SNS Seminar (Dec. 12, 2002)

Laser Stripping for High Intensity Proton Ring

Isao Yamane, KEK

1. Introduction
- **Why we need laser stripping? (Problems with foils)**
- **Basic idea and a serious problem**
- **3 schemes of laser stripping proposed at ICFA-HB2002**

2. Laser stripping via a broad Stark state
- **Broad Stark state**
- **Estimation of necessary laser and magnetic field**
- **High finesse Fabry-Perot resonator**

3. Application to actual accelerator
- **Laser stripping system using undulator and high finesse Fabry-Perot resonator**
- **Emittance growth**
- **Effect of level broadening**

4. Summary

Major Concerns on Stripping Foil

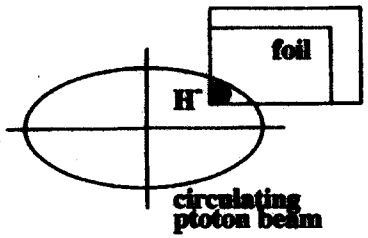
1) Residual Activity

Beam loss due to scattering by foil atoms generates untolerably high residual activity around accelerator !

2) Degradation of Foil Performance

Reliability of foil is lost by extremely high temperature due to energy losses accompanying beam passage through foil !

Minimum of Average Foil-Hit Number*



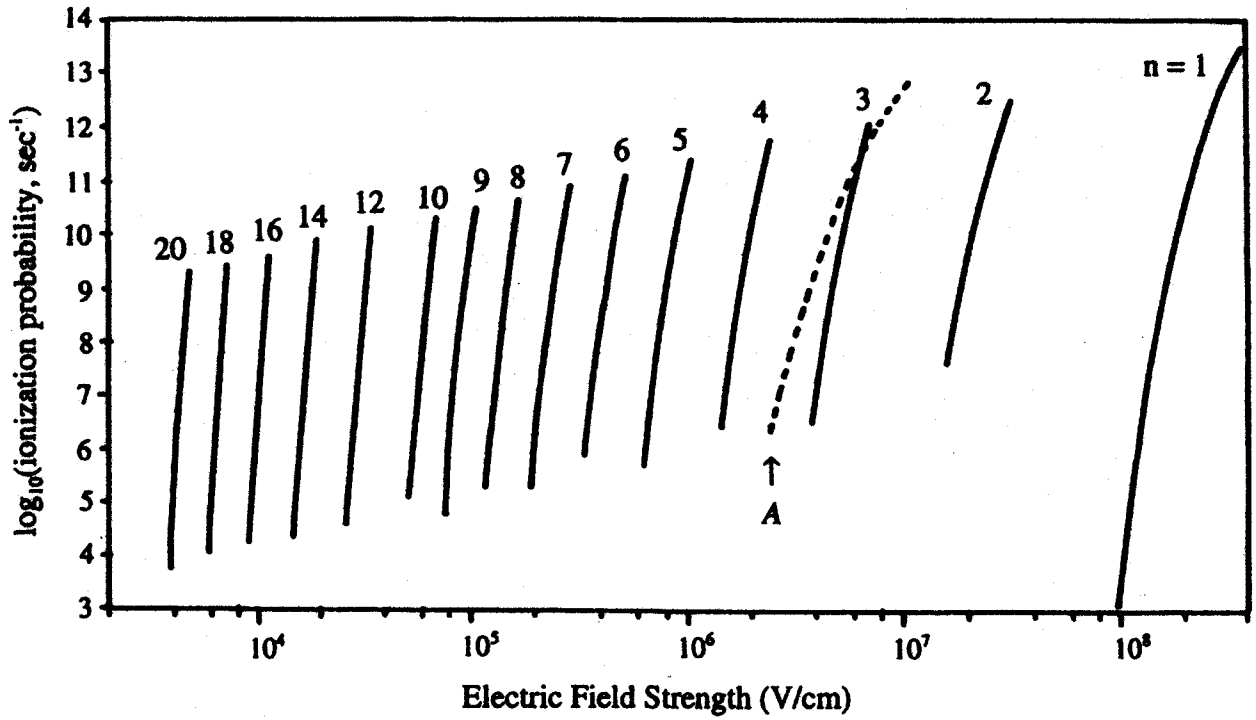
$$N_t \frac{a}{A}$$

$N_t \cdots\cdots$ *Injection turn number*

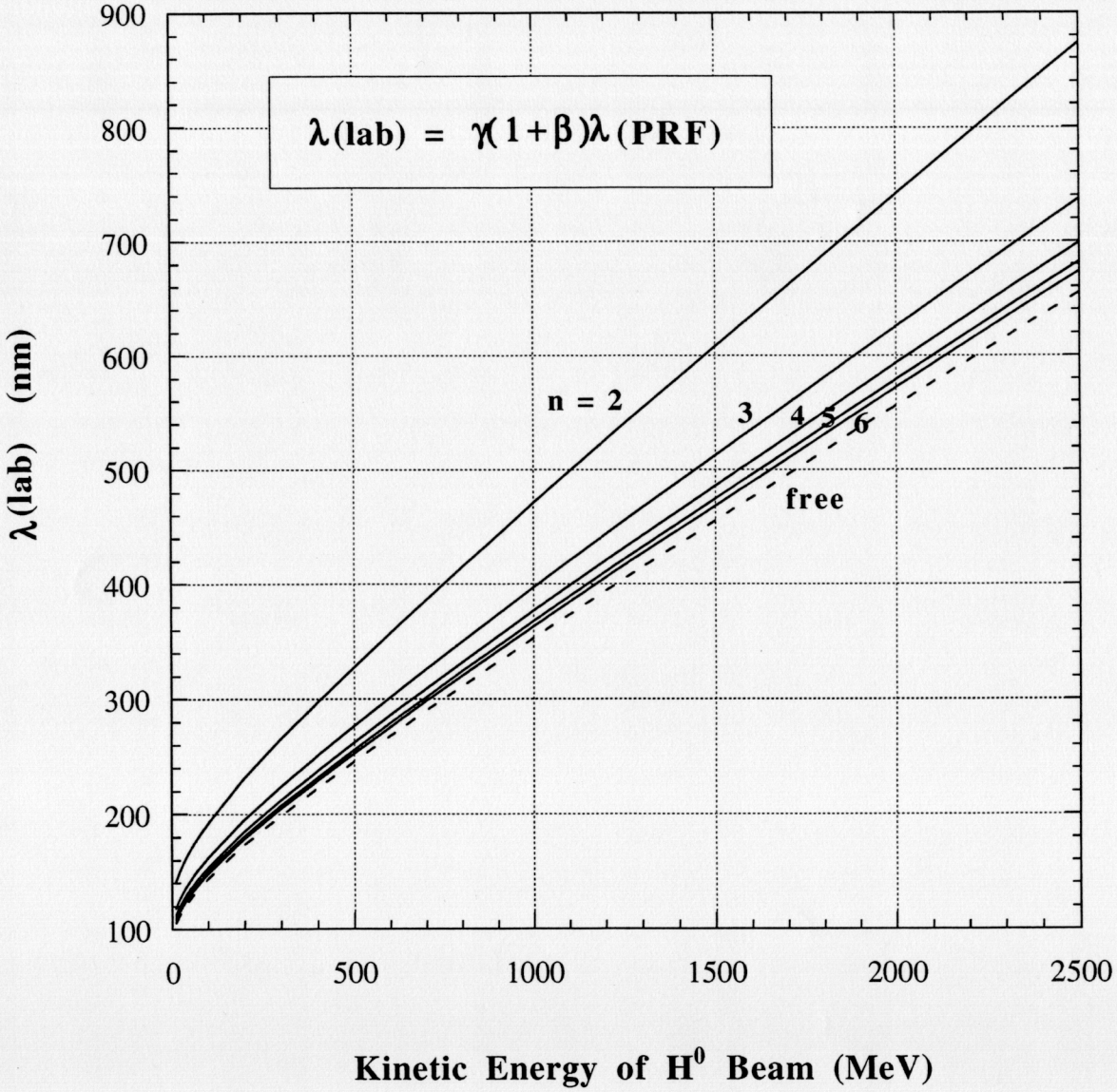
$a \cdots\cdots$ *Cross sectional area of* H^- *beam*

