"The beam's the thing"
Jefferson Lab Now and at 12 GeV

Michael Tiefenback,
Jefferson Lab

- What we do now
- What will change for 12 GeV
- How this affects YOU

The beam’s the thing….

Shakespeare’s Hamlet wanted to read the King’s heart

“…the play's the thing

wherein I'll catch the conscience of the King.”

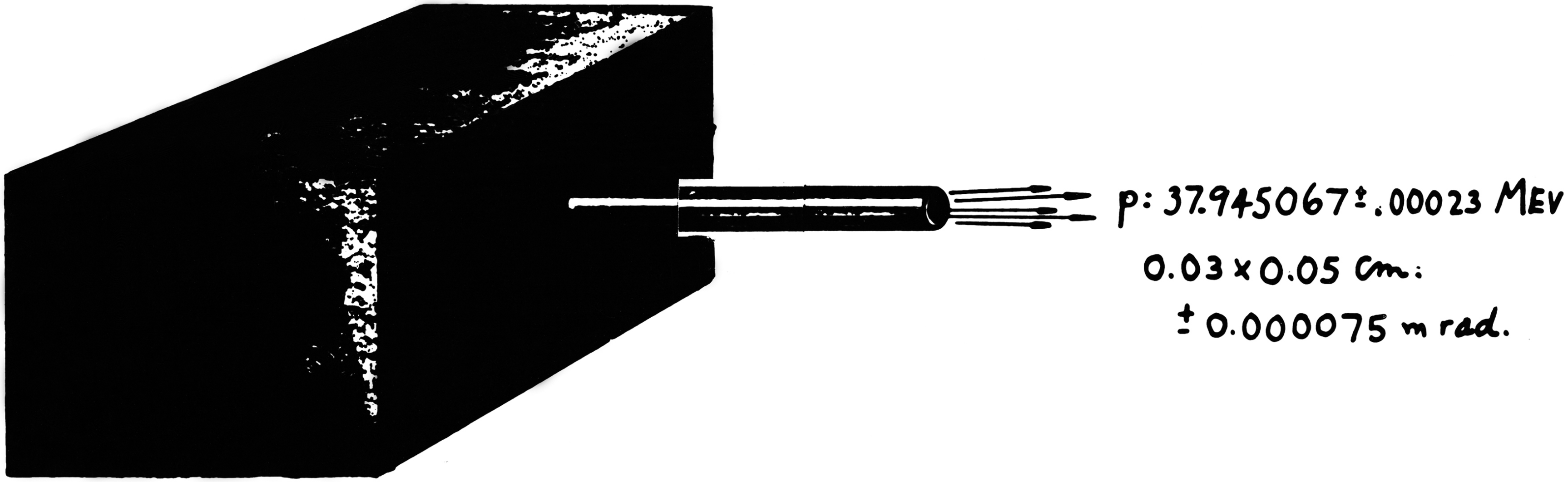
We want to reveal the heart of matter…

“the beam’s the thing…”

Outline

- Physical layout of accelerator at JLab
- Beam delivery options – multiple halls
- CEBAF beam parameters at present
- Upgrade to 12 GeV:
  - New components to support 12 GeV operation
  - Revised beam delivery options
  - Extended beam parameter range (and schedule)
- What this means to YOU as a "user"
- What happens? When?
- Summary

CEBAF as seen by



. . . the experimental physicist

Dave Judd and Ronn MacKenzie, "The Cyclotron as seen by..." series,
Magnet, Vol 11, No. 10, October 1967, p. 9-10

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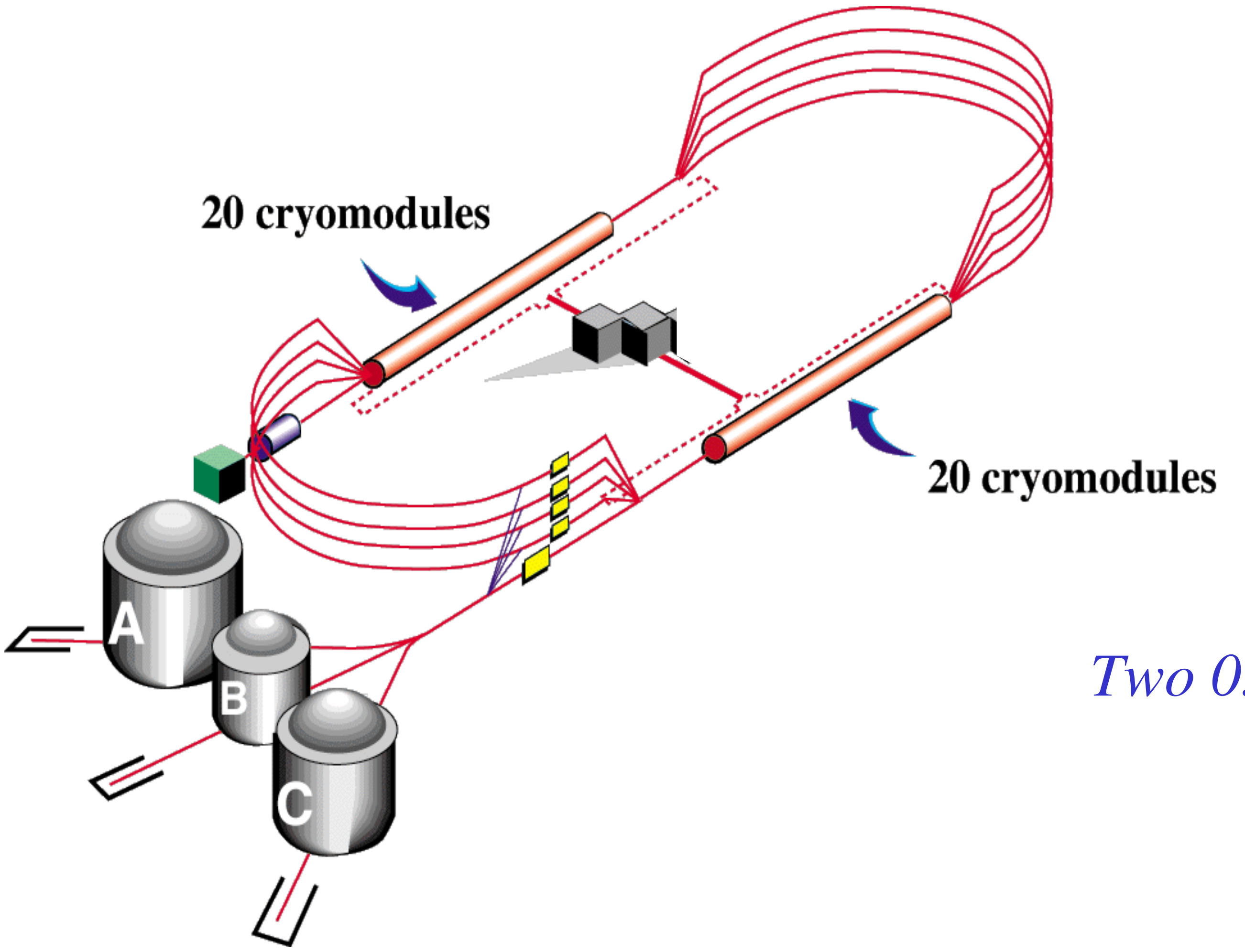
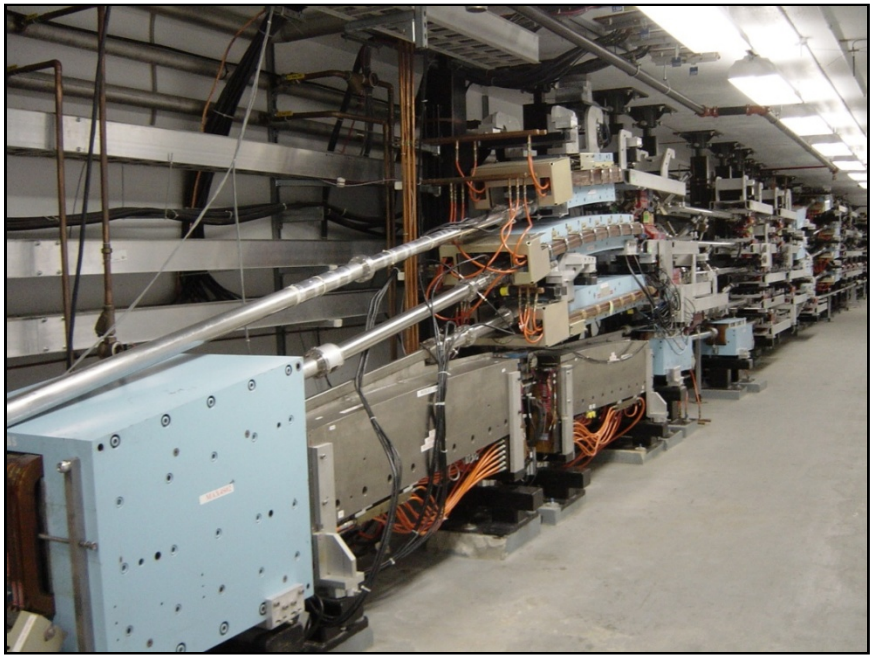
Hall B housing CLAS

