

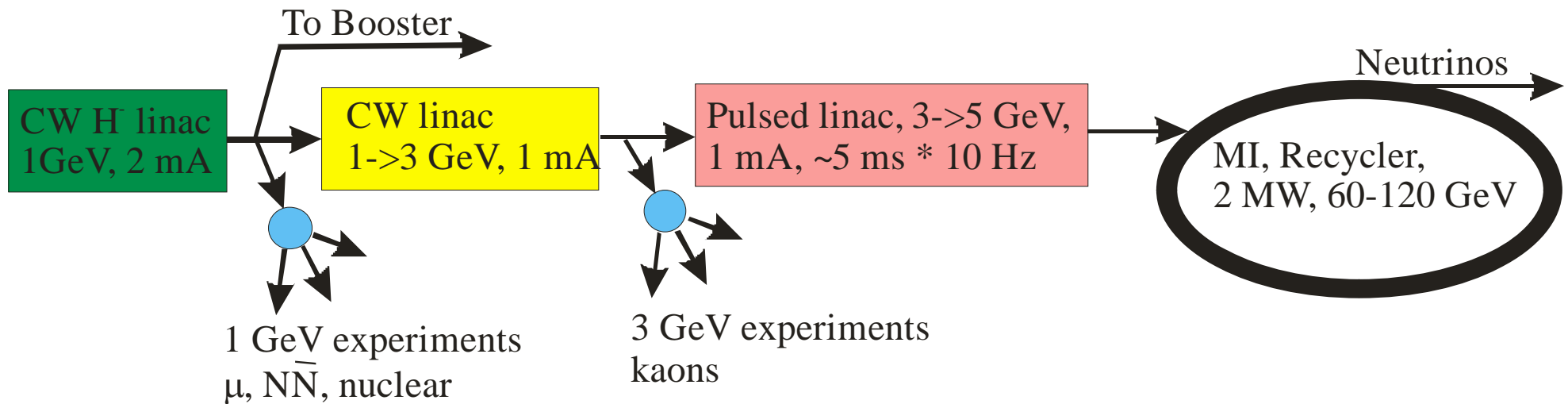
Acceleration of Muons with Project X Linac

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Mini-Workshop on Muon
Collider Higgs Factory
Fermilab
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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; $(4.5\rightarrow 6)10^{12}$ /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 \times 10 Hz(?)
(b) MI upgrade from 0.7 MW to 2 MW

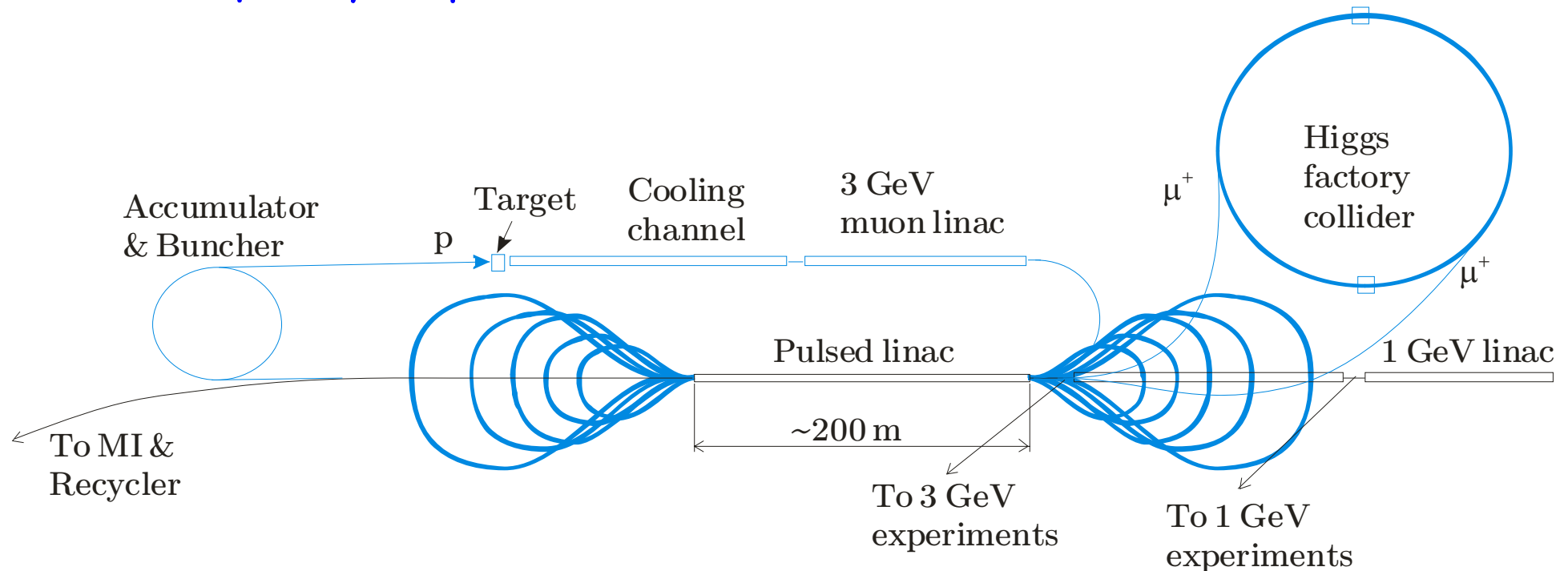


Project X Pulsed linac (3 -> 8 GeV, 5 GeV installed V)