$A \cdots\cdots$ *Cross sectional area of proton beam*

*** I. Yamane, KEK Report 2002-2, June 2002, A**


14
13
12
11
10
9
8
7
6
5
4
3
log10(ionization probability, sec-1)
20
18
16
14
12
10
9
8
7
6
5
4
3
2
n = 1
A
10^4
10^5
10^6
10^7
10^8
Electric Field Strength (V/cm)

Doppler Shift of Transition Wave Length



3, Basic idea

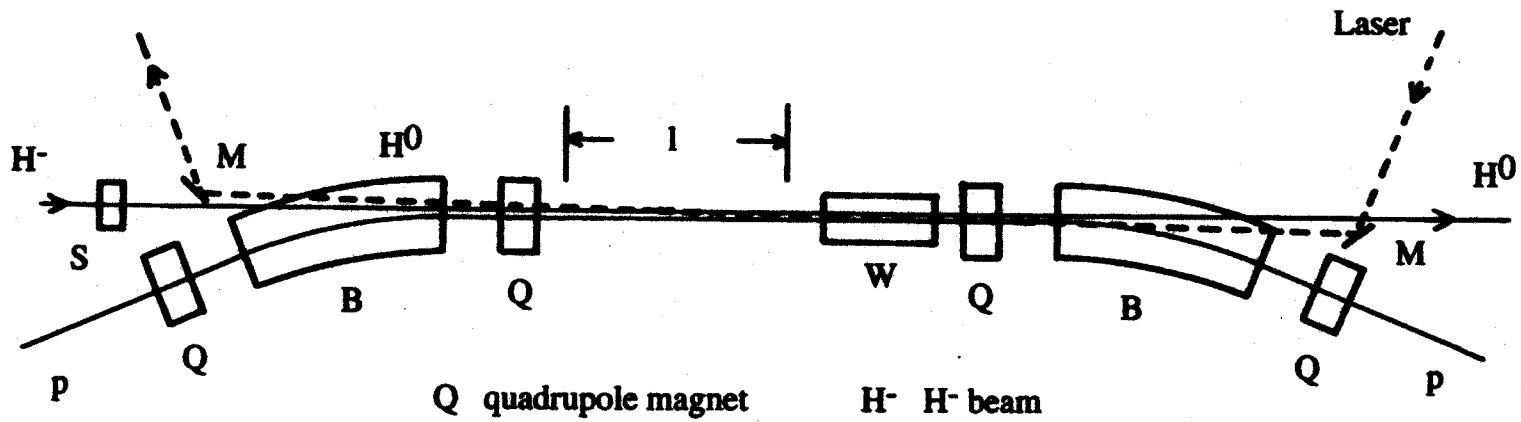
(Physical Review Special Topics-Accelerators and Beams, Vol. 1, 053501, 1998.)

States of H^0 with principal quantum number: n no less than 3 can be stripped as H- beam.

1, H- beam is first stripped to H^0 beam by a magnetic field gradient.

2, H^0 is excited to a higher excited state with n no less than 3.

3, Excited H^0 beam is finaly stripped by a magnetic field gradient to form a proton beam.



Q quadrupole magnet
B bending magnet
S stripper magnet for H^-
M laser mirror
l H^0-Laser interaction region
W stripper for $H^0(3P)$ atoms

H^- H^- beam
H^0 H^0 beam
p proton beam

4, Most Serious Hurdle to Overcome

Doppler broadening due to the momentum spread of $H^-(H^0)$ beam;

$$\Delta\omega_D = \omega_0 \beta \left(\frac{\Delta p}{p} \right)$$

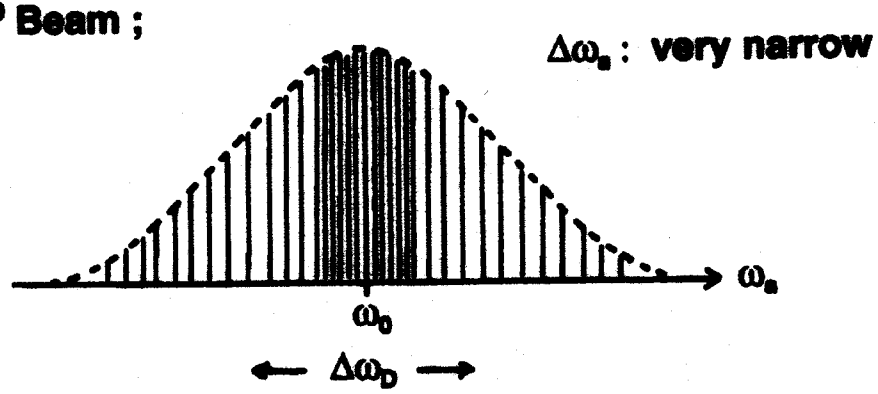
$\Delta p/p \approx 10^{-3}$, $\omega_0 \approx 10^{16}$Hz $\Rightarrow$ $\Delta\omega_D \approx 10^{13}$Hz !!

