University Gliding Centre, Bezmiechowa Górna

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indico.cern.ch/event/1308137/

TES HEP Trans European School of High Energy Physics

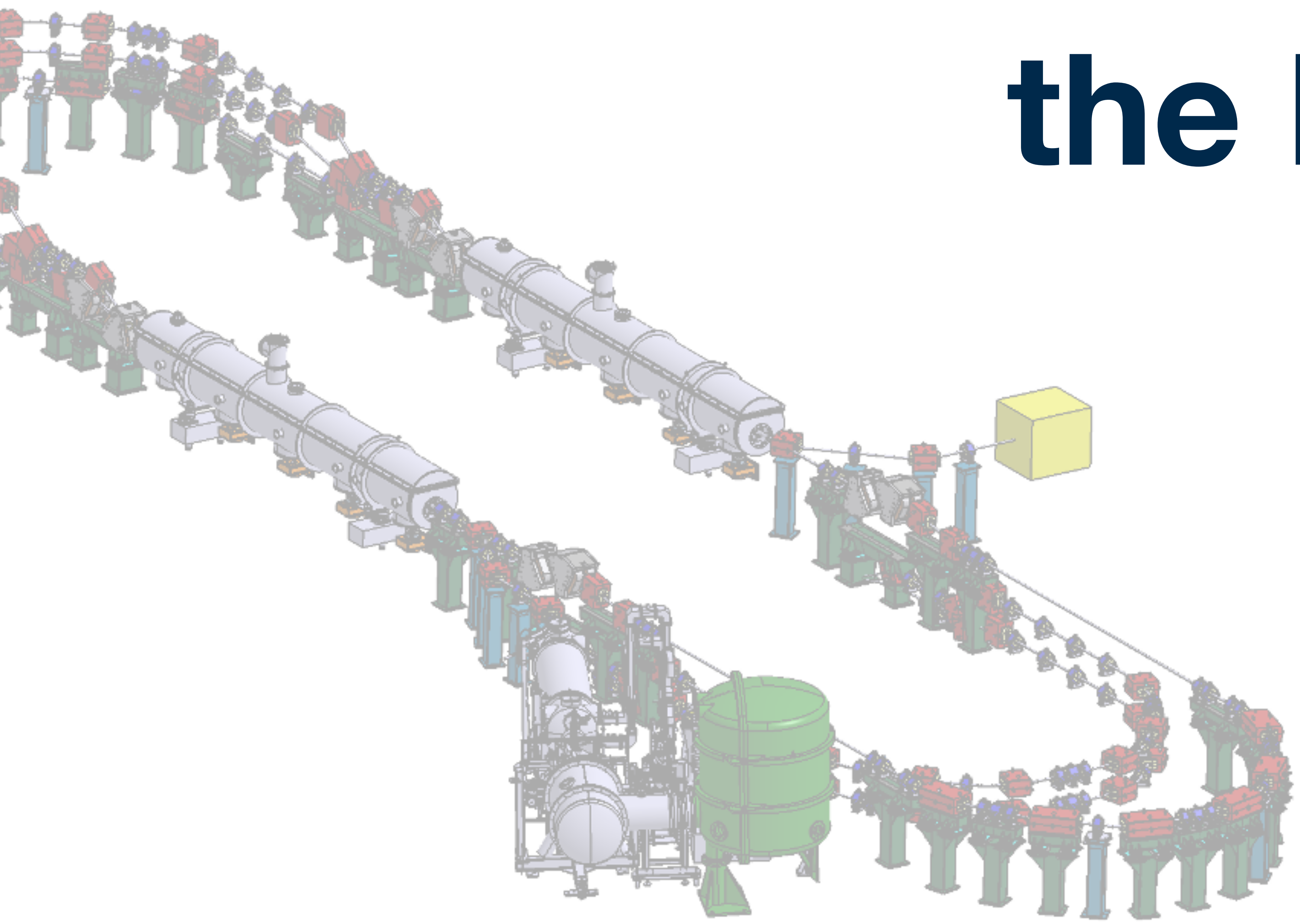
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

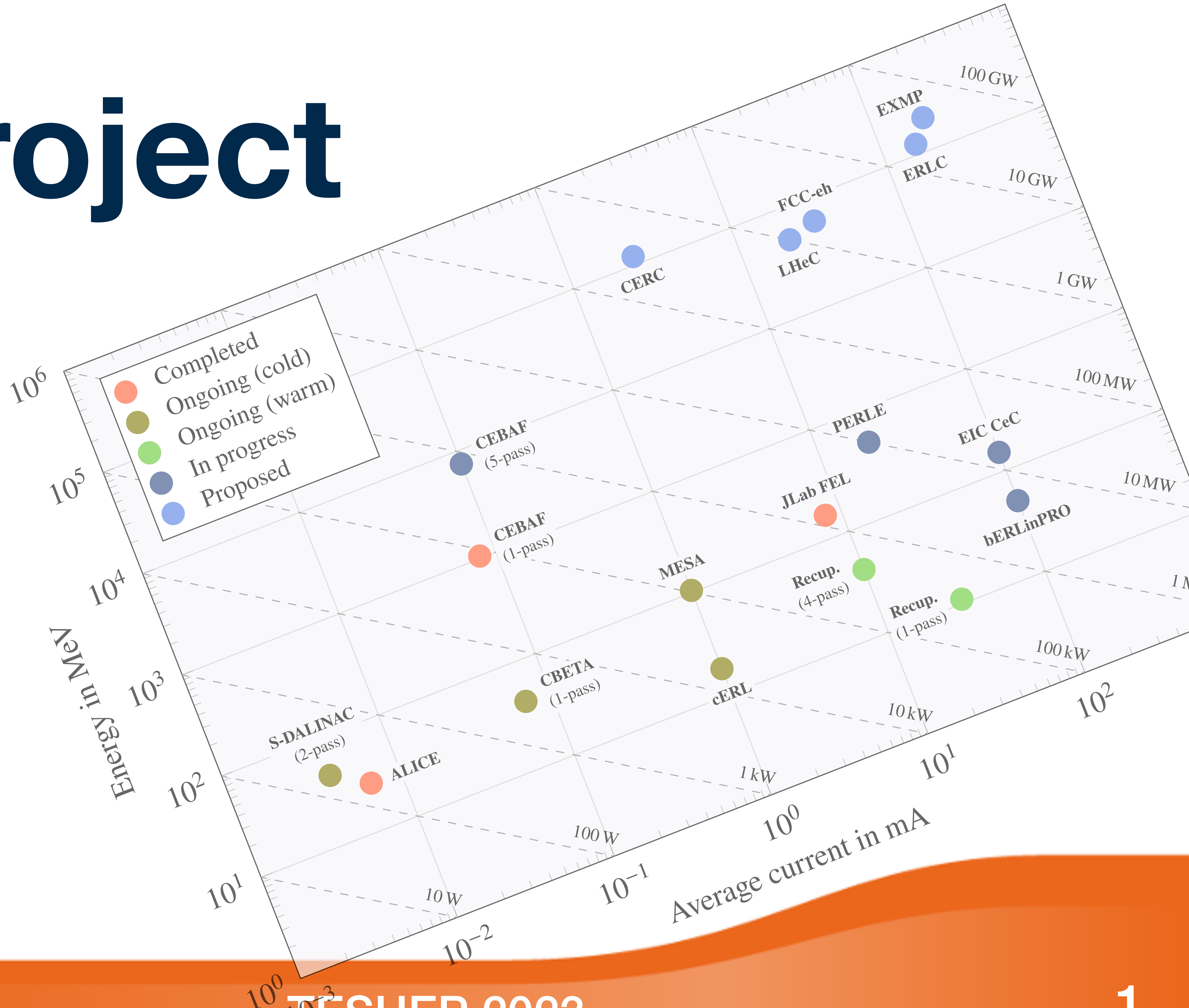
université PARIS-SACLAY

PERLE

the PERLE Project

Alex Fomin





Accelerators evolution

The two main tasks of an accelerator

Increase the particle **energy**

Change the particle direction

(follow a given trajectory, focusing)

Lorentz equation: $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} = \vec{F_E} + \vec{F_B}$

$\vec{F_B} \perp \vec{v} \rightarrow \vec{F_B}$ does no work on the particle

Only $\vec{F_E}$ can increase the particle energy

Deflecting a relativistic particle $(v \approx c)$

bending power $\vec{F_B} = 1\,\mathrm{T} \leftrightarrow \vec{F_E} = 10^8\,\mathrm{V/m}$

Is it feasible?

YES! planar channeling in a crystal, is used at the LHC

$\vec{F_E} \sim 10\,\mathrm{V/Å} = 10^{11}\,\mathrm{V/m} \leftrightarrow \vec{F_B} = 1000\,\mathrm{T}$

not 100% efficient → but perfect for multi-turn halo cleaning

Lasers? might be too hot 🥵

$\vec{F_E} \sim 10^{12}\,\mathrm{V/m}$

Some Milestones for Accelerators

20th century first 25 years: fu**ndamental discoveries m**ade with "beams"

from radioactive source tr**igger the demand for higher energies**

1928-32 Cockcroft&Walton develop a 700kV el**ectrostatic accelerator**

based on a voltage multiplier

1928 First Linac by Rolf Widerøe based on re**sonant acceleration**

1929 Ernest O. Lawrence invents the cy**clotron**

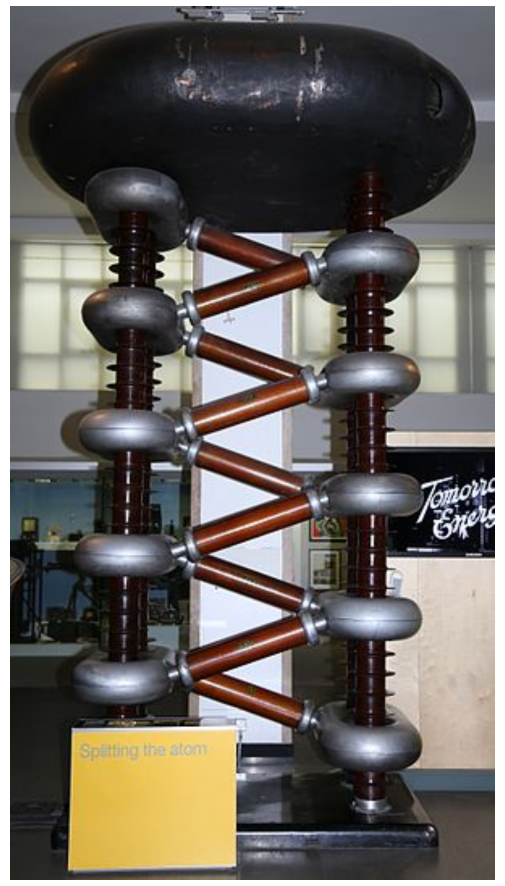
1944 MacMillan, Oliphant & Veksler develop the sy**nchrotron**

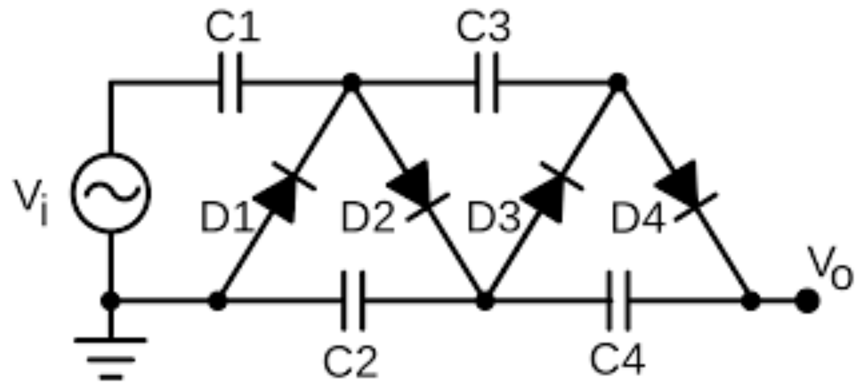
1946 Luis Alvarez built a proton linac with Al**varez structures (**2 mode)

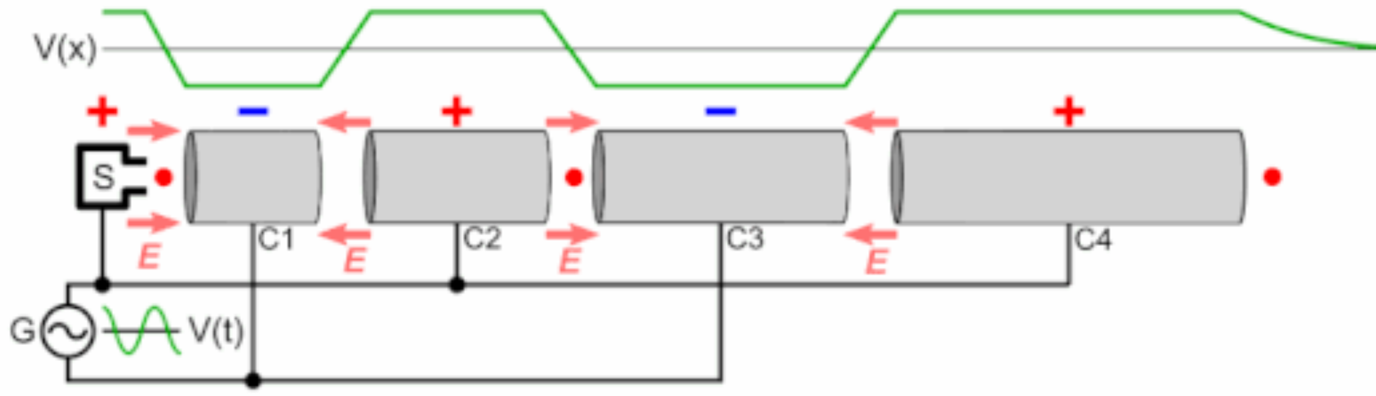
1950 Christofilos patents the concept of st**rong focusing**

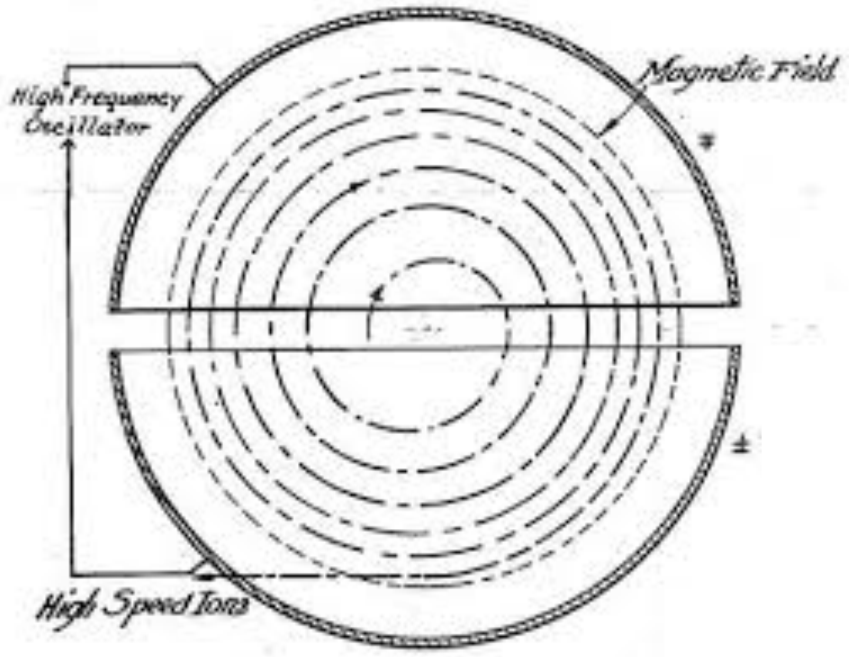
1951 Luis Alvarez conceives the t**andem**

1956 Donald W. Kerst stresses in a paper the co**ncept of a collider**









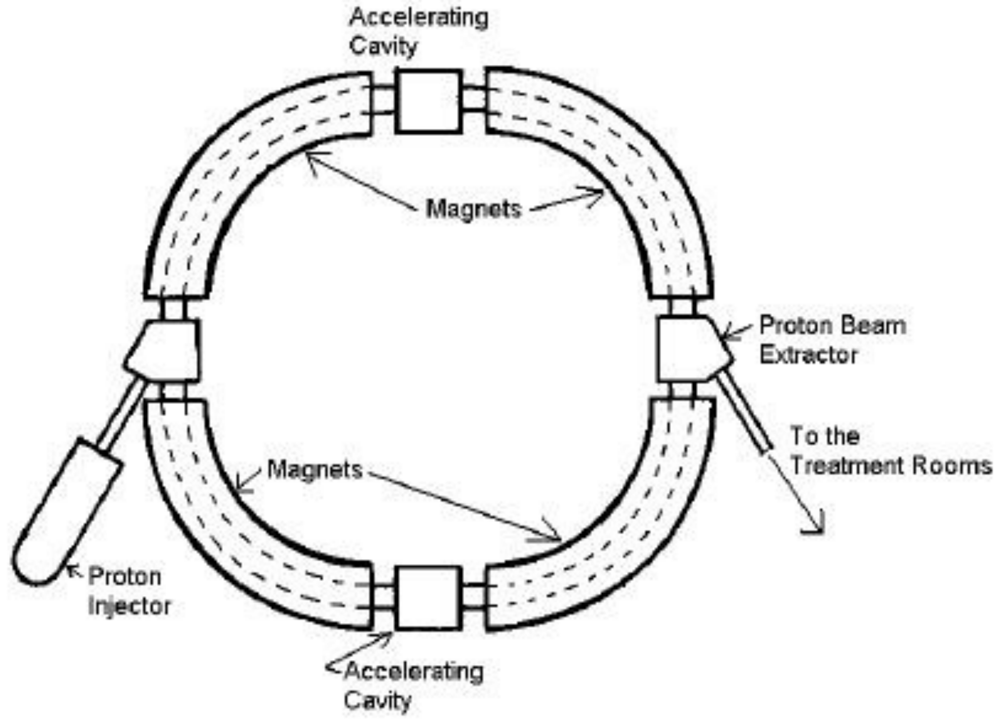


Diagram of a Proton Synchrotron

Accelerators evolution: the Livingston chart

20th century first 25 years: fundamental discoveries made with "beams" from radioactive source trigger the demand for higher energies

1928-32 Cockcroft&Walton develop a 700kV electrostatic accelerator based on a voltage multiplier

1928 First Linac by Rolf Widerøe based on resonant acceleration

1929 Ernest O. Lawrence invents the cyclotron

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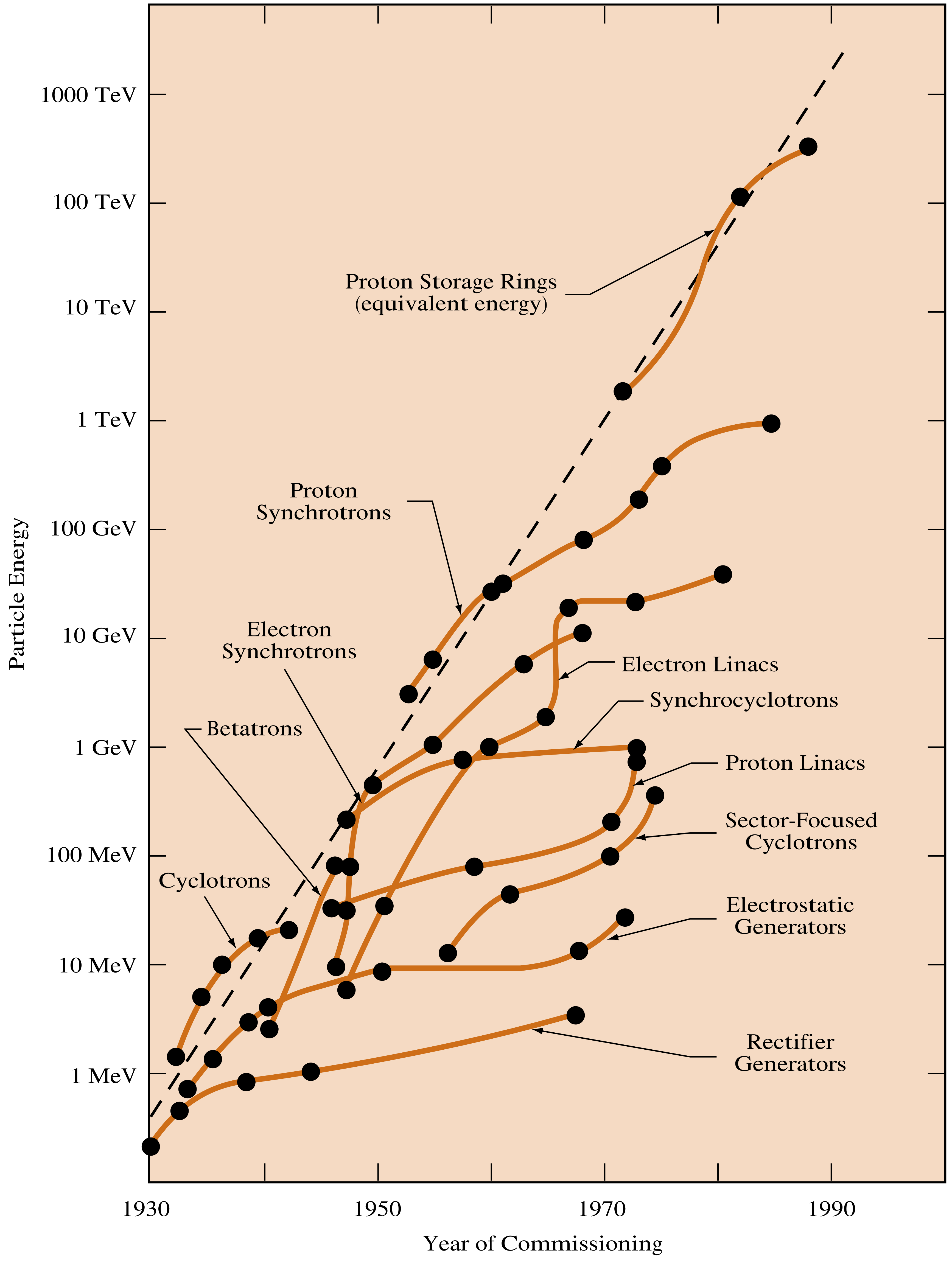
slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf



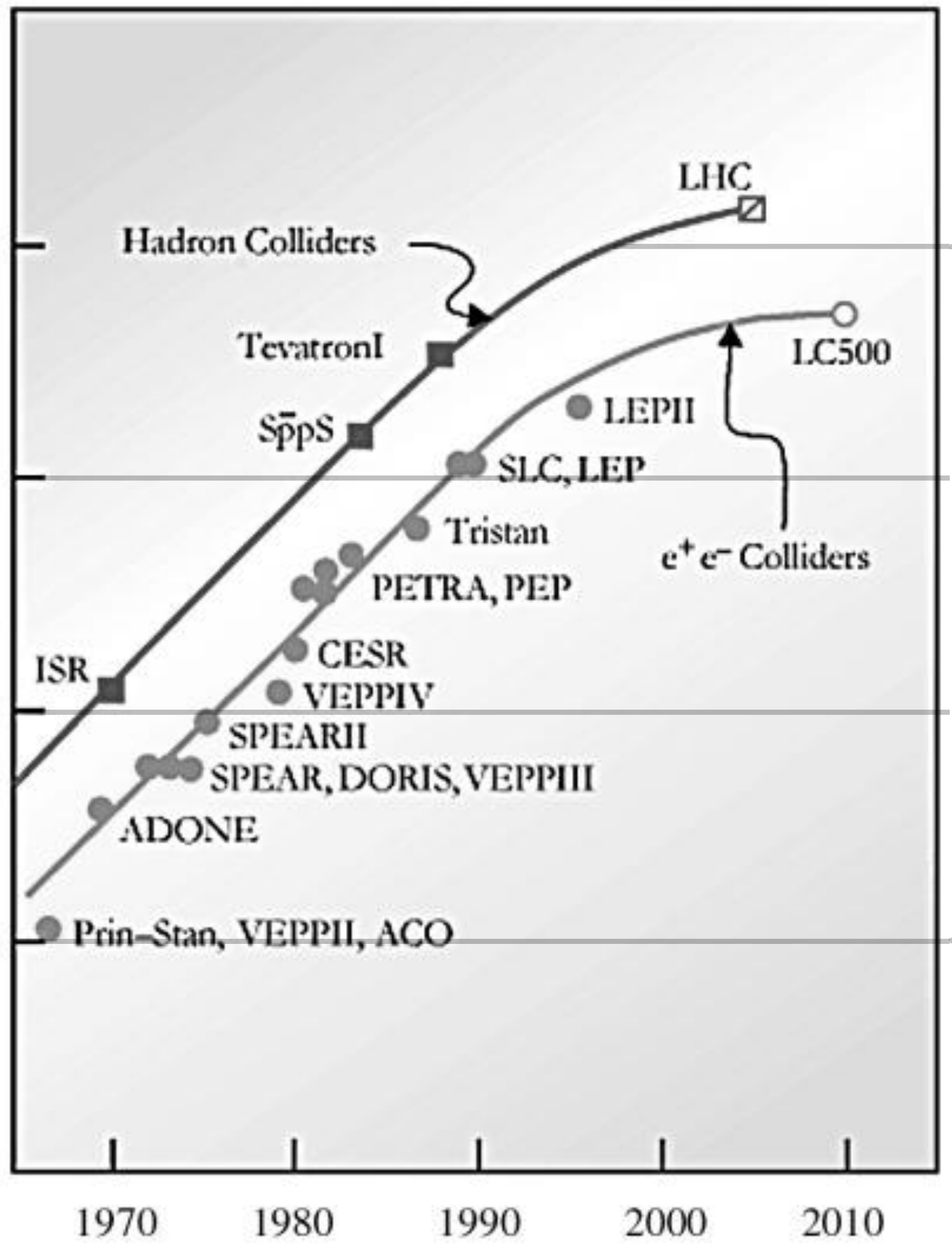
Around 1950, Stanley Livingston made a quite remarkable observation:

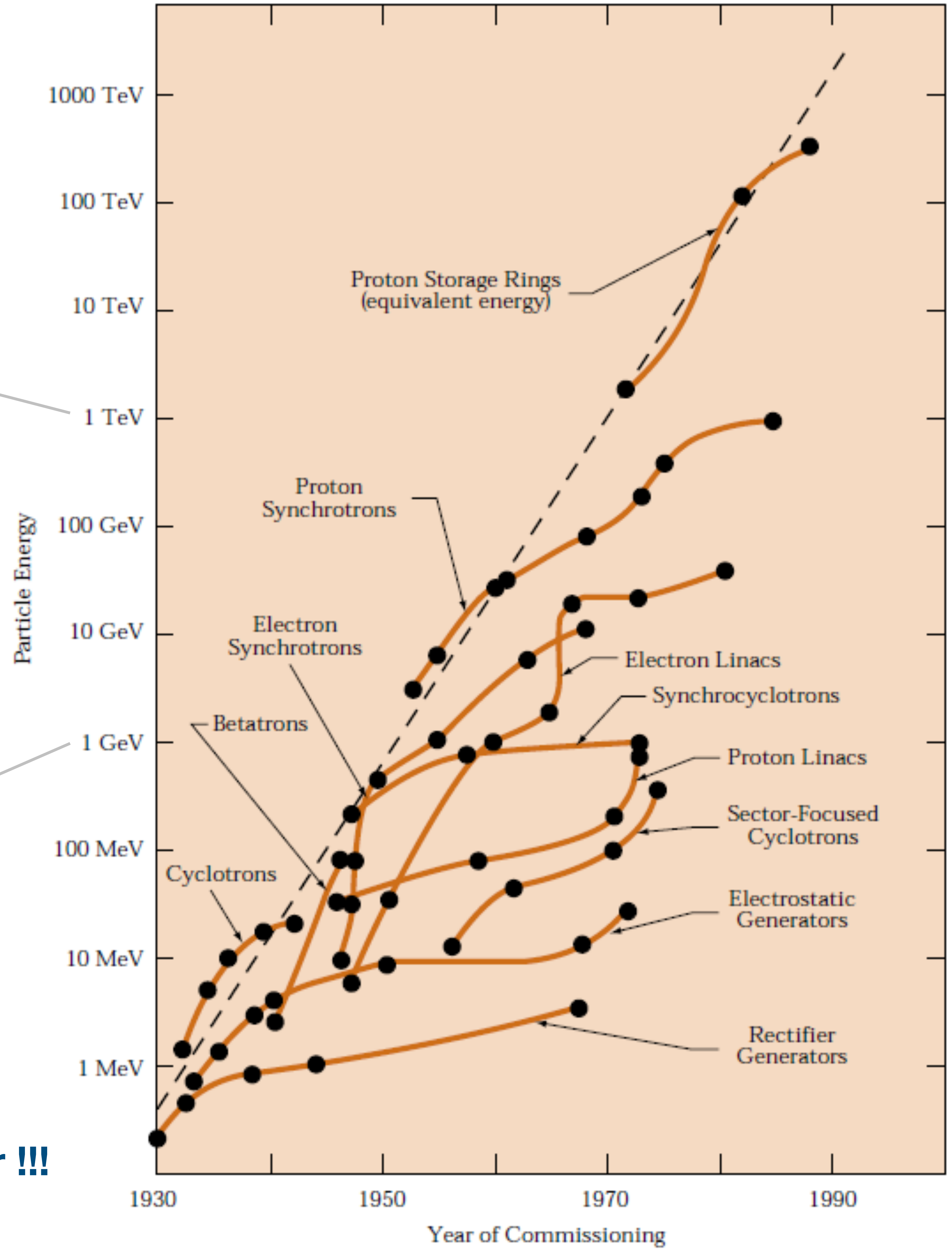
Plotting the energy of an accelerator as a function of its year of construction, on a semi-log scale, the energy gain has a linear dependence.