6 GeV CEBAF



Two 0.6 GV linacs

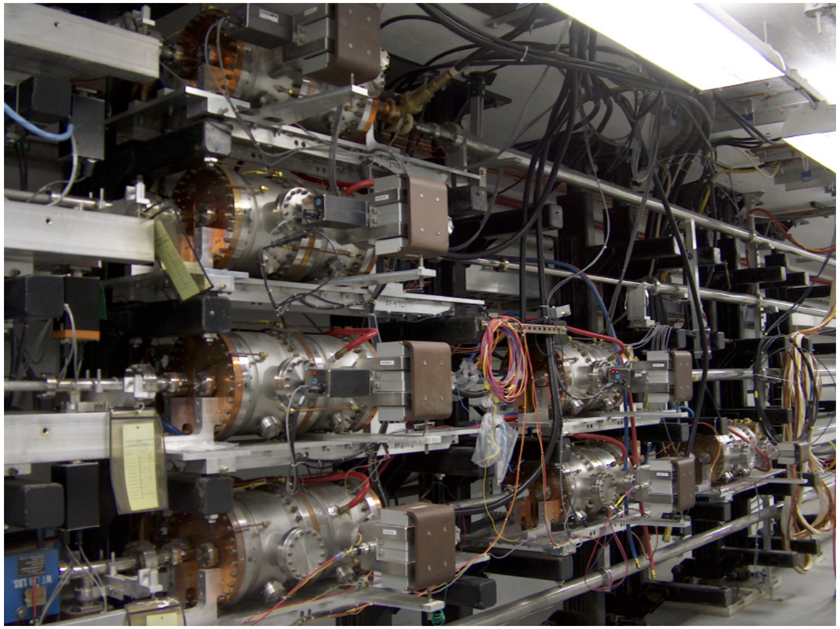
Existing Spreaders/Arcs



"Spreader" beam line

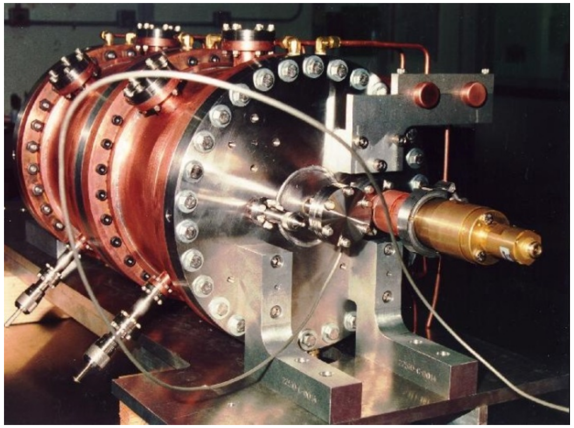
East side
recirculation
Arcs (5)

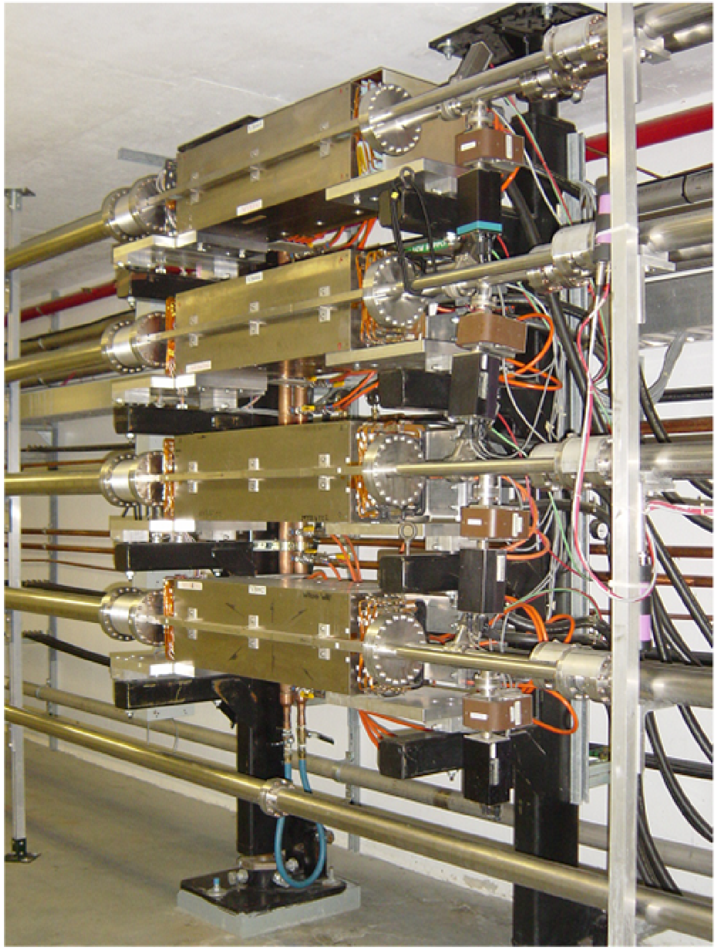
Existing Components: Extraction



RF

Separators





Septum Magnets

Cryogenic Support

- CHL heat load capacity
  - 4600 W at 2 K
  - 12000 W at 50 K (shield)
- End Station Refrigerator (cryo-targets, etc)
  - 1500 W at 4.5 K (total for all three halls)
    - Some diversion to 20 K load is supported
    - Only Halls A and C have 20 K support now
  - Halls A and C dominate the head load for the ESR
  - Total load from Hall B (4.5 K) is only 140 W

