International MUON Collider Collaboration

Jefferson Lab
Thomas Jefferson National Accelerator Facility

RF Systems Issues of Low Energy Muon Acceleration – Linac and RLAs

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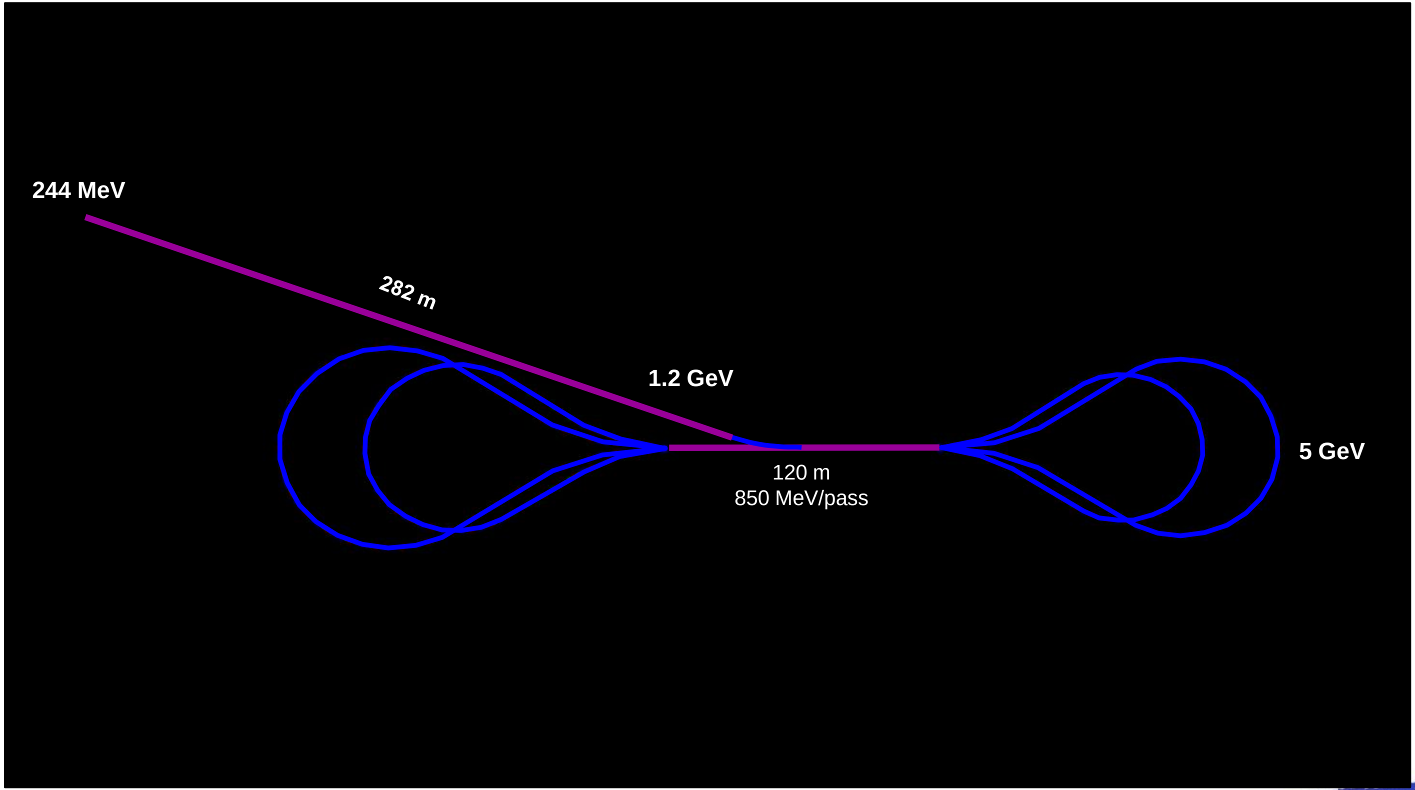
Overview

