Circular-Linear energy recovery accelerator to probe the energy-frontier

I. V. Konoplev, S.A. Bogacz
Ya. Shashkov

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https://iopscience.iop.org/article/10.1088/1748-0221/17/01/P01011/pdf

Introduction: Different types of limitations*

1. physical limits on high-gradient acceleration, high-field bending, beam size, beam brightness, and luminosity
2. technology-dependent limits e.g. material properties (critical current, tensile properties, …)
3. societal imprints (e.g. size, cost, electrical energy)

* Frank Zimmermann, "the grand challenges and opportunities of ultimate high energy colliders", CPM, A10, Tuesday 6 October 2020

Introduction: Different types of limitations to be addressed

1. physical limits on high-gradient acceleration, high-field bending, beam size, beam brightness, threshold current and luminosity
2. technology-dependent limits e.g. material properties (critical current, tensile properties, …)
3. societal imprints (e.g. size, cost, electrical energy)

Introduction: Different types of ERL limitations to be addressed

1. Physical limits (ERL): threshold current to increase beam intensity for ERL → brightness, luminosity
2. Societal impact (ERL): threshold current →
    1. financial (construction and energy efficiency)
    2. societal cost (delivering blue sky research and giving immediate reward to society - acceptance by society)

Introduction
History: AERL (JAI, Oxford & JLab, 2015-2019)

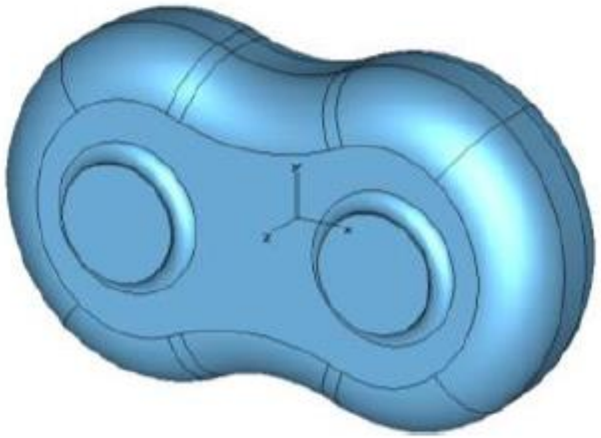
Aim:

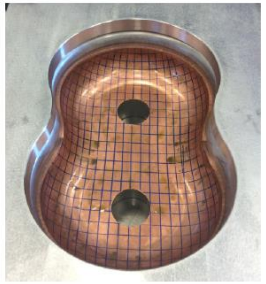
To surpass any existing designs of ERL in the e-beam current handling capabilities

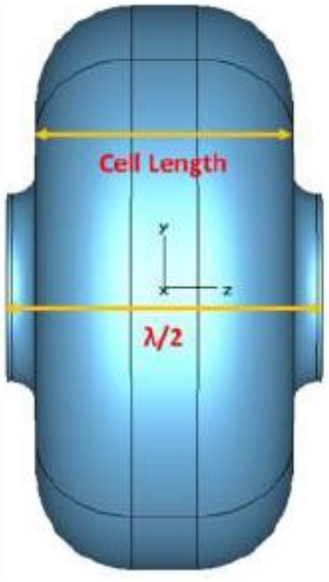
Radio frequency cavities
I Konoplev, G Burt
US Patent 10,237,963

R. Ainsworth, G. Burt, I.V. Konoplev and A. Seryi, *Asymmetric dual axis energy recovery linac for ultrahigh flux sources of coherent x-ray and THz radiation: Investigations towards its ultimate performance*, Phys. Rev. Accel. Beams 19 (2016) 083502 [arXiv:1509.03675].

Introduction: JLAB dual axis cavity







The cavity was used as a prototype during the optimisation

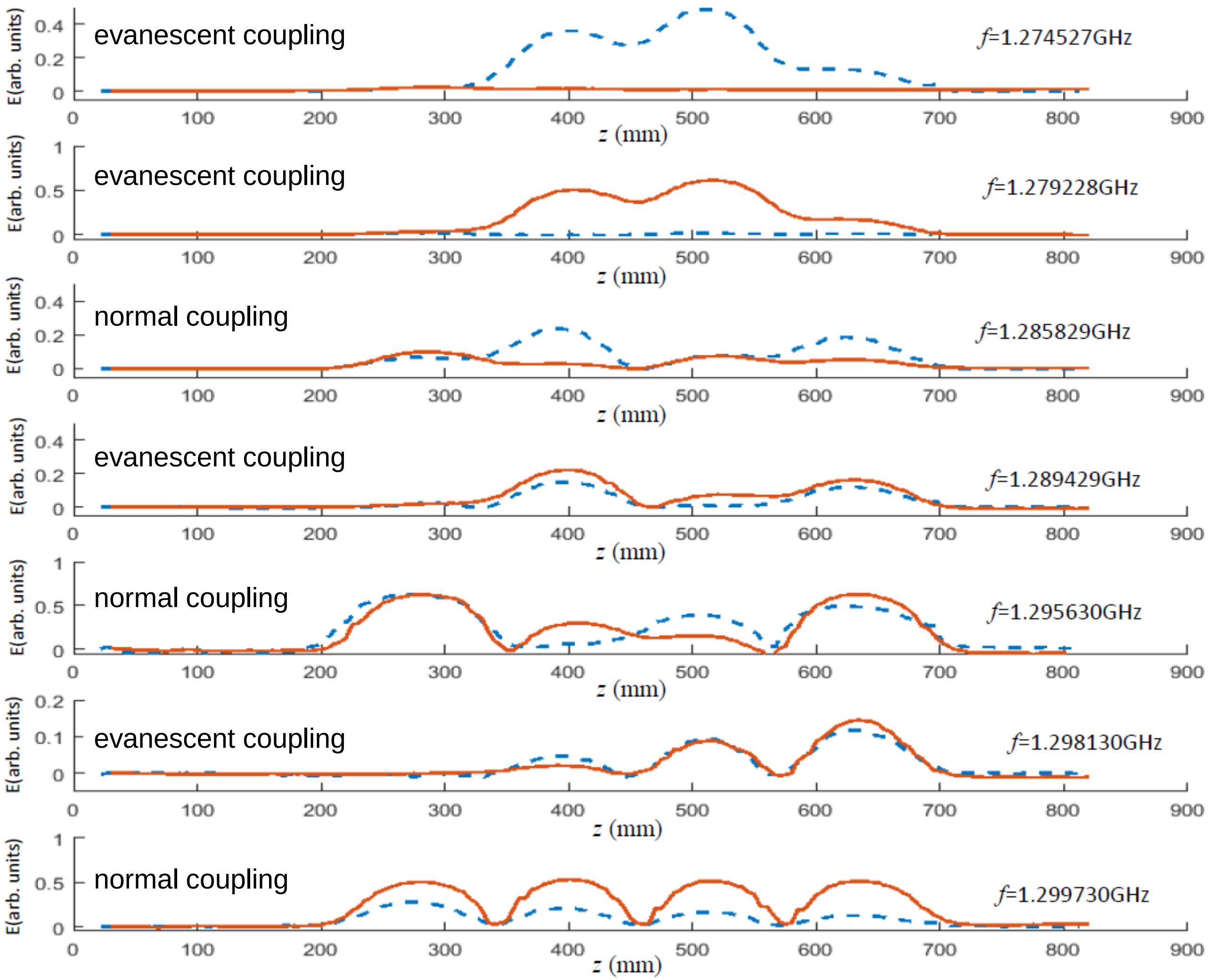
It was considered as an indication that such structure can be machined

Parameter	Value	Units
Cavity height	202.5	mm
Cavity width	300.0	mm
Cavity length	100.13	mm
Cell length	81.13	mm
Iris curvature	8.0	mm
Beam aperture	60.0	mm
Beam axis separation	136.5	mm
V_{acc}	0.1	MV
$E_p/E_{acc}{}^*$	2.68	
$B_p/E_{acc}{}^*$	5.5	mT/(MV/m)
$[R/Q]$	60.1	Ω
G	320.8	Ω
R_tR_s	1.93×10^4	Ω^2
LOM	1103	MHz
Nearest HOM	1806	MHz
V_t	26.4	V

*At $E_{acc} = 1$ MV/m

[1] A. Hutton and H. Areti, *Accelerator stewardship test facility program — Elliptical twin cavity for accelerator applications*, JLAB-HEP15-03 (2015) and online at https://www.osti.gov/biblio/1209532.
[2] S.U. De Silva, H. Park, J.R. Delayen, F. Marhauser and A. Hutton, *Electromagnetic design of a superconducting twin axis cavity*, in proceedings of the 28th Linear Accelerator Conference (LINAC2016), East Lansing, MI, U.S.A., 25–30 September (2016).
[3] H. Park, F. Marhauser, A. Hutton, S.U. De Silva and J.R. Delayen, Development of a superconductingtwin axis cavity, in proceedings of the 28th Linear Accelerator Conference (LINAC2016), East Lansing, MI, U.S.A., 25–30 September (2016).

Pass band modes experimental studies at two axes



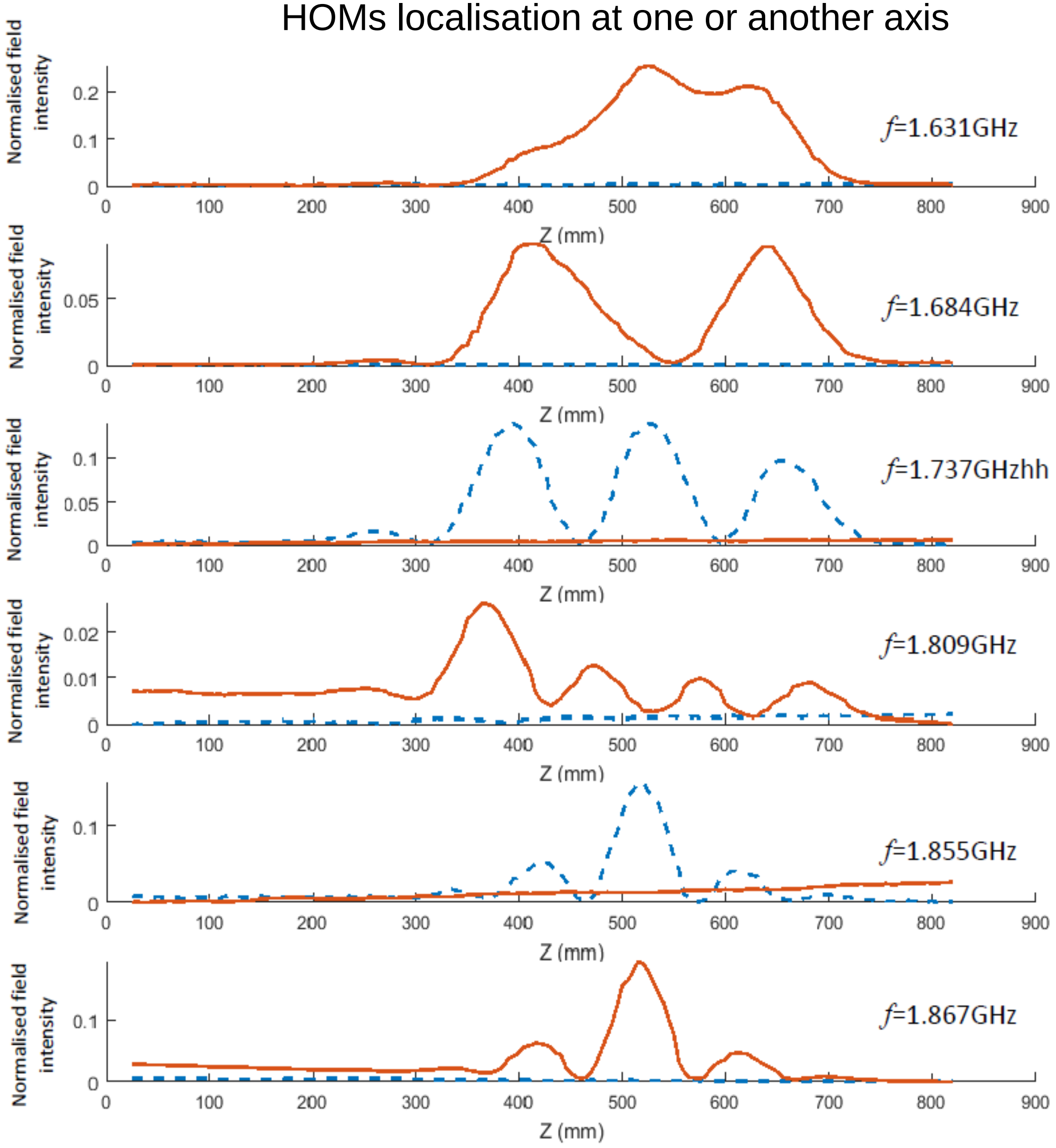
The RF coupler is located on one axis (active) while the field measurements are conducted on both axes

