7th IPAC, May 8-13, 2016, Busan, Korea

ER@CEBAF

A High-Energy, Multiple-Pass, Energy Recovery Experiment at CEBAF

On behalf of the JLab-BNL ER@CEBAF collaboration :

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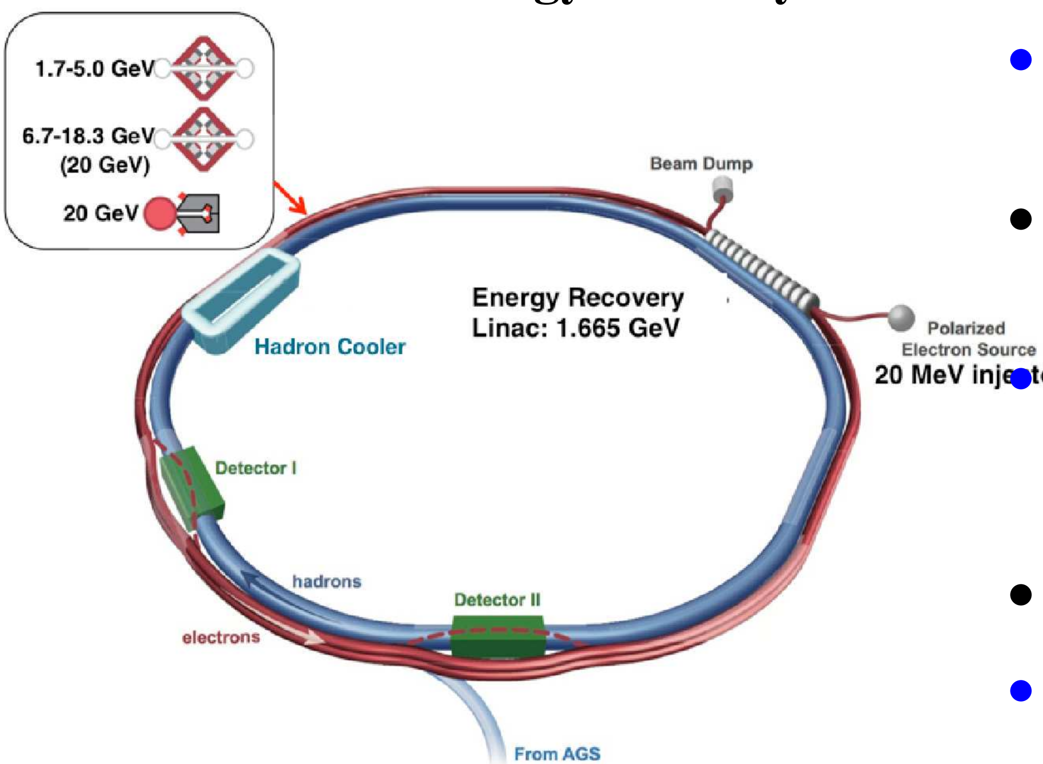
1 CONTEXT OF THIS PROJECT

WEPMW027: "The ERL-based Design of Electron-Hadron-Collider eRHIC"
WEPMW044: "Start-to-End Simulation of eRHIC ERL"

1.1 eRHIC Electron-Ion Collider

- **EIC is next high priority large facility in the 2015 DOE NP Long Range Plan**
- **BNL develops a linac-ring scheme**
  - **based on the existing RHIC collider,**
  - **and on a 20 GeV energy recovery linac.**



eRHIC EIC - in short

Luminosity [/cm^2/s]	$10^{32} - 10^{34}$			
Center-of-mass energy [GeV]	20 to 140			
Species	e	p	^{3}He	A
Energy, max. [GeV, GeV/u]	20	250	167	100
Beam current, max. [mA]	50	400	200	
Polarization [%]	80	70	70	-

Advantages of ERL method :

- **high brightness e-bunches, undergo single collision, then ER'ed,**
- **high beam power with reduced RF drive power,**
- **yet**
  - **beam current on lower side, thus**
  - **SR power loss as well,**
- **low energy, low power beam dump,**
- **wall-plug eff ciency (a necessity, given e-beams of 100s of MW).**

