USPAS course on

Recirculated and Energy Recovered Linacs

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Ongoing ERL R&D Cornell
• Challenges
• Cornell ERL prototype
• Experimental program
Challenges

• CW injector: produce 100 mA, 80 pC train @ 1300 MHz, in < 1 mm-mrad normalized emittance, low halo with very good photo-cathode longevity

• Maintain high Q and $E_{\text{acc}}$ in high current beam conditions

• Extract HOM’s with very high efficiency ($P_{\text{HOM}} \sim 10x$ previous)

• Control BBU by improved HOM damping

• Maximize loaded $Q_L$ (control microphonics)

• Beam instrumentation and diagnostics of low energy high power beams
Beam breakup: challenge

\[ I_{th} = -\frac{2p_r c}{e(R/Q)_{\lambda} Q_{\lambda} k_{\lambda} R_{12} \sin \omega_{\lambda} t_r} \]

Highest current recirculated in SRF linac was **4.5 mA** in year 2001
Beam breakup: figured out

- **BBU code & theory developed for ERLs (JLAB, Cornell, JAERI)**
- Benchmarked with good accuracy in JLAB FEL
  

- Various suppression techniques successfully tested
BBU: Theory & Computation

• Several different codes (JLAB, Cornell, JAERI)
• Mature theory; excellent agreement with codes

\[ \frac{R}{Q} = 50 \, \Omega, \quad Q = 2 \times 10^4, \quad m_{12} = -10^{-6} \text{ m/(eV/c)} \]

\[ t_r \times c = 24 \text{ m} \]

\[ t_r \times c = 232 \text{ m} \]

\[ t_r \times c = 2307 \text{ m} \]

\[ f_x = 2.2 \text{ GHz}, \quad f_y = 2.3 \text{ GHz} \]

\[ \propto \frac{1}{\sqrt{Q}} \quad \propto \frac{1}{Q} \]

Hoffstaetter, Bazarov, Song
• Demonstrate efficacy of achieving thermal emittance at the end of the injector at a bunch charge of 77 pC/bunch or some large fraction thereof

• Understand the limitations in the injector (both physics and technology) to allow for improved design in the future
• Sub-micron stability (rms) is required for ERL LS in both horizontal and vertical planes
• E.g. CEBAF demonstrates 20 µm rms (limited by BPM noise)
• $10^{-4}$ energy stability is needed
• demonstrated at CEBAF
SRF Challenges

- $Q_0 = 2 \times 10^{10}$ at 15-20 MV/m is desirable
- cavity/cryomodule design that minimizes microphonics
- $Q \leq 10^4$ for primary dipole and $Q \leq 10^3$ for (resonant) monopole HOMs is desired
- smart HOM power handling
- superior LL RF control
High Current SRF Cavities

- **BNL**
- **Calaga**
- **CESR style ferrite absorbers**
- **Cornell**
- **GHe cooling**

- **optimized cavity shape**
- **calculated dipole HOM Q's**
- **ferrite at 80 K**
- **bellows**

- **Jefferson Lab**

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**January 26, 2008 USPAS'08 R & ER Linacs**

- High Current SRF Cavities
- Optimized cavity shape
- CESR style ferrite absorbers
- Cornell GHe cooling
- Ferrite at 80 K
- Bellows
Cornell Low Level RF Control System

- Successfully tested at JLAB FEL

**Demonstrated:**

- $Q_L = 1.2 \times 10^8$ with $I = 5.5$ mA energy recovered beam
- Field stability $10^{-4}$
- Phase stability $0.02^\circ$
Two main limiting mechanisms:

- Phase space scrambling due to nonlinear space charge

**3D Gaussian initial distribution**

\[ \varepsilon_{n,x} = 1.7 \, \mu m \]

**Optimal initial distribution**

\[ \varepsilon_{n,x} = 0.13 \, \mu m \]