The Livingston chart shows, in a very striking way, how the succession of new ideas and new technologies has relentlessly pushed up accelerator beam energies over five decades at the rate of over one and a half orders of magnitude per decade.

Accelerators are the biggest scientific instruments human mankind has built

- Large size (~ 30 km footprint)
- High cost (~ billion Euro)
- Needs lots of electricity
- Technology pushed to its limits
- ~ 20-30 years to make one
- Global co-ordination





The future holds many challenges for the accelerator engineers.

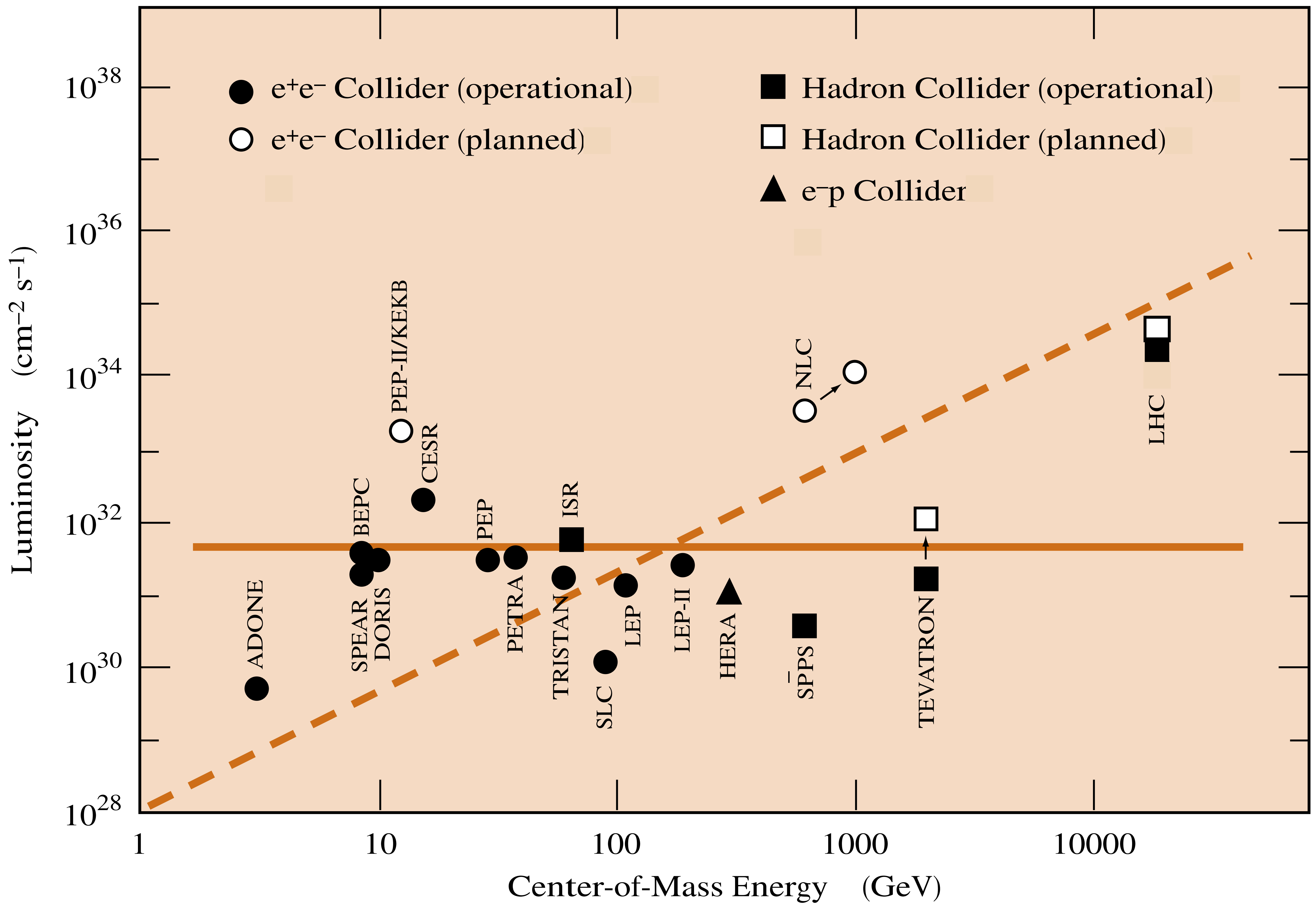
All this effort justified by the chance to discover new particles, forces, properties of matter !!!

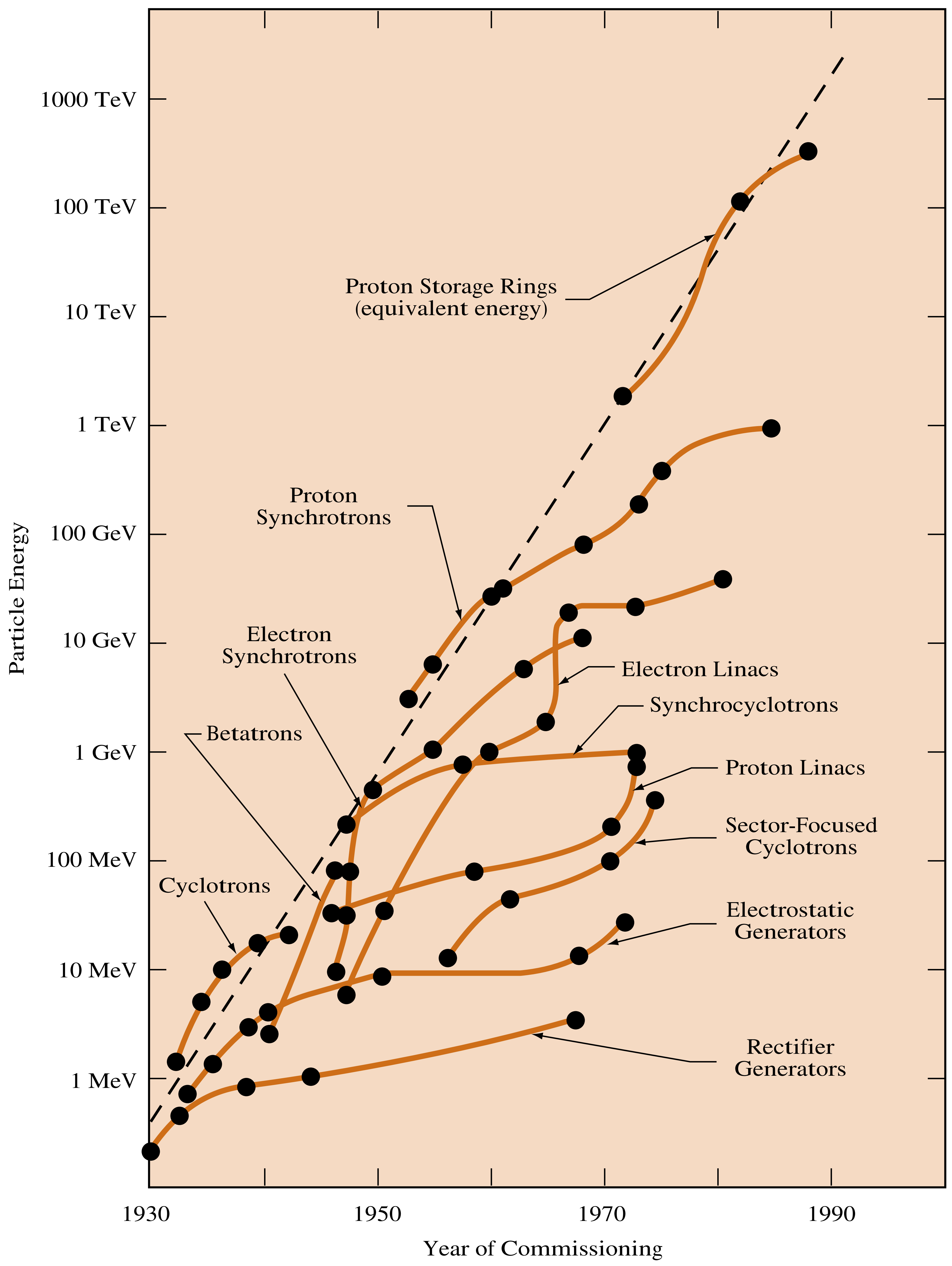
Accelerators evolution: the Livingston chart

slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf

In another respect, however, the Livingston plot is misleading. It suggests that energy is the primary, if not the only, parameter that defines the discovery potential of an accelerator or collider.

Luminosity is the key





Energy Recovery Linacs (ERL)

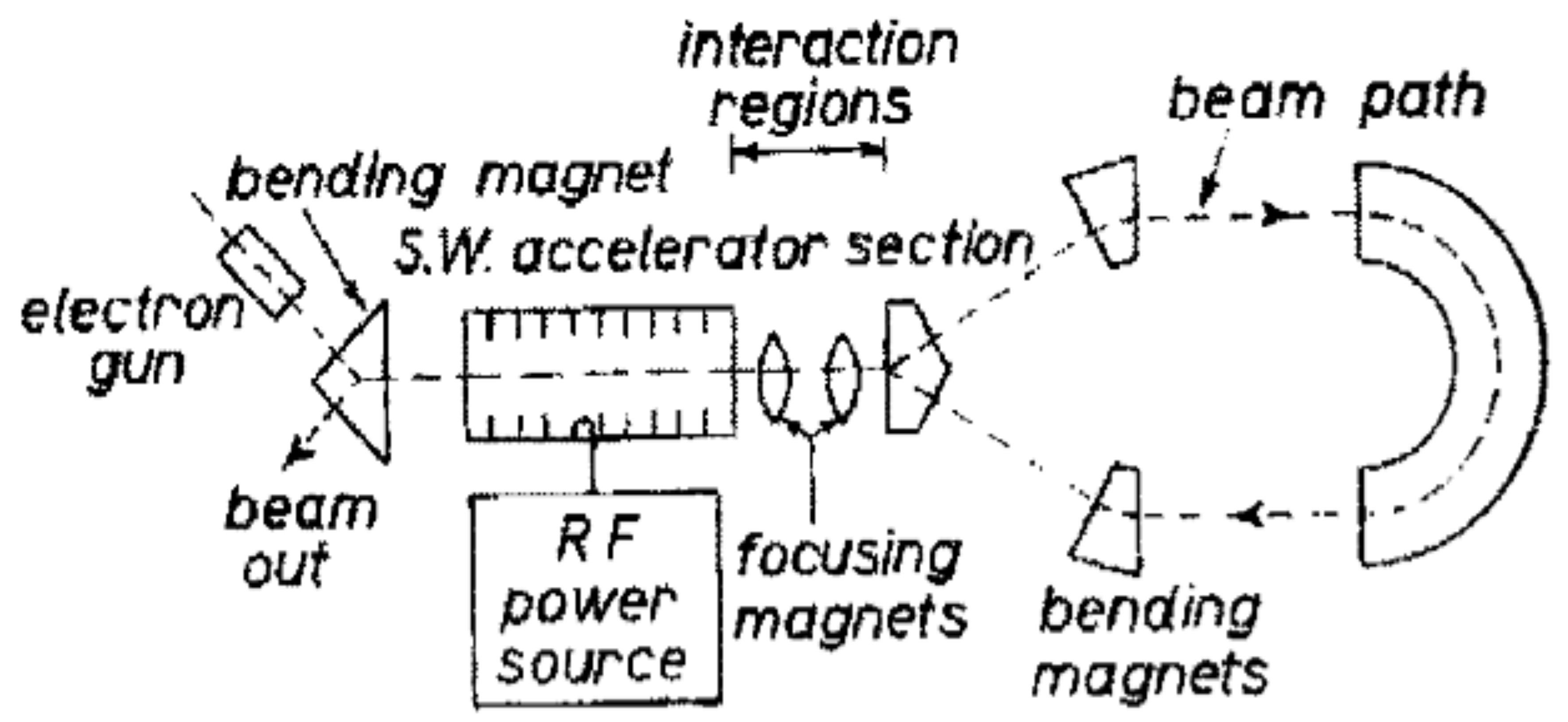
Accelerating two beams, colliding them, and then dumping them is extremely inefficient.

In 1965 Maury Tigner proposed idea of an energy-recovery linac

- to enhance the current in a collider for high-energy physics
- recover the energy of the beams in the same cavities in which they were accelerated, then the machine efficiency could be greatly increased
- the design of the final dump also becomes much simpler

The implementation of an efficient solution relied on the development of reliable superconducting radio frequency (SRF) accelerating cavities. These were developed over the next decade.

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)

What is superconductivity ?

A superconductor (SC) material has the property to transport a DC electric current without any loss.

Its resistivity is exactly zero!!!

- has been observed for the first time in 1911 by Kamerlingh Onnes while measuring the resistance of a mercury sample in liquid helium.
- observed in several materials:

Matériau	Ti	Al	Sn	Hg	Pb	Nb	Nb_3Sn	$YBa_2Cu_3O_7$
T_c[K]	0,4	1,14	3,72	4,15	7,9	**9,2**	18	92

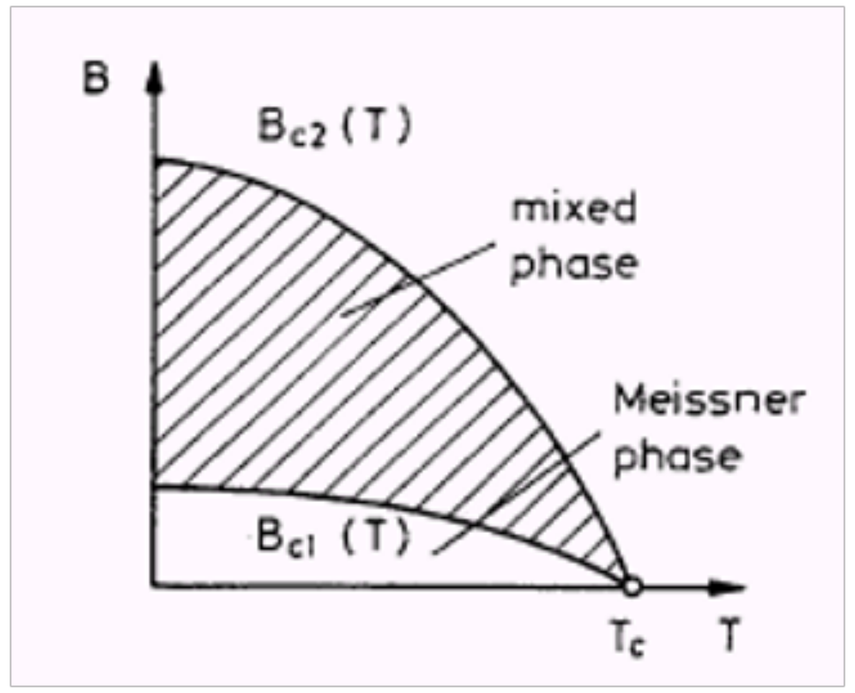
Liquid Helium 4,2 K   Liquid Nitrogen 77 K

- appears below a critical temperature
- all magnetic fields are totally expeled from its volume "Meissner effect" (1933)
- is destroyed by a too strong magnetic field (or by a too strong current), i.e. when B > Bc

Type I SC	Ti	Al	Hg	Sn	Pb
B_c[mT] à 0 K	10	10,5	41,2	30,9	80,3

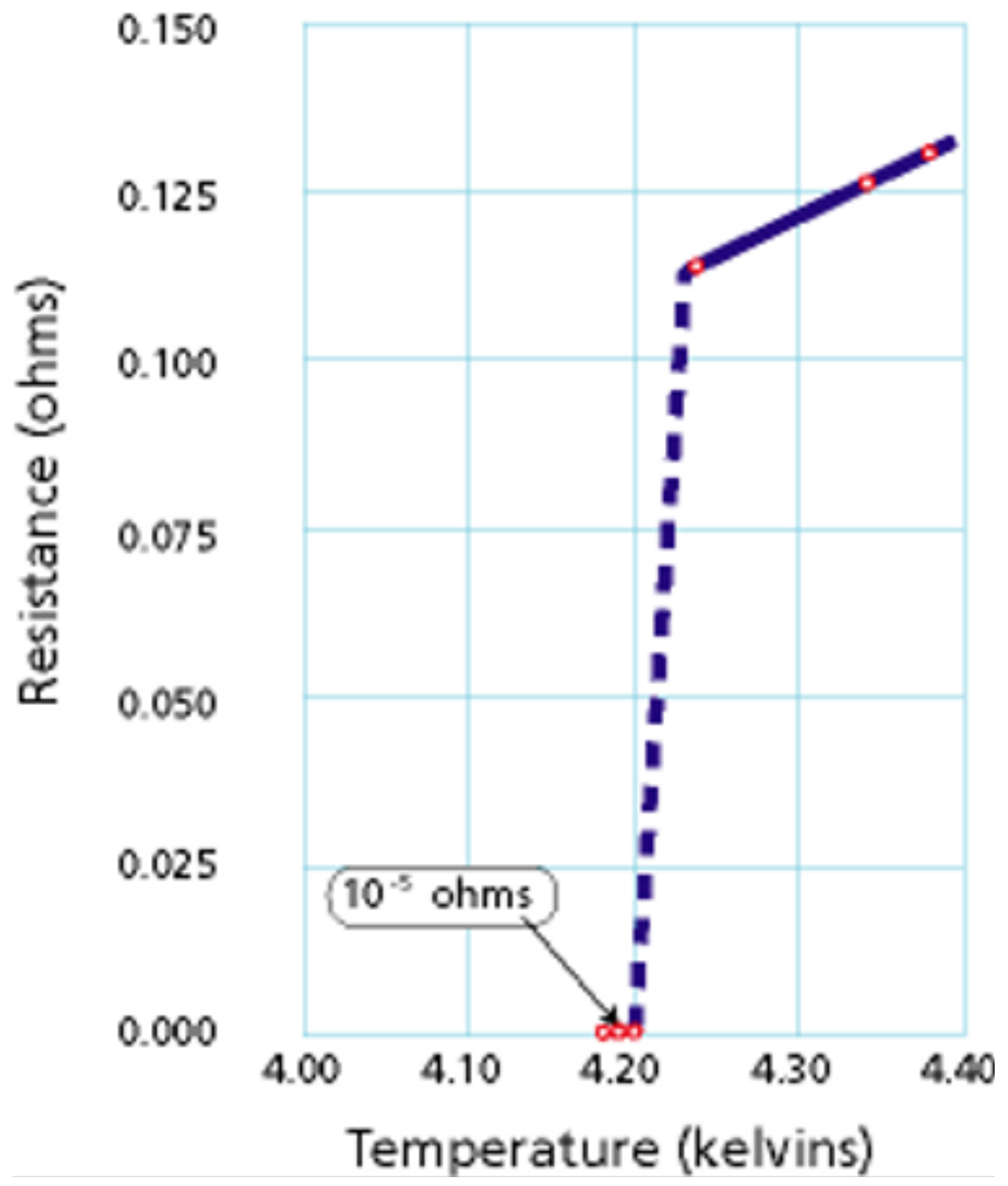
- (of type II) is not destroyed abruptly at B > Bc they experience an intermediate « mixed state »

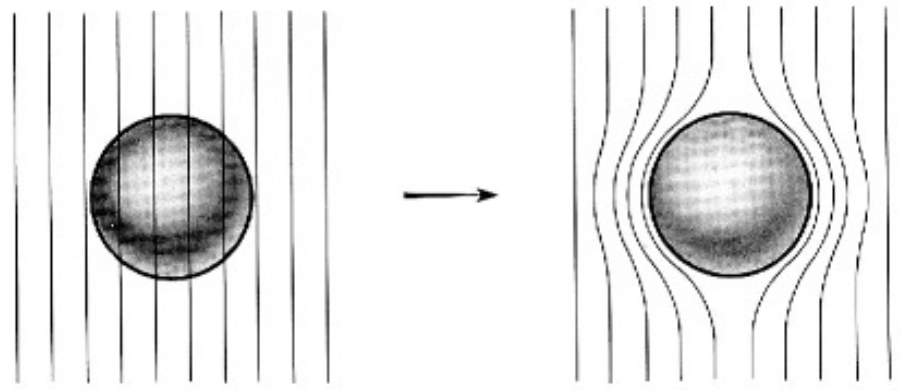
Nb (type II)	Bc_1	Bc_2
B_c[mT] à 0 K	~170	~240



In recent years, R&D on Type 2 superconductors in SRF cavities

The 1911 measurement of a Hg sample by K. Onnes





Superconductivity in accelerator

From the superconductivity discovering in 1911 to the use in accelerator cavities and magnets, a long time of R&D has been needed.

- 1977 : first superconducting LINAC at Stanford : 1.3GHz, 50MeV, 27m
- 1986 – 1992 : machine commissioning using superconducting cavities around 5MV/m (like CEBAF, LEP, HERA)
- Today, almost all machines are using superconducting cavities : SOLEIL, LHC, SNS, J-PARC ...

The use of superconductivity in proton machines has made the very highest energies possible.

We have access now to high intensity and high duty cycle machines.

In short:

NC linac: lower capital cost, but high operational cost

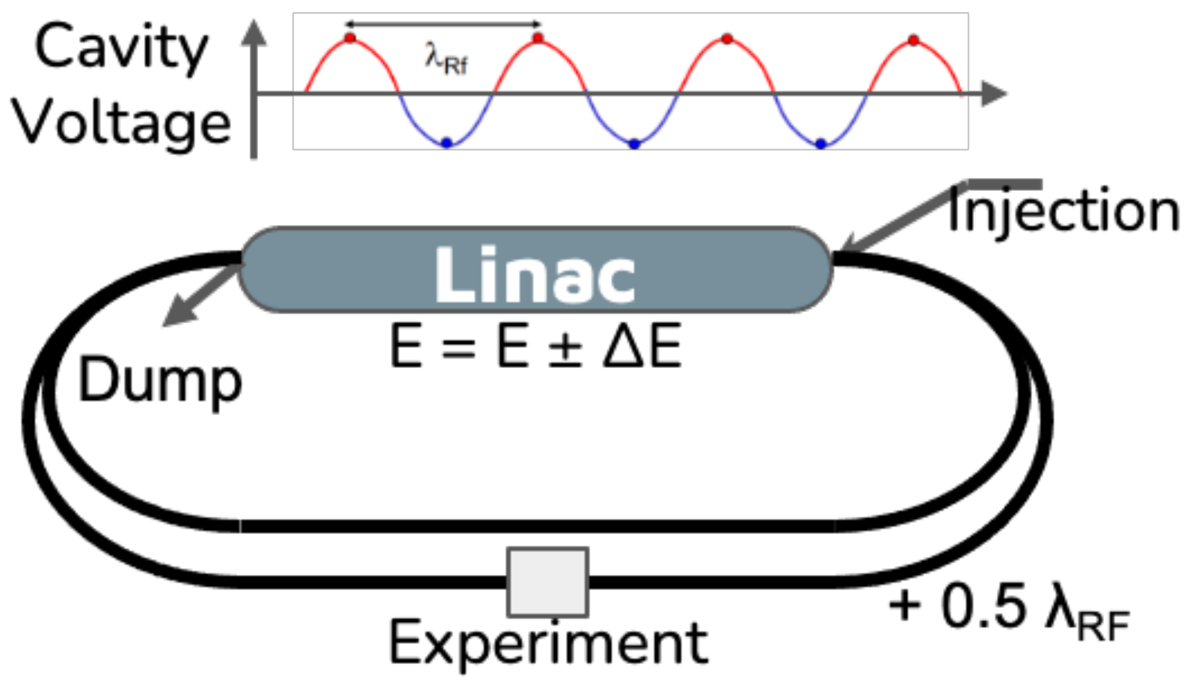
SC linac: slightly higher capital cost, but low operational cost

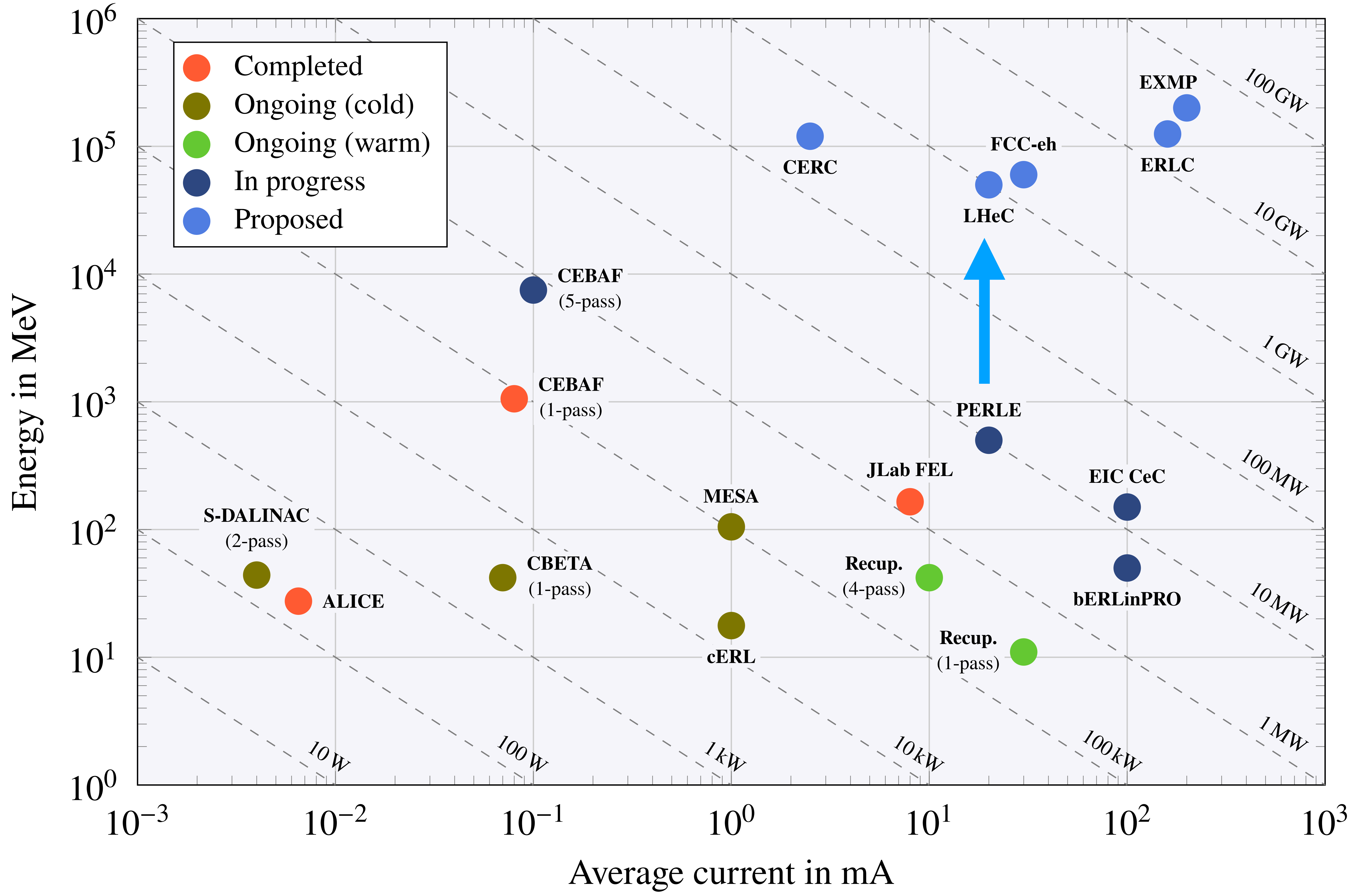
early 80's superconducting magnets for cyclotrons and synchrotrons considerably boost the performance (energy for size)

the last years the development of superconducting accelerating cavities provides very high power conversion efficiency

Proven accelerator technology, pushing for higher energy and beam current reaching in view of collider applications above 1GW.