1.2 Objective of ER@CEBAF : EIC R&D

- **We want to do big, pioneering science :**

multi-GeV, multiple-pass energy recovery

- **Goal : perform a practical study of bunch phase space preservation**

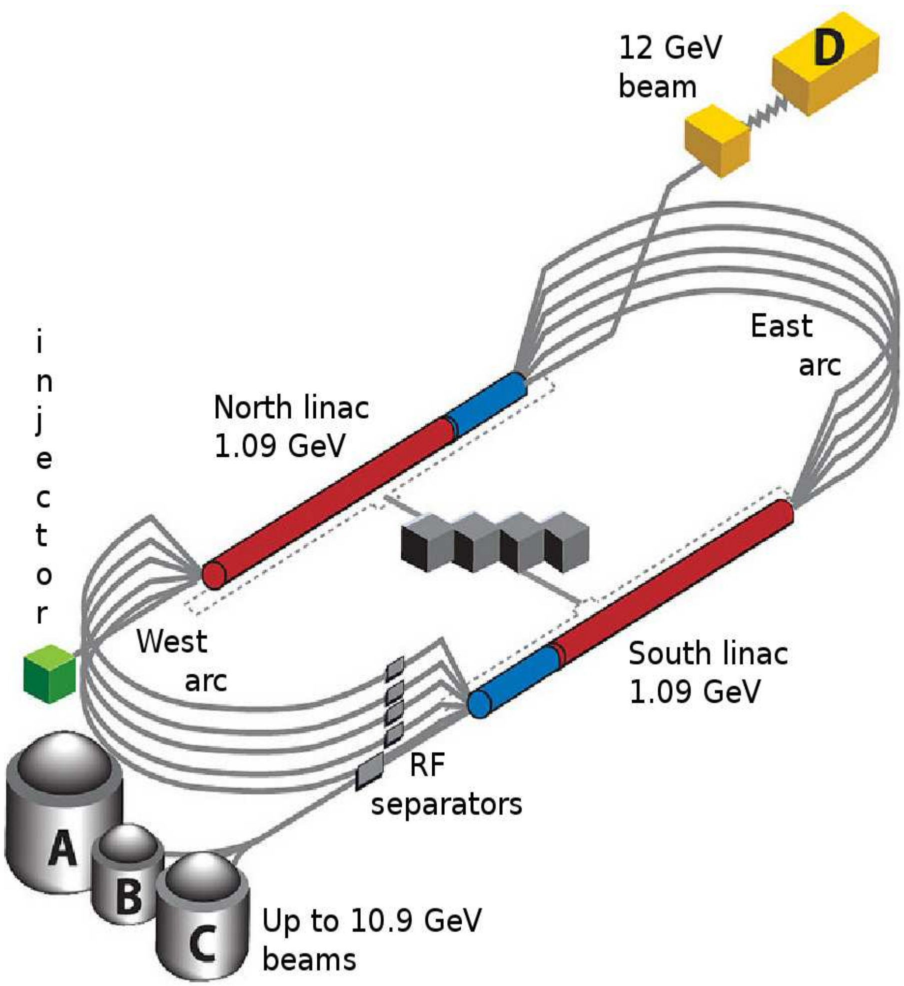
- **Which - in passing - also means commissioning and operation of a large-scale superconducting recirculating linac in energy recovery mode**

Further :

- **Evaluate the limitations and ultimate performance, anticipate on diff culties in relation with eRHIC ERL R&D**

- **Anticipate on eRHIC ERL operation : provide guidance, learn, form people**

2 CEBAF 12 GeV RLA



Parameters	CEBAF	eRHIC
Energy [GeV]	**12**	**3.3 - 20**
Beam current [mA]	$\lesssim$**0.1**	**26 - 50**
Beam power [MW]	$\boxed{1}^{(a)}$	**up to 400**
SR loss [MW]	**0.008**	$\boxed{2.5}^{(a)}$
Numb. of linacs	**2**	**1**
Linac energy [GeV]	**1.09**	**1.67**
Linac passes	$\leq$**11**	$\leq$**12**
Bunch :		
Bunch freq. [MHz]	**31-1497**	**9.4**
ppb, max. $[10^{10}]$	10^{-4}	**1.7 - 3.3**
rms $\epsilon_{x,y,\mathrm{norm.}}$ $[\pi\mu$**m]**	**3**	**10 - 70**
rms **length [mm]**	**0.09-0.15**	**3**
rms $\Delta E/E$	$< 10^{-4}$	$< 10^{-3}$
Linac :		
Length [m]	**250**	**176**
RF freq. [MHz]	**1497**	**647**
Numb. of cavities/linac	**200**	**80**
Cavity type	**5- & 7-cell**	**5-cell**
Gradient [MV/m]	**7 - 20**	**18**

(a) Practical constraint

- **CEBAF is the only installation that allows multiple-pass, multi-GeV ER.**

- **Other installations are limited**

- in energy

- or in the number of passes

Operated ERLs, in short :

Facilities	CEBAF -ER	JLab FEL IR+	JLab FEL UV	BINP	KEK
Linac E [MeV]	1000	165	135	10	17
Numb. passes	1	1	1	4	1
ER'ed curr. [mA]	0.08	9	2.5	30	0.1

- **JLab has a long expertise in design, commissioning, operation of multiple ERLs:**

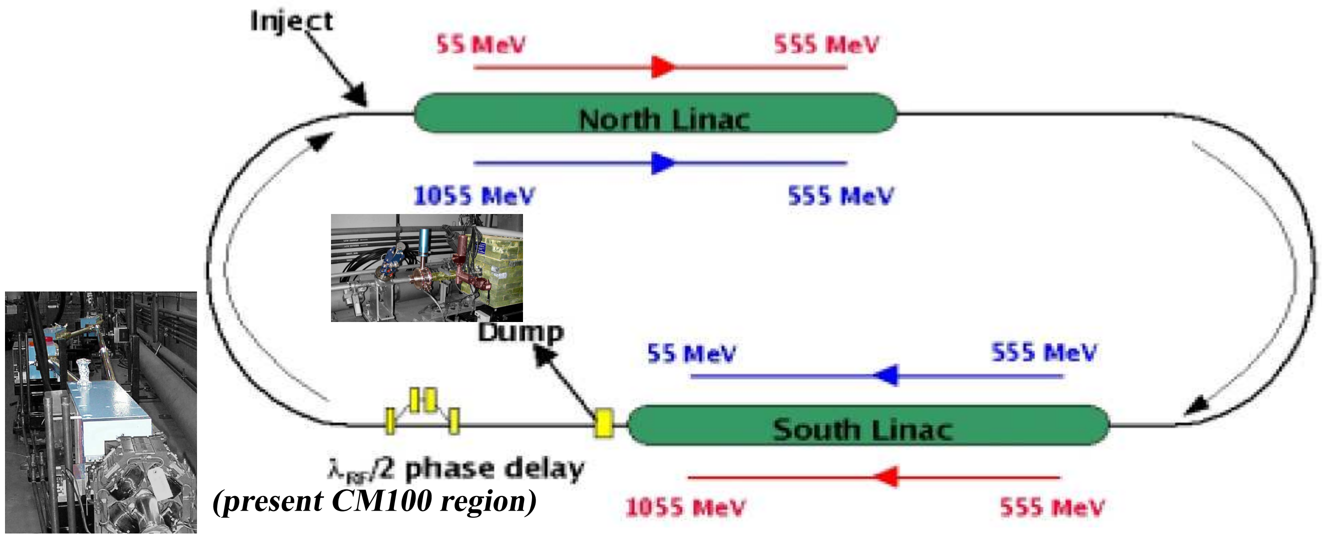
- CEBAF Front-End Test (*1992*, 42.8 MeV, 31 μA CW beam, 100% ER'ed)

