USPAS Course

on

Recirculated and Energy Recovered Linear Accelerators

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Lecture 15
Beam Performance at CEBAF at Jefferson Lab

- Most radical innovation (had not been done before on the scale of CEBAF):
  - choice of srf technology
- 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>
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<tbody>
<tr>
<td>Beam energy</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>A 100 $\mu$ A, B 10-200 nA, C 100 $\mu$ A</td>
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<tr>
<td>Normalized rms emittance</td>
<td>1 mm mrad</td>
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<tr>
<td>Repetition rate</td>
<td>500 MHz/Hall</td>
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<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>$&lt; 0.1/\gamma$</td>
</tr>
</tbody>
</table>
Calculated Longitudinal Phase Space
Some Early Results
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

\[ \Delta E(t) \]

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
MO Modulation System Layout

North Linac

Single-Pass Relative Phase Components

Multi-Pass Relative Phase Components

RF Phase Modulators

North Linac Master Oscillator

South Linac Master Oscillator

DL

SL

NL

SL

NL

Dedicated first pass BFM signal to lockins

Reference signals to multipass lockins

Lock-in Amplifiers

Lock-in Amplifiers

(multi-pass detection)

Courtesy: Michael Tiefenback
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

-0.5 -0.25 0 0.25 0.5 1 1.5
Cumulative Phase (degrees)

-36 -30 -24 -18 -12 -6 0
Time (Days)

=250 microns

Sept 14

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

0 100 200 300 400 500 600 700 800 900 1000 1100

0 10 20 30 40 50

Courtesy: Valeri Lebedev
Fast Feedback Residual Fluctuations

![FFB_D_FFT.adl](image)

1C12_Horizontal_FFT

Frequency

30.0
22.5
15.0
7.5
0.0
0 100 200 300 400 500 600 700 800 900 1000 1100

Courtesy: Valeri Lebedev
Fast Feedback rms position fluctuations

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<td>5.29</td>
<td>33.74</td>
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</table>

Courtesy: Valeri Lebedev
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 \( E \geq 2 \) GeV
- Open frame => not invasive upon insertion.
- Effect of foil on beam:
  - Energy loss => negligible
  - Beam scattering: OK for \( E > 2 \) GeV; 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: [Select Options]

DataValid: Yes

Units: mm

X Position: 355.8
X Width (rms): 4.0
Y Position: 292.1
Y Width (rms): 4.3

Mode: Free Run

Acquire Gain: 1000

Calibration screen: Hall C

DOB: [Select Options]

Acquire Gain: 100

LUT1 Mode: Subtract

Acquire Gain: 10

LUT1 Threshold: [Select Options]

Set up Scripts: [Select Options]

X profile

Y profile

Masks: [Select Options]

MAX pixel: 128

Saturated: 0

MAX pixel: 255

150
100
50
0

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)
- X Position => relative energy drift
- rms X width => Energy Spread

Secondary Hall (Hall A)

Energy drift

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

Energy spread

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

Energy drift

Energy spread

1E-4

X and sigma X in mm

0.4

0.8

1.2

0

0.4

0.8

1.2

0

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

Courtesy: Jean-Claude Denard
dp/p Stability versus Beam Current

OTR beam size versus Beam Current at 4 m dispersion point

Horizontal beam size

Vertical Beam Size

Courtesy: Jean-Claude Denard
Jefferson Lab FEL

X-ray Set-up

IR wiggler

Optical system

Dump


e\textsuperscript{-} recirculation beam line

10 m


Thomas Jefferson National Accelerator Facility

Operated by the Southeastern Universities Research Association for the U. S. Department of Energy

29 June 2005

Recirculating and Energy Recovering Linacs
The Jefferson Lab IR FEL

Wiggler assembly

Optical cavity mirrors

Water dump

West arc

Beam start

Power supply

Injector gun

Cryomodule

Beam dump

Beam dump

Beam finish

East arc
## FEL Accelerator Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Designed</th>
<th>Measured</th>
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<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>
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<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).
In an effort to address the issues of energy recovering high energy beams, Jefferson Lab performed a minimally invasive energy recovery experiment utilizing the CEBAF superconducting, recirculating, linear accelerator.
CEBAF Modifications

