USPAS Course on
4th Generation Light Sources II
ERLs and Thomson Scattering

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Introduction to Energy Recovering Linacs
Optics Issues for Recirculating Linacs

D. Douglas
The Naïve Recirculator

- Injector

• Linac
  • accelerating sections
  • focussing

• Recirculator
  – bending & focussing

• Beam goes around & around, is accelerated/decelerated as needed for the application at hand
Design and Performance Issues

- How many passes?
  - 1 pass/0 recirculations = straight linac: $$$$$!!
  - 1 RF cell/ $\sim \infty$ recirculations = storage ring: performance!!
- Multipass focusing in linac(s)
  - Injection/final energy ratio, linac length, “halo”
- Machine design with recirculation
  - Transverse/longitudinal phase space control
    - Transverse matching; path length & compaction management
- Instabilities
  - BBU, other impedance driven effects, FEL/RF interaction, beam loss instability during energy recovery
- Beam quality degradation
  - Space charge, synchrotron radiation, CSR, environmental impedances
Number of Passes

- Cost/Performance optimization
  - RF costs $\propto 1/N_{\text{pass}}$
  - Beamline costs $\propto N_{\text{pass}}$
  - Typical cost optimum $N_{\text{pass}} > 1$

However!

- Minimum is shallow, broad, and influenced by many additional factors:
  - Civil costs ("tunnel")
  - Single vs. split linac
  - Beamline complexity (& cost) grows faster than $N_{\text{pass}}$
  - Performance issues:
    - lower construction vs. higher commissioning costs
    - meeting user-driven performance requirements
Multipass Focussing In Linac(s)

Beam envelope/spot size control is the transverse optical issue in recirculating linacs

- Recirculation leads to mismatch between beam energy and excitation of focusing elements
  - set focusing for first pass $\Rightarrow$ higher passes get “no” focusing/blow up (linac looks like a drift, $\beta_{\text{max}} \sim$ linac length)
  - set focusing for higher passes $\Rightarrow$ first pass over-focused/blows up
  - Large envelopes lead to scraping, error sensitivity, lower instability thresholds
- Imposes limits on
  - injection energy (higher is better but costs more),
  - linac length (shorter is better but gives less acceleration), and/or
  - achievable control over $\beta_{\text{max}}$
CEBAF Envelopes

– FODO quad lattice with 120° phase advance on 1st pass
**Panaceas**

- Focus 1st pass as much as possible (whilst maintaining adequate betatron stability)

- Use a “split linac” – 2 halves rather than 1 whole
  - Shorter linac \(\Rightarrow\) lower peak envelopes (“shorter drift length”)

- **Linac interruptus**

- High injection energy

- “Graded gradient” focusing in energy-recovering linacs

- Use high gradient RF

- Use an “inventive” linac topology
  - “Counter-rotated” linacs
  - “Bisected” linac topology
  - “Asymmetric” linac topology
CEBAF Envelopes, reduced focusing

– FODO quad lattice with 60° phase advance on 1st pass
- shorter linacs ⇒ lower peak envelopes ("shorter drift length")
- higher "injection" energy in 2\textsuperscript{nd} linac ⇒ even lower peak envelopes (relatively stronger focusing on higher passes)
- requires more complex beam transport system (multiple splitting/reinjection regions at ends of multiple linacs)
“Linac interruptus”: use of focussing insertions

- periodically replace accelerating sections with high phase advance focusing insertions
  - Gives additional focusing on higher passes
Injection Energy

- Injection energy “must” be high enough to avoid significant levels of pass-to-pass RF phase slip
  - CEBAF $E_{\text{inj}} = 45$ MeV, $\delta \phi_{RF} \sim 1-2^\circ$ on 1st pass, little thereafter
  - IR Demo FEL $E_{\text{inj}} = 10$ MeV, $\delta \phi_{RF} \sim 10^\circ$ from pass to pass
- Injection energy “should” be high enough to allow adequate pass-to-pass focusing in a single transport system
  - “adequate” is system dependent
    - CEBAF (45 MeV $\Rightarrow$ 4 GeV): $\beta_{\text{max}} \sim 200$ m – adequate to run 200 $\mu$A
    - IR Demo (10 MeV $\Rightarrow$ 45 MeV): $\beta_{\text{max}} \sim 25$ m – adequate to run 5 mA
  - Higher is better (front end focusing elements stronger) but more expensive
    - SUPERCEBAF (1 GeV $\Rightarrow$ 16 GeV), using same type of linac focusing as in CEBAF: $\beta_{\text{max}} \sim 130$ m
- Naïve figure of merit: $E_{\text{final}}/E_{\text{inj}}$, with smaller being better
“Graded-gradient” Focusing

- There are 2 common focusing patterns:
  - constant gradient (all quads have same pole tip field; sometimes used in microtrons)
  - constant focal length (quad excitation tracks energy; often used in linacs)
- Neither works well for energy recovering linacs
  - Beam envelopes blow up, limiting linac length & tolerable $E_{\text{final}}:E_{\text{in}}$ ratio
- “Graded-gradient” focusing ⇒ match focal length of quads to beam of lowest energy
  - Excitation of focusing elements increases with energy to linac midpoint, then declines to linac end
  - Allows “exact” match for half of linac, produces “adiabatically induced” mismatch in second half
“Graded-gradient” Focusing, cont.

1 km, 10 MeV→10 GeV linac (111 MV/module), triplet focusing:

![Graph](graph.png)

222 MV
Higher accelerating gradient very helpful in limiting beam envelope mismatch

- Shortens linac
- Increases excitation of front end (after 1st accelerating section) focusing elements, reducing mismatch on higher passes
- ½ km 10 MeV→10 GeV linac (~222 MV/module), using triplets:

![Graph showing beta x and beta y](image-url)
High Accelerating Gradient, cont.

- “Focal Failure Factor”
  - Ratio of energies after 1st/before final accelerating section
  - Figure of merit for multipass mismatch – more descriptive than ratio of injected to final energies
  - For the two example machines:

<table>
<thead>
<tr>
<th>Average Gradient</th>
<th>E after 1st</th>
<th>E before last “FFF”</th>
</tr>
</thead>
<tbody>
<tr>
<td>111 MeV/module</td>
<td>121 MeV</td>
<td>9889 MeV ~82</td>
</tr>
<tr>
<td>222 MeV/module</td>
<td>232 MeV</td>
<td>9778 MeV ~42</td>
</tr>
</tbody>
</table>

(compare to $E_{out}/E_{in} = 1000...$)
“Inventive” Linac Topologies

- Must transcend naïve topology to achieve adequate performance
- “Nominal” linac topologies:
  - Single linac
  - Split linac

- Peak beam envelope ~ linac length on higher passes
- Complex beam handling after linac/during reinjection, particularly for many passes
Topologies, cont.