PERLE demonstrator facility for the LHeC at Orsay with 3-turn, 20mA, 802 MHz SRF cavities



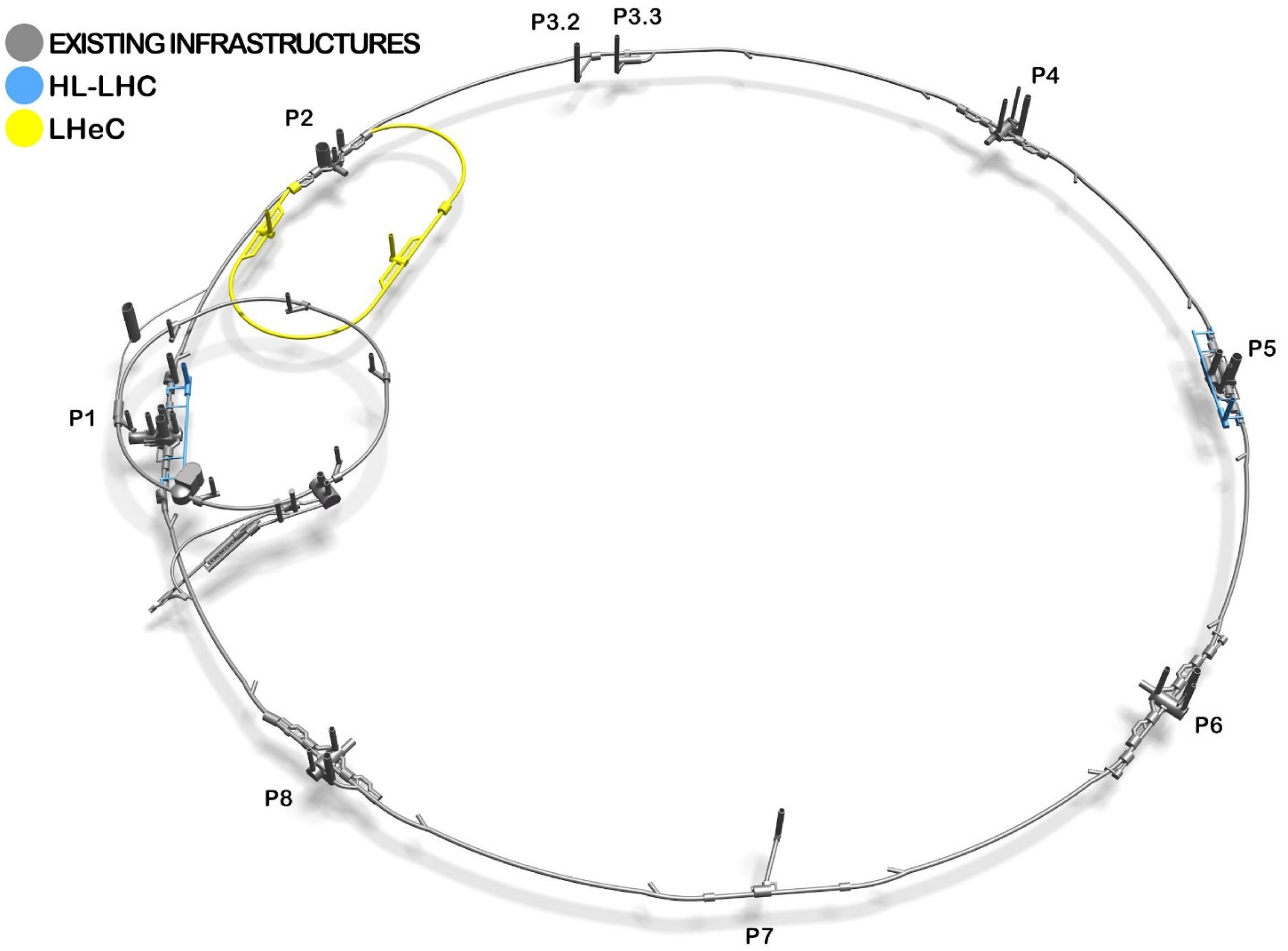


The future of hadron colliders, such as FCC-hh or HE-LHC, relies on a considerable extrapolation of superconducting, high-field dipole magnet technology.

The new ERL proposals are close to becoming the base of future energy frontier electron-hadron and e+e– colliders

Beam parameters for the LHeC experiment

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.

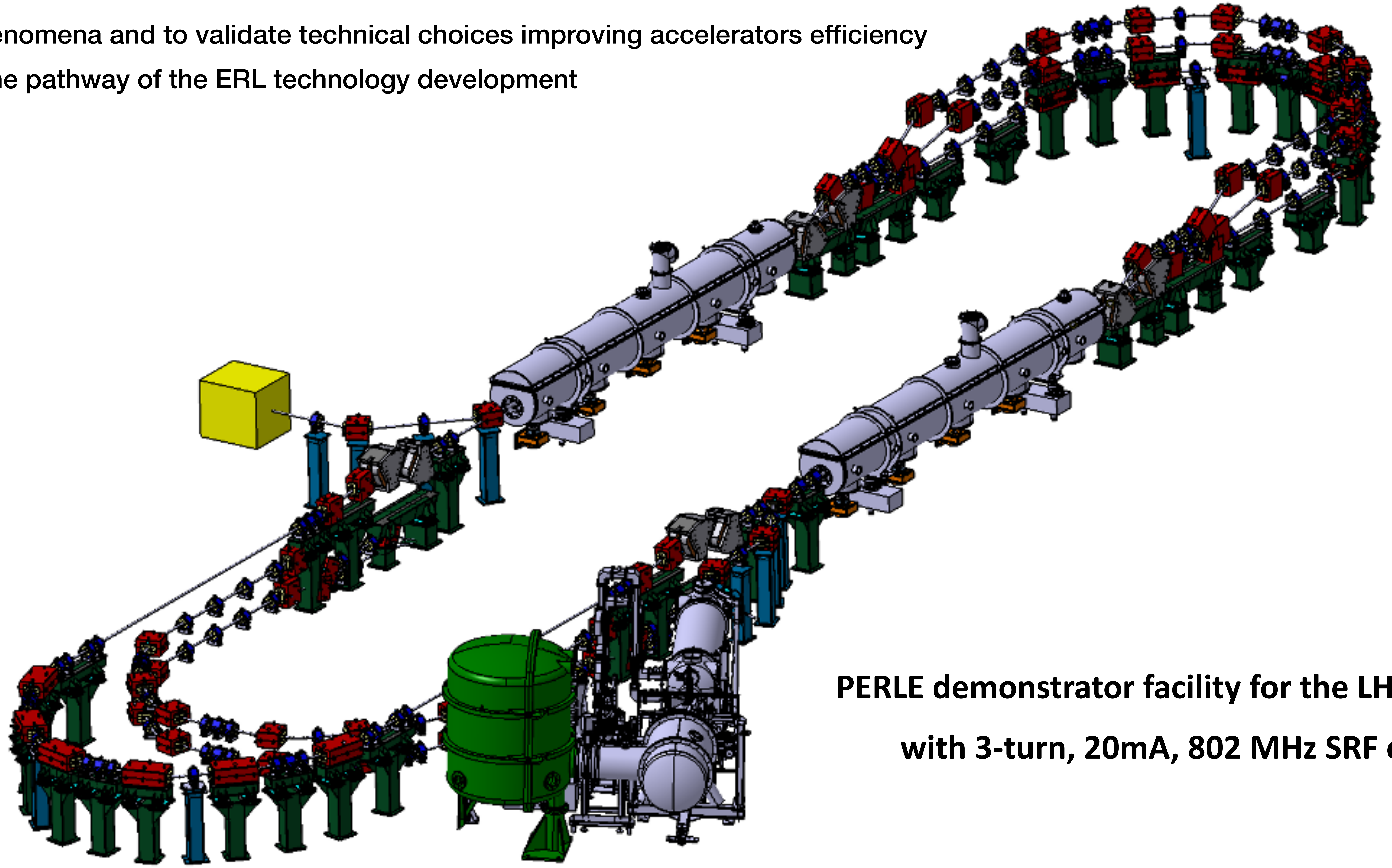
PERLE Project

PELRE: Powerful Energy Recovery Linac for Experiments

PELRE: **first multi-turn ERL, based on SRF technology, designed to operate at 10MW (20 mA, 500 MeV) power regime**

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



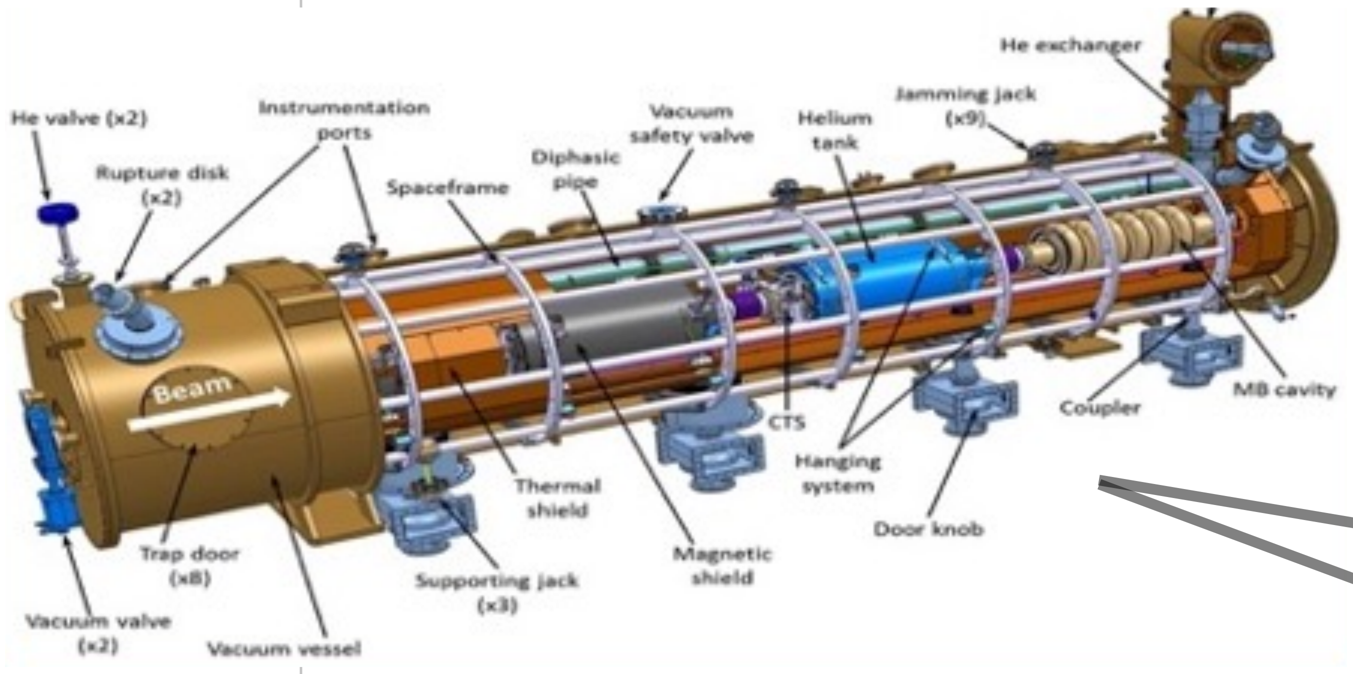
PERLE demonstrator facility for the LHeC a

with 3-turn, 20mA, 802 MHz SRF cavit

PELRE: Powerful Energy Recovery Linac for Experiments

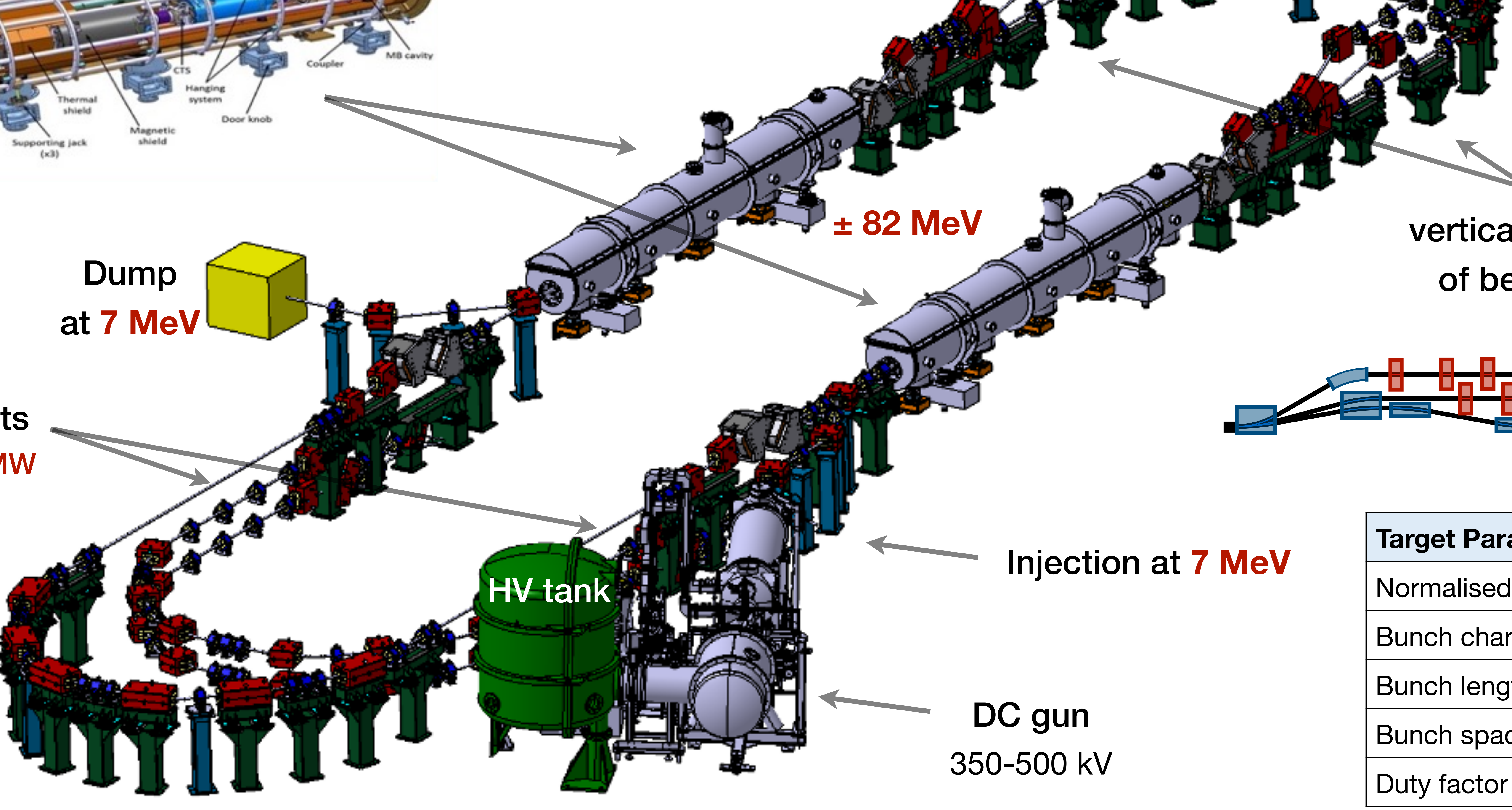
Two cryo-modules with 4 five-Cell cavities, each provides a total gradient of 82 MeV

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



Three staked isochronous recirculation Arcs for beams at different energies

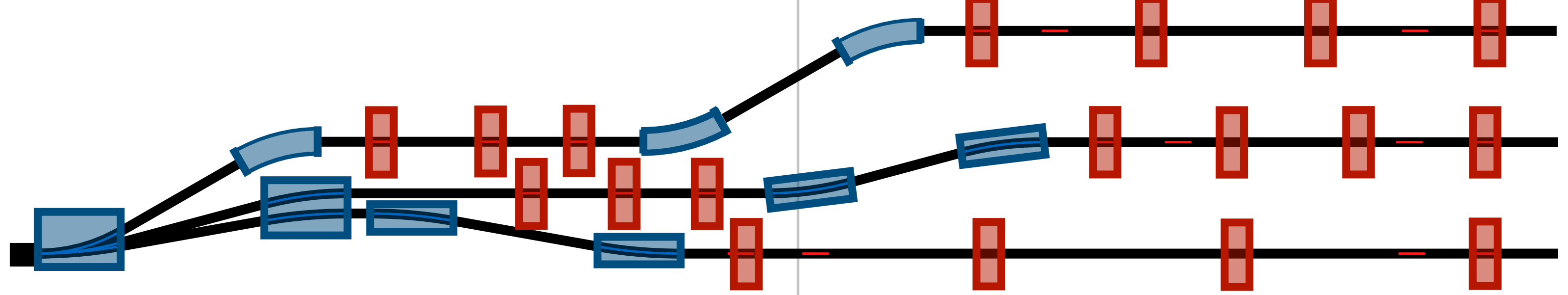
89 MeV
253 MeV
418 MeV



± 82 MeV

Dump at 7 MeV

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



Two Interaction Points
500 MeV × 20 mA = 10 MW

Injection at 7 MeV

171 MeV
366 MeV
500 MeV

DC gun
350-500 kV

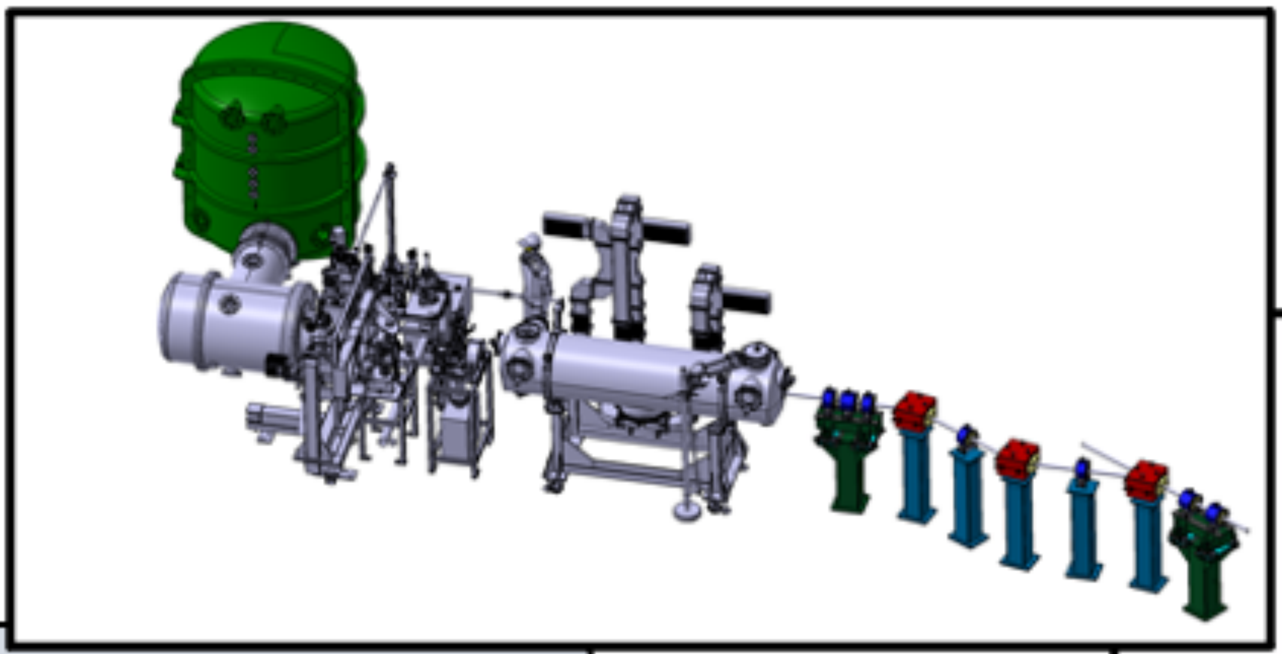
Target Parameter	Unit	Value
Normalised Emittance	mm mrad	6
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
Duty factor		CW

PELRE Timeline: Phasing Strategy

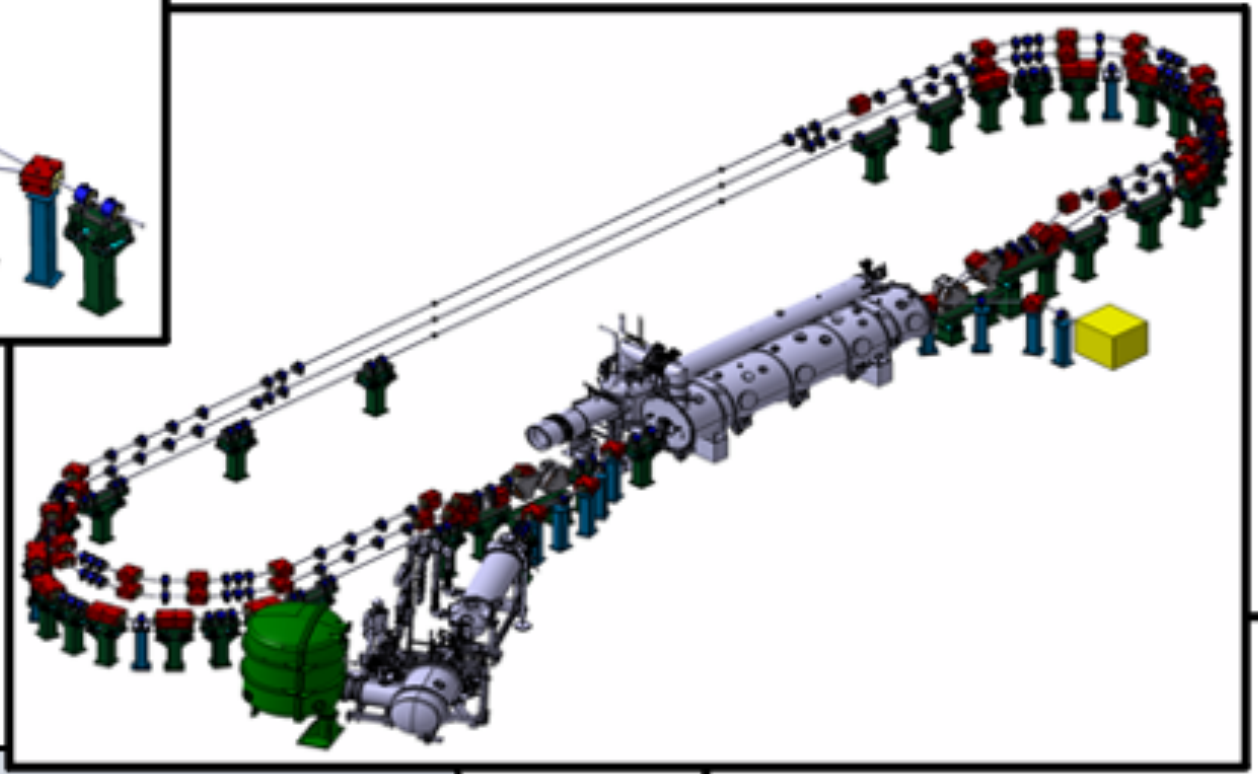
Technical Design phase (TDR)

Prepare to Build phase (P2B)

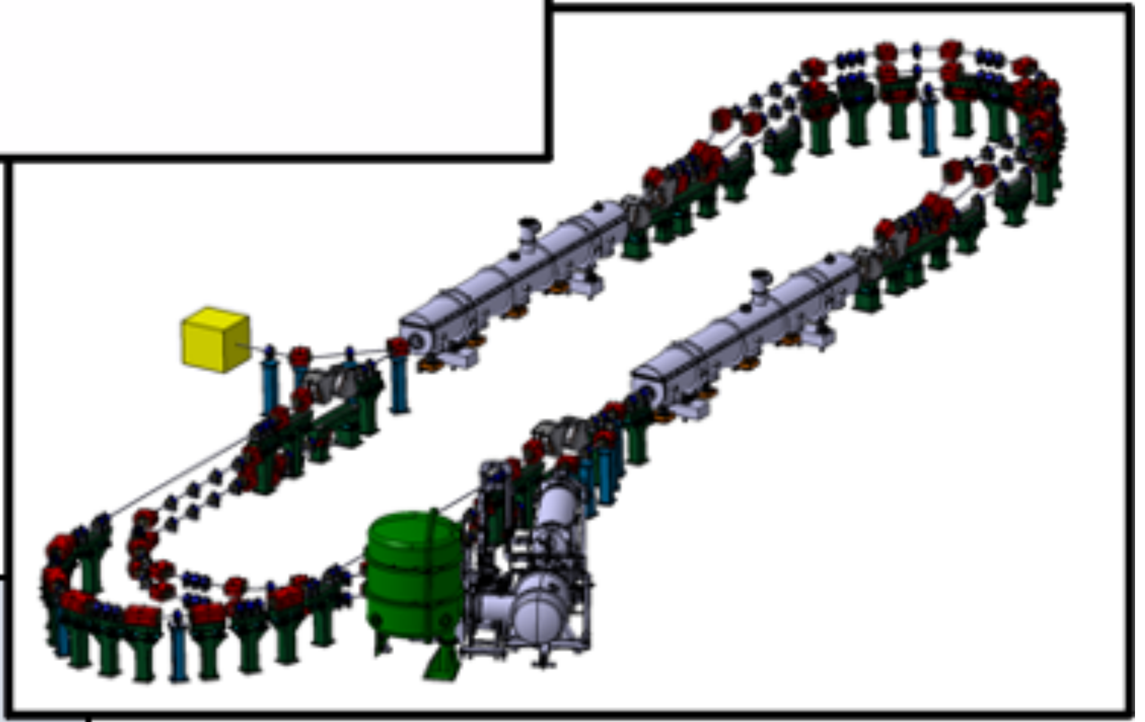
Phase 1: Installation of the injection line