Photoionization via a Broad Stark state

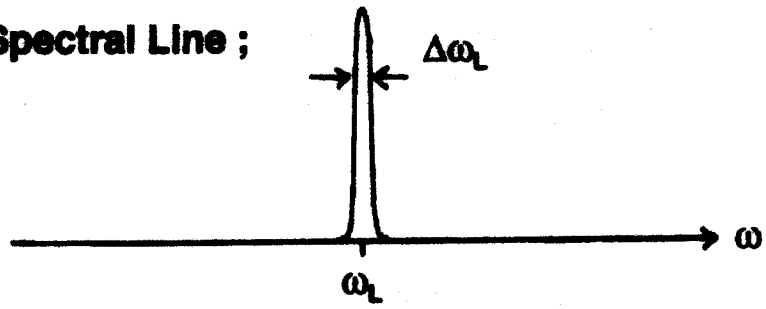
Doppler Broadening due to Beam Momentum Spread

$$\Delta\omega_D = \omega_0 \beta \left(\frac{\Delta p}{p} \right)$$

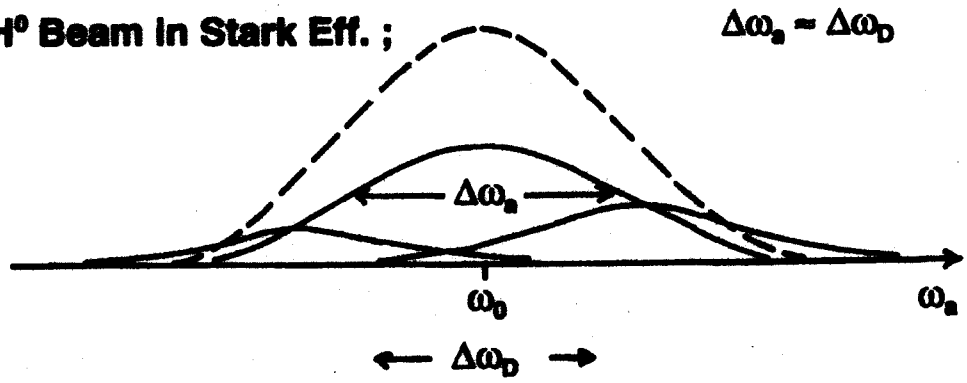
Trans. Freq. Distr. of Free H^0 Beam ;



Laser Spectral Line ;



Trans. Freq. Distr. of H^0 Beam in Stark Eff. ;



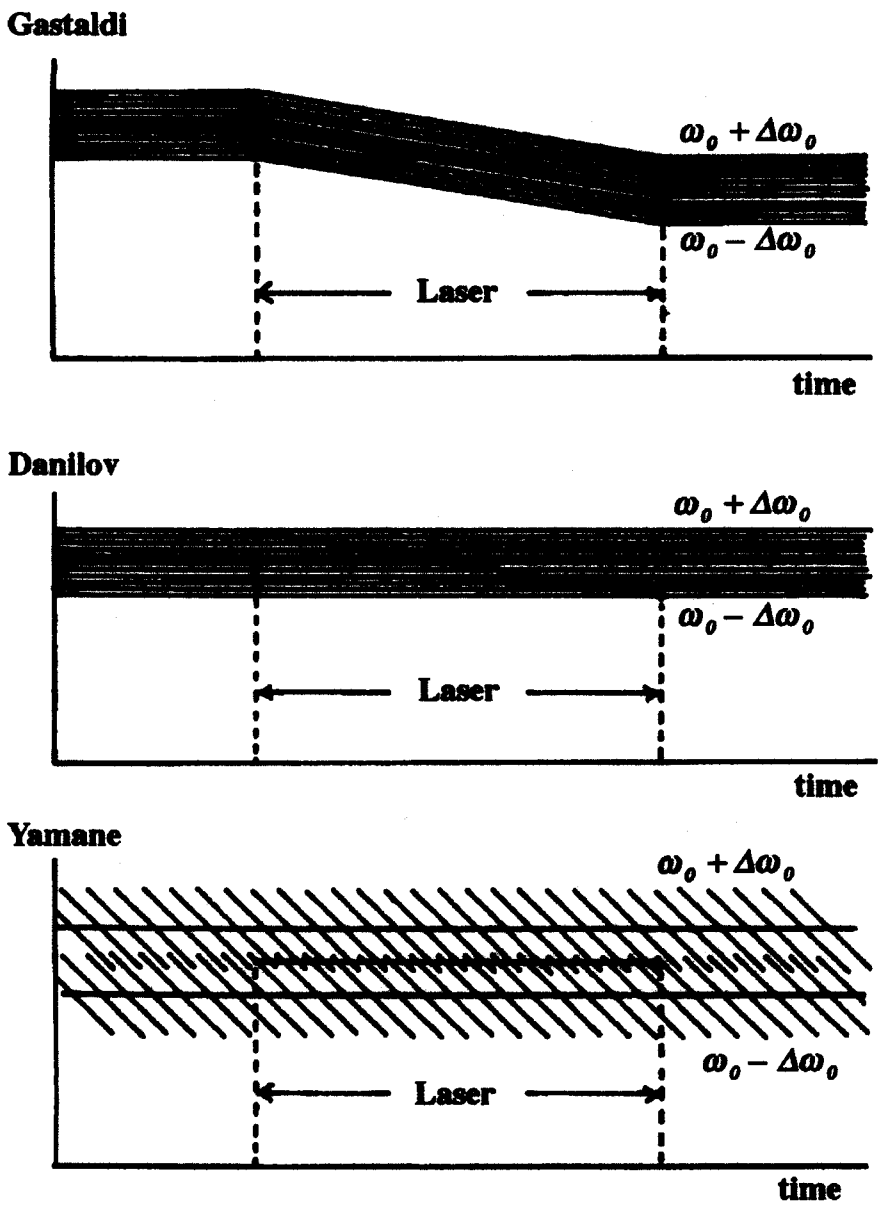
K. H^- Stripping, 1East

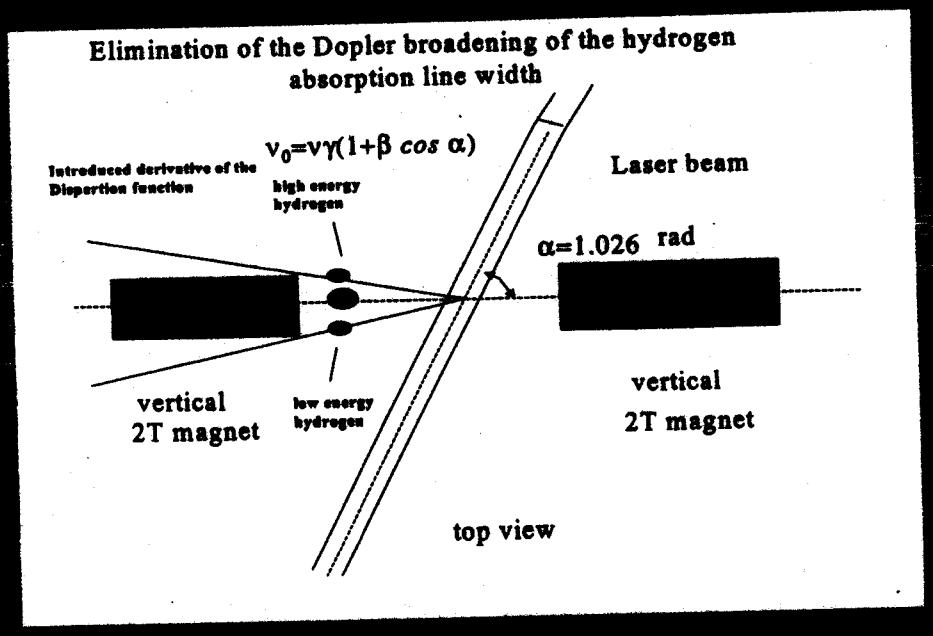
Conveners: Isao Yamane (KEK), Y.Y. Lee (BNL)

