The Continuous Electron Beam Accelerator Facility at Jefferson Lab

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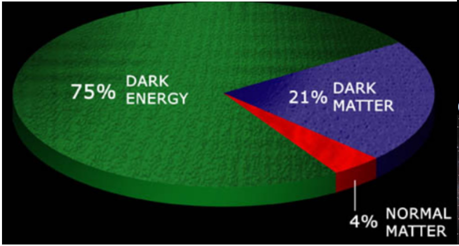
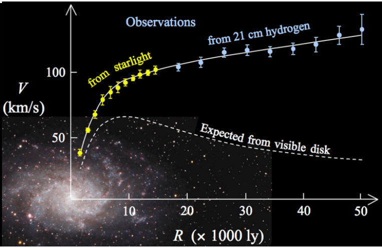
Introduction

- The **Continuous Electron Beam Accelerator Facility** (CEBAF) is a recirculating linac at Jefferson Laboratory in Newport News, VA dedicated to studying the interface of nuclear and particle physics
- One such type of experiment is the **Heavy Photon Search** (HPS) which searches for hidden sector vector bosons (i.e. fundamental forces)
- HPS requires a high intensity continuous beam with low tails and low emittance in y
- CEBAF provides such a facility - an overview and key design considerations will be presented

Evidence for Extra Forces in Nature

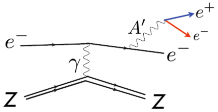
- Very strong evidence for **extra invisible matter** in the universe (dark matter) seen through galactic rotation curves, gravitational lensing, and CMB
- WIMPs are most popular candidate but have not detected
- Possibility for lighter dark matter - **requires a new mediator** (Lee-Weinberg Bound at 2 GeV)

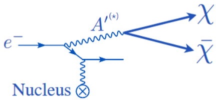


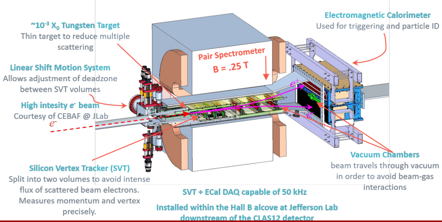


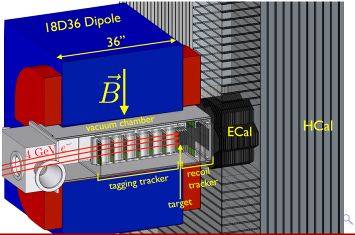
Signatures for Extra Forces

- Some models predict an **extra massive U(1) symmetry** in nature where the force carrier (A') that can decay to lepton pairs (HPS left) invisible particles (LDMX right)

