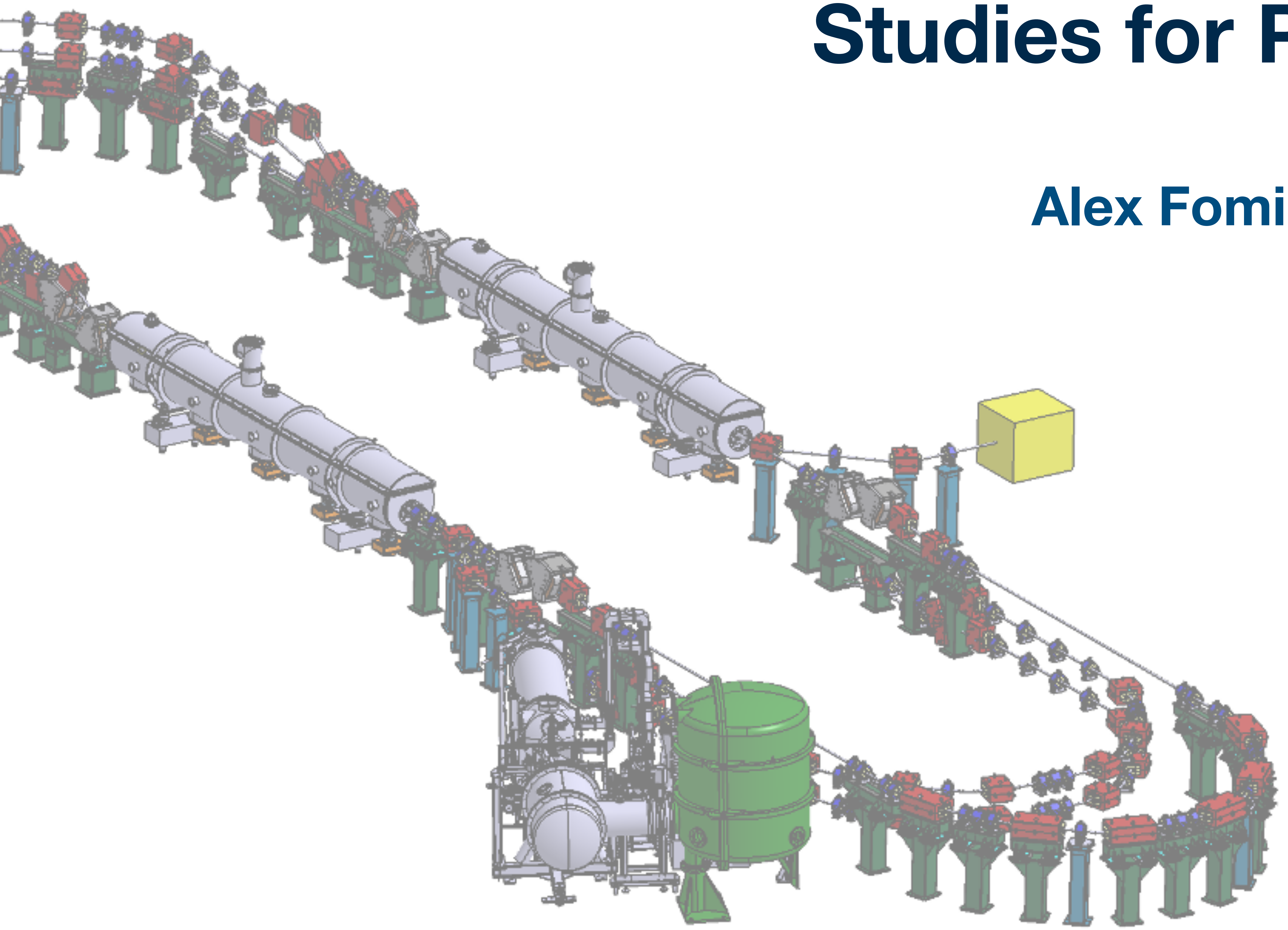
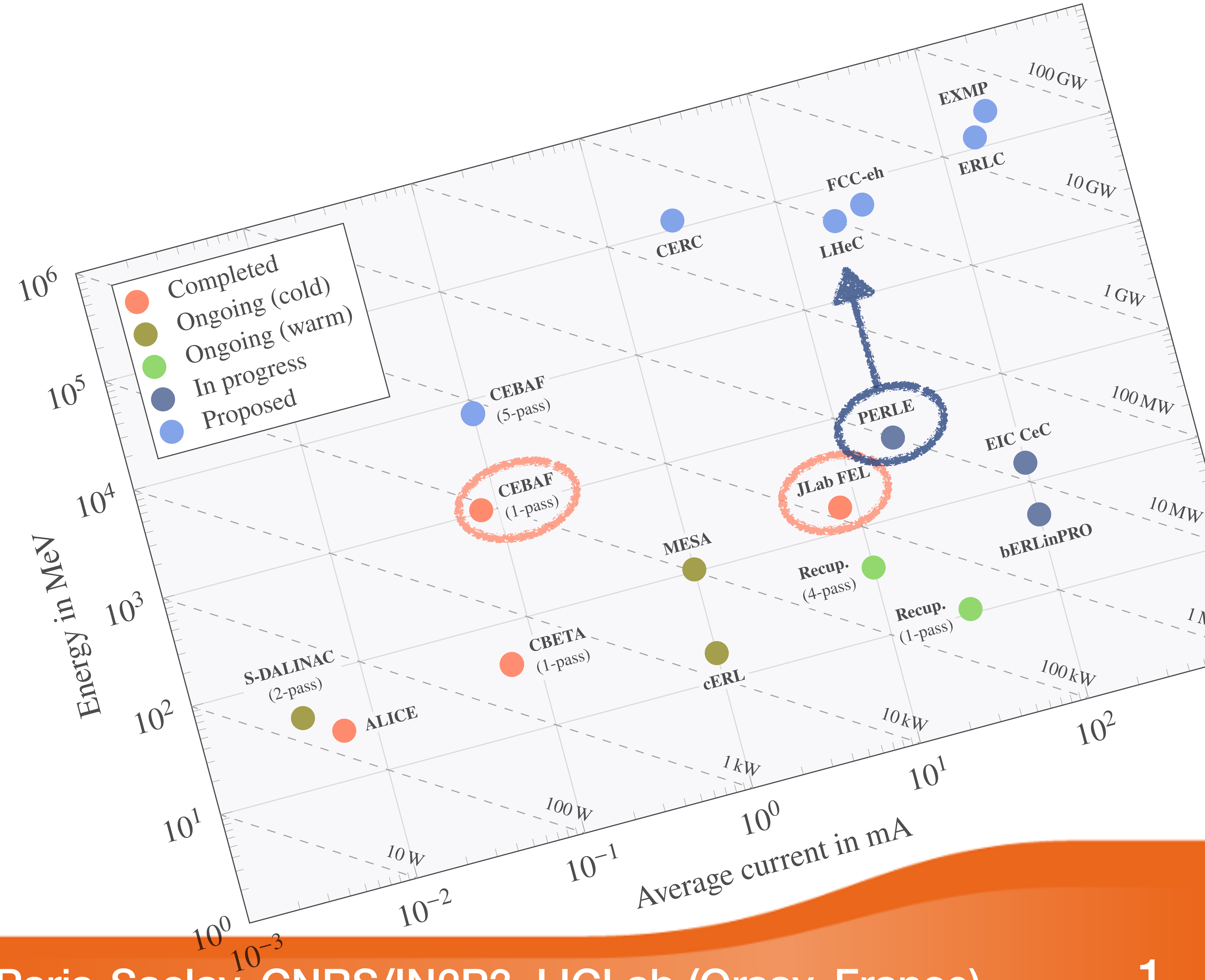
université PARIS-SACLAY
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Lattice Design and Beam Dynamics Studies for PERLE

Alex Fomin





the PERLE project. Work Package 2: Accelerator Design

WP2: Accelerator Design

Task 2.1:	Task 2.2:	Task 2.3:
Lattice and optics	Beam Dynamics	PERLE Footprint

Injection line
- Source
- booster
- buncher
- Connection section

Main ERL
- LINAC
- Arcs

Extraction lines
- Extraction section
- Junction line to users
- Junction line to dump

Full design
- Optics / beam dynamic
- Footprint

- **Task leader : IJCLab : Luc Perrot / Jlab : Alex Bogacz**
- **IJCLab members of WP2**
  - Alex Fomin, IN2P3 Post-doc, since February 2022, 100%
  - Rasha Abukeshek, UPSay-IJCLab PhD, WP2 & WP6, 100%
  - Julien Michaud, CNRS researcher, from November 2022, 100%
  - Coline Guyot, UPSay-IJCLab PhD, 50% (Christelle Bruni, CNRS)
- **Partners of WP2**
  - Bertrand Jacquot, CNRS GANIL-SPIRAL2, 30% for WP2
  - Hadil Abualrob, prof. Naplouse Univ. (Palestine)
  - Rodolphe Marie, IJCLab workshop, mechanic
  - Connor Monaghan, PhD at Liverpool University, since October 2022
  - Robert Apsimon, Cockcroft Institute (UK)
  - Peter Williams, STFC Daresbury (UK)
- **Former Partners of WP2**
  - Gustavo Pérez Segurana, PhD at Lancaster University (March 2021)
  - Ben Hounsell, PhD at Liverpool University (March 2022)
  - Kevin André, Post-doc at CERN

Outline

Historic perspective and PERLE timeline

Lattice design (250 and 500 MeV versions with maximal compatibility)

Filling patterns (optimal for lower energies)

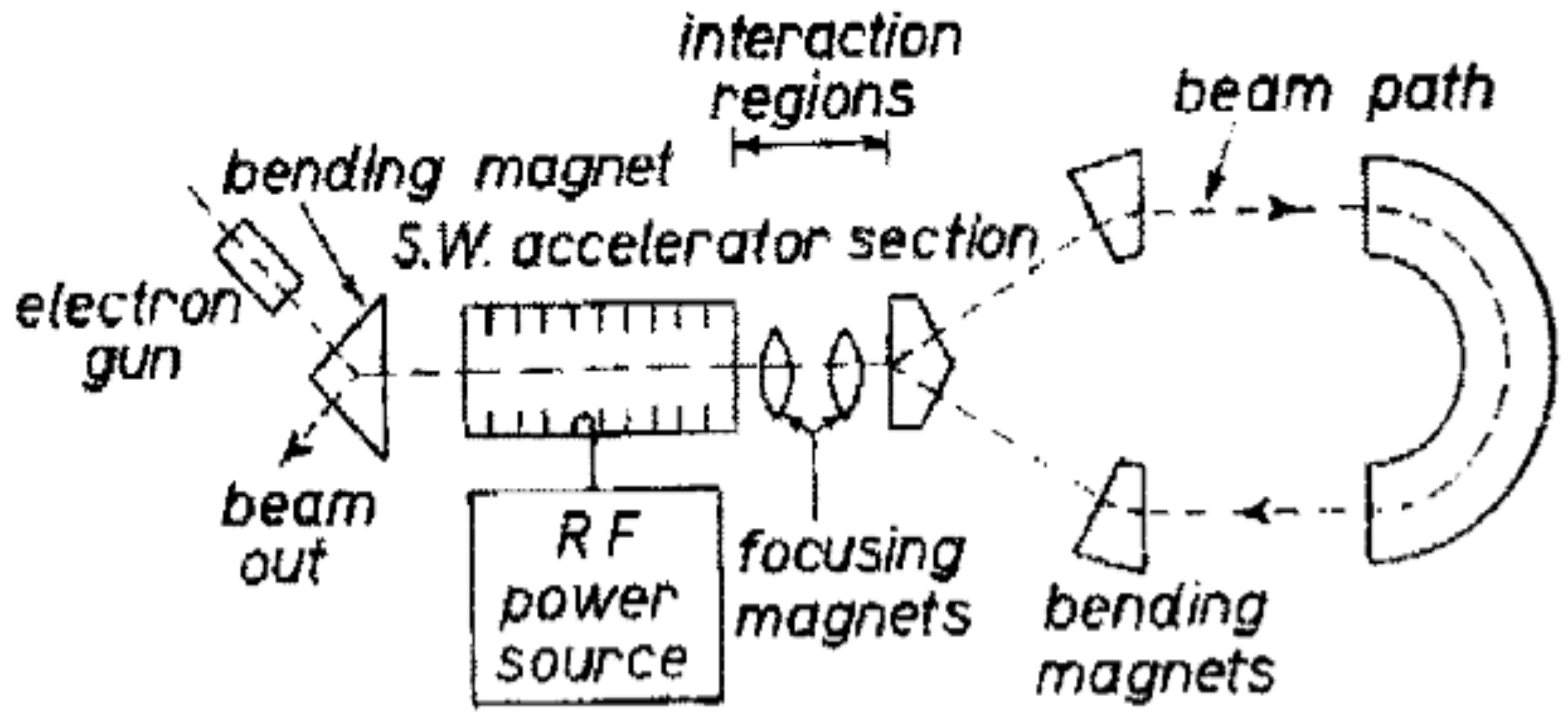
Optics (comparison of 250 and 500 MeV version)

Beam Dynamics Studies

Historic perspective and PERLE timeline

Accelerating two beams, colliding them, and then dumping them is extremely inefficient.

Maury Tigner, A Possible Apparatus for Electron Clashing-Beam Experiments, N.Cim 10(1965)1228



Recirculation lattice to recycle kinetic beam energy of a decelerating beam for acceleration of a newly injected low energy beam.

Avoid synchrotron loss initiated emittance growth as in storage rings.

Minimize power consumption (by an order of magnitude) and dump at E_{inj}

"There will be no future large-scale science project without an energy management component, an incentive for energy efficiency and energy recovery among the major objectives"

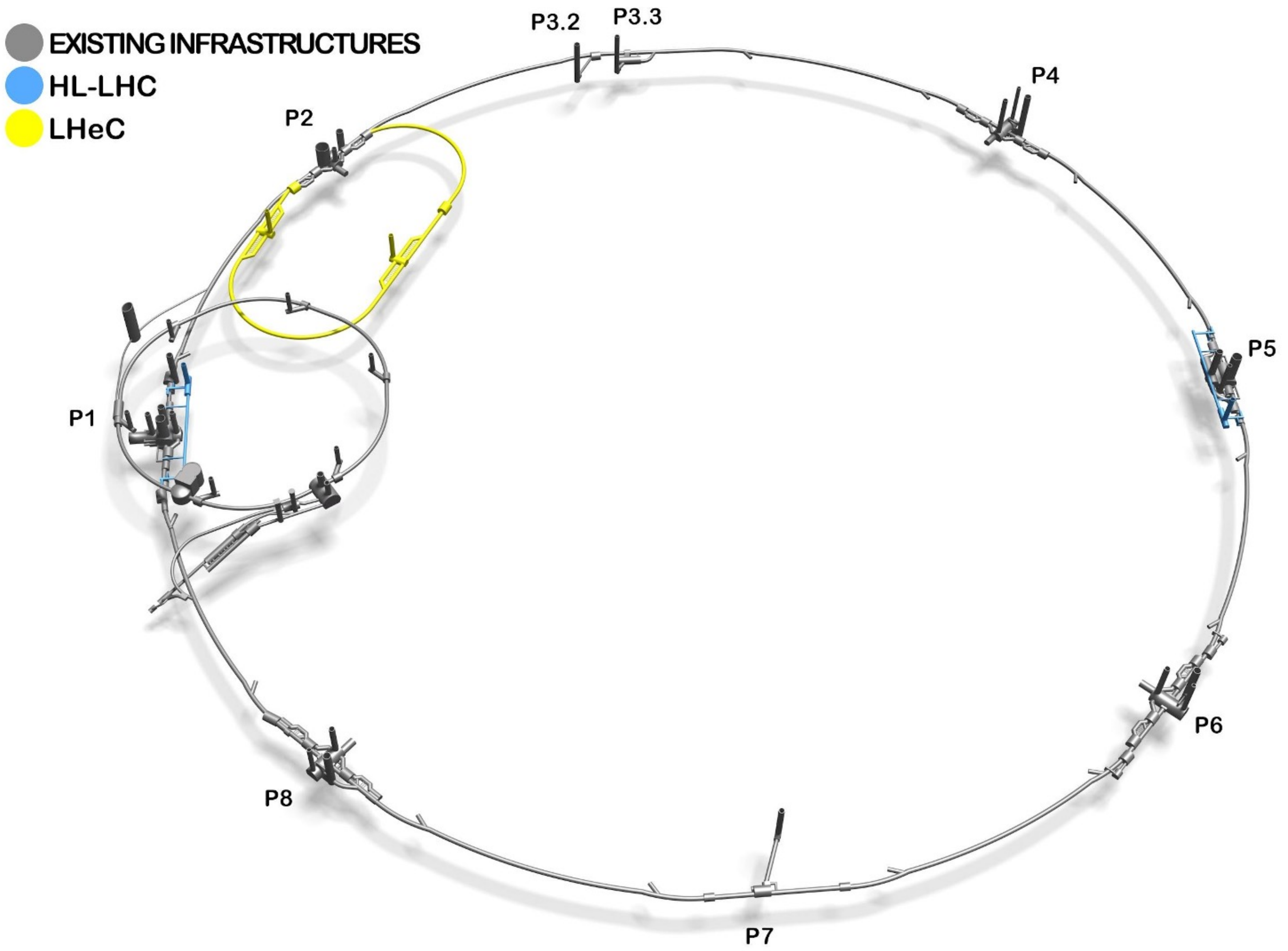
Frédérick Bordry, Director for Accelerators and Technology at CERN (2019)

Beam parameters for the LHeC experiment

M. Klein, Status Report on LHeC to ECFA (CERN, 28 Nov **2008**)

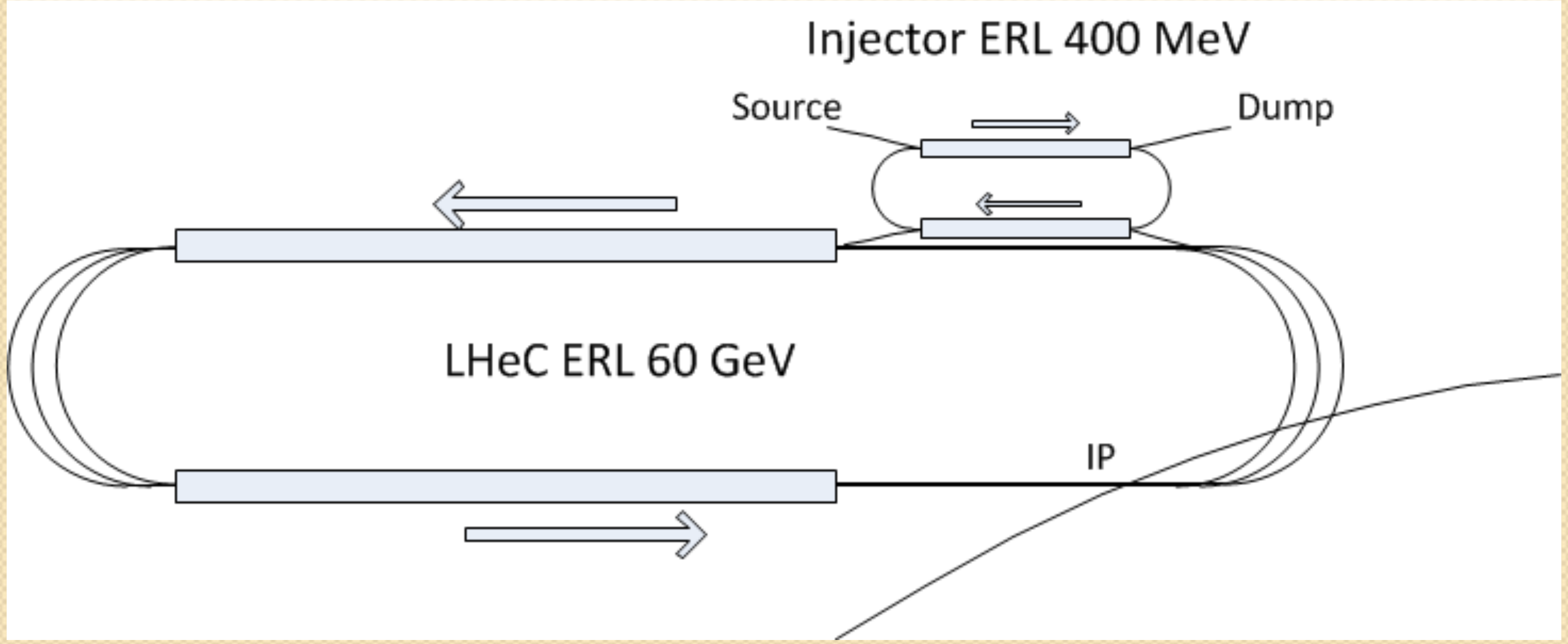
LHeC Study Group, Report on the Physics and Design Concepts for Machine and Detector (CERN, 13 Jun **2012**)

Parameter	Unit	LHeC Electron	LHeC Proton
Beam energy	GeV	50.0	7000.0
Beam current	mA	20.0	1400
Bunches per beam		1188	2808
Bunch population	10^{10}	0.3	22.0
Bunch charge	nC	0.50	35.24
Normalised emittance at IP	mm.mrad	30.0	2.5
Betatron function at IP	cm	10.0	10.0
RMS bunch length	cm	0.06	7.55
Installed RF voltage	GV	17.2*	0.016
Beam-beam disruption		14.3	1×10^{-5}
Luminosity	$cm^{-2}.s^{-1}$	6.5×10^{33}	



High power electron beam based on three-turn ERL racetrack utilising 100 MW electrical power consumption as a result of the high energy recovery efficiency. ERL circumference equivalent to one-third of the LHC. The ERL could be realised in staged phases.

Could the TF later become the LHeC ERL injector ERL?



very preliminary – just an idea by Rama and me yesterday.

First Idea

E. Jensen: ERL and Frequency Choice

presented at 2012 CERN-ECFA-NuPECC

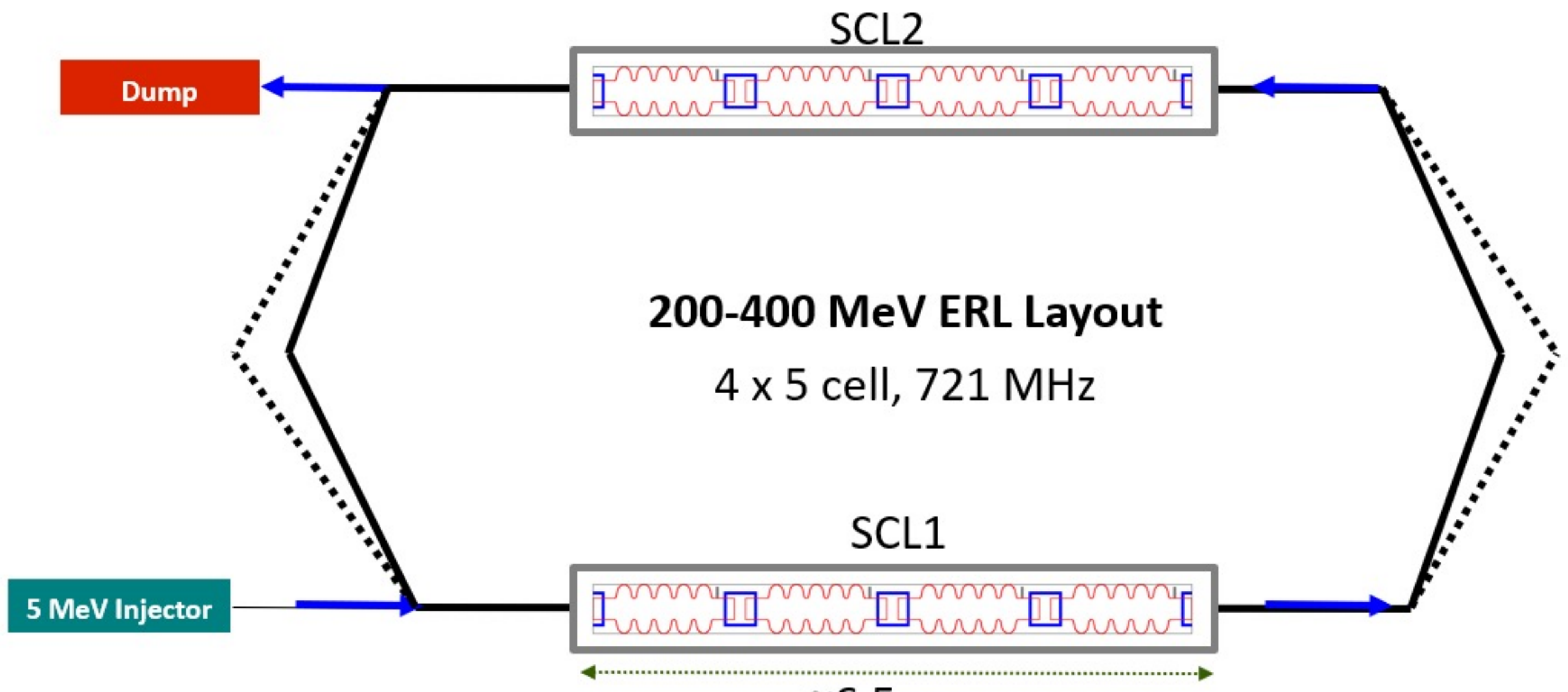
Workshop on the LHeC

(14–15 Jun 2012 Switzerland)

First lattice design of ERL TF (by A. Bogacz)

JLAB Seminar: E. Jensen, ERL Test Facility at CERN (August 2012)

JLAB Seminar, August 2012



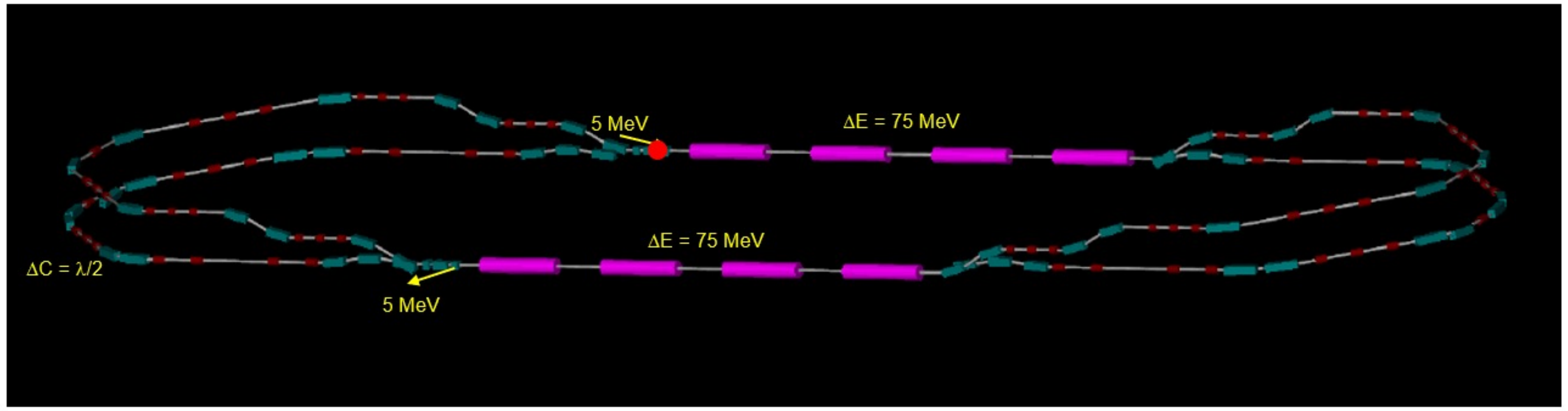
	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep rate		CW	CW

August 2012 E. Jensen: ERL TF @ CERN ? 21

ERL-TF (300 MeV) – Layout

Thanks, Alex (received this morning)!

Alex Bogacz

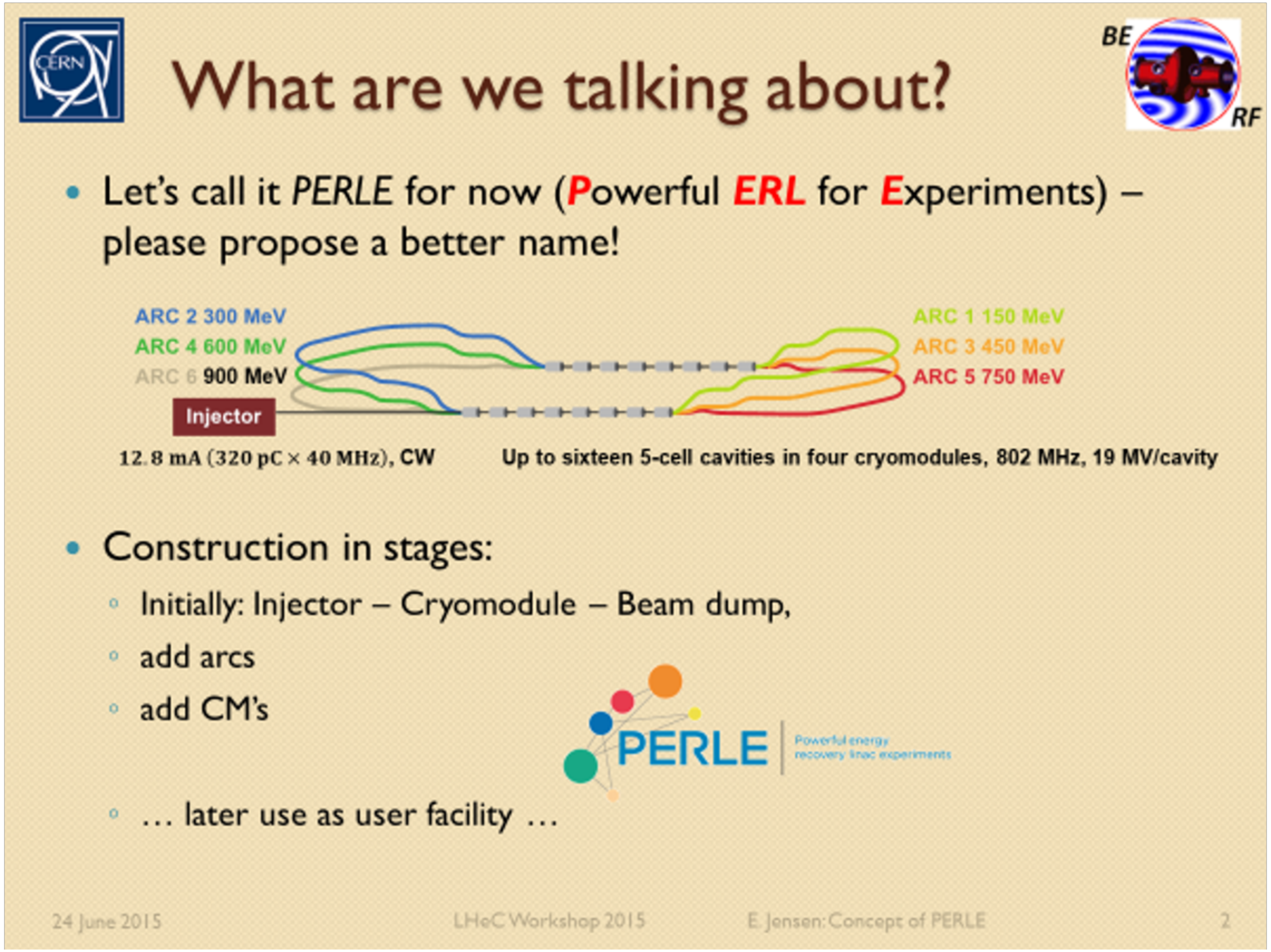


Two passes ‘up’ + Two passes ‘down’

Jefferson Lab Thomas Jefferson National Accelerator Facility

August 2012 E. Jensen: ERL TF @ CERN ? 22

The name PERLE

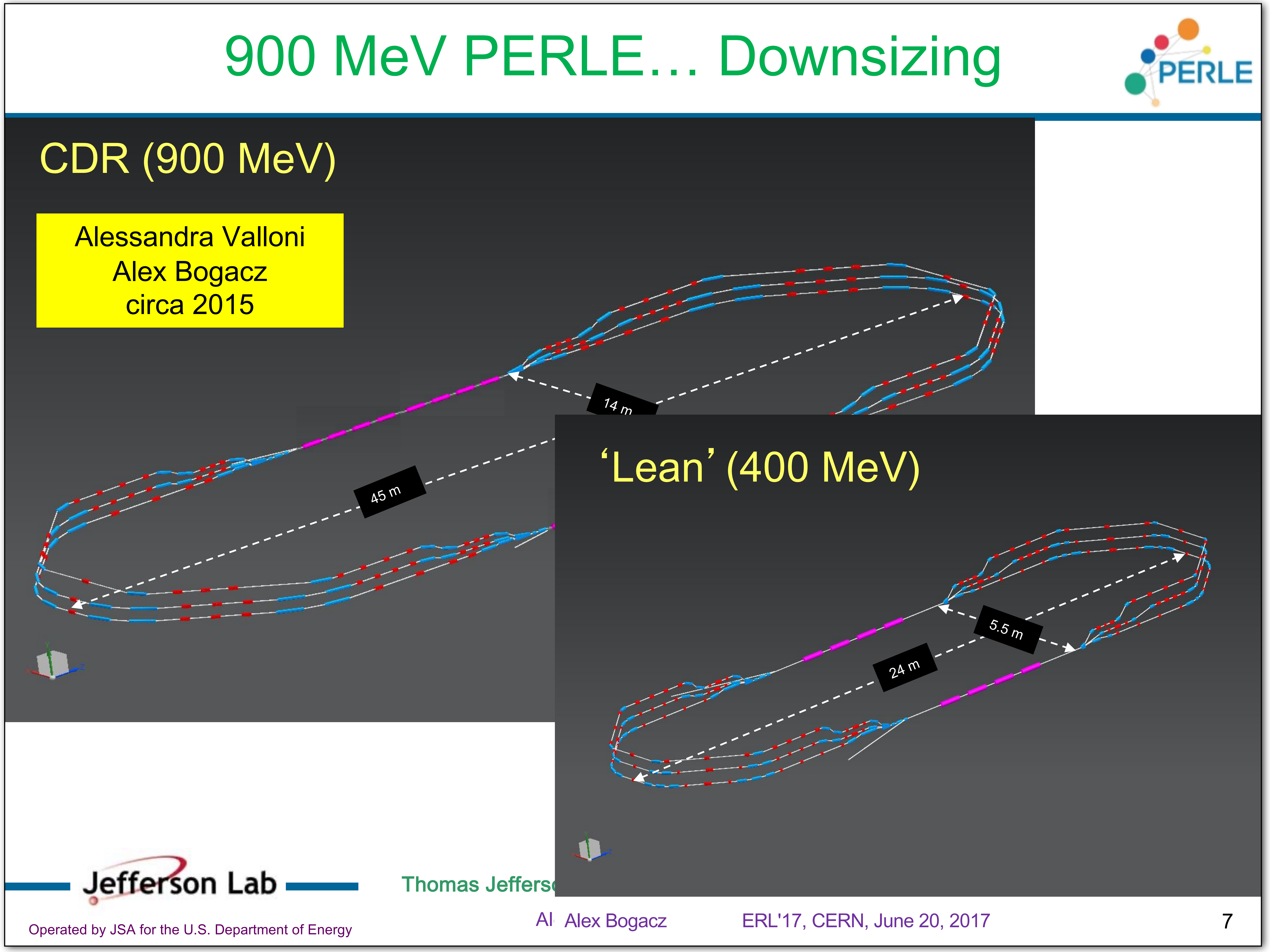


E. Jensen: **Concept of PERLE**
presented at LHeC Workshop 2015
(24–26 Jun 2015, CERN)

M. Klein, Meeting on **PERLE at Orsay**
Report on Discussions with LAL+INP directors
(21 Oct 2016, CERN)

PERLE
Conceptual Design Report
(24 May 2017)