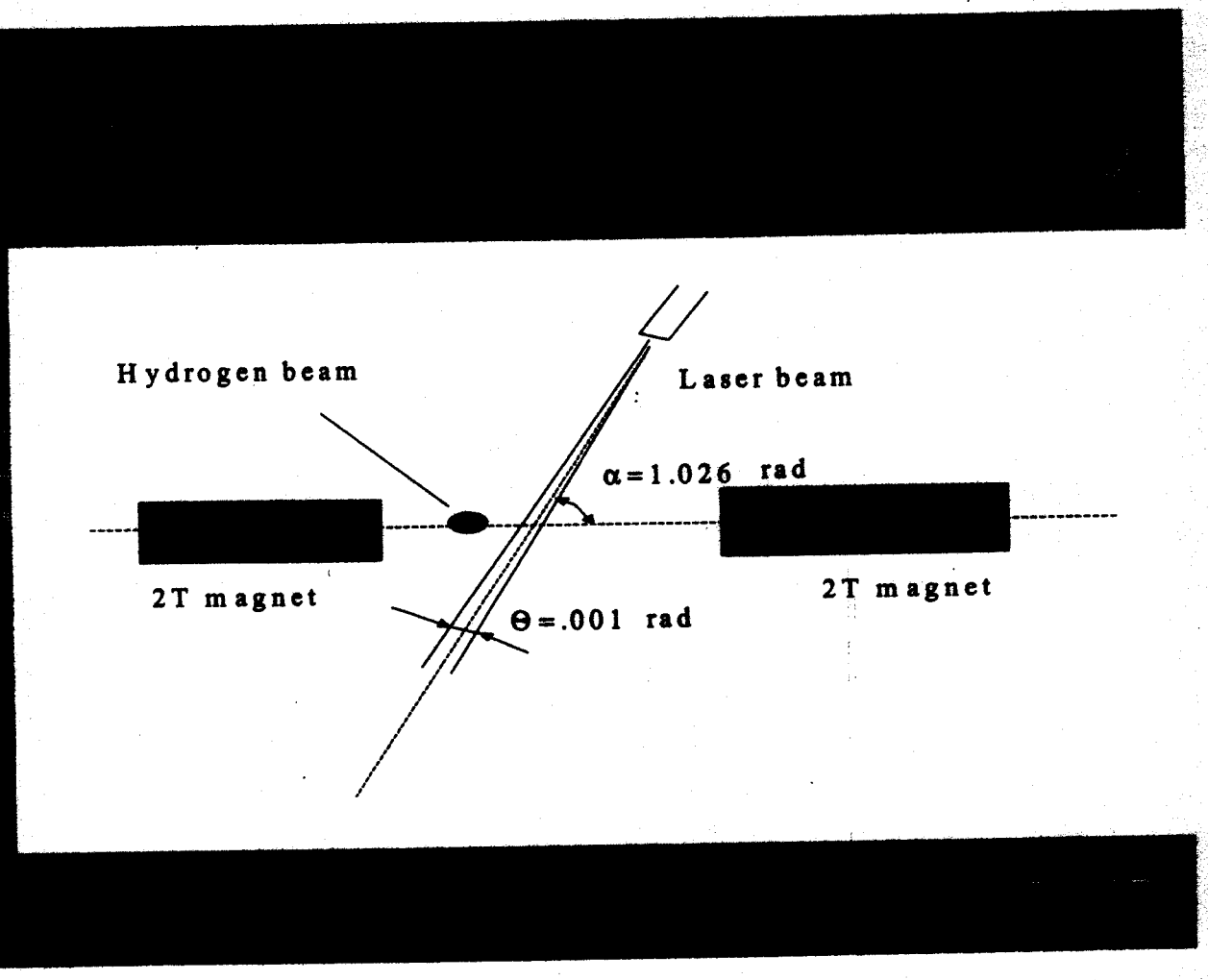
Secretary: Aimin Xiao (Fermilab)

1. Motivation of this session	I. Yamane (KEK)
2. Review on laser assisted stripping	Ugo Gastaldi (INFN)
3. Feasibility of laser stripping via a broad Stark state for charge-exchange injection into a high intensity proton ring	I. Yamane (KEK)
4. A novel solution for H^- laser stripping	Slava Danilov (ORNL)
5. PVLAS developments on Fabry-Perot resonators locked to CW lasers and suitable for laser assisted Lorentz stripping of H^- beams	G. Cantatore et al. (INFN)
6. Carbon stripping foil experience at PSR	M. Borden et al. (LANL)
7. Present status of development of carbon stripper foils at KEK	Isao Sugai et al. (KEK)
8. The SNS strategy for H^- stripping	Y.Y. Lee (BNL)

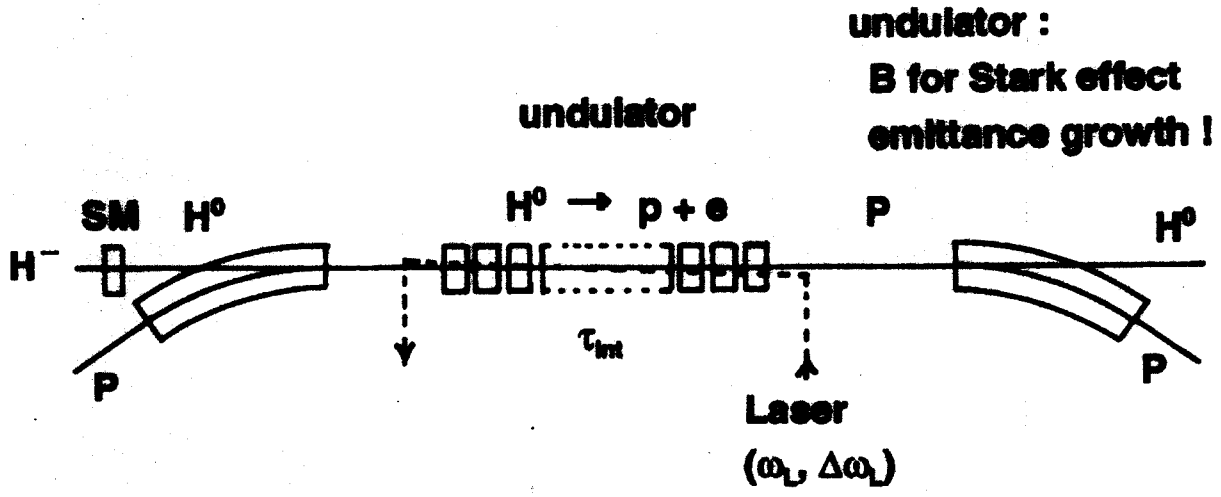
Transition Frequency Distribution and Laser Frequency