- CEBAF-ER experiment (*2003*, 1 GeV, 80 μA, CW)

- JLab FEL, *since 1997* : IR Demo, IR Upgrade, UV FEL, Darklight

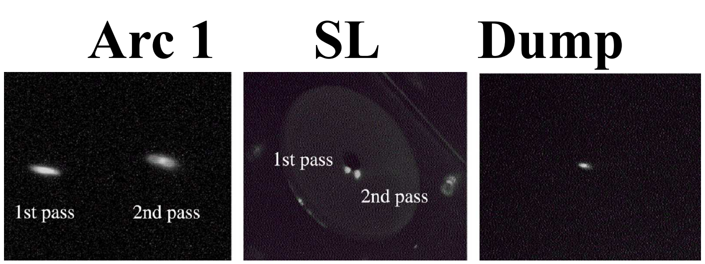
CEBAF-ER experiment, 2003

- **It demonstrated 1-pass up/1-pass down, 1 GeV energy recovery, CW beam,**



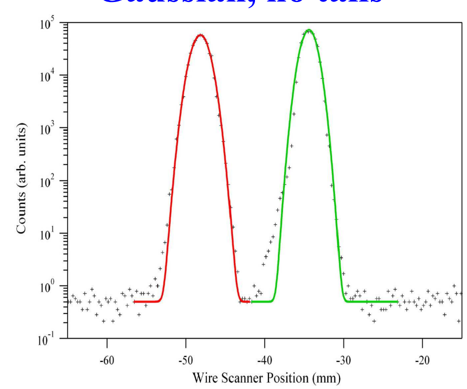
- **Measurements included (at injector, arcs, dump) transverse emittances, momentum spread, halo. Included RF system response to ER.**

[Details : C. Tennant, Studies of ERLs at Jefferson Laboratory, PhD Dissertation, JLab, 2006.]



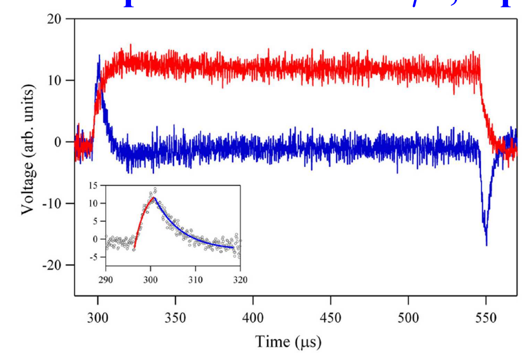
V / H beam prof les at dump

Gaussian, no tails

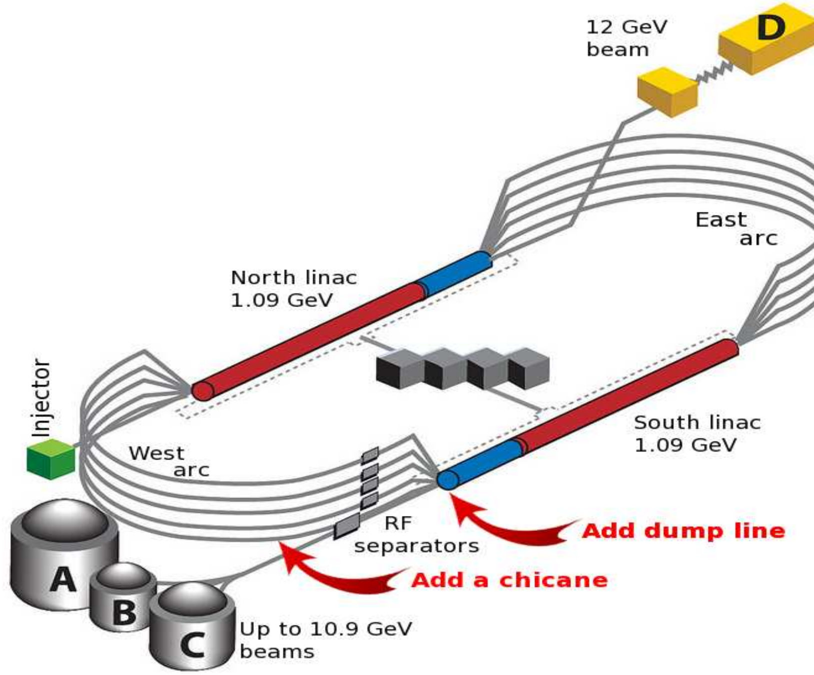


LLRF signal w/o ER and w/ ER.

Transient power draw is 4.3μs, 1-pass.



