CEBAF Energy Recovery Experiment – Proposal

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Introduction – The Experiment

Physics Motivation

High energy (multi-GeV)/high current (hundreds of milli-Amperes) beams require GWatt-class RF systems in conventional linacs – a prohibitively expensive proposition. Energy recovery technique alleviates extreme RF power demands, improves linac efficiency and increases cost effectiveness.

Several newly proposed accelerator systems are based on high energy/high current Energy Recovering Linac (ERL) concept. ERLs are potentially powerful recirculating linear accelerators; they deliver beams of superior quality (short pulses, small emittances and energy spreads determined by the source) with efficiencies approaching those of storage rings. Apart from being used as high current injectors, they are being contemplated for a variety of other applications, such as the high brilliance storage rings (eg. Cornell ERL prototype), electron cooling devices for e-RHIC (at BNL) and linac-ring colliders for nuclear and particle physics (eg. ELIC and eRHIC).

The largest scale demonstration of energy recovery to date has taken place in the Jefferson Lab IR FEL where 5 mA of average beam current have been accelerated up to 50 MeV and the energy stored in the beam was recovered subsequently via deceleration and given back to the RF power source. Some of the ERL-based accelerator applications that are being proposed require beam currents of the order of 100 mAs. The beam energy for these applications ranges from the currently achieved 50 MeV up to 5 GeV. For example, the present design for ELIC, the Jefferson Lab proposal for a CEBAF-based Electron-Ion Collider (EIC), is based on electrons recirculating once through CEBAF, and gaining energy of about 5 GeV (assuming ~20 MV/m gradient and Upgrade-style cryomodules) and then colliding with 50-100 GeV light ions (stored in a separate storage ring). After the collisions the electrons are re-injected into CEBAF for deceleration and energy recovery.

There are several important accelerator physics and technology issues that must be resolved before any of these applications can be realized for the full benefit of nuclear physics applications. The Jlab FEL Upgrade, presently under construction and designed to accelerate 10 mA up to 150-200 MeV and then subjected to energy recovery, and the proposed Cornell/Jlab ERL Prototype, designed to accelerate 100 mA up to 100 MeV and then decelerated for energy recovery will be ideal test beds for the understanding of high current phenomena in ERL devices. However, in both these devices the energy will be limited to 100-200 MeV. Until the present proposal, there were no plans aimed to address issues related to beam quality preservation in systems with large final beam energy (up to 1 GeV) or large energy ratio between final and injected beams (up to factors of 40-80). Investigation of physics issues for such machines is warranted and timely. The proposed CEBAF-ER Experiment aims at showing just that – an operational feasibility of running a large-scale superconducting recirculating linac in energy recovery and current doubling modes. A full-scale demonstration of energy recovery would provide practical evidence of the usefulness of such machines for future projects. It will allow us to evaluate the limitations and ultimate performance of ERLs, including providing a unique opportunity to address an important regime of machine operation, in the context of preservation of beam quality and management of beam phase space in a complex machine. Finally, together with the high-current experiments, CEBAF-ER will directly address the feasibility of ELIC.

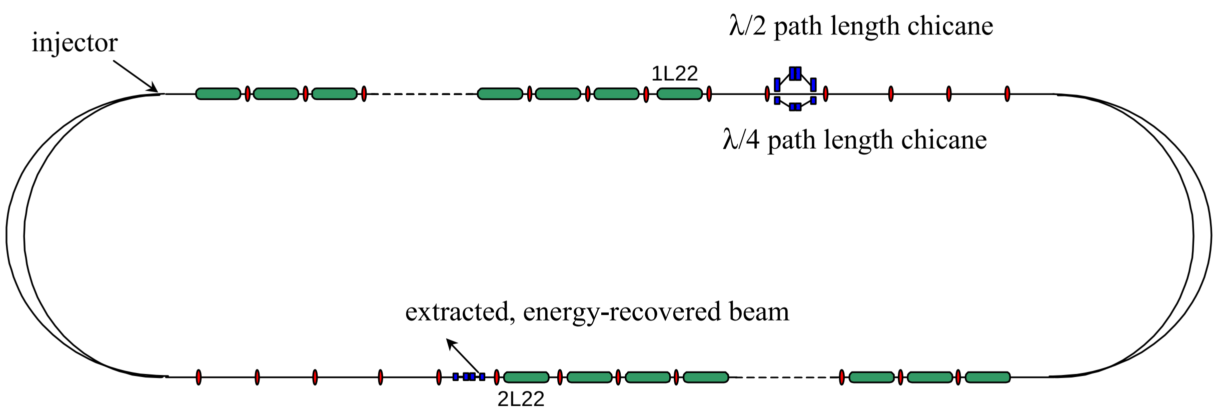
"CEBAF-ER on the ERL Landscape" – A Complement to the Cornell ERL Prototype

	Current		
Energy/Size	"low" (< 1 mA)	"intermediate" (1-10 mA)	"high" (10-100 mA)
"low"/"small" (≤100 MeV / several 10s of m)	HEPL & CEBAF-FET recirculation (1993; 15 kW)	JLab IR Demo FEL (1999-2001, 250 kW)	Cornell ERL Prototype (~2006; 10 MW)
"intermediate"/"medium" (few 100's of MeV / ~100+ m long system)	Bates recirculator (1983; 15 kW)	JLab FEL Upgrade (~2003; 1 MW)	JLab 100 kW FEL (~2006, 20 MW)
"high" / "large" (~1 GeV & above / km-scale system)	CEBAF-ER (~2003; 170 kW)	Multipass CEBAF-ER: 5-10 GeV/20 mA (~2009 100-200 MW)	ELIC, eRHIC, JERBAL (~2012; 1 GW)

Experimental Layout

Adding a simple 'twin' chicane (half/quarter-RF-wavelength delay chicane for path length shift) at the end of the North Linac and a small extraction dump/chicane for depositing the energy recovered beam at the end of the South Linac turns the CEBAF accelerator into a powerful test-bed for exercising various operational modes of a recirculating linac with energy recovery and current doubling.

