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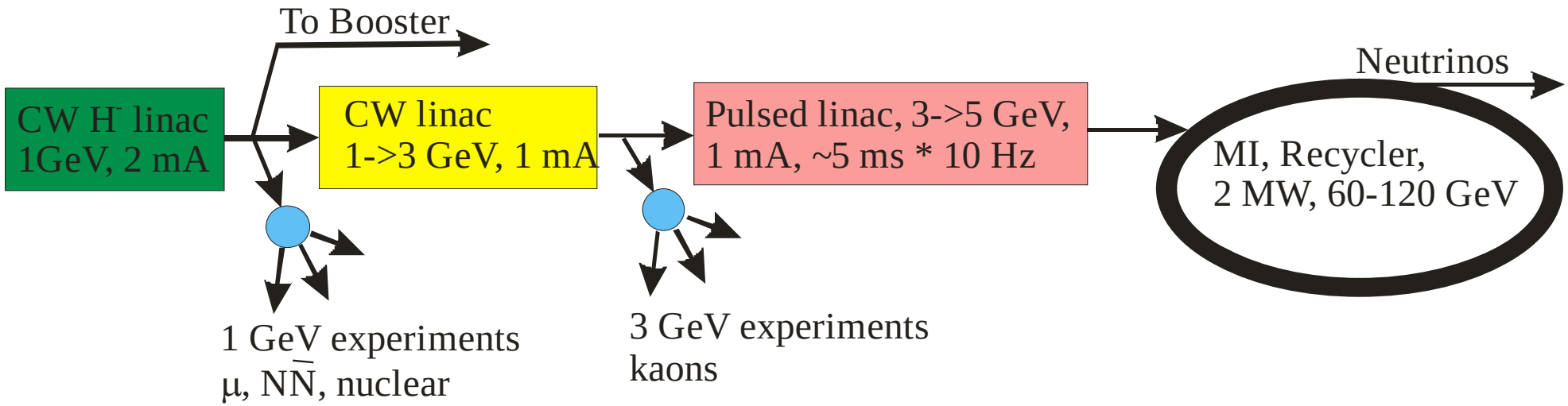
Acceleration of Muons with Project X Linac

Valeri Lebedev
Fermilab

Mini-Workshop on Muon Collider Higgs Factory
Fermilab
November 13, 2012

Project X & Project X SRF Technology

- Present plan – Project X to be constructed in 3 stages
  - Stage 1 –H^- (a) CW linac, 1 GeV, 1 mA (2 mA?), 162.5→325→650 MHz
    (b) Beam to Booster, 15→20 Hz rep. rate; (4.5→6)10^{12}/pulse
  - Stage 2 – (a) H^- CW linac, 1→3 GeV, 1 mA, 650 MHz;
    (b) 1 mA→2 mA for 1 GeV linac
  - Stage 3 – (a) Pulsed linac, 1 mA, ~5 ms × 10 Hz(?)
    (b) MI upgrade from 0.7 MW to 2 MW

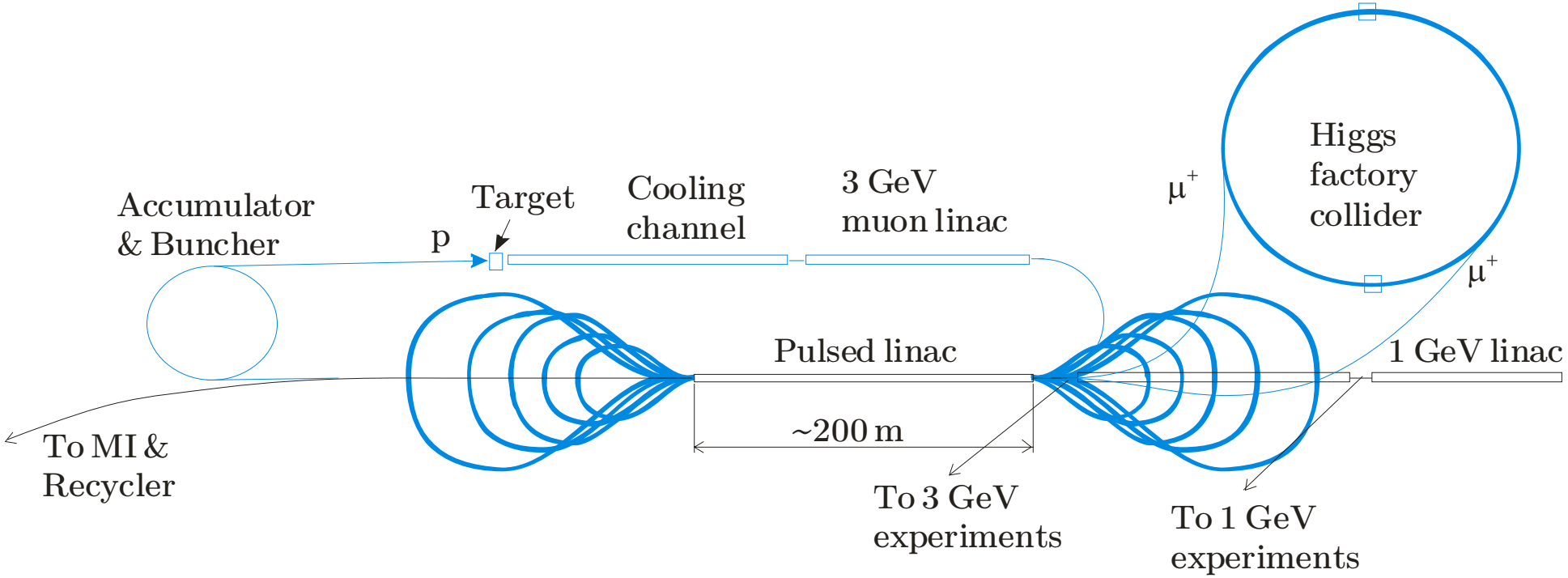


Project X Pulsed linac (3 -> 8 GeV, 5 GeV installed V)