4 ER@CEBAF



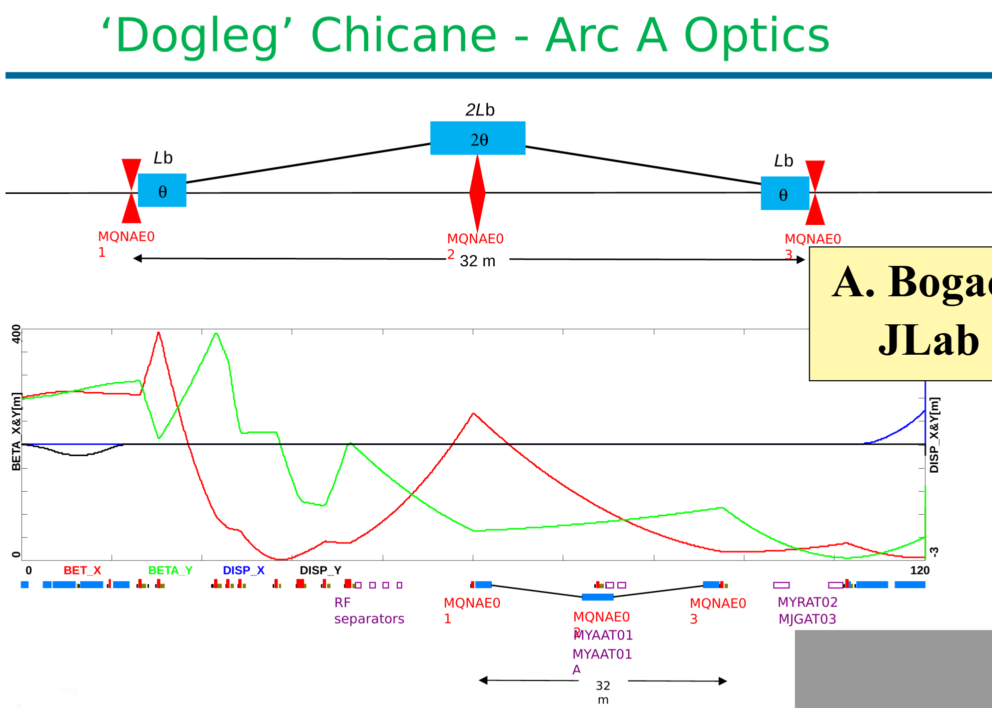
- **HIGH ENERGY : up to 7+ GeV**
- **MULTIPLE-PASS : 1 up + 1 down, 3 up + 3 down, 5 up + 5 down**
- **Experiments can start with 1-pass up/1-pass down (similar to 2003 CEBAF-ER), to test procedures, equipments, diagnostics, verify beam, etc.**
- **Then increase number of turns, up to 5 up/5 down, at low energy enough that SR does not harm (400$\sim$500 MV/linac)**
- **Then push energy to 7+ GeV**

Limitation momentum acceptance in Arc 1, $\frac{\Delta p}{p} \approx 2-3\times10^{-3}$ ***(beam up and beam down have different energies due to SR loss)***