Schematic location of both new installations is illustrated below (in blue). They turn the ordinary CEBAF into the CEBAF-ER/CD



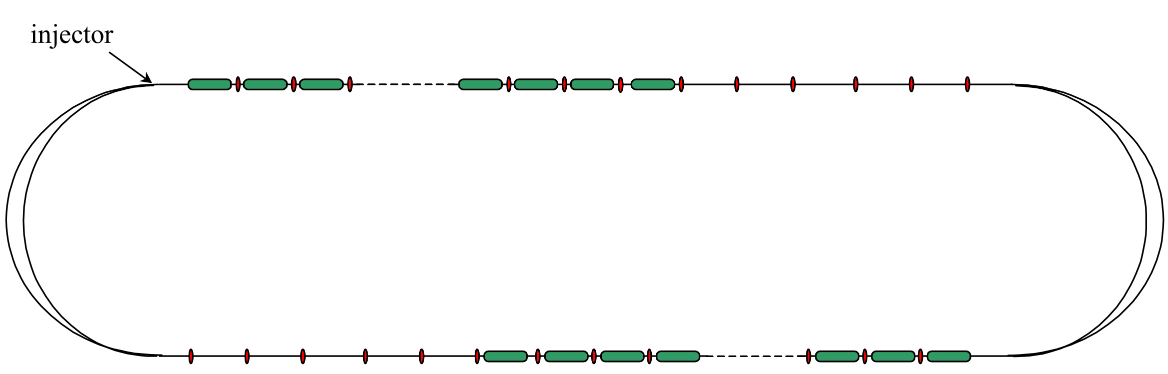
Concept of CEBAF-ER/CD Experiment

Staging of the Experiment

The intention is to stage the Energy Recovery Experiment into a logical sequence of different phases according to their operational complexity. The proposed sequence goes as follows:

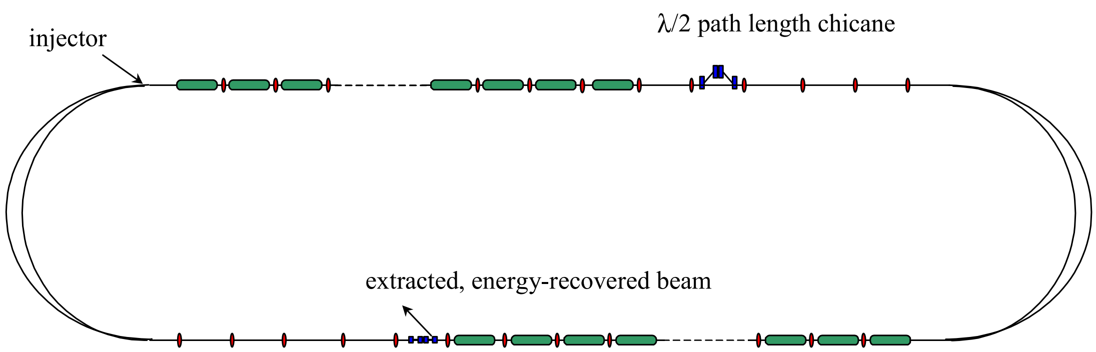
- **Phase 0 – The Deceleration Commissioning Test** – No new hardware required. The beam is accelerated in the North Linac and decelerated in the South Linac.

	Phase wrt North Linac		Phase wrt South Linac			
Element	Phase In	Phase Out	Phase In	Phase Out	Energy In	Energy Out
Injector	0	0	+180		0	45
Pass 1						
N Linac	0	0			45	445
Arc 1					445	445
S Linac	0	0	+180	+180	445	45
Arc2					45	45
Insertable Dump					45	0



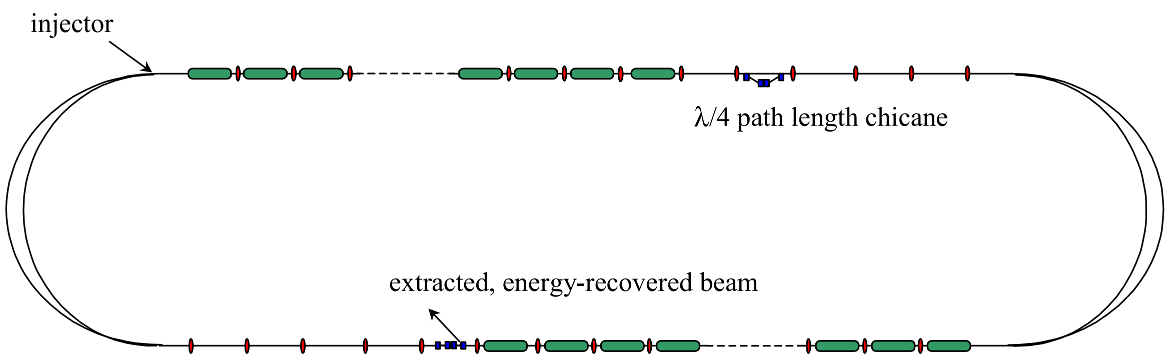
- **Phase 1 – The Energy Recovery Experiment** – Requires a $\lambda/2$ chicane at the end of the North Linac and a beam dump/chicane at the end of the South Linac. The beam is accelerated in the North Linac and South Linac then decelerated through the North Linac and South Linac.

	Phase wrt North Linac		Phase wrt South Linac			
Element	Phase In	Phase Out	Phase In	Phase Out	Energy In	Energy Out
Injector	0	0	+180		0	45
Pass 1						
N Linac	0	0			45	445
N Chicane	0	+180			445	445
Arc 1					445	445
S Linac	+180	+180	0	0	445	845
Arc 2					845	845
Pass 2						
N Linac	+180	+180			845	445
N Chicane	+180	+360			445	445
Arc 1					445	445
S Linac	+360	+360	+180	+180	445	45
S Dump					45	0



- **Phase 2, Part 1 – The 2-Pass Current Doubling Experiment** – Requires a $\lambda/4$ chicane at the end of the North Linac (appropriate reconfiguration of the twin chicane) and the same dump at the end of the South Linac. The beam is accelerated in the North Linac, drifts through the South Linac and North Linac, and is then decelerated in the South Linac.

	Phase wrt North Linac			
Element	Phase In	Phase Out	Energy In	Energy Out
Injector	0	0	0	45
Pass 1				
N Linac	0	0	45	445
N Chicane	0	90	445	445
Arc 1			445	445
S Linac	**90**	**90**	445	445
Arc 2	**Head Tail Inversion**		445	445
Pass 2				
N Linac	**90**	**90**	445	445
N Chicane	90	180	445	445
Arc 1			445	445
S Linac	180	180	445	45
S Dump			45	0