- Present plan for muon collider pulsed linac
  - Future upgrade implies
    - Beam current increase from 1 to 5 mA
      $\Rightarrow$ will require upgrade of CW part to 5 mA too
    - Beam power increase from 0.34 to 4 MW
      $\Rightarrow$ 10 Hz $\rightarrow$15 Hz (?)
      $\Rightarrow$ 4.2 ms$\rightarrow$6.7 ms (?)
  - Pulsed linac upgrade does not imply that it will be used for acceleration of muons
- Possible modification of the plan
  - 1.3 GHz $\rightarrow$650 MHz
    $\Rightarrow$ Acceleration of muons in the Project X pulsed linac
    - Modest (if any) increase in the price for Project X
    - Very significant savings for muon based Higgs factory or ν-factory
  - Cavities are spaced by integer number of cell lengths to allow acceleration into both directions
  - The Project X and the Project X technology are well aligned with Higgs factory needs

Details of Modified Plan

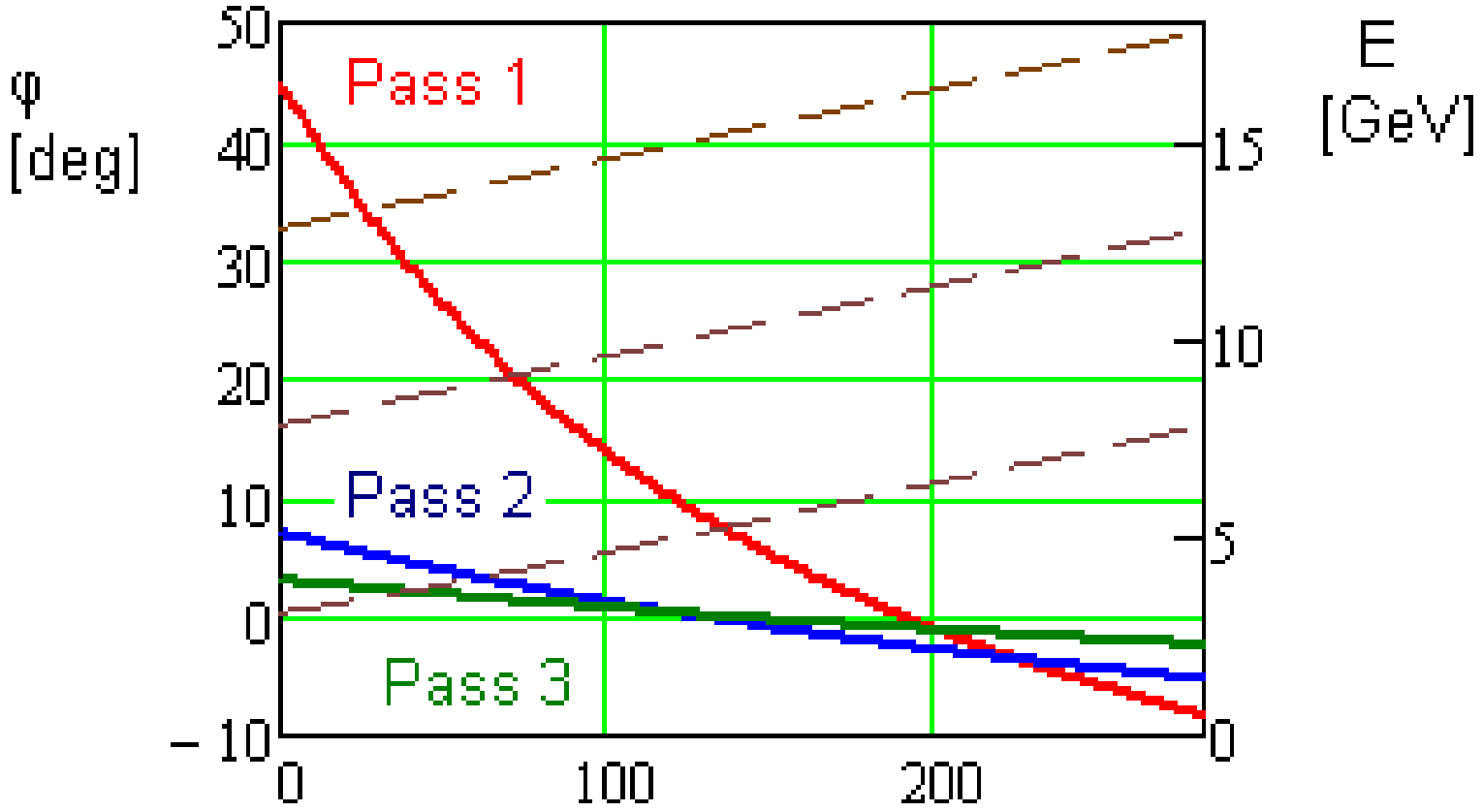
- 12 pass recirculator accelerates muons from 3.1 GeV to 62.5 GeV
  - s-channel muon based Higgs factory
- Beam power on the muon production target is reduced: 4 →~1 MW
  - Beam current stays the same (1 mA)
  - No need to modify CW part
- RF frequency of pulsed linac decreased from 1.3 GHz to 650 MHz



Schematic of the Project X and Higgs factory (shown by blue)

