Research Frontiers: Applications and Opportunities using the Intense Primary Beams of High Energy Physics

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Long-range planning committee

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Advancements in many areas of physics can be achieved through parasitic use of the intense ion beams generated for High Energy Physics.

Why primary?

With clean access to a primary beam, precision control can be established over secondary beam parameters.

Intensity, availability?

The Fermilab Linac is the highest-intensity, highest-availability accelerator in the complex - capable of delivering $2x10^{14}$ H^-/sec

Resources?

A new facility presently under construction is being developed to accept the full beam intensity that can be delivered by the Fermilab Linac and accommodate broad flexibility in the beam parameters as required by different experiments and research applications.

This talk will cover both novel and program-relevant research opportunities in this new, general-purpose experimental area (MuCool Test Area or MTA facility)

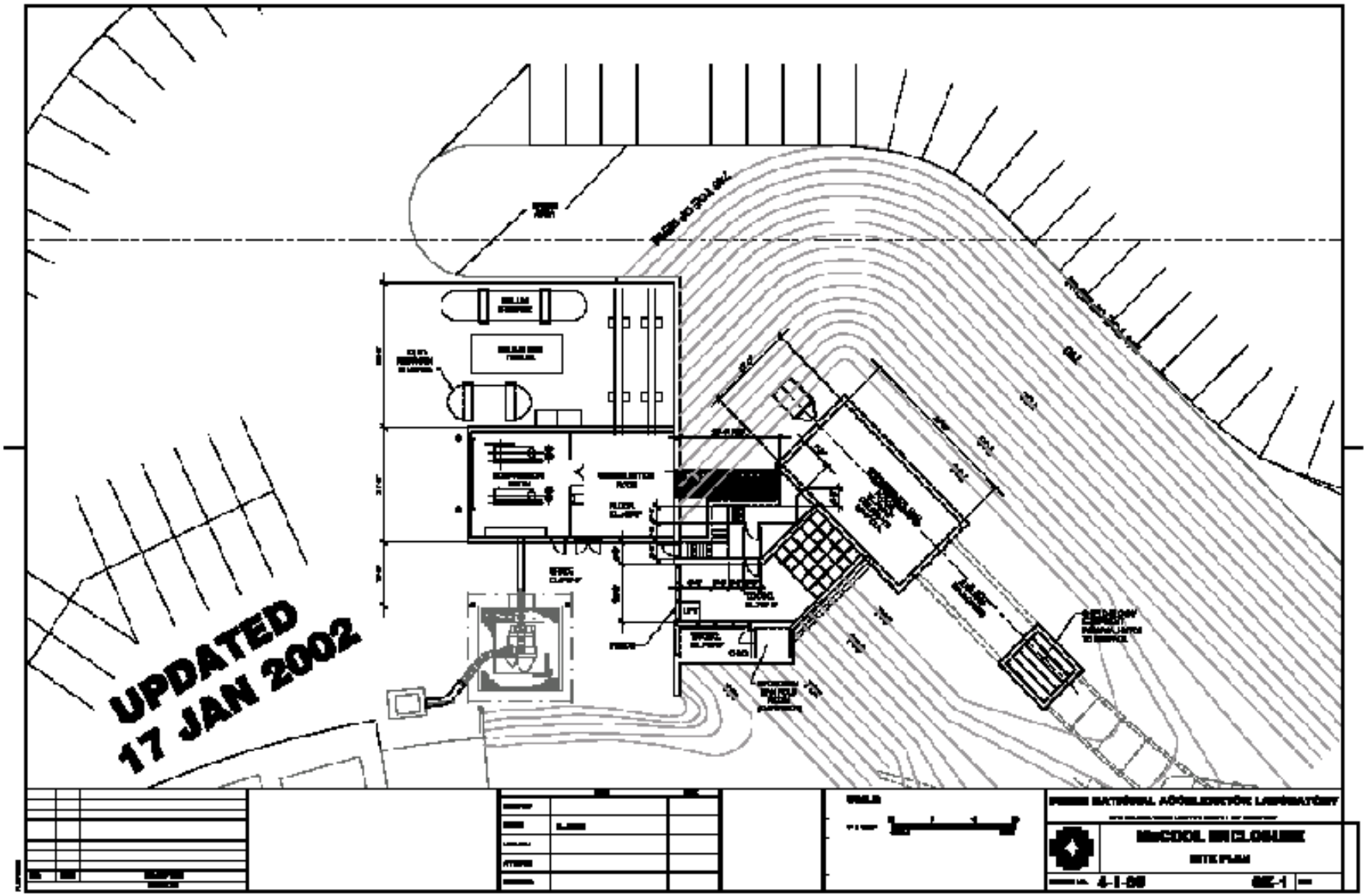
Beam Parameters of the Fermilab Linear Accelerator

Kinetic Energy	401.5 MeV
Energy Spread (95%)	1 MeV**
Peak Current	52 mA
RF Structure	800 MHz
Min Bunch spacing	201.2 MHz**
Bunch Length	0.2 ns**
Max Pulse Length	50 μsec
Particles/bunch	1.6×10^{9}**
Max. Particles/macropulse	1.6×10^{13}
Max. Beam Power	15.7 kW
Min Beam Emittance(95%)	8π mm-mr**

