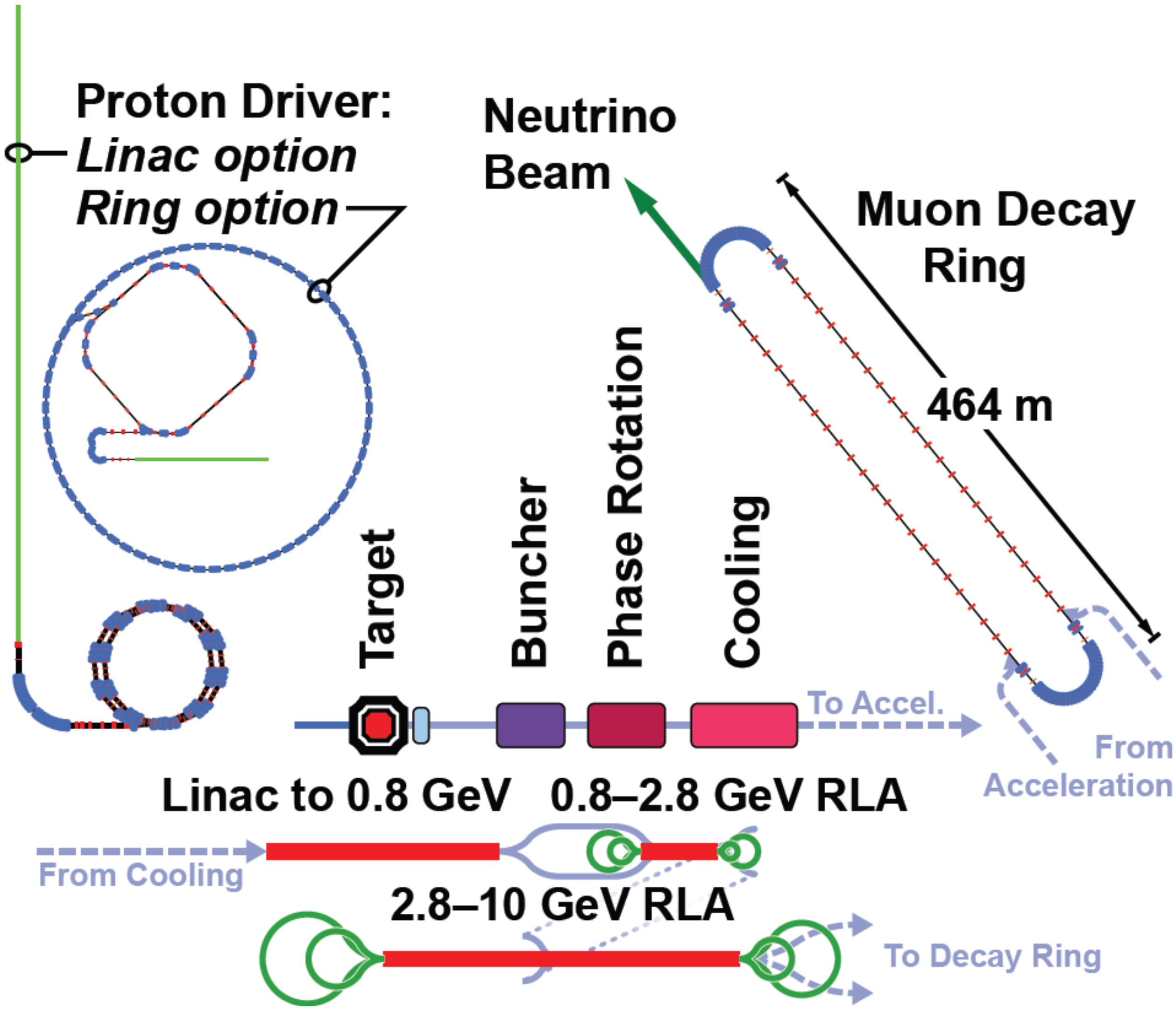
Report on Accelerator Studies for IDS-NF

Alex Bogacz

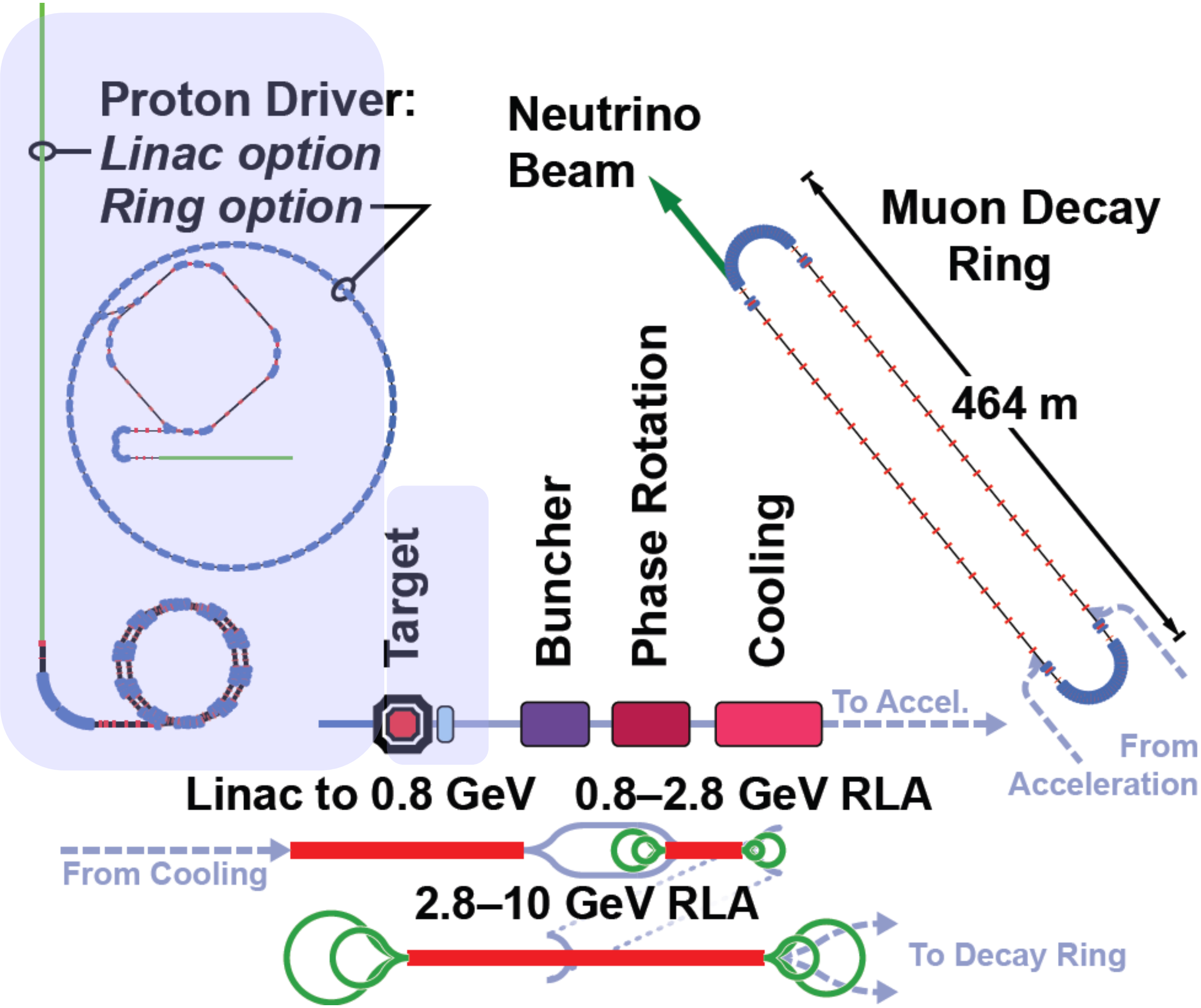
IDS-NF Goals

- Provide 10^{21} muon decays per year toward a far detector
- Decays from 10 GeV muon beam
- Angular divergence below $0.1 \times \frac{1}{\gamma}$
- Beam directed toward detector 2000 km away



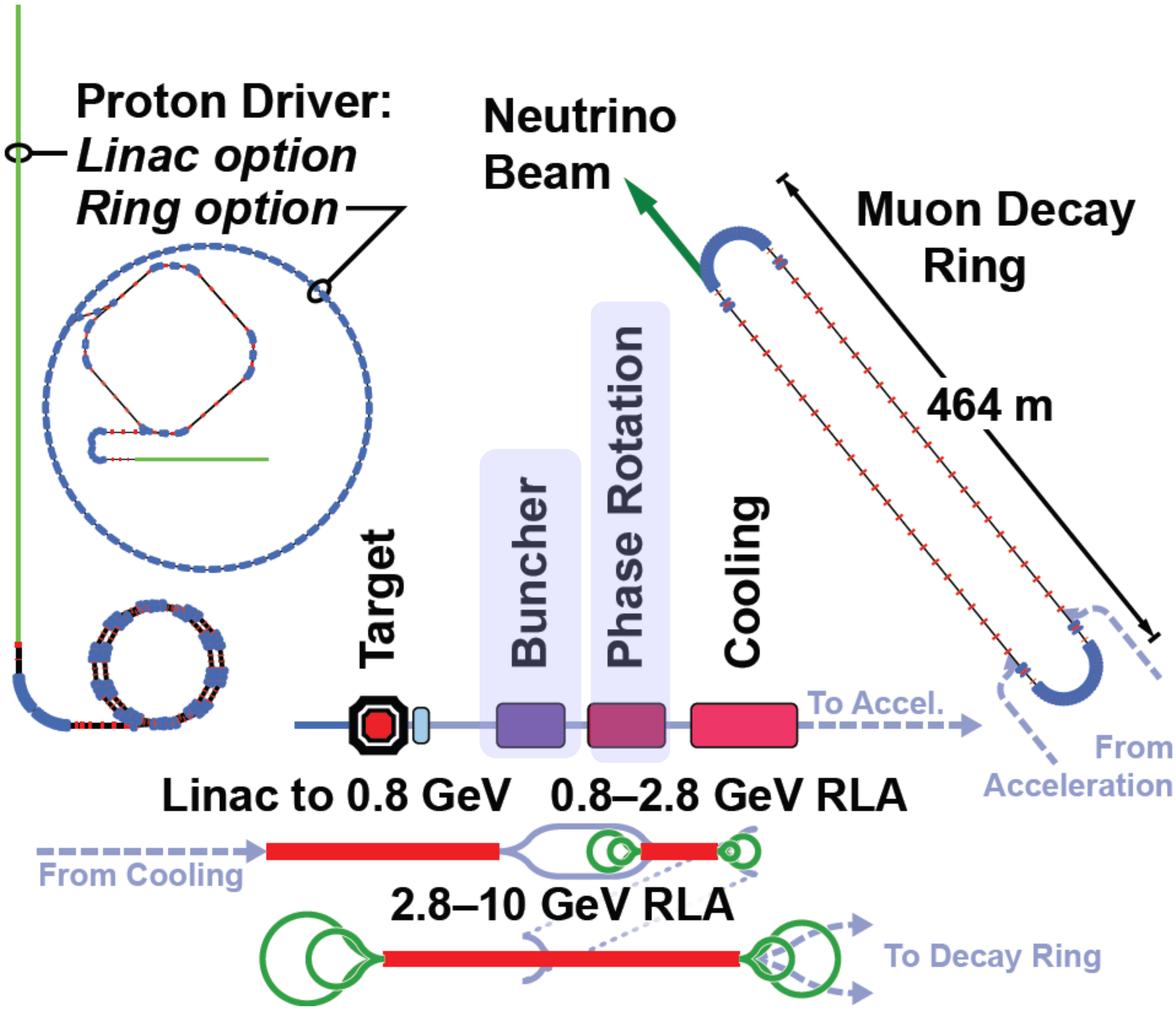
IDS-NF Accelerator Systems

- A proton source producing a high-power multi-GeV bunched proton beam
- A pion production target that operates within a high-field solenoid. The solenoid confines the pions radially, guiding them into a decay channel



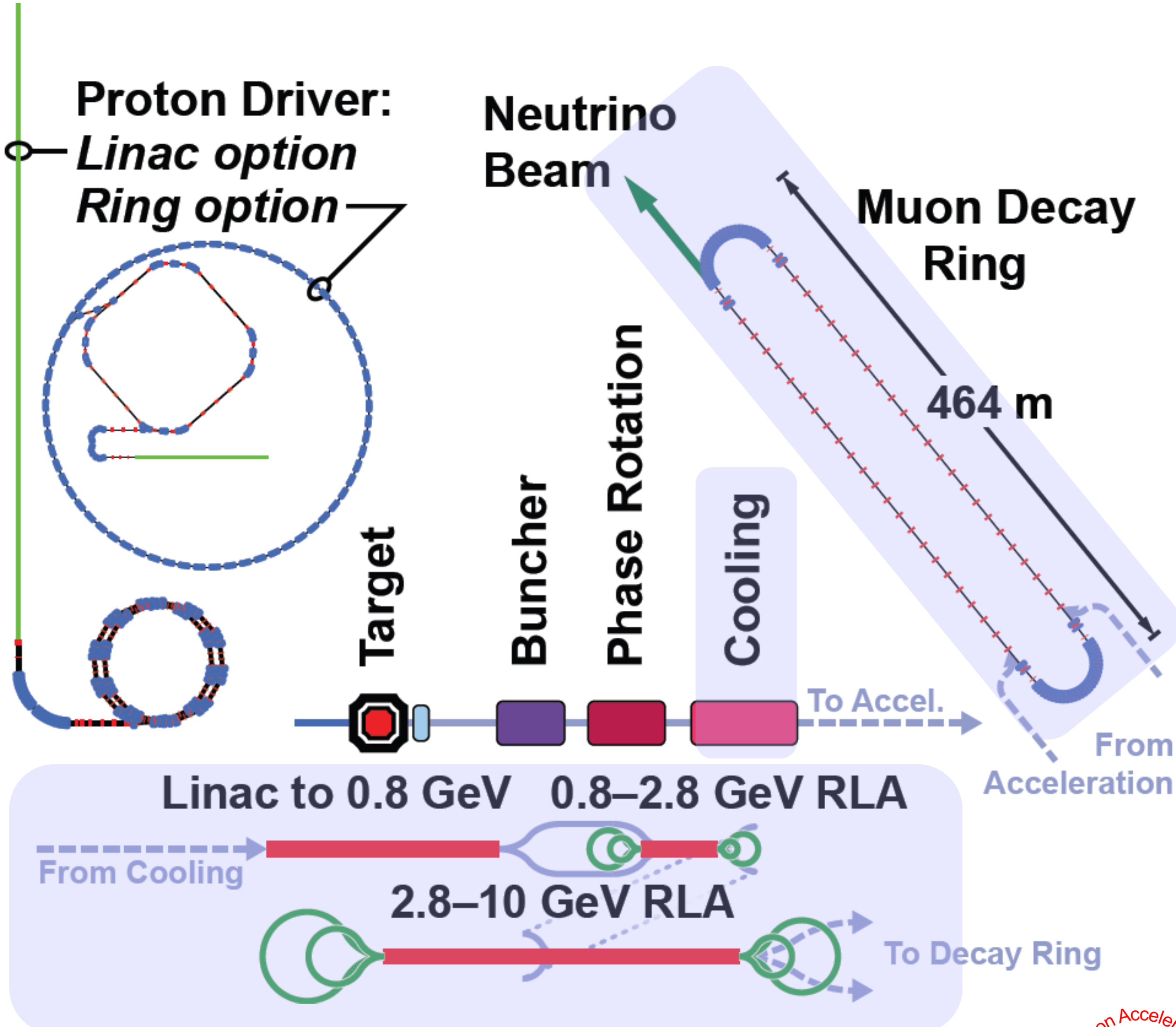
IDS-NF Accelerator Systems

- A system of rf cavities that capture the muons longitudinally into a bunch train, and then applies a time-dependent acceleration that increases the energy of the slower bunches and decreases the energy of the faster bunches – all bunches ended up at the same energy



IDS-NF Accelerator Systems

- A cooling channel that uses ionization cooling to reduce the transverse phase space occupied by the beam, so that it fits within the acceptance of the first acceleration stage
- An acceleration complex (Linac + 2× RLA) that accelerates the muons to 10 GeV
- A 10 GeV 'racetrack' storage ring with long straight sections



Proton Driver

Proton Driver

- Challenges:
  - High power; short proton bunches at ~10 GeV
- IDS-NF approach:
  - Consider two ‘generic’ options:
    - Linacs:

      Possible development option for HP-SPL at 5 GeV (CERN) or Project X at 3 GeV (FNAL)

      Requires accumulator & compressor rings
    - Rings:

      Development option for J-PARC or ISIS at RAL or possible ‘green-field’ option

      Requires accumulator & compressor rings

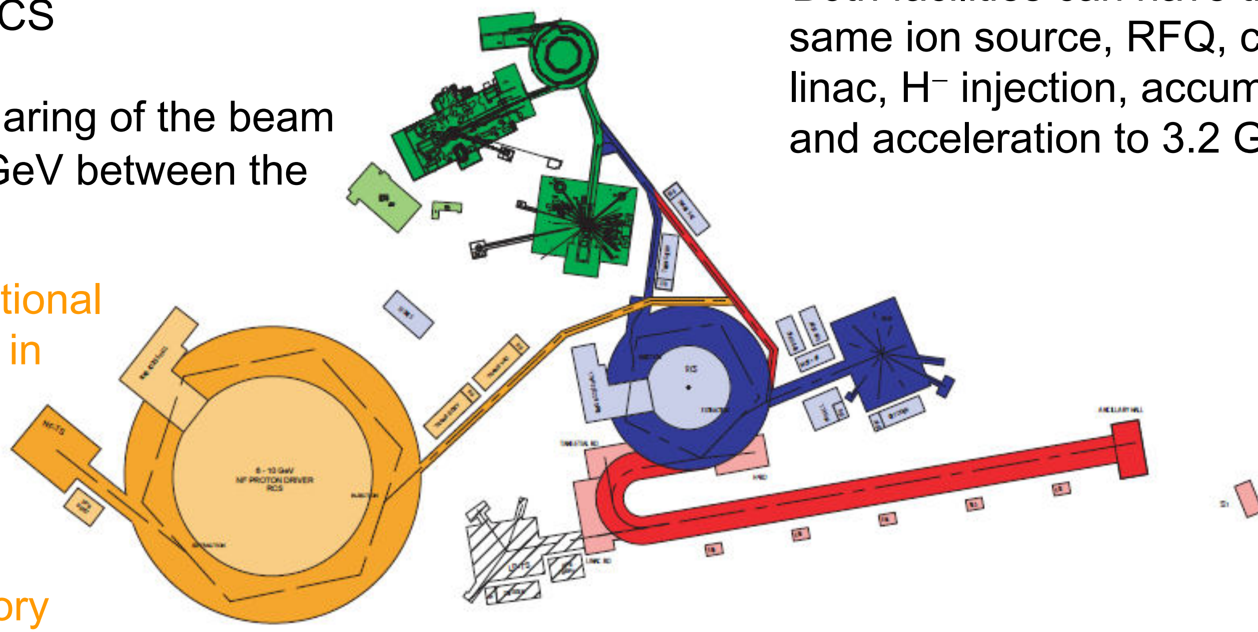
Parameter	Value
Kinetic energy	5–15 GeV
Average beam power	4 MW (3.125×10^{15} protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	< 5 μm
β^* at target	≥ 30 cm

Proton driver option at RAL

Common Proton Driver for the Neutron Source
and the Neutrino Factory

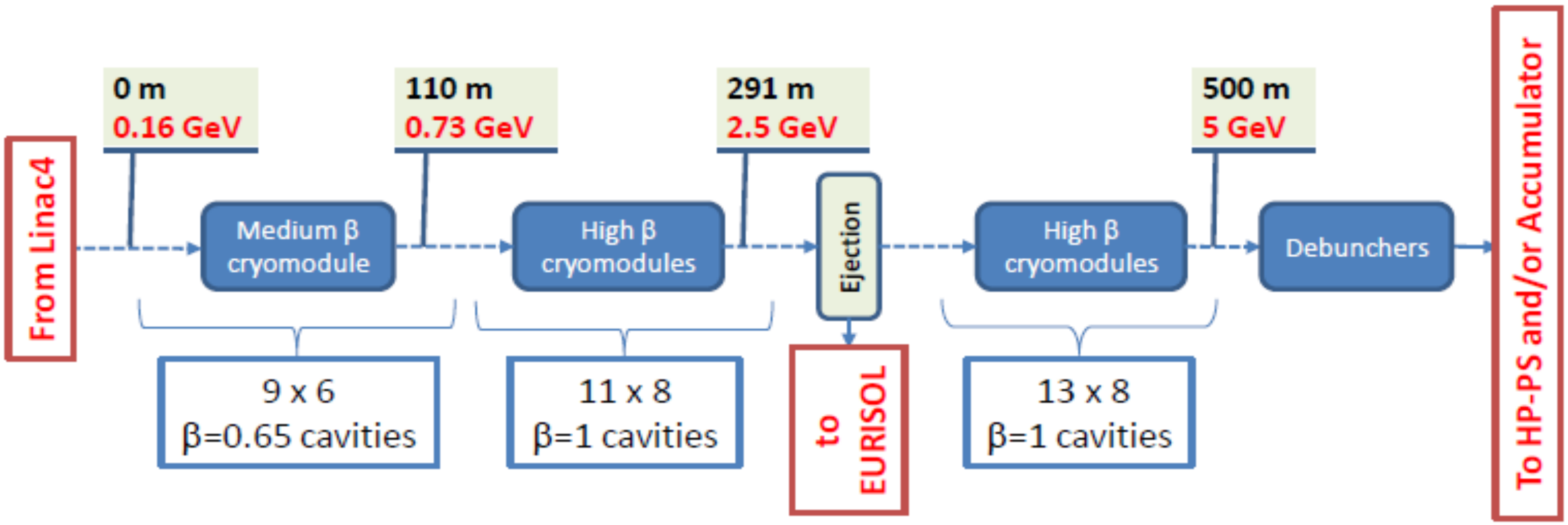
- Based on MW ISIS upgrade with 800 MeV Linac and 3.2 (≈ 3.3) GeV RCS
- Assumes a sharing of the beam power at 3.2 GeV between the two facilities
- Requires additional RCS machine in order to meet the power and energy needs of the Neutrino Factory

- Both facilities can have the same ion source, RFQ, chopper, linac, H^- injection, accumulation and acceleration to 3.2 GeV



- Options for the bunch compression to 1 – 3 ns RMS bunch length:
  - adiabatic compression in the RCS
  - ‘fast phase rotation’ in the RCS
  - ‘fast phase rotation’ in a dedicated compressor ring

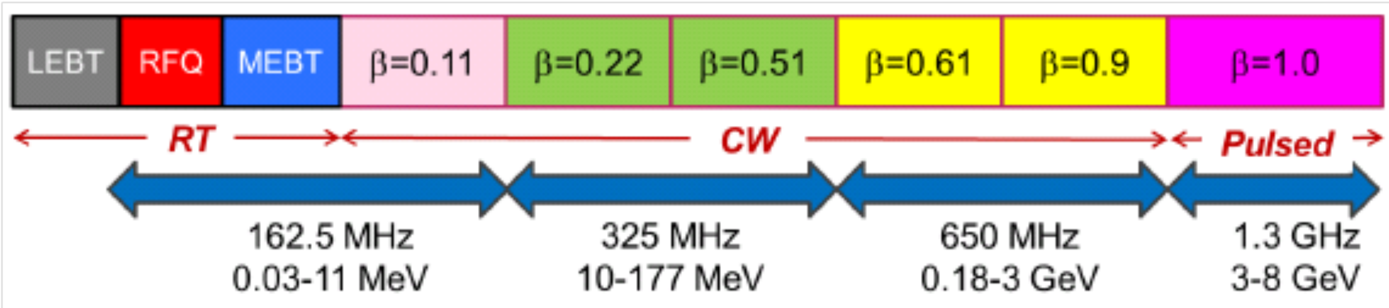
SPL- Based NF Proton Driver at CERN

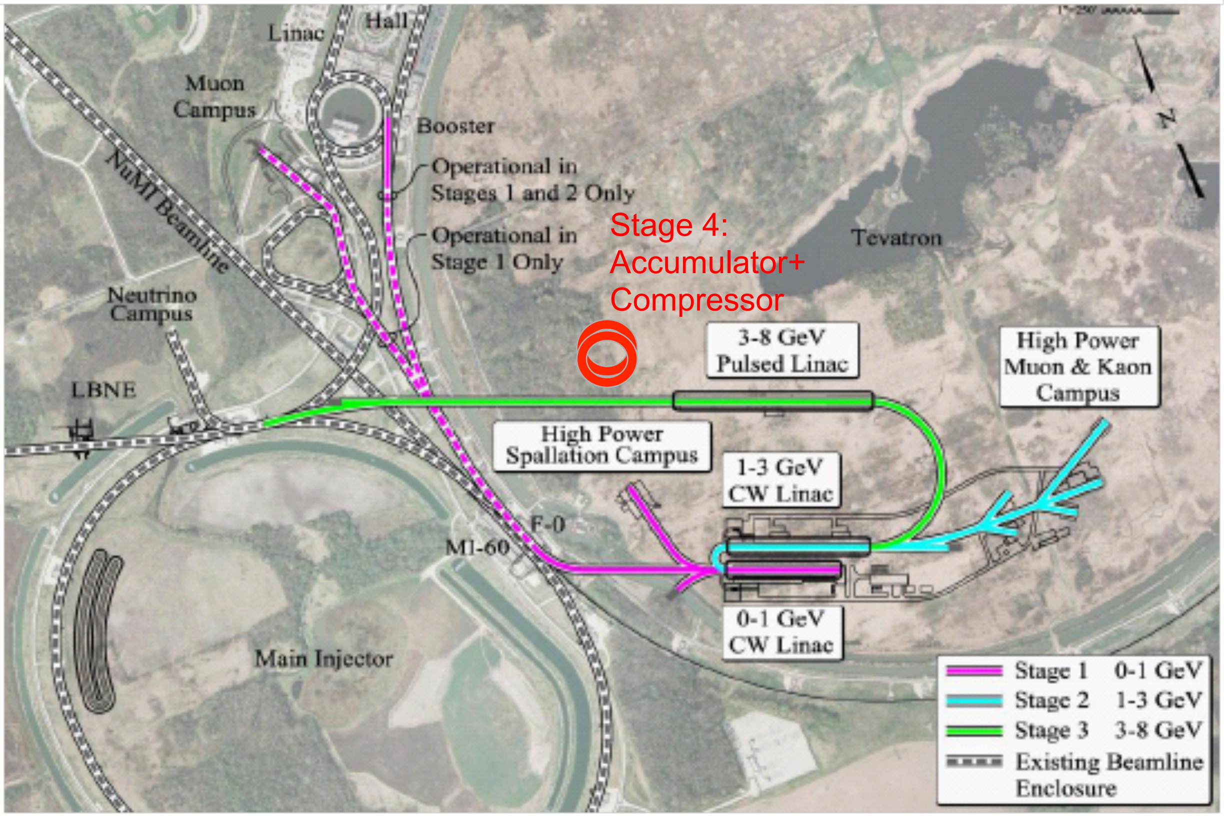


- Beam acceleration in HP-SPL
- Accumulation of beam from the High Power SPL in a fixed energy Accumulator (5 GeV, 4MW beam power).
- Bunch compression (rotation) in a separate Compressor ring

Proton Driver at FNAL: Project X

Linac Schematic



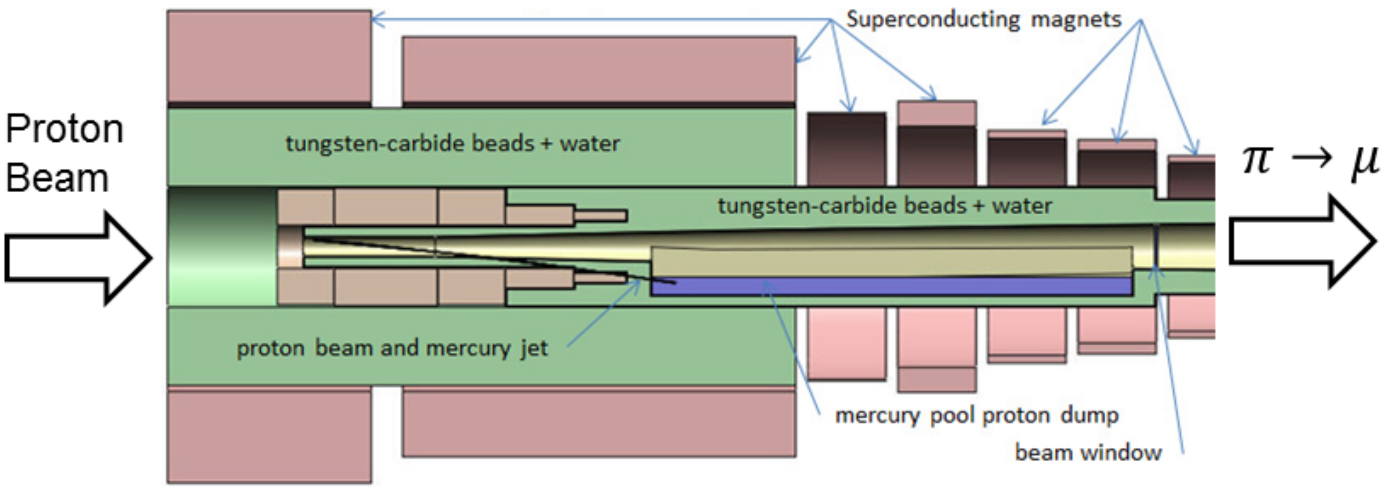


Project-X Layout

Target & Front-End

Target & Capture section

- An intense 8 GeV, 4 MW proton beam impacts a mercury jet immersed in a 20 T solenoid
- Create a flux of pions that decay into muons
- 20 T fields of the target tapers to 1.5 T within 15 m

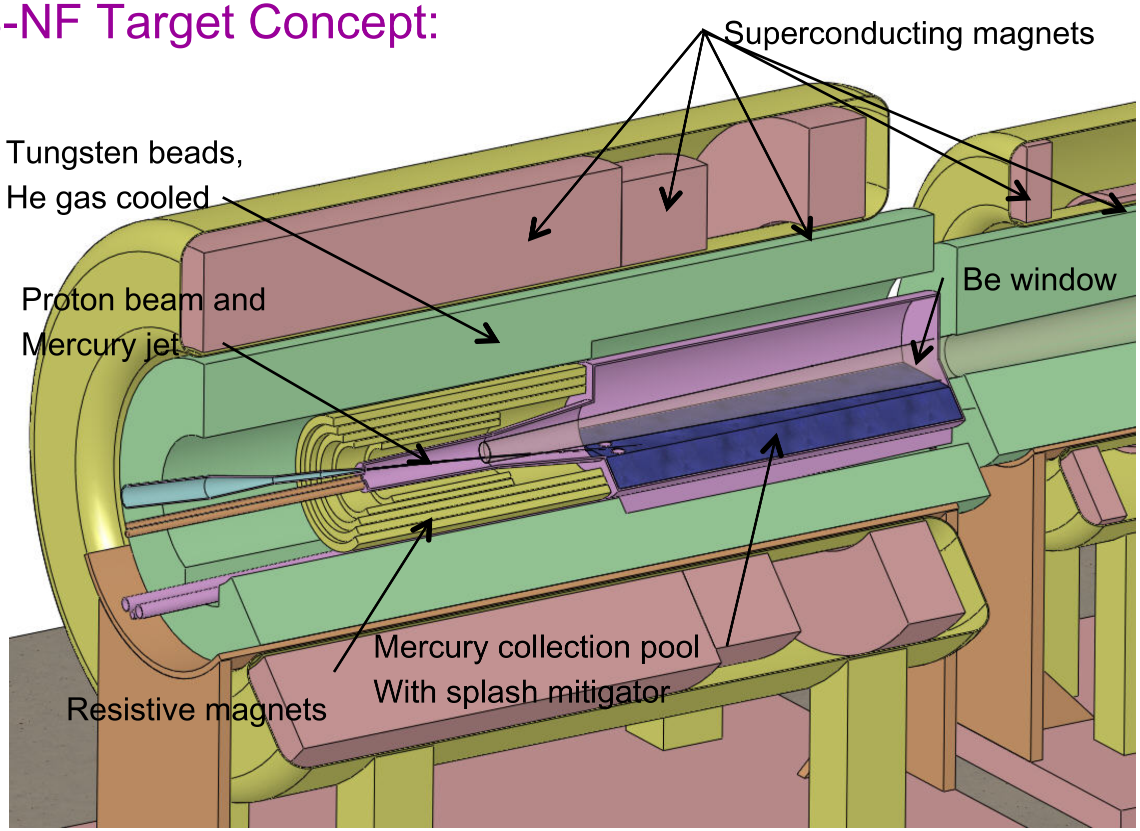


H. Kirk

Target inside Capture Solenoid

Desired Performance ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam)

IDS-NF Target Concept:



Low-energy π's collected from side of long, thin cylindrical target.

