Lattice design of 250 MeV version of PERLE

Alex Fomin

Rasha Abukeshek, Alex Bogacz, Coline Guyot, Julien Michaud and Luc Perrot

Outline

Motivation for 250 MeV version (pros and cons)

Lattice design (maximal compatibility with 500 MeV design prepared by Alex Bogacz)

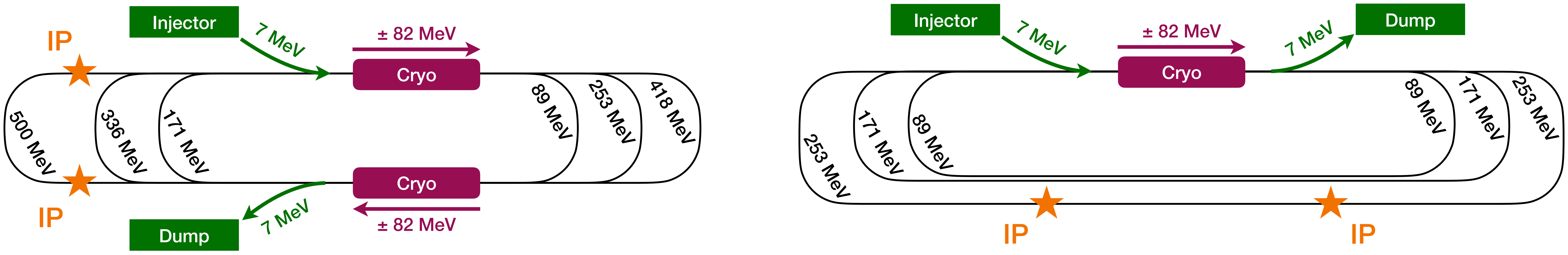
Optics (comparison with 500 MeV version)

Filling patterns (optimal for lower energies)

Conclusions

Motivation for one cryo-module phase (250 MeV versions)

250 MeV version features **three Straight Sections** replacing **Recombiner, Common Section 2,** and **Spreader**



Pros:

→ **reduction of immediate expenses (time for the first results)** (second cryo-module and 18 dipoles can be purchased later)

→ **demonstration of ERL with 6 paths at high current** (same as in 500 MeV version, but with half of the power)

→ more space for experimental areas

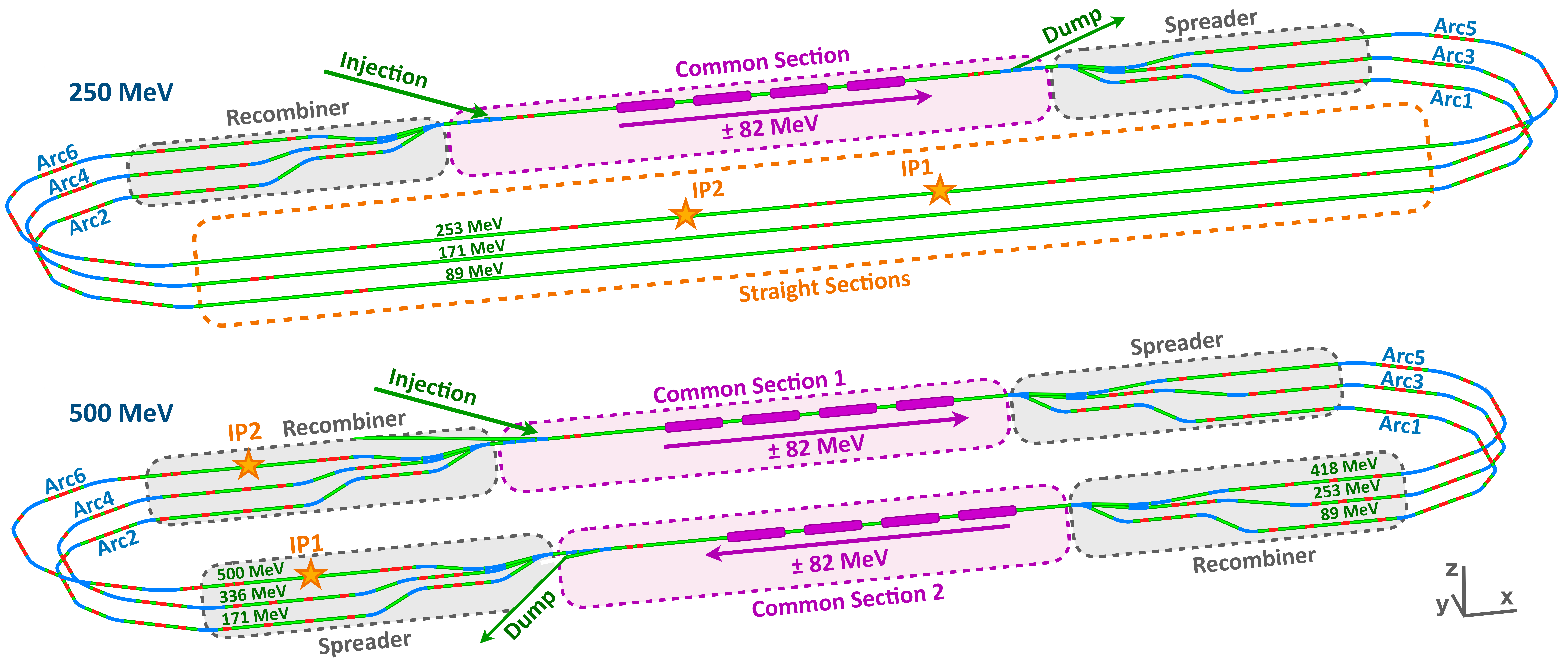
Cons:

→ **additional expenses / manpower / shutdown time** (rebuilding / recommissioning for the full power machine)

→ about 30 meters of extra beam pipes (all other main elements are chosen to be compatible with both versions)

→ a slightly larger footprint (28.6 m → 29.9 m)

Lattice design. 500 MeV vs 250 MeV versions



250 MeV version features three Straight Sections replacing Recombiner, Common Section 2, and Spreader

All elements are compatible with both versions !

Types of dipoles (optics v2.0 → 2.1) 250 MeV vs 500 MeV

The dimensions of dipoles were slightly adjusted in order to reduce the variety of magnets → In optics v2.1 there are 7 types of magnets

Type	Name	Plane	Number		Function	Geometry	L, cm	Deflection, deg		|B|, T		I, mA	
			v.250	v.500				min	max	min	max	min	max
1	Chicane 15cm	hor.	**4**		Injection and Dump /spreader/correctors/merger	R-Bend	15	0.2	15	0.040		100	120
2	Chicane 30cm	hor.	**2**		corrector with double length and inverted field (w.r.t. Type 1)	R-Bend	30	0.4	2.3	0.040		100	120
3	B-Com 3-lines	vert.	**2**	**4**	spreaders/recombiners for 3 energy lines (for all Arcs)	R-Bend	33	6.1	30	0.451	0.866	100	120
4	B-Com 2-lines	vert.	**2**	**4**	spreaders/recombiners for 2 energy lines (for Arcs 3, 5 & 4, 6)	R-Bend	33	6.1	15.1	0.451	0.866	60	80
5	R-Bend 33cm	vert.	**8**	**16**	spreaders (one energy line) for Arcs 3, 4, 5 & 6	R-Bend	33	6.1	15.1	0.451	0.873	20	40
6	S-Bend 33cm	**vert.**	**6**	**12**	spreaders (one energy line) for Arcs 1 & 2	S-Bend	33	30		0.472	0.907	40	
		hor.	**18**		180° turn of the Arc 1, 2, 3 (6 dipoles per Arc)	S-Bend	33	30		0.472	1.342	20	40
7	S-Bend 66cm	hor.	**18**		180° turn of the Arc 4, 5, 6	S-Bend	66	30		0.453	1.323	20	40
Total			**60**	**78**									

Total number of dipole (ERL only)

- **60** dipoles for 250 MeV version
- **78** dipoles for 500 MeV version

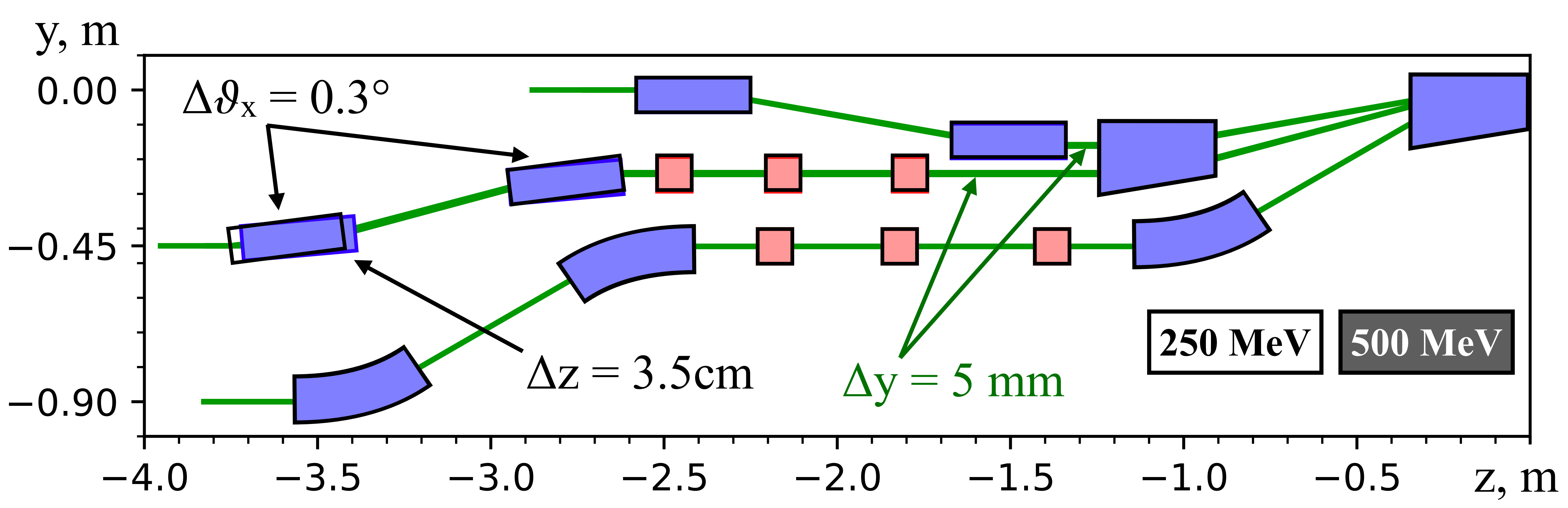
- the required magnetic field (and beam current) might vary by the factor 2—3 (and 2 respectively) within the same Type of dipole
- "S-Bend 33cm" at the Spreader/Recombiner sections is in vertical orientation and in horizontal at the Arcs

  Is it possible to have the same dipole design?

Spreaders / Recombiners / Arcs   250 MeV vs 500 MeV

The ratio of the energies in 250 MeV version is very close to the one in Arcs 2,4,6:

$\Delta E \approx 82$ MeV
$E_0 \approx 7$ MeV

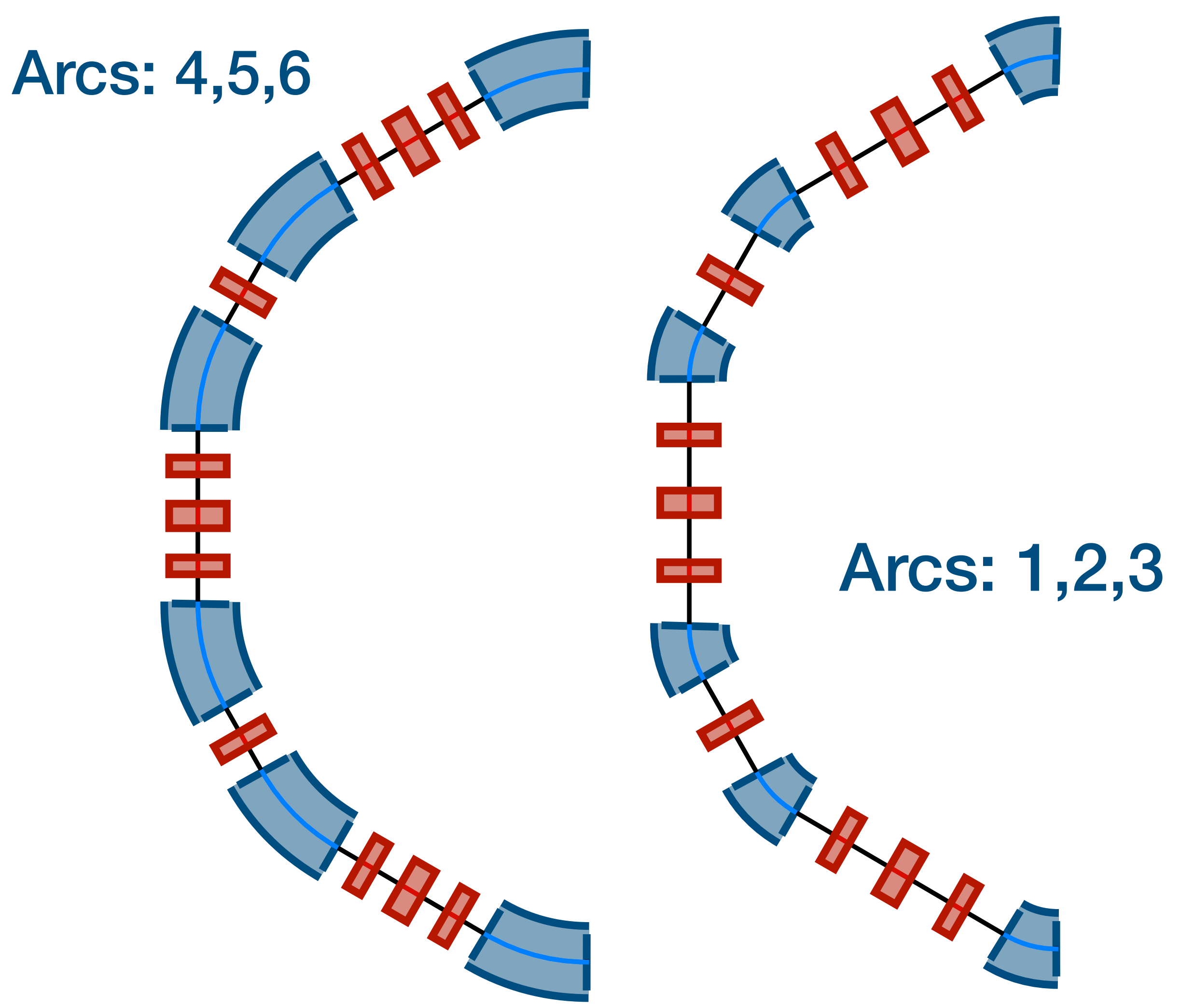


$\Delta E + E_0 \ : \ 2\Delta E + E_0 \ : \ 3\Delta E + E_0 \ \approx \ 1 : 1.92 : 2.84$

$2\Delta E + E_0 \ : \ 4\Delta E + E_0 \ : \ 6\Delta E + E_0 \ \approx \ 1 : 1.96 : 2.92$

→ we can use the same magnets,

→ the lattice should be adjusted



All six arcs are chosen to be **the same** as in 500 MeV version (**for compatibility**)

- lengths of dipoles are 33 cm (at arcs 1, 2 & 3) and 66 cm (at arcs 4, 5 & 6)

If designing 250 MeV version from scratch (no compatibility with 500 MeV)

- all dipoles at arcs would be 33 cm (**18 shorter magnets**)
- arcs could be slightly shorter → **smaller footprint**

Distance between the Arcs and Spreaders should be adjustable

- to form an optimal filling pattern, i.e. placement of accelerated bunches between the injected bunches
- tune phase adjustment between accelerations at RF cavities

Two-step beam separation/recombining (proposed by A.Bogacz)

- → **reduction of dispersion** (quadruple triplet between dipoles)
- → **distance between the beam pipes < size of the quadrupoles** (current design)

Grouping into two doublets

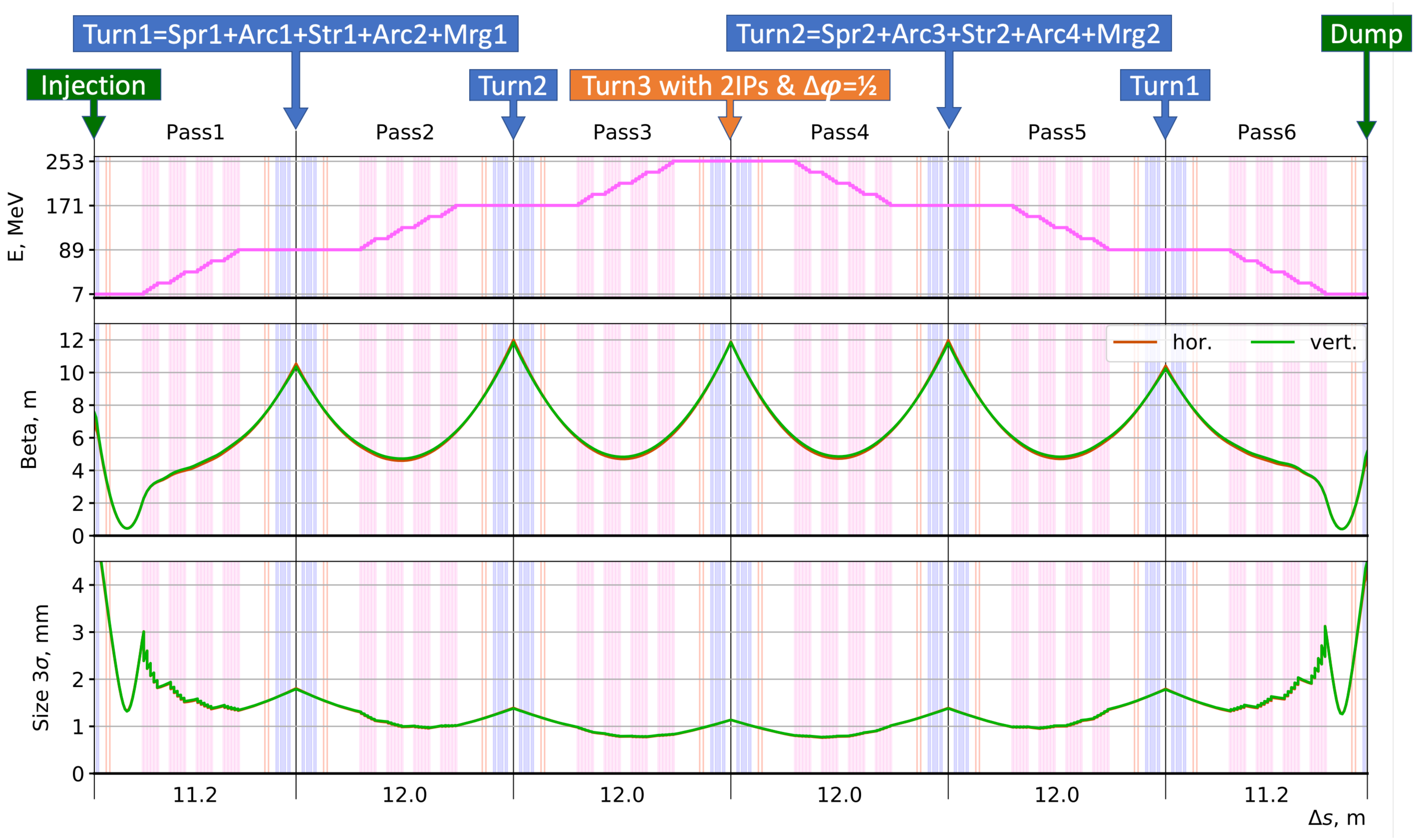
- → **more space for instrumentation** (if needed)
- → **possibility to host IRs at the spreader** (like 500 MeV)
- → **not enough to install chicanes** (phase adjustment for RF)

