Lattice design and optimisation of the 250 MeV version of PERLE

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Outline

Motivation for 250 MeV stage (pros and cons)

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

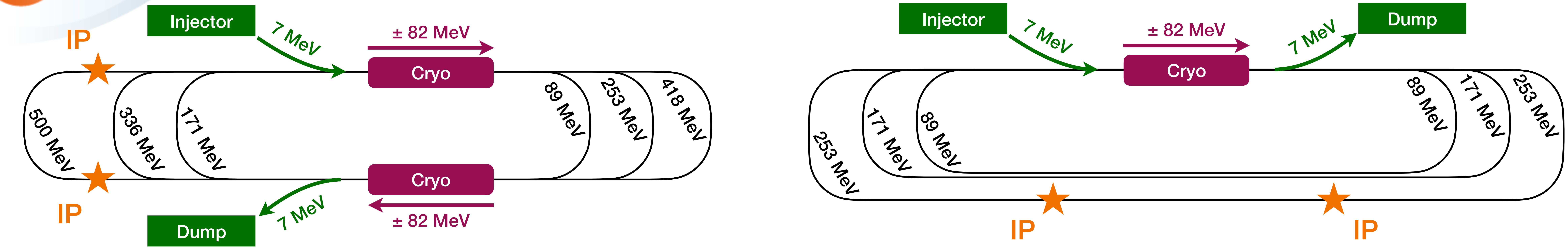
- general layout
- common beam pipe sections
- spreaders / mergers

Filling patterns (optimal for lower energies)

Optim6 → MadX (optimal for lower energies)

Conclusions

500 MeV → 250 MeV ?



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

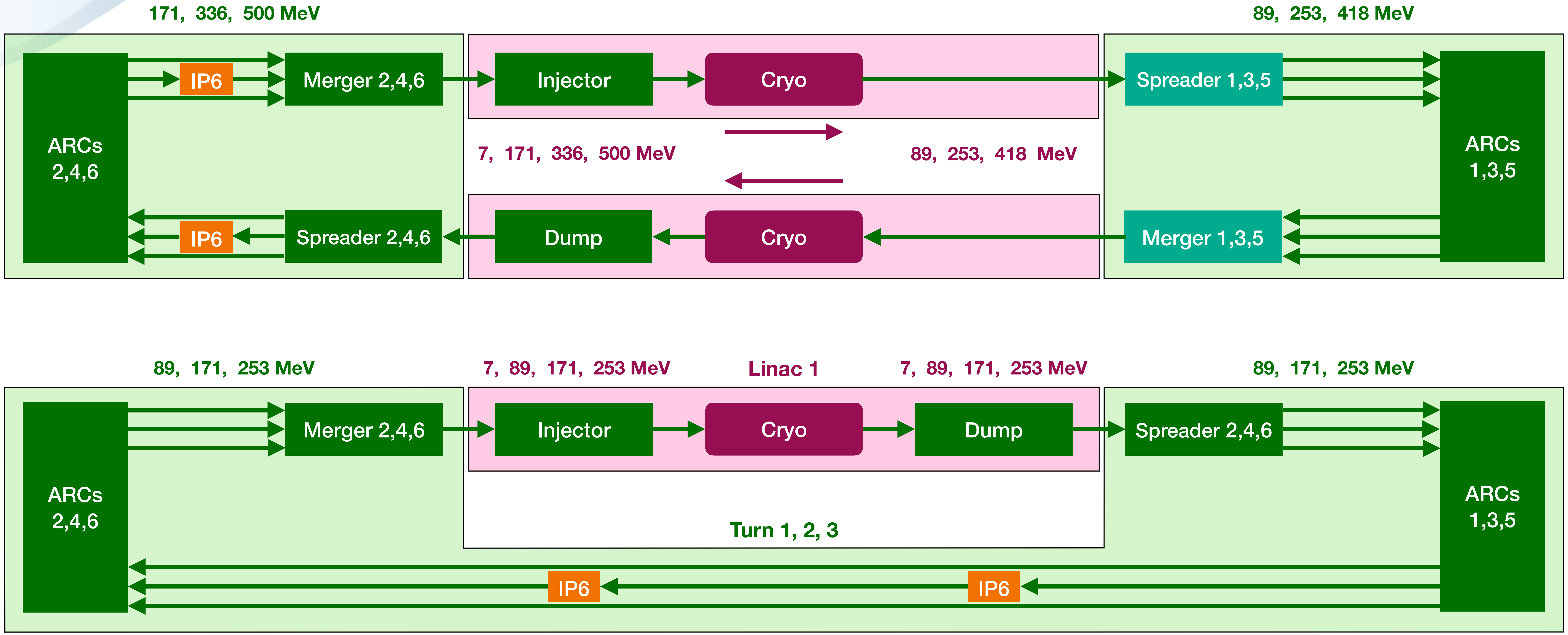
Cons:

- → **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 → 29.4 m)

Lattice design. 500 MeV vs 250 MeV versions

* Flipping the lattice vertically → IP with access from the top

Lattice design. 500 MeV vs 250 MeV versions



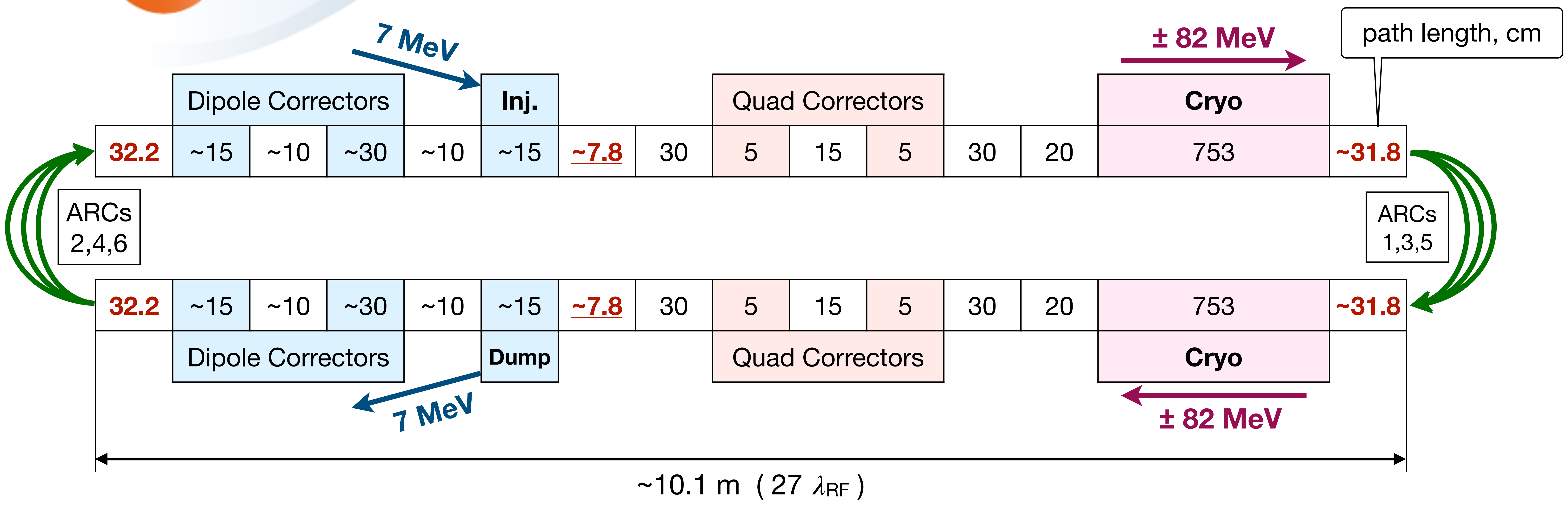
500 MeV (two cryo-modules)