Red line active axis
Blue line passive axis

I.V. Konoplev, K. Metodiev, A.J. Lancaster, G. Burt, R. Ainsworth and A. Seryi, *Experimental studies of 7-cell dual axis asymmetric cavity for energy recovery linac*, Phys. Rev. Accel. Beams 20 (2017)103501 [arXiv:1712.00494]

HOMs measurements

HOMs localisation at one or another axis



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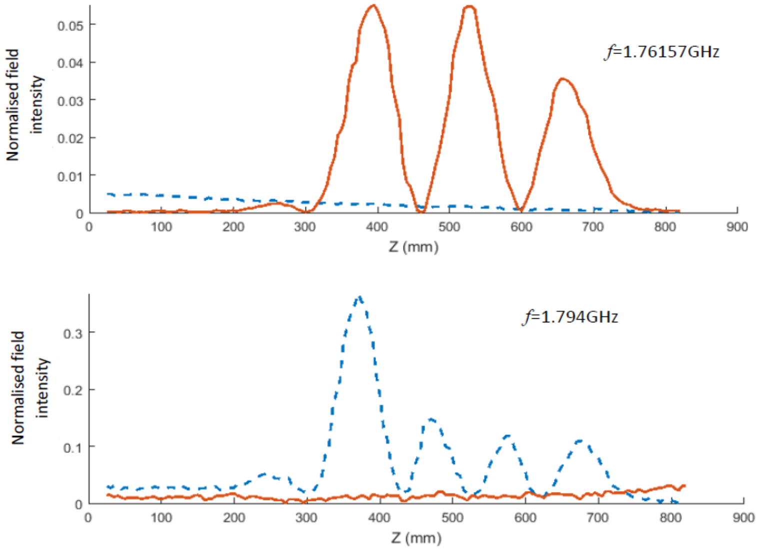
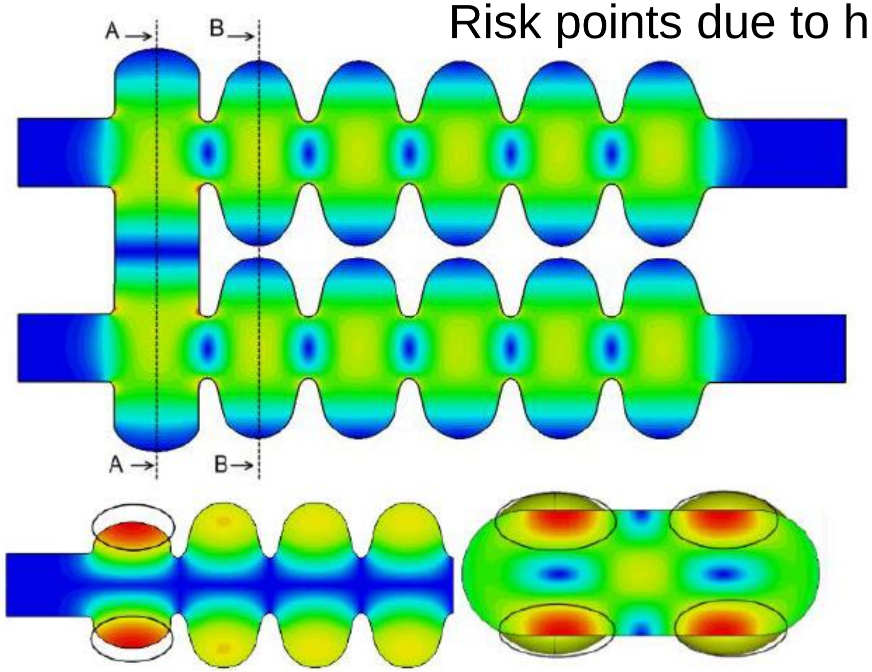
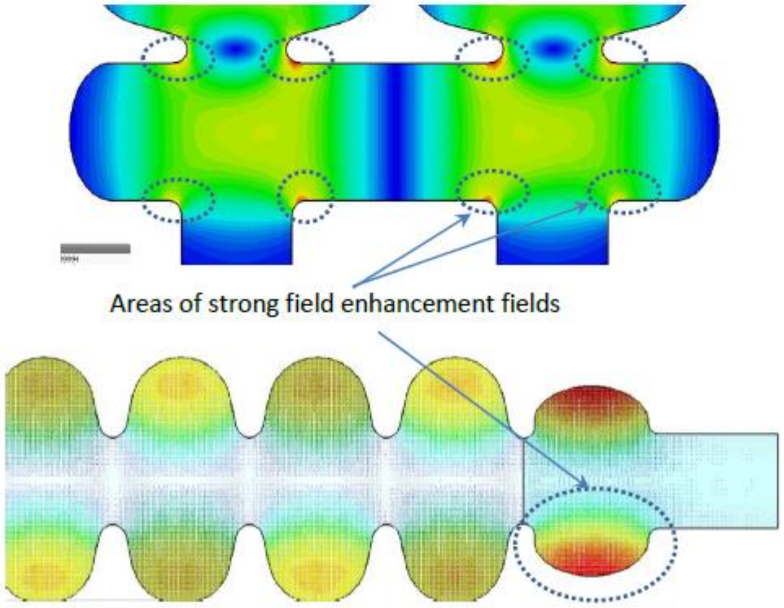


M. Topp-Mugglestone, I.V. Konoplev, H. Zhang and A. Seryi, *Studies of high order modes in asymmetric dual-axis cavity*, Appl. Phys. Lett. 113 (2018) 243503.

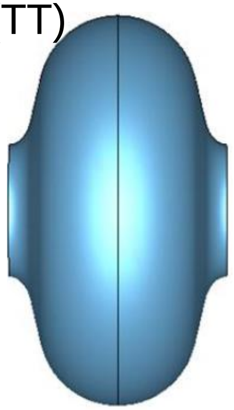
Cavity optimisation

Risk points due to high field intensity on the surface





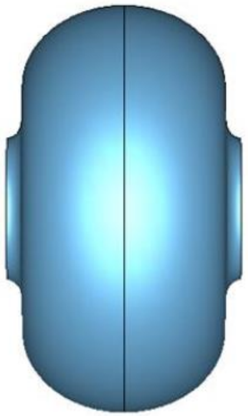
Tesla like cavity (TT)



Other risk factors:

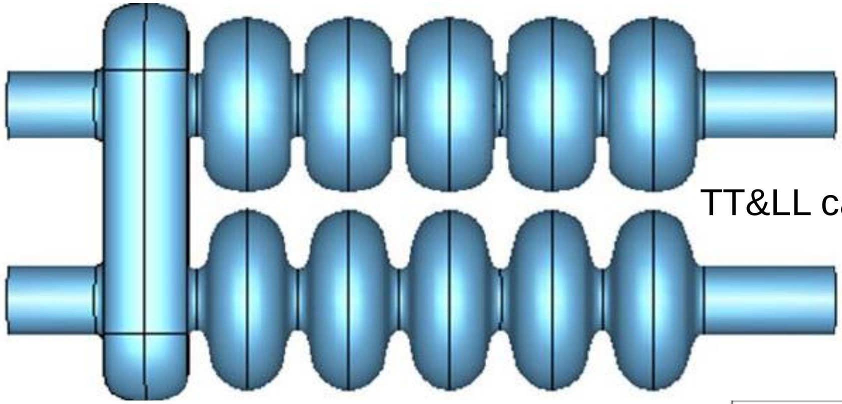
- Multipacting
- Proximity on modes to operating mode
- Cost

Low Loss like cavity (LL)

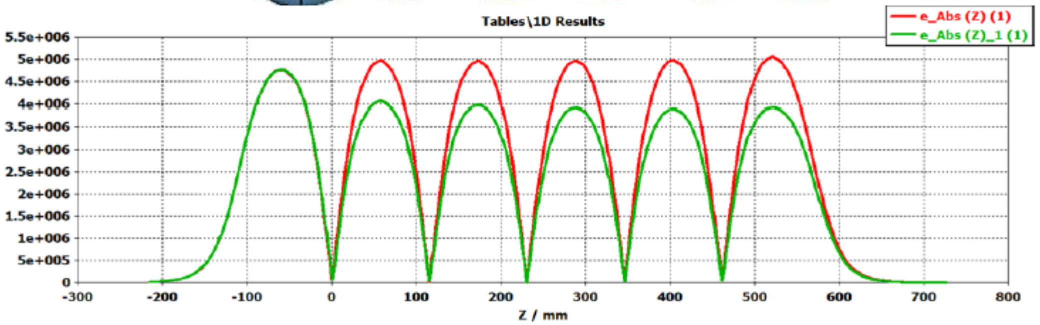


I.V. Konoplev, Y. Shashkov, A. Bulygin, M.A. Gusarova and F. Marhauser, *Ultimate energy recovery from spent relativistic electron beam in energy recovery linear accelerators*, Phys. Rev. Accel. Beams 23 (2020) 071601

