Mini-workshop on energy recovery

Timetable :

I. Presentations

   i. Context and state of the art (Julien)
   ii. Principle of energy recuperation (Frederic)
   iii. Application on PERLE (Christophe)

II. Discussions

State of the art

Energy recuperation is more in fact **power** recuperation. Two quantities are important :

Beam energy : financial issue. Basically increase the size of the linac (pure cost) or multi-turns (cost+optics)
Best energy recuperated : CEBAF (1GeV). 2nd is JLAB FEL (165 MeV)

Beam intensity : technical issue. Intensive R&D needed.
Best current recuperated : CBETA (8mA) and JLAB FEL (8mA). BerlinPro aim for 100mA.

Beam power : energy * intensity
Best power : JLAB FEL (1,3MW) and CBETA 4pass (1200MW).

A fonctionné et data available
A fonctionné mais manque data
A venir bientôt
Not funded

///////////// /	Pays	Année	Courant (mA)	Energie (MeV)	Puissance (kW)	Tours ERL (total)	Transmission	Efficacité	Commentaires
JLAB IR FEL	USA	2007	8	165	1320	1	?	?	
Recuperator	Russie	2015	30	10(42)	1260	4	?	mauvais (cavités chaudes)	
CEBAF	USA	2003	0,08	1000	80	1 (4)	100%	?	faisability test only
S-Dalinac	Allemagne	2021	0,002	50	0,1	2 (3)	?	87%	
MESA	Allemagne	soon	1	105	105	2	a venir	a venir	polarized
BerlinPro	Allemagne	Not funded	100	50	5000	1	0	0	Not funded
BerlinPro	Allemagne	futur	5	32	160	1	a venir	a venir	
cERL	Japon	2018	1	20	20	1	100%	quasi 100%	
Cbeta 1 pass	usa	2020	8	42	336	1	100%	99.4 %	FFAG
Cbeta 4 pass	usa	2020	8	150	1200	4	36%	<36%	FFAG
ALICE	Angleterre	2009	1,6	21	33,6	1	1	1	sur 100us uniquement

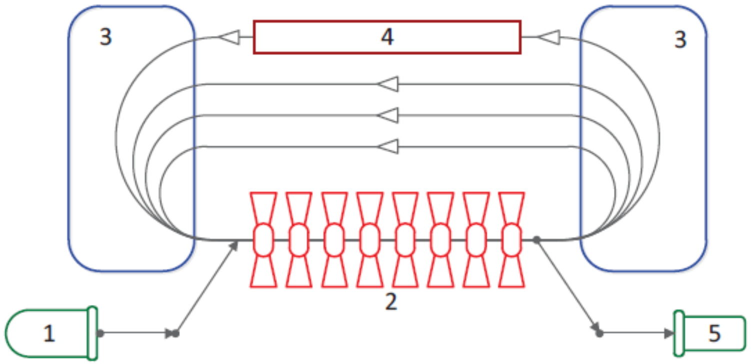
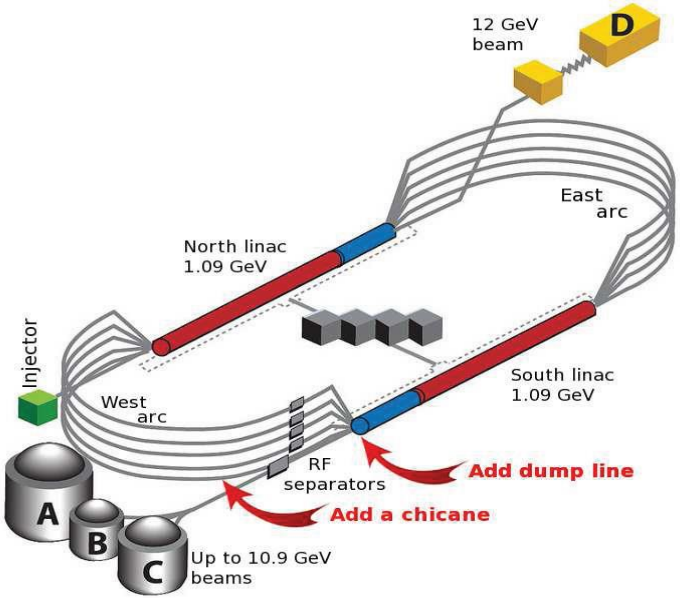


FIGURE 1. Simplified multi-turn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump.