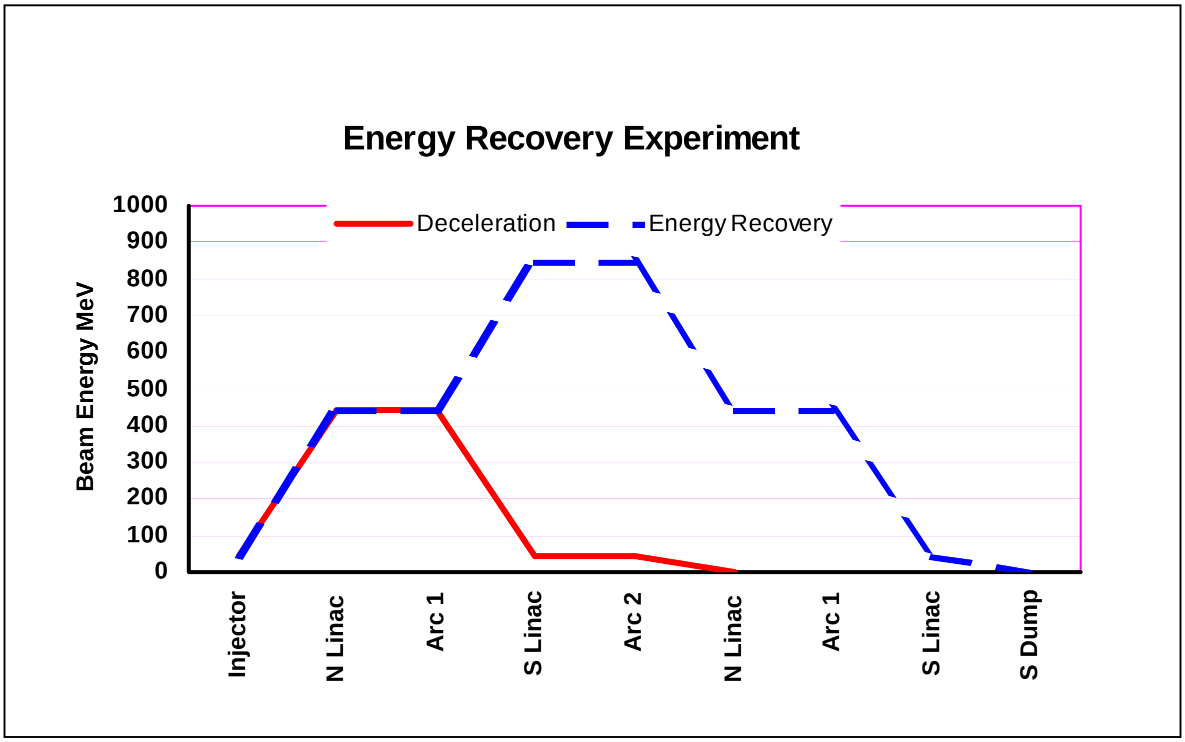


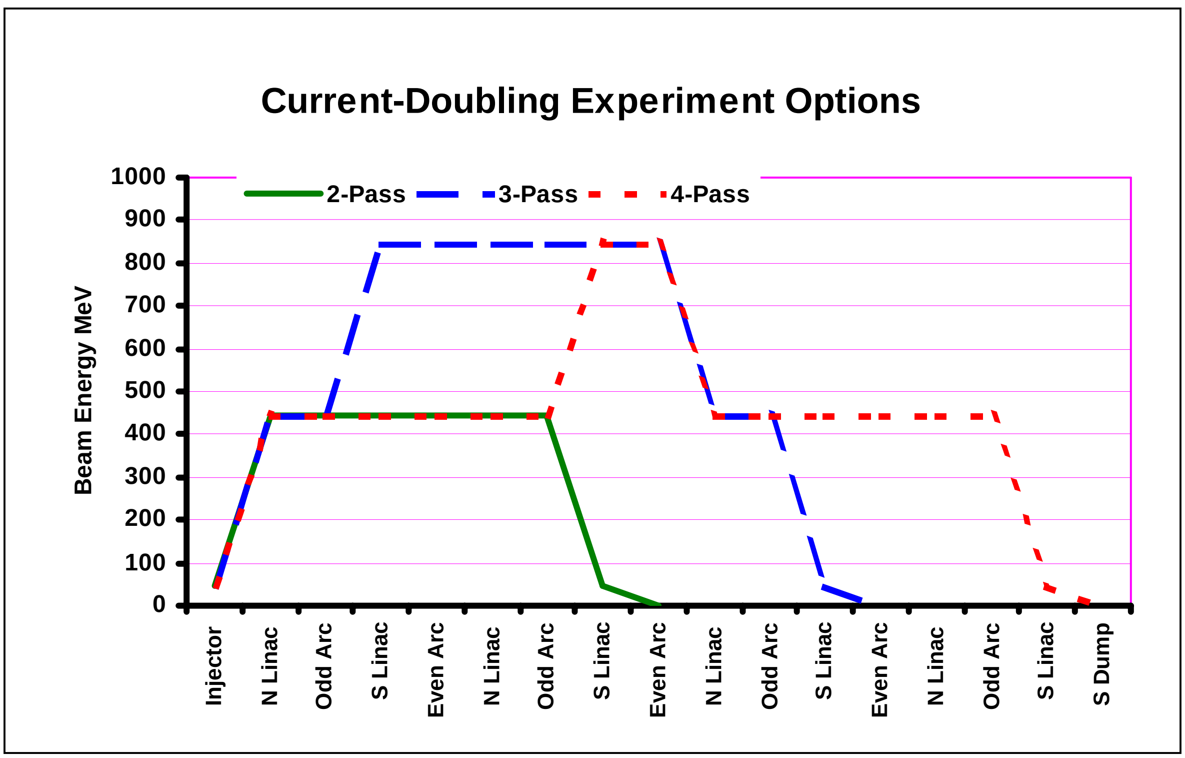
- **Phase 2, Part 2 – The 4-Pass Current Doubling Experiment** – Requires identical hardware to the 2-pass Current Doubling experiment. The beam is accelerated in the North Linac, drifts through the South Linac and North Linac, is accelerated in the South Linac, decelerated in the North Linac, drifts through the South Linac and North Linac, and is then decelerated in the South Linac.

	Phase wrt North Linac		Phase wrt South Linac			
Element	Phase In	Phase Out	Phase In	Phase Out	Energy In	Energy Out
Injector	0	0	+180		0	45
Pass 1						
N Linac	0	0			45	445
N Chicane	0	+90			445	445
Odd Arc					445	445
S Linac	+90	+90	**-90**	**-90**	445	445
Even Arc					445	445
Pass 2						
N Linac	**+90**	**+90**			445	445
N Chicane	+90	+180			445	445
Odd Arc					445	445
S Linac	+180	+180	0	0	445	845
Even Arc					845	845
Pass 3						
N Linac	+180	+180			845	445
N Chicane	+180	+270			445	445
Odd Arc					445	445
S Linac	+270	+270	**+90**	**+90**	445	445
Even Arc					445	445
Pass 4						
N Linac	**+270**	**+270**			445	445
N Chicane	+270	+360			445	445
Odd Arc					445	445
S Linac	+360	+360	+180	+180	445	45
S Dump					45	0

Summary

Energy profile of various scenarios of energy recovery/current doubling experiments are summarized on the graphs below





Beam Transport Requirements – Optics Design and Coupling

Introduction

This section discusses optics design and coupling issues required to facilitate beam transport for different phases of CEBAF-ER/CD Experiment. A compendium of ideas regarding coupling addressed at different phases of the experiment is also presented.