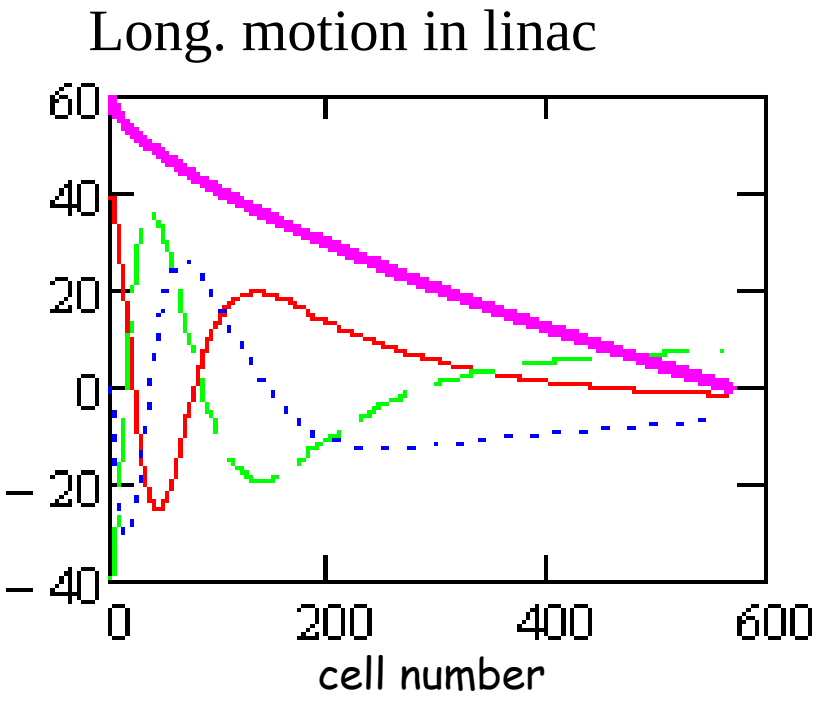
Initial energy of Recirculation

- Phase slip limits the initial energy of recirculation to ~3.1 GeV



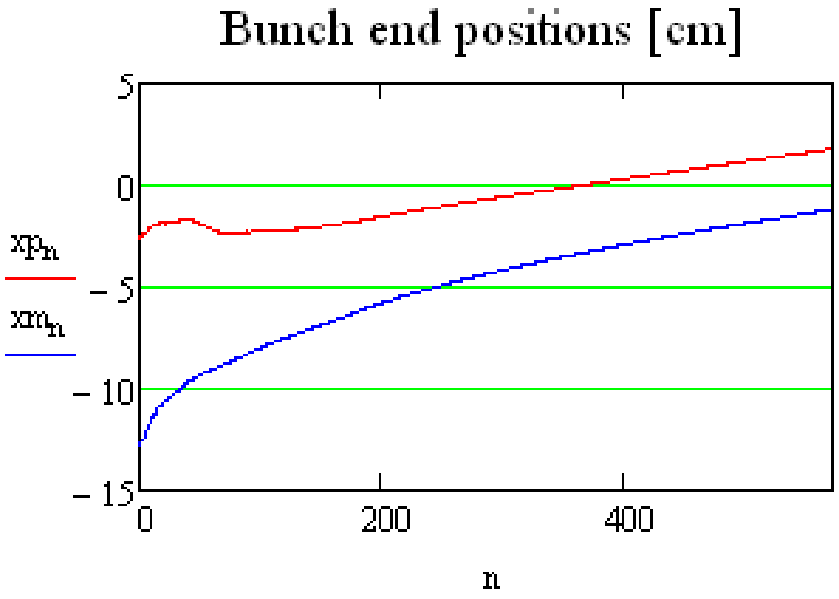
Phase slip for the first 3 of 12 passes

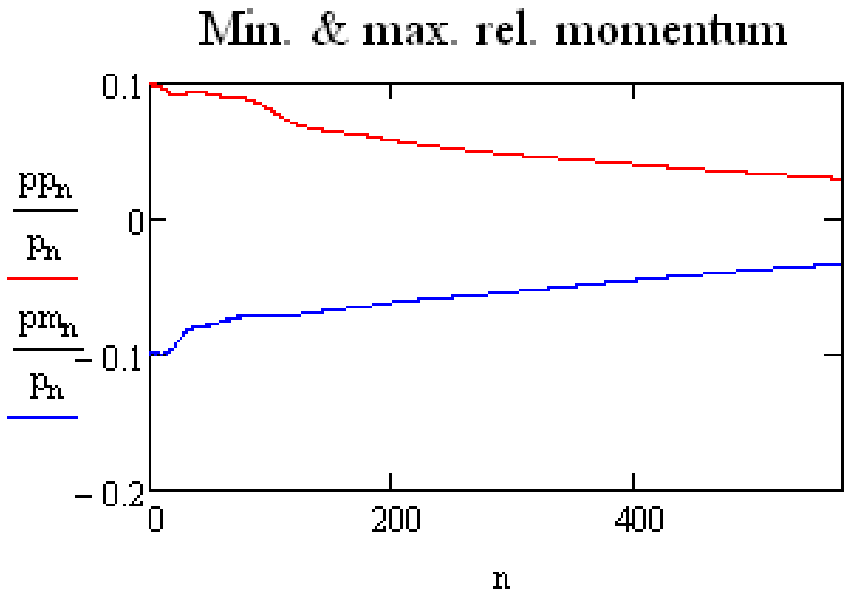
Acceleration in the Muon Linac



Main parameters

Momentum range, pc = [0.3-3.2 GeV]
Accelerating frequency = 650 MHz
Accelerating gradient = 25 MeV/m
Accelerating cavities: 5 cell, β =1
Linac length ≈ 250 m
Longitudinal acceptance, ε_{ns} = $3^2 \times 1500$ mm mrad
Transverse acceptance, ε_{ns} = $3^2 \times 300$ mm mrad
Number of RF cavities = 114
Particles per bunch = $6 \cdot 10^{11}$
Repetition rate = 10 Hz