Phase 2: PERLE 250 MeV

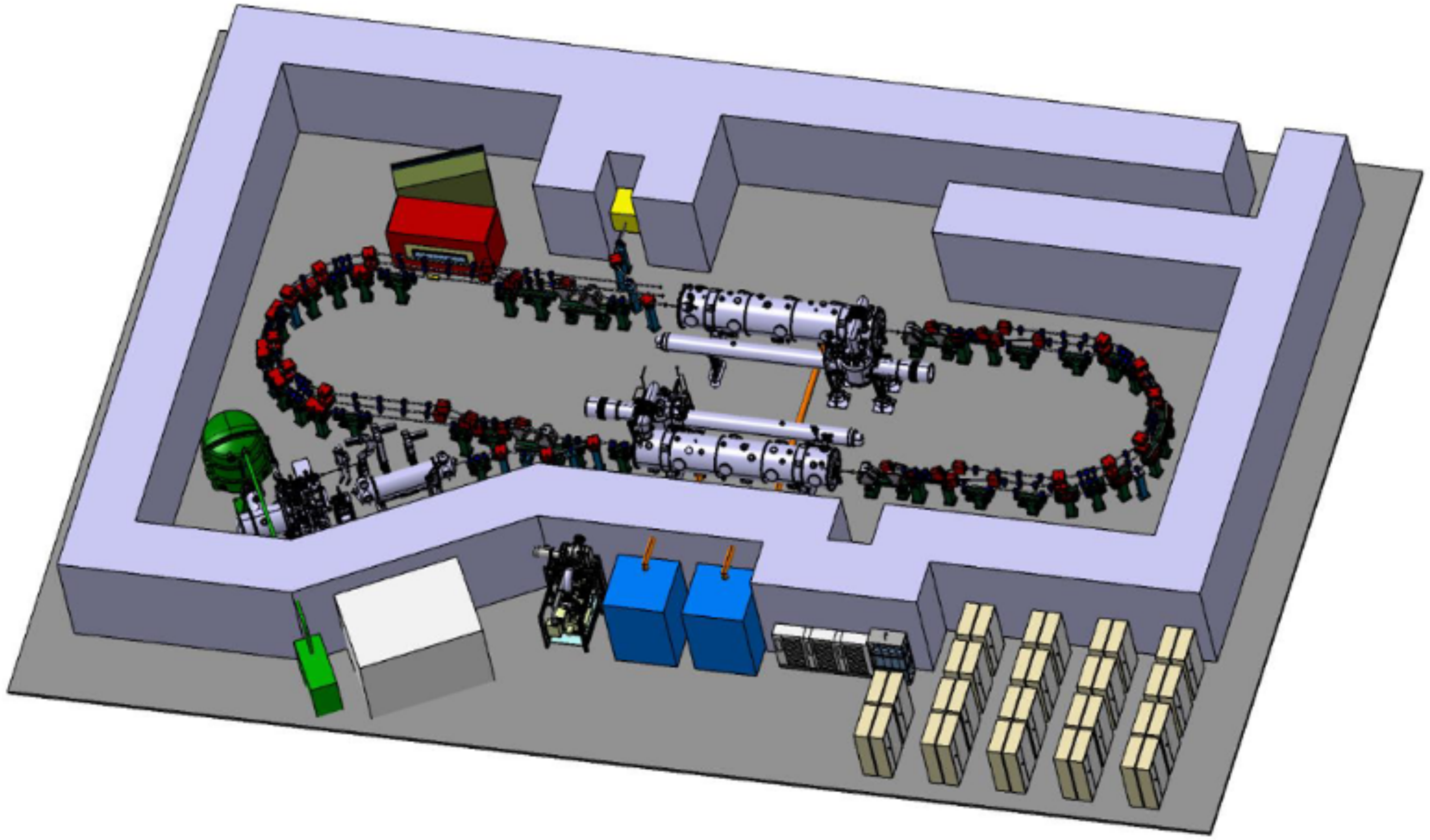


Phase 3: PERLE 500 MeV



2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031

PERLE Footprint: Site studies

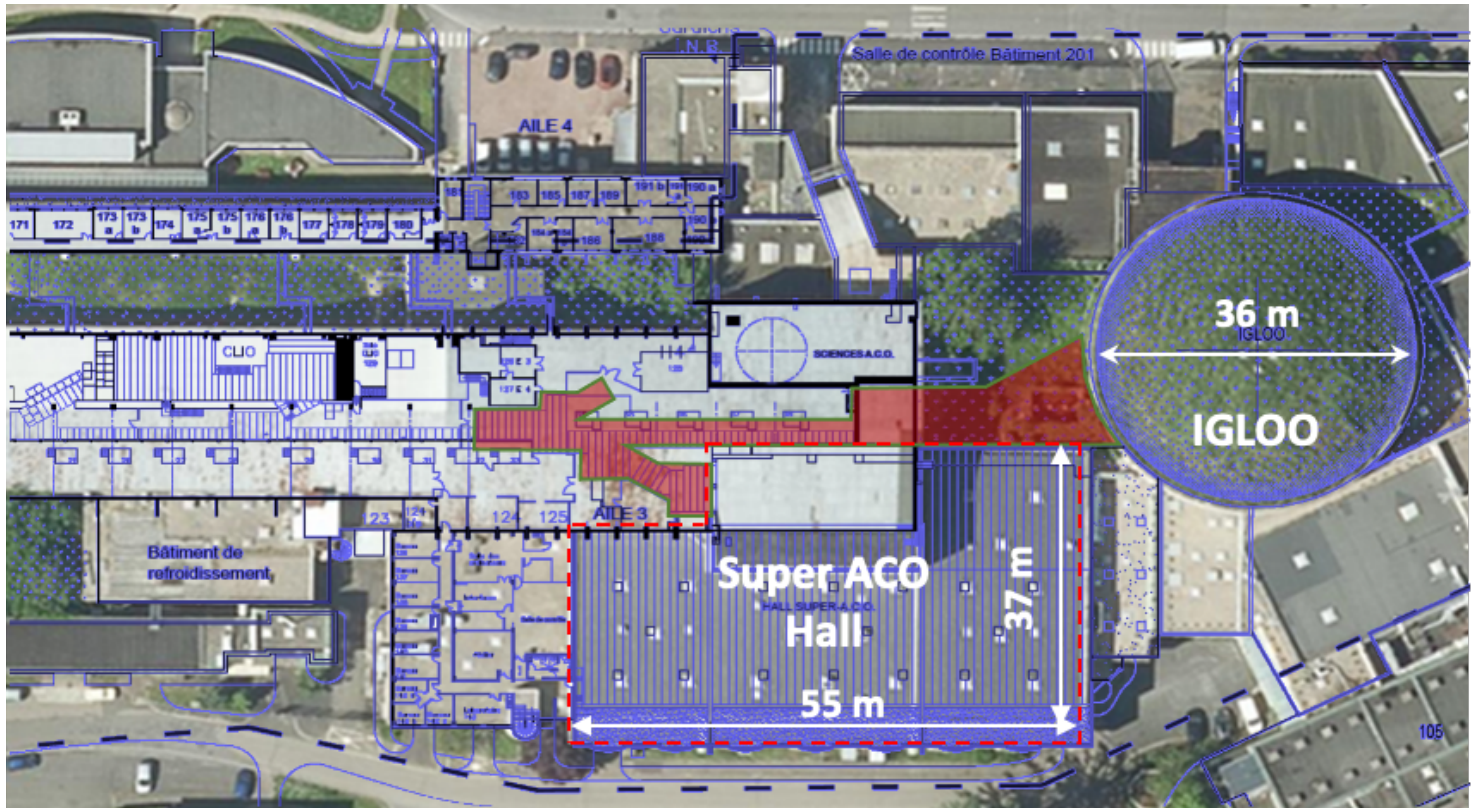


PERLE feature a total footprint of:

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.

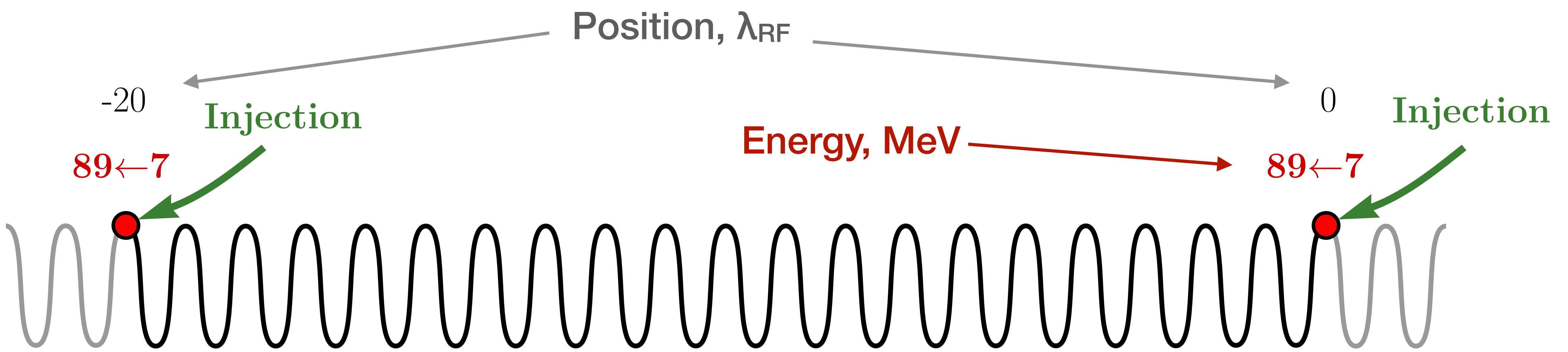


Consecutive injections (ν_{inj} = 40 MHz), RF cavity (ν_{RF} = 801.58 MHz) → spacing between injections **20** × λ_{RF}

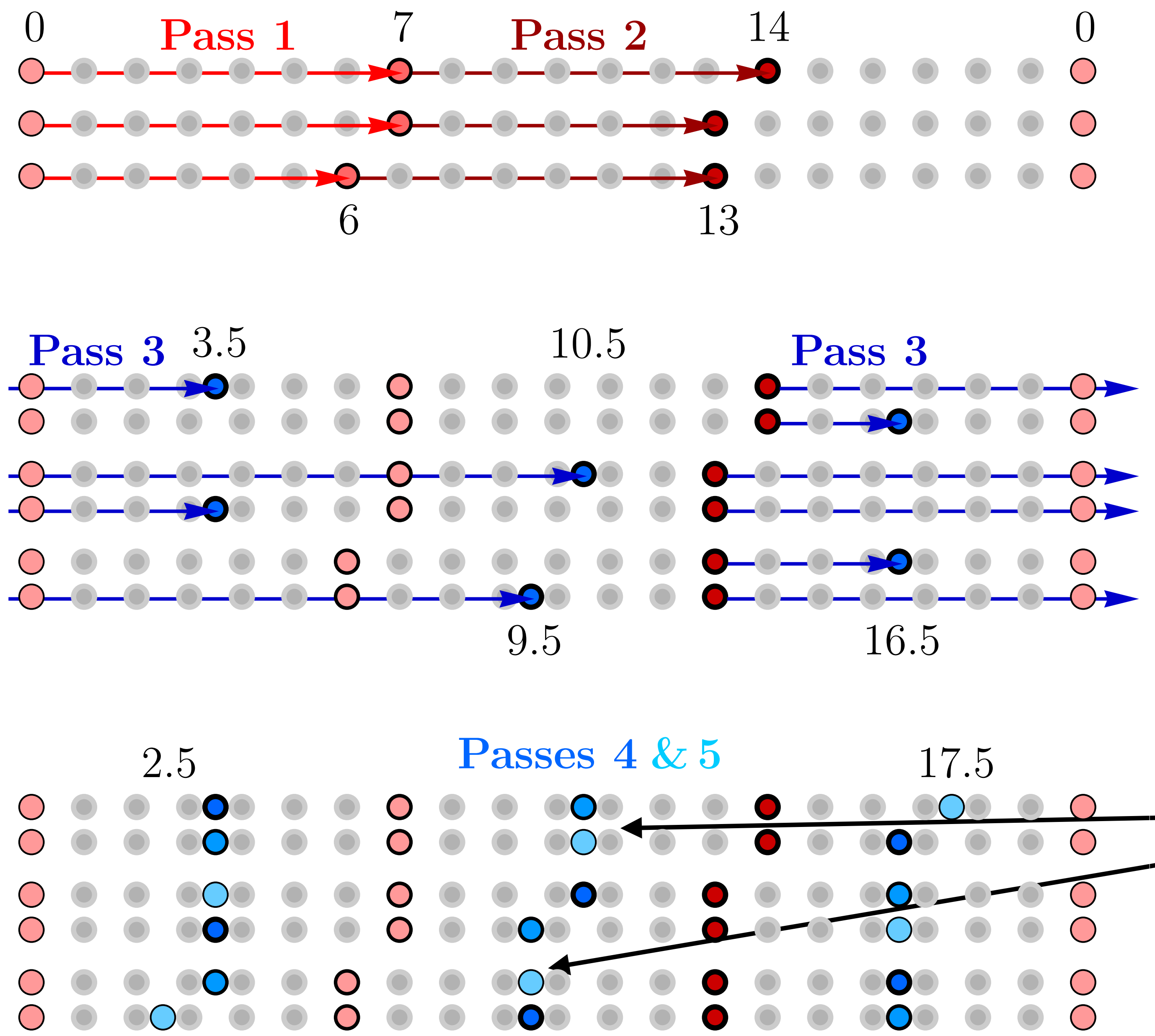
$\nu_{RF} / \nu_{inj} \approx 20$, λ_{RF} = 37.4 cm

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

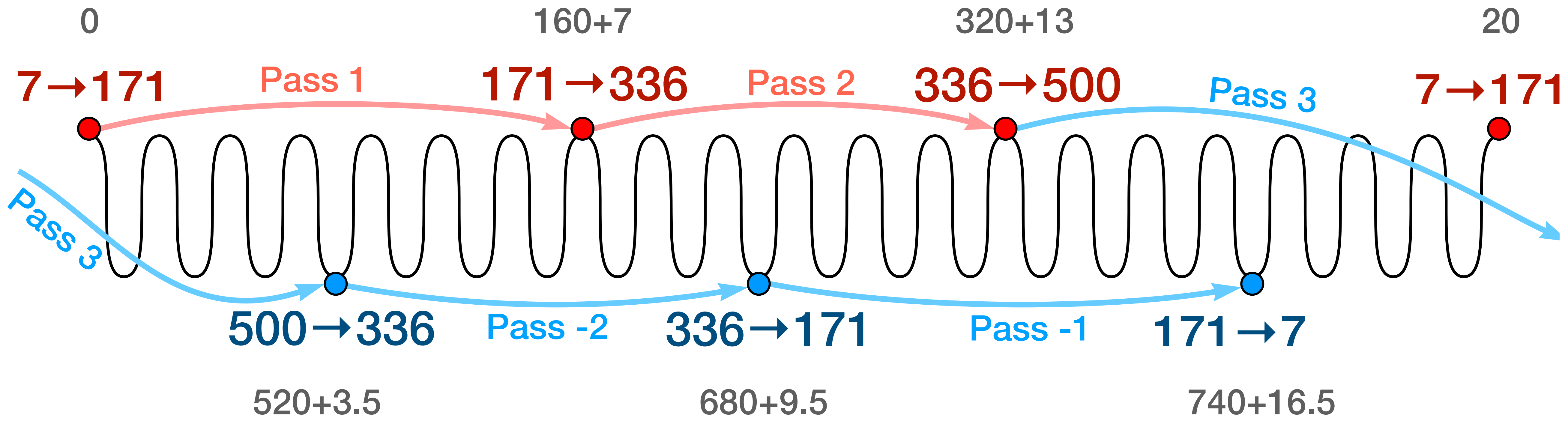


Six possible options of uniform filling patterns



option 2 & 5 have bunches of lowest energies separated

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



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 $L_{inj} = 20\ \lambda_{RF}$

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

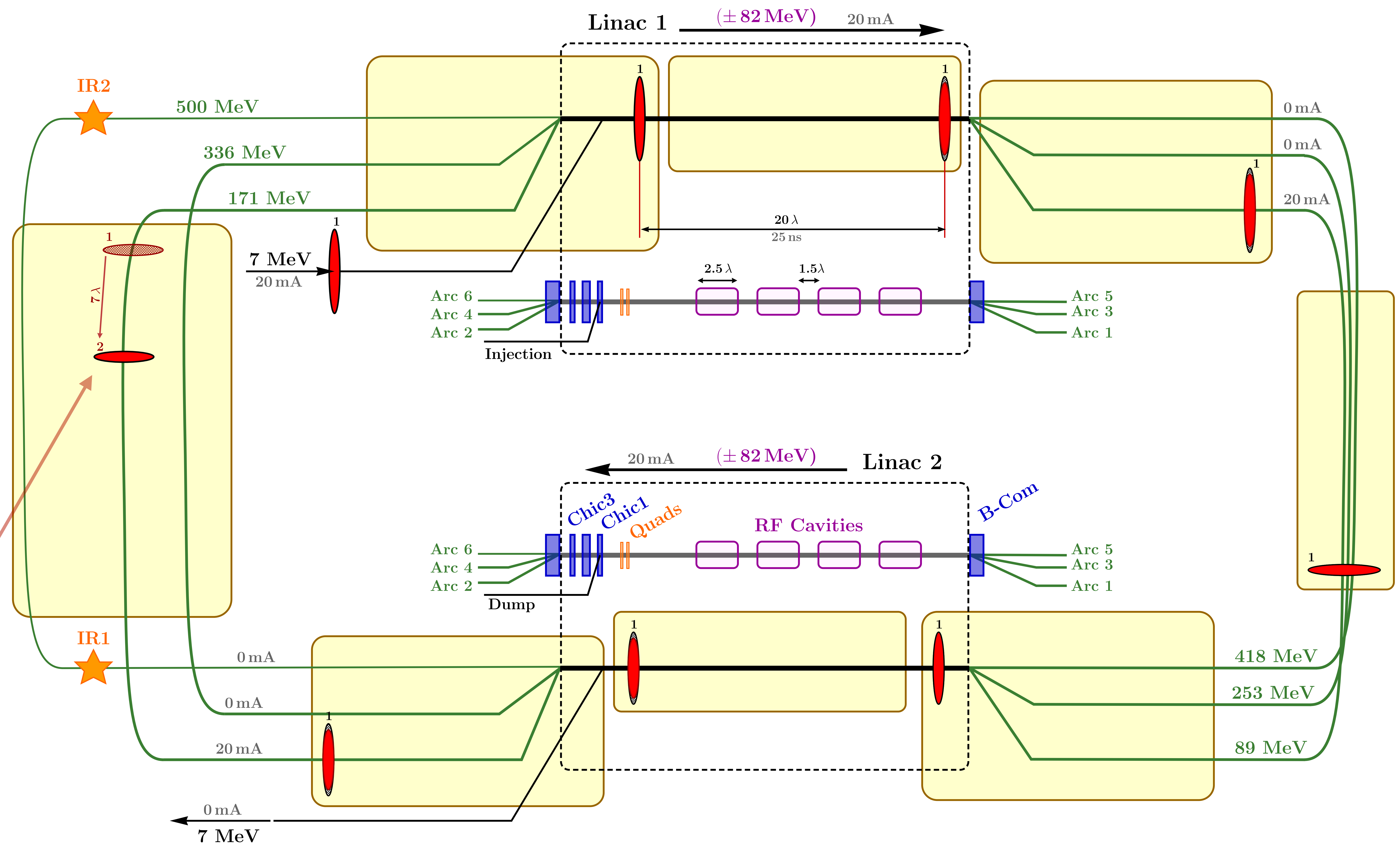
Pass 1

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 $7\ \lambda_{RF}$



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^-)

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Linac 1 → Arc 1 → Linac 2 → Arc 2

7→ 89 MeV 89→171MeV

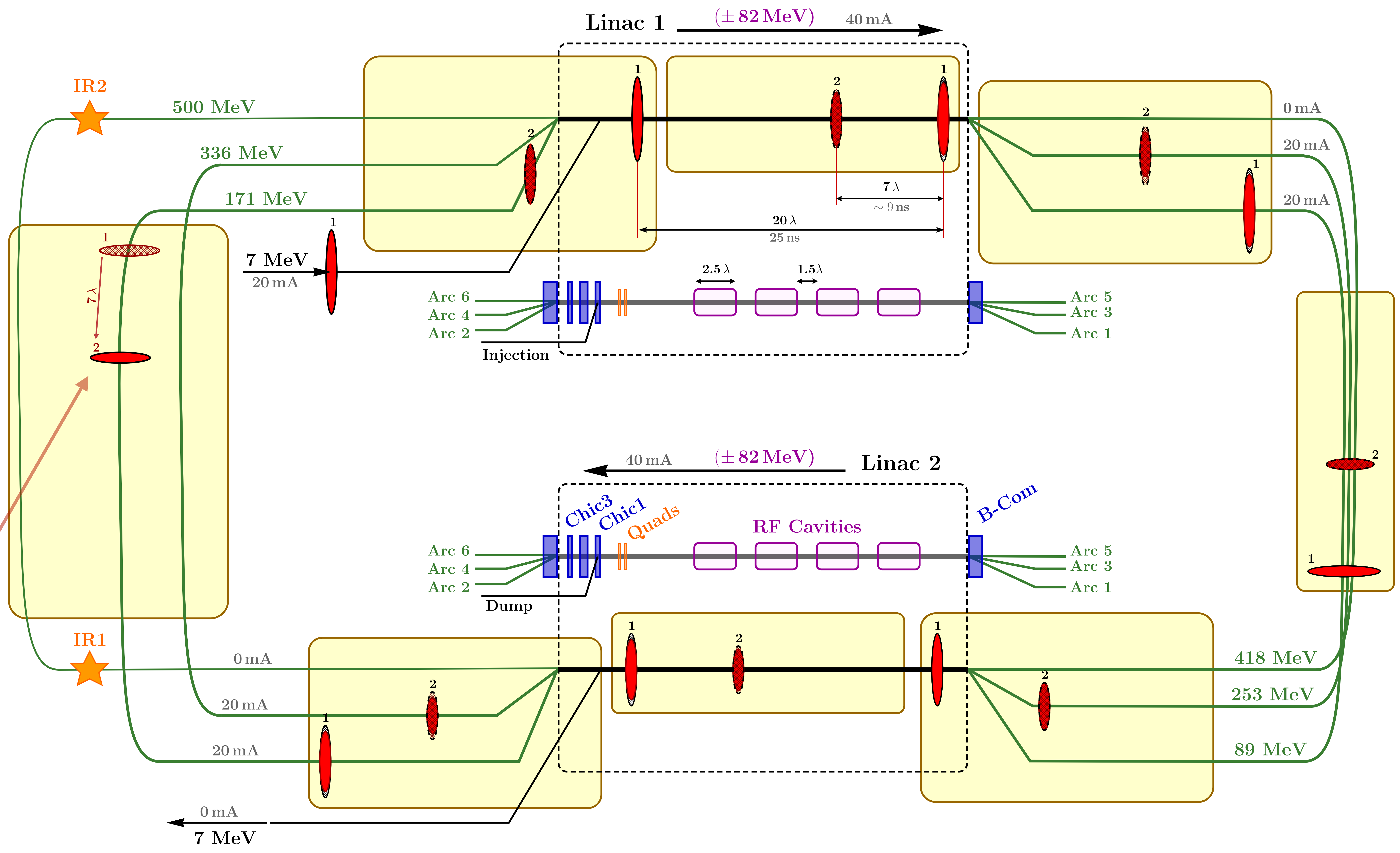
Pass 1 length (Arc1 + Arc2 + 2 Linac) $L_{Pass\,1} = 167\ \lambda_{RF}$

→ 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

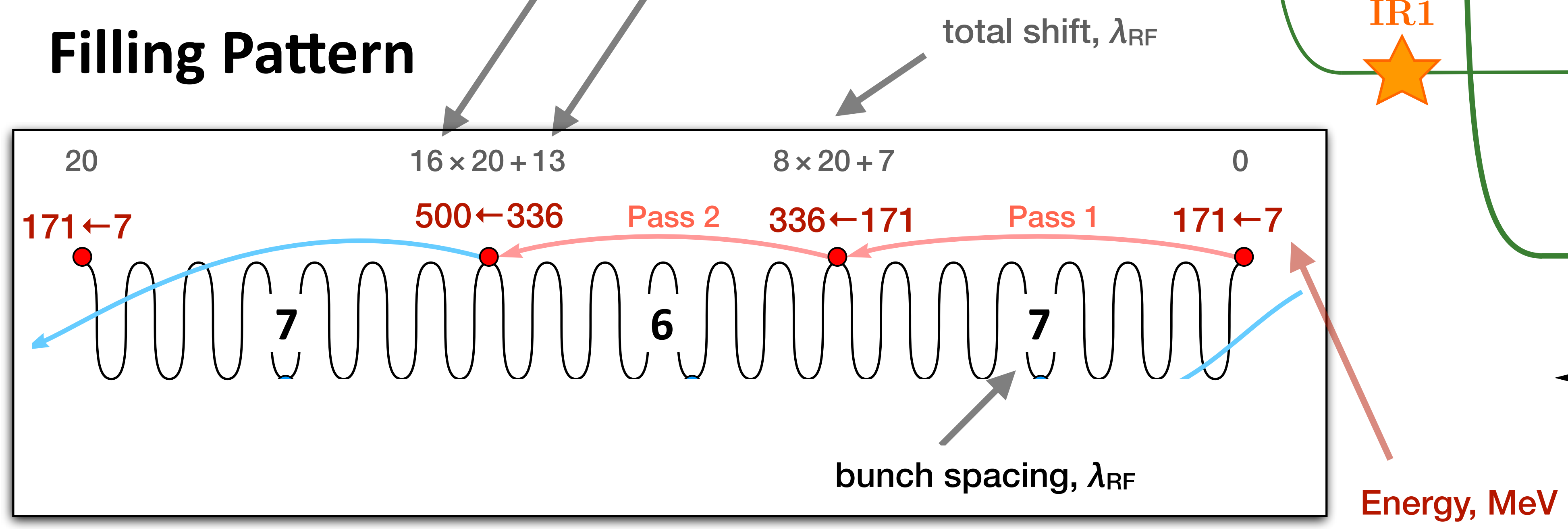
Injection ($\nu_{\rm inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{\rm inj} = 25$ ns)

