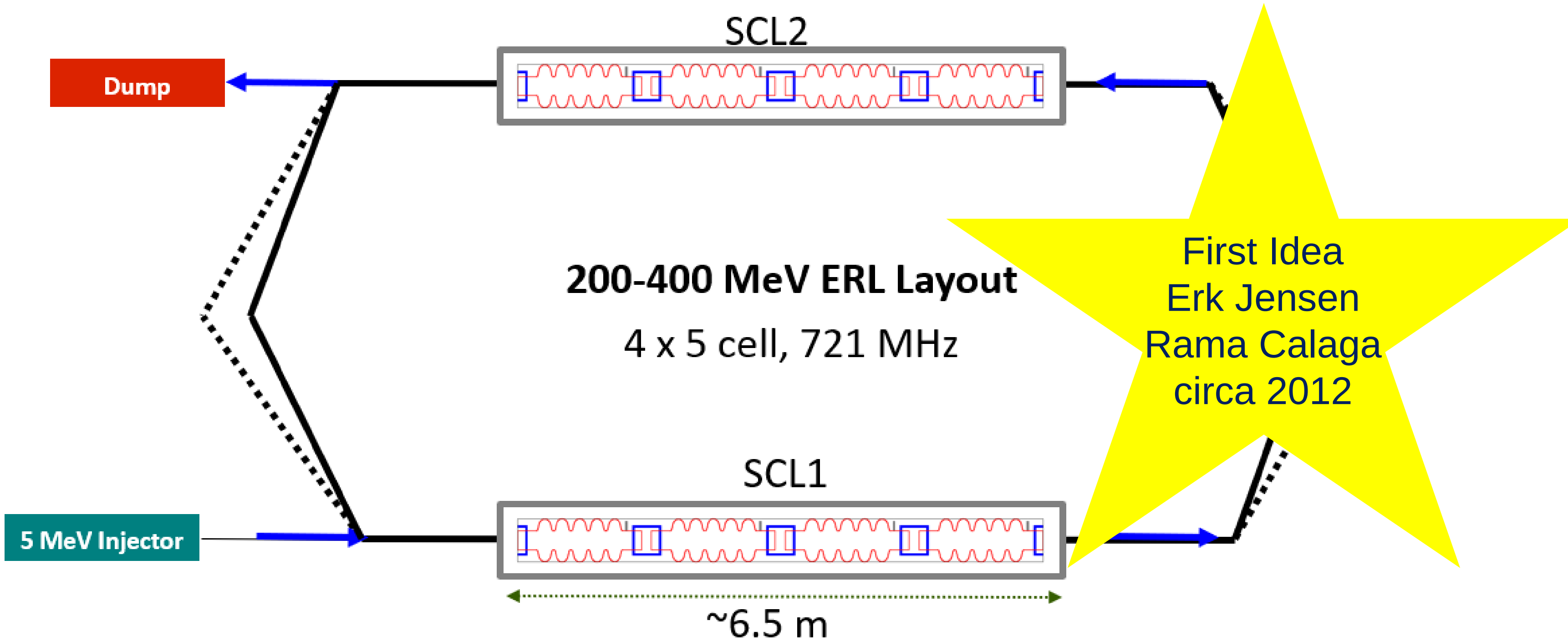
500 MeV PERLE – Lattice Design and Beam Dynamics

Alex Bogacz

Outline

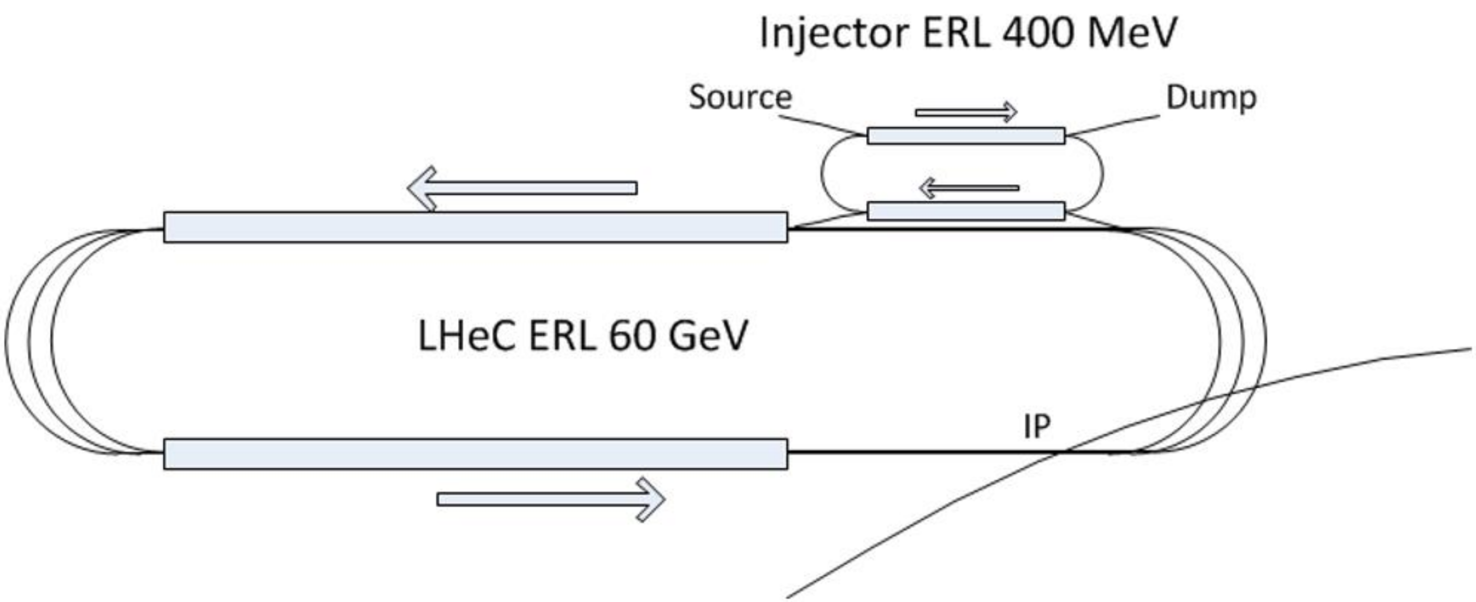
- Historic perspective on PERLE (2012 – 2023)
- PERLE – Baseline Design (500 MeV): Layout, Optics, Lattices
  - Multi-pass linac Optics in ER mode (3 passes 'up' + 3 passes 'down')
    - Configured with the SPL style cryomodules
    - Quad doublet after the merger – 'splitting' initial Twiss functions in both planes
  - Switchyard Configuration
    - Compact 'two step' Spr/Rec with two B-com magnets
  - Experimental Areas – Low-β inserts in both matching straights of Arc 6
    - Tunable 2.7 meter long IR configured with a triplet – doublet pair
  - Arc Optics Architecture
    - 'Six bend' arc configuration – better balanced M_{56} across the arc (vs 'Four bend' arc)
    - Arc pathlengths compatible with 25 nsec injection – uniform bunch 'filling pattern'
  - Beam Dynamics Studies
- Summary and Outlook



	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep rate		CW	CW

Could the TF later become the LHeC ERL injector ERL?

Erk Jensen

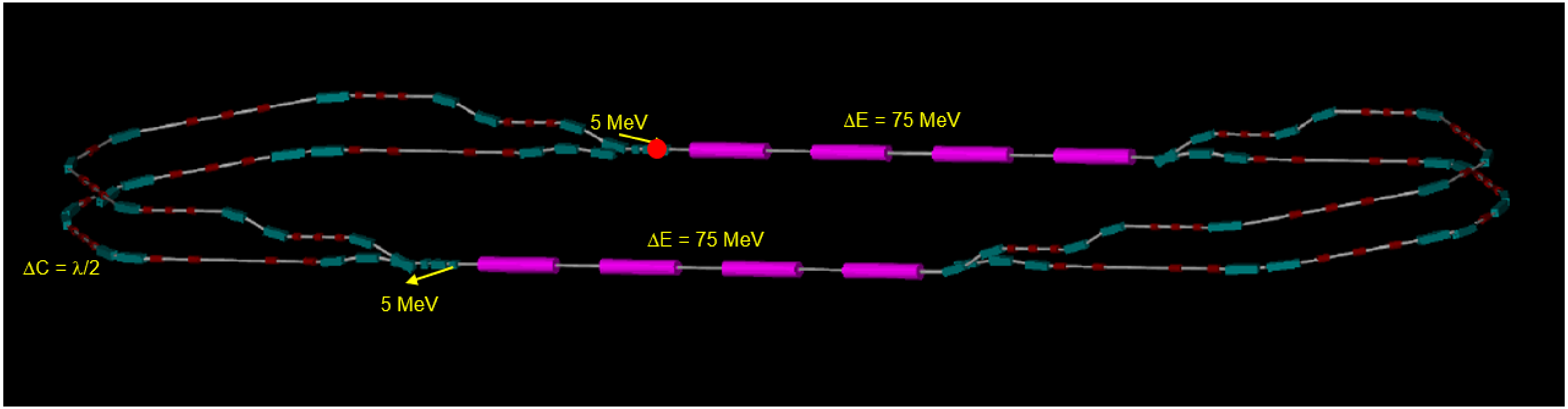


very preliminary – just an idea right now

ERL-TF (300 MeV) – Layout

Thanks, Alex (received this morning)!