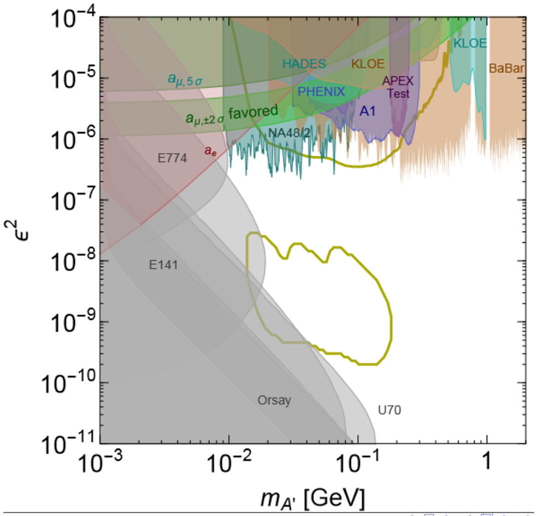








Heavy Photon Parameter Space



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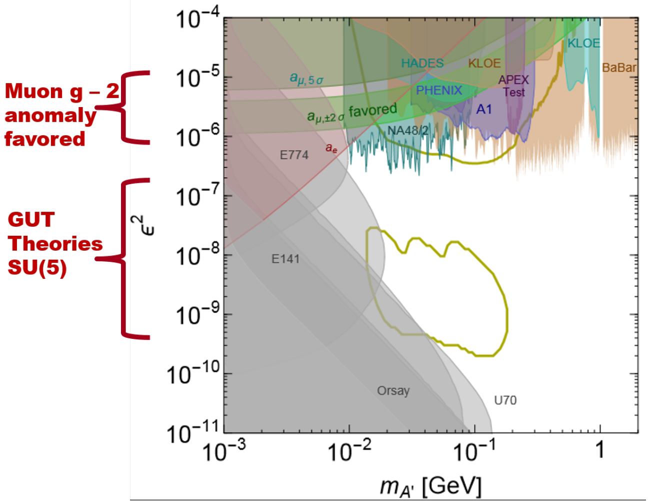
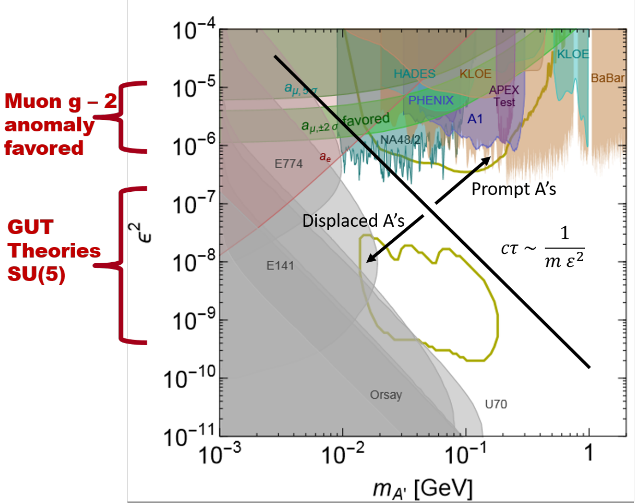


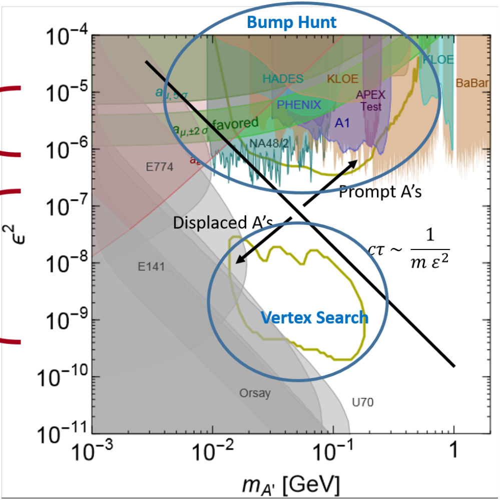
Heavy Photon Parameter Space



Heavy Photon Parameter Space

Muon g – 2 anomaly favored

GUT Theories SU(5)



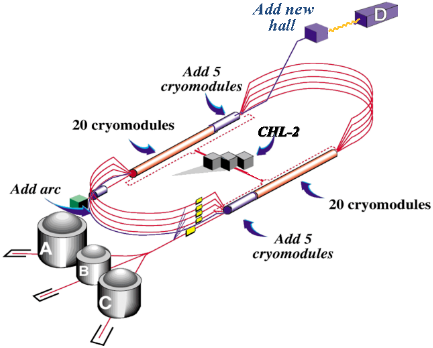
HPS Beam Requirement

- HPS requires intermediate beam energies, flat beam with low tails and halo, and excellent position stability

Parameter	Requirement	Unit
Beam Energy (E)	1 to 6.6	GeV
$\delta E/E$	$< 10^{-4}$	
Beam Current	50 to 500	nA
Current Stability	~ 5	%
σ_x	< 300	μm
σ_y	< 50	μm
Position Stability	< 30	μm
Divergence	< 100	μrad
Beam Halo ($> 5\sigma$)	$< 10^{-5}$	