- “counter-rotated” linac(s)

- recirculator directs 2\textsuperscript{nd} pass (usually energy recovered) beam through linac antiparallel to 1\textsuperscript{st} pass
  - ensures (in energy recovered system) exact match of focusing to energy throughout transport
  - beam-beam interaction can cause degradation of beam quality
  - requires specific cavity-to-cavity phase relation
More “Inventive” Linac Topologies

Split linacs allow at least two useful topological contortions:

- “bisected” linacs

- modification of split linac reducing focal failure factor
- start energy recovery at *higher* energy linac
- requires an additional beam transport – approx. 1 pass equivalent
- allows extensible user area
Still More “Inventive” Linac Topologies

- “asymmetric” linac(s)

- modification of split/bisected linac topologies – allows further reduction of focal failure factor & linac length-induced mismatch

- 1st linac is “the problem” (weak front-end focusing, drift-like transport on higher passes) so make 1st linac short!
  - Shorter linac gives smaller $\beta_{\text{max}}$
  - Does degrade focal failure factor in 2nd linac with commensurate increase in $\beta_{\text{max}}$, but effect tolerable (esp. with 1st linac improvement)
Why it Matters ("Halo")

Performance of recirculated linacs may ultimately be limited by loss of "halo" – particles far from the beam core

- There is "stuff" in the beam not necessarily well described by core emittance, rms spot sizes, gaussian tails, etc.
- This "stuff" represents a small fraction ($<10^{-4} \text{?} 10^{-5}?$) of the total current, but it can get scraped away locally, causing heating, activation, and damaging components.
- Heuristically:
  - Higher current leads to more such loss
  - Smaller beam pipe results in greater loss
  - Bigger beam envelopes encourage increased loss

\[ I_{\text{loss}} \propto I \times \frac{\beta}{a} \]
Phenomenology

. In CEBAF, BLM/BCMs induced trips ⇒ losses of ~1 μA out of 100 μA in 1 cm aperture where β ~100 m
  ⇒ proportionality const. ~ \((1 \, \mu A/100 \, \mu A)x (0.01 \, m/100 \, m) \sim 10^{-6}\)
. In the IR Demo FEL, BLMs induce trips ⇒ losses of ~ 1 μA out of 5000 μA in 2.5 cm aperture where β ~5 m
  ⇒ proportionality const. ~ \((1 \, \mu A/5000 \, \mu A)x (0.025 \, m/5 \, m) \sim 10^{-6}\)
. One might then guess

which, in a 100 mA machine tolerating 5 μA loss in a 2.5 cm bore, implies you must have β ~ 1.25 m (ouch!)

Moral: There will be great virtue in clean beam and small beam envelope function values!

\[
I_{loss} = 10^{-6} I \times \frac{\beta}{a}
\]
Example: An Energy-Recovered Linac for SR

- The “JLab Energy-Recovering Bisected Assymmetric Linacs”, or JERBAL, is a 10 GeV driver for SR production

<table>
<thead>
<tr>
<th>JERBAL Machine Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Topology</td>
</tr>
<tr>
<td>Injection Energy</td>
</tr>
<tr>
<td>Final Energy</td>
</tr>
<tr>
<td>Single pass energy gain Linac 1:</td>
</tr>
<tr>
<td>Linac 2:</td>
</tr>
<tr>
<td>Linac accelerating structure Linac 1:</td>
</tr>
<tr>
<td>Linac 2:</td>
</tr>
<tr>
<td>Linac focussing structure</td>
</tr>
<tr>
<td>RF Gradient</td>
</tr>
<tr>
<td>Cryomodule structure</td>
</tr>
<tr>
<td>Cryomodule energy gain</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Beam power Injected</td>
</tr>
<tr>
<td>Full</td>
</tr>
<tr>
<td>Dumped</td>
</tr>
</tbody>
</table>
JERBAL, cont.

- Machine configuration:

![Machine configuration diagram](image)

- Transverse optics

![Graph showing transverse optics](image)
JERBAL, cont.

- Site plan
Machine Design Process

- Set # passes
  - Cost/performance optimization
- Characterize linac optics
  - a dominant feature of the machine behavior; once under control, the “rest” of the machine – the recirculator – can be specified
- Develop recirculator design
Recirculator Design Requirements (which of course apply to the full linac as well!)

- Preservation of beam quality & stability:
  - Space charge
  - BBU/other environmental impedance & wake effects
  - SR (incoherent & coherent) degradation of phase space
  - FEL/RF interaction
  - Beam loss instability during energy recovery

- Transverse phase space control, as in linac
  - Typically requires betatron matching, e.g., into/out of linacs
  - Dispersion management; relates to:

- Manipulation of longitudinal dynamics
  - Path length control (pass-to-pass RF phase)
  - Momentum compaction control

- User support requirements
  - Extraction systems
  - Production of multiple beams
  - Configuration of SR properties
Recirculator Features

It is often useful to employ a functionally modular design philosophy: the recirculator consists of a sequence of beam line modules, each with a specific & more or less self-contained function.

Examples of functions:

- Beam separation/recombination
  - Dispersion management
- Transverse (betatron) matching
  - Beam envelope, phase advance management (e.g., for BBU)
- Arcs
  - Bend, SR production/management, longitudinal matching
- Utility transport
  - path length adjustment,
  - extraction,
  - insertion devices
  - interaction regions
Conclusions, Advice, Polemic

- Keep gradients high, linacs short, envelopes and dispersions low.
- Use lots of symmetry and periodicity.
- When basing decisions on cost, base them on cost to the taxpayer, not your own project budget
  - don’t skimp on construction costs only to blow the commissioning budget
  - Take the long view – optimize cost from groundbreaking to 1st PRL, not just within a project phase
- Remember – as a machine designer, the operator is your best friend. She knows what works and what doesn’t. Listen!!!
- Spend time driving beam. Suffering breeds greatness.
Typical Recirculator Configuration

Matching/utility region

Beam separation region

Beam recombination region

Recirculation Arcs
The recirculator must
- accommodate multiple beams at significantly different energies, or
- separate the beams, transport each energy individually and recombine for further acceleration

Typically (though not always – e.g., microtrons) simpler to separate beams

Design choices:
- H or V split
- Dispersion suppression or not ("yes" is simpler – "functional modularity" – and helps maintain beam quality (SR))
  - Method of dispersion suppression
Spreader styles

Simple, but requires strong focusing & is error sensitive

More complex & congested but focusing weaker, less error sensitive, more robust

Least congested, weakest focusing, most robust, but requires the most space
Betatron matching

- As in linac(s), beam envelope control is a significant performance issue
  - Made more manageable by beam separation; only 1 beam to deal with at a time
- Use quad telescopes within each recirculator transport line to match beam envelopes from linac to recirculator and from recirculator back to linac
  - Gives best behavior in recirculator
  - Allows some independent control over transverse optics in linac on each pass (through adjustment of reinjection condition)
  - Allows control of turn-to-turn phase advance (BBU control)
  - Can be used to compensate uncontrolled lattice errors
    - “beam envelopes” and “lattice functions/transfer matrices” are distinct objects in a beam transport system!
Arches

- Used to transport beam “around the corner”
- Provided means of longitudinal phase space management
  - IR Demo provides example
  - Compaction management
- Can be source of beam quality degradation
  - Synchrotron radiation
  - CSR
IR Demo Longitudinal Matching/Energy Recovery