Extending distance between dipoles at middle spreader

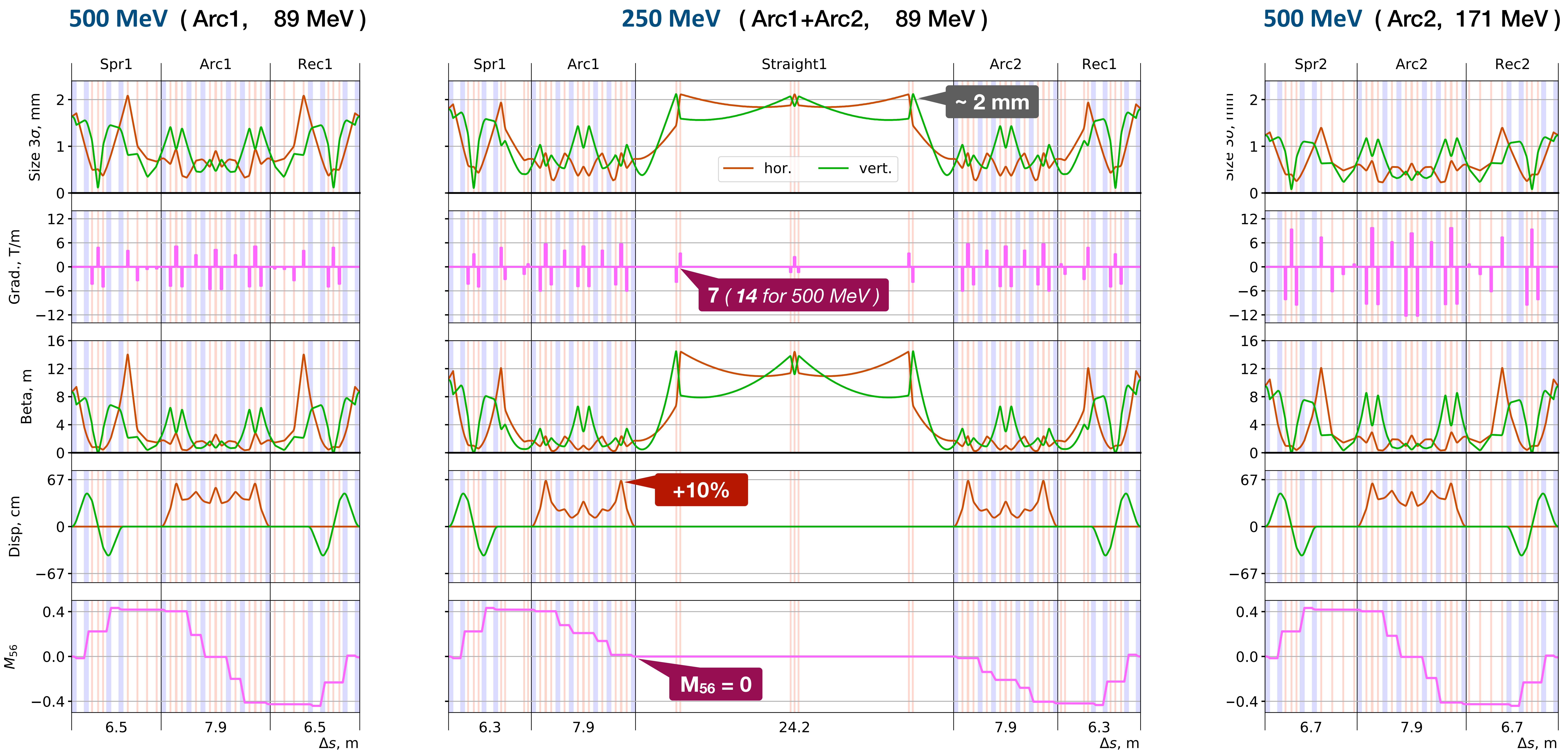
- → no overlap of **quadrupoles**

Optics
(comparison with 500 MeV version)

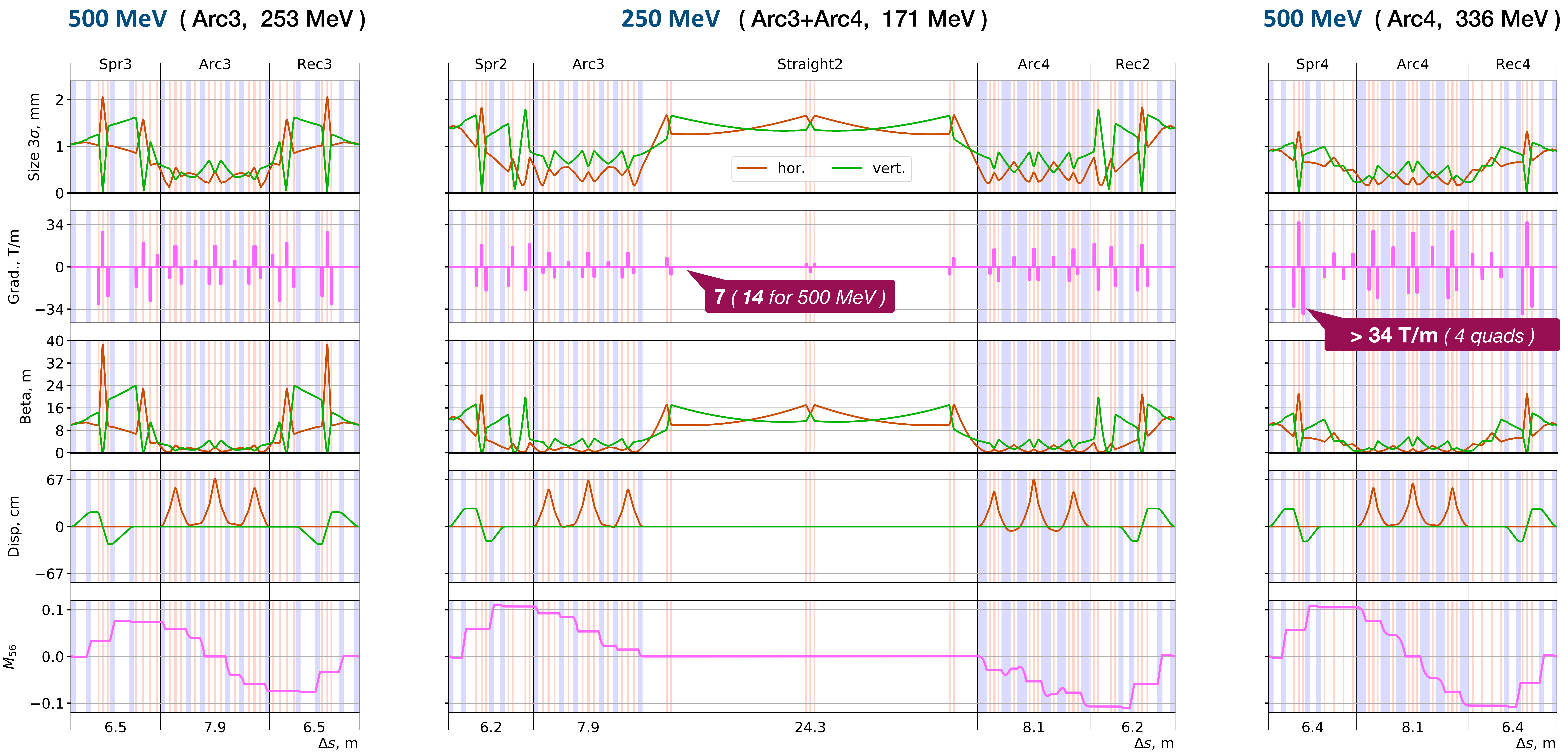
Optics comparison 250 & 500 MeV versions



Optics comparison 250 & 500 MeV versions

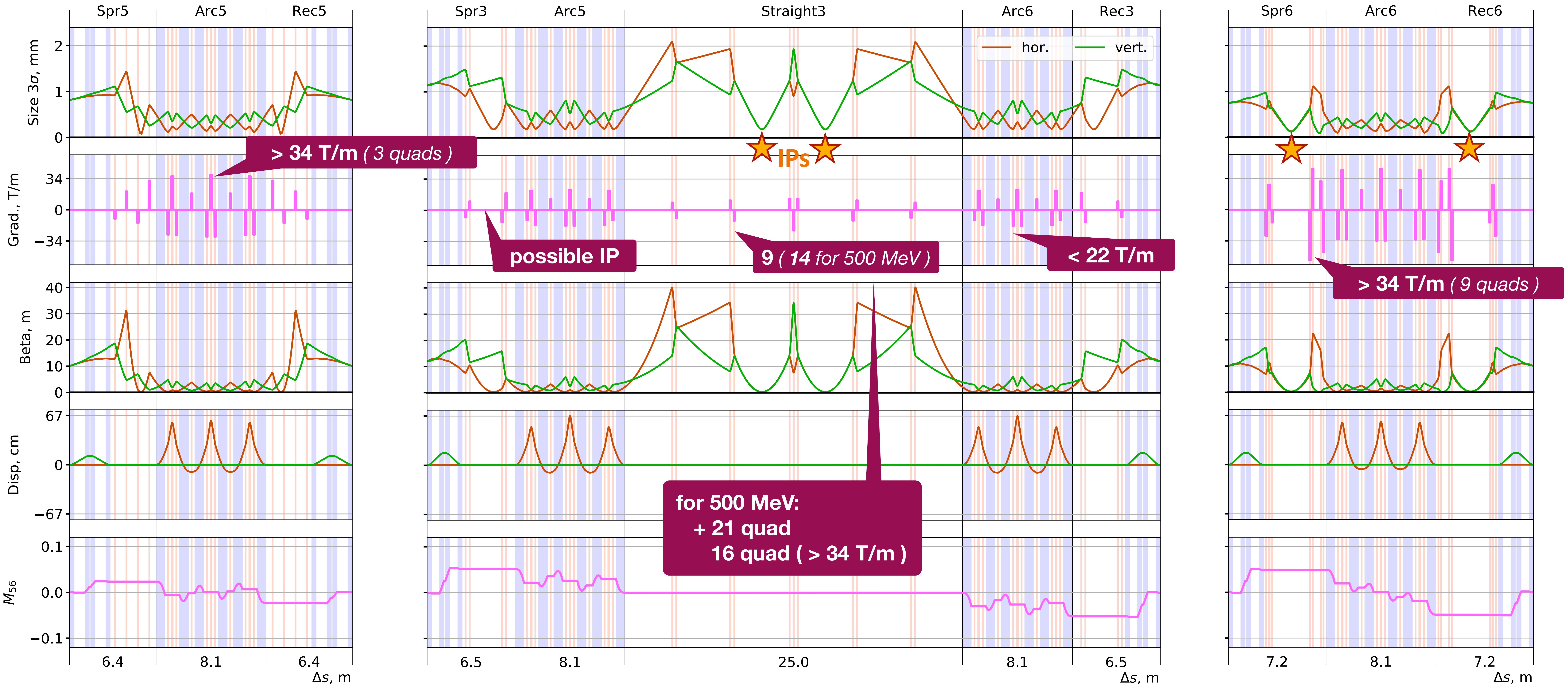


Optics comparison 250 & 500 MeV versions



Optics comparison 250 & 500 MeV versions

500 MeV (Arc5, 418 MeV) **250 MeV** (Arc5+Arc6, 253 MeV) **500 MeV** (Arc6, 500 MeV)



Filling pattern

(size of the Arcs)

Forming the Filling Pattern. Injection and Pass 1

Pass 1

Injection

7 MeV bunches are injected at **Linac 1** section

at the rate of $\nu_{inj} \approx 40$ MHz (every $t_{inj} = 25$ ns)

target current is $I = 20$ mA

→ charge of one bunch $Q \approx 500$ pC (3×10^9 e^-)

RF Cavity ($\nu_{RF} = 801.58$ MHz)

→ spacing between injections $L_{inj} = 20\ \lambda_{RF}$

$\nu_{RF} / \nu_{inj} = 20$, $\lambda_{RF} \approx 34.7$ cm

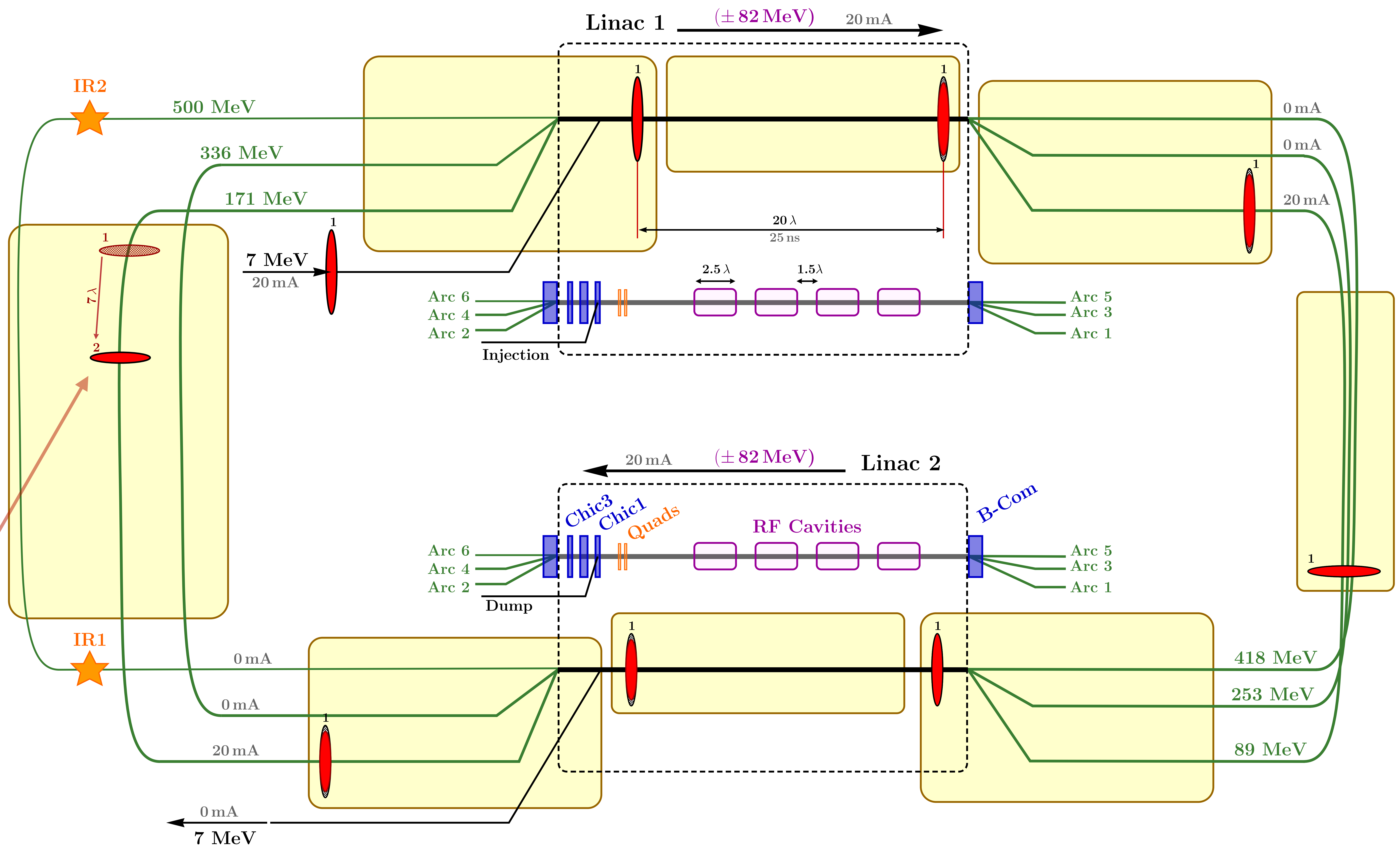
Pass 1

Linac 1 → **Arc 1** → **Linac 2** → **Arc 2**

7→ 89 MeV 89→171MeV

Pass 1 length (Arc1 + Arc2 + 2 Linac) $L_{Pass\,1} = 167\ \lambda_{RF}$

→ the 9th injected bunch is followed by the accelerated bunch shifted by $7\ \lambda_{RF}$



Forming the Filling Pattern. Passes 1 & 2

Passes 1–2

Injection

7 MeV bunches are injected at **Linac 1** section

at the rate of $\nu_{inj} \approx 40$ MHz (every $t_{inj} = 25$ ns)

target current is $I = 20$ mA

→ charge of one bunch $Q \approx 500$ pC (3×10^9 e^-)

RF Cavity ($\nu_{RF} = 801.58$ MHz)