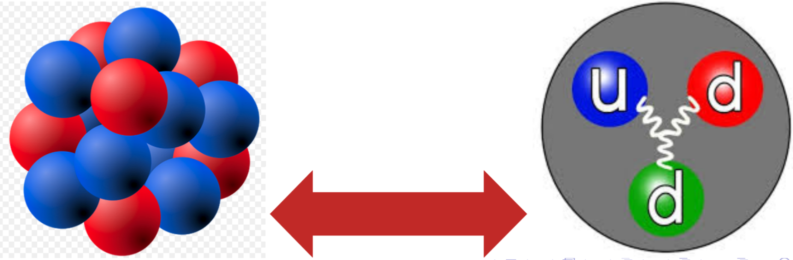
CEBAF

- CEBAF is a five-pass recirculating srf linac located at Jefferson Lab in Newport News, VA. **Capable of simulatneously delivering intense electron beams of different energies and currents** to 4 experimental halls (2.2 GeV/pass).



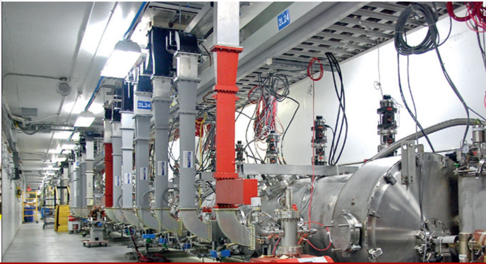
History of CEBAF

- High enery physics explores quark-quark interactions ($>\approx$100 GeV). Nuclear physics explores nucleon-nucleon interactions ($<\approx$1 GeV)
- In 1980's, there was a consensus to explore nuclear physics at the transition between these (intermediate energy physics). Also good for high intensity particle physics experiments



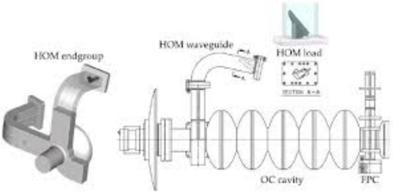
CEBAF Recirculation and SRF Cavities

- **Largest scale for srf technology and recirculating linac at the time**
- Srf technology drastically reduced operating costs, but still needed to adopt beam recirculation (linac section needs to be $\frac{1}{n}$ the length of a full-energy linac where n is the number of passes)



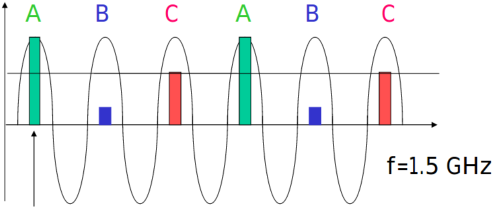
CEBAF SRF Cavities

- Construction began in 1987. Each five-cell cavity is 0.5 m long (total of 160 cavities) and total active linac length is 4.5 km
- f_{rf} **operates at 1497 MHz** and a acceleration gradient of 5 MV/m
- Each linac contains 20 cryomodules of srf cavities (now 25 for 12 GeV upgrade)



CEBAF Beam Pulse

- Each transports system must accommodate the unique momentum of beam after each pass
- In accelerating sections, **bunches of different energy occupy the same space**. Each pulse is directed into a different hall
- Bend sections are generous enough to allow for a 12 GeV

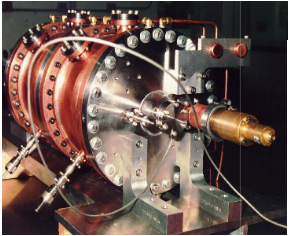


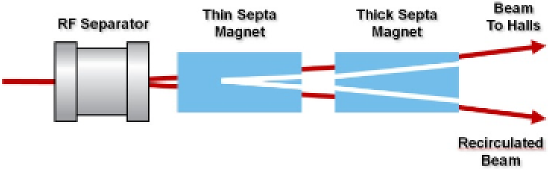
12 GeV CEBAF Upgrade

- Ten new higher-voltage cryomodules, i.e., superconducting radio-frequency (SRF) accelerating elements (five per Linac).
- Ten new RF stations to power the 10 new cryomodules.
- Approximately double the refrigeration capacity.
- Modifications to the magnets in the recirculation arcs and their power supplies to keep the higher energy beam confined to the existing beam path.
- Modifications to the extraction system to support the higher energy beams.
- A tenth arc-beamline to provide an extra pass through the North Linac. This additional acceleration pass will bring the beam up to the 12 GeV required to accommodate the experimental program in the **new hall (Hall D)**.
- A new beamline connecting Hall D to the baseline accelerator.
- Room for a 24 GeV upgrade in the future.