- Present plan for muon collider pulsed linac
 - ◆ Future upgrade implies
 - Beam current increase from 1 to 5 mA
 - ⇒ will require upgrade of CW part to 5 mA too
 - Beam power increase from 0.34 to 4 MW
 - ⇒ 10 Hz → 15 Hz (?)
 - ⇒ 4.2 ms → 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 → 650 MHz
 - ⇒ 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

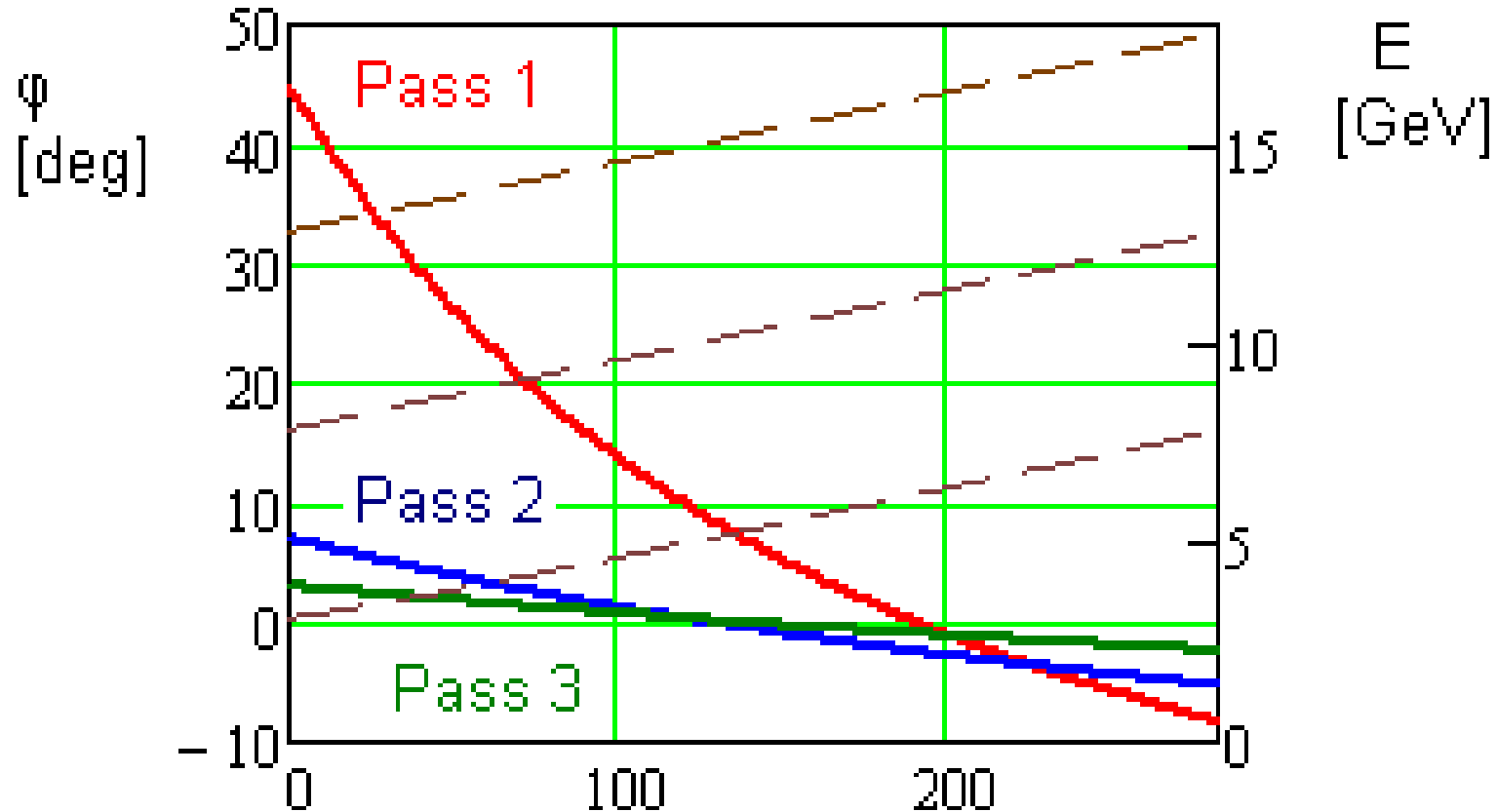
- 12 pass recirculator accelerates muons from 3.1 GeV to 62.5 GeV
 - ◆ s-channel muon based Higgs factory
- Beam power on the muon production target is reduced: 4 → ~1 MW
 - ◆ Beam current stays the same (1 mA)
 - ◆ No need to modify CW part
- RF frequency of pulsed linac decreased from 1.3 GHz to 650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