Solenoid coils can be some distance from proton beam.

⇒ ≥ 10-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

⇒ Beam dump (mercury pool) out of the way of secondary π's and μ's.

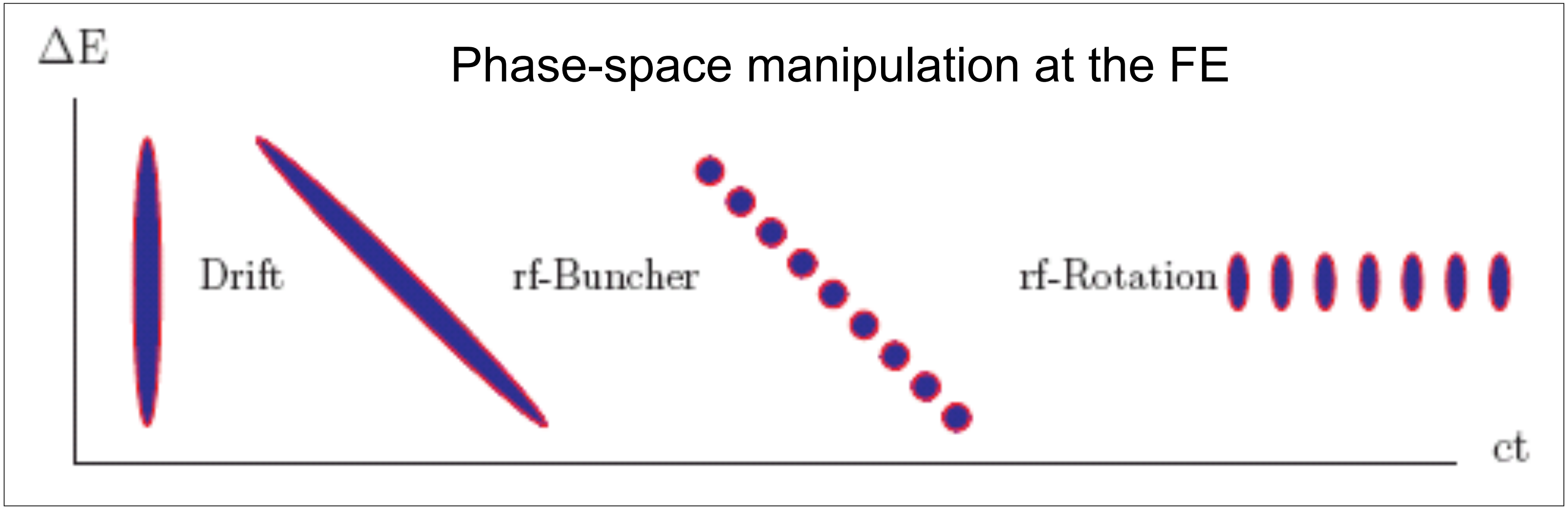
Shielding of the superconducting magnets from radiation is a major issue.

Magnet stored energy ~ 3 GJ!

K. McDonald

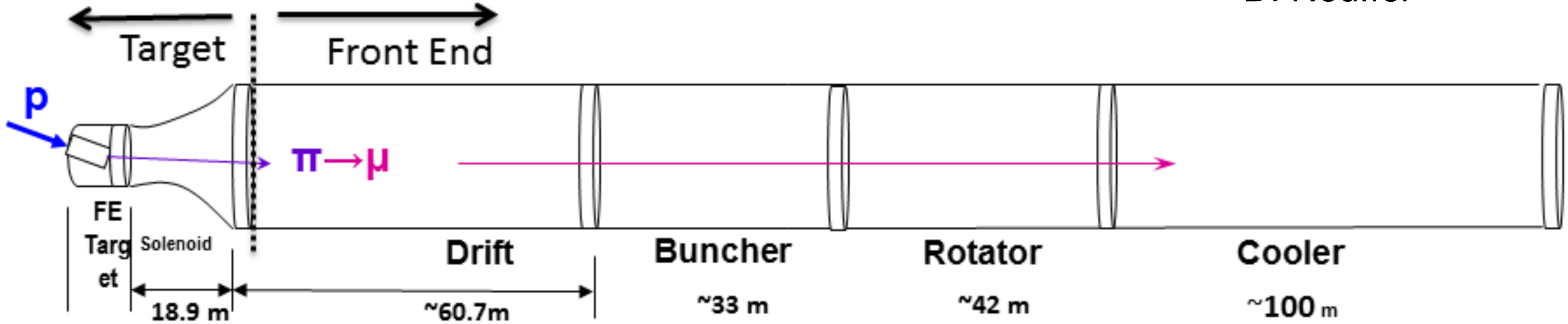
Front-End (FE) channel

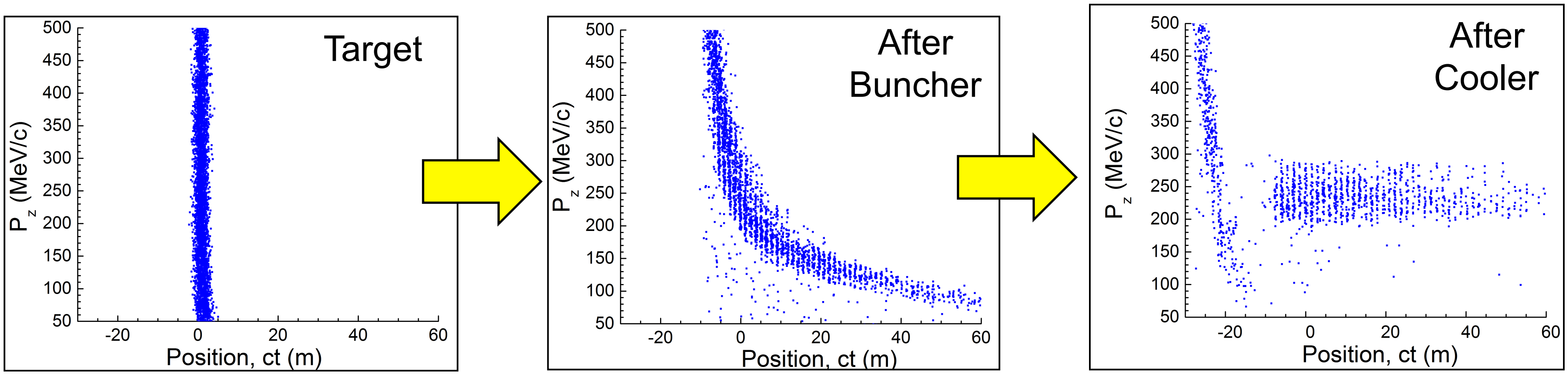
- Dual Purpose of FE:
  - Capture the muon beam generated at the target
  - Reduce its phase space to meet the acceptance criteria of downstream accelerators



Major Front-End subsystems

D. Neuffer



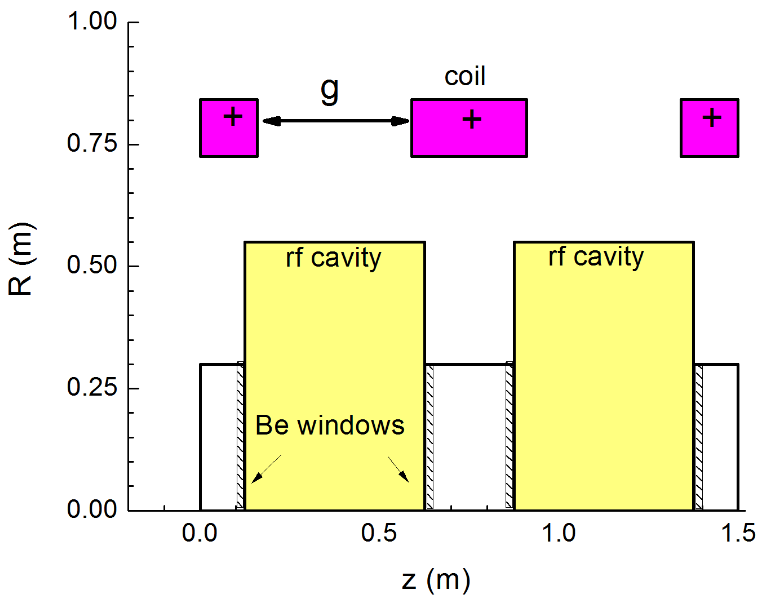


- Bonus : Front-End captures both μ^+ and μ^-

Buncher & Rotator parameters

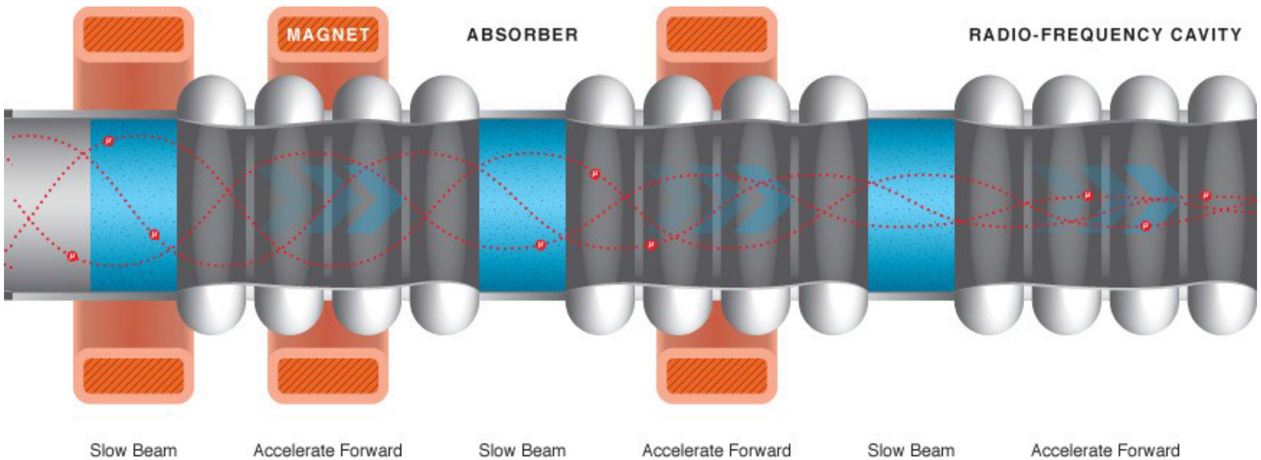
D. Stratakis

- Buncher (33 m long)
  - 33 rf cavities
  - 319.6 to 233.6 MHz (13 freq.)
  - RF voltage: 3.4 to 9.0 MV/m
  - 1.5 T magnetic field
- Rotator (42 m long)
  - 56 rf cavities
  - 230.2 to 202.3 MV/m (15 freq.)
  - RF voltage: 13 MV/m
  - 1.5 T magnetic field



Cooler - Ionization cooling channel

D. Stratakis

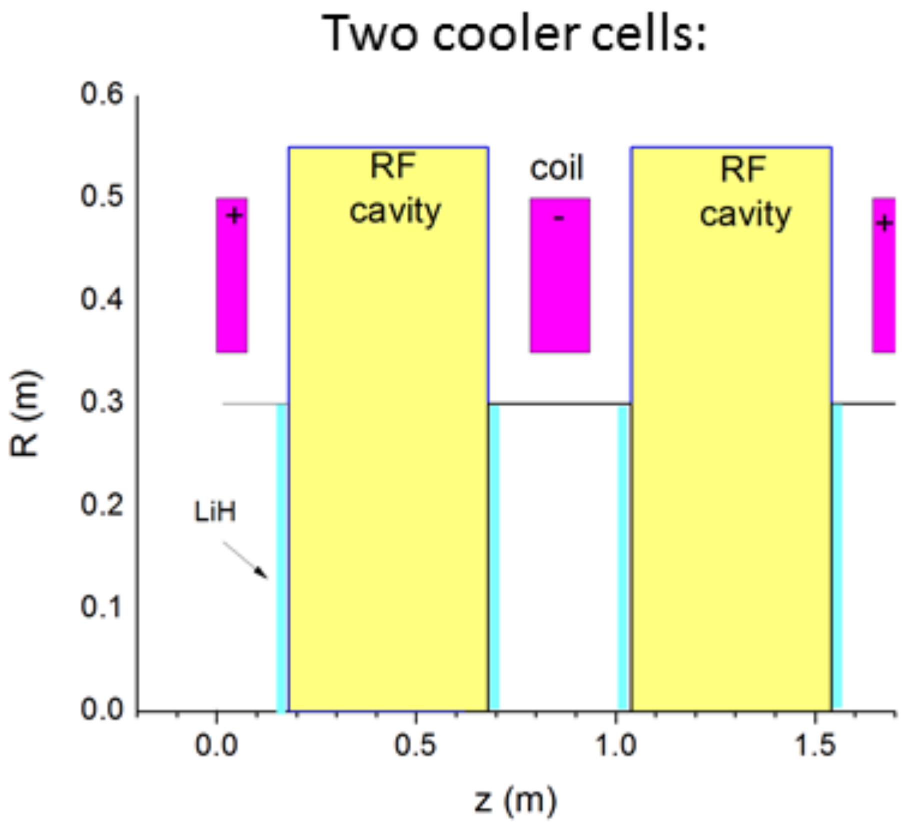


- Energy loss in absorbers
- rf cavities to compensate for lost longitudinal energy
- Magnetic field focusing to confine muon beams
- Leads to a compression of the 4D phase space

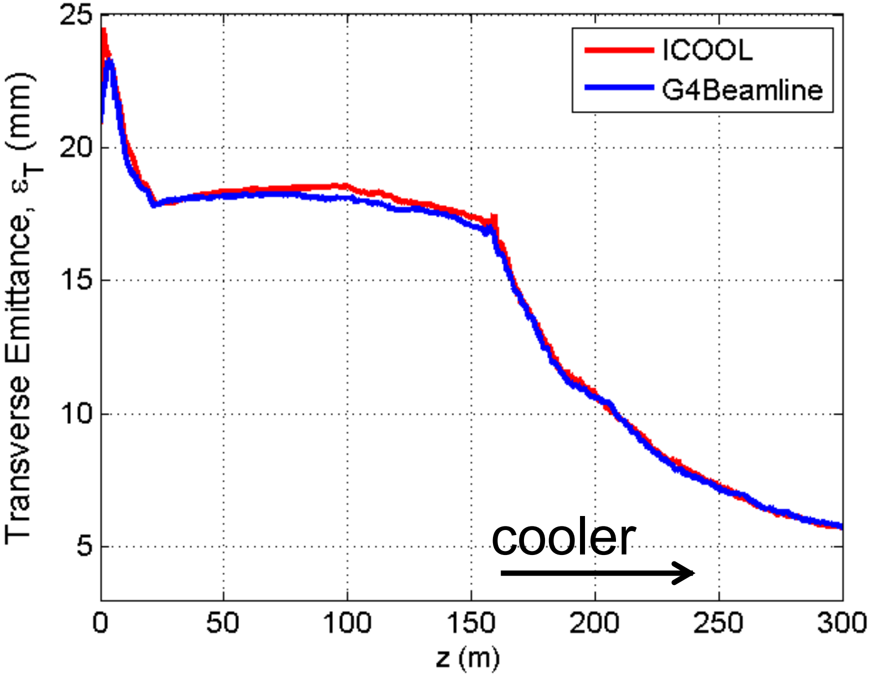
Cooler parameters

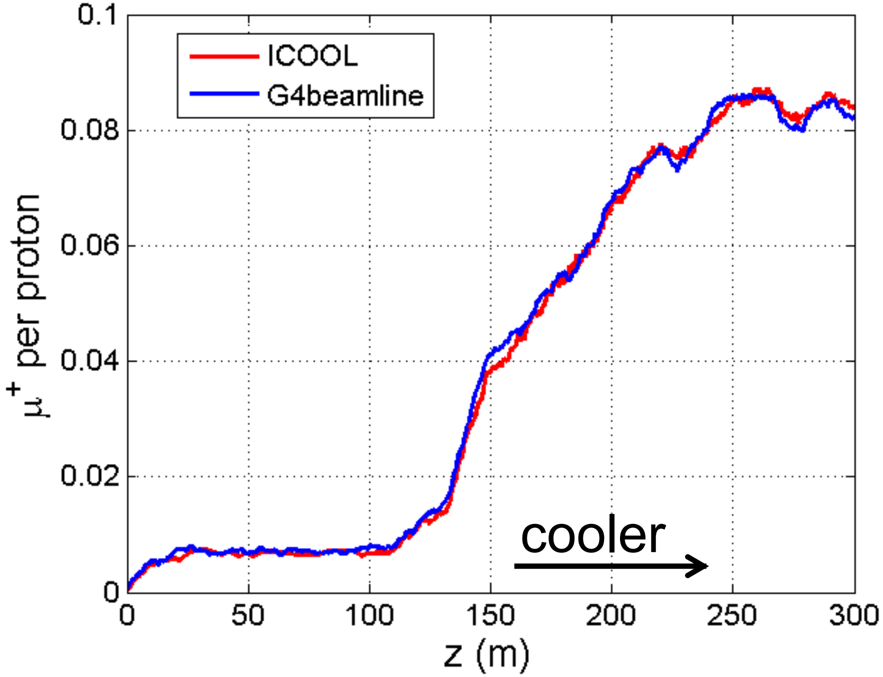
D. Stratakis

- Cooler (~100 m long)
  - 0.75 m cell length
  - 201.25 MHz
  - RF voltage: 16 MV/m
  - 2.8 T peak field on axis
  - 2.7 T field on the iris
  - Lithium Hydride absorber
  - 4D cooling only



Lattice performance



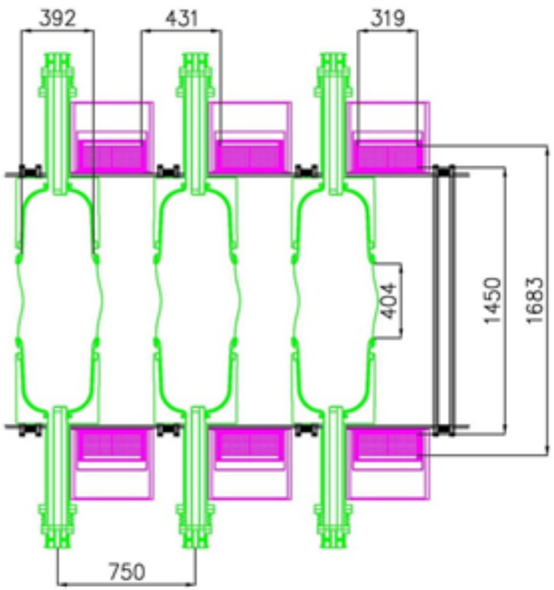


- Result benchmarked with both ICOOL & G4BL
- Acceptance within A_T < 30 mm, A_L< 150 mm and cut in momentum $100<P_z<300$ MeV/c
- Similar result for μ^-

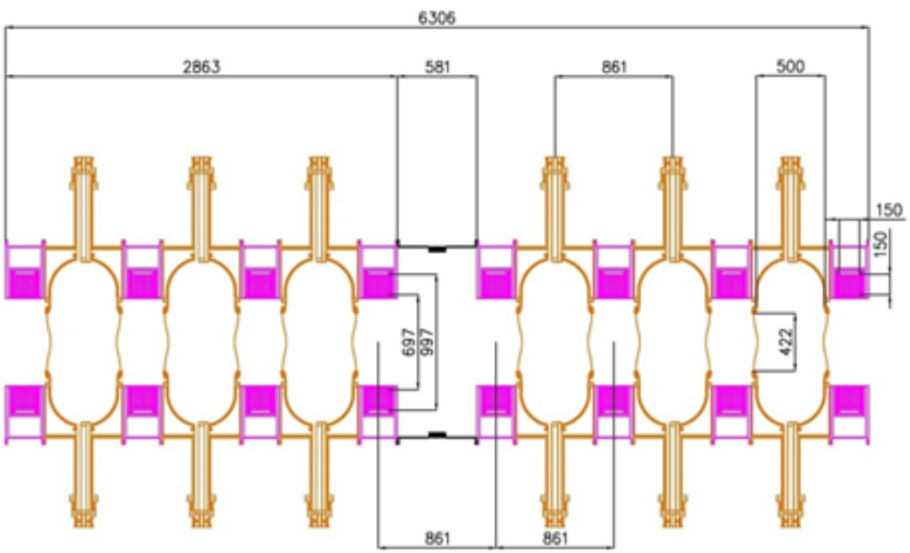
D. Stratakis

Engineering constraints

Rotator



Cooler

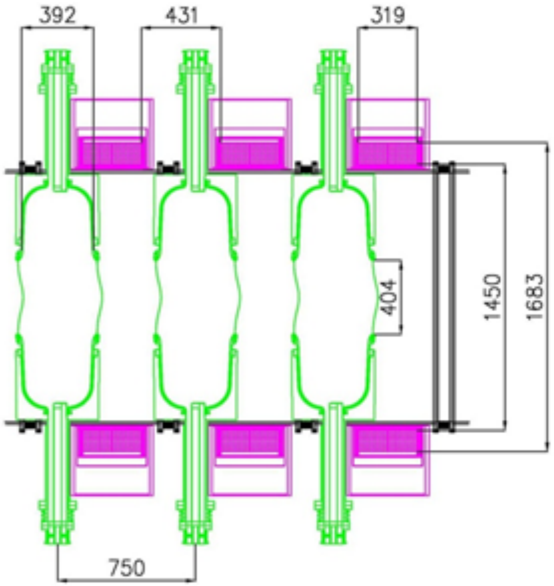


D. Stratakis

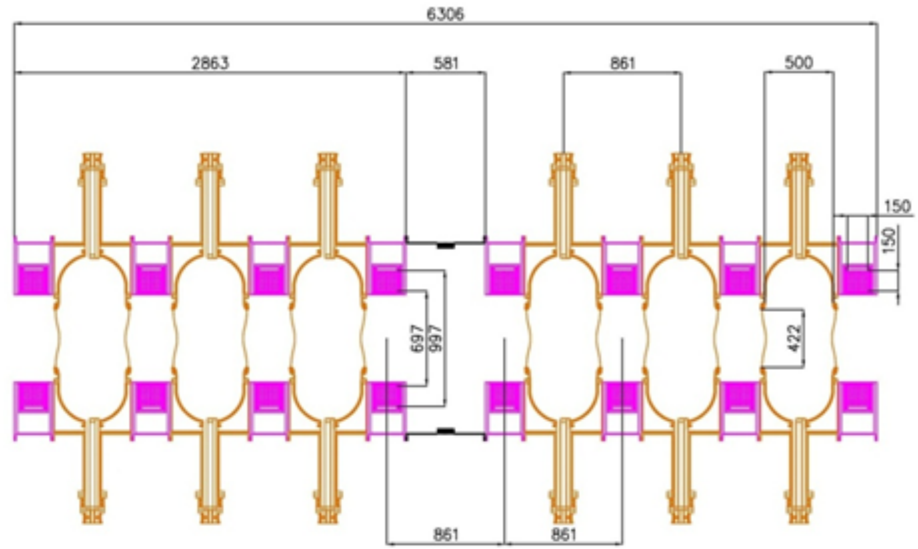
- IDS-NF Engineering studies:
  - Increase gap between coils in Buncher & Rotator
  - Increase cell length of cooler from 75 cm to 86 cm
  - Add one empty lattice cell (without a cavity) after a series of cavities

Engineering constraints

Rotator



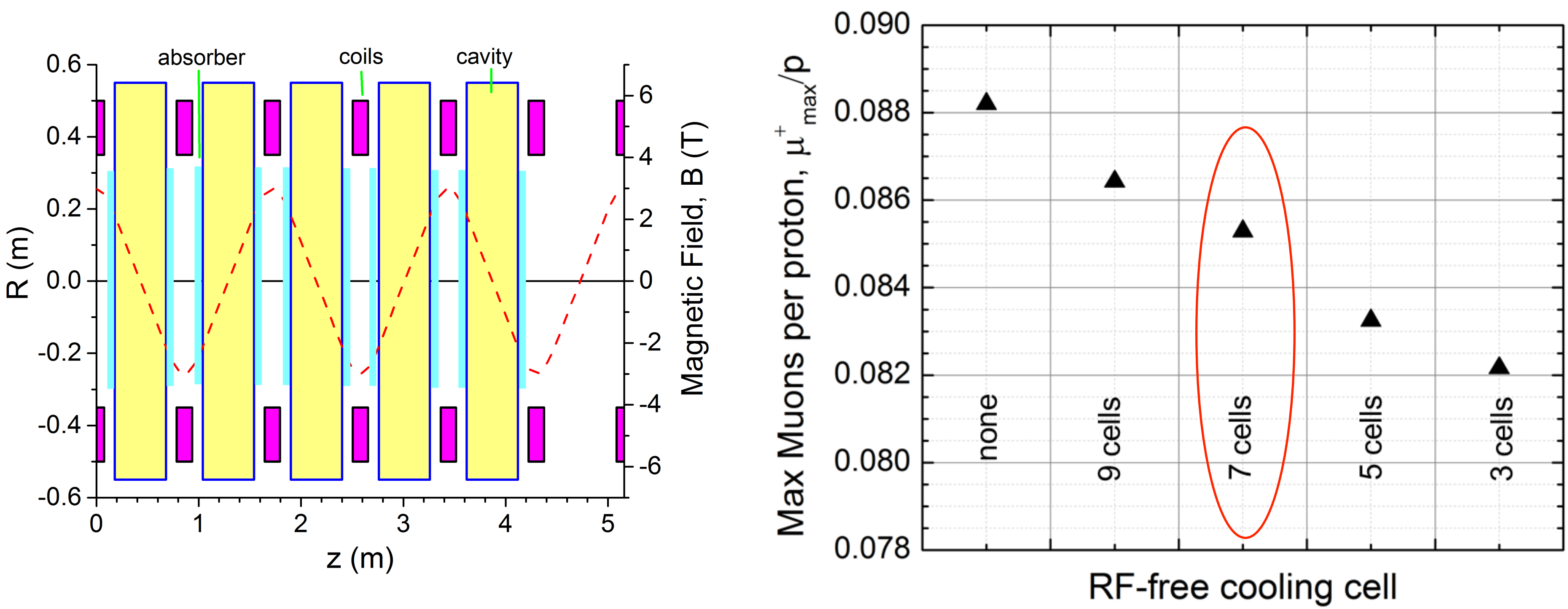
Cooler



- To properly fit the cavity input coupler, one had to reduce the axial length of the coils in the buncher & phase-rotator sections.
- For the same reason the cooler cell length was increased by 11 cm.
- A sequence of lattice cells is followed by an empty cell, so that a group of cavities and coils can be removed without disassembling the entire beam-line

D. Stratakis

Lattice feasibility studies

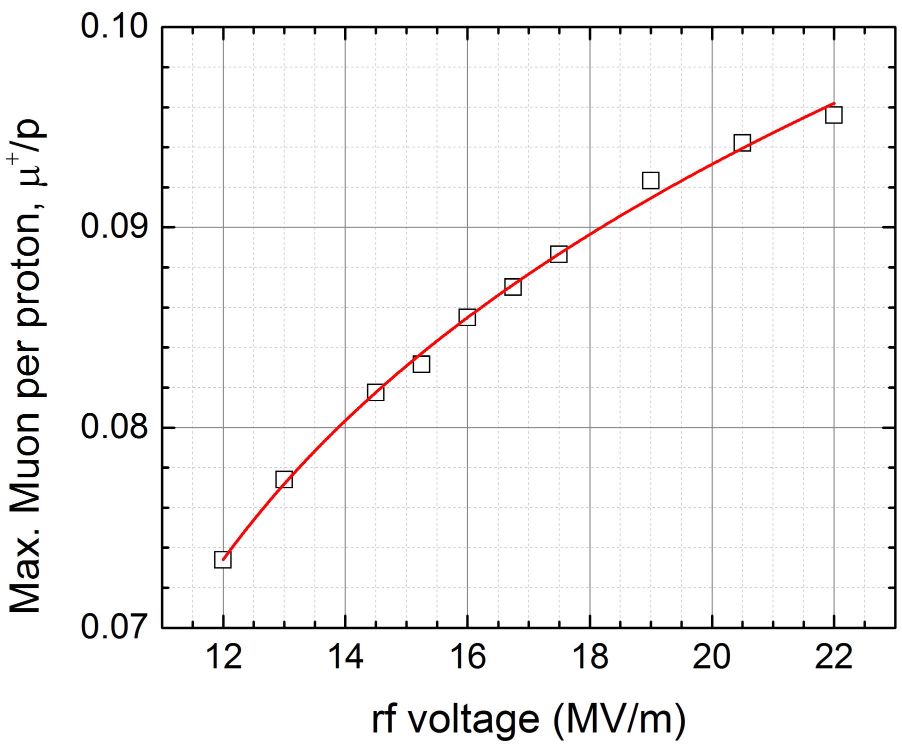


- Results sensitive to the location of "empty cell"
- Every 7-th cell is the optimum but there is a 5% loss