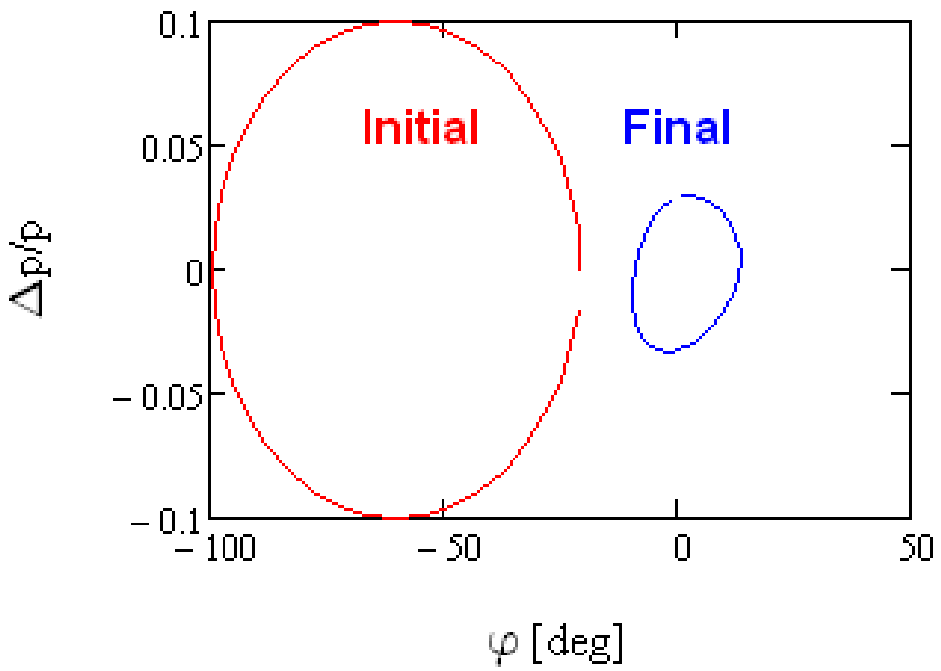


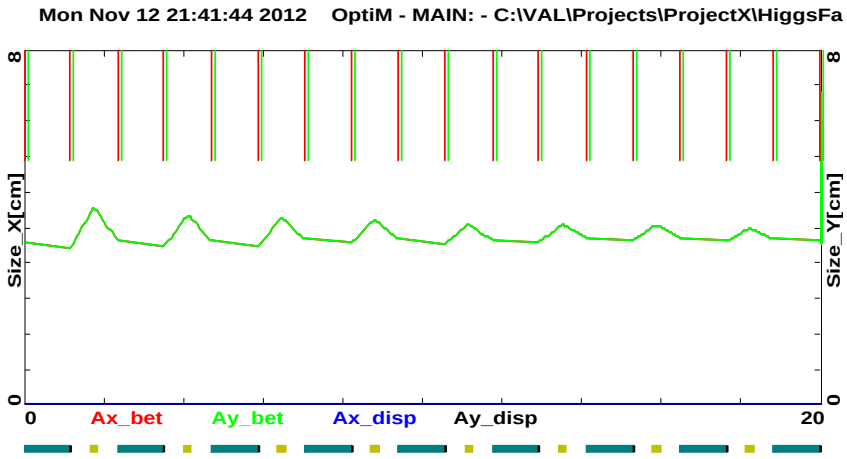


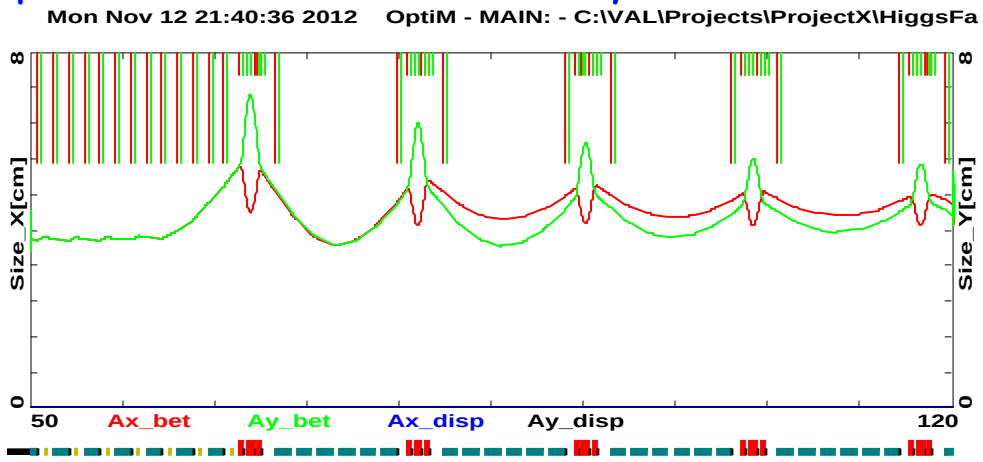
Bunch boundaries for 3σ

Acceleration in the Muon Linac (continue)