PERLE
Technical Design Report
(scheduled for 2023)



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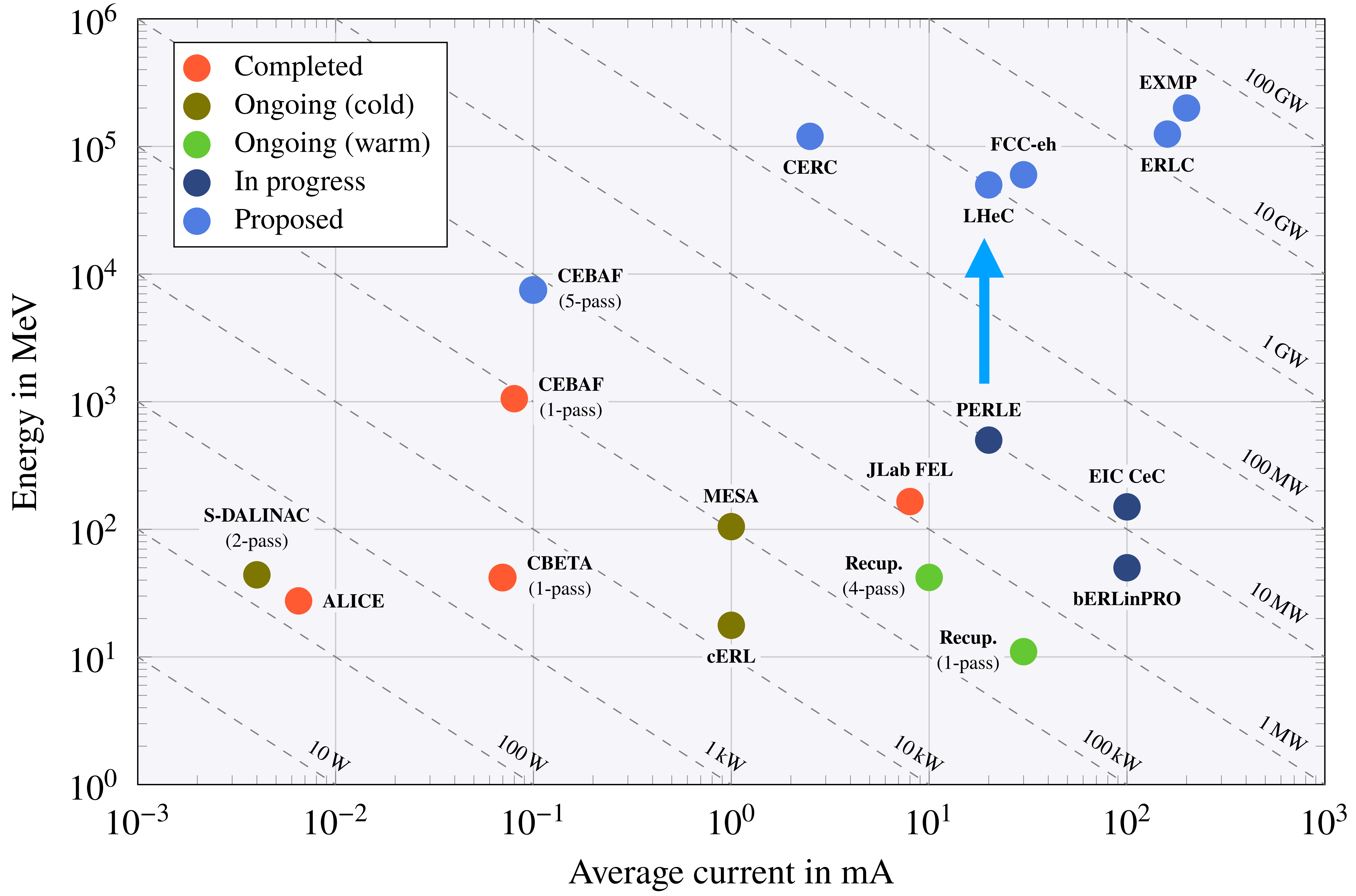
PERLE Target parameters

A hub to explore a broad range of accelerator phenomena and to validate technical choices improving accelerators efficiency in **an unexplored operational power regime** on the pathway of the ERL technology development for future energy and intensity frontier machines.

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

Matching the LHeC parameters

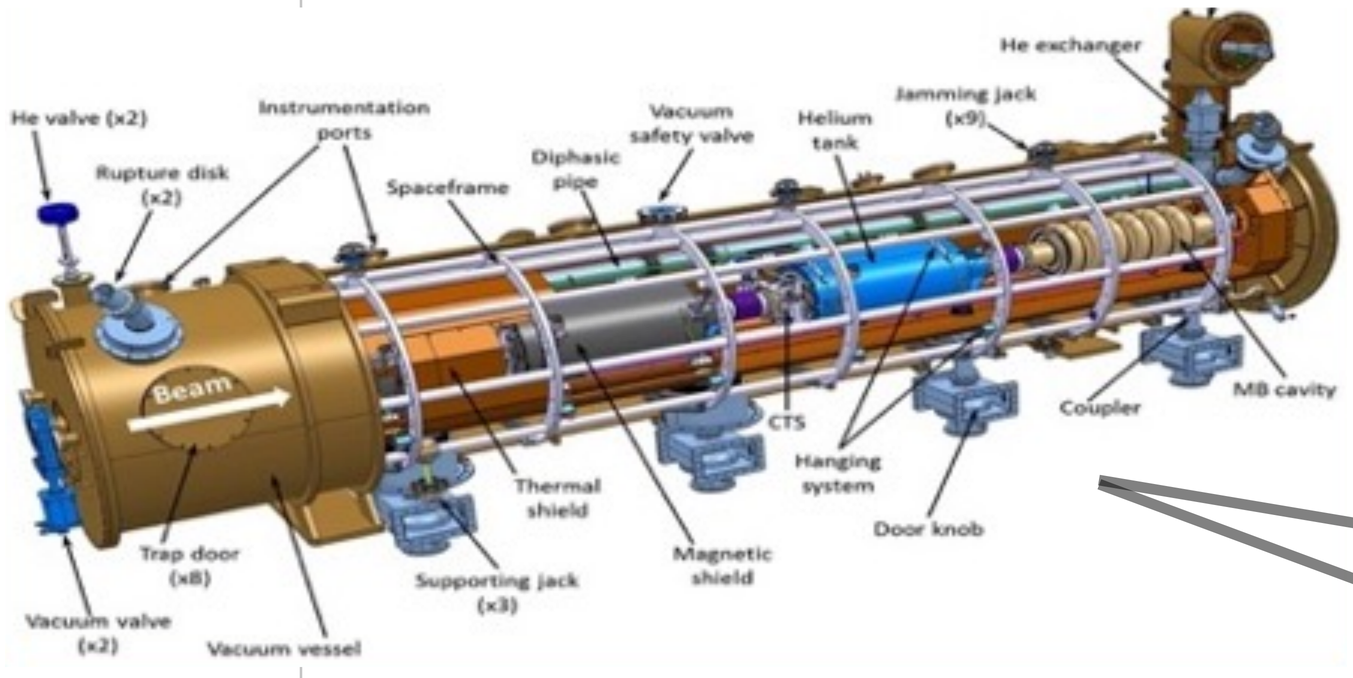
PERLE at Orsay as a demonstrator facility for the LHeC



PELRE: Powerful Energy Recovery Linac for Experiments

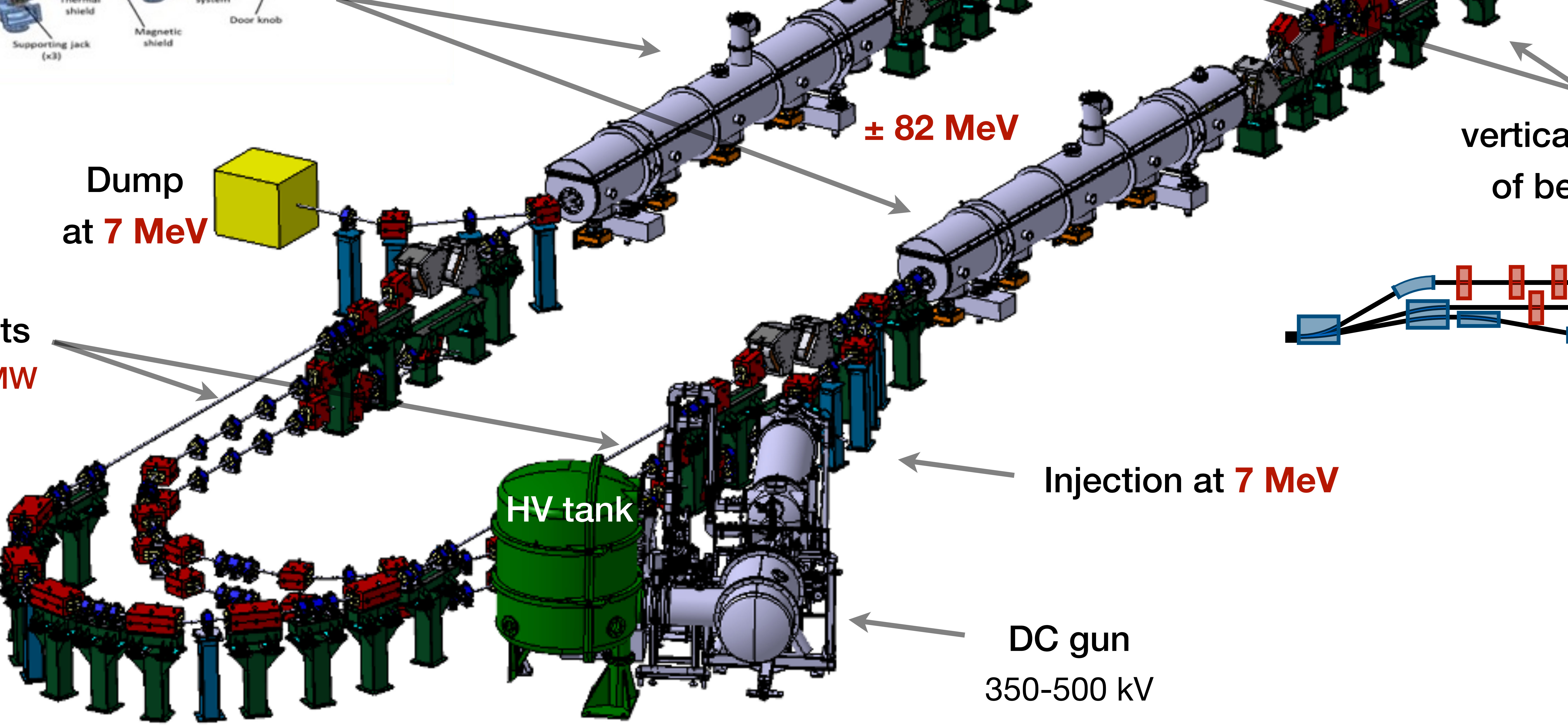
Two cryo-modules with 4 five-Cell cavities, each provides a total gradient of 82 MeV

3 accelerating & 3 decelerating beams at different energies travelling in the CM



Three staked isochronous recirculation Arcs for beams at different energies

89 MeV
253 MeV
418 MeV

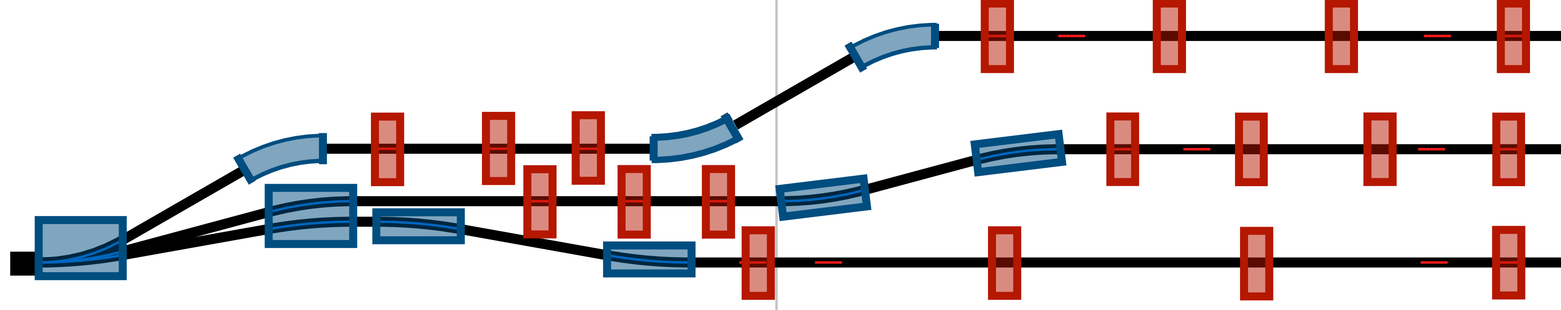


Dump at 7 MeV

Two Interaction Points
500 MeV × 20 mA = 10 MW

171 MeV
366 MeV
500 MeV

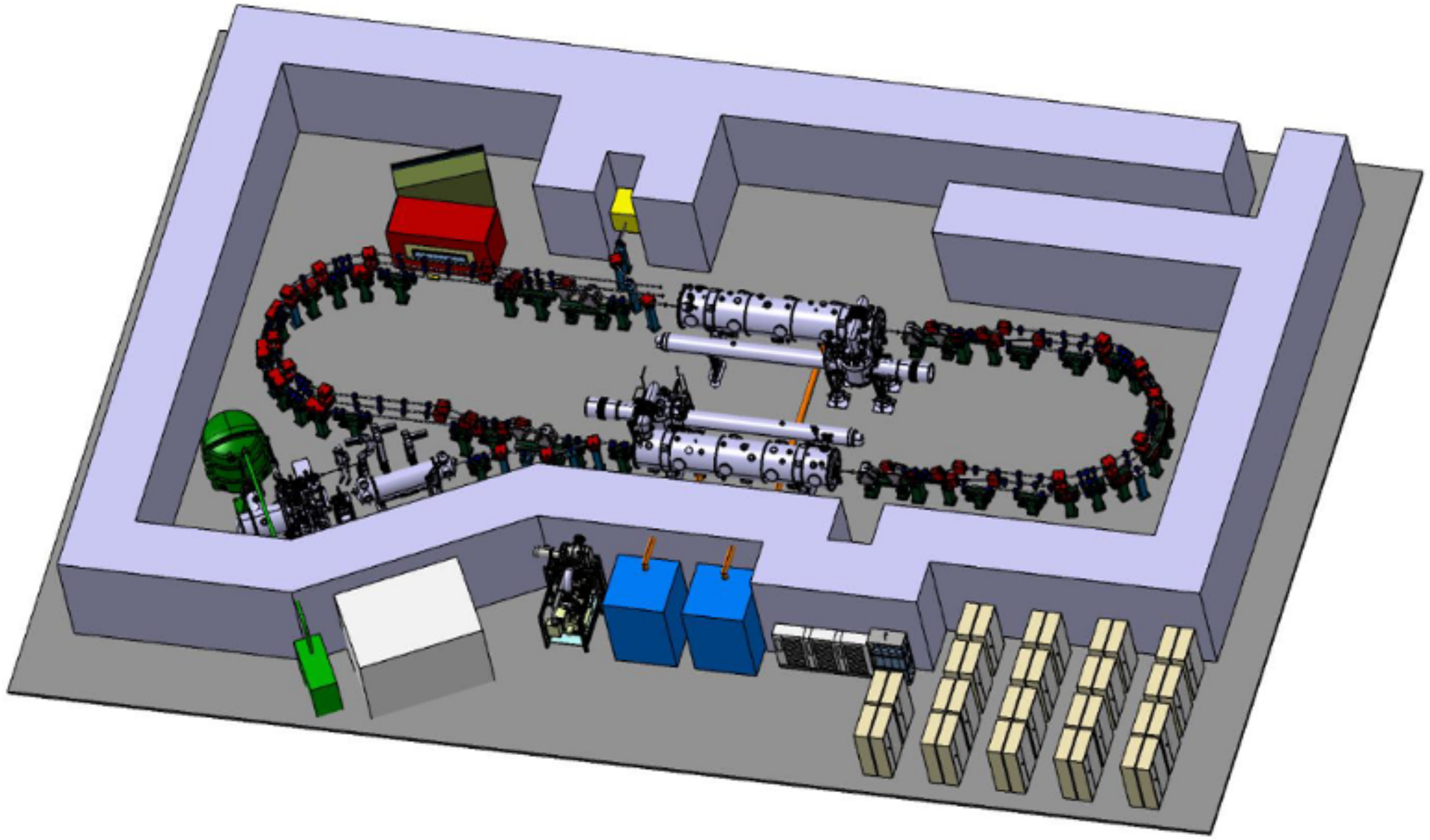
Two switchyard: vertical separation/recombination of beams at different energies



Injection at 7 MeV

DC gun
350-500 kV

PERLE Footprint: Site studies

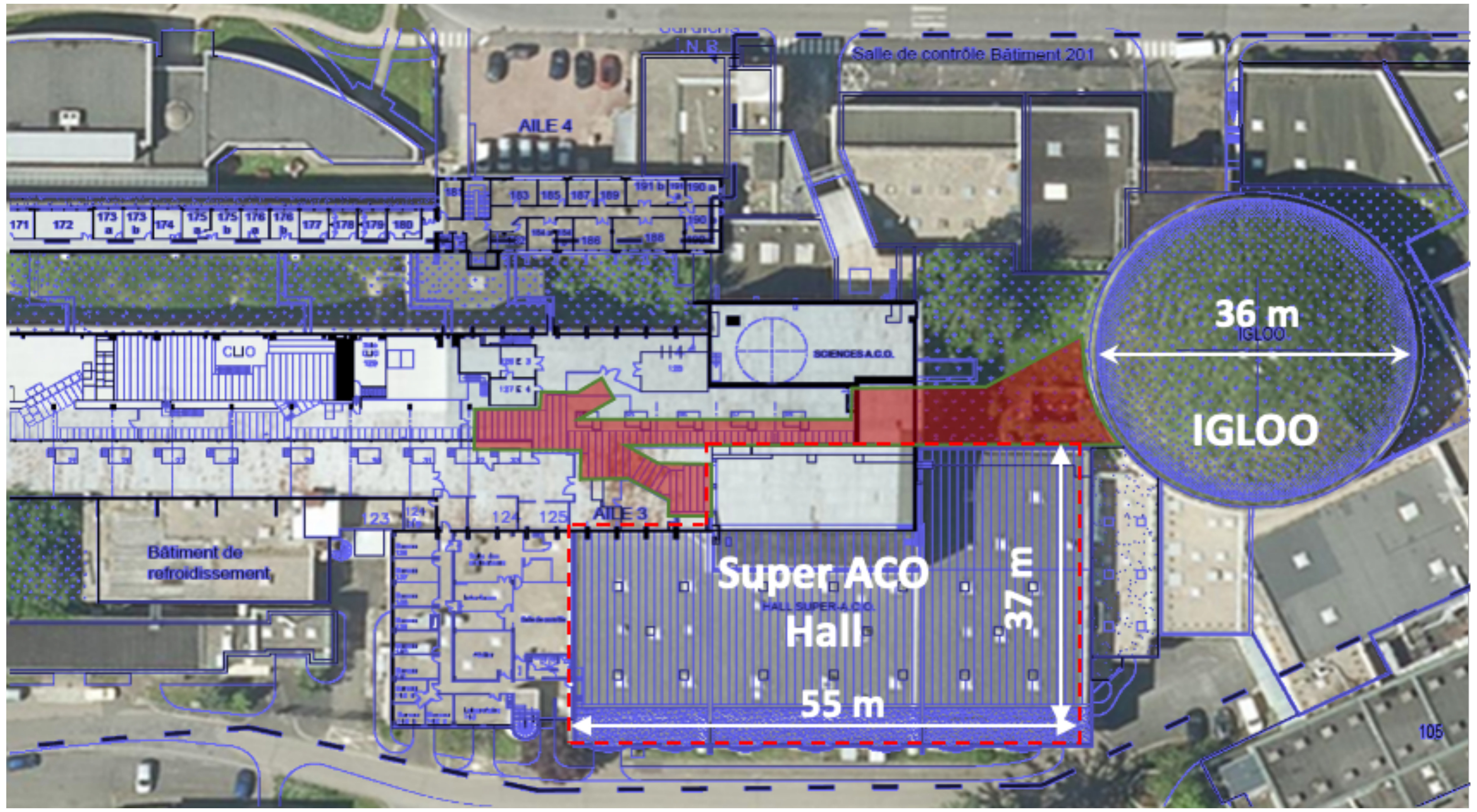


PERLE feature a total footprint of:

30 meters long, 15 meters wide and 3.4 meters high.

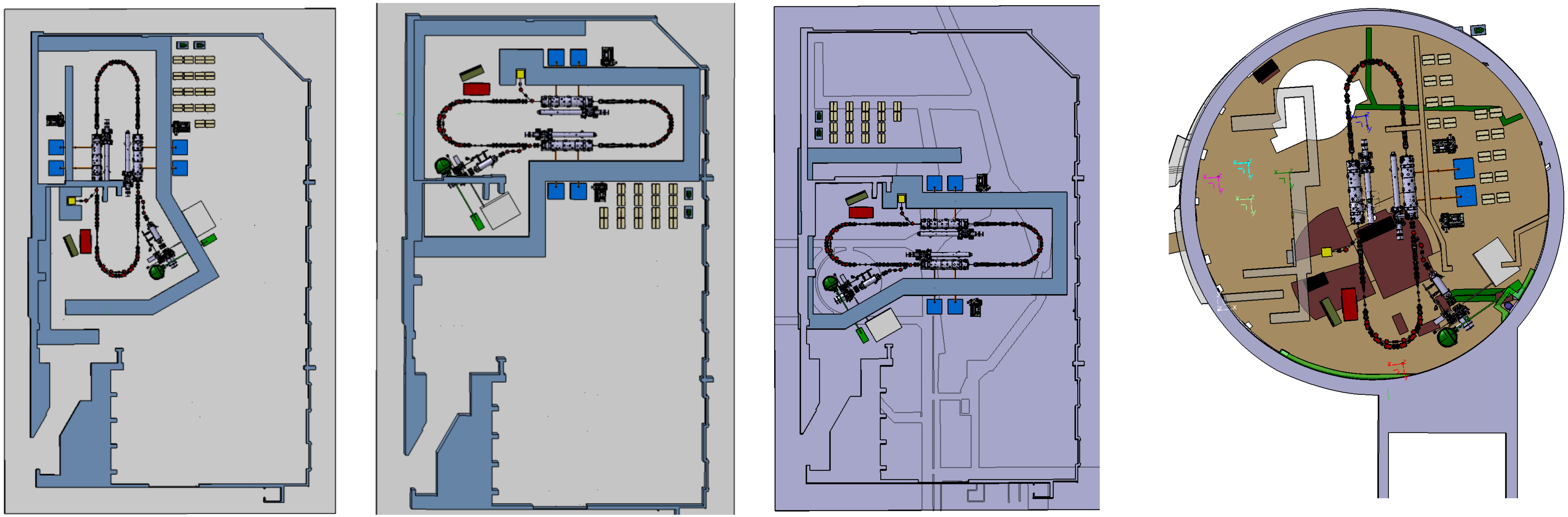
Two sites are currently considered and will be studied in details for possibly host PERLE at IJCLAB (Orsay, France)

- the Super ACO Hall
- the IGLOO.



PERLE Footprint: Site studies

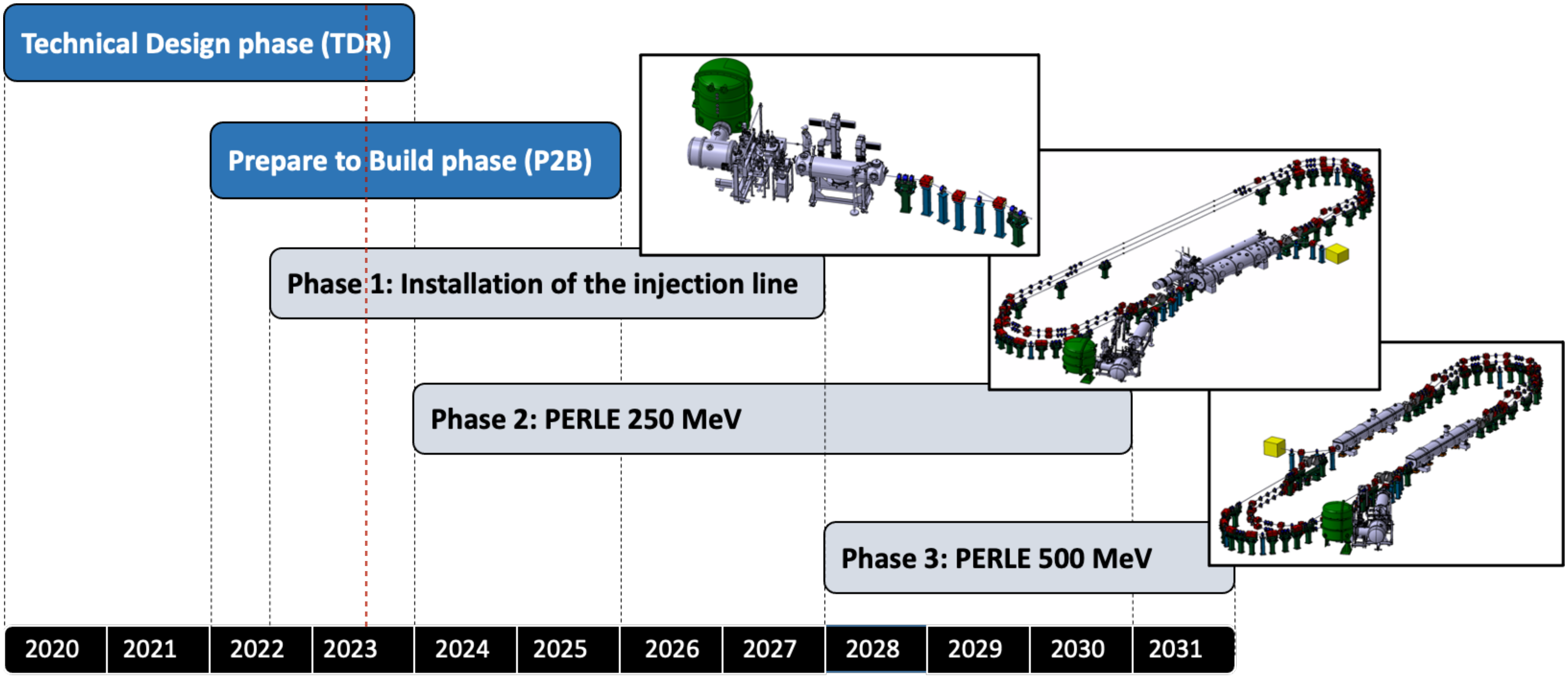
- Studies of special and structural feasibility in the two sites just started.
- Several scenario of PERLE implantation will be proposed with solutions to deal with constrains of each site. Costing of each scenario will also be provided.



Important available space for the machine and ancillaries installation
Low ground charge capability

Limited space for the machine and ancillaries installation
High ground charge capability

PELRE Timeline: Phasing Strategy



The global cost of the full machine ~27 MEuros.
(This estimation did not include manpower cost)

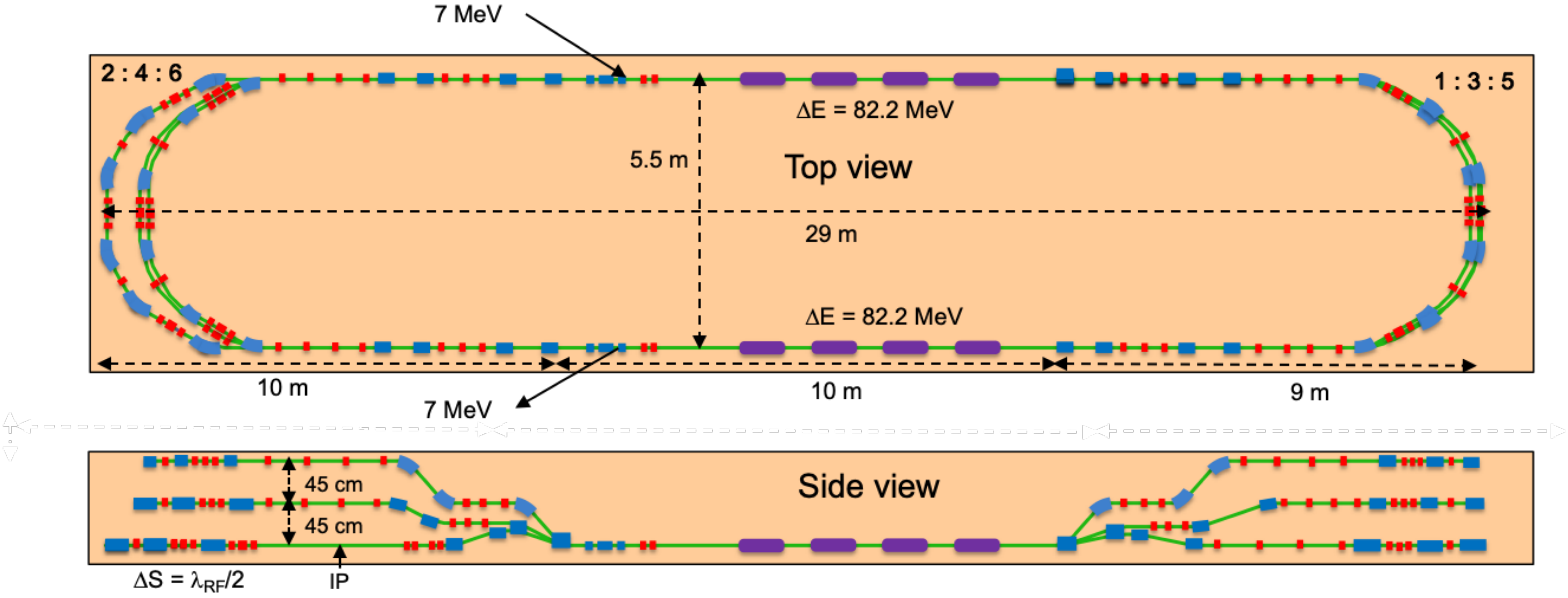
The following table presents an Ideal Spending Profile splitted in P2B phase, Construction, Construction-Infra (infrastructure equipment installation) and Upgrade to 500 MeV.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	Total (k€)
P2B (k€)	168,5	630	610	218	0	0	0	0	0	0	1626,5
Construction (k€)	0	0	0	2970	7300	6200	1050	0	0	0	17520
Constr.-Infra (k€)	0		100	500	1100	1600	500	0	0	0	3800
Upgrade 500 MeV (k€)	0	0	0	0	0	0	350	1600	1830	550	4330

Lattice design

PERLE 2.0 (500 MeV) - Baseline Layout (by A. Bogacz)

Footprint: 29 m × 5.5 m × 0.9 m



PERLE 2.0 (500 MeV) - Baseline Layout (by A. Bogacz)