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

Initial energy of Recirculation

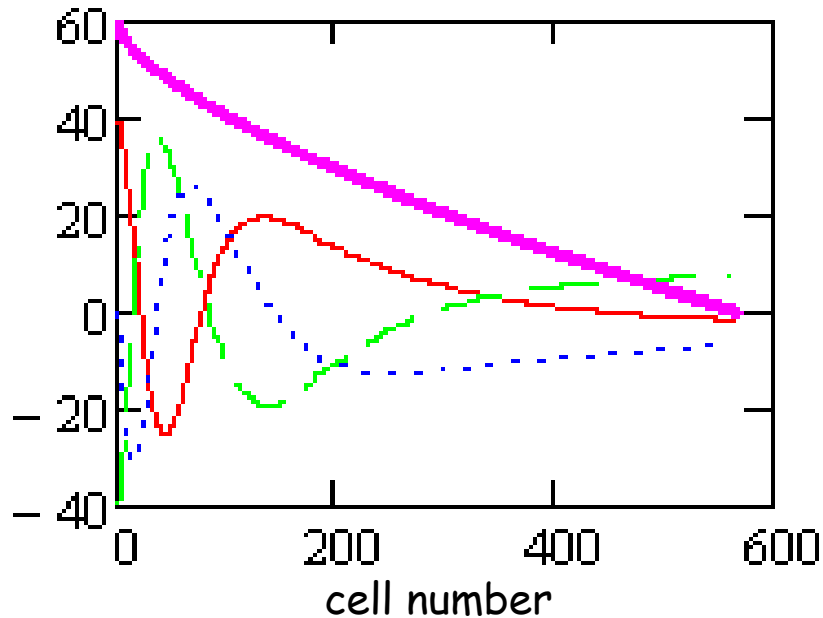
- Phase slip limits the initial energy of recirculation to ~ 3.1 GeV



Phase slip for the first 3 of 12 passes

Acceleration in the Muon Linac

Long. motion in linac



Main parameters

Momentum range, $p_c = [0.3-3.2 \text{ GeV}]$

Accelerating frequency = 650 MHz

Accelerating gradient = 25 MeV/m

Accelerating cavities: 5 cell, $\beta = 1$

Linac length $\approx 250 \text{ m}$

Longitudinal acceptance, $\varepsilon_{ns} = 3^2 \times 1500 \text{ mm mrad}$

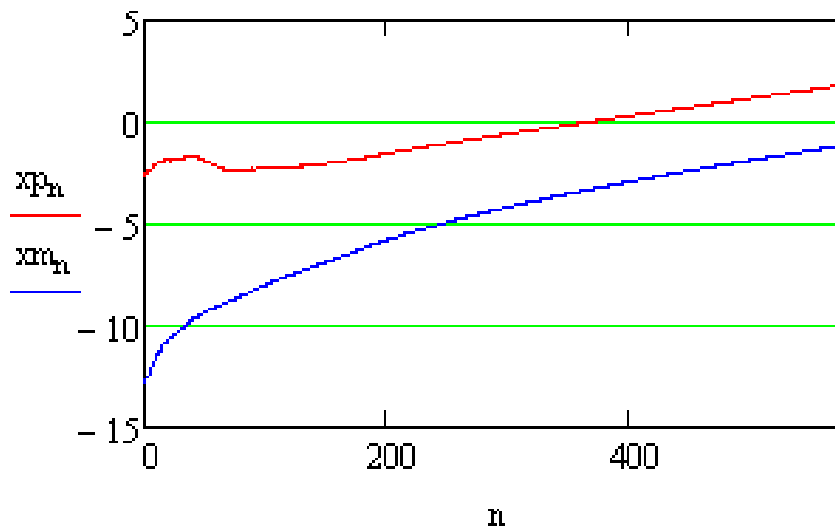
Transverse acceptance, $\varepsilon_{ns} = 3^2 \times 300 \text{ mm mrad}$