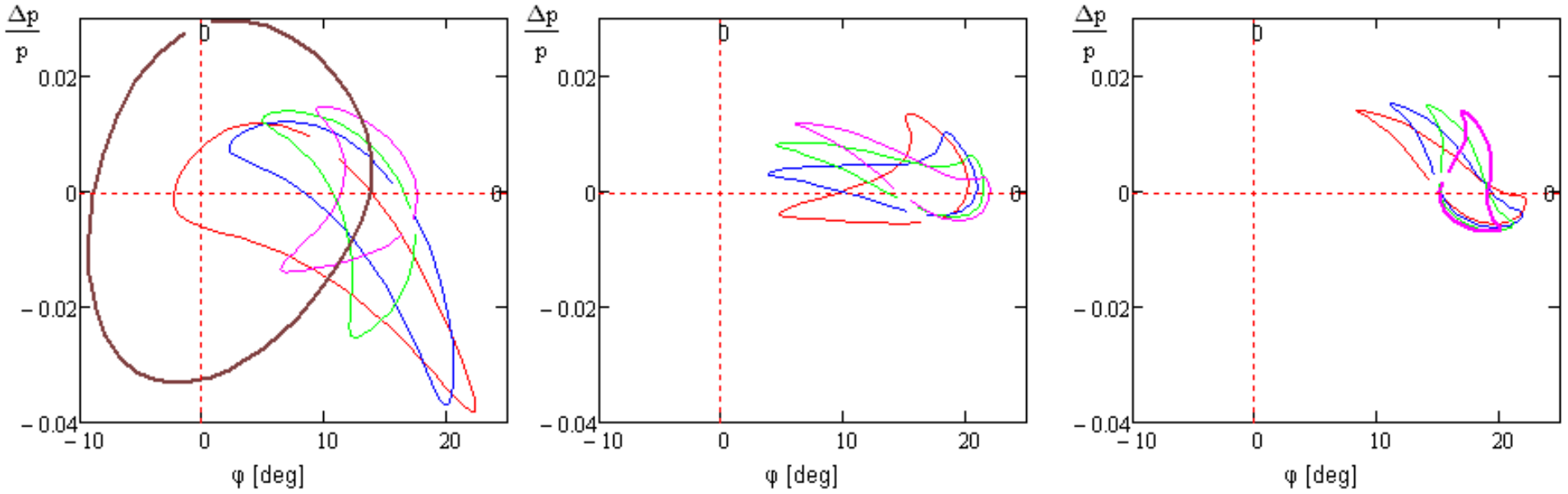
- Synchrotron motion suppresses the sag of particle energy at bunch edges
- No longitudinal emittance increase during acceleration
- Design of Cryomodules is based on the Project X and ILC technologies
  - Two types of cryomodules
    - With solenoidal focusing: 1 solenoid per cavity
    - With Triplet focusing: 6 cavities per triplet
  - All but 2 solenoids and all but 2 triplets are connected serially







Acceleration in Recirculator (based on Proj. X linac)



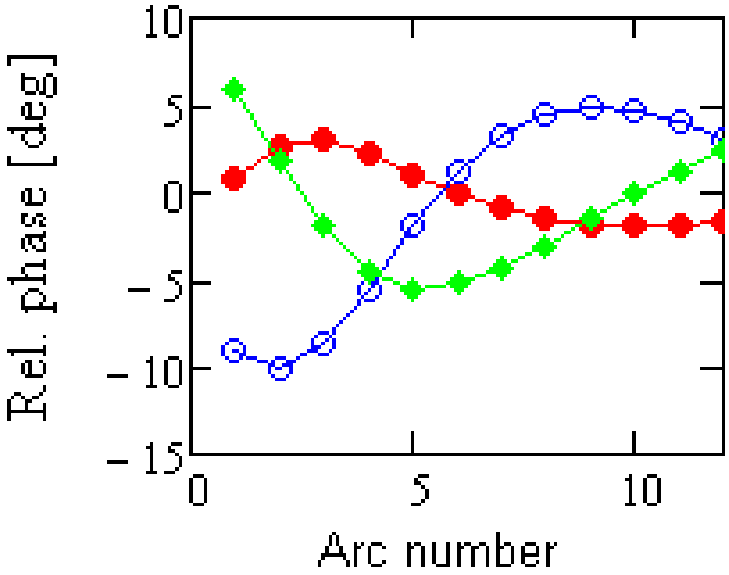
Phase spaces at the beginning and at the end of each linac end for 3σ beam envelopes

- Adjustments of M_{56} and accelerating phases for each arc and linac pass control the momentum spread and bunch length