- Requirements on phase space:
  - high peak current (short bunch) at FEL
  - bunch length compression at wiggler
  - “small” energy spread at dump
  - energy compress while energy recovering
  - “short” RF wavelength/long bunch ⇒ get slope and curvature right

\[
\begin{align*}
\sigma_z &\sim 0.4 \text{ psec} \\
\sigma_E &\sim 100 \text{ KeV} \\
\Delta z &\sim 30 \text{ psec} \\
\Delta E &\sim 100 \text{ keV} \\
\sigma_z &\sim 2.5 \text{ psec} \\
\sigma_E &\sim 100 \text{ KeV} \\
\Delta z &\sim 30 \text{ psec} \\
\Delta E &\sim 2 \text{ MeV} \\
\sigma_z &\sim 2.5 \text{ psec} \\
\sigma_E &\sim 15 \text{ KeV} \\
\end{align*}
\]
Why we need the “right” $T_{566}$
Phase space at 10 MeV Dump

E (MeV) vs. t (nsec)

6-poles off

lasing off

phase space after energy recovery

9.5 10 10.5 11
362.49 362.51 362.53 362.55

6-poles on

lasing on

phase space after energy recovery

9.5 10 10.5 11
362.49 362.51 362.53 362.55

6 poles on

phase space after energy recovery

9.5 10 10.5 11
362.49 362.51 362.53 362.55
Momentum Compaction Management

- “Momentum Compaction” \( (M_{56}) \) is a handle on longitudinal phase space given to you by the lattice

\[
\delta l = M_{56} \frac{\delta p}{p} = \int \eta \, d\theta \, \frac{\delta p}{p}
\]

(warning – this is NOT the same as the storage ring \( \alpha_p \))

- By changing \( M_{56} \) you alter the phase energy correlation in longitudinal phase space (the tilt of the bunch) and can thereby “match”
  - Consider \( M_{56} \) to be a longitudinal drift; you’re changing its length

- Alter \( M_{56} \) \( (T_{566}, \ldots \text{ etc.}) \) by altering the dispersion (second order dispersion, \ldots etc.) pattern
Momentum Compaction Management Examples

- In CEBAF (one superperiod):

\[ \Delta \psi = 180^\circ \]

- In the IR Demo (one end-loop):

\[ \Delta \psi = 180^\circ \]
Quantum Excitation/Synchrotron Radiation

A mechanism for phase space degradation:

- an on-momentum electron at origin of phase space (A)
- emits photon at dispersed location, energy shifts by $\delta p/p$
- electron starts to betatron oscillate around dispersed orbit (B)

emittance grows
**Estimate of degradation**

. Estimate of effect:

\[ \sigma_E^2 = 1.182 \times 10^{-33} \text{ GeV}^2 \text{m}^2 \frac{\gamma^7}{\rho^2} \]

with

\[ \Delta \varepsilon = 1.32\pi \times 10^{-27} \text{ m}^2 - \text{rad} \frac{\gamma^5}{\rho^2} \langle H \rangle \]

\[ \langle H \rangle = \frac{1}{L_{bends}} \int ds \left( \frac{1}{\beta} \right) \left[ \eta^2 + \left( \beta \eta' - \frac{1}{2} \beta' \eta \right)^2 \right] \]

. “just like storage rings” – except that within a recirculator arc there’s no damping (it happens in the linac – adiabatically) and so there’s not an equilibrium

. limit effect by keeping dispersion, beam envelopes under control
Example of magnitude: CEBAF, SUPERCEBAF

![Graphs showing rms momentum spread and rms emittance versus energy](image-url)
Coherent Synchrotron Radiation

. Another mechanism for phase space degradation:
  . electromagnetic field radiated from tail of bunch during bending accelerates energy of head

. accelerated electron at head begins to betatron oscillate around dispersed orbit, emittance grows
Images of initially Gaussian phase space after simulated transport through IR Upgrade
Coherent Synchrotron Radiation - Suppression

- Effect is coherent – so can be suppressed
  - image bunch in 6-d phase space from radiation point to homologous downstream point
    - same envelopes, dispersion, half betatron wavelength away with isochronous transport
  - distribution the same \( \Rightarrow \) radiation pattern identical \( \Rightarrow \) head of bunch gets *same* energy shift – *and move ONTO the dispersed orbit!*

- emittance growth suppressed (simulation results)

\[
\frac{\delta p}{p}, \frac{\delta p}{p}, \frac{\delta p}{p}, (\eta \frac{\delta p}{p}, \eta' \frac{\delta p}{p})
\]
Utility transport

- Extraction
  - CEBAF multibeam production
- Path length control
  - CEBAF doglegs
  - FEL path length adjustment
- Use of insertion devices
  - FEL wiggler insertion
- Interaction Regions
Single Particle Optics for Recirculating Linacs

- The Naïve Recirculator
  - Machine description
  - Innocence Endangered: Design/performance issues
    - # passes
    - Multipass focussing in linacs
    - Halo
    - JERBAL
    - Transverse/longitudinal phase space control; matching, path length & compaction management
  - Instabilities
    - BBU, other impedance driven effects, FEL/RF interaction, beam loss instability during energy recovery
  - Beam quality degradation
    - Space charge, synchrotron radiation, CSR, environmental impedances
. Machine design process
  . Set pass count
  . Characterize linac optics
  . generate arc design
. Cost optimization - # passes, single/split linacs
. Multipass focusing effects
  . Types of focusing:
    . Constant gradient
    . Constant focal length
    . Graded gradient
  . Energy ratio ($E_{in}:E_{out}$) limitations and the virtue of high accelerating gradient; focal failure factor
  . Bisected linac topology


- Recirculation arc design
  - Functional modularity
  - Beam separation (extraction)/recombination (reinjection) geometry
    - Single step
    - Staircase
    - Overshoot
  - Beam quality preservation
    - Incoherent synchrotron radiation control
      - Energy spread \( \sim g_5/r^2 \)
      - Emittance excitation \( \sim <H>g_7/r^2, H \sim b_2, h_2 \)
    - CSR control & compensation (e.g. ½ betatron wavelength correction in IR Demo; don’t squeeze entire phase at one time; keep betas, etas small)
    - Space charge control (don’t squeeze entire phase space at one time)
  - Matching
    - Transverse – linac to recirculator, vice versa
    - Longitudinal phase space management
      - Orthogonal knobs useful: e.g. IR Demo – path length, \( M_{56}, T_{566} \) all decoupled & more or less separate from transverse
Talk Outline

- Recirculating Linacs Defined and Described
- Review of Recirculating SRF Linacs
  - University of Illinois
  - Darmstadt
  - CEBAF
- Summary of Present State-of-the-art
- Energy Recovering Linacs
  - Stanford SCA
  - CEBAF Beam Recirculation Experiment
  - Jefferson Lab IRFEL
- Future Possibilities
  - High Energy Electron Cooling (BNL)
  - Electron-Ion Colliders (BNL, JLAB)
  - Recirculated Linac Light Sources (Cornell/JLAB, BNL, Berkeley)
  - Higher Power Lasers
- Conclusions
Accelerator Types

Linac

Recirculating Linac

Ring

RF Installation
Beam injector and dump
Beamline
Comparison: Linacs/Storage Rings

- Advantage Linacs

  Total transit time is quite short

  Emittance dominated by source emittance and emittance growth down linac

  Beam polarization “easily” produced at the source, switched, and preserved

  Beam is easily extracted. Utilizing source control, flexible bunch patterns possible

  Long undulators are a natural addition

  Bunch durations can be SMALL
Comparison Linacs and Storage Rings

- **Advantage Storage Rings**
  
  Up to now, the stored average current is much larger
  
  Very efficient use of accelerating voltage
  
  Technology well developed and mature

- **Disadvantage of Storage Rings**
  
  Technology well developed and mature
  
  There’s nothing you can do about synchrotron radiation damping and the emittance and bunch length it generates
Why Recirculate?