- two common sections: Injector+Cryo and Cryo+Dump (~10m)
- two Spreader and two Merger sections

250 MeV (one cryo-module)

- one common sections: Injector+Cryo+Dump (~12m)
- one Spreader and one Merger section

Section(s) with common beam pipe



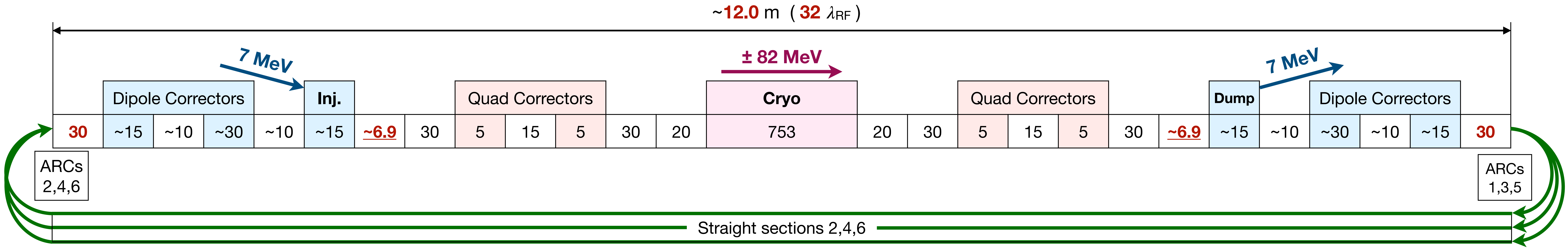
500 MeV → 250 MeV

- **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
- Can we move **Quad Correctors** to **Injection Line** ?

  - it can save up to 0.75 m (1.9 m) of the length

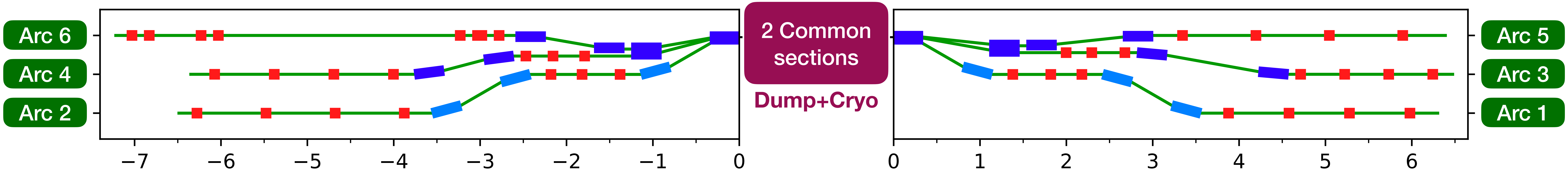
  - reduce the number of Quads by 2



Spreaders / Mergers

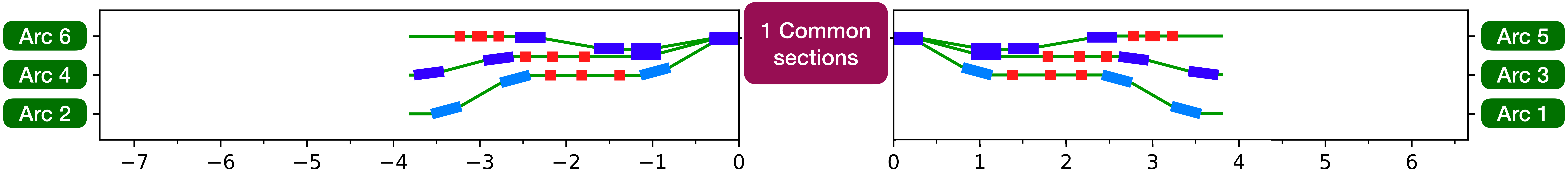
500 MeV

Merger + Spreader — Injection+Cryo — Spreader + Merger



250 MeV

Merger — Injection+Cryo+Dump — Spreader

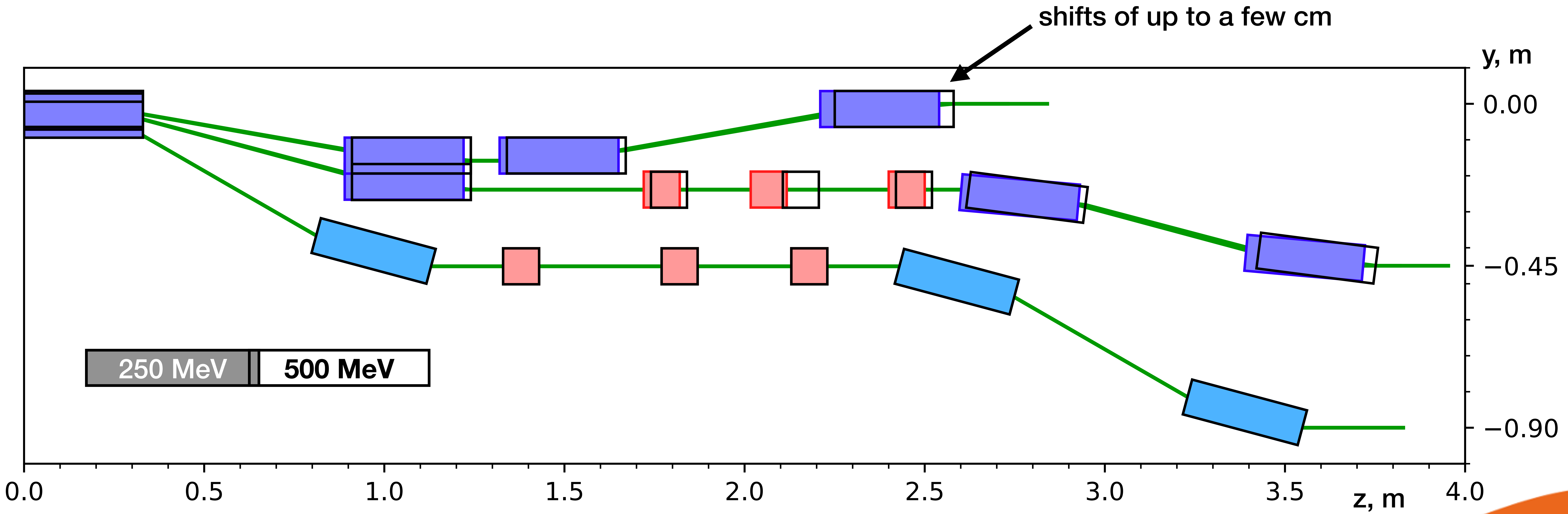


Spreaders / Mergers

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

→ we can use the same magnets, but the lattice should be adjusted (pipe lengths and tilts)

$$\Delta E + E_0 \;/\; 2\Delta E + E_0 \;/\; 3\Delta E + E_0 \approx 2\Delta E + E_0 \;/\; 4\Delta E + E_0 \;/\; 6\Delta E + E_0$$