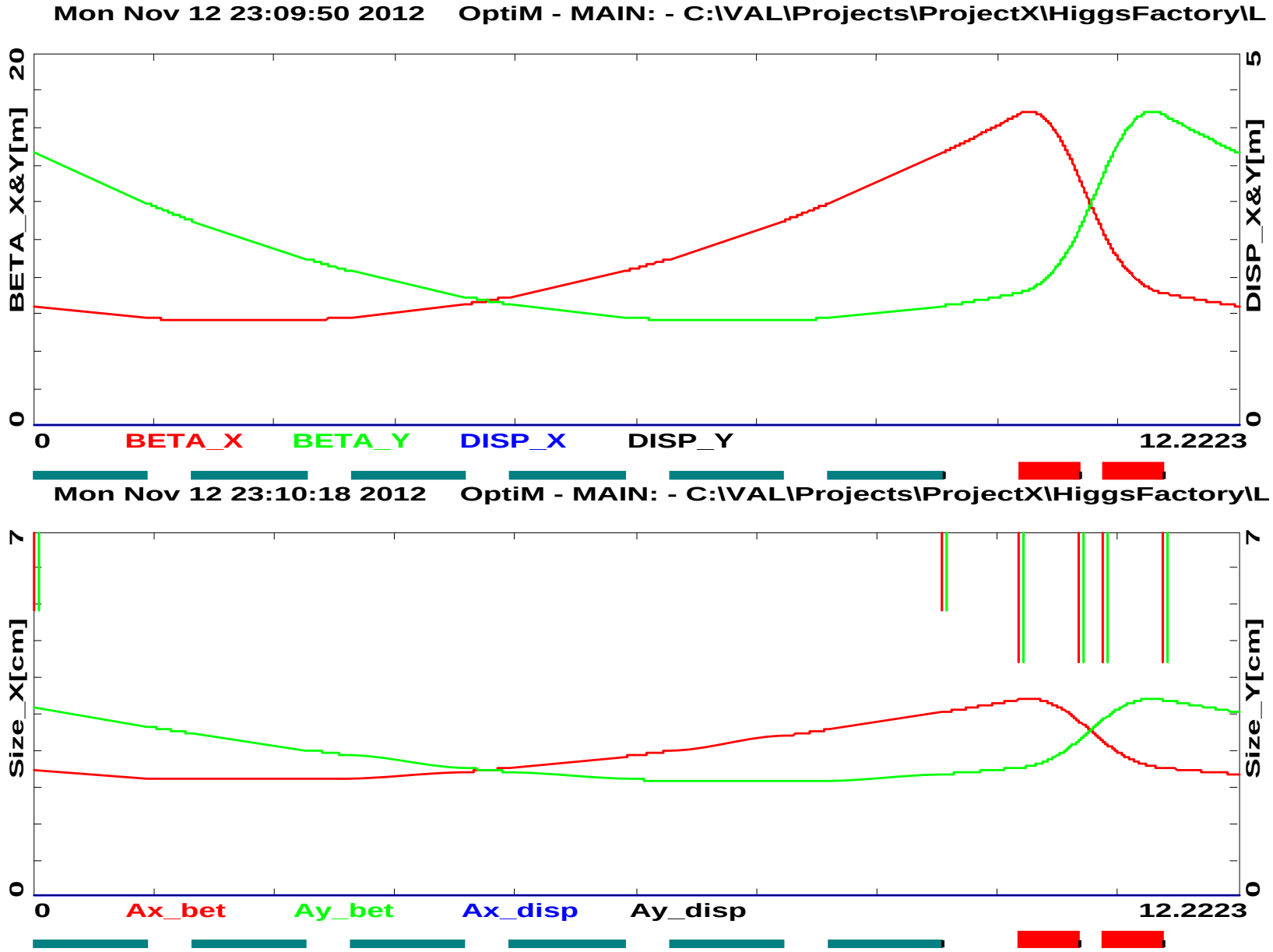
$$M56 := (10 \;\; 25 \;\; 30 \;\; 35 \;\; 35 \;\; 30 \;\; 27 \;\; 25 \;\; 25 \;\; 25 \;\; 25 \;\; 25)^{T} \text{ cm}$$

$$\varphi a := -(8 \;\; 13 \;\; 14 \;\; 15 \;\; 17 \;\; 17 \;\; 17 \;\; 17 \;\; 17 \;\; 17 \;\; 17 \;\; 17)^{T} \text{ deg}$$

- Negligible longitudinal growth for major part of particles (within 2σ)