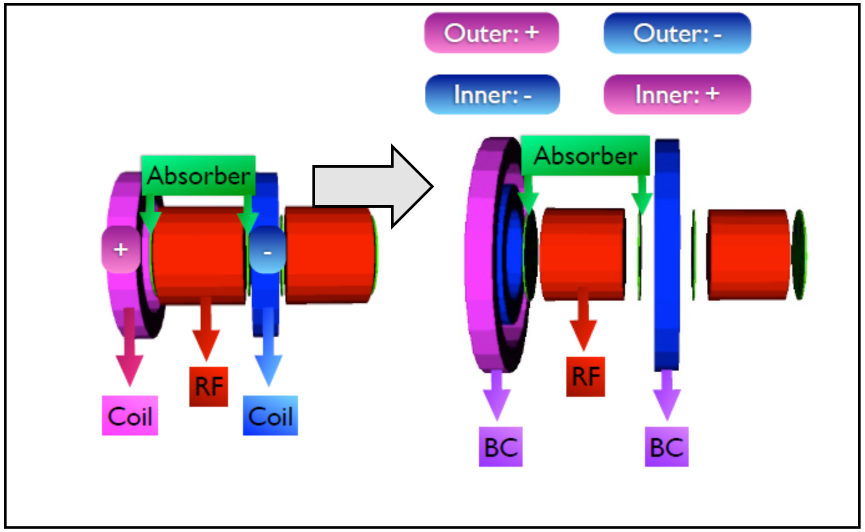
D. Stratakis *et al.*, Proc. of IPAC 2013, TUPFI087

Magnetic field constraints

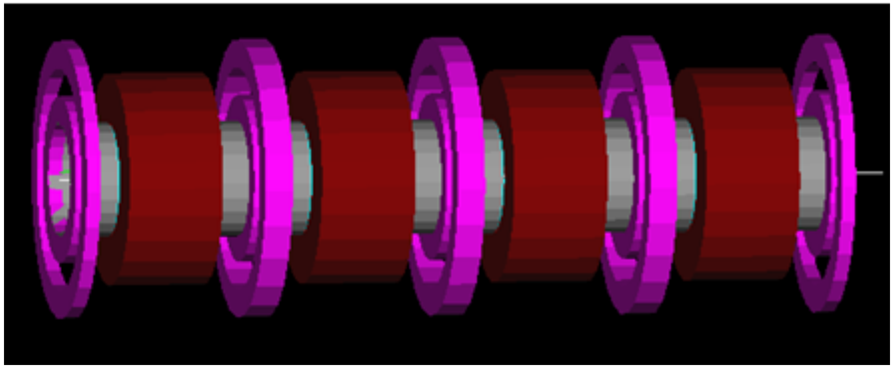
- Machine performance sensitive to rf gradient limitations
- Alternative cooling lattice options:
  - Magnetic insulation
  - Bucked-Coil Lattice
  - Shielded Coli Lattice
  - High pressure rf cavities

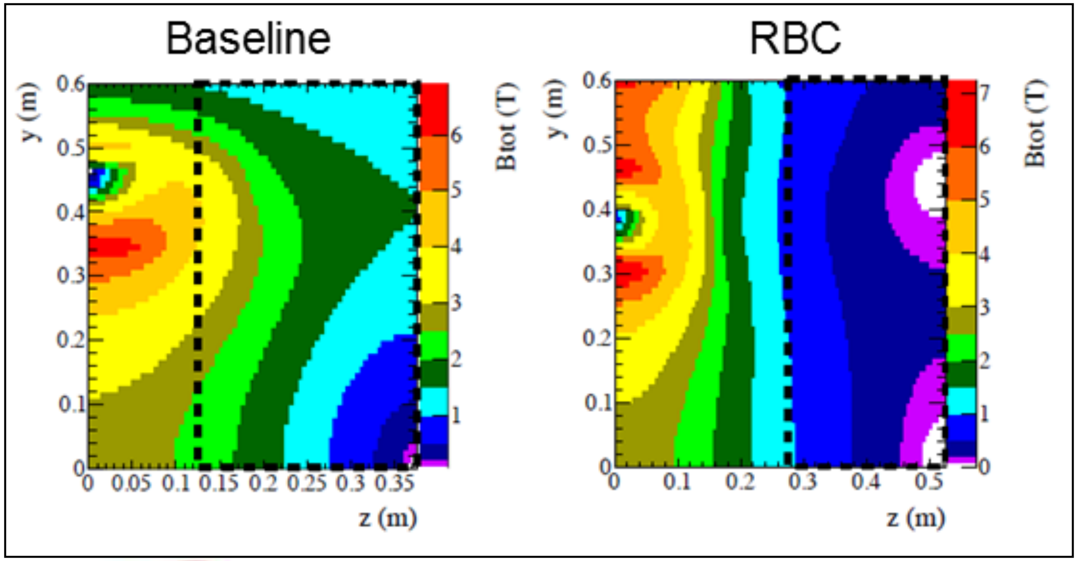


Radial Bucked-Coil lattice (RBC)



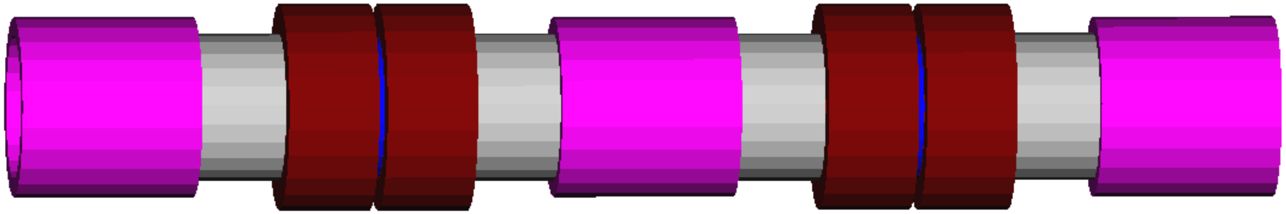
4 lattice cells with bucked coils

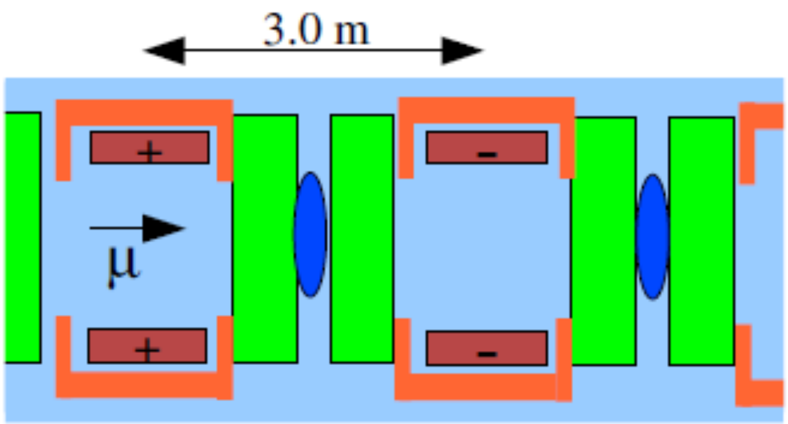


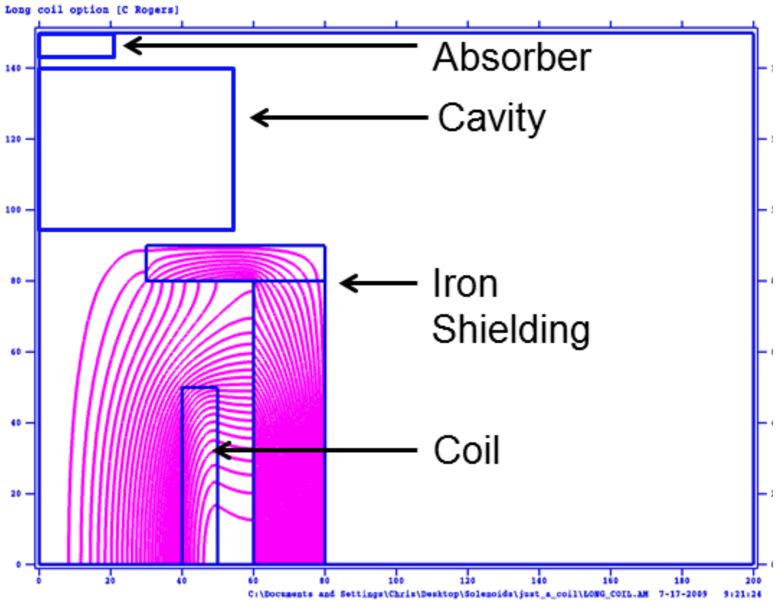


Alekou & Pasternak, JINST 7, P08017 (2012)

Shielded Coil Lattice (SHLD)



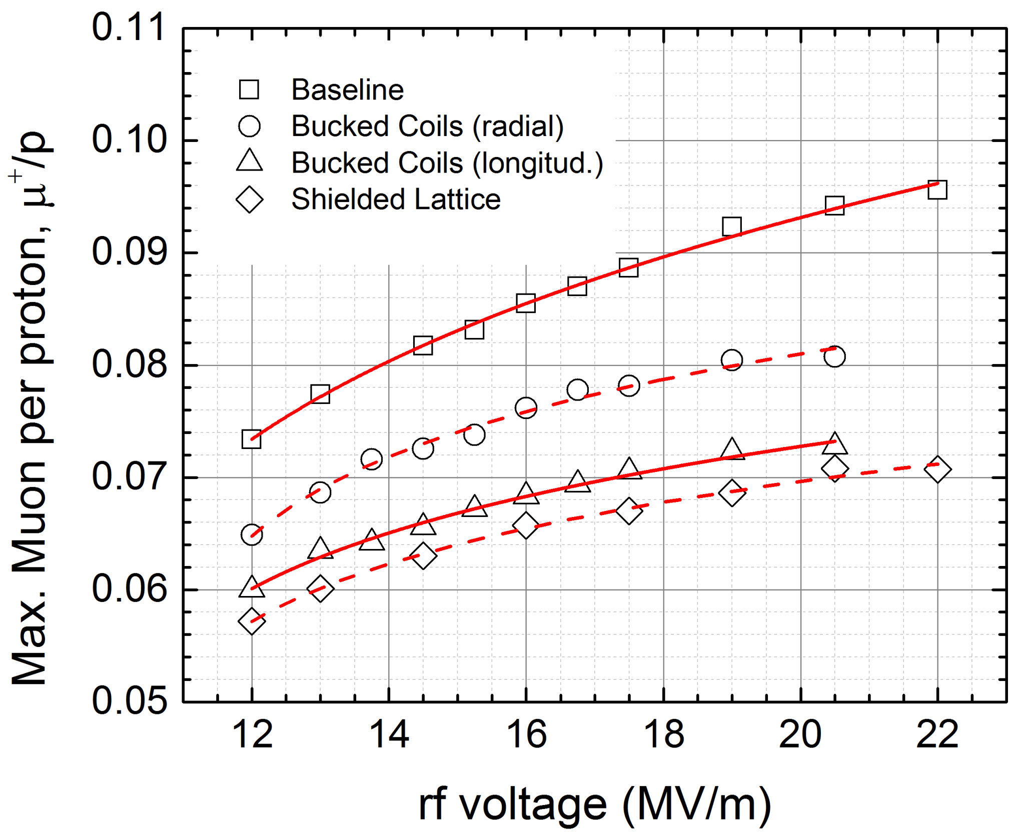




- Increase cell length to remove RF from fringe fields
  - Further shielding with iron
  - Fields below <0.5 T in rf

C. T. Rogers, AIP Conf. Proc.1222, 298 (2010)

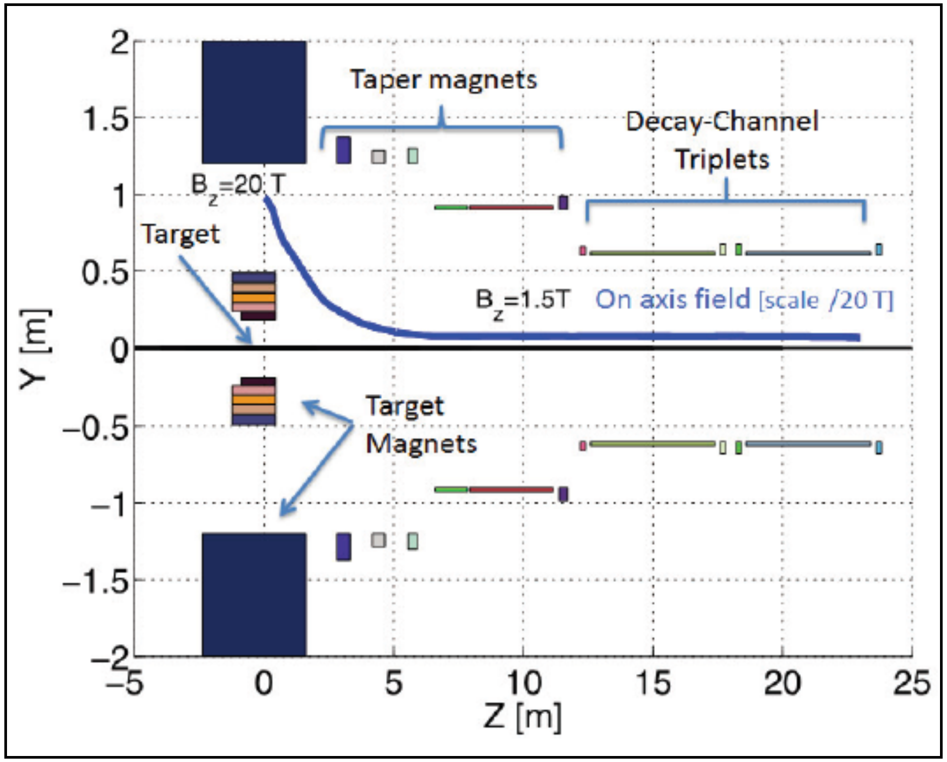
Lattice performance

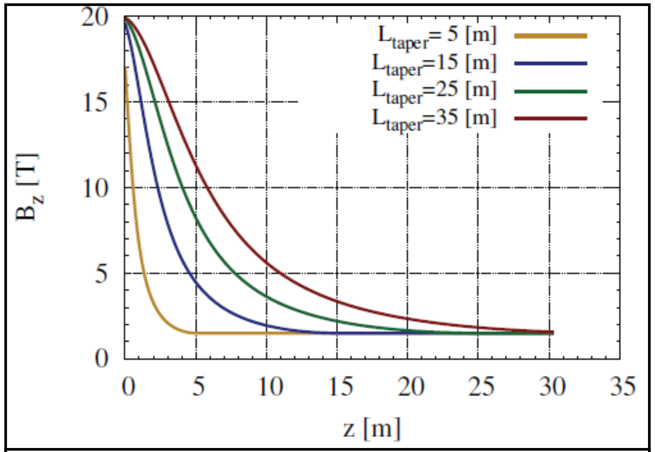


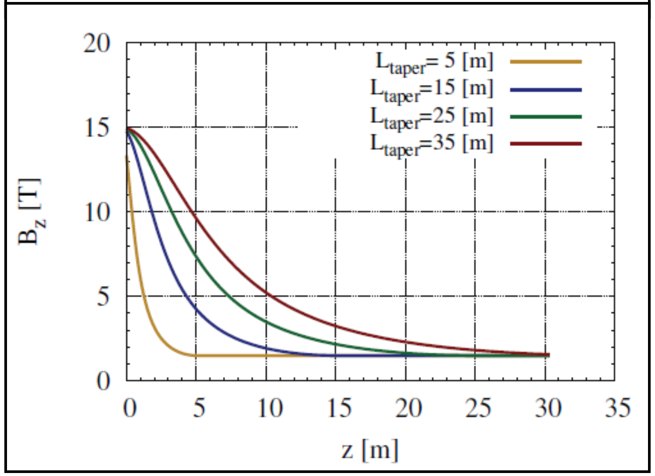
- Bucked Coils lattices are pending matching optimization.

Muon capture optimization

- Reduce peak field at target from 20 T to 15 T
- Results sensitive to taper length

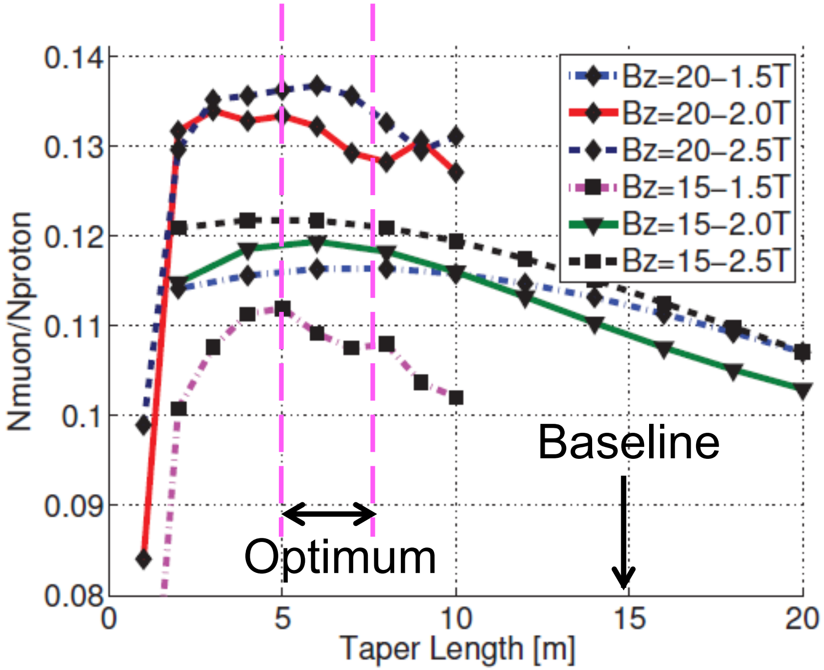


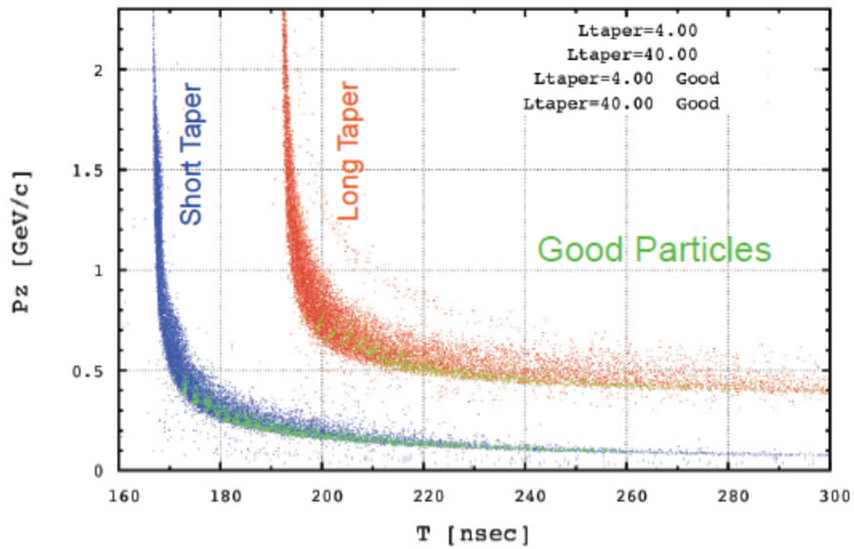




H. Sayed *et al.*, Proc. of IPAC 2013, TUPFI075

Target taper studies



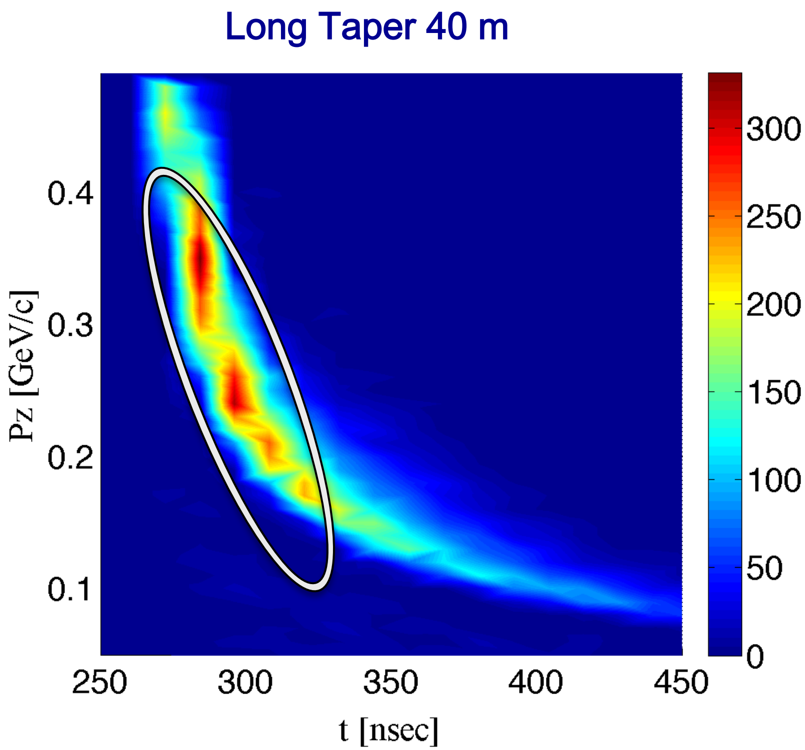


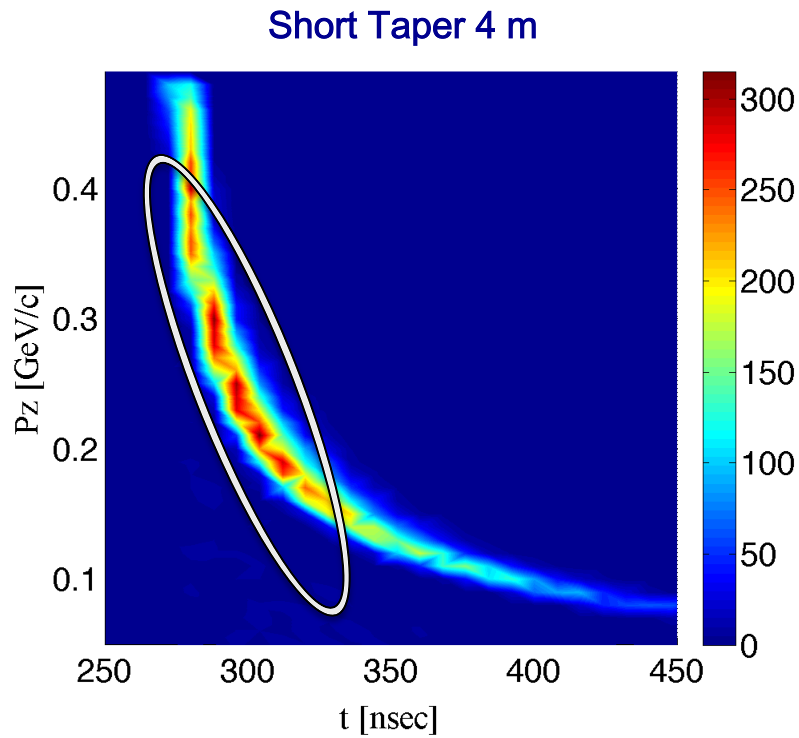
- Enhanced performance for taper lengths between 5 to 7 m
- There is a ~5% decrease when peak field is decreased from 20 T to 15 T.

H. Sayed *et al.*, Proc. of IPAC 2013, TUPFI075

Phase space distributions (short vs long taper)

T-Pz phase space at end of decay channel





Long Solenoid taper:

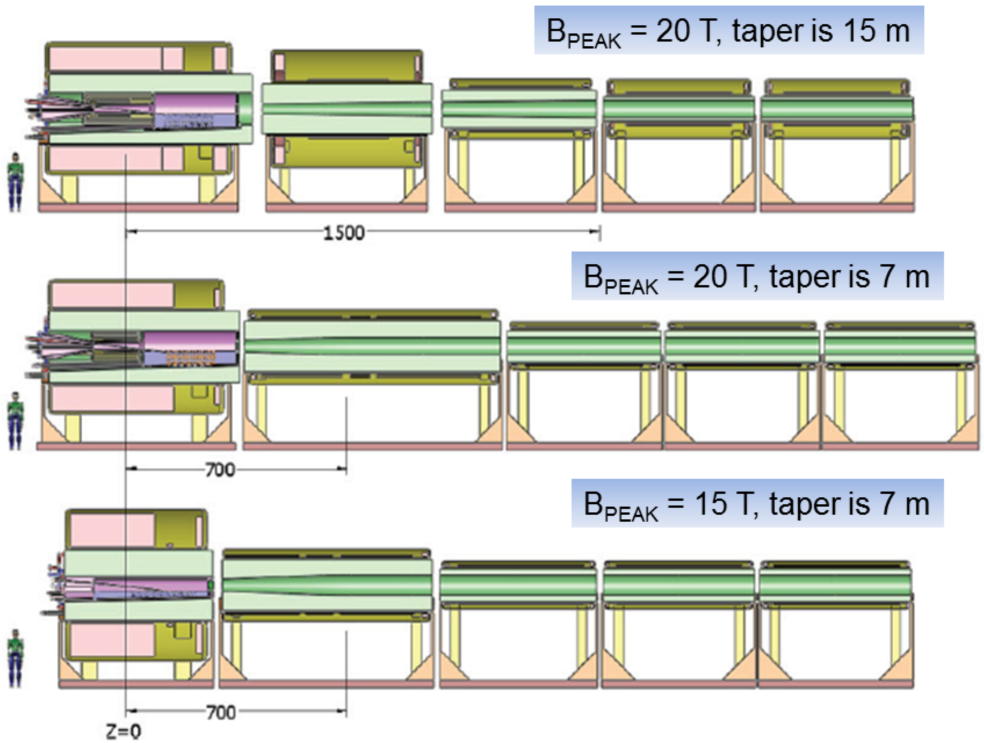
- More particles
- More dispersed (misses the buncher acceptance windows)

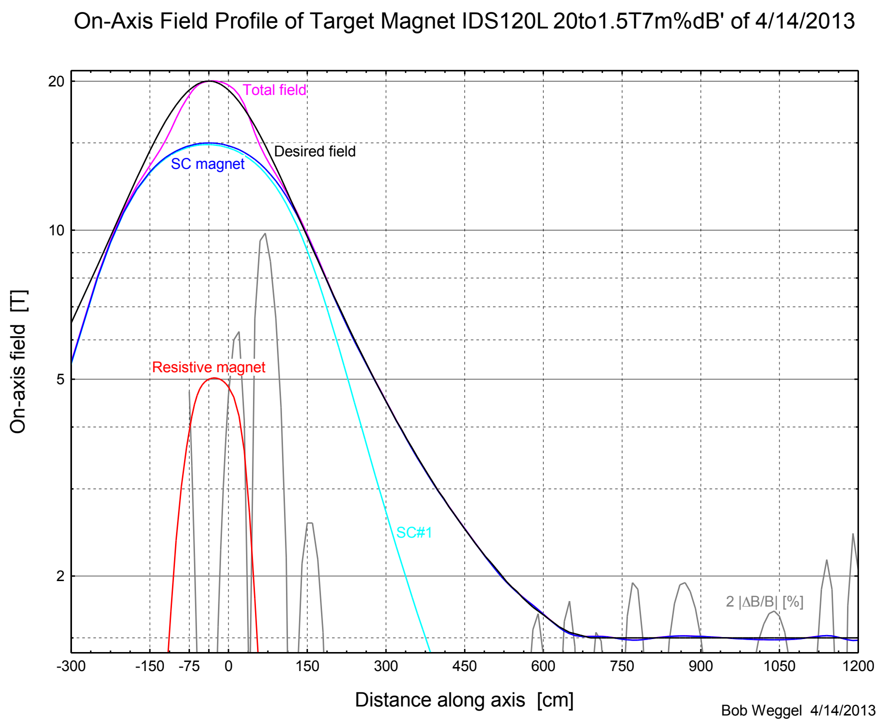
Short Solenoid taper:

- Higher density t-pz distribution
- Fits more particles within the acceptance of buncher/rotator

H. Sayed

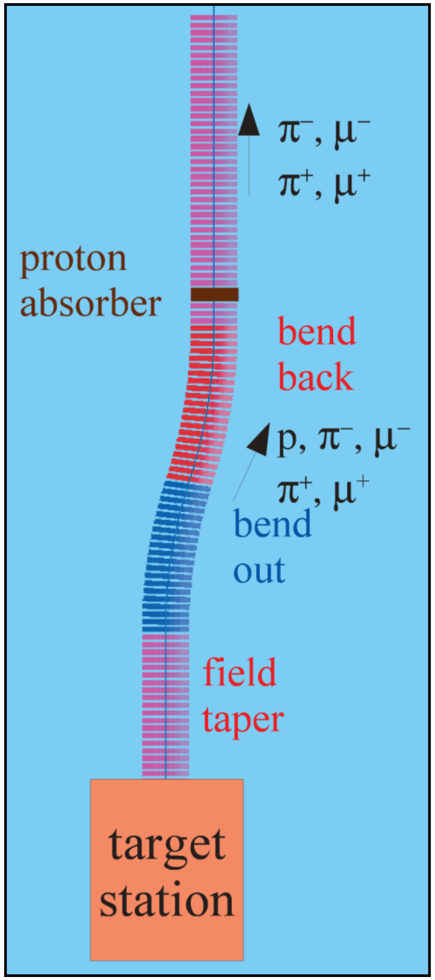
Realistic coil design for new taper





R. J. Weggel *et al.*, Proc. of IPAC 2013, TUPFI073

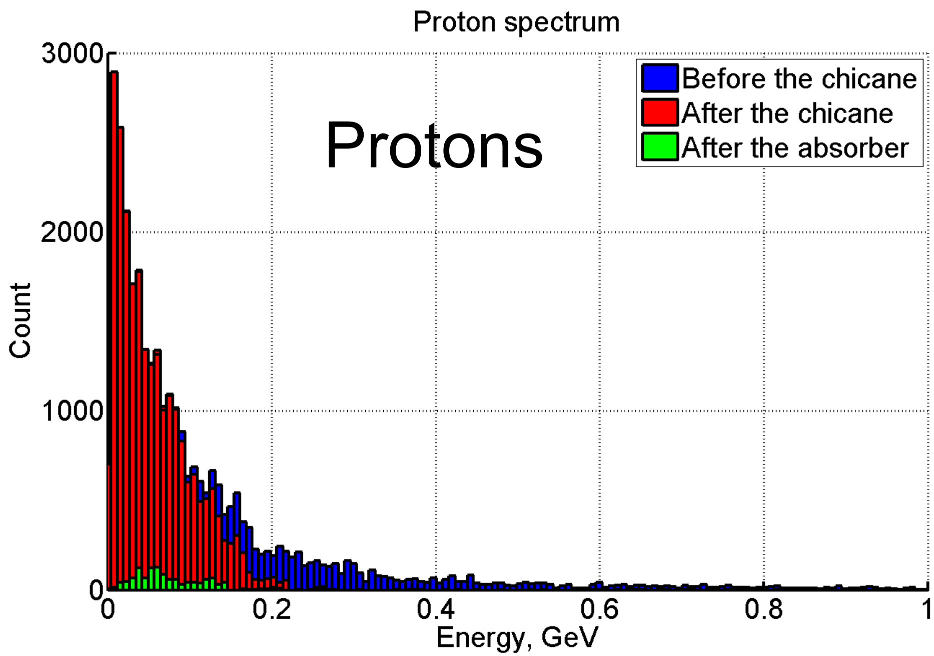
Chicane integration in the Front-End

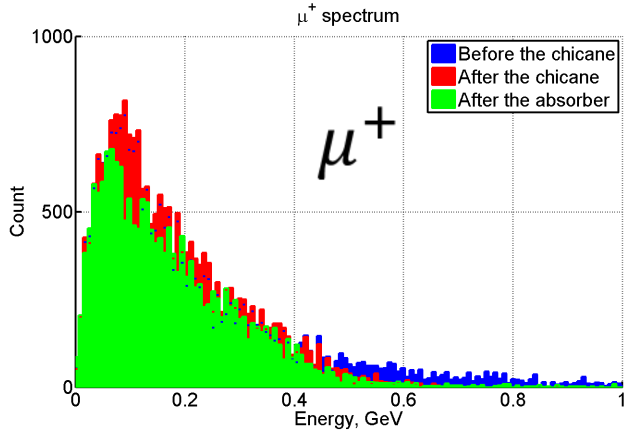


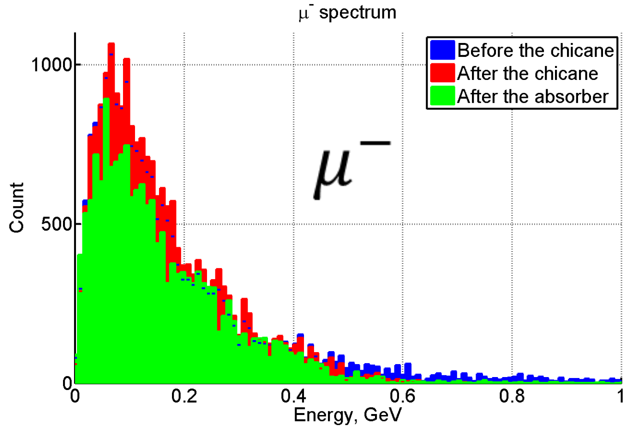
- The goal of the chicane is to remove high energy protons (p > 500 MeV/c)
- The remaining proton are removed by a 10 cm Be absorber
- Adequate for both signs of muons
- Central coils take a serious hit from high-energy particles going straight through.