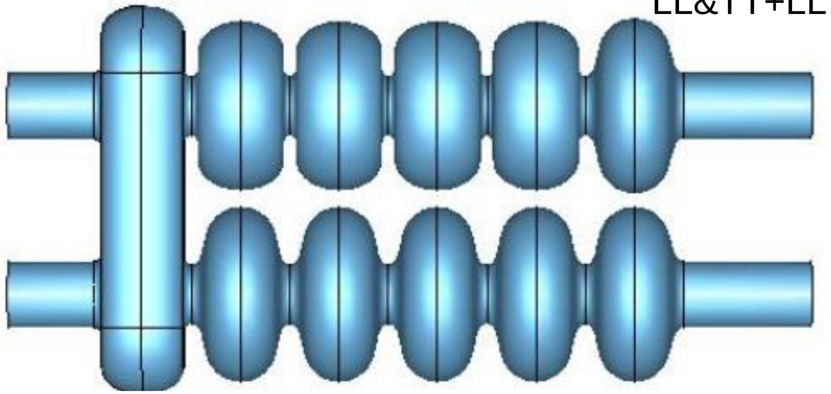
Cavity optimisation

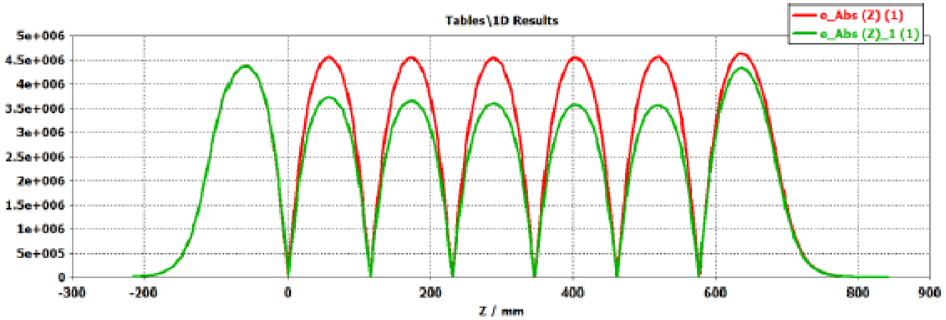


TT&LL cavity

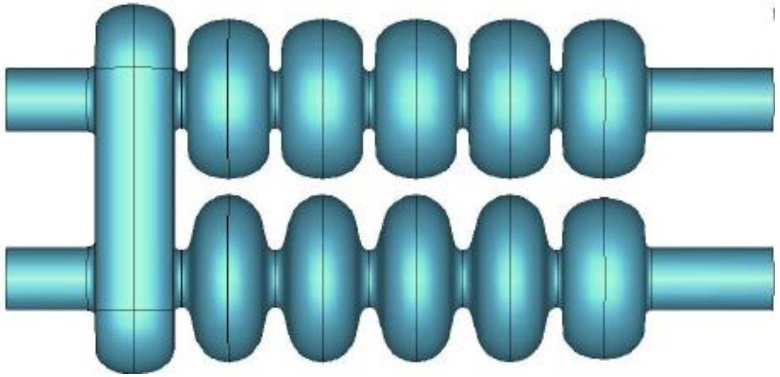


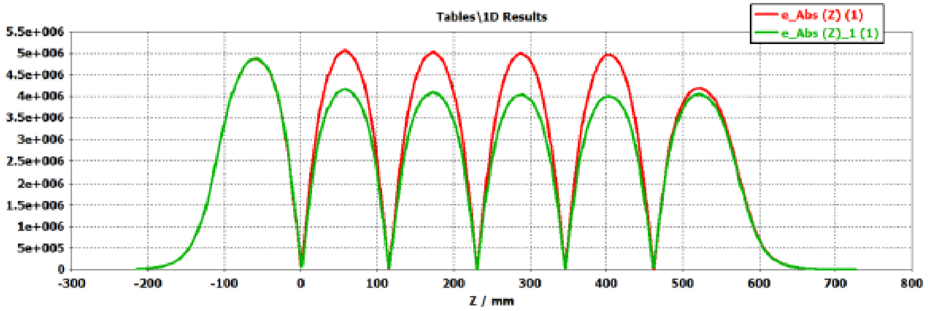
LL&TT+LL cavity





TT&LL+TT cavity





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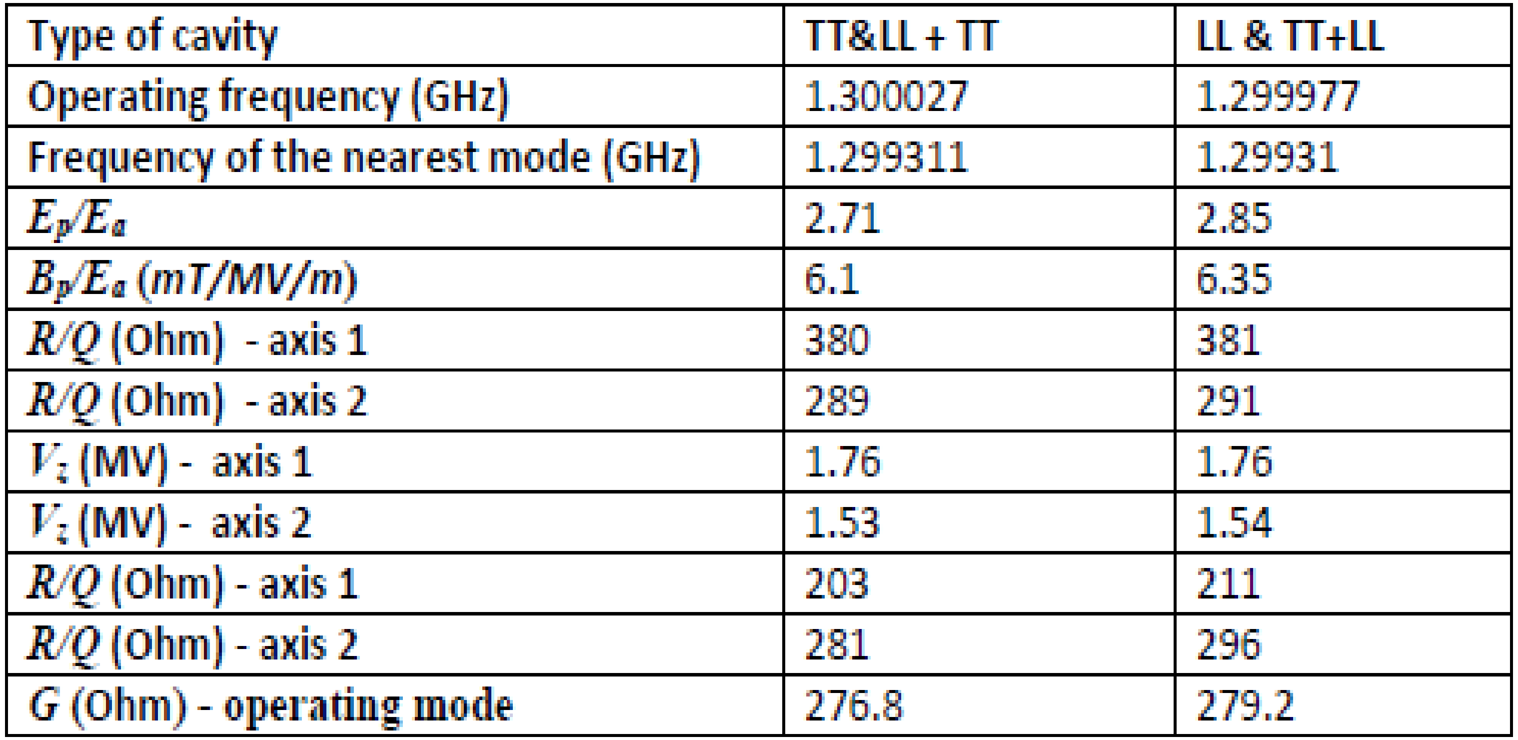
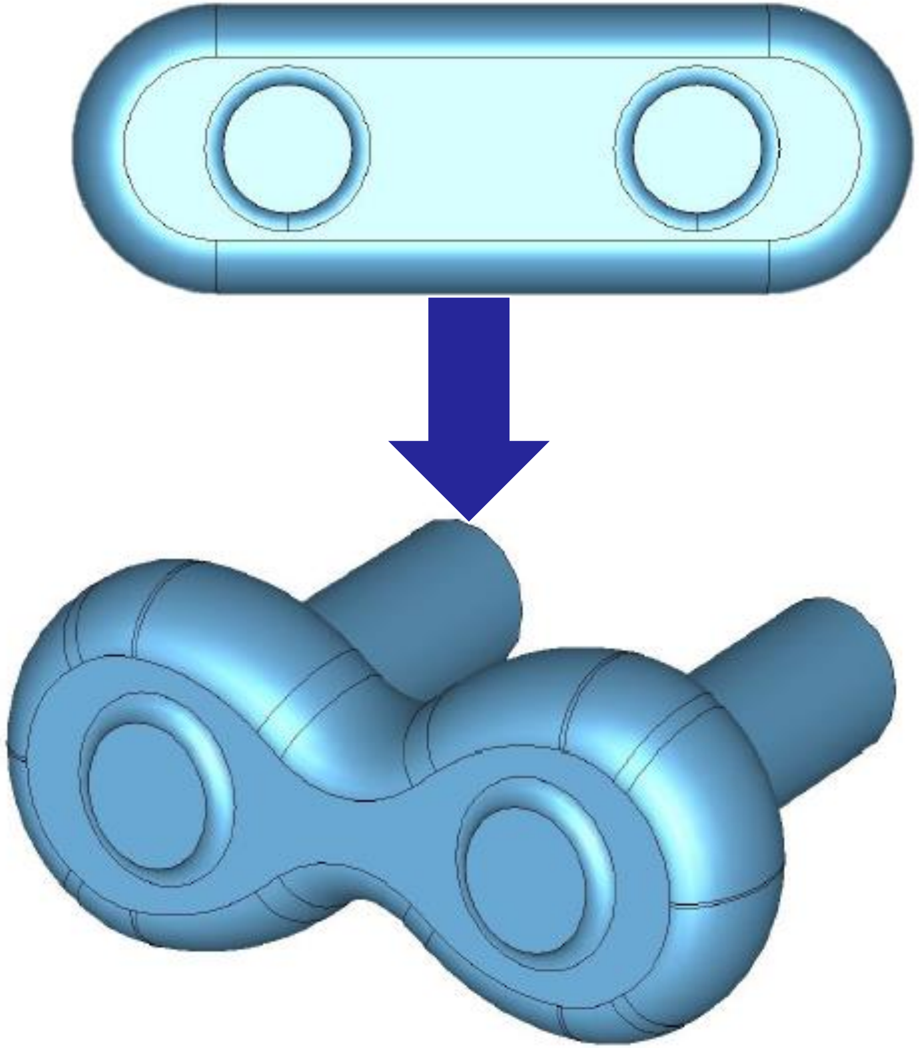
Asymmetric dual axis cavity with different number of cells on the axes

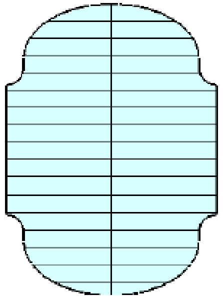


Type of cavity	TT&LL + TT	LL & TT+LL
Operating frequency (GHz)	1.300027	1.299977
Frequency of the nearest mode (GHz)	1.299311	1.29931
E_p/E_a	2.71	2.85
B_p/E_a $(mT/MV/m)$	6.1	6.35
R/Q (Ohm) - axis 1	380	381
R/Q (Ohm) - axis 2	289	291
V_z (MV) - axis 1	1.76	1.76
V_z (MV) - axis 2	1.53	1.54
R/Q (Ohm) - axis 1	203	211
R/Q (Ohm) - axis 2	281	296
G (Ohm) - operating mode	276.8	279.2

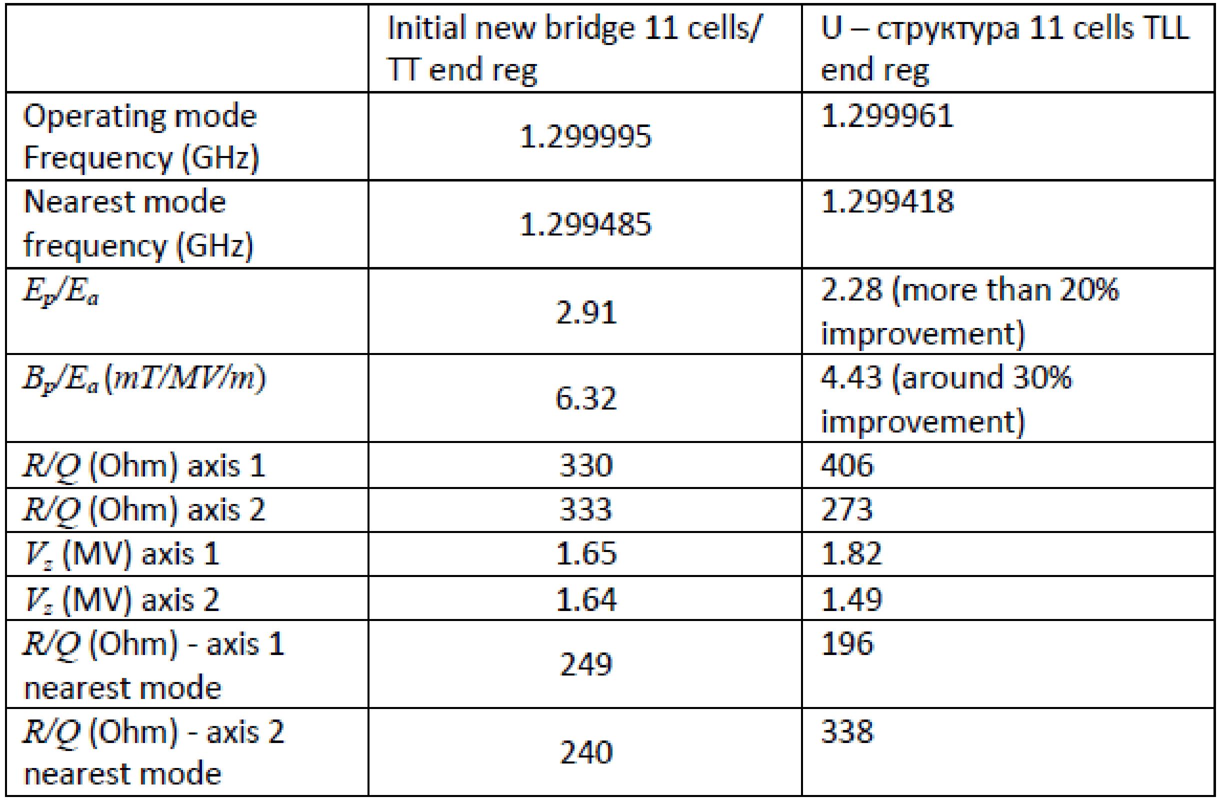
I.V. Konoplev, Y. Shashkov, A. Bulygin, M.A. Gusarova and F. Marhauser*, Ultimate energy recovery from spent relativistic electron beam in energy recovery linear accelerators*, Phys. Rev. Accel. Beams 23 (2020) 071601