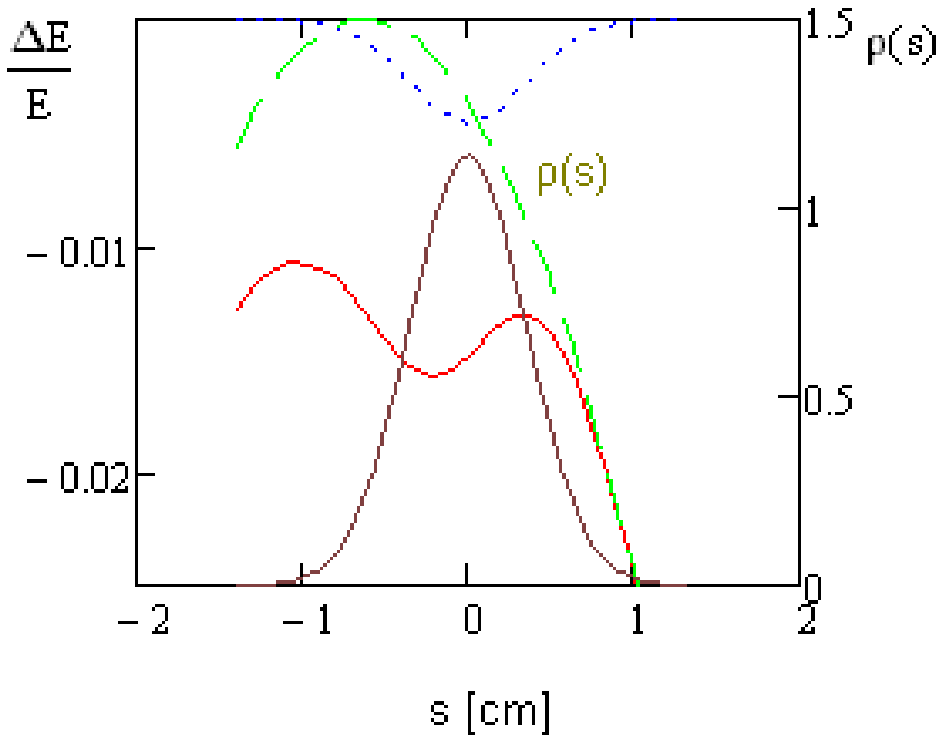


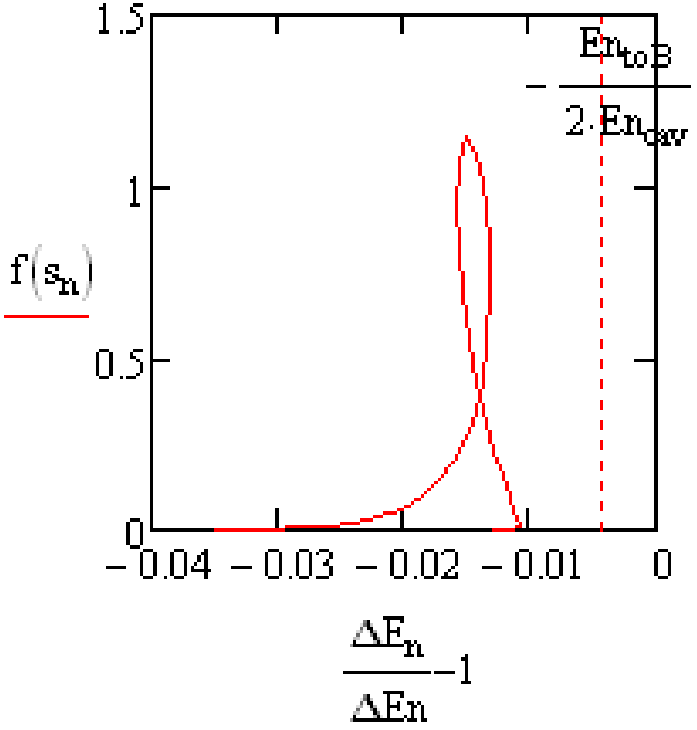
Acceleration in Recirculator (continue)



Beta-functions and 3σ beam envelopes for the first pass period

Beam Loading



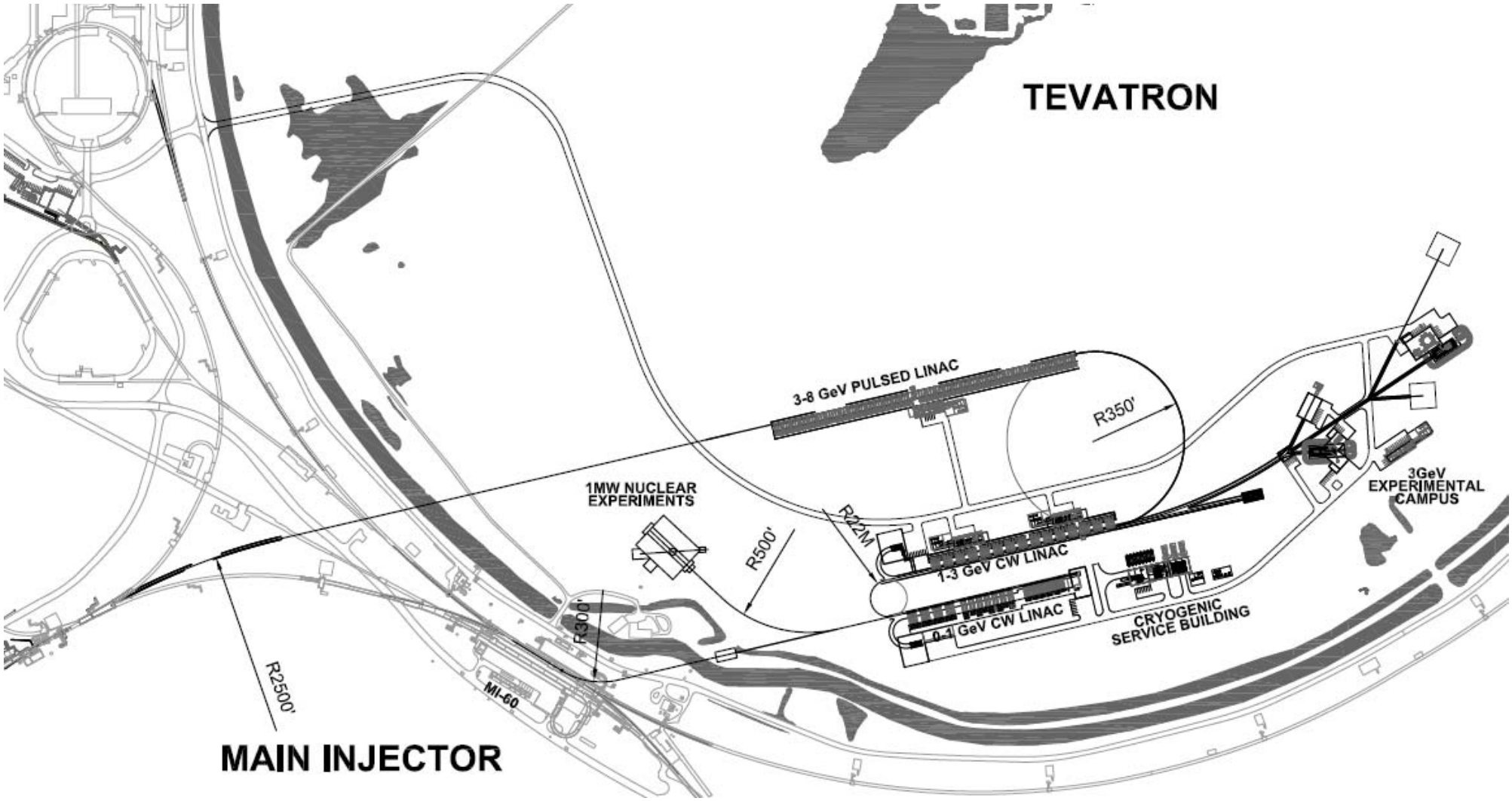


Beam loading for single pass of $6 \cdot 10^{11}$ particles per bunch;

ϕ_{acc} = 4.9 deg, σ_s = 3.5 mm => σ_E = 0.15%

- Single bunch takes 0.82% out of energy stored in a cavity
- 12 passes + (μ^+ & μ^-) yield 20% of energy taken by the beam
  - 10% accelerating gradient droop to the last pass
- Synchrotron motion in Recirculator additionally reduces momentum spread
  - Longitudinal auto-phasing reduces the dependence of final beam energy on the bunch intensity