→ spacing between injections $L_{inj} = 20\,\lambda_{RF}$

$\nu_{RF} / \nu_{inj} = 20, \quad \lambda_{RF} \approx 34.7$ cm

Pass 1

Linac 1 → Arc 1 → Linac 2 → Arc 2

7→ 89 MeV 89→171MeV

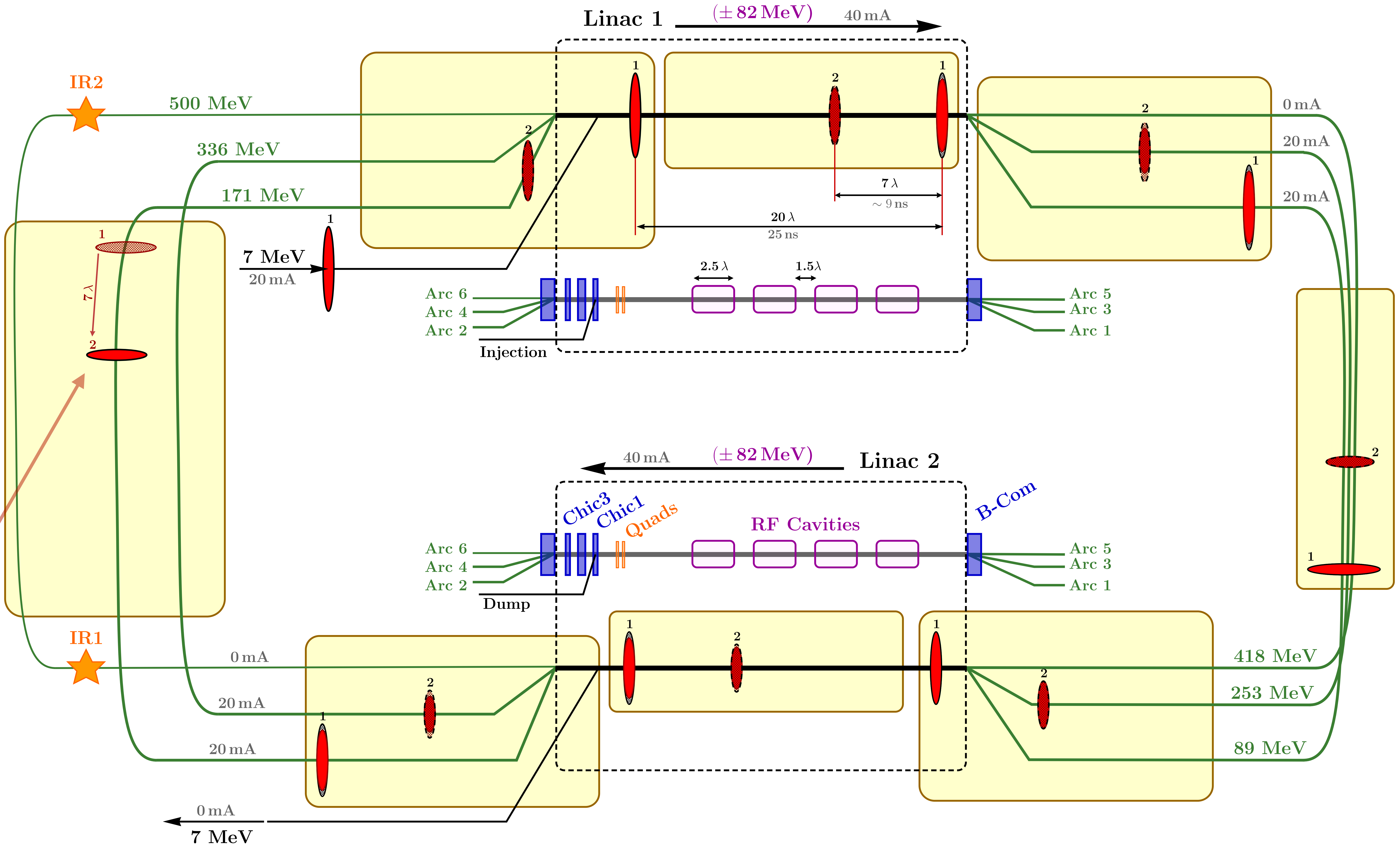
Pass 1 length (Arc1 + Arc2 + 2 Linac) $L_{Pass\,1} = 167\,\lambda_{RF}$

→ the 9th injected bunch is followed by the accelerated bunch shifted by $7\,\lambda_{RF}$

Pass 2

Linac 1 → Arc 3 → Linac 2 → Arc 4

171→253 MeV 253→336 MeV



Forming the Filling Pattern. Passes 1—3

Passes 1–3

Injection ($\nu_{inj} \approx 40$ MHz) I = 20 mA ($Q \approx 500$ pC, t_{inj} = 25 ns)

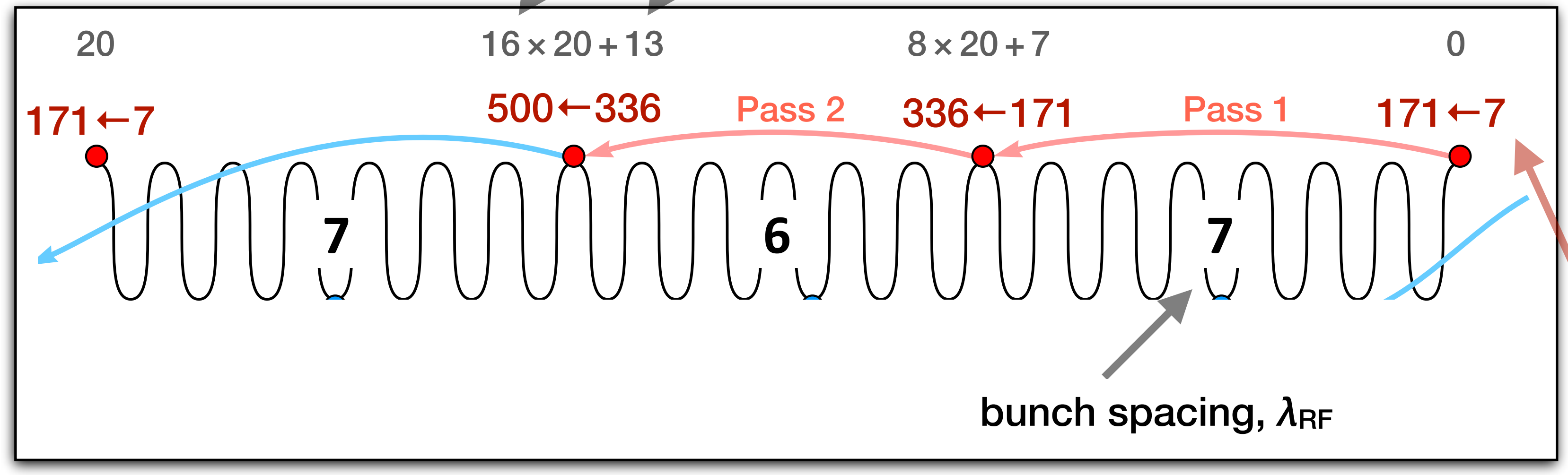
RF Cavity (ν_{RF} = 801.58 MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

Pass Lengths Linac 1 + Arc j + Linac 2 + Arc k

Pass	Arcs	L_{Arcs}, λ_{RF}	L_{Pass}, λ_{RF}	n_{inj}	Δ, λ_{RF}	Δt, μs
1	1+2	56 + 57	167	8	7	0.209
2	3+4	56 + 56	166	16	13	0.416
3						

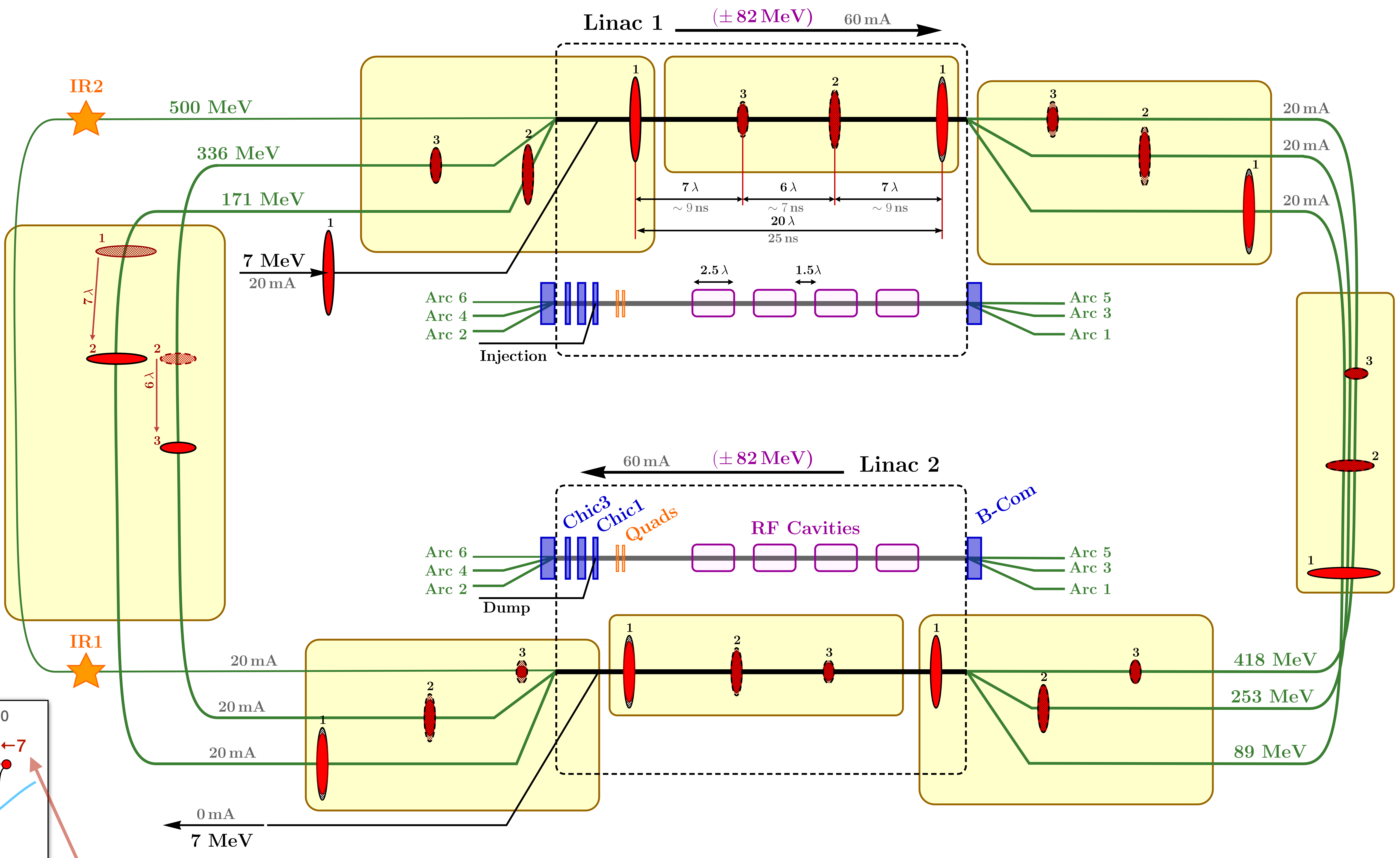
Filling Pattern

total shift, λ_{RF}



bunch spacing, λ_{RF}

Energy, MeV



Forming the Filling Pattern. Passes 1—4

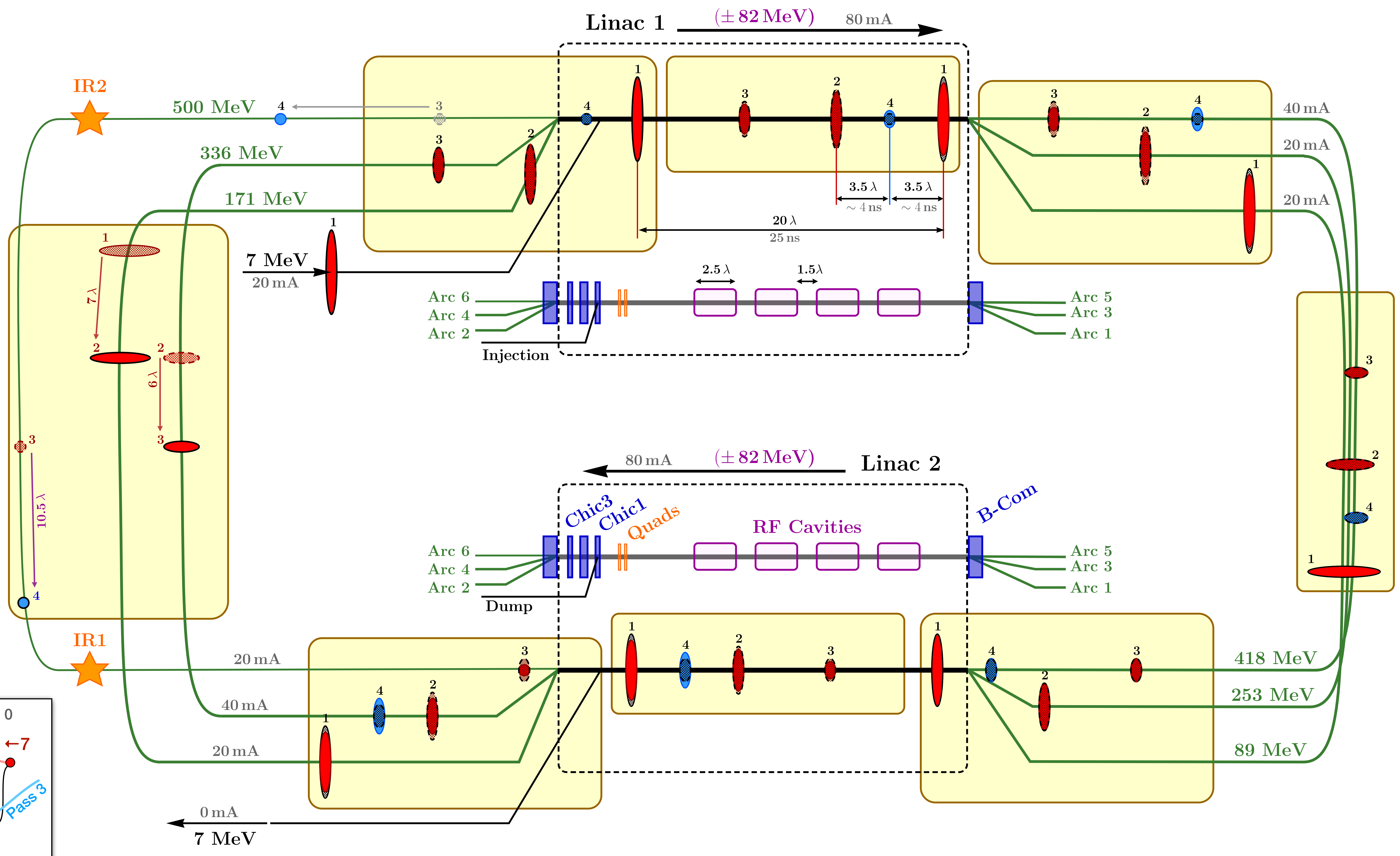
Passes 1–4

Injection ($\nu_{inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{inj} = 25$ ns)

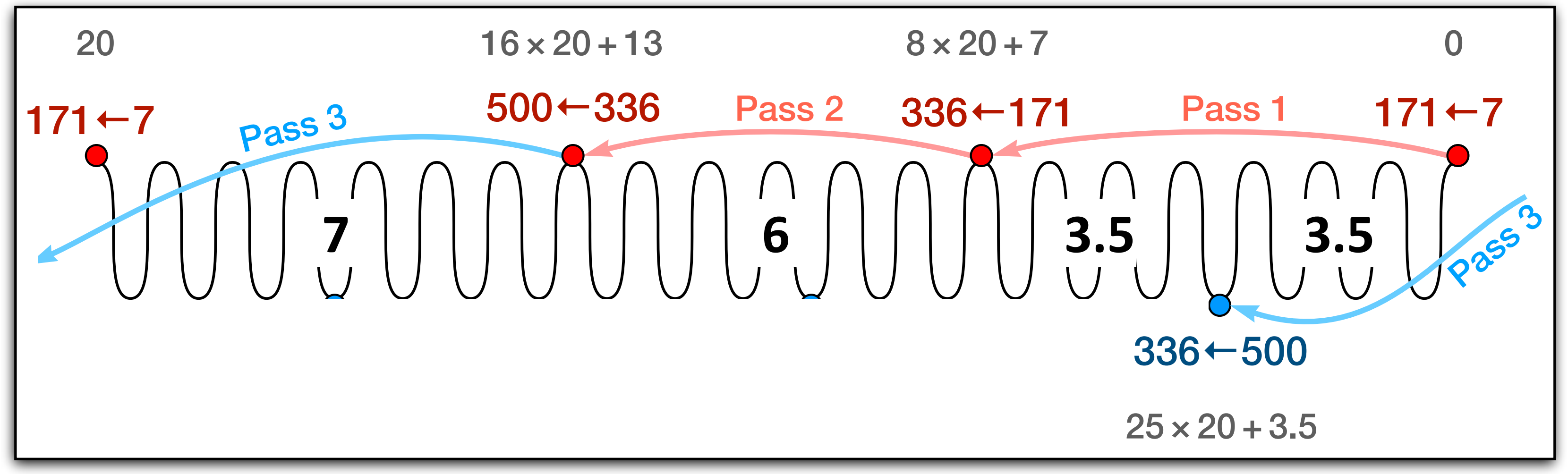
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

Pass Lengths Linac 1 + Arc j + Linac 2 + Arc k

Pass	Arcs	L_{Arcs}, λ_{RF}	L_{Pass}, λ_{RF}	n_{inj}	Δ, λ_{RF}	Δ*t*, μs
1	1+2	56 + 57	167	8	7	0.209
2	3+4	56 + 56	166	16	13	0.416
3	5+6	56 + 60.5	170.5	25	3.5	0.629
4						