**potentially variable in a secondary line

Locating a Linac-based beamline and facility

MuCool Site Plan as Jan-02

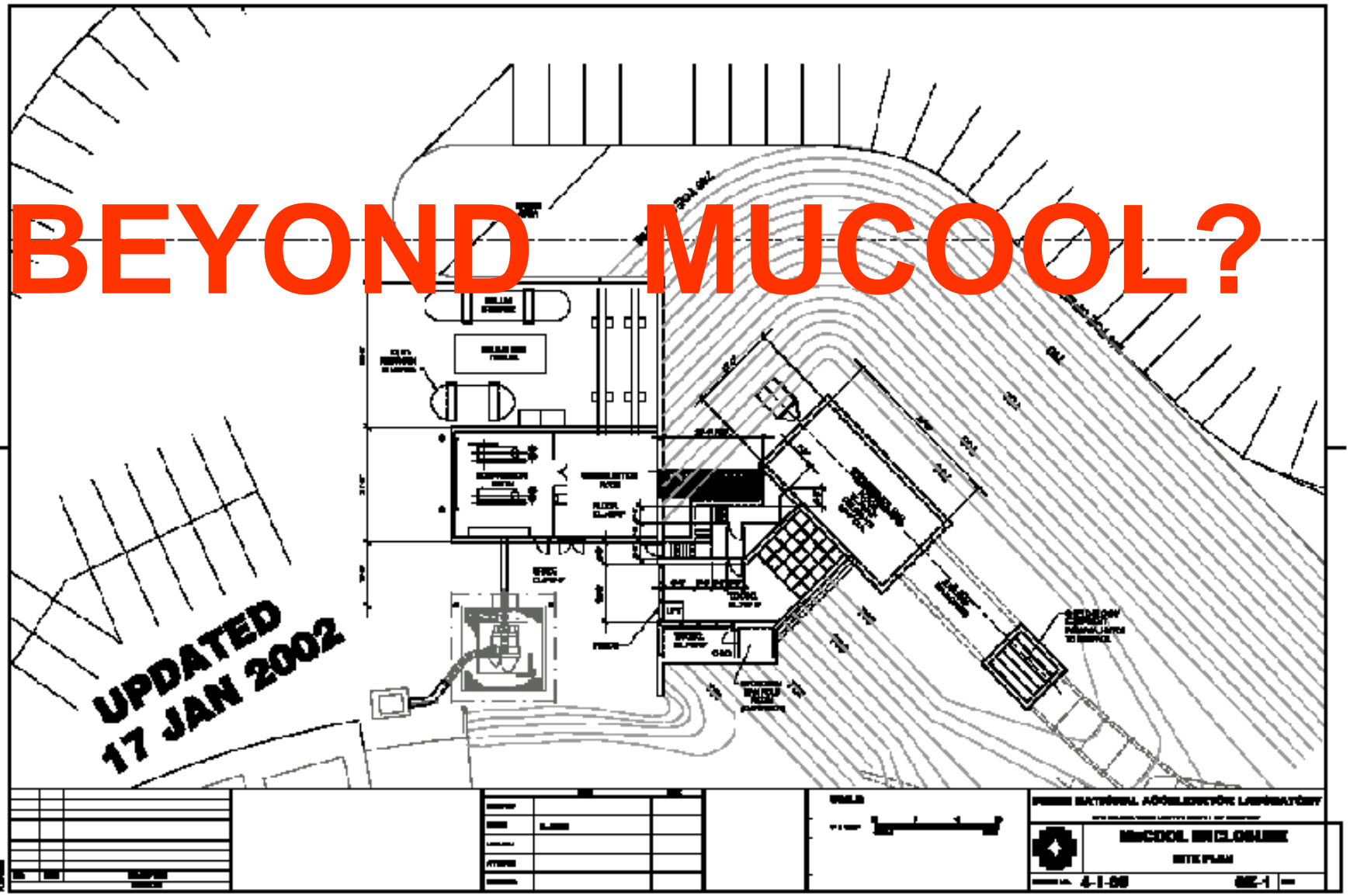


Beam Parameters for the MuCool Experiment

Beam emittance (95%)	8π	80(?)	mm-mr
Beam size ($\pm 3\sigma$)	1	30	cm
Beam divergence ($\pm 3\sigma$)	0.3	0.01	mr
Repetition Rate	no lower limit	15	Hz
Protons/Pulse	1.6	16	10^{12}
Pulse Duration	5.0	50	μsec

Not only the intensity, but the ability to vary beam conditions over an unprecedented range make this facility unique and powerful in range of applications

MuCool Site Plan as Jan-02



H^- and Relativity: The concept and design of a multipurpose experimental facility

- Controlling and changing H^- beam parameters further rely on changing or stripping the charge
  - Conventional approach: stripping foils/targets
  - Advanced approaches: laser and magnetic field stripping

Conventional approach: Complete or partial charge change of H^- into H^0 and/or protons via a stripping foil followed by field selection of desired beam state

- Accurate intensity control by ~ 2 orders of magnitude
- Limited ability to change transverse beam dimensions of H^0 or proton beam
- 3-beams produced; large radiation backgrounds
- No timing or longitudinal profile control

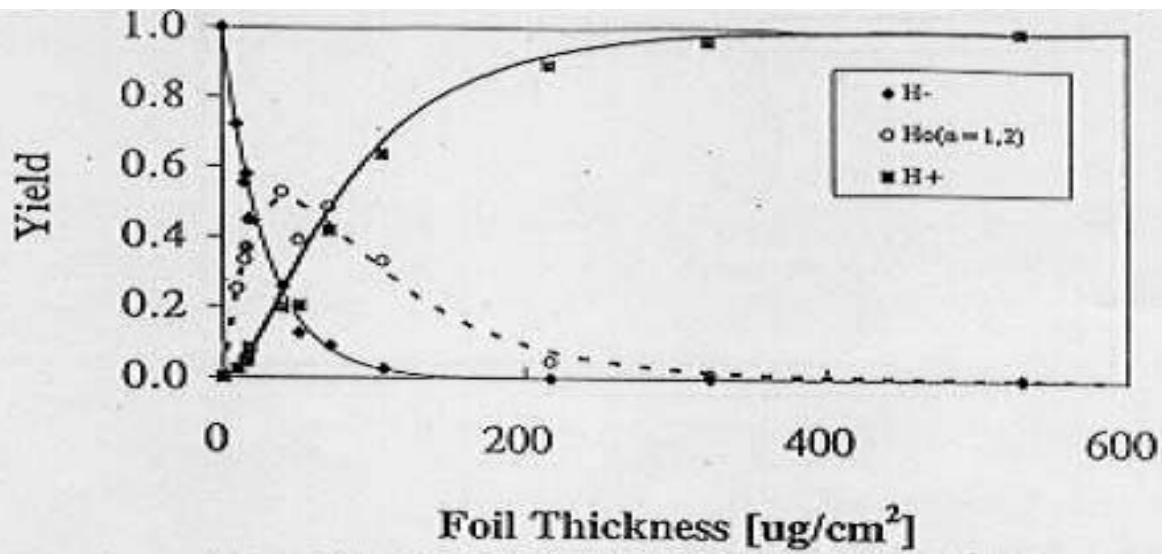
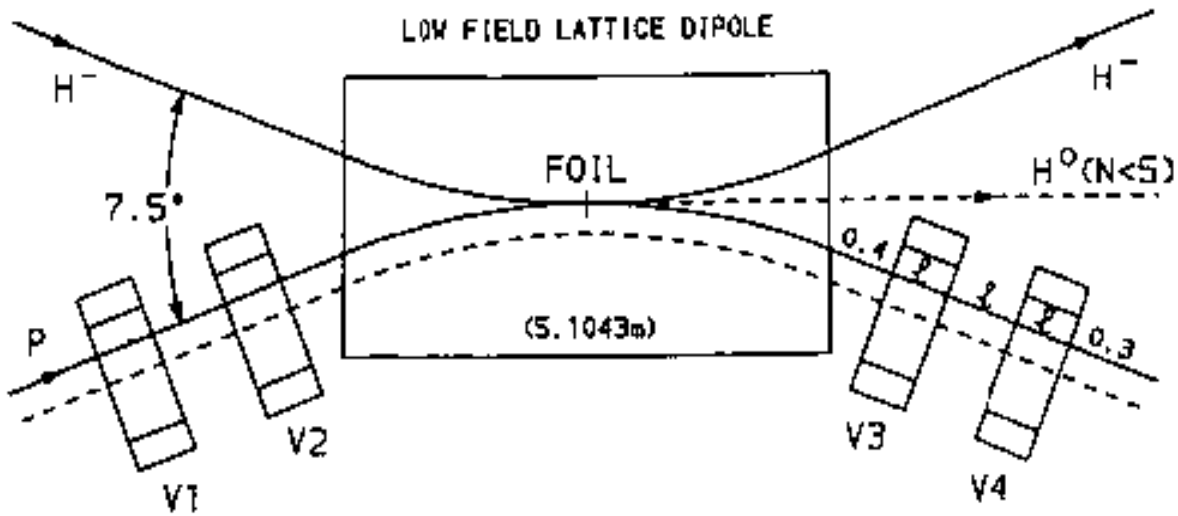
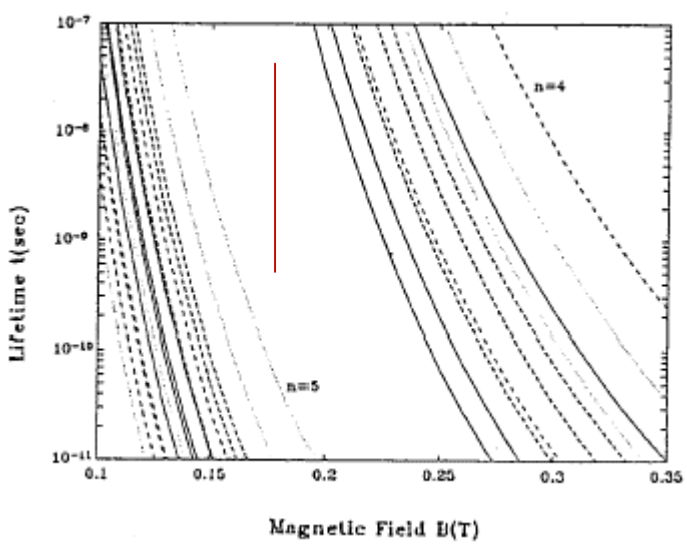