A renewed general interest in beam recirculation has been driven by the success of Jefferson Lab’s high average current FEL, and the realization that it may be possible to achieve beam parameters “unachievable” in either linacs without recirculation or storage rings, separately.

- Easily understood example: Recirculated Linac Light Source. In a “typical” synchrotron light source the beam power is (100 mA)(5 GeV)=500 MW. For economic and beam dumping reasons, a non-recovered linac is not a suitable driver (500 MW is a third of a nuclear plant!). A recirculated linac arrangement that is energy recovered (beam is both accelerated and decelerated in the same RF structures) overcomes this limitation. On the other hand, pulse lengths of order 100 fsec and small emittance are demonstrated in recirculated linacs. Such parameters are “impossible” (for the full beam current!) at a storage rings.

- The limits, in particular the average current carrying capacity of possible designs, are unknown and may be far in excess of what the FEL can do!
Power Multiplication Factor

- An advantage of energy recovered recirculation is nicely quantified by the notion of a power multiplication factor:

\[ k = \frac{P_{b,ave}}{P_{rf}} \]

where \( P_{rf} \) is the RF power needed to accelerate the beam

- By the first law of thermodynamics (energy conservation!) \( k < 1 \) in any linac not recirculated. Beam recirculation with beam deceleration somewhere is necessary to achieve \( k > 1 \)

- If energy IS very efficiently recycled from the accelerating to the decelerating beam

\[ k \gg 1 \]
Will use the words “High Multiplication Factor Linac” for those designs that feature high $k$. 

- Normal Conducting Recirculators $k<<1$
  - LBNL Short Pulse X-ray Facility (proposed) $k=0.1$
  - CEBAF (matched load) $k=0.99$; (typical) $k=0.8$
  - JLAB IR DEMO $k=16$
  - JLAB 10 kW Upgrade $k=33$ (12/02)
  - Cornell/JLAB ERL $k=200$ (proposed)
  - BNL PERL $k=500$ (proposed)

- Recirculated Linacs
- High Multiplication Factor Superconducting Linacs
## Comparison Accelerator Types

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Energy Electron Linac</th>
<th>High $k$ Recirculated Superconducting Linac</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating Gradient [MV/m]</td>
<td>&gt;50</td>
<td>10–20</td>
<td>NA</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>&lt;1%</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Average Current [mA]</td>
<td>&lt;1</td>
<td>5 going to 100</td>
<td>1000</td>
</tr>
<tr>
<td>Average Beam Power [MW]</td>
<td>0.5</td>
<td>0.25 going to 700</td>
<td>3000</td>
</tr>
<tr>
<td>Multiplication Factor</td>
<td>&lt;1</td>
<td>13 going to 200</td>
<td>1000</td>
</tr>
<tr>
<td>Normalized Emittance [mm mrad]</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>100 fsec</td>
<td>100 fsec</td>
<td>20 psec</td>
</tr>
</tbody>
</table>

Best results by accelerator type
Upsides to Beam Recirculation

- Possibilities to reuse same RF installation to accelerate the beam many times.

- Possibilities, utilizing energy recovery, to increase the average current being accelerated, without necessarily increasing the size and capital and operating costs of the RF installation.

- Possibilities of making the beam power multiplication factor much greater than 1, and at a level approaching, and maybe even exceeding (if we’re lucky!), that of storage rings.

- By comparison to storage rings, the possibility of beams with smaller emittance for the same average current, and with much greater flexibility and control in the longitudinal distribution delivered to the users.
Challenges for Beam Recirculation

- Additional Linac Instability
  - Multipass Beam Breakup (BBU)
  - Observed first at Illinois Superconducting Microtron
  - Limits the average current at a given installation
  - Made better by damping HOMs in the cavities
  - Best we can tell at CEBAF, threshold current is around 20 mA, similar in the FEL
  - Changes based on beam recirculation optics

- Turn around optics tends to be a bit different than in storage rings or more conventional linacs. Longitudinal beam dynamics gets coupled strongly to the transverse dynamics.

- HOM cooling will perhaps limit the average current in such devices.
Challenges for Beam Recirculation

- High average current source to provide beam
  - Right now, looks like a good way to get there is with DC photocathode sources as we have in the Jefferson Lab FEL.
  - Need higher fields in the acceleration gap in the gun.
  - Need better vacuum performance in the beam creation region to reduce ion back-bombardment and increase the photocathode lifetimes.
  - Goal is to get the photocathode decay times above the present storage ring Toushek lifetimes. (In contrast to what some of the advocacy literature one reads might lead you to believe, this goal may NOT be so easy to achieve!)

- Beam dumping of the recirculated beam can be a challenge.
Figure 5.3 The second Illinois superconducting race-trace microtron, MUSL-2 (Axel et al., 1977; © 1977 IEEE)
Layout of S-DALINAC (Darmstadt)
## S-DALINAC Beam Parameters

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Energy (MeV)</th>
<th>Current (µA)</th>
<th>Mode</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\gamma,\gamma'))</td>
<td>2.5 – 10</td>
<td>50</td>
<td>3 GHz, cw</td>
<td>6400</td>
</tr>
<tr>
<td>LEC, PXR</td>
<td>3 – 10</td>
<td>0.001 - 10</td>
<td>3 GHz, cw</td>
<td>2100</td>
</tr>
<tr>
<td>HEC, PXR</td>
<td>35 – 87</td>
<td>0.1</td>
<td>3 GHz, cw</td>
<td>800</td>
</tr>
<tr>
<td>((e,e'), (e,e'x))</td>
<td>22 – 120¹)</td>
<td>5</td>
<td>3 GHz, cw</td>
<td>7800</td>
</tr>
<tr>
<td>FEL</td>
<td>30 – 38</td>
<td>2.7 A&lt;sub&gt;peak&lt;/sub&gt;</td>
<td>10 MHz, cw</td>
<td>2900</td>
</tr>
</tbody>
</table>

¹) Dutycycle 33%  

**Resolution:**  
\[ \Delta E_{FWHM} = 50 \text{ keV} \at 85 \text{ MeV}, \quad \Delta E/E = \pm 3 \cdot 10^{-4} \]
### Superconducting 20-Cell Cavity

<table>
<thead>
<tr>
<th>Material:</th>
<th>Niobium (RRR=280)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency:</td>
<td>3 GHz</td>
</tr>
<tr>
<td>Temperature:</td>
<td>2 K</td>
</tr>
<tr>
<td>Accelerating Field:</td>
<td>5 MV/m</td>
</tr>
<tr>
<td>$Q_0/Q_L$:</td>
<td>$3 \cdot 10^9 / 3 \cdot 10^7$</td>
</tr>
<tr>
<td>$\Delta f/\Delta l$:</td>
<td>500 Hz/µm</td>
</tr>
</tbody>
</table>

![Image of the Superconducting 20-Cell Cavity](image_url)
The CEBAF at Jefferson Lab

- Most radical innovations (had not been done before on the scale of CEBAF):
  - choice of srf technology
  - use of multipass beam recirculation
- Until LEP II came into operation, CEBAF was the world’s largest implementation of srf technology.
CEBAF Accelerator Layout*