Phase 0 – The Deceleration Commissioning Test

Requires no new hardware; an introductory step to be exercised before installing anything. The beam is accelerated in the North Linac and decelerated in the South Linac.

Optics – the North Linac will have the standard optics (120° betatron phase advance per cell). The South linac optics will be matched to the standard 120° lattice for the decelerating beam (linacs setups exactly as for the linac energy balancing exercise)

Coupling – Since the coupling kick from the cryomodules inverts when the cavities are phased to provide deceleration, the integrated coupling from the North and South Linac cryomodules will cancel. Therefore the integrated coupling created by the skew quads must cancel. This is a sufficient condition that the beam be uncoupled at the dump (in other words, zero skew quads everywhere would meet this condition). It we would also like to keep the beam small throughout the deceleration in the South Linac, then the best skew quad condition is to have the skew quads set in the North and South to cancel the coupling everywhere. Again, this is the way the skew quads were set up for the linac energy balancing.

Phase 1 – The Energy Recovery Experiment

Requires a λ/2 chicane to be installed at the end of the North Linac and a beam dump installed at the end of the South Linac. The beam is accelerated in the North Linac and South Linac then decelerated through the North Linac and South Linac.

Optics – maintaining the correct 120° focusing in both linacs for the lowest pass. Note, this is exactly the same optics as used for the Phase 0 (Deceleration Commissioning Test), which will therefore serve to test the set-up.

Coupling – The sufficient condition is that the integral skew quadrupole components in the North and South Linacs must cancel. If this condition is applied, after acceleration through the North and South Linacs, the beam will have exactly the coupling due to the sum of the cryomodule skew kicks in the two linacs independent of the skew quadrupole distribution (a somewhat surprising conclusion!). Therefore, we should again apply the criteria to have the beams uncoupled at the lowest energies. This means that the best solution is to cancel the coupling on the first pass in the North and the last pass in the South. This is exactly the same skew quadrupole distribution that is best for the Deceleration Commissioning Test , which again will serve to test the set-up.

Phase 2, Part 1 – The 2-Pass Current Doubling Experiment

Requires a $\lambda/4$ chicane at the end of the North Linac (appropriate reconfiguration of the twin chicane) and the same dump at the end of the South Linac. Beam is accelerated in the North Linac, drifts through the South Linac and North Linac, and is then decelerated in the South Linac.

Optics – Since we again would like to have 120° phase advance for the lowest energy beams, the same quad configuration used in the previous two experiments is the best.

Coupling – The optimum correction of the coupling created by acceleration in the North Linac and deceleration in the South Linac requires the same settings as the previous experiments. However, as the beam drifts through the South and North Linacs at the same zero crossing phase (+90°), the skew kicks add rather than subtract. This needs to be cancelled by using the linac skew quadrupoles. However, the cryomodule coupling is created on a single pass through each linac, while the skew quadrupole correction occurs on each of the two passes. Therefore, one half of the appropriate correction should be added to the skew correction required to correct the acceleration and deceleration coupling. The net result is that the beam will be pre-corrected for the drift coupling during the first passage of Arc1 after acceleration in the North Linac, which will create an elongated and rotated ellipse in four-dimensional space. The beam will be under-corrected during the second passage of Arc1 prior to deceleration in the South Linac, so the ellipse will again be elongated by the same amount, but rotated by an equal and opposite amount to the first passage. Since it is the projection of these ellipses that is seen in real space, the two cases produce identical projections on the real axes. In other words, both beams should be identical in Arc1. Again, a surprising result that should be confirmed by measured.

Phase 2, Part 2 – The 4-Pass Current Doubling Experiment

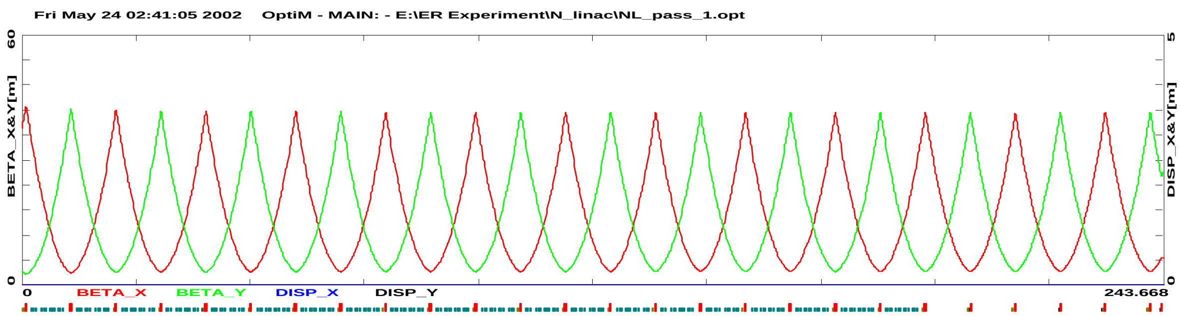
Requires identical hardware to the 2-pass Current Doubling experiment. The beam is accelerated in the North Linac, drifts through the South Linac and North Linac, is accelerated in the South Linac, decelerated in the North Linac, drifts through the South Linac and North Linac, and is then decelerated in the South Linac.

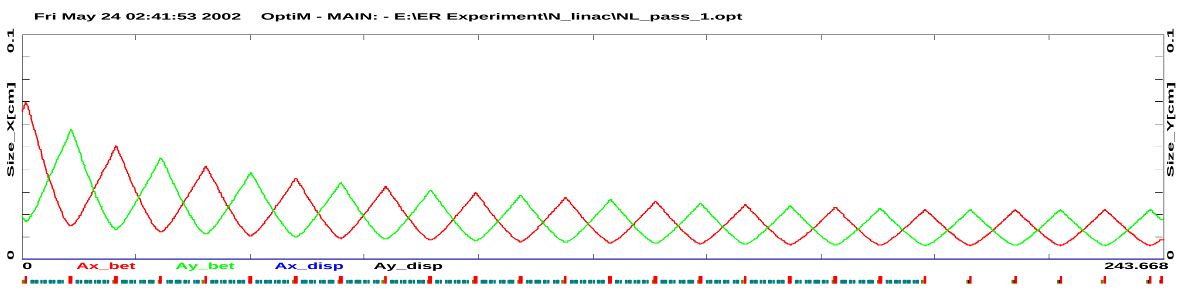
Optics – The optics are identical to the three previous cases.