Number of RF cavities = 114

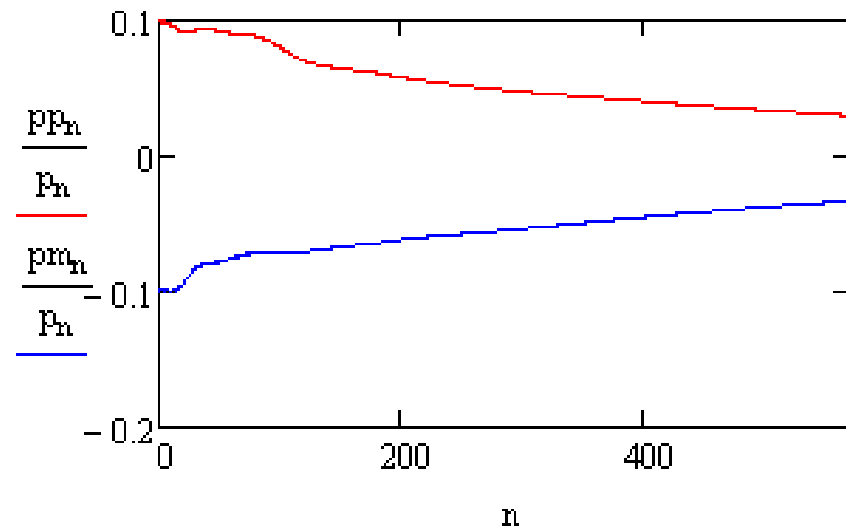
Particles per bunch = $6 \cdot 10^{11}$

Repetition rate = 10 Hz

Bunch end positions [cm]



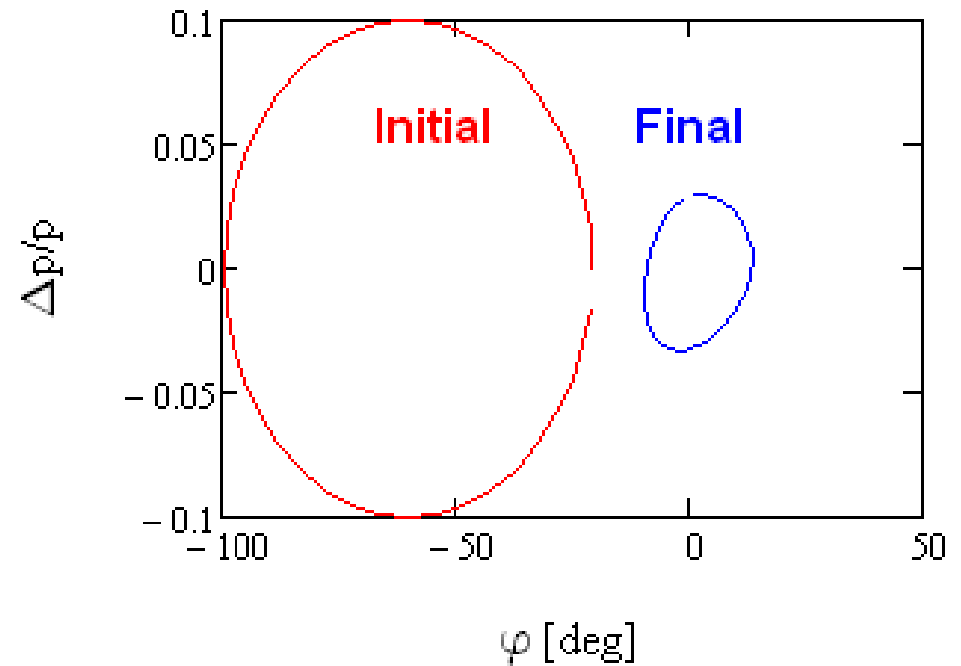
Min. & max. rel. momentum



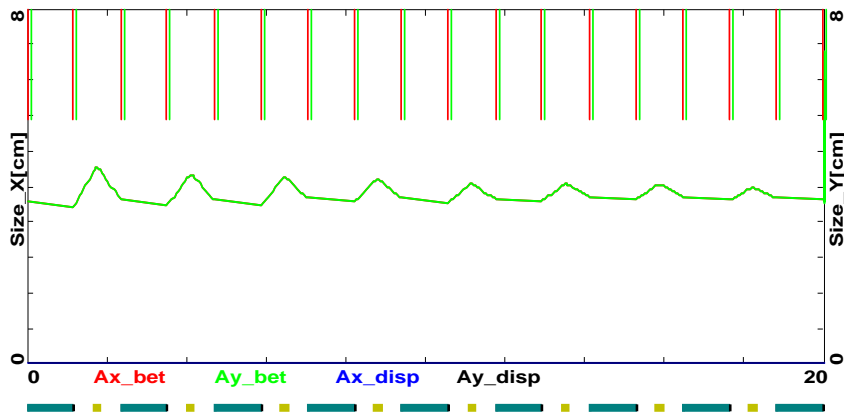
Bunch boundaries for 3σ

Acceleration in the Muon Linac (continue)