C. T. Rogers *et al.,* Proc. of IPAC 2012, MOPPC041

Front-End performance with the chicane





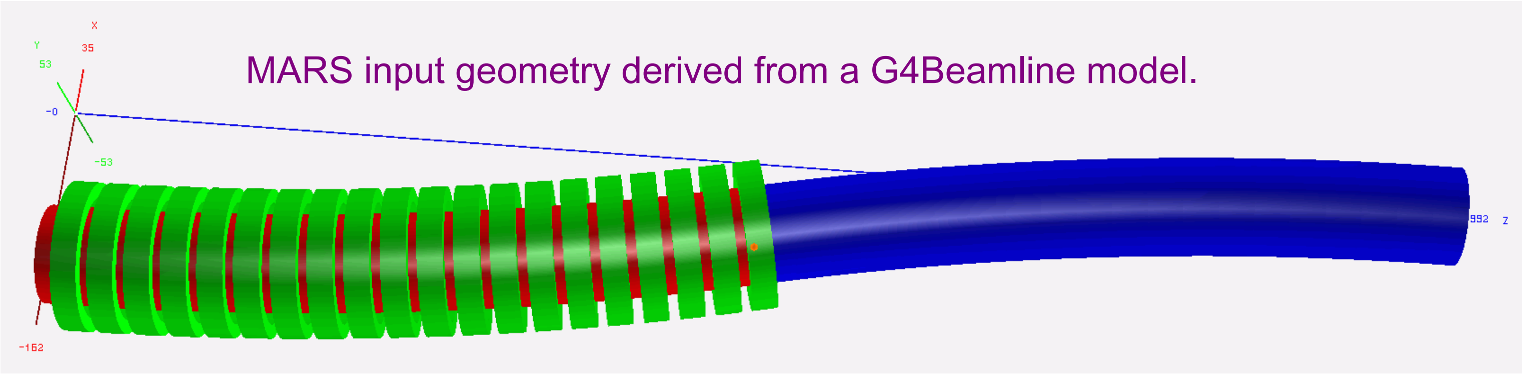


- System efficiently removes unwanted particles
- 10% muon losses compared to baseline (no chicane)

Chicane energy deposition & shielding

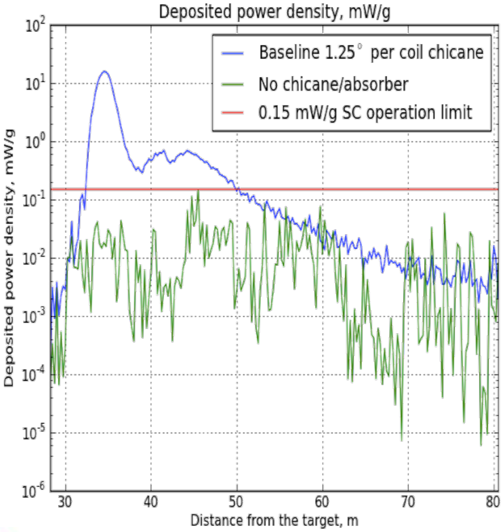
A chicane in the Decay Channel could mitigate the 500-kW power in scattered protons which otherwise would impact on the Buncher/Phase Rotator (C. Rogers).

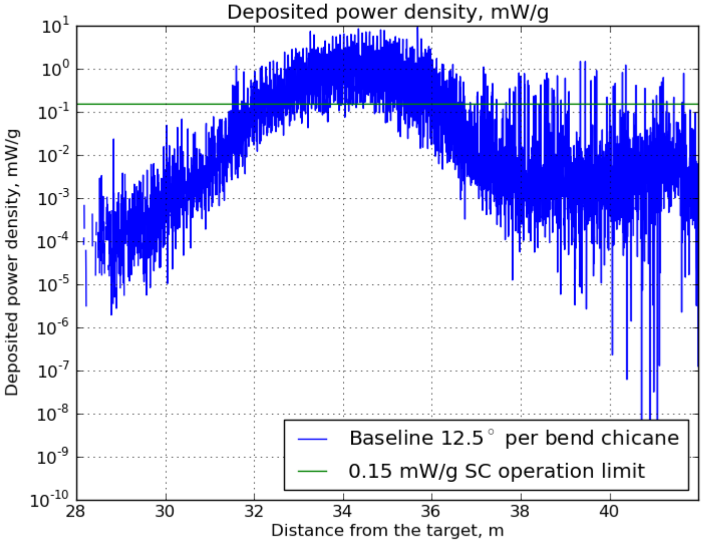
MARS input geometry derived from a G4Beamline model.



MARS15 simulations shows 10-cm-thick sleeve of pure W helps, but the "hot spot" is still a factor of 50 too "hot."

No shielding





10-cm W sleeve

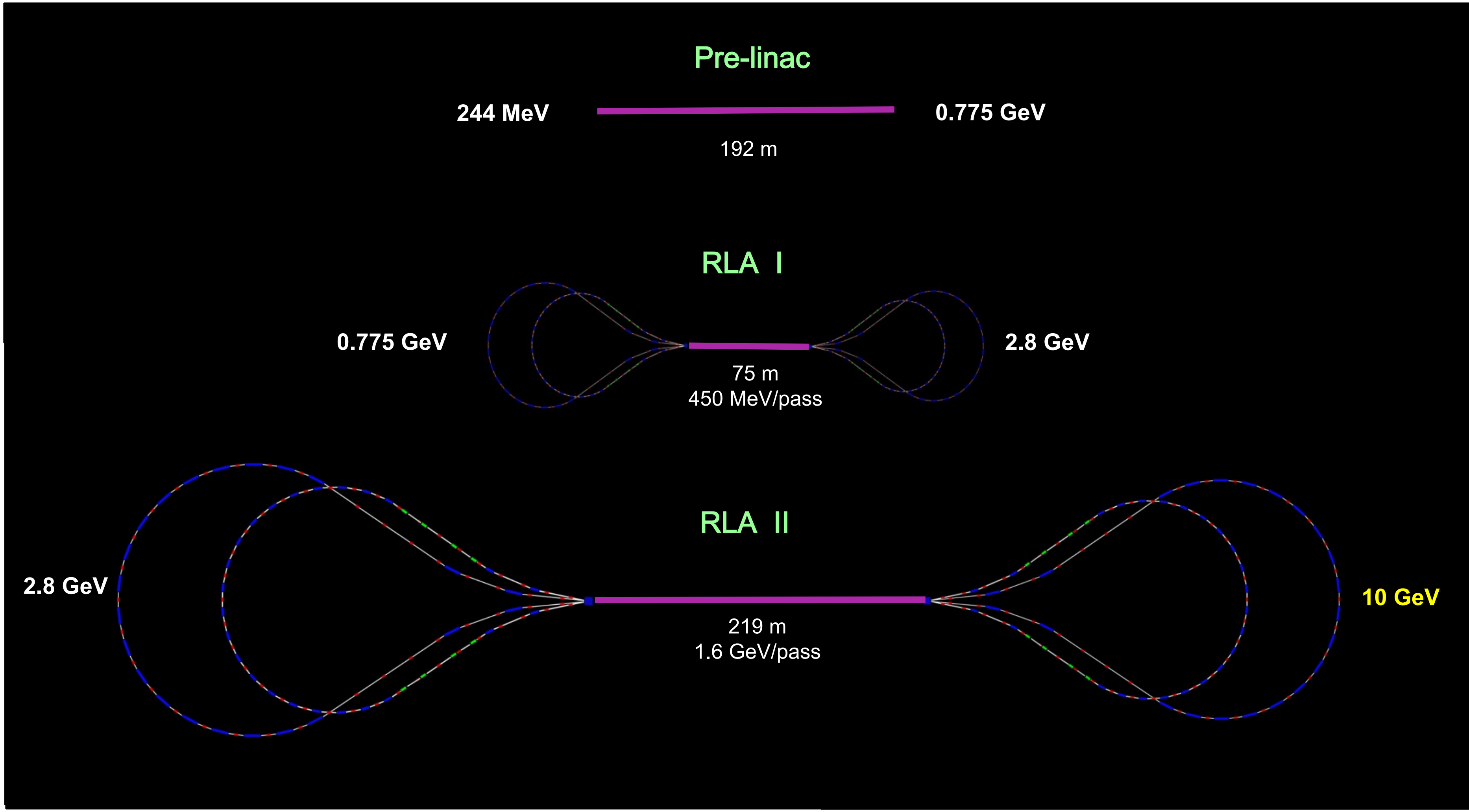
P. Snopok *et al*, Proc. IPAC 2013, TUPFI067

Front-End Summary

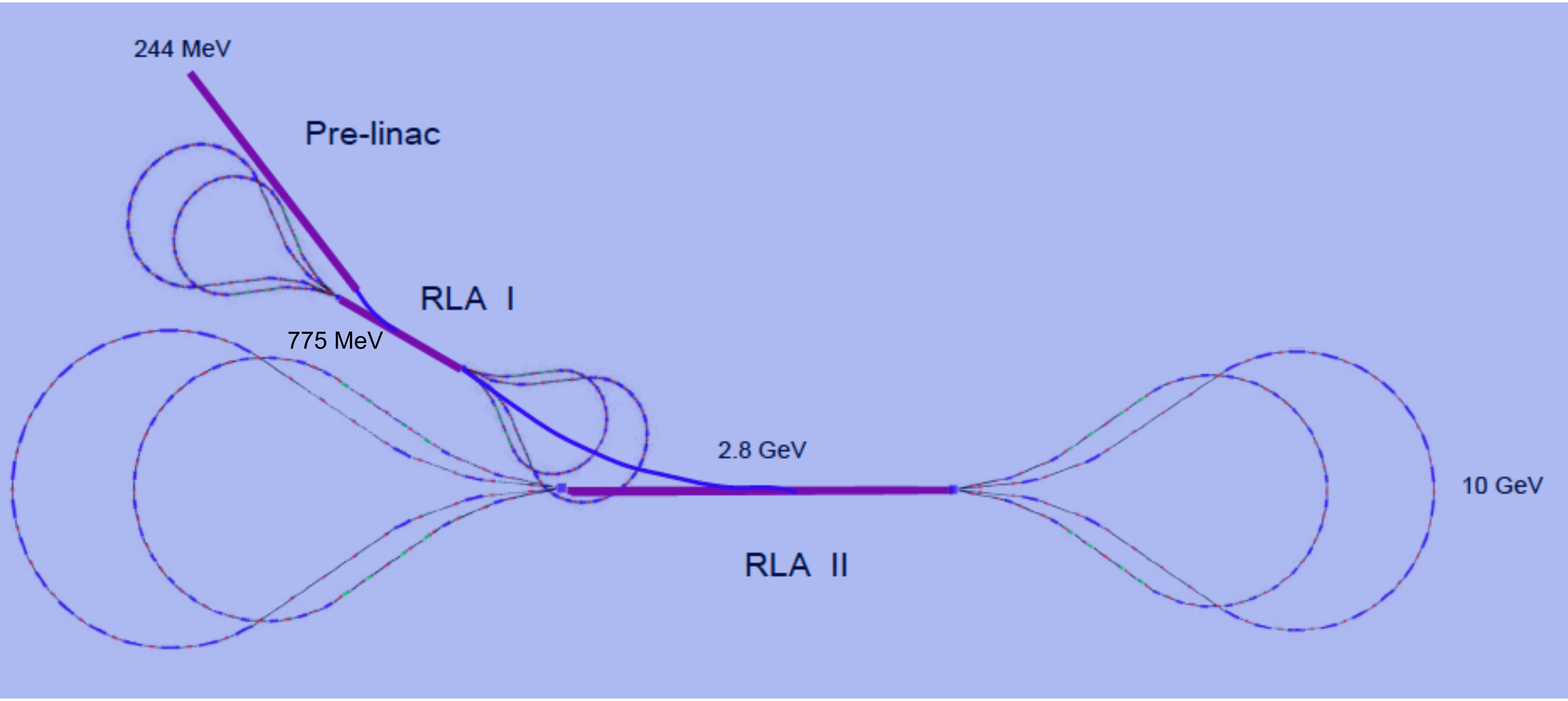
- Key challenges
  - Engineering constraints
  - Magnetic field constraints
  - Chicane Integration
    - A chicane/ absorber system to remove unwanted particles from the FE has been simulated. Energy deposition requires further shielding studies.
  - Energy deposition and shielding
  - Optimization of the solenoid taper
    - A shorter taper scheme enhances performance.
  - Global optimization algorithms underway…So far very promising results

Acceleration

Acceleration complex



Acceleration complex – ‘in plane’ layout



Initial Acceptance

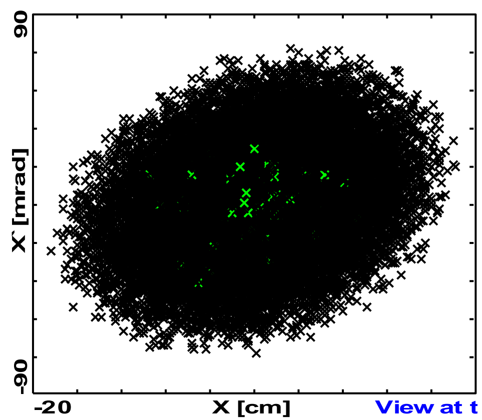
Initial phase-space after the cooling channel at 220 MeV/c

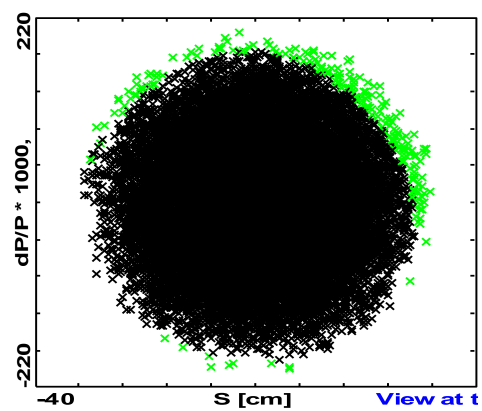
IDS		ε_{rms}	**A = $(2.5)^2$ ε**
normalized emittance: $\varepsilon_x/\varepsilon_y$	mm·rad	**4.8**	**30**
longitudinal emittance: ε_ℓ	mm	**24**	**150**
($\varepsilon_\ell = \sigma_{\Delta p}\ \sigma_z/m_\mu c$)			
momentum spread: $\sigma_{\Delta p/p}$		**0.07**	**±0.17**
bunch length: σ_z	mm	**165**	**±412**

$\beta_{x,y}$ = 2.74 m

$\alpha_{x,y}$ = -0.356

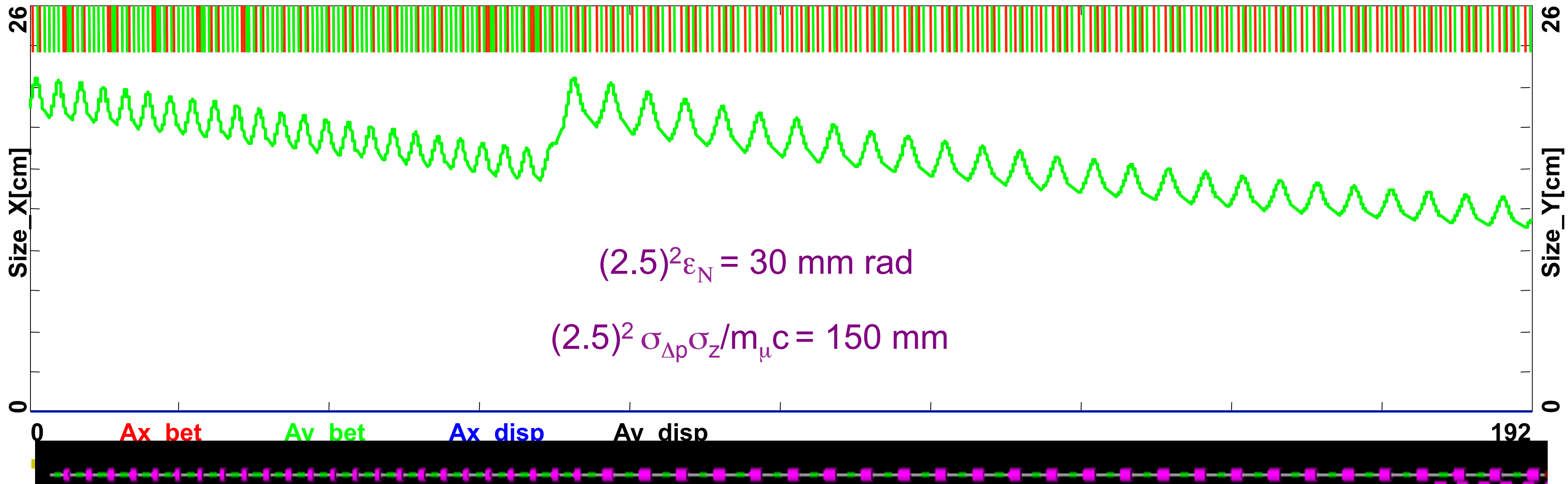
$\beta\gamma$ = 2.08





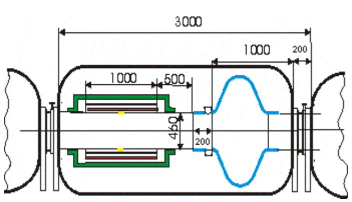
E = 244 MeV
γ = 2.3

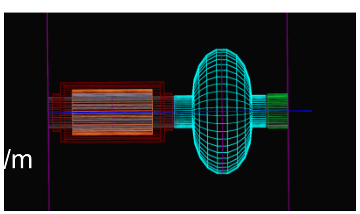
Linac (244 – 775 MeV)

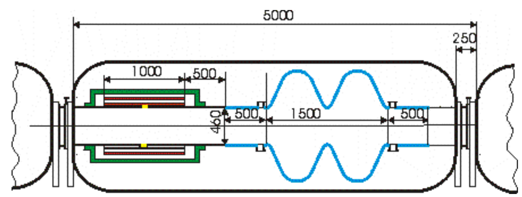


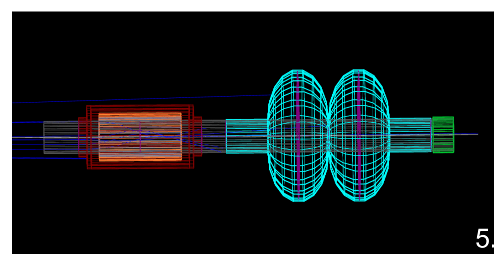
24 short cryos

24 medium cryos









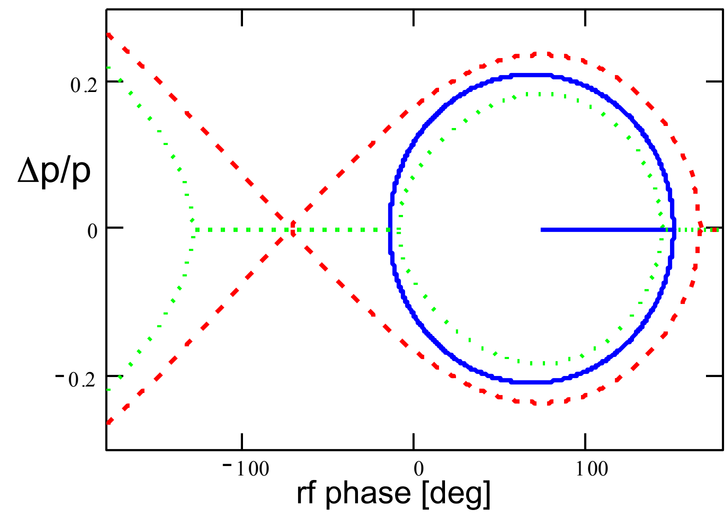
Linac – Longitudinal compression

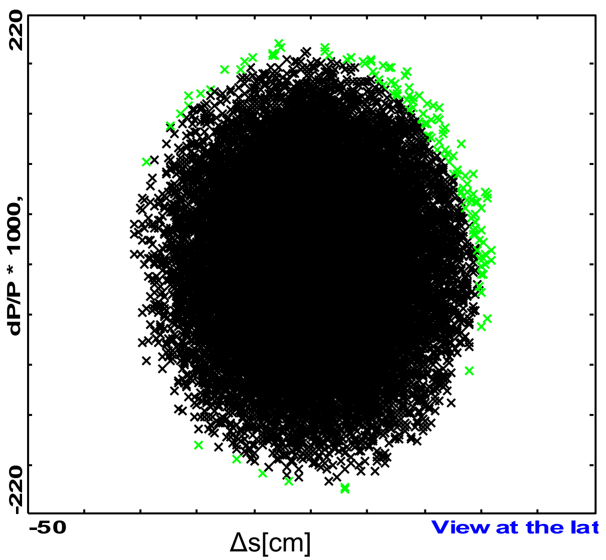
201 MHz, 15 MeV/m

E = 244 MeV
γ = 2.3

longitudinal emittance: ε_ℓ	mm	**24**
($\varepsilon_\ell = \sigma_{\Delta p}\, \sigma_z / m_\mu c$)		
momentum spread: $\sigma_{\Delta p/p}$		**0.084**
bunch length: σ_z	mm	**137**

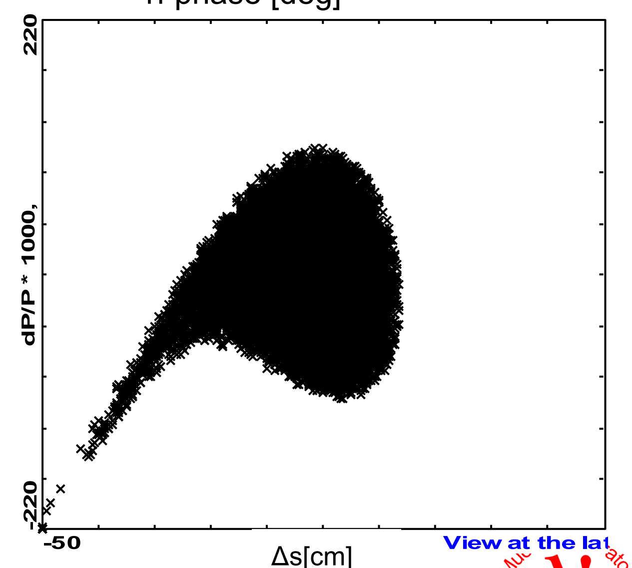
72 deg. off-crest





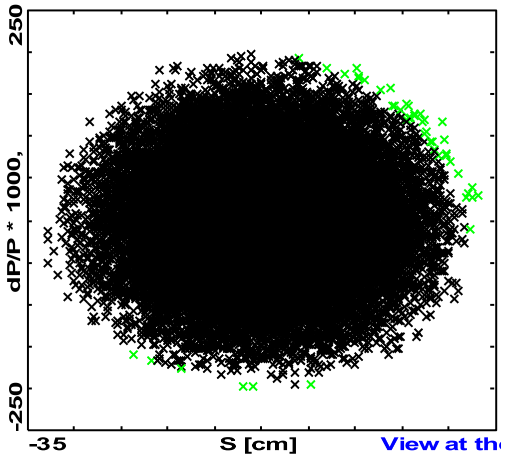
Tracking with OptiM
(Transfer Matrix)

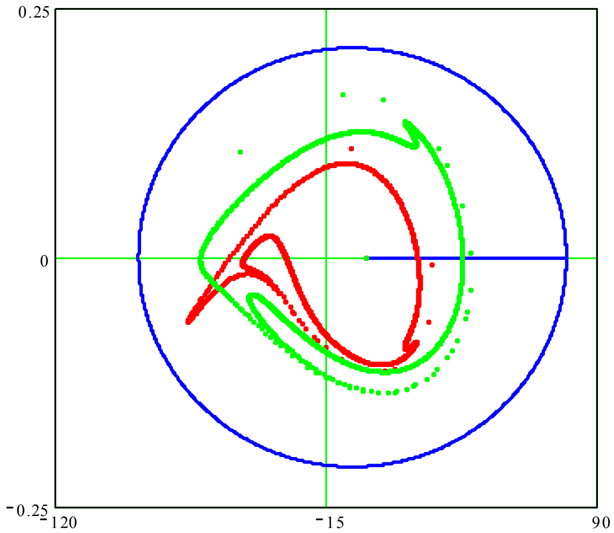
Dynamic Loss: 0.4%

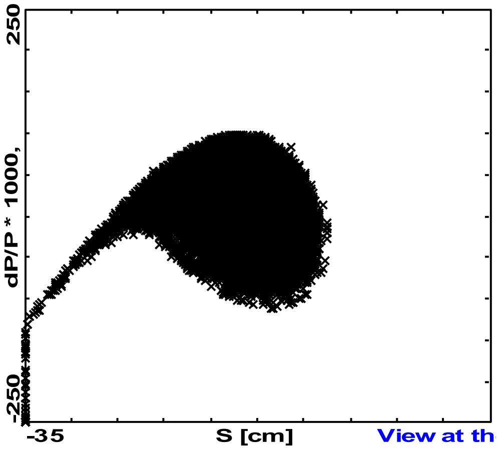


244 – 0.775 MeV Linac – Transmission

Dynamic Loss: 0.5%

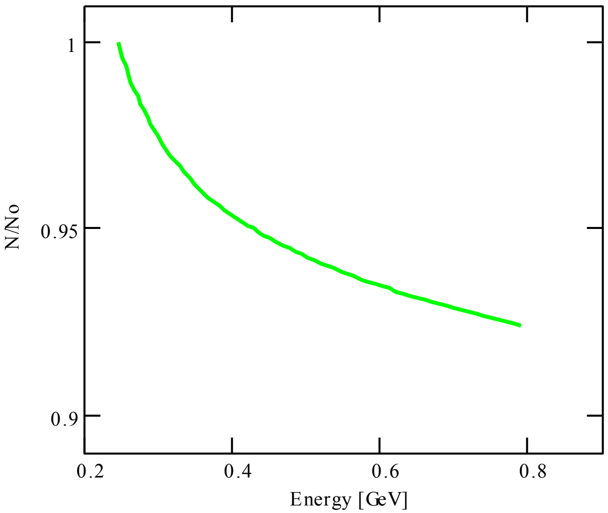






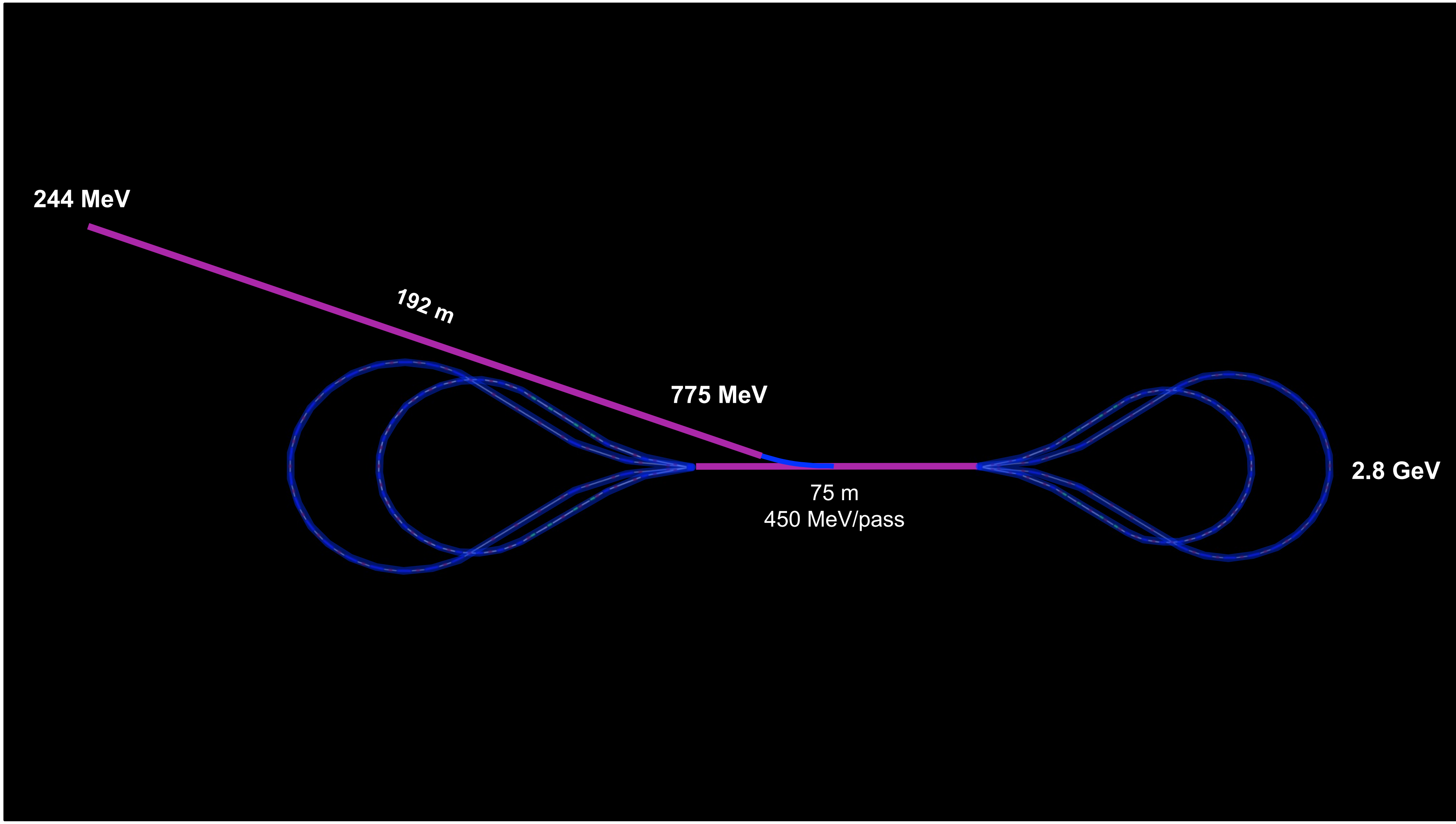
$$\frac{N}{N_0} = e^{-\frac{\tau}{\tau_\mu}}$$