Alex Bogacz



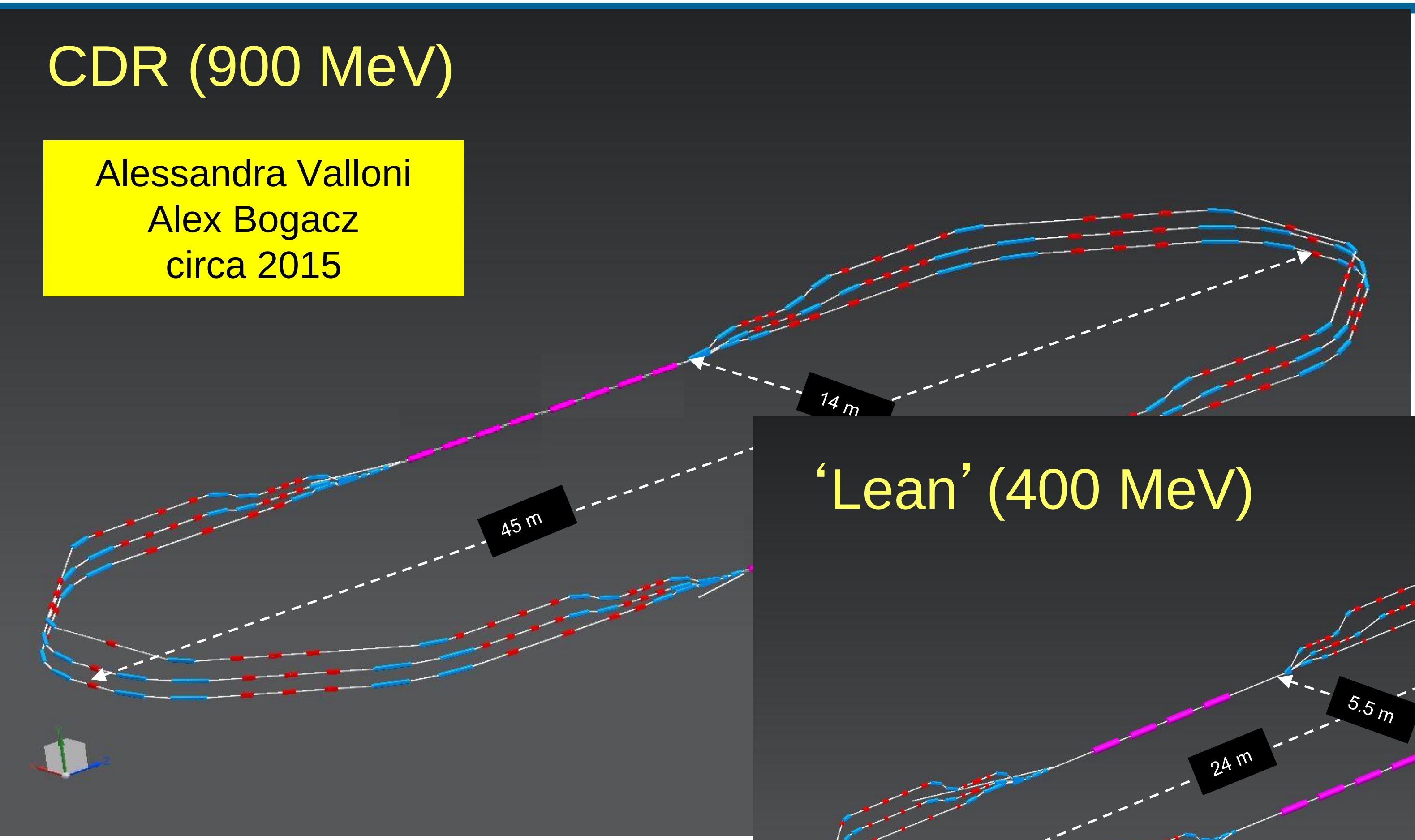
Two passes 'up' + Two passes 'down'

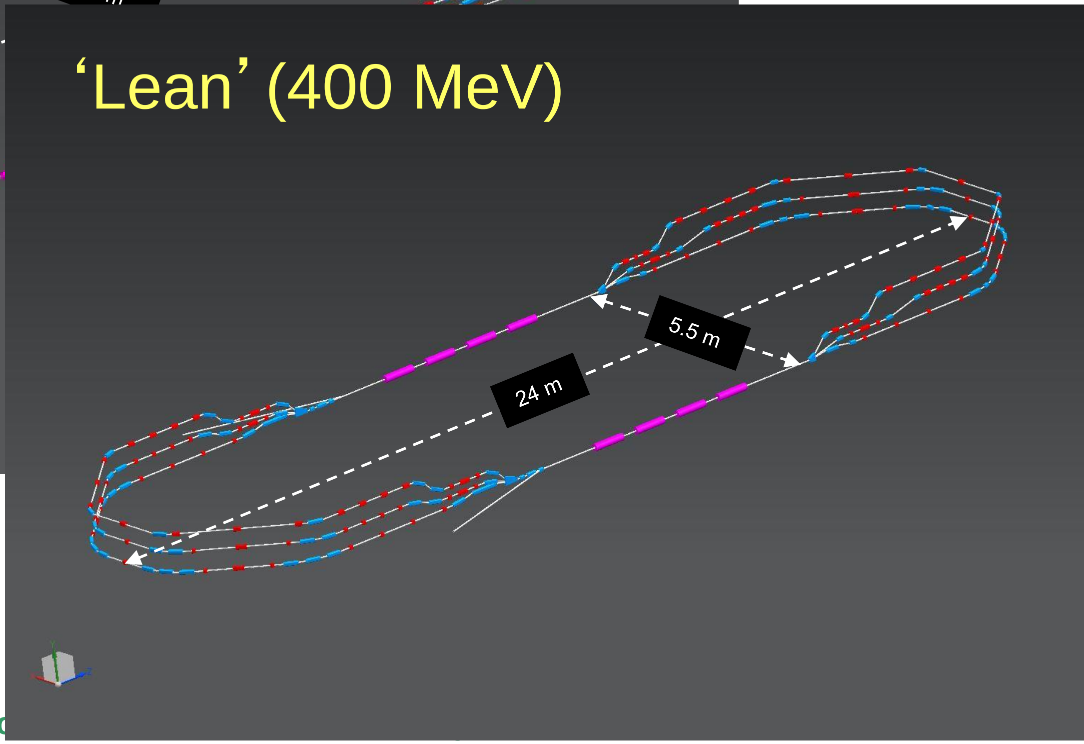
The name *PERLE*

Erk Jensen

- ***P**owerfull **ERL** for **E**xperiments*
- We think the name sounds nice…
- … and in Italian it means “string of pearls”

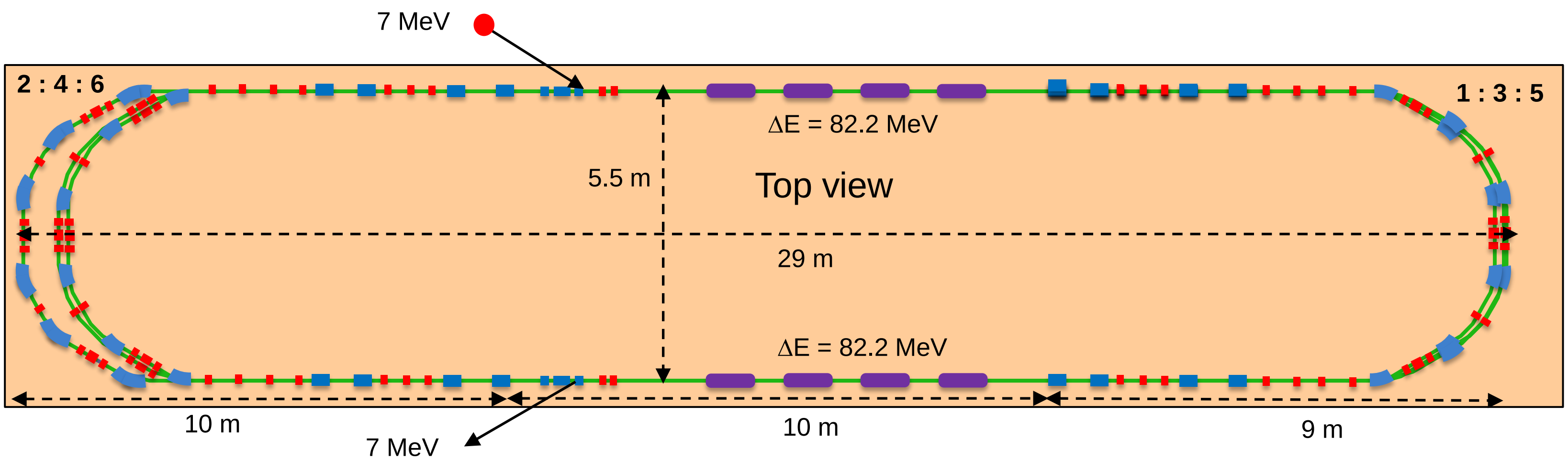
900 MeV PERLE… Downsizing

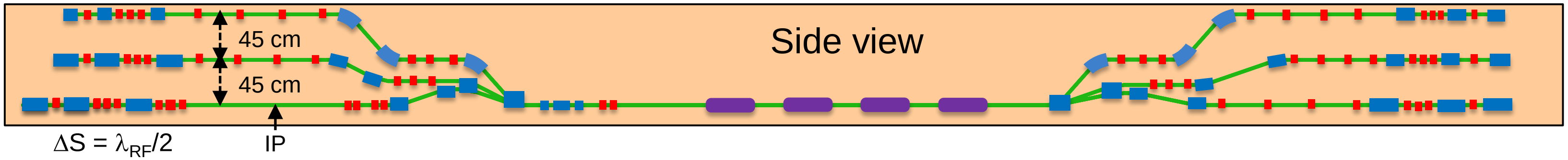




PERLE 2.0 (500 MeV) – Baseline Layout

Footprint: 29 m × 5.5 m × 0.9 m

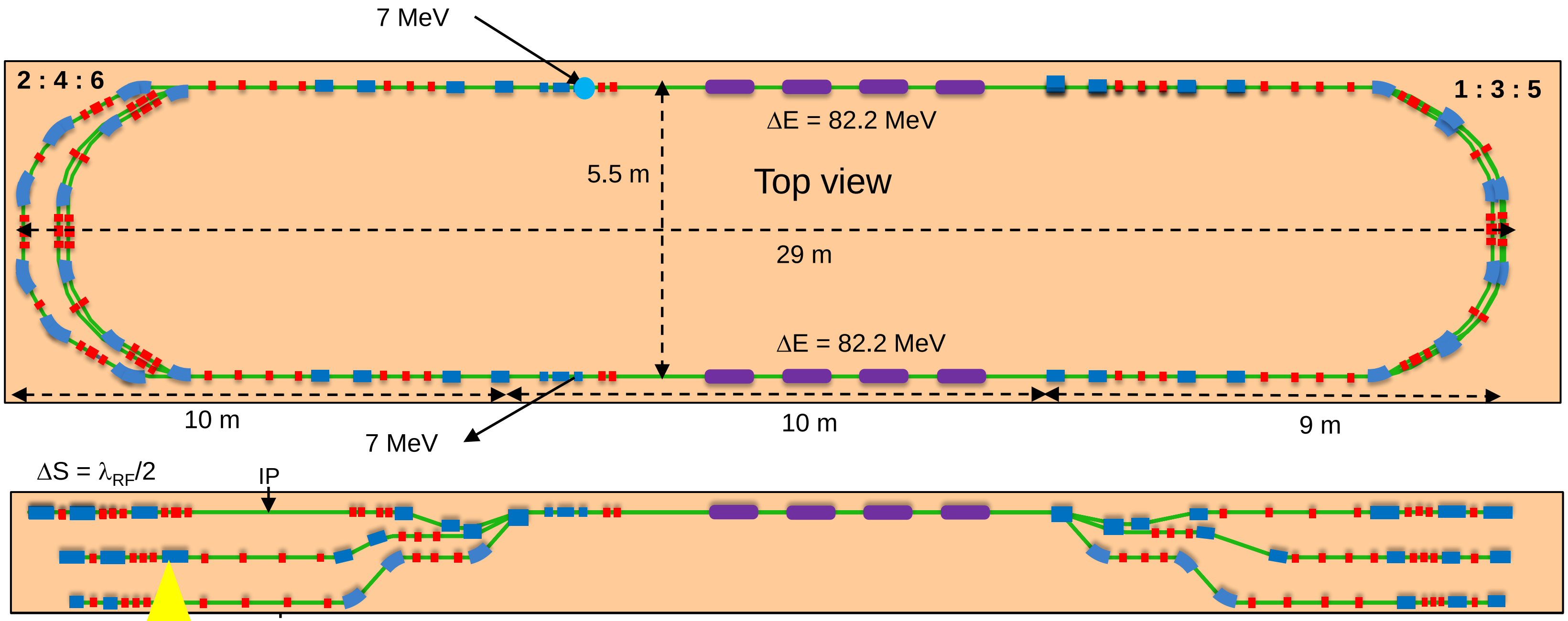




Target parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Norm. emittance $\gamma\epsilon_{x,y}$	mm·mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.6
Duty factor		CW

