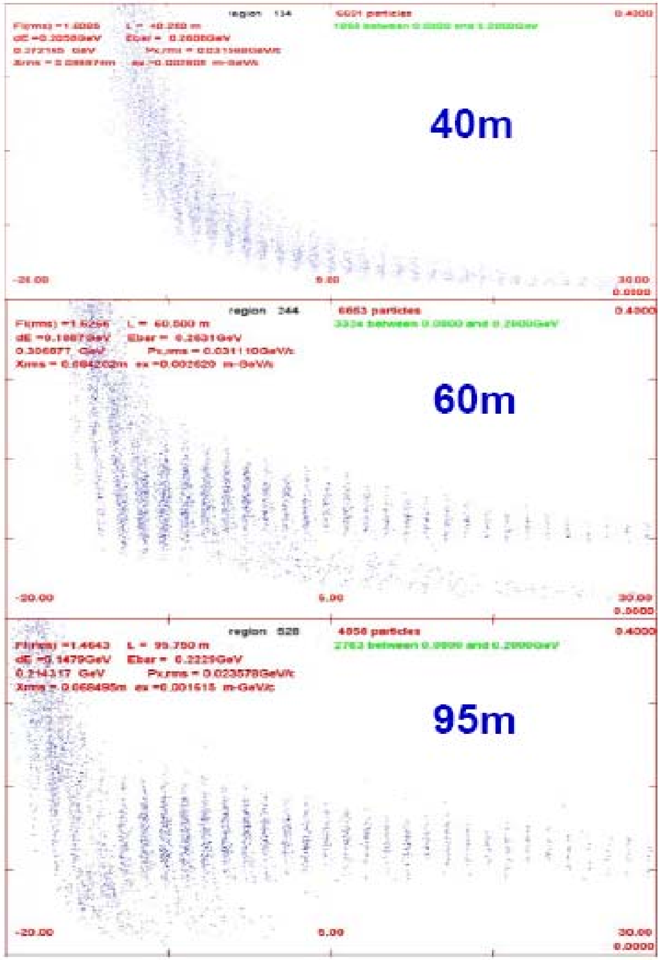
- At end of buncher, change rf to decelerate high-energy bunches, accelerate low energy bunches
- Reference bunch at zero phase, set λ_{rf} less than bunch spacing (increase rf frequency)
- Place low/high energy bunches at accelerating/decelerating phases
- Can use fixed frequency (requiresfast rotation) or change frequency along channel to maintain phasing (Study 2A)
  - "Vernier" rotation –A. Van Ginneken



D. Neuffer

Adiabatic Buncher

- Drift (20m), Bunch–20m (100 MV)
  - Vrf = 0 to 15 MV/m (× 2/3)
  - P1 at 205.037, P2=130.94
  - δN = 5.0
- Rotate – 20m (200MV)
  - δN = 5.05
  - Vrf = 15 MV/m (× 2/3)
- Palmer Cooler up to 100m
  - Match into ring cooler
- ICOOL results
  - 0.12 μ/p within 0.3π cm