Filling pattern

(size of the Arcs)

Filling pattern

Consecutive injections (υ_{inj} = 40 MHz)

RF cavity (υ_{RF} = 801.58 MHz)

→ spacing between injections **20** × λ_{RF}

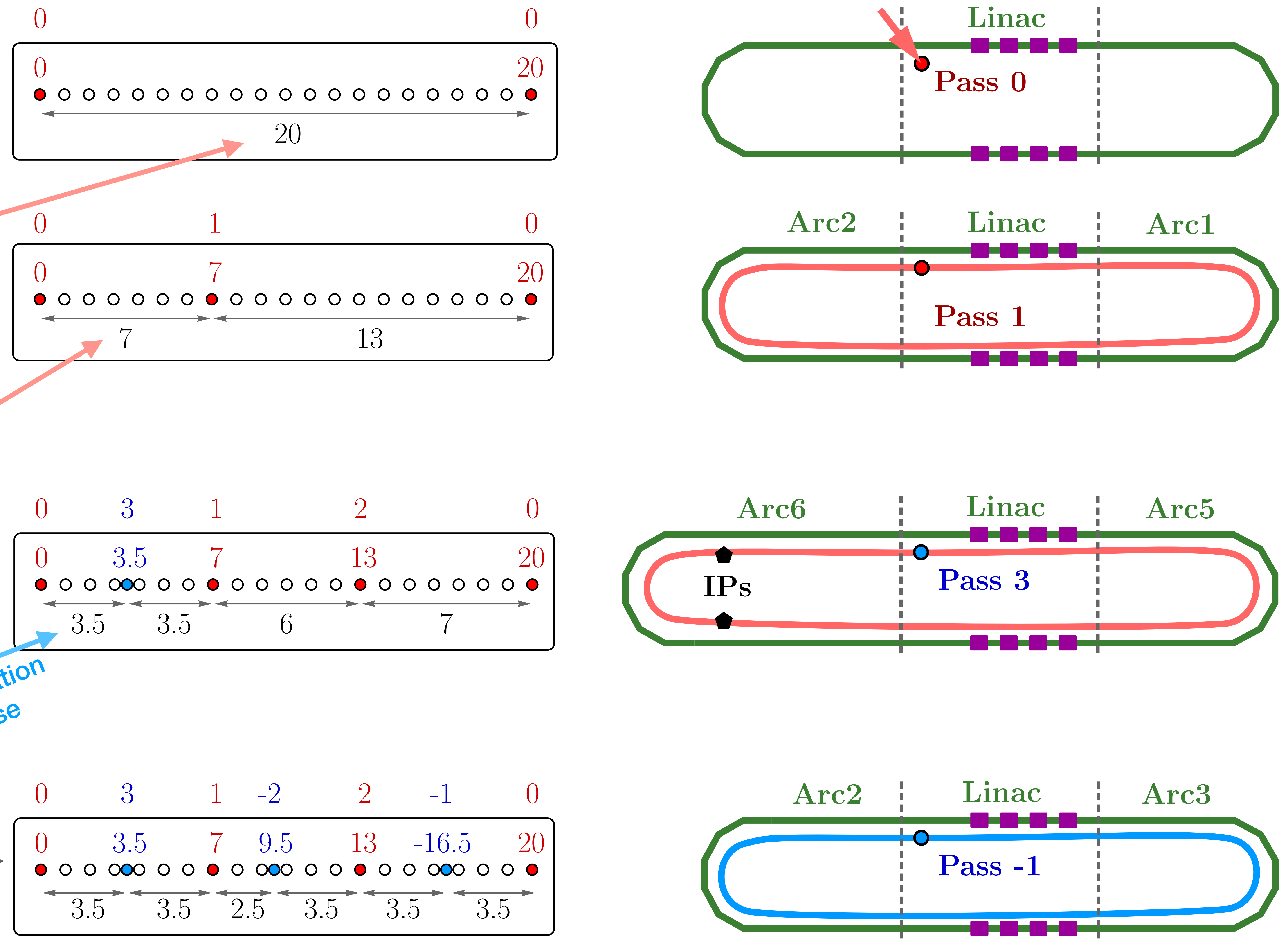
$\upsilon_{RF} / \upsilon_{inj} \approx 20$, λ_{RF} = 34.7 cm

Pass length of first turn is 20 × n + 7

Pass length of third turn is 20 × n + 7 + 3.5

deceleration phase

After 6 turns → uniform bunch filling pattern



* studies of Alex Bogacz, Peter Williams and Robert Apsimon

Filling pattern

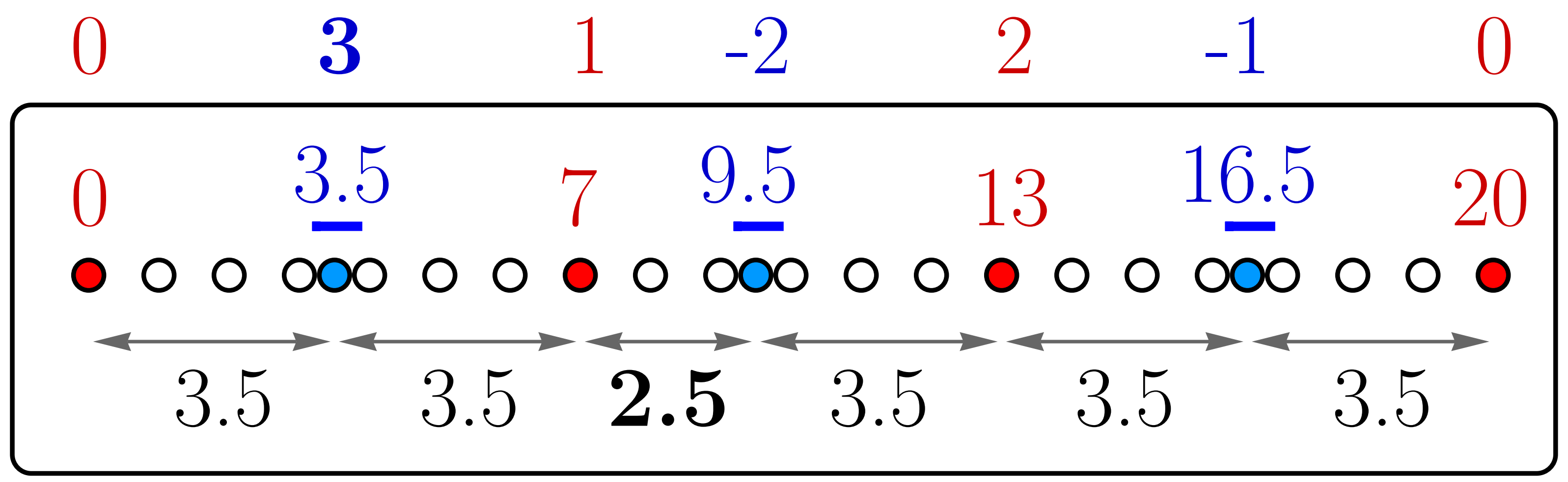
Adjusting the drifts lengths in spreader section → Match the filling pattern:

Linac section length 27 λ_{RF} (32 λ_{RF} for 250 MeV)

Full length of one turn >160 λ_{RF} (<180 λ_{RF} for 250 MeV)
(2 Arcs + 2 Linacs)

Length of the Arc without a shift:

$$\frac{160\ \lambda_{RF} - 2 \times 27\ \lambda_{RF}}{2} = 53\ \lambda_{RF}$$



Arc			Pass		
#	Length L_A, λ_{RF}	Shift (L_A - 53) ΔL_A, λ_{RF}	Shift ($\Delta L_A + \Delta L_A$) ΔL_P, λ_{RF}	Position ($\sum \Delta L_P$) s, λ_{RF}	#
0	0	-	-	0	0
1	57	4	7	7	1
2	56	3			
3	57	4	6	13	2
4	55	2			
5	57	4	10.5	20 + 3.5	3
6	59.5	6.5			
5	57	4	6	20 + 9.5	-2
4	55	2			
3	57	4	7	20 + 16.5	-1
2	56	3			

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

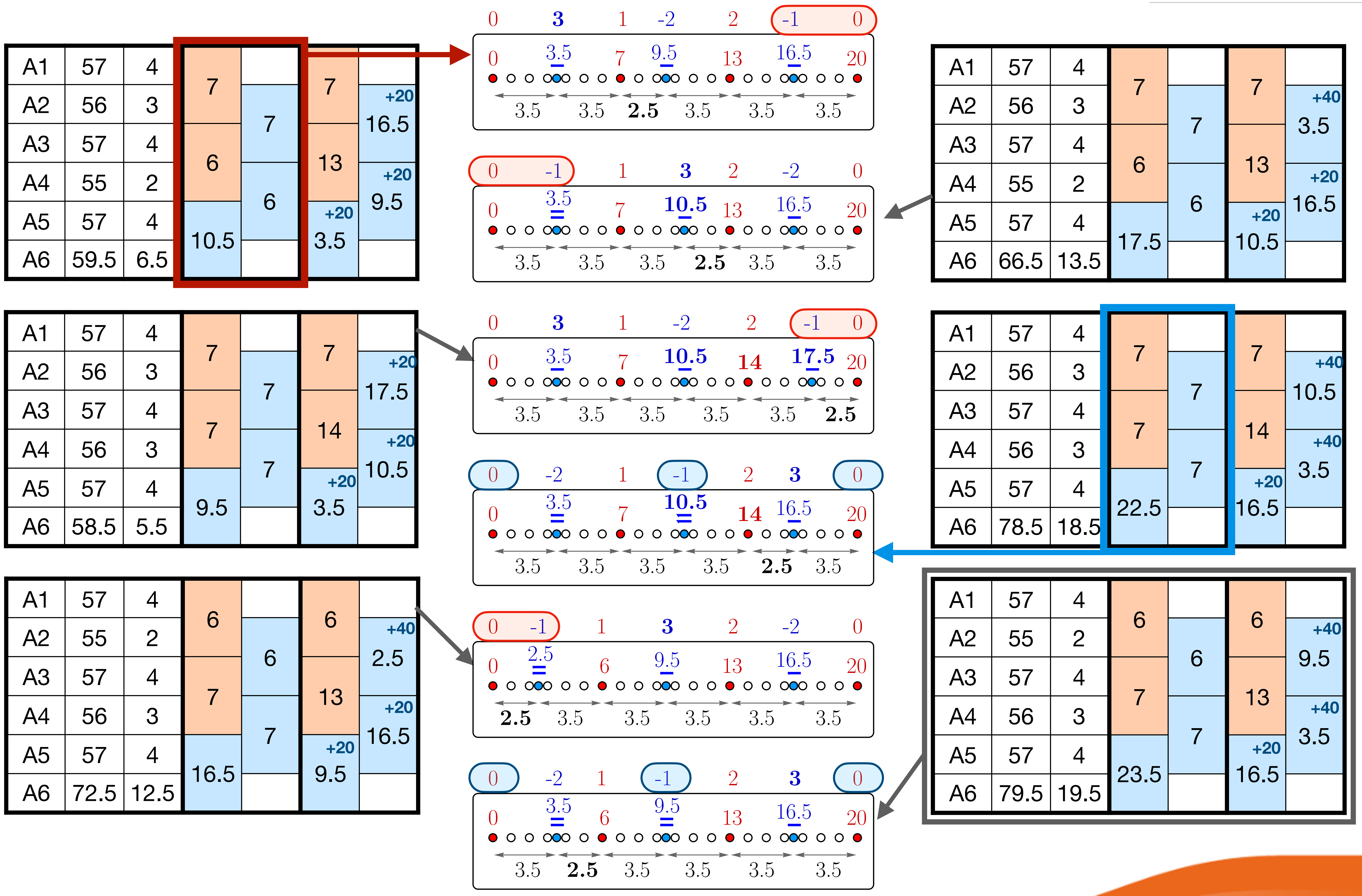
shifts after each turn: Δ = 7, 7, 2.5, 7, 7

→ 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)