- Photocathode thermal emittance

\[ \varepsilon_{n,th} = \sigma_{x,y} \sqrt{\frac{kT}{mc^2}} \]

transverse temperature of photoemitted electrons
Shaping approaches

- Refractive beam shaper from Newport for transverse

- Birefringent crystal set pulse stacker for temporal
Design approaches

- Cut the number of decision variables to some reasonable number (2-4) perhaps by using a simplified theoretical model to guide you in this choice

- **Large regions of parameter space remain unexplored**

- Optimize the injector varying the remaining variables with the help of a space-charge code to meet a fixed set of beam parameters (e.g. emittance at a certain bunch charge and a certain length)

- **One ends up with a single-point design without capitalizing on beneficial trade-offs that are present in the system**

*Primary challenge in exploring the full parameter space is computational speed*
Doing it faster

- work harder
- work smarter
- get help

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

*Multi*Objective Genetic Algorithm

- throw in all your design variables
- map out whole Pareto front, i.e. obtain multiple designs all of which are optimal
- use realistic injector model with your favorite space charge code
maximize \( f_m(x_1, x_2, \ldots, x_n), \quad m = 1, 2, \ldots, M; \)
subject to \( g_j(x_1, x_2, \ldots, x_n) \geq 0, \quad j = 1, 2, \ldots, J; \)
\( x_i^{(L)} \leq x_i \leq x_i^{(U)}, \quad i = 1, 2, \ldots, n. \)

**Definition 1.** A solution \( \mathbf{x}_a \) is said to dominate the other solution \( \mathbf{x}_b \) if the solution \( \mathbf{x}_a \) is not worse than \( \mathbf{x}_b \) in all objectives and \( \mathbf{x}_a \) is strictly better than \( \mathbf{x}_b \) in at least one objective. In other words, \( \forall m \in 1, 2, \ldots, M : f_m(\mathbf{x}_a) \geq f_m(\mathbf{x}_b) \) and \( \exists m' \in 1, 2, \ldots, M : f_{m'}(\mathbf{x}_a) > f_{m'}(\mathbf{x}_b). \)

**Definition 2.** Among a set of solutions \( \mathcal{P} \), the nondominated subset of solutions \( \mathcal{P}' \) are those that are not dominated by any member of the set \( \mathcal{P} \).

When the set \( \mathcal{P} \) is the entire search space resulting nondominated set is called the
\textbf{Pareto-optimal set.}
10 bounded decision variables, 10 constraints
minimize Total Cost

maximize Luminosity

Generation = 1
Evolving into optimal injector design

Parallel Multiobjective Evolutionary Algorithm
Optimization results

MOO problem:

\[ \begin{align*}
\text{minimize emittance} \\
\text{minimize bunch length} \\
\text{maximize bunch charge}
\end{align*} \]

\[ E_{th} = 35 \text{ meV (aka GaAs @ 780 nm)} \]

Takes some \(10^5\) simulations

FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).
Parallel multi-objective optimizations is a powerful tool to explore limits of the system. It is not meant to substitute but rather complement analytical & intuitive picture of what’s going on. Not a substitute for accurate model of the physics of what’s going on (i.e. ‘garbage in, garbage out’).
• Virtual injector allows absolute control of parameters, real system with a dozen of sensitive parameters will not

Pulse duration rms $21.5 \pm 1.4$ ps  
Spot size rms $0.640 \pm 0.057$ mm  
Charge $80 \pm 5.8$ pC 
Solenoid1 $B_{max}$ $0.491 \pm 0.010$ kG  
Solenoid2 $B_{max}$ $0.532 \pm 0.010$ kG  
Cavity1 phase $-41.6 \pm 1.7$ deg  
Cavity2 phase $-31.9 \pm 2.0$ deg  
Cavity3-5 phase $-25.7 \pm 2.0$ deg  
Buncher $E_{max}$ $1.73 \pm 0.04$ MV/m  
Cavity1 $E_{max}$ $15.4 \pm 0.3$ MV/m  
Cavity2 $E_{max}$ $26.0 \pm 0.5$ MV/m  
Cavity3-5 $E_{max}$ $27.0 \pm 0.5$ MV/m  
$q_{1,\text{grad}}$ $-0.124 \pm 0.002$ T/m  
$q_{2,\text{grad}}$ $0.184 \pm 0.002$ T/m  
$q_{3,\text{grad}}$ $0.023 \pm 0.002$ T/m  
$q_{4,\text{grad}}$ $-0.100 \pm 0.002$ T/m