Figure 1. Yields of H^-, $H^0(n = 1,2)$, and H^+ as a function of carbon foil thickness. The data was taken during the Fall 1993 experiments at LAMPF. The curves are theoretical fits to the experimental data.

ESS Injection Dipole





- Injection in a low field dipole
- Field chosen for optimal handling of H^0 excited states
- Simple magnet layout

Advanced Techniques: Charge change using a high-power laser, atomic resonance excitation followed by foil or field stripping, …..many combinations

- Introduction to H^-
- Charge-changing options using lasers and H^- beams
  - Single electron photodetachment
  - Resonance-driven detachment (requires a relativisitic H^- beam)

Introduction to H^-

- Simplest 3-body system in nature
  - Infinite-range Coulomb potential produces a rich, well-differentiated spectrum; an infinite series of states which eventually merge into a continuum
  - Very different from 2-body systems
    - No singly-excited states; rather a series of manifolds of states embedded in the continuum, each with a characteristic set of correlated quantum numbers which converge on the excited states of neutral hydrogen
    - Like neutral hydrogen, the excited states of H^- lie in the vacuum ultraviolet, well beyond the excitation energies of any laser system; precision spectroscopy of hydrogen cannot be performed in the laboratory
    - H^- excited states auto-detach a single electron, producing a unique, identifiable H^0 signature: <u>THIS IS UNIQUE</u> and allows resonances with large cross sections to be exploited in secondary beam definition

Single-electron photodetachment of a H^- beam

- Single-electron photodetachment
  - Threshold is 0.75 eV (non-resonance process)
  - Requires high-power IR industrial laser for intense secondary beams
  - Neutralized beam converted to protons to maintain magnetic confinement--most reliable is via stripping foil
- Intensity modulation
  - When gated to a fast-switched laser trigger:
    1p/pulse finely tunable up to 99% of maximum p/pulse
- Bunch length or longitudinal profile control
  - Depends on technical specs of laser
  - Single picosecond beam bunch straightforward
  - Picosecond bunch train more difficult but possible (uses laser optics)

Resonance excitation + electron detachment of a hydrogen beam

- Resonant photoexcitation followed by electron detachment
  - Doppler boost the laser photon energy; requires relativistic H^- or H^0 beam and high-power UV industrial laser
  - Resonance driven; lower laser intensity
  - Resonant H- beam autodetaches one electron; convert to protons through magnetic field or foil stripping
  - Resonant H^0 beam easily converted to protons through magnetic or foil stripping
- Intensity modulation and longitudinal control
  - Essentially the same as in single electron photodetachment
- Momentum spread and energy selection
  - Narrow resonance linewidths combined with angular energy dependence of laser beam

Doppler shifting the laser energy

- The relativistic velocity of the accelerated atomic beam is used to Doppler shift the photon beam from industrial lasers into the vacuum ultraviolet according to the relativistic Doppler formula:

$$E_{CM} = \gamma E_{LAB}(1+\beta\cos\alpha);\ \alpha = 0\ is\ head-on$$

$$at\ \ 400\,MeV:\quad 0.41E_{LAB} \le E_{CM} \le 2.4E_{LAB}$$

- the shifted photon energy is now capable of exciting the high-lying states of both neutral and negatively-charged hydrogen—states simply not accessible in a non-accelerated environment

Doppler-boosted laser intensity

- Further, the intensity (in Watts/cm2) of the laser increases by the square of the Doppler factor:

$$I_{CM} = \gamma^2 (1 + \beta \cos\alpha)^2 I_{LAB}$$

- So, for a head-on collision of atomic and photon beams, the intensity gain is a factor of 6 at 400 MeV.