## CEBAF Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>A 100 µA, B 10-200 nA, C 100 µA</td>
</tr>
<tr>
<td>Normalized rms emittance</td>
<td>1 mm mrad</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>500 MHz/Hall</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>&lt; 0.2 pC</td>
</tr>
<tr>
<td>Extracted energy spread</td>
<td>&lt; 10^{-4}</td>
</tr>
<tr>
<td>Beam sizes (transverse)</td>
<td>&lt; 100 microns</td>
</tr>
<tr>
<td>Beam size (longitudinal)</td>
<td>100 microns (330 fsec)</td>
</tr>
<tr>
<td>Beam angle spread</td>
<td>&lt; 0.1/°</td>
</tr>
</tbody>
</table>
Calculated Longitudinal Phase Space -

\begin{align*}
\Delta E (\text{keV}) & \quad \Delta \phi (\text{deg}) \\
\Delta E (\text{keV}) & \quad \Delta \phi (\text{deg}) \\
\Delta E (\text{keV}) & \quad \Delta \phi (\text{deg}) \\
\Delta E (\text{keV}) & \quad \Delta \phi (\text{deg}) \\
\end{align*}
Phase Space from CEBAF Bunching –

\[ \Delta E \]

\[ \text{z} \]

-3 cm  3 cm

\[ \Delta E \]

\[ \text{z} \]

5 keV

-5 keV

>100 bunching factor!
Schematic of CEBAF Injector Phase Distribution

Chopper 1  Chopper 2  Buncher  Capture Section  6 GHz Pickup  Superconducting Cavity 1  Superconducting Cavity 2  6 GHz Pickup

Aperture  70 MHz Reference

Modulator

40 MeV Accelerator

USPAS 4th Generation Light Sources II Krafft/Bazarov 16 January 2003
Phase Transfer Technique

Simultaneously, digitize phase modulation and arrival time determined by a phase detector
Some Early Results
Phase Space Correction Scheme

\[ \phi_{\text{in}} \rightarrow \phi_{\text{out}} \]

a)

\[ \phi_{\text{in}} \rightarrow \phi_{\text{out}} \]

b)

c)

\[ \phi_{\text{in}} \rightarrow \phi_{\text{out}} \]
Short Bunches in CEBAF

Short Bunch Configuration

Path Length System

Elements
- Fundamental mode pickup cavities at end of either linac
- Precision phase detectors
- 10 Msample/sec triggered transient recorder

Software

Beam conditions
- Around 3 microA macropulse current
- 4 microsec beam pulse

Performance
- Several tenths of a degree single shot
- Under one tenth of a degree (185 fsec/56 micron) with averaging
- M56 to under 10 cm
Beam Based Phase Monitoring

Bunch “Crested” when \( \frac{d\Delta E}{dt} = 0 \)

- Get offset by phase modulating around operating point and measuring the energy fluctuation at the same frequency
Multi-Pass Beam-RF phase detection

- Pass to Pass Phase Drift => Relative Energy Drifts
- Goal: Stabilization of Multi-Pass Beam-RF phases
- Small phase reference modulation for each linac
  - +/- 0.05 degree Phase Modulation
  - Amplitude Modulation suppressed
- Beam Position Detection in Recirculation Arcs ($\eta = 2.5$ m)
  - Multiplexed beam position monitor electronics
  - Each pass individually selectable
  - Measures Cumulative Phase Error (vector gradient sum)
- Phase information is available during CW running
  - On-line monitoring of drifts in recirculation path length
  - Corrections can be made on-line (non-invasive)
- Simultaneous Single- and Multi-Pass phase measurement
  - Equalize Single- and Multi-Pass phases
  - Single-Pass feedback system then keeps all passes on crest
Beam-RF Relative Phase Resolution

- Single-Pass phase resolution ~ 0.2 degrees, beam to RF
  - Finer than the phase set point resolution of 0.1 degree
- Multi-Pass phase resolution
  - Minimum desired measurement resolution: 0.2 degree
  - Expected resolution 0.1 degree
  - Improved over Single-Pass value because of higher dispersion
- Typical phase error feedback limit +/- 0.2 degrees (0.12 degree deadband)
Multipass Phase Shifts

Cumulative Phase (degrees)

Time (Days)

Š250 microns

Courtesy: Michael Tiefenback
Feedback System Elements

**Beam position and energy stabilization**

- 6 dimensional phase space
- Fast feedback system for beam position and energy stabilization
  - Only one hall line provides energy measurement
  - Two-hall operation (common SC linacs)
    - Halls A & C - (1 - 100) μA
      - Magnetic spectrometers
    - Hall B - (1 - 10) nA
      - $4\pi$ detector
Dispersion Suppressed Optics

Courtesy: Valeri Lebedev
Fast Feedback Off

1C12_Horizontal_FFT

Frequency

Courtesy: Valeri Lebedev
Fast Feedback Residual Fluctuations –

1C12_Horizontal_FFT

Courtesy: Valeri Lebedev
# Fast Feedback rms position fluctuations

![Graph showing Fast Feedback rms position fluctuations](image)

<table>
<thead>
<tr>
<th>Horiz Position (microns)</th>
<th>Vert Position (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>min</strong></td>
<td><strong>max</strong></td>
</tr>
<tr>
<td>1C07</td>
<td>-49</td>
</tr>
<tr>
<td>1C08</td>
<td>-70</td>
</tr>
<tr>
<td>1C11</td>
<td>-5</td>
</tr>
<tr>
<td>1C12</td>
<td>-91</td>
</tr>
<tr>
<td>1C14</td>
<td>-28</td>
</tr>
<tr>
<td>1C16</td>
<td>-44</td>
</tr>
<tr>
<td>1C18</td>
<td>-77</td>
</tr>
<tr>
<td>1C20</td>
<td>-59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Horiz Corrector (gauss-cm)</th>
<th>Vert Corrector (gauss-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>min</strong></td>
<td><strong>max</strong></td>
</tr>
<tr>
<td>1C04H</td>
<td>-4.95</td>
</tr>
<tr>
<td>1C07H</td>
<td>-19.92</td>
</tr>
</tbody>
</table>
Beam Diagnostics: OTR

- ¼ µm carbon foil, 10 X 10 mm square
- Can stay in maximum CEBAF CW beam current (200 µA)
- Dynamic range: 0.2 to 200 µA with neutral density filters.
- Continuous monitoring during beam delivery for E ≥ 2 GeV
- Open frame => not invasive upon insertion.
- Effect of foil on beam:
  - Energy loss => negligible
  - Beam scattering: OK for E > 2GeV; at 1.2 GeV, limit is ~ 50 µA (radiation level on sensitive electronics on beamline).
- Resolution limited by CCD camera to ≈ 60 µm. Could be improved, but is OK.
- Update rate: 5 measurements / second for 2 instruments simultaneously.
"MaxVideo 200" Image Processor Control Screen

DataCube Setup for Hall C - Multiplex

- **Sources**: Halls A and C
- **DataValid**: Yes
- **Units**:
  - X Position: 355.8 mm
  - X Width (rms): 4.0 mm
  - Y Position: 292.1 mm
  - Y Width (rms): 4.3 mm
- **Mode**: Free Run
- **Calibration screen**: Hall C
- **Acquire Gain**: 1.000
- **LUT1 Mode**: Subtract
- **LUT1 Threshold**: 17
- **Setup Scripts**: 1
- **Viewer Lights**: ON
- **Current**: 0.350 microAmp