100 random seeds (outliers removed)

\[
\begin{align*}
\text{ave}(\varepsilon_x) &= 1.04 \, \mu\text{m} & \text{ave}(\varepsilon_y) &= 0.95 \, \mu\text{m} \\
\text{std}(\varepsilon_x) &= 0.52 \, \mu\text{m} & \text{std}(\varepsilon_y) &= 0.62 \, \mu\text{m}
\end{align*}
\]
Tolerances for optimum

10% increase in emittance (p-t-p)

- $\text{BunPhase}$: $3.5^\circ$
- $\text{Cav1Phase}$: $3.0^\circ$
- $\text{Ecav1}$: $3.8\%$
- $\text{Lphase}$: $2.4^\circ$
- $\text{B1}$: $0.37\%$
- $\text{B2}$: $0.85\%$
- $\text{Qbunch}$: $3.7\%$
- $\text{Trms}$: $8.0\%$
- $\text{Vgun}$: $0.39\%$
- $\text{XYrms}$: $2.4\%$
BNL R&D ERL

2.5 MeV

20 MeV

$q \sim 20 \text{nC} $

$\varepsilon_n \sim 30 \text{ mm-mrad}$

$I_{\text{max}} = 0.2 \text{ A}$

$q \sim 1.3 \text{ nC} $

$\varepsilon_n \sim 1-3 \text{ mm-mrad}$

$I_{\text{max}} = 0.5 \text{ A}$
Superlattice photocathode?

- equipped to accurately (~meV) measure transverse temp. of e\(^-\) at different wavelengths
- photoemission temporal response resolution (~ps)

<table>
<thead>
<tr>
<th>Q.E.</th>
<th>kT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>small</td>
</tr>
<tr>
<td>B</td>
<td>large</td>
</tr>
<tr>
<td>C</td>
<td>large</td>
</tr>
</tbody>
</table>

Gun development lab in Wilson
Cathode lifetime

Re-cesiation recovers Q.E. → damage is only at the surface

Collision, deposition of residual gases
Dark current (and its enhancement)
Ion back bombardment

Existing guns

CEBAF polarized gun (100kV, 0.1mA)
Life ~ 2 x 10^5 C/cm²

JLAB-ERL gun (350kV, 9mA)
Life ~ 2 x 10^3 C/cm²

Improvement is required

ERL-LS
Life ~ 10^6 C/cm²
100mA / φ 2mm, 100 hours
ERL Phase 1a

ERL Prototype

- Injection Energy: 5 – 15 MeV
- Max Avg. Current: 100 mA
- Charge / bunch: 1 – 400 pC
- Emittance (norm.): ≤ 2 μm@77 pC
- Bunch Length: 2 ps

*Eds. Gruner, Tigner; Bazarov, Belomestnykh, Bilderback, Finkelstein, Fontes, Krafft, Merminga, Padamsee, Shen, Rogers, Sinclair, Talman, ERL prototype proposal to the NSF, 2001*
Gun & cathode package

Gun cathode package

E\textsubscript{cath} = 120 MV/m
τ\textsubscript{laser} = 2.7 ps rms
σ\textsubscript{laser} = 0.5 mm rms
τ\textsubscript{laser} \rightarrow z = 0.08 mm

E\textsubscript{cath} = 43 MV/m
τ\textsubscript{laser} = 5.8 ps rms
σ\textsubscript{laser} = 0.85 mm rms
τ\textsubscript{laser} \rightarrow z = 0.12 mm