“Tunable” laser setup

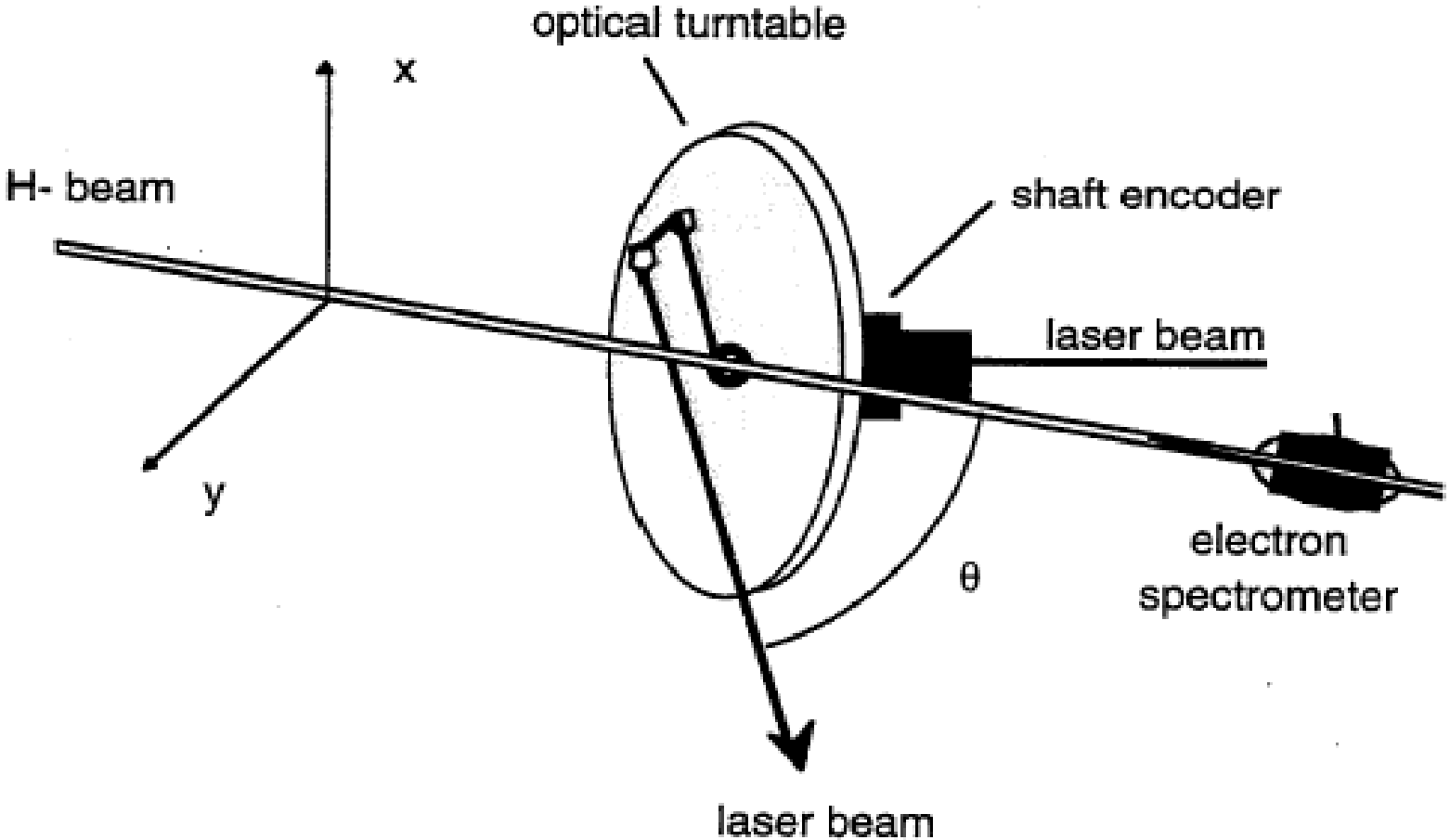


Figure 3. Schematic of the photodetachment apparatus used in the LAMPF experiments. The laser beam is directed onto the ion beam by a mirror system and the relative angle between the laser beam and ion beam is measured by a shaft encoder. The photodetached electrons are collected by the electron spectrometer and directed into a scintillation counter.

Two strong H⁻ resonances accessible with 400 MeV beam

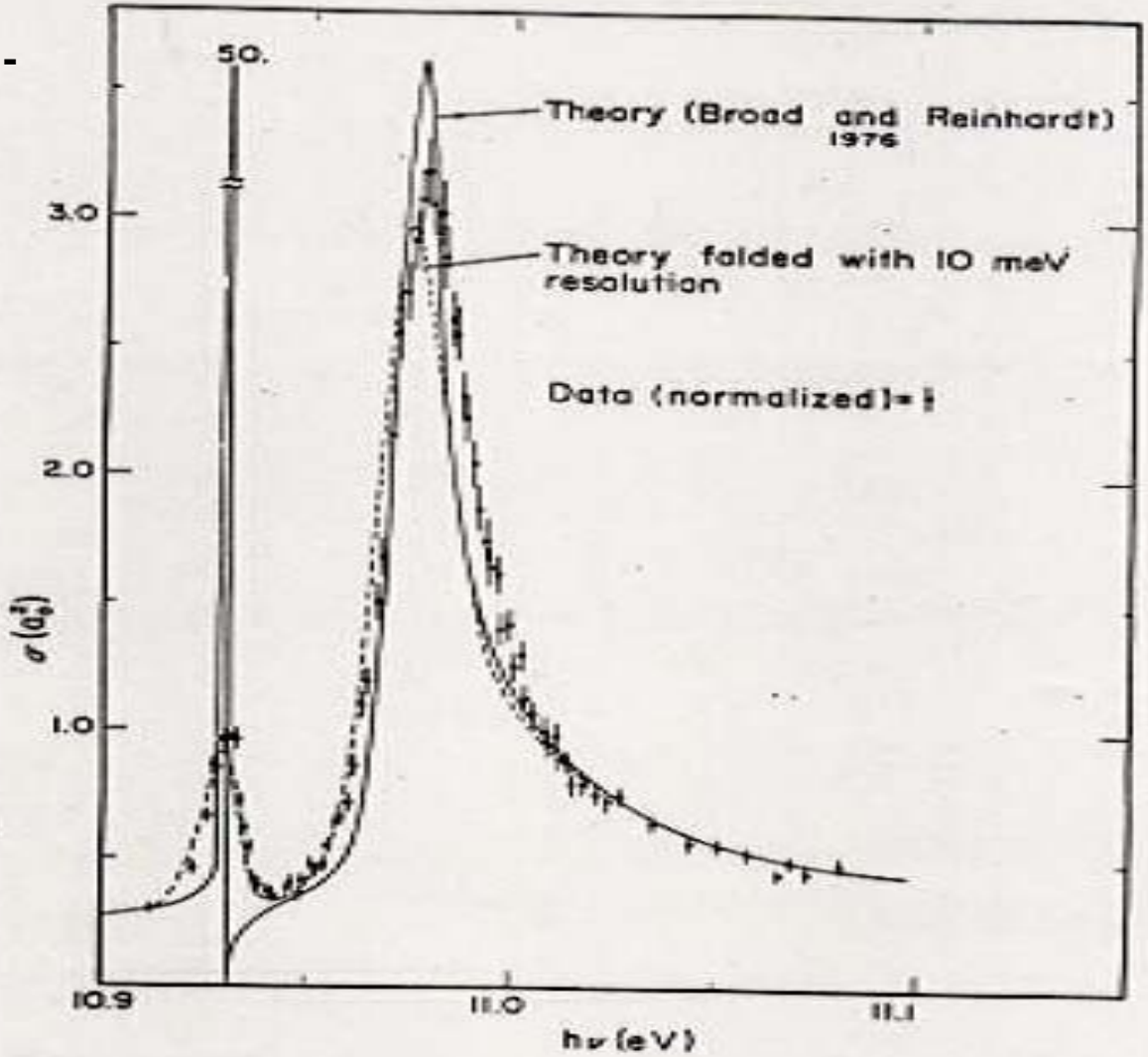


Fig. 1. The ^1P doubly excited resonances in H^-. The resonance on the left is known as the Feshbach resonance and the one on the right as the "shape resonance." See reference 2.