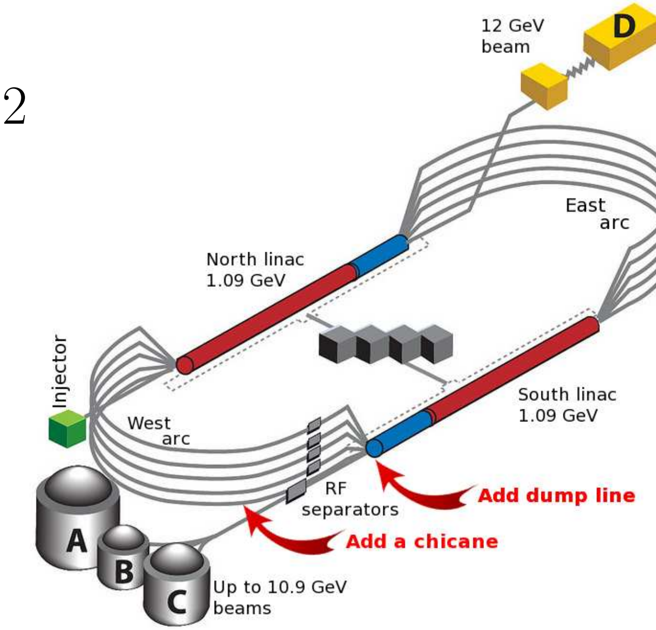
4.1 Hardware modif cations to CEBAF

- **(1/2) Phase chicane at entrance of Arc 10 ($\delta l = \lambda/2$**

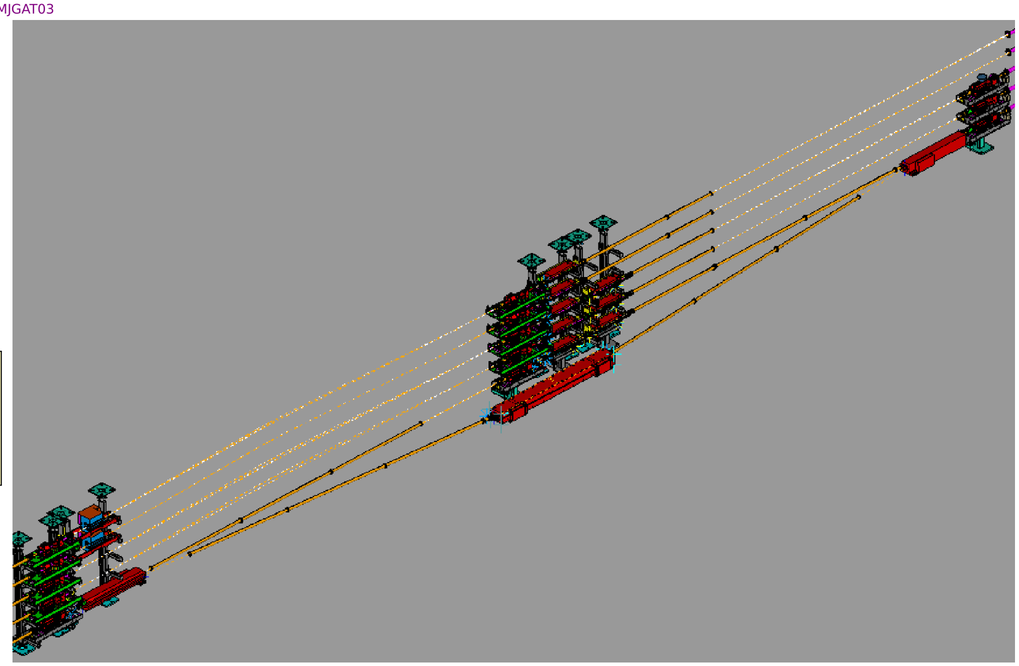
  - **Design complete**



A. Bogacz JLab



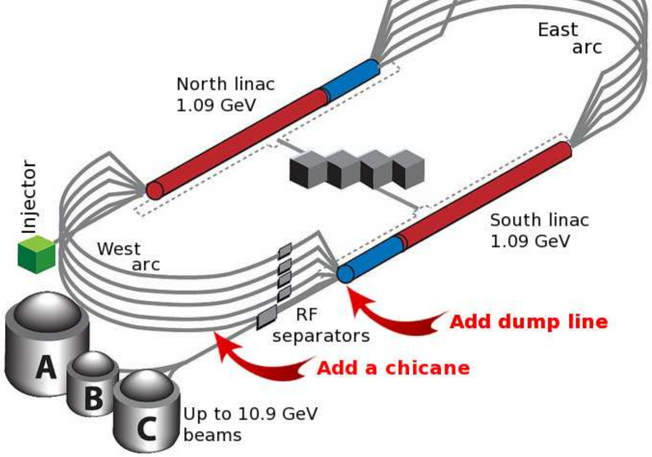
C. Dubbe JLab



• (2/2) Extraction line and dump

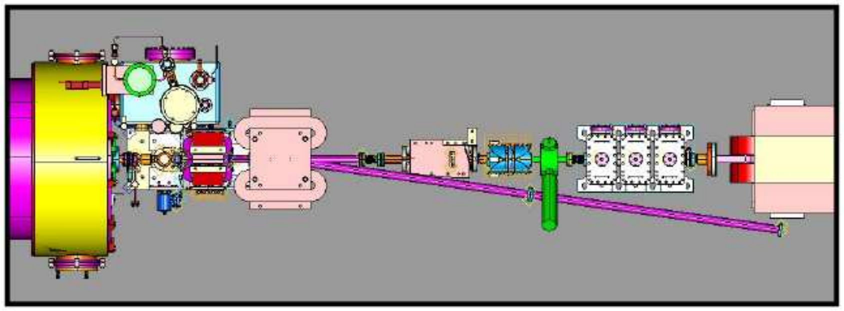
- Design complete

M. Spata & C. Dubbe - JLab

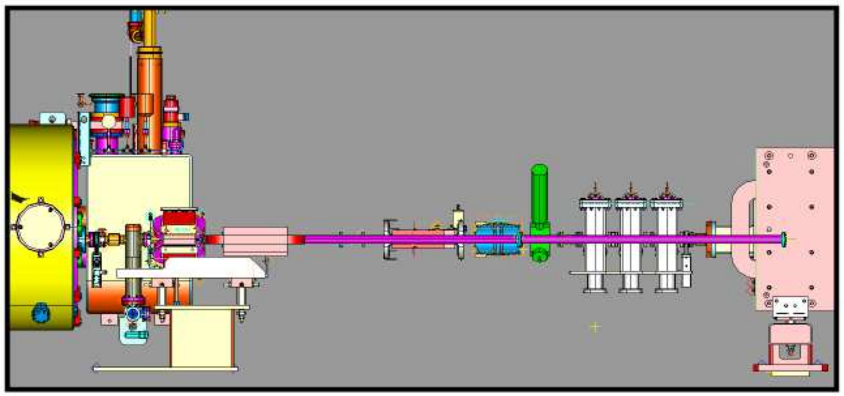


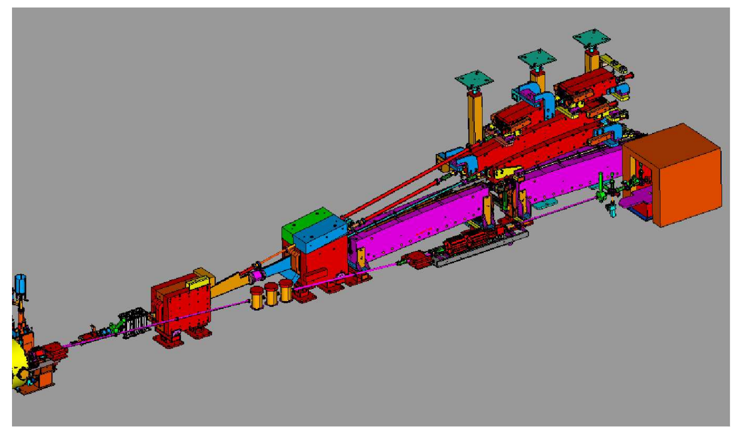
Bend Angle 8°

SOUTH LINAC →



→ SPREADER





• Chicane and dump are both transparent to CEBAF Nuclear Physics program.