PERLE 2.0 (500 MeV) – Baseline Layout

Footprint: 29 m × 5.5 m × 0.9 m

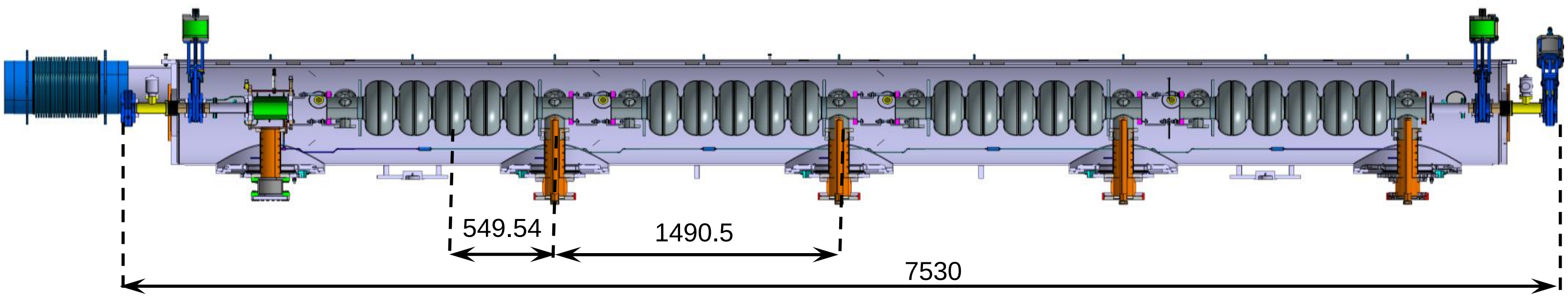


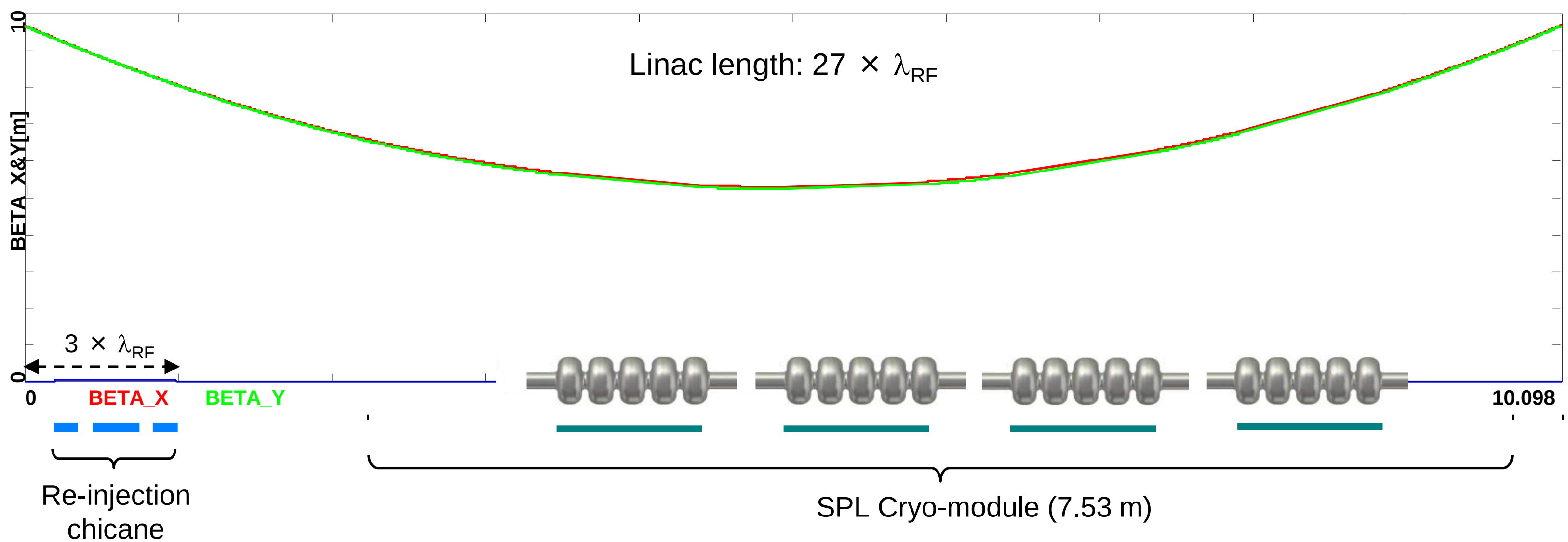
Inverting Vertical Stack Alex Fomin

Final Energy [MeV]	500
Geometric Arc Radius [m]	2.75
ρ [m]	0.62/1.24
Total Energy Loss [MeV]	6.E-03
Net Normailzed Emittance Dilution [mm mrad]	1.E-04
Net Natural Momentum Spread	5.E-06

Linac, Cryo-module – Layout

PERLE cavity string inside the SPL cryomodule





Linac, Cryo-module – Layout

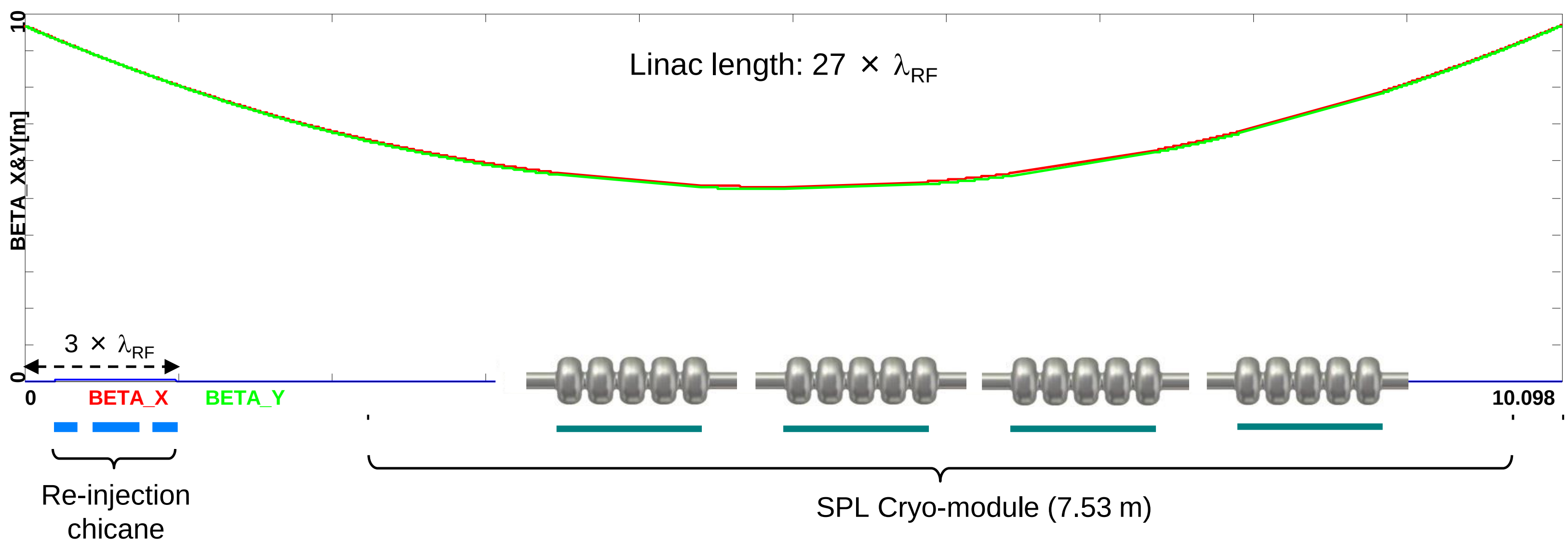
801.58 MHz RF, 5-cell cavity**:**

λ_{RF} = 37.40 cm

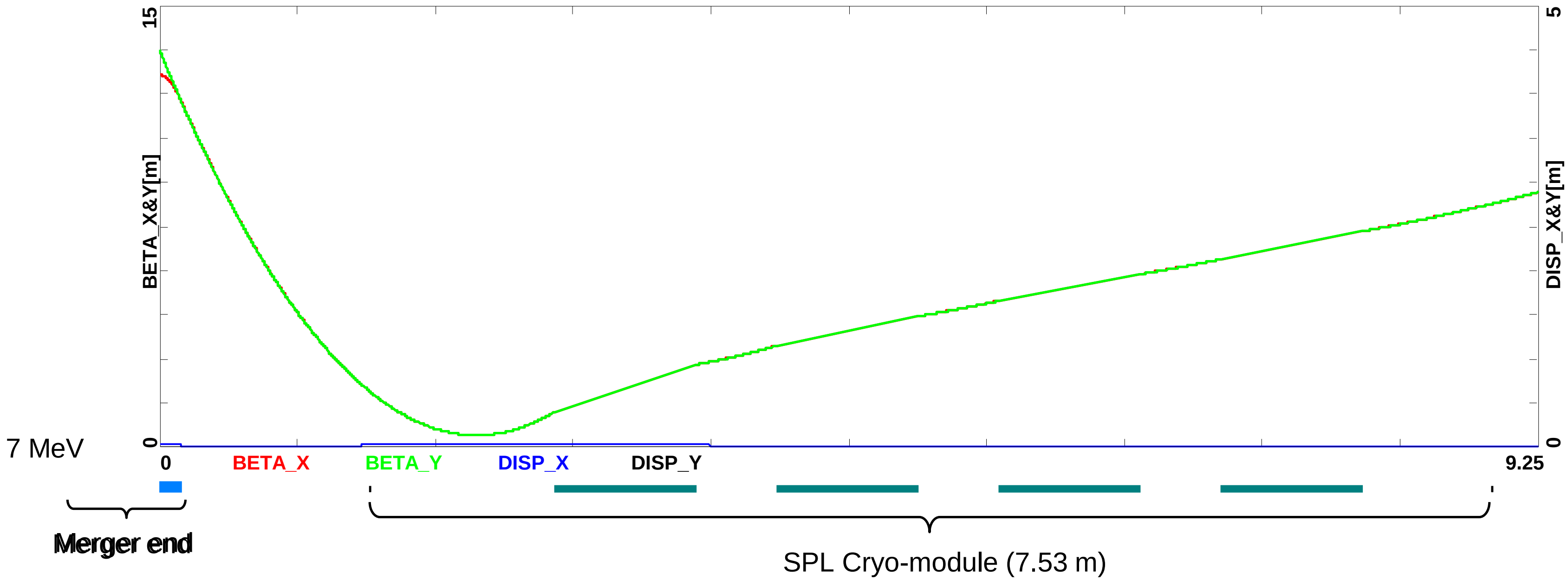
$L_c = 5\lambda_{RF}/2 = 93.50$ cm

Grad = 22 MeV/m (20.5 MeV per cavity)