- 5 GeV Neutrino Factory based on ‘Dogbone’ RLA
  - Linac (255 MeV – 1.25 GeV) Longitudinal compression
  - RLA (1.25 – 5 GeV) 4.5 pass
- Optimized RLA scheme for Higgs Factory (63 GeV)
  - RLA (5 – 63 GeV) 5-pass
  - Beam loading considerations

Muon Acceleration – Choice of Technology

- Acceleration of short-lived muons requires high average gradient, while maintaining very large transverse and longitudinal accelerator acceptances.
  - The above requirement drives the design to low RF frequency, e.g. 325 MHz, 650 MHz
  - If normal-conducting cavities at that frequency were used, the required high gradients would demand uneconomically high peak RF sources.
  - Superconducting RF is a much more attractive solution – the RF power can then be delivered to the cavities over an extended time, and thus RF source peak power can be reduced.
- While recirculation (RLA) provides significant cost savings over a single linac, it cannot be used at low energy since the beam is not sufficiently relativistic and will therefore cause a phase slip for beams in higher passes

State of Thought for Multi GeV Muon Acceleration (Circa 2017)



Choice of Linac Repetition Rate

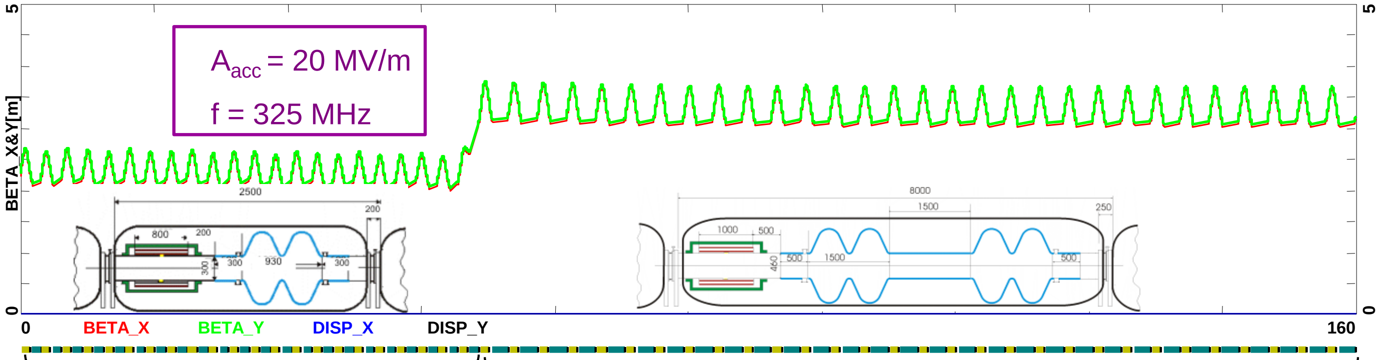
- For optimum performance – to maximize number of events ($\mu \rightarrow \nu$ decays NF, $\mu^{\pm}$ collisions MC) – the linac repetition rates should scale inversely with the laboratory lifetime of the muon in its storage ring:
  - Repetition rates as **high** as 10 kHz for a 5 GeV Neutrino Factory
  - Repetition rates as **low** as 10 Hz for a 5 TeV Muon Collider.