Coupling – In this case, the successive drifts through the South and North Linacs occur at opposite zero crossings (90°, 270°) so the coupling due to drifting through the linacs cancels. Therefore the skew quadrupoles should be set to cancel the coupling on the first acceleration in the North Linac and the final deceleration in the South Linac; i.e. set exactly the same as the first two experiments.

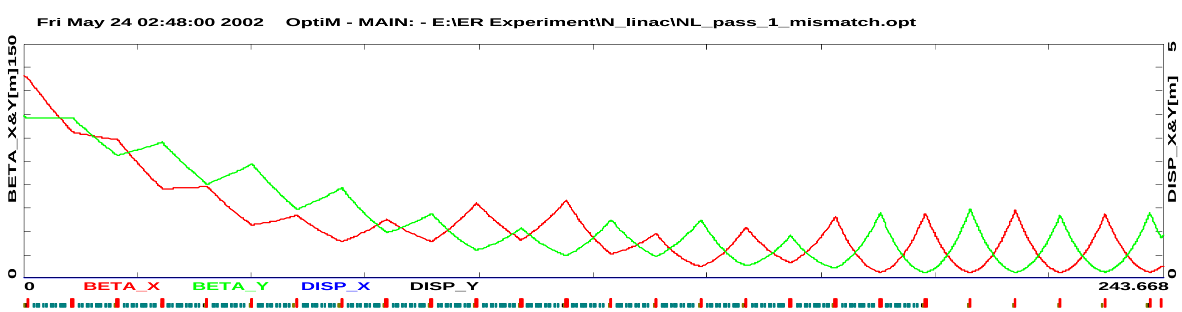
Optics Design Principles

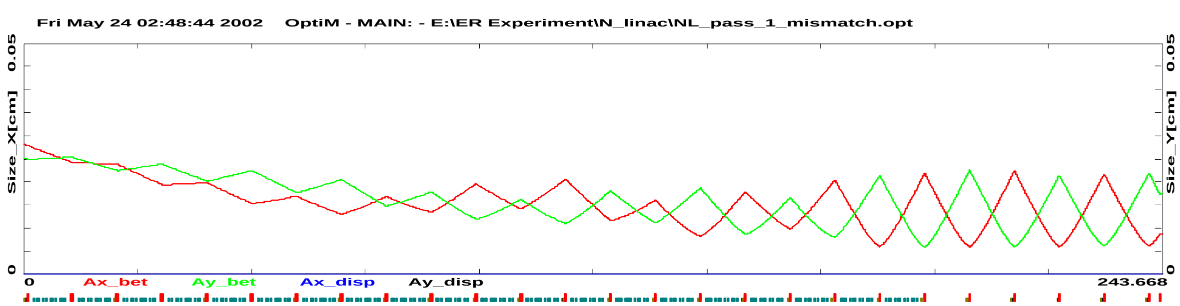
- North Linac will have the standard optics (120° betatron phase advance per cell) for the accelerating beam (45-445MeV)



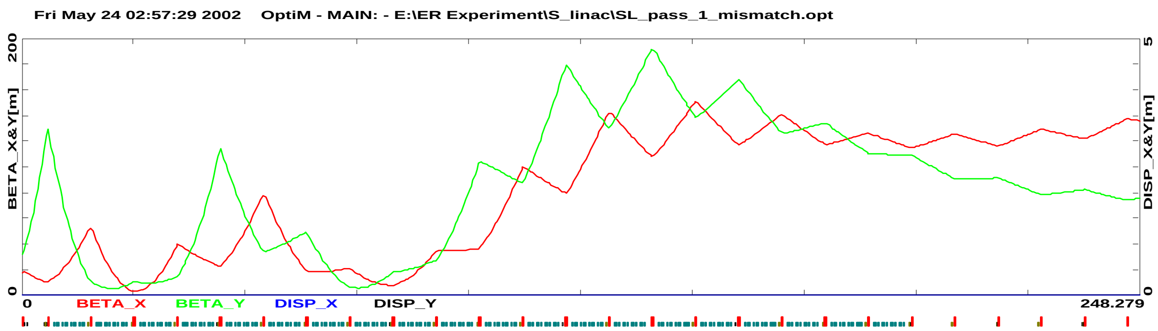


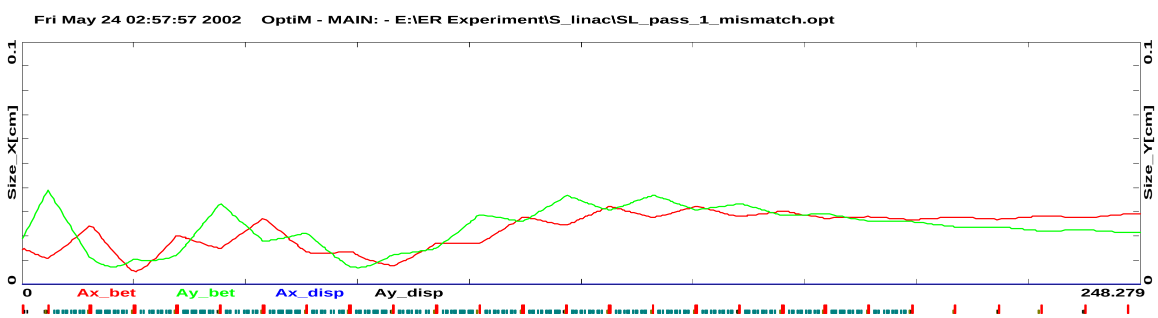
- North Linac decelerating beam will be mismatched (845-445MeV)