Leaving them in place will allow more, long-term, ER R&D

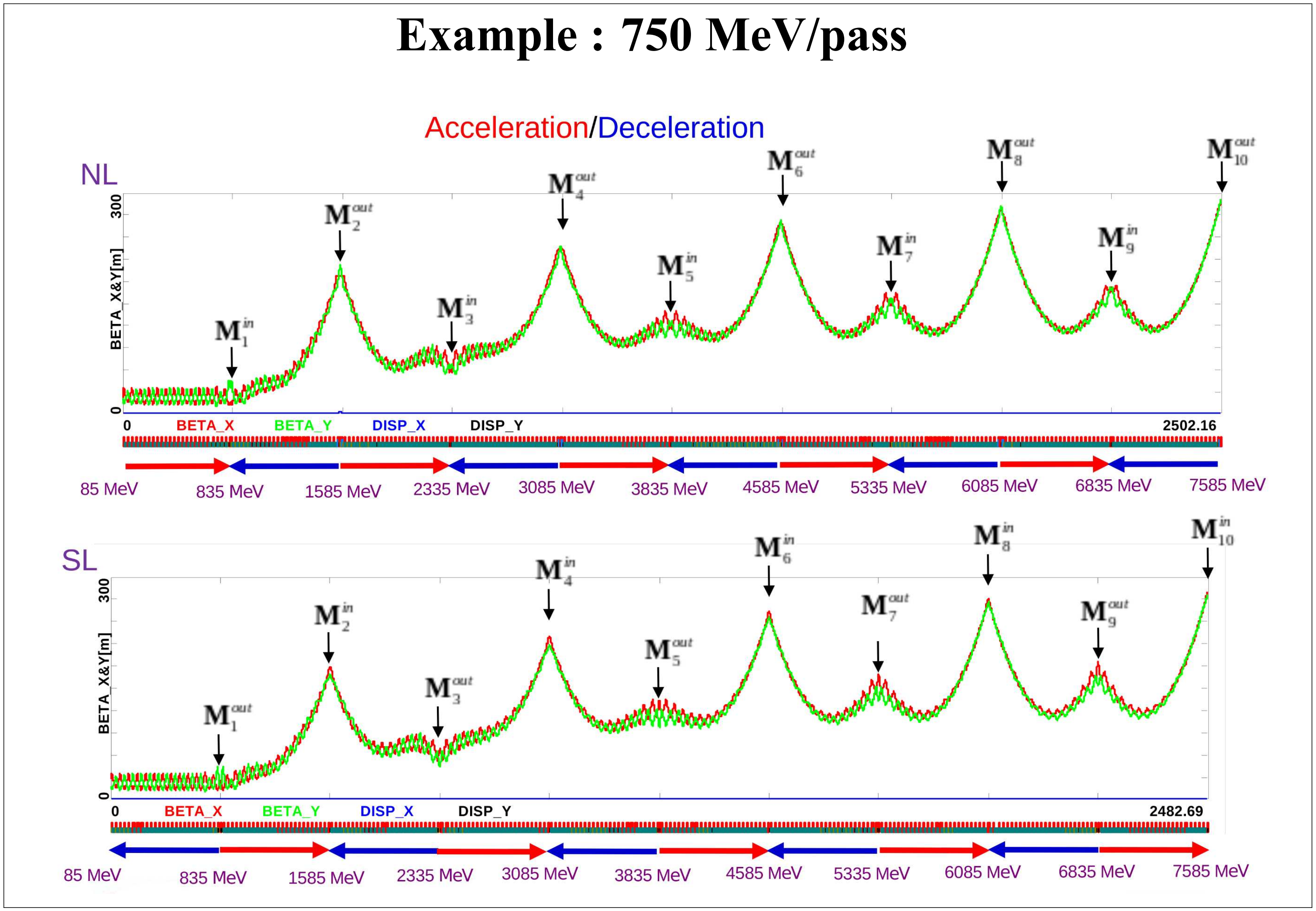
4.2 Dedicated optics

- **(1/3) Linacs**

  - **Constraints :**
    - **- limiting beta functions as energy increases**
    - **- and along each linac pass (minimize $<\beta/E>_{\rm linac}$)**