Muon decay: 7%

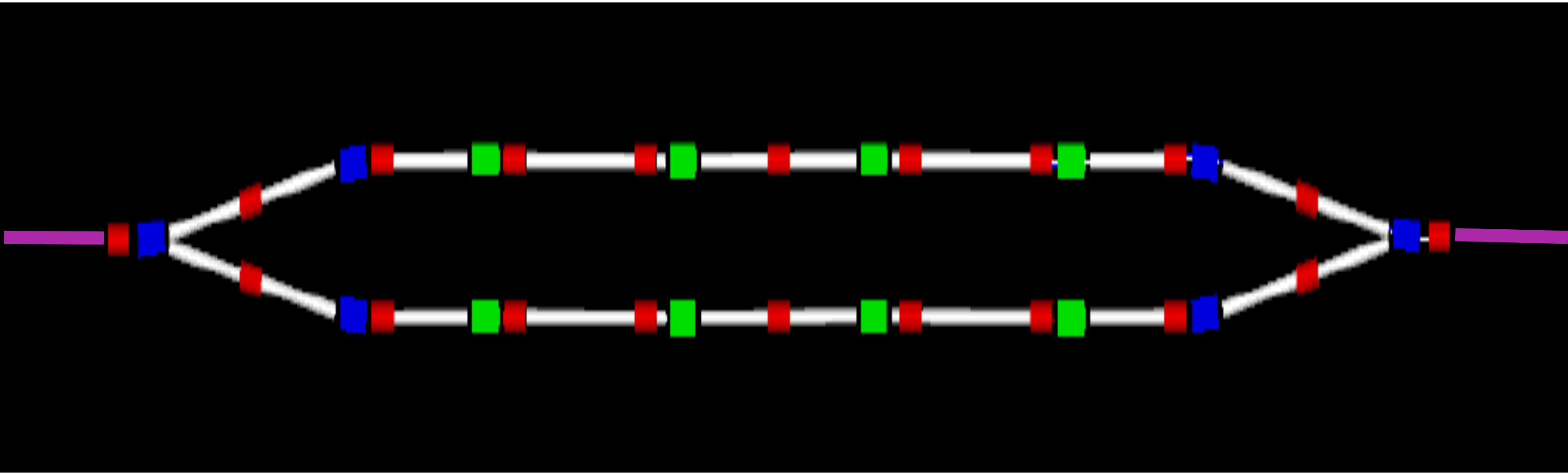


Total loss: 7.4%

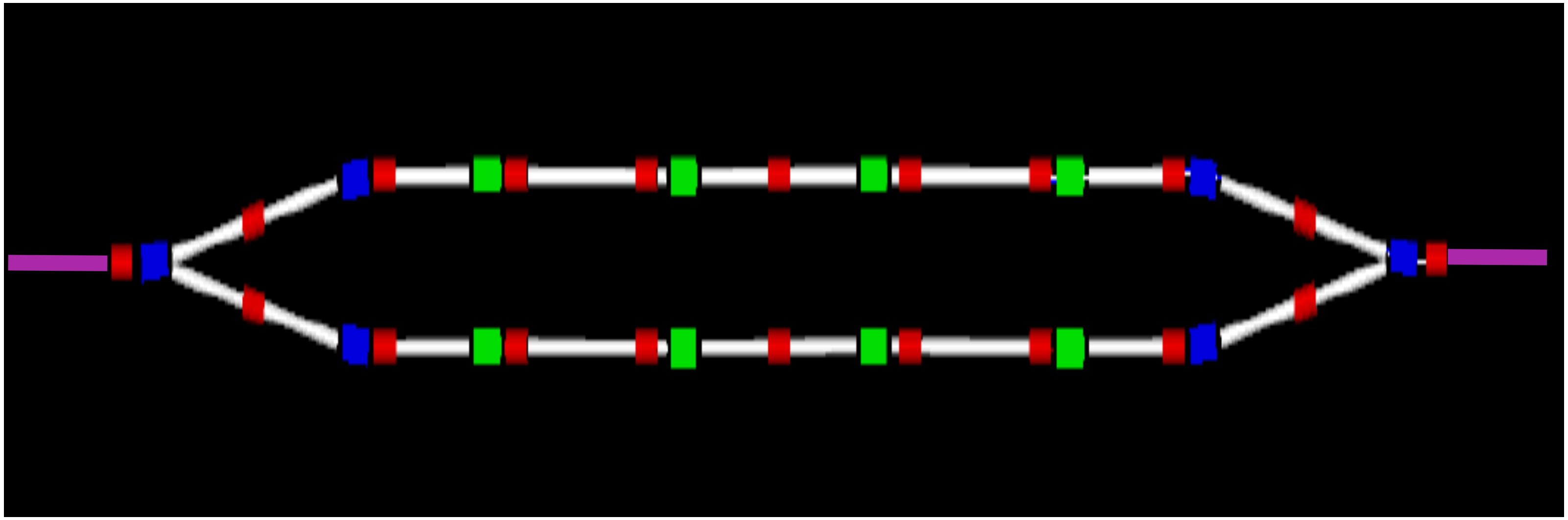
Linac and RLA I – ‘in plane ‘ layout

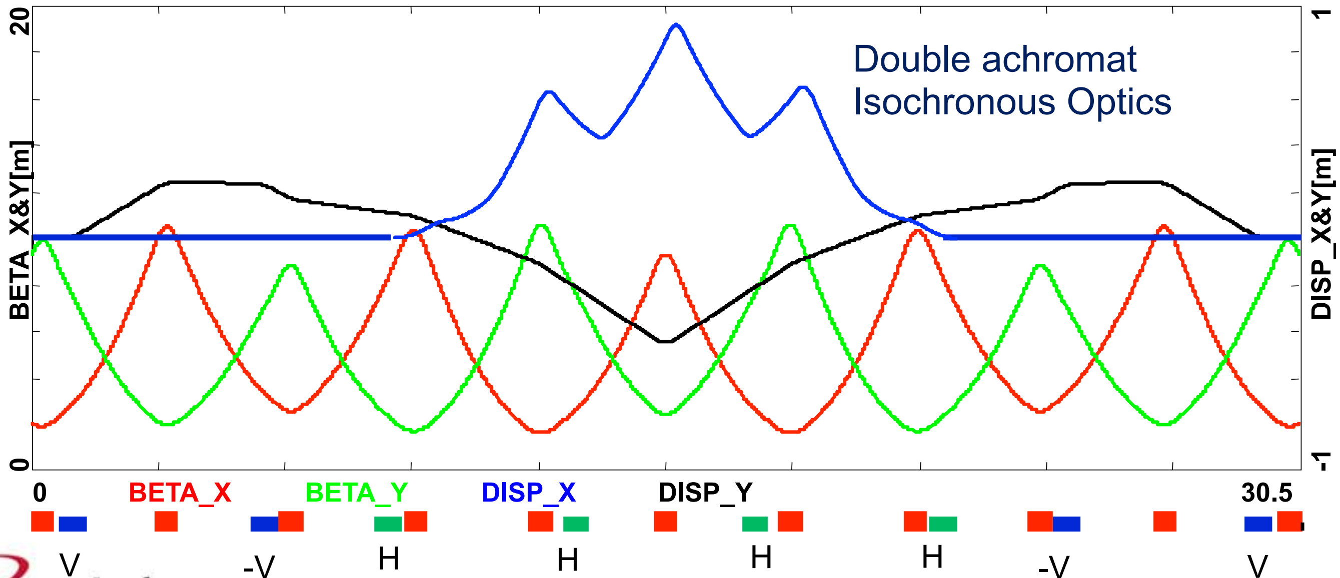


Double Arc Chicane



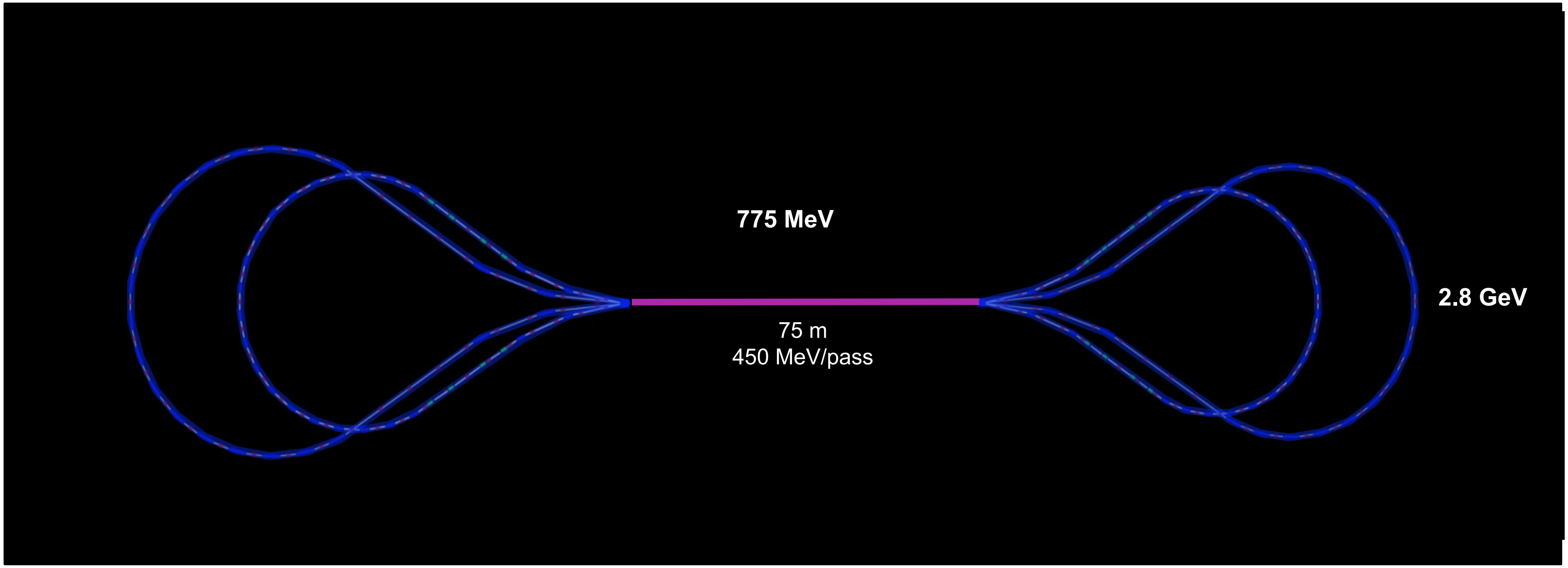
Double Arc Chicane – Optics



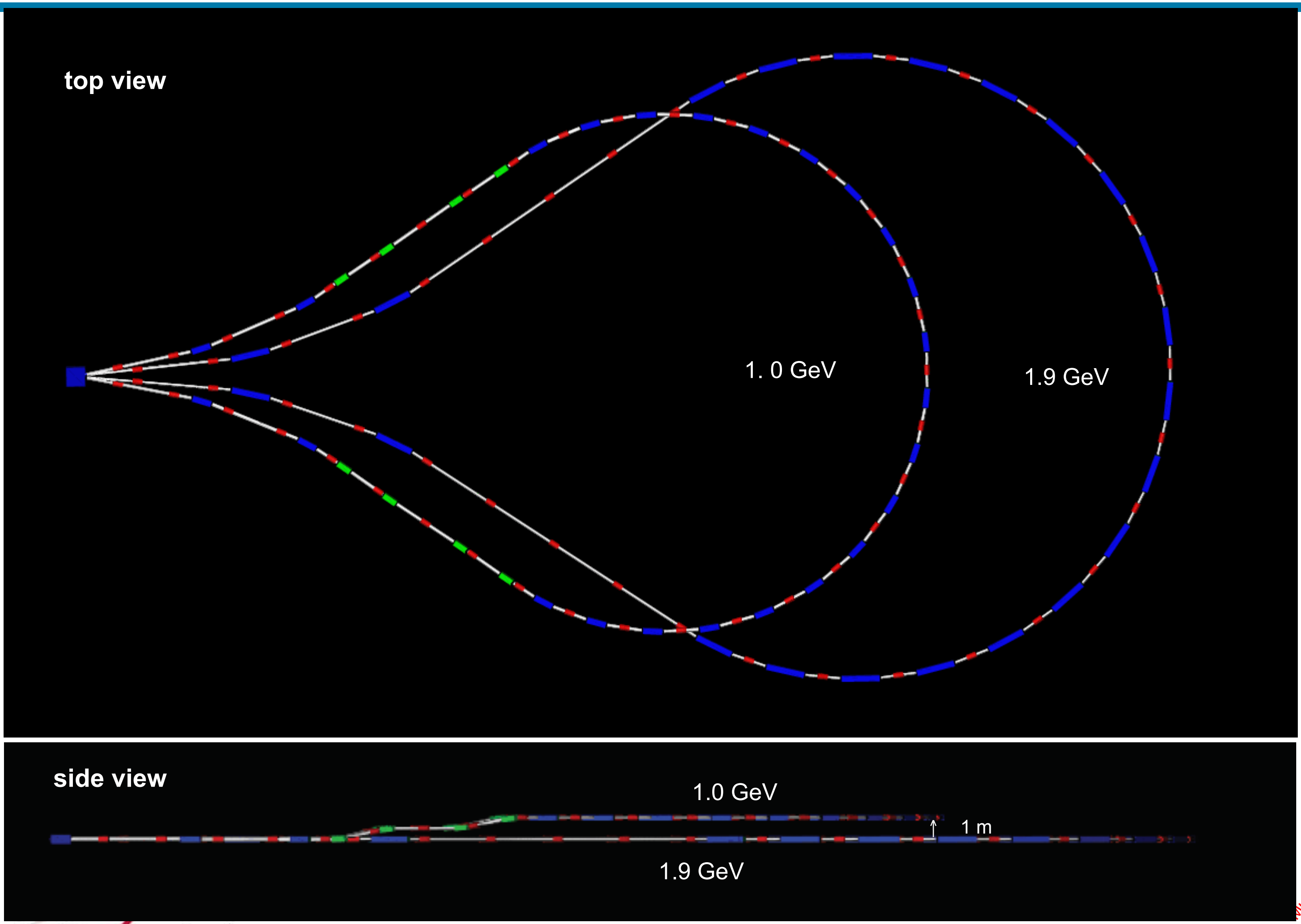


FODO lattice:
$90^0/90^0$ (h/v)
betatron phase
adv. per cell

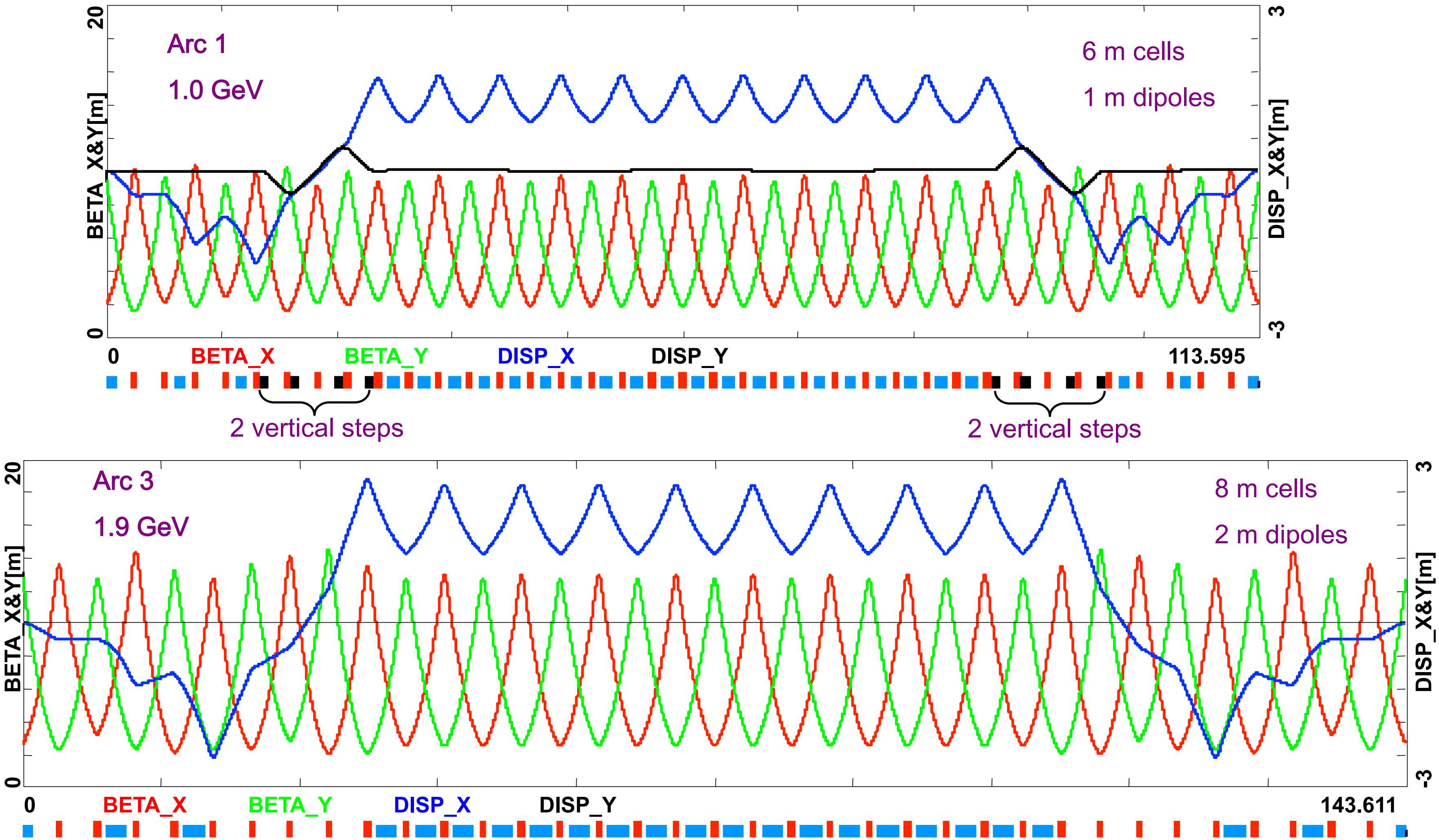
RLA I



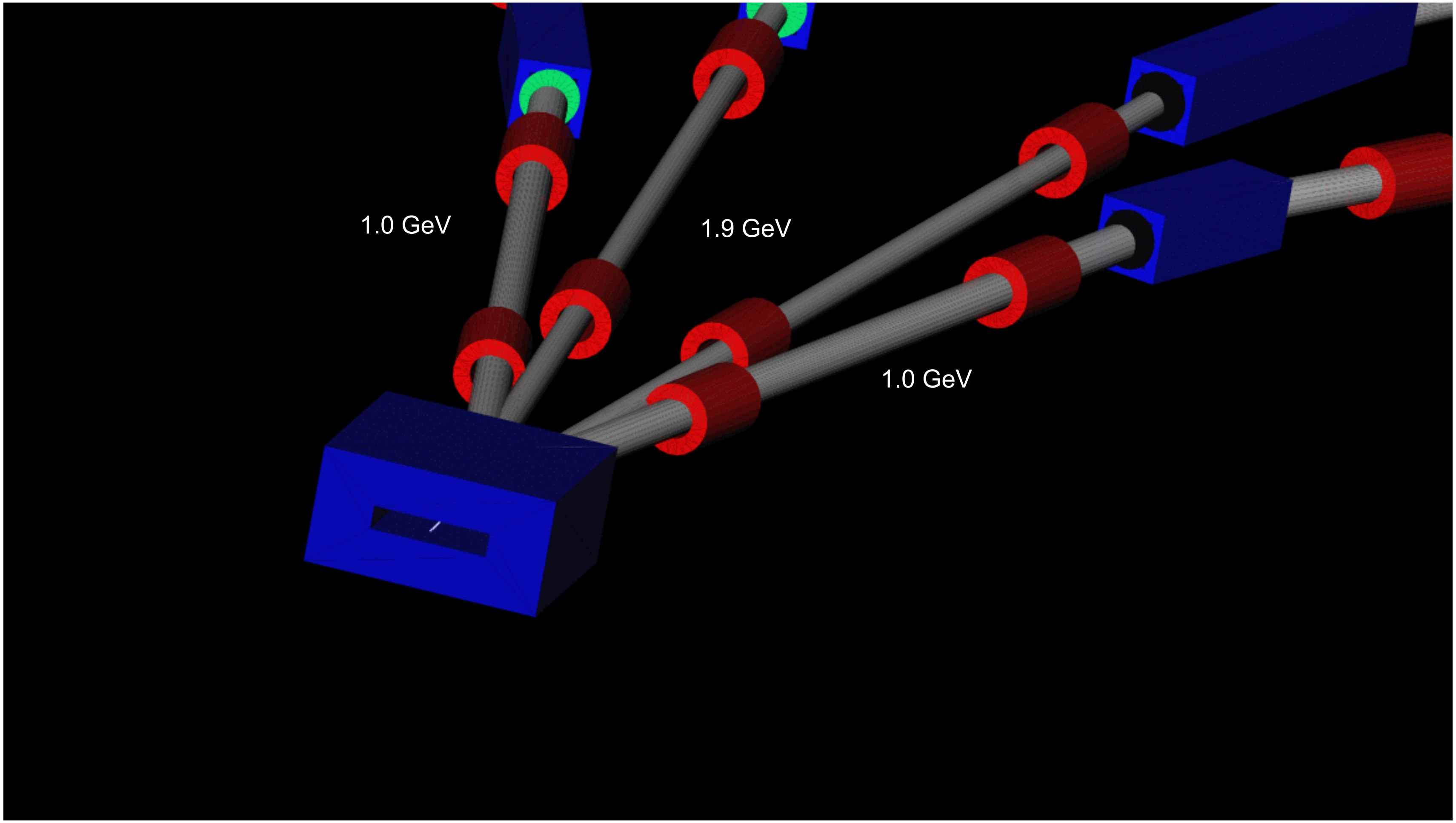
Arc 1 and Arc 3



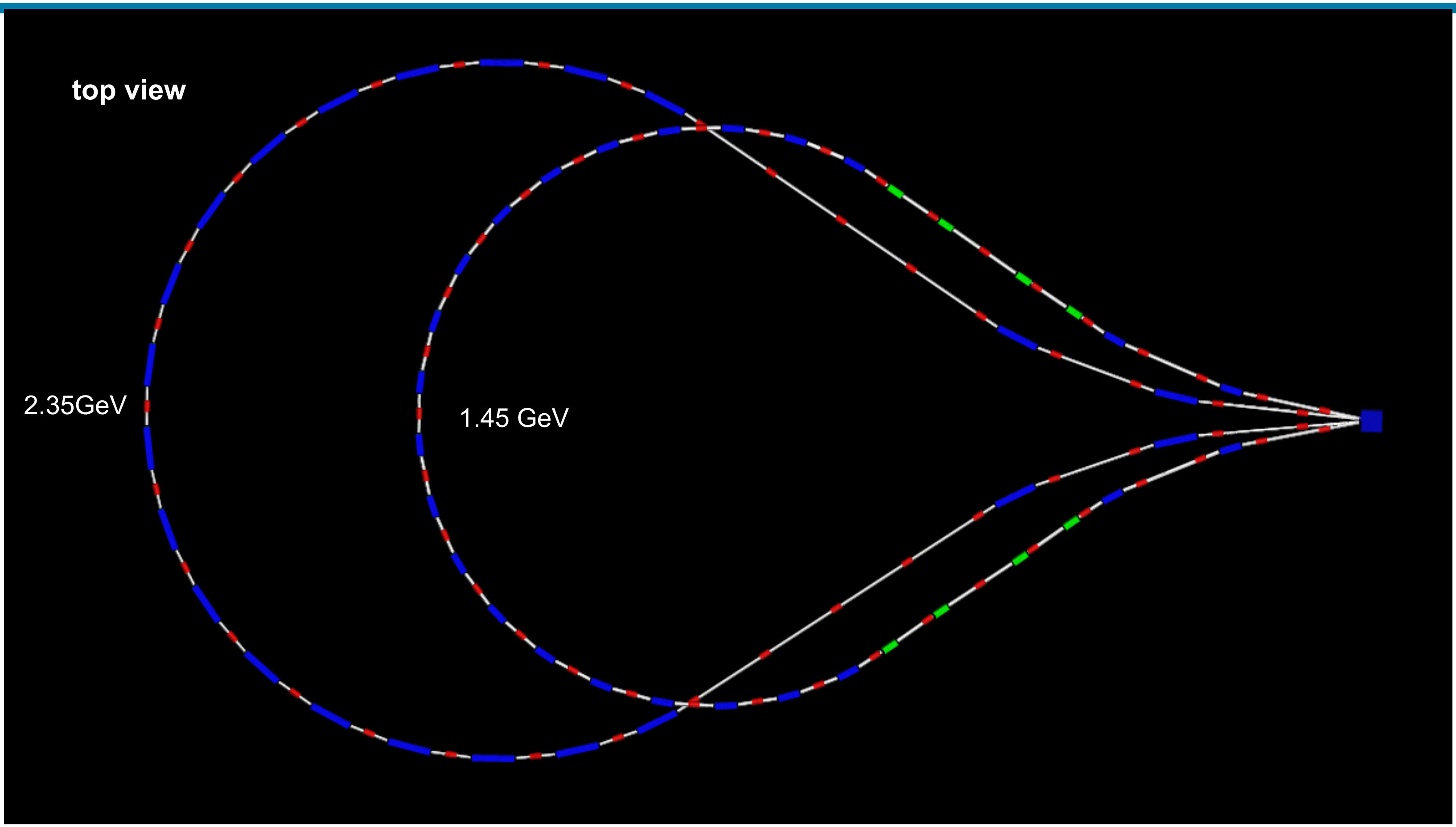
Arc 1 and 3 – Optics

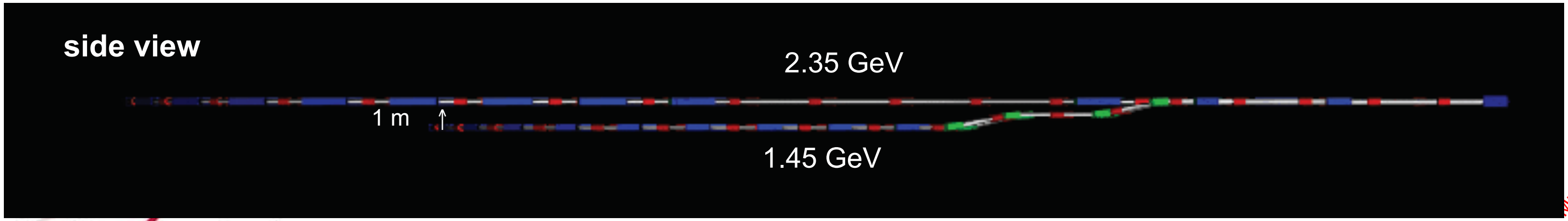


Switchyard – Arc 1 and 3



Arc 2 and Arc 4

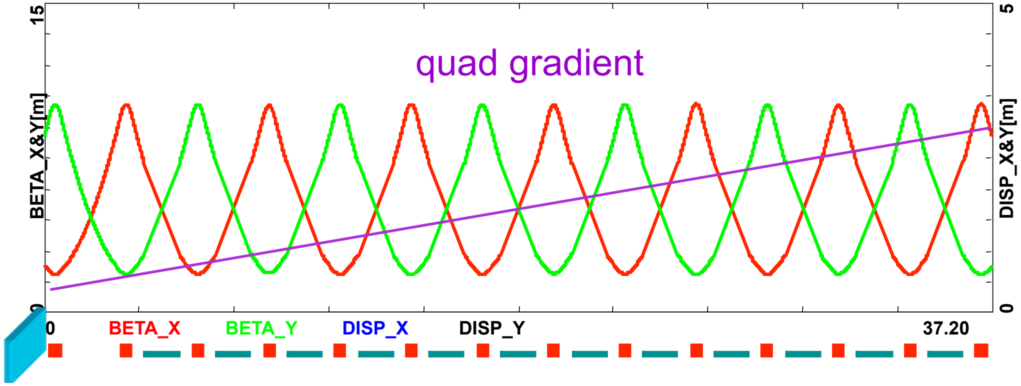




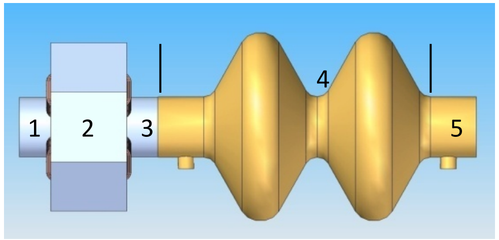
RLA I - Multi-pass linac optics

‘half pass’, 0.775-1.0 GeV

initial phase adv/cell 90 deg. scaling quads with energy
6 meter 90 deg. FODO cells
17 MV/m RF, 2 cell cavities