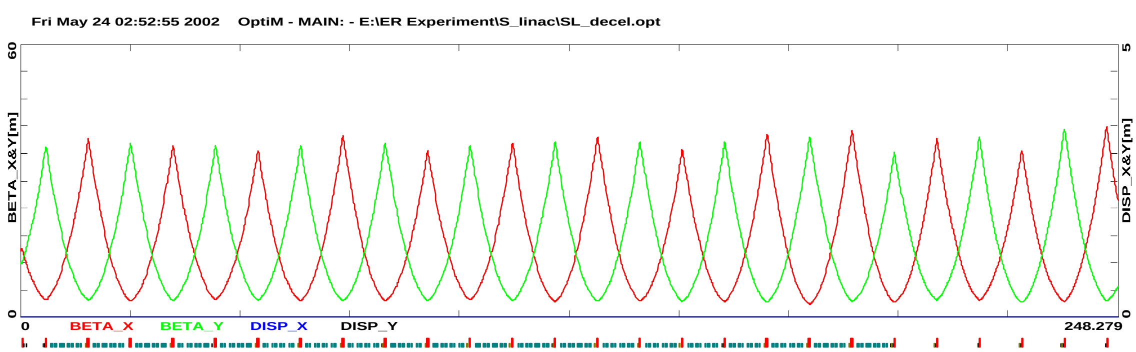


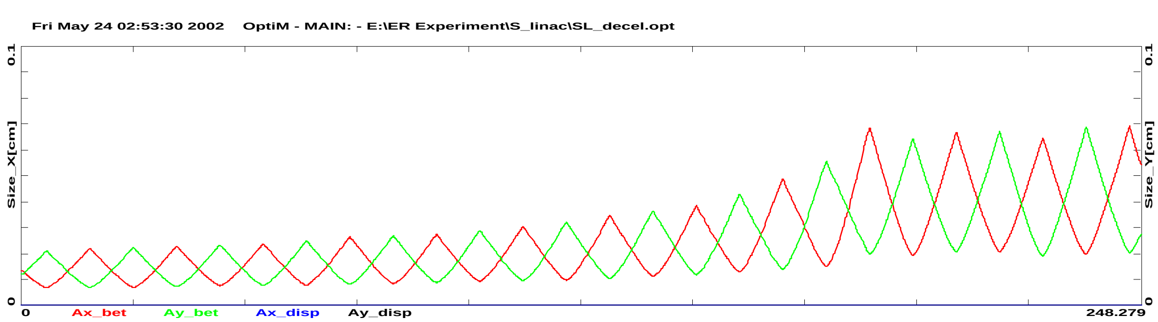
- South Linac accelerating beam will be mismatched (445-845MeV)





- SL – optics matched to the standard 120° lattice for the decelerating beam (445-45MeV)





Summary

In conclusion, the Optics set-up is identical for all four experiments. Mismatched linacs require special Optics for S/R of Arc1 and Arc2. Optimization of initial Twiss functions for mismatched linacs alleviates matching. The coupling is identical for the Deceleration Commissioning Test, the Energy Recovery, and the 4-Pass Current Doubling experiments. The coupling in the 2-Pass Current Doubling experiment is different by half the correction required to cancel the coupling due to drifting through a linac at the zero crossing.

Chicane Options for CEBAF-ER/CD Experiment

Introduction

We survey various ¼- and ½ -RF wavelength chicane configurations required for the testing of energy recovery and current doubling in CEBAF. Based on the geometries of the configurations and space limitations, an outline of a feasible chicane is presented.

It has been proposed that energy recovery and current doubling can be tested in CEBAF with only minor modifications to the transport line. To test energy recovery (current doubling) we required that a ½-RF (¼-RF) wavelength path differential be introduced after the north linac. This is simply done via a 'twin' magnetic chicane. This allows for machine studies of CEBAF-ER/CD with the chicane on, while not affecting beam delivered to experimental halls with the chicane off.

Chicane Options

One possible configuration uses the new, smaller (in width) magnets for the ¼-RF chicane, but also places the chicane on the *opposite* side of the beamline (see Figure 1). In this way the GW dipoles will not be obstructing any beam. Investigating this geometry a bit further allows us to impose several constraints specifying the new magnets. In addition to requiring that all the bend angles of the chicane sum to zero, we would also like to make the effective length of the new magnets the same as that of the GW dipoles. Therefore the new magnet should have the same bend angle and radius of curvature as a GW operating at 445 MeV. The main difference is that we also require that the width of the magnet be less than around 0.5m so as not to interfere with the CEBAF beamline. The sagitta can be readily calculated and yields ~3.5cm. Of course this is assuming all the particles are on the design/central orbit. To take into account off-momentum particles, we require an additional 4cm of stay clear. A summary of the magnet constraints/requirements appears in Table 1.

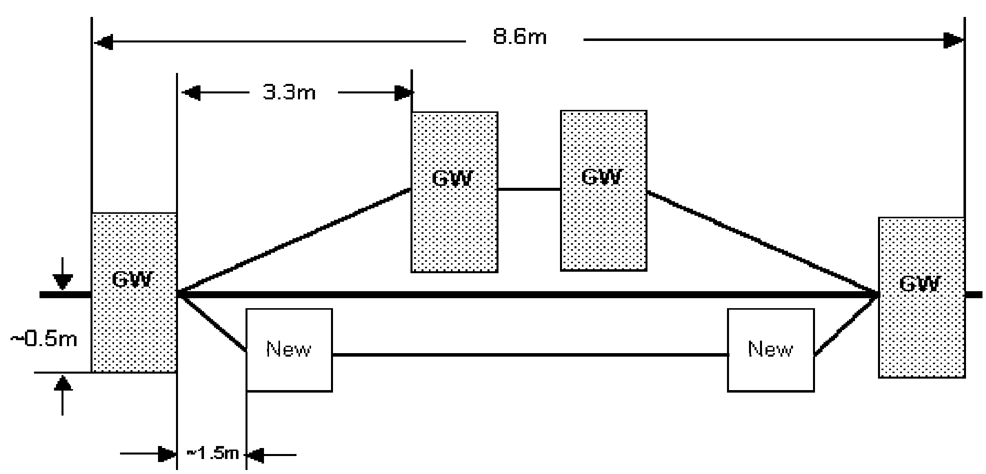


Figure 1: Proposed chicane configuration with ¼-RF chicane on opposite side of baseline transport

Table 1

Magnet Requirements (at 445 MeV)	
Radius (m)	2.548
Bend Angle (deg)	9.548
Effective Length (m)	0.4218
Width (m)	< 0.50
Field (kG)	5.8
Sagitta (m)	0.035
Stay Clear (m)	0.04

Conclusions

It has been determined that the most feasible way of constructing the ½-RF chicane is to use four of the FEL upgrade GW dipoles. We also propose to allow the two “outboard” dipoles to service the ¼-RF chicane placed on the opposite side of the beamline transport (see Figure 1). This configuration requires that two new magnets be commissioned with the properties listed in Table 1. After successful completion of the CEBAF-ER experiment, and after the GW dipoles are returned to the FEL, we anticipate commissioning four more of these new magnets as replacements to the GW dipoles. As they are of smaller transverse profile, potentially these can be arranged on a common side of the baseline transport (see Figure 2).