Filling Pattern



Forming the Filling Pattern. Passes 1—5

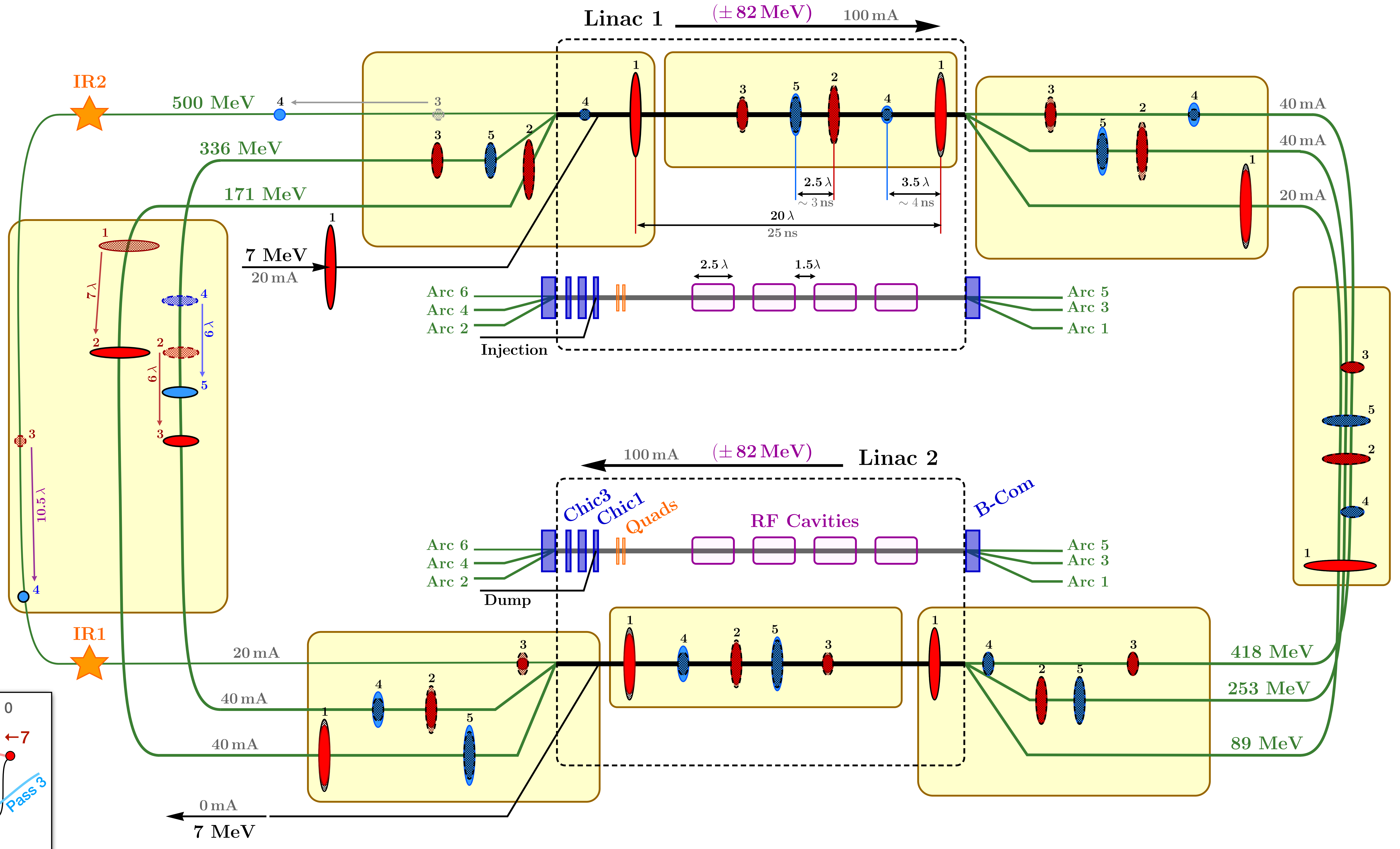
Passes 1–5

Injection ($\nu_{inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{inj} = 25$ ns)

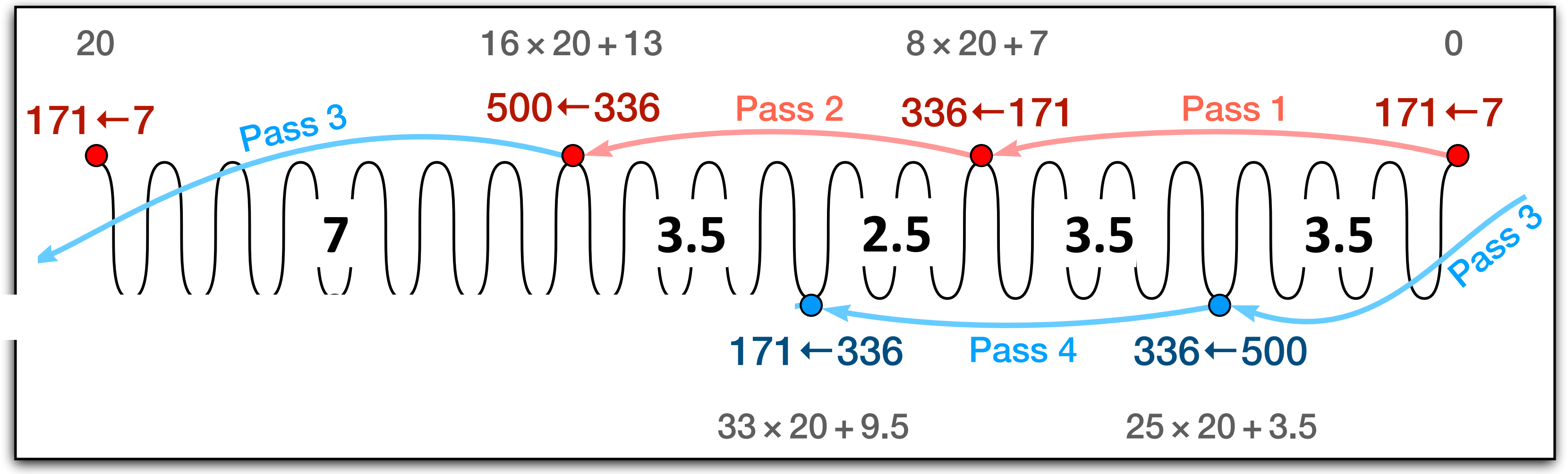
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

Pass Lengths Linac 1 + Arc j + Linac 2 + Arc k

Pass	Arcs	L_{Arcs}, λ_{RF}	L_{Pass}, λ_{RF}	n_{inj}	Δ, λ_{RF}	Δt, μs
1	1+2	56 + 57	167	8	7	0.209
2	3+4	56 + 56	166	16	13	0.416
3	5+6	56 + 60.5	170.5	25	3.5	0.629
4	5+4	56 + 56	166	33	9.5	0.837
5						



Filling Pattern



Forming the Filling Pattern. Continues cycle

Passes 1–6

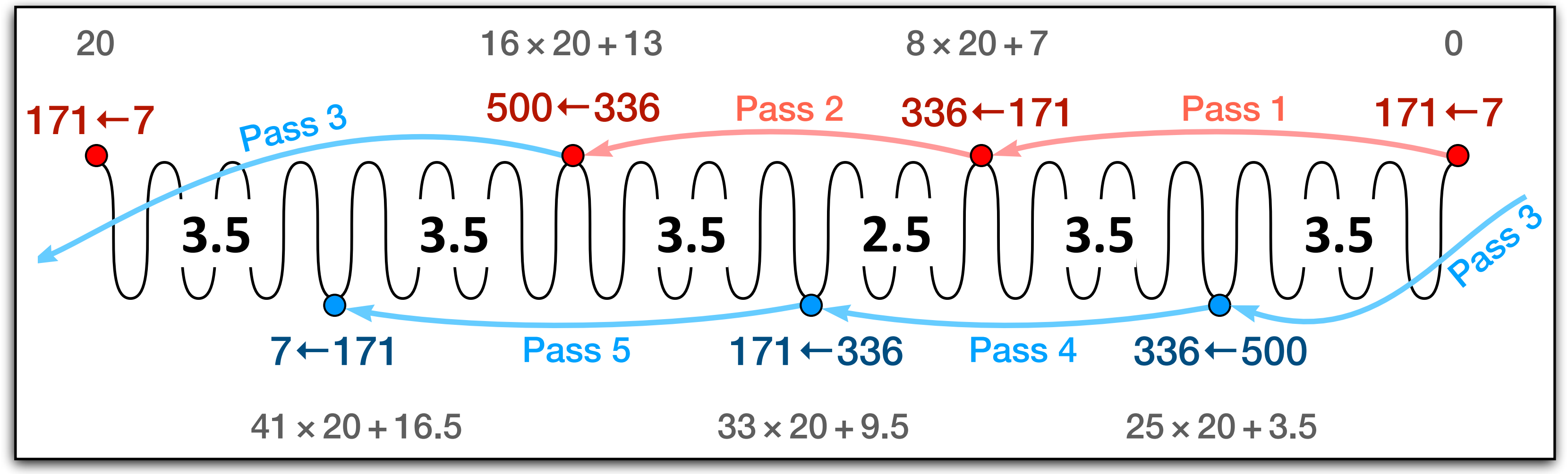
Injection ($\nu_{inj} \approx 40$ MHz) I = 20 mA ($Q \approx 500$ pC, t_{inj} = 25 ns)

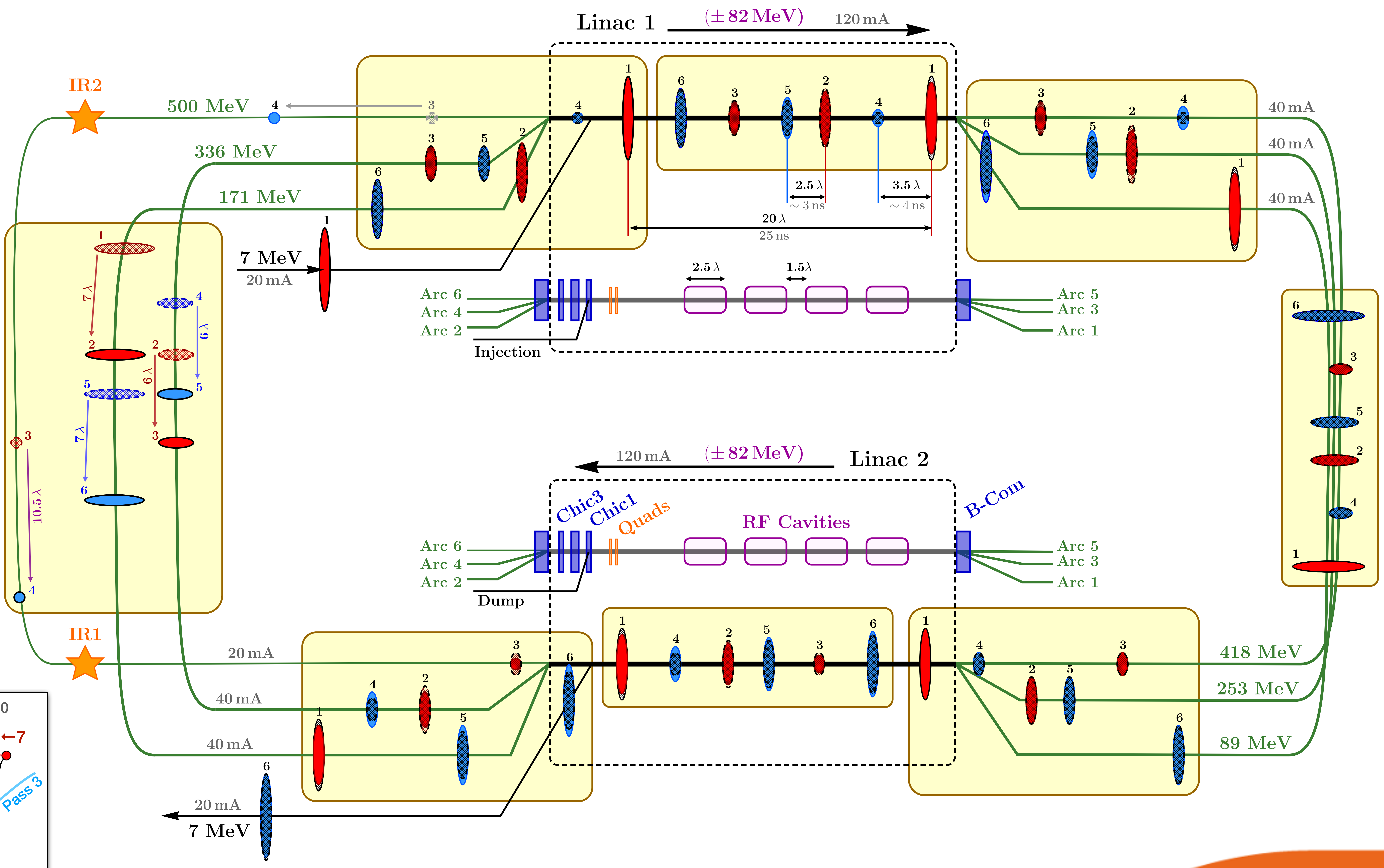
RF Cavity (ν_{RF} = 801.58 MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

Pass Lengths Linac 1 + Arc j + Linac 2 + Arc k

Pass	Arcs	L_{Arcs}, λ_{RF}	L_{Pass}, λ_{RF}	n_{inj}	Δ, λ_{RF}	Δt, μs
1	1+2	56 + 57	167	8	7	0.209
2	3+4	56 + 56	166	16	13	0.416
3	5+6	56 + 60.5	170.5	25	3.5	0.629
4	5+4	56 + 56	166	33	9.5	0.837
5	3+2	56 + 57	167	41	16.5	1.046
6	1	56	–	–	–	-

Filling Pattern





Filling pattern for 250 MeV version

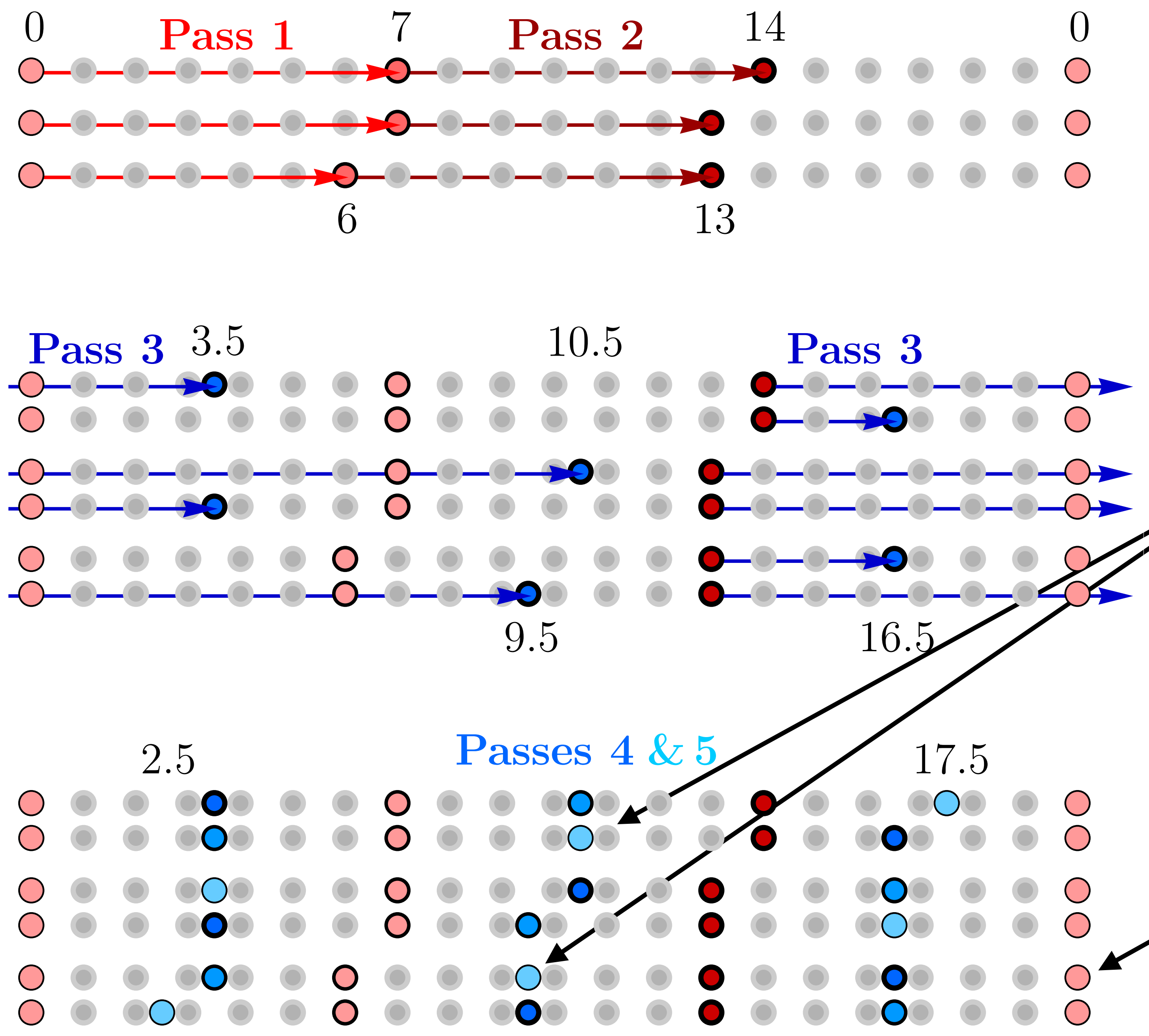
Consecutive injections (ν_{inj} = 40 MHz), RF cavity (ν_{RF} = 801.58 MHz) → spacing between injections **20** × λ_{RF}

$\nu_{RF} / \nu_{inj} \approx 20$, λ_{RF} = 37.4 cm

Distance between the arcs → path length of the bunch between consecutive passes → form the filling pattern (placement of accelerated bunches between the injected bunches)

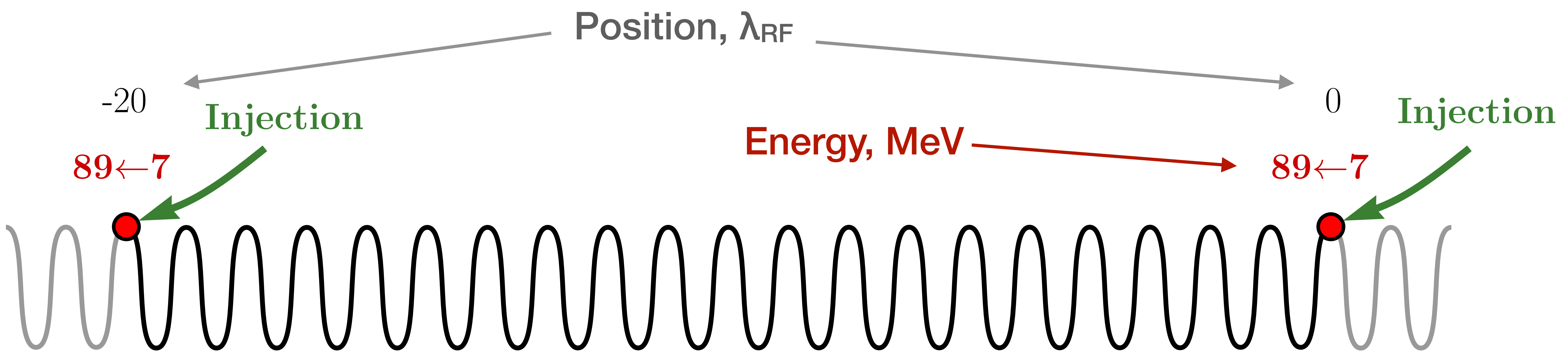
To reduce the risk of beam break-ups → uniform filling pattern