Bridge optimisation



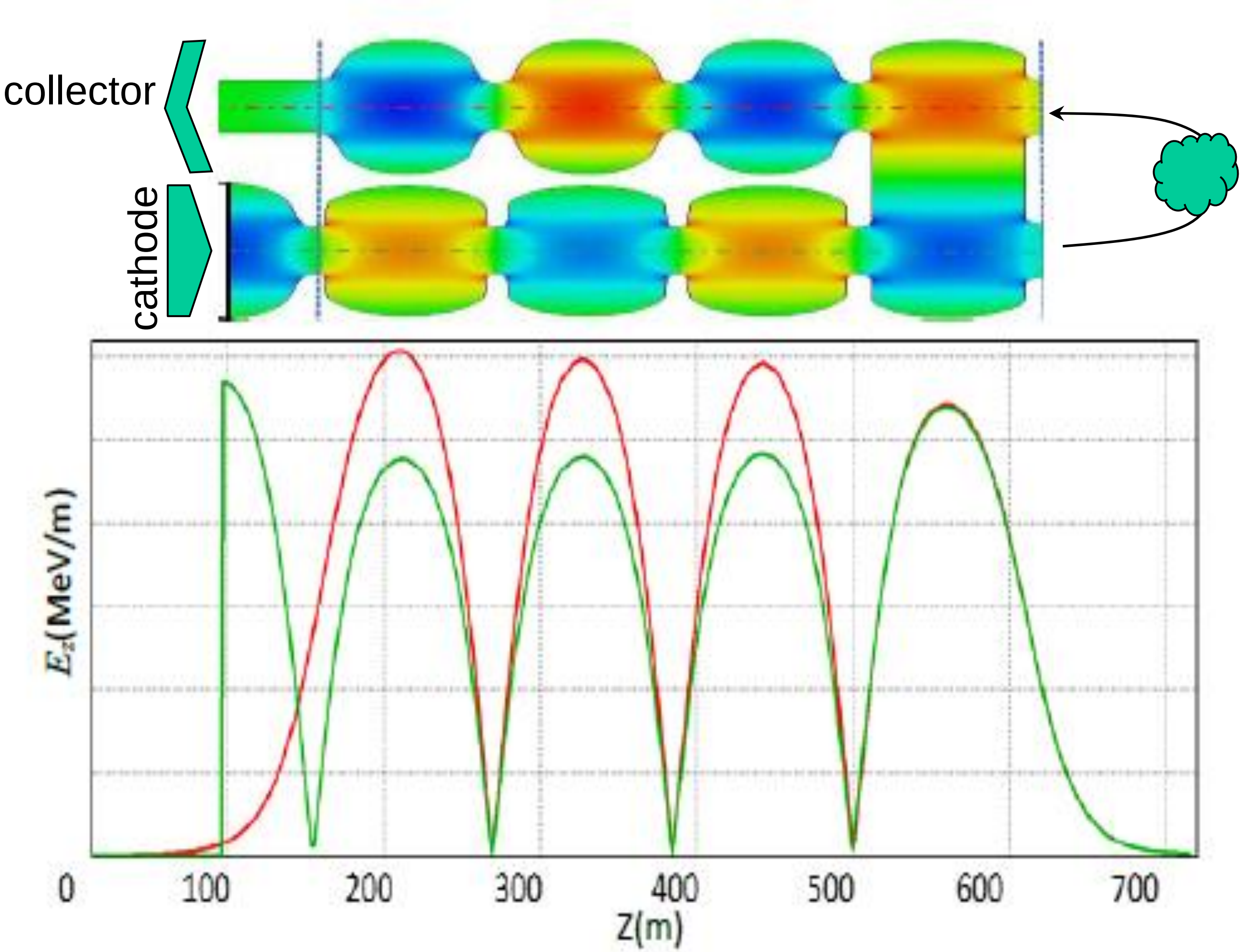


- Resolved high field risk
- Improved the modes proximity
- Resolve the challenge with multipacting



	Initial new bridge 11 cells/ TT end reg	U – структура 11 cells TLL end reg
Operating mode Frequency (GHz)	1.299995	1.299961
Nearest mode frequency (GHz)	1.299485	1.299418
E_p/E_a	2.91	2.28 (more than 20% improvement)
$B_p/E_a\,(mT/MV/m)$	6.32	4.43 (around 30% improvement)
R/Q (Ohm) axis 1	330	406
R/Q (Ohm) axis 2	333	273
V_z (MV) axis 1	1.65	1.82
V_z (MV) axis 2	1.64	1.49
R/Q (Ohm) - axis 1 nearest mode	249	196
R/Q (Ohm) - axis 2 nearest mode	240	338

Asymmetric dual axis cavity with different number of cells on the axes



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Circular-Linear energy recovery accelerator to probe the energy-frontier

Circular-Linear energy recovery accelerator to address

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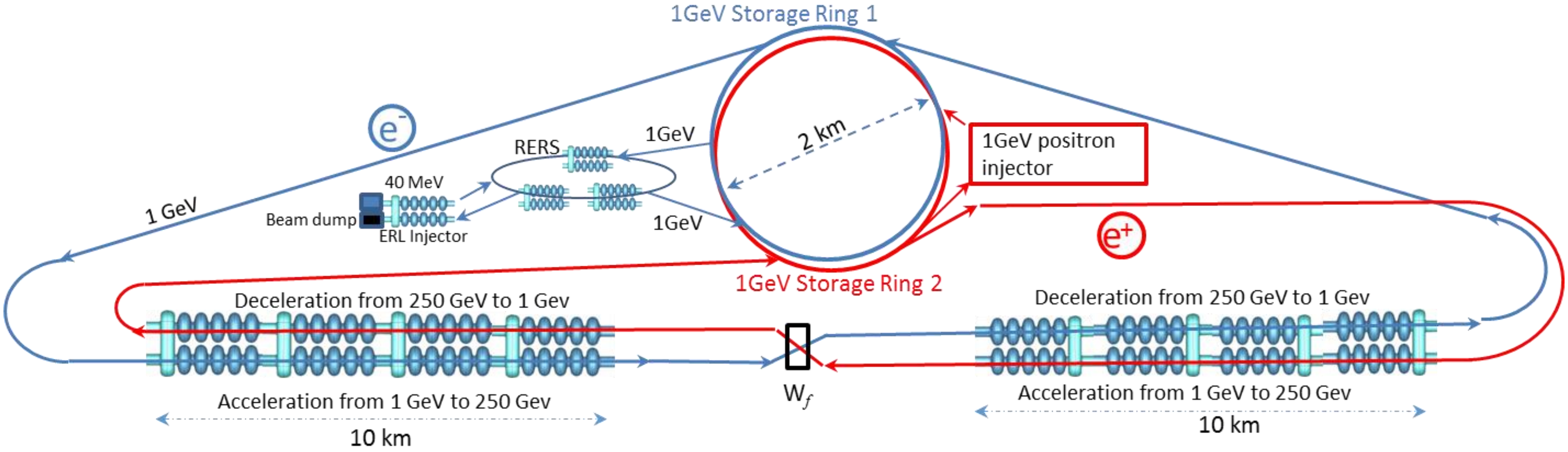
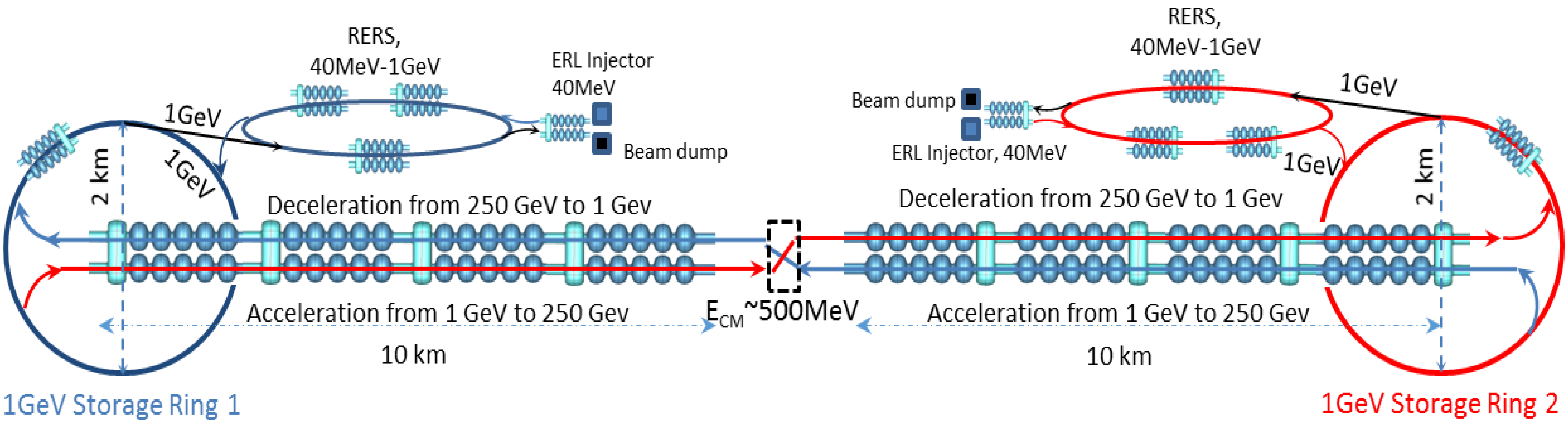
Circular-Linear Energy Recovery Collider

“Triangular” or ILC-configuration



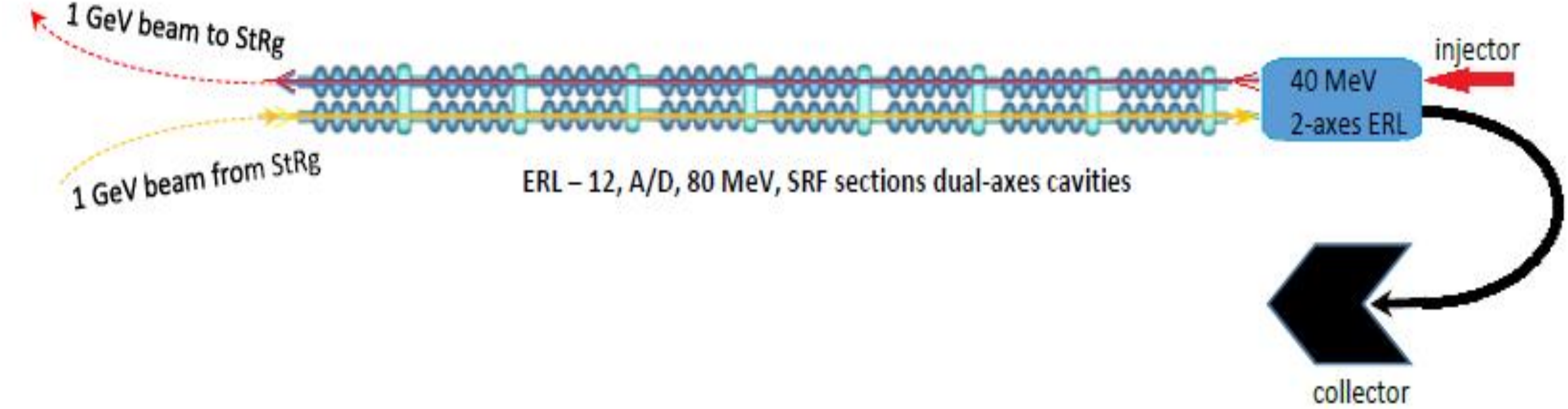
Circular-Linear Energy Recovery Collider