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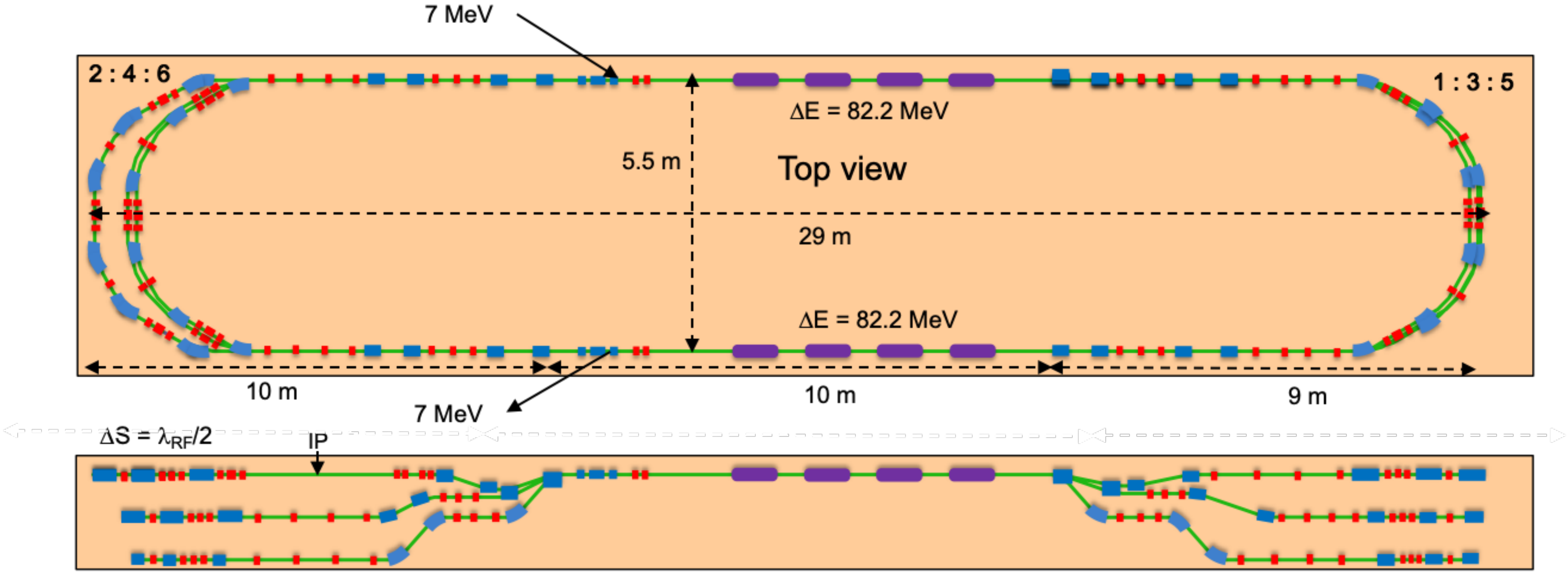
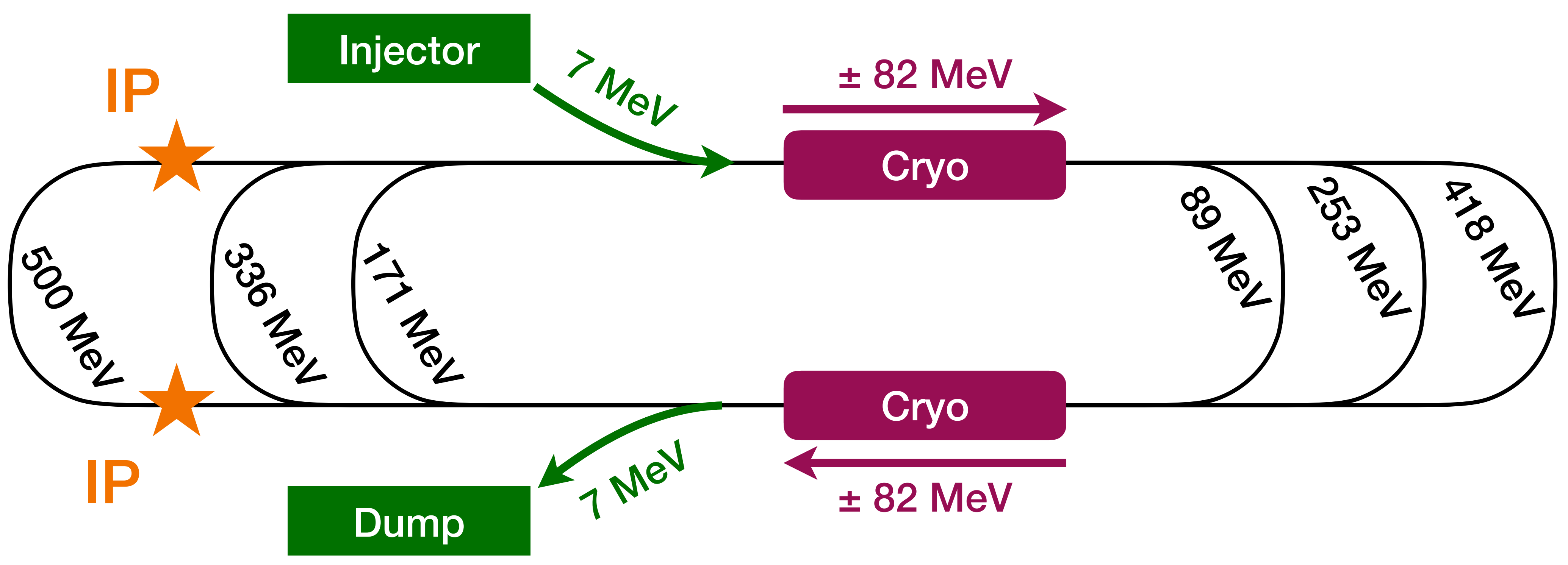
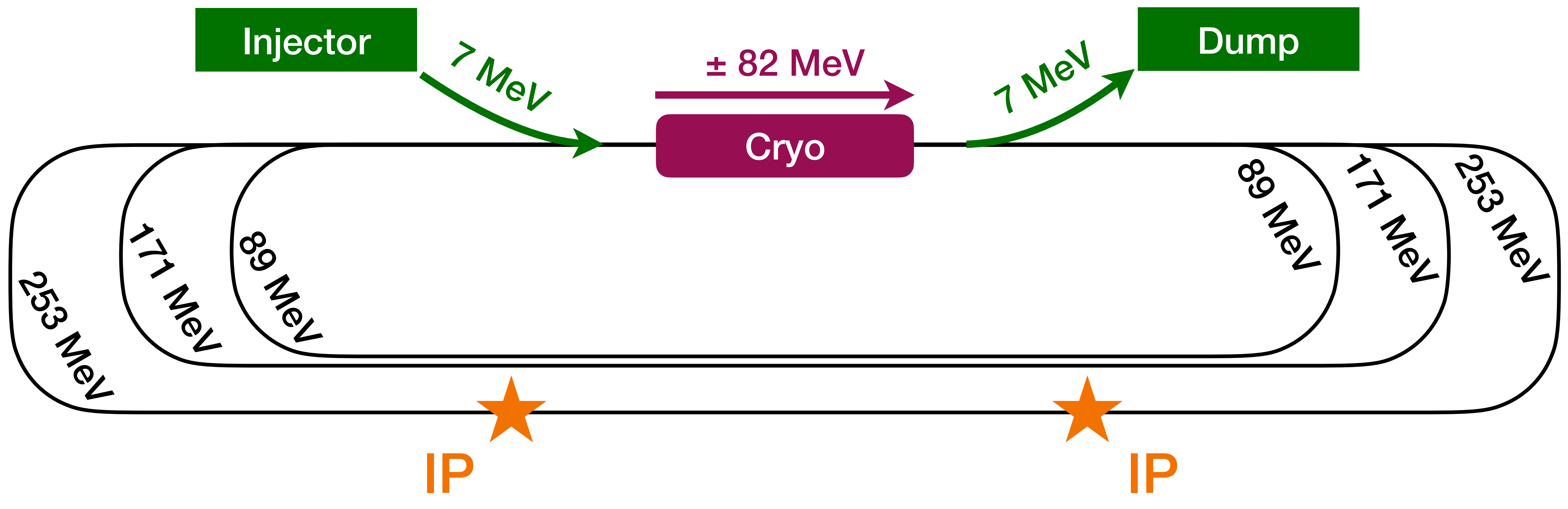


Denis Reynet (Département Mécanique, IJCLab) proposed to **flip the lattice vertically** to have an easier access to the IPs

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

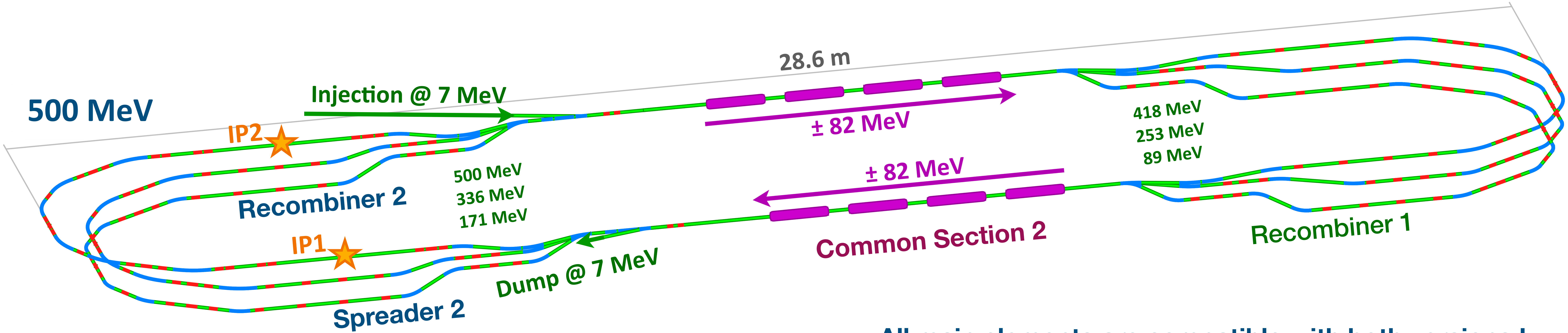
Cons:

→ **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)

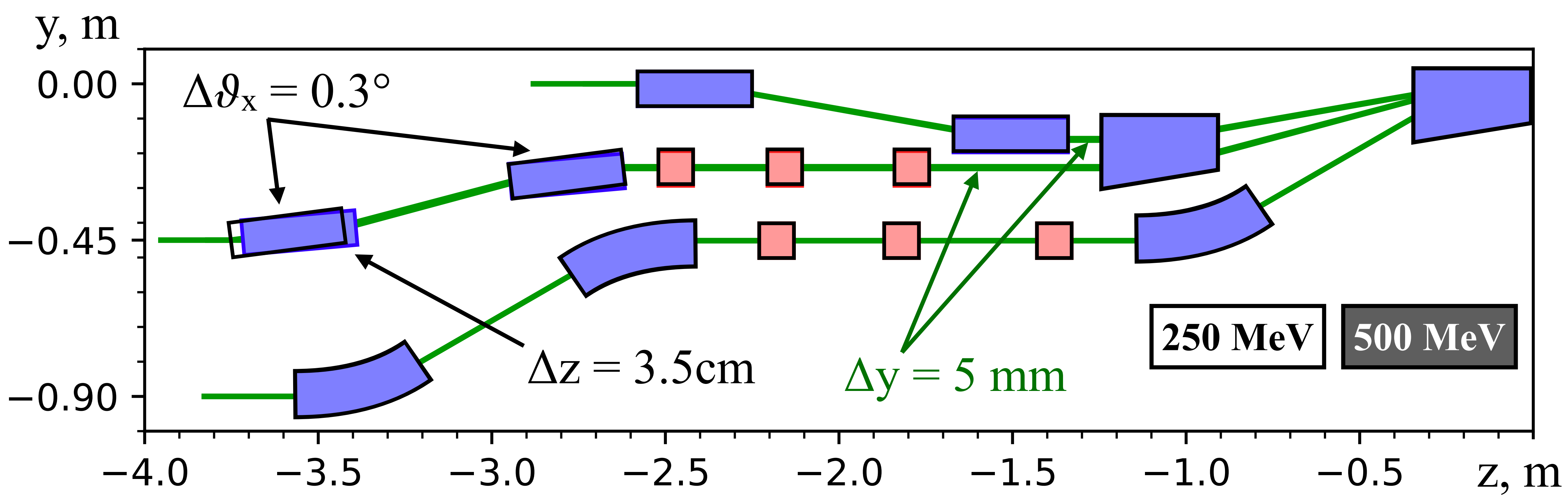
Lattice design. 250 MeV & 500 MeV versions



All main elements are compatible with both versions !

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

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

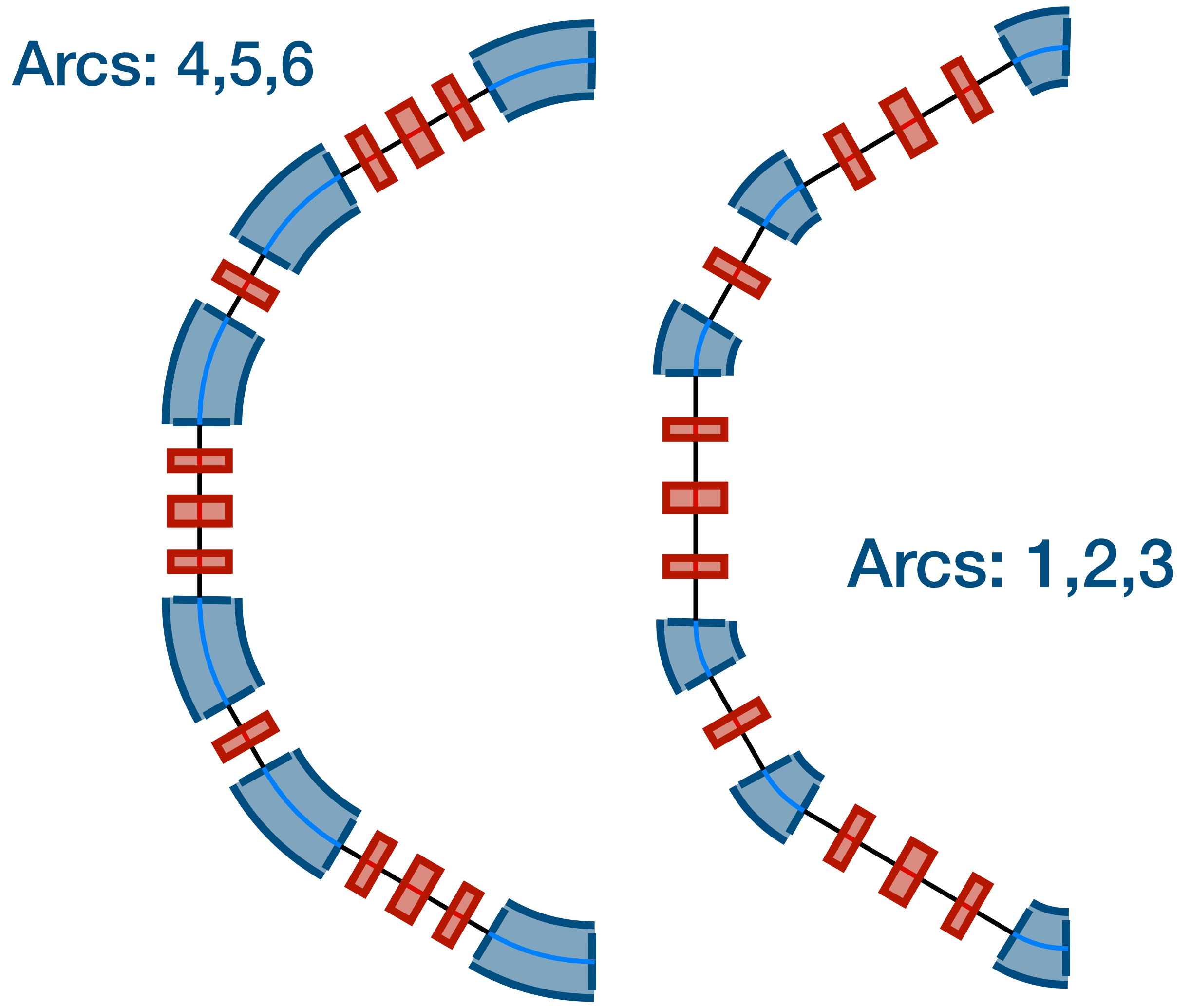


$\Delta E + E_0 \;:\; 2\Delta E + E_0 \;:\; 3\Delta E + E_0 \;\approx\; 1 : 1.92 : 2.84$

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

→ 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)

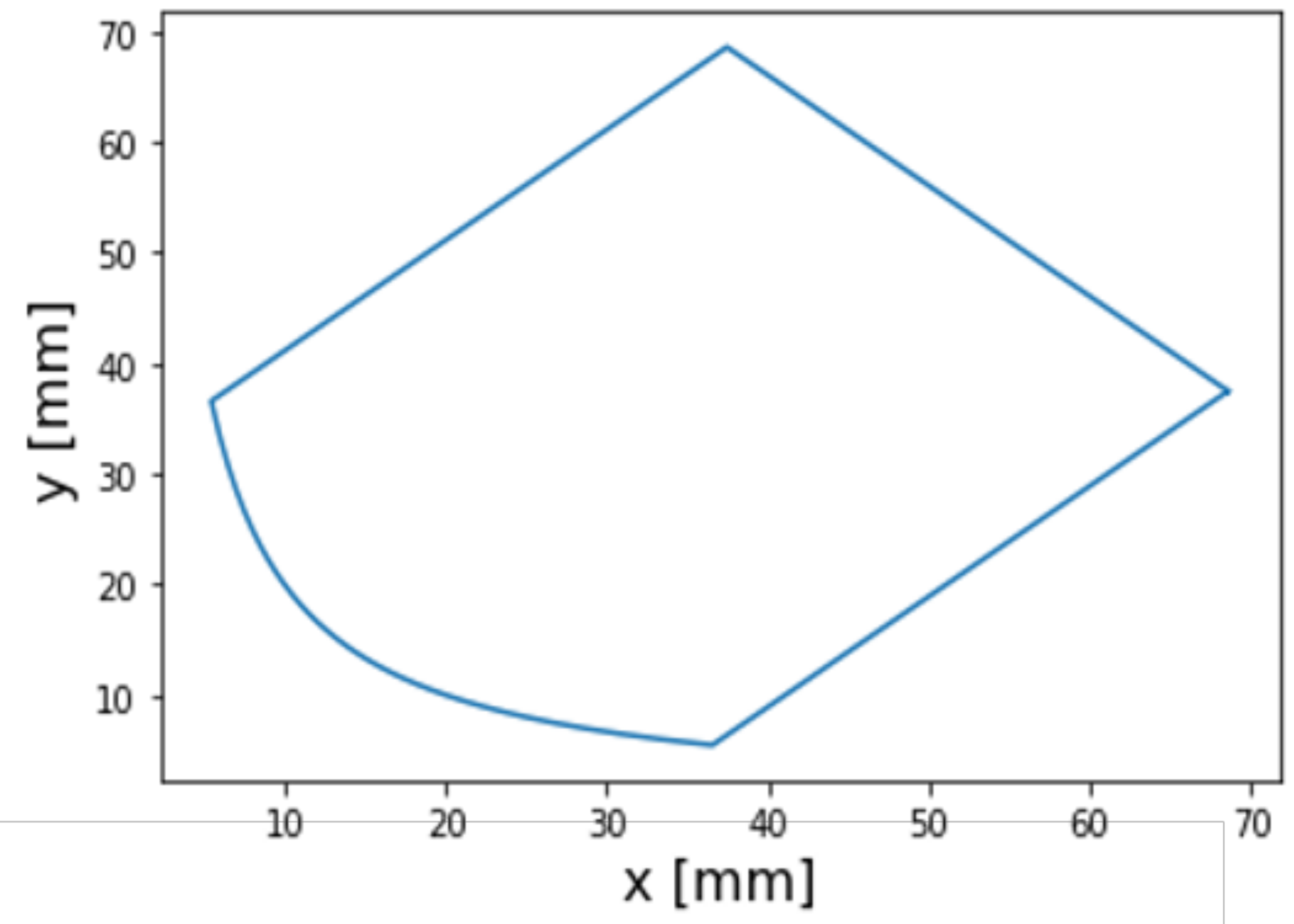
- all dipoles at arcs would be 33 cm (**18 shorter magnets**)
- arcs could be slightly shorter → **smaller footprint**

Distance between the Arcs and Spreaders should be adjustable

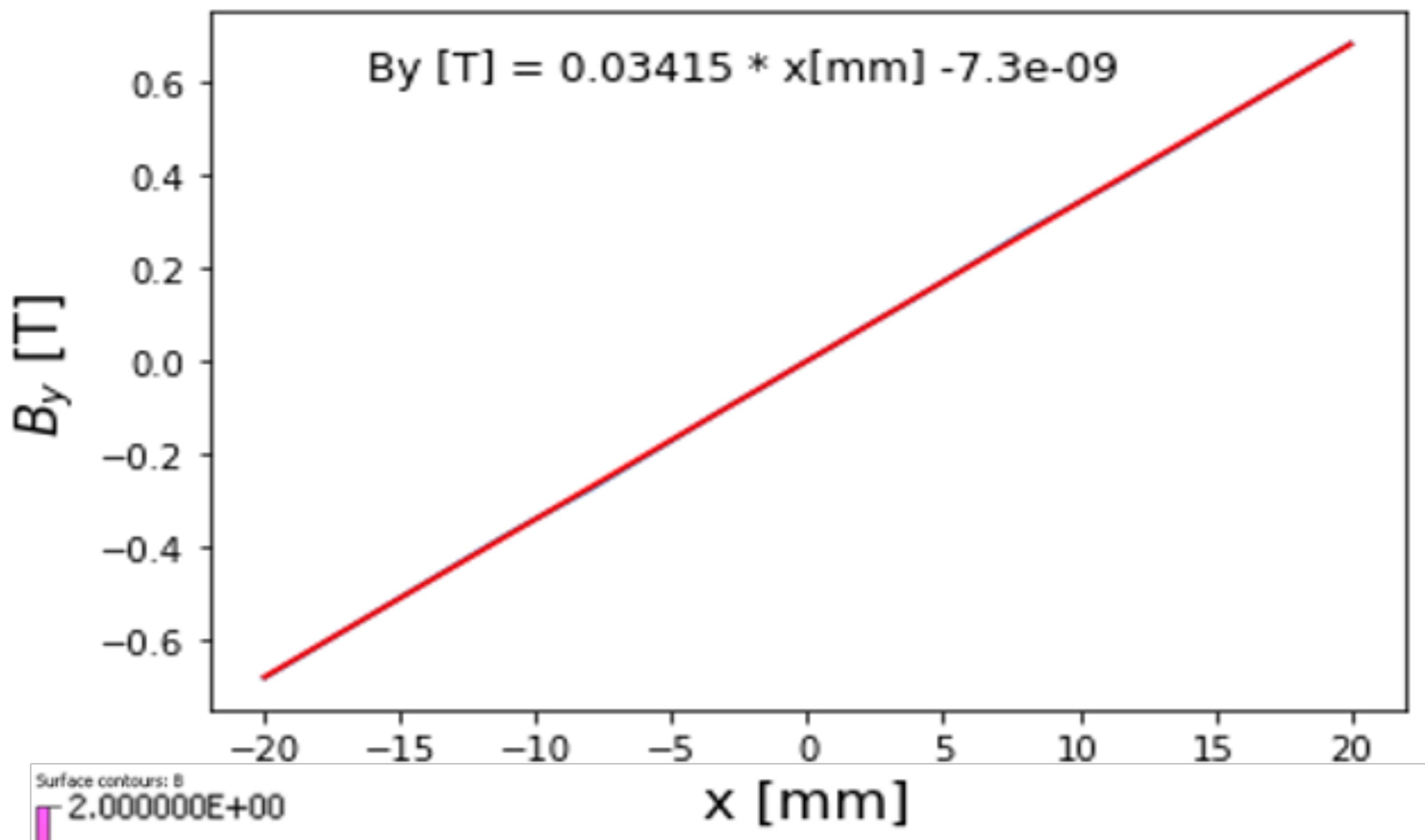
- to form an optimal filling pattern, i.e. placement of accelerated bunches between the injected bunches
- tune phase adjustment between accelerations at RF cavities

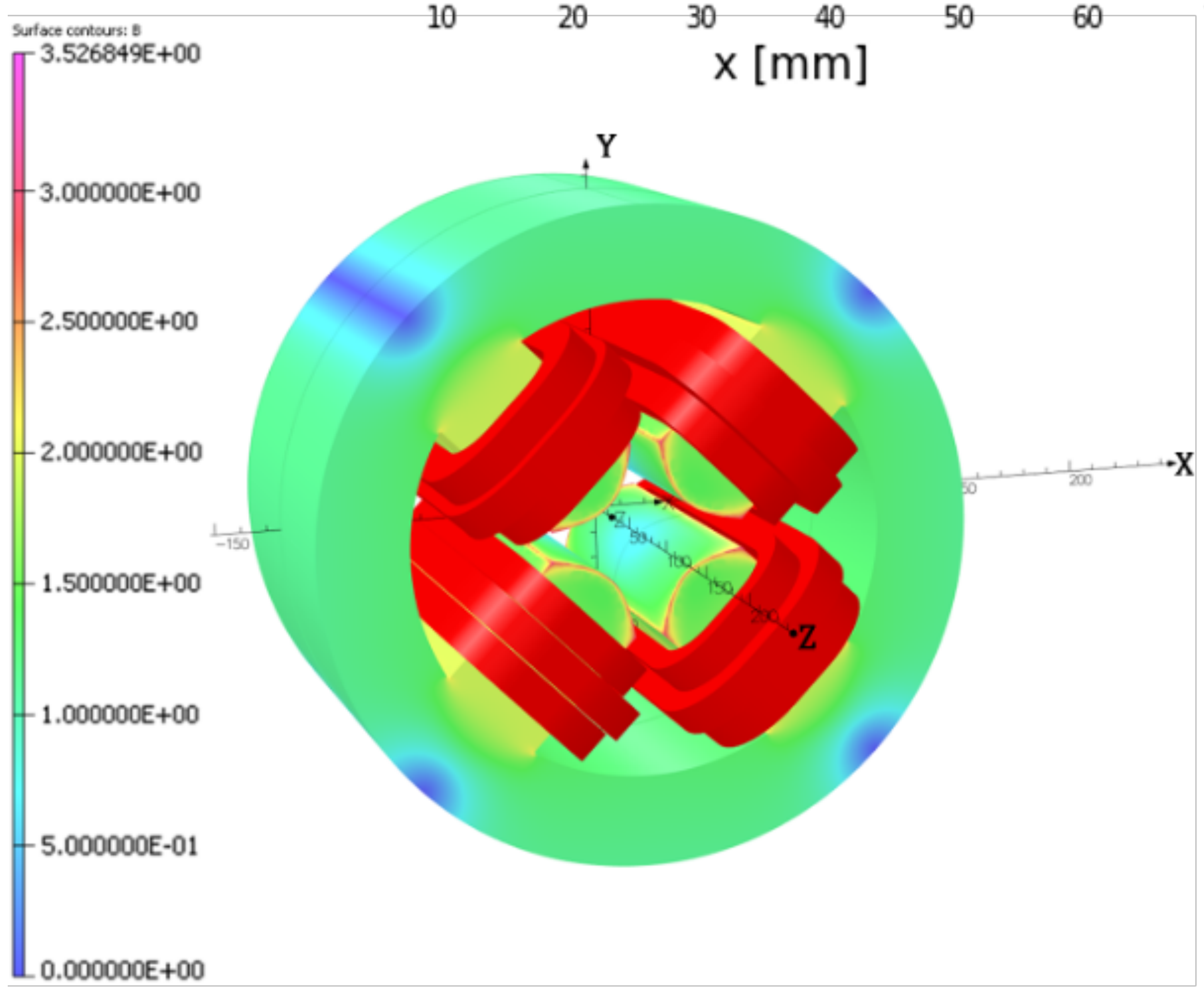
Quadrupole Magnet (work by Rasha Abukeshek)

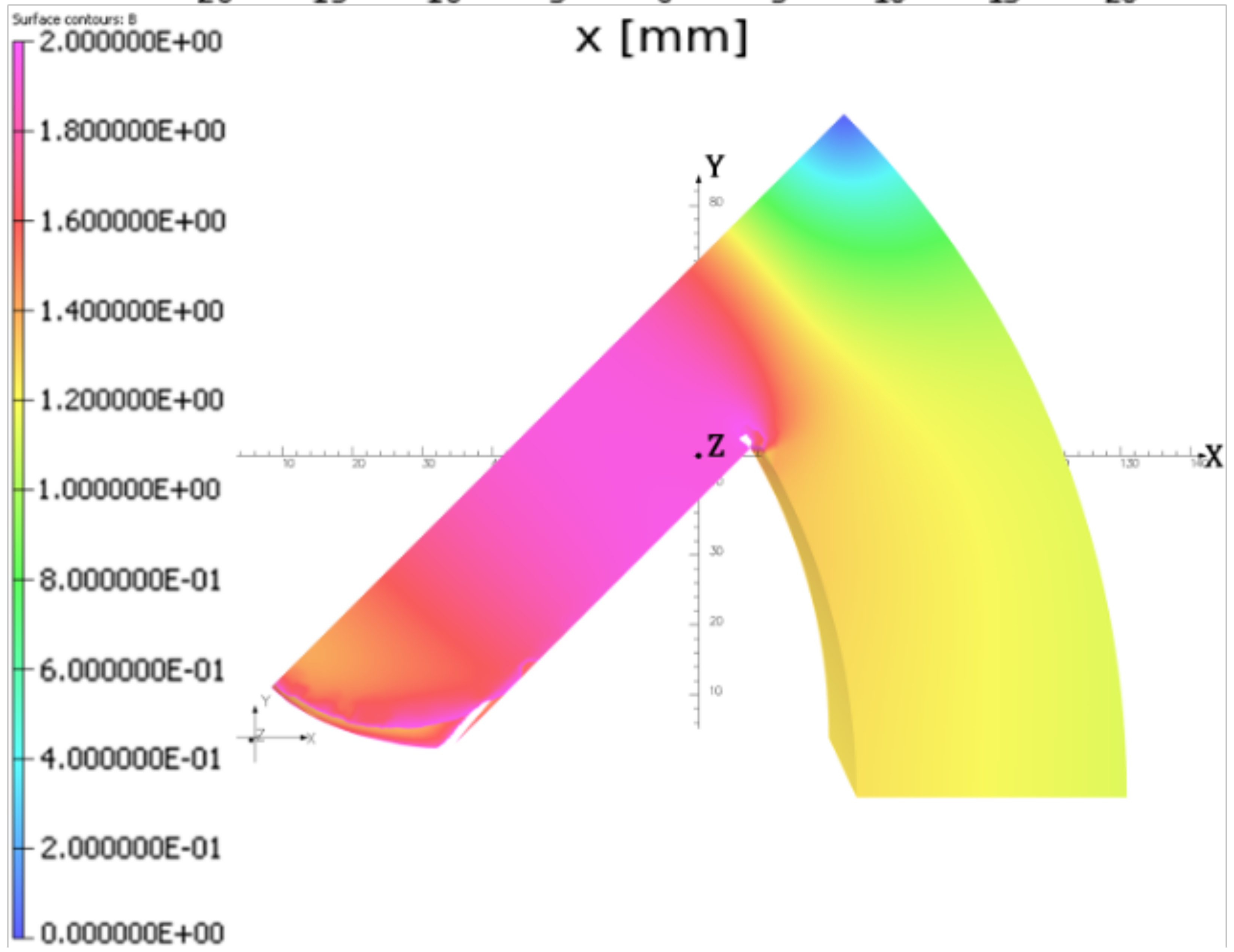
Multi-coil design



G = 34.15 T/m







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

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**

Types of dipoles for ERL part. 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

Filling Pattern

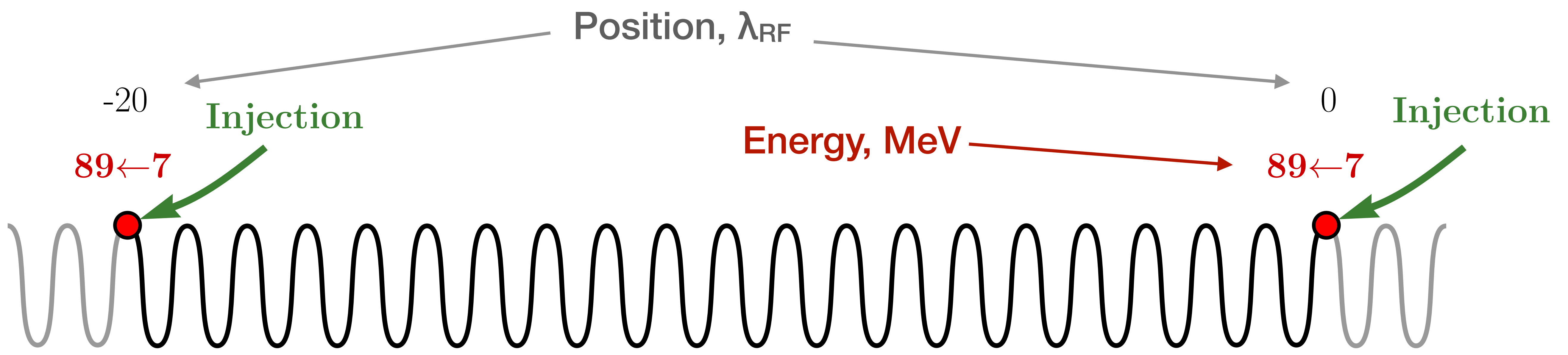
Filling pattern for 250 MeV version

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

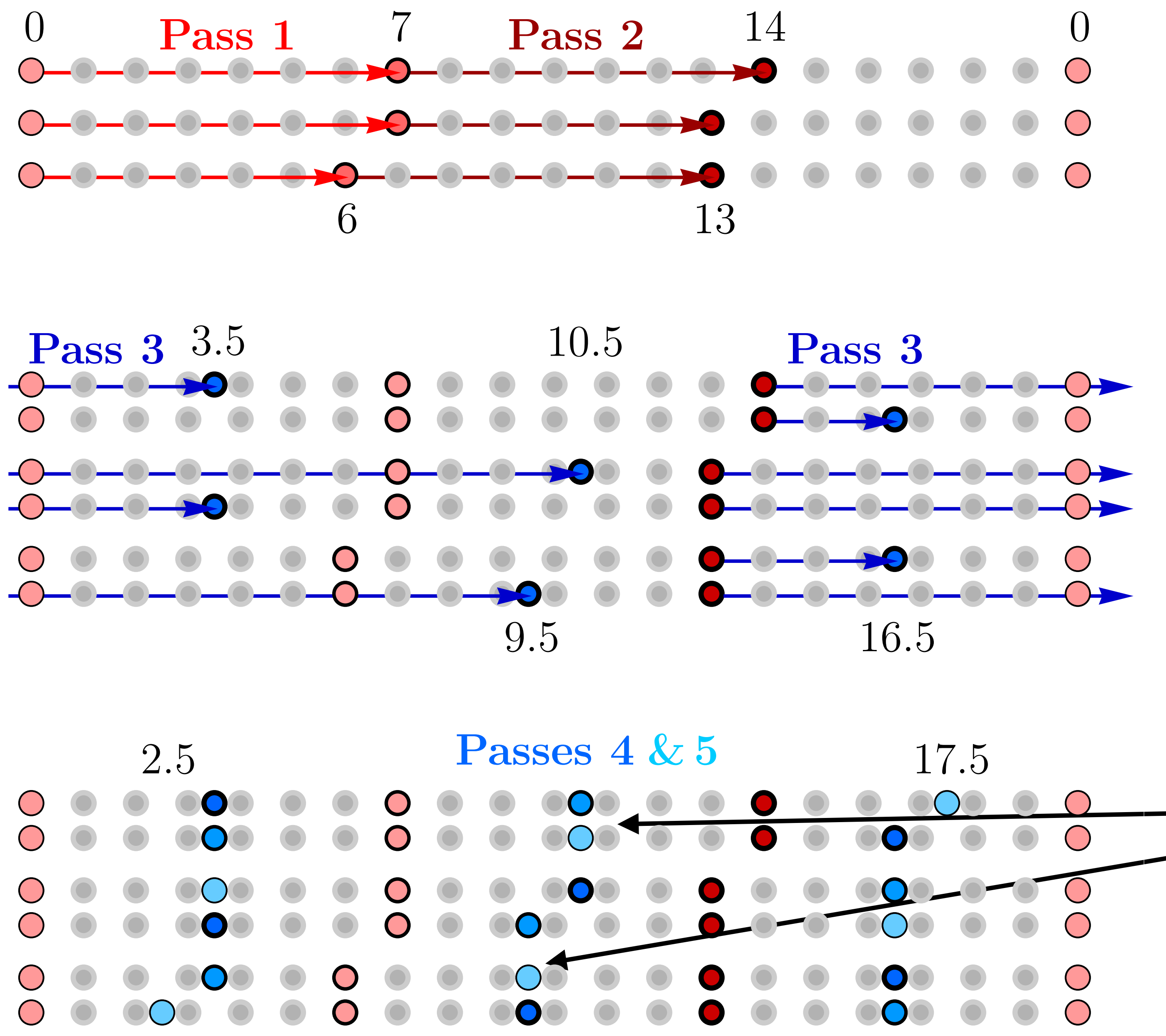
$\nu_{RF} / \nu_{inj} \approx 20$, λ_{RF} = 37.4 cm