Schematic of laser-excited Lyman resonances in H^0 using tunable laser setup

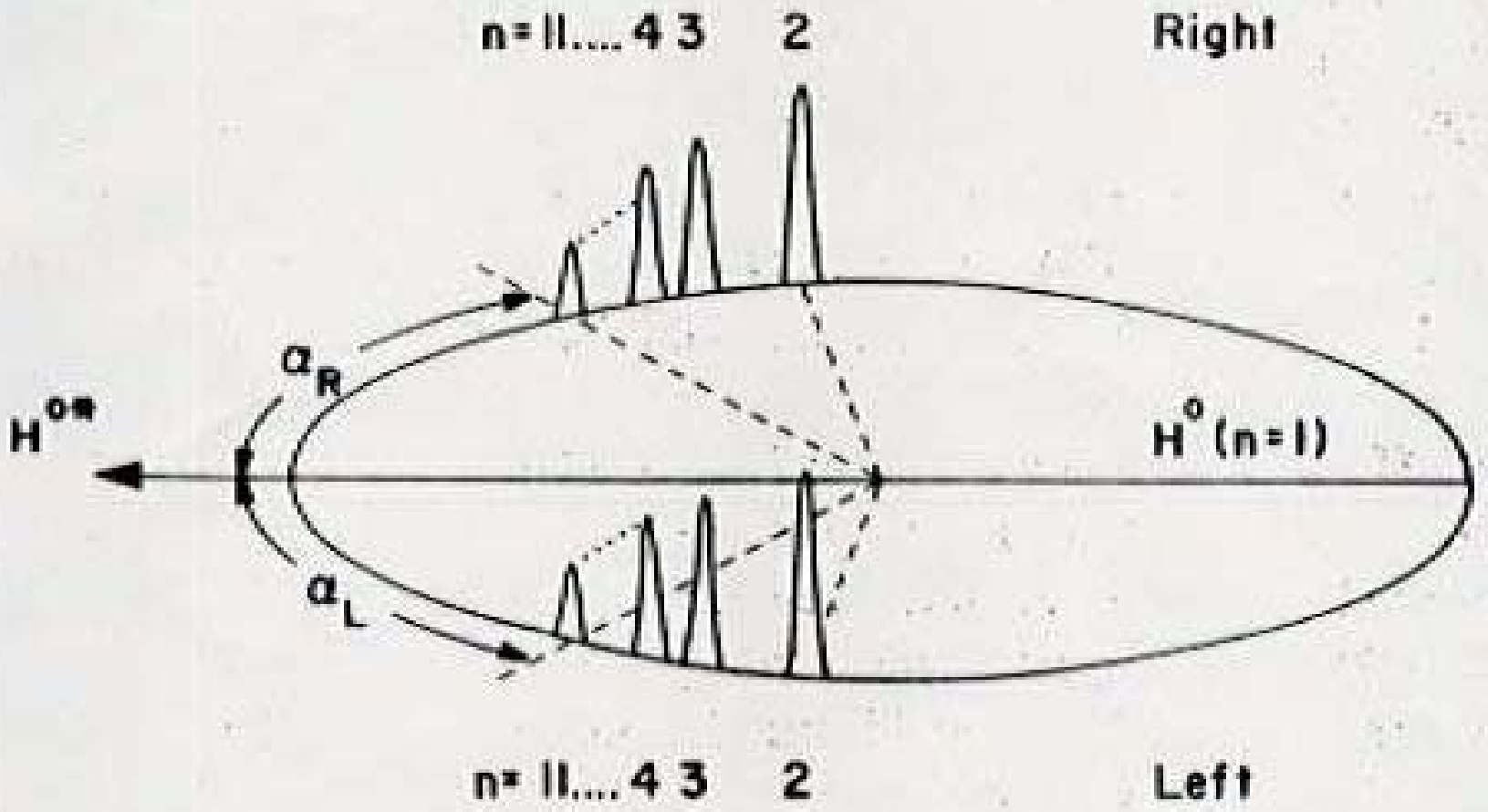


FIG. 3. A schematic drawing of the Lyman resonance lines in H^0 showing the position of the laser beam on both sides of the H^0 beam.

Applications of an advanced H^- beam facility:

- Accelerator applications
  - Foil studies
  - Laser-based beam diagnostics
  - Beam detector and accelerator R&D
- Relativistic ion studies
  - Quantum chaos
  - Multiphoton processes
  - Instantaneous—femtosecond—radiation fields
- Other
  - Technology—Beam-based coherent laser
  - Medical
  - Radiation
  - Health physics

Injection Foil Studies

- Foil material and thickness
  - ISIS and RAL PD use Al_2O_3; ESS and SNS use graphite; CEA CONCERT investigating diamond.
  - Increased thickness improves conversion efficiency of H^- to H^+ but at expense of increased beam emittance through Coulomb scattering and nuclear interactions. Balance suggests thickness of ~500 mg cm^{-2} is appropriate and will convert >95% of H^- beam to protons
- Two stage stripping $H^- \rightarrow H^0 \rightarrow H^+$ with double foil or all in one stage $H^- \rightarrow H^+$?
- Handling of H^0 excited states
- Collection of stripped electrons
  - water cooled collector (ISIS, ESS)
  - specially tapered magnets (SNS)
  - mirror field and magnetised surface (LANL proposal)

Laser-based beam diagnostics: momentum spread determination

- The two prominent resonances in H^- near 11 eV ($^1P^o$ states excited by strong single-photon absorption from the H^- ground state) are extraordinarily sensitive to the momentum distribution of the H^- beam. The lowest resonance, the Feshbach, at 10.9264 eV is only 30 μeV wide and is followed by the much broader shape resonance.
- Since all resonances of H^- are doubly-excited states followed by auto-detachment of one of the electrons, a characteristic H^0 signature is produced, with a strong signal to noise when the excitation is produced by and the neutral signal timed gated to a pulsed laser.