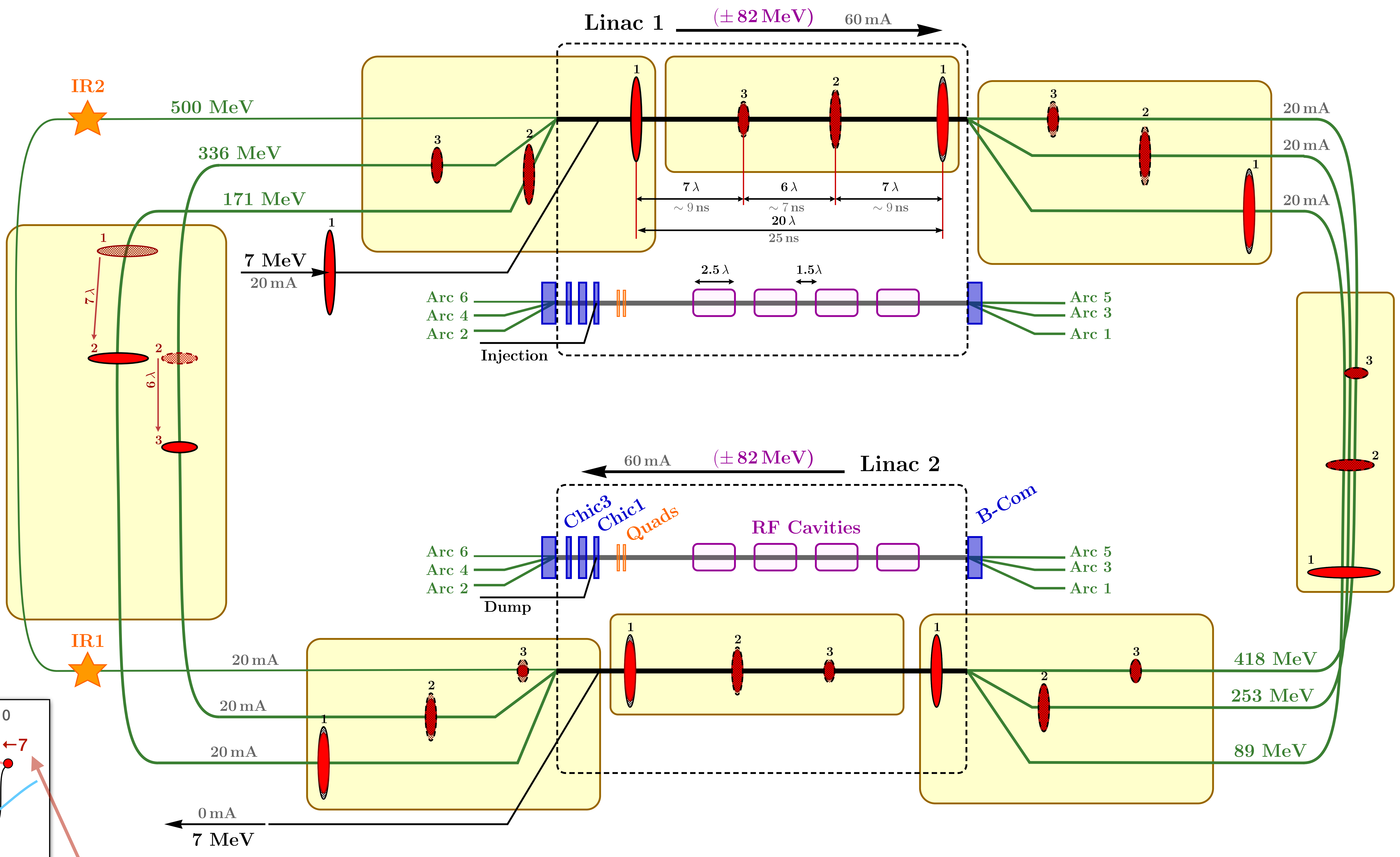
RF Cavity ($\nu_{\rm RF} = 801.58$ MHz) $L_{\rm inj} = 20\ \lambda_{\rm RF}$ ($\lambda_{\rm RF} \approx 34.7$ cm)

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

Pass	Arcs	$L_{\rm Arcs}$, $\lambda_{\rm RF}$	$L_{\rm Pass}$, $\lambda_{\rm RF}$	$n_{\rm inj}$	Δ, $\lambda_{\rm RF}$	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





Forming the Filling Pattern. Passes 1—4

Passes 1–4

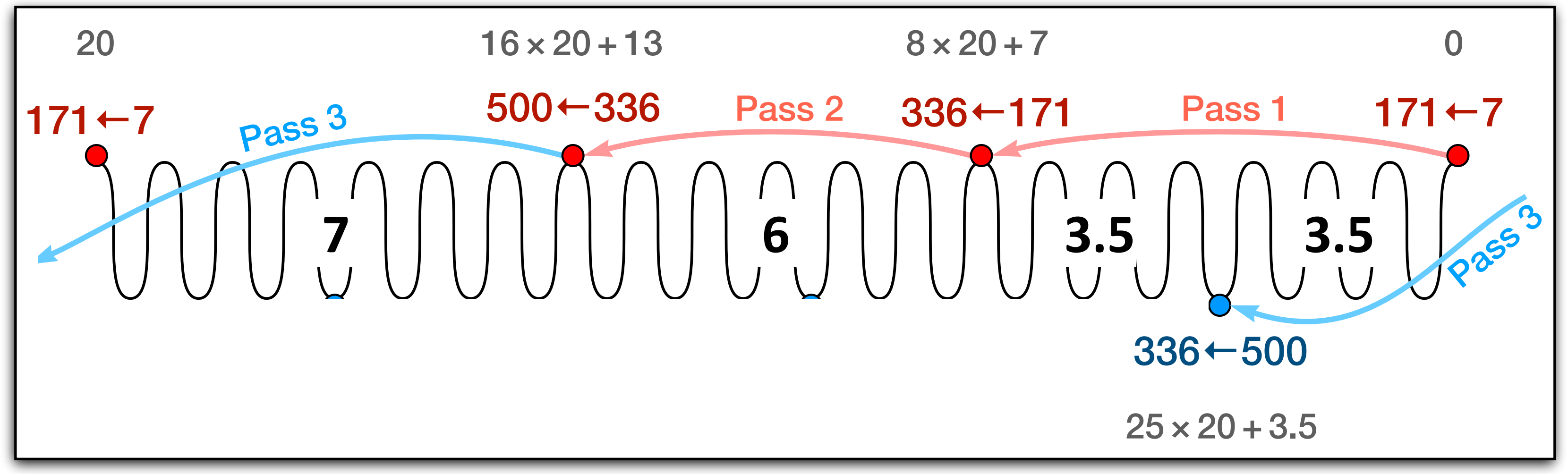
Injection ($\nu_{inj} \approx$ 40 MHz) I = 20 mA ($Q \approx$ 500 pC, t_{inj} = 25 ns)

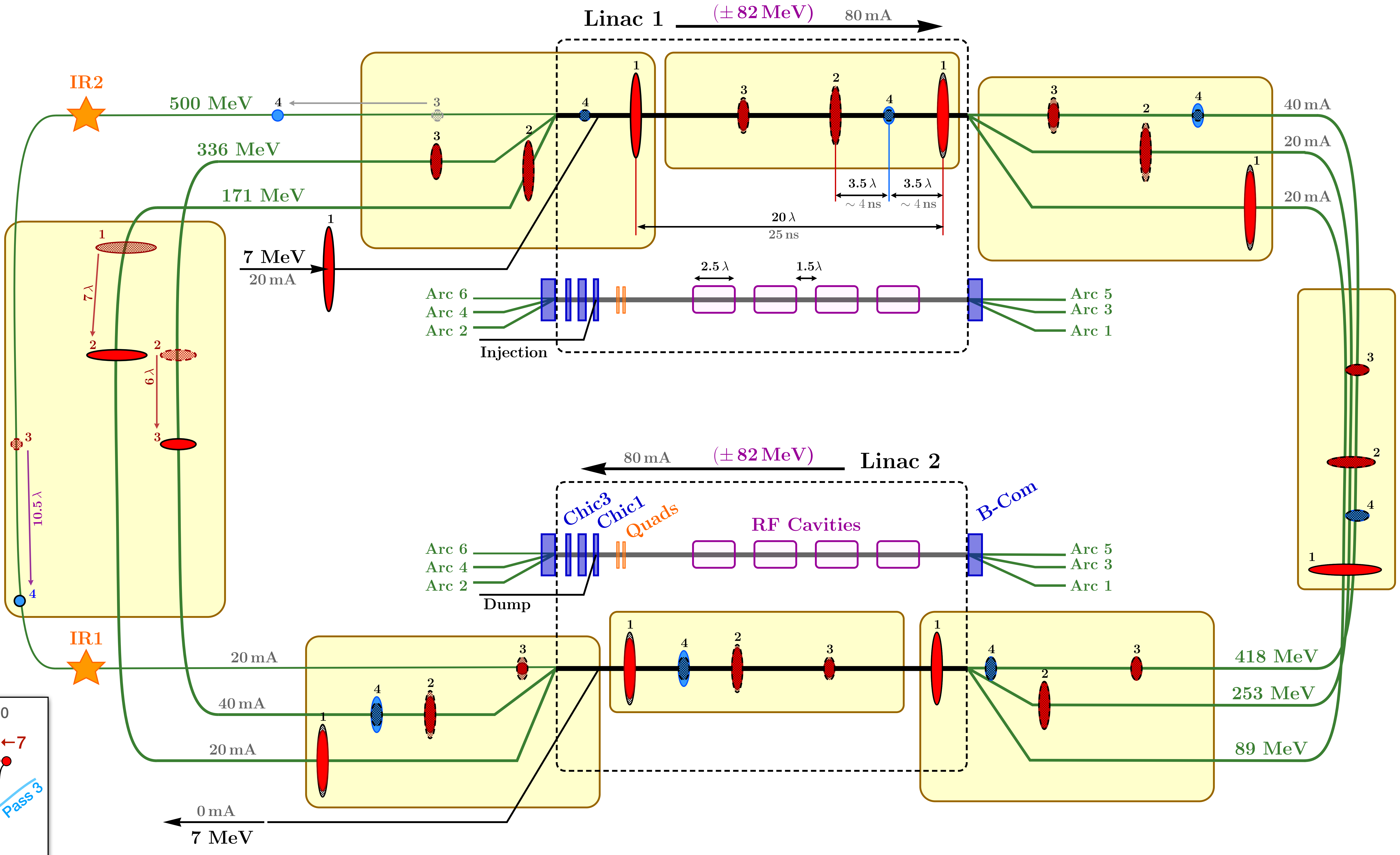
RF Cavity (ν_{RF} = 801.58 MHz) L_{inj} = 20 λ_{RF} ($\lambda_{RF} \approx$ 34.7 cm)

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





Passes 1–5

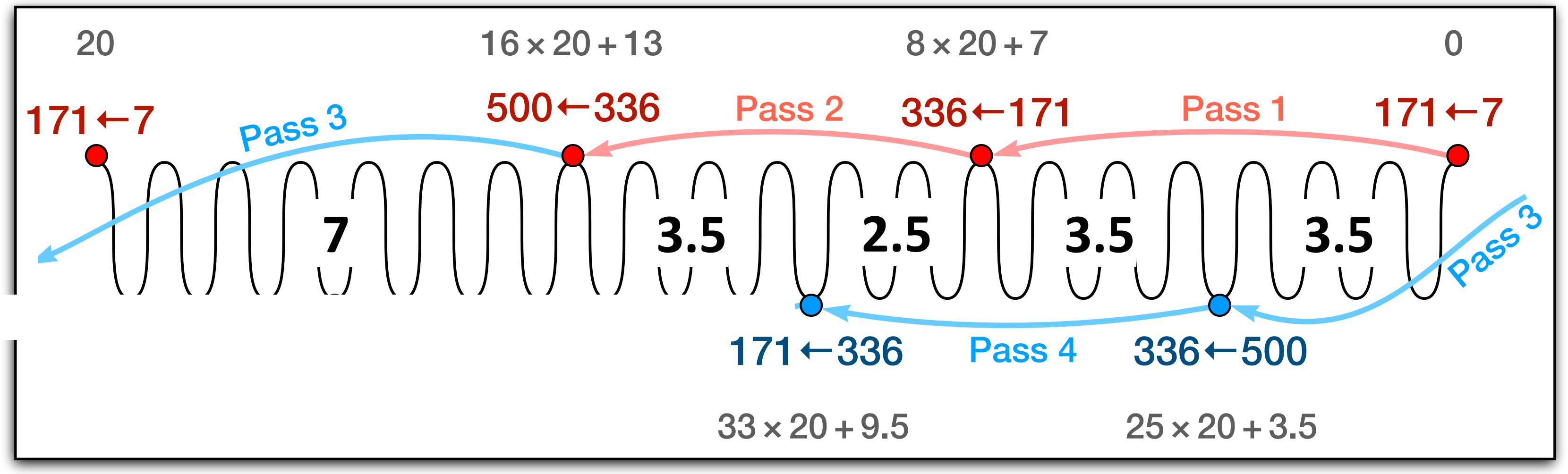
Injection ($\nu_{inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{inj} = 25$ ns)

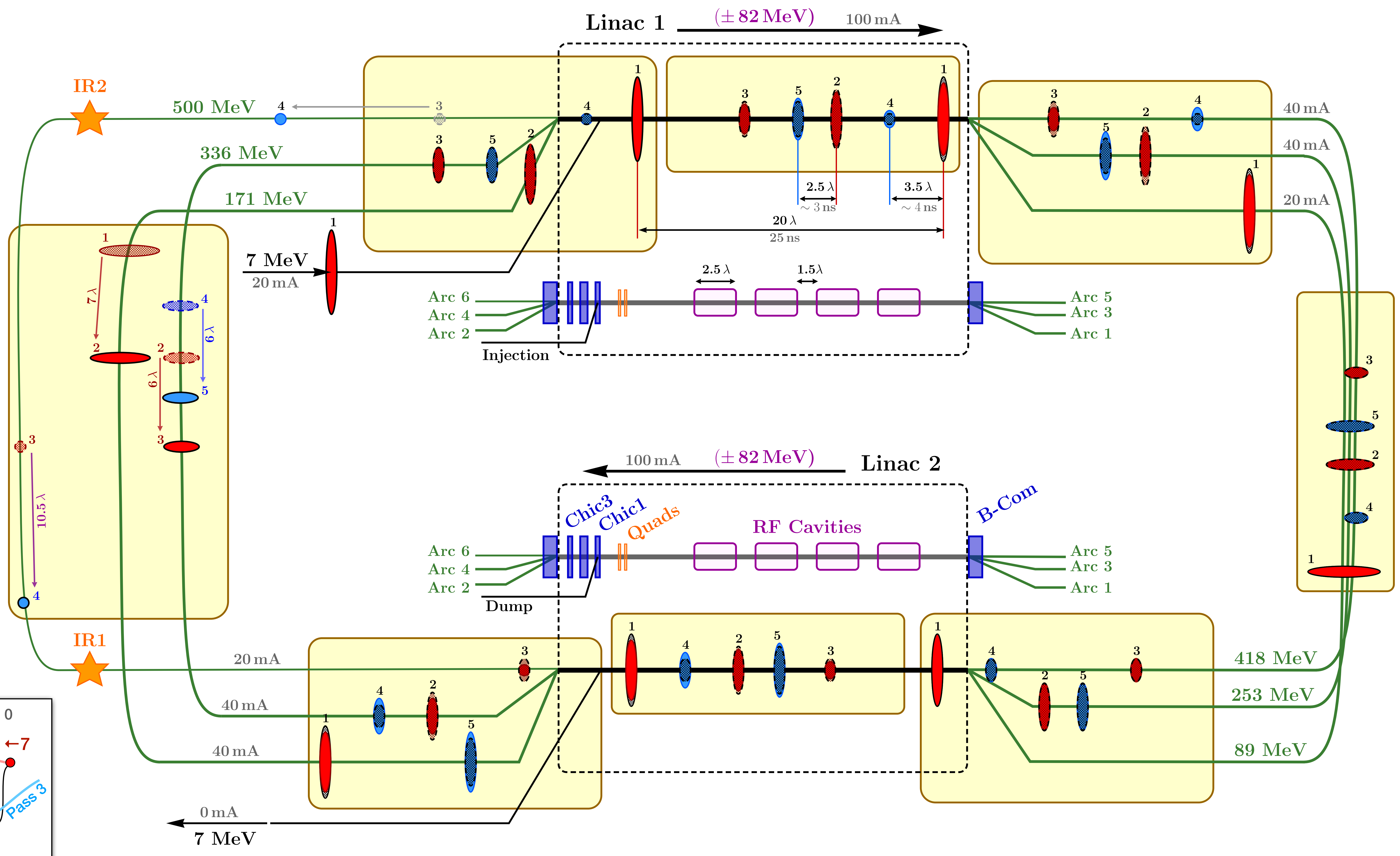
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\ \lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

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

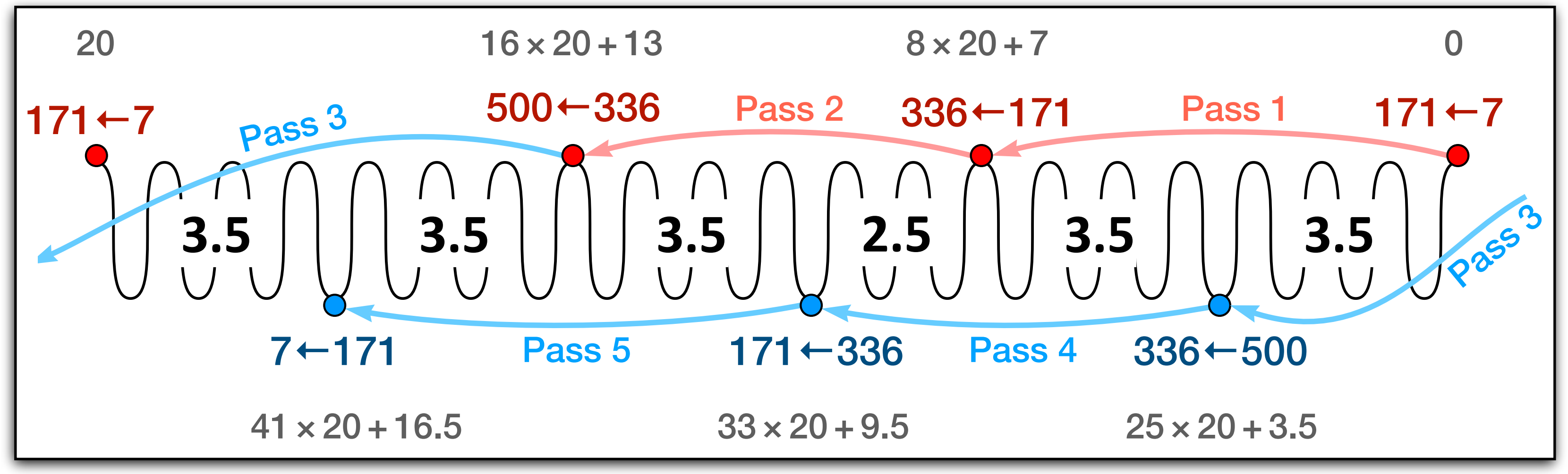
Injection ($\nu_{inj} \approx 40$ MHz) $I = 20$ mA ($Q \approx 500$ pC, $t_{inj} = 25$ ns)

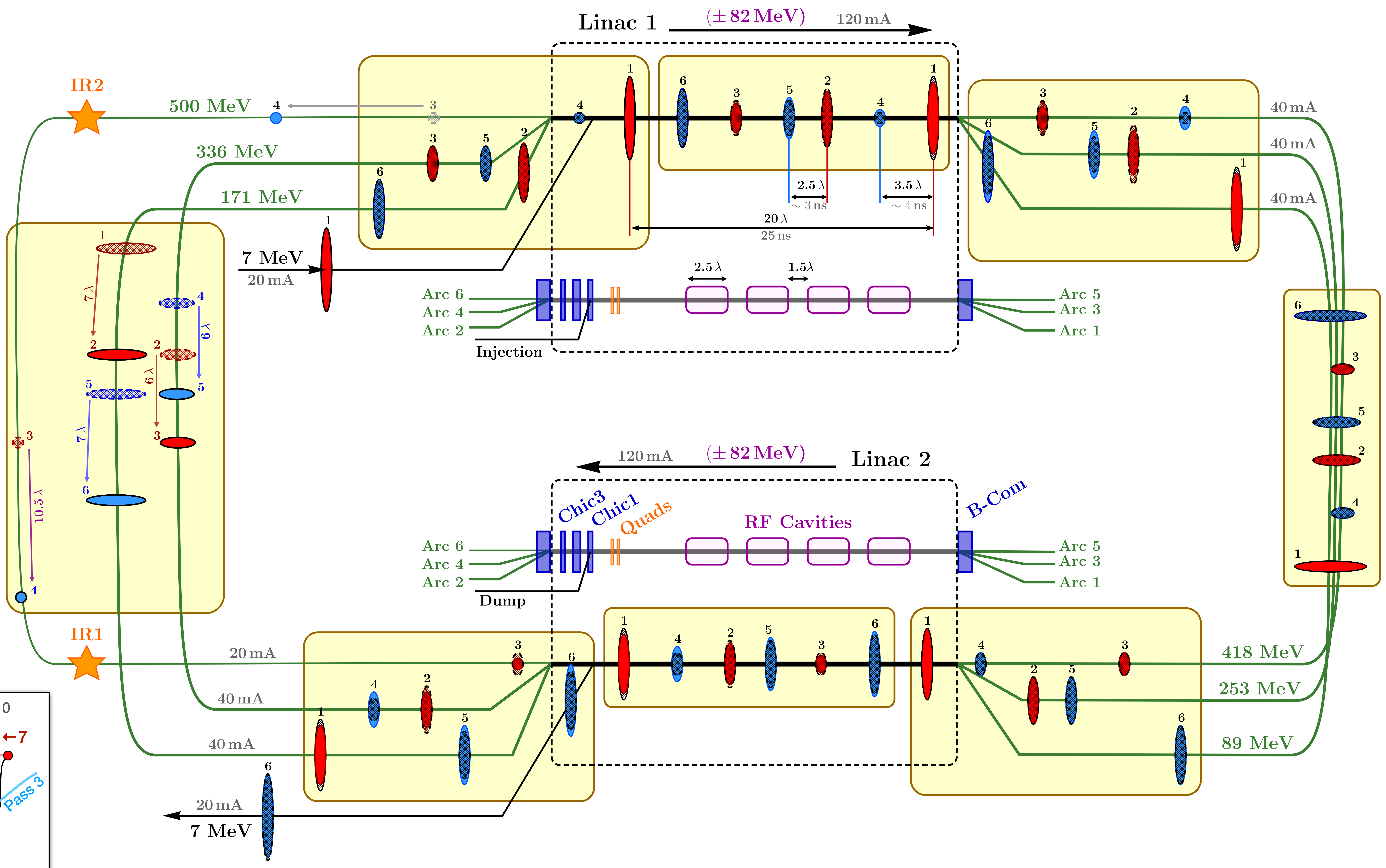
RF Cavity ($\nu_{RF} = 801.58$ MHz) $L_{inj} = 20\,\lambda_{RF}$ ($\lambda_{RF} \approx 34.7$ cm)

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	3+2	56 + 57	167	41	16.5	1.046
6	1	56	–	–	–	-

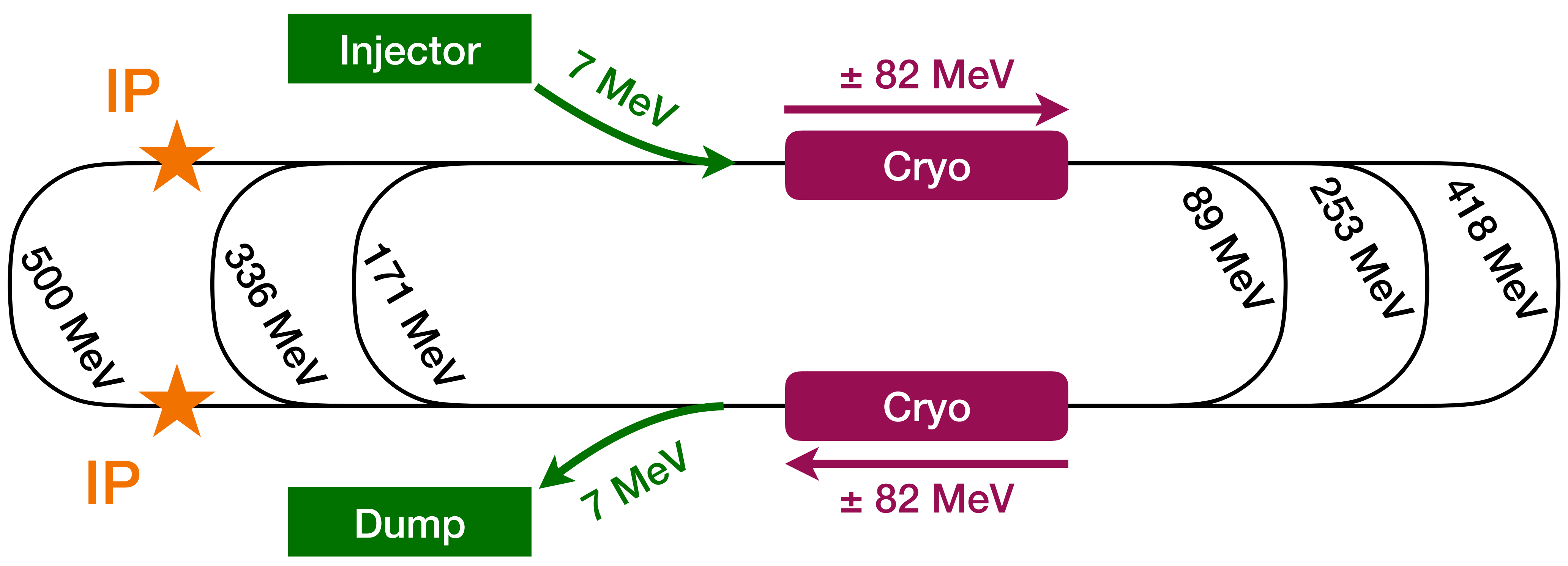
Filling Pattern

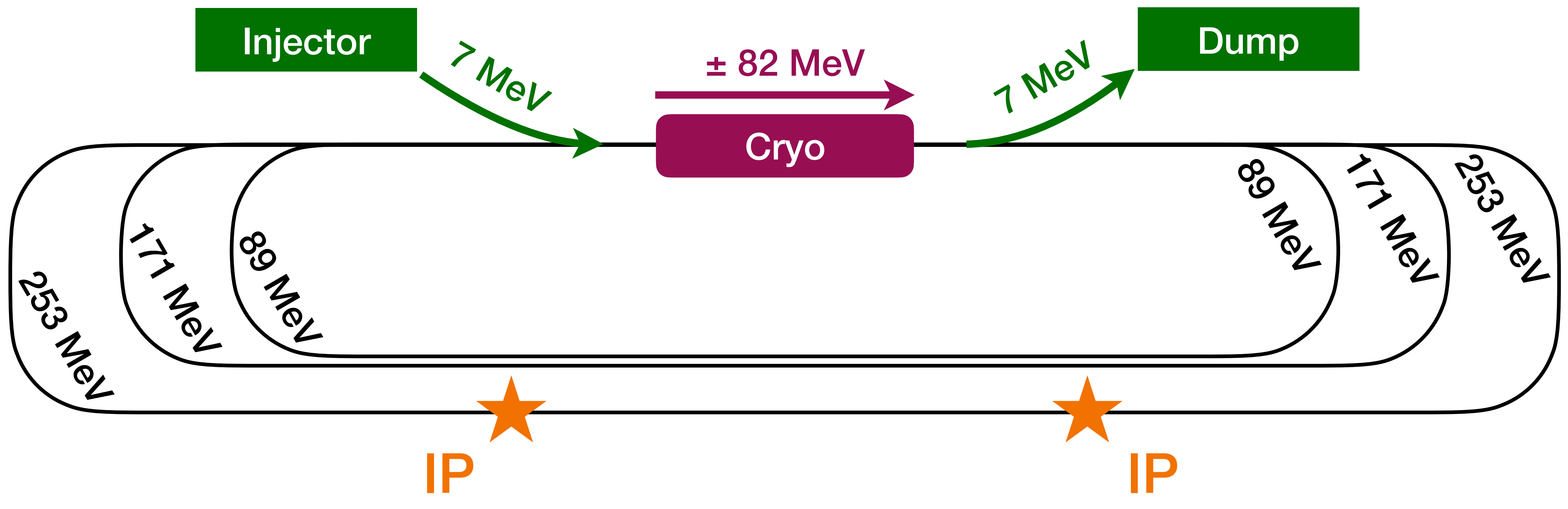




Motivation for one cryo-module phase (250 MeV versions)

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





Pros:

→ **reduction of immediate expenses & first results time** (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

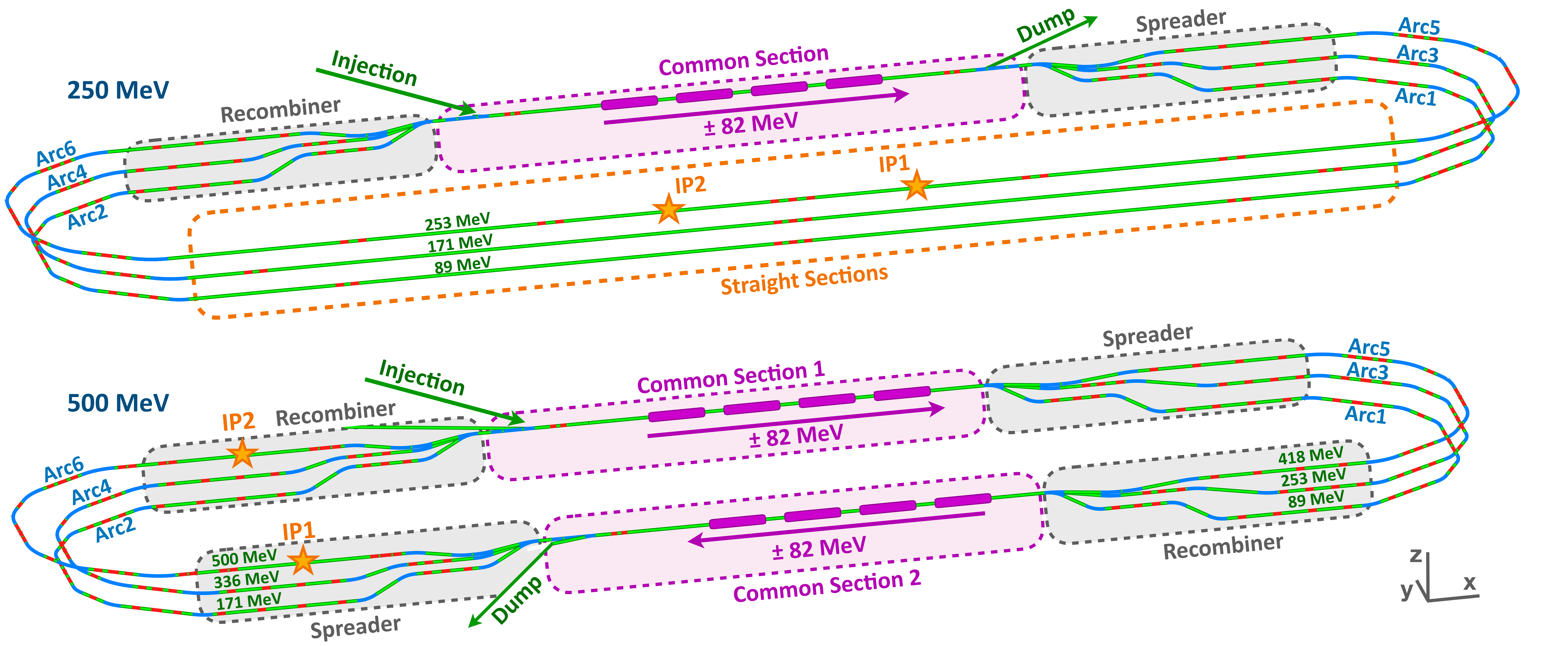
Cons:

→ **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 !