Six possible options of uniform filling patterns

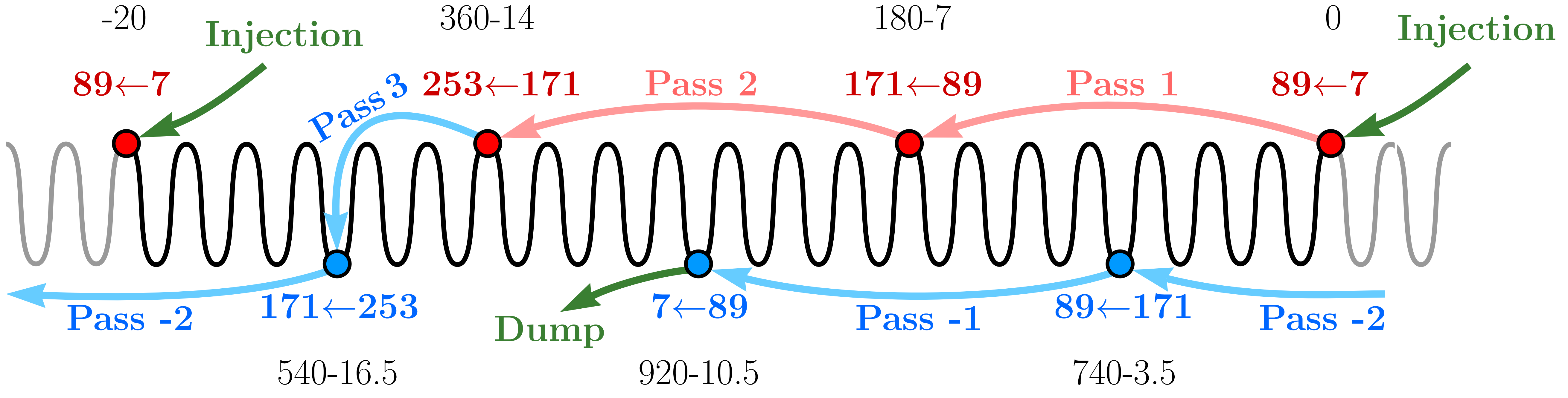


option 2 & 5 have bunches of lowest energies separated

option 5 is chosen for 250 MeV version (more detailed studies will follow)



Uniform filling pattern, $L_{Pass} = 180 - \Delta_i$, Δ_i = 7, 7, 2.5, 7, 7



Filling pattern 500 vs 250 MeV versions

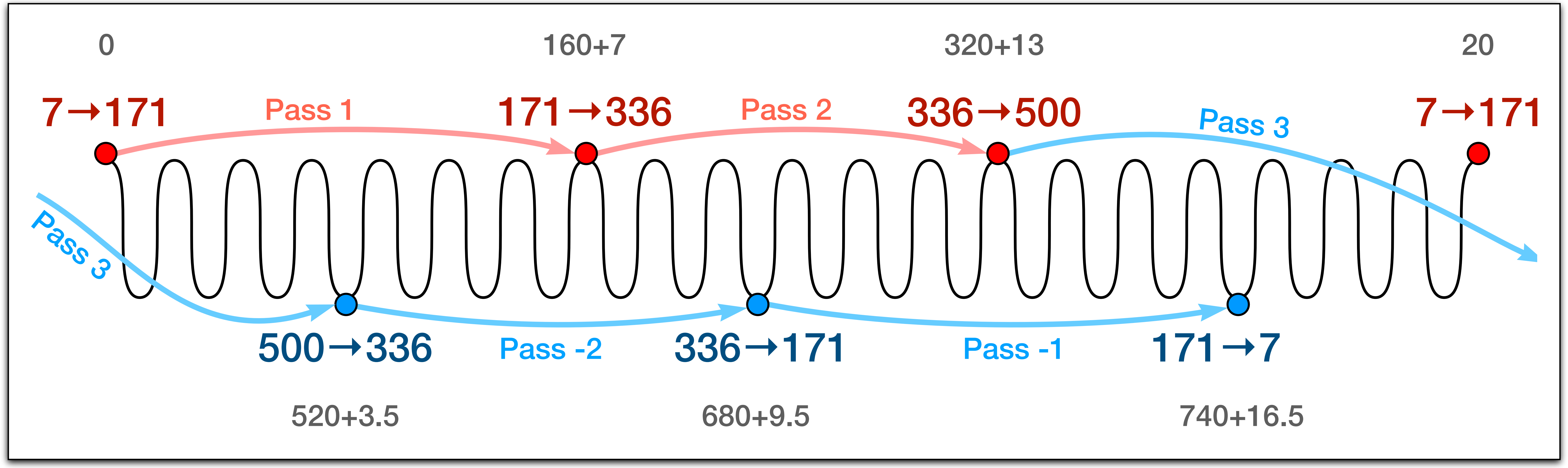
500 MeV

Full length of one turn: (160 + Δ) λ_{RF}

chosen shift: Δ = 7, 6, 10.5, 6, 7

→ 2.7 m at IPs (28.6 m total)

studies by A. Bogacz, P. Williams, R.Apsimon, and K. Andre



250 MeV

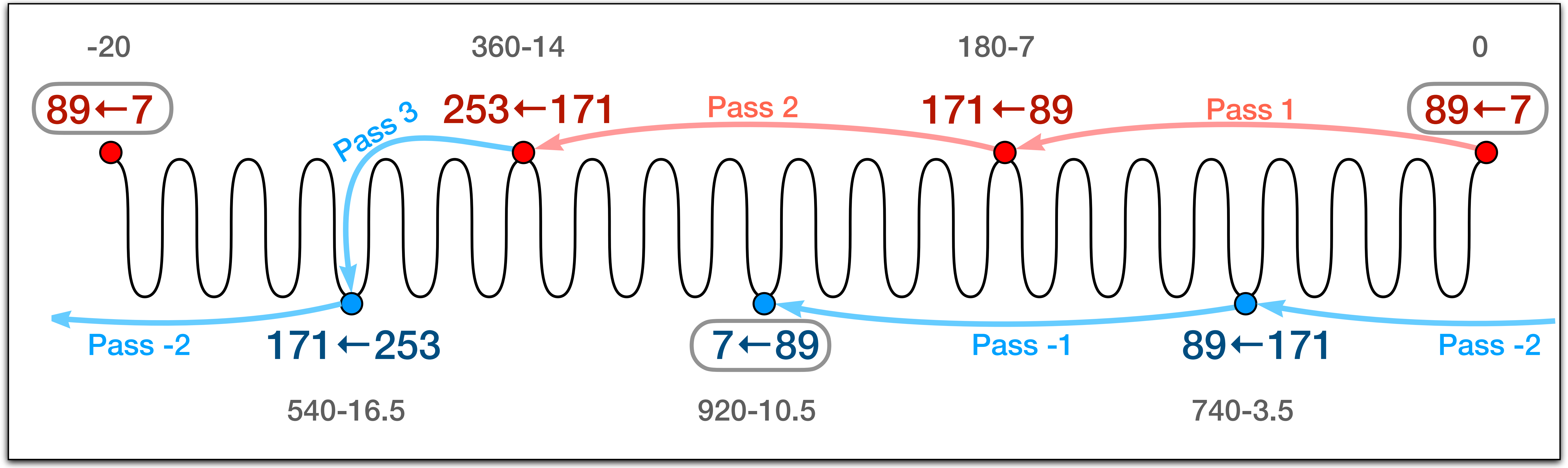
Full length of one turn: (180 - Δ) λ_{RF}

optimal shift: Δ = 7, 7, 2.5, 7, 7

→ bunches of lowest energies are separated (more important than for 500 MeV version)

→ more detailed studies will follow)

→ 29.9 m of total length



(177.5—170.5) λ_{RF} / 2 = 3.5 λ_{RF} ≈ 1.3 m (λ_{RF} = 37.4 cm)

Conclusions

Motivation of 250 MeV version of PERLE

- **compatible with the upgrade to 500 MeV version** (the same elements used, only about 30 meters of extra beam pipes)
- **reduced immediate expenses** (second cryo-module, 18 dipoles and 21 quads can be purchased later)
- **demonstration of ERL with 6 paths at high current** (same as in 500 MeV version, but with half of the power)
- more space for experimental areas
- **additional expenses / manpower / shutdown time** (rebuilding / recommissioning for the full power machine)

Main differences of 250 MeV

- a slightly larger footprint (28.6 m → 29.9 m) shorter Arc6, but longer common section
- different filling pattern (optimal for low energies) — more detailed studies will follow
- less quadruple magnets — all compatible with current design (< 22 T/m < 34 T/m)

Benchmarking codes for lattice design and beam dynamics simulation

- small difference between Optim6 and MadX calculations of dipole fringe field effect (~1% correction of the quad field)
- longitudinal beam dynamic from 7MeV to 82MeV with field-map & calculation tool (work of Coline Guyot)

Thank you

Lattice design. 500 MeV vs 250 MeV versions

500 MeV

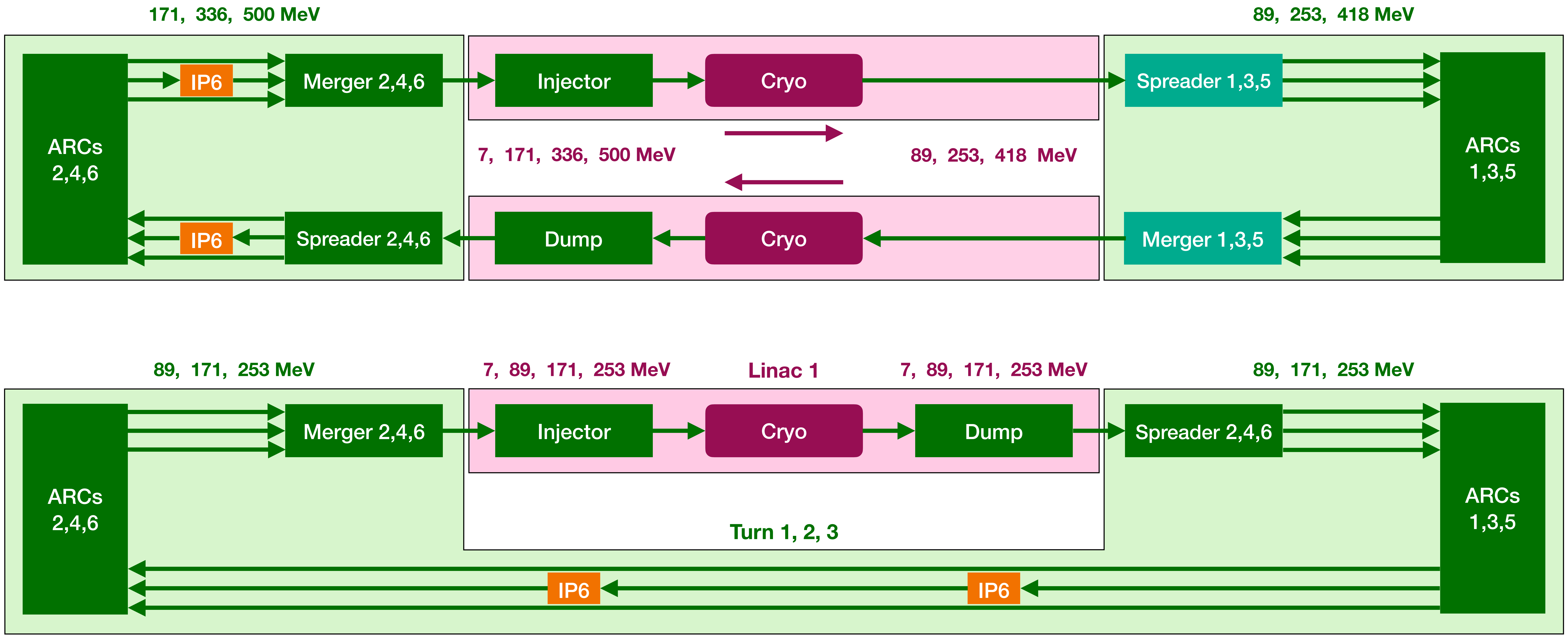
Shorter **common area**

→ 28.6 m total length

250 MeV

Shorter **Arc 6**

→ 29.4 m total length



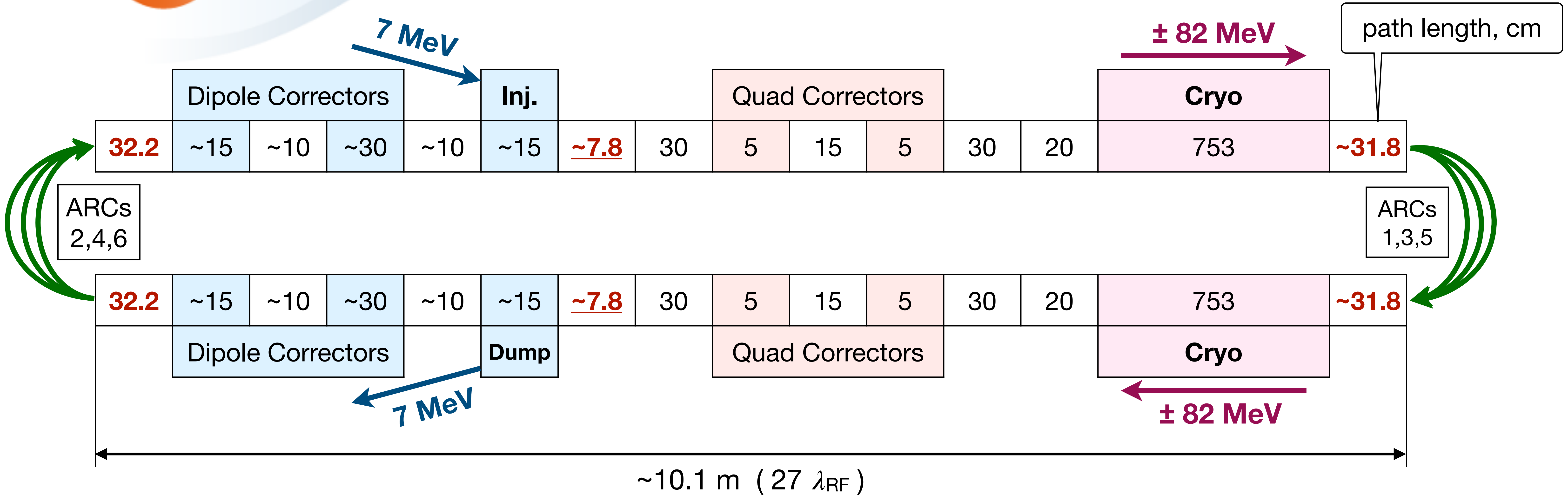
Two cryo-modules (500 MeV)

- two common sections: Injector+Cryo and Cryo+Dump (~10m)
- two Spreader and two Merger sections
- extended Arc6 (hosting low-beta IRs)

One cryo-module (250 MeV)

- one common sections: Injector+Cryo+Dump (~12m)
- one Spreader and one Merger section
- low-beta IRs at the straight line (between Arcs 5 & 6)

Section(s) with common beam pipe

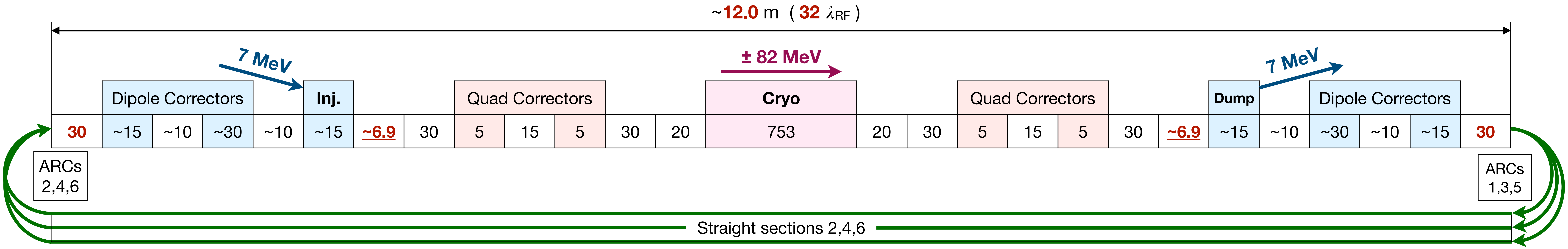


500 MeV → 250 MeV

- **Injection and Dump** are on the <u>same side</u>
- Drifts around **Dipole Correctors** shortened by <u>**1-2 cm**</u>
- Length of the straight section

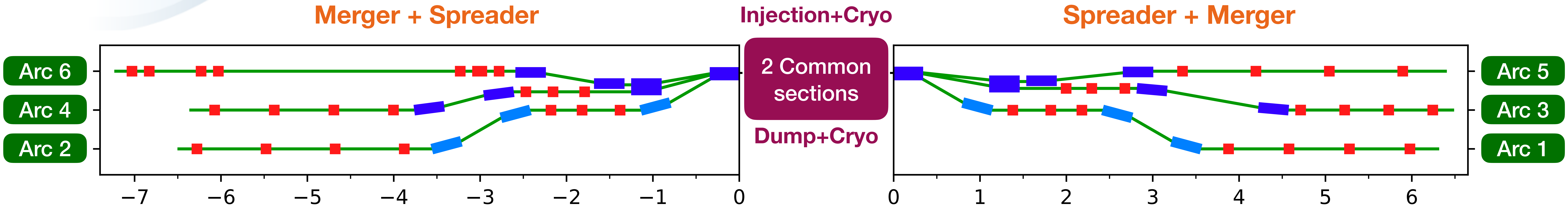
  $27\lambda \rightarrow 32\lambda$ (λ = 37.4 cm)