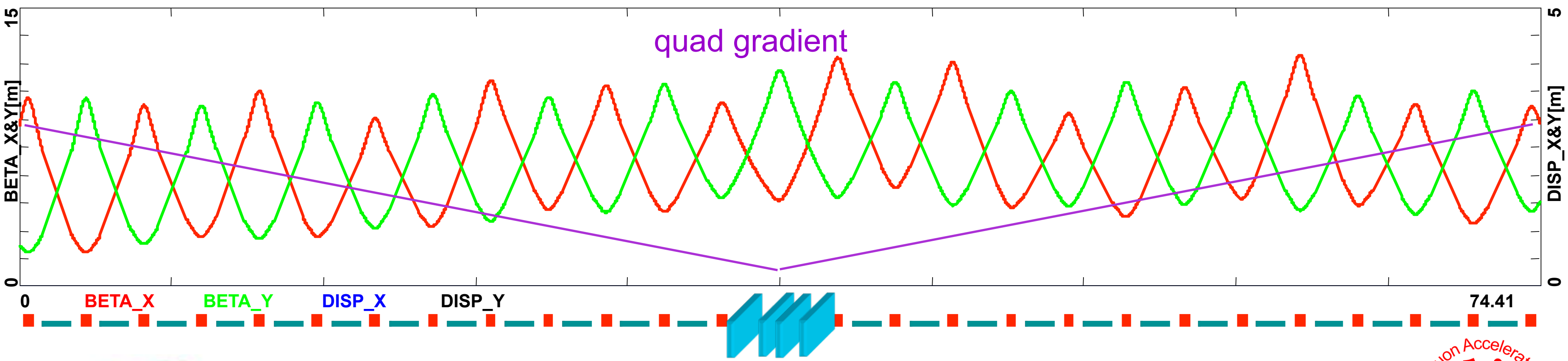


3m RLA II LINAC Module core:

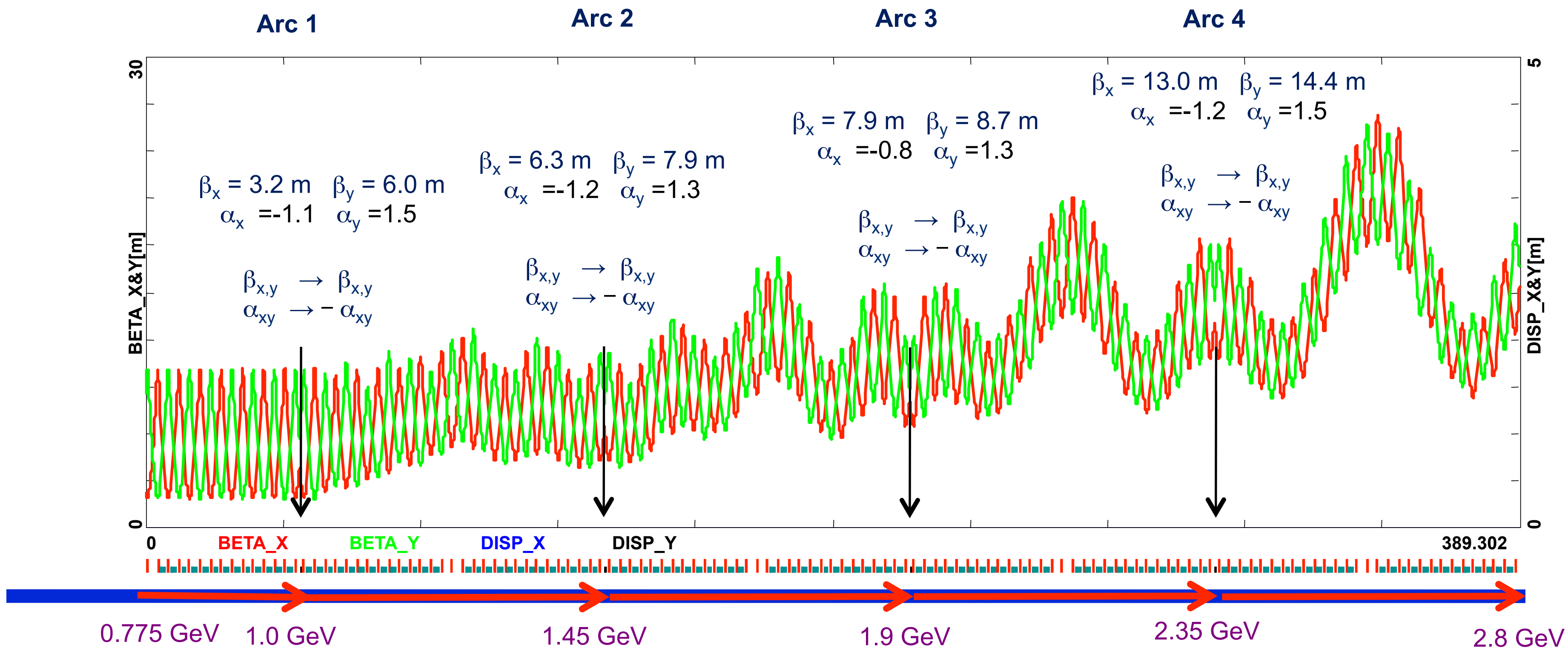


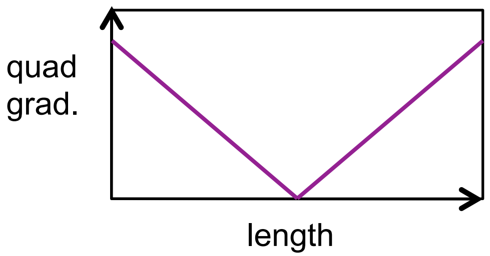
1-pass, 1.0-1.45 GeV

mirror symmetric quads in the linac

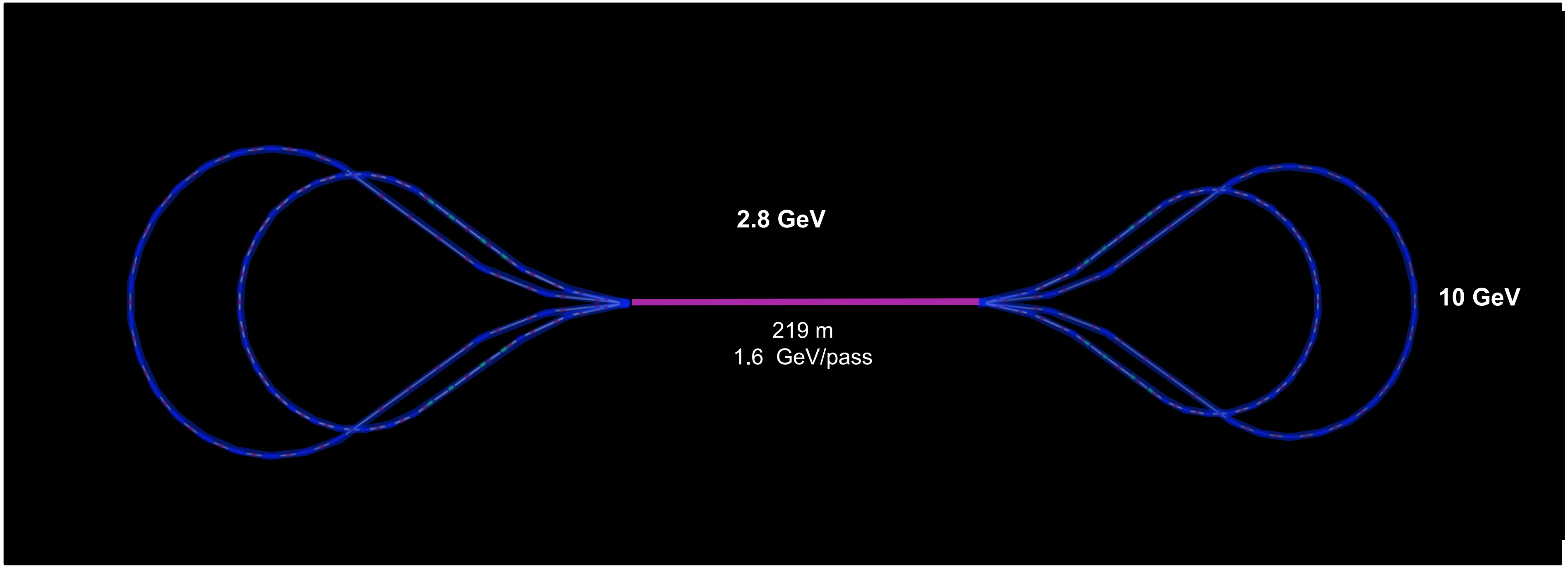


Multi-pass bi-sected linac optics



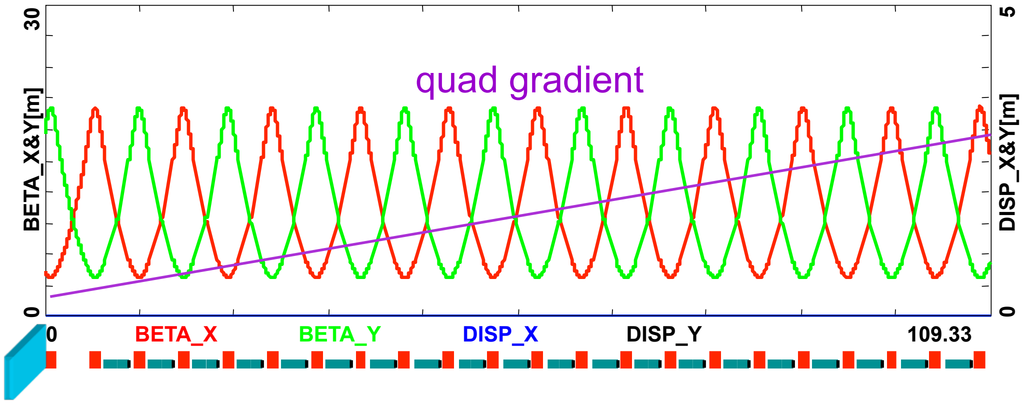


RLA II



RLA II - Multi-pass linac optics

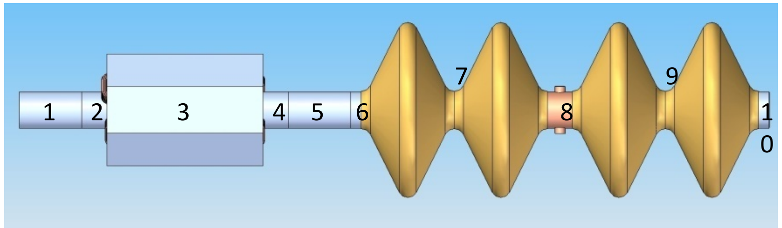
'half pass', 2.8-3.6 GeV



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

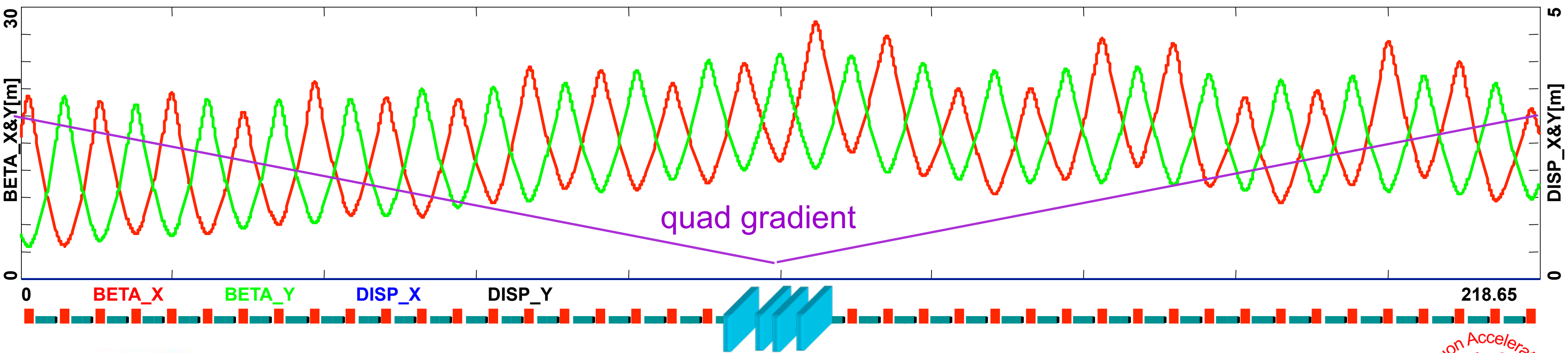
12 meter 90 deg. FODO cells
17 MV/m RF, two 2 cell cavities

6m RLA II LINAC Module core:

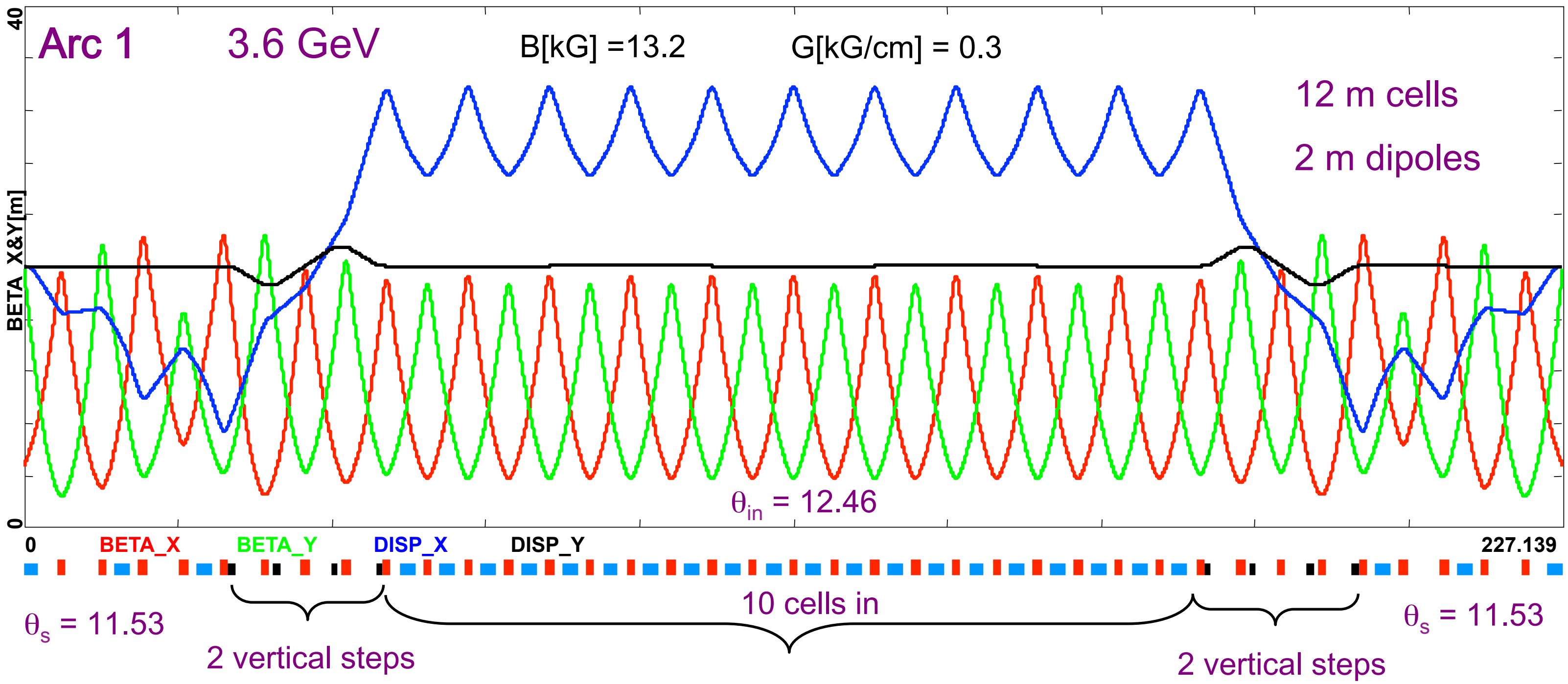


1-pass, 3.6-5.2 GeV

mirror symmetric quads in the linac

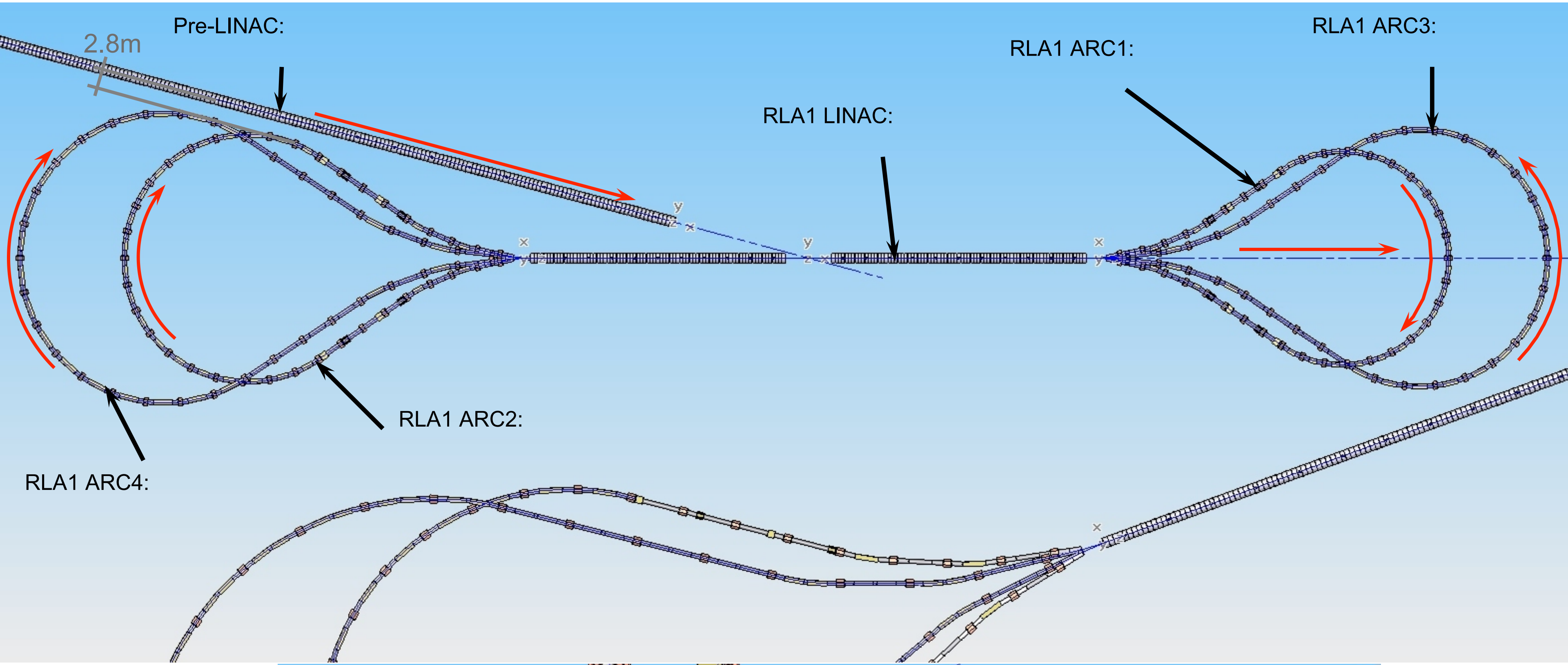


RLA II – Arc optics

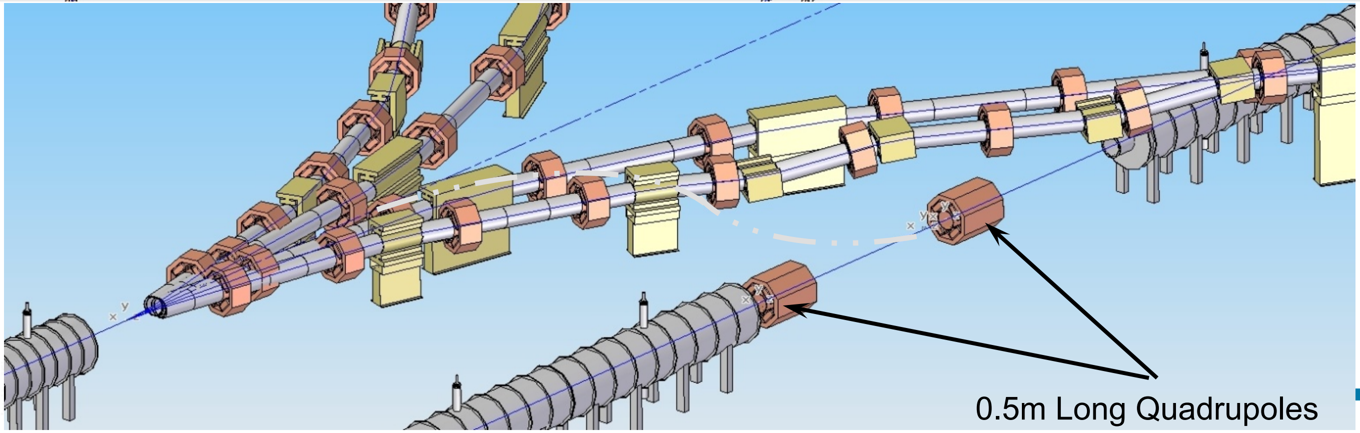


Arc 2	5.2 GeV	14 m cells	3 m dipoles	
Arc 3	6.8 GeV	16 m cells	4 m dipoles	(2×2 m dipoles)
Arc 4	8.4 GeV	18 m cells	5 m dipoles	(2×2.5 m dipoles)

Engineering layout



N. Collomb



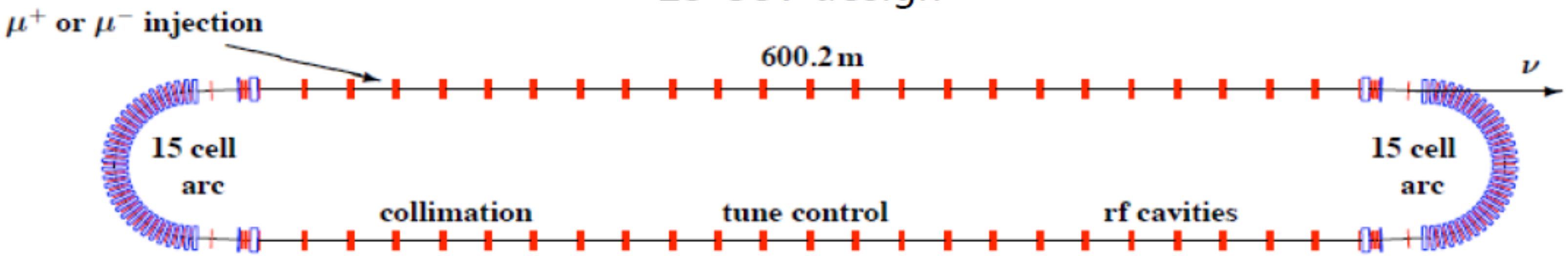
Acceleration - Summary

- IDS baseline (Linac + 2×RLA to 10 GeV)
  - Linac (244 – 775 MeV) Longitudinal compression
  - RLA I (0.775 – 2.8 GeV) Arcs and multi-pass linac Optics
  - RLA II (2.8 – 10 GeV) Arcs and multi-pass linac Optics
  - Linac + RLA I – 'in plane' layout
  - 25^0 Double Arc Chicane (transfer line prototype)
  - RLA I + RLA II – 'in plane' layout
  - 40^0 Double Arc Chicane (transfer line prototype)

Decay Ring

Introduction – Decay Ring

25 GeV design

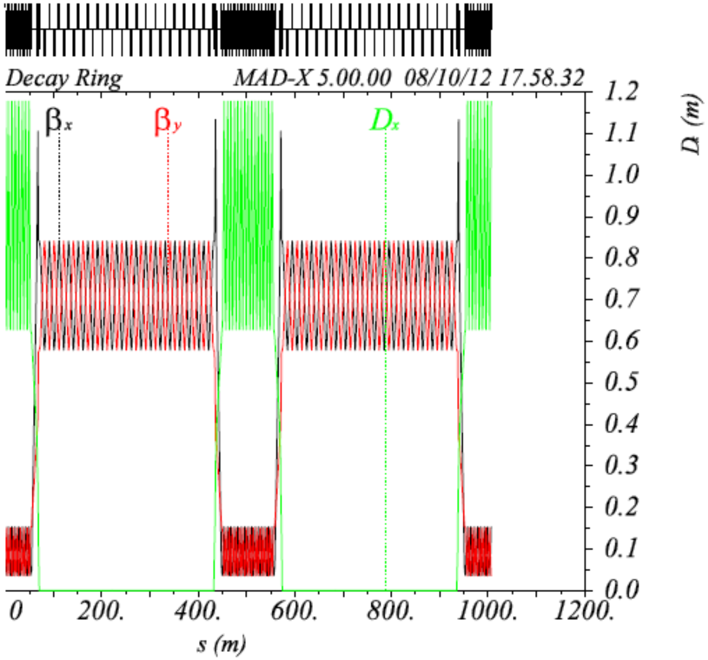


J. Pasternak and D. Kelliher

Design Aims
Reasonable neutrino production efficiency (η)
Low beam divergence in production straight (<0.1/γ)
Maintain bunch separation (100 ns)
Allow realistic injection scheme

10 GeV Decay Ring Design (no insertion)

- Circumference 1006 m
- γ_T 13.927
- Production efficiency 35.8%
- Assumed total momentum spread ±2.5%
- Production straight length 360 m
- Arc length 106.2 m
- $(Q_{H,} Q_V) = (9.71, 9.55)$



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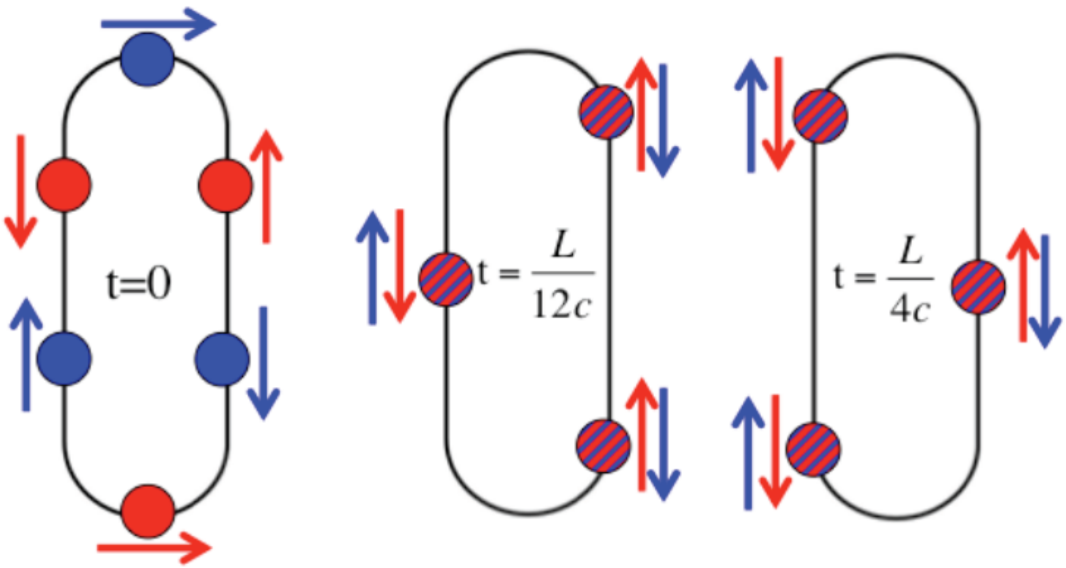
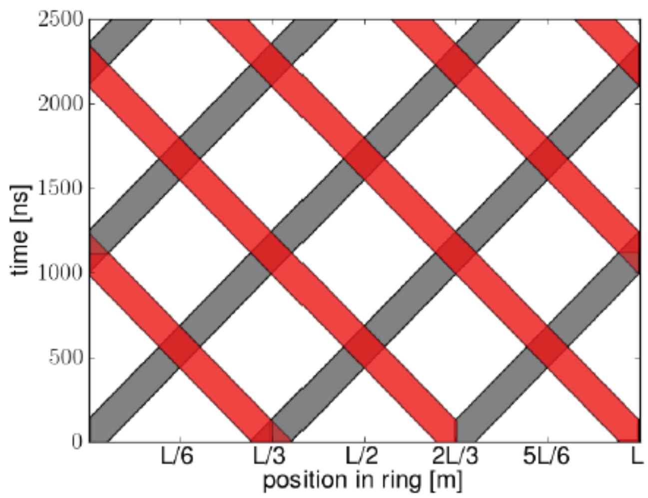
Ideal bunch crossing points

J. Pasternak and D. Kelliher

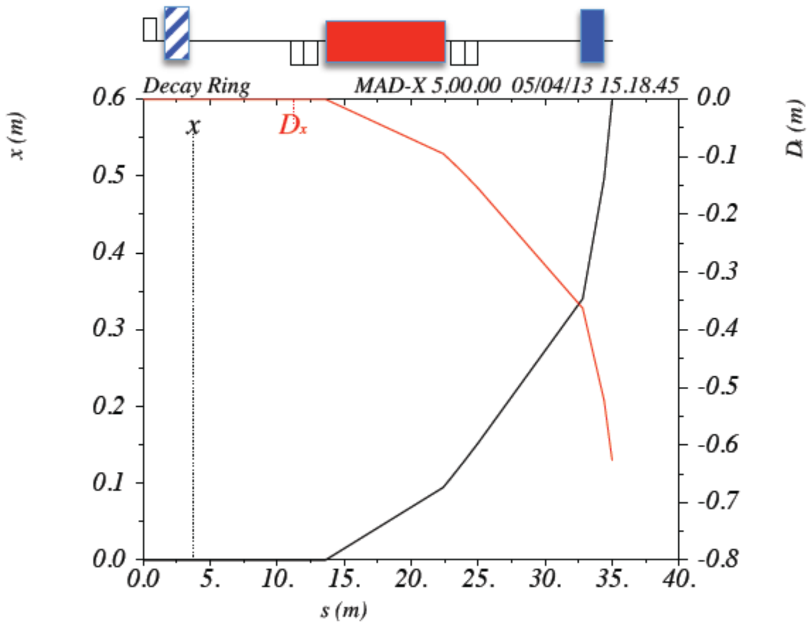




- When muon bunches are equally spread around the ring, two must be at arc centres to ensure equally spaced neutrino bursts.
- Bunches must cross at centre of production straight and ±L/6 away where L is the ring circumference.
- If η≥2/3, all crossing points will lie in production straight.