Initial 325 MHz Linac – Transverse Acceptance

p = 255 MeV/c

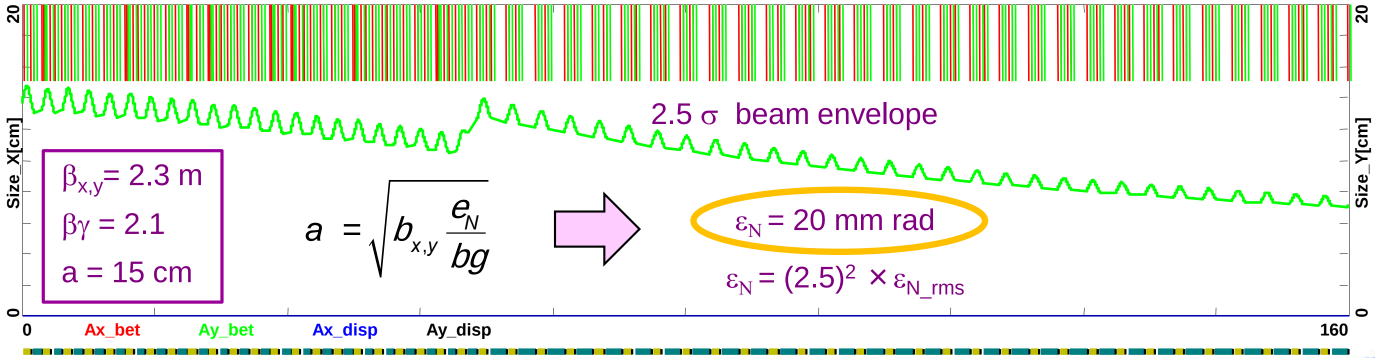
beta functions

1250 MeV



22 short cryos (2.5 meter, 2-cell cavity)

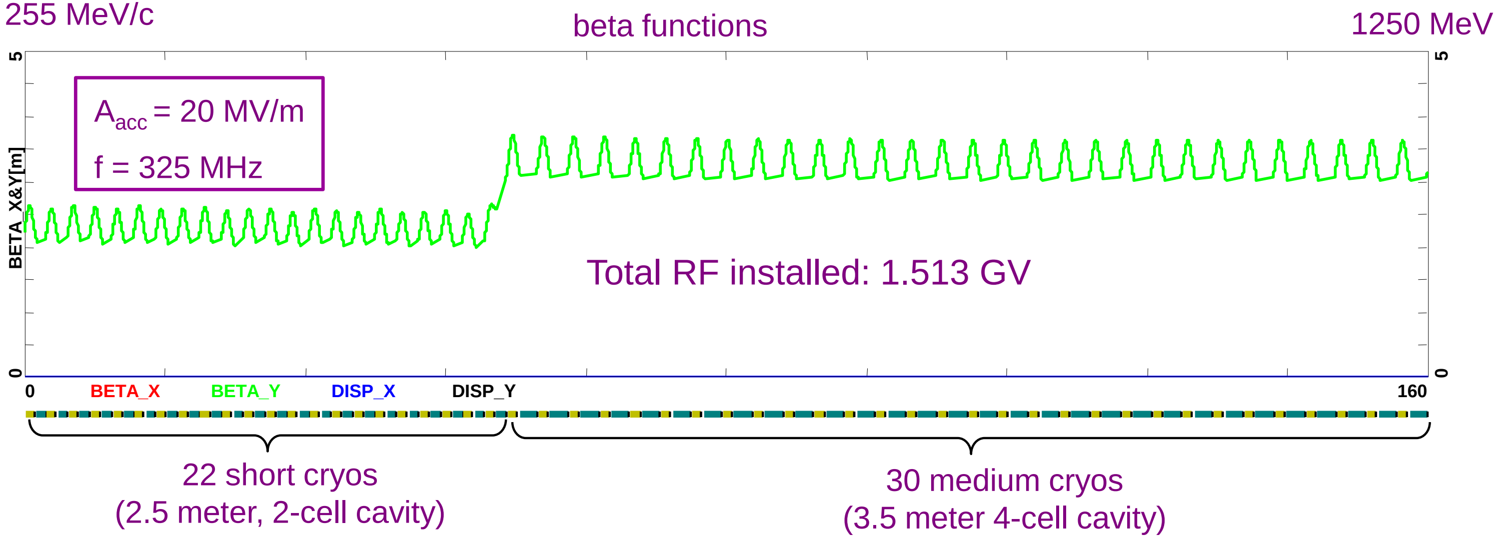
30 medium cryos (3.5 meter 4-cell cavity)