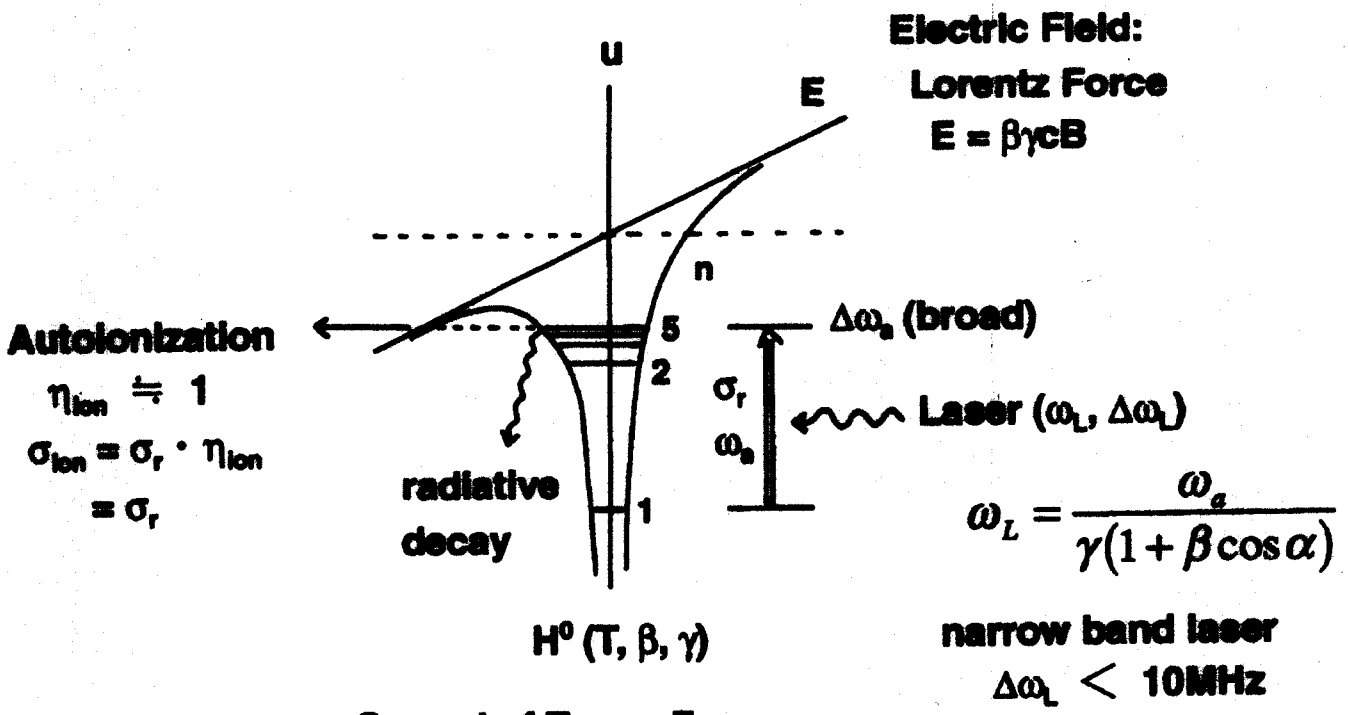



Elimination of the Dopler broadening of the hydrogen absorption line width
$\nu_0=\nu\gamma(1+\beta \cos \alpha)$
Introduced derivative of the Dispertion function
high energy hydrogen
Laser beam
α=1.026 rad
vertical 2T magnet
low energy hydrogen
vertical 2T magnet
top view


Hydrogen beam
Laser beam
α=1.026 rad
2T magnet
2T magnet
Θ=.001 rad

Photoionization via BSS





$$\omega_L = \frac{\omega_a}{\gamma(1+\beta\cos\alpha)}$$

narrow band laser

$\Delta\omega_L < 10\text{MHz}$

Spread of Trans. Freq.
due to Doppler shift

$$\Delta\omega_D = \omega_a \beta \left(\frac{\Delta p}{p}\right) \approx 10^{13}\,Hz$$

Roles of Broad Stark State

1. To cover the spread of transition frequency distribution due to the momentum spread of H^0 beam.

   Broad level width, $\Delta\nu \cong 10^{12}$ Hz.