Modifications include the installation of:

\(\lambda_{RF}/2\) path length delay chicane

Dump and beamline with diagnostics
“1 Pass-Up / 1 Pass-Down” Operation

North Linac

South Linac

Inject

Dump

$\lambda_{RF}/2$ phase delay

55 MeV

555 MeV

1055 MeV

55 MeV

555 MeV

1055 MeV

555 MeV

Recirculating and Energy Recovering Linacs

Operated by the Southeastern Universities Research Association for the U. S. Department of Energy
Machine Optics

**Linacs** - standard 120° lattice for the lowest energy beam in each linac and mismatched optics on the other pass.

North Linac, Accelerating

South Linac, Accelerating

North Linac, Decelerating

South Linac, Decelerating

Recirculating and Energy Recovering Linacs

Operated by the Southeastern Universities Research Association for the U. S. Department of Energy
CEBAF-ER Experimental Run

Beam viewer near the exit of the South Linac

~ 55 MeV Decelerated beam

~ 1 GeV Accelerated beam

3-wire scanner x 2 beams = 6 peaks
Beam Profiles of ER Beam (cont’d)

Beam profiles (20 MeV, 1μA beam) measured with a wire scanner and 3 downstream PMTs

The Y-profile shows a good Gaussian fit over 6 orders of dynamic range.

The width of the X-profile is scaled by (ΔE/E) from the $E_{\text{inj}} = 55$ MeV case.

Width of X-profile could potentially explain the increased scraping observed at $E_{\text{inj}} = 20$ MeV.
RF Response to Energy Recovery

- Gradient modulator drive signals with and without energy recovery in response to 250 µsec beam pulse entering the RF cavity (SL20 Cavity 8)
Conclusions

- **Achievements**
  - Demonstrated the feasibility of energy recovering a high energy (1 GeV) beam through a large (~1 km circumference), superconducting (39 cryomodules) machine.
  - 80 µA of CW beam accelerated to 1055 MeV and energy recovered at 55 MeV.
  - 1 µA of CW beam, accelerated to 1020 MeV and energy recovered at 20 MeV, was steered to the ER dump.
  - Tested the dynamic range on system performance by demonstrating high final-to-injector energy ratios \( \frac{E_{\text{final}}}{E_{\text{inj}}} \) of 20:1 and 50:1.

- **Future Activities**
  - Important accelerator physics and technology challenges are topics of vigorous research at JLab. They will also be addressed experimentally by a number of prototypes, such as the 10 mA JLab FEL, 100 mA FEL upgrade and continued activities with CEBAF-ER.
I would like to acknowledge and thank the members of the CEBAF-ER collaboration:

Kevin Beard
Alex Bogacz
Yu-Chiu Chao
Swapan Chattopadhyay
David Douglas
Arne Freyberger
Andrew Hutton
Lia Merminga
Mike Tiefenback
Hiro Toyokawa
IR FEL 10 kW Upgrade
## IR FEL 10 kW Upgrade Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
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<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>
</tr>
<tr>
<td>Transverse Emittance</td>
<td>10 mm mrad</td>
</tr>
<tr>
<td>Longitudinal Emittance</td>
<td>30 keV deg</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>75 MHz</td>
</tr>
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</table>
Recent Results From FEL Upgrade

- Achieved basic accelerator parameters and FEL operating characteristics
- Multipass Beam Breakup (BBU) Instability observed directly with high current beam and studied as shown in previous material
- FEL bend chicanes operate as high average power THz sources due to emission of Coherent Synchrotron Radiation. This heat load added nontrivial complexity to the operation of the FEL optical resonater.
- With BBU suppressed 9.1 mA, recirculated current
- Beam charge-per-bunch of 135 pC
- Time averaged 10 kW laser power at several microns
Recirculated Linacs Have Flexible Timing

\[ T_{rep} \quad \sigma_t = \sigma_z / c \quad (rms) \quad T_{macropulse} \quad T_{macropulse \ rep} \]
# Timing Possibilities

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

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