Filling pattern   500 vs 250 MeV versions

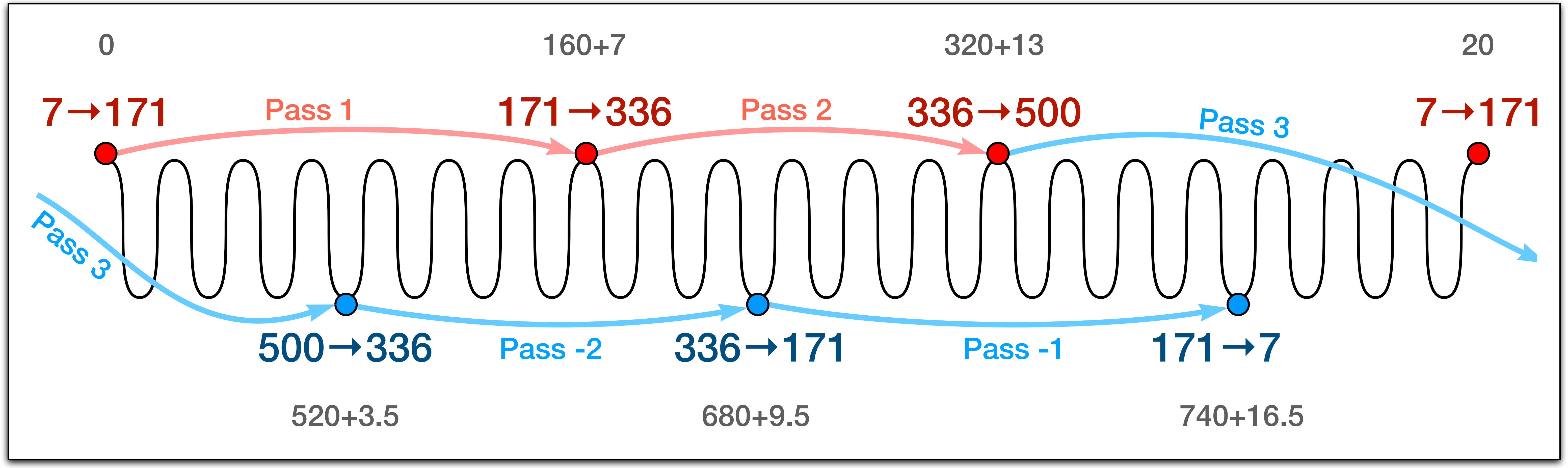
500 MeV

Full length of one turn: $(160 + \Delta)\ \lambda_{RF}$

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

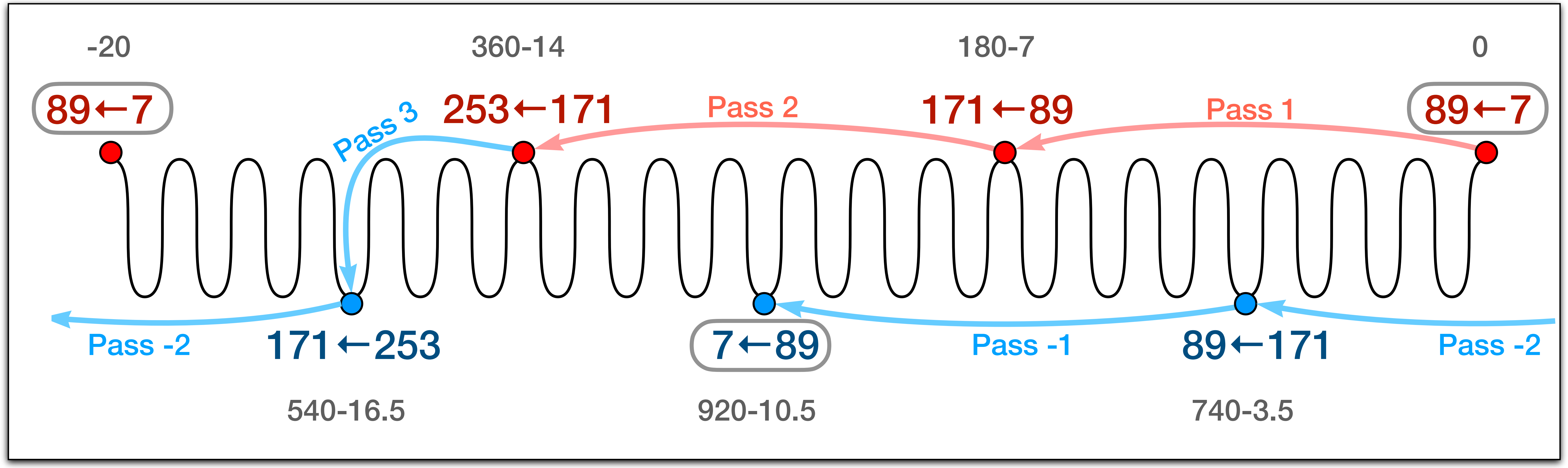
Full length of one turn: $(180 - \Delta)\ \lambda_{RF}$

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



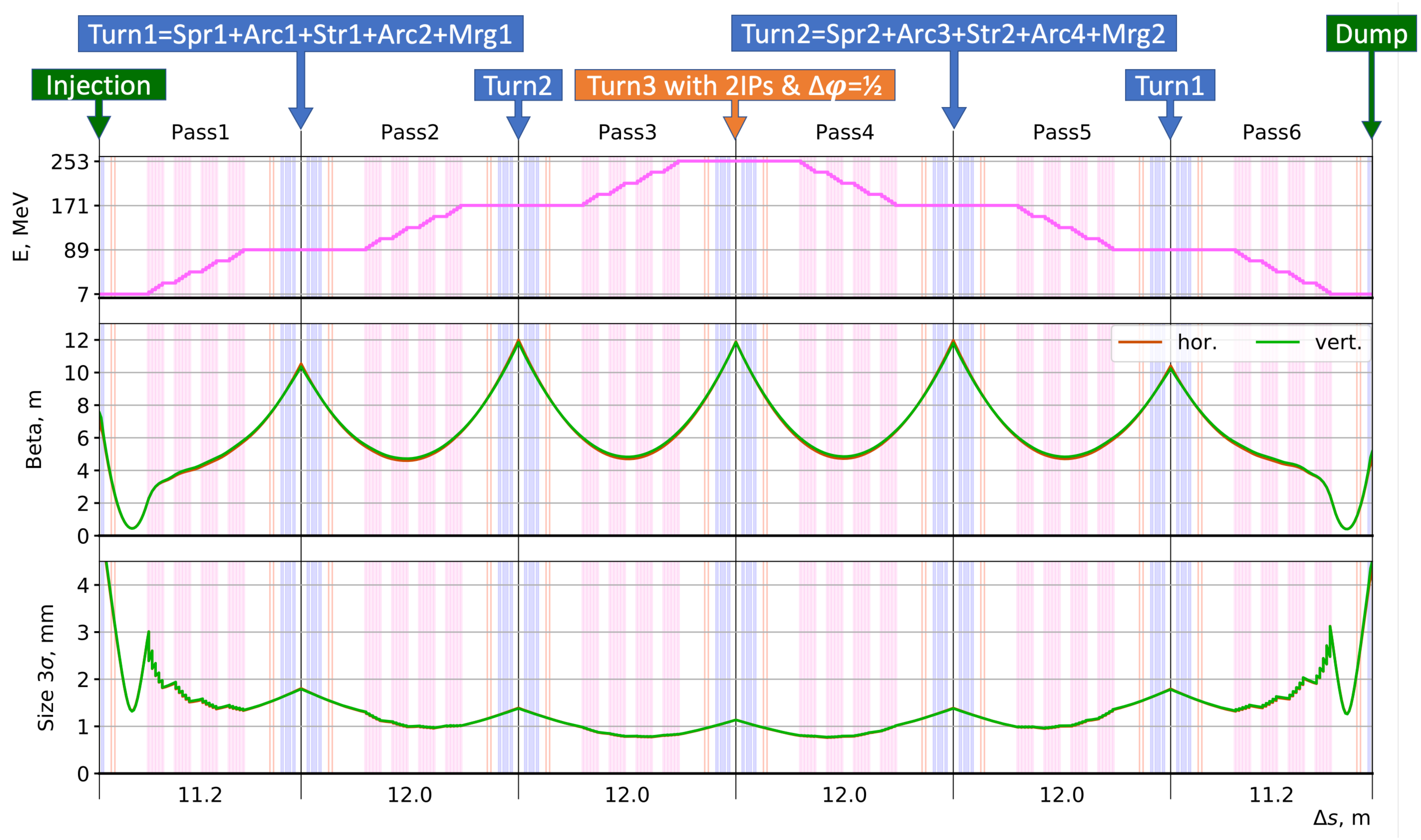
$(177.5 — 170.5)\ \lambda_{RF} / 2 = 3.5\ \lambda_{RF} \approx 1.3$ m (λ_{RF} = 37.4 cm)

PERLE Optics: Common section (250 MeV version)

The optics for one “Turn” (excl. common section) is symmetric

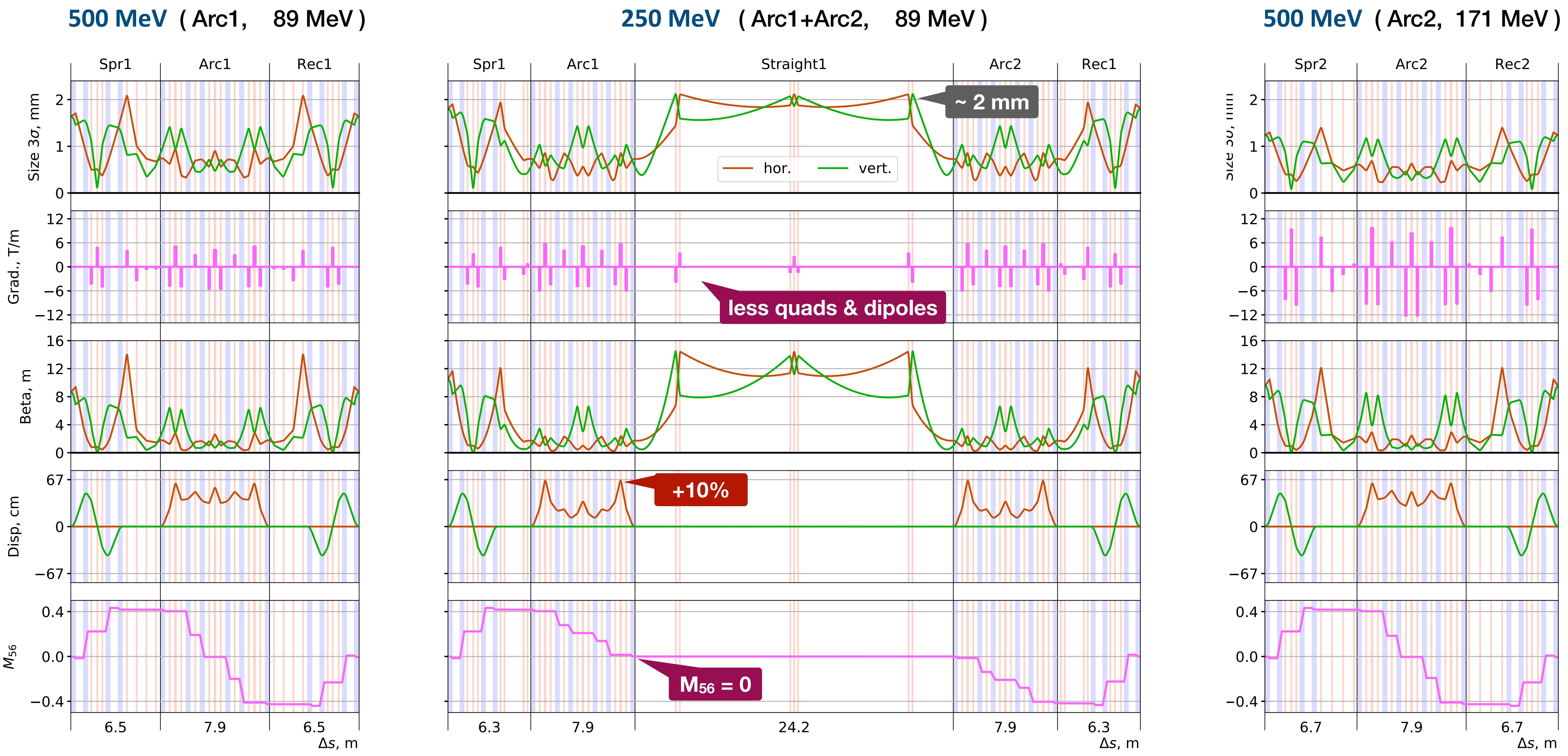
→ beam parameters are the same at the exit and next entrance of common section

PERLE Optics: Common section (250 MeV version)

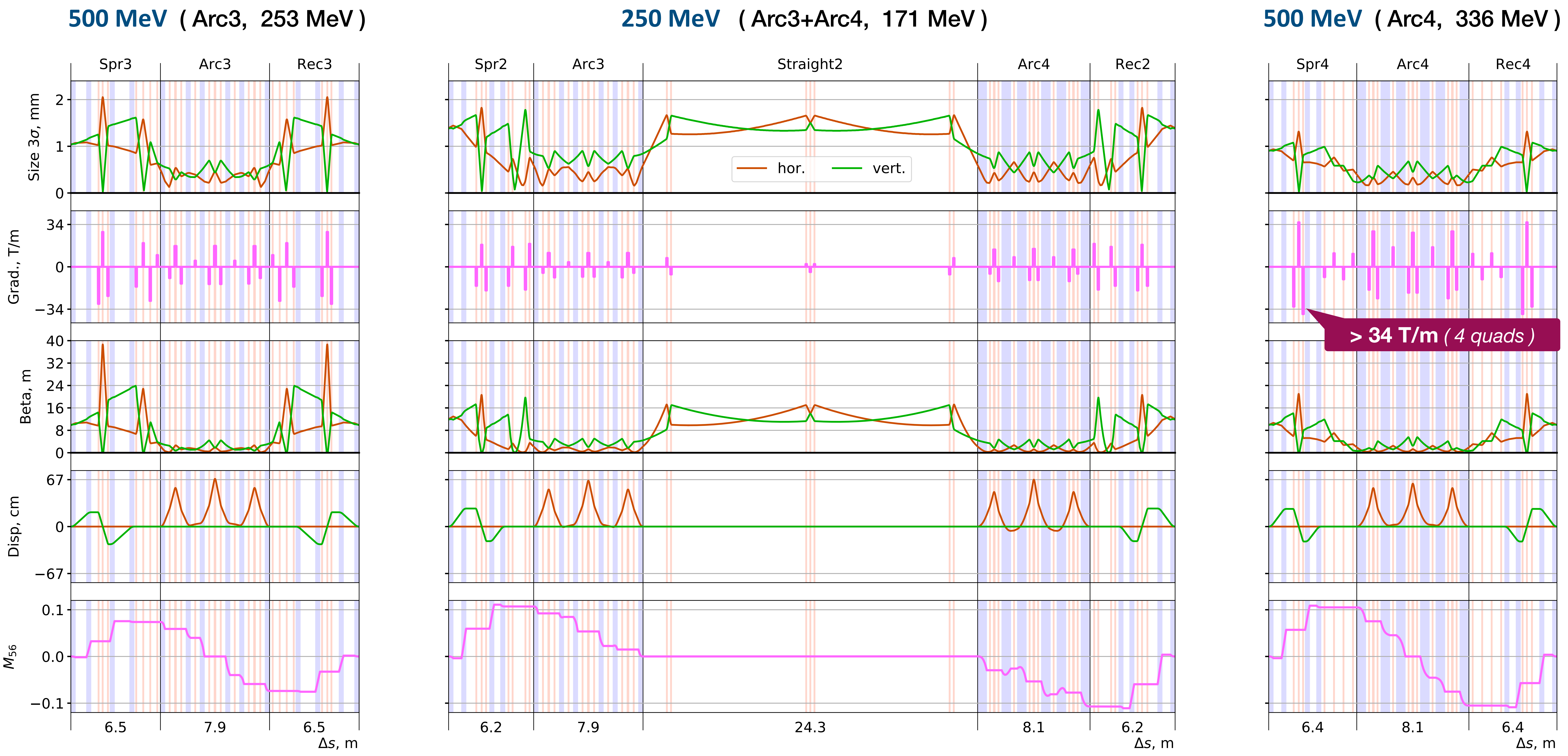


PERLE Optics: from Injection to Dump (250 MeV version)

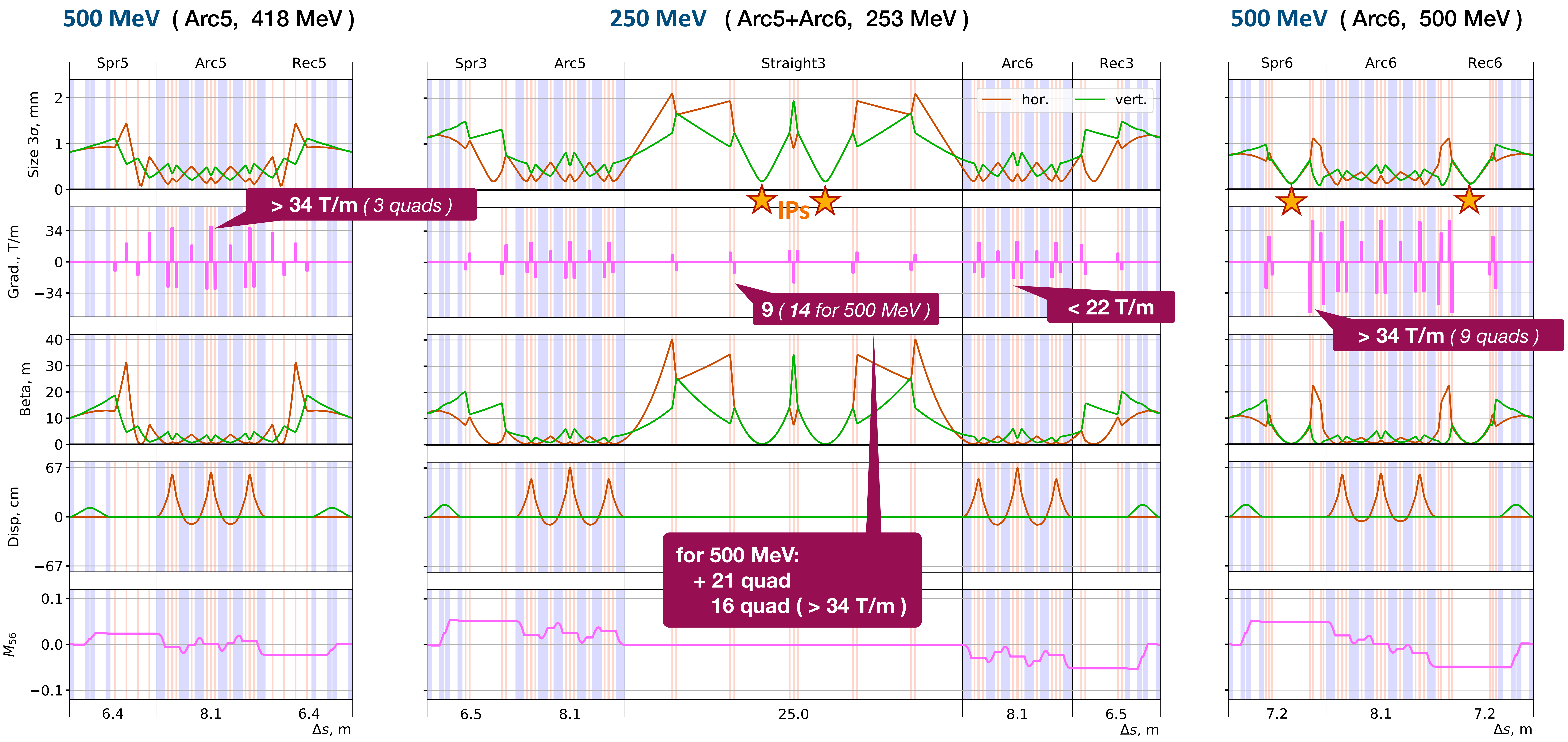
PERLE Optics: Turns (500 & 250 MeV versions)



PERLE Optics: Turns (500 & 250 MeV versions)



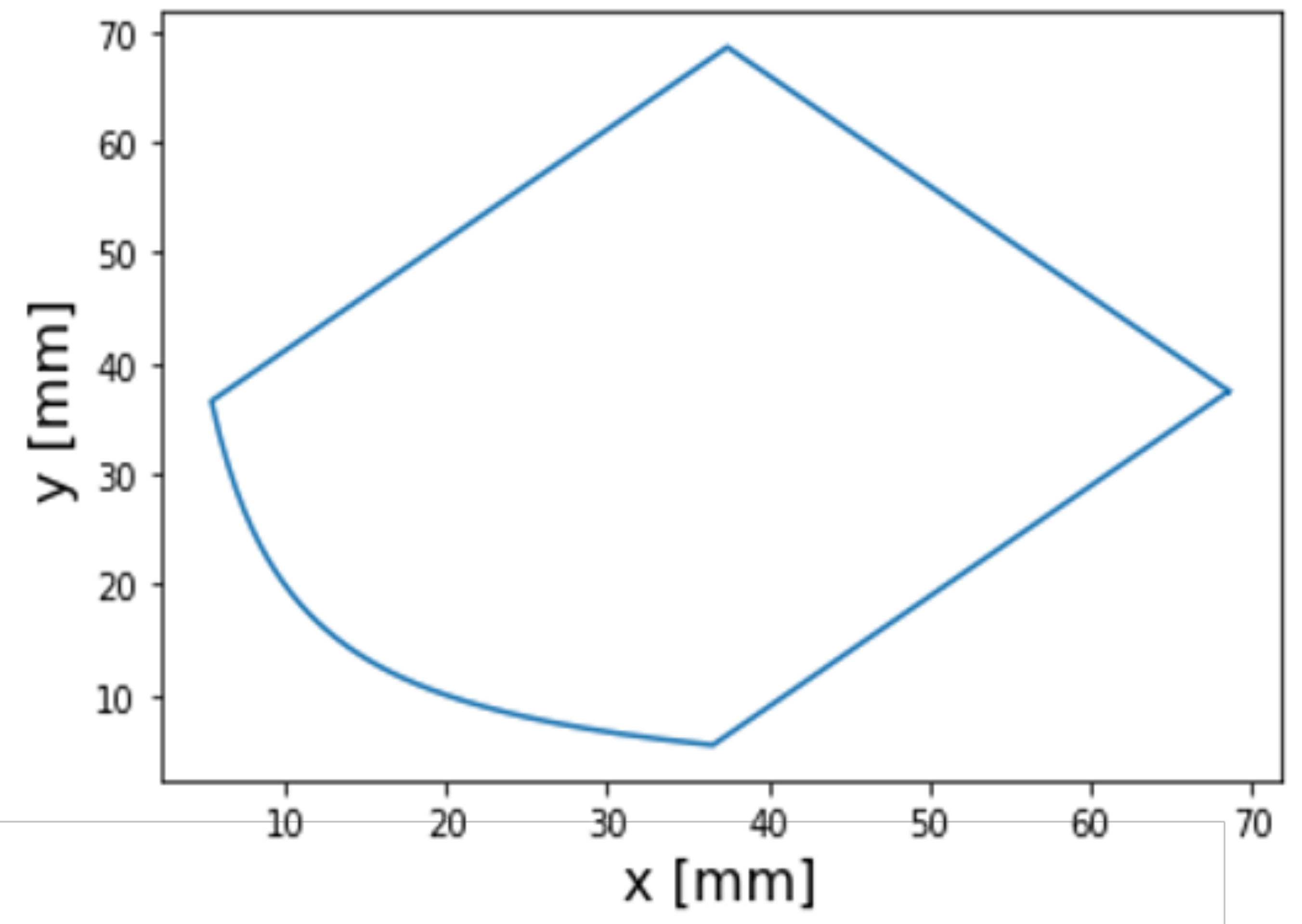
PERLE Optics: Turns (500 & 250 MeV versions)