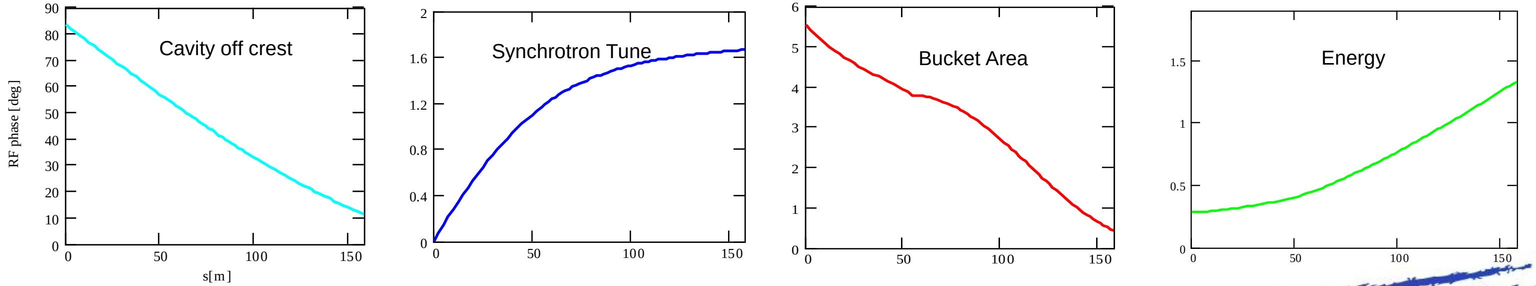


Initial 325 MHz Linac – Longitudinal Compression

p = 255 MeV/c

1250 MeV





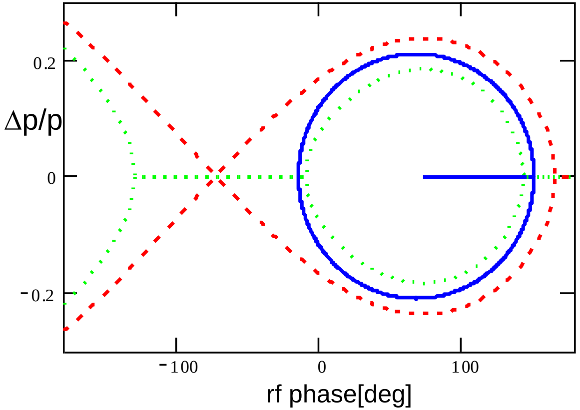
Longitudinal Compression

325 MHz, 20 MV/m

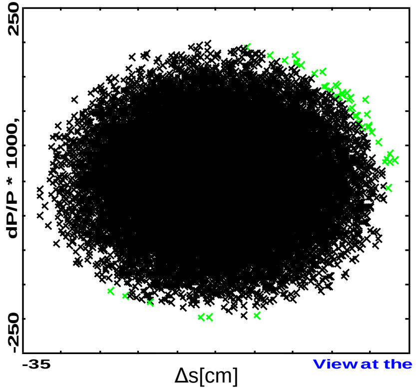
E = 244 MeV
γ = 2.3

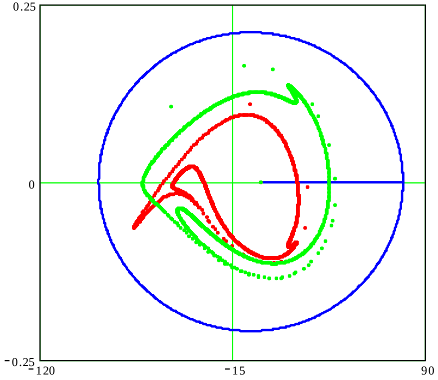
longitudinal emittance: ε_l	mm	**150**
($\varepsilon_l = \sigma_{\Delta p}\, \sigma_z / m_\mu c$)		
momentum spread: $\sigma_{\Delta p/p}$		**0.112**
bunch length: σ_z	mm	**103**

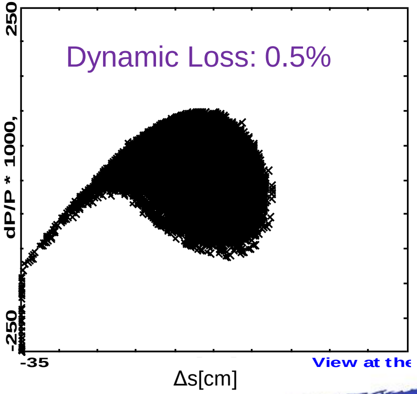
84 deg. off-crest



Tracking with OptiM)

