What are Advantages and Limits of Multi Turn ERLs?

Setting the Stage

- I’m presenting some numbers to get the discussion going
- Since costs depend on future manufacturing efficiencies, conclusions may be sensitive to level of “optimism”
- “Back of the envelope” numbers only flag issues for design and simulation

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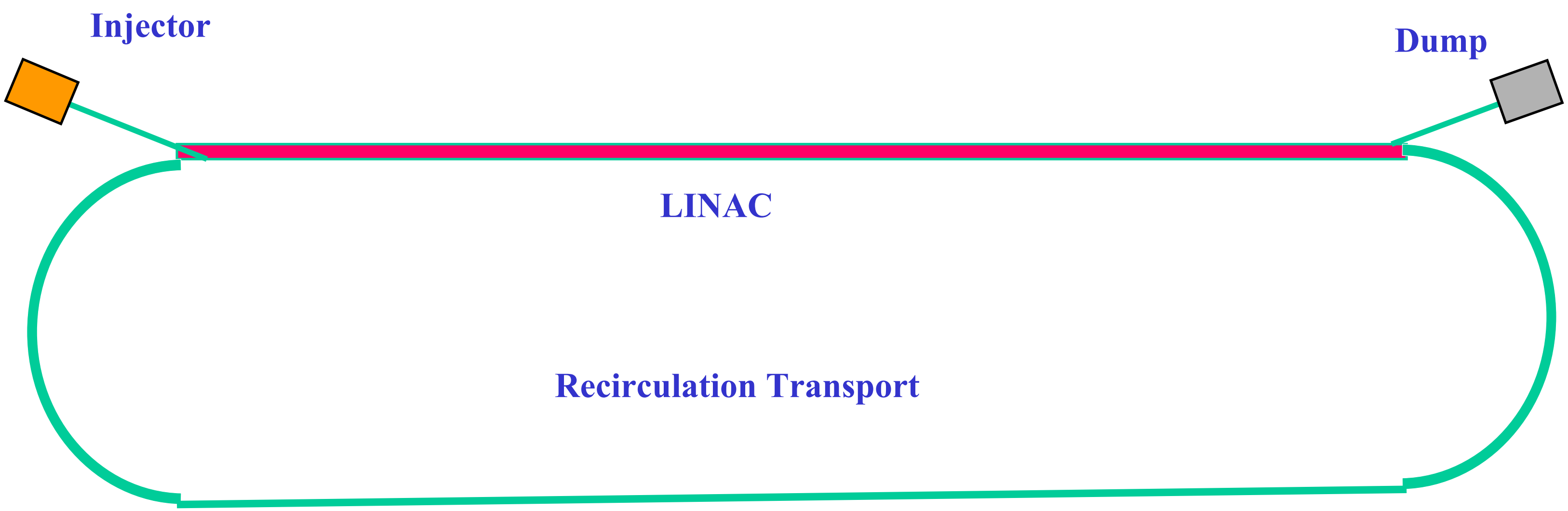
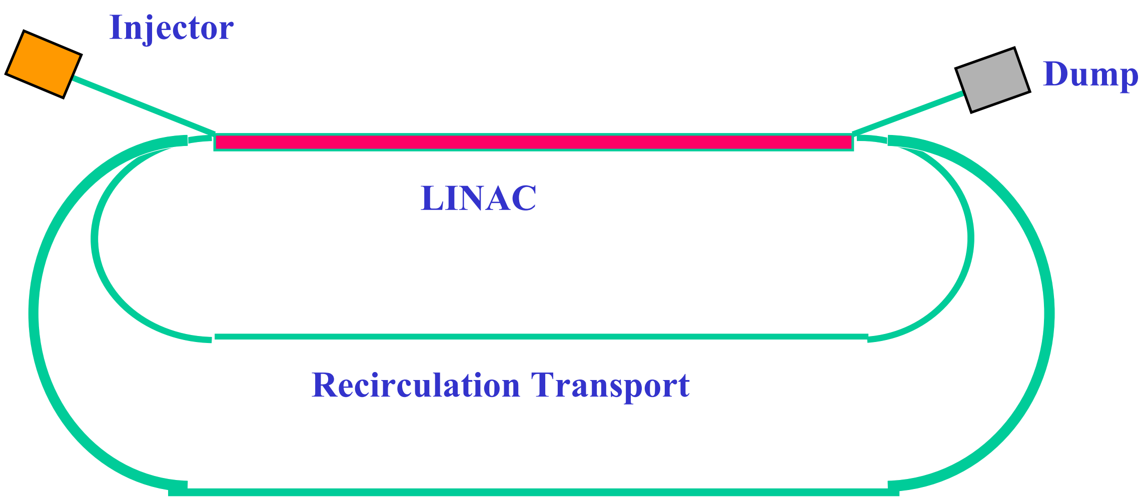
ERL Linac Configurations