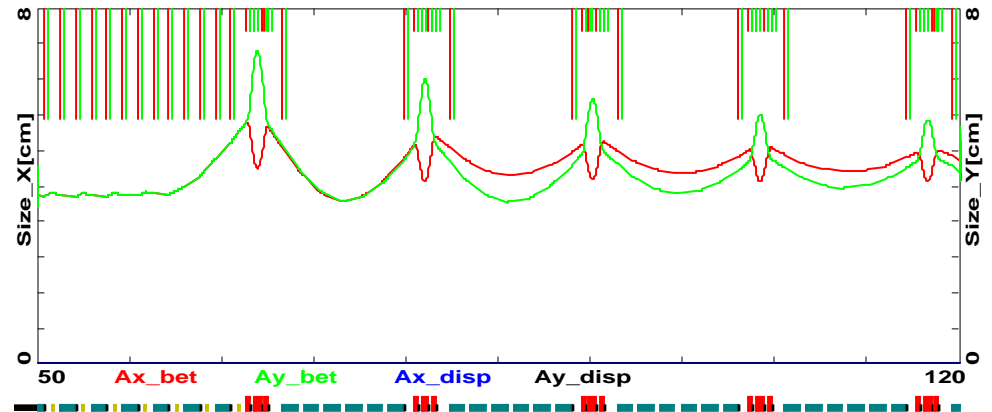
- Synchrotron motion suppresses the sag of particle energy at bunch edges
- No longitudinal emittance increase during acceleration
- Design of Cryomodules is based on the Project X and ILC technologies
 - ◆ Two types of cryomodules
 - With solenoidal focusing: 1 solenoid per cavity
 - With Triplet focusing: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



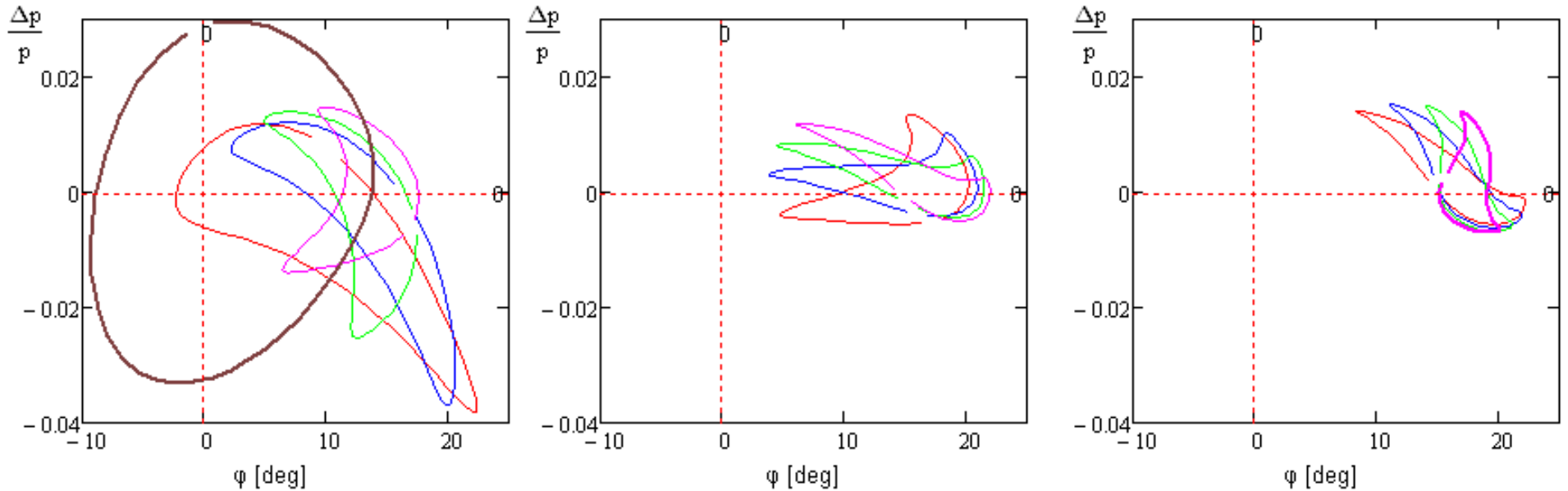
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Acceleration in Recirculator (based on Proj. X linac)



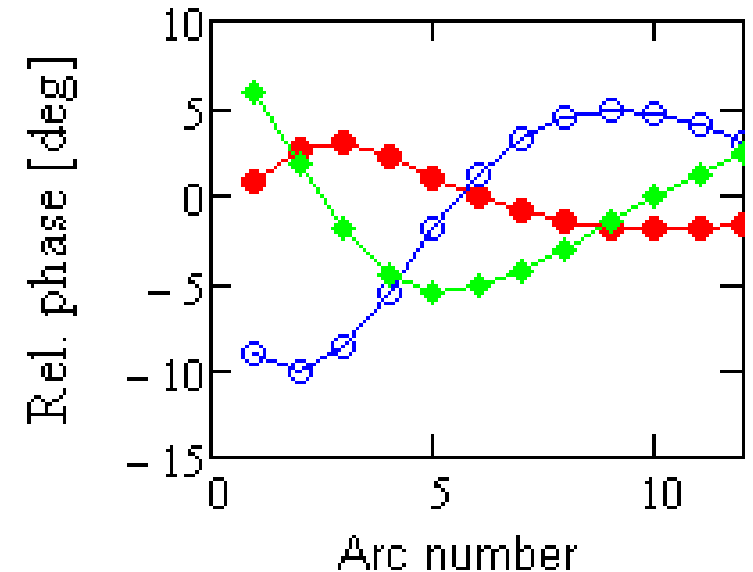
Phase spaces at the beginning and at the end of each linac end for 3σ beam envelopes