Injection into production straight

- Ensure 2cm separation between injected and circulating beam at septum exit.
- Injected beam excursion in kicker magnet 9.5 cm, in D magnet 15.2 cm.



	Length (m)	Field (T)	Angle (rad)
Kicker	8.8	0.08	0.022
Septum	1.6	3.06	0.147

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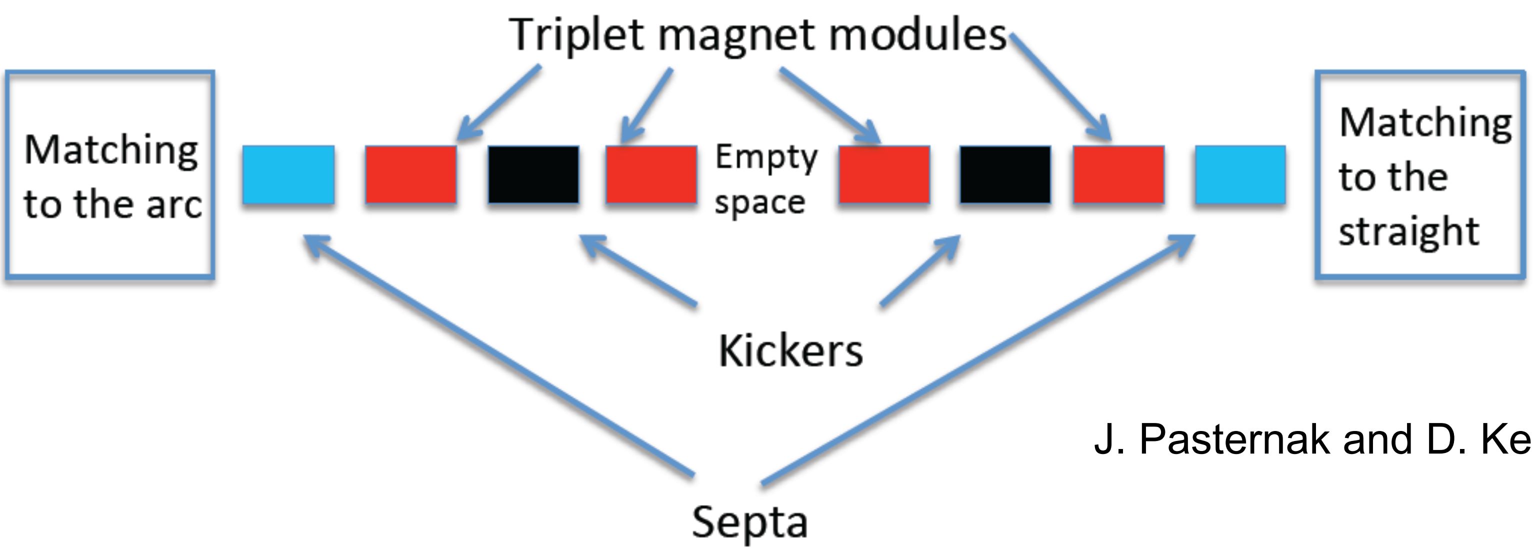
Conceptual layout of the injection insertion

- Arc-type cells are to compact and straight cells has very large beam size and non-ideal phase advance for injection.
- Insertion based on triplets may provide additional length in the drift and phase advance can be optimised.
- Two kickers and two septa are needed in a symmetric configuration.



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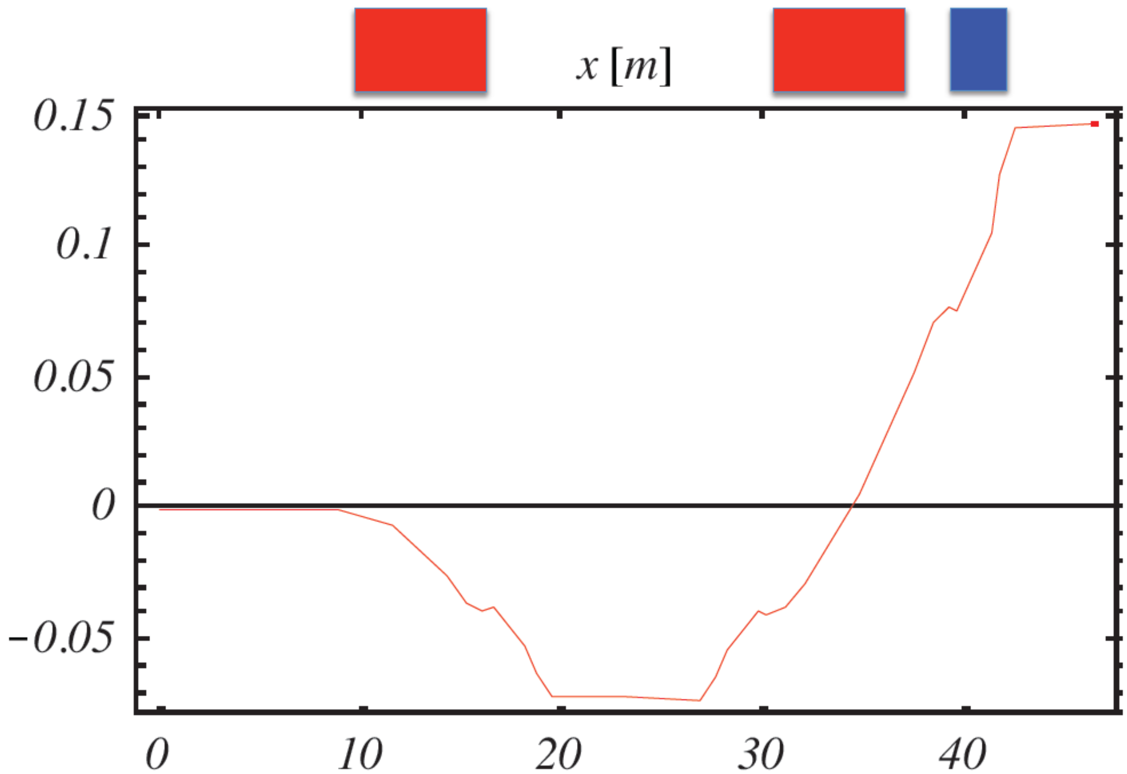
Injection trajectory



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Ring with insertion

Circumference	1575.8
Production efficiency	35.56% x 2
Total tune	14.25, 14.88
Phase slip	2.8 x 10^{-3}
Turns per mean lifetime	39.6

The current design allows for a realistic injection of 3 negative and 3 positive muon bunches.

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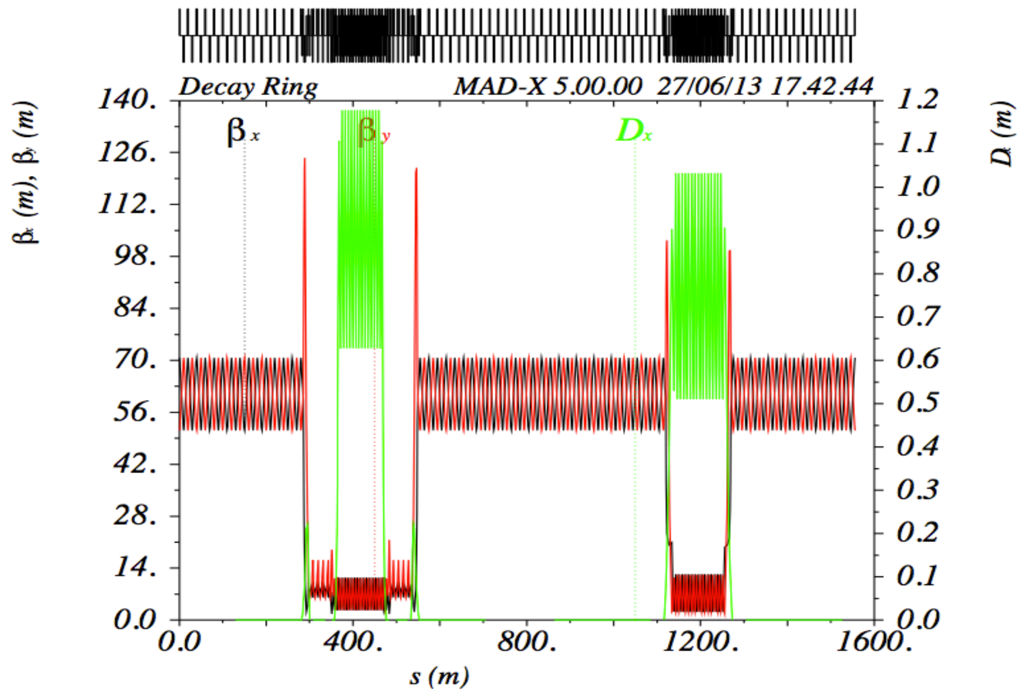
Decay ring optics



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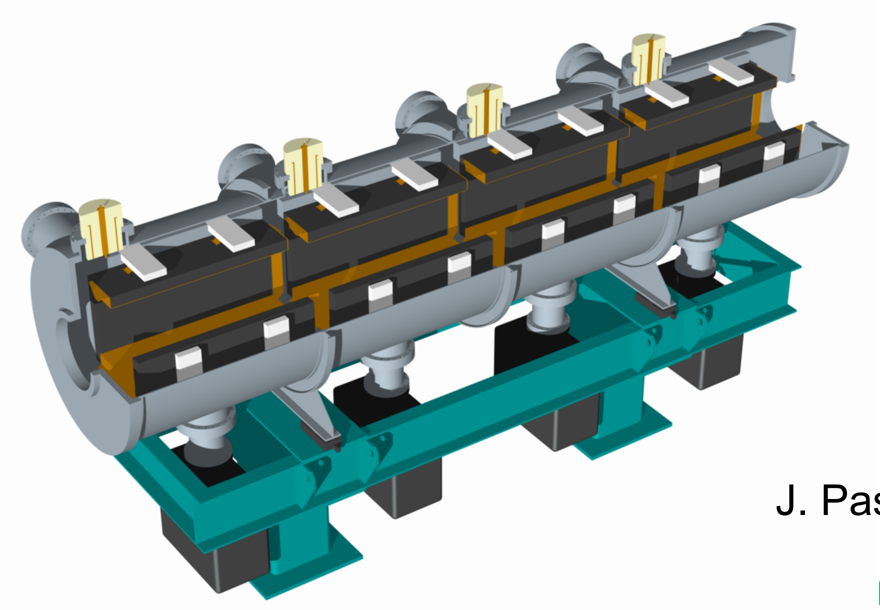
- There is no need for insertions in lower part of the ring.
- The insertion contributes to the width of the racetrack since the arcs bend by less than 180 degrees. The lower arc should be scaled up to match this extra width.
- In order to use the same magnets as upper arc, just the drift lengths are scaled up. However, the focusing is adjusted by a small amount to optimise the working point.

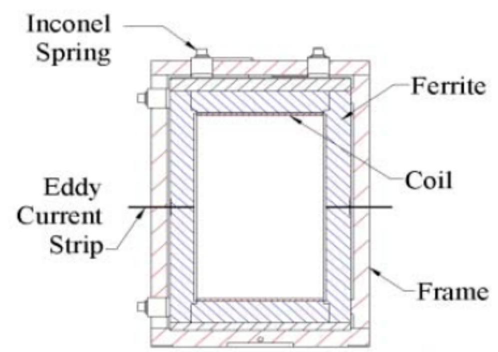
Towards the realistic kicker parameters

No of kickers	2
No of sub kickers	10
PFNs per kicker sub units	3
No of Pulse Forming Networks	30
Thyratrons	30
Travelling wave system design	
B field	0.06 T

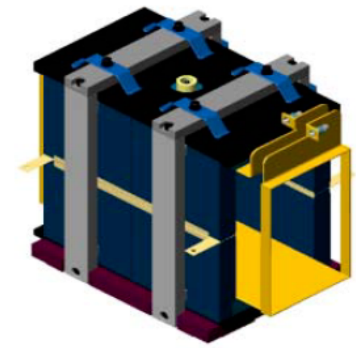
Kicker aperture	0.18 x 0.18 m
Kicker length	5.4 m
Rise/Fall (5-95%)	1370 ns
Pulse duration at top	0.3 μS

Parameters of kickers are now relaxed.





Cross Section



Magnet

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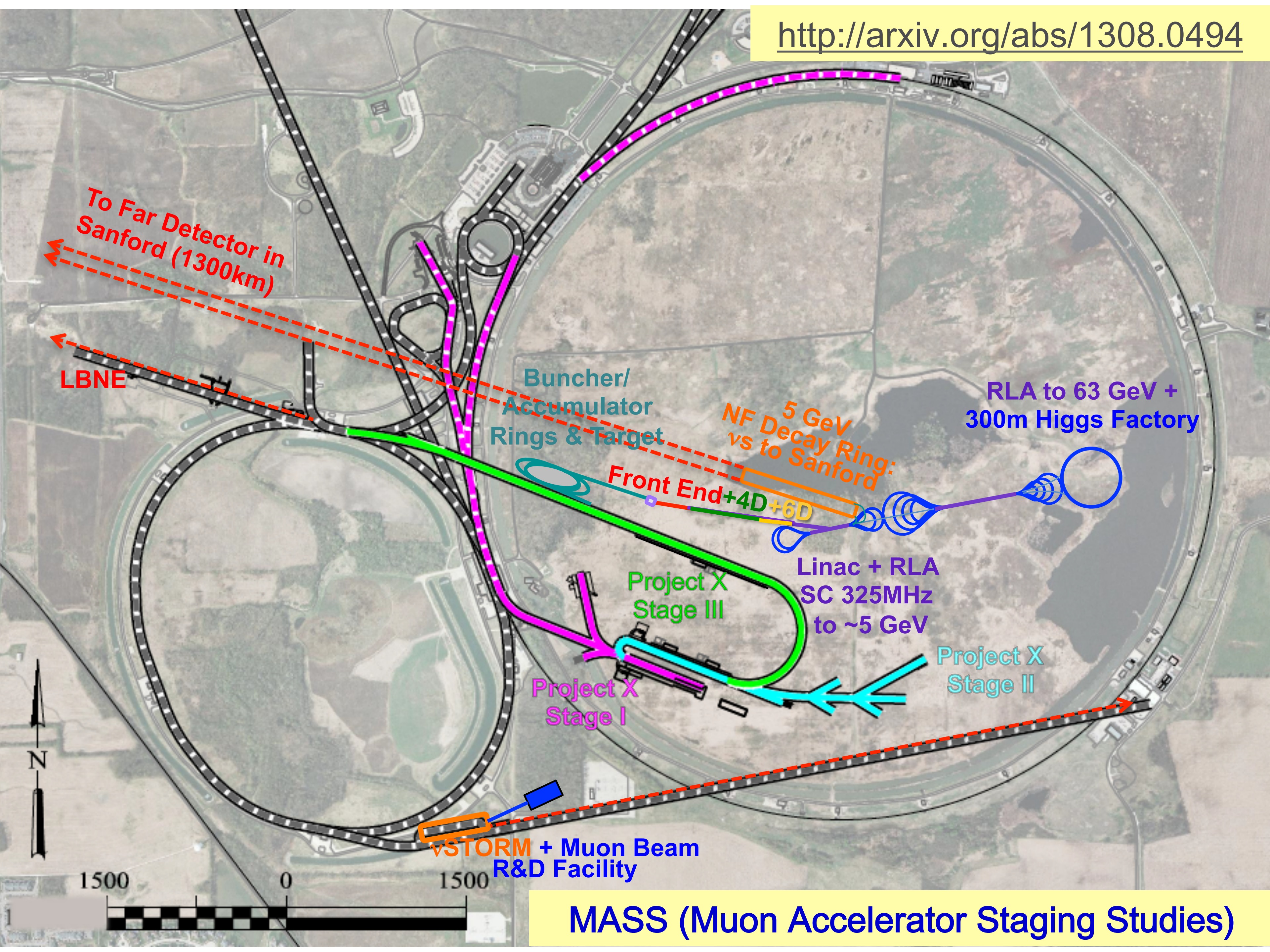
Summary

- Injection into the production straight requires large aperture kickers with <1μs rise/fall time.
- Instead we consider adding an injection insertion. This adds to the decay ring circumference but allows a realistic injection scenario.

Outlook

MASS (Muon Accelerator Staging Studies)

http://arxiv.org/abs/1308.0494



Baseline parameters for 325 MHz Front-End

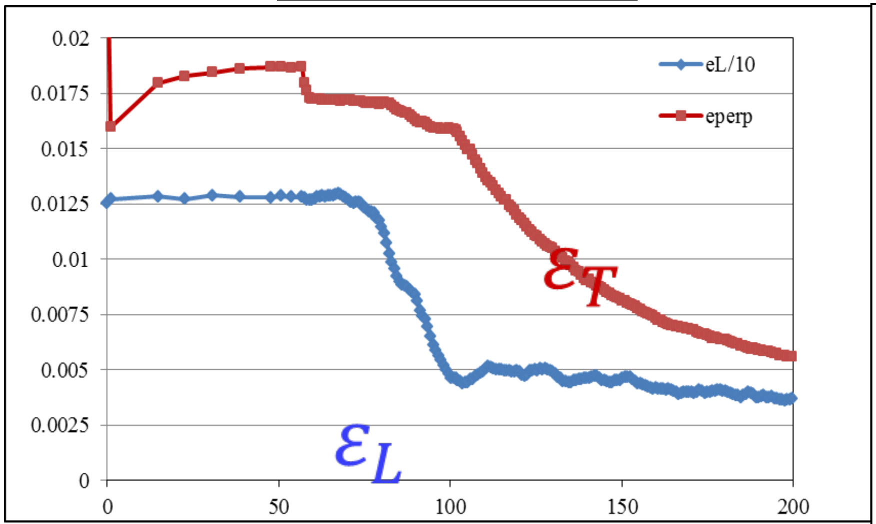
- Drift [42 m, 60 m]
  - 20 T → 2 T (20 T → 1.5 T)
- Buncher [21 m, 33 m]
  - 490 MHz → 365 MHz (319 MHz → 233 MHz)
  - 0 → 15.0 MV/m (3.4 → 9 MV/m)
- Rotator [24 m, 42 m]
  - 364 MHz →326 MHz (232 MHz → 201 MHz)
  - rf voltage: 20 MV/m (13 MV/m)
- Cooler [~60 m, ~100 m]
  - 325 MHz (201 MHz) @ 25 MV/m (16 MV/m)
  - LiH absorbers

NOTE: Red is the 201 MHz FE version

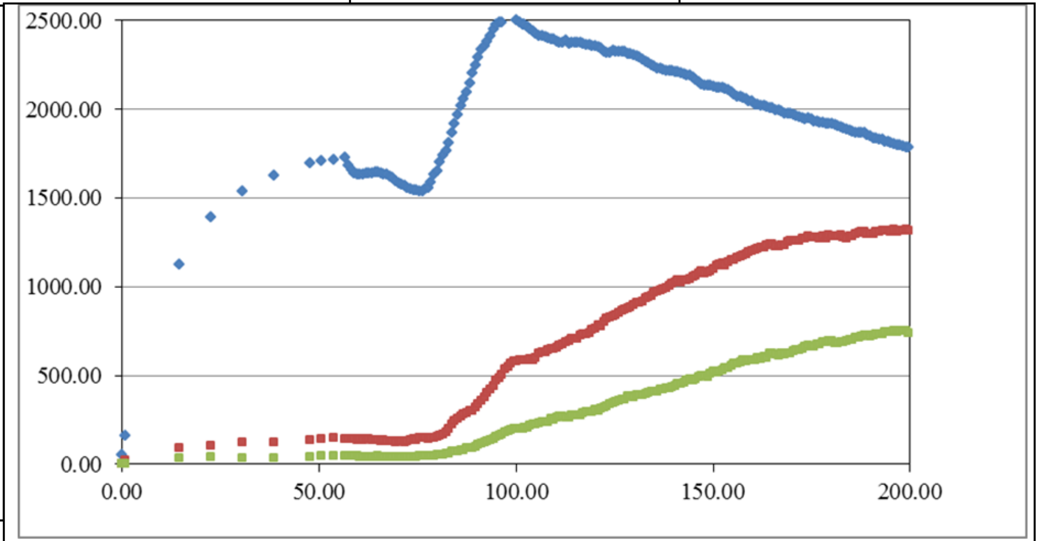
Lattice performance

- 325 MHz FE version has been simulated with ICOOL

Emittances



Muon rate



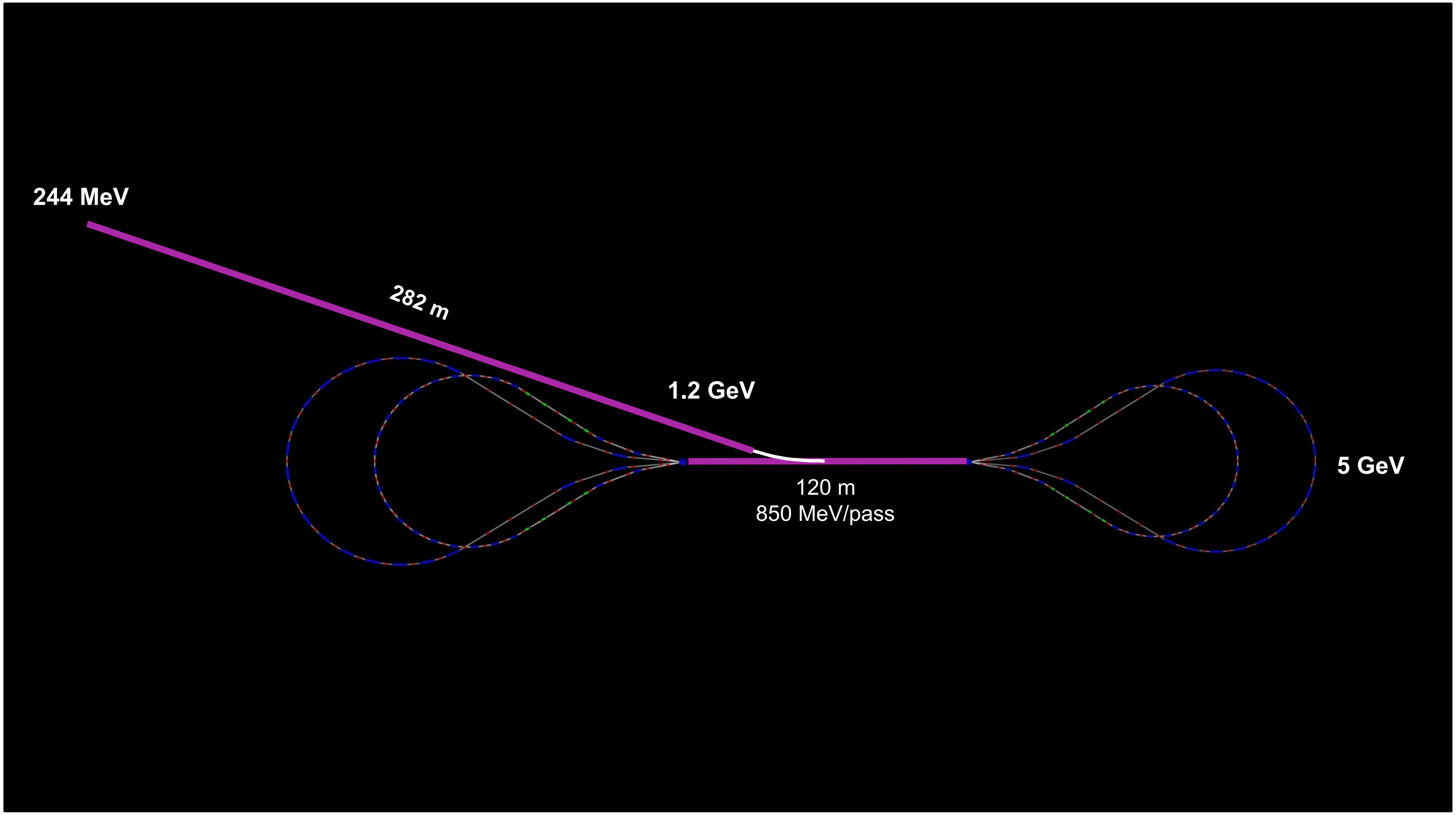
μ per 10,000 p within: 0.15 GeV/c $<P_{mu}<$ 0.35 GeV/c

μ per 10,000 p within: $A_T < 0.03$ m, $A_L < 0.2$ m

μ per 10,000 p within: $A_T < 0.015$ m, $A_L < 0.2$ m

D. Neuffer & C. Yoshikawa, MAP-Note 4355

Linac and RLA to 5 GeV



SRF at 325 MHz – scaling 201 MHz cavity design

$$f_0 = 201 MHz,$$
$$\lambda_0 = 150\ cm,$$
$$E_0^{acc} = 17 MV/m,$$
$$E_0^{peak} = 31.5 MV/m,$$
$$a_0 = 23 cm.$$

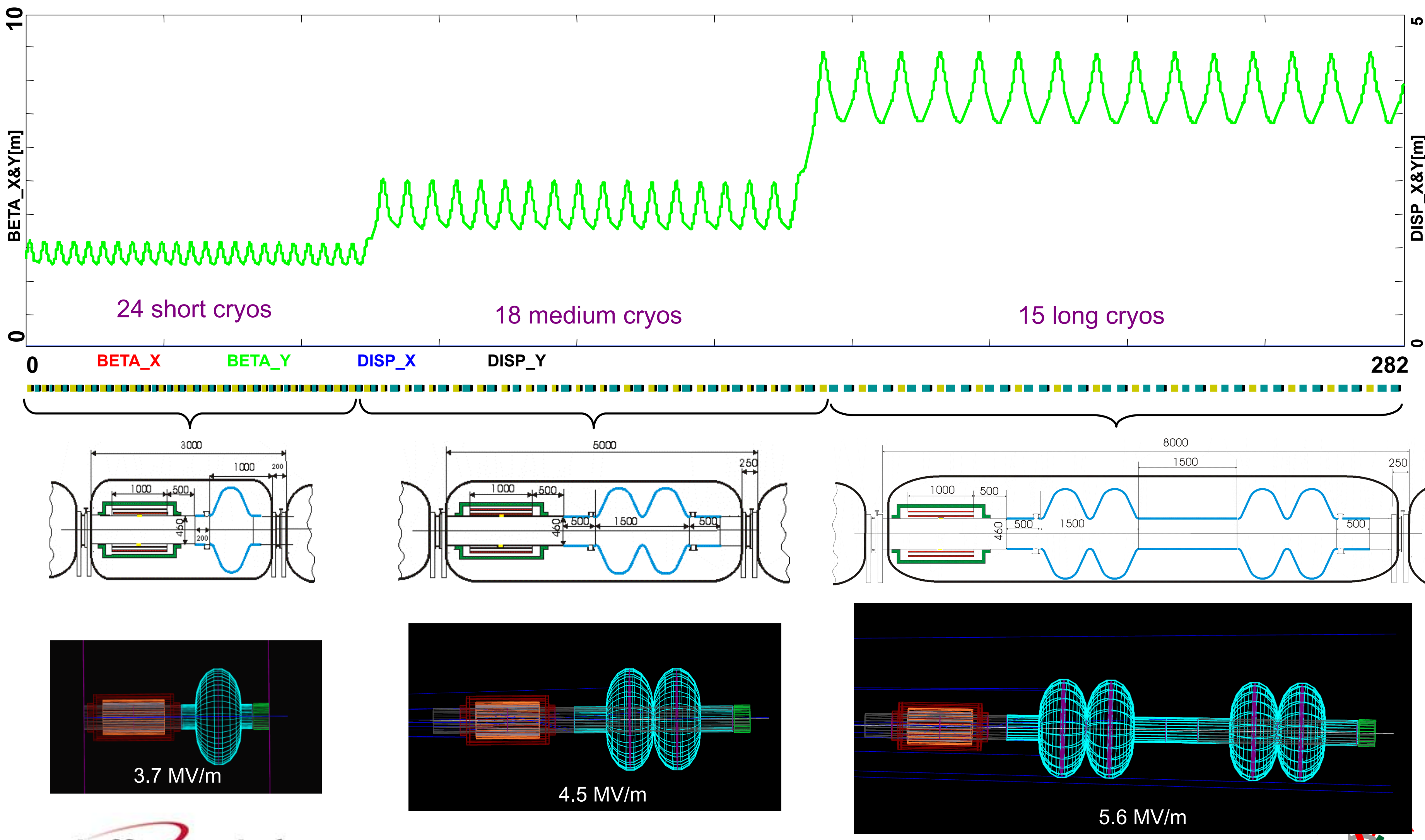
$$f_1 = 325 MHz,$$
$$\lambda_1 = 93\ cm,$$
$$E_1^{acc} = E_0^{acc}\frac{\lambda_0}{\lambda_1} = 27.5 MV/m,$$
$$E_1^{peak} = E_0^{peak}\frac{\lambda_0}{\lambda_1} = 50 MV/m,$$
$$a_1 = a_0\frac{\lambda_1}{\lambda_0} = 14.2 cm.$$

Need a higher gradient from a cavity to obtain the same voltage assuming scaling down of the cavity aperture radius for both frequencies

D. Hartill

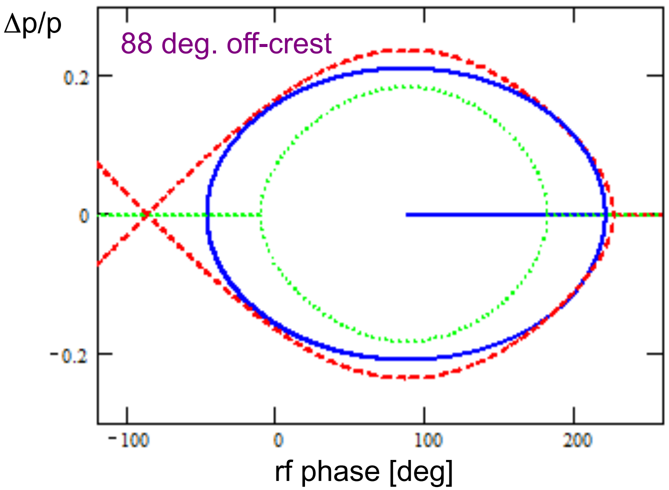
Linac (244 MeV – 1.2 GeV)