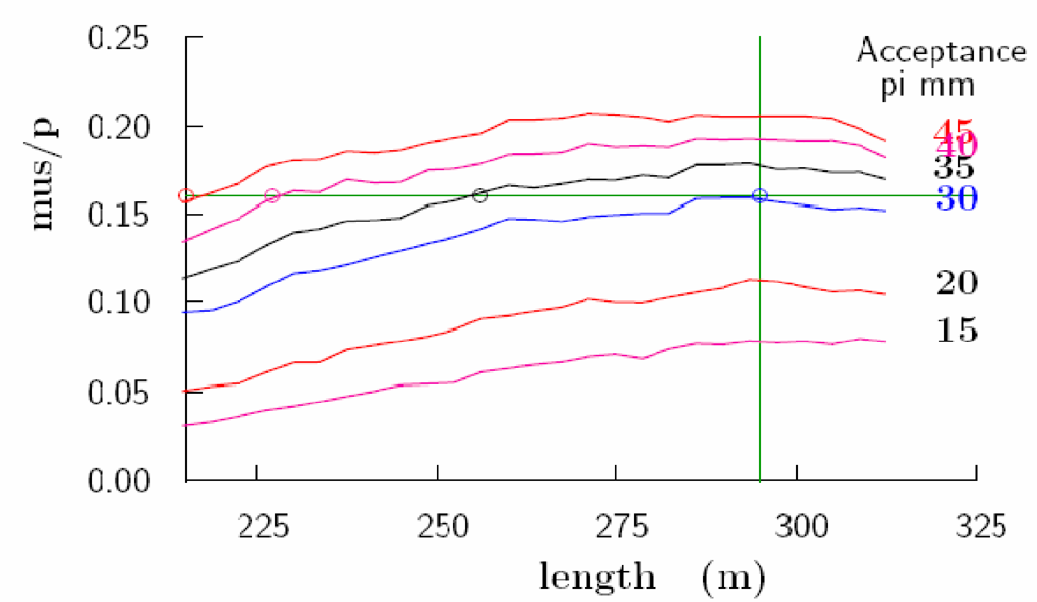


D. Neuffer

Cooling vs Acceptance

- Trade-off between **Cooling** and **Accelerator Acceptance**
  - important concept for cost optimization
- Some cooling may be necessary
- Large (> 30 mm-rad) FFAG transverse acceptances may not be possible
  - longitudinal phase-space distortions caused by the dependence of the time-of-flight on transverse amplitude)

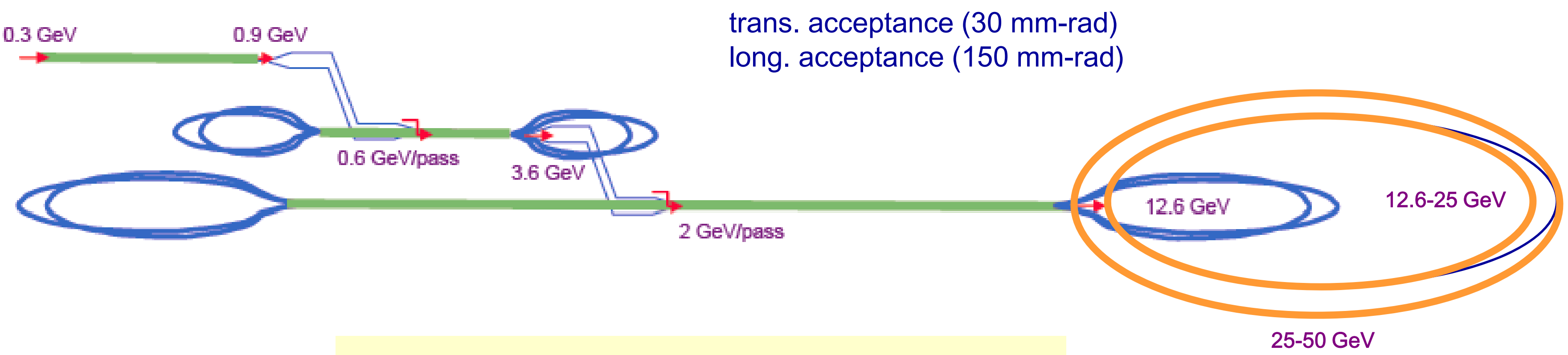
ISS simulation



R. Palmer

Acceleration Scenario

- Extended work to optimize Cost vs Performance
  - Linac to 0.9 GeV
    - phase slippage, RF cavities synchronized for a speed of light particle
  - Two-step, vertically stacked ‘dogbone’ RLAs to 12.6 GeV
    - dogbone gives better orbit separation for higher passes (vs Racetrack)
    - symmetric acceleration for μ^+ and μ^-
    - FODO focusing with ‘flat’ quad grad. profile in RLA linacs
  - One or two FFAGs to ~25-50 GeV (physics & detector dependent)



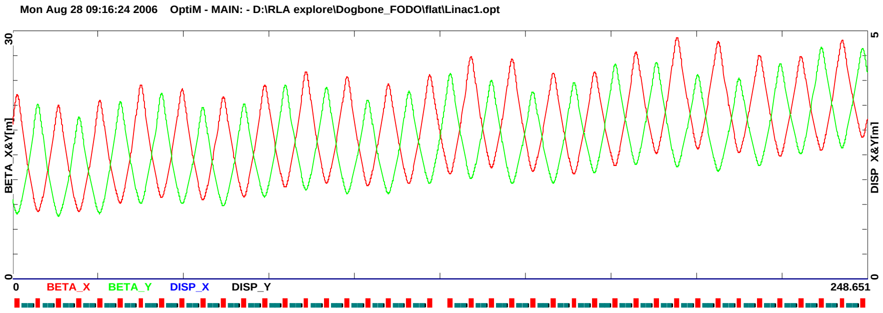
trans. acceptance (30 mm-rad)
long. acceptance (150 mm-rad)