H^- resonance widths for different beam momentum spreads at 800 and 400 MeV

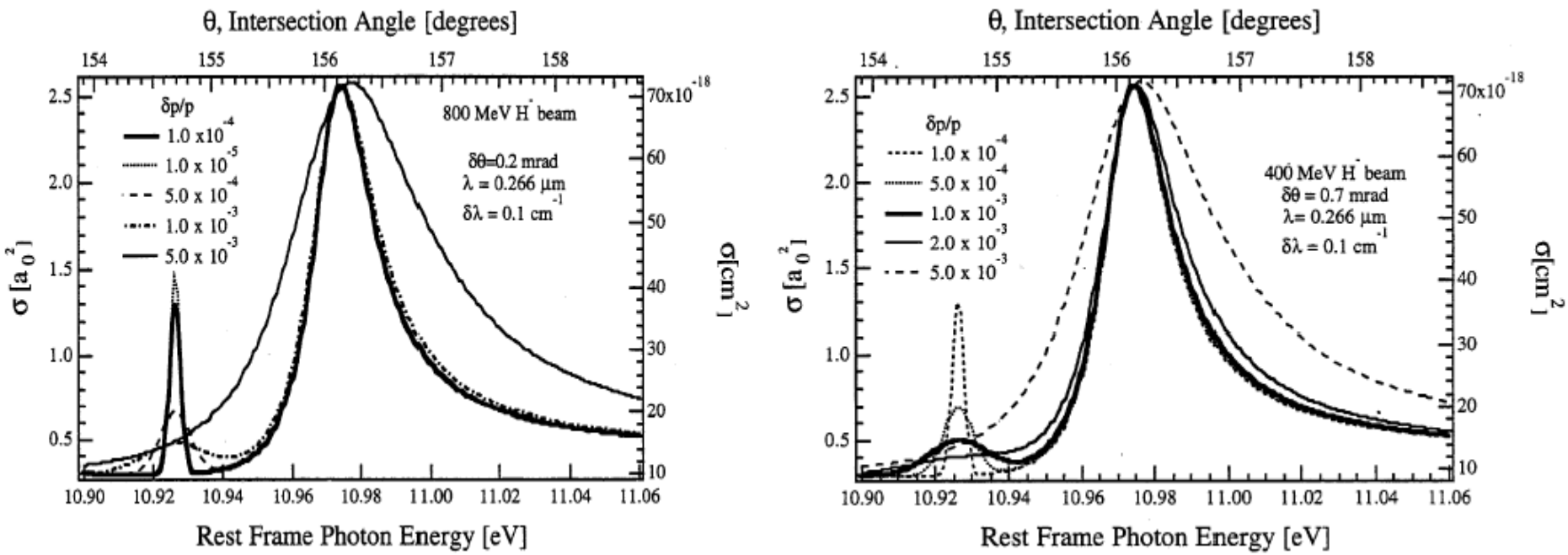
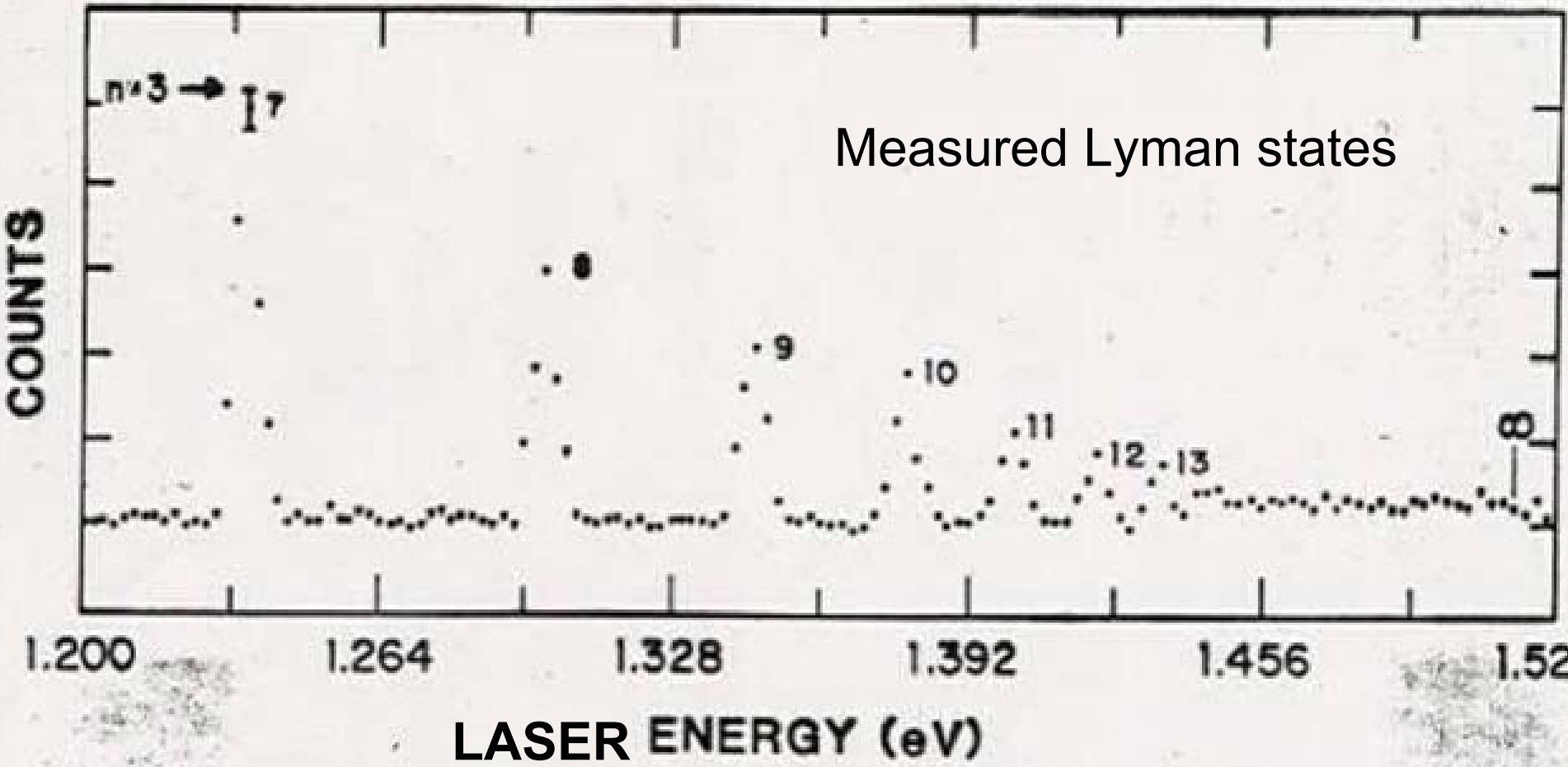


Figure 5. The H^- photodetachment spectrum at (a) 800 MeV and (b) at 400 MeV. Note that the Feshbach resonance is spread out into the continuum for $\delta p/p>0.1\%$. The shape resonance is sensitive to momentum spread for $\delta p/p>0.1\%$.

Laser beam diagnostics: energy determination

- For a largely systematic-free measurement, one would want to observe a series of states, such as the strong, very narrow, high-lying Rydberg (n=2,3,4,5…) states of H^0, where the inter-resonance spacing is ultra-sensitive to and varies, resonance to resonance, with the velocity (β) of the beam.
- Such states are readily formed in a foil, and, again, observed by stripping the electron off leaving a proton signal. Examples of data measured in the 800-MeV LANL H^- beam follow.