“Linear” configuration



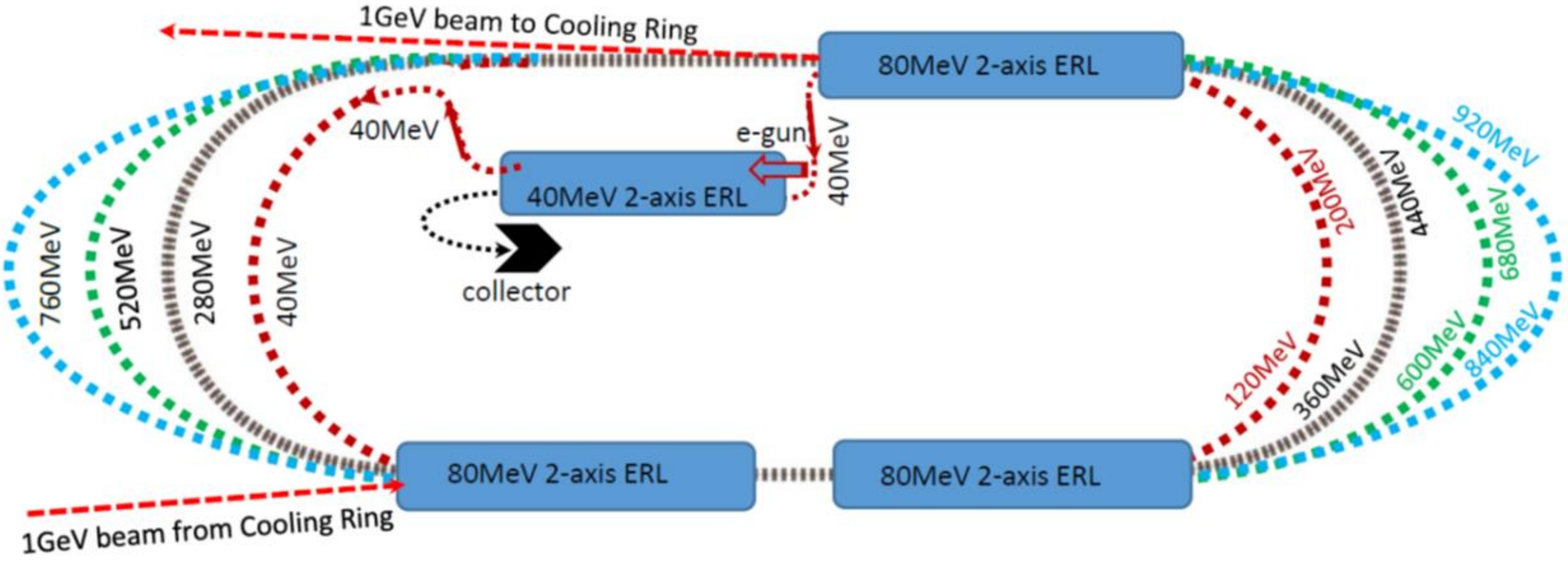
Injection into storage ring

Conventional ERL based on dual axes asymmetric cavity



Injection into storage ring

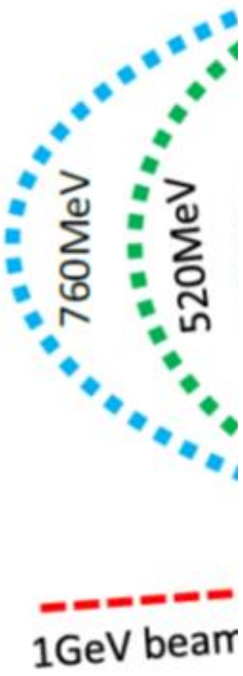
Recirculating Energy Recovery system (RERS)

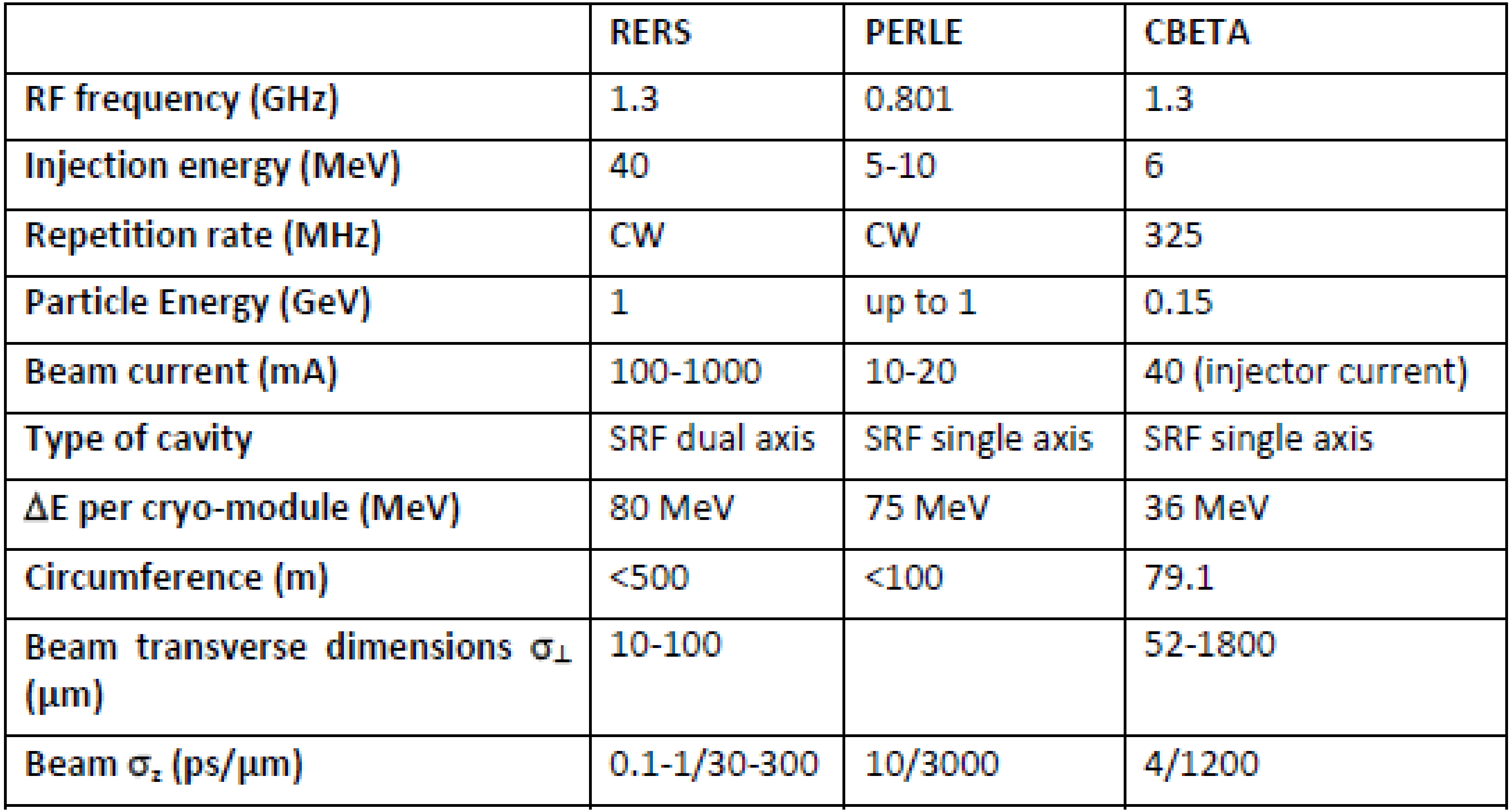


Recirculating Energy Recovery System (RERS)

Injection into storage ring

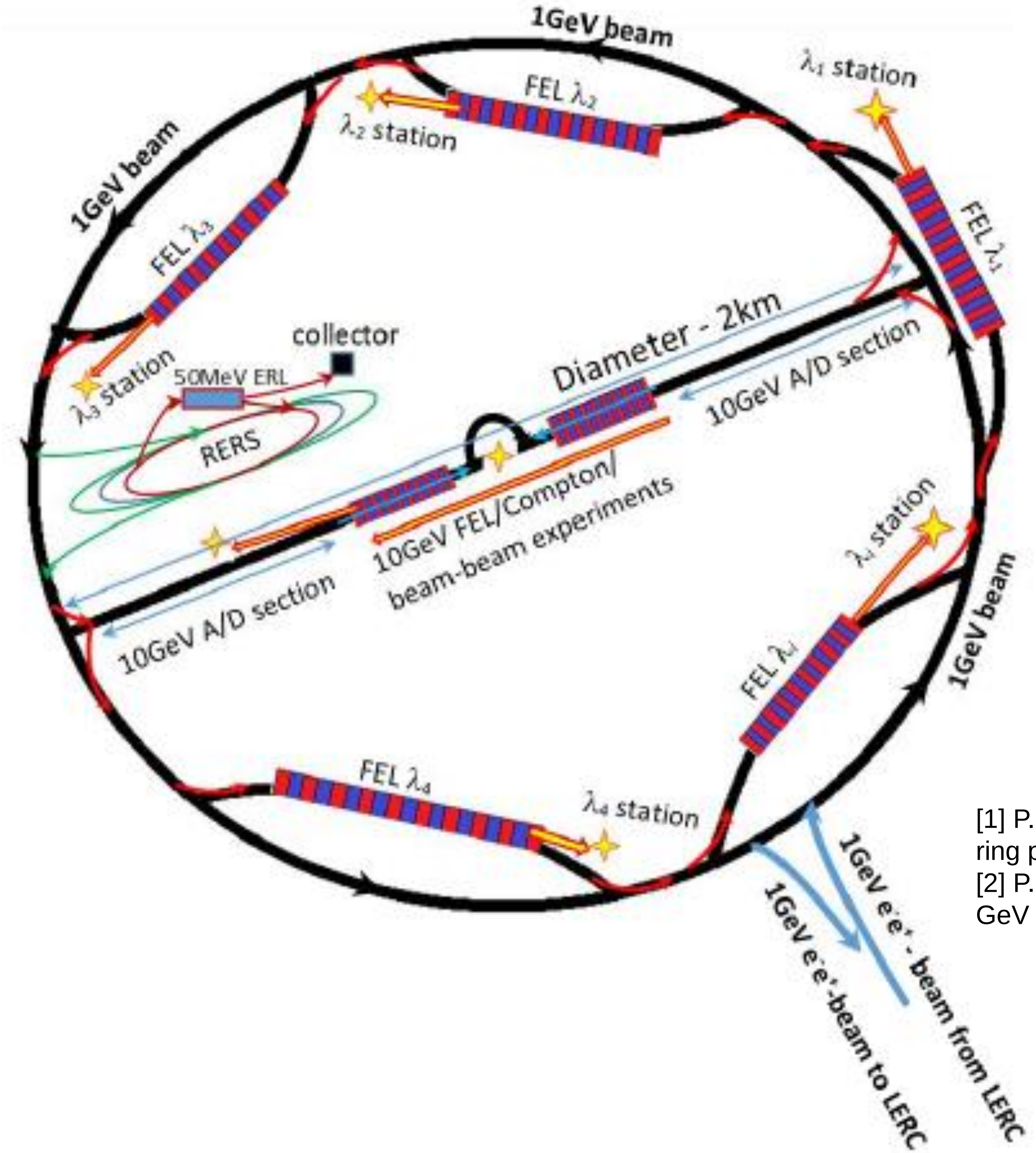
Recirculating Energy Recovery system





	RERS	PERLE	CBETA
RF frequency (GHz)	1.3	0.801	1.3
Injection energy (MeV)	40	5-10	6
Repetition rate (MHz)	CW	CW	325
Particle Energy (GeV)	1	up to 1	0.15
Beam current (mA)	100-1000	10-20	40 (injector current)
Type of cavity	SRF dual axis	SRF single axis	SRF single axis
ΔE per cryo-module (MeV)	80 MeV	75 MeV	36 MeV
Circumference (m)	<500	<100	79.1
Beam transverse dimensions $\sigma_\perp$ (μm)	10-100		52-1800
Beam σ_z (ps/μm)	0.1-1/30-300	10/3000	4/1200