ΔE= 82.2 MeV per Cryo-module



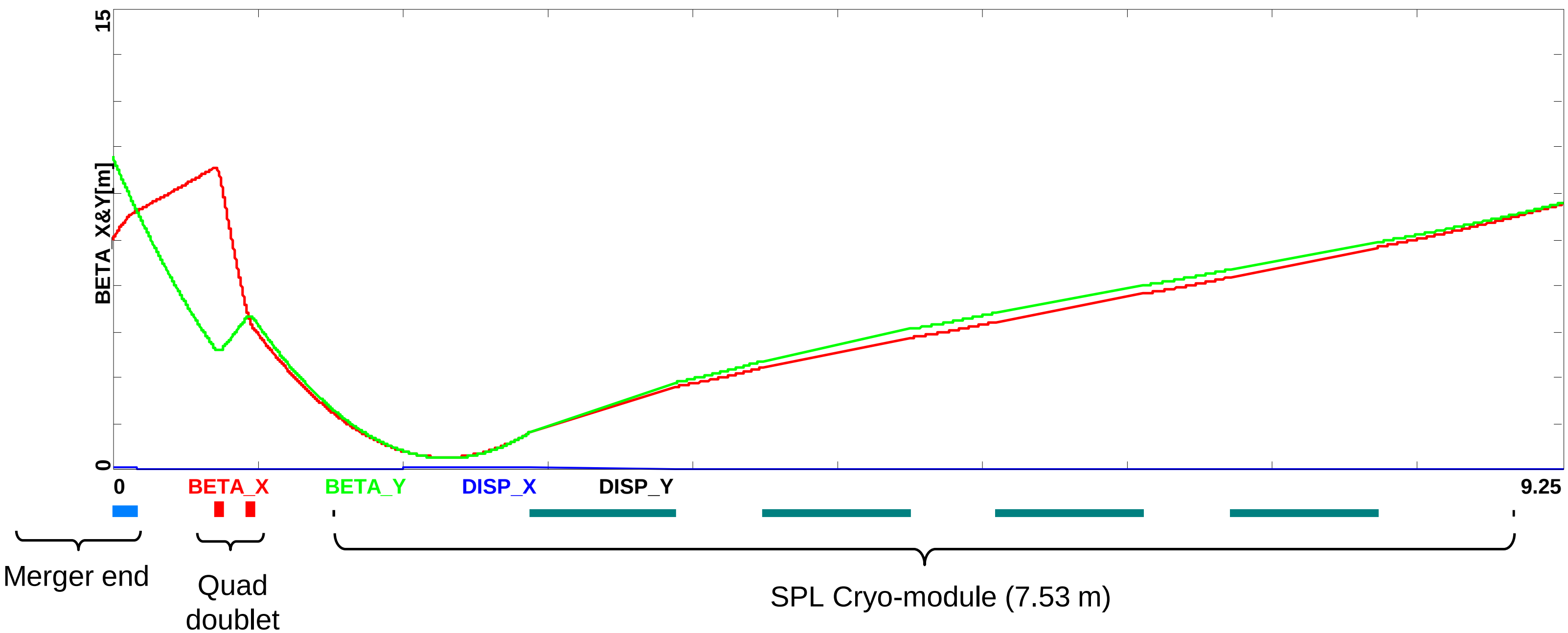
Linac 1-st pass, Tunability



Initial Twiss: BetaX[cm] = 1170
BetaY[cm] = 1170

AlfaX = 5.74
AlfaY = 5.74

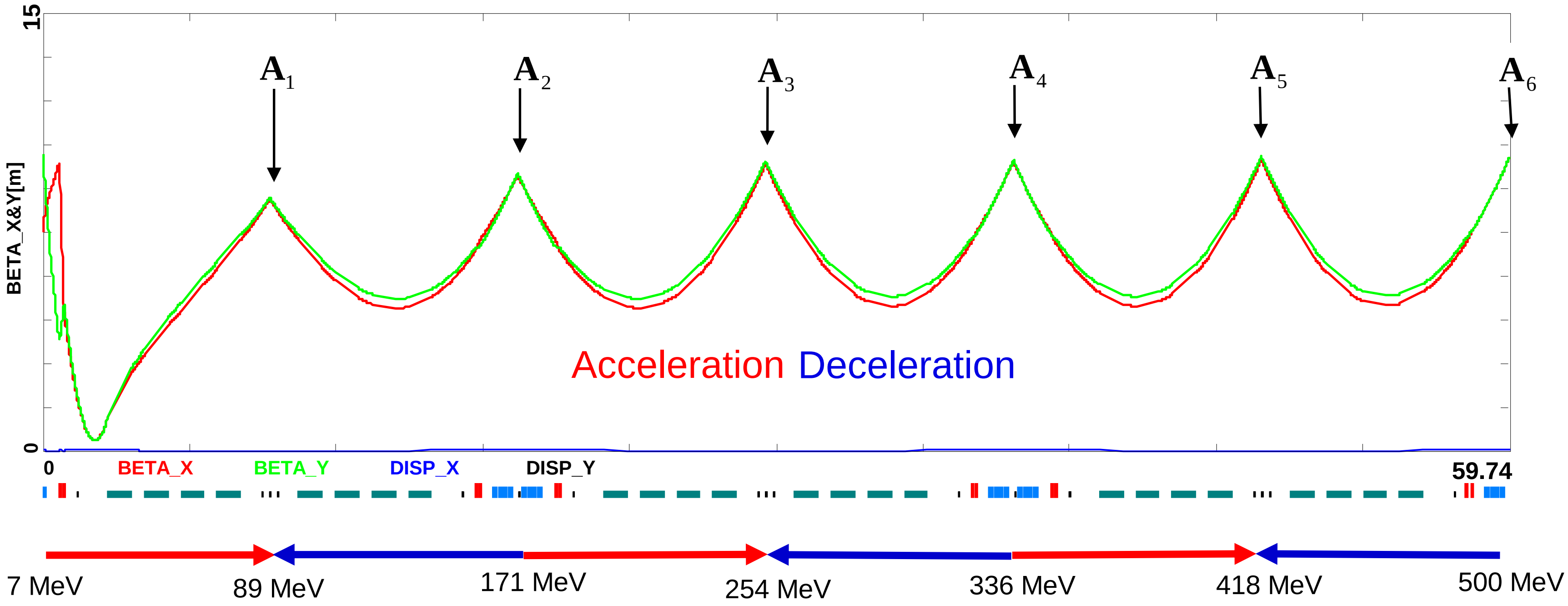
Linac 1-st pass, Tunability



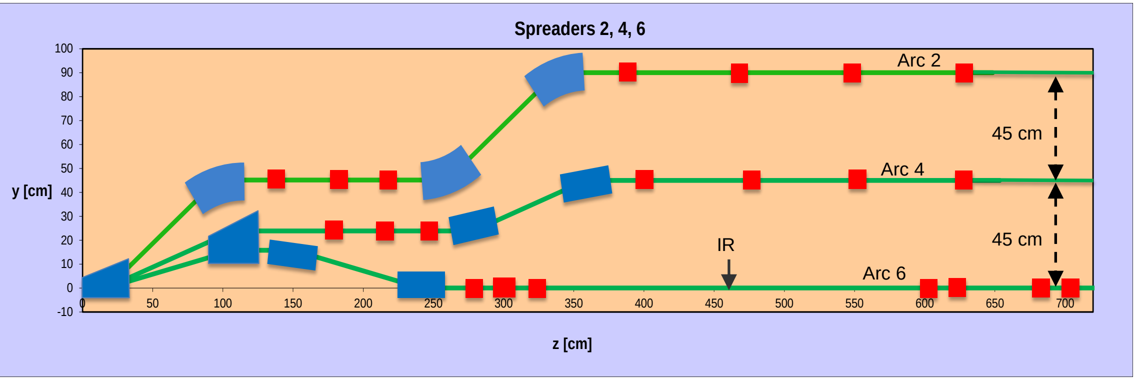
QL1F	L[cm] = 5	G[kG/cm] = 0.080
QL1D	L[cm] = 5	G[kG/cm] = -0.068