The Beam: Parameters and Limits

- Energy spread: ~ 3 x10^{-5} < $\Delta E/E$ < 5 x 10^{-5}
  - Bunching process (instrinsic ΔE ~ 15 keV)
  - Bunch length (intra-bunch cos(ϕ) variation in E)
  - RF regulation (μsec time scale variation in <E>)
  - Dipole field stability (spectrometer reference)
- Beam current: $0 < I < 180\ \mu A$ (dump capacity, data rate)
- Polarization: ~ 85% (photo-cathode physics)
- Position on target: ~20 μm (magnet and RF fluctuations)
- Halo: Stability of RF bunching system; beam scraping
- Beam size on target: ~30%; field drift in magnets

Beam Delivery Options to Halls - 2009

6 GeV System:

Up to five acceleration passes through linacs

Each pass 1-4 can be RF extracted to at most one Hall

Any set of Halls can simultaneously receive 5th pass beam

Note: 12 GeV design supports Hall D + one 5-pass Hall

Upgrade path exists to restore 5-pass to multiple Halls

Polarization – 85% at cathode

Certain discrete energies give all users peak polarization

Differential spin precession in final transport lines

Collaborations negotiate spin division at other energies

Beam Quality Continues to Improve

Limitations on beam performance change

- Bare RF system regulation (~2 x 10^{-4})
- "Energy locks" for total energy feedback (5 x 10^{-5})
- Fast FeedBack: better regulation (10^{-5}) and bandwidth
- "Orbit locks" compensates for magnet system drifts.
- Fast FeedBack stabilizes target positions to ~20 μm
- Improved photo-cathode polarization
- Improved techniques for rejecting drift artifacts
- Improved operational procedures stabilize:
  - Long term average energy
  - Energy spread

Beam Requirements (10/31/01)

Parameter	Nominal Value and Range	stability (during 8 hours) (note 1)	helicity correlated unbalance averaged over 1 hour
rms spot size at the target	A: σx and y = 50 to 200 μm; B: 50 < σx and y < 250 μm; C: σx and y= 100 to 500 μm A & C may request specific sizes (note 2)	A & C: 25% of requested value; B: any value within nominal range	A & C: 100% of nominal size; B: 60 μm
angular divergence at the target	σx', σy' < 100 μr	50% of value	100% of beam divergence tolerance
Beam position	any value requested by experiment within 3 mm of optics axis	drifts A: < 50% of spot size; B: < 120 μm; C: < 250 μm; transients A, B, C: < 1 mm	A & C < 10 μm; B < 60 μm
Beam direction	any value requested by experiment within 1 mr of optics axis to dump center	< 50 μr (1/2 beam divergence tolerance)	100% of beam divergence tolerance
Energy (average)	multipass operation: 0.63 to 5.75 GeV; 1 pass 1 hall dedicated operation: 0.33 GeV to 0.63 GeV	A or C: ΔE/E < 1E-4 B: ΔE/E < 5E-4 and ΔE/E < 1E-3 over days for all	100% of energy spread tolerance
100% of energy spread tolerance	A & C: σE/E < 5E-5 for E>1GeV B: σE/E < 4E-4	A & C: σE/E < 5E-5 for E>1GeV B: σE/E < 4E-4	N/A

Beam Requirements (10/31/01)

Parameter	Nominal Value and Range	stability (during 8 hours) (note 1)	helicity correlated unbalance averaged over 1 hour
Background (Beam halo) close to the target	A, B, C: < 1 E-4 outside of 5 mm radius **(notes 3 & 4)**	any value within the nominal range	100% of nominal halo tolerance
CW average current (Note: 5 & 6)	1 μA < A < 120 μA 1 nA < B < 1 μA 1 μA < C < 120 μA A+C < 180 μA ; A + C < 800 KW A or C < 180 μA (single hall)	within +/- 5% of nominal value (includes high frequency fluctuations)	A < 200 ppm; B & C< 1000 ppm 3 Halls: excursions of 5 sec samples up to 5 x nominal value are acceptable.
Polarization (current range to be determined between physics and Accelerator Divisions)	> 70% all halls with currents up to 100 μA in A or C	polarization > 70%	N/A
Effective duty factor DF	loss (1-DF) including trips: <5% 0.33 < E < 5 GeV (5 + (E-5)*20) %: 5 < E < 6 GeV	N/A	N/A

note 1: With continuous monitoring the beam is good when within tolerances. With invasive diagnostics, one does not know the beam quality between measurements. The user accepts the uncertainty except if he can provide a continuous non-invasive diagnostic.

note 2: Some beam size requests in the range will preclude the Moller optics to be the same as the beam-delivery-on-target optics

note 3: After the halo monitors for halls A and C are operational

note 4: Hall A requests for FY2002 that the total halo outside a 5 mm radius be < 10-6

note 5: Lower currents can be delivered with relaxed tolerances

note 6: Proper impingement on beam dump has to be checked with accelerator operation (centering on dump face, current density on dump face, visibility on dump viewer, amount of radiation in the hall, on the site, etc…

J-C. Denard; beam_parameters

Helicity-correlated asymmetry performance

Experiment	Physics Asymmetry	Max run-average helicity correlated Position Asymmetry		Max run-average helicity correlated Current Asymmetry	
		Target	Achieved	Target	Achieved
HAPPEx-I	13 ppm	10 nm	10 nm	1 ppm	0.4 ppm
G⁰ Forward	2 to 50 ppm	20 nm	(4 ± 4) nm	1 ppm	(0.14 ± 0.3) ppm
HAPPEx-He [2004] HAPPEx-He [2005]	8 ppm	3 nm	3 nm 20* nm	0.6 ppm	0.08 ppm 0.1 ppm
HAPPEx-II-H [2004] HAPPEx-II-H [2005]	1.3 ppm	2 nm	8** nm 1 nm	0.6 ppm	2.6** ppm 0.1 ppm
PREX	0.5 ppm	1 nm	-	0.1 ppm	-
Q_{weak}	0.3 ppm	20 nm	-	0.1 ppm	-

* Results affected by electronic crosstalk at injector.
** Results at Hall A affected by Hall C operation. Spec was met in 2005 run.