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Why and Why Not

- Good
  - Save money: SRF, RF, cryo
  - Beams of different energy might be available
  - More compact; what's the shape of your site?
- Bad
  - Costs of more beam transport
  - Beam breakup average current limits
  - Another arc to coherent synchrotron radiate (CSR)
    - Emittance growth
    - Energy spread growth
  - CSR instability at high peak current
  - Space charge in bends
  - Weaker focusing: head tail could be worse
  - RF constraints; e.g., off phase choices
- Bottom line
  - **Multipass harder, but are limits limiting and are the savings significant**

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A Guess at Costs
(US Dollars)

2 GeV ERL						
Components		1 Pass Up		2 Pass Up		
		1 Pass Dn		2 Pass Dn		
Injector		same		same		
Final Arc		same		same		
Low Energy Arc				10000		
Linac w/RF		40000		20000		
Cryo plant		30000		15000		
		70000		45000		
					64.29%	

ILC Costs Much Lower

Today's costs actually might be higher

Beam Breakup

$$D_i = I \sum_{p=2}^{n_p} \sum_{r<p} \sum_{\ell=1}^{n_o} \left(T^{pr}_{i,\ell}\right)_{12} e^{M_0 \Omega \tau\ (p-r)}\ Z_\ell\, h_\ell(\Omega) D_\ell$$

$$+I \sum_{p=1}^{n_p} \sum_{\ell=1}^{i-1} \left(T^{pp}_{i,\ell}\right)_{12} Z_\ell h_\ell(\Omega) D_\ell$$

$T^{pq}_{n,m}$ is the transfer matrix on (x, p_x)

$$Z_n = \frac{Z''_n \ell e}{2Q f_b}$$

$$G = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

Z''_n = transverse impedance of cavity/unit length

M_0 = number of bunches in one recirculation

ℓ = cavity length

$f_b = \frac{1}{\tau}$ = bunching frequency

$s_k(\omega_n \tau) = e^{-\frac{k\omega_n \tau}{2Q}} \sin(k\omega_n \tau)$

n_p = passes

n_o = number of cavity sites

I = average beam current

Beam Breakup
Recirculation Number Dependence

- At first looks like ~ $n_{pass} (n_{pass}-1)/2$
- But
  - Not all transfer matrix elements the same
    - Implicit momentum dependence tends to weight lower energy matrix elements
  - As passes increase, number of cavities decrease
    - HOMs for well damped cavities overlap from cavity to cavity, so peak impedance falls
- For example, when CEBAF (JLab) went from 4 to 5 pass configuration, threshold for BBU remained unchanged