Initial Twiss: BetaX[cm] = 744
BetaY[cm] = 1016
AlfaX = -1.29
AlfaY = 1.25

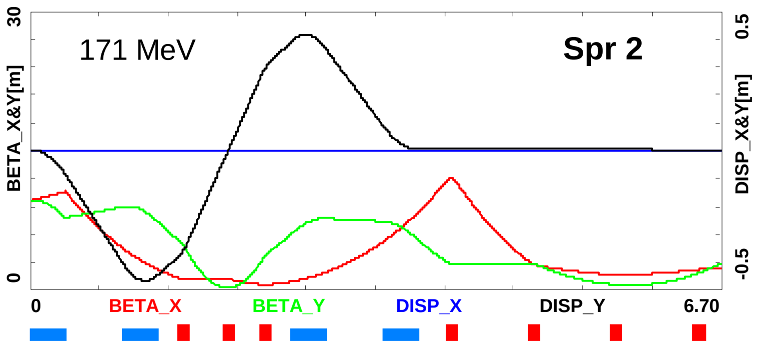
Multi-pass ER Optics

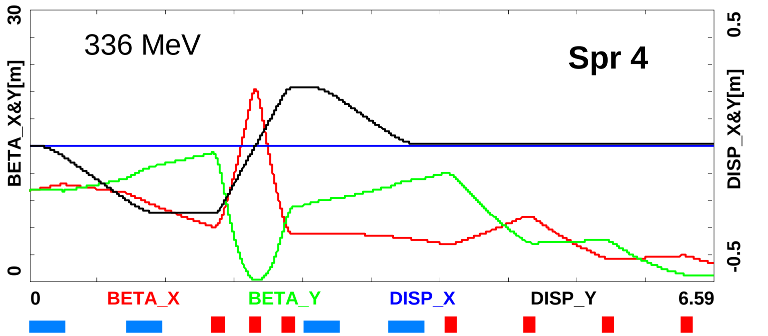


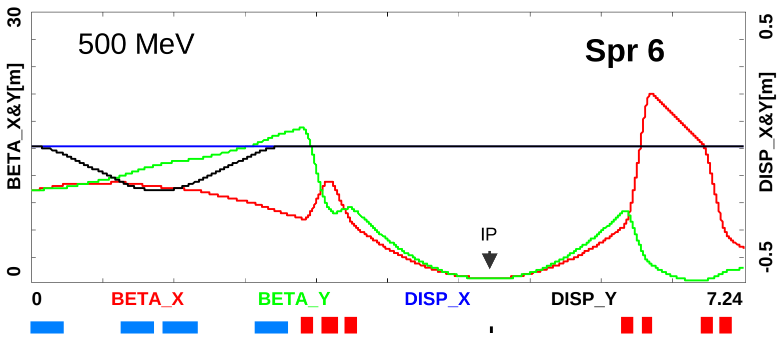
Switchyard Layout with Two B-coms



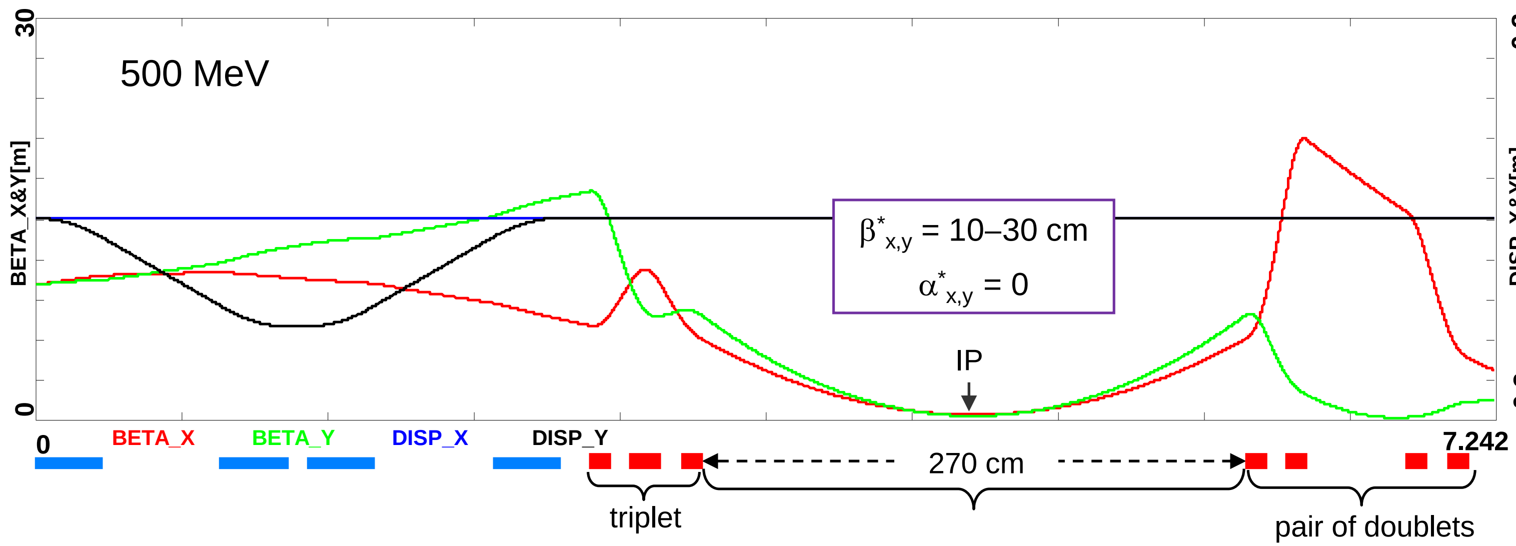
L [cm]	B [kG]	Bend Ang [deg]
33	9.0	30







Experimental Area – Tunable Low-β Squeeze

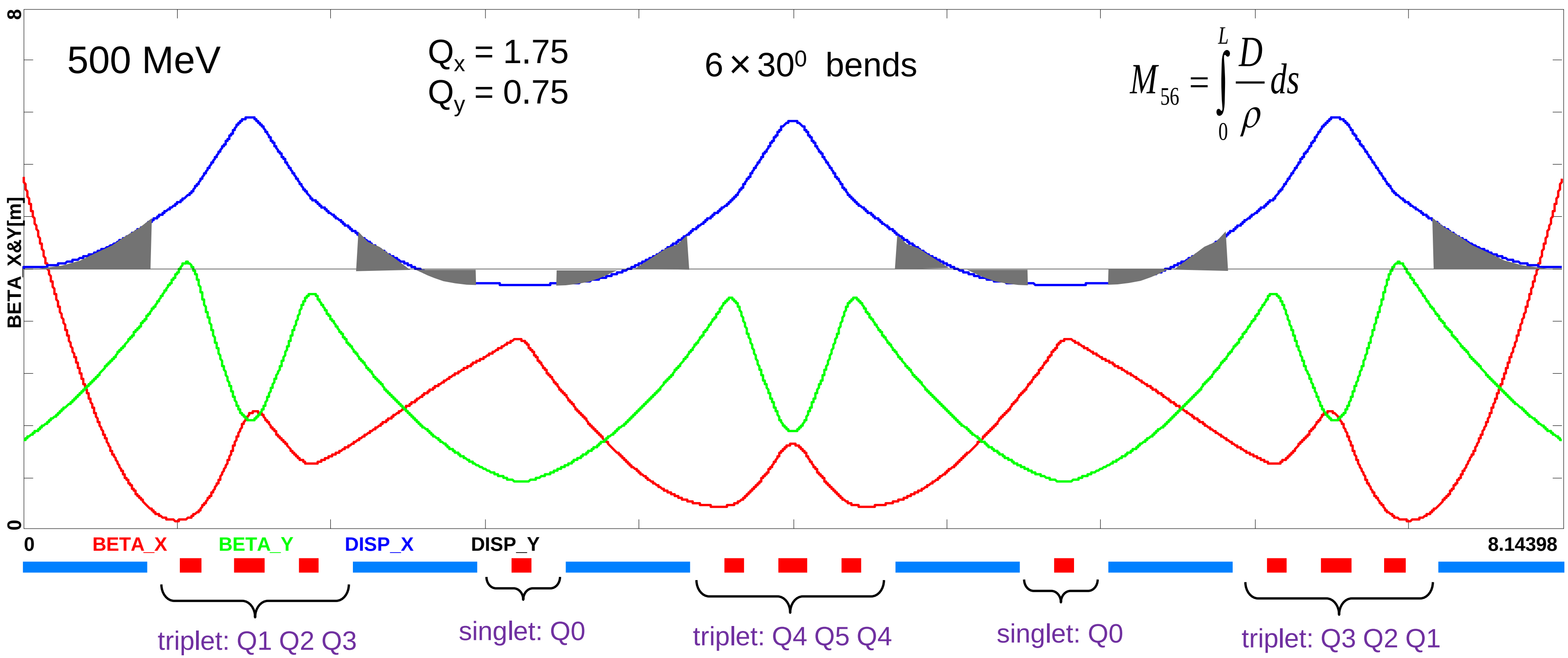


Triplet	L[cm]	G[kG/cm]
Q6S04A	10	-2.81
Q6S04B	15	2.77
Q6S04C	10	-1.64

Doublets	L[cm]	G[kG/cm]
Q6S05	10	-5.49
Q6S06	10	4.44
Q6S07	10	3.09
Q6S08	10	-4.62

- Present design EA: 2.7 meter long
- EA length may be increased in increments of $7/2 \times \lambda_{RF}$ = 131 cm

Arc 6 (5,4) Optics – 'Six-Bend' Lattice



Dipoles: (66 cm long)

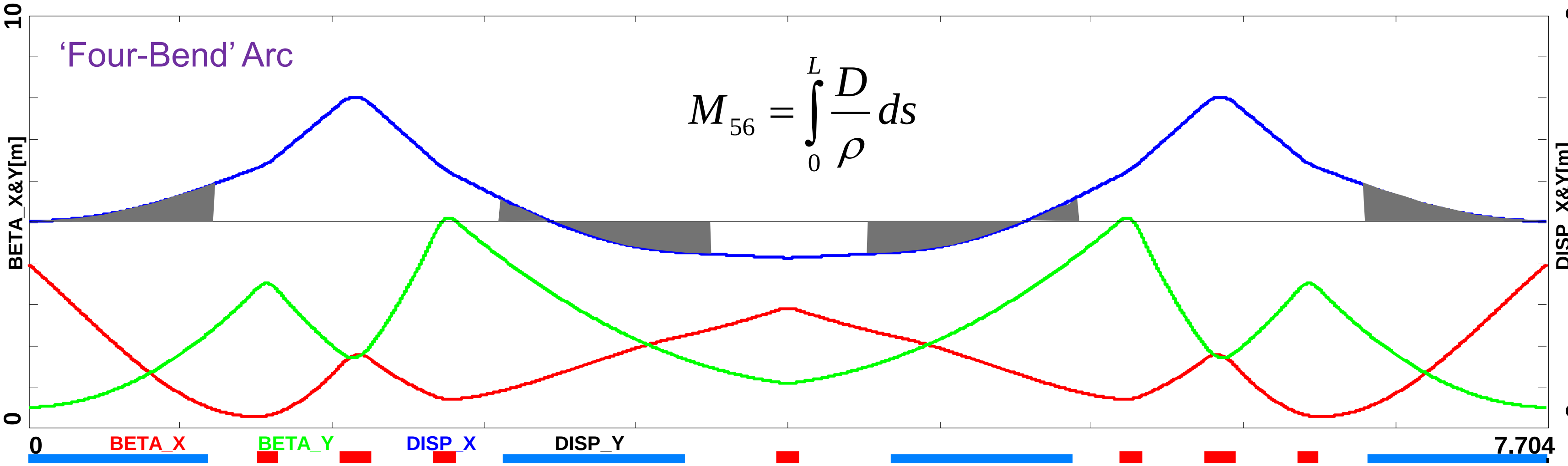
B = 1.3 Tesla

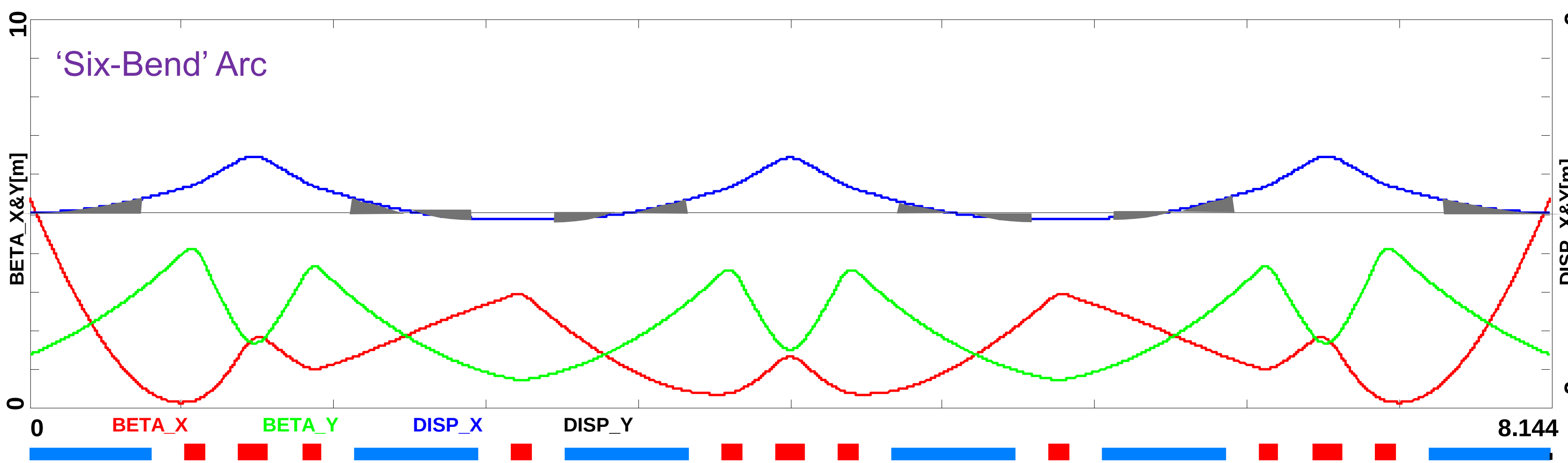
(1.1 Tesla, 0.9 Tesla)