Preliminary Acceleration Layout ISS

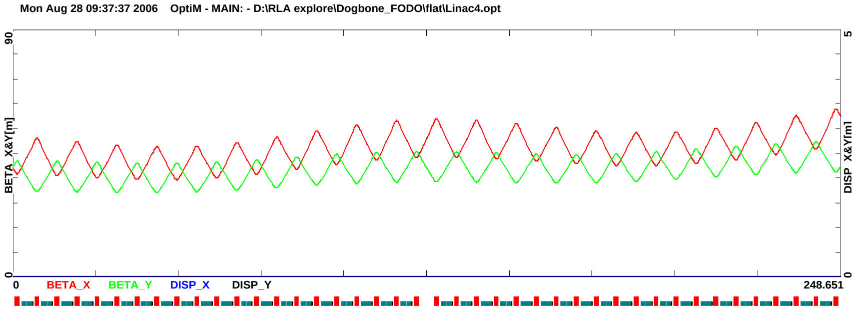
S. Berg and A. Bogacz

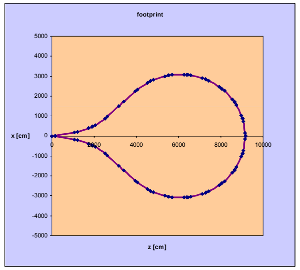
Multi-pass Linac, ‘Droplet’ Arc, Injection double-chicane – Optics