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

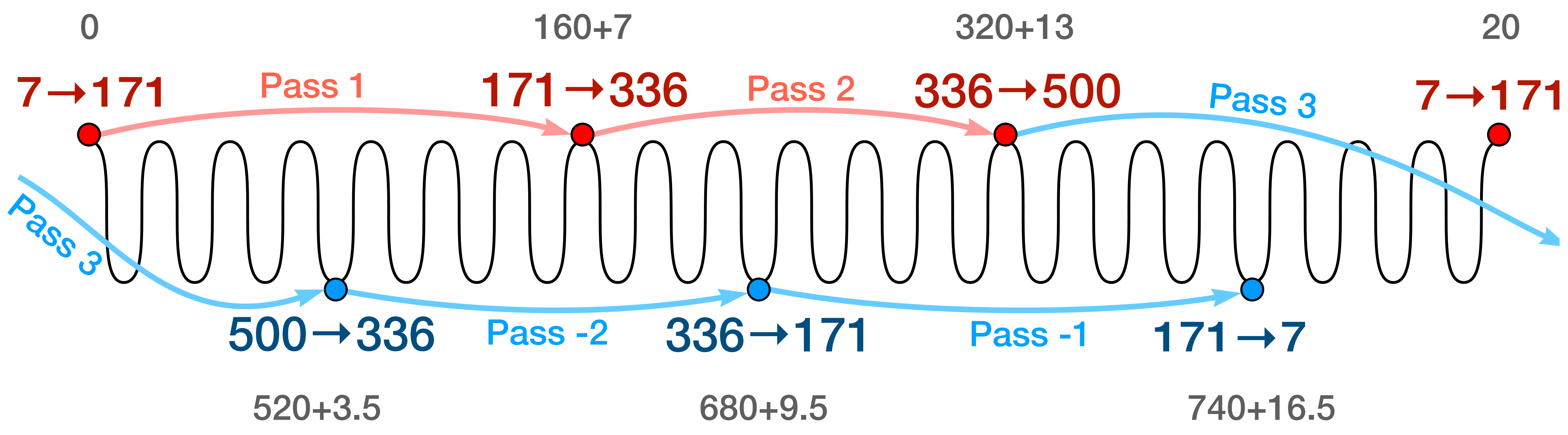


Six possible options of uniform filling patterns



option 2 & 5 have bunches of lowest energies separated

Uniform filling pattern, L_{Pass} = 160 + Δ_i , Δ_i = 7, 6, 10.5, 6, 7



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

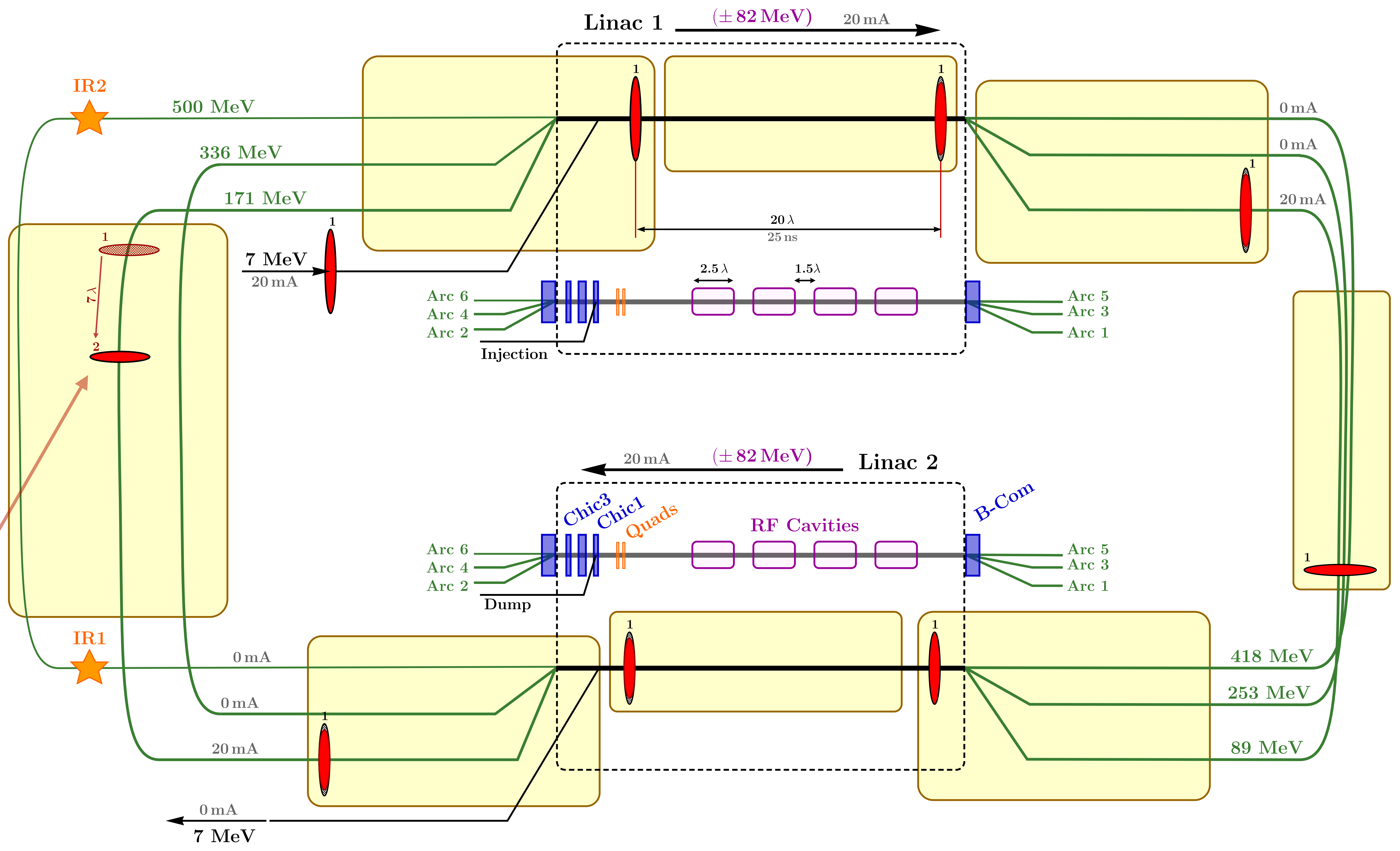
Pass 1

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 $7\,\lambda_{RF}$



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 ($3{\times}10^9$ 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

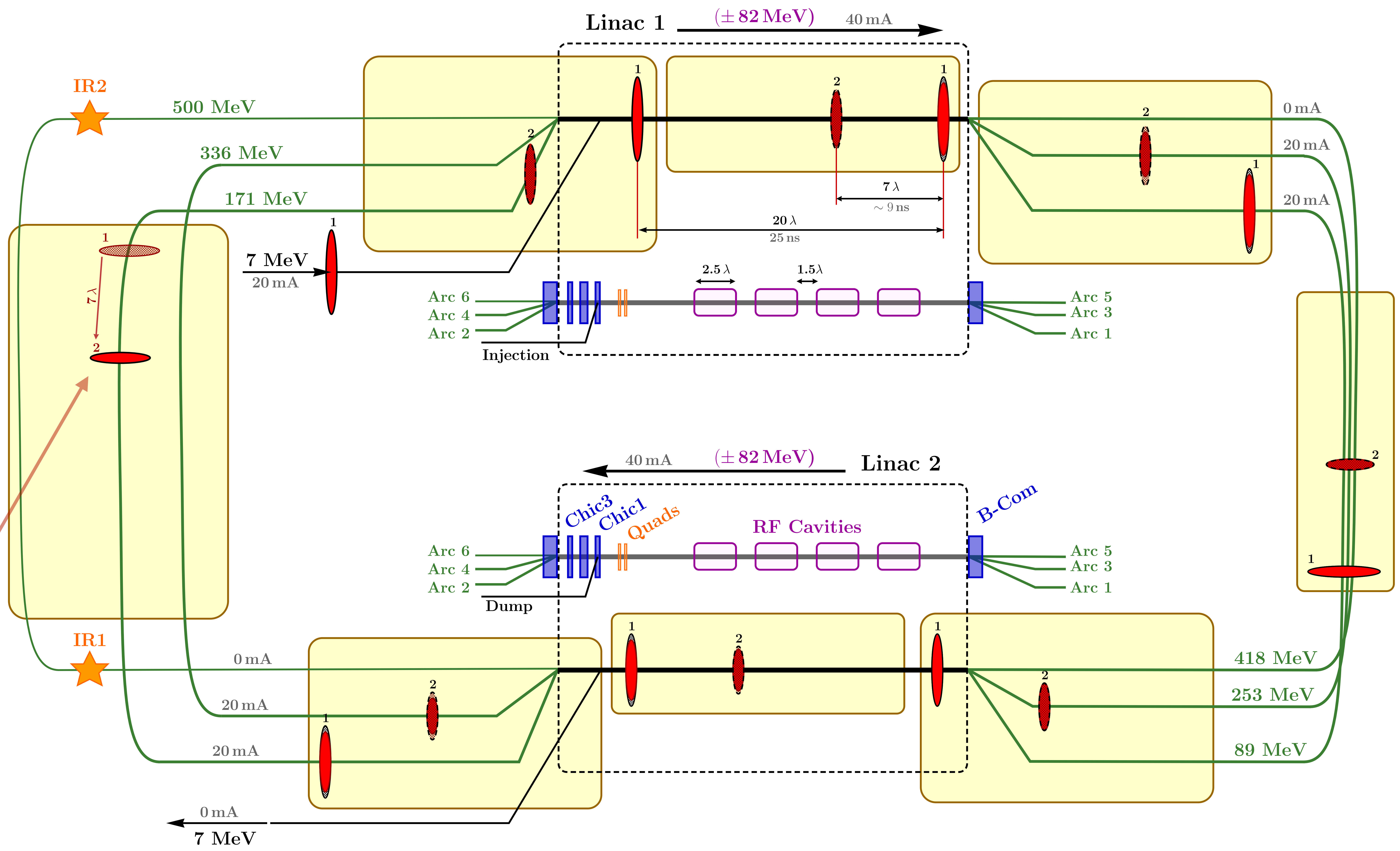
Pass 1 length (Arc1 + Arc2 + 2 Linac) $L_{Pass\ 1} = 167\ \lambda_{RF}$

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

Pass 2

Linac 1 → Arc 3 → Linac 2 → Arc 4

171→253 MeV 253→336 MeV



Passes 1–3

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

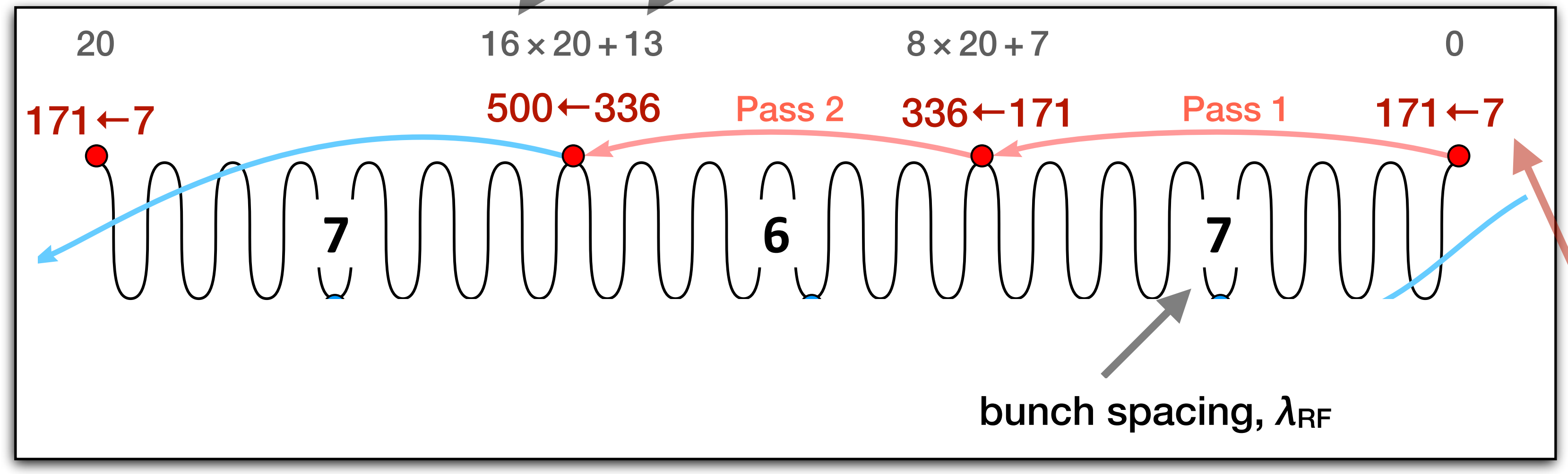
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

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						

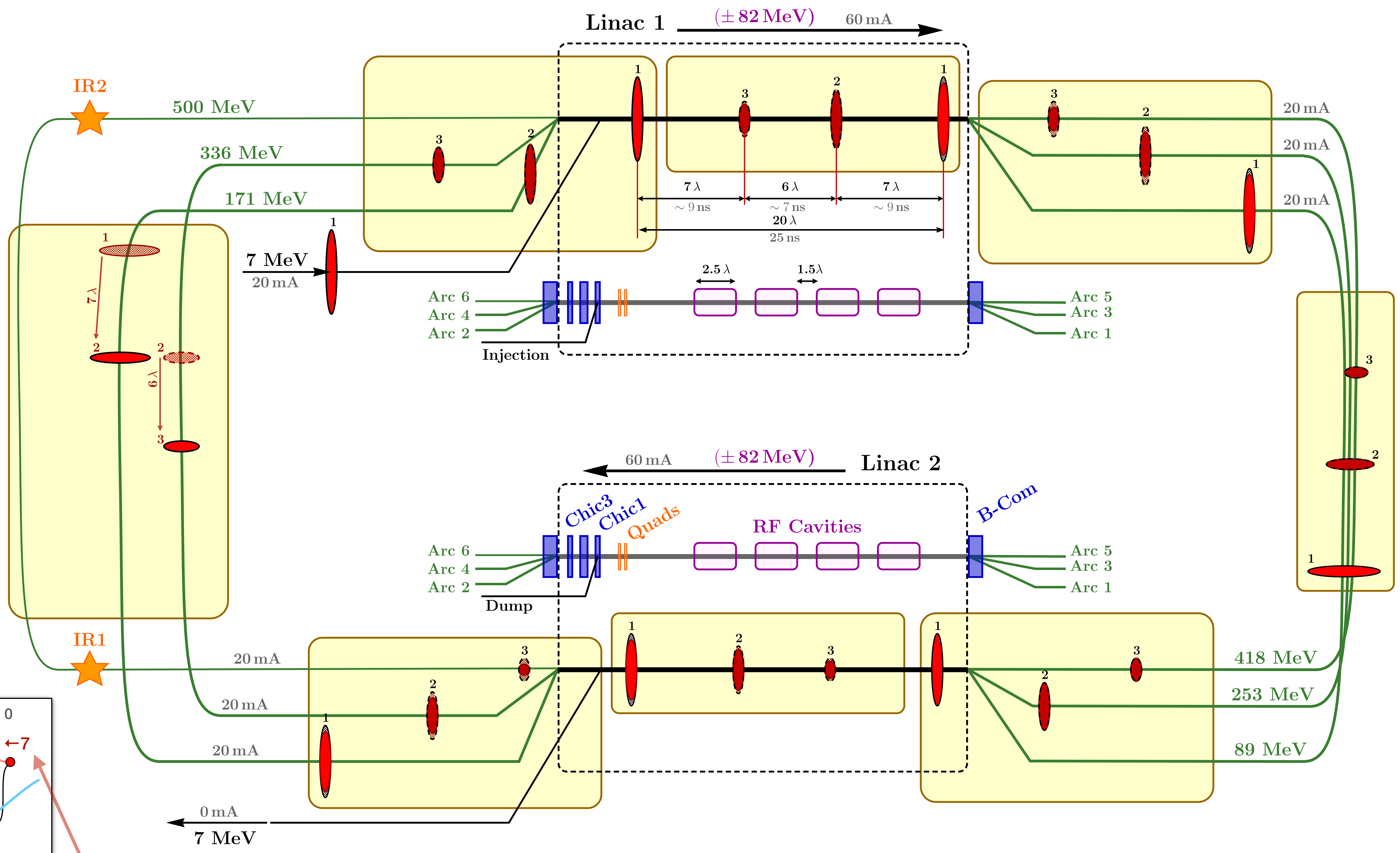
Filling Pattern

total shift, λ_{RF}



bunch spacing, λ_{RF}

Energy, MeV



Passes 1–4

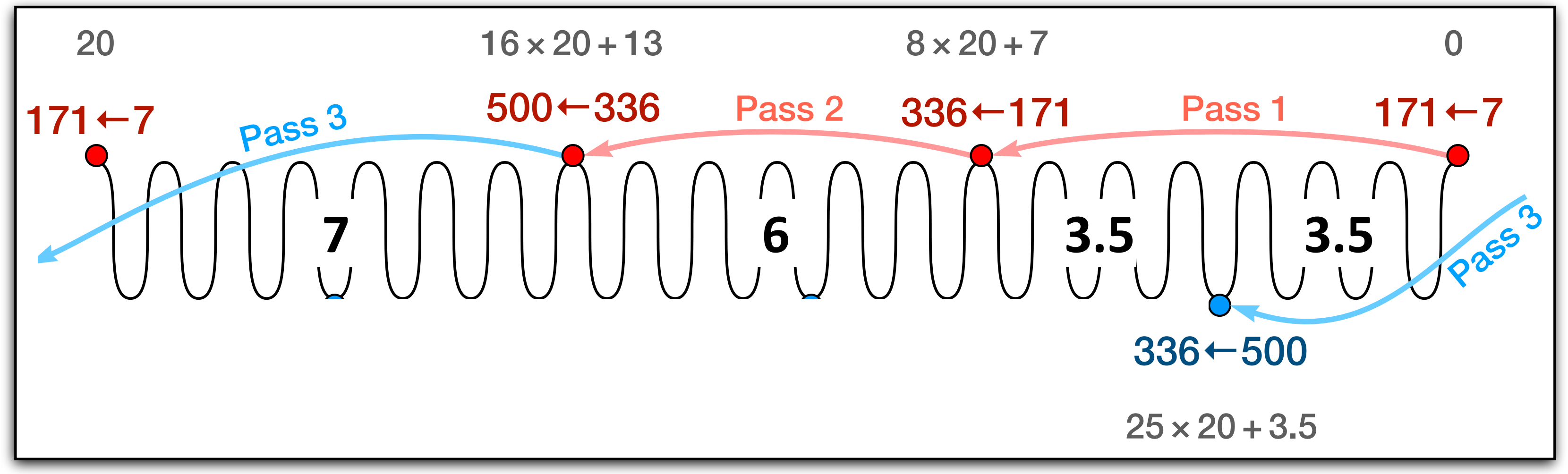
Injection ($\nu_{inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{inj} = 25$ ns)

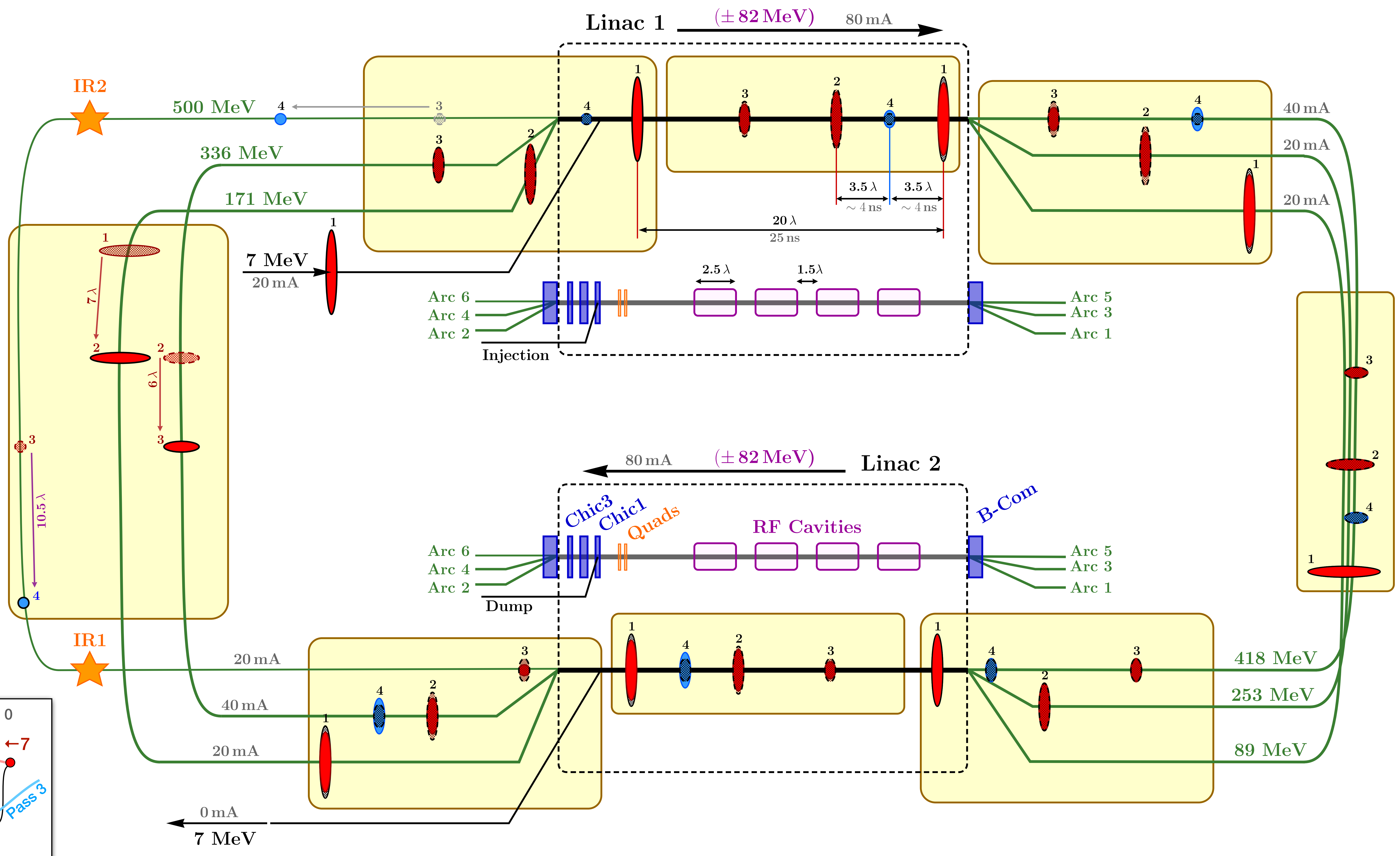
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

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}	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						

Filling Pattern





Forming the Filling Pattern. Passes 1—5

Passes 1–5

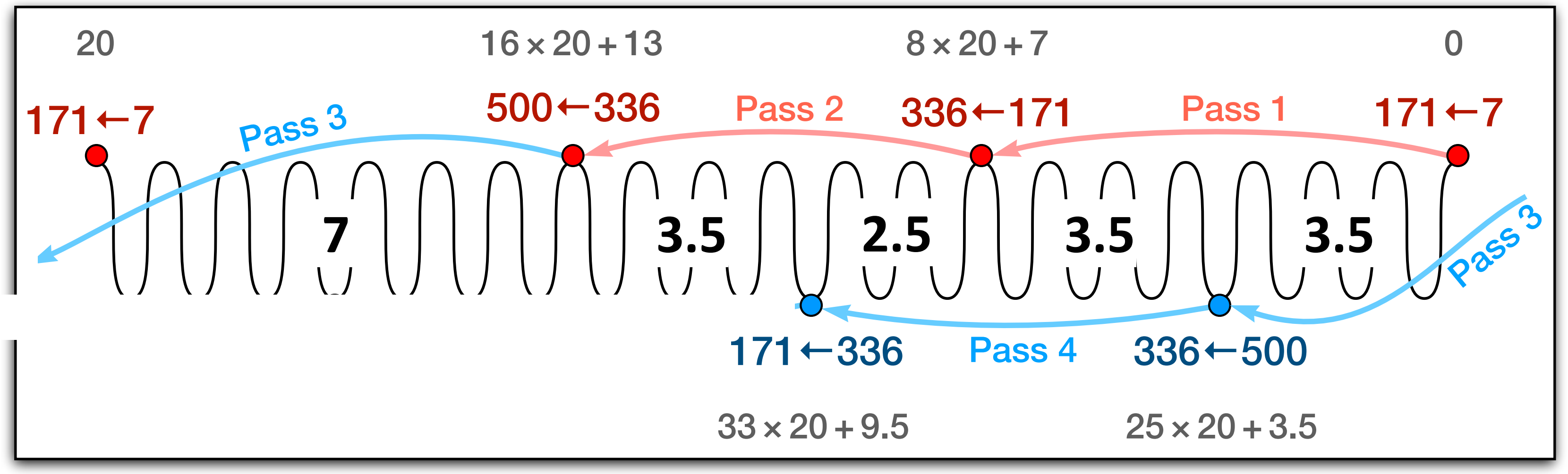
Injection ($\nu_{inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{inj} = 25$ ns)

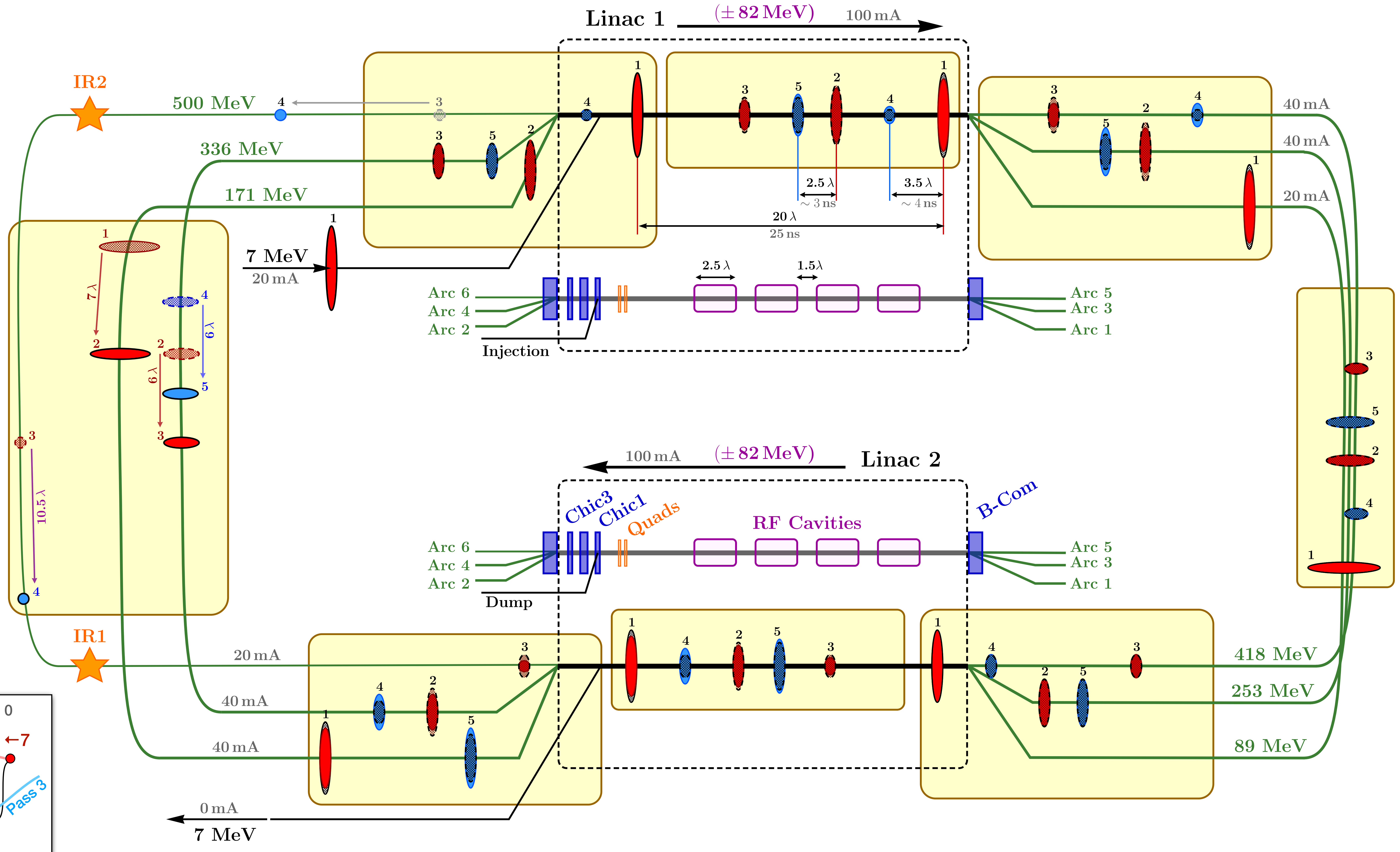
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

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

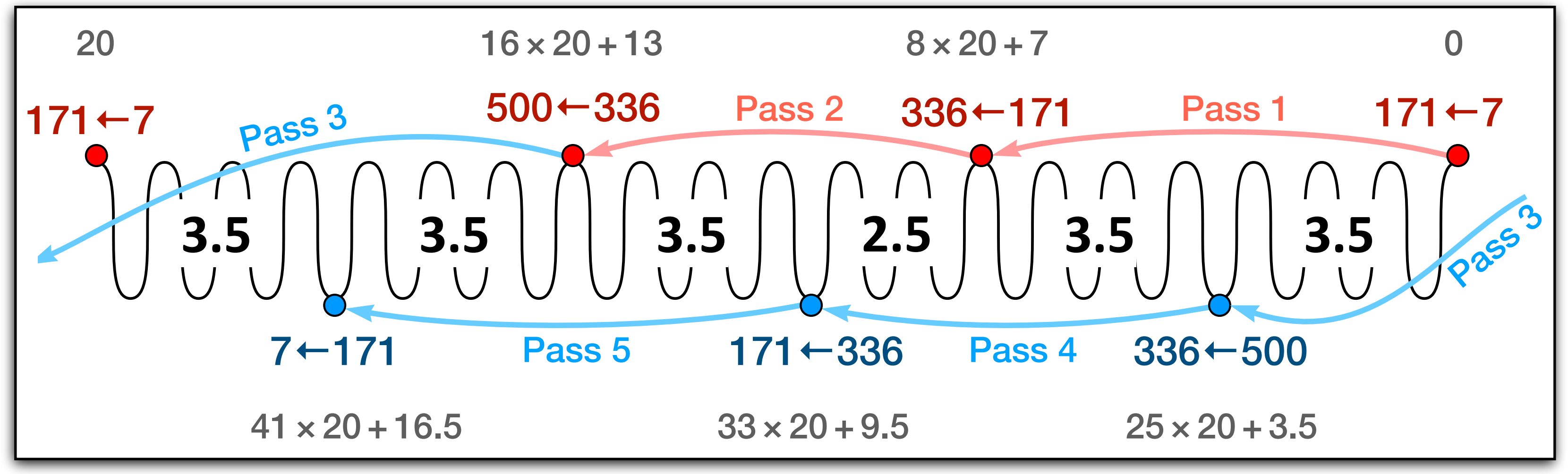
Injection ($\nu_{inj} \approx 40$ MHz) I = 20 mA ($Q \approx 500$ pC, t_{inj} = 25 ns)

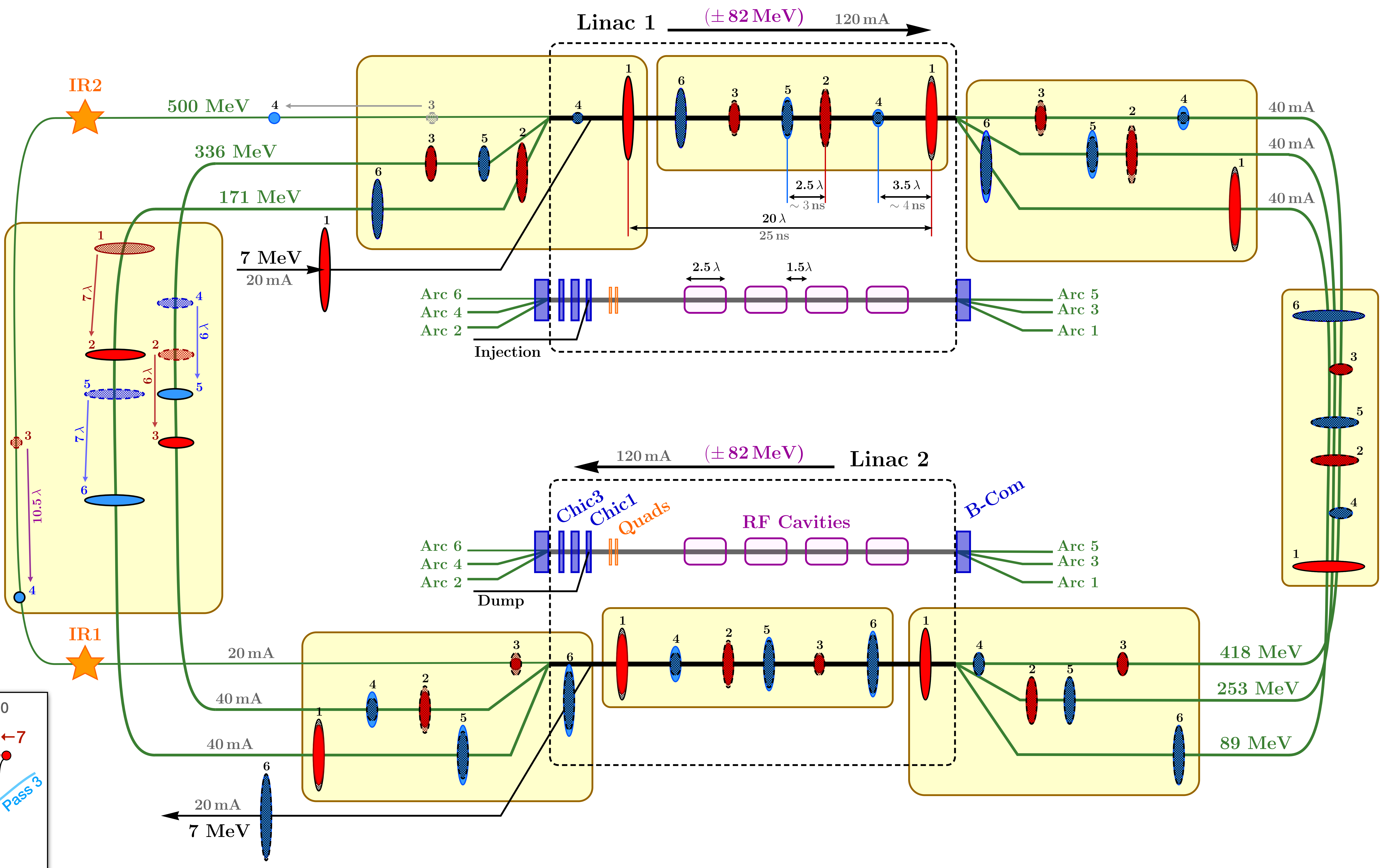
RF Cavity (ν_{RF} = 801.58 MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