2. To elongate interaction time of individual H^0 atom with laser beam.

   Interaction time, $\tau_{int} \geq 10^{-9}$ sec

3. To avoid pumping down to the ground state.

   Short lifetime, $\tau_a \cong 10^{-13}$ sec

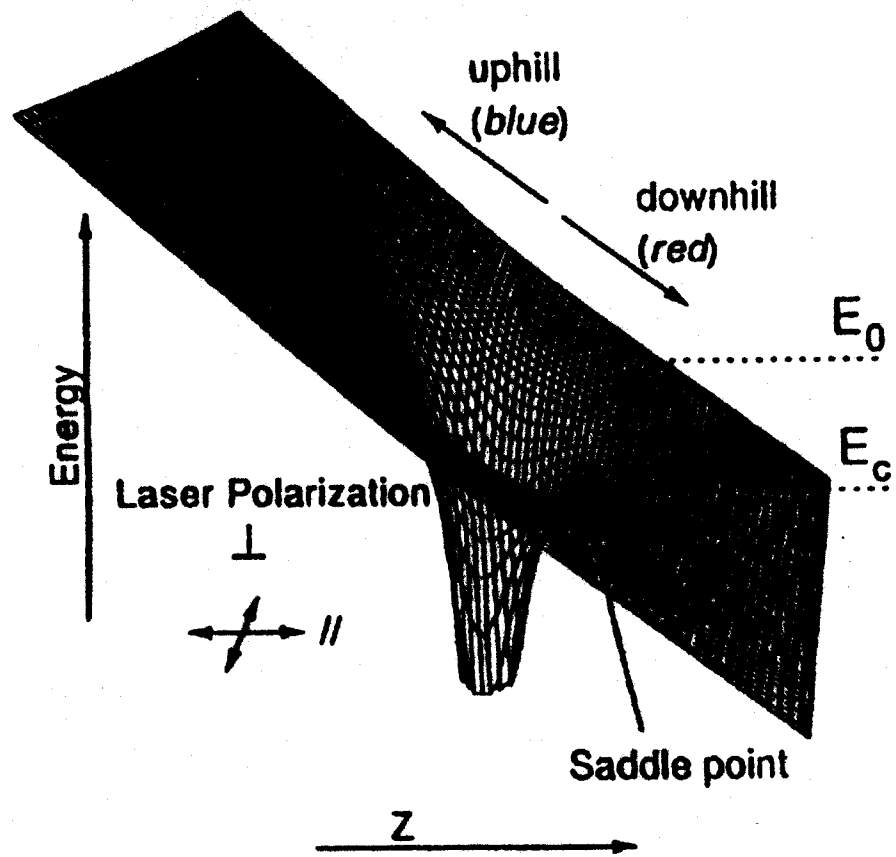


FIG. 3. Potential-energy surface of an electron in a combined Coulomb and electric field ($V = -1/r - Fz$). The classical ionization energy is lowered by the external electric field to $E_c = -2\sqrt{F}$. An electron with energy larger than E_c can escape over the saddle point.

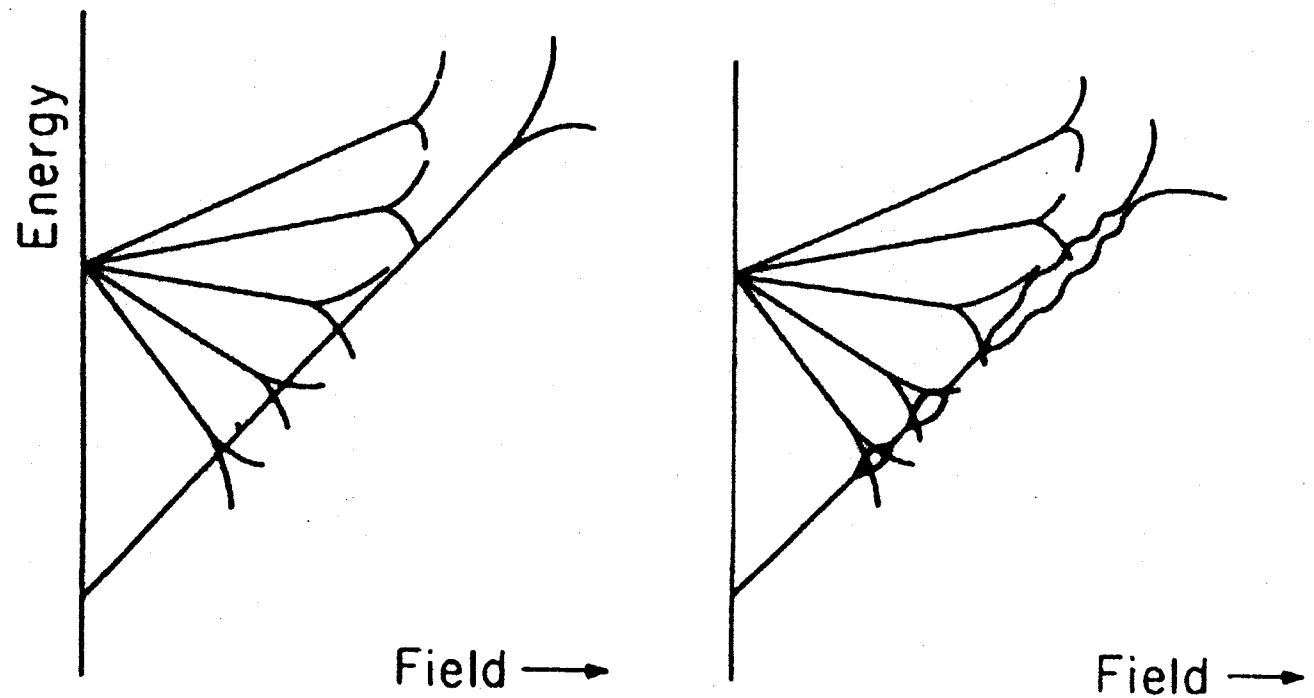


Fig. 3.15. Sketch of Stark levels of hydrogen in strong electric fields (*left*) and of an alkali-metal atom (*right*). Hydrogenic Stark levels do not interact; in an alkali, the levels can mix, causing an otherwise stable level to decay. Level widths indicate the decay rates.

Bergeman et al.
~~Atomic Physics 9~~
~~Seattle 1984~~
Phys. Rev. Letts.
Vol 53 (1984)
p. 775

H^0 (n=4)