E\textsubscript{cath} = 8 MV/m
τ\textsubscript{laser} = 13 ps rms
σ\textsubscript{laser} = 2 mm rms
τ\textsubscript{laser} \rightarrow z = 0.12 mm

\begin{align*}
\frac{E\text{\textsubscript{cath}}}{E\text{\textsubscript{s.charge}}} &= \frac{E\text{\textsubscript{cath}}}{E\text{\textsubscript{s.charge}}} = \frac{E\text{\textsubscript{cath}}}{E\text{\textsubscript{s.charge}}}
\end{align*}

\textbf{same simulated emittance}
Emittance compensation can be achieved despite reduced flexibility in solenoid positioning

<table>
<thead>
<tr>
<th></th>
<th>$Q$ [nC]</th>
<th>Rms bunch Length (compressed)</th>
<th>$E_x$ [mm-mrad]</th>
<th>Cathode material(&amp;)</th>
<th>Band Peak field</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>1 / 0.2</td>
<td>2.8 ps / 1.7 ps</td>
<td>0.72 / 0.3 (**)</td>
<td>Copper, 700 meV</td>
<td>S-Band [120 MV/m]</td>
</tr>
<tr>
<td>DC</td>
<td>1/ 0.1</td>
<td>3ps / 3ps</td>
<td>0.8 / 0.14 (**)</td>
<td>GaAs 35 meV</td>
<td>[15 MV/m] (Average)</td>
</tr>
<tr>
<td>SRF</td>
<td>1 / 0.1(*)</td>
<td>5.7 ps/ 2.7 ps</td>
<td>0.8 / 0.23 (**)</td>
<td>“metallic” 184 meV</td>
<td>L-Band [60MV/m]</td>
</tr>
</tbody>
</table>

(*) scaled  
(**) limited by thermal emittance  
(&) Copper and GaAs use measured values, but SRF gun uses generic metallic cathode number for thermal emittance (0.3 mm-mrad per 1 mm full radius)

\[ \epsilon_x [\text{mm-mrad}] = 4 \sqrt{\frac{q[nC] E_{th}[\text{eV}]}{E_{cath}[\text{MV/m}]]}} \]

RF and DC guns computations are based on optimum emission pulse “3D-ellipsoid”, whereas SRF gun computation uses “beer can”
• **HV DC gun** based photo-injector
• up to **100 mA** average current, **5-15 MeV** beam energy
• norm. rms emittance \( \leq 1 \, \mu m \) at 77 pC/bunch
• rms bunch length **0.6 mm**, energy spread **0.1%**

Cathode

Laser rep. rate 1.3 GHz
Wavelength 520 nm
Duration (rms) 10 ps
Vacuum <10^{-12} Torr

Cs:GaAs

goal: 750 kV

\[ q = 4 \pi \varepsilon_0 E_{cath} \sigma_x^2 \]
DC gun focusing

- Focusing at the cathode is achieved through electrode shaping (25° angle), brings emittance down by a factor of ~2.
- The drawback is increased aberrations from the gun (an issue when scanning laser spot on the cathode to increase re-Cs interval).

80 pC / bunch
Challenges

• Beam has to be matched into the main linac and taken through the merger while being space-charge dominated → work out procedures for space-charge friendly optics tune-up procedures

• Final beam properties are very sensitive to about ten different parameters that need to be ‘set right’ → controls and diagnostics must be up to the task to provide the necessary guidance
Merger issues

- Asymmetric transport $\rightarrow$ x-y coupling term in beam envelope equation
- Energy change in non-zero dispersion section (CSR and space charge) $\rightarrow$ emittance growth
• BNL’s “zigzag” merger

- Good: emittance growth due to linear correlated energy spread from space charge is canceled to first order
- Bad: does not separate 2 beams (works for BNL because recirculating energy is only 15-20 MeV)
- Bad: is longer than Cornell’s present 3-bend acrhomat, comparison yielded similar emittance growth for the two
I. Photocathode phenomena
II. Space charge dominated regime
III. Longitudinal phase space control
IV. Emittance preservation in the merger
V. High average current phenomena
VI. Achieving ultimate ‘tuned-up’ performance
R128 vs. L0