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

$$M_{56} := (10 \ 25 \ 30 \ 35 \ 35 \ 30 \ 27 \ 25 \ 25 \ 25 \ 25 \ 25)^T \text{ cm}$$

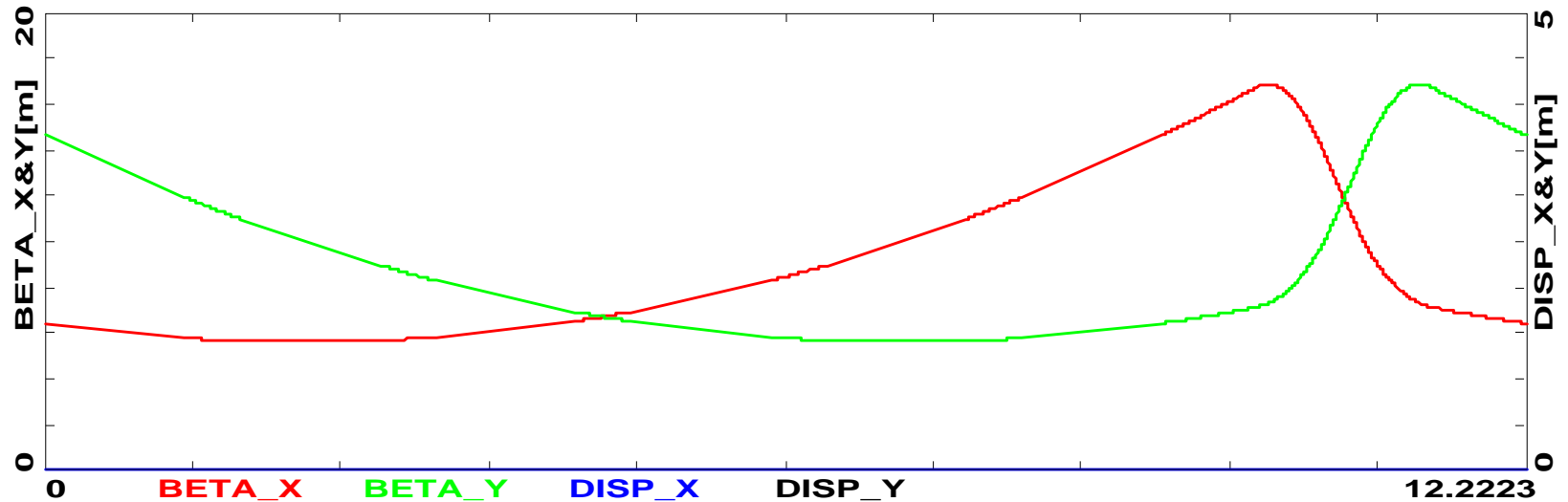
$$\phi_a := -(8 \ 13 \ 14 \ 15 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17)^T \text{ deg}$$