**X profile**

**Y profile**

**Masks**

- **ENABLE MASK**:
- **ENABLE DISP MASK**:

**Saturated**

- 255
- 150
- 100
- 50
- 0

MAX pixel

128

Courtesy: Jean-Claude Denard
dp/p data: 2-Week Sample Record

Energy Spread less than 50 ppm in Hall C, 100 ppm in Hall A

Primary Hall (Hall C)

Secondary Hall (Hall A)

X Position => relative energy Drift
rms X width => Energy Spread

Energy drift

Energy spread

Date

23-Mar 27-Mar 31-Mar 4-Apr

X and sigma X in mm

0 0.4 0.8 1.2

Secondary Hall (Hall A)

Energy drift

Energy spread

Time

23-Mar 27-Mar 31-Mar 4-Apr

1E-4

Courtesy: Jean-Claude Denard
OTR beam size versus Beam Current
at 4 m dispersion point

Horizontal beam size

Vertical Beam Size

rms Beam Sizes in um

Beam Current in uA

0 20 40 60 80 100 120

0 20 40 60 80

Courtesy: Jean-Claude Denard
Energy Recovering Linacs

- The concept of energy recovery first appears in literature by Maury Tigner, as a suggestion for alternate HEP colliders*

- There have been several energy recovery experiments to date, the first one at Stanford SCA/FEL**

- Same-cell energy recovery with cw beam current up to 5 mA and energy up to 50 MeV has been demonstrated at the Jefferson Lab IR FEL. Energy recovery is used routinely for the operation of the FEL as a user facility

* Maury Tigner, Nuovo Cimento 37 (1965)
The SCA/FEL Energy Recovery Experiment

- Same-cell energy recovery was first demonstrated in the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac
- The previous recirculation system (SCR, 1982) was unsuccessful in preserving the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- All energy was recovered. FEL was not in place.

Jefferson Lab FEL

X-ray Set-up

IR wiggler

Linac

Optical system

Dump

e⁻ recirculation beam line

10 m

## FEL Accelerator Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Designed</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy</td>
<td>48 MeV</td>
<td>48.0 MeV</td>
</tr>
<tr>
<td>Average current</td>
<td>5 mA</td>
<td>4.8 mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>60 pC</td>
<td>Up to 135 pC</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>&lt;1 ps</td>
<td>0.4±0.1 ps</td>
</tr>
<tr>
<td>Peak current</td>
<td>22 A</td>
<td>Up to 60 A</td>
</tr>
<tr>
<td>Trans. Emittance (rms)</td>
<td>&lt;8.7 mm-mr</td>
<td>7.5±1.5 mm-mr</td>
</tr>
<tr>
<td>Long. Emittance (rms)</td>
<td>33 keV-deg</td>
<td>26±7 keV-deg</td>
</tr>
<tr>
<td>Pulse repetition frequency (PRF)</td>
<td>18.7 MHz, x2</td>
<td>18.7 MHz, x0.25, x0.5, x2, and x4</td>
</tr>
</tbody>
</table>
Gradient modulator drive signal in a linac cavity measured without energy recovery (signal level around 2 V) and with energy recovery (signal level around 0).

![Graph showing signal levels over time](image_url)

Courtesy: Lia Merminga
With energy recovery the required linac rf power is ~ 16 kW, nearly independent of beam current. It rises to ~ 36 kW with no recovery at 1.1 mA.
Instability Mechanism

Threshold Current

Growth Rate

\[
\text{Im}(\omega) \approx -\frac{\kappa \sin(\omega t_r)}{2t_0} - \frac{\omega}{2Q}\]

where

\[
\kappa = (R/Q)k^2_t e T_{12} I_0 t_0 / 2
\]

If the average current exceeds the threshold current

\[
I_{\text{th}} = \frac{1}{e} \left( \frac{2\omega}{(R/Q)k^2_t e T_{12} \sin(\omega t_r)} \right)
\]

have instability (exponentially growing cavity amplitude!)
Transverse BBU: Experiment

- Network Analyzer
- $\omega_{\text{HOM}}$
- Signal from cavity under study
- Amplifier
- Hybrid
- Cryomodule
- Recirculation path
- 10 MeV Dump
- BPM
Typical RF Cavity Response to Beam Excitation

HOM Frequency [Hz]

$S_{21}$ [dB]

0 mA
2 mA
3 mA
4 mA

1887.22 1887.23 1887.24 1887.25 1887.26 1887.27 1887.28

Courtesy: Lia Merminga
### Table of BBU Data

<table>
<thead>
<tr>
<th>Cavity</th>
<th>HOM Freq. (Measured)</th>
<th>R/Q (Meas.)</th>
<th>Q (Meas.)</th>
<th>Energy</th>
<th>Optics Setting</th>
<th>I&lt;sub&gt;th&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[MHz]</td>
<td>[Ω]</td>
<td></td>
<td>MeV</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>4</td>
<td>1730</td>
<td>0.08</td>
<td>3.8x10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>48</td>
<td>Nominal</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>1730</td>
<td>0.08</td>
<td>3.8x10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>37</td>
<td>1</td>
<td>18.4</td>
</tr>
<tr>
<td>4</td>
<td>1895</td>
<td>22.02</td>
<td>1.6x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>48</td>
<td>Nominal</td>
<td>21.4</td>
</tr>
<tr>
<td>4</td>
<td>1895</td>
<td>22.02</td>
<td>1.6x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>37</td>
<td>1</td>
<td>15.6</td>
</tr>
<tr>
<td>4</td>
<td>1895</td>
<td>22.02</td>
<td>1.6x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>37</td>
<td>Nominal</td>
<td>&lt;0</td>
</tr>
<tr>
<td>5</td>
<td>1818</td>
<td>13.74</td>
<td>4.5x10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>37</td>
<td>2</td>
<td>15.0</td>
</tr>
<tr>
<td>5</td>
<td>1818</td>
<td>13.74</td>
<td>4.5x10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>37</td>
<td>3</td>
<td>6.9</td>
</tr>
<tr>
<td>5</td>
<td>1887</td>
<td>22.21</td>
<td>4.0x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>37</td>
<td>3</td>
<td>12.5</td>
</tr>
<tr>
<td>5</td>
<td>1887</td>
<td>22.21</td>
<td>4.0x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>37</td>
<td>4</td>
<td>11.3</td>
</tr>
<tr>
<td>5</td>
<td>1887</td>
<td>22.21</td>
<td>4.0x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>37</td>
<td>2</td>
<td>32.0</td>
</tr>
<tr>
<td>5</td>
<td>1887</td>
<td>22.21</td>
<td>4.0x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>37</td>
<td>3</td>
<td>16.4</td>
</tr>
</tbody>
</table>
Conclusions from BBU Experiment

- Threshold current in the IR FEL recirculating linac varies between 7 mA and 32 mA for varying accelerator setup.

- Under the nominal FEL configuration, threshold current is between 16 mA and 21 mA.

- Theoretical prediction is 27 mA ⇒ agreement within ~40%.

- Observed optics dependence has not been quantified yet.