Quadrupoles:

Q0	L[cm] =10	G[kG/cm] = 2.117
Q1	L[cm] = 10	G[kG/cm] = -3.259
Q2	L[cm] = 15	G[kG/cm] = 4.300
Q3	L[cm] = 10	G[kG/cm] = -3.253
Q4	L[cm] = 10	G[kG/cm] = -3.405
Q5	L[cm] = 15	G[kG/cm] = 4.415

M_{56} Variance Across Arcs





'Six-Bend' vs 'Four-Bend' Arc Architecture

PERLE

- Optics more resilient to CSR (micro bunching)
  - Larger number of periods (3 vs 2) – Smaller M_{56} variance.
  - Lattices with smaller variation in M_{56} generate lower CSR gain*, ideally, lattices that are composed of multiple super-periods, each period being achromatic and isochronous.
- Smaller bend angle of individual dipoles (30^0 vs 45^0)
  - Alleviates strong edge focusing effects of the bends
  - Results in a better balanced optics with smaller alphas

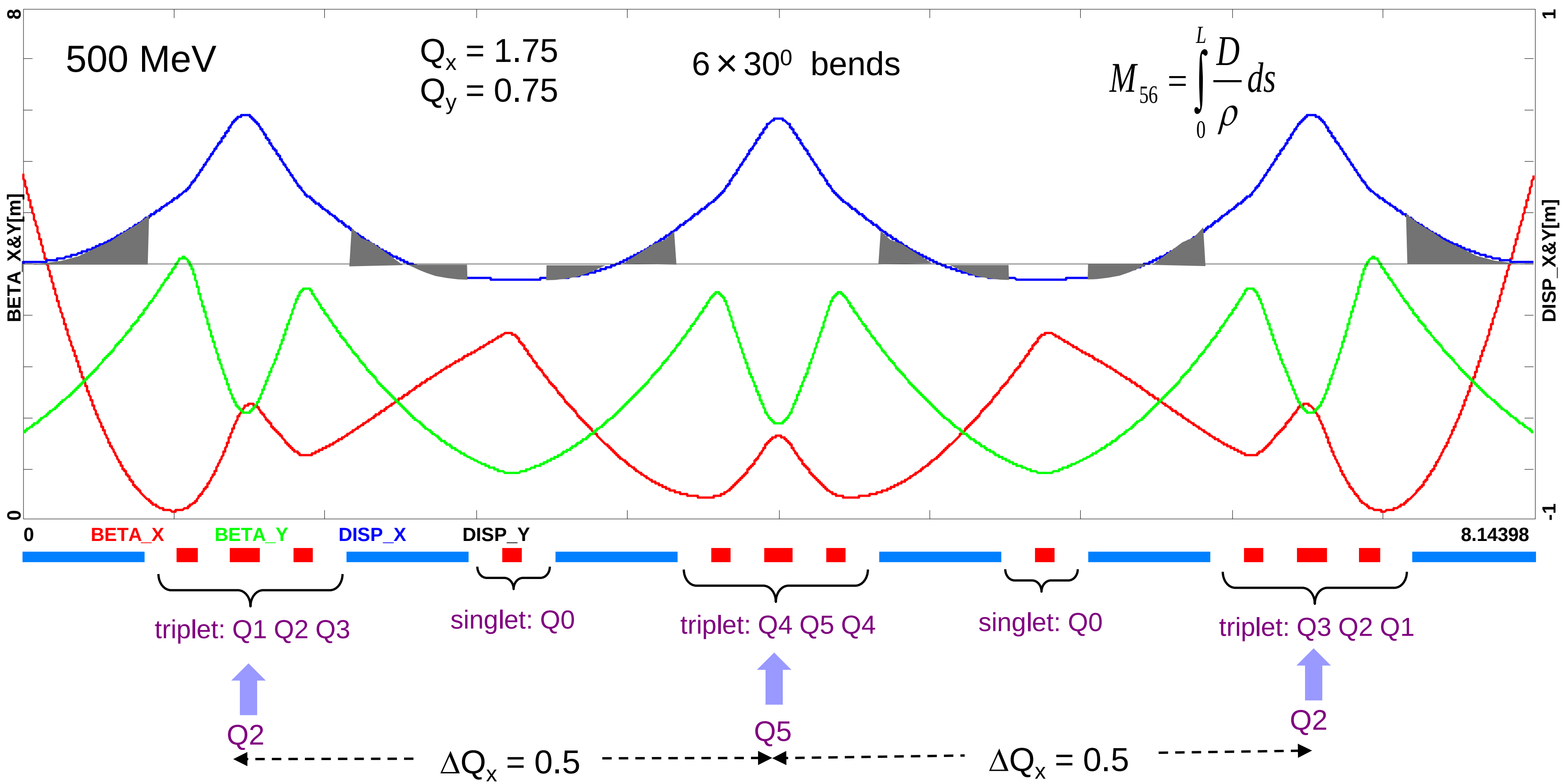
PHYSICAL REVIEW ACCELERATORS AND BEAMS **20**, 024401 (2017)

*

Conditions for coherent-synchrotron-radiation-induced microbunching suppression in multibend beam transport or recirculation arcs

C.-Y. Tsai,[1,*] S. Di Mitri,[2] D. Douglas,[3] R. Li,[1,3] and C. Tennant[3]

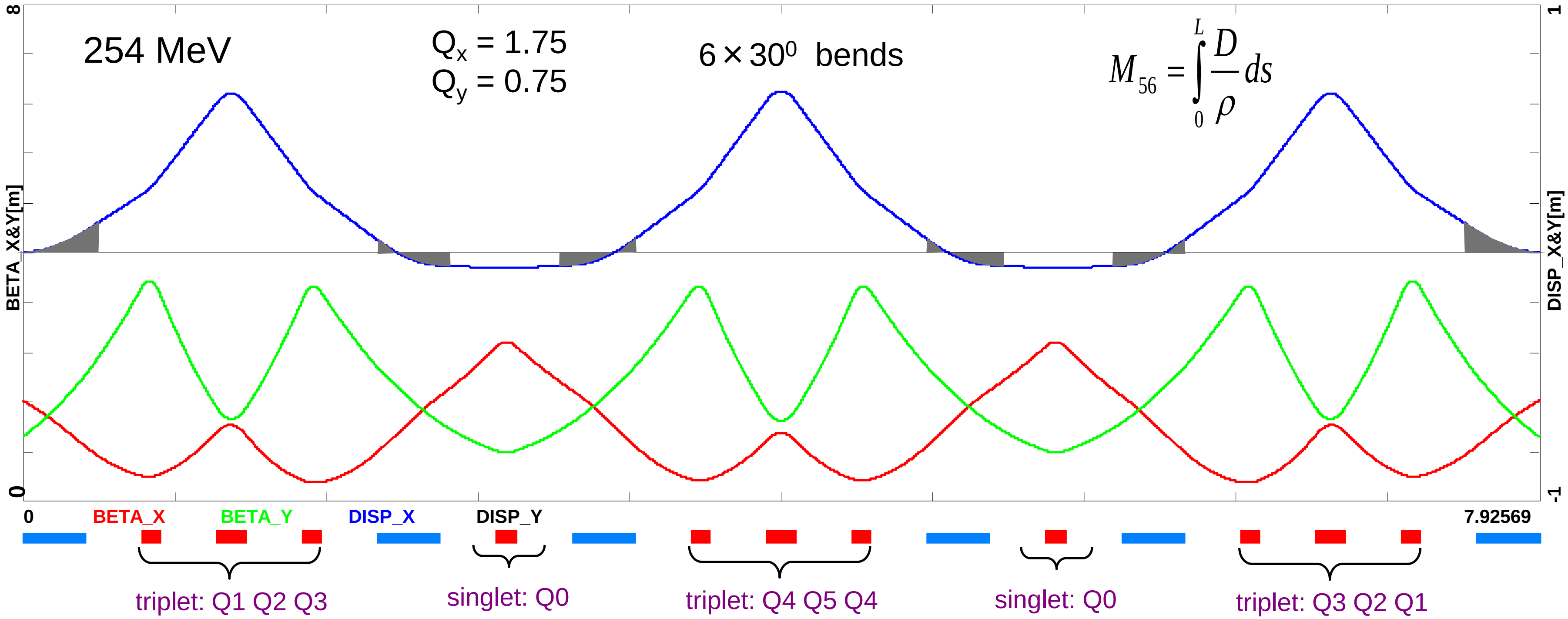
Arc 6 (5,4) Optics – Dispersion/M_{56} Control



Independent Control of Dispersion and M_{56}

'Orthogonal Knobs': Q2 Q5 Q2

Arc 3 (2,1) Optics – ‘Six-Bend’ Lattice



Dipoles: (33 cm long)

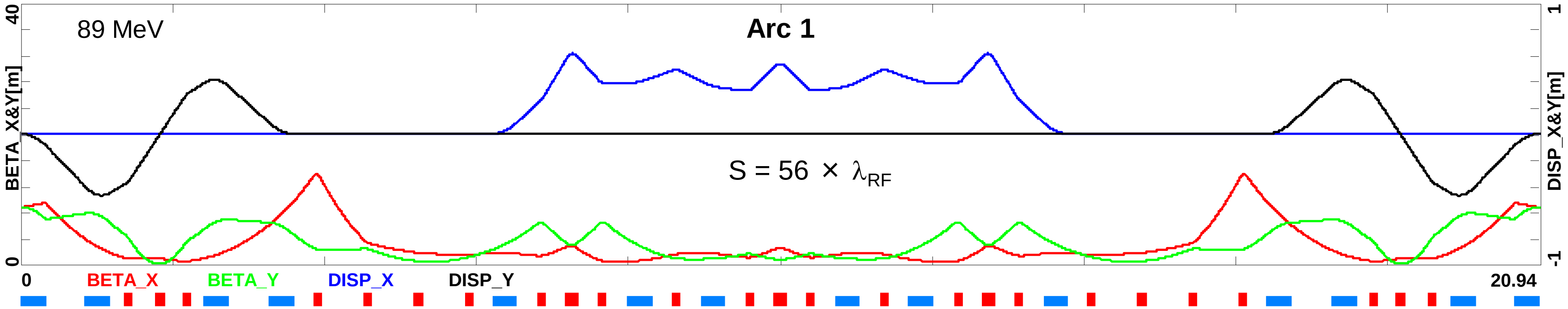
B = 1.4 Tesla

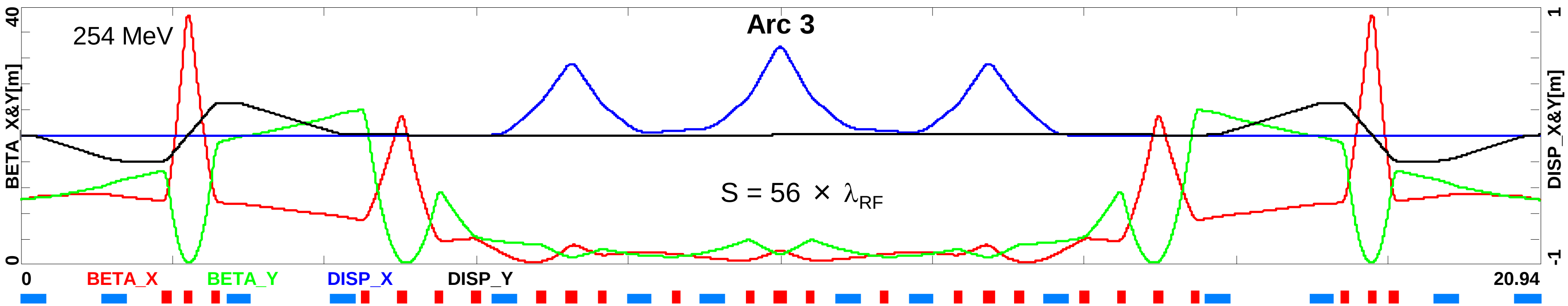
(0.9 Tesla, 0.5 Tesla)