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

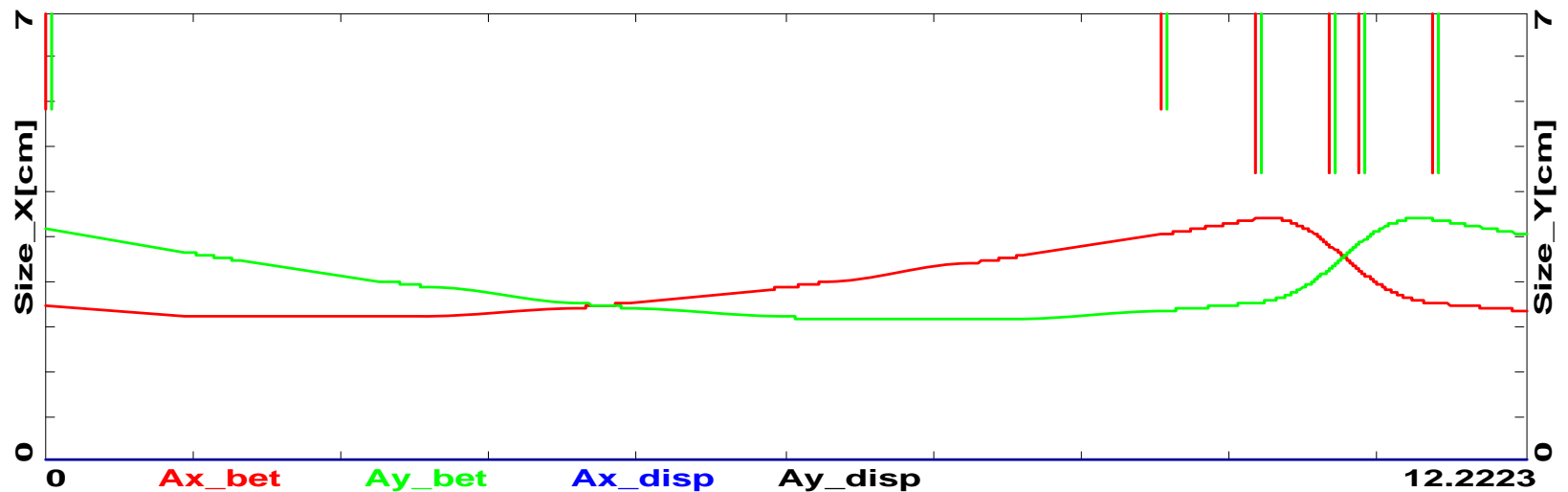


Acceleration in Recirculator (continue)

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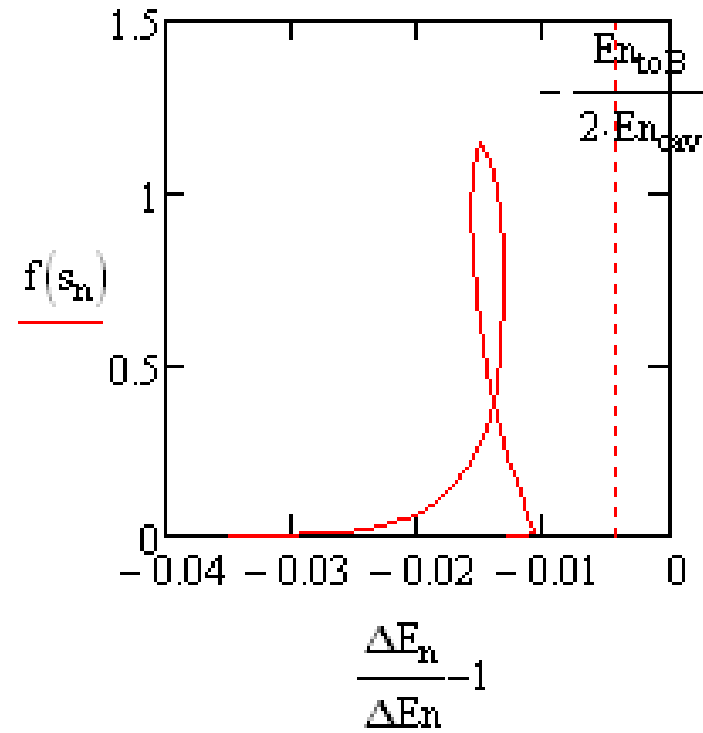
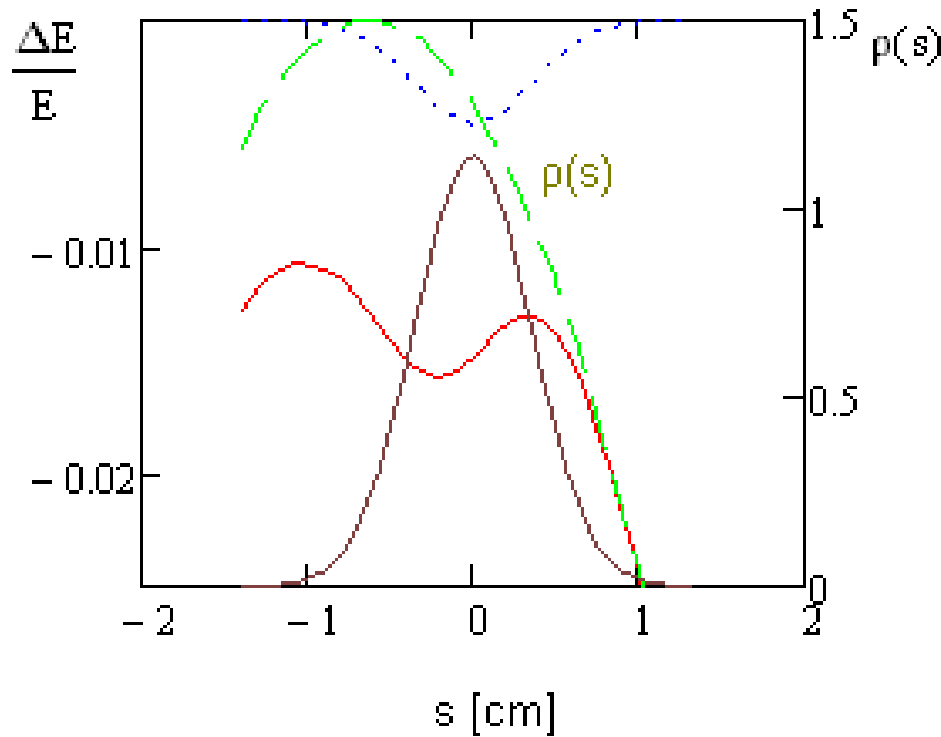