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   500 vs 250 MeV versions

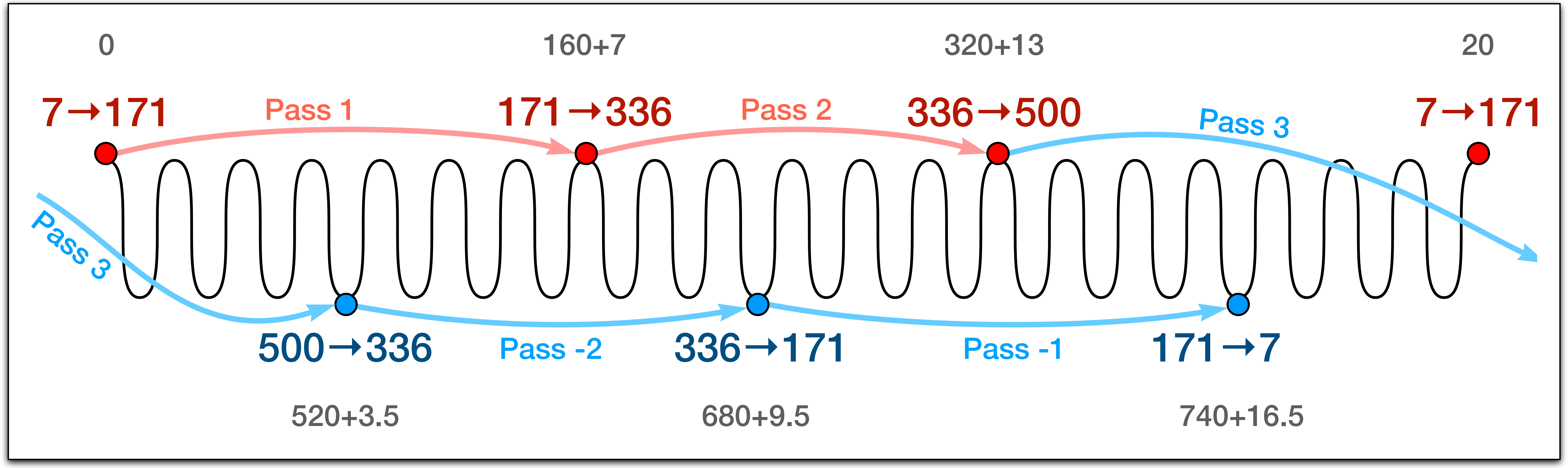
500 MeV

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}

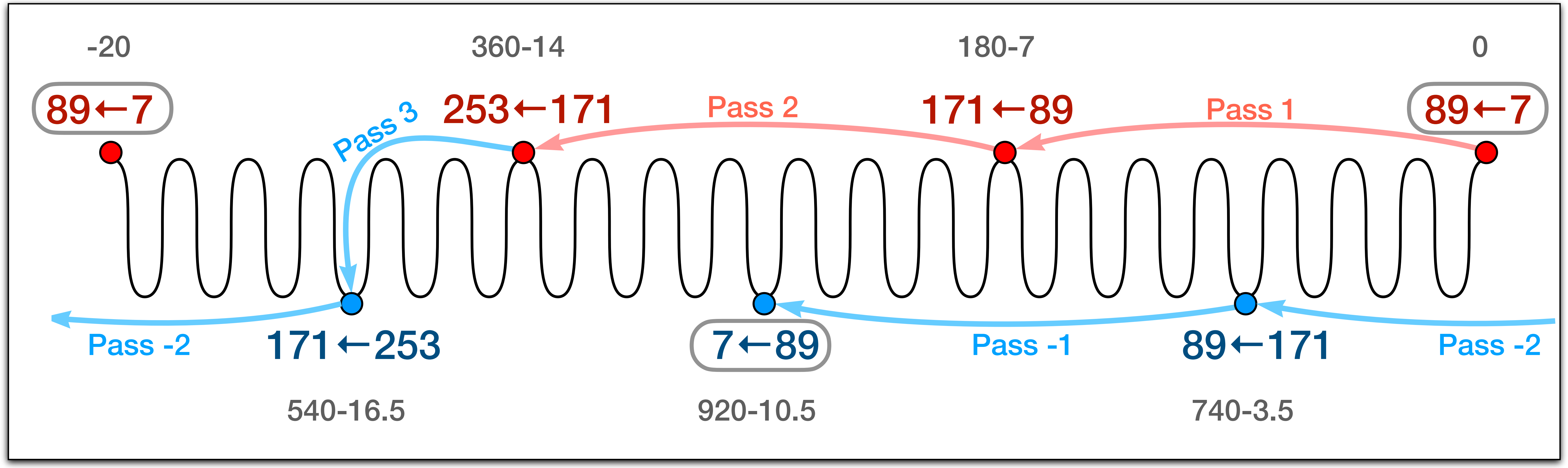
optimal shift: Δ = 7, 7, 2.5, 7, 7

→ bunches of lowest energies are separated

(more important than for 500 MeV version)

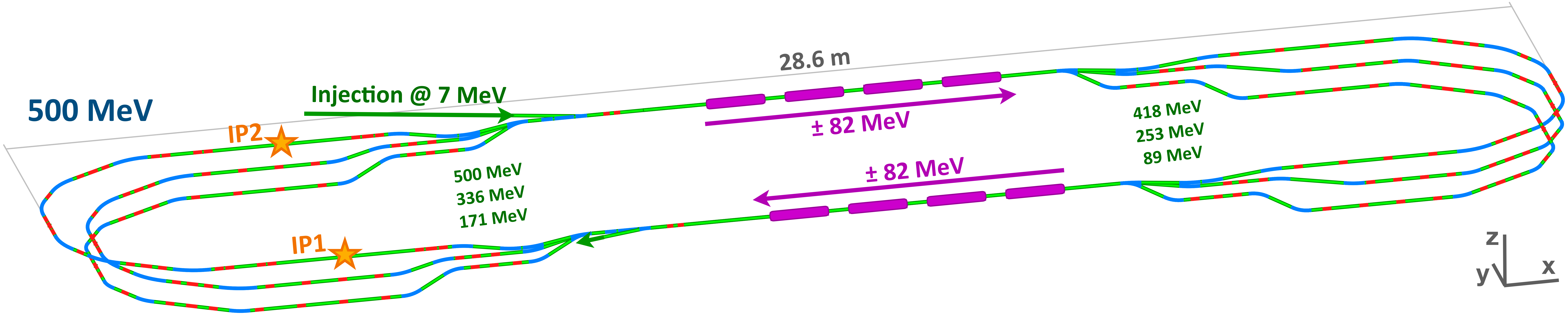
→ more detailed studies will follow)

→ 29.9 m of total length



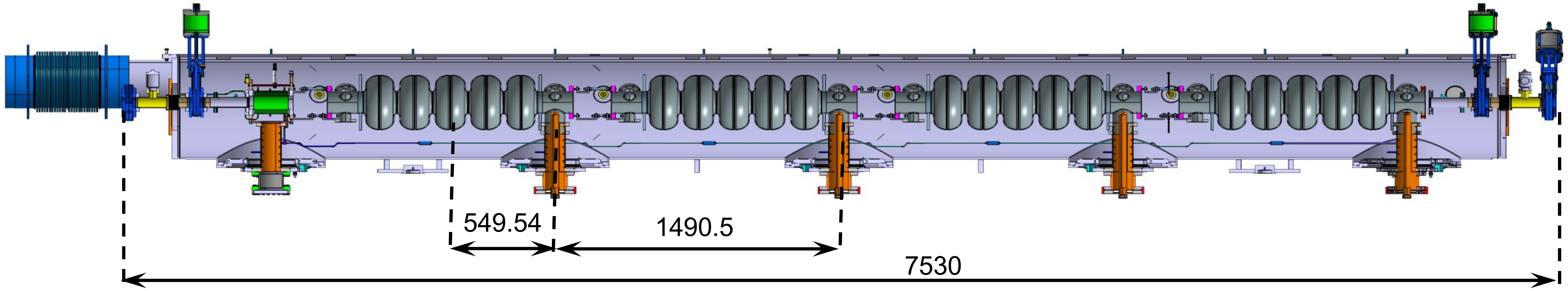
(177.5—170.5) λ_{RF} / 2 = 3.5 λ_{RF} ≈ 1.3 m   (λ_{RF} = 37.4 cm)

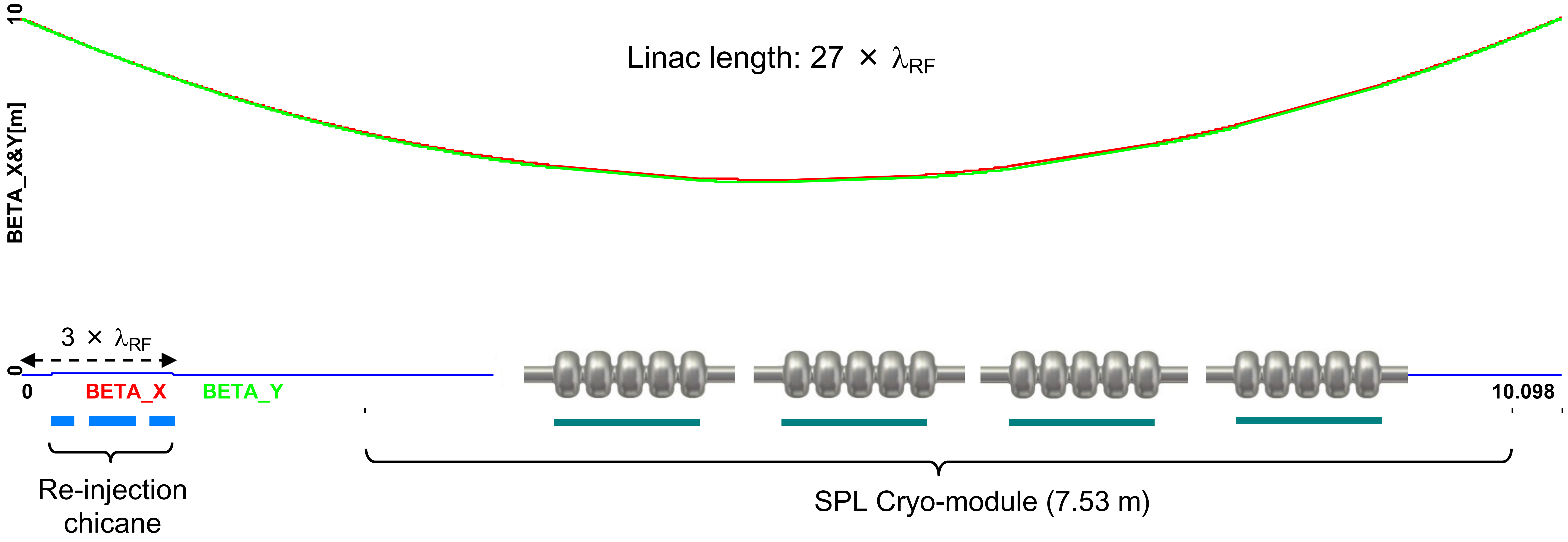
Optics


500 MeV
28.6 m
Injection @ 7 MeV
IP2
IP1
± 82 MeV
± 82 MeV
500 MeV
336 MeV
171 MeV
418 MeV
253 MeV
89 MeV
z
y
x

(work by A. Bogacz)

PERLE cavity string inside the SPL cryomodule





Linac, Cryo-module - Layout

(work by A. Bogacz)

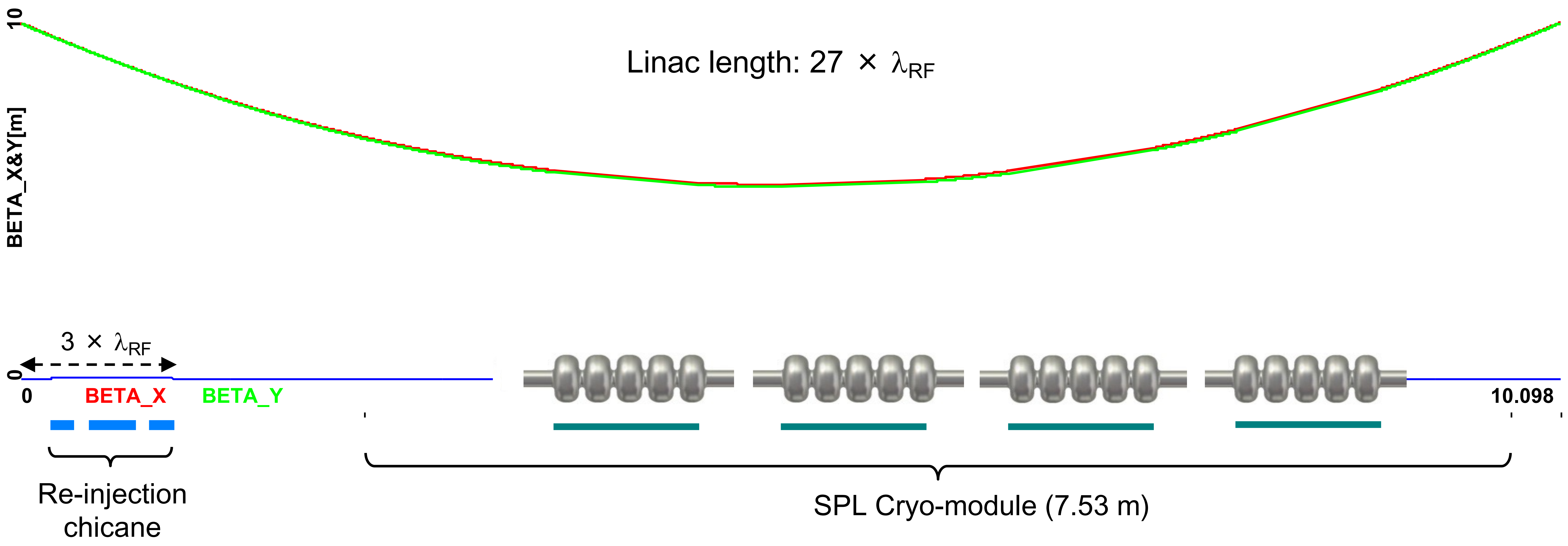
801.58 MHz RF, 5-cell cavity:

λ_{RF} = 37.40 cm

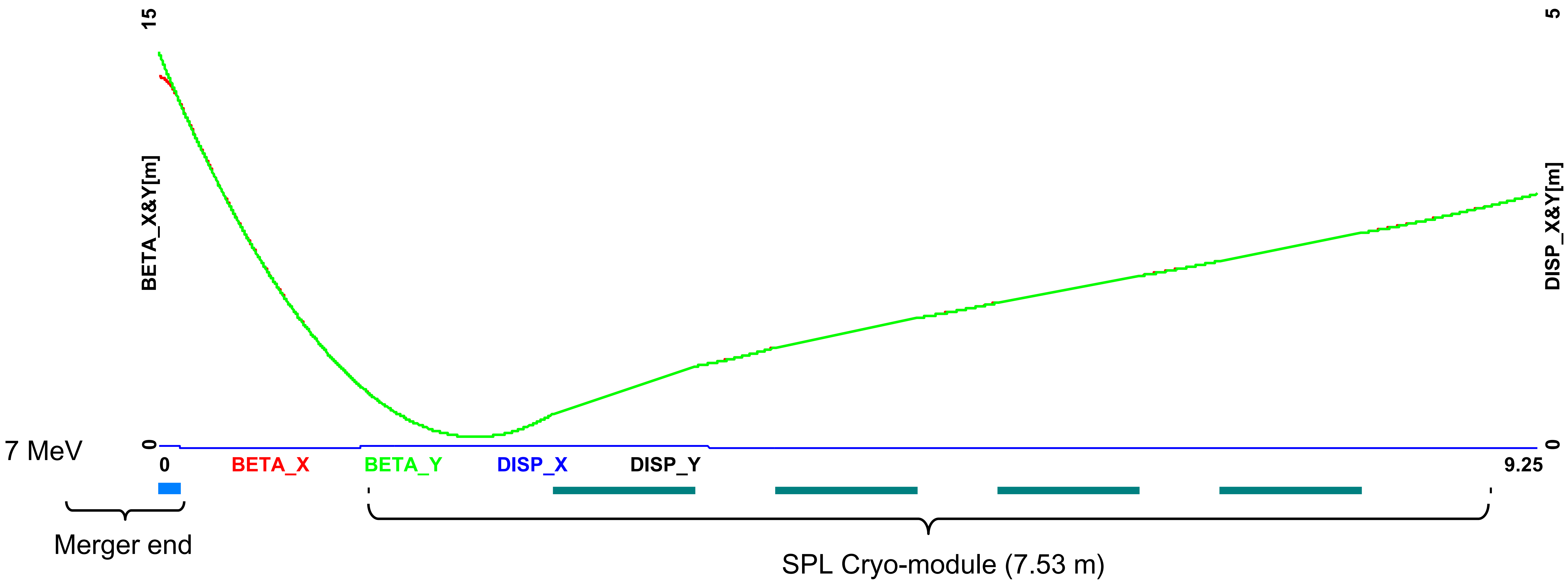
$L_c = 5\lambda_{RF}/2 = 93.50$ cm

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

ΔE= 82.2 MeV per Cryo-module



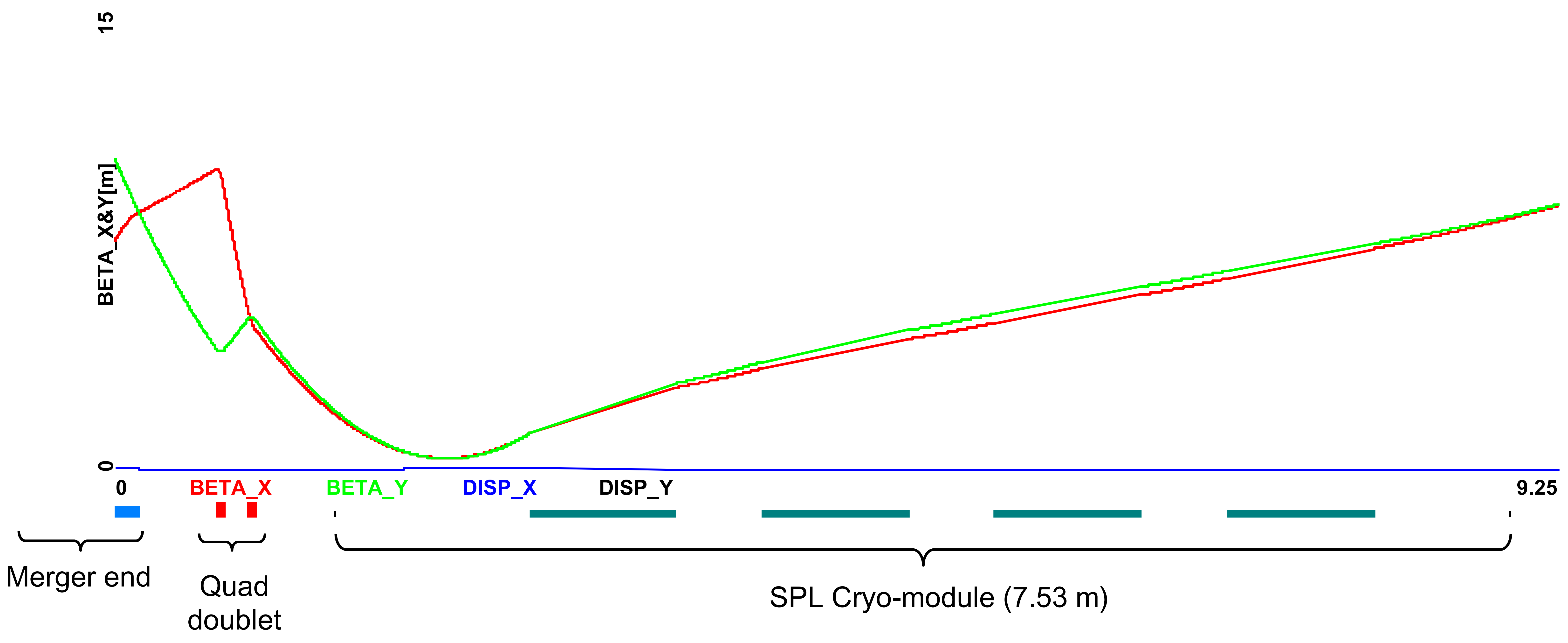
(work by A. Bogacz)



Initial Twiss: BetaX[cm] = 1170
BetaY[cm] = 1170
AlfaX = 5.74
AlfaY = 5.74

Linac 1-st pass, Tunability

(work by A. Bogacz)

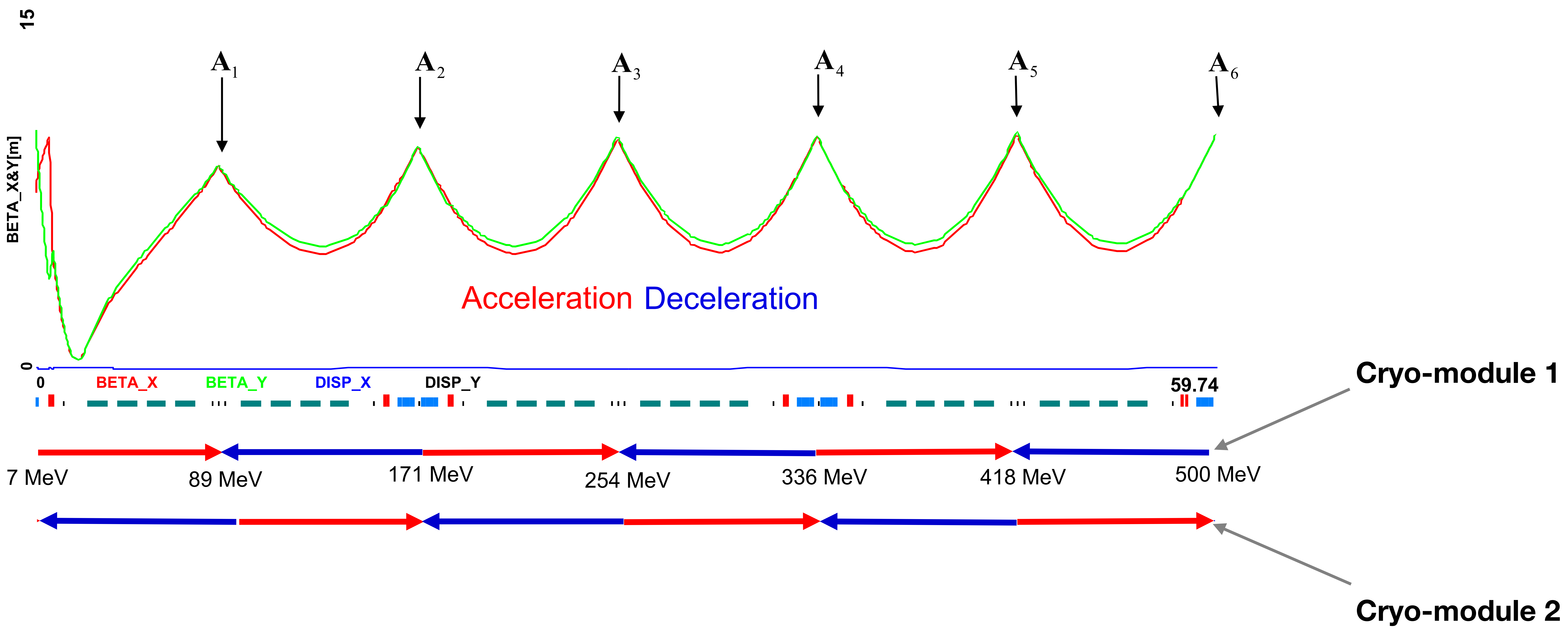


QL1F	L[cm] = 5	G[kG/cm] = 0.080
QL1D	L[cm] = 5	G[kG/cm] = -0.068

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

Multi-pass ER Optics

(work by A. Bogacz)



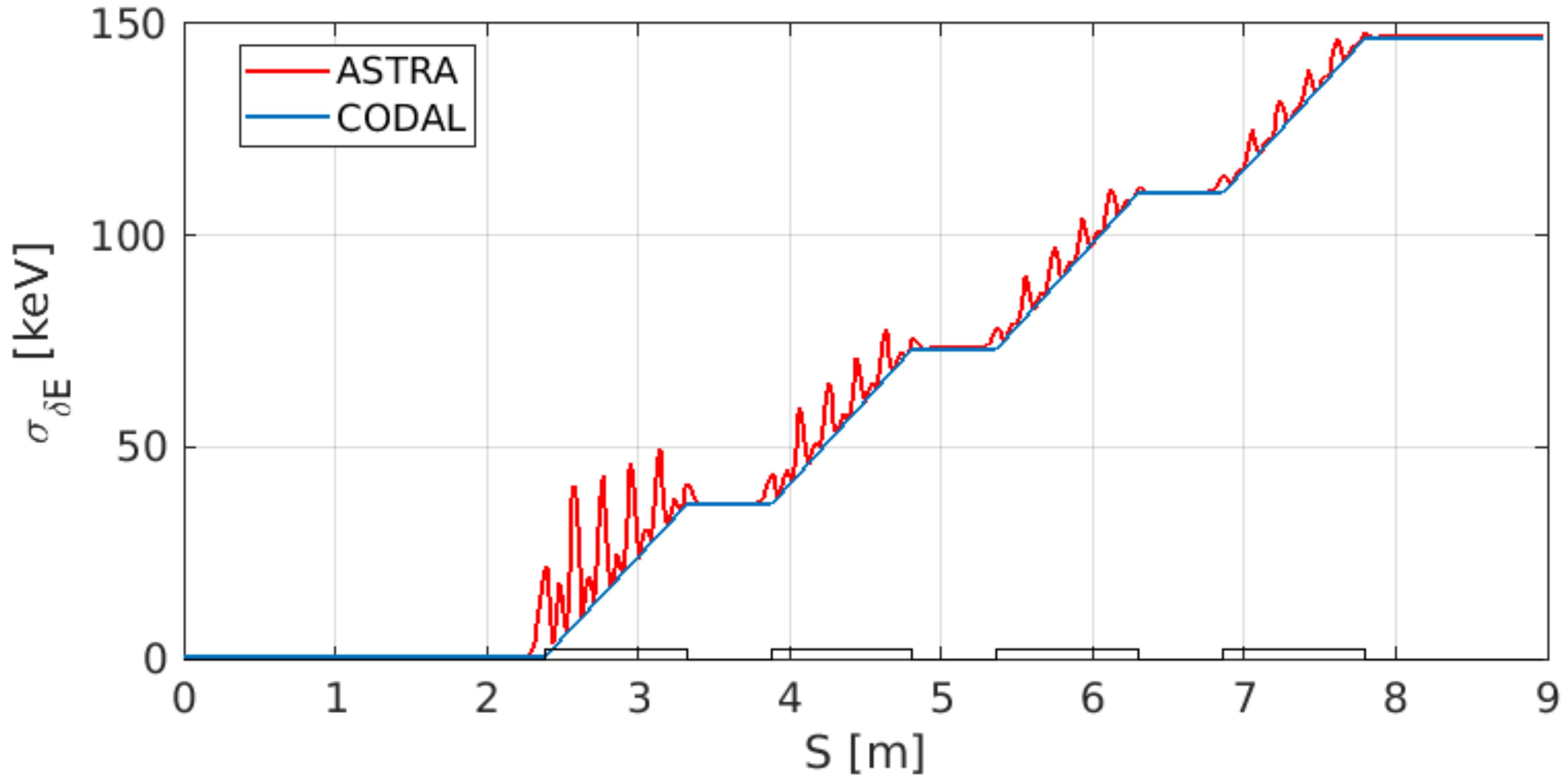
Benchmarking CODAL (analitical) with ASTRA (field maps)

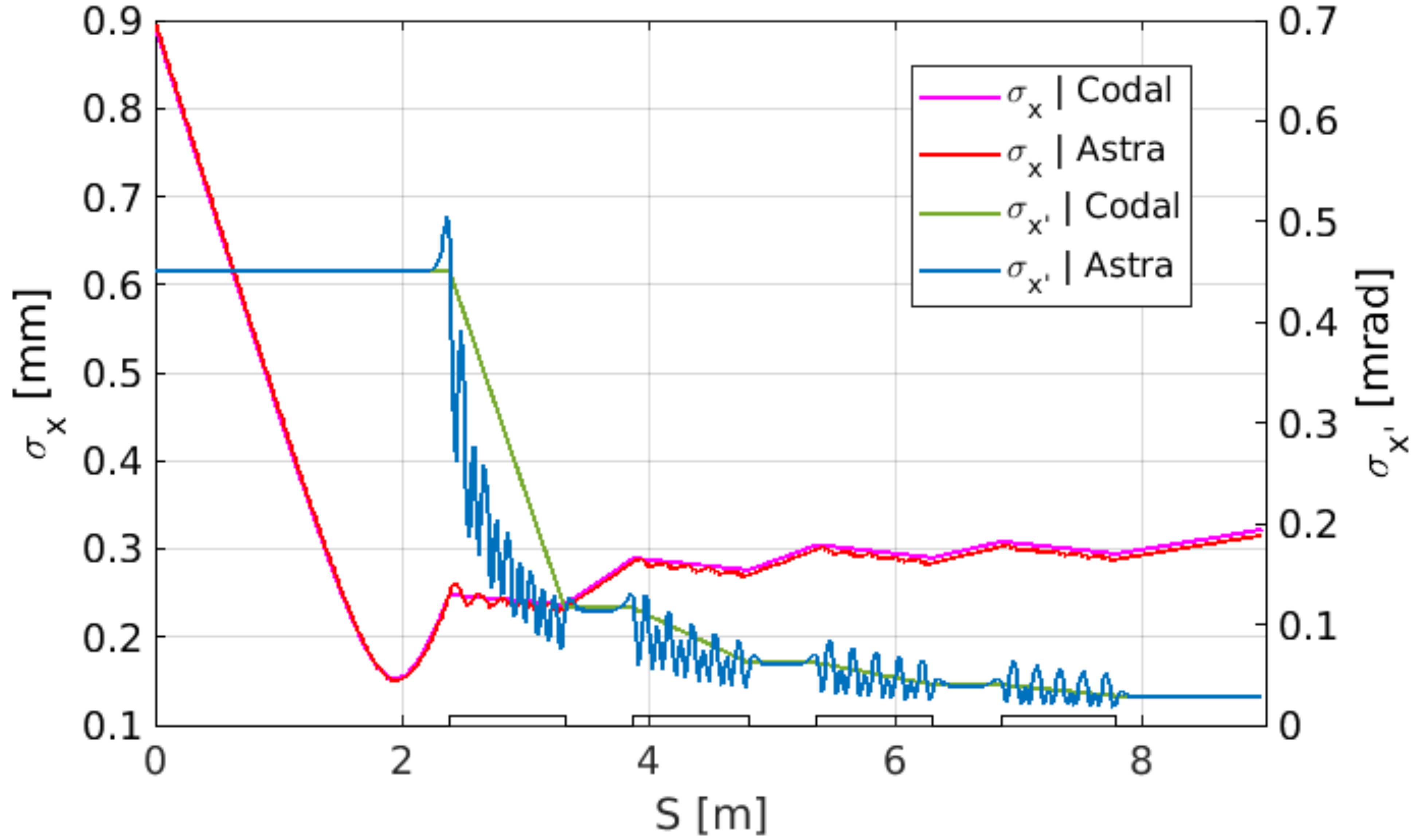
(work by C. Guyot)

CODAL (home-made code, courtesy of A. Loulergue) developed for:

- damping free ring → multi-turn without reaching steady-state;
- for small ring → exact transverse integration of the dipoles
- short electron bunches collective effects → short range effects studies
- analytical free particle tracking → fast execution

added a 6D RF cavity analytic model





[5] J.Rosenzweig and L.Serafini. Transverse Particle Motion in Radio-Frequency Linear Accelerator. Phys. Rev. E, 49:1599-1602, Feb 1994

[6] T.Vinatier, C.Bruni, P.Puzo. Analytical modeling of longitudinal beam dynamics in an rf-gun : from almost zero to relativistiv veolcities. Nuclear Instruments and Methods in Physics Reasearch. Section A : Accelerators, Spectrometers, Detectors and Associated Equipement, 953:162914, 2020.