- New analysis tools have been developed.
Longitudinal Phase Space Manipulations

Simulation calculations of longitudinal dynamics of JLAB FEL
Transfer Function Measurements

Experiment

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># 2</td>
<td>0.1172</td>
<td>0.0008</td>
</tr>
<tr>
<td># 3</td>
<td>-0.0801</td>
<td>0.0016</td>
</tr>
<tr>
<td># 4</td>
<td>0.0911</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Simulation

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># 2</td>
<td>0.1070</td>
<td>0.0007</td>
</tr>
<tr>
<td># 3</td>
<td>-0.0834</td>
<td>0.0003</td>
</tr>
<tr>
<td># 4</td>
<td>0.0256</td>
<td>0.0004</td>
</tr>
</tbody>
</table>
Longitudinal Nonlinearities Corrected by Sextupoles

Basic Idea is to use sextupoles to get $T_{566}$ in the bending arc to compensate any curvature induced terms.
Correction of Nonlinearities by “Linearizers”

\[
V_c = V_0 \cos \theta \approx V_0 \left(1 - \frac{\theta^2}{2} + \cdots\right)
\]

\[
V_{\text{lin}} = \frac{V_0}{9} \cos 3\theta \approx \frac{V_0}{9} \left(1 - \frac{9\theta^2}{2} + \cdots\right)
\]

\[
V_c - V_{\text{lin}} = \frac{8V_0}{9} + o(\theta^4), \quad \text{independent of phase!}
\]

Phase Space Evolution Without Linearizer
Correction of Nonlinearities by “Linearizers”
State of the Art in SRF in 2000

Total installed voltage capability with srf cavities for electron and heavy-ion accelerators.

Courtesy: Jean Delayen
High Energy Demonstration of Energy Recovery

- Beam will be accelerated from 45 MeV to 845 MeV and energy recovered to 45 MeV. Plan to inject at 10 to 20 MeV and test energy recovery with energy ratio up to 80
- Beam properties, beam halo to be measured at several locations
- Experiment is approved and scheduled for March 2003

D. Douglas, A. Bogacz
Recirculated Linacs Have Flexible Timing

\[ \sigma_t = \sigma_z / c \text{ (rms)} \]
Timing Possibilities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ERL Possibilities</th>
<th>Jlab FEL Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_t$</td>
<td>100 fsec – 10 psec</td>
<td>&lt; 330 fsec</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>1 MHz – 1.3 GHz</td>
<td>2 – 75 MHz</td>
</tr>
<tr>
<td>Macropulse Duration</td>
<td>1 microsecond - CW</td>
<td>1 microsecond - CW</td>
</tr>
<tr>
<td>Macropulse Repetition Frequency</td>
<td>1 Hz-10 kHz</td>
<td>0.5 Hz – 60 Hz</td>
</tr>
</tbody>
</table>

* In Jlab FEL, fluctuation in pulse centroid measured less than 1 sigma
Brookhaven PERL Projects

- Showed 4 PDF viewslides, available at Brookhaven, dealing with the energy recovered linac plans being developed there.


- Electron Cooling with a PERL
- eRHIC
- PERL Light Source
The BNL Electron Cooling Prototype -

Beam Energy: 50 MeV
Beam current: 100 mA

Courtesy: I. Ben-Zvi
Electron–Light Ion Collider @ L >10^{34} cm^{-2}s^{-1} 

One accelerating & one decelerating pass through CEBAF

5 GeV electrons

50-100 GeV light ions

CEBAF with Energy Recovery
5 GeV/pass

ERL Phase II X-ray SR Source Conceptual Layout

TBA (Optical Unit) + ID

Main Linac

5 - 7 GeV

Injector

x-rays

Dump
### ERL Phase II Sample Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>5-7</td>
<td>GeV</td>
</tr>
<tr>
<td>Average Current</td>
<td>100 / 10</td>
<td>mA</td>
</tr>
<tr>
<td>Fundamental frequency</td>
<td>1.3</td>
<td>GHz</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>77 / 8</td>
<td>pC</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>10</td>
<td>MeV</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>2 / 0.2*</td>
<td>μm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.02-0.3*</td>
<td>%</td>
</tr>
<tr>
<td>Bunch length in IDs</td>
<td>0.1-2*</td>
<td>ps</td>
</tr>
<tr>
<td>Total radiated power</td>
<td>400</td>
<td>kW</td>
</tr>
</tbody>
</table>

* rms values
Brilliance Scaling and Optimization

- For 8 keV photons, 25 m undulator, and 1 micron normalized emittance, X-ray source brilliance

\[ B \propto \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p} \]

- For any power law dependence on charge-per-bunch, \( Q \), the optimum is

\[ AQ^p \approx \varepsilon_{th}^2 / (p - 1) \]

- If the “space charge” generated emittance exceeds the thermal emittance \( \varepsilon_{th} \) from whatever source, you’ve already lost the game!

- BEST BRILLIANCE AT LOW CHARGES, once a given design and bunch length is chosen!

- Unfortunately, best flux at high charge
**ERL X-ray Source Average Brilliance and Flux**

![Graphs showing ERL X-ray source average brilliance and flux across different photon energies and beamlines.](image)

**Courtesy:** Qun Shen, CHESS Technical Memo 01-002, Cornell University
Short Pulses

- In high brilliance mode, with bunch lengths above several mm, there shouldn’t be any problem with the micro m emittance level.
- There is great interest in finding short-pulse (<100 fsec) modes of operation.
- CSR is probably the emittance limiter for short-bunch operation, and I think it unlikely that one would be able to run short bunches and high brightness simultaneously. On the plus side, I don’t think this is a “problem” for the users I’ve interacted with. My guess is that we’ll lose 1-2 orders of magnitude in brilliance going to short pulses; this result is still far better than any proposed competitor.
- The curve brilliance vs. charge for constant bunch length will require some sort of simulation beyond what can be done easily now. Having this curve is EXTREMELY important for evaluating a short-bunch mode of operation. One should sit at the top of this curve for maximum short-pulse brilliance, whatever the anticipated repetition rate.
ERL Peak Brilliance and Ultra-Short Pulses

Peak Brilliance (ph/s/0.1%/mm²/mr²)

Photon Energy (keV)

10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹ 10²² 10²³ 10²⁴ 10²⁵ 10²⁶ 10²⁷

ESRF U35
CHESS 49-pole G/A-wiggler
τ=153ps, f=17.6MHz (9x5)
CHESS 24-pole F-wiggler

0.15nm 100mA 4.7ps
0.15nm 100mA 0.3ps
0.15nm 0.1A 4.7ps
0.15nm 0.1A 0.3ps
0.15nm 0.01A 0.3ps
0.15nm 0.01A 4.7ps
0.015nm 0.01A 0.3ps
0.015nm 0.01A 4.7ps

Peak Brilliance @ 8 keV (ph/s/0.1%/mm²/mr²)

X-ray Pulse Duration τ (ps)

1000 100 10 1 0.1
10
16
10
17
10
18
10
19
10
20
10
21
10
22
10
23
10
24
10
25
10
26
10
27