Upcoming Experimental Needs Already Demonstrated

Time Structure of the Beam

- Photoinjector laser for each Hall locks to 499 MHz (2 nsec)
- Three interleaved pulse trains are accelerated at 1497 MHz

Full bunch length is $(4 \cdot \sigma_z)$ ~400 μm, or 1 picosecond

  - Reduces intra-bunch energy spread

100 μA to HallA: about 1.25 Million electrons per RF bunch

1 nA to Hall B: about 12 electrons every 2 nanoseconds

Some experiments in Hall B use sub-nA current

(Beam-synchronous RF signal can be provided)

Beam Parameters in Halls A and C

- Beam power < 800 kW (administrative limit)
  - Dump design capacity 1 MW continuous beam power
  - Administrative limit 180 μA
- Beam stability (Fast FeedBack System)
  - Relative energy drift $\Delta E/E < 1 \times 10^{-5}$
  - Beam position on target stabilized to 20 μm
- Polarization up to 85% (less during multi-Hall operation)
- "Adequately low" halo ($\leqslant 10^{-6}$ outside 3-5 mm radius)

Compton polarimeter spot sizes $\leqslant$ 50 μm (near target)

- Target beam size on target ~ 100 μm x 150 μm (typical)

Target Examples

Hall A "Soda Straw" target

(pressurized and polarized He^3 gas target)

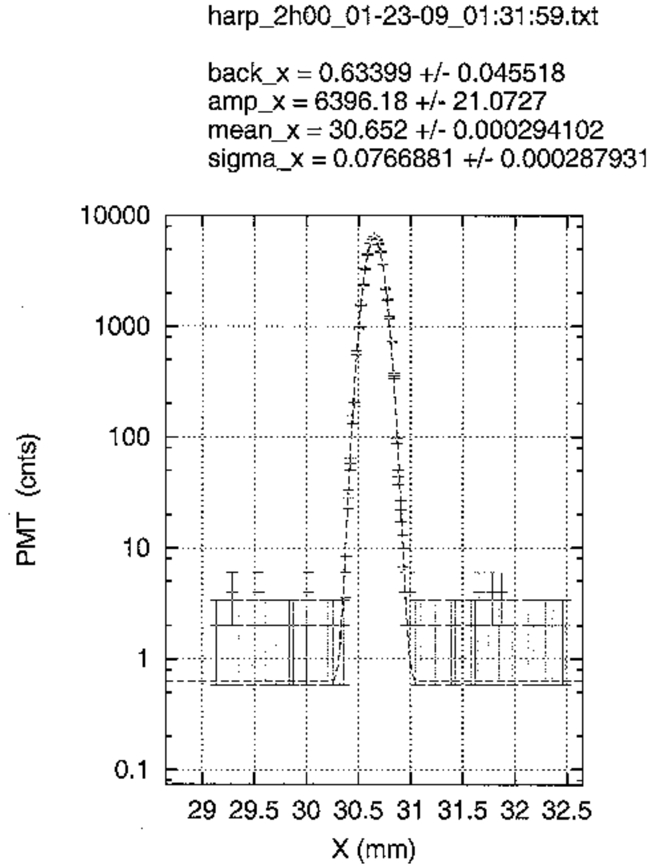
Length of Target Tube	~40 cm
Inner Radius of Target Tube	~8 mm
Beam Current (typ.)	12 μA
Spot size on Target Window	100 μm < $\sigma_{x,y}$ < 200 μm

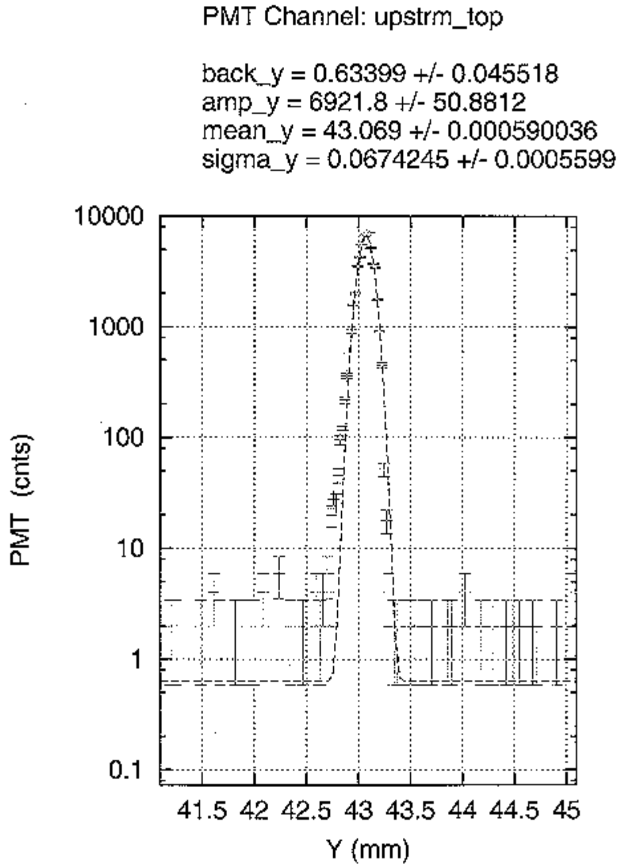
Beam position rastered +/- 3 mm

1-2 mm of beam clearance each side of target

How is Hall B different? I

- High dynamic range profile monitors provide ability to measure (and tune) beam profile