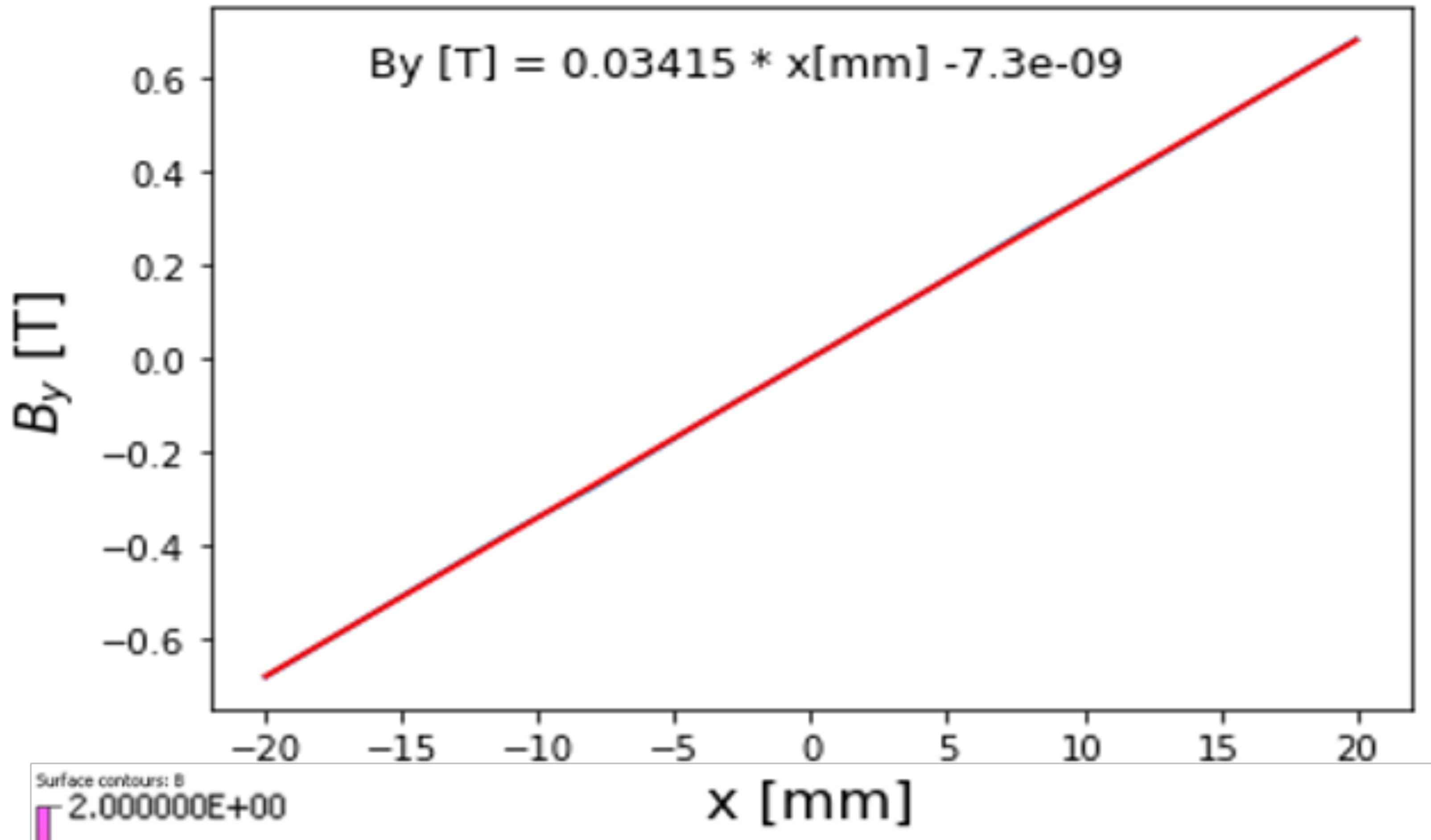


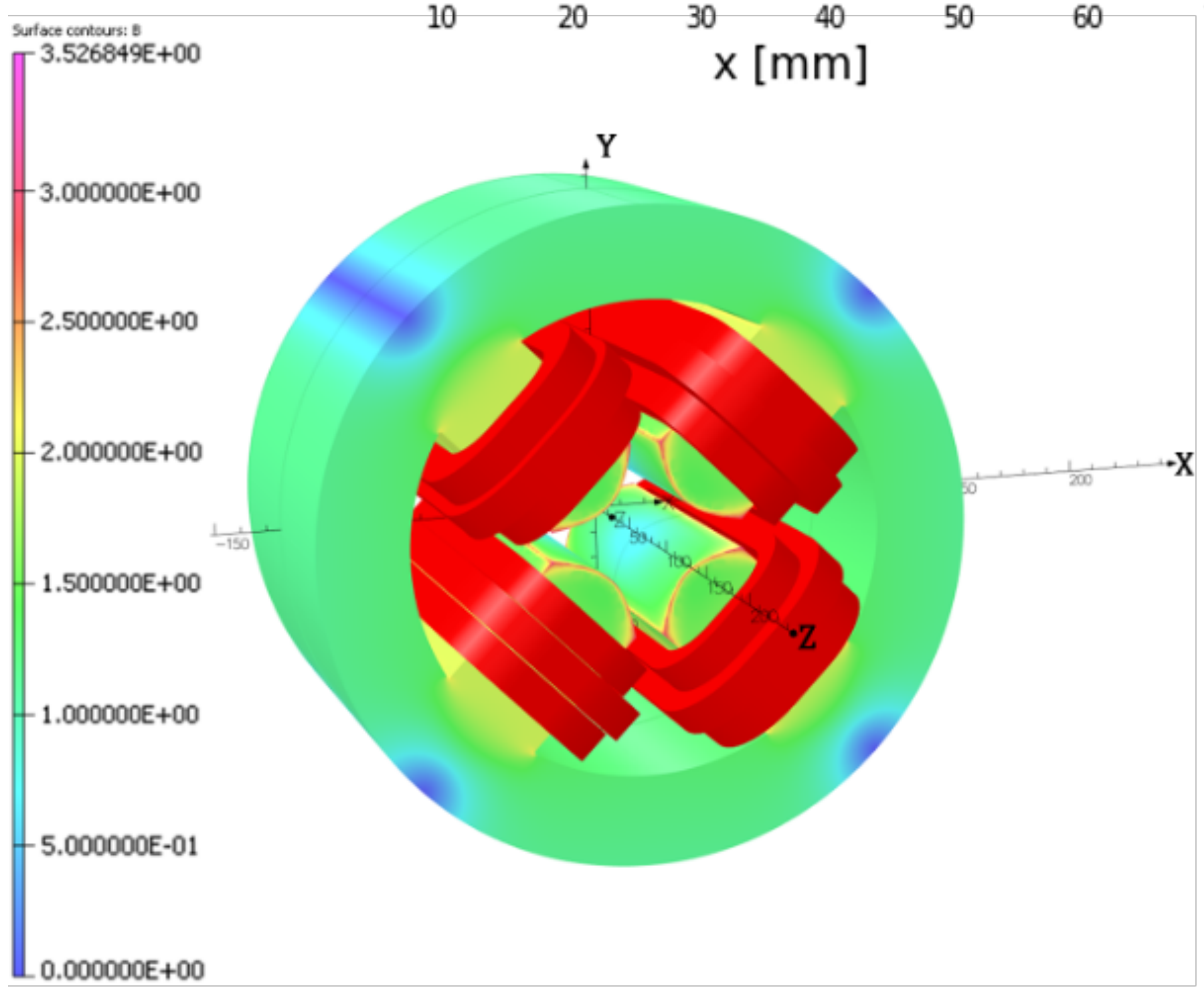
Quadrupole Magnet (work by Rasha Abukeshek)

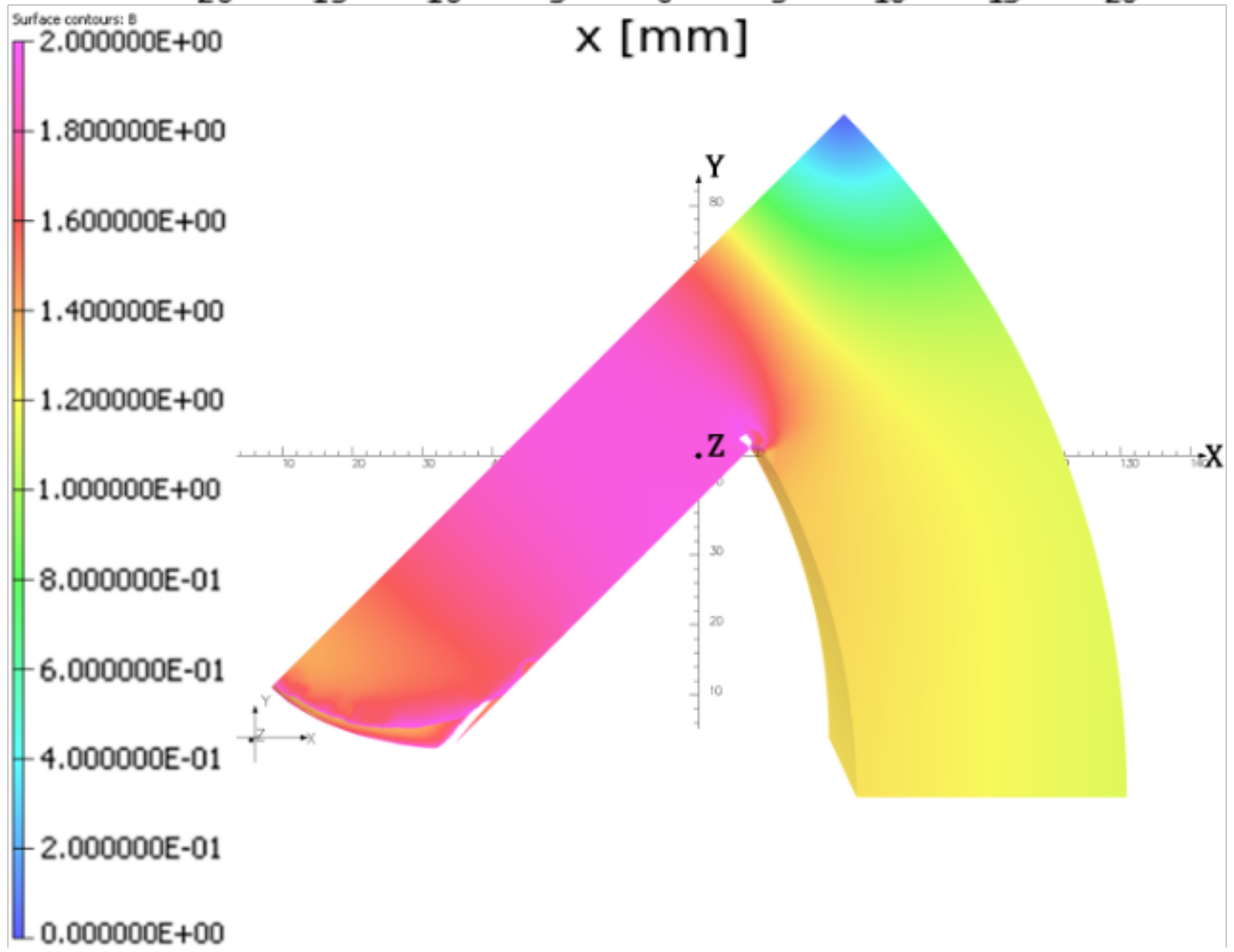
Multi-coil design

G = 34.15 T/m







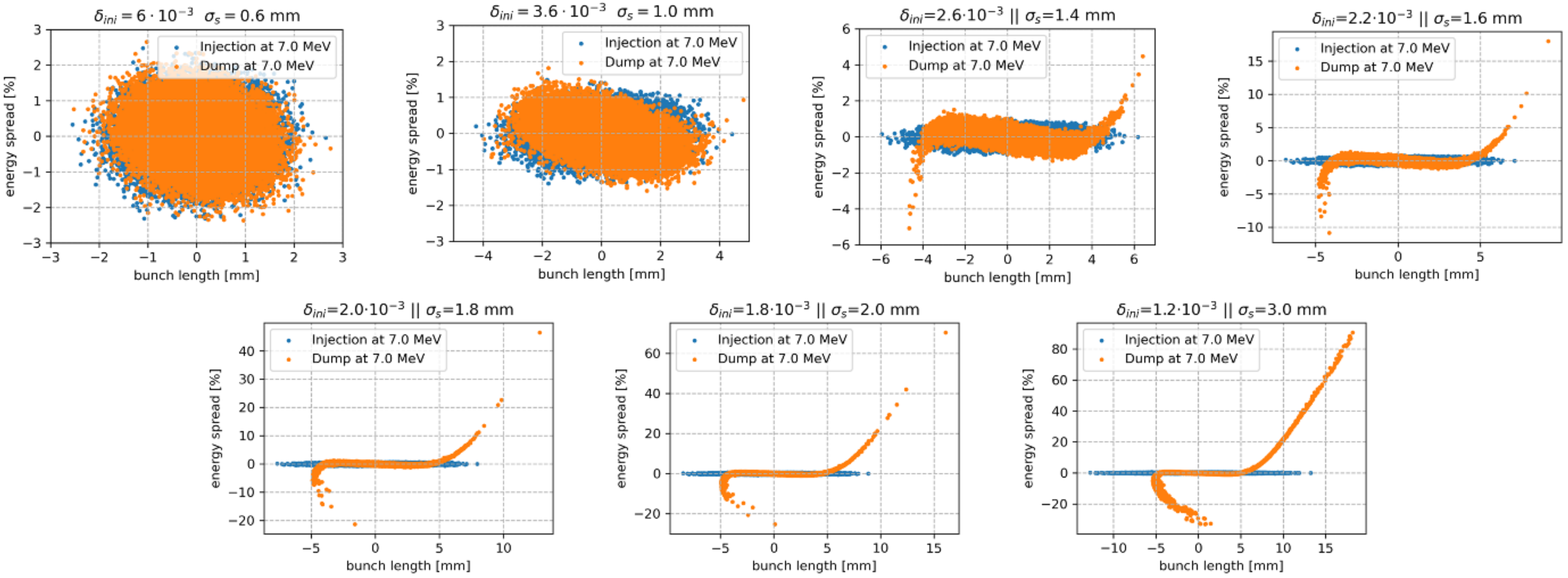


Parameters	Value
Height	250 mm
Yoke thickness	35 mm
Length	150 mm
Aperture radius	20 mm
Pole width	44 mm
Max. gradient	44.1 T/m
NI per coil	1750.7 A.turn
Pole tip field	0.685 T

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

Suggested solution: pole tapering

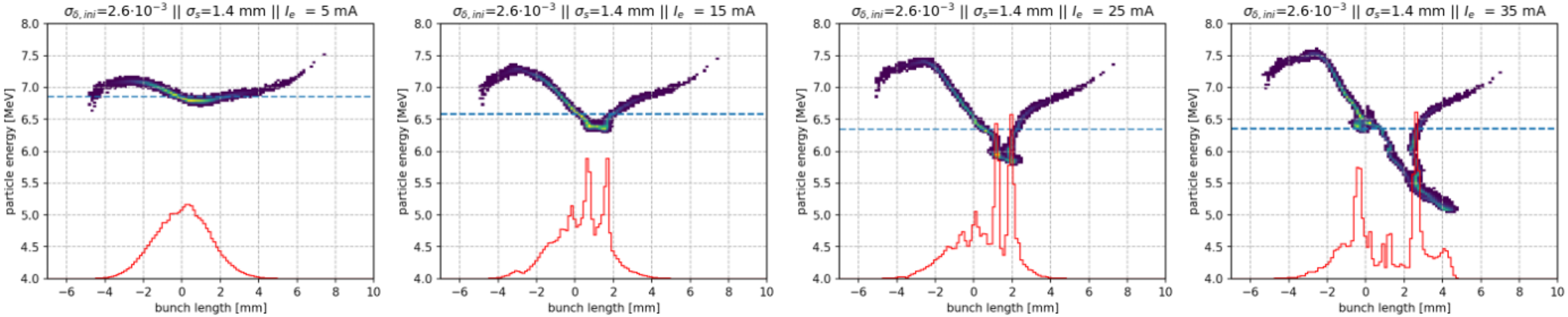
Longitudinal phase space curvature from the RF field



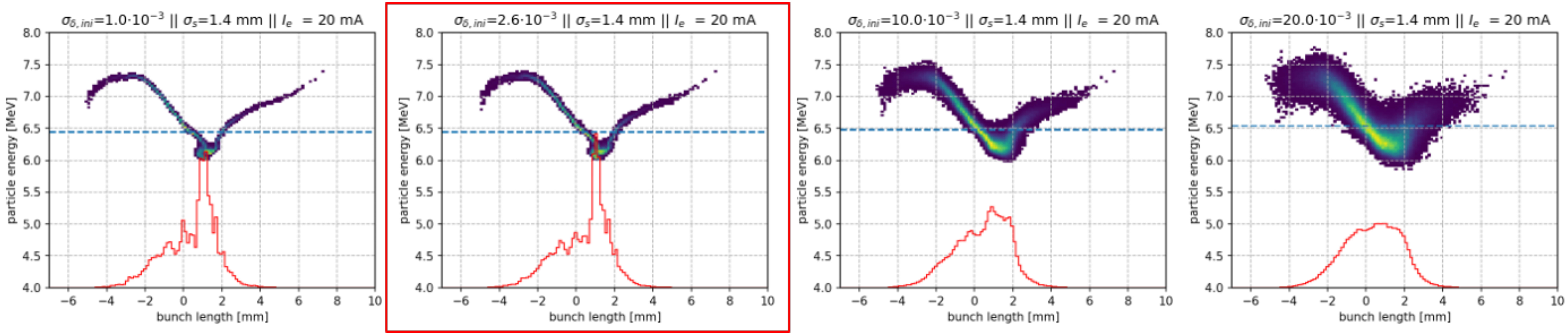
A hook shape forms and bunch elongation is visible as the initial bunch length increases. A longitudinal matching can mitigate the bunch elongation.

Multi-bunch tracking (work by Kevin André)

CSR with beam current increase



CSR with initial relative energy spread variation, Ie=20 mA



CBETA

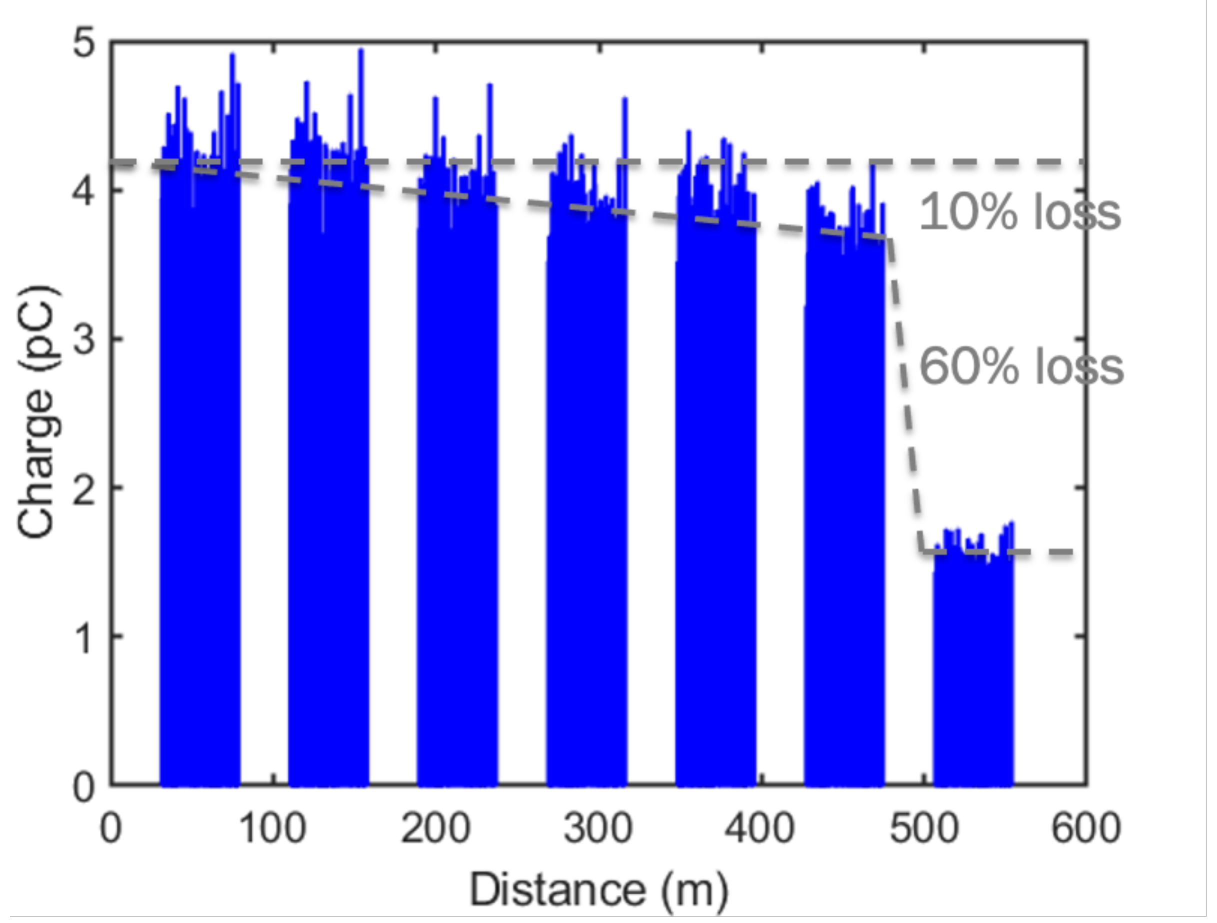
(some insights for commissioning)

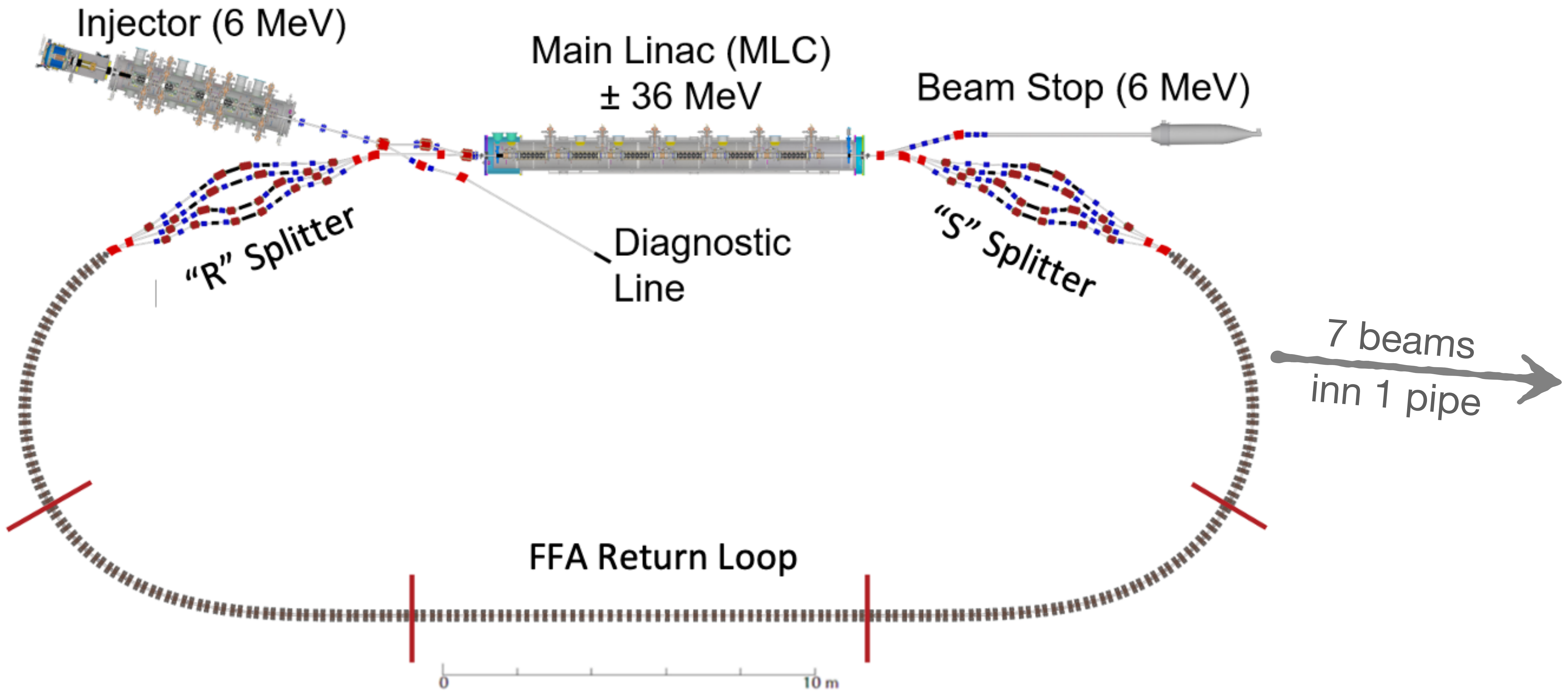
CBETA (Cornell-Brookhaven Energy-Recovery-Linac Test Accelerator)

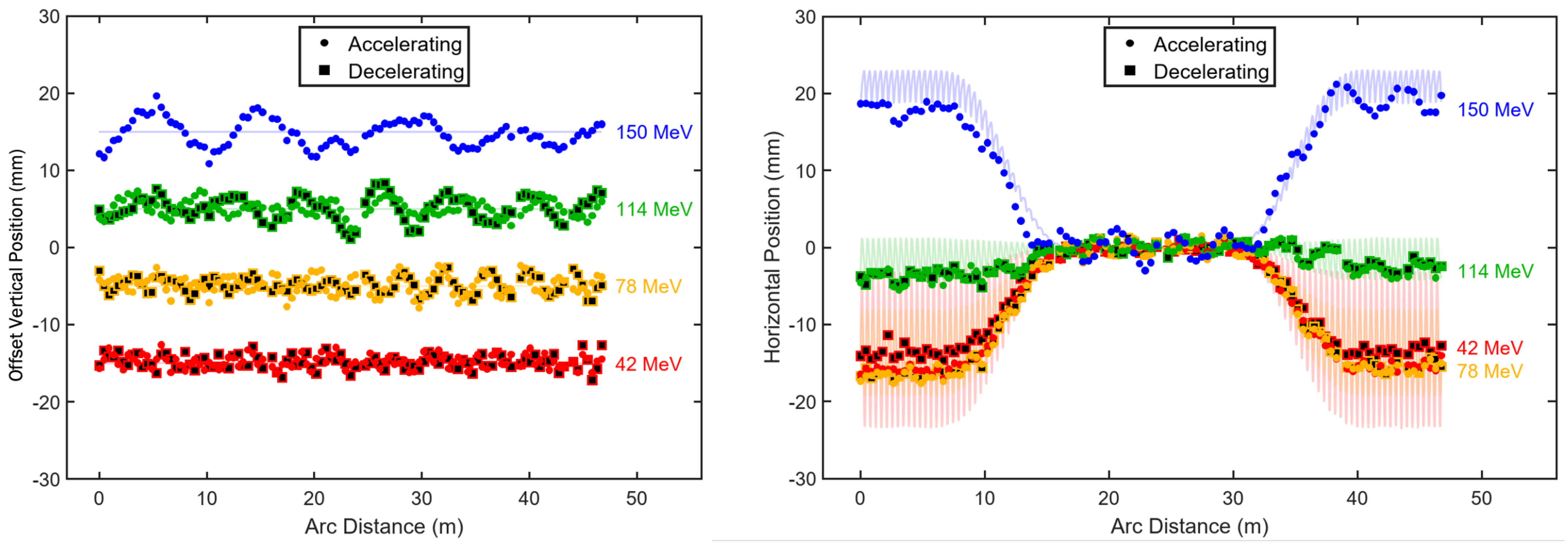
Multi-pass ERL, with single return loop

"Green accelerator"