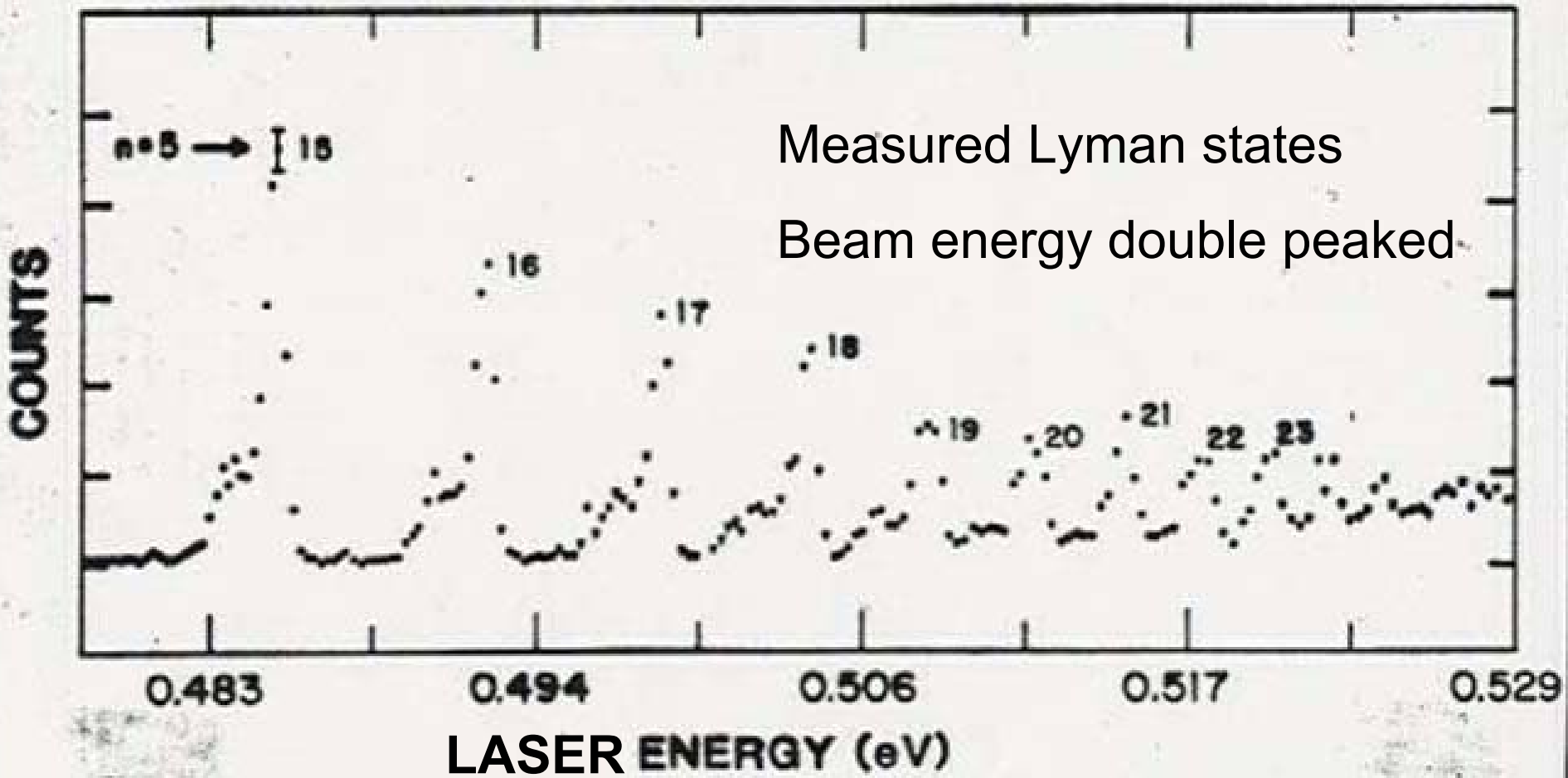
H^0 (n) FOIL DATA



Measured Lyman states

(Doppler-shifted)

H^0(n) FOIL DATA



Measured Lyman states

Beam energy double peaked

(Doppler-shifted)

Laser beam diagnostics: emittance measurements: **noninterceptive**

- Transverse emittance measurements by stripping a transverse monochromatic slice of beam.
- Bunch length measurements, again by stripping.
- Momentum measurements give the momentum distribution; when combined with a bunch length measurement, the longitudinal emittance can be determined.
- Emittance collapse by charge exchange injection/stripping with a laser (one selects a region of phase space to strip)

Final example:
A coherent, H^- based laser

THE SCENARIO

- The most prominent and broadest resonance excited by single photon absorption from the ground state of H^- lies at 10.97 eV and is the so-called shape resonance. It is much stronger and wider (+/- 21meV) than other H^- resonances and has a large cross section.
- It decays preferentially into the ^2P state of H^0
- It's lifetime is only 10^{-11} sec !
- Instantaneous population inversion

$$H^- + \gamma \rightarrow H^{-*}(\text{shape}) \rightarrow H^{0*}(^2P) + e$$

The residual ^2P State in H^0

- Decays via single photon emission
- High-lying, 122 nm Lyman-α line, 10.95 eV

  ONLY .02 eV difference
- Short lifetime, 1.6 nsec, also fast, but long on the timescale of the shape resonance

$$H^{0*}(^2P) \rightarrow H^0(^1S) + \gamma(\text{Lyman-}\alpha)$$

Example:

For the 400-MeV Fermilab Linac, the Doppler-shifted, emiited photon beam is 50 nm

For the 800-MeV LANL beam it is 36 nm

If the emitted Lyman-α line overtakes the next bunch at the same time the laser has pumped that bunch into the shape resonance, then stimulated emission can occur.