5-pass beam to Hall B, 5892 MeV, 23 January 2009

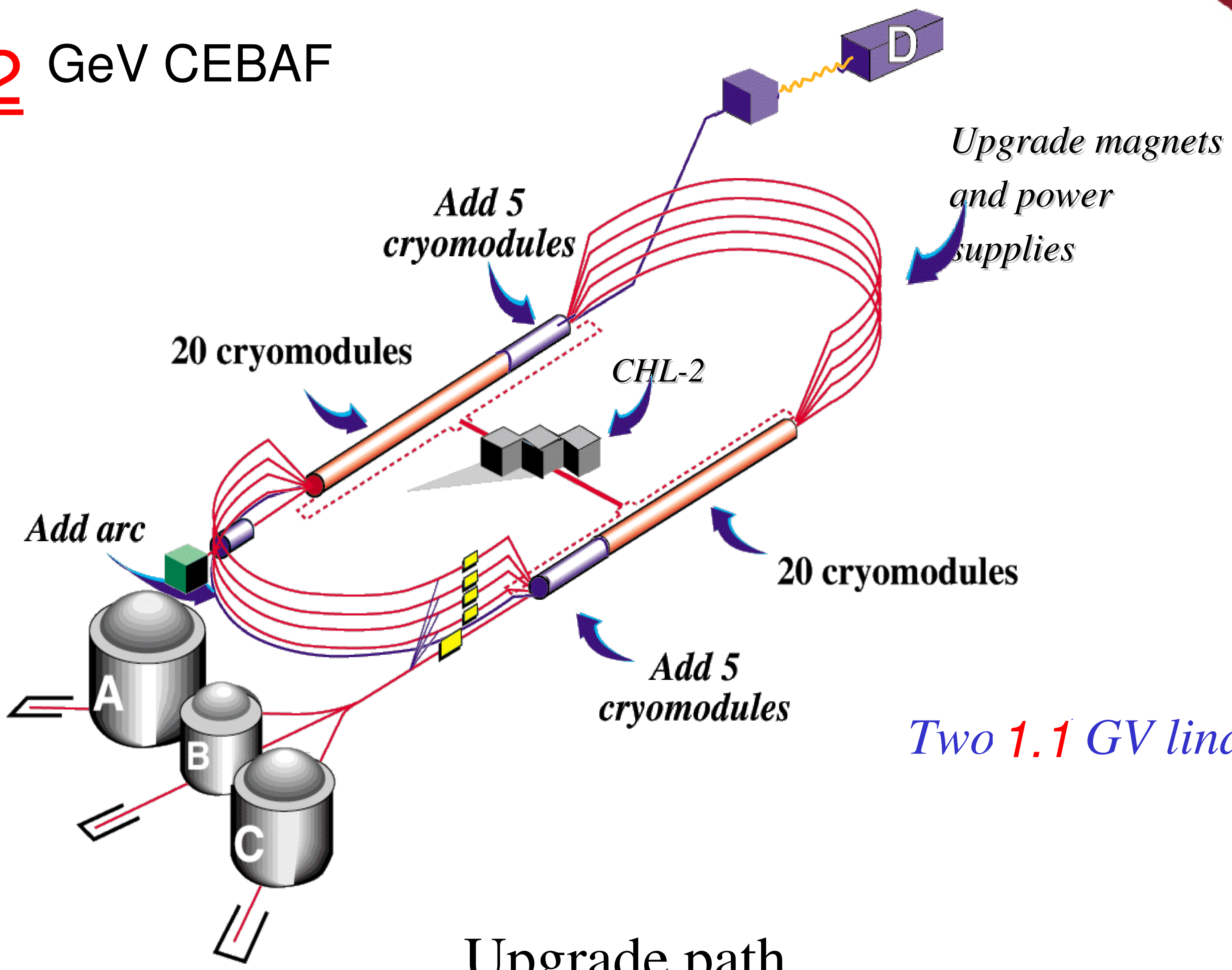
How is Hall B different? II

- Beam current in Hall B: 0.3 nA < I < 50 nA
  - Beam positions not as precise as in A and C
  - Resonant cavity BPMs: lower detection BandWidth
- Radiologically more benign – less prospect of activation
  - Can provide equipment access without Radiation Survey
- Orbit control somewhat looser (but satisfies needs)
- Depends upon other Halls for certain energy issues:
  - Fast FeedBack in A or C stabilizes accelerator energy
    - Without FFB, may wander by 10^{-4} over minutes
  - Absolute energy spectrometry better in A and C

Multi-Hall Interdependencies (E, ΔE/E)

- Only one Hall can be the energy reference for RF.
- $E \sim E_{acc} * (\cos(\phi_1) + \cos(\phi_2) + \ldots)$
- Total energy decreases when times of flight drift
  - Total machine circumference varies (annual cycle)
  - Circumference changes by ~ 1 cm
- Energy spread also increases for off-crest arrival phase
- Constant transit time → energy stability for all passes

12 GeV CEBAF



Two 1.1 GV linacs

Upgrade path

12 GeV Changes

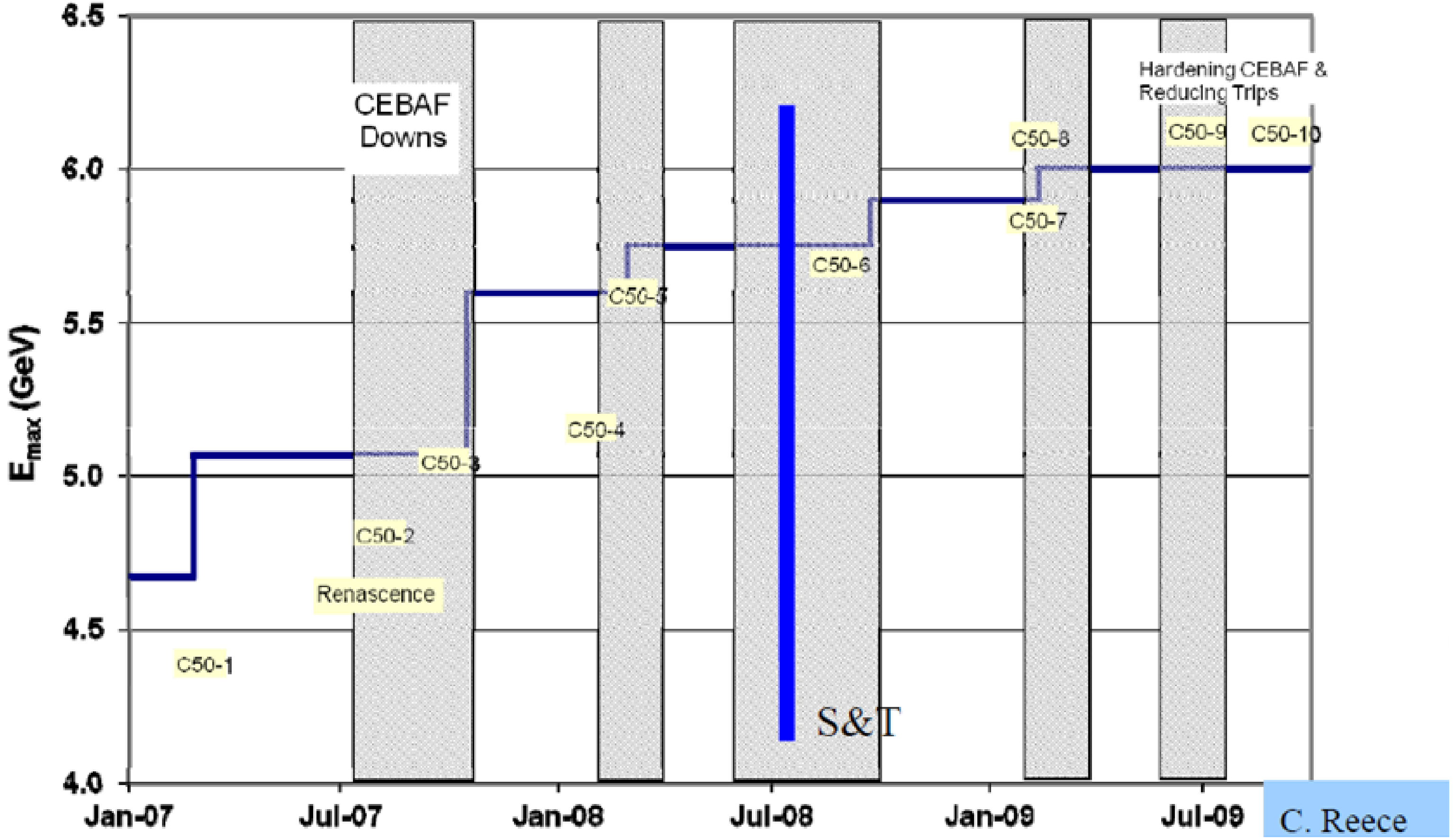
- 10 new cryomodules: 100 MV each
- Doubled CHL capacity for 12 GeV
- New recirculation Arc 10
- Upgrades for existing recirculation Arcs 1-9
- New Hall D with beam transport and dump
- Hall D cryogenic installation: 200 W at 4.5 K

PLUS

- Infrastructure upgrades like improving the 6 GeV base

Accelerator Hardening Program Restoring 6 GeV Reach

Maximum 5-pass Energy (GeV)



Successful 5.75 GeV run, ~600kW of beam power

• Lower than expected RF trip rate (<10 trips/hour)