CEBAF RF Separators

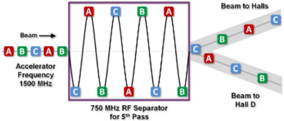
- RF separators are installed at the end of each pass to deflect beams (about 0.1 mrad)
- After some drifting, septa magnets direct beam to another pass or to the experimental halls
- Another RF separator directs beam to Hall A, B, and C

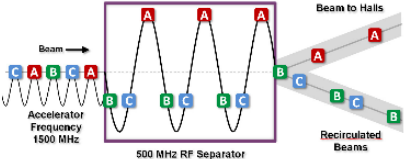


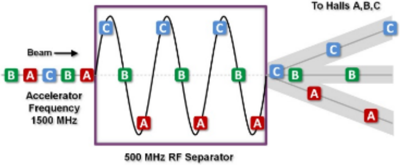


CEBAF RF Separators

- RF separators operate at 500 MHz ($\frac{1}{3} f_{rf}$) and can direct either beam 2 (left) or 3 (right) different directions
- Hall D requires a new RF separator at the last pass for 12 GeV and operates at 750 MHz ($\frac{1}{2} f_{rf}$)





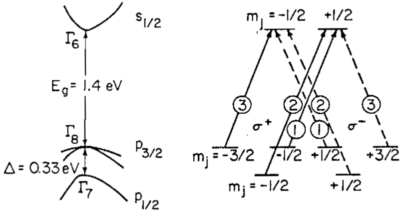


CEBAF Polarized Electron Source

- Polarizated electron beams are extremely useful for spin-dependent physics but was not a part of the original CEBAF design
- Polarization P_e is defined $P_e = \frac{N_+ - N_-}{N}$ where N_+ and N_- are spin up and down electrons, respectively, and N is the total number of electrons
- CEBAF obtains about 80% polarization and begins at the source
- CEBAF uses photoemission from GaAs as a polarized electron source (first done at SLAC for parity violation)

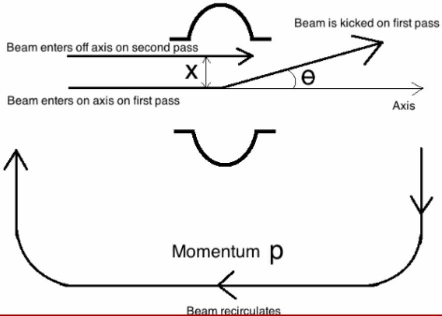
CEBAF Polarized Electron Source

- User a laser to selectively populate a the conduction band with electrons of a particular spin state
- Some of these electrons diffuse to the surface and some leave the material (but more of a particular spin state)
- One can reduce the work function by p-doping the GaAs, and one monolayer of Cs and oxidant reduces the work function below the conduction band



Beam Breakup Instability

- Concerns about multiple pass beam breakup. A beam passing off-axis through a cavity excites deflecting higher-order modes
- **Beam breakup severely limits current** in superconducting linacs due to inherently high Q's of transverse deflecting modes of the rf cavities
- This can happen in both longitudinal and transverse directions



Beam Breakup Theory

- CEBAF srf runs using TM_{010} mode (non-zero E field on cylinder axis), however higher order modes (HOMs) of TM_{mnp} and TE_{mnp}, or parasitic modes, can be **induced externally from beam particles**
- Off axis beam particles produce a transverse wake at a given HOM W_λ which is a function of cavity impedance R/Q, HOM wavenumber k_λ, HOM frequency ω_λ, and loaded quality factor Q_λ

$$W_\lambda = \frac{(R/Q)_\lambda k_\lambda \omega_\lambda}{2} e^{\frac{\omega_\lambda \tau}{2Q_\lambda}} \sin \omega_\lambda \tau \quad (1)$$