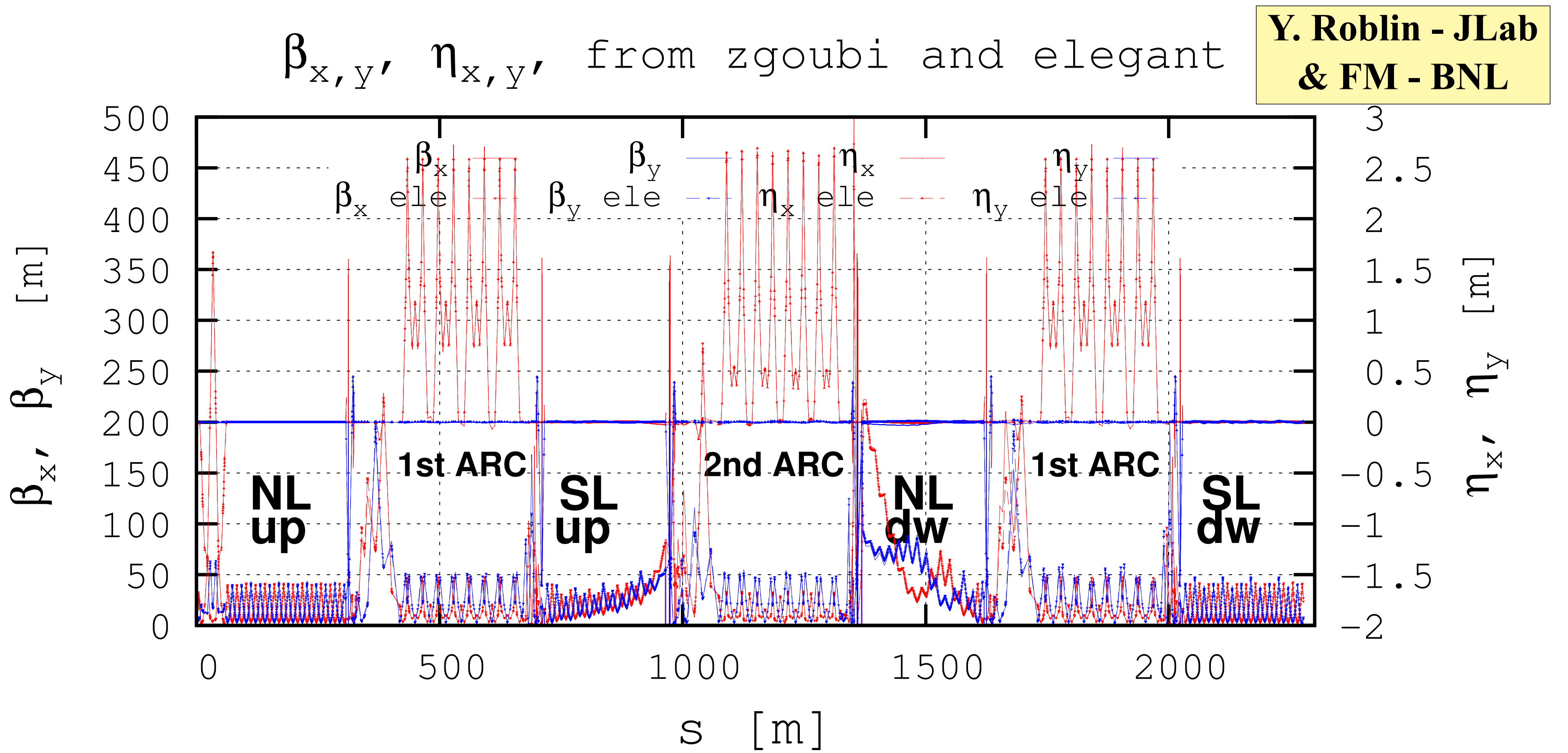
  - **Optimal : 60^o FODO-like**

A. Bogacz - JLab



• **(2/3) Spreaders/recombiners**

- They ensure match between linacs and arcs.



Example : optics 1.4 GeV, 1-pass up + 1-pass down

- Arc sextupoles are not used in normal operation. They can be included for ER experiment if necessary (e.g., 2nd order path length, chromatic aberrations)

• **(3/3) Longitudinal optics**

D. Douglas
JLab

• **ISR will degrade the beam energy spread and cause energy loss;**

- this must be allowed for by the longitudinal match

- phases and momentum compactions must be adjusted to insure that the beam stays within the machine momentum aperture during recovery:

- energies must be matched during transport through corresponding recirculation arcs

- energy spread must be compressed

• **CEBAF transport system provides phase (path length) and compaction (M_56 trim) knobs providing appropriate controls**

4.3 Parameter list

T. Satogata - JLab

MACHINE/LATTICE

f_{RF}	1497	MHz	Standard CEBAF RF frequency
λ_{RF}	20	cm	Standard CEBAF RF wavelength
E_{linac}	700	MeV	Energy gain per linac pass
E_{inj}	79	MeV	$= E_{linac} \times 123/1090$
N passes	1, 3, 5		Number of $\left\{ \begin{array}{l} \text{accelerated} \\ \text{decelerated} \end{array} \right.$ passes
ϕ FODO, linacs	60	deg	Phase advance per cell
M_{56} (Arc A)	80-90	cm	M56 compression of Arc A
M_{56} (other arcs)	0	cm	M56 compression of other arcs
Extraction angle	8	deg	Angle to dump line (3)
Dump power	20	kW	Max. ER'ed beam power
$\Delta\phi$ MOmod[4]	0.25	deg	Pathlength control tolerance

1. Master Oscillator modulation feedback that provides pathlength/phase control for main RF. 0.1 degree with new electronics.

BEAM

$f_{\rm beam}$, CW	31 - 499	MHz	CW bunch repetition frequency
$f_{\rm beam}$, tune (1)	7.485	MHz	Tune bunch repetition frequency
$I_{\rm beam}$, max. CW	100	μA	Maximum CW beam current
$q_{\rm bunch}$, max. CW	0.2	pC	Bunch charge at 100 μA CW
σ_l	90 - 150	μm	Bunch length (high energy)
σ_t	300 - 500	fs	
$\epsilon_{x,y}$ geom., inj.	$\sim 10^{-8}$	m	Transverse rms, at injection
dp/p$_{inj}$	??		Energy spread at injector
$\epsilon_{x,y}$ geom., extr.	$\mathcal{O}(10^{-8})$	m	ER'ed bunch, 5 pass up/down
dp/p$_{extr}$	??	$10^{-??}$	Energy spread at extraction

1. Tune mode beam: $\{$250 μs macro-pulse f lled, 100 μs off, 4 μs macro-pulse f lled, then off$\}$ repeating at 60 Hz (16.67 ms). 4 μs trailing pulse used for linac BPM orbits and linac arrival time cavities.