- 7 beams of 4 energies in 1 pipe: 42, 78, 114, 150 MeV
- Uses the wide energy acceptance of Fixed Field Alternating-gradient (FFA) permanent magnets
- Successful demonstration of first four-pass superconducting ERL and single FFA beam line to transport 7 different accelerated and decelerated beams







- Problems in Splitter Line R2

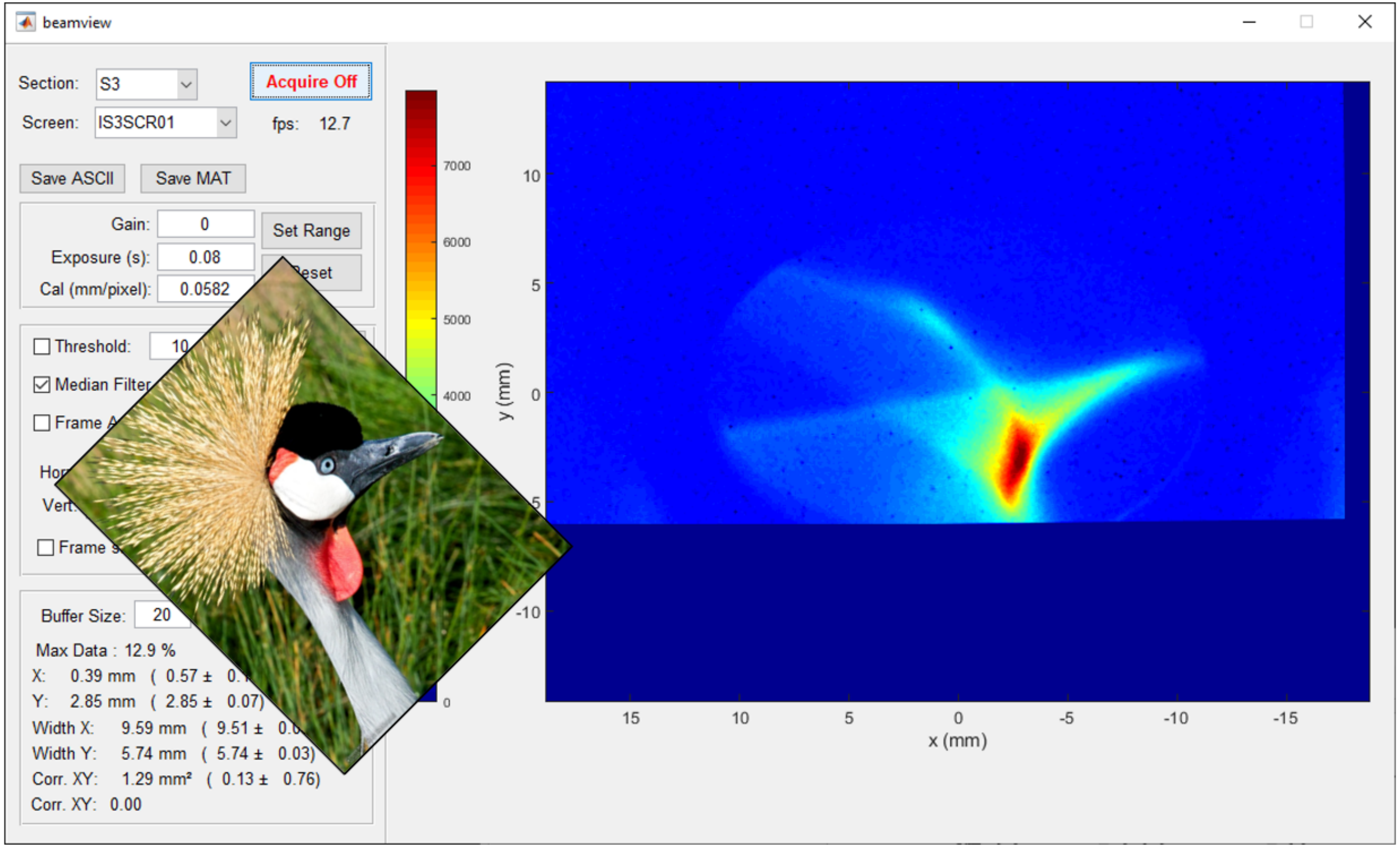
  Here are some images taken during a dispersion response measurement, i.e. all images are related by relatively small R2 quad changes…

Links:

[CBETA PROJECT REPORT]

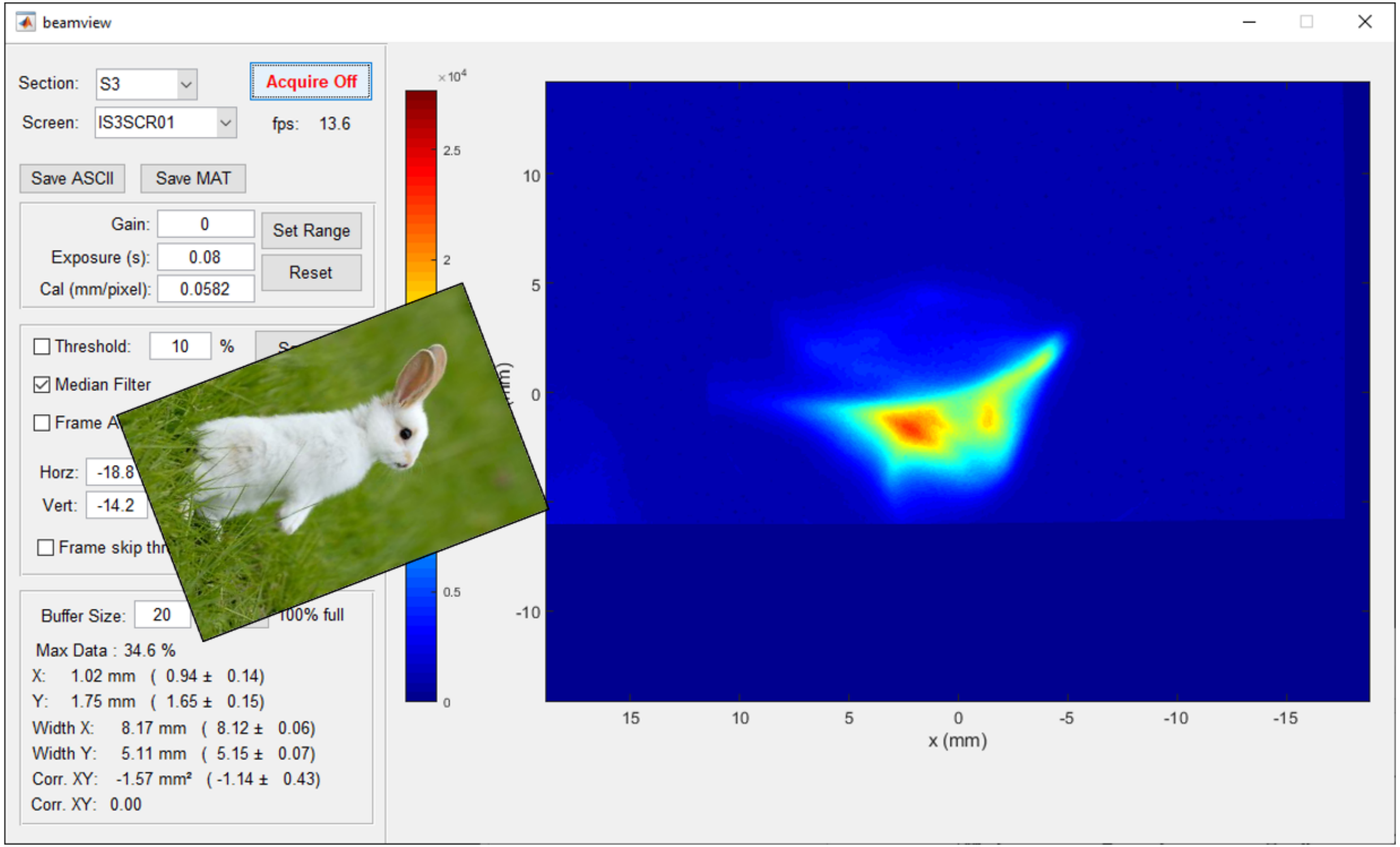
[Experience with CBETA (A.Bartnik)]

CBETA Peacock (from Adam Bartnik presentation)



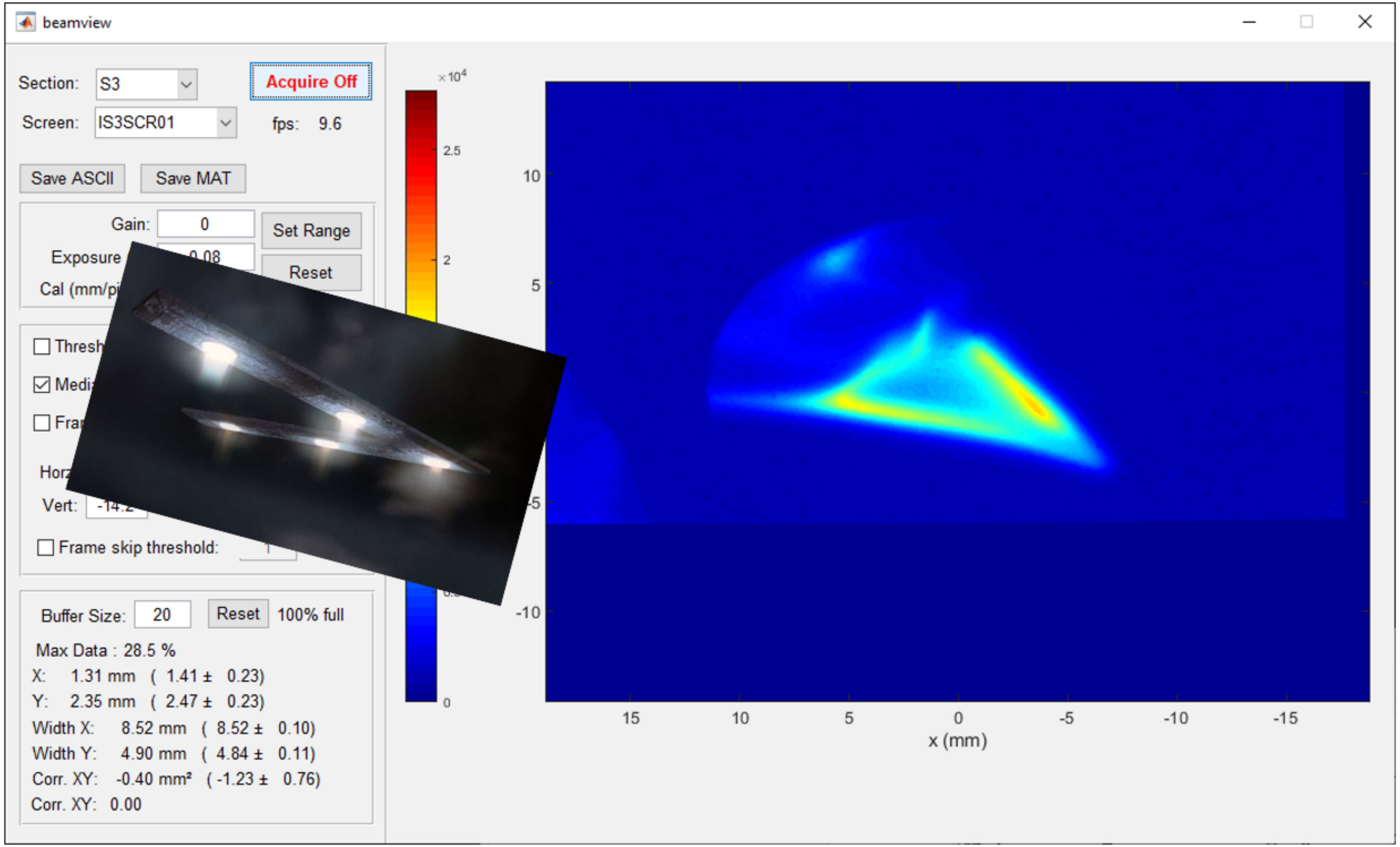
https://indico.ijclab.in2p3.fr/event/7907/contributions/24623/attachments/18126/23958/Experience%20with%20CBETA.pptx

CBETA Sideways Bunny (from Adam Bartnik presentation)



https://indico.ijclab.in2p3.fr/event/7907/contributions/24623/attachments/18126/23958/Experience%20with%20CBETA.pptx

CBETA UFO (from Adam Bartnik presentation)



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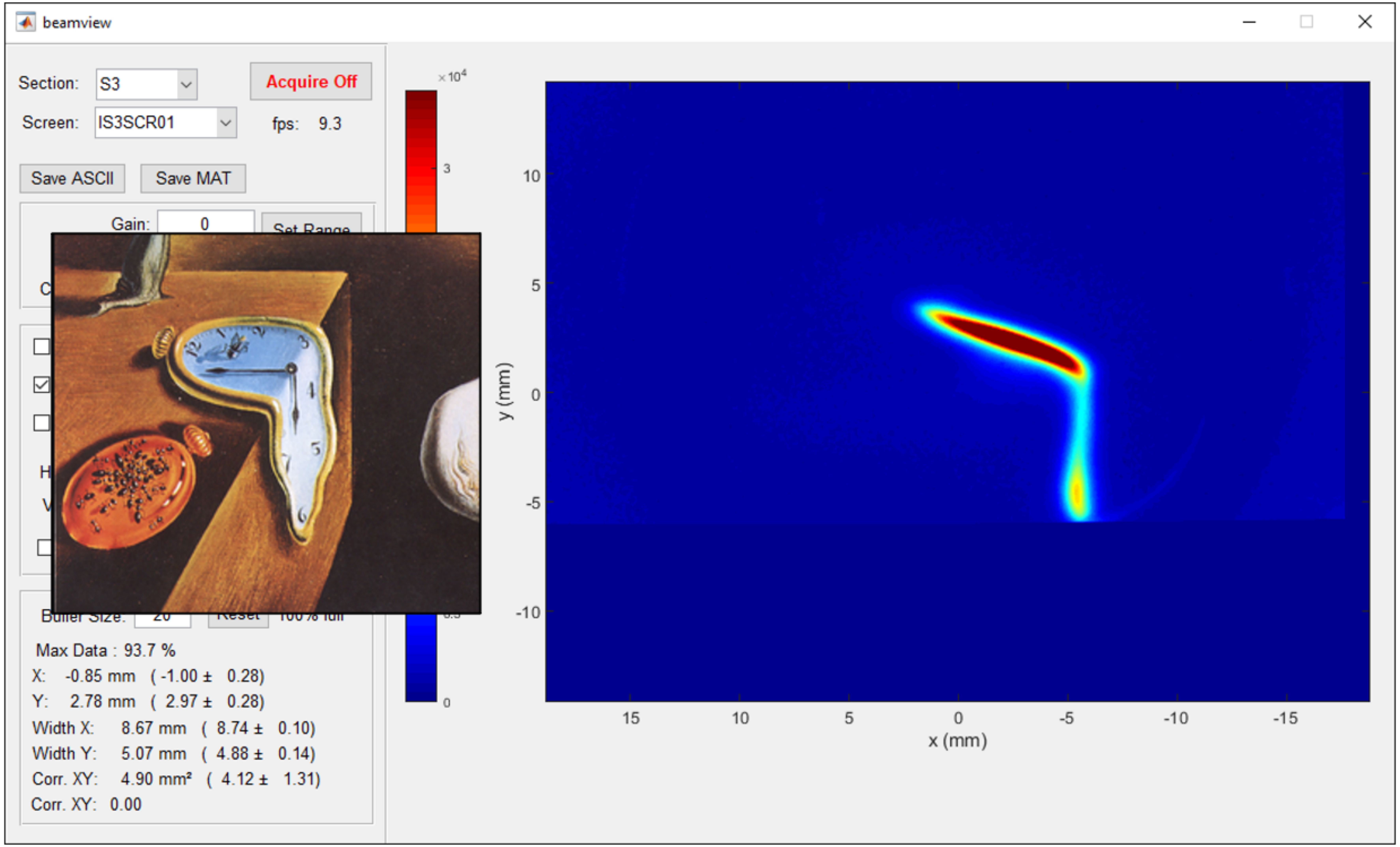


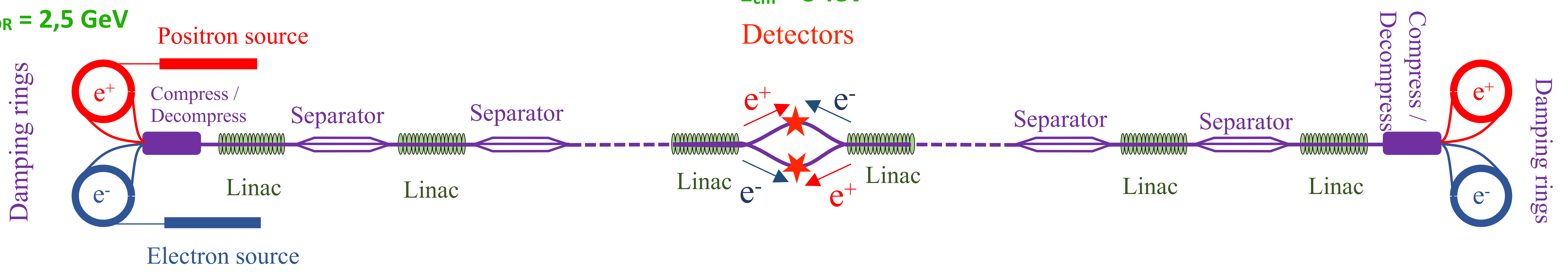
https://indico.ijclab.in2p3.fr/event/7907/contributions/24623/attachments/18126/23958/Experience%20with%20CBETA.pptx

Future

The ReLiC– Recycling Linear e+e- Collider

(Design concept by Vladimir N Litvinenko, et al.)

https://arxiv.org/ftp/arxiv/papers/2203/2203.06476.pdf

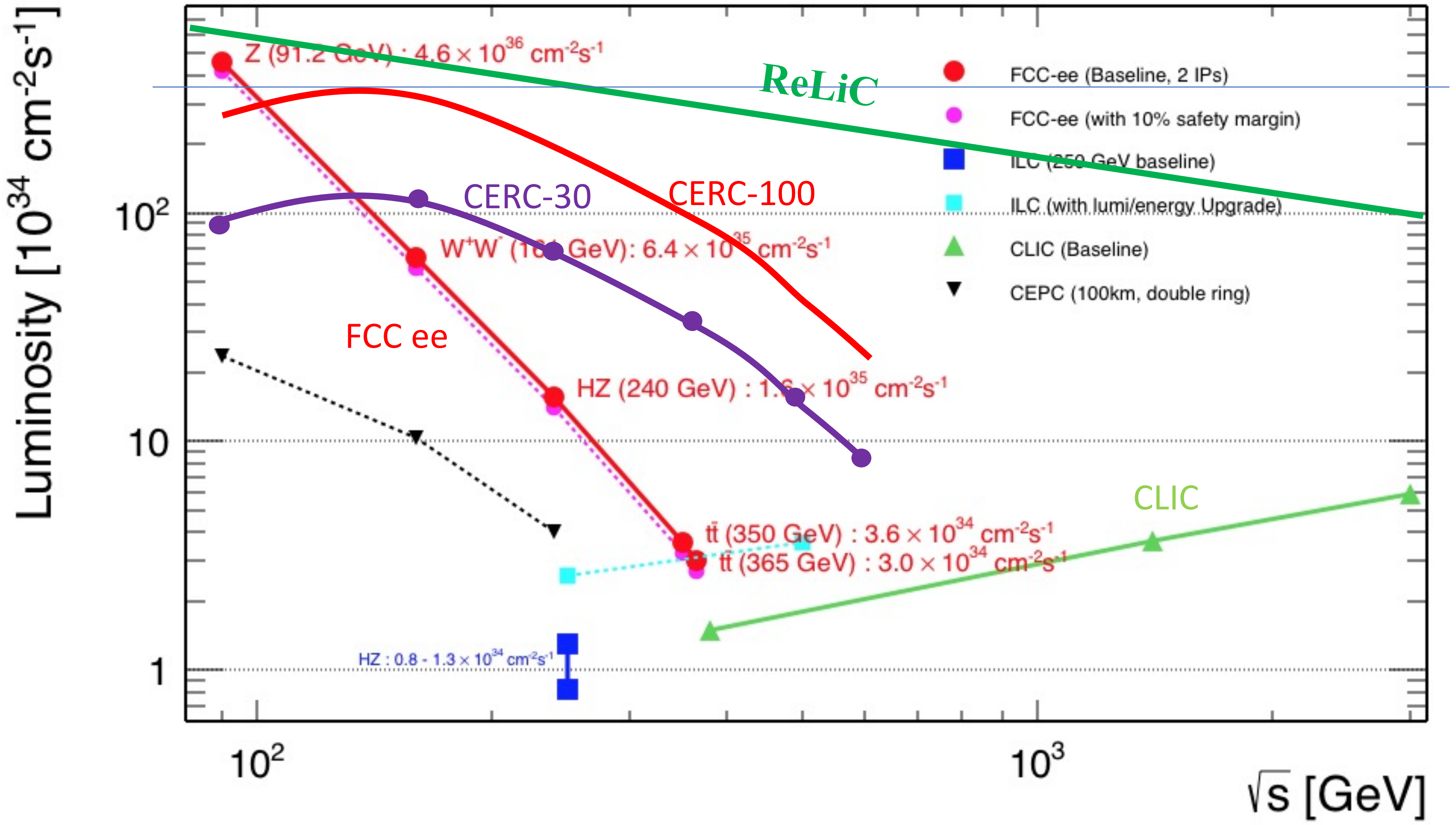


Electrons and positrons are stored and cooled in damping rings located at both ends of the collider.

Bunches of electrons and positrons circulate in damping rings for about two damping times to achieve natural emittances and energy spreads.

Short trains of bunches – typically from one to three bunches - are periodically ejected from damping rings and accelerated to the collision energy in SRF linacs.

ReLiC design practically **evades synchrotron radiation losses**, which limit average beam currents in circular e+e- colliders



The ReLiC– Recycling Linear e+e- Collider

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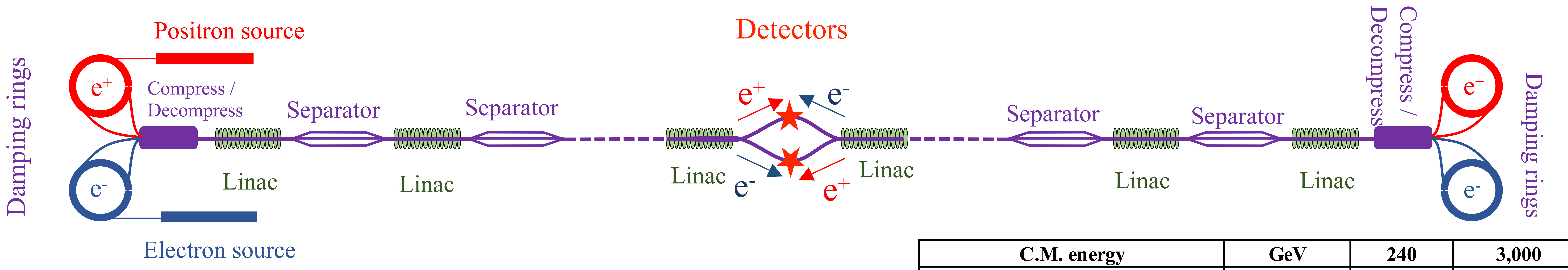

POWER BUDGETS AND PERFORMANCE CONSIDERATIONS FOR FUTURE HIGGS FACTORIES

Proposal	CEPC		FCC-ee		CERC		C^3	HELEN	CLIC	ILC‡	RELIC		EIC
Beam energy [GeV]	120	180	120	182.5	120	182.5	125	125	190	125	120	182.5	10 or 18
Average beam current [mA]	16.7	5.5	26.7	5	2.47	0.9	0.016	0.021	0.015	0.04	38	39	0.23–2.5
Total SR power [MW]	60	100	100	100	30	30	0	3.6	2.87	7.1	0	0	9
Collider cryo [MW]	12.74	20.5	17	50	18.8	28.8	60	14.43	–	18.7	28	43	12
Collider RF [MW]	103.8	173.0	146	146	57.8	61.8	20	24.80	26.2	42.8	57.8	61.8	13
Collider magnets [MW]	52.58	119.1	39	89	13.9	32	20	10.40	19.5	9.5	2	3	25
Cooling & ventil. [MW]	39.13	60.3	36	40	NE	NE	15	10.50	18.5	15.7	NE	NE	5
General services [MW]	19.84	19.8	36	36	NE	NE	20	6.00	5.3	8.6	NE	NE	4
Injector cryo [MW]	0.64	0.6	1	1	NE	NE	6	1.96	0	2.8	NE	NE	0
Injector RF [MW]	1.44	1.4	2	2	NE	NE	5	0*	14.5	17.1	192	196	5
Injector magnets [MW]	7.45	16.8	2	4	NE	NE	4	13.07*	6.2	10.1	0†	0†	5
Pre-injector [MW]	17.685	17.7	10	10	NE	NE	–	13.37	–	–	NE	NE	10
Detector [MW]	4	4.0	8	8	NE	NE	NE	15.97*	2	5.7	NE	NE	NI
Data center [MW]	NI	NI	4	4	NE	NE	NE	NI	NI	2.7	NE	NE	NI
Total power [MW]	259.3	433.3	301	390	89	122	150	110.5	107	138	315	341	79
Lum./IP [10^{34} $cm^{-2}s^{-1}$]	5.0	0.8	7.7	1.3	78	28	1.3	1.35	2.3	2.7	200	200	1
Number of IPs	2	2	4 (2)	4 (2)	1	1	1	1	1	1	2	2	1 (2)
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	10000	3600	210	390.7	276	430	79600	79000	145
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.3	1.3	1.6	2.89	1.2	1.6	2	2	1.45
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.34	0.47	0.67	0.89	0.6	0.82	2	2.2	0.32

https://lss.fnal.gov/archive/2023/conf/fermilab-conf-23-113-ad-td.pdf

C.M. energy	**GeV**	**240**	**3,000**
Length of accelerator	km	20	288
Section length	m	250	250
Bunches per train		10	21
Particles per bunch	10^{10}	2.0	1.0
Collision frequency	MHz	12.0	25.2
Beam currents in linacs	mA	38	40
εx, norm	mm mrad	4.0	4.0
εy, norm	µm mrad	1.0	1.0
βx	m	5	100
βy, matched	mm	0.34	9.7
σ_z	mm	1	17
Disruption parameter, Dx		0.01	0.002
Disruption parameter, Dy		43	15
Luminosity per detector	10^{34} $cm^{-2}sec^{-1}$	172	47
Total luminosity	10^{34} $cm^{-2}sec^{-1}$	343	94

Conclusions

ERL (Energy Recovery Linac)

is a proven accelerator technology, pushing for higher energy and higher beam current,

reaching in view of collider applications above 1GW.

Features:

minimising the power consumption by recycling the kinetic energy of a used beam for accelerating a newly injected beam

avoiding the emittance growth of storage rings

dumping at injection energy

PERLE at IJCLab (Orsay)

demonstrator facility for the LHeC

3 accelerating + 3 decelerating passes

20mA, 40 MHz injection (same as LHeC)

802 MHz SRF cavities

with IRs top energy 500 MeV (10 MW power)

Thank you