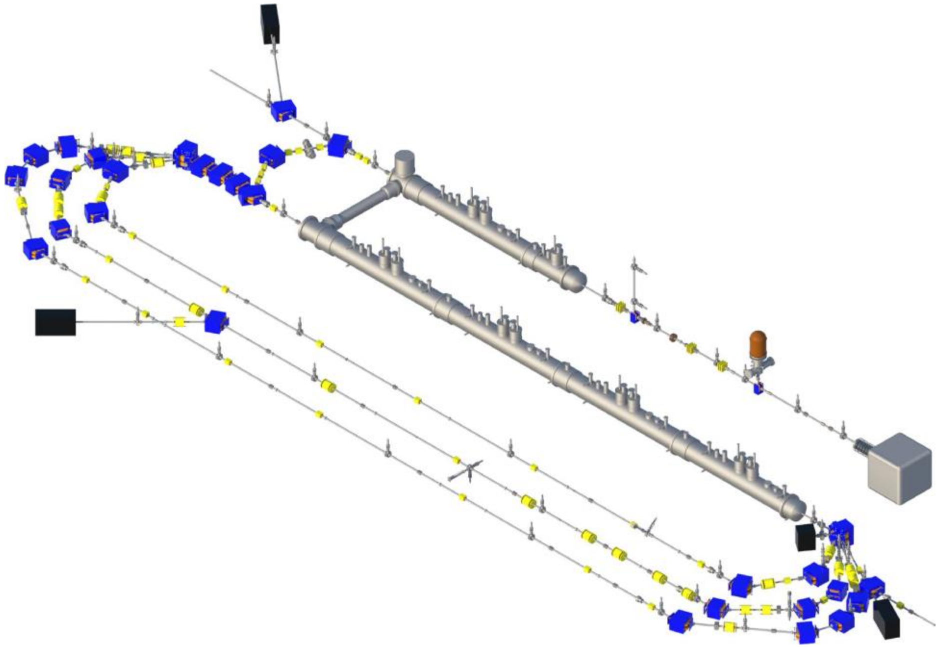
- FEL installation
- Hot cavities : no real energy recup but more energy dumping

O. A. Shevchenko et al., “The Novosibirsk Free Electron Laser Facility,” AIP Conference Proceedings 2299 020001 (2020).



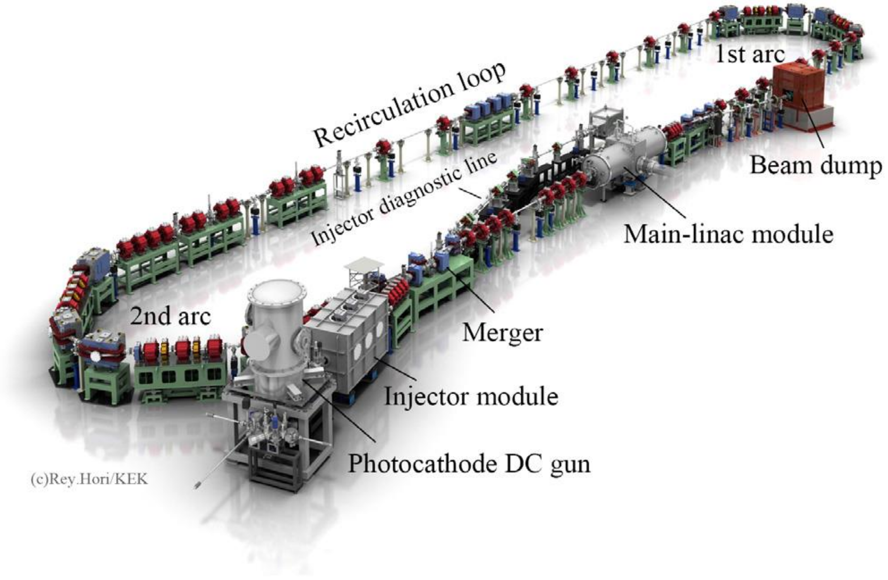
- Biggest energy recup. (1GeV), but very low current (80µA)
- Just used for demonstrated but never used in real operation (for experiments)
- Plan to test energ recup. on 5 passes (11GeV)

F. Meot et al, "ER@CEBAF - A High Energy, Multi-pass Energy Recovery Experiment at CEBAF," Proceedings, 7th International Particle Accelerator Conference (IPAC 2016), Busan, Korea, May 8-13, 10.18429/JACoW-IPAC2016-TUOBA02 (2016).



- 2021 : demonstration of energy recup. at 50 MeV and 2,3 µA. P = 100W.
- Efficiency of 84%
- At 7 µA, efficiency of 50%

Schliessmann, F., Arnold, M., Juergensen, L. *et al.* Realization of a multi-turn energy recovery accelerator. *Nat. Phys.* **19**, 597–602 (2023). https://doi.org/10.1038/s41567-022-01856-w

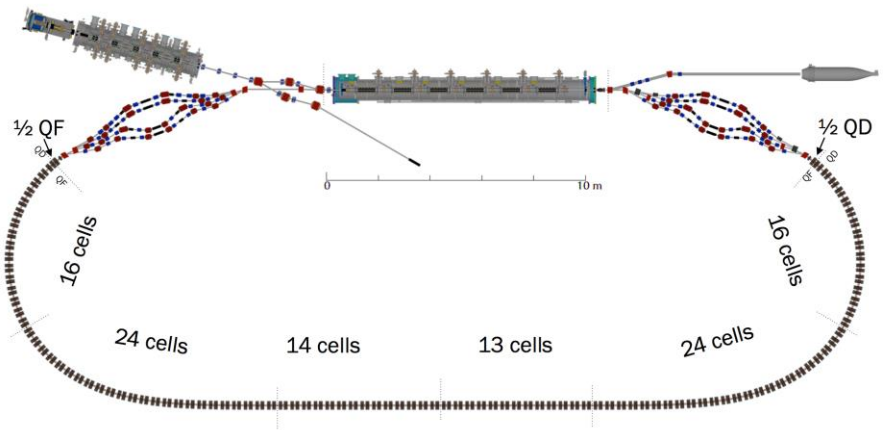


Design parameters of the compact ERL.