Filling pattern

500 MeV

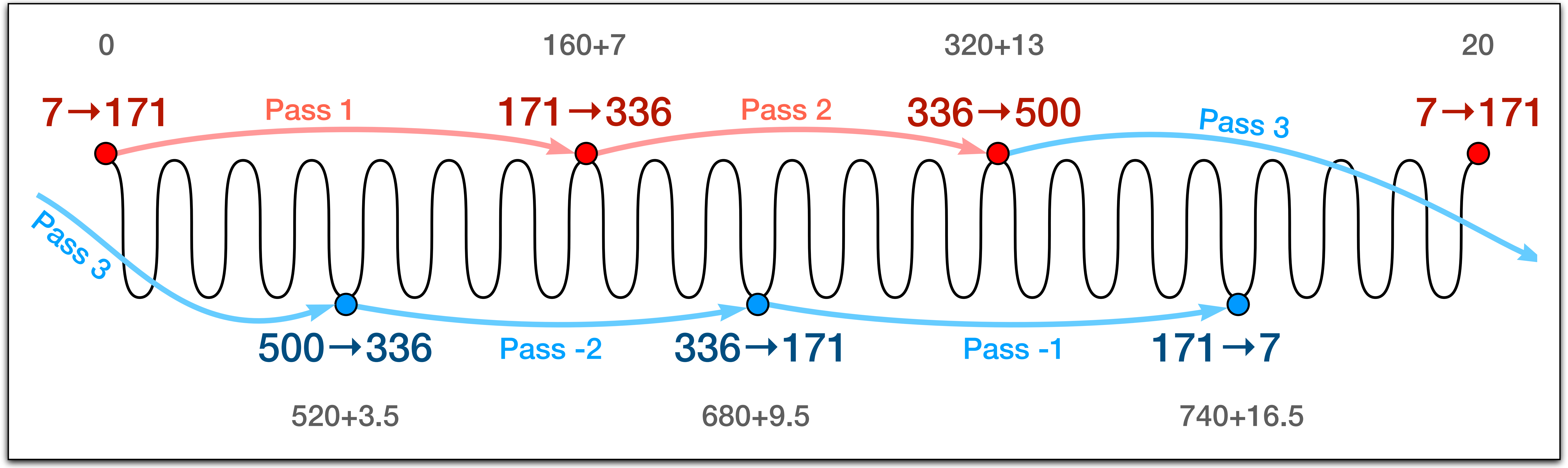
Full length of one turn: (160 + Δ) λ_{RF}

chosen shift: Δ = 7, 6, 10.5, 6, 7

→ 2.7 m at IPs (28.6 m total)

optimal shift

→ *4.7 m at IPs (30.6 m total)*



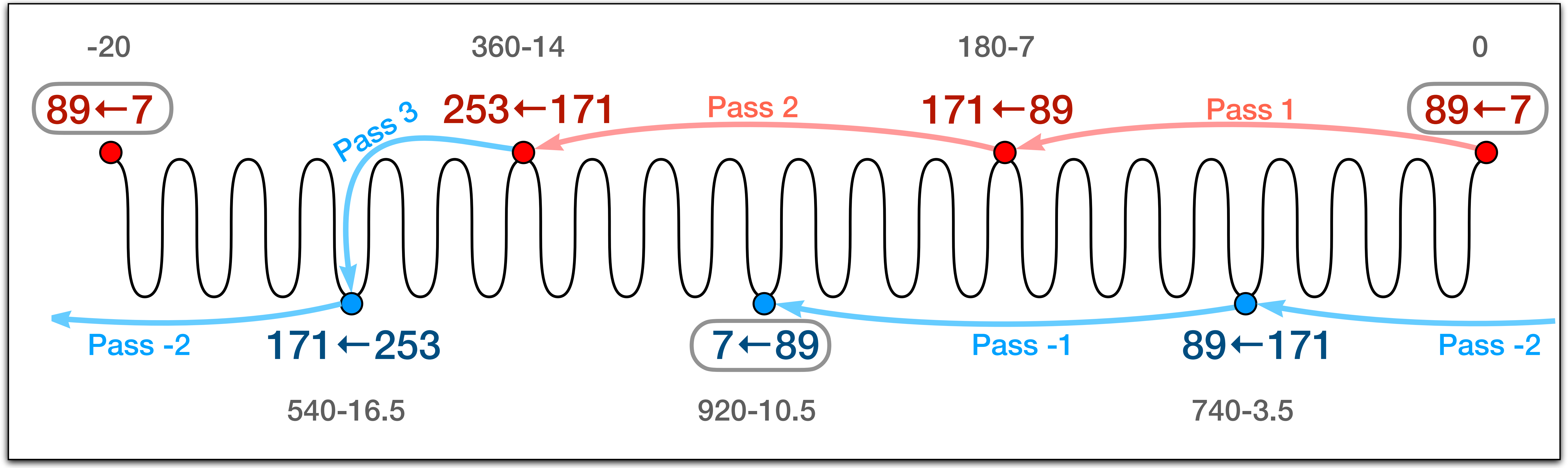
250 MeV

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)



Optim6 → MadX

Transition between Optim6 and MadX

Optim6 generates MadX sequence file with some errors, that have to be corrected:

OptiM6 (all in vertical plane: TILT = π/2)

```
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
```

MadX (generated by OptiM6)

```
b1S01: SBEND, L= 0.3455752, ANGLE=-π/6, E1= 0,   FINT =0.5, HGAP =0.02,
                                      E2=-π/6, FINTX=0.5, HGAPX=0.01039…;
```

MadX (corrected)

```
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;
```

OptiM6

```
A1   L[cm]=93.50048   Ncell=5        Eff_L[cm]=10
     A[MeV]=20.54167  Phase[deg]=0   WaveL[cm]=37.4002
```

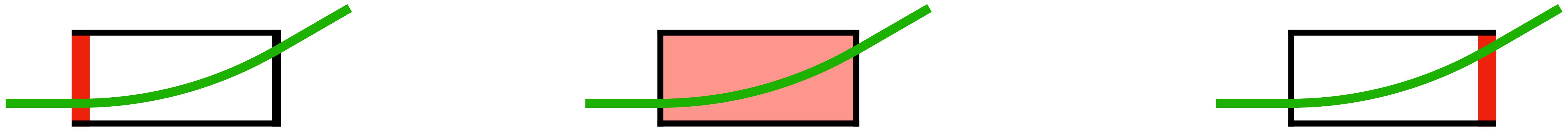
MadX (generated by OptiM6)

```
A1: LCAV, L= 0.9350048, DELTAE=20.54167, PHI0=0, FREQ=801580040.1;
```

MadX (corrected)

```
A1a: RFCAVITY, L=0.9350048 , VOLT=20.54167, LAG=0,
FREQ=801580040.1;
```

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 = $\pi/2$)

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;
```

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

Matching

	Place	Inital	Matched
Field gradient, T/m	qq1s01	-4.26551	-4.26582
	qq1s02	4.87074	4.92812
	qq1s03	-4.96549	-4.96547
	qq1s04	-5.28356	-5.28686
	qq1s05	4.07249	4.07428
α_x	center	-0.014401	0
α_y	center	0.00017	0

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
```