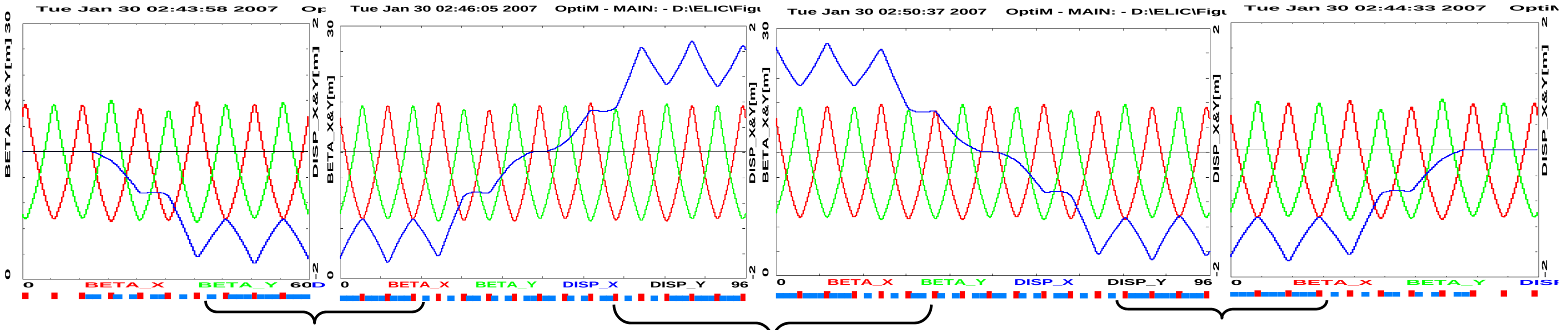
Linac - pass 1



Linac - pass 4



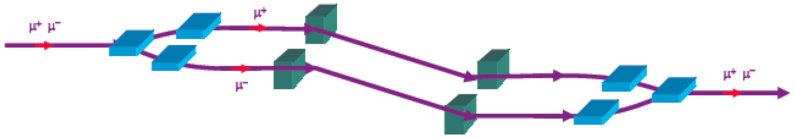


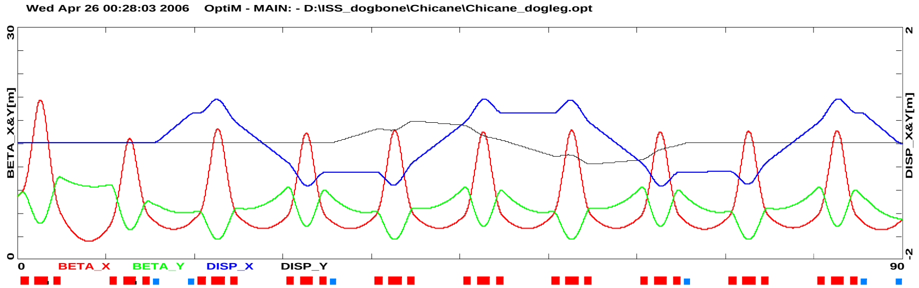


2cells

16cells

2cells

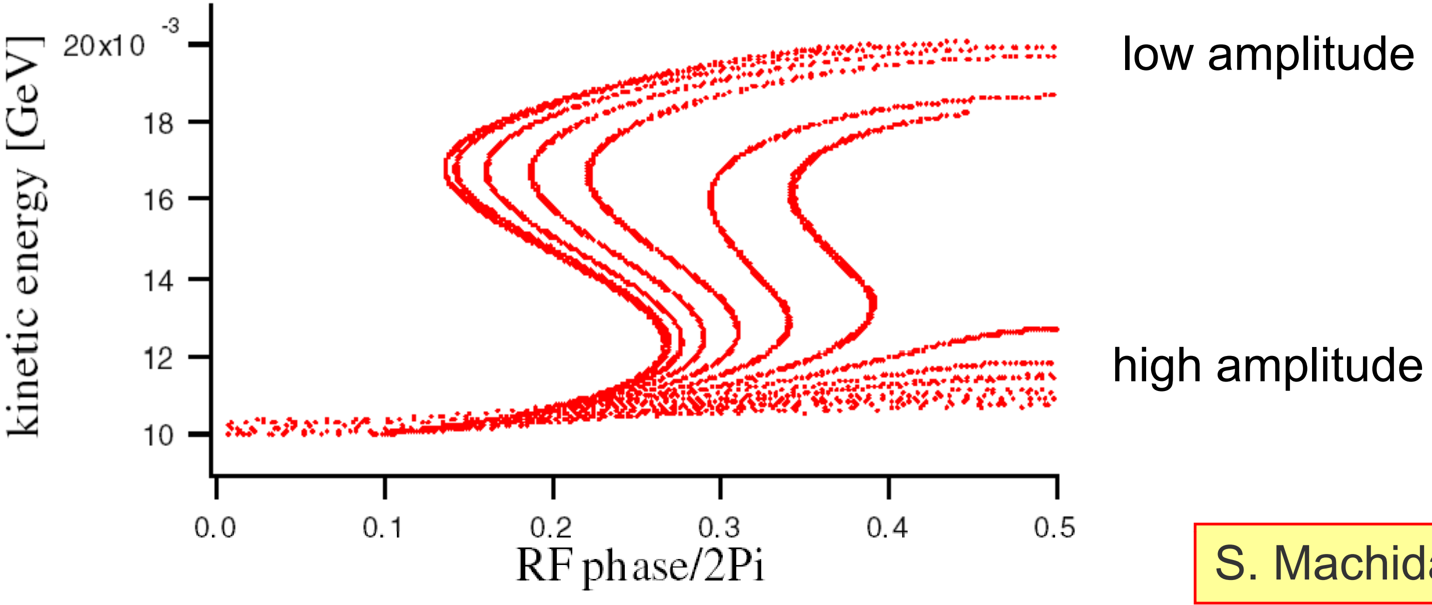




A. Bogacz

FFAG

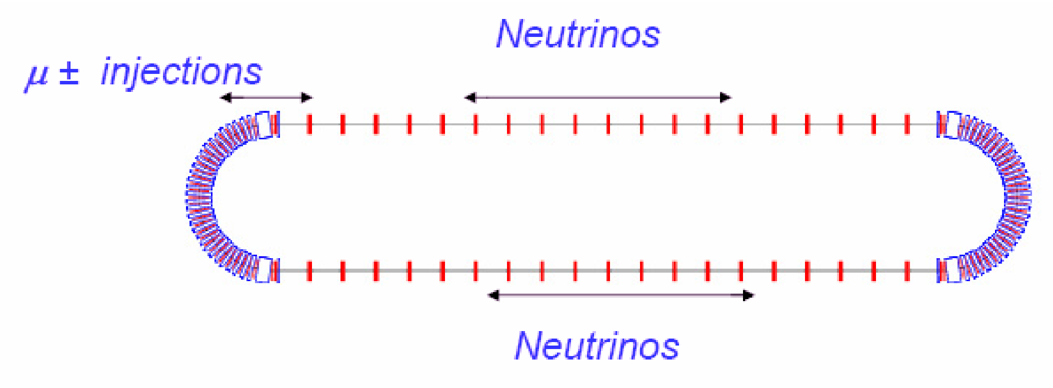
- Dependence of TOF on amplitude limits acceptance and ability to stage rings
- high transverse amplitude particles get out of synch with RF
- possible solutions under investigation:
  - reduce tune range during acceleration
  - increase energy gain per cell
  - add higher RF harmonics