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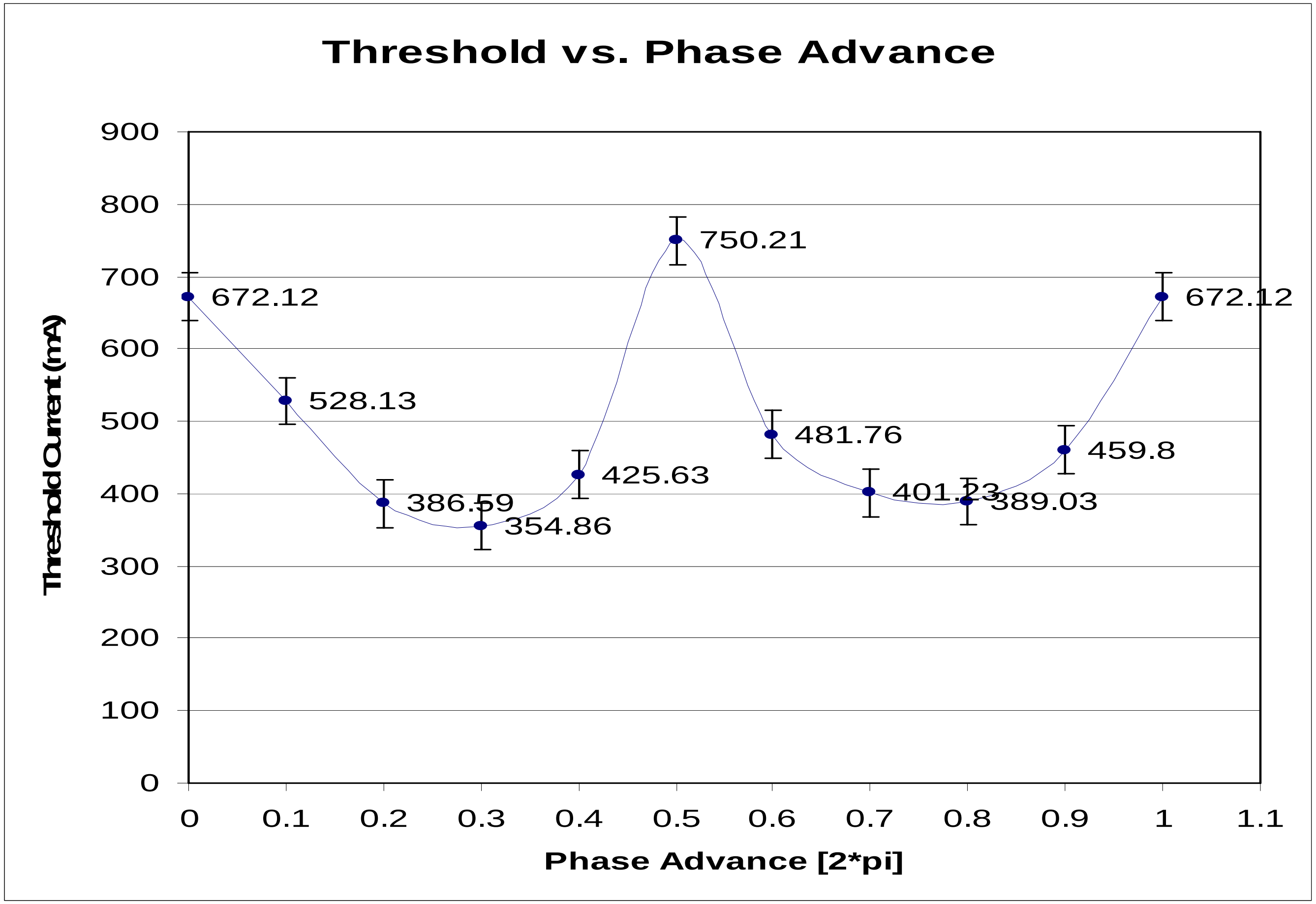
An Example: Beam Breakup-1 pass up/down