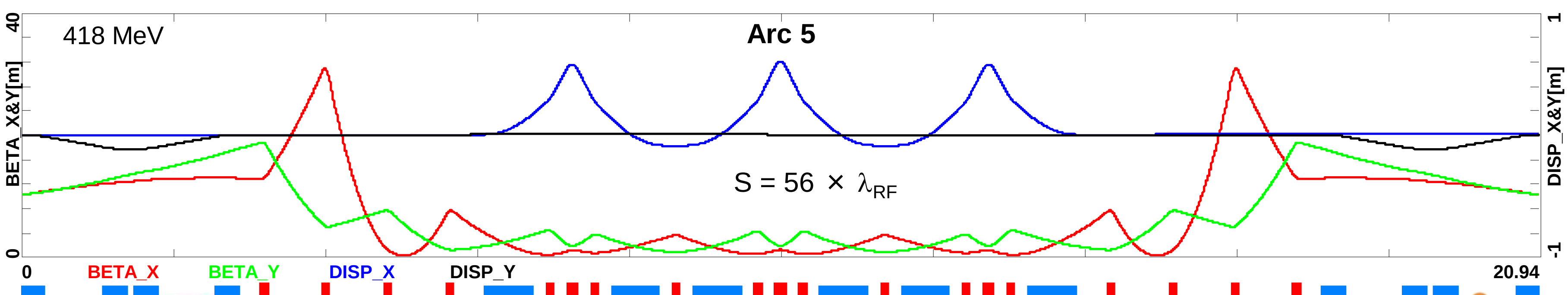
Quadrupoles:

Q0	L[cm] = 10	G[kG/cm] = 0.452
Q1	L[cm] = 10	G[kG/cm] = -0.922
Q2	L[cm] = 15	G[kG/cm] = 1.673
Q3	L[cm] = 10	G[kG/cm] = -1.351
Q4	L[cm] = 10	G[kG/cm] = -1.408
Q5	L[cm] = 15	G[kG/cm] = 1.686

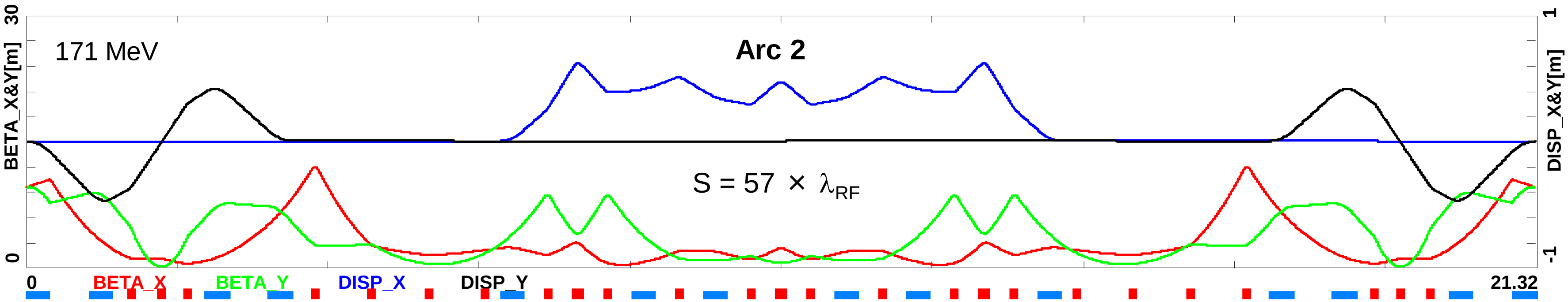
Isochronous Arc (1, 3, 5) Optics

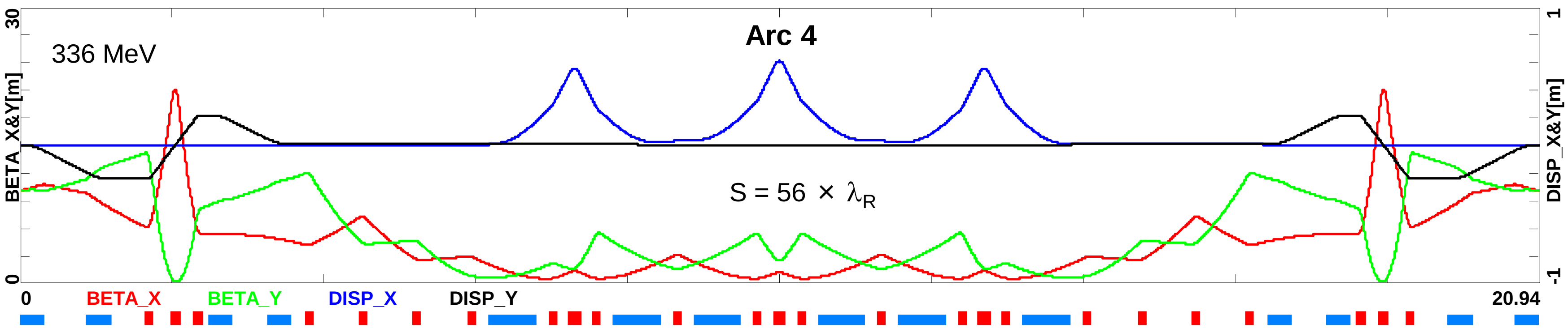


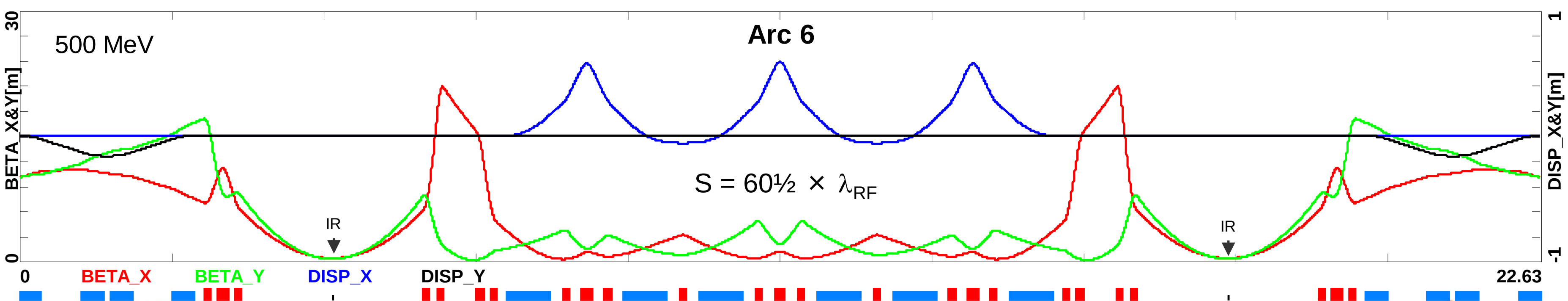




Isochronous Arc (2, 4, 6) Optics

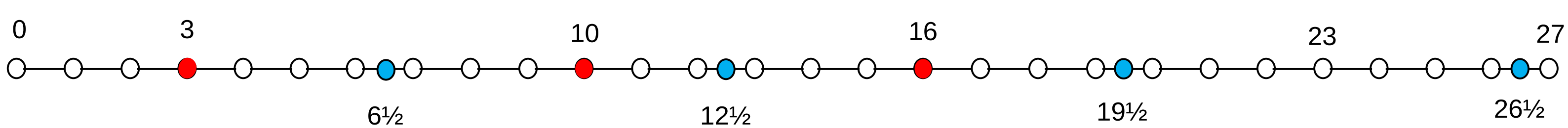




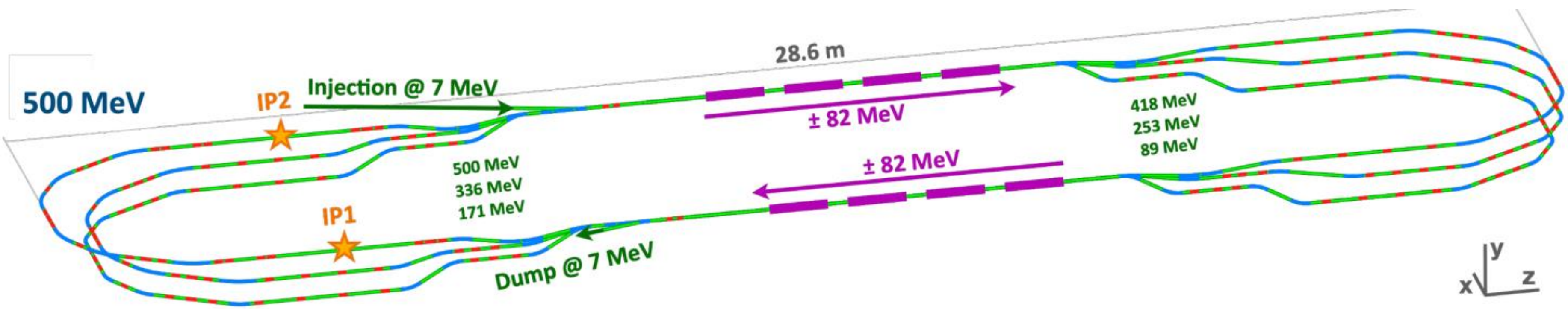


Filling Pattern – Pathlength 'Arithmetic'

- $20 \times \lambda_{RF}$ spacing between consecutive injections (25 nsec injection),
- Painting a 'uniform' bunch pattern for accelerated and decelerated bunches
- Pass-by-pass pathlengths (in units of λ_{RF}).
  - Pass 1: $8 \times 20 + n_1$ — $n_1 = \mathbf{7}$
  - Pass 2: $8 \times 20 + n_2$ — $n_2 = \mathbf{6}$
  - Pass 3: $8 \times 20 + (n_3 + ½)$ — $n_3 = 3, \mathbf{10}, 17$
  - Pass -2: $8 \times 20 + n_{-2}$ — $n_{-2} = \mathbf{6}$
  - Pass -1: $8 \times 20 + n_{-1}$ — $n_{-1} = \mathbf{7}$
- Arc pathlengths
  - $A_1 = 56$
  - $A_2 = 57$
  - $A_3 = 56$
  - $A_4 = 56$
  - $A_5 = 56$
  - $A_6 = 60\ ½$