Storage Ring

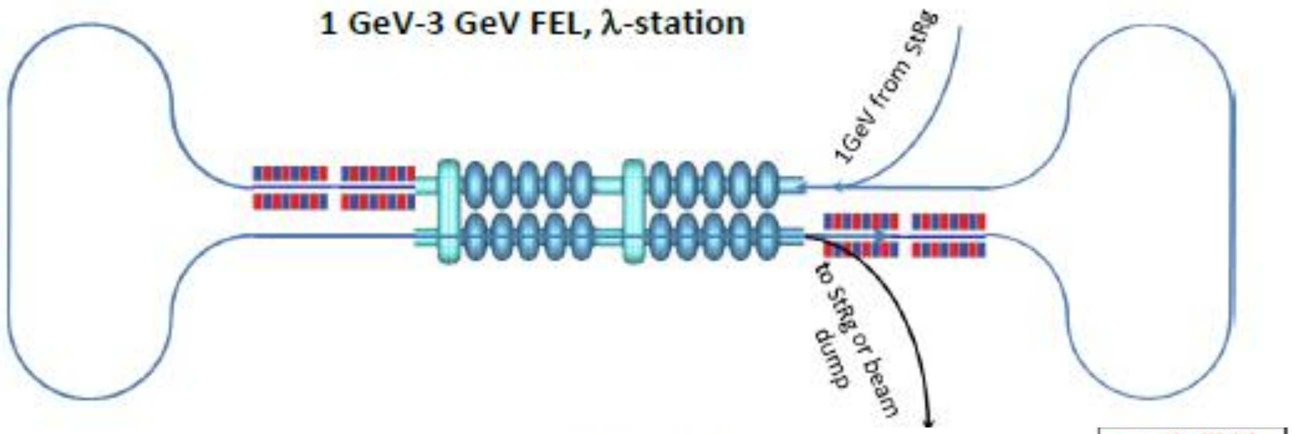


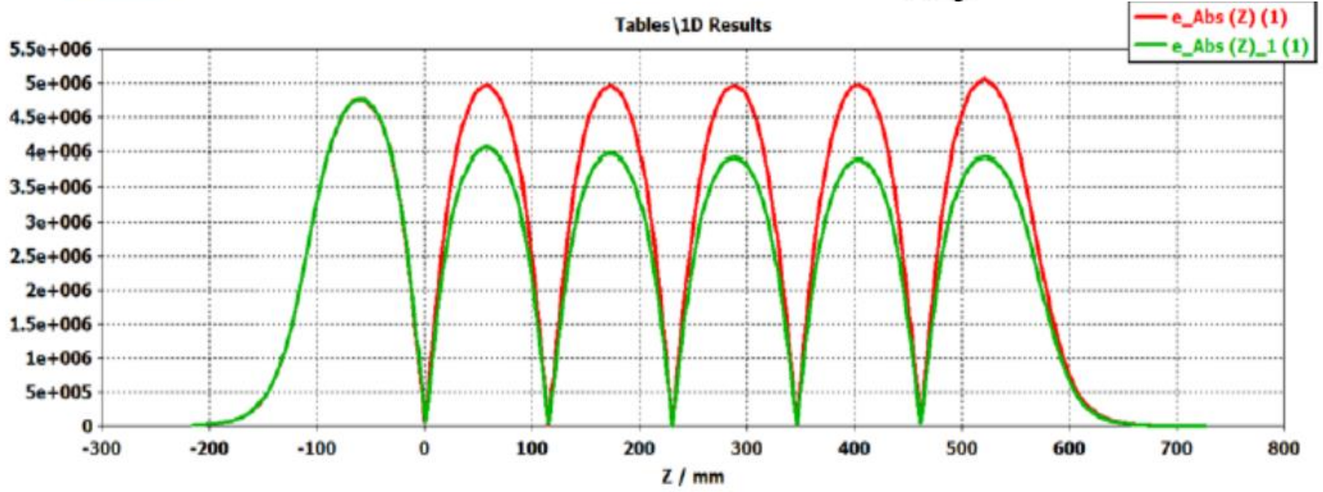
intermediate energy (1 GeV), large (2 km) diameter, weekly radiating (below 1kW) storage ring with indication of the FEL stations for photon production.

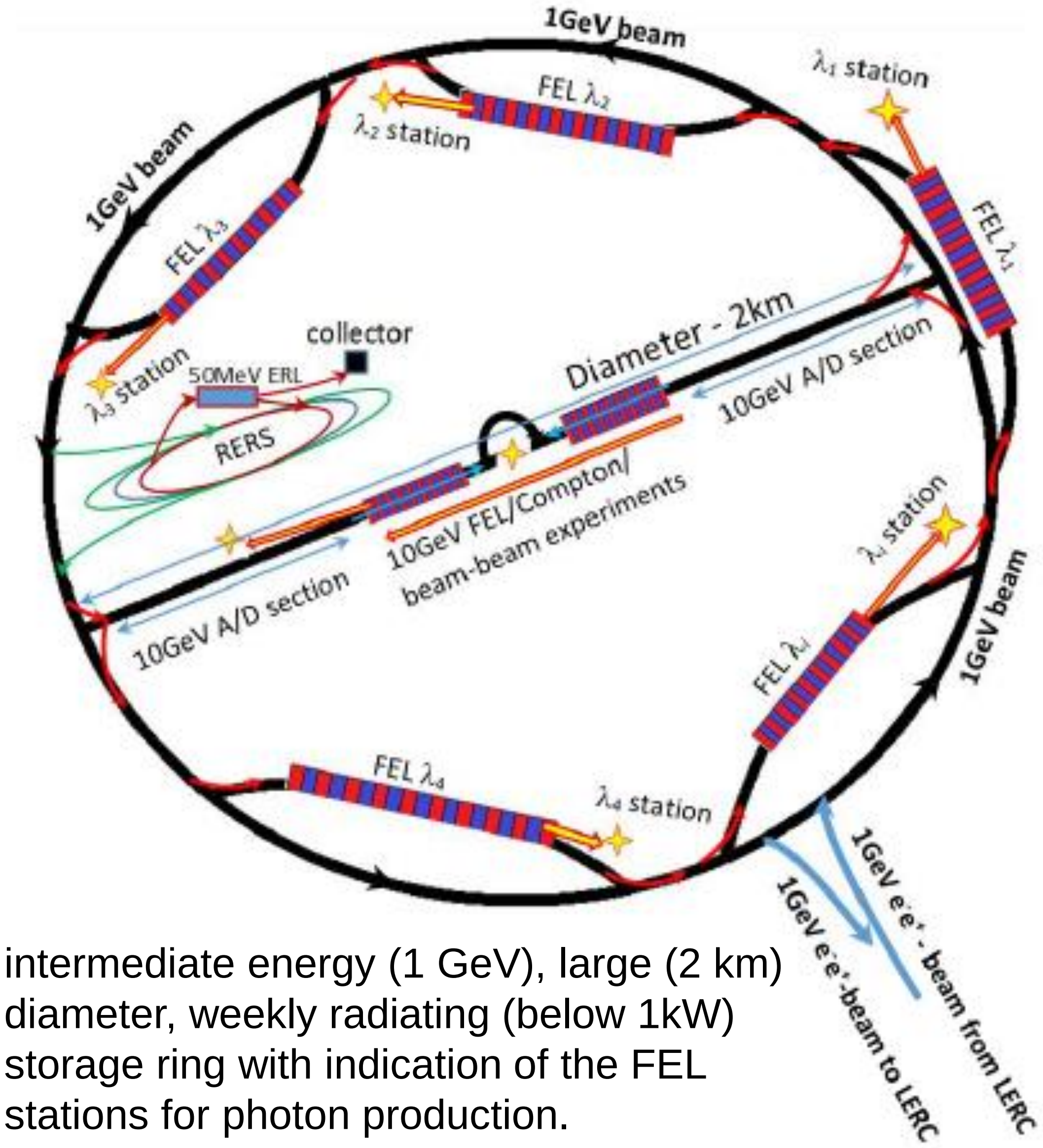
[1] P.F. Tavares, S.C. Leemann, M. Sjöström and Å. Andersson, The MAX IV storage ring project, J. Synchrotron. Radiat. 21 (2014) 862.
[2] P.F. Tavares et al., Commissioning and first-year operational results of the MAX IV 3 GeV ring, J. Synchrotron. Radiat. 25 (2018) 1291.

Storage Ring

Illustration of an example of the FEL station with dog-bone beam line for the beam energy recovery







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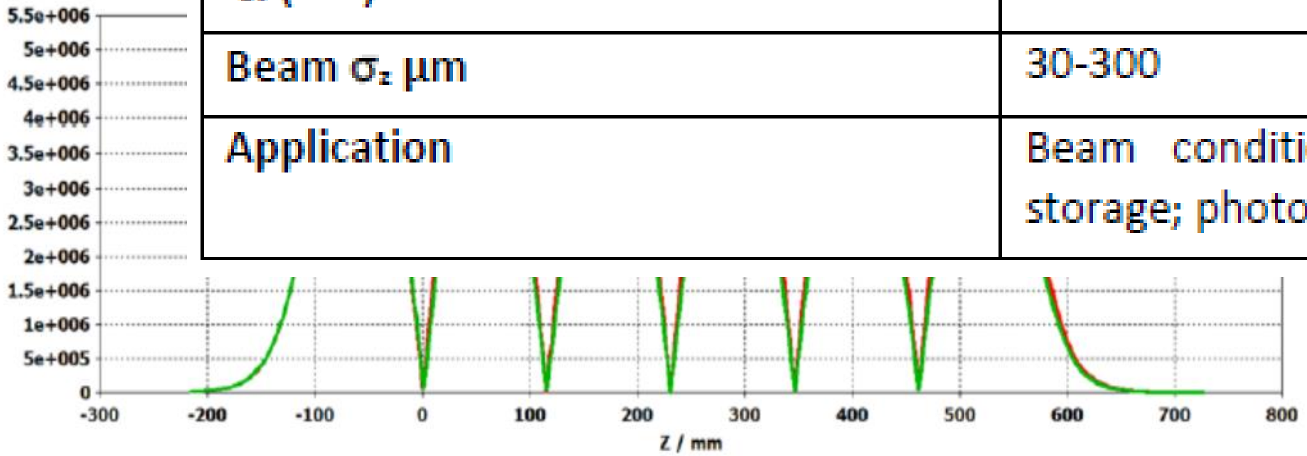
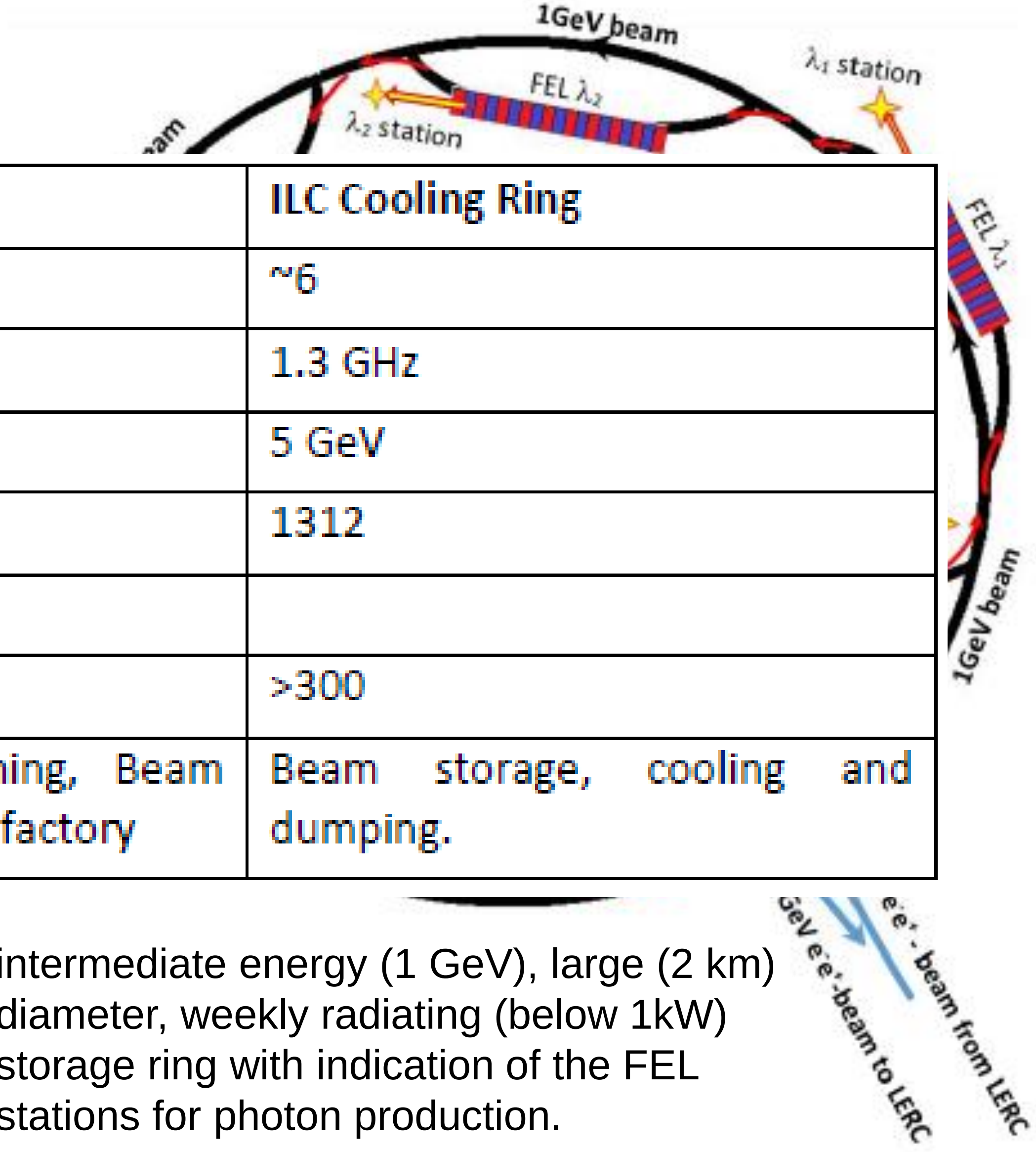
Storage Ring