Beam energy[a] E	35 MeV
Average beam current I_0	10 mA
Injection energy[a] E_{inj}	5.5 MeV
Accelerating gradient in ML cavities E_{acc}	15 MV/m
Rms normalized emittance (@charge/bunch) ε_n	0.3 mm·mrad (@7.7 pC)
	1 mm·mrad (@77 pC)
Rms bunch length σ_τ	1–3 ps
	100 fs (with bunch compression)
RF frequency f_{rf}	1.3 GHz
Repetition frequency of bunches f_b	1.3 GHz (for usual operation)
	162.5 MHz (for LCS experiment)

- Mostly used for X-Rays
- Efficiency of 100% ???
- At 10 mA, 20 MeV ➔ 200kW

M. Akemoto et al., "Construction and commissioning of the compact energy-recovery linac at KEK," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 877 197 (2018).



1-pass

- 8mA, 42MeV ➔ P = 336kW
- Efficiency of ~100%

4-pass

- 8mA, 150MeV ➔ P = 1,2MW
- Transmission of ~36% (➔ efficiency ≤ 36%)

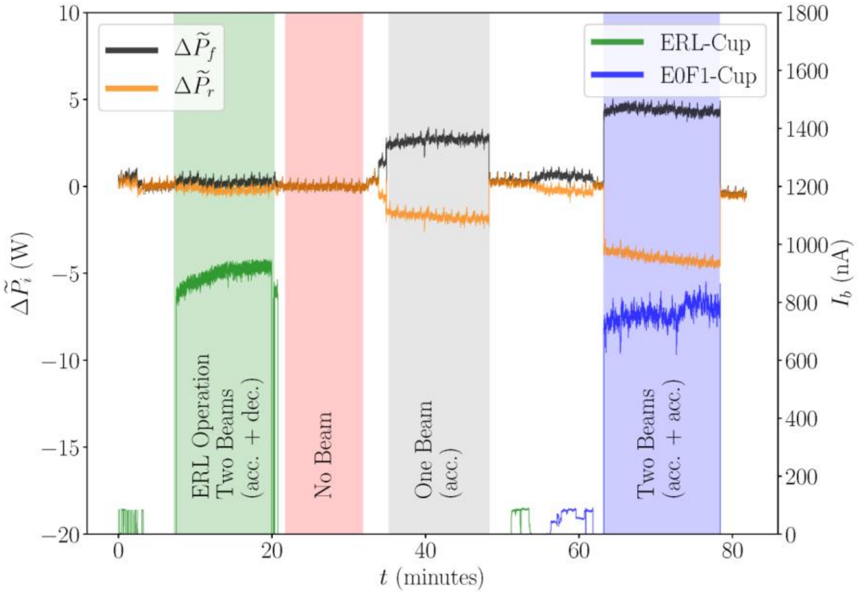
J. Berg et al., "CBETA FFAG Beam Optics Design," in Proc. 59th ICFA Advanced Beam Dynamics Workshop (ERL'17), Geneva, Switzerland, June 18–23, 2017, no. 59 in ICFA Advanced Beam Dynamics Workshop, (Geneva, Switzerland), pp. 52–57, JACoW Publishing, 05, (2018), DOI.

Problematics

Lack of information about energy recuperation in litterature :

- Either the facilities are not really interested in energy recuperation (JLAB FEL, CEBAF…)
- Or lack of proper definition for energy recuperation
- Or even no information at all…

Best information from S-Dalinac :



Proof of energy recuperation can be seen in the cavity load !

Questions to be answered

- How is energy recuperation working ?
  - Frederic's talk + discussions
- What are the sources of energy loss ? Is an official ER definition existing ?
  - Identify energy/power consuming elements
  - Try to define precisely what we call energy recuperation
    1. From cavity/beam perspective only (Q0, beam-RF interaction…) ~100% if everything is perfect. Is <100% if for example phase-shift is not complete.
    2. From ERL perspective (include SR/CSR losses, beam losses etc…) ~100% - ϵ
    3. From full machine (substract injector energy) => max 97,2% for PERLE
    4. Overall energy « bilan » . Cryo, magnets, RF…
    5. \+ can we use dump energy to compensate (dump at 5 MeV to gain 2 MeV for example) ?
- What do we expect for PERLE ?
  - Christophe's talk + discussions
- On which real observables ?
  - RF load ? Field measurement ? Energy measure at dump ?