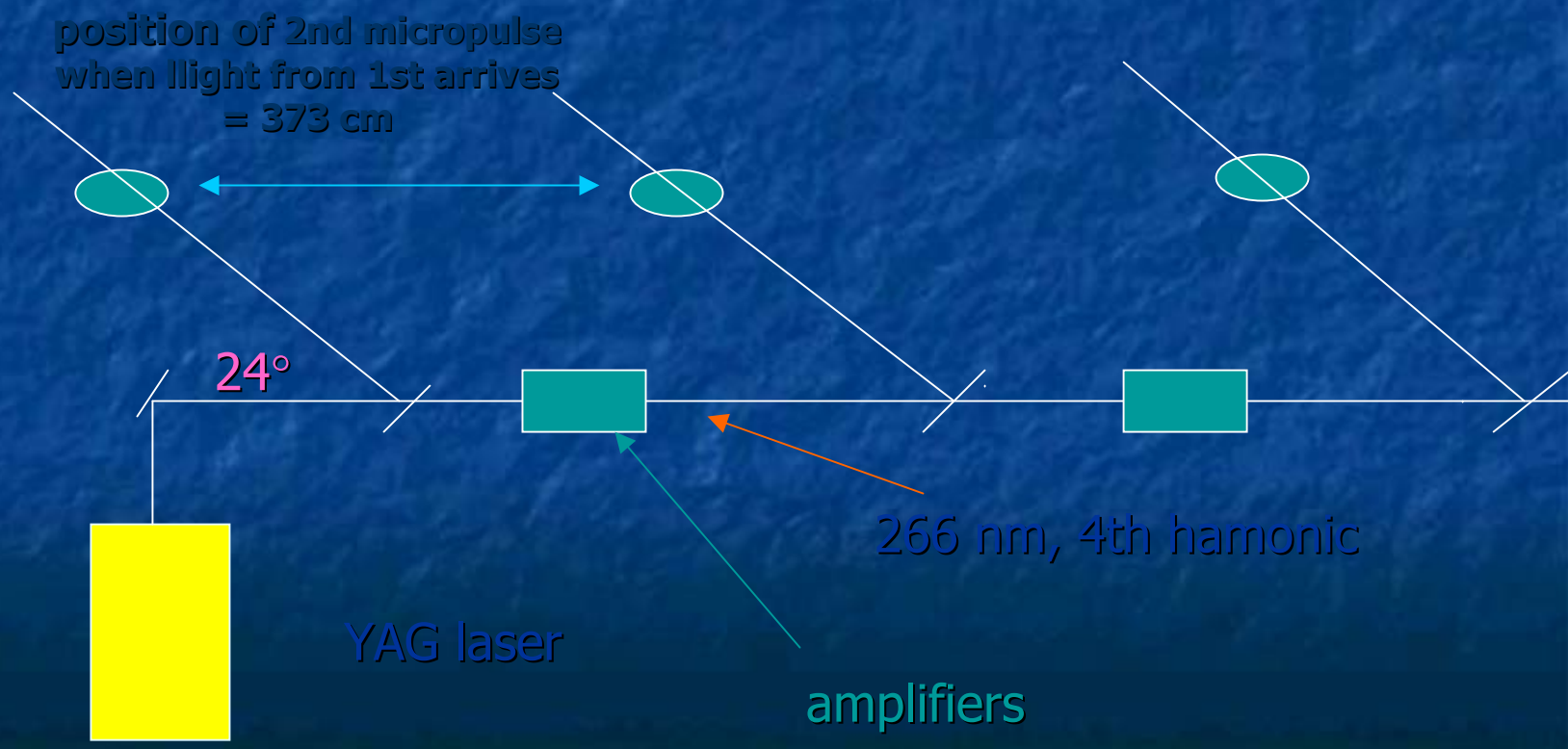
The cross section for this resonance process is α-6 larger than the Thomson cross section, which determines the power in free electron lasers.

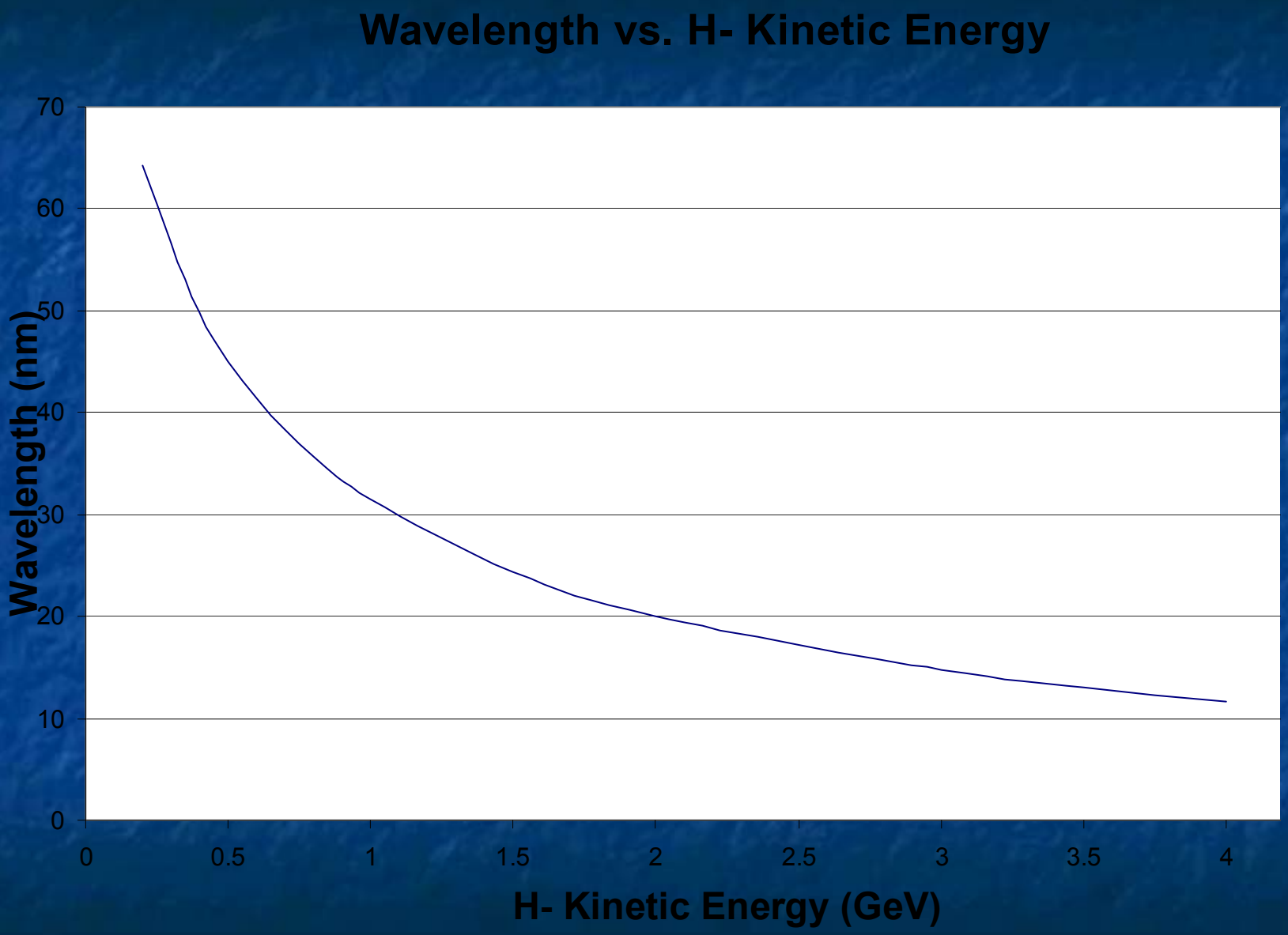
The power level of the pump laser is α8 or 17 orders weaker than that needed for an FEL

Simple Demonstration Experiment on the Fermilab Linac

HERE IS THE PROPOSED SCHEME,

based on the 400-MeV, 800MHz, H^- beam from the Fermilab Linac (every 4th rf bucket contains beam, so the spacing is actually 200 MHz),




Wavelength vs. H- Kinetic Energy
Wavelength (nm)
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
H- Kinetic Energy (GeV)

In summery, with appropriate planning, the new Linac Facility can support vigorous experimental programs in

- HEP R&D (detectors, diagnostics, radiation damage studies)
- medical physics
- atomic physics
- health physics
- accelerator R&D
- laser R&D

in the “wake” of MuCool