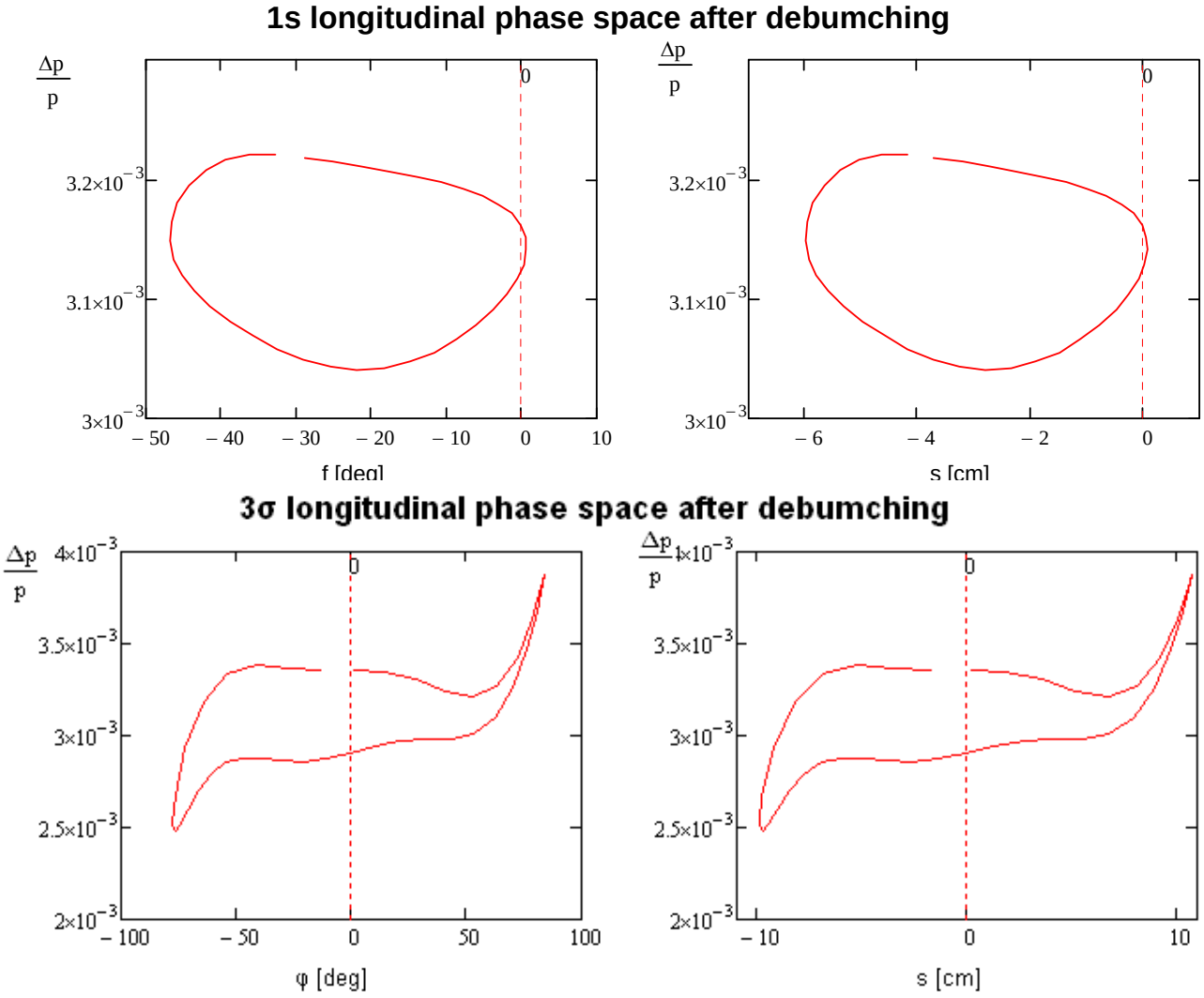
Project X and Higgs Factory Siting



- Recently adopted Project X siting fits well to the Higgs factory needs
  - Cost reduction for the first stage
  - Enough place for Recirculator arcs and the rest of the Higgs factory
  - Penalty: Emittance growth in arcs; isochronicity helps but the beam space charge induces the emittance growth

Beam Debunching

- Beam debunching is used to reduce momentum spread
  - For given longitudinal emittance of 1.5 mm one can use the same 650 MHz cryomodules with additional 1.3GHz cryomodules for non-linearity compensation. It also requires an arc with large value of M_{56}.
  - That results in the rms length of ~3 cm, and momentum spread of ~7 10^{-5}.
  - Twice smaller value of $\Delta p/p$ can be achieved with twice larger M_{56} and linacs with two times smaller frequency and approximately the same voltage



Longitudinal phase spaces
$(\Delta p/p, \phi)$ and $(\Delta p/p, s)$ after debunching
M_{56}=10 m, $V_{(650\ MHZ)}$=0.64 GeV, $V_{(1.3\ MHZ)}$=0.1 GeV

Conclusions

- There is a considerable synergy between Project X and Higgs factory ($L \sim 5 \cdot 10^{29}$ $cm^{-2}s^{-1}$)
  if the pulsed Project X linac is based on 650 MHz technology and its cavities are spaced by integer number of cell length
  - The linac can be used for acceleration of $\sim 6 \cdot 10^{11}$ muons per bunch for both μ^+ and μ^- bunches with 12 pass recirculator
  - Only modest upgrade of pulsed linac RF will be required
    - to ~1.5 MW (0.6 MW for acceleration of muons and 1 MW for acceleration of protons)
    - ~20% duty factor (13 ms proton beam pulse, f_{rep}=10 Hz)
    - No upgrade for CW part
  - Very significant price reduction for the Higgs factory or neutrino factory
- Technology developed for CW Project X linac well suits for the muon linac (3.1 GeV)
  - Cavities, solenoids, etc.