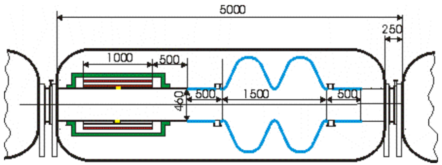


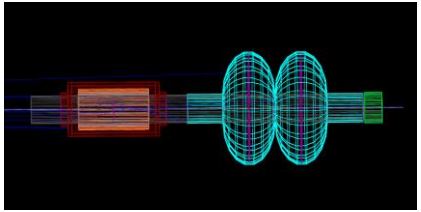


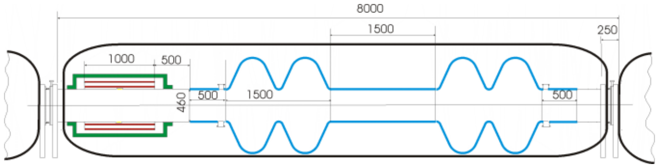


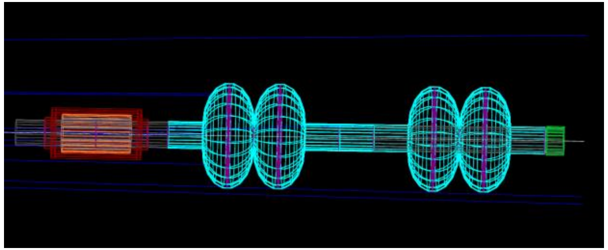
Single Pass Linac – RF Components

Beam energy	**Initial**	**GeV**	**0.255**	
	Final	**GeV**	**1.25**	
			Type 1	**Type 2**
RF cavities	**Technology**		SRF	SRF
	Number of cavities	**#**	22	30
	RF length/cavity	**m**	1	2
	Frf	**MHz**	325	325
	Grf	**MV/m**	20	20
	Magnetic Field	**T**	0	0
	Integrated RF Field	**MV**	440	1200
	Energy gain	**MeV**	tapered off-crest cavity	
	Recirculations	**#**	1	1
	Prf/cavity	**MW**	1	1
RF power sources	**Technology**		klystron	klystron
	Cavities/Power Source	**#**	1	1
	RF Pulse length	**ms**	0	0
	Prf/Power Source	**MW**	1	1
	Number Power Source	**#**	22	30
	Total RF Power	**MW**	22	30
	Total RF Energy/pulse	**kJ**	0	0
Cryogenics			2.2 K	2.2 K