• **5.9 GeV operations in Fall 2008.** **(proceeding now)**

Two cryomodules have new 70 cm 7-cell cavities installed

Energy Spread

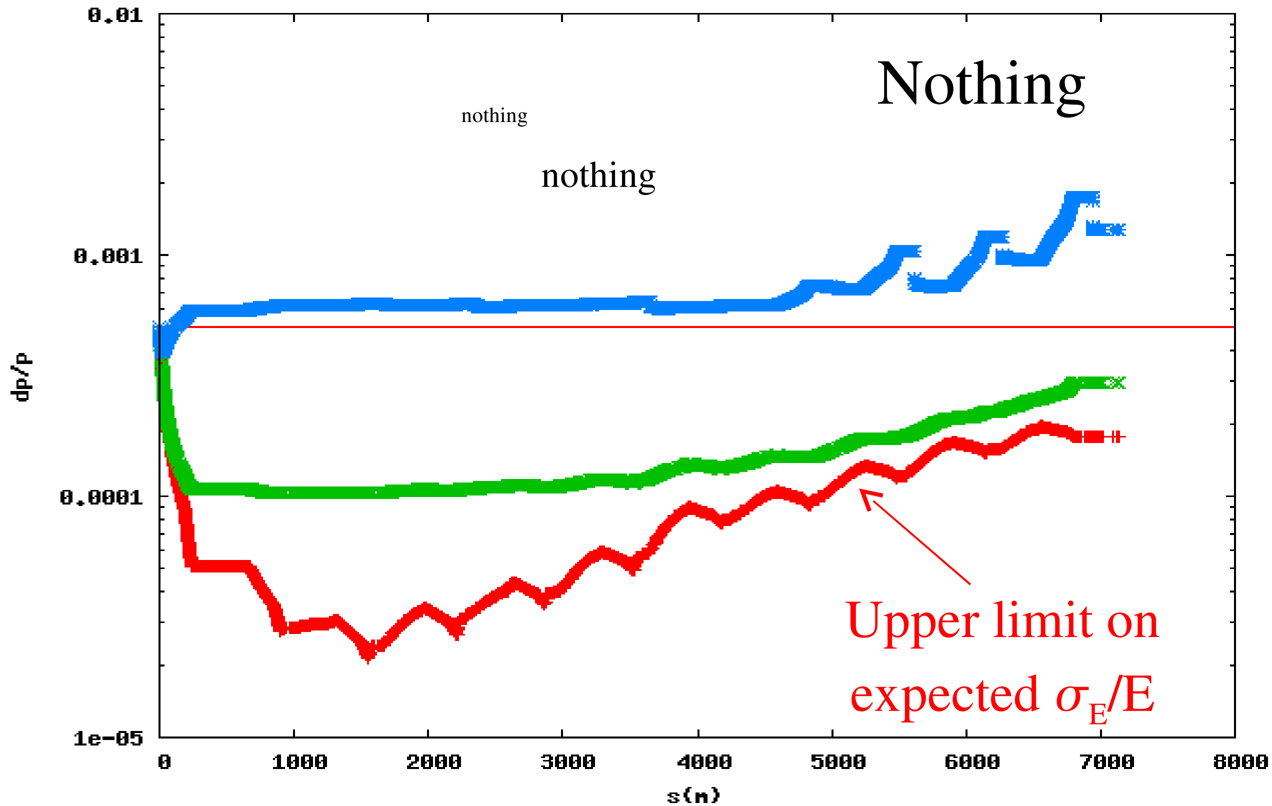
- RF regulation retains original CEBAF specifications
- Intermediate beam passes must continue to support low energy-spread experiments as before up to 6 GeV
- Some experiments require today's low energy spread
- Synchrotron Radiation will degrade high-energy σ_E

Synchrotron Radiation Effects

- The energy per radiated photon is a quantum mechanical effect.
- Average energy loss due to synchrotron radiation
  - $\Delta E_\gamma(GeV) = 8.85 \times 10^{-5} \frac{E^4}{\rho}$
- M. Sands relations for emittance (ε) and energy spread (σ_E) growth
  - $\Delta\varepsilon \propto \frac{\gamma^5}{\rho^2}\langle H \rangle$
  - $\sigma_E^2 \propto \frac{\gamma^7}{\rho^2}$
- $\langle H \rangle$ (emittance dispersion) is a property of the transport lattice $(\beta, \alpha, \eta, \eta')$.
- σ_E growth depends on γ and bending radius (ρ).
- ε growth depends on $\langle H \rangle$, γ and ρ.

Increased emittance in Halls: we won't have to magnify the beam optically to avoid target damage

Energy Spread vs. Injected Bunch Length (12GeV Full-Energy Simulation)



DBA Optics

σ_z = 1000 μm

dp/p=0.05%

σ_z = 400 μm

σ_z = 100 μm

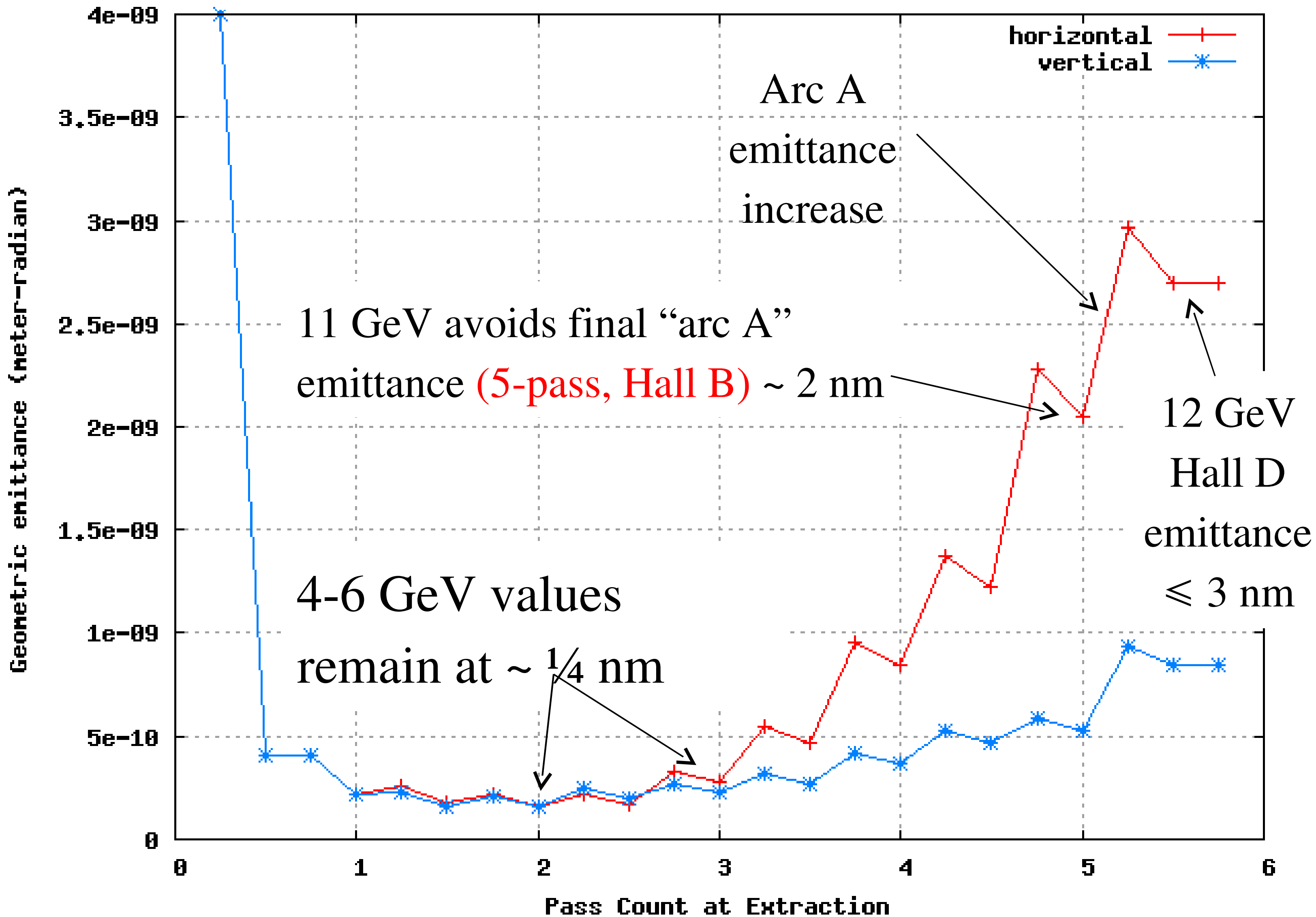
CEBAF injector RMS bunch length < 100 μm (red trace)