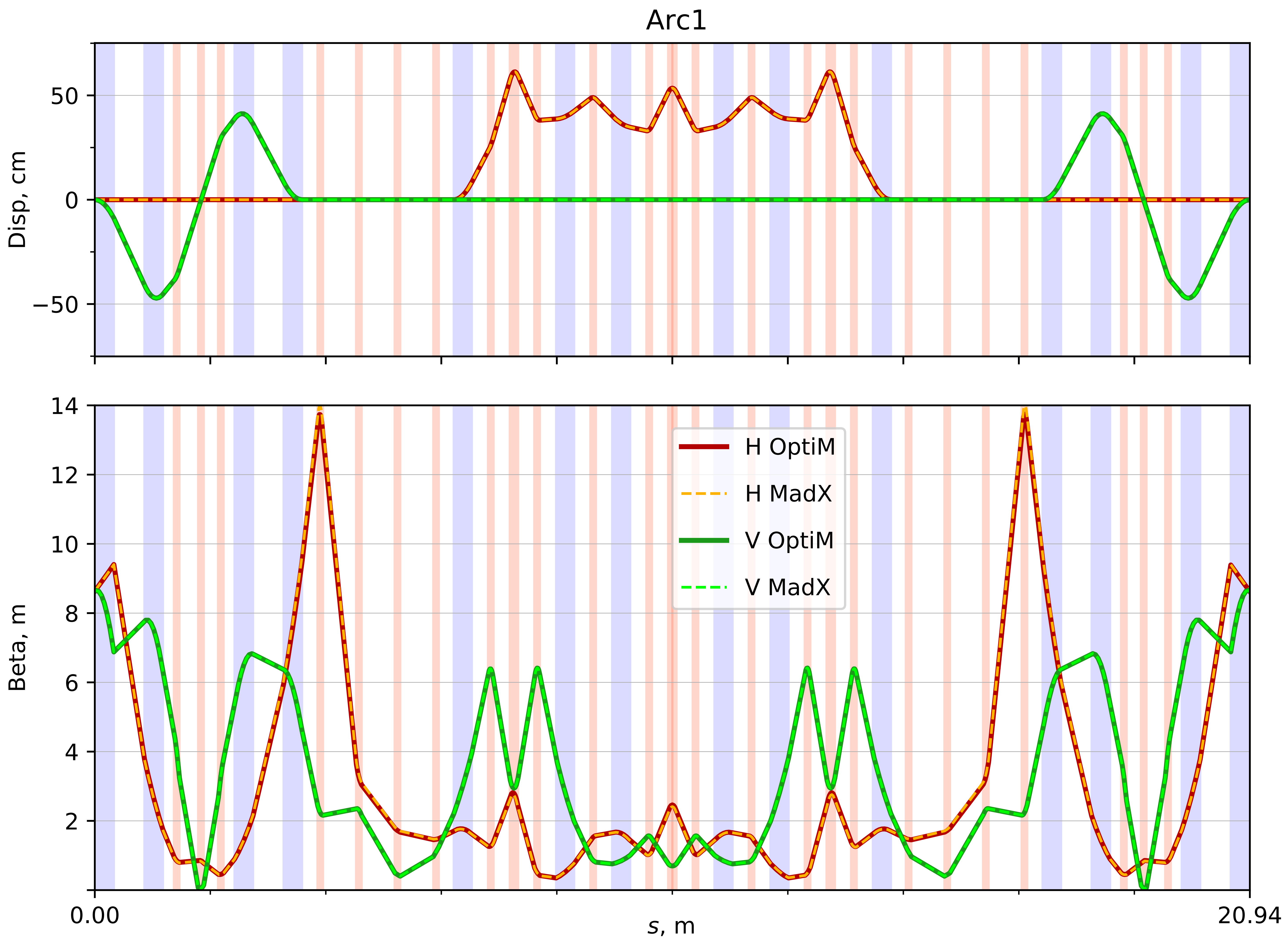
(all in vertical plane: TILT = π/2)

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)

Conclusions

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

Filling pattern (Arc optics architecture)

- the optimal filling pattern for 500 MeV version requires extra space (28.6 m → 30.6 m)