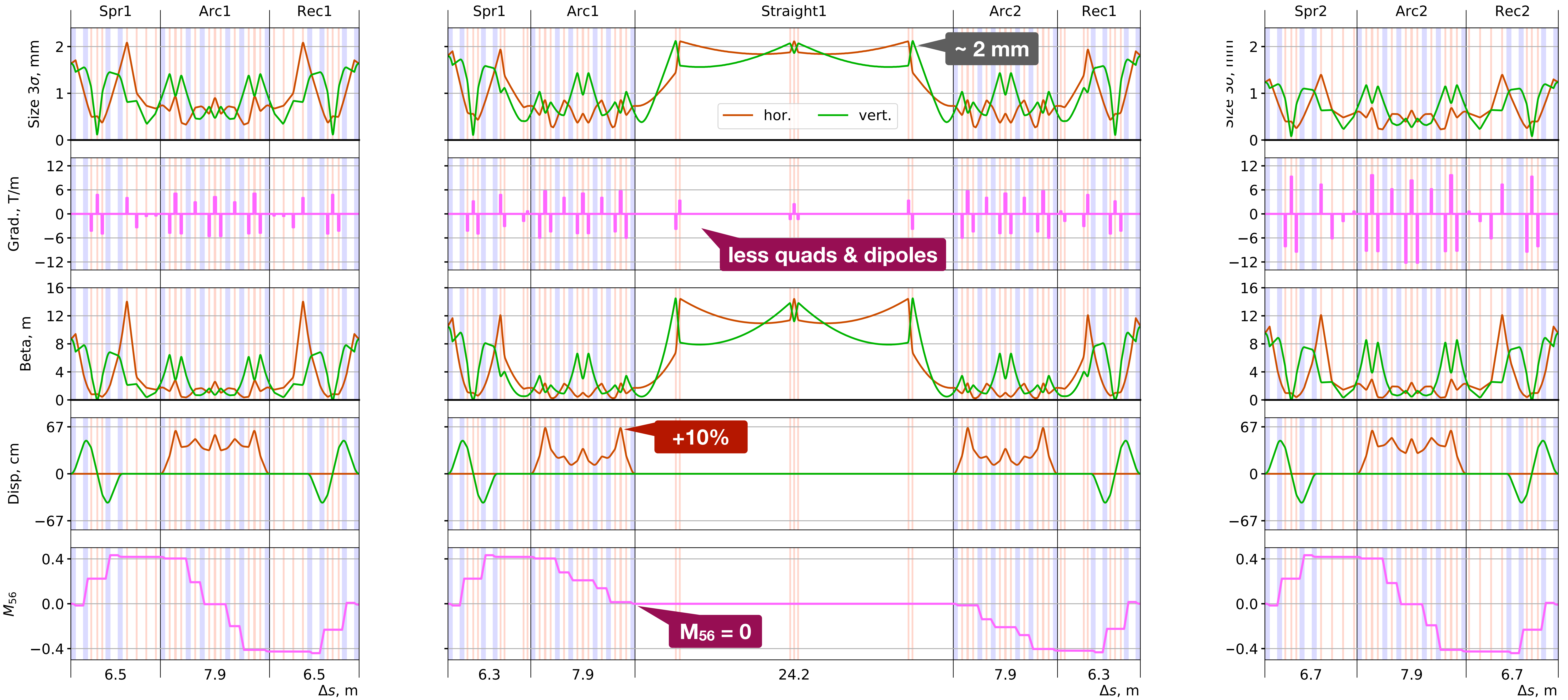
[7] C.Guyot and al. “modeling of standing wave cavities for tracking through multi-pass energy recovery linac”, IPAC’23 proceedings (2023)

Symmetry of the common section and turns

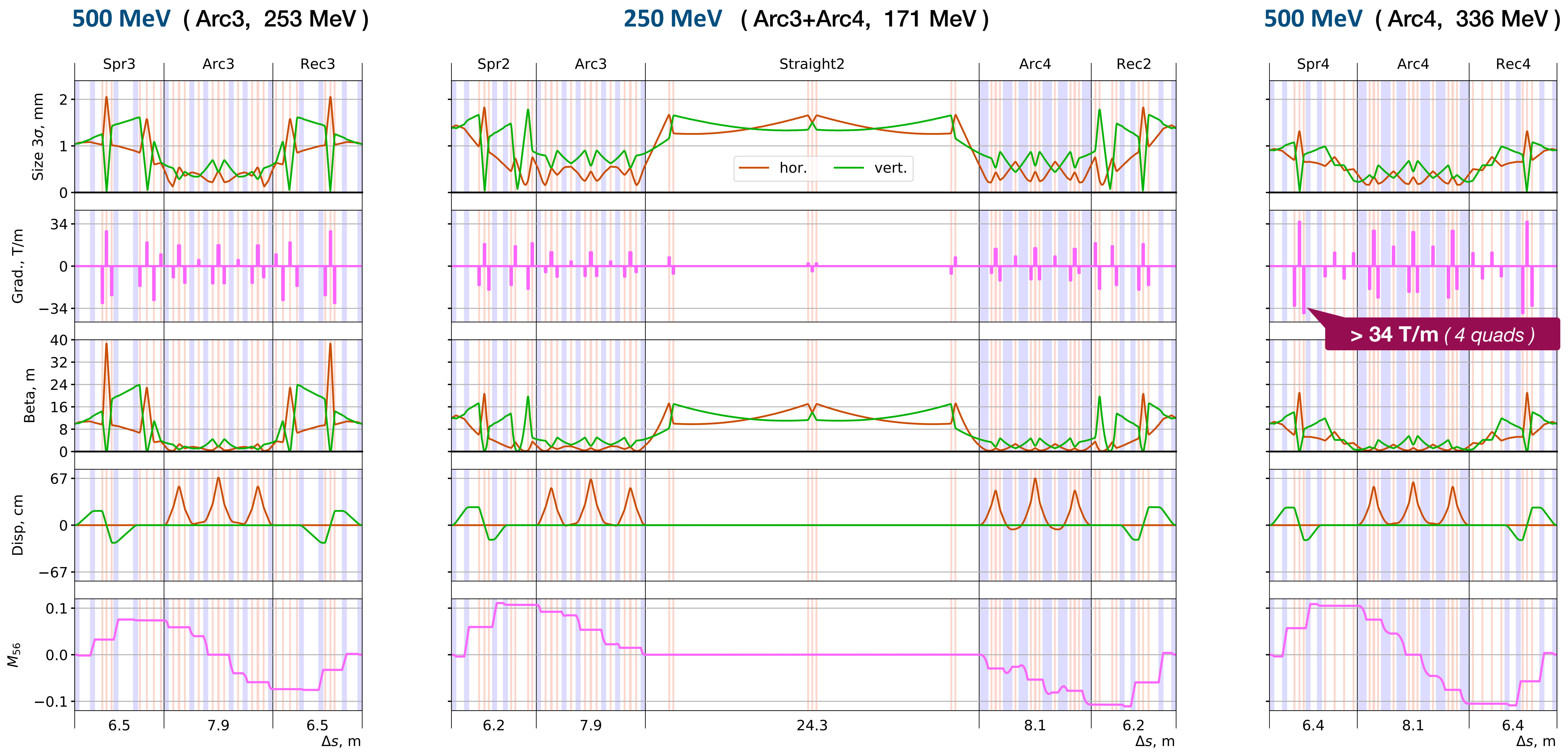
PERLE Optics: from Injection to Dum (250 MeV version)

PERLE Optics: Turns (500 & 250 MeV versions)

500 MeV (Arc1, 89 MeV) **250 MeV** (Arc1+Arc2, 89 MeV) **500 MeV** (Arc2, 171 MeV)

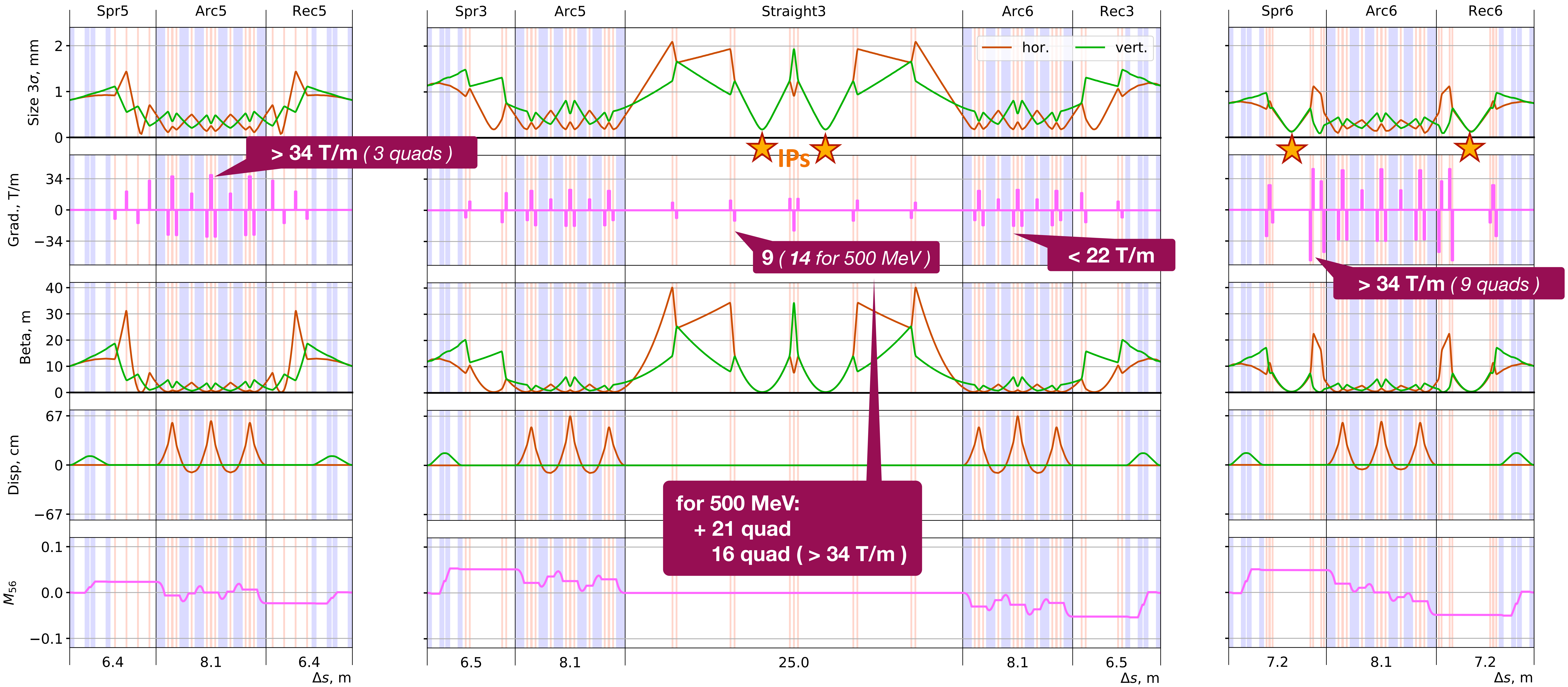


PERLE Optics: Turns (500 & 250 MeV versions)



PERLE Optics: Turns (500 & 250 MeV versions)

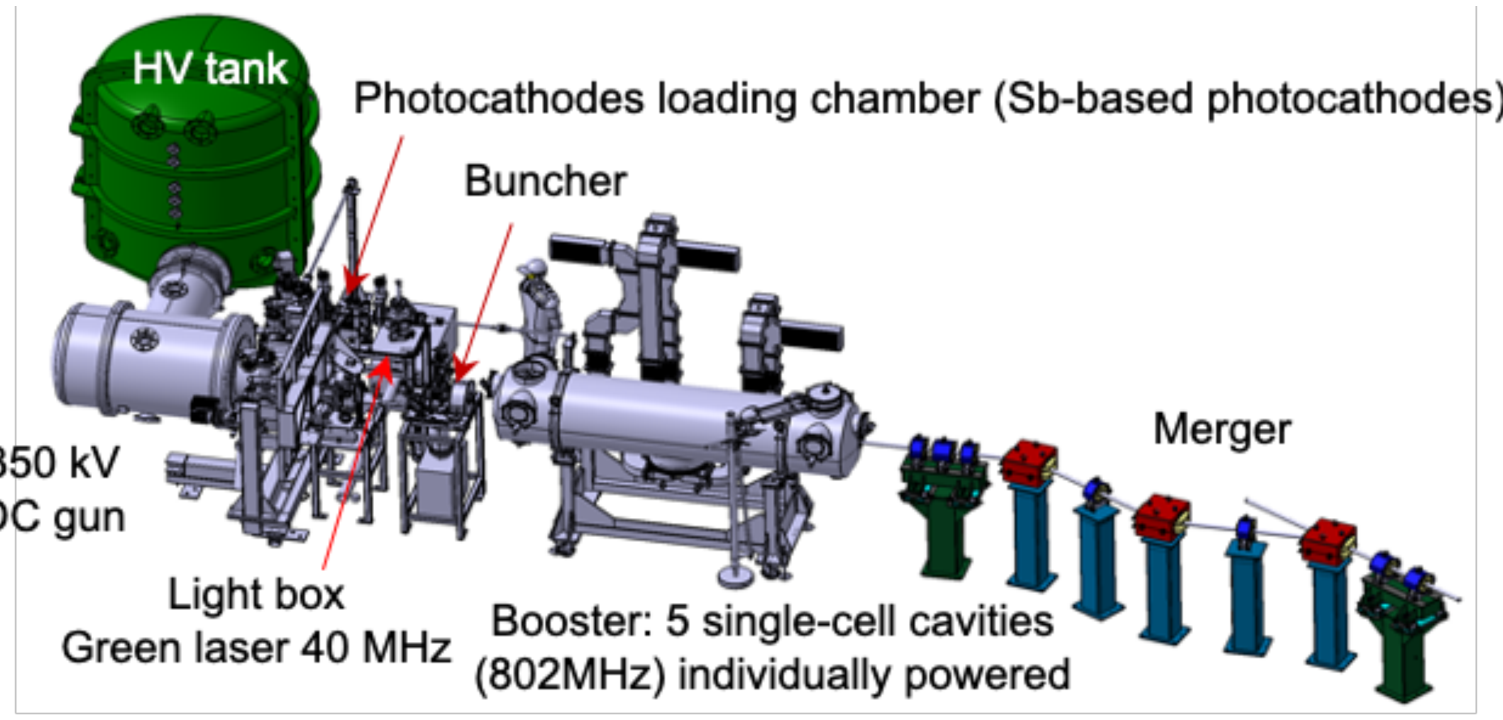
500 MeV (Arc5, 418 MeV) **250 MeV** (Arc5+Arc6, 253 MeV) **500 MeV** (Arc6, 500 MeV)



Beam Dynamics Studies

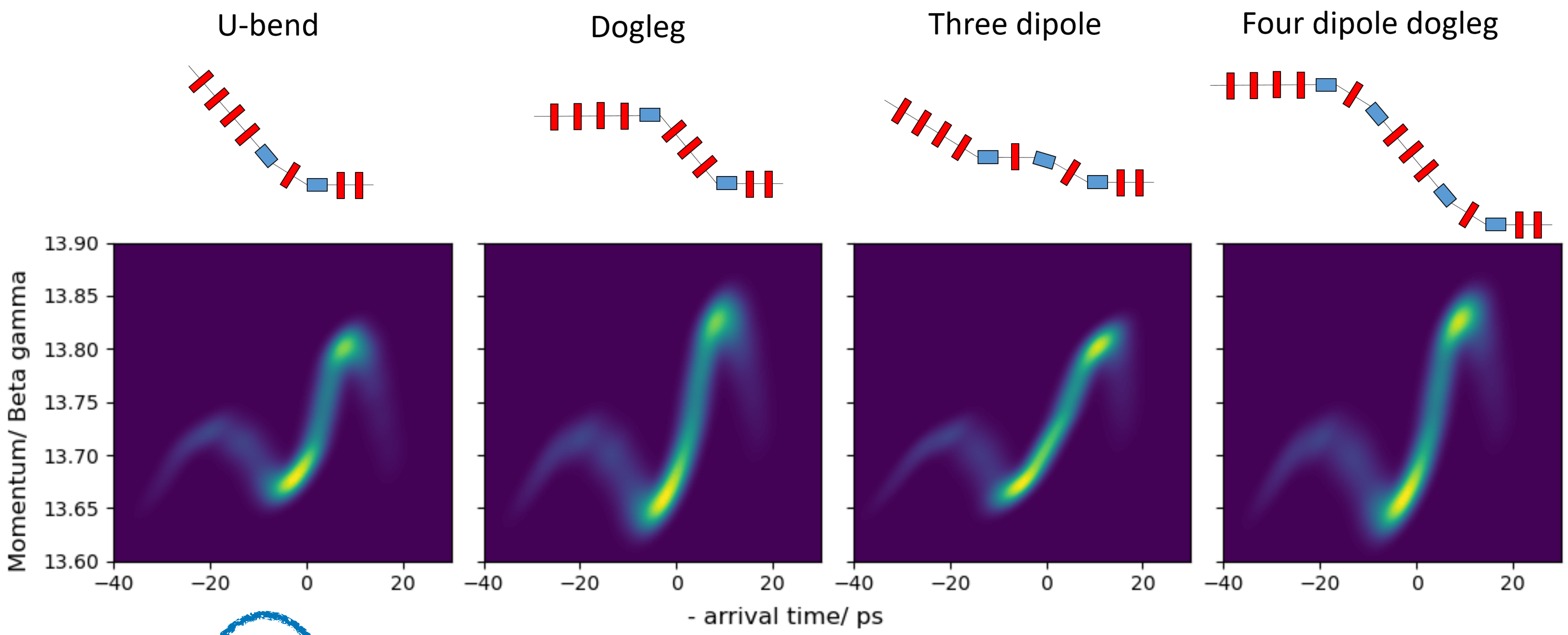
Injector/merger design and initial space-charge studies

(PhD of B. Hounsell)



A conceptual design of the PERLE injector was made within a collaboration between AsTeC-Daresbury, UoL and IJCLab.

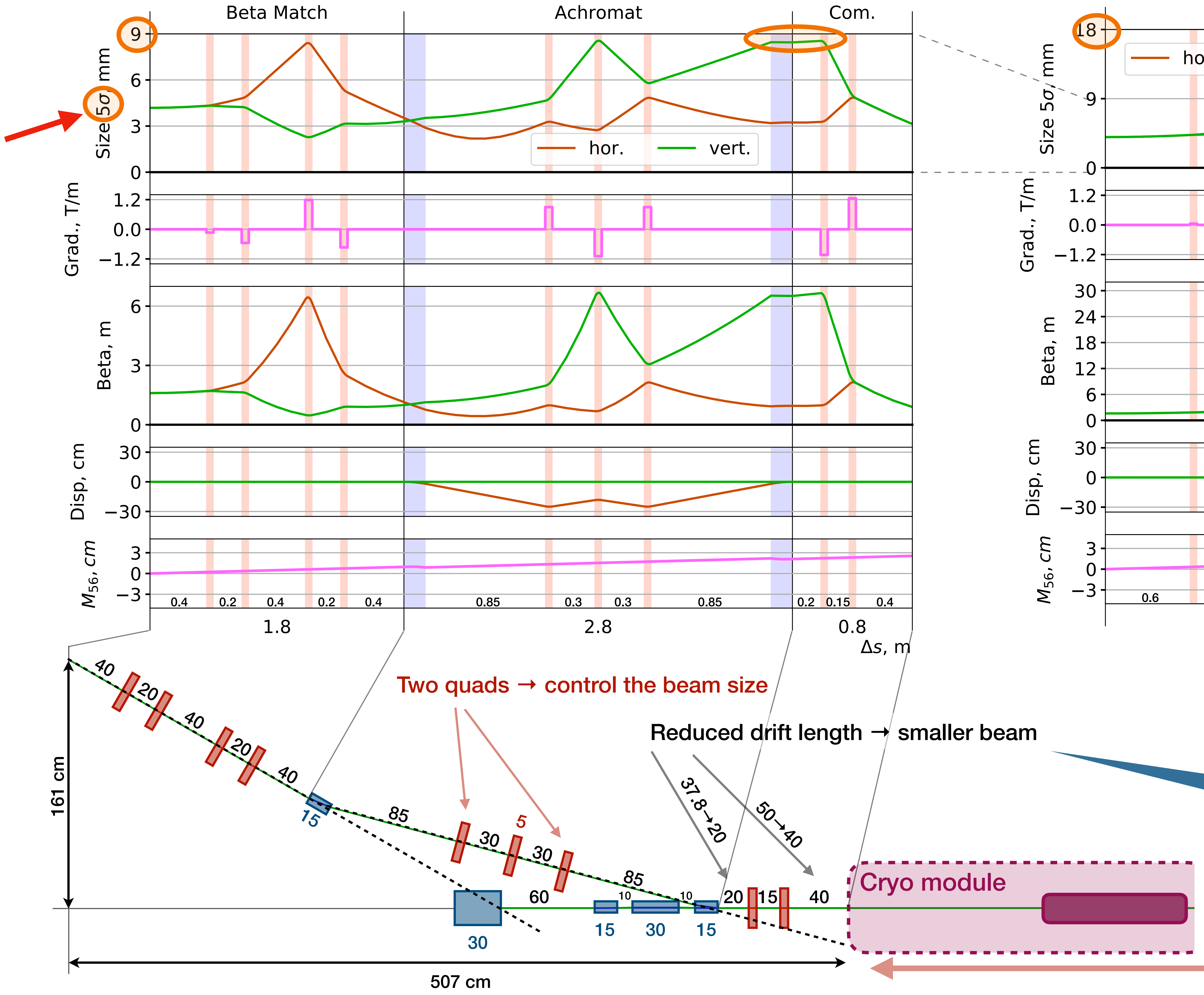
Four merger schemes

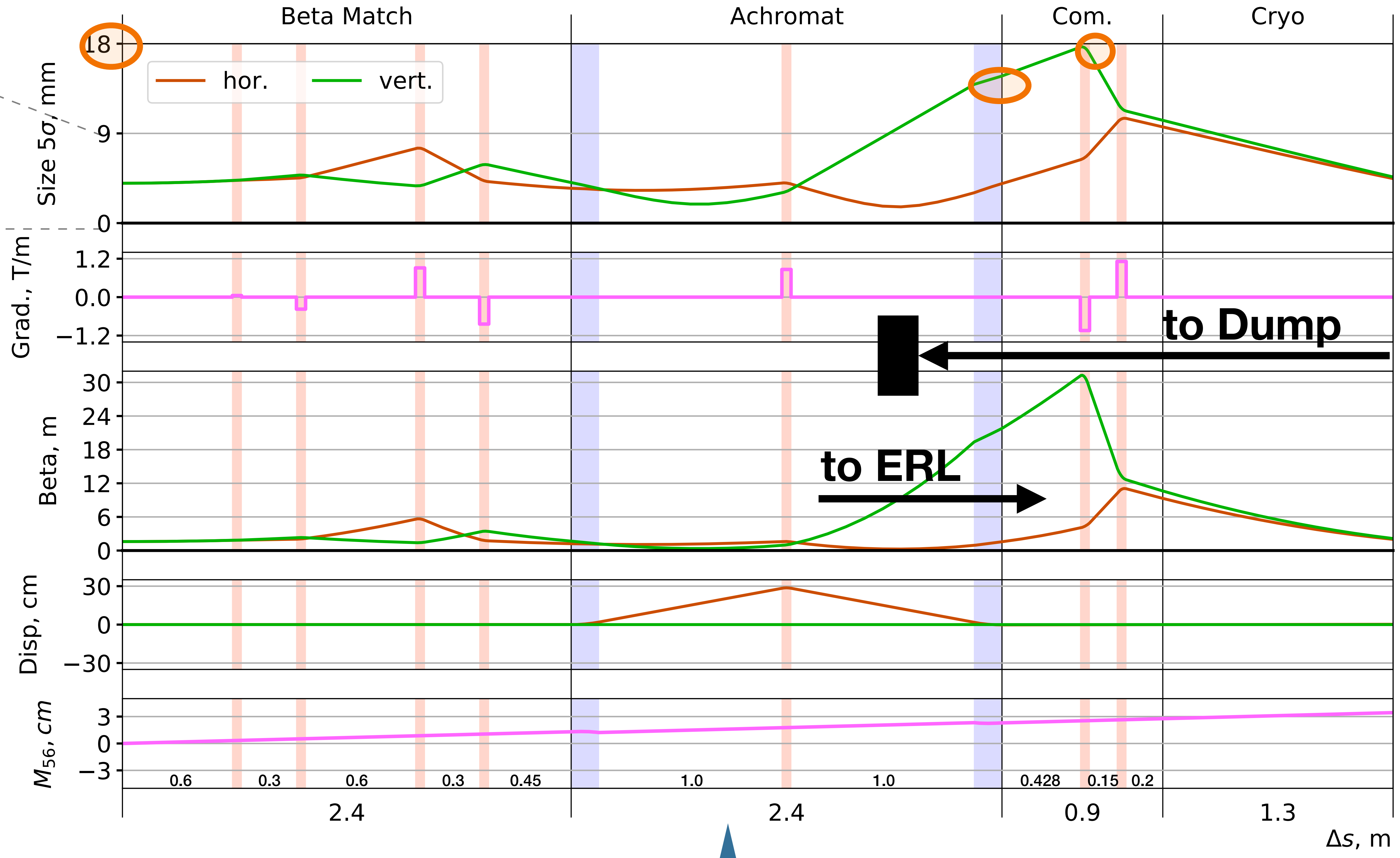


	U-bend	Dogleg	Three dipole	Four dipole dogleg	**Spec**
εx/ mm·mrad	4.3	5.2	5.9	4.7	< 6
εy/ mm·mrad	4.4	4.5	3.2	7.0	< 6
Mismatch factor	0.014	0.72	0.05	0.11	0
R56/ m	0.023	0.0185	-0.155	0.031	0

Preferred scheme

Merger: Ubend v2 update proposal (work in progress)



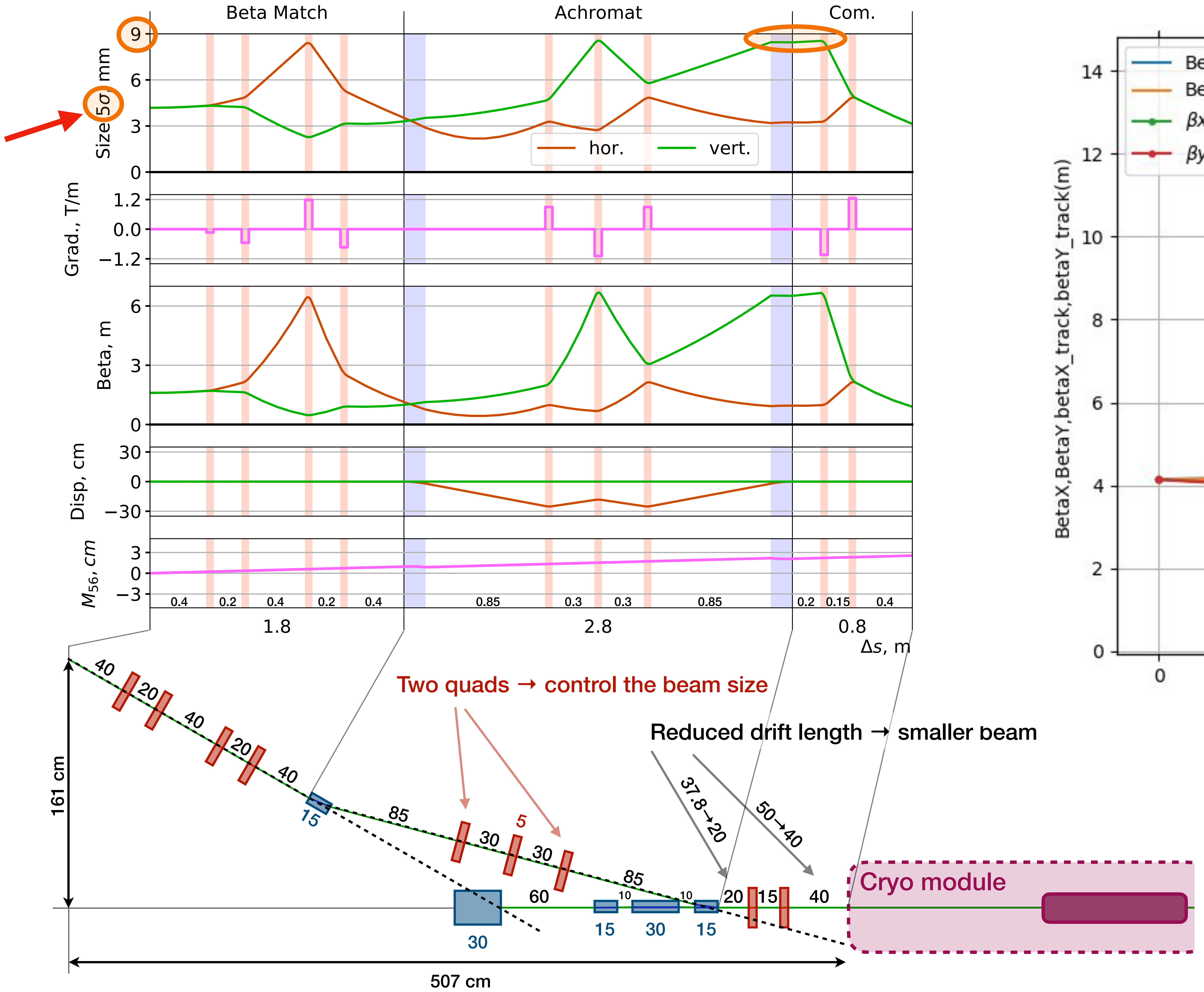


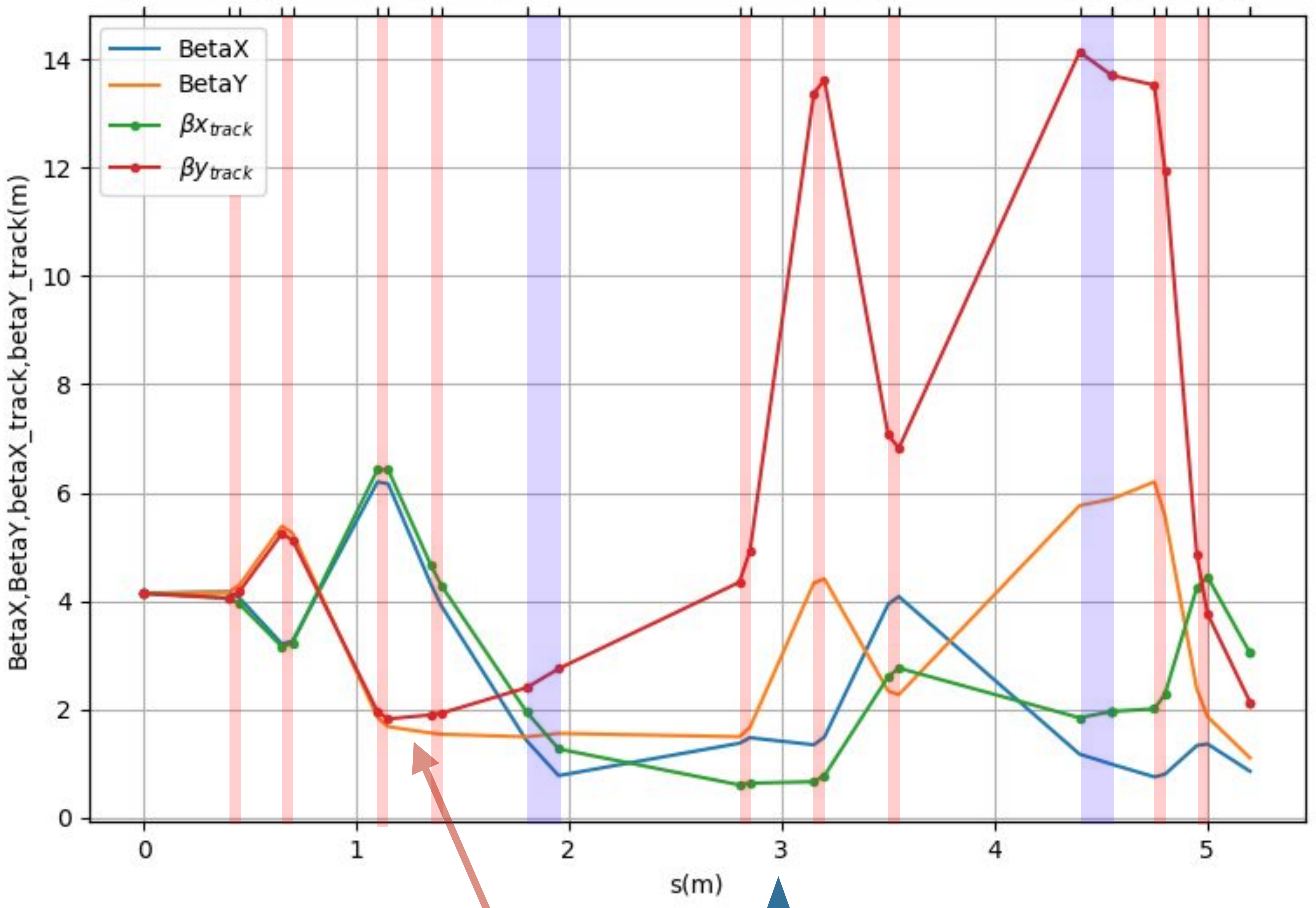
UBEND v1 first proposal by B. Jacquot

UBEND v2 update proposed by A. Fomin

more space needed for diagnostics

Merger: Ubend v2 update proposal (work in progress)



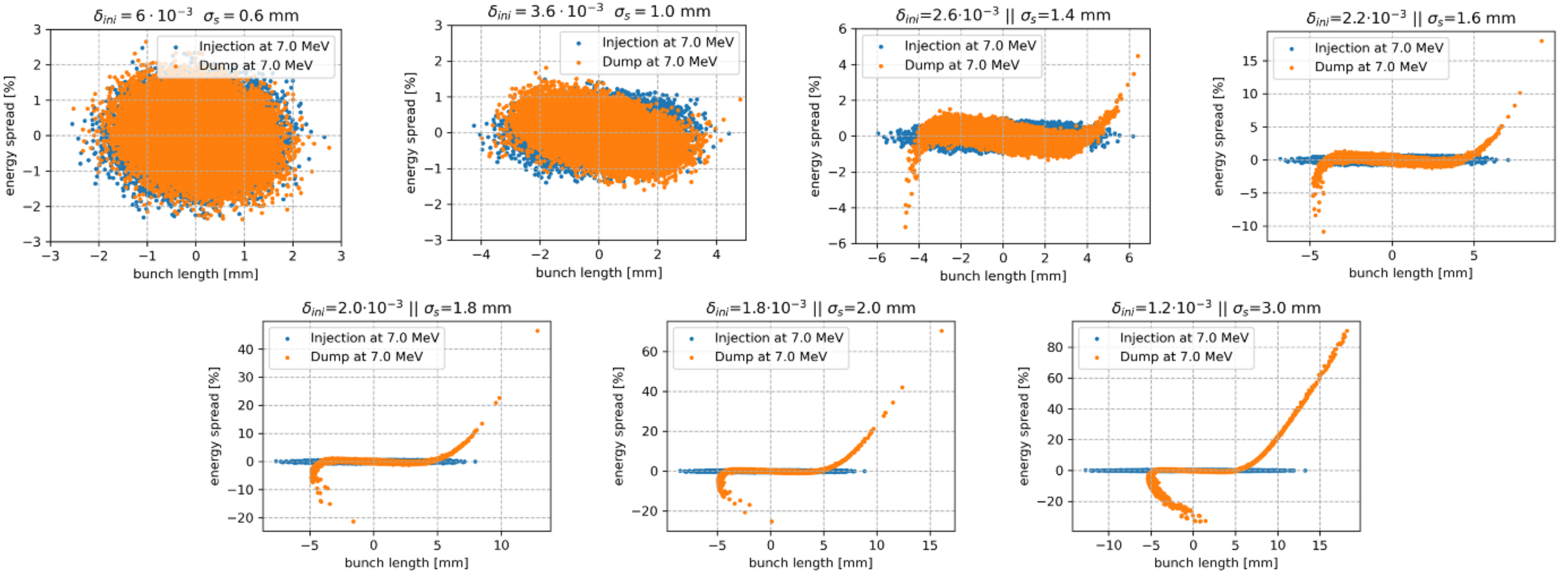


BMAD simulation by J. Michaud

Significant SC effect potentialy from over-focusing

Multi-bunch tracking   (work by K. André)

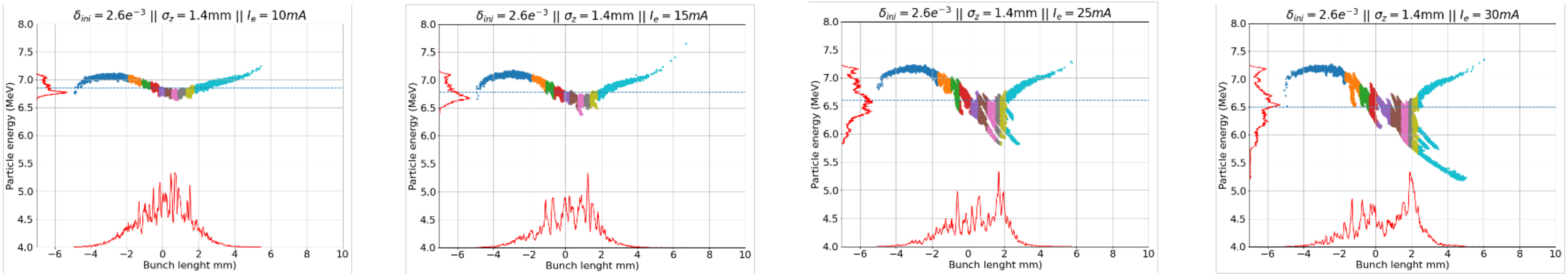
Longitudinal phase space curvature from the RF field



A hook shape forms and bunch elongation is visible as the initial bunch length increases. A longitudinal matching can mitigate the bunch elongation.