- Simple: gun & diagnostics line
- Full phase space characterization capability after the gun
- Temporal measurements with the deflecting cavity

- Limited diagnostics after the gun (before the module)
- Full interceptive diagnostics capabilities at 5-15 MeV

- Some full beam power diagnostics
L0 layout: near the gun
L0 layout: 15 MeV straight-thru

IA5DQD01
quadrant detector

IA4FCA01
Faraday cup

IA4SYR01
viewscreen

IA4WFS01
flying wire

IA4SL[H,V]01
hor & vert slits

IA3SDR01
viewscreen

IA5BPB01

IA5BPB02
BPM type B

IA4BPC01

IA3BPC02
BPM type C

IA3BPC01

IA3BCM01
fast current monitor

1 m
1 ft
L0 layout: merger & chicane

merger
diagnostics chicane
Diagnostics overview

- Beam position resolution: 10 µm (spec)
- Energy spread resolution: $10^{-4}$
- Transverse beam profile resolution: 30 µm (viescreens)
  10 µm (slits)
  30 µm (flying wire)
- Angular spread resolution: 10 µrad
- Pulse length (deflecting cavity & slits): 100 fs
- RF phase angle: 0.5°

Ability to take phase space snapshots of the beam, both transverse planes, and longitudinal phase space
Emittance measurement system

- no moving parts
- fast DAQ
- 10 mm precision slits
- kW beam power handling capability

measured phase space
Deflecting cavity

- 100 fs time resolution (with slits)
- Used in:
  - photoemission response meas.
  - slice transverse emittance meas.
  - longitudinal phase space mapping
Flying wire

- 20 m/s flying carbon wire
- Applicable with 0.6 MW of beam power
- Two units, one in dispersive section to allow studies of long-range wake fields
THz radiation

- One of chicane dipole magnets to be used in the analysis of FIR radiation spectrum
- Applicable with 0.6 MW of beam power
- Provides the autocorrelation of the bunch profile
- OTR foils for low beam power measurements
Beam experiments

I. Photocathode phenomena
   – Exp1. Thermal emittance (R128) done
   – Exp2. Photoemission response time (R128) 2 weeks

II. Space charge regime
   – Exp3. Space charge limited extraction from the cathode (R128) done
   – Exp4. Effect of laser pulse shaping on emittance compensation (R128) 2 weeks
   – Exp5. Phase space tomography of bunched beam (R128 & L0) 2 weeks R128 + 2 weeks L0
   – Exp6. Benchmarking of space charge codes (R128 & L0) 1 week R128
   – Exp7. Slice emittance studies (L0) 2 weeks
III. Longitudinal phase space control

– Exp8. Ballistic bunch compression (L0) 2 weeks
– Exp9. Longitudinal phase space mapping (L0) 2 weeks

IV. Emittance preservation in the merger

– Exp10. Space charge induced emittance growth in dispersive sections (L0) 2 weeks
– Exp11. CSR effect (L0) 2 weeks
V. High average current phenomena

– Exp12. Ion effect (R128 & L0) 1 week \textit{R128} + 2 weeks \textit{L0}

– Exp13. Long range wakefield effects (L0) 1 week

VI. Achieving ultimate ‘tuned-up’ performance

– Exp14. Orbit stability characterization and feedback (L0) 2 weeks

– Exp15. Exploration of ‘multi-knobs’ and online optimization (L0) 3 weeks
Exp1. Thermal emittance

- \( kT_\perp = 121 \pm 8 \, \text{meV} \) at 520 nm
- or 0.49 mm-mrad per 1 mm rms
- GaAs still best overall perform.

\[ kT_\perp (\text{meV}) = 309.2 - 0.3617 \lambda \, (\text{nm}) \]
Exp4. Laser shaping effect

- Effective means of laser shaping have been devised and tested
- Beer-can distribution is the goal for Phase 1a (better shapes exist)

**laser shape: where we were August 2007**

**temporal**

**spatial**

**goal to achieve (picture on the right is actual data)**

**gaussian**

**flat-top**
Exp4. Temporal shaping

Laser and e-beam shape: where we are Dec 2007

Top: laser cross-correlation

Bottom: electron beam profile measured with deflecting cavity
First space charge running