3rd SR
APS upg
Sp8-25m
ESRF

2nd SR
CHESS 49p
24p

ALS fs BLs
ALS sect.6
undulator

ERL
0.15nm 0.01A
0.15nm 0.1A
0.15nm 0.1A
1.5nm 0.1A

Courtesy: Q. Shen, I. Bazarov
Phase I ERL

Beam Energy 100 MeV
Injection Energy 5 MeV
Beam current 100 mA

Charge per bunch 77 pC
Emittance, norm. 2* μm
Shortest bunch length 100* fs

* rms values
Simulations Results ($E_{\text{inj}}=5$ MeV)

**Courtesy: I. Bazarov**

- Emittance* $x,y$: 1.0 $\mu$m
- Bunch length*: 0.63 mm
- Energy spread*: 0.1 %

* r.m.s. value
Superconducting RF Technology

9-cell 1.3 GHz cavity

Superconducting RF cavities (Q ~ $10^{10} \text{ @ } 20 \text{ MV/m}$)
- Low emittance production & preservation
  - Achieving thermal emittance from gun (emittance compensation)
  - CSR, wakes (77 pC, not 1 nC!)
- Photocathode longevity at high average current (vacuum)
- Longitudinal phase space preservation in bunching (curvature correction)
- BBU in the main linac (HOMs damping)
- Beam loss ~ μA (halo)
- Highest $Q_0$ possible (reduced heat load and best efficiency)
- Highest $Q_L$ possible (fighting microphonics)
- Diagnostics ...
IR FEL Upgrade
## IR FEL 10 kW Upgrade Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy</td>
<td>160 MeV</td>
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<tr>
<td>Average Current</td>
<td>10 mA</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>135 pC</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>&lt;300 fsec</td>
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<tr>
<td>Transverse Emittance</td>
<td>10 mm mrad</td>
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<tr>
<td>Longitudinal Emittance</td>
<td>30 keV deg</td>
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<tr>
<td>Repetition Rate</td>
<td>75 MHz</td>
</tr>
</tbody>
</table>
Conclusions

- In this talk I’ve introduced the ideas of **Beam Recirculation** and **Energy Recovery** and discussed how these concepts may be combined to yield a **new class of accelerators** that can be used in many interesting applications. I’ve given you some indication of the historical development of recirculating SRF linacs.

- I’ve given you some indication of the current status of the single existing recirculating high energy linac, and of the highest average current energy recovered linac in existence.

- The present knowledge on beam recirculation and its limitations in a superconducting environment, leads us to think that recirculating accelerators of several GeV energy, and with beam currents approaching those in storage ring light sources, are possible.

- Cornell University, in collaboration with Jefferson Laboratory has proposed to the United States National Science Foundation to build a prototype superconducting energy recovery linac as a proof-of-principle for the high average current injector, and as a way to investigate in detail some of the limitations of ERLs.
HOM Power

- High average current, short bunch length beams in srf cavities excite HOMs. Power in HOMs, primarily longitudinal:

  \[ P_{\text{HOM}} = k_{||} Q^2 f_{\text{bunch}} \]

- For \( I_{\text{ave}} = 100 \text{ mA}, \ Q = 0.5nC \Rightarrow P_{\text{HOM}} \sim 1 \text{ kW per cavity for } k_{||} = 10.3 \text{ V/pC at } \sigma_z \sim 0.7\text{mm} \)

- In the IRFEL: \( I_{\text{ave}} = 5 \text{ mA}, \ P_{\text{diss}} \sim 6 \text{ W} \)

- Fraction of HOM power dissipated on cavity walls depends on the bunch length

- It can potentially limit \( I_{\text{ave}} \) and \( I_{\text{peak}} \) due to finite cryogenic capacity
HOM Power Dissipation: Theory

- The fraction of HOM power dissipated on cavity walls increases with HOM frequency, due to $Q_0 \sim \omega^2$ degradation from BCS theory

- We developed a model that estimates fraction of power dissipated on the walls and specifies HOM-power extraction efficiency required

- We found:
  - > 90% of HOM power is in modes < 100 GHz
  - Power dissipated on the cavity walls is a strong function of bunch length, $\sigma^{-5/2}$
  - Fraction of power dissipated on the walls is much less than the fundamental mode load
Frequency Distribution of HOM power

![Graph showing frequency distribution of HOM power with different psec values: 1 psec, 2 psec, and 3 psec. The x-axis represents HOM frequency in GHz, and the y-axis represents dissipated power in kW. The graph has three lines: red for 1 psec, green for 2 psec, and blue for 3 psec.](image-url)
HOM Power: Experiment

- HOM power dissipation may impose design choices to improve cryogenic efficiency

- HOM power was measured with temperature diodes placed on the two HOM loads of the 5-cell CEBAF cavity

- Measurements were repeated at different values of the bunch charge and bunch repetition frequency
HOM Power vs. Bunch Charge

\[ k_{||}^{(1)} = 1.4 \text{ V/pC} \quad + \quad k_{||}^{(2)} = 8.0 \text{ V/pC} \]

\[ k_{||}^{\text{total}} = 9.4 \text{ V/pC} \]

\[ k_{||}^{\text{URMEL}} = 11.0 \text{ V/pC} \]

⇒ agreement within 15%
About 4 years ago, after a Science article by Schoenlein, et al., I spent some time trying to figure out how we could do same work at Jlab. Settled on a Thomson scatter source that has recently produced a substantial X-ray flux.

In mean time LBNL proposed short-pulse source based on short-pulse laser and the Inverse FEL interaction.

In this idea, only a small portion (<1%) of the beam is actually used to generate X-rays. By comparison, a CEBAF-like machine can achieve at least 1% of ½ A, and in principal make at least as many X-rays.

The only question is whether you can make the pulses short enough.

The answer is yes, as we’ve seen, under 100 fsec was done many years ago on the nuclear physics accelerator.
60 sec FEL Short-pulse X-ray Spectrum

FEL X-ray Spectra

- $E_0 = 36.7$ MeV
- $\lambda_L = 5.181$ $\mu$m
- IR = 250 Watts, cw
- Live run time = 60 sec.
- $E_{X\text{-ray}} = 5.12$ keV
- FWHM = 0.319 keV

Boyce, Krafft, et al.
Sept. 30, 1999
Preliminary
Berkeley Short Pulse X-ray Facility —

**Diagram:**

- **A:** 30 ps electron bunch
- **B:** Bend magnets
- **C:** X-ray beamline
- **D:** Mirror
- **E:** Femtosecond x-rays

**Diagram Details:**

- Femtosecond laser pulse
- Wiggler

**Relevant Information:**

This diagram illustrates the process of creating femtosecond X-rays through the interaction of a femtosecond laser pulse with a 30 ps electron bunch in a wiggler, followed by bending magnets to focus the beam, and then using a mirror to produce the femtosecond X-rays.
AVERAGE BRILLIANCE FROM CEBAF BENDS

![Graph showing average brilliance vs. photon wavelength for different magnets.](image)

- Magnet 1
- Magnet 2
- Magnet 3
- Magnet 4
Interesting?

E ~ 40 MeV

150 m

6 GeV

E ~ 40 MeV

150 m

3 GeV

ε ~ 10^{-9} mrad

I ~ 10-20 mA

Δt_B ~ 100 fs

f_B ~ 1-10 MHz

ΔE / E ~ several \times 10^{-5}

several $100 M
Interesting New Direction?

C$_9$H$_{10}$N$_2$ Bending

Techert, Schotte, and Wulff, March PRL (2001), quoted in *Physics Today*