- where the loaded quality factor $Q_\lambda = \omega_\lambda \frac{U}{P_{tot}}$, U is the energy stored in the cavity, and P_{tot} is the total power dissipated

Beam Breakup Theory

- The frequencies ω_{mnp} for different modes are given as functions of radius of the cylinder R and length of cavity d

$$\omega_{mnp} = \frac{1}{\mu\epsilon}\sqrt{\left(\frac{u_{mn}}{R}\right)^2 + \left(\frac{p\pi}{d}\right)^2} \qquad \text{TM modes} \tag{2}$$

$$\omega_{mnp} = \frac{1}{\mu\epsilon}\sqrt{\left(\frac{u'_{mn}}{R}\right)^2 + \left(\frac{p\pi}{d}\right)^2} \qquad \text{TE modes} \tag{3}$$

- The sum of all the modes produces a total wake effect

$$W(\tau) = \Sigma_\lambda W_\lambda(\tau) \text{ and } V(\tau, d) = W(\tau)q'd \tag{4}$$

Beam Breakup Theory

- Particles will undergo a change in momentum Δp in the transverse direction from a potential induced by the wake $V(t)$

$$\Delta p = \frac{e}{c} V(t) \tag{5}$$

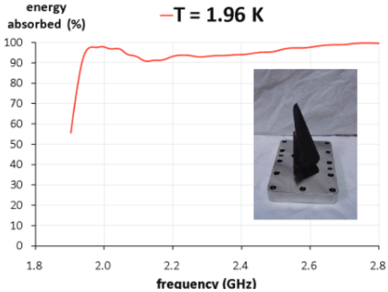
- and a corresponding displacement at the same location the next pass

$$x = M_{12} \frac{\Delta p}{p} \tag{6}$$

- where M_{12} is the transfer matrix element. Beam can lose stability if not properly damped

Damping HOMs

- HOMs must be damped for beam stability!
- CEBAF uses waveguide dampers to damp the HOMs



Threshold Current

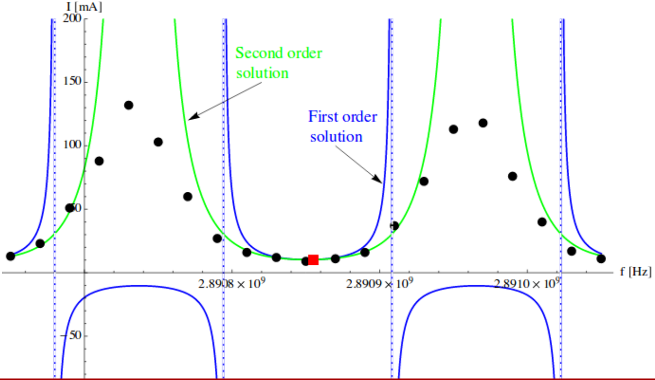
- There is a **maximum current in the accelerator before beam becomes unstable**
- Using how multiple particles produce and react to wake, the 1st order current threshold I_{th} is given by

$$I_{th} = -\frac{2pc/e}{(R/Q)_\lambda Q_\lambda k_\lambda M_{12} \sin(\omega_\lambda T_r) e^{\frac{\omega\lambda T_r}{2Q_\lambda}}} \tag{7}$$

- where T_r is the revolution period
- This diverges (and becomes negative) at certain frequecies, need the second order solution