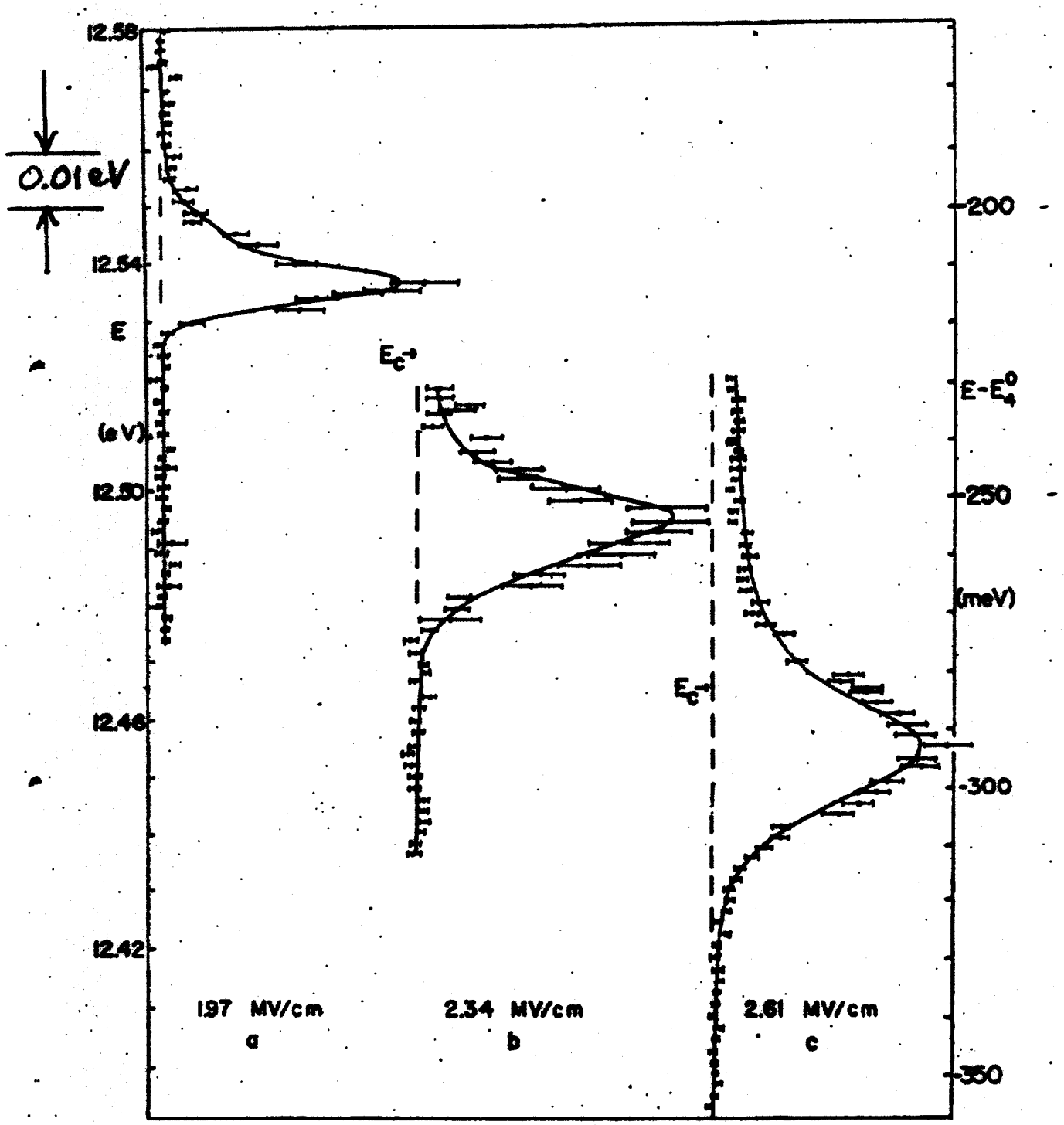


Fig 21
Bergeman et al.

~ 2 kGauss ⇒ 0.1 eV shift
~ 100 Gauss ⇐ 0.005 eV
⇕
~5 10^{-4} $\frac{\Delta E}{E}$

Bergeman et. al.
~~Atomic Physics 9~~
~~Seattle 1984~~

H^0 (n)

Phys. Rev. Letts
Vol 53 (1984)
P 775

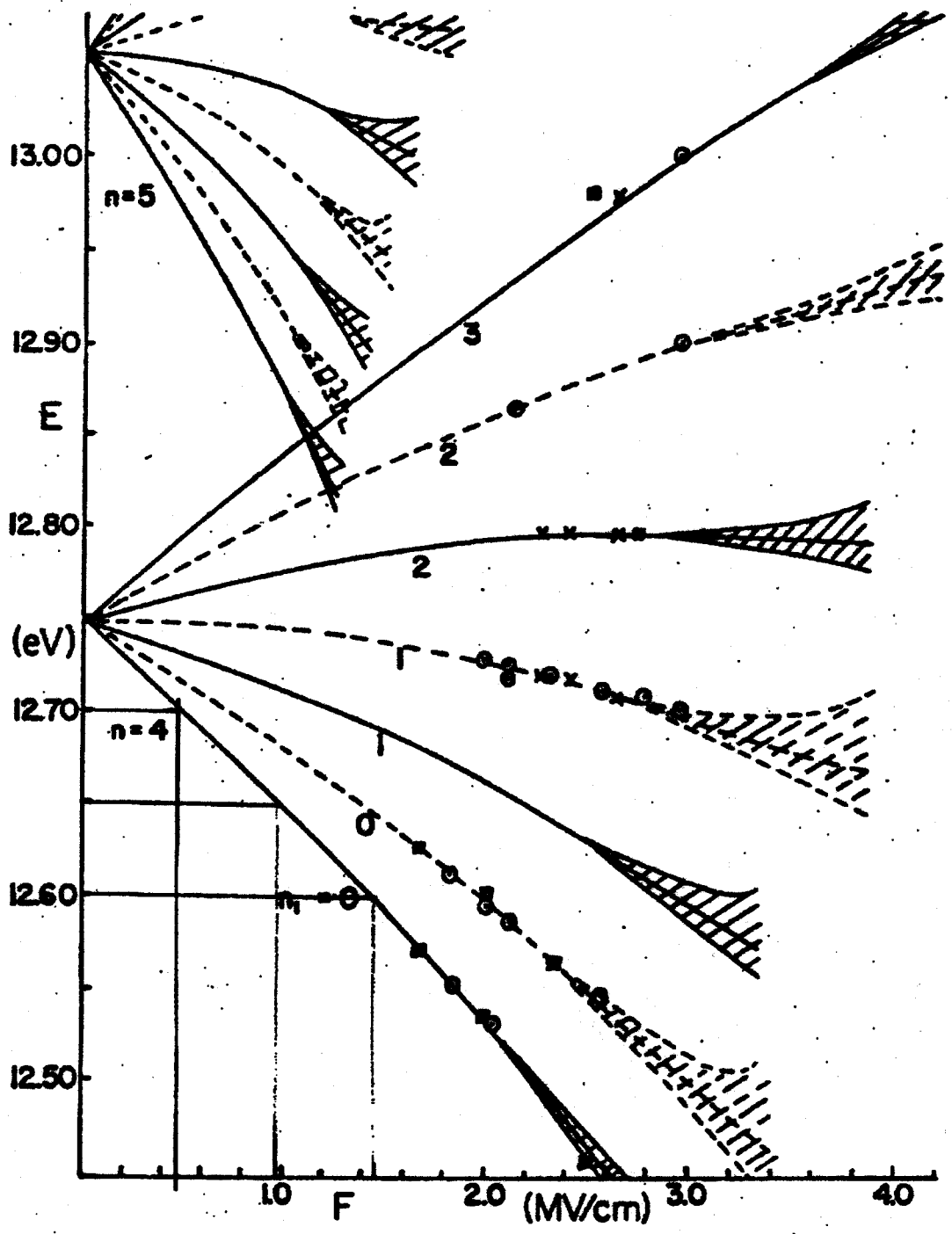


Fig. 2

ref. 21
Bergeman et al

6, Broad Stark state

Lorentz field, E(V/cm) vs B(T) for a high energy proton;