Initial distribution : 3x2D gaussian distribution at the beginning of the first linac
Tracking : from first linac to dump

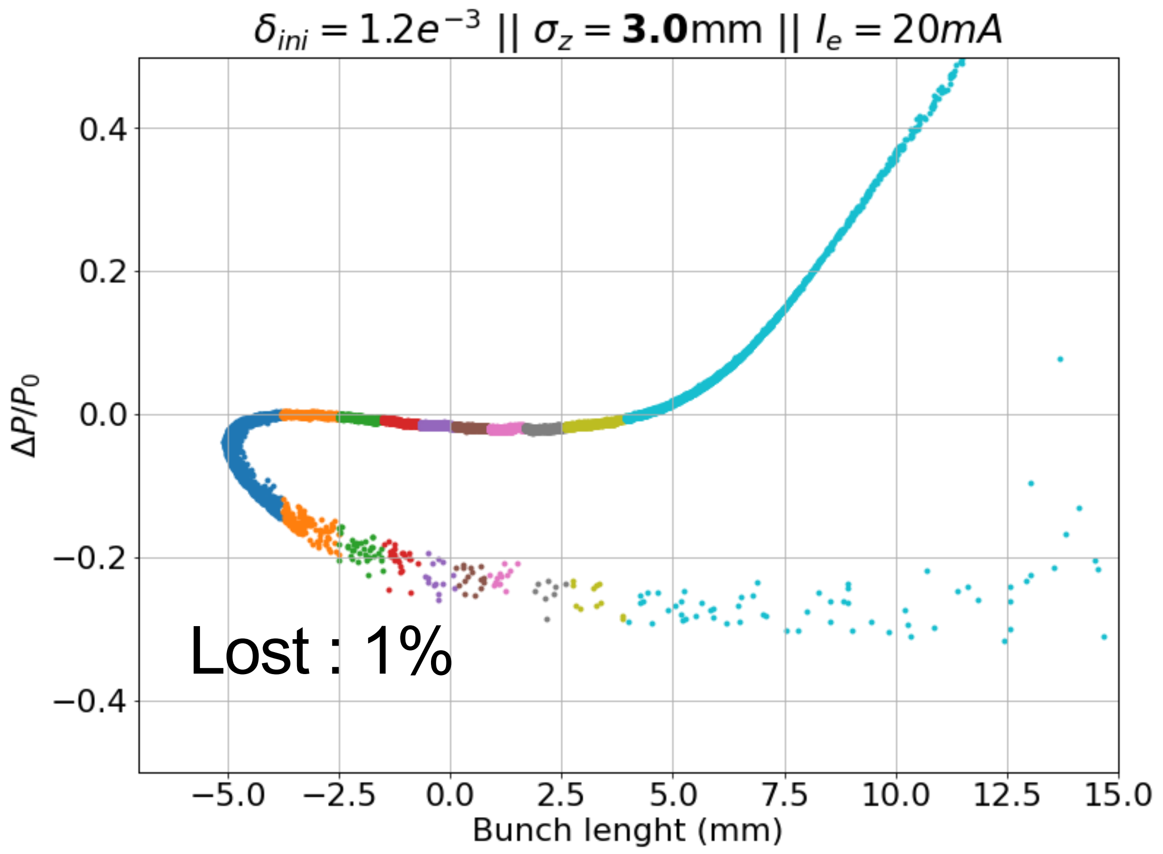
PLACET2 (K. Andre)



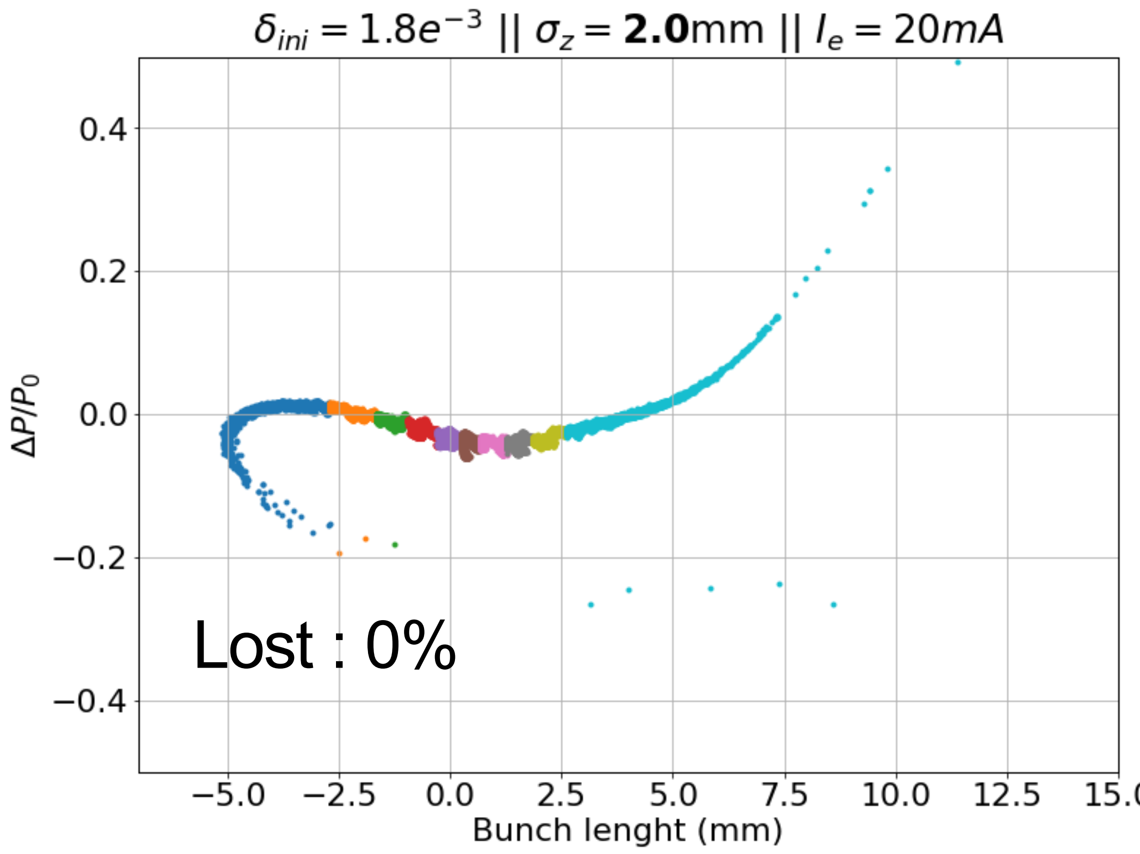
BMAD (J. Michaud)

RF curvature vc CSR (work by K. André and J. Michaud)

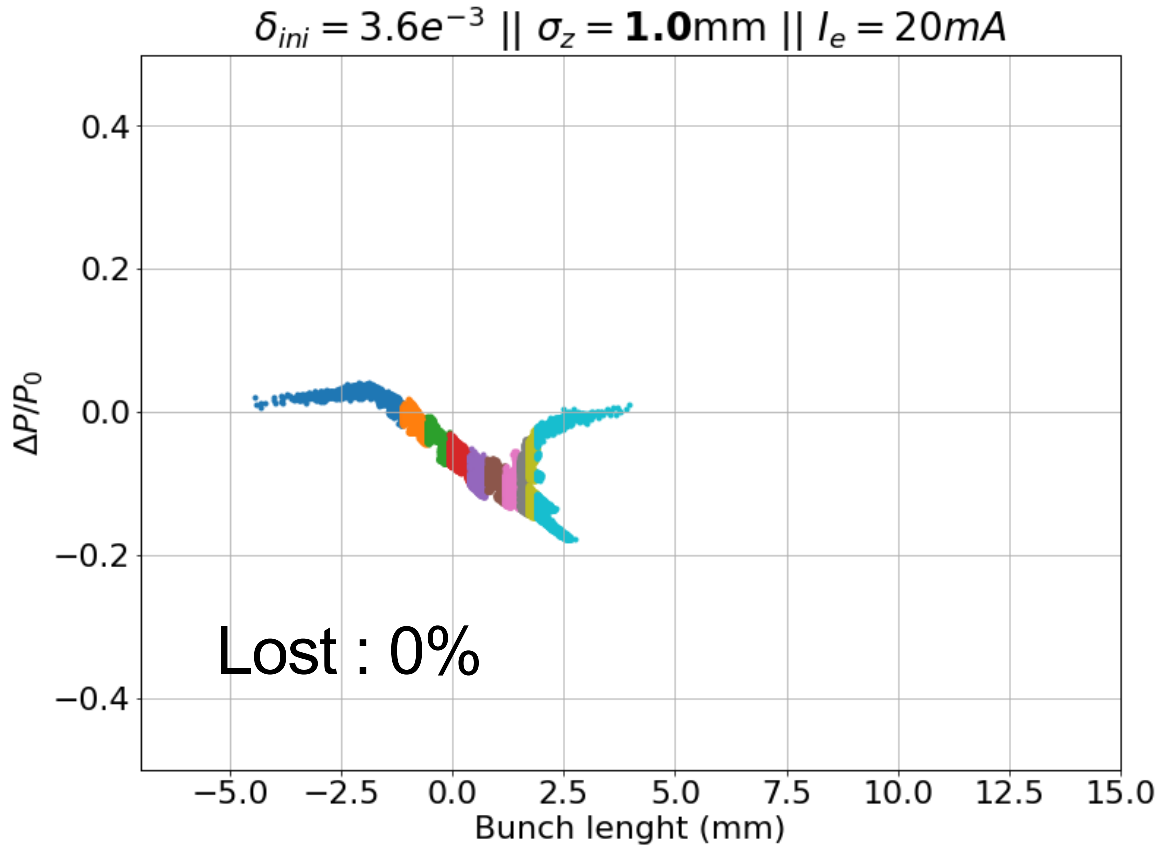
3 mm bunch length



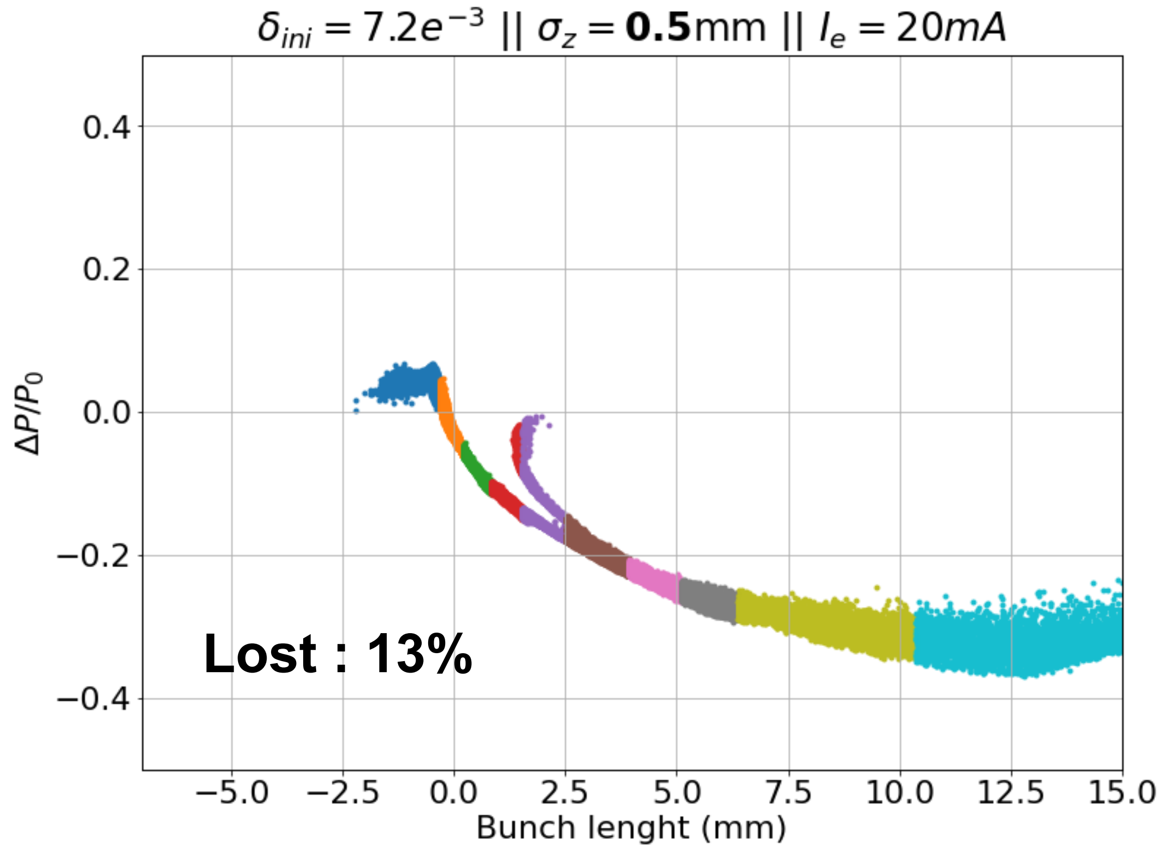
2 mm bunch length



1 mm bunch length



0,5 mm bunch length



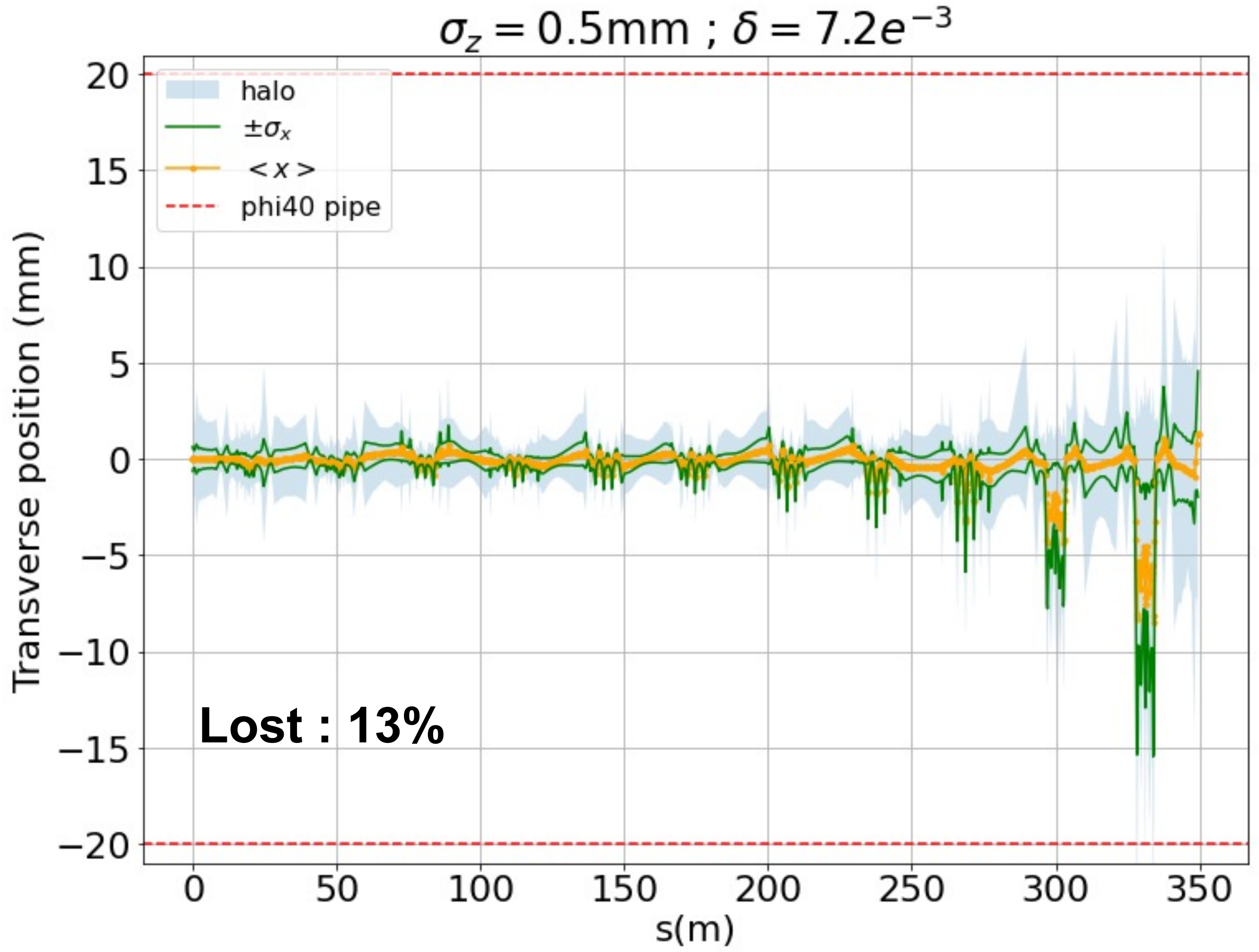
RF curvature dominated

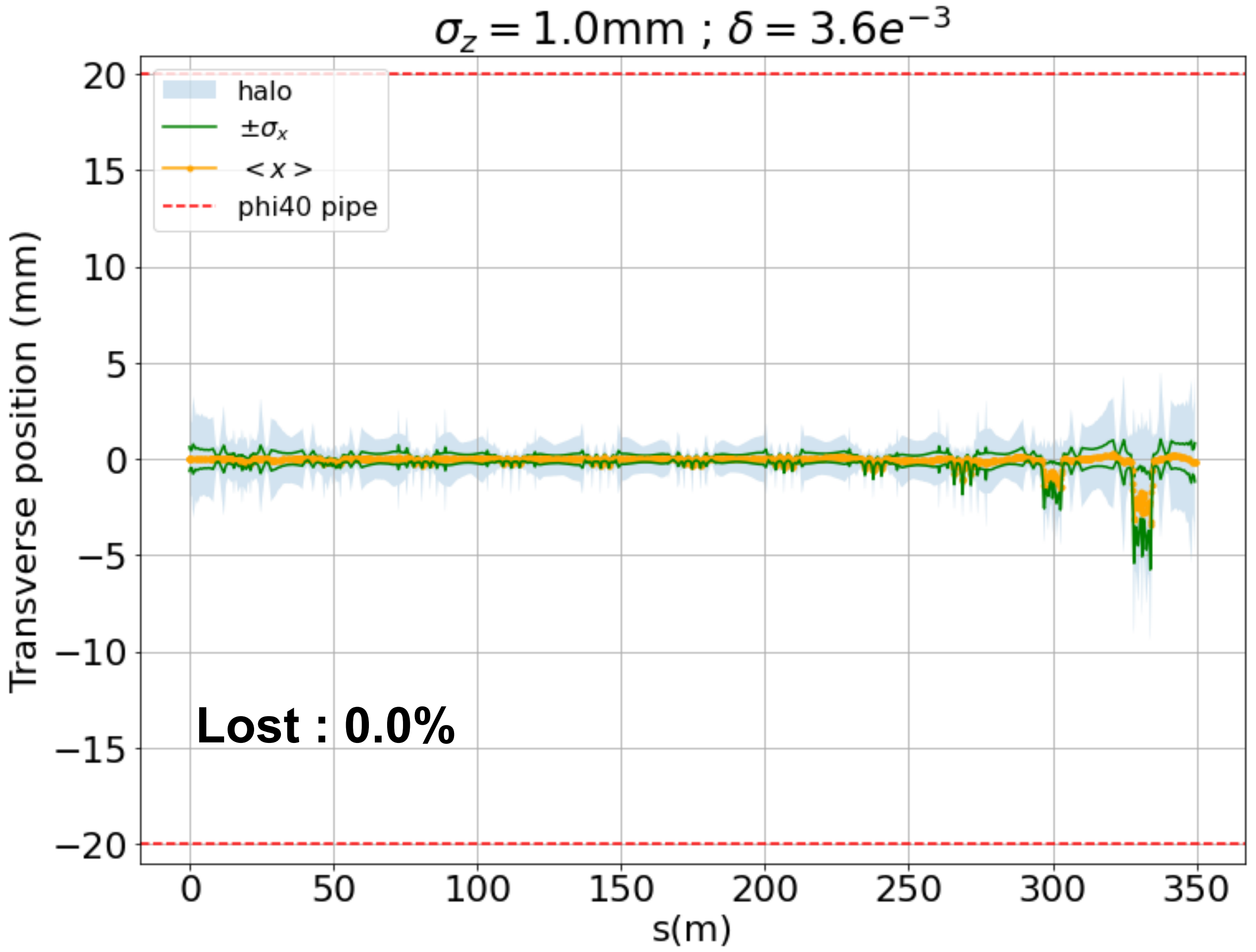
CSR dominated

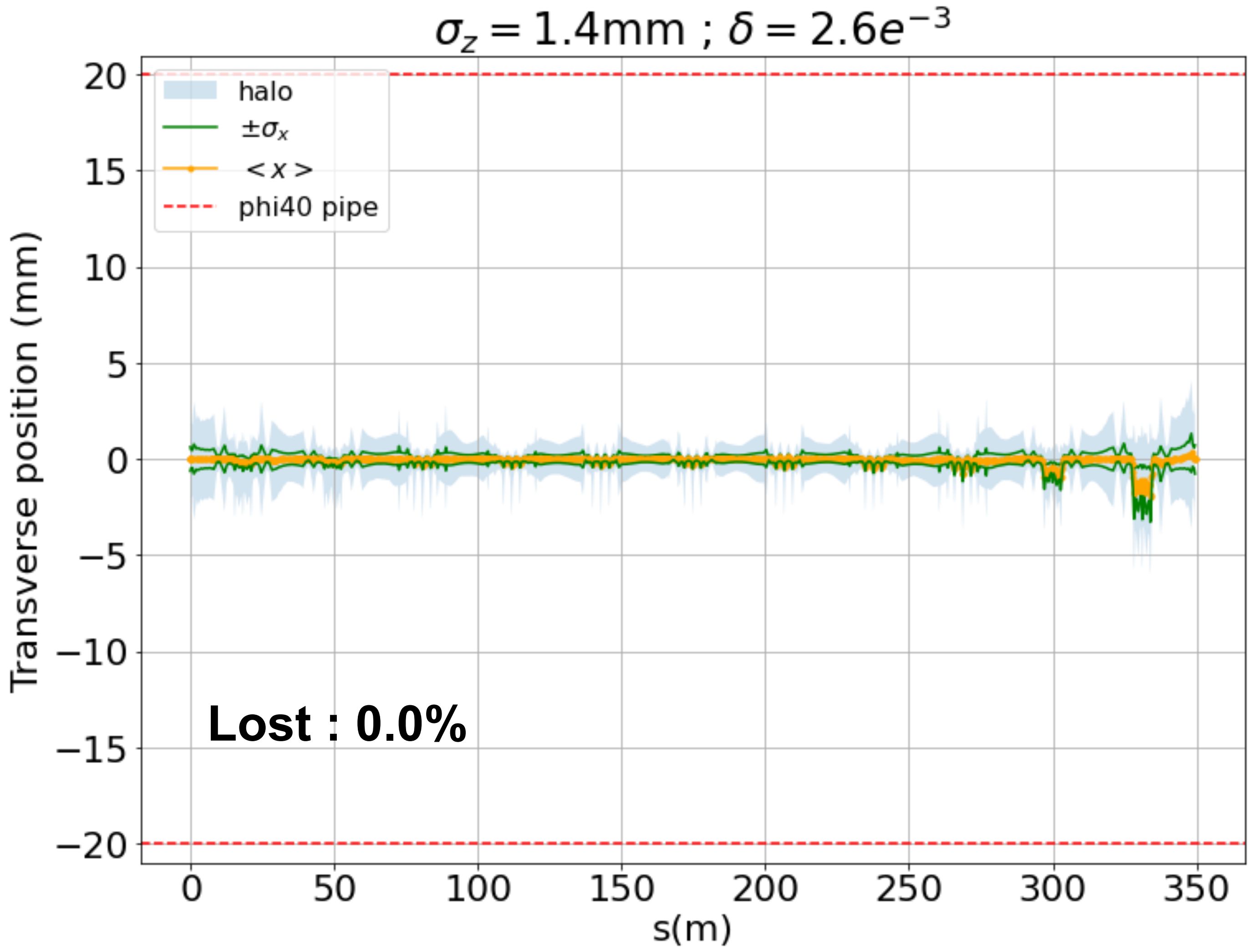
Need to specify an optimum bunch length for simulations and injector

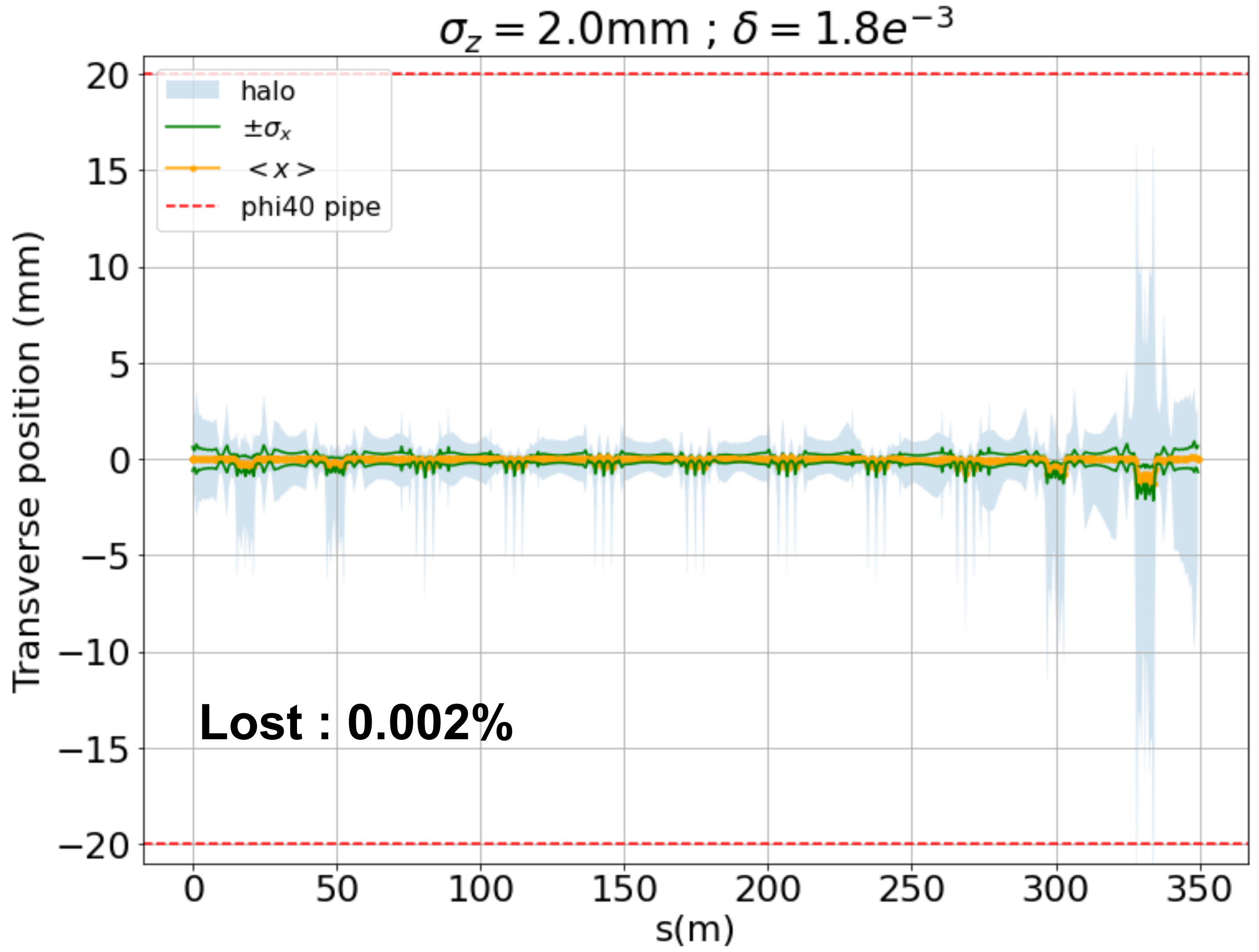
1,4mm optimal value from K. Andre simulations

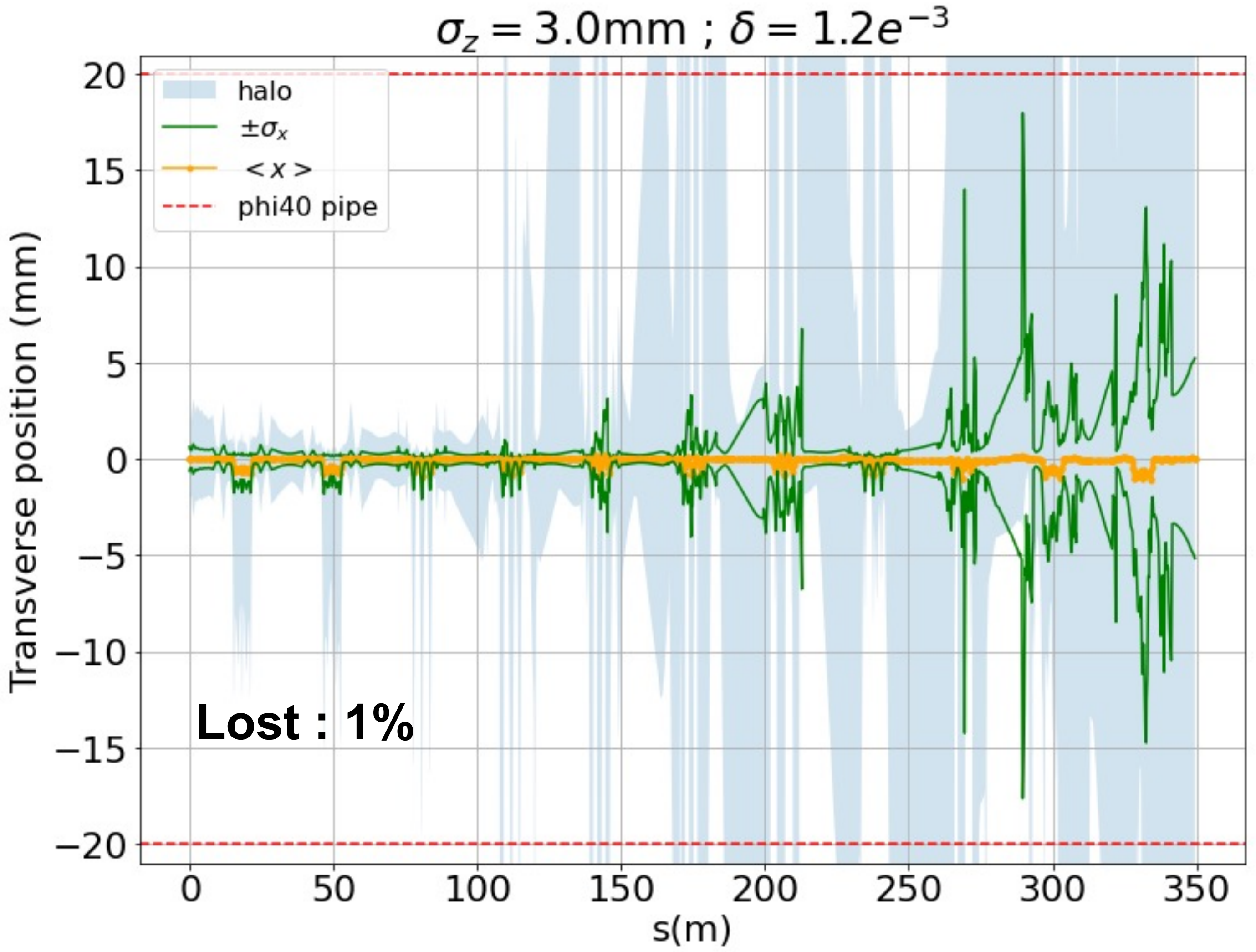
Beam X envelop for different bunch lengths (50 000 particles)









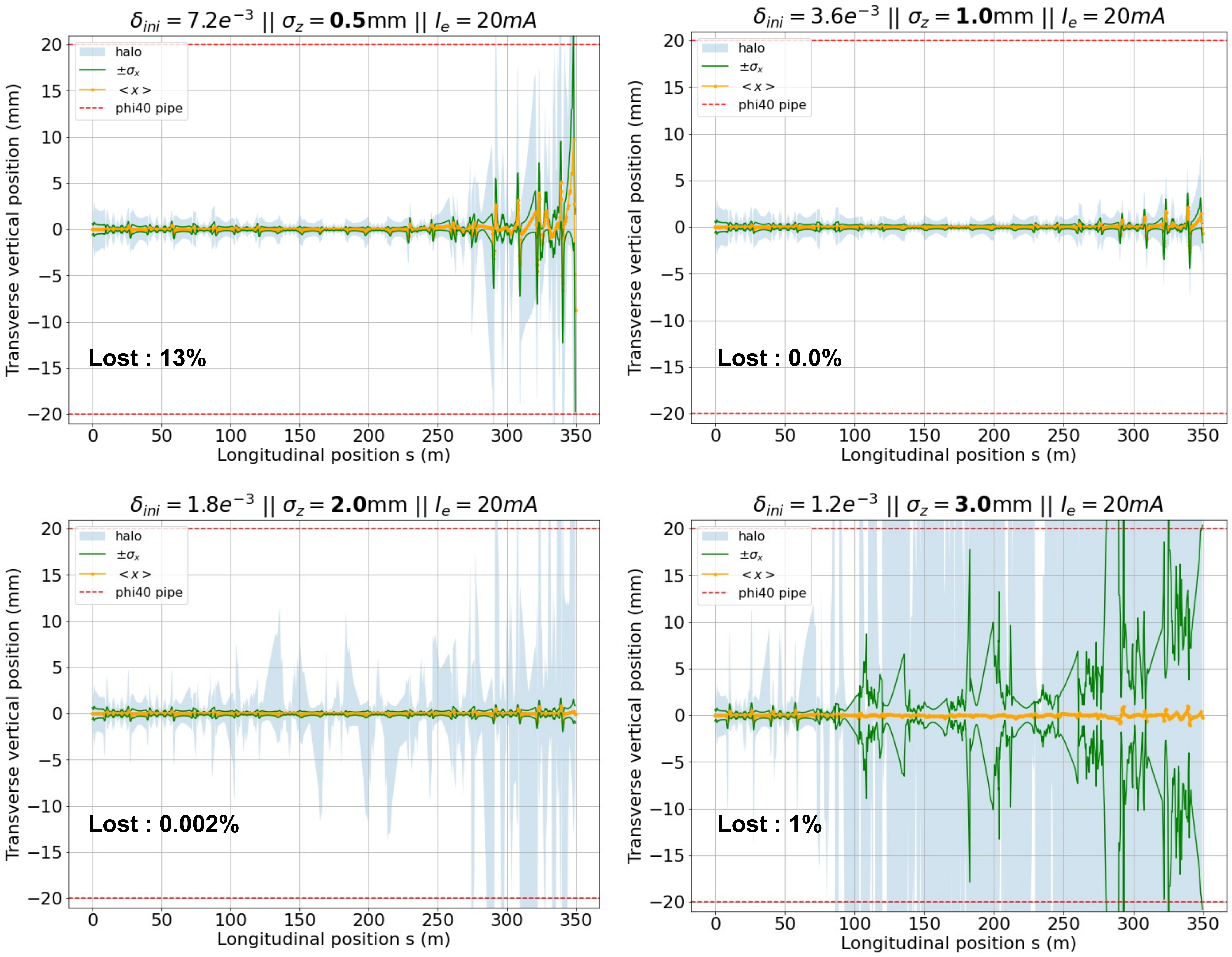


- We observe CSR vs RF curvature effects
- No loss range : [1mm ; 2mm] bunch length
- Best result around 1.4mm

➔ Longer bunch length are easier to achieve with the injector

Q : Possible corrections of RF curvature effects ?