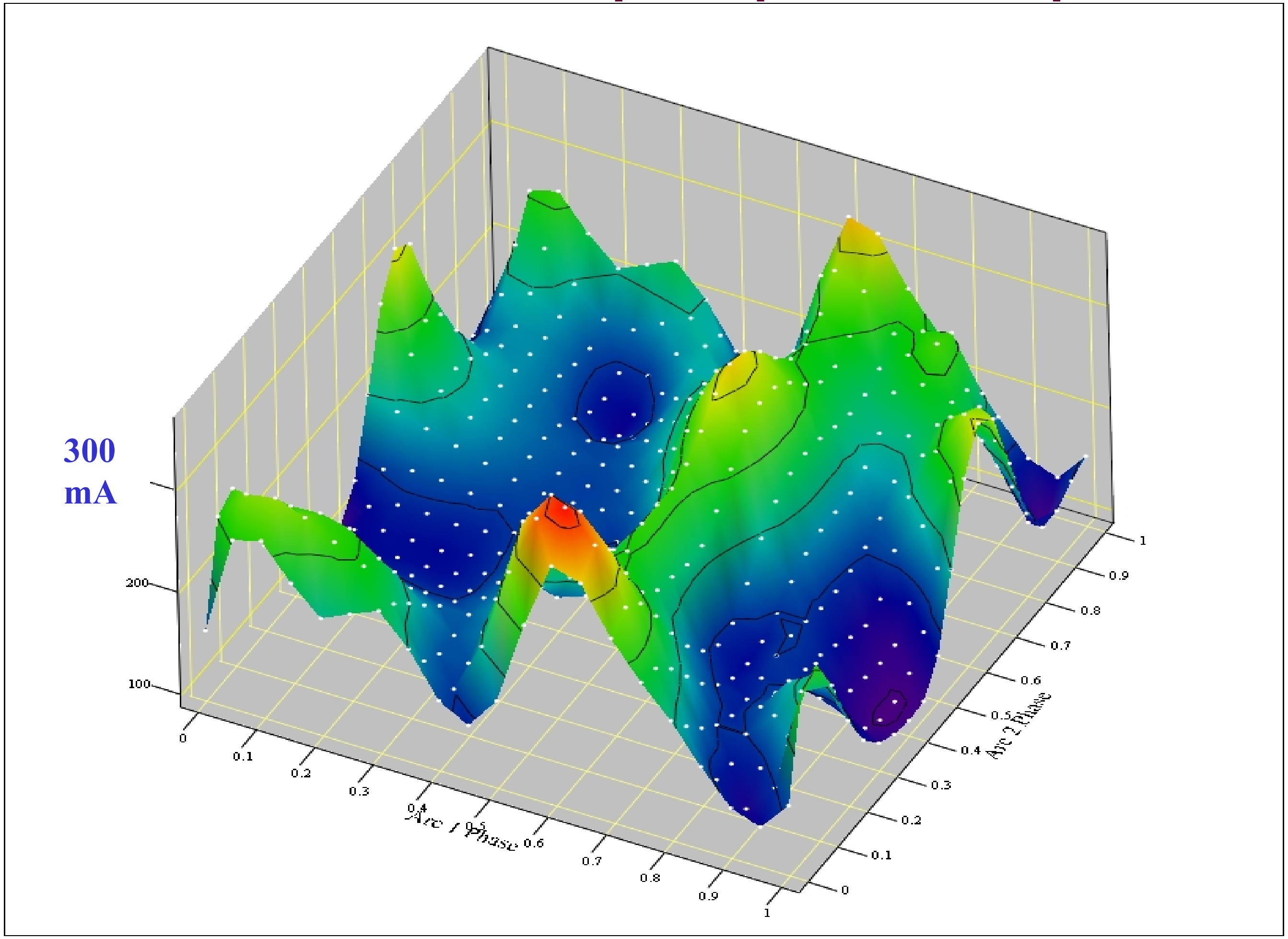


Robert Bosch, Marcus Medley, and Accelerator Group, SRC

1 GeV ERL
Assumed 1500 MHz fundamental, HOM Q~3000
Scales like ~1/√Q for many cavities and increases with energy (√ to linear)

An Example:
Beam Breakup-2 passes up/down

300 mA



1 GeV total ERL

Assumed 1500 MHz, HOM Q~3000   Scales like ~1/√Q

Robert Bosch, Marcus Medley, and Accelerator Group, SRC

Rub: Threshold of 100s milliamps possible in both cases; maybe lose a “two” in safety margin

CSR “back of envelope” (gaussian)

$$\Delta E = 3 \cdot 10^9 \frac{qe(L_{bend})}{\rho^{2/3} \sigma_l^{4/3}}$$

MKS

Suggests waiting for final compression until higher pass to keep relatively under control

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BESSY FEL ARC (an example)

- 180 degree bend to fit on site
  - 2.5 nC
  - Bunch length 2.7 mm, 200 amps peak after BC 1 with fractional momentum spread of 0.024 at 219 MeV
  - Bending radius ~ 2.5 meters
  - For 753 MeV Arc, dispersion ~0.05 m in bends
  - Normalized emittance of 2 mm mrad
  - Lattice function β ~2m

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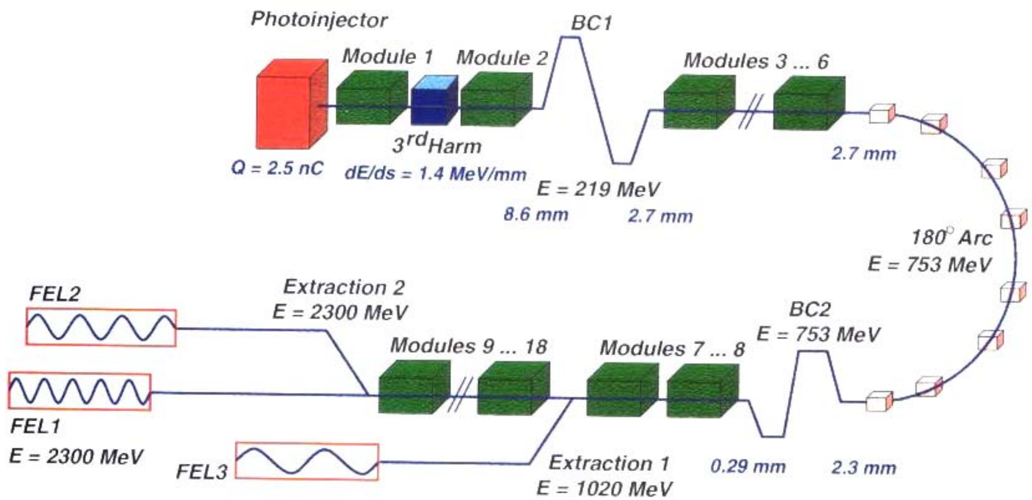
BESSY FEL ARC



Emittance Degradation Estimates

- For BESSY bunch in arc
  - Horizontal beam size ~ 50 micron
  - Back of the envelope CSR
    - Induced momentum spread ~.0001
    - Induced beta oscillation ~5 microns

Table 7.6: Results of start-to-end simulations: bunch charge, Q = 2.5 nC, emittances, and energy spread are projected values.