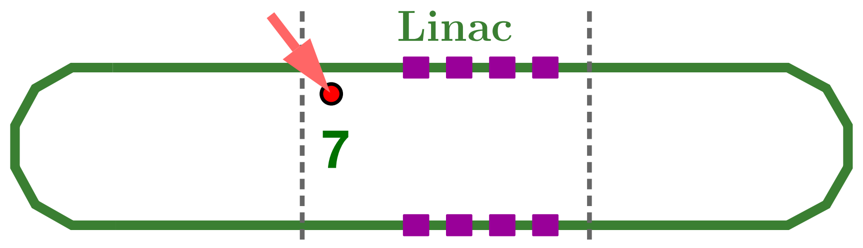
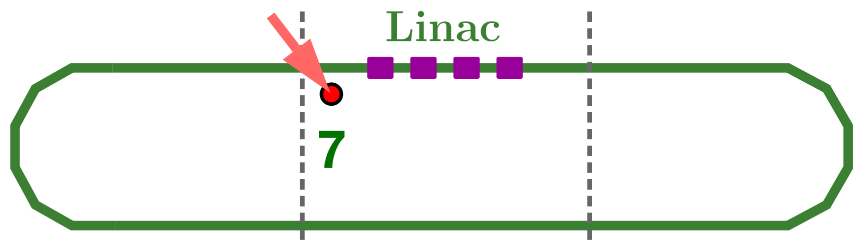
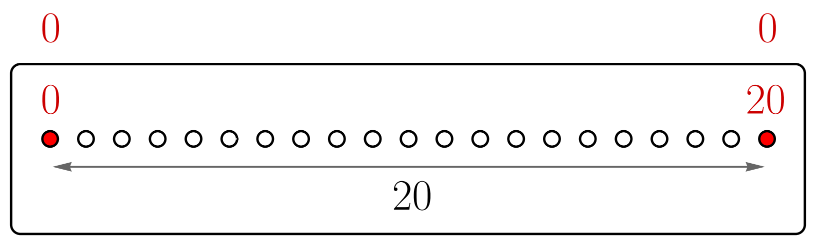
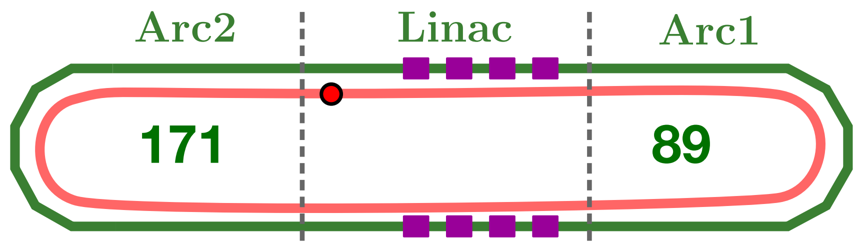
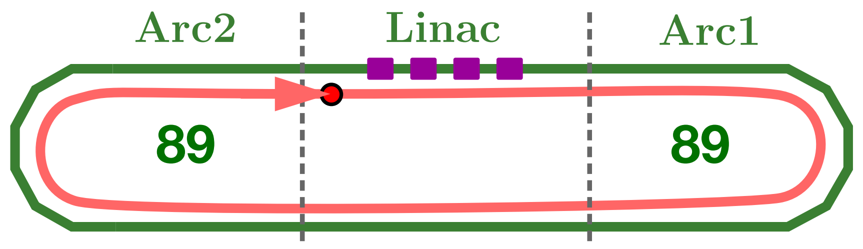
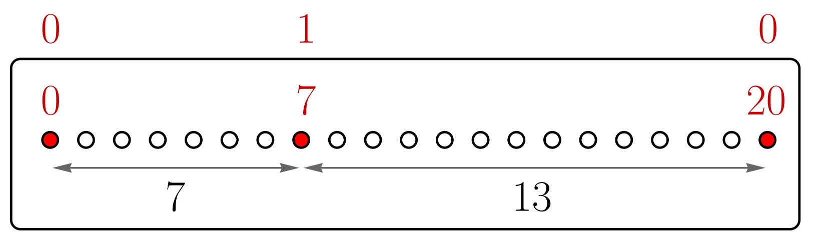
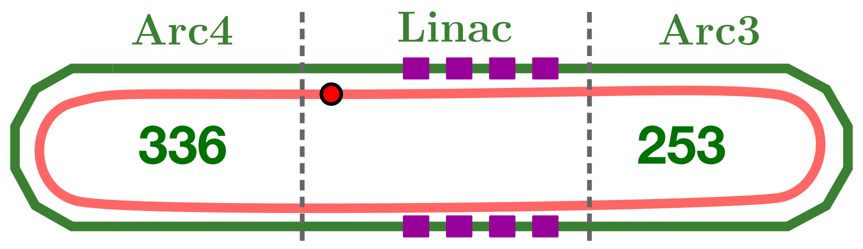
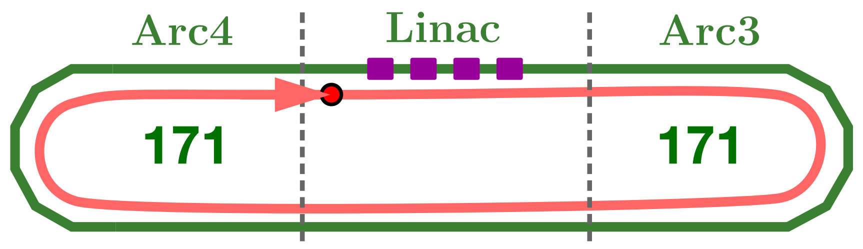
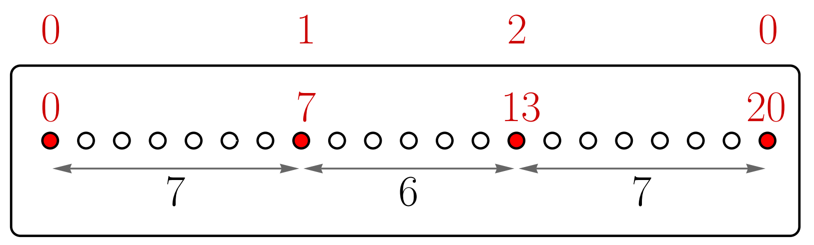
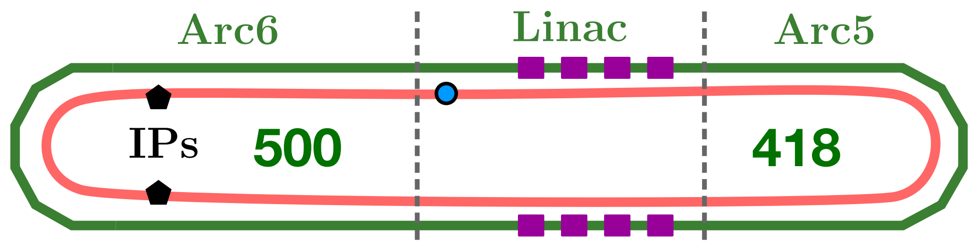
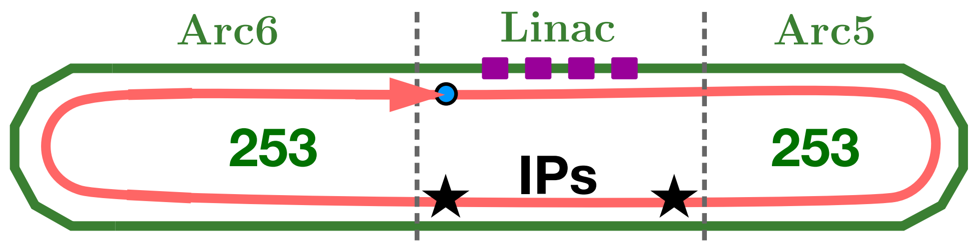
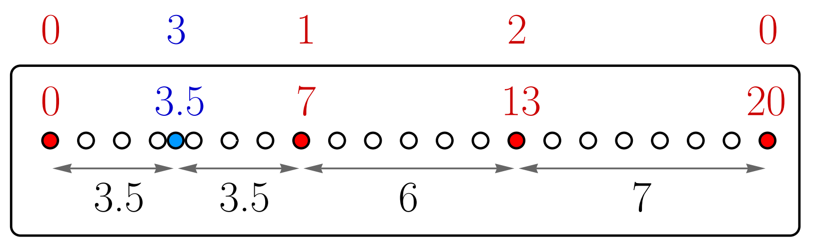
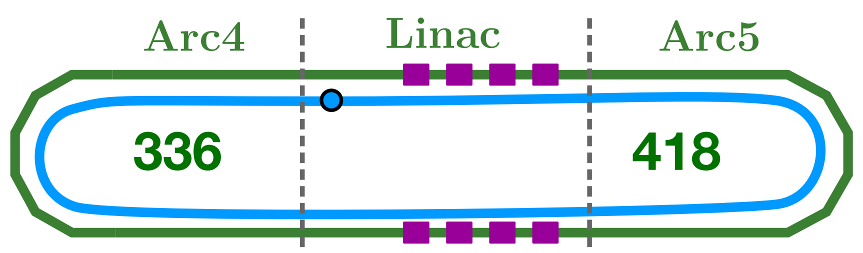
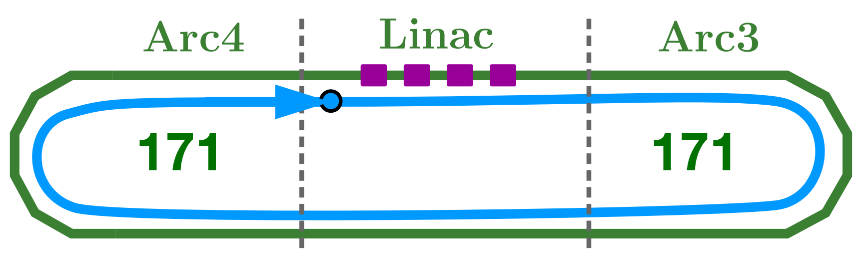
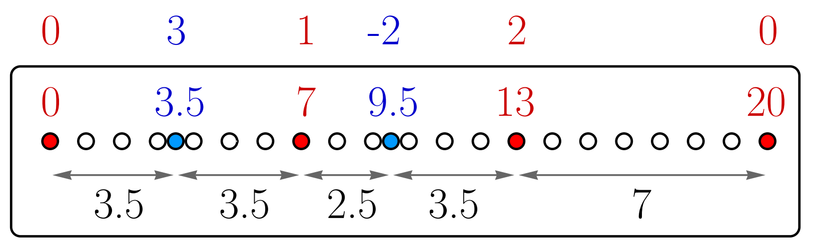
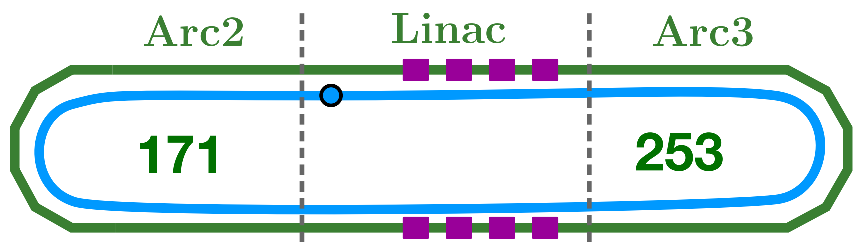
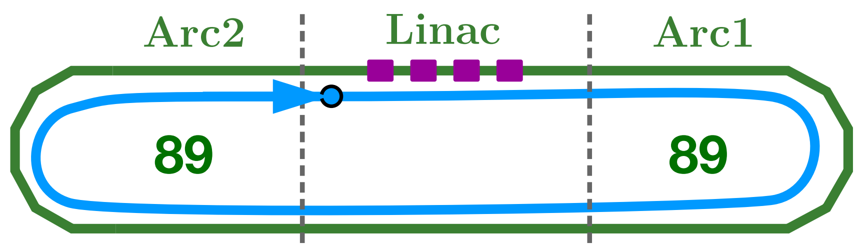
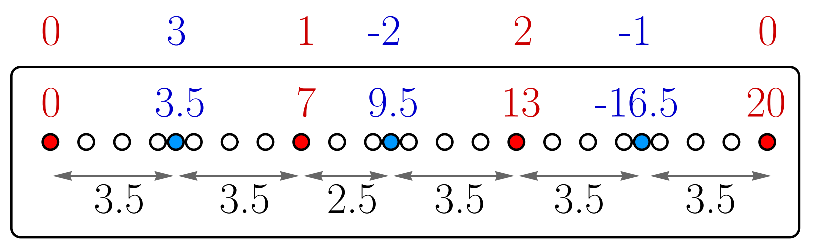
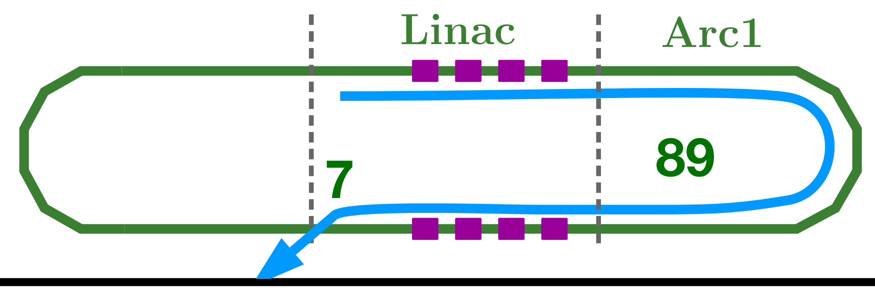
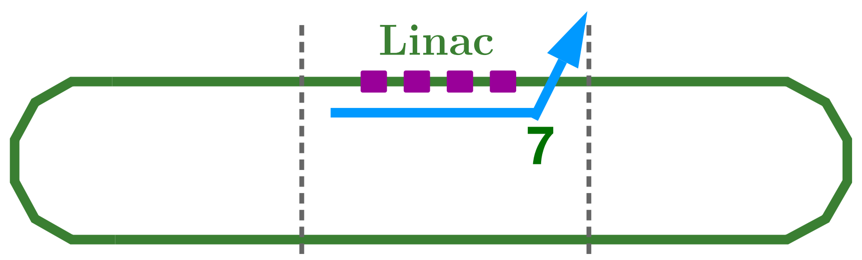
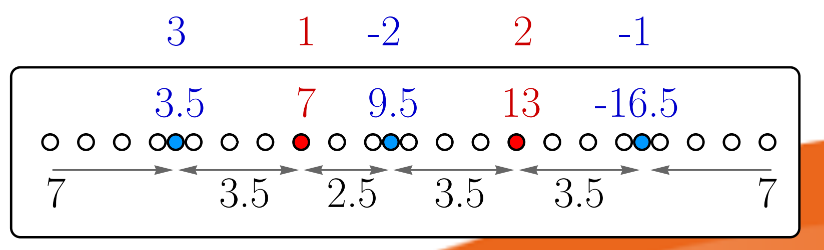
  but current configuration is fine (Alex Bogacz, Peter Williams, Robert Apsimon)
- for the 250 MeV version we consider the optimal filling (more essential at lower energies, inline with the optics)