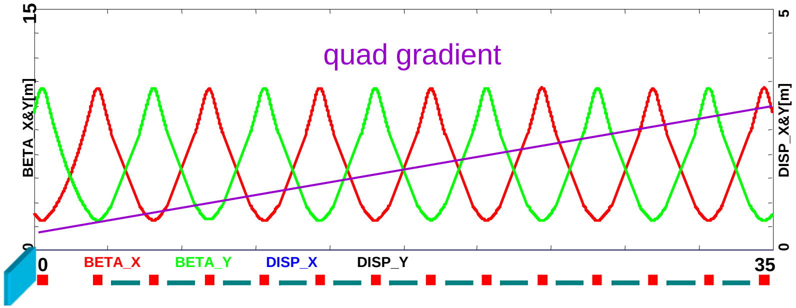


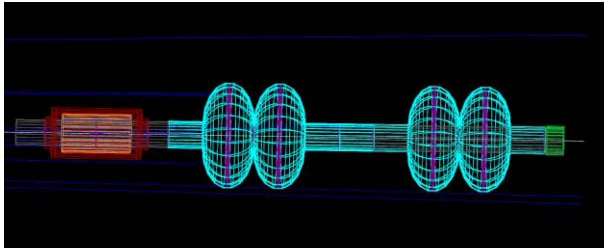


‘Dogbone’ RLA Linac

‘half pass’, 1250-1625 MeV

initial phase adv/cell 90 deg. scaling quads with energy

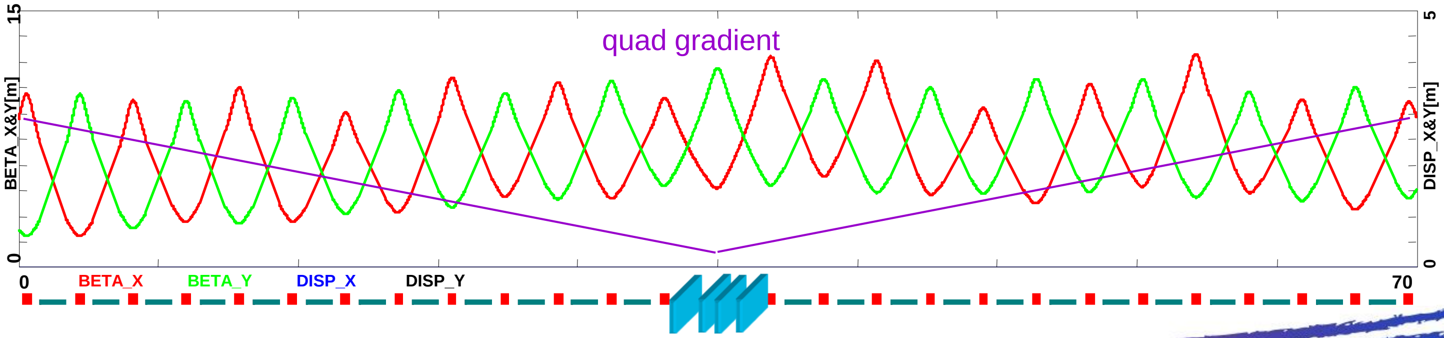




4 meter 90 deg. FODO cells
25 MV/m, 650 MHz, 2 × 4-cell cavity

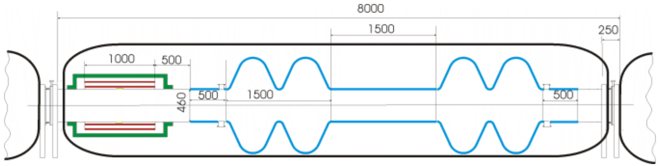
1-pass, 1625-2475 MeV

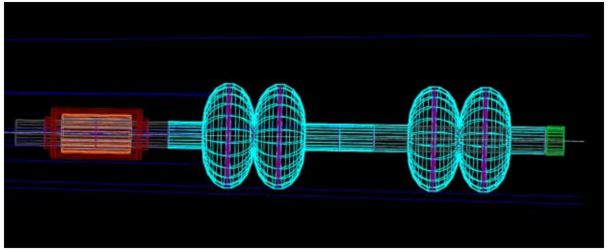
mirror symmetric quads in the linac



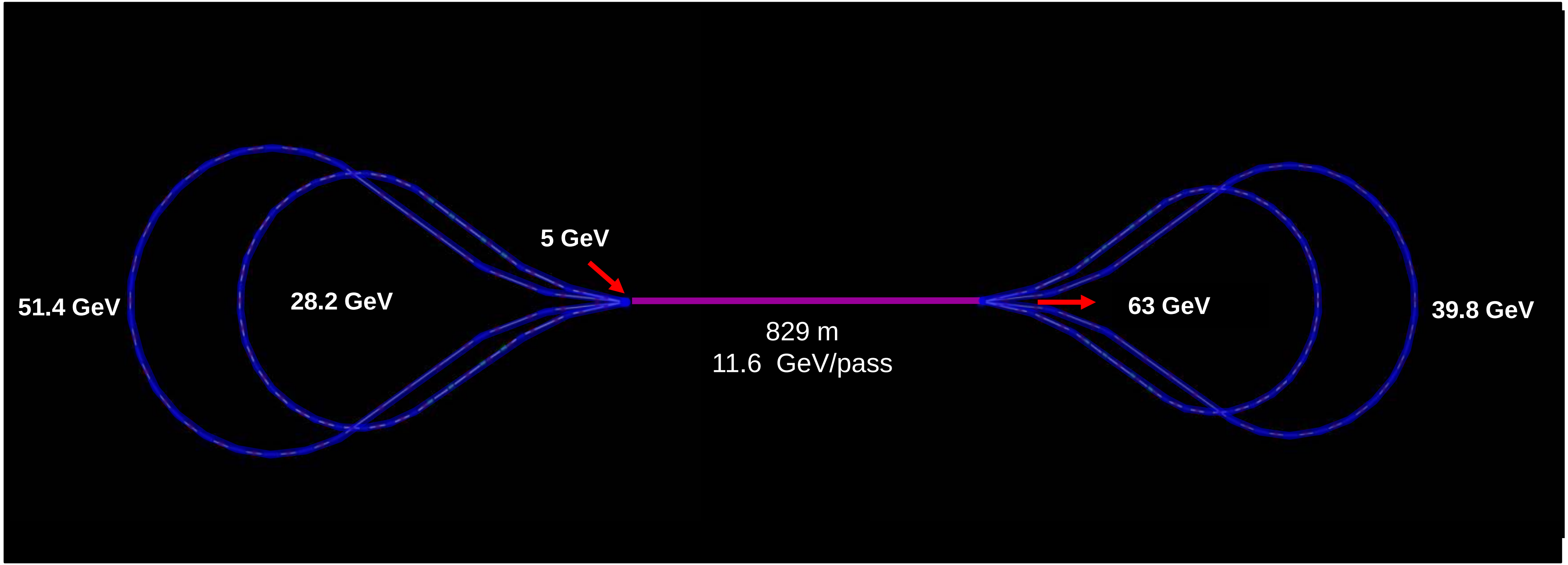
‘Dogbone’ RLA 1 – RF Components

Beam energy	**Initial**	**GeV**	**1.25**
	Final	**GeV**	**5**
			Type 3
RF cavities	**Technology**		SRF
	Number of cavities	**#**	38
	RF length/cavity	**m**	2
	Frf	**MHz**	650
	Grf	**MV/m**	25
	Magnetic Field	**T**	0
	Integrated RF Field	**MV**	1900
	Energy gain	**MeV**	22
	Recirculations	**#**	4.5
	Prf/cavity	**MW**	1
RF power sources	**Technology**		IOT
	Cavities/Power Source	**#**	2
	RF Pulse length	**ms**	0
	Prf/Power Source	**MW**	1
	Number Power Source	**#**	19
	Total RF Power	**MW**	19
	Total RF Energy/pulse	**kJ**	0
Cryogenics			2.2 K