	E (MeV)	σ_l (fwhm) (mm)	I_p (A)	$\varepsilon_{x,n}$ (π mm mrad)	$\varepsilon_{y,n}$ (π mm mrad)	σ_p/p (x 1000)
Before BC1	219	8.6	65	2.12	2.12	24.1
After BC1	219	2.7	200	2.14	2.20	24.1
After arc	753	2.3	240	2.82	2.14	9.3
After BC2	753	0.29	2000	2.82	2.40	8.9

BESSY FEL Design Report

- To minimize emittance growth, could invoke betatron phase cancellation for superperiods as long as we don't compress in the arc
- But CSR energy spread very distribution sensitive, but also in final arc

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CSR Instability

Applying Old Resistive Wall Formula, but with CSR Impedance peak Z/n~100 h/R ohms

$$(\Delta\Omega)^2 = \frac{e\eta\omega^2 n^2 \frac{Z}{n} I_{peak}}{2\pi E}$$

Growth Rate

$$(\frac{\Delta p}{p})^2 = \frac{I_{peak}\frac{Z}{n}}{\eta E / e}$$

Stabilizing momentum spread;

Emittance can also help, so may be pessimistic

$$n \sim \pi \frac{R}{\rho}(\frac{\rho}{h})^{3/2}$$

Like ALS stability formula for CSR, save a factor of two or so

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CSR Instability: Some Numbers

- Say 100 meter total circumference arcs, and momentum compaction small, say 0.001
- Let bending radius 2.5 meters, beam pipe of 2 cm
- Say we have ERL with 200 A peak current
- Get growth time of ~microsecond (300 meters) at CSR cutoff frequency
  - Could be significantly faster depending on what "n" is stable,
  - So a little too interesting
- Stabilizing momentum spread of ~0.005, a bit large, and some higher "n" modes will grow faster

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Other Stuff

- Space charge in bending, but BESSY bend modeling is an existence proof
- Head tail effects with weaker focusing, but wakefields are much smaller in SRF than at SLAC where issue important
- Incoherent synchrotron radiation effects, but arc is at low energy
- Real layout with bunch compression scenarios, linac phasing, etc. may be real constraint, as flexibility is limited

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So Far

- Recirculation makes life harder, safety margins smaller, but may not be limiting
- A “value engineering” decision?
- Compression and other niceties should be avoided in lower energy recirculation
  - Allow emittance cancellations between superperiods
  - Keeps energy spread reasonable
  - In general, optimize lower energy arc optics for recirculation, not bunch manipulations
- My favorite issues
  - Microwave-like CSR instabilities
  - Cost model

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What are Advantages and Limits of Multi Turn ERLs

Adding extra passes for acceleration and energy recovery offers the possibility of cost savings that must be weighed against a variety of performance limitations and operational constraints. For example, it is estimated that two passes of acceleration followed by two passes of energy recovery could save roughly one-third of the capital costs for accelerator hardware (SRF, RF, cryogenics, and extra beam transport) relative to the more standard one-pass-acceleration/one-pass-recovery configuration. Clearly, the overall cost-savings proportion for a full ERL user facility would be a smaller. Beam breakup current limits would be reduced, but since the coupling impedance is also reduced with fewer overlapping higher order cavity modes, this may only be a linear effect. With expected HOM damping, 100 mA average current is not unreasonable. CSR and other wakefield effects on emittance and energy spread in the lower-energy extra arc can be controlled by having the final bunch compression after the first recirculation to keep the bunch lengths relatively long. In this way, these effects will be a fraction of those in the higher-energy arc. Multiple recirculations do constrain the tunability of the overall acceleration system, with linac phase adjustment, for example, impacting two beams simultaneously. This may be the primary reason to avoid multi turn arrangements. The interactions between the added multiple beams in the linac and the CSR microbunching instability in the arcs deserve further study.

To summarize, multiturn ERLs will be more challenged in achieving various important beam parameters (e.g., current, emittance, energy spread), but still may able to reach the required performance goals. The reduced safety margins need to be balanced against possible cost savings. Constraints on operational flexibility for tuning critical beam parameters may prove to be the real limitation

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