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Beta-functions and 3σ beam envelopes for the first pass period

Beam Loading

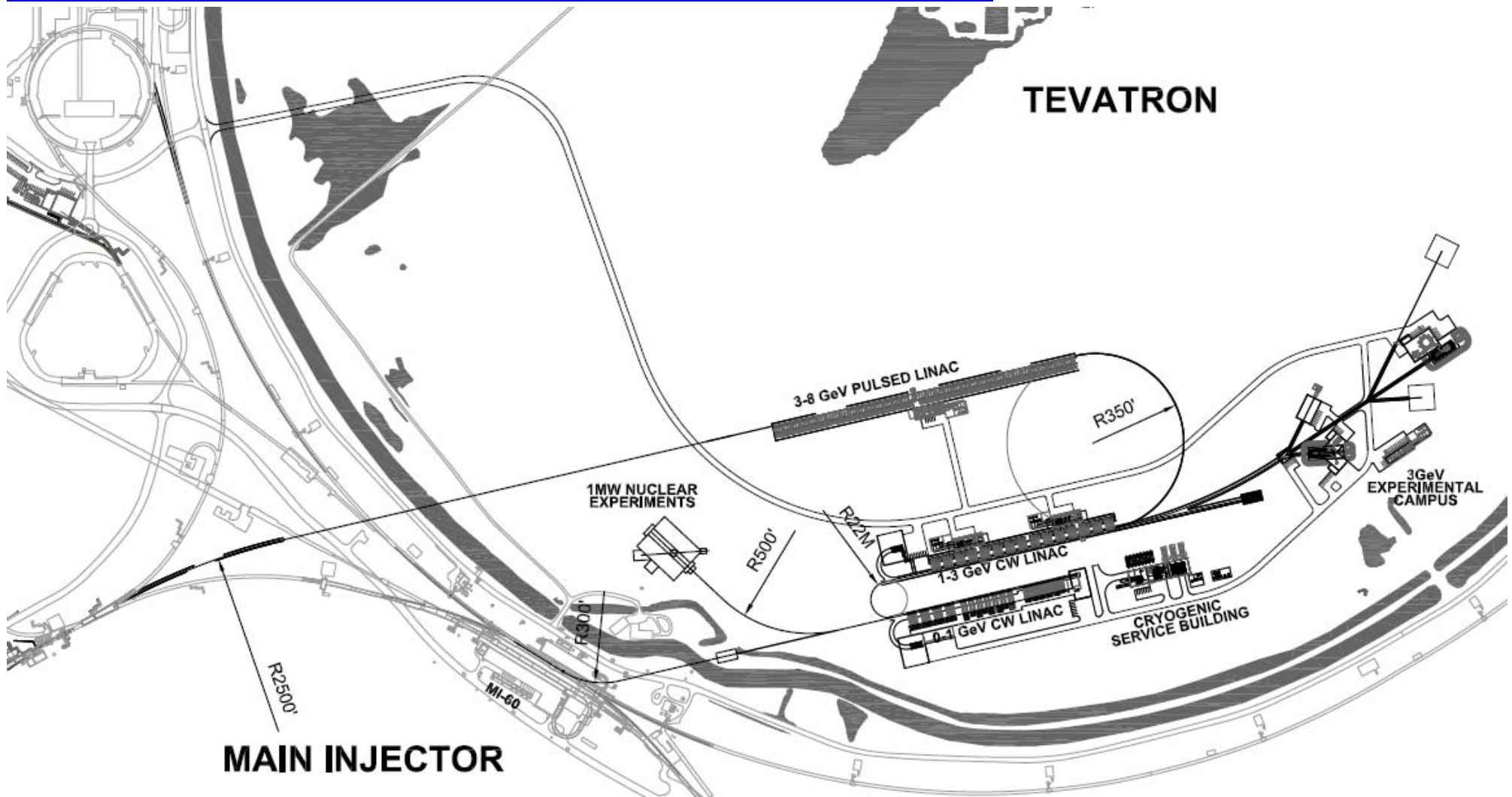


Beam loading for single pass of $6 \cdot 10^{11}$ particles per bunch;

$$\phi_{acc} = 4.9 \text{ deg}, \sigma_s = 3.5 \text{ mm} \Rightarrow \sigma_E = 0.15\%$$

- 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

Conclusions

- There is a considerable synergy between Project X and Higgs factory ($L \sim 5 \cdot 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$)
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 $\sim 1.5 \text{ MW}$ (0.6 MW for acceleration of muons and 1 MW for acceleration of protons)
 - $\sim 20\%$ duty factor (13 ms proton beam pulse, $f_{\text{rep}} = 10 \text{ Hz}$)
 - 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.