  10.1 m → 12.0 m

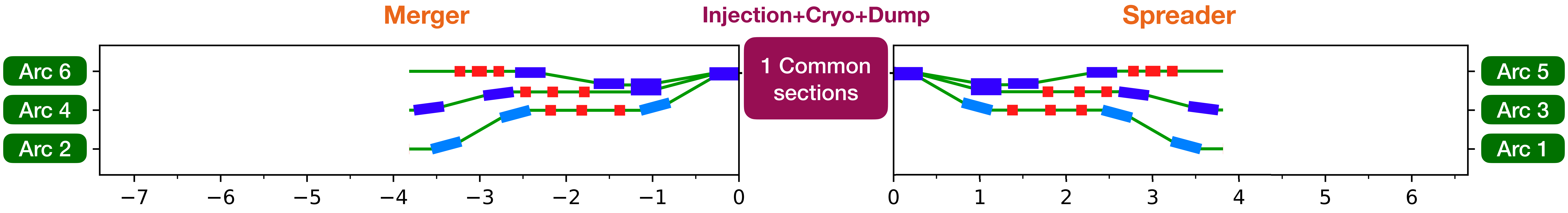


Spreaders / Mergers

500 MeV



250 MeV



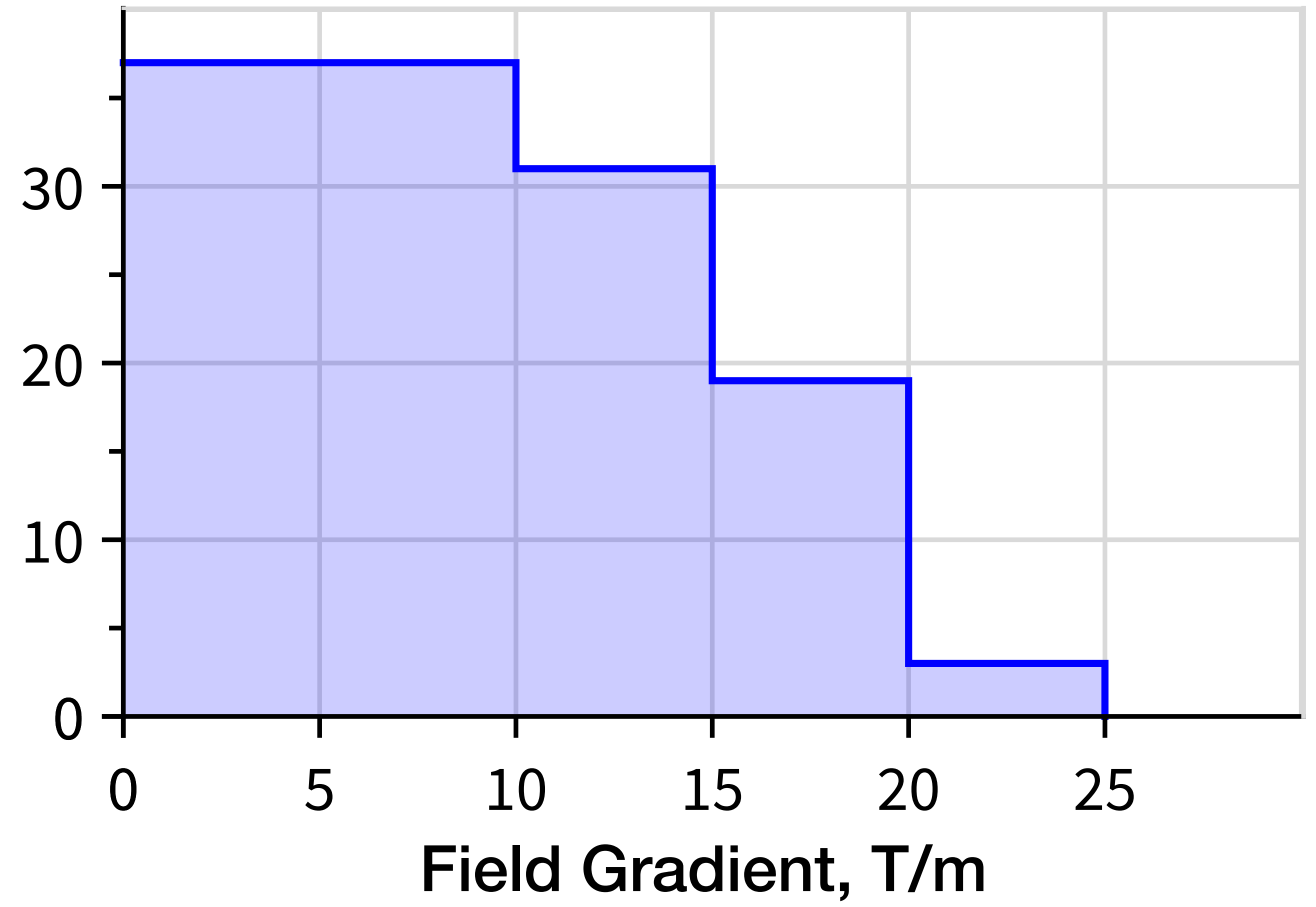
Optics for 250 MeV version (preliminary)

Quadrupole Magnets

Field, T and Field Gradient, T/m (500 MeV)

			10 cm	15 cm	10 cm	Spreaders			10 cm	10 cm	10 cm	10 cm		10 cm	15 cm	10 cm	Arcs	10 cm		10 cm	15 cm
1	-0.45	0.47	-4.3	4.9	-5.0	-0.47	0.47		4.0	-3.4	-0.53	-0.42	0.48	-4.7	5.1	-4.9	0.48	2.9	0.48	-5.3	4.1
2	-0.87	0.9	-8.2	9.5	-9.5	-0.9	0.9		7.3	-6.1	-1.8	0.61	0.92	-9.2	9.7	-9.3	0.92	6.2	0.92	-11.2	7.8
3	-0.45	0.45	-29.7	28.0	-23.4	-0.45	0.45		-16.0	19.0	-27.2	9.6	1.36	-9.2	16.7	-13.5	1.36	4.5	1.36	-14.1	16.9
4	-0.87	0.87	-32.0	35.7	-37.9	-0.87	0.87		-7.6	10.6	-10.8	10.2	0.9	-18.6	28.4	-25.3	0.9	15.7	0.9	-20.1	27.0
5	-0.45	0.45	0.45	-0.45	10 cm	15 cm	10 cm		-9.5	20.0	-14.8	31.9	1.12	-27.2	36.4	-27.5	1.12	17.9	1.12	-29.2	37.8
6	-0.87	0.87	0.87	-0.87	-28.1	27.7	-16.4	iIR	-54.9	44.4	30.9	-46.2	1.34	-32.6	43.0	-32.5	1.34	21.2	1.34	-34.1	44.1

Number of quadrupoles vs gradient (250 MeV)

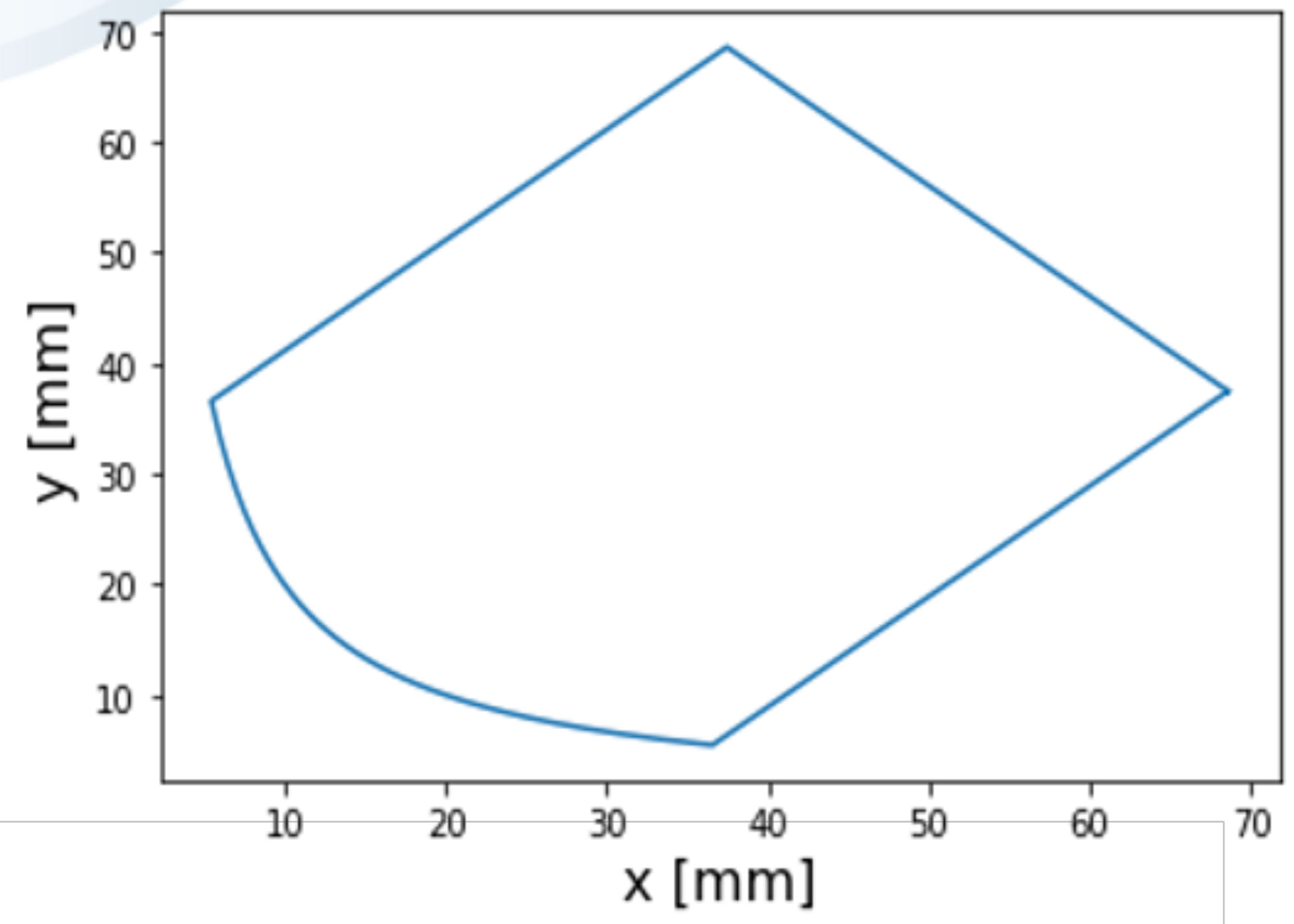


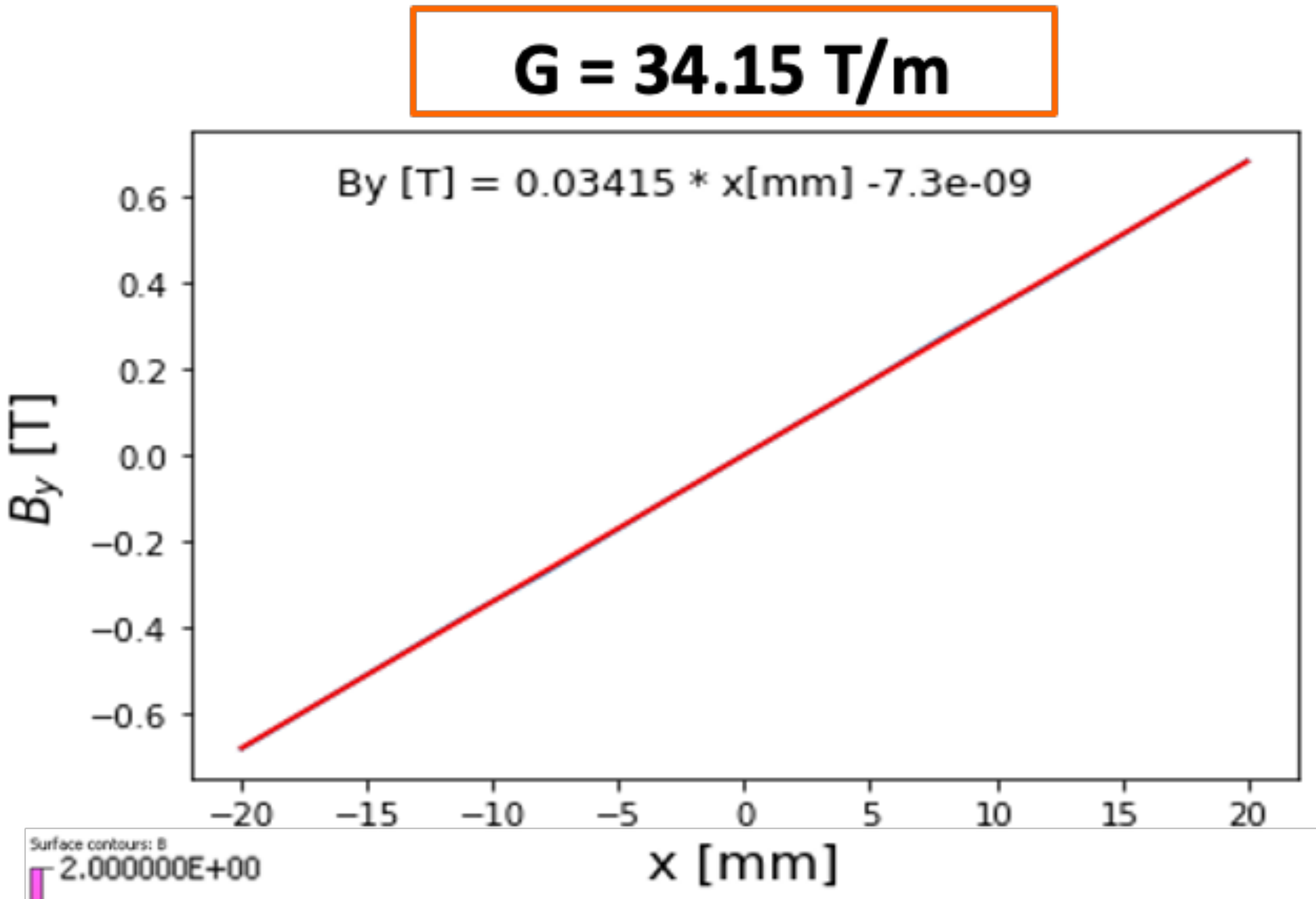
500 MeV: 144 quadruples (**16 at saturation**)

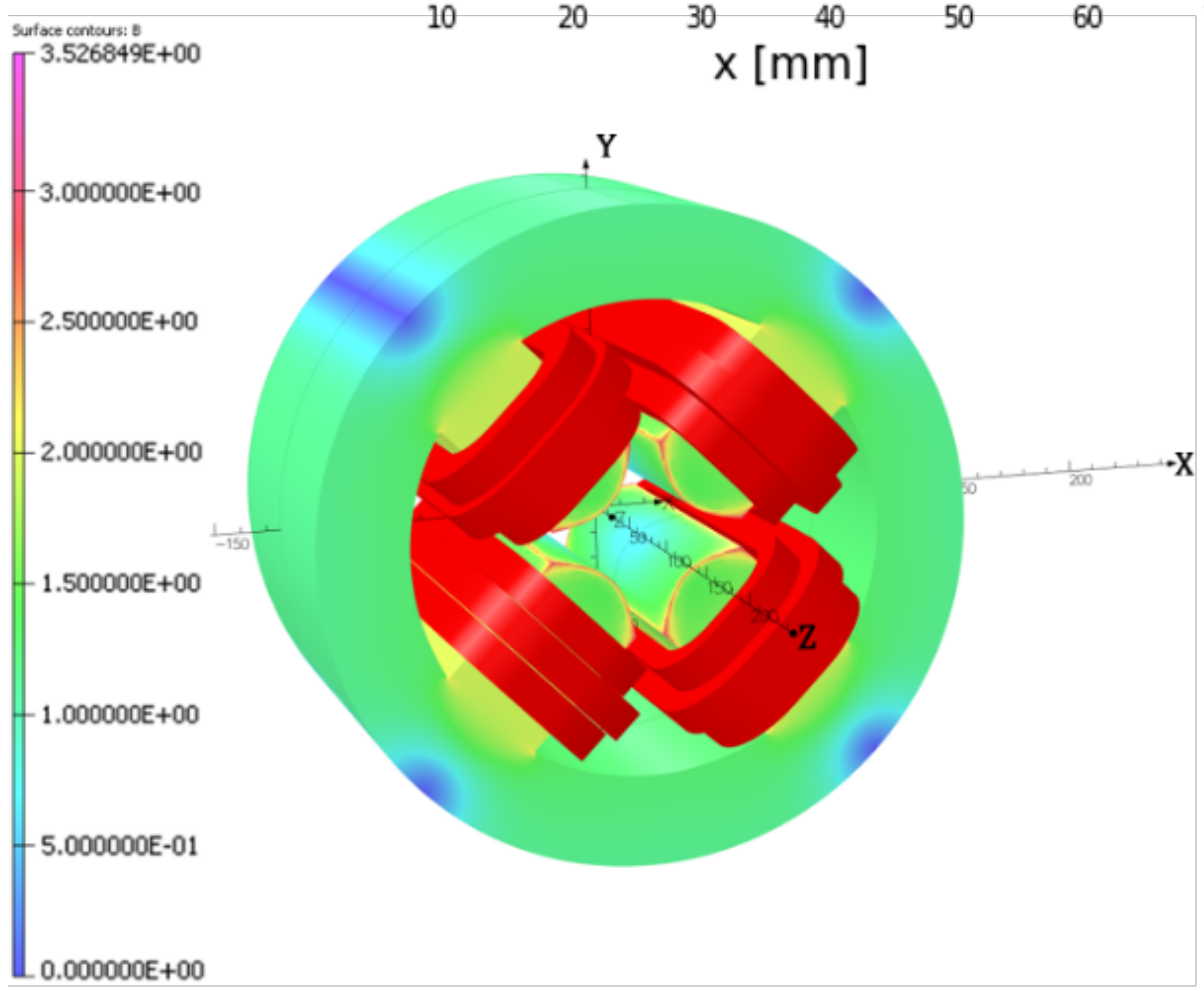
250 MeV: 127 quadruples (17 quads less) **all are below the saturation** (34.15 T/m)