4.4 Measurements foreseen

• The ultimate goal of the measurements is, characterizing the bunch at all steps in the ER process all the way from injection to dump line : similar to 2003's CEBAF-ER, in many more locations

• In particular, transverse emittances can be characterized at all energies (up, down) by extraction to Halls' line, using RF separators

• Will study RF system response to ER regime

• A host of open topics :

- Increase beam current beyond 0.1 mA. How far / what limitations ?
- 6D tomography at the dump

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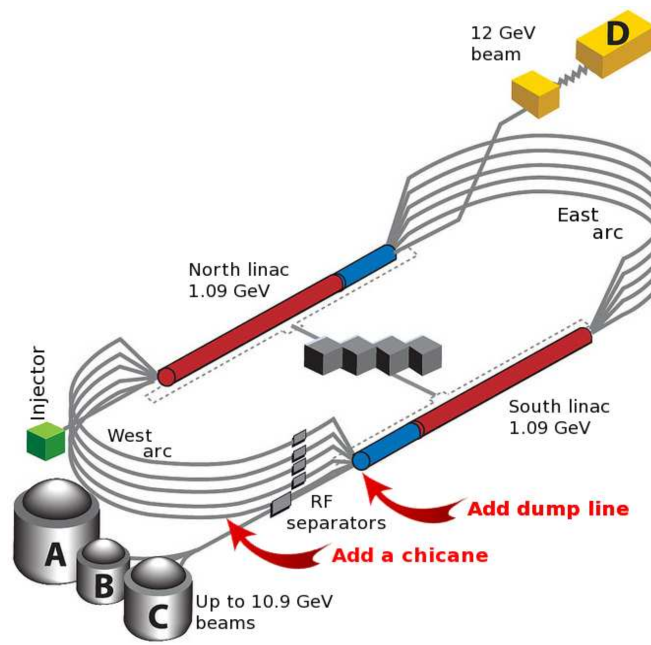
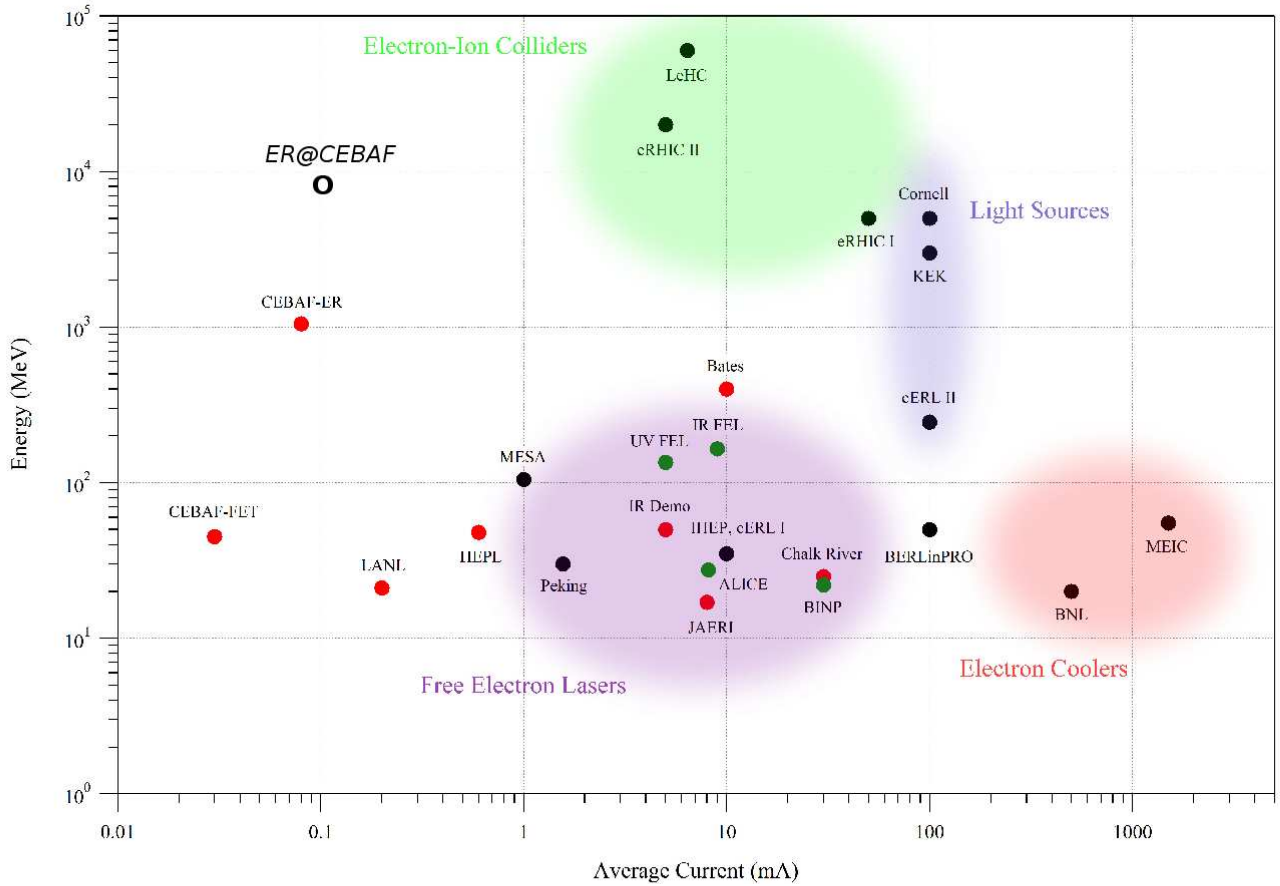


• Beyond EIC ER R&D, additional possibilities of experiments are contemplated :

- BBU
- halo
- polarization transport to 12 GeV (SR effects, RF compensation)
- multiple-beam diagnostics instrumentation

...

ERL LANDSCAPE



Red markers : previous demonstrations of ER

Green markers : ERLs in operation (2014)

[C. Tennant, Energy Recovery Linacs, *in* "Challenges and Goals for Accelerators in the XXI Century", World scientif c]

THANK YOU FOR YOUR ATTENTION