Beam Y envelop for different bunch lengths (50 000 particles)



- We observe CSR vs RF curvature effects
- No loss range : [1mm ; 2mm] bunch length
- Best result around 1.4mm

➔ Longer bunch length are easier to achieve with the injector

Q : Possible corrections of RF curvature effects ?

Lattice Design and Beam Dynamics Studies for PERLE

Historic perspective and PERLE timeline

- the idea of TF that can become the LHeC ERL injector ERL (Rama Calaga and Erk Jensen in 2012)
- current status and the roadmap for the PERLE project at Orsay (**injection line by 2027, 500 MeV by 2031**)

Lattice design and Optics (compatible with the phasing: 250 MeV and 500 MeV versions)

- **250 MeV version** using the **same main elements**, optics is simpler with **less constraints on the magnets**
- **reduced immediate expenses** (second cryo-module, 18 dipoles and 21 quads can be purchased later)
- 250 MeV phase → **demonstration of ERL with 6 paths at high current** (same as in 500 MeV, but with half of the power)

Beam Dynamics Studies (work in progress)

- **RF curvature vc CSR**
- Over-focusing in the merger
- **Start to End** simulation from the injector cathode to the dump
- **Beam diagnostics** and correctors (tbd for the ERL part)

Special Thanks to:

Alex Bogacz

Luc Perrot

Achille Stocchi

Guillaume Olry

Carmelo Barbagallo

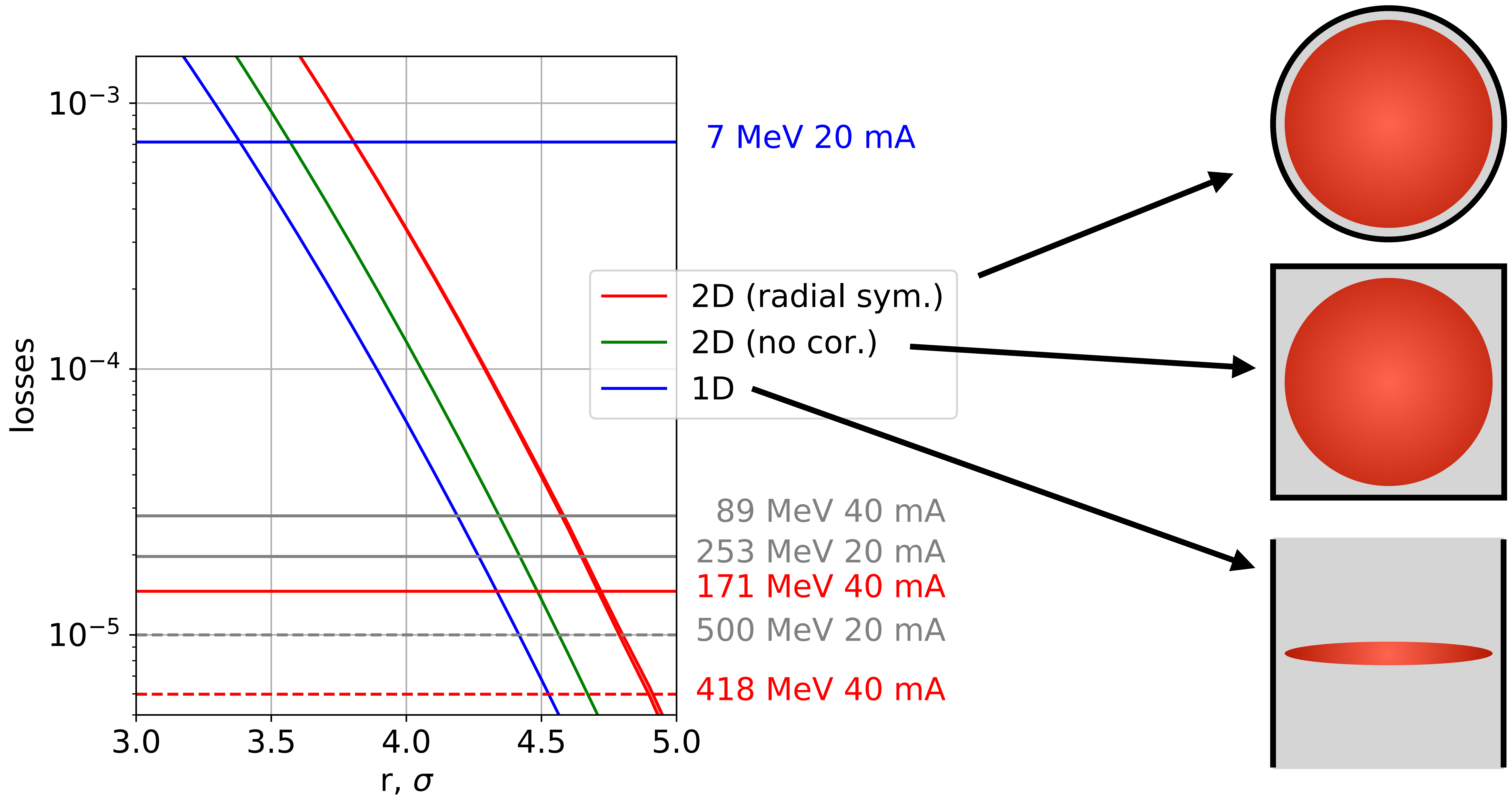
Coline Guyot

Julien Michaud

Thanks for your attention!

Back Up

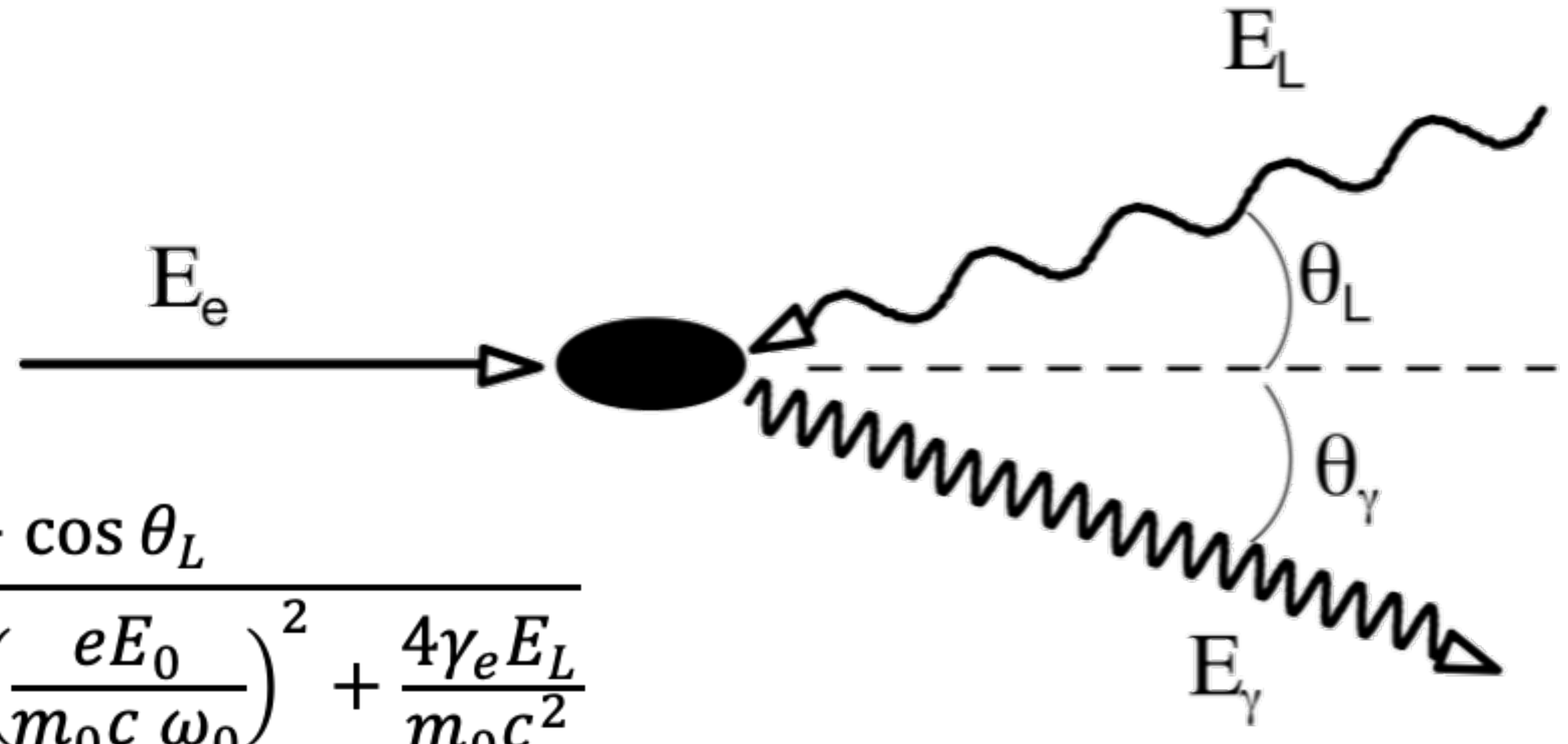
Tolerable beam losses (100 W) at various energies



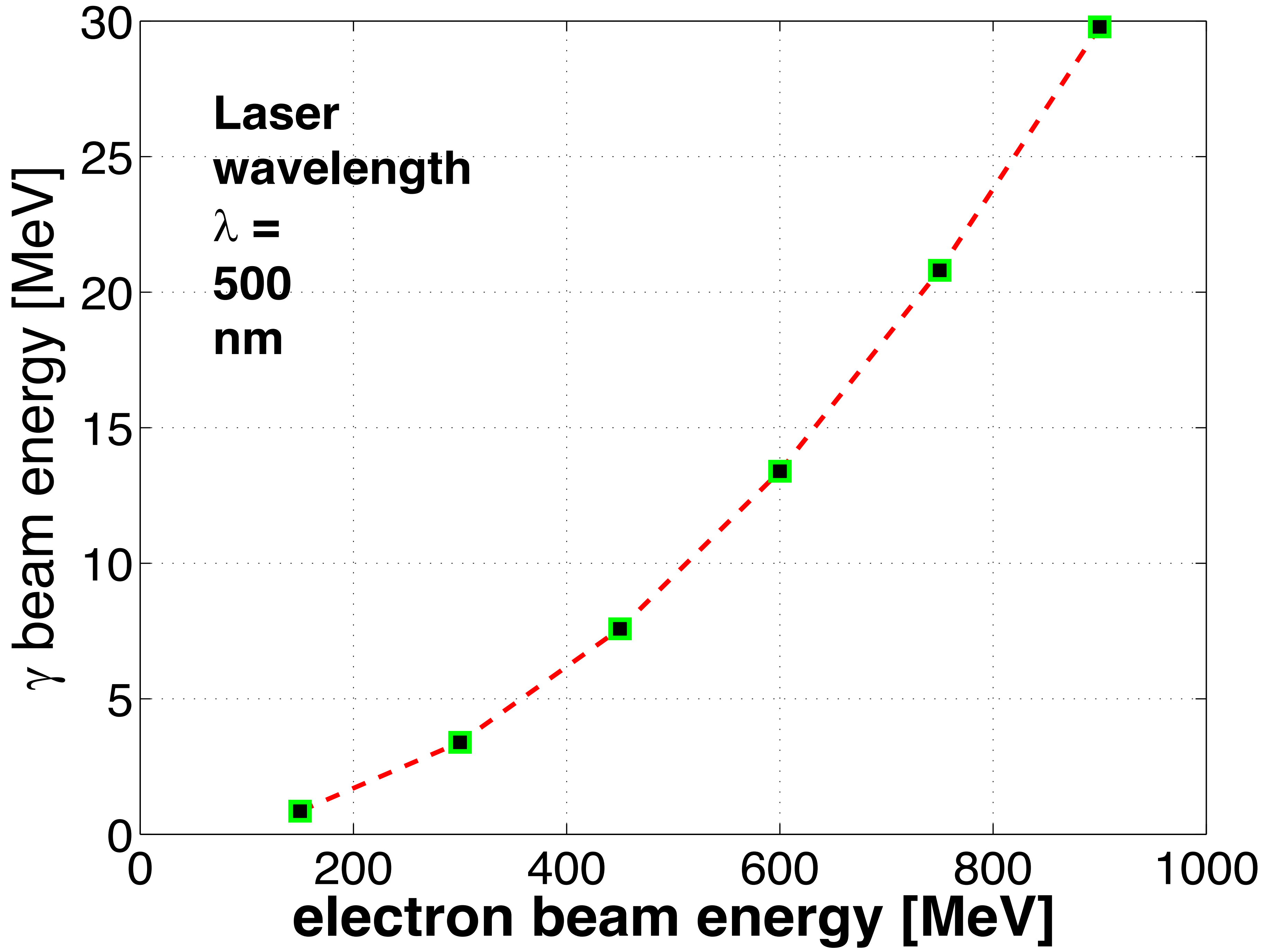
γ beam properties from PERLE

from E. Jensen: Concept of PERLE presentation at LHeC Workshop 2015

Goal: generation of high-energy, monochromatic, polarised photons via Compton scattering (for nuclear physics research)



$$E_\gamma = 2\gamma_e^2 E_L \frac{1+\cos\theta_L}{1+(\gamma_e\theta_\gamma)^2+\left(\frac{eE_0}{m_0c\,\omega_0}\right)^2+\frac{4\gamma_e E_L}{m_0c^2}}$$



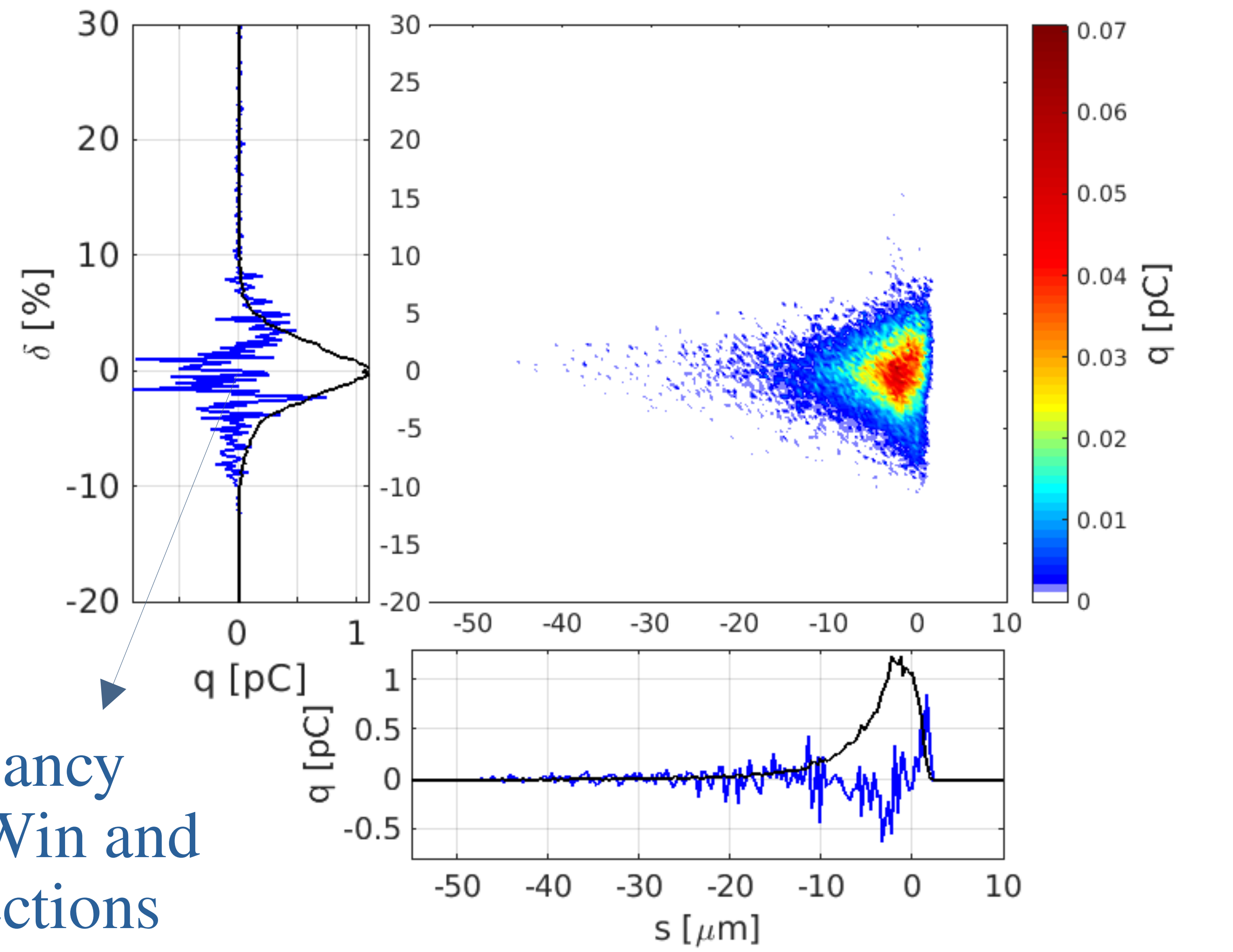
GAMMA BEAM PARAMETERS	
Energy	30 MeV
Spectral density	$9*10^4$ ph/s/eV
Bandwidth	< 5%
Flux within FWHM bdw	$7*10^{10}$ ph/s
ph/e- within FWHM bdw	10^{-6}
Peak Brilliance	$3*10^{21}$ ph/s*mm^2*mrad^2 0.1% bdw

Several comparisons with other codes have been done, including :

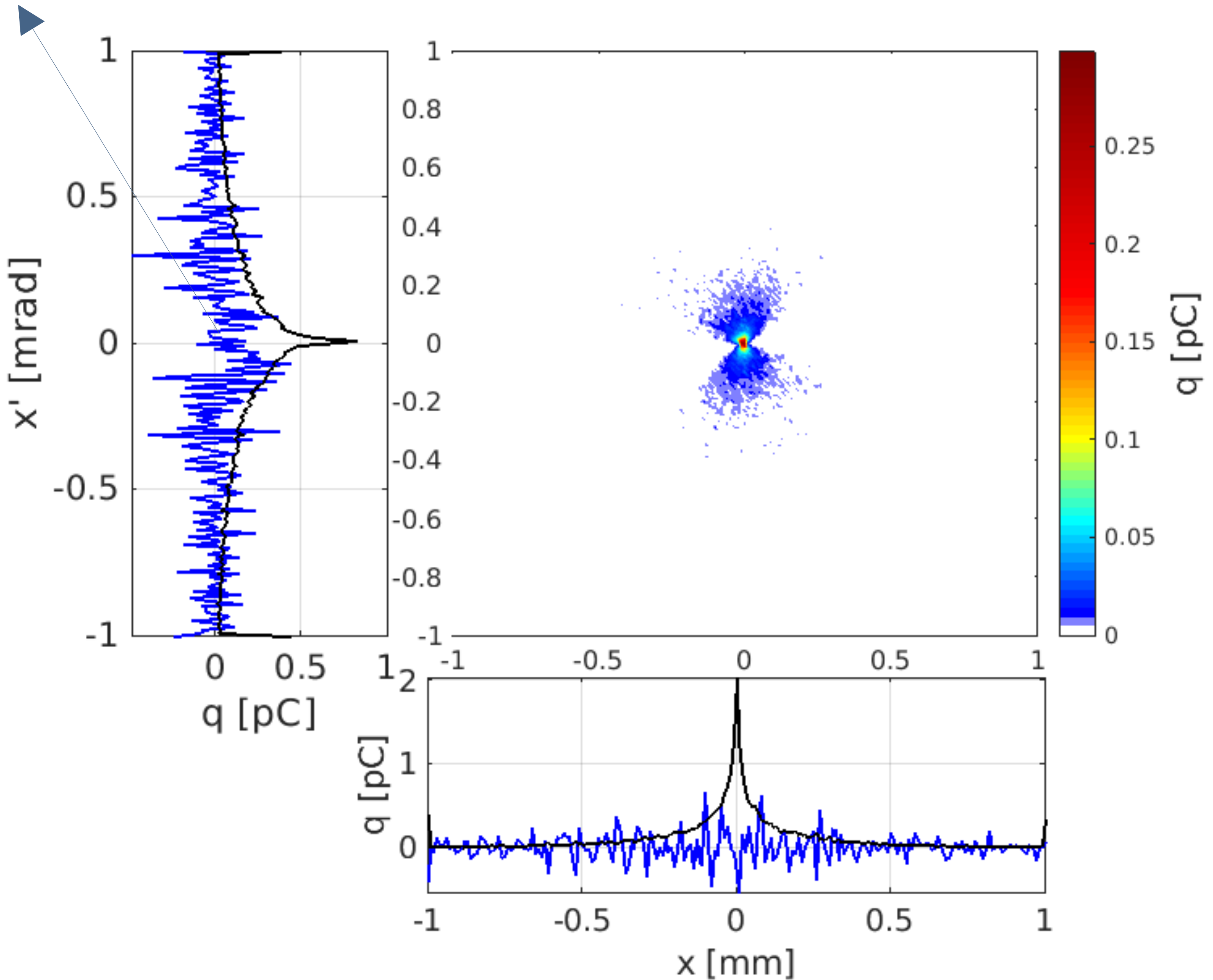
→ free particle tracking for highly off-momentum and off-axis (laser-plasma) beams compared with TraceWin [1]

→ space charge simulation for relativistic electrons benchmarked with ASTRA [2]

→ used as a comparison on LPA studies [3-4]



10 * Discrepancy between TraceWin and CODAL projections



[1] C.Guyot and al. “benchmarking for codal beam dynamics code : laser-plasma accelerator case study”, IPAC’23 proceedings (2023)

[2] Alexis Gamelin. Collective effects in a transient microbunching regime and ion cloud mitigation in ThomX. PhD Thesis, Université Paris-Saclay, September 2018

[3] T. André et al., “Control of laser plasma accelerated electrons for light sources”, Nature communications 9 (2018) 10.1038/s41467-018-03776-x

[4] M. Khojoyan et al., “Transport studies of LPA electron beam towards the FEL amplification at COXINEL”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 829 (2016) 10.1016/j.nima.2016.02.030.

BMAD CSR calculation methods :

1-Dim CSR calculation :

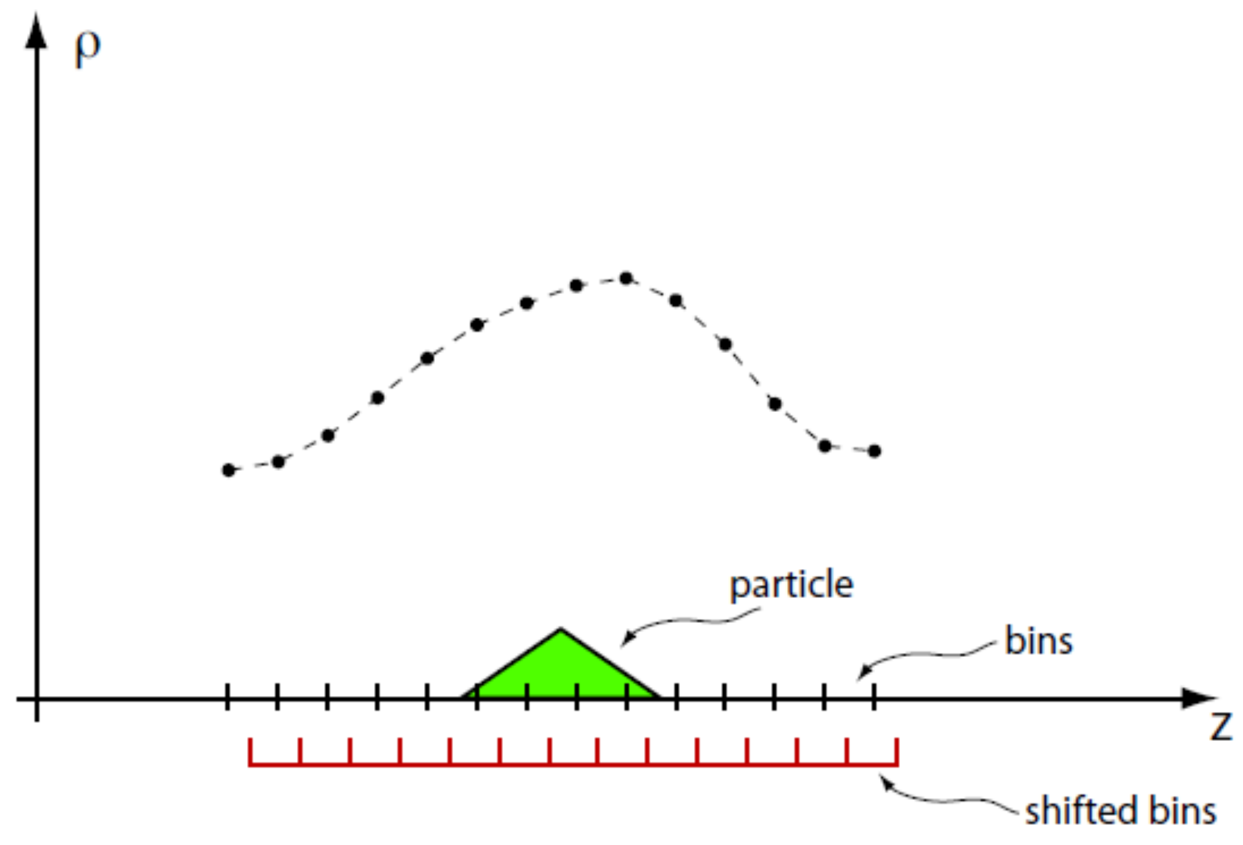
- The particle-particle CSR kick is calculated by dividing the bunch longitudinally into a number of bins
- Triangular densities distributions

Slice Space Charge calculation :

- The particle-particle CSR kick is calculated by dividing the bunch longitudinally into a number of bins
- Longitudinal + transverse kick

FFT_3D Space Charge Calculation:

- Uses OpenSC package from someone else
- 3D grid with FFTs
- Slower method, but handles low energy space charge

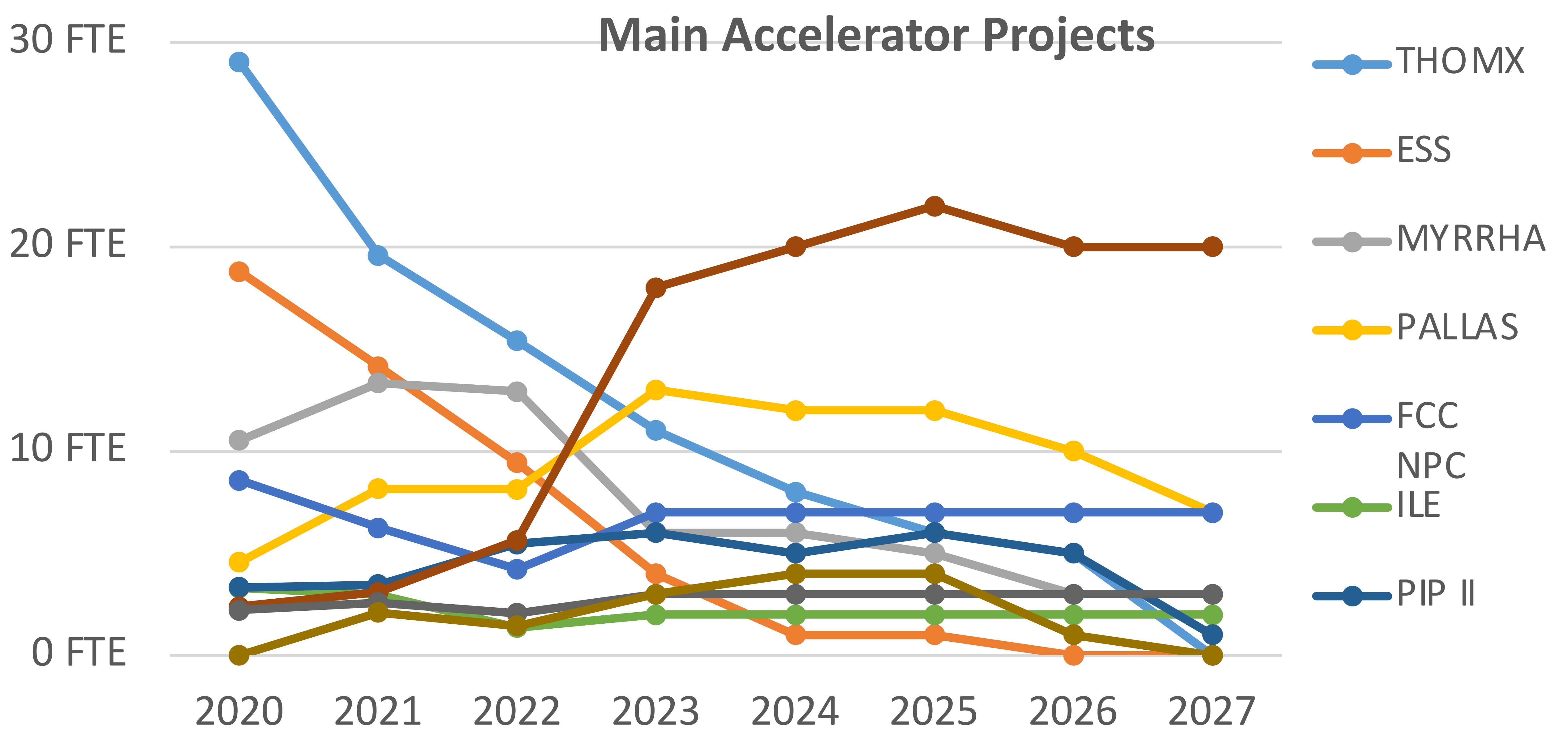


High Energy Space Charge :

- Totally different formalism that other methods
- Very fast as more statistical
- Acceptable for storage rings at relatively high energy but not accurate in other situations

HR involvement and projection - French level mostly

Significant increase in 2022 of the forces contributing to PERLE that will continue in the coming years according to the phasing strategy.



Up to 20 FTE secured.
IJCLab/ France has to increase that.
BUT
We need similar exercise from the other partners.

Action on going.

→ Here the evolution of IJCLab manpower implication on the project in the past three years and an estimation for the 3 upcoming ones:

Year	2020	2021	2022	2023	2024	2025
FTEs	1,9	3	7	16	18	20

* For the past years, the table do not include other French lab involvements (LPSC + GANIL) + a split site PhD with Liverpool University.