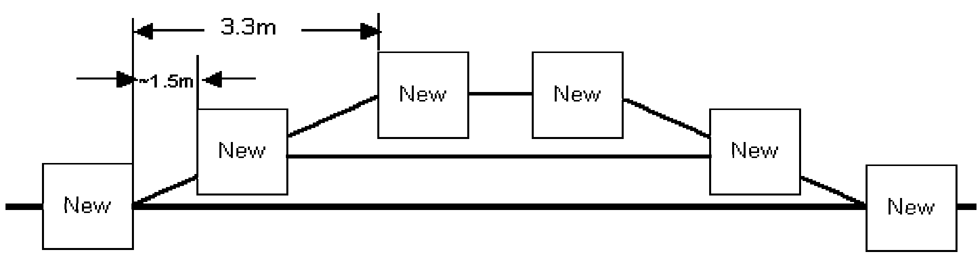
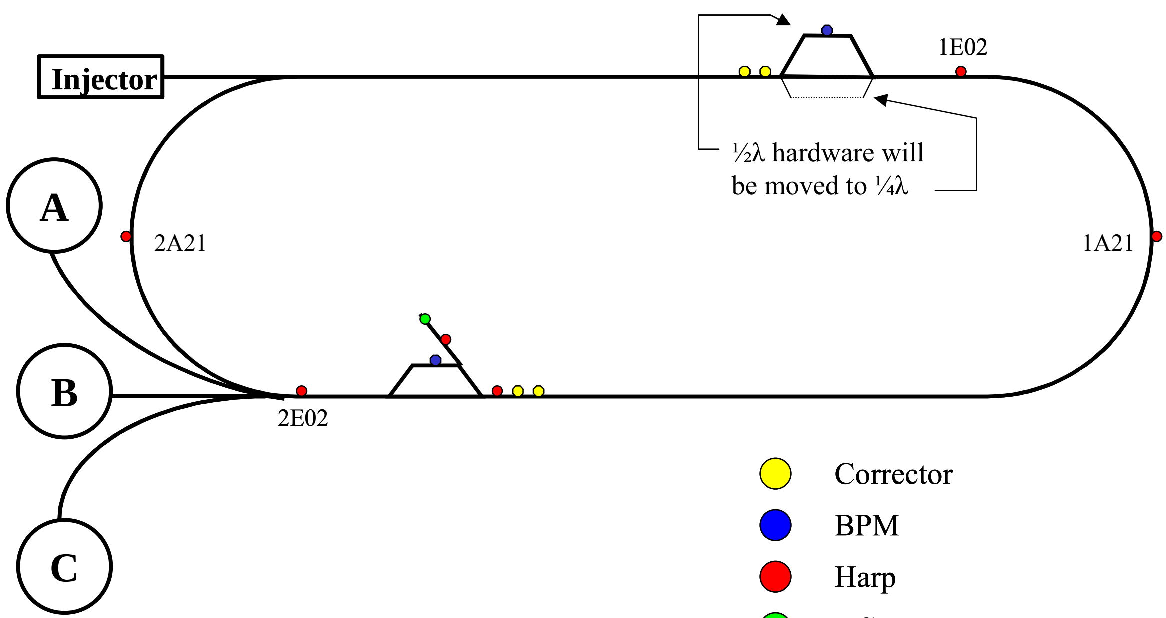


Figure 2: Possible layout with both chicanes on a common side

Proposed measurements and diagnostics

CEBAF-ER/CD - Instrumentation



The following setup procedures for all stages of the experiment (Deceleration, ER, CD) are required:

- Optics
  - generate design optics
  - optimize gradient/focusing scheme
  - measure/validate optics
- Autosteer and Automatch (multiple beams)
- NL/SL energy balance
- Skew quad optimization for global decoupling

Required measurements for all stages of the experiment can be summarized as follows:

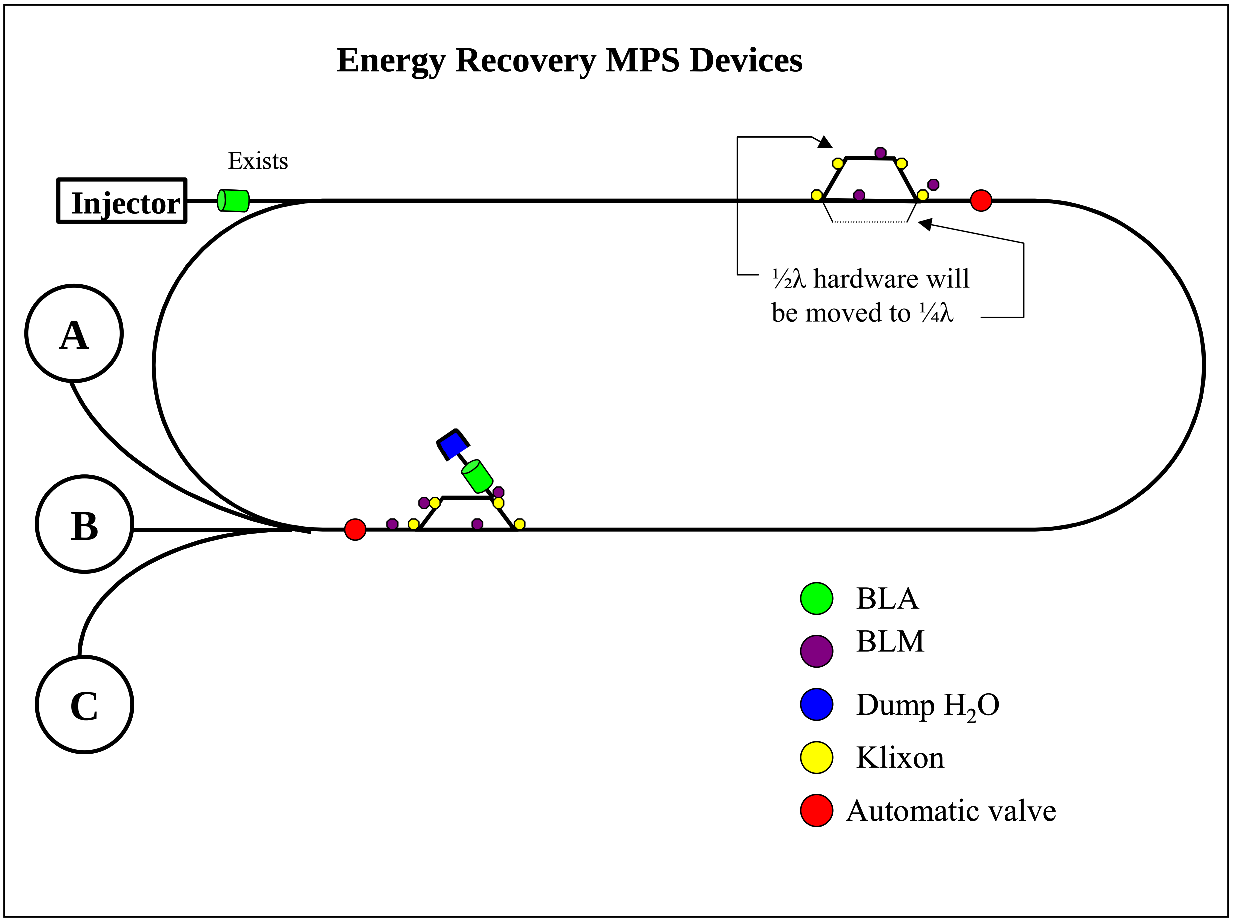
- Emittance and $\Delta p/p$ measurement (CW beam) at:
  - Arc 1 and Arc 2: (harp at $\eta = 0$ & harp at η^{max}) (445MeV, 845MeV)
  - the tune-up dump (45MeV)