DBA reduces emittance without increasing dp/p

Tightest 12 GeV requirement: dp/p < 0.05% (Hall A)

Retains support for ΔE/E < 0.003% at 4 GeV

Geometric Emittance at full 12 GeV Settings



Jefferson Lab

12 GeV Beam Parameters: Early Experiments

Hall	Emittance	Energy spread (σ)	Spot size (s)	Halo
A	ϵ_x < 10 nm-rad, ϵ_y < 5 nm-rad	12 GeV: 0.05% 2-4 GeV: 0.003%	12 GeV: σ_x<400μm, σ_y< 200μm 2-4 GeV: σ_y < 100 μm	<0.01% (1)
B	ϵ_x < 10 nm-rad, ϵ_y < 10 nm-rad	0.1%	σ_x < 400 μm σ_y < 400 μm	<0.02% (1)
C	ϵ_x < 10 nm-rad, ϵ_y < 10 nm-rad	0.05%	σ_x < 500 μm σ_y < 500 μm	<0.02%(1)
D	ϵ_x < 50 nm-rad, ϵ_y < 10 nm-rad	<0.5%	At radiator: σ_x < 1550 μm, σ_y < 550 μm At collimator: σ_x < 540 μm, σ_y < 520 μm	<1% (2)

1) Ratio of non-Gaussian tail to Gaussian core
2) Ratio of Halo background event rate to physics event rate.

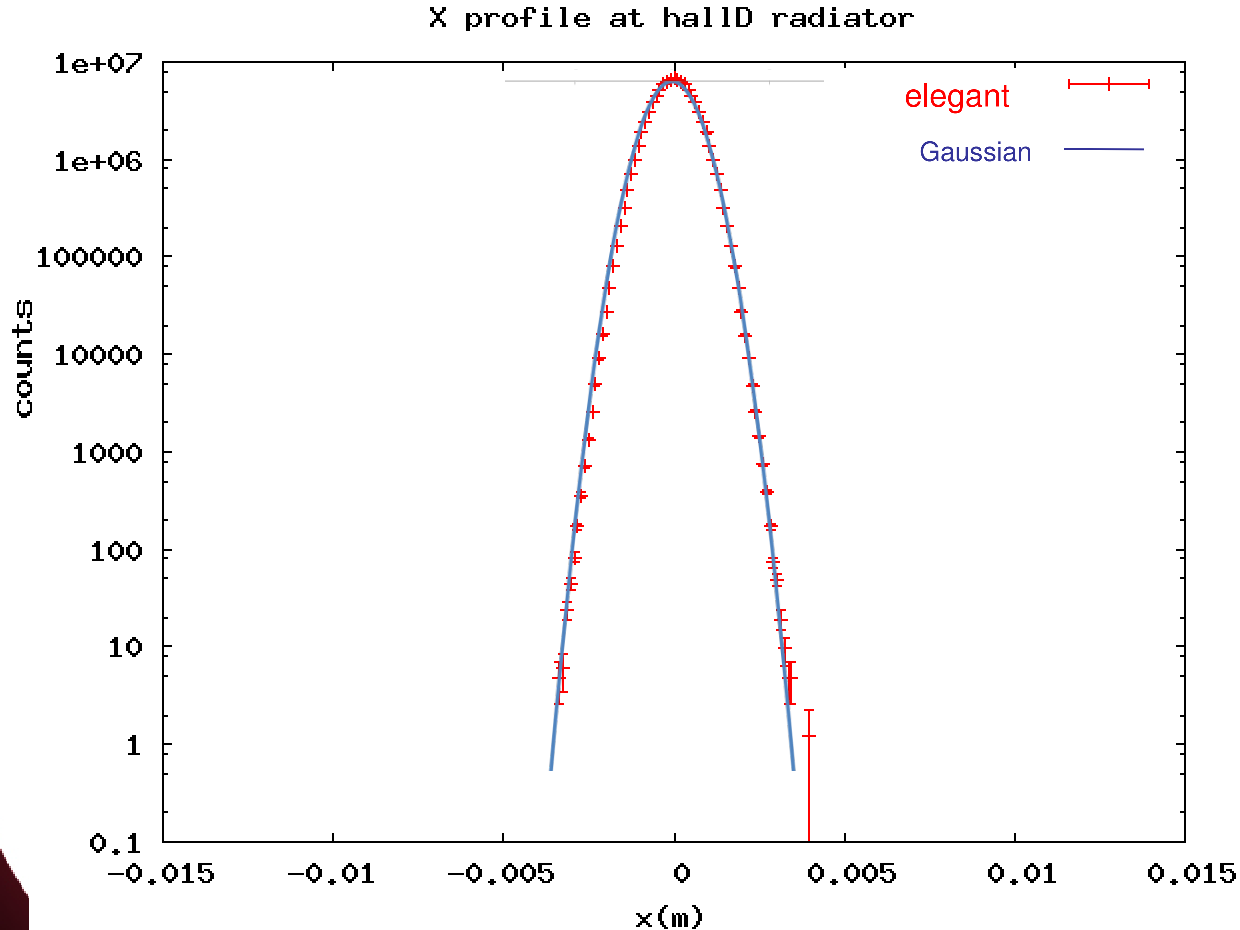
12 GeV Beam Parameters: “Out-years”

Hall	Emittance	Energy spread (σ)	Spot size (s)	Halo
A	ϵ_x < 10 nm-rad, ϵ_y < 5 nm-rad	12 GeV: 0.05% 2-4 GeV: 0.003%	12 GeV: σ_x<400μm, σ_y< 200μm 2-4 GeV: σ_y < 100 μm	<0.01%(1)
B	ϵ_x < 10 nm-rad, ϵ_y < 10 nm-rad	0.1%	σ_x < 400 μm σ_y < 400 μm	<0.01%(1)
C	ϵ_x < 10 nm-rad, ϵ_y < 5 nm-rad	0.05% **6 GeV:0.03%**	**σ_x < 400 μm** **σ_y < 200 μm**	**<0.01%(1)**
D	ϵ_x < 10 nm-rad, ϵ_y < 5 nm-rad	<0.5%	At radiator: σ_x < 1550 μm,σ_y < 550 μm At collimator: σ_x < 540 μm,σ_y < 520 μm	<1% (2)

Items that changed from “Early experiments”

1) Ratio of non-Gaussian tail to Gaussian core
2) Ratio of Halo background event rate to physics event rate.