Illustration of an example of the FEL station with dog-bone beam line for the beam energy recovery

	CLER-C StRg	ILC Cooling Ring
Circumference (km)	~6	~6
RF frequency (GHz)	1.3 GHz	1.3 GHz
Energy (GeV)	1 GeV	5 GeV
Number of microbunches	CW	1312
I_{av} (mA)	100-1000	
Beam σ_z μm	30-300	>300
Application	Beam conditioning, Beam storage; photon factory	Beam storage, cooling and dumping.





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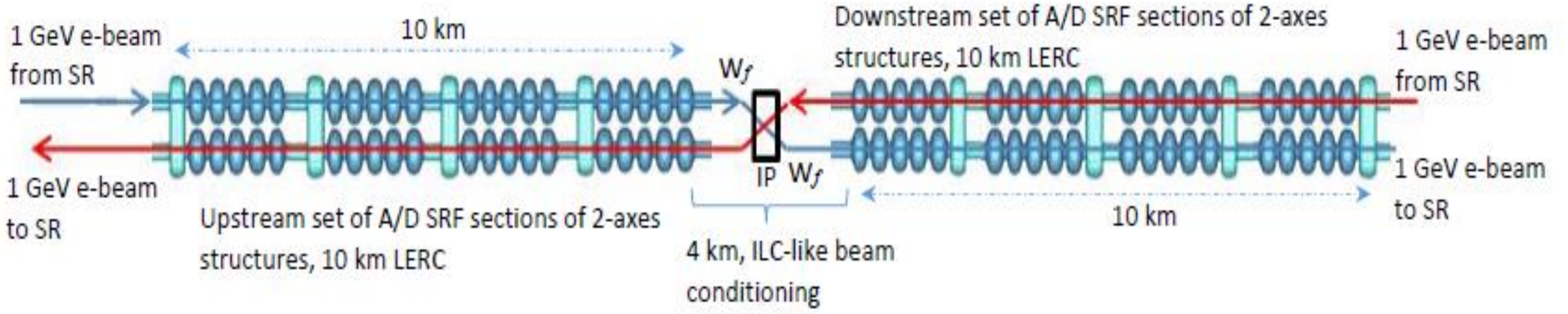
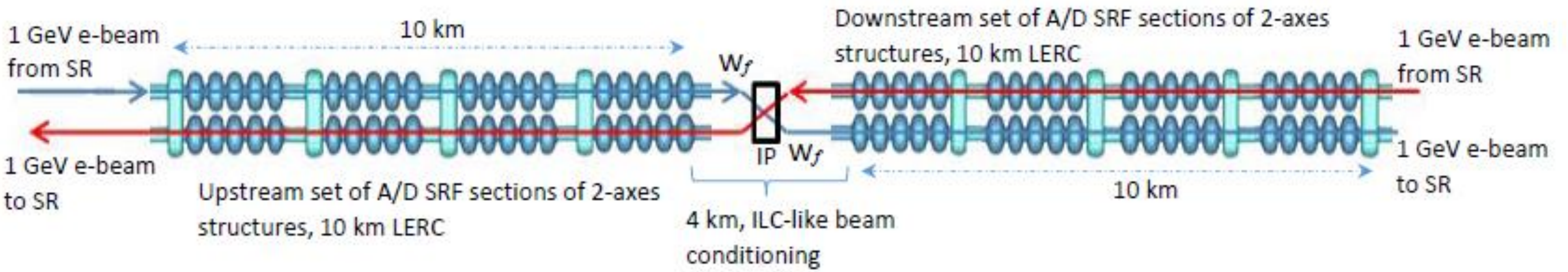
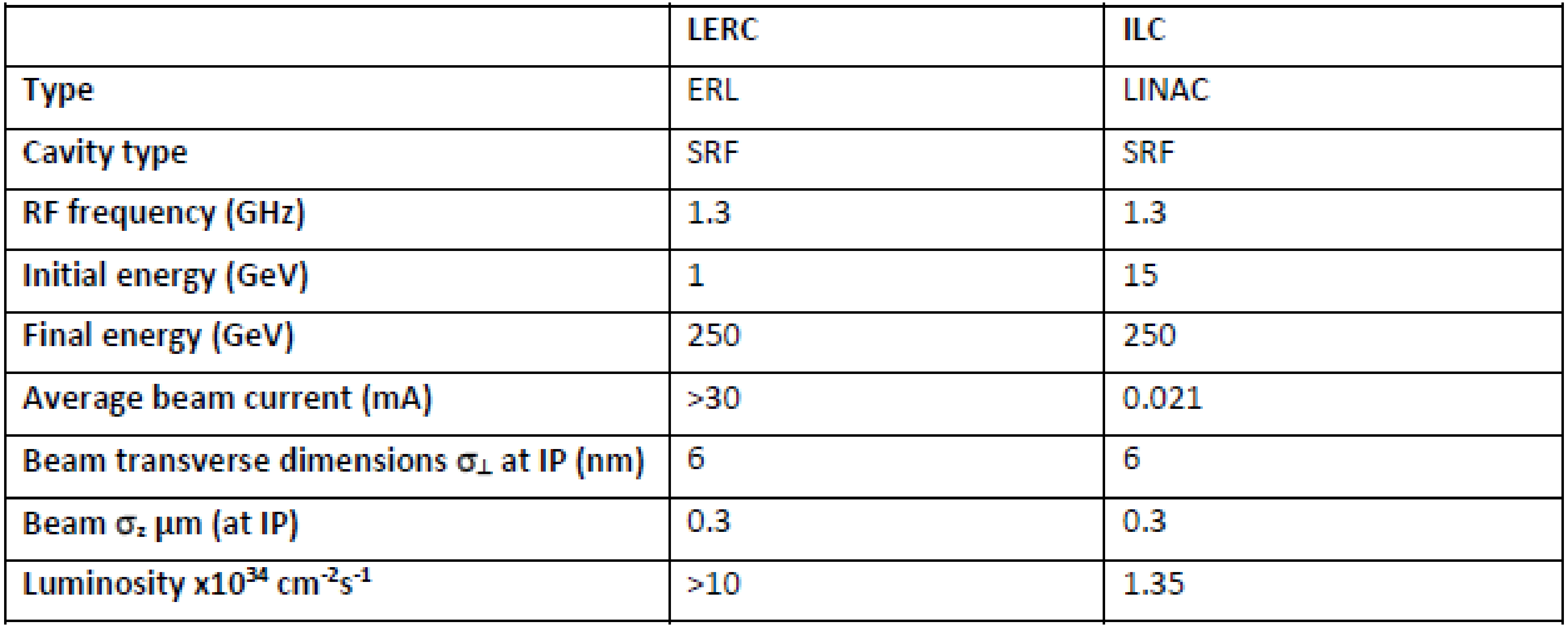
Liner Energy Recovery Collider