- Halo at low energy (BSM, BLM) (CW beam)
    - assure low loss
    - quantify loss
    - distinguish core vs. tails
- RF transients at full charge (pulsed beam)
    - using scopes on cavities
- Parametric studies; exercise low injection/final energy ratio , eg, $\frac{11}{845}$

Instrumentation work required for CEBAF-ER (February '03 Shutdown) is listed below:

- Move 3A03 harp to 1E03
- Move 2E01 harp to 2A21
- Install one BPM in the center of North Chicane (NL25)
- Install 3 BLMs in North Chicane
- Install one harp downstream at the end of SL, close to the arc
- Install one BCM in the South Linac Dump and hook into the Beam Accounting System.
- Install a harp, BPM, BLMs and a view screen in the South Linac Dump.

Machine Protection for the Energy Recovery Experiment



In order to protect the new chicanes and beam dump from damage, a number of Machine Protection Systems (MPS) must be incorporated into the overall design. All of the proposed protection devices are presently being used in other areas of the accelerator and have been proven to be very effective.

The vacuum chambers at the beginning and end of the chicanes are a "Y" design and therefore susceptible to beam damage at the intersection. Many chambers of this type are already in use throughout the accelerator and are easily protected through the use of Photo Multiplier Tubes (PMTs). Jefferson Lab developed and presently uses a Beam Loss Monitoring (BLM) system that is based on the use of a basic subsystem comprising a PMT, a high voltage power supply and a signal conditioning board. The vacuum chamber is protected by intelligently selecting the PMT location, and the appropriate HV setting and signal trip level. The BLM system is interfaced to the Fast Shut Down (FSD) system, which terminates beam within 50 microseconds of a detected beam strike. Experience has shown that three BLMs will be sufficient to protect each new chicane.

Jefferson Lab also developed and presently uses a Beam Loss Accounting (BLA) system to detect beam loss. The amount of beam actually leaving the Injector is measured with a high degree of precision and then compared to the total beam detected by current monitoring devices strategically located at all beam destinations (i.e., BSY and hall lines). Because this experiment is adding a new beam destination, a current monitor must be added in front of the new beam dump. This system is also interfaced to the Fast Shut Down (FSD) system and immediately shuts down the beam if beam loss capable of burning a hole in the vacuum chamber should occur.

In addition, in order to protect the new beam dump from damage, and FSD interlock will prevent the running of beam if the water to the dump is not flowing. Interlocked over-temperature protection devices will also be added to the large dipole magnets.

MPS requirements:

<u>MUST:</u>

- BLA System
    - Additional cavity at the SL dump
    - Movement of downconverter spares
    - Parts available for borrowing
    - Minimal software
- BLM System
    - Three detectors at NL chicane, four at SL chicane
    - Parts exist, mostly a cabling exercise
    - Minimal software
- Dump
    - Water flow switch
- FSD
    - BLM's
    - Water flow on dump
    - Valves (if automatic)

<u>SHOULD:</u>

- Magnets (in addition to standard interlocks)
    - Klixon temperature sensors
    - Stick on temperature dots
- Vacuum
    - Automatic valves downstream of the chicanes

<u>LIKE:</u>

- Operations
    - Training
    - Procedures

RadCon Issues

Overview

Major radiological considerations for the dump include:

- limited tunnel space for shielding
- associated localized groundwater activation potential
- adequate shielding to minimize radiation levels on ground surface and nearby penetrations during operation
- localized airborne radioactivity and activation products in the AC condensate and filters,
- adequate shielding to allow immediate access to the area after shutdown
- cooling water activation and radiation levels in cooling water service building
- beam accounting and beam loss diagnostics to protect accelerator hardware and minimize activation

Cost Estimate

1 Energy Recovery Test Estimate - Half WL and Quarter WL Drift

Item	Description	Eng	Design	Coord	C/u	Qty	Total
1	Scheduling	32					
2	***Conceptual Design***	***24***	***48***				
3	***Design Reviews & Interface***	***24***	***16***	***8***			
4	Girders	48	120	32		8	
5	Pedestals	12	32	20	$ 600	6	$ 3,600
6	Cartridges	2	2	16	$ 300	18	$ 5,400
7	Vacuum Chambers	32	120	48	$3,200	6	$ 19,200
8	Bellows and Beamline Tubes	4	16	4	$ 600	7	$ 4,200
9	Water Systems and Hoses	16	16	16	$1,800	2	$ 3,600
10	Overall Assembly	16	120				
11	Song Sheets	4	24				
12	Grout, Cables, and Consumables	4	4	2	$1,800	2	$ 3,600
		218	518	146			$ 39,600

882	Hours
22.05	M-weeks

2 Energy Recovery Test Estimate - 2 New Magnets for Intermediate Phase

Item	Description	Eng	Design	Coord	C/u	Qty	Total
1	Scheduling	32					
2	***Conceptual Design***	***12***	***16***				
3	***Design Reviews & Interface***	***12***	***16***	***4***			
4	Coil Sets	48	64	24	$3,800	2	$ 7,600
5	Core Sets	24	80	32	$3,600	2	$ 7,200
6	Assembly	8	4	32	$ 400	18	$ 7,200
7	Magnet Code Analysis	32	4	48			
8	Magnet Testing	16	0	0	$ 300	2	$ 600
		184	184	140			$ 22,600

508 Hours
12.7 M-weeks

3 Energy Recovery Test Estimate - 4 New Magnets for Final Phase

Item	Description	Eng	Design	Coord	C/u	Qty	Total
1	Coil Sets			24	$3,200	4	$ 12,800
2	Core Sets			32	$3,000	4	$ 12,000
3	Assembly			32	$ 400	18	$ 7,200
4	Magnet Testing	16	0	0	$ 300	2	$ 600
		16	0	88			$ 32,600

104 Hours
2.6 M-weeks

Total Project Summary

Item	Description	Eng	Design	Coord	C/u	Qty	Total
1	First Phase- Jan 2003	218	518	146			$ 39,600
2	Intermediate Phase	184	184	140			$ 22,600
3	Final Phase	16	0	88			$ 32,600
		418	702	374			$ 94,800

1494 Hours

37.35 M-weeks