15 MV/m, r = 23 cm



Longitudinal acceptance (325 vs 201 MHz)

325 MHz, 25 MeV/m

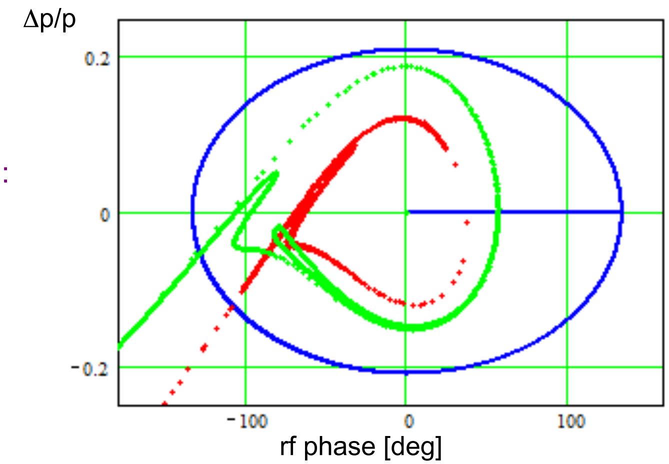


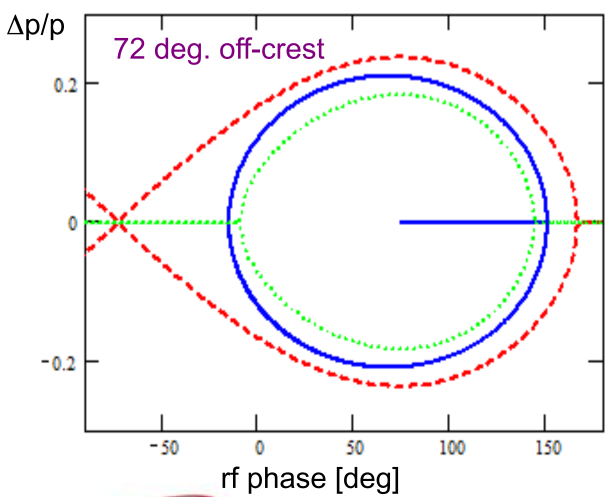
Linac from 244 MeV to 1.2 GeV :

282 meter long

1.25 GV RF installed

dynamic losses limited to less than 2%





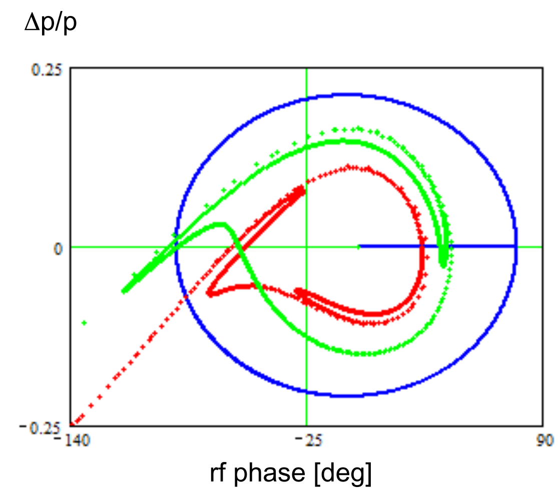
201 MHz, 15 MeV/m

Linac from 244 MeV to 1.2 GeV

268 meter long

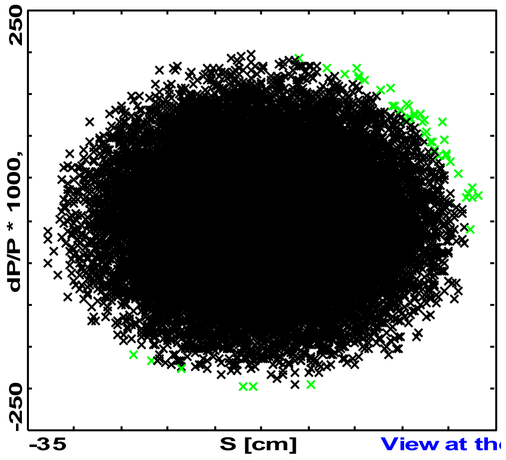
1.15 GV RF installed

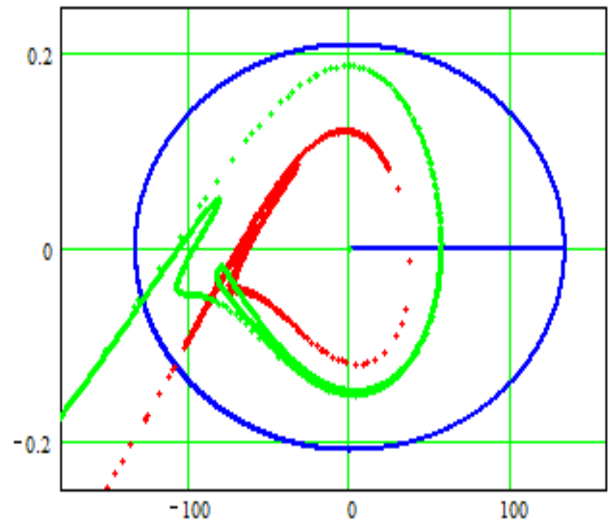
dynamic losses limited to less than 1%

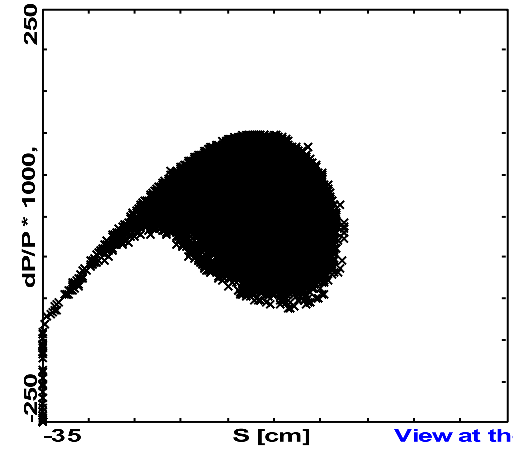


0.244 -1.2 GeV Linac – Transmission

Dynamic Loss: 1.5%

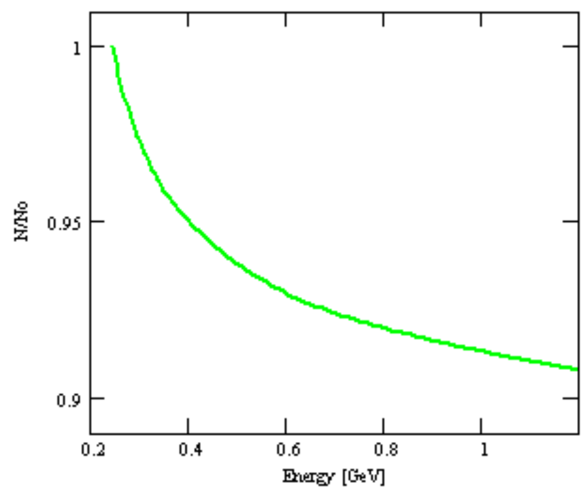






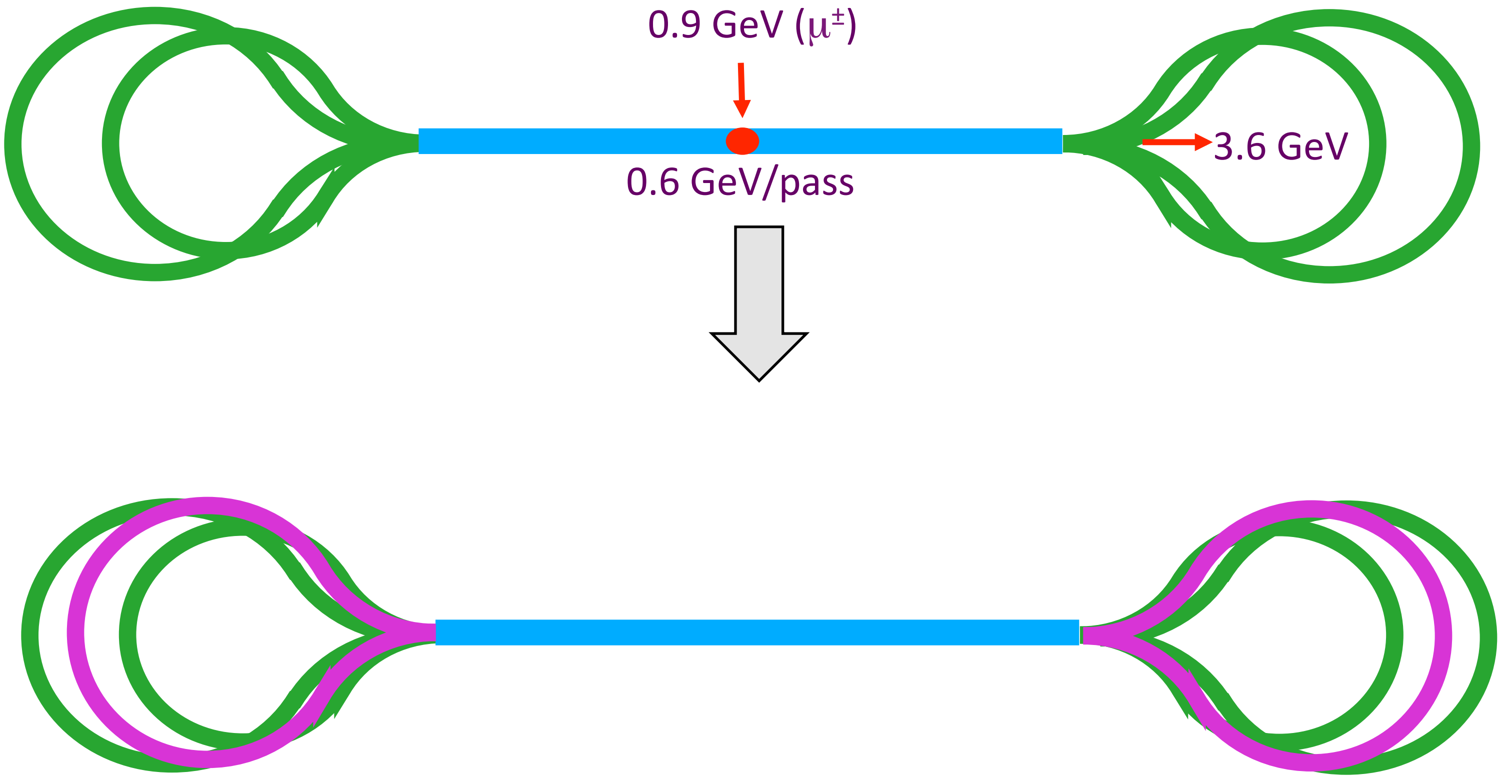
$$\frac{N}{N_0} = e^{-\frac{\tau}{\tau_\mu}}$$

Muon decay: 9%

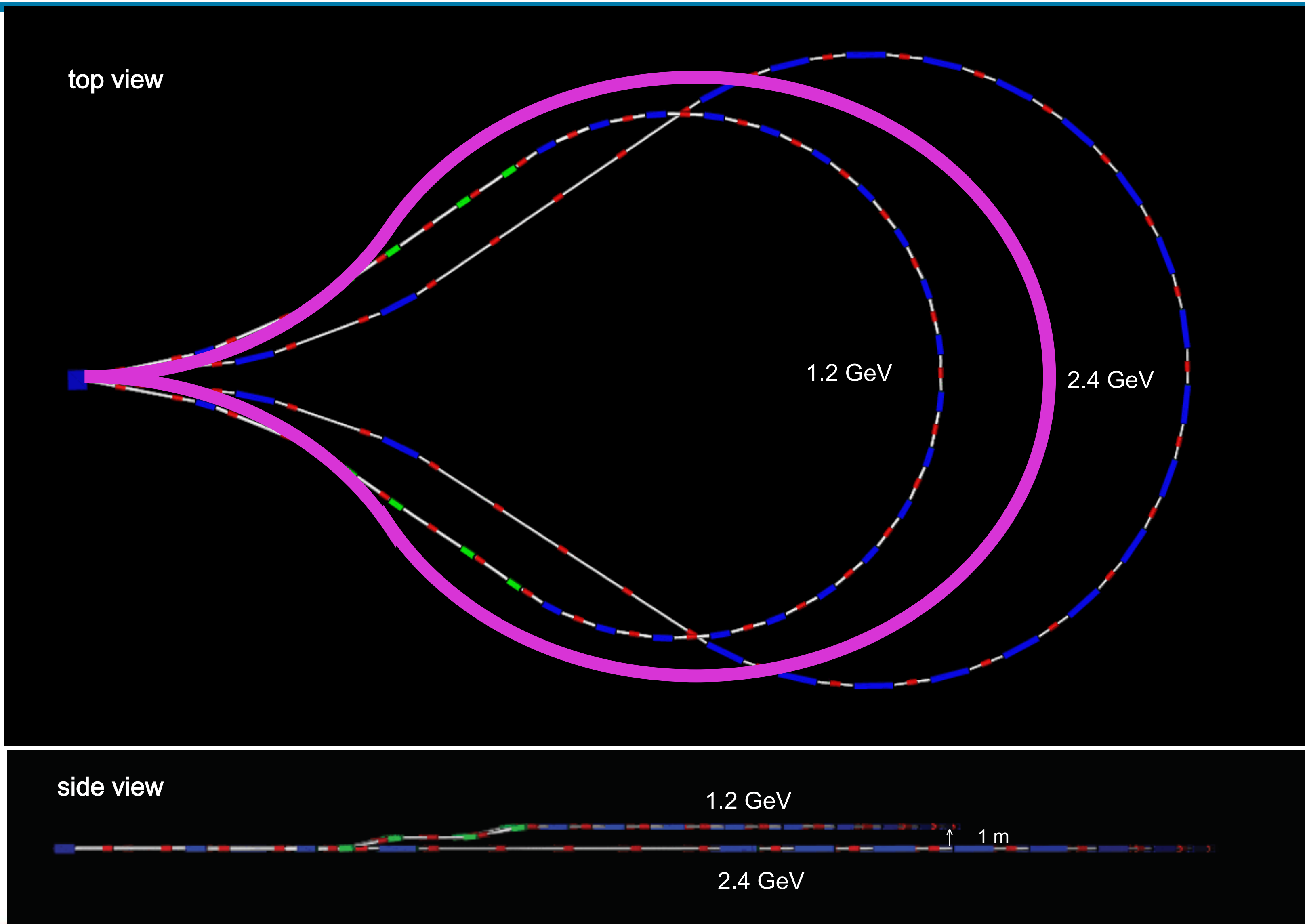


Total loss: 10.5%

Multi-pass Arc Muon RLA

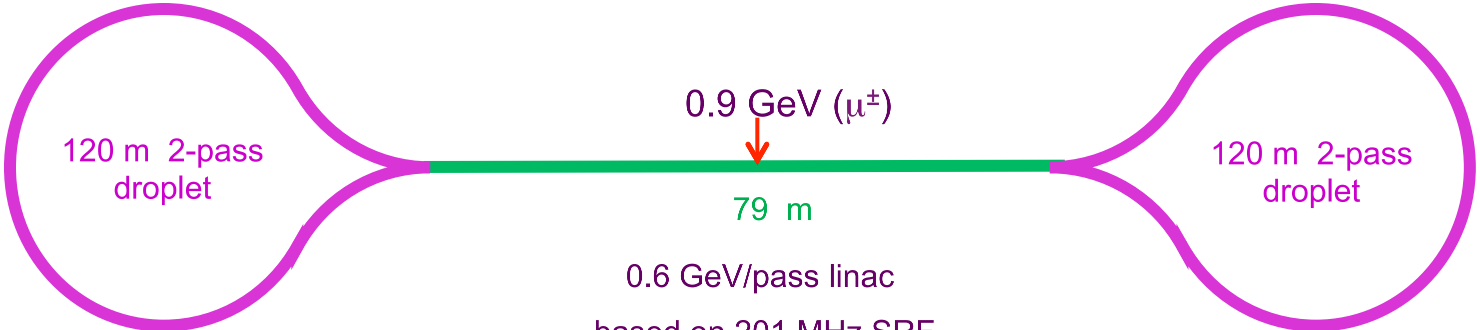


Conventional single-pass droplet arcs



JEMMRLA (Jlab Electron Model of Muon RLA)

Droplet Arcs: 7 (1+5+1) super-periods × 24 combined function magnets



0.6 GeV/pass linac

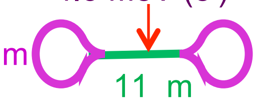
based on 201 MHz SRF

B	2.6 Tesla
G	45 Tesla/m

B	1 .7 Tesla
G	28 Tesla/m

energies reduced by factor of ~**200** (m_μ/m_e)

size reduced by factor of ~**7.5** (1497/201)



B	975 Gauss
G	1275 Gauss/cm

B	638 Gauss
G	825 Gauss/cm

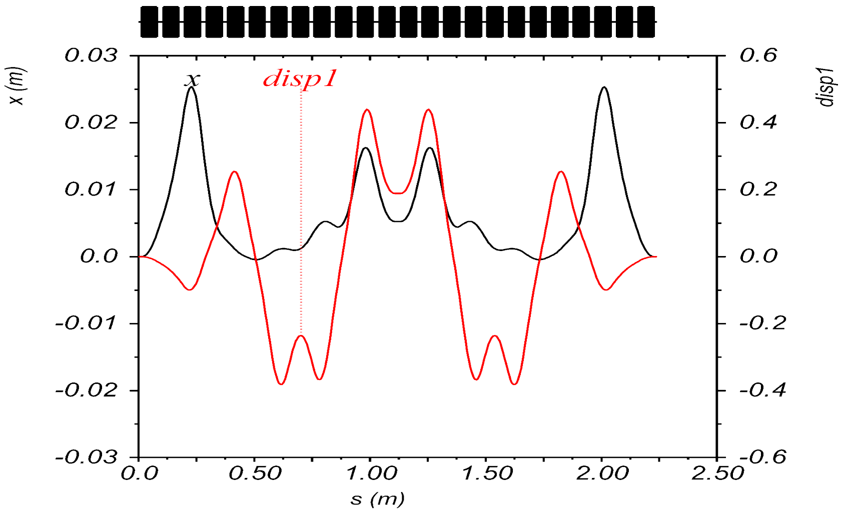
3 MeV/pass linac based

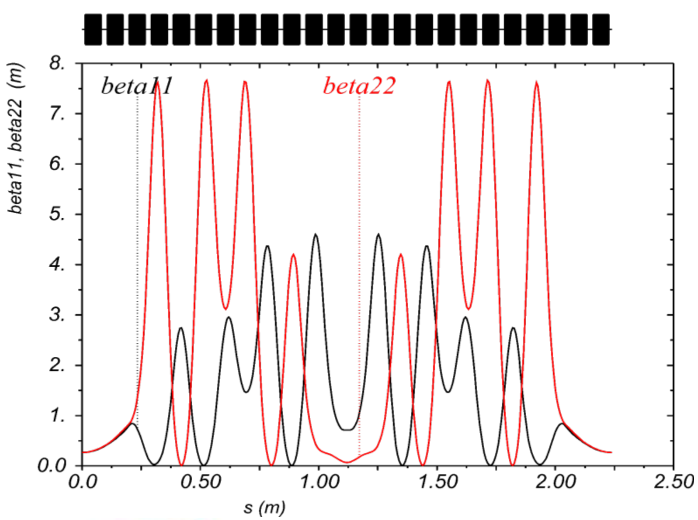
on 1497 MHz SRF

Fits in 25m × 7m

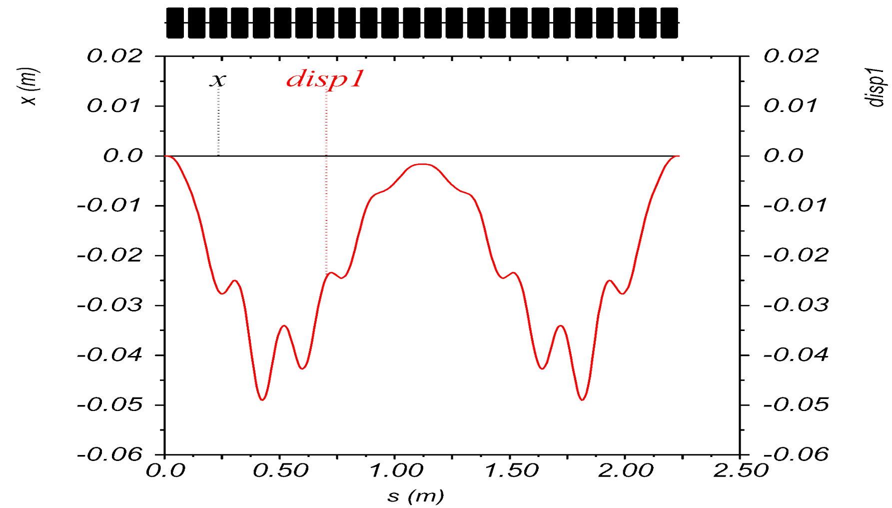
Super-period optics for $P_2 / P_1 = 2$

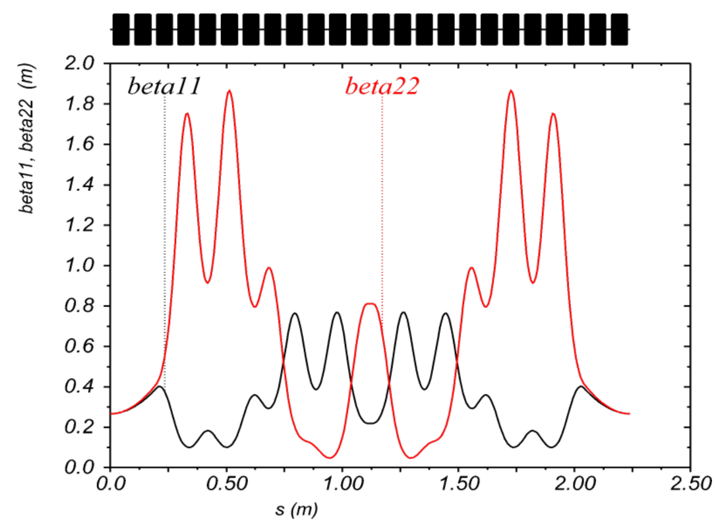
P_1 (6 MeV/c)





P_2 (12 MeV/c)



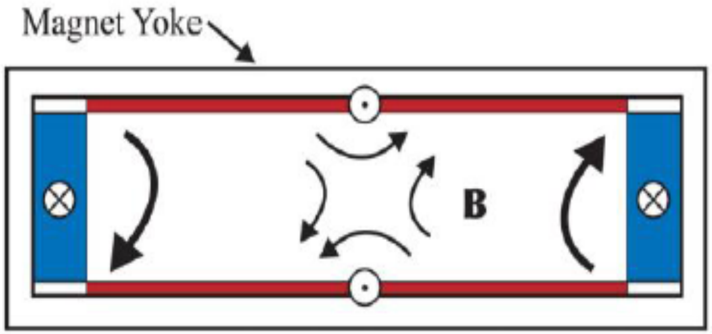


Three-coil Panofsky quad

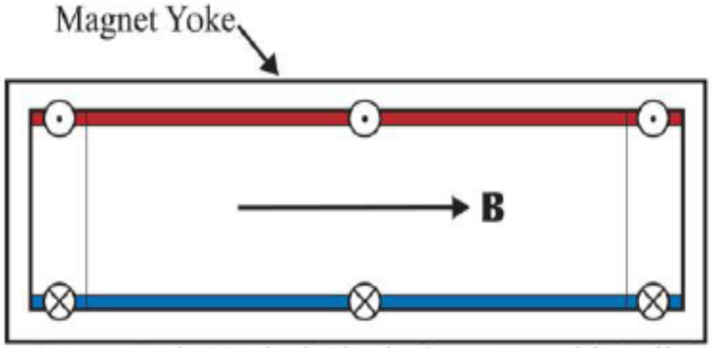
PAC 20007 Proceedings

COMBINED PANOFSKY QUADRUPOLE & CORRECTOR DIPOLE *

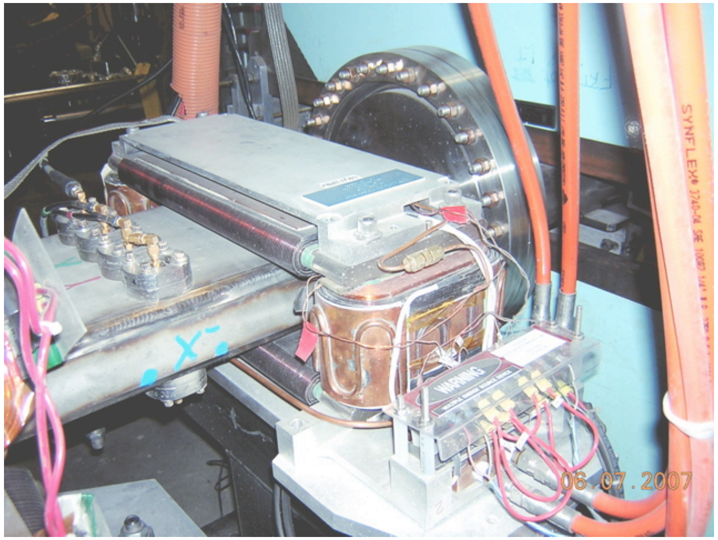
George H. Biallas[#], Nathan Belcher, David Douglas, Tommy Hiatt, Kevin Jordan, Jefferson Lab,



Rectangular Panofsky Quadrupole with Coil Currents
(Looking Downstream, Focusing Electrons)

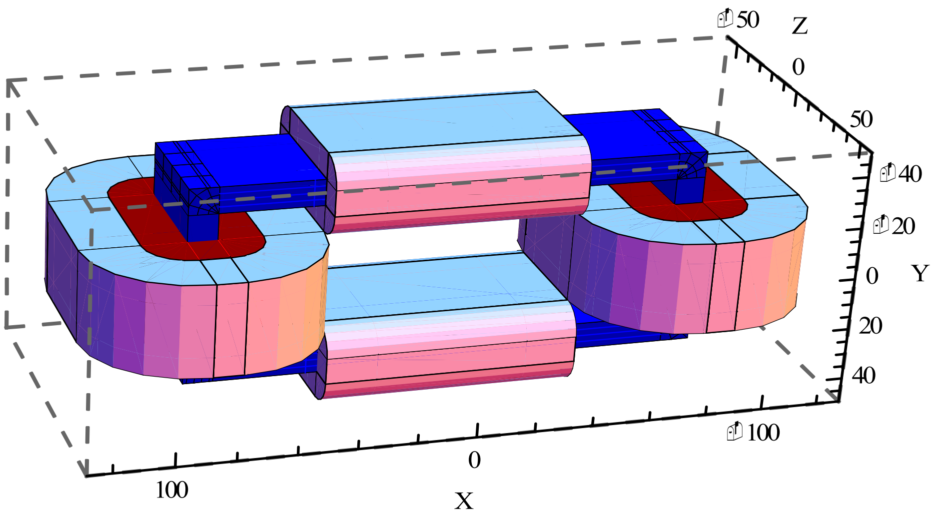


Window Frame Style Vertical Dipole Corrector with Coil Currents
(Looking Downstream, Bending Electrons Up)

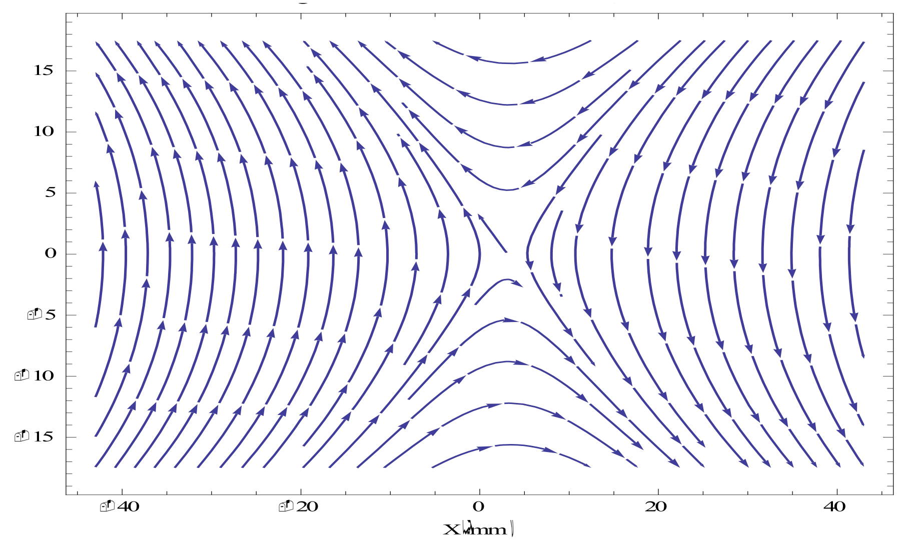


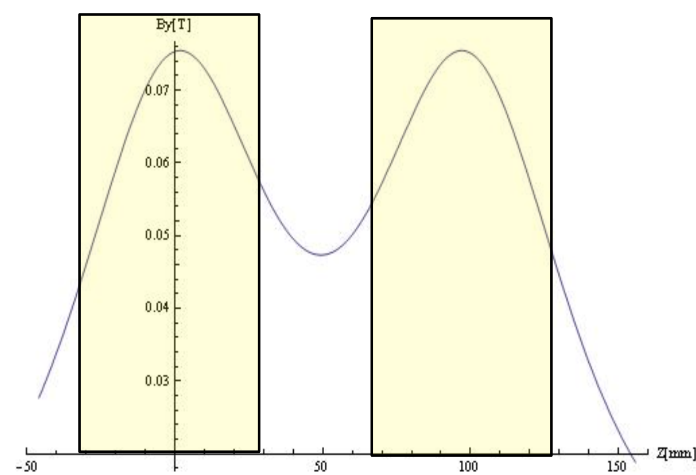
Preliminary magnet modeling

Radia (ESRF)



Field affected by neighboring magnets





TOSCA will be used for detailed studies and generation of field maps

R. Roussel

Conclusions

- Wrap-up of IDS-NF (10 GeV)
  - RDR is being written….
- Next MASS NF Scenario (5 GeV)
  - Based on 325 MHz SRF
  - R&D on rapid acceleration
  - Launch a new international study?