**E-beam right after the gun (250 kV) and the solenoid**

- SOL1 = SOL2 = 3A
- SOL1 = SOL2 = 4.5 A

Measured

- well-defined halo

Simulated

- cathode: uniform
- gaussian
- viewscreen
- longitudinal tail overfocused
- particles folding-over forms well-defined boundary
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70 pC/bunch

log scale

smallest emittance

\[ \varepsilon_{ny} = 1.8 \pm 0.1 \text{ mm-mrad} \]
Agreement with simulations

Good agreement with Astra prediction:
77 pC/bunch: about 2 mm-mrad

![Graph showing agreement with Astra prediction](image1)

![Graph showing normalized σ at SL1](image2)

![Data vs. Astra comparison](image3)
Exp6. Codes’ benchmarking

R128: gun & solenoid

- Emittance right after the gun is within 50% of the final value
- Establish the validity of space charge codes & high degree of emittance compensation in R128
• Combination of slits & deflecting cavity to allow detailed longitudinal phase space mapping
• Temporal resolution 0.1 ps, energy resolution $10^{-4}$
• Will be used in a variety of studies, e.g.
  – ensuring small energy spread, a prerequisite for successful transport through the merger
  – optimizing compression scheme
Exp11. CSR in the merger

\[ \Delta \varepsilon_{x,n,CSR} \approx 0.25 \, \mu m \]

elegant

- EMS systems placed before and after the merger to isolate the CSR emittance growth
- Phase space dilution studies as a function of varying charge and bunch length
- Longer term possibilities – smaller bends, shielded chamber
Exp12. Ions

- Initial calculations show that running 100 mA CW will cause problems with safe beam dump operation
- Full beam neutralization over 4 s at $10^{-9}$ Torr
- Possible approaches:
  - develop the average-current dependant optics to account for the full beam neutralization and slowly ramp up the current (test in R128)
  - introduce the ion gap, e.g. 6 $\mu$s every 60 ms (test in R128)
  - the ion gap will cause large RF transients, it won’t work in L0
    - Energy stored in the gun: $15.6 \text{ J} \rightarrow 1\%$ transient over 1.5 $\mu$s
    - Energy stored in a cavity: $0.5-5 \text{ J} \rightarrow 1\%$ transient over 0.1 $\mu$s
  - introduce clearing electrodes (non-trivial changes to the beamline, would rather avoid)
DC beam in R128 (250 kV)

- Ions ‘helping’ to have a small beam
- 250 kV → 25 kW over 4 cm diameter is probably safe on the dump
- 0.6 MW will not be so forgiving!

Nominal size at the dump $4\sigma = 20$ cm
• Two extremely short focal-length quads near the dump blow up the beam by a factor of more than a hundred

• Even with the raster, the spot size cannot be less than 8 cm rms at the dump plane. Ions will throw a monkey wrench into the optical setting.

• The optics will have to incorporate the ions to avoid the dump failure mechanism

• Challenge: we are essentially blind at 0.6 MW near the dump as far as the beam profile is concerned.
• Should develop ad-hoc means to tune-up the nonlinear system for optimal performance

• ‘Manual’ optimization using a calculated Hessian matrix of the beam emittance from the space charge codes:

\[ H_{ij} = \frac{\partial^2 C}{\partial p_i \partial p_j} \]

• Use SVD of the Hessian to form ‘multi-knobs’ that correspond to top few eigenvalues

• Other potentials: use online direct search method (e.g. simplex) or a stochastic search (e.g. genetic algorithms). Analog computer evaluations will be limited to a few hundred at most.
Summary

- Experimental plan outlined, both R128 and L0 parts are essential
- There are things we know we don’t know (e.g. ions), and there are things we don’t know we don’t know. We are concentrating on the former.
Going full steam ahead

Gun development lab: 750 kV gun with diagnostics line
Going full steam ahead