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

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		

Magnets for PERLE

Dipoles and Quadruploes names (in Arcs)

	Spreaders												Arcs								
1	b1S01	b1S02	qQ1S01	qQ1S02	qQ1S03	b1S03	b1S04		qQ1S04	qQ1S05	qQ1S06	qQ1S07	bAA1	qQ1A01	qQ1A02	qQ1A03	bAA1	qQ1A00	bAA1	qQ1A04	qQ1A05
2	.	.	.	.	.	.	.		.	.	.	.	.	.	.	.	.	.	.	.	.
3	.	.	.	.	.	.	.		.	.	.	.	.	.	.	.	.	.	.	.	.
4	b4S01	b4S02	qQ4S01	qQ4S02	qQ4S03	b4S03	b4S04		qQ4S04	qQ4S05	qQ4S06	qQ4S07	bAA4	qQ4A01	qQ4A02	qQ4A03	bAA4	qQ4A00	bAA4	qQ4A04	qQ4A05
5	b5S01	b5S02	b5S03	b5S04					qQ5S04	qQ5S05	qQ5S06	qQ5S07	bAA5	qQ5A01	qQ5A02	qQ5A03	bAA5	qQ5A00	bAA5	qQ5A04	qQ5A05
6	b6S01	b6S02	b6S03	b6S04	qQ6S04A	qQ6S04B	qQ6S04C	iIR	qQ6S05	qQ6S06	qQ6S07	qQ6S08	bAA6	qQ6A01	qQ6A02	qQ6A03	bAA6	qQ6A00	bAA6	qQ6A04	qQ6A05

Field, T and Field Gradient, T/m

	Spreaders		10 cm	15 cm	10 cm				10 cm	10 cm	10 cm		Arcs								
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

Beam size (in Arcs)