Simulation: Negligible Halo at Hall D



Results of particle tracking with elegant

- 10^8 electrons
- Non-linear fields
- Residual orbit errors
- Synchrotron radiation induced emittance growth
- Mis-powered magnets

Profile at radiator is fully Gaussian

Beam Parameters Can Be Adjusted

- Some parameters are inter-dependent – not a fixed set
  - Energy spread, Emittance, Current
- Especially relevant for higher energies (> 10 GeV)
- Procedures and hardware can change
- Accomodation may involve other users
- Define and communicate clearly
  - what you need
  - what you want
- Be involved

12 GeV Project Update Information

Last 6 Months

- September 2008: Critical Decision 3 Approval
- October 2008: Start of Construction
  - $13.5M funding per Continuing Resolution (full funding=$28.5M)
- November 2008: Director's Project Review
- November 2008: first construction procurement
  - Hall D TDC chips (~$200K)
- December 2008: two major construction awards
  - Hall D Barrel Calorimeter fibers (~$3.5M)
  - CHL Building Addition (~$1.5M)
- January 2009: major civil construction contract
  - Hall D Complex (~$14.1M)

12 GeV Upgrade: Phases and Schedule

(based on funding guidance provided by DOE-NP in June-2007)

- 2004-2005 Conceptual Design (CDR) - ***finished***
- 2004-2008 Research and Development (R&D) – ***finished (but 1 task)***
- 2006 Advanced Conceptual Design (ACD) - ***finished***
- 2006-2009 Project Engineering & Design (PED) - ***ongoing***
- 2009-2014 ***Construction – started !!***
  - **Parasitic machine shutdown May 2011 through Oct. 2011**
  - **Accelerator shutdown start mid-May 2012**
  - **Accelerator commissioning start mid-May 2013**
- 2013-2015 Pre-Ops (beam commissioning)
  - **Hall A commissioning start October 2013**
  - **Hall D commissioning start April 2014**
  - **Halls B and C commissioning start October 2014**

6 months → (Parasitic machine shutdown)

12 months → (Accelerator shutdown to accelerator commissioning)

12 GeV Major Procurement Effort

Of the 29 Advance Procurement Plans, 22 major procurements are being actively worked (**~$60M Phased**). A summary of their status is as follows:

3	Request for information completed
3	Specifications completed
4	Open Solicitations (including SOL)
8	Bids Received (including TORUS) **~$45M**
1	Vendor Selected (Hall D Civil Construction Manager)
3	Awarded (Hall D B-Cal Fiber, CHL Civil, Hall D Civil) **~$20M**
22	Active Major Procurements

12 GeV Upgrade Summary

- R&D is essentially complete
- PED (Engineering Design) finishes this year (18% remaining)
- <u>Construction has started !</u>

- Significant progress:
  - Procurement planning and awards
  - MOU development
  - Installation planning
  - Space planning

Last 6 months – very exciting!

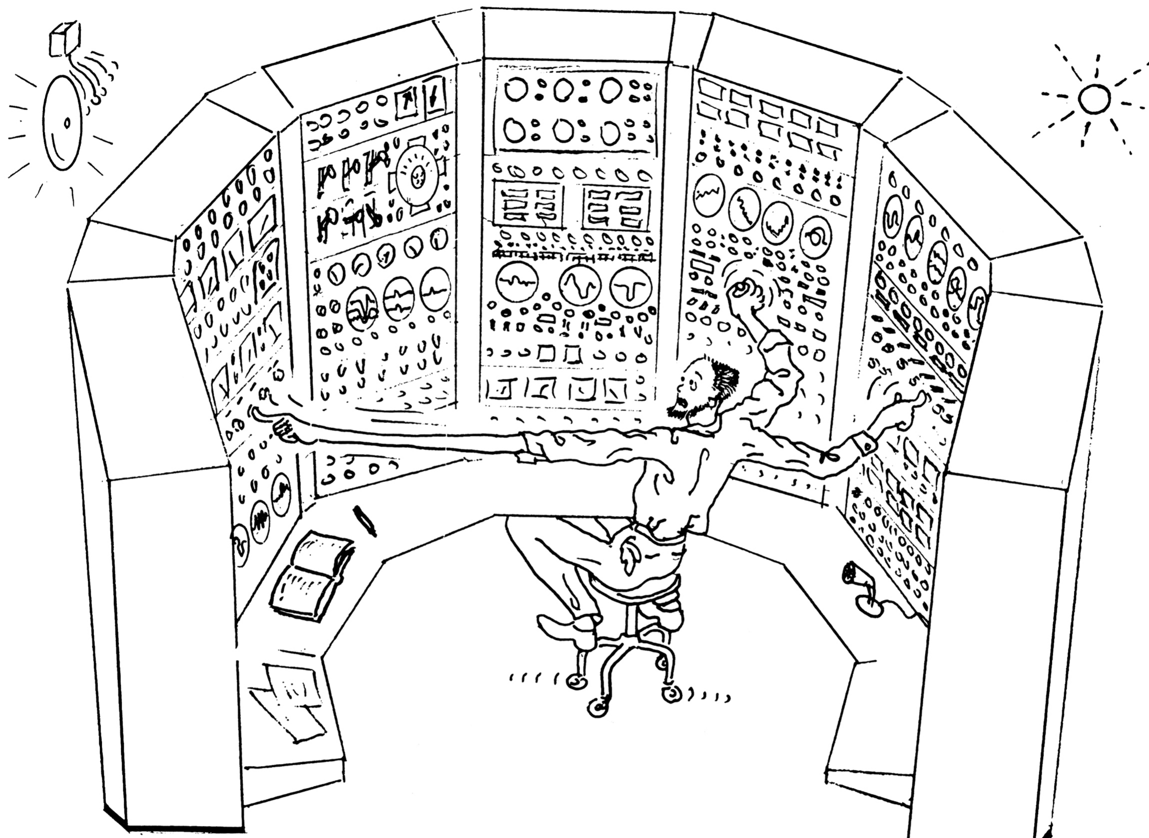
Next 6 months – lots of hard work ahead

Continued strong User participation is critical to success

The Jlab "Machine Control Center"

Accelerator staff attend to beam delivery, working with users to maintain and improve beam quality.

CEBAF as seen by



. . . the operator

Dave Judd and Ronn MacKenzie, "The Cyclotron as seen by..." series,

Magnet, Vol 11, No. 10, October 1967, p. 9-10

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La bella macchina ha bisogno di attenzione,
di comprensione e forse di un poco affetto.
Sarete soddisfatti.

Like the car I drive to work,
most days.

End of Presentation