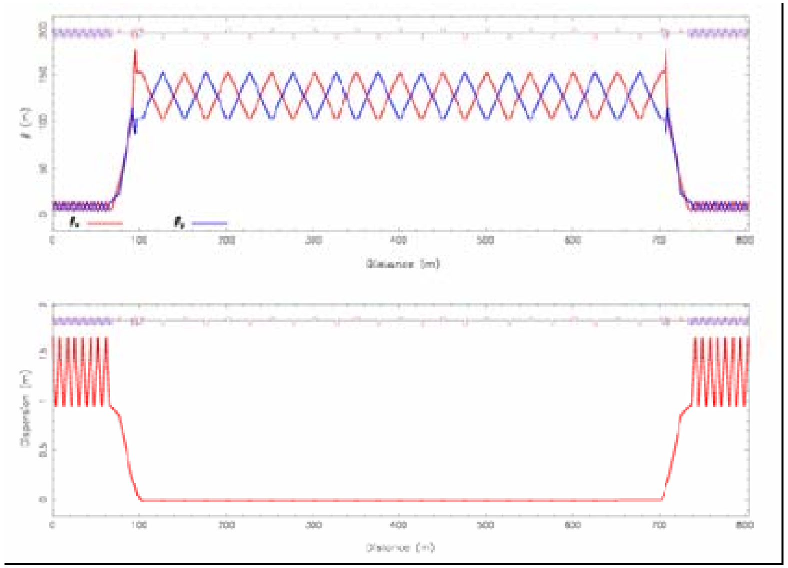
S. Machida

Decay ring

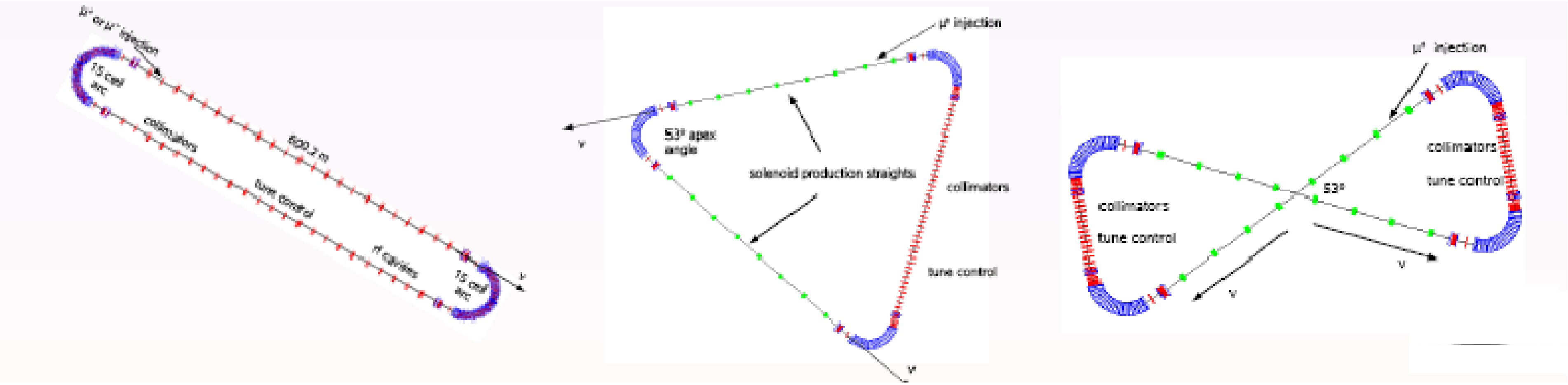
- Goal: maximize muon decays in straight sections
- Racetrack, Triangle/Bowtie geometries have been examined
- 2 racetracks are currently favored (most flexibility)
- use long straight sections ~400 m
- vertical depth of ring (~200-400 m) is issue for long baselines



G. Rees



Decay ring – alternative geometries



G. Rees

International Scoping Study Decisions

- Proton energy: 5–15 GeV
- Proton driver bunch structure: 3–5 bunches spaced by 17 μs
- Proton bunch length: 2 ns rms
- Repetition rate: 50 Hz
- Target: liquid Hg jet
- Pion collection: 20 T solenoid capture system
- RF frequency: 201MHz
- Phase rotation: Neuffer's bunched beam rotation scheme
- Cooling: 50m of ionization cooling
- Acceleration: linac + two dogbone RLAs + one or two FFAGs
- Muon decay ring: nominally racetrack, but the final choice is site dependent

Conclusions

- Compelling case for a precision neutrino program exists
  - Based on present assumptions Neutrino Factory out-performs other options …..more studies are needed …..
- Excellent progress on R&D on the major sub-systems
  - Targetry – MERIT
  - Muon Cooling – MUCOOL and MICE
  - FFAG – EMMA ring
  - Acceleration Design Studies
- Recently completed International Scoping Study
  - Move on to the **International Design Study** (RDR by 2012)