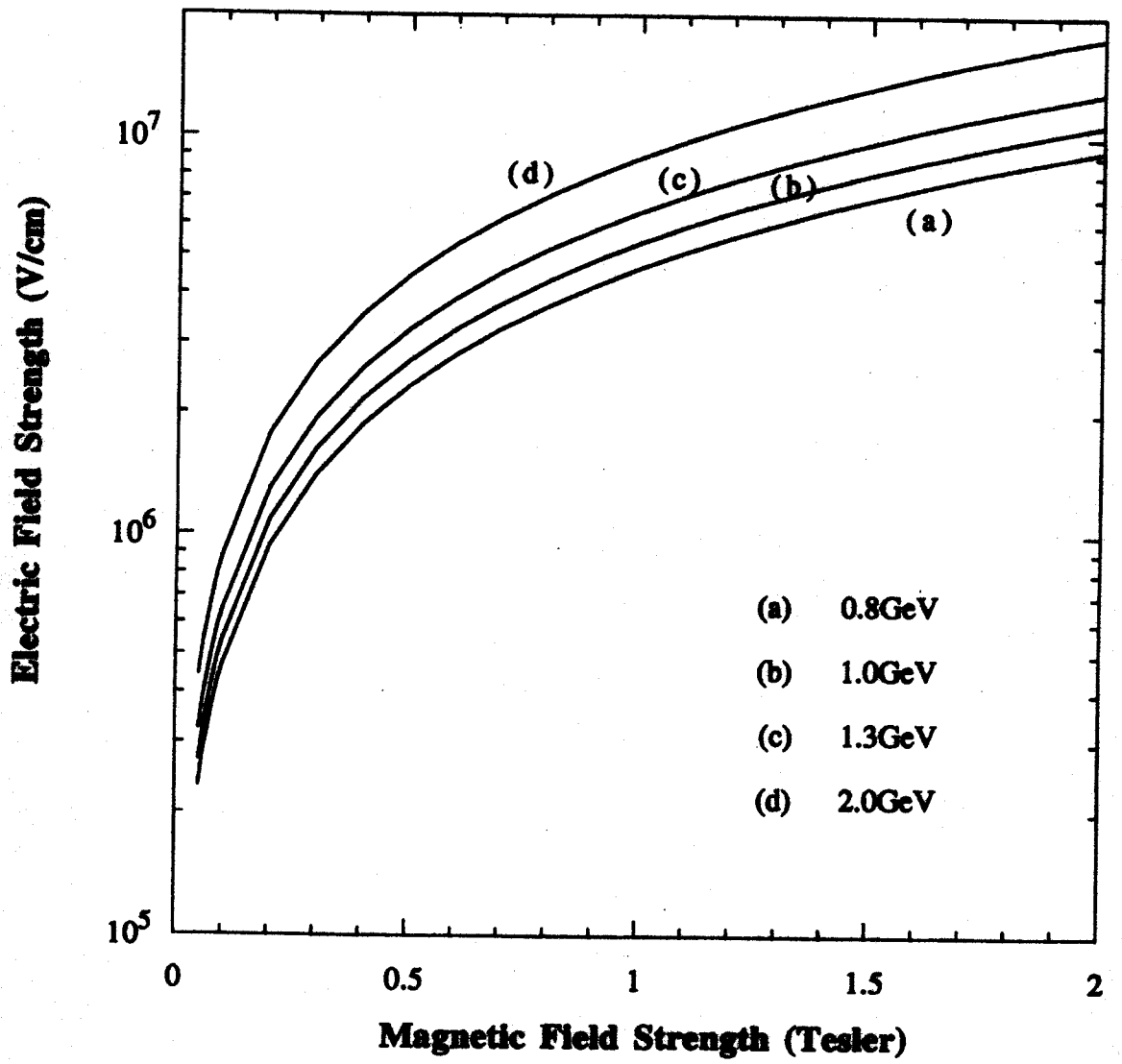
$$E = \beta\gamma c B$$

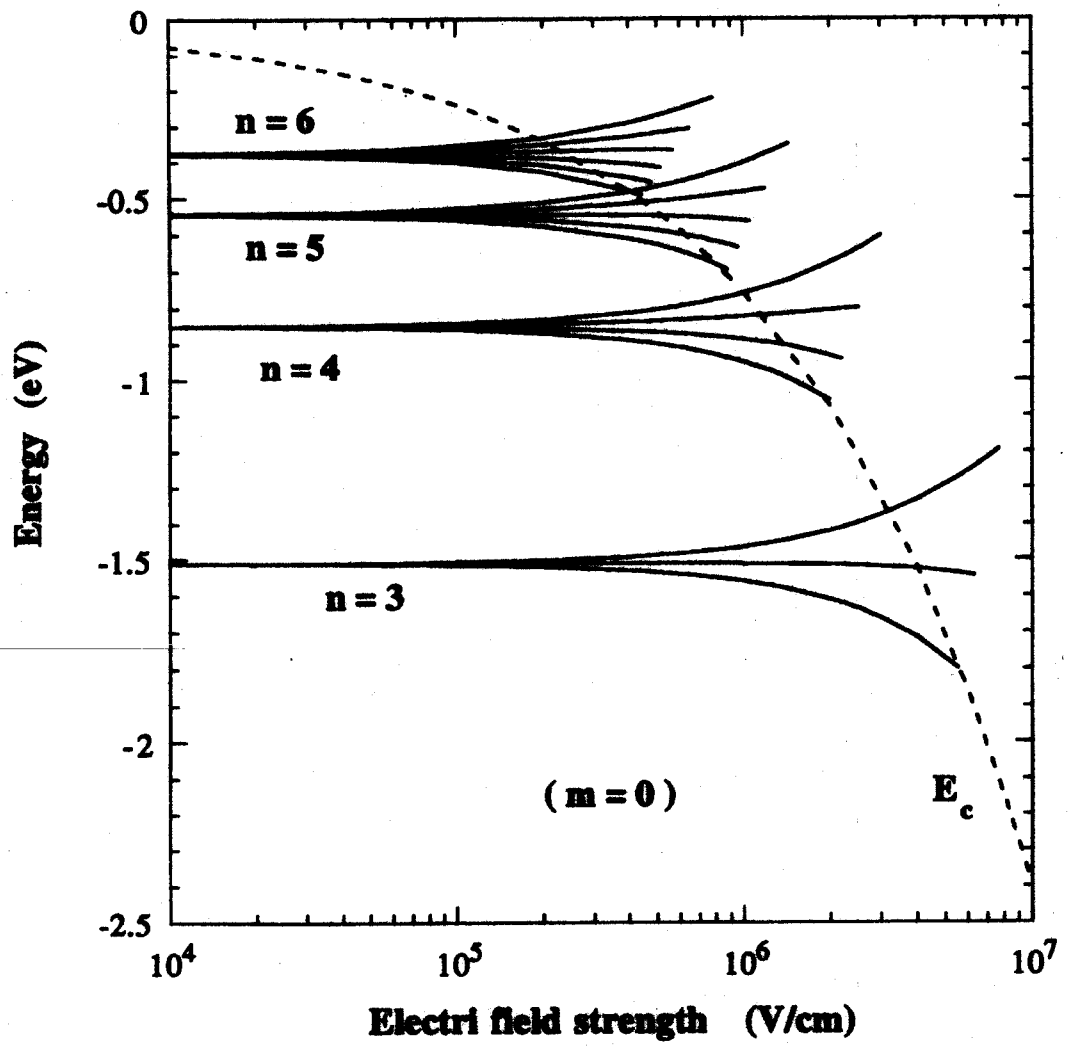
Level shift by Stark Effect;