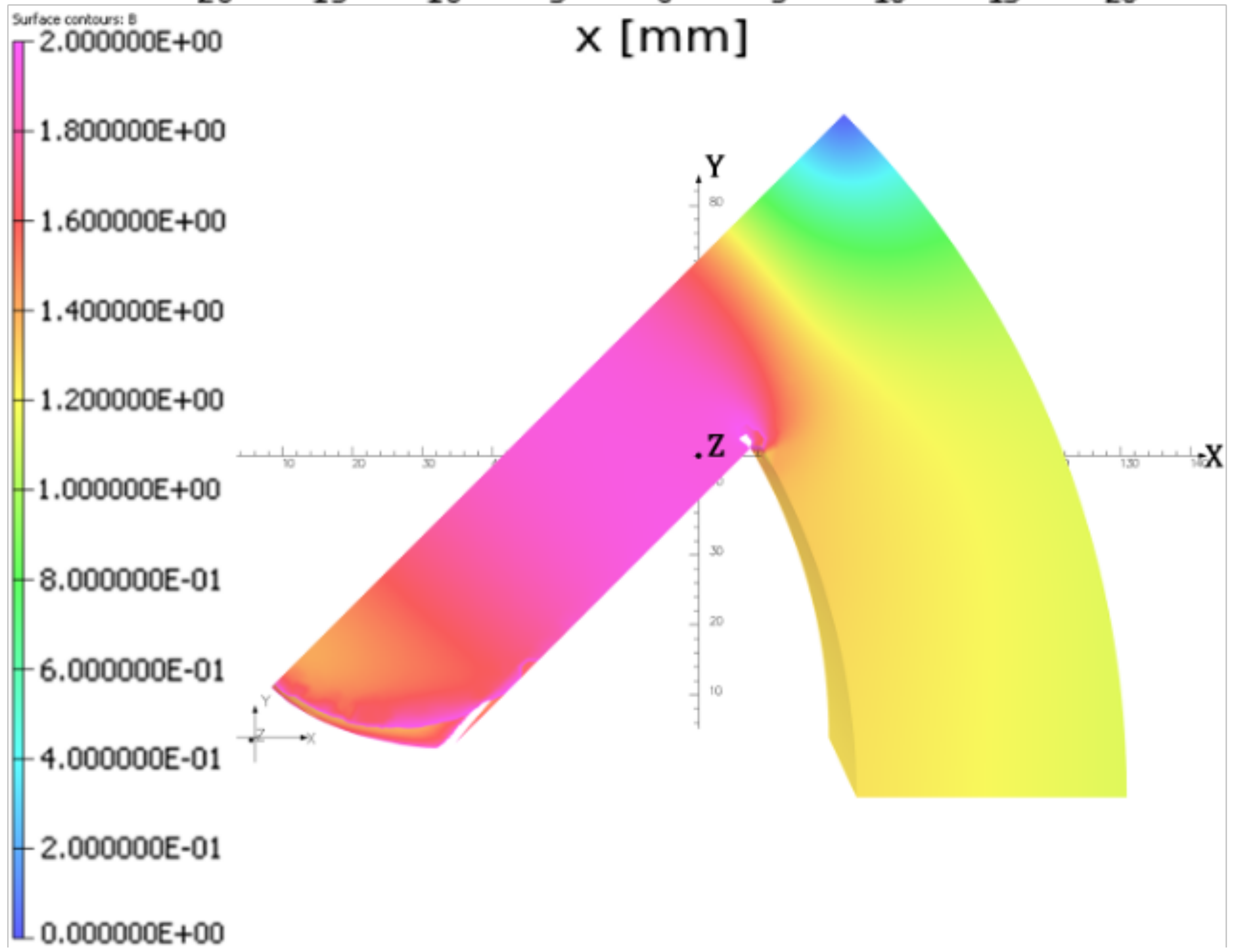
Quadrupole Magnet (work by Rasha Abukeshek)

Multi-coil design







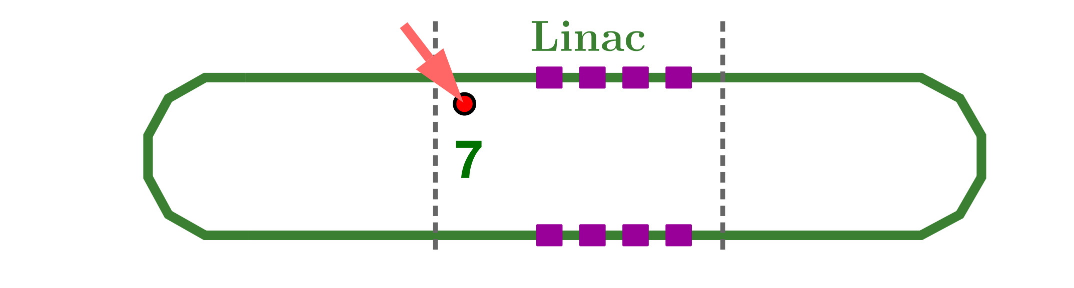
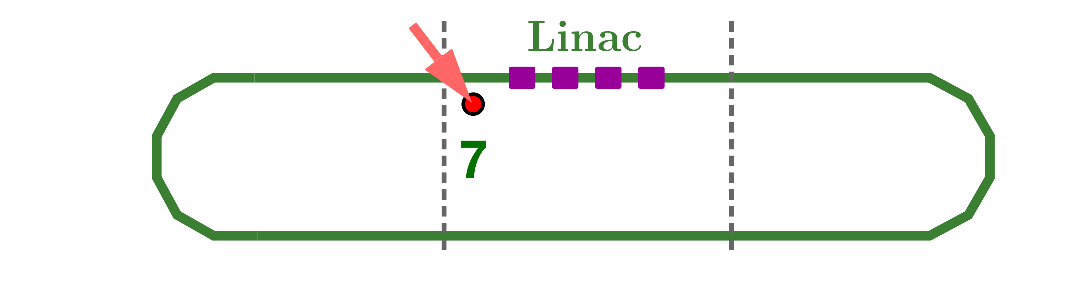
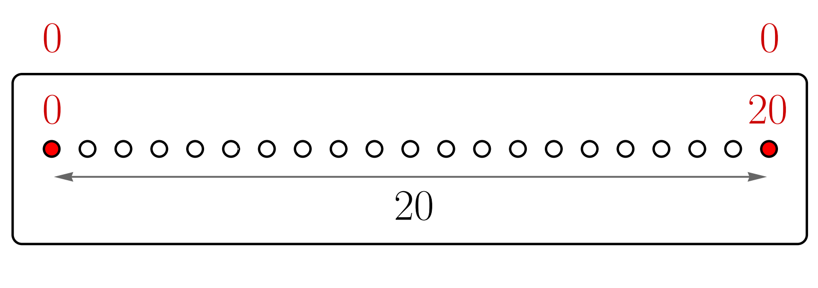
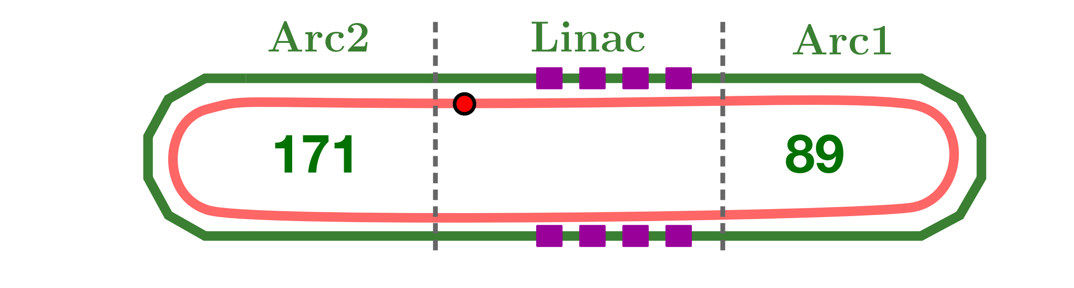
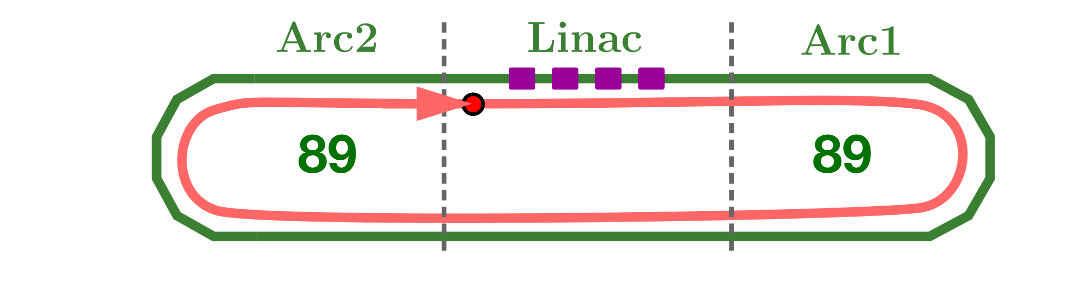
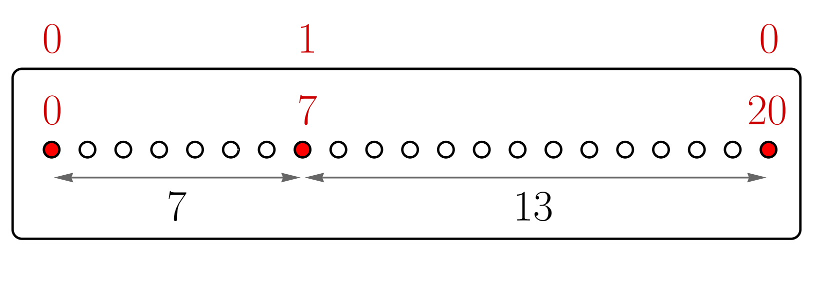
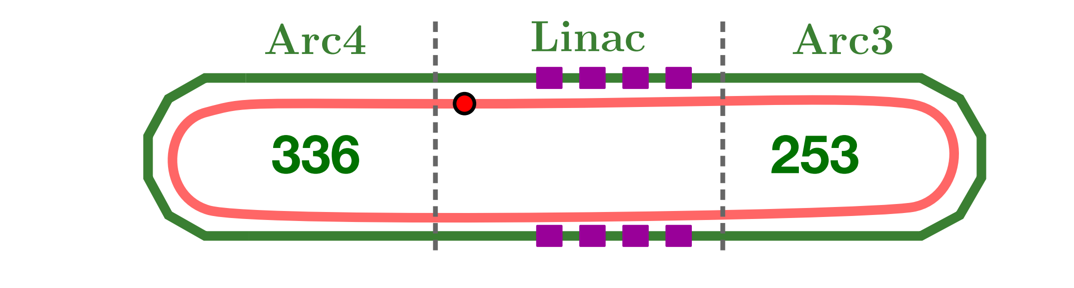
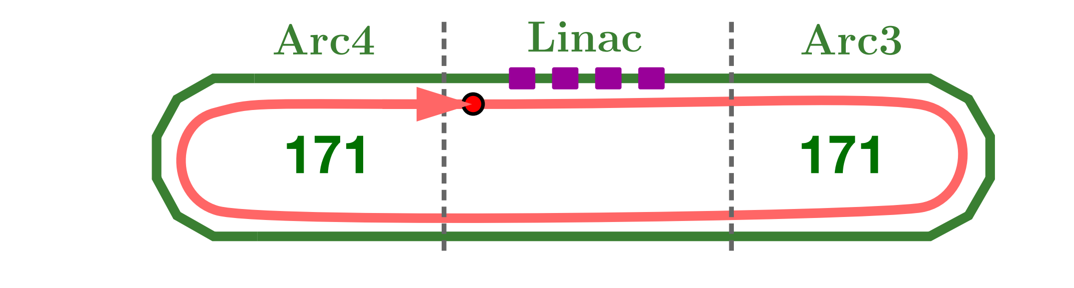
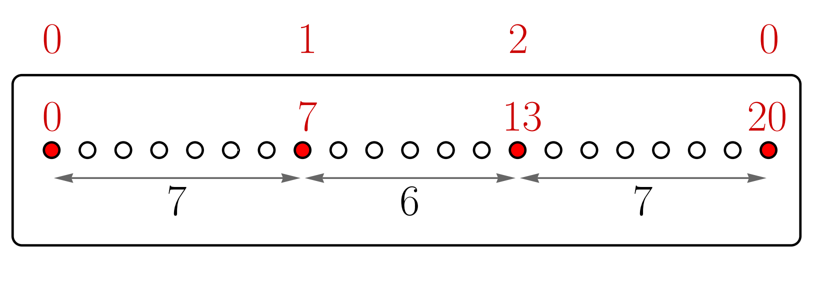
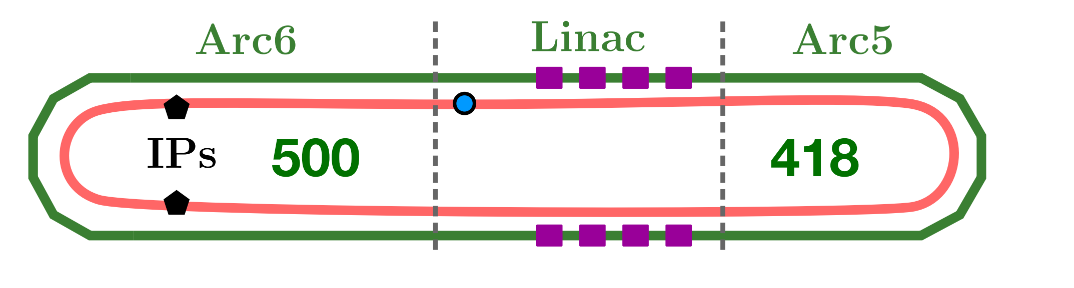
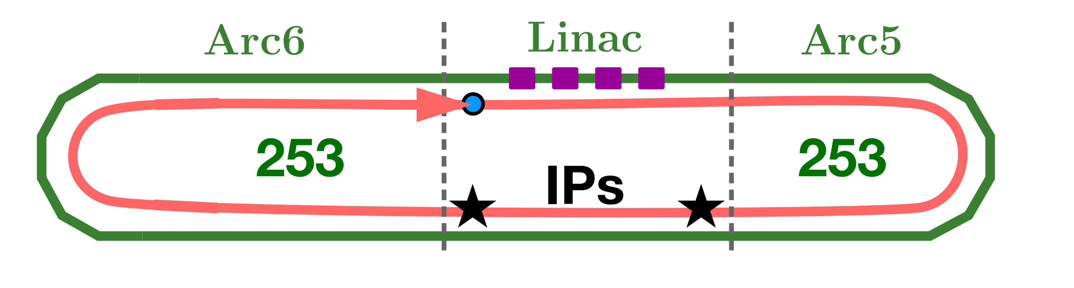
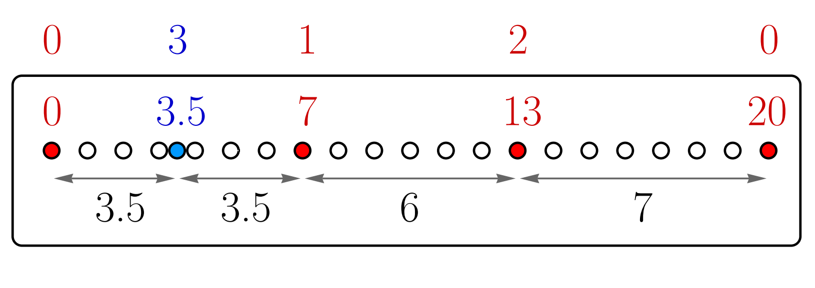
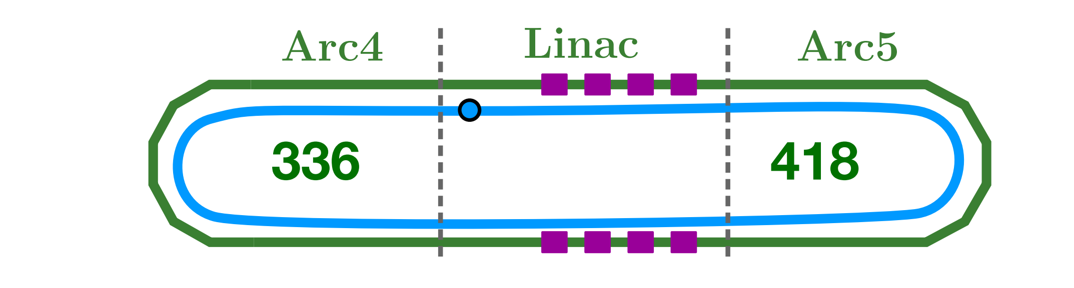
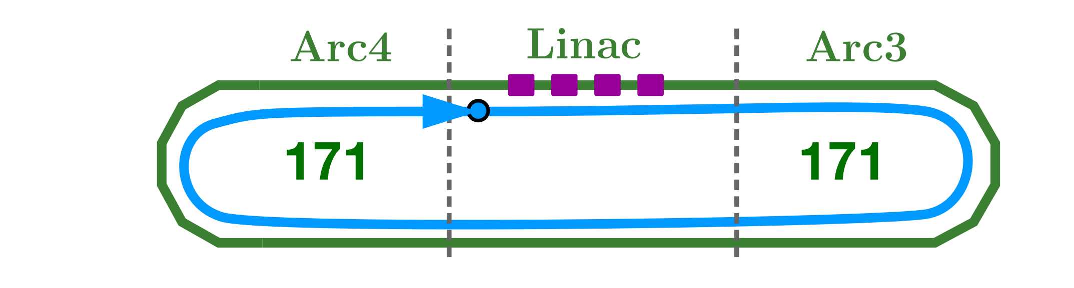
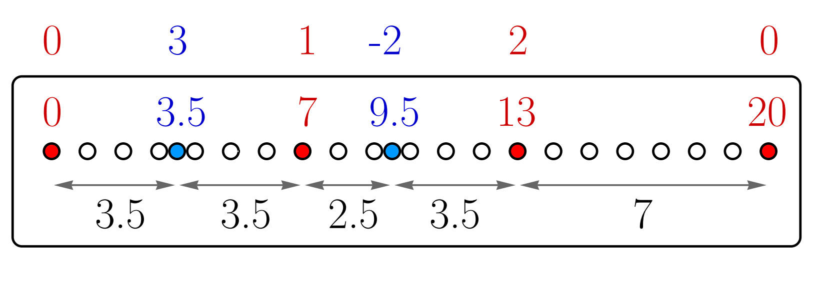
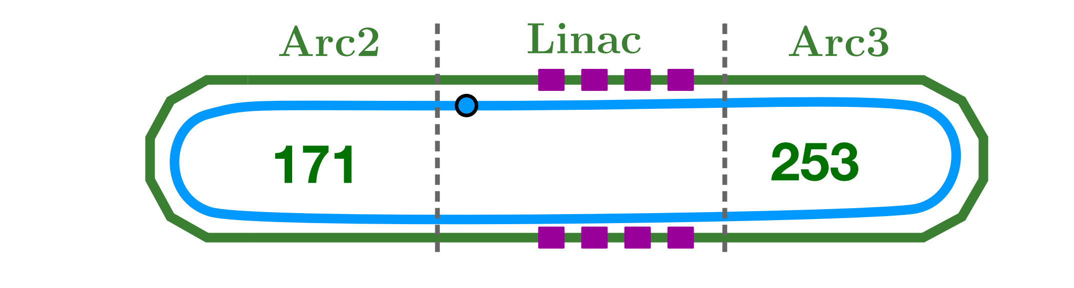
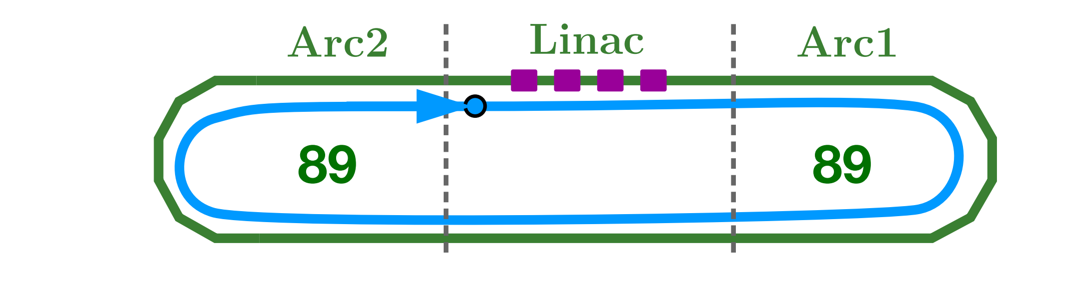
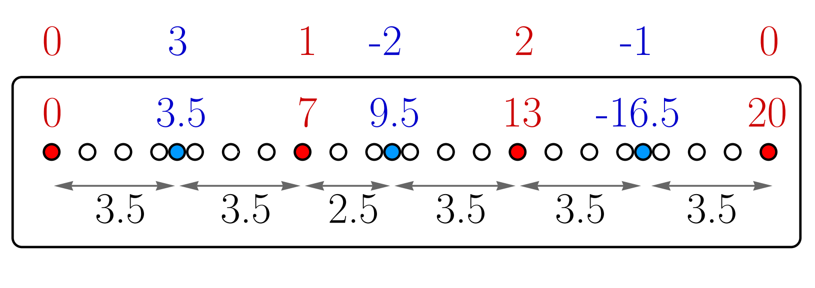
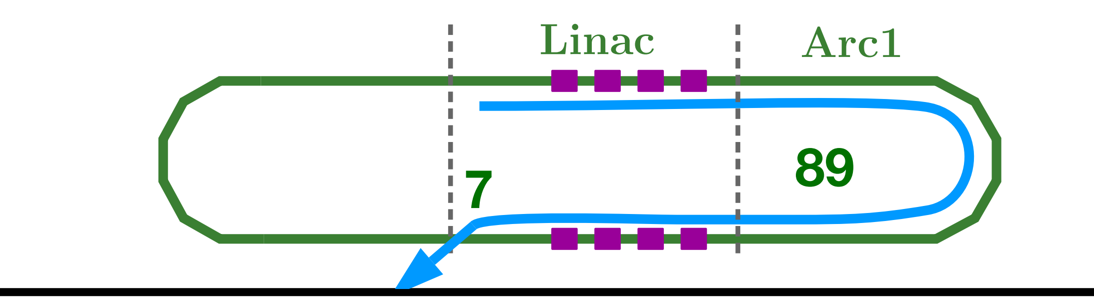
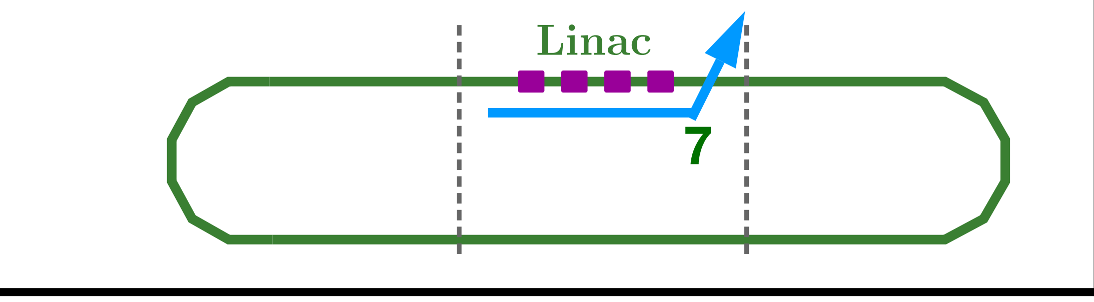
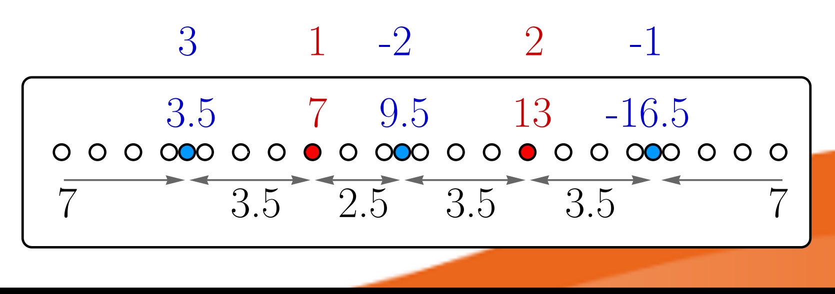