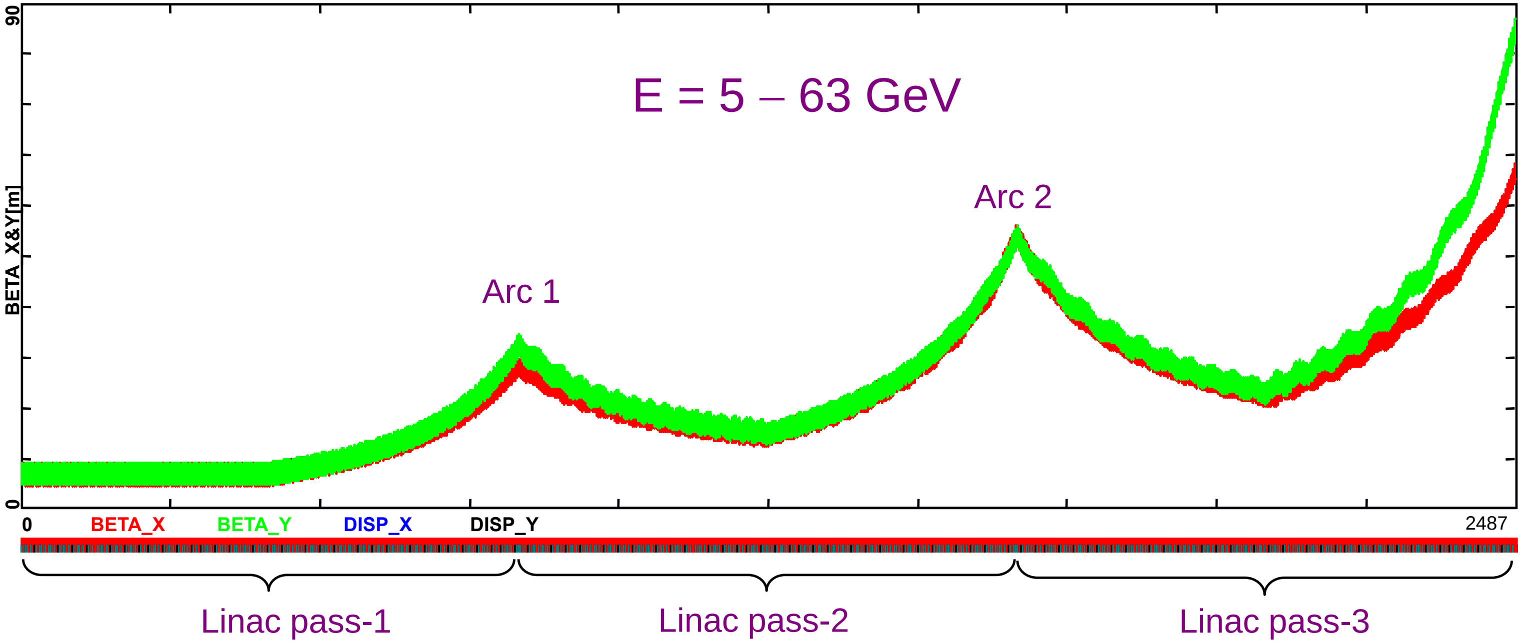




Higgs Factory: 5-pass RLA (5 – 63 GeV)



Multi-pass Linac – Bisected Optics



RF	f [MHz]	cells/cavity	Grad [MV/m]	phase [deg]
	1300	9	38	12

Beam Loading Consideration

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stored energy in a cavity: $$\frac{V^2}{\omega(R/Q)}$$

fractional reduction in the cavity voltage : $$\frac{\Delta V}{V} = \frac{enN\omega(R/Q)\cos\phi}{V}$$

RF gradient G defined as: $$V = n_C G\pi c/\omega,$$

$$\frac{\Delta V}{V} = \frac{enN\omega^2[(R/Q)/n_C]\cos\phi}{\pi G c}$$

fractional voltage reduction:

$$(R/Q)/n_C = 114\,\Omega$$

$$\phi = 0$$

Particles	2×10^{12}	4×10^{12}	2×10^{12}	4×10^{12}
Frequency	325 MHz	325 MHz	650 MHz	650 MHz
Passes	Relative reduction (%)			
3	2	5	8	16
5	4	8	13	26
7	6	11	18	36
9	7	15	23	47

‘Dogbone’ RLA 2 – RF Components

Beam energy	Initial	GeV	5
	Final	GeV	62.5
			Type 4
RF cavities	Technology		SRF
	Number of cavities	#	322
	RF length/cavity	m	4
	Frf	MHz	1300
	Grf	MV/m	38
	Magnetic Field	T	0
	Integrated RF Field	MV	48944
	Energy gain	MeV	36
	Recirculations	#	5
	Prf/cavity	MW	1
RF power sources	Technology		IOT
	Cavities/Power Source	#	1
	RF Pulse length	ms	0
	Prf/Power Source	MW	1
	Number Power Source	#	322
	Total RF Power	MW	322
	Total RF Energy/pulse	kJ	0
Cryogenics			2.2 K

Summary

- RF system specs for low energy acceleration stages:
  - Linac (255 MeV – 1.25 GeV) 1-pass
  - RLA 1 (1.25 – 5 GeV) 4.5-pass
  - RLA 2 (5 – 63 GeV) 5-pass
- Next step….
  - Optimized Linac + RLAs scheme for Higgs Factory and beyond…

Thanks for your for attention

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