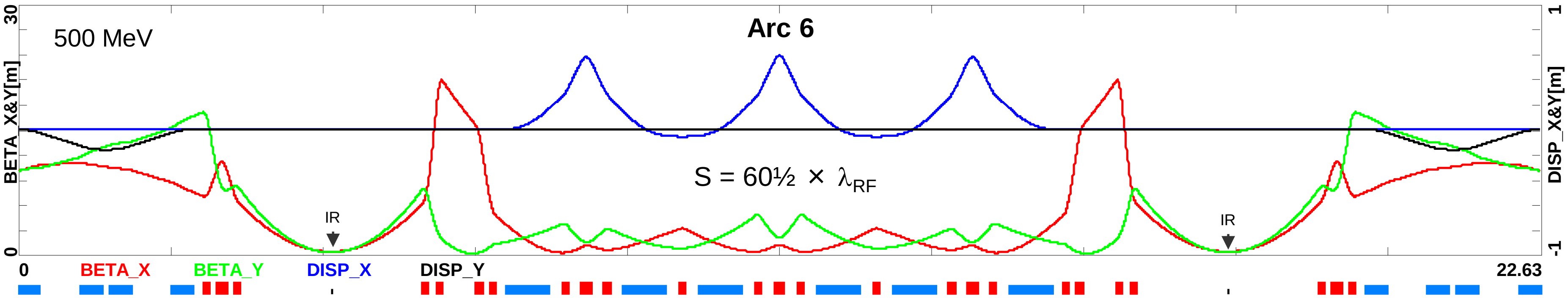
PERLE 2.1 Configuration

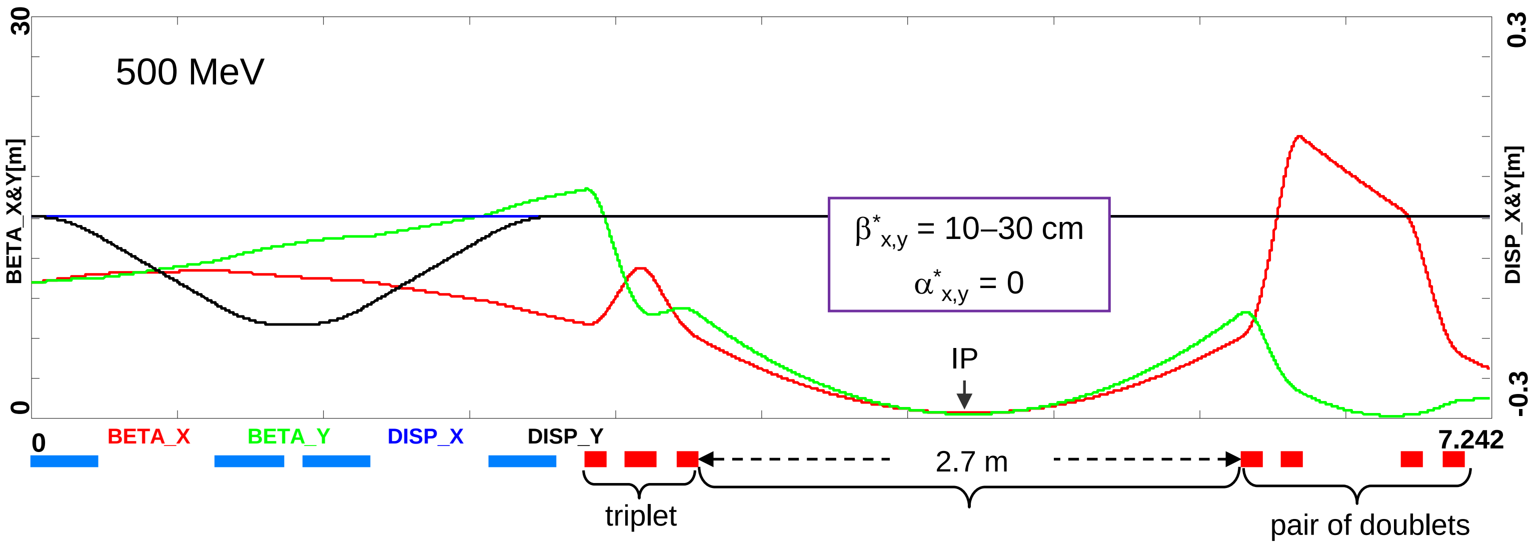


Alex Fomin

Expanding Length of Experimental Areas

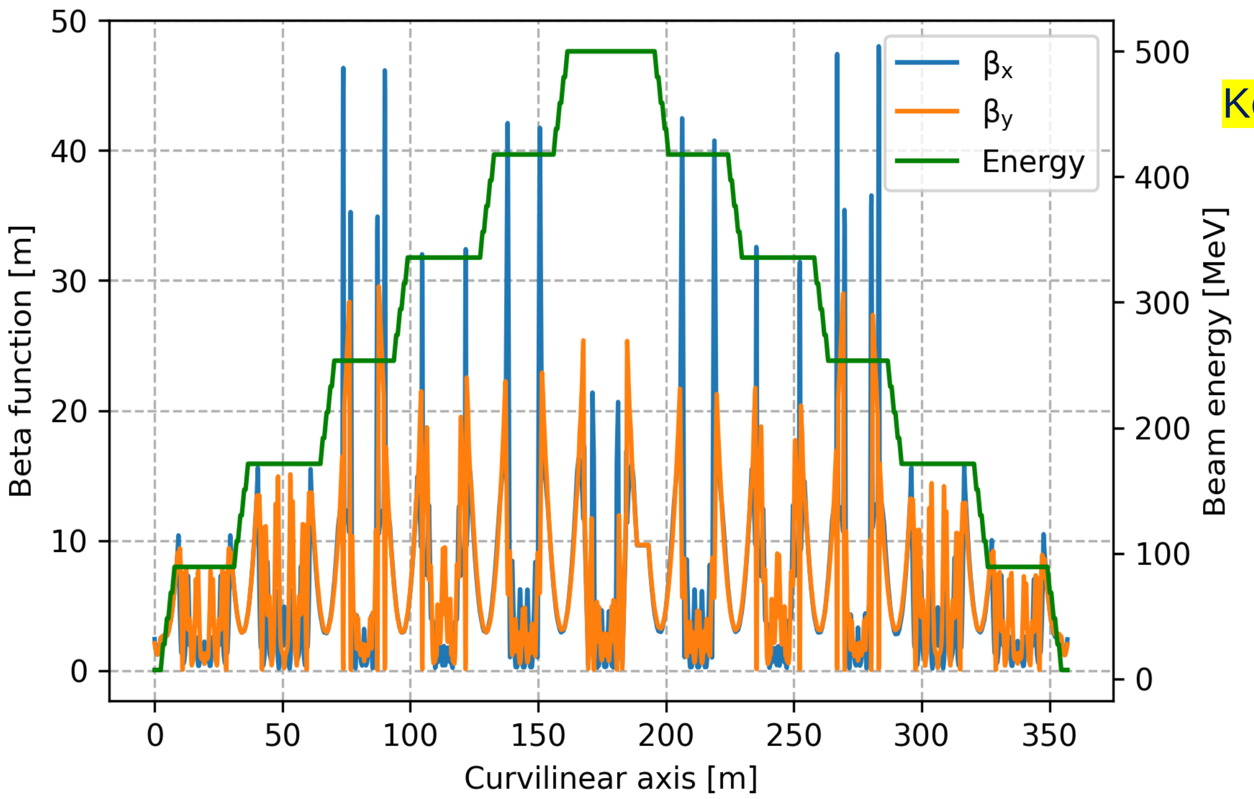
$n_3 = 10,\ \mathbf{17},\ \mathbf{24}$





- EA length may be increased (in increments of $7/2 \times \lambda_{RF}$ = 131 cm) to **4.0** m, **5.3** m etc.

Multi-turn Optics, Beam Dynamics Studies



Kevin André

- Injector/merger design and initial space-charge studies – Ben Hounsell
- Initial End-to-End tracking with PLACET2 (including CSR and wakefields) – Kevin André
- Longitudinal matching and bunch compression studies – Gustavo Pérez Segurana

Current Beam Dynamics Studies

- Complete Start-to-End simulation with synchrotron radiation effects, including CSR and micro-bunching with BMAD – Julien Michaud
- Space-charge studies from merger through the first acceleration pass – Connor Monaghan
- Collective effects, cavity modelling for the ERL – Coline Guyot
- Integrate diagnostics into lattice, linked with a diagnostics WP – Alex Fomin
- Preliminary error analysis – Rasha Abukeshek
- HOM optimized cavity design, test of a dressed cavity – Carmelo Barbagallo
- Study multi-pass wake-field effects, BBU studies – Carmelo Barbagallo

Summary, Outlook

- A decade evolution of PERLE Concept
- PERLE 2.0 - Baseline Design
  - Multi-pass Linacs
    - Configured with the SPL style cryomodules
    - A weak quad doublet added just after the merger
  - Switchyard Configuration
    - Compact 'two step' Spr/Rec with two B-com magnets (30 deg. bend)
  - Experimental Areas – Low-β inserts in both matching straights of Arc 6
    - Tunable IR configured with a triplet – doublet pair (**2.7 m**, 4.0 m, 5.3 m long EA)
  - Arc Optics Architecture
    - 'Six bend' arc configuration – balanced M_{56} across the arc
    - Uniform bunch 'filling pattern' compatible with 25 nsec injection
- Beam Dynamics Studies (Initial and Ongoing)

Special Thanks to:

Erk Jensen

Max Klein

Kevin Andre

and

Alex Fomin

Thanks for your attention!

OptiM deck (Arcs + Linacs) and equivalent **MADX** deck:

- Featuring two linacs, configured with the SPL style cryomodules. A weak quad doublet added just after the merger to give one a flexibility of 'splitting' initial Twiss functions in both planes coming out of the merger.

- All six arcs are configured with six horizontal bends (33 cm bends for Arcs 1-3 and 66 cm bends for Arcs 4-6).

- The switchyard on both sides of the racetrack is configured with 33 cm bends (some curved sector bends some rectangular). Each Spreader and Recombiner features two B-com magnets: one common for all 3 passes and the second one common for 2 higher energy passes.

- The new design includes two dedicated experimental inserts, 2.7 meter long each, located in both matching straights of Arc 6. They are configured as tunable low beta IR, 'flanked' with a triplet and a pair of doubles.

- The lattice files need to be strung together as the following sequence of individual pieces:
  - 3 passes up: L1 Arc1 L2 Arc2 L3 Arc3 L4 Arc4 L5 Arc5 L6 Arc6
  - 3 passes down: L-5 Arc5 L-4 Arc4 L-3 Arc3 L-2 Arc2 L-1 Arc1 L-0