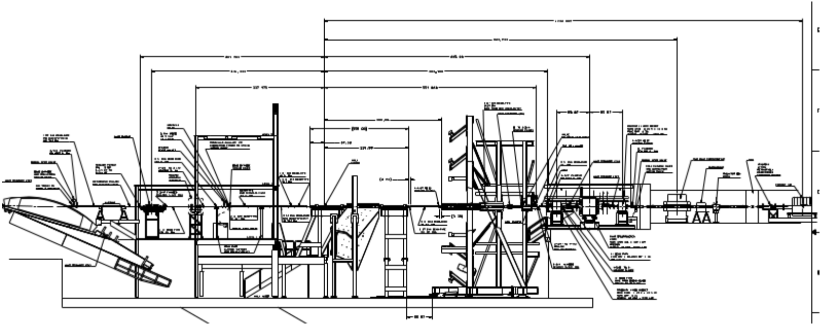
Threshold Current

- The I_{th} as a function of frequency for first order solution (blue), second order solution (green), and simulation (black)
- The mimimum I_{th} (red dot) is about 10 mA which is orders of maginitude above the design of 200μA



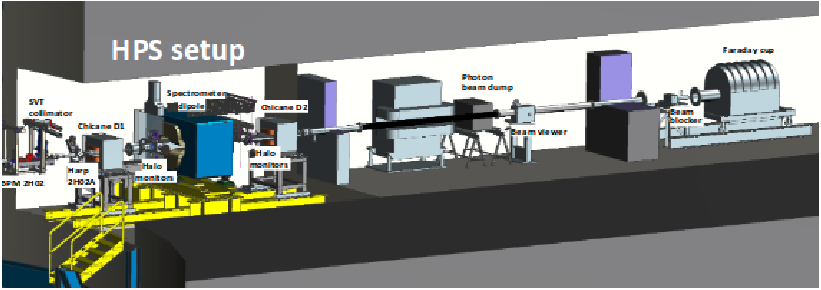
Hall B Beamline

- Hall B beamline consists of harp and wire scanners, tagger magnet, collimators, Clas12 detector, HPS dipole/chicane magnet, Faraday Cup, and beam dump
- Tagger magnet dumps beam into ground while beam is tuned



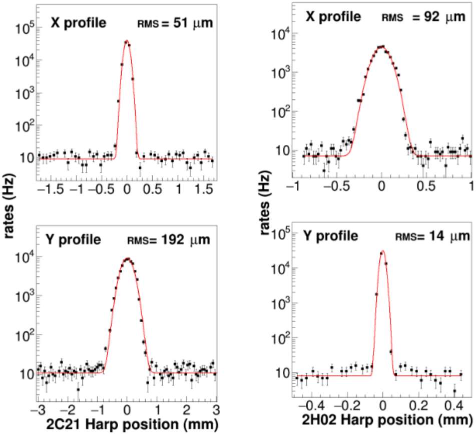
HPS Beamline

- Harp/wire scans measure beam profile before sending it to HPS
- Chicane magnet steers beam to beam dump/Faraday Cup
- Faraday cup measures total integrated current



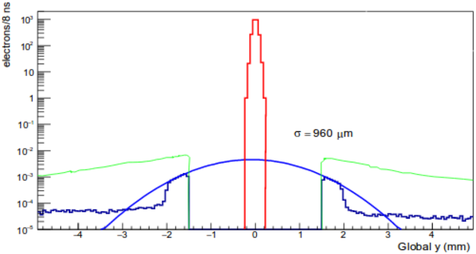
Harp Scans 2016 Data

- 2C21 harp scan before tagger (left) and 2H02 harp scan 2.2 m before target (right)



Beam Halo 2016 Data

- Measurement of beam halo in 2016 data. Red is gaussian core of beam, green is occupancies (rates) in 1st tracking layer with target, blue is occupancies in 1st layer without target, and fitted blue is fitted beam halo



Conclusion

- CEBAF provides, and has been providing, sufficient electron beams for experiments on the interface between nuclear and particle physics
- Large scale srf and recirculation technology put CEBAF on the forefront of accelerator physics
- CEBAF recently underwent a 12 GeV upgrade from the 6 GeV machine
- HPS has had two successful runs at different energies at CEBAF (1.05 GeV and 2.3 GeV), and **HPS looks forward to more beam time in 2018 and beyond**

References

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