Parameters	Value
Height	250 mm
Yoke thickness	35 mm
Length	150 mm
Aperture radius	20 mm
Pole width	44 mm
Max. gradient	44.1 T/m
NI per coil	1750.7 A.turn
Pole tip field	0.685 T

- ✓ 15 cm quadrupole: design is ready up to the 4th arc.
- ✓ arcs 5 and 6: design saturation.

Suggested solution: pole tapering

Filling pattern

	Two Cryomodules (500 MeV)		One Cryomodule (253 MeV)		
After	*E*, MeV		*E*, MeV		Filling Pattern
Pass 0	7		7		
Pass 1	171		89		
Pass 2	336		171		
Pass 3	500		253		
Pass -2	336		171		
Pass -1	171		89		
Dump	7		7		

Filling pattern

Chosen for 500 MeV

shifts after each turn: Δ = 7, 6, 10.5, 6, 7

→ 2.7 m free space at IPs

→ total length 28.6 m

Optimal filling pattern

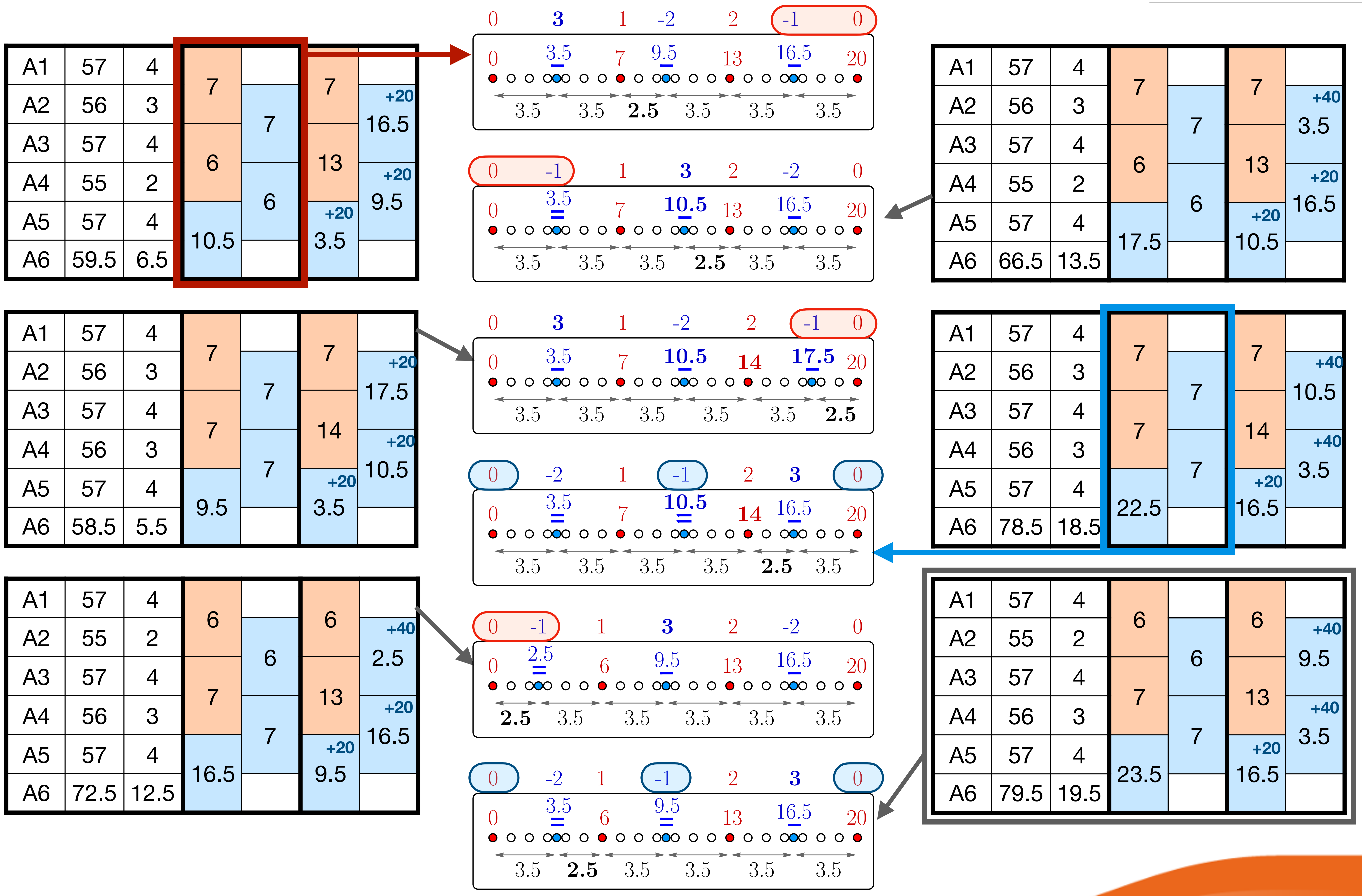
shifts after each turn: Δ = 7, 7, 2.5, 7, 7

→ separation of lowest energies bunches

→ more important for 250 MeV version

Possible adjustments

- the lengths of each even Arcs can be reduced by the same value as each of all odd Arcs increased (and vice versa)
- length of any Arc can be adjusted by integer number of 20 (Δ → Δ ± 20n)
- all shifts can be inverted (Δ → -Δ)



Transition between Optim6 and MadX

Optim6

```
g1S01 B[kG]=-4.506411 Angle[deg]=0    EffLen[cm]=2
b1S01 L[cm]=34.55752  B[kG]=-4.506411 G[kG/cm]=0
G1S01 B[kG]=-4.506411 Angle[deg]=30   EffLen[cm]=3.849
```

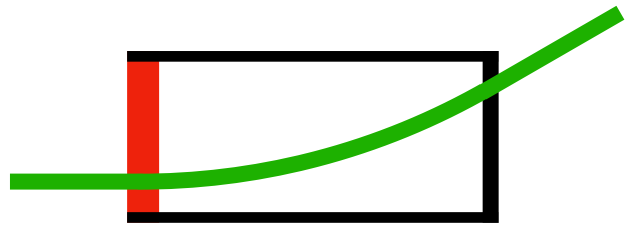
(all in vertical plane: TILT = π/2)

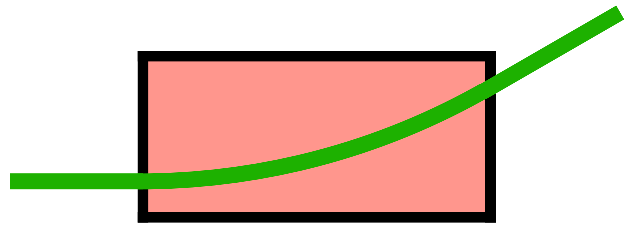
MadX

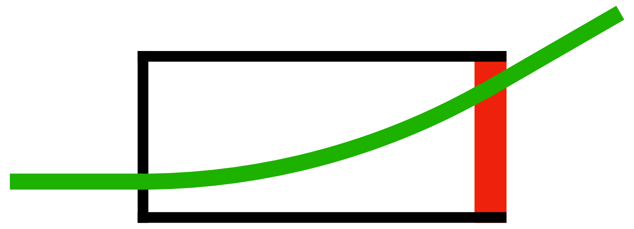
```
b1S01a: DIPEDGE, H=1.5151515, E1=0,      FINT=0.5, HGAP=0.02;
b1S01b: SBEND,   L=0.3455752, ANGLE=-π/6;
b1S01c: DIPEDGE, H=1.5151515, E1=-π/6,   FINT=0.5, HGAP=0.02;
```

Matching

	Place	Inital	Matched
Field gradient, T/m	qq1s01	-4.26551	-4.265**82**
	qq1s02	4.87074	4.**92812**
	qq1s03	-4.96549	-4.9654**7**
	qq1s04	-5.28356	-5.28**686**
	qq1s05	4.07249	4.07**428**
α_x	center	-0.0**14401**	0
α_y	center	0.000**17**	0







1					
0.04591	1				
		1			
			1		
				1	
					1

1	0.34558				
0	1				
		0.86603	0.33		-0.08842
		-0.75758	0.86603		-0.50000
		-0.50000	0.08842	1	-0.01556
					1

1					
-0.7864	1				
		1			
		0.87477	1		
				1	
					1

1					
0.04593	1				
		1			
			1		
				1	
					1

1	0.34558				
0	1				
		0.86603	0.33		-0.08842
		-0.75758	0.86603		-0.50001
		-0.50001	0.08842	1	-0.01556
					1

1					
-0.7885	1				
		1			
		0.87477	1		
				1	
					1

The edge focusing of a dipole is not identical in two codes

With a small correction (~1%) of the filed gradient
in quadrupoles the lattice can be symmetrized

Transition between Optim6 and MadX

Optim6

```
g1S01 B[kG]=-4.506411 Angle[deg]=0    EffLen[cm]=2
b1S01 L[cm]=34.55752  B[kG]=-4.506411 G[kG/cm]=0
G1S01 B[kG]=-4.506411 Angle[deg]=30   EffLen[cm]=3.849
```

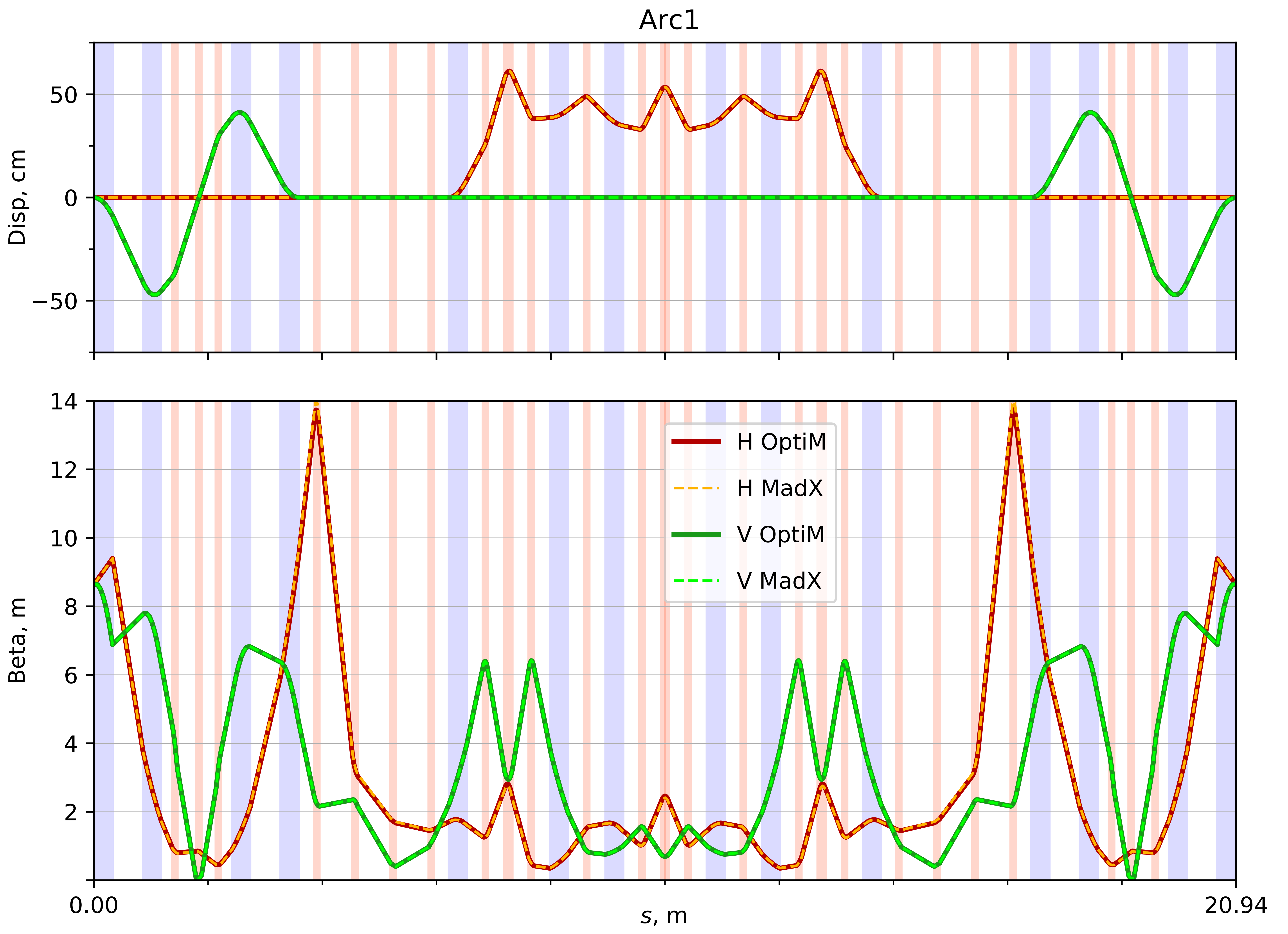
(all in vertical plane: TILT = π/2)

MadX

```
b1S01a: DIPEDGE, H=1.5151515, E1=0,      FINT=0.5, HGAP=0.02;
b1S01b: SBEND,   L=0.3455752, ANGLE=-π/6;
b1S01c: DIPEDGE, H=1.5151515, E1=-π/6,   FINT=0.5, HGAP=0.02;
```

Matching

	Place	Inital	Matched
Field gradient, T/m	qq1s01	-4.26551	-4.265**82**
	qq1s02	4.87074	4.**92812**
	qq1s03	-4.96549	-4.9654**7**
	qq1s04	-5.28356	-5.28**686**
	qq1s05	4.07249	4.07**428**
α_x	center	-0.0**14401**	0
α_y	center	0.000**17**	0



also benchmarked with CODAL (Coline Guyot)