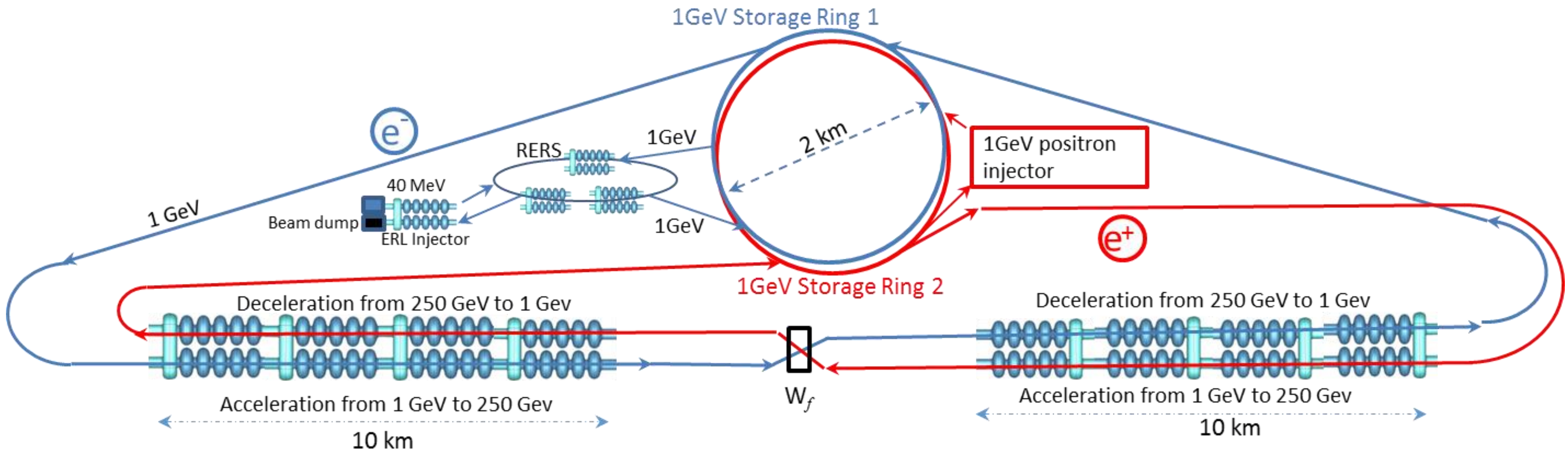
Liner Energy Recovery Collider



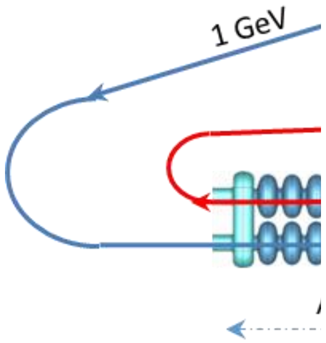


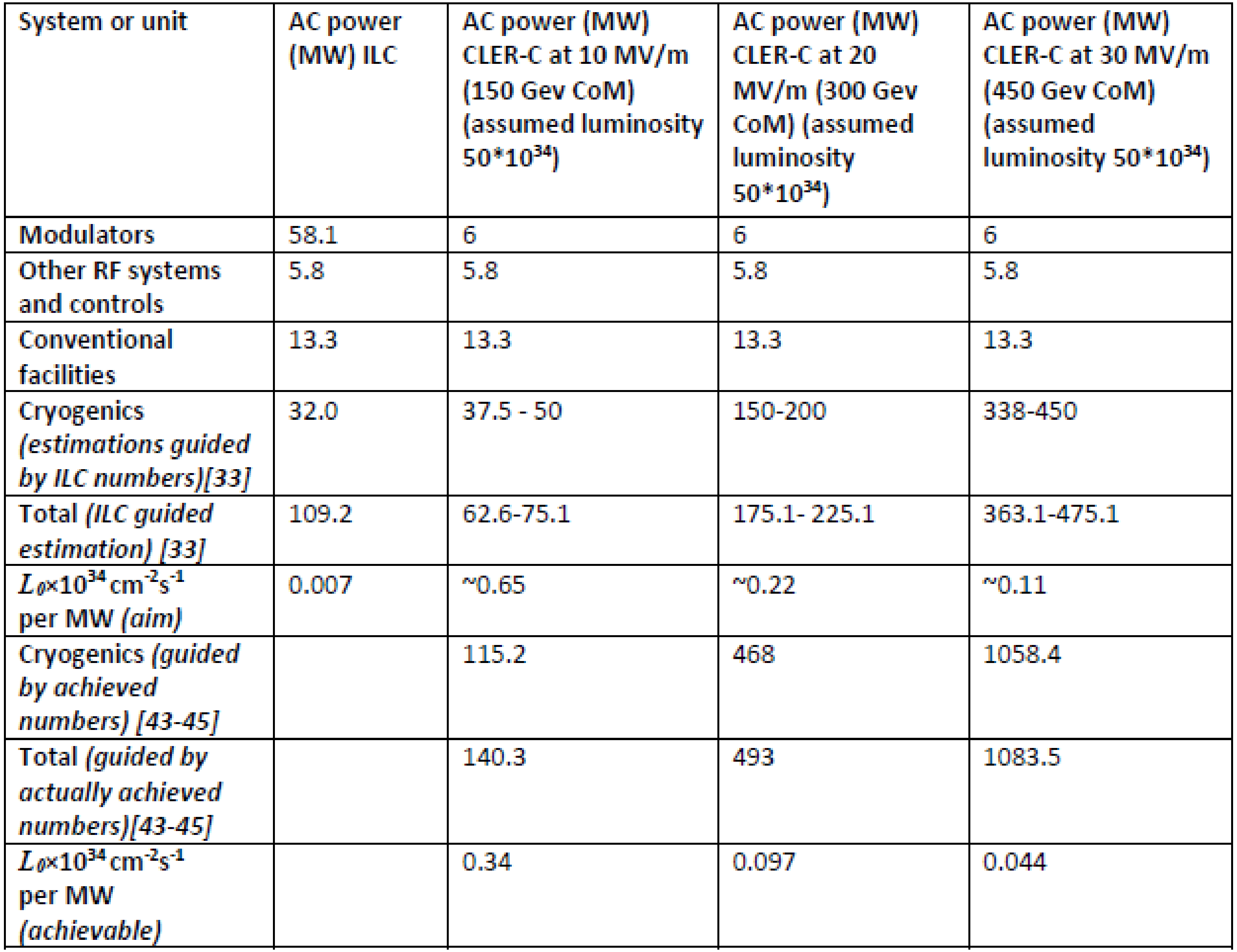
	LERC	ILC
Type	ERL	LINAC
Cavity type	SRF	SRF
RF frequency (GHz)	1.3	1.3
Initial energy (GeV)	1	15
Final energy (GeV)	250	250
Average beam current (mA)	>30	0.021
Beam transverse dimensions $\sigma_\perp$ at IP (nm)	6	6
Beam σ_z μm (at IP)	0.3	0.3
Luminosity x10^{34} cm^{-2}s^{-1}	>10	1.35

Circular-Linear Energy Recovery Collider

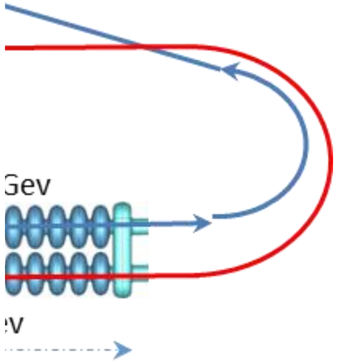


Circular-Linear Energy Recovery Collider





System or unit	AC power (MW) ILC	AC power (MW) CLER-C at 10 MV/m (150 Gev CoM) (assumed luminosity $50*10^{34}$)	AC power (MW) CLER-C at 20 MV/m (300 Gev CoM) (assumed luminosity $50*10^{34}$)	AC power (MW) CLER-C at 30 MV/m (450 Gev CoM) (assumed luminosity $50*10^{34}$)
Modulators	58.1	6	6	6
Other RF systems and controls	5.8	5.8	5.8	5.8
Conventional facilities	13.3	13.3	13.3	13.3
Cryogenics *(estimations guided by ILC numbers)[33]*	32.0	37.5 - 50	150-200	338-450
Total *(ILC guided estimation) [33]*	109.2	62.6-75.1	175.1- 225.1	363.1-475.1
$L_0 \times 10^{34}$ cm^{-2}s^{-1} per MW *(aim)*	0.007	~0.65	~0.22	~0.11
Cryogenics *(guided by achieved numbers) [43-45]*		115.2	468	1058.4
Total *(guided by actually achieved numbers)[43-45]*		140.3	493	1083.5
$L_0 \times 10^{34}$ cm^{-2}s^{-1} per MW *(achievable)*		0.34	0.097	0.044



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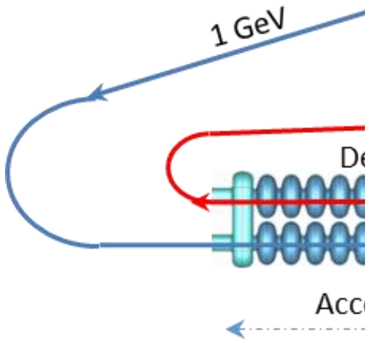

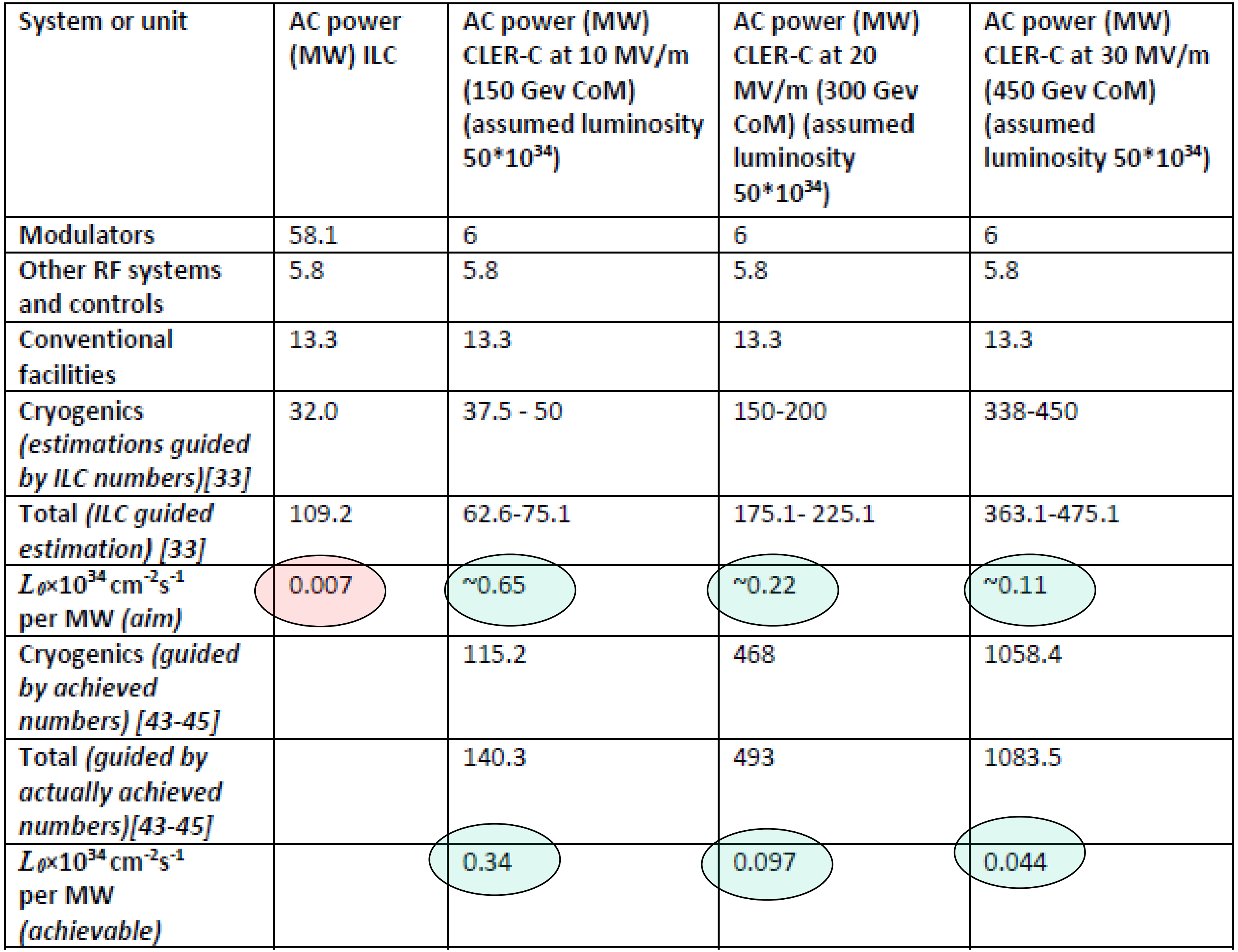

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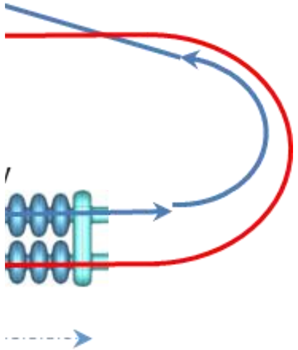
Conventional facilities	13.3	13.3	13.3	13.3
Cryogenics *(estimations guided by ILC numbers)[33]*	32.0	37.5 - 50	150-200	338-450
Total *(ILC guided estimation) [33]*	109.2	62.6-75.1	175.1- 225.1	363.1-475.1
$L_0 \times 10^{34}$ cm^{-2}s^{-1} per MW *(aim)*	0.007	~0.65	~0.22	~0.11
Cryogenics *(guided by achieved numbers) [43-45]*		115.2	468	1058.4
Total *(guided by actually achieved numbers)[43-45]*		140.3	493	1083.5
$L_0 \times 10^{34}$ cm^{-2}s^{-1} per MW *(achievable)*		0.34	0.097	0.044



Conclusion

- The aluminium (7-cells) and copper (11-cells) dual axis asymmetric cavities were constructed
- Preliminary studies of HOMs and path-band modes were carried out and HOMs localisation has been demonstrated
- The first design of the SRF dual axes asymmetric cavity has been completed
- Outlines of the new concepts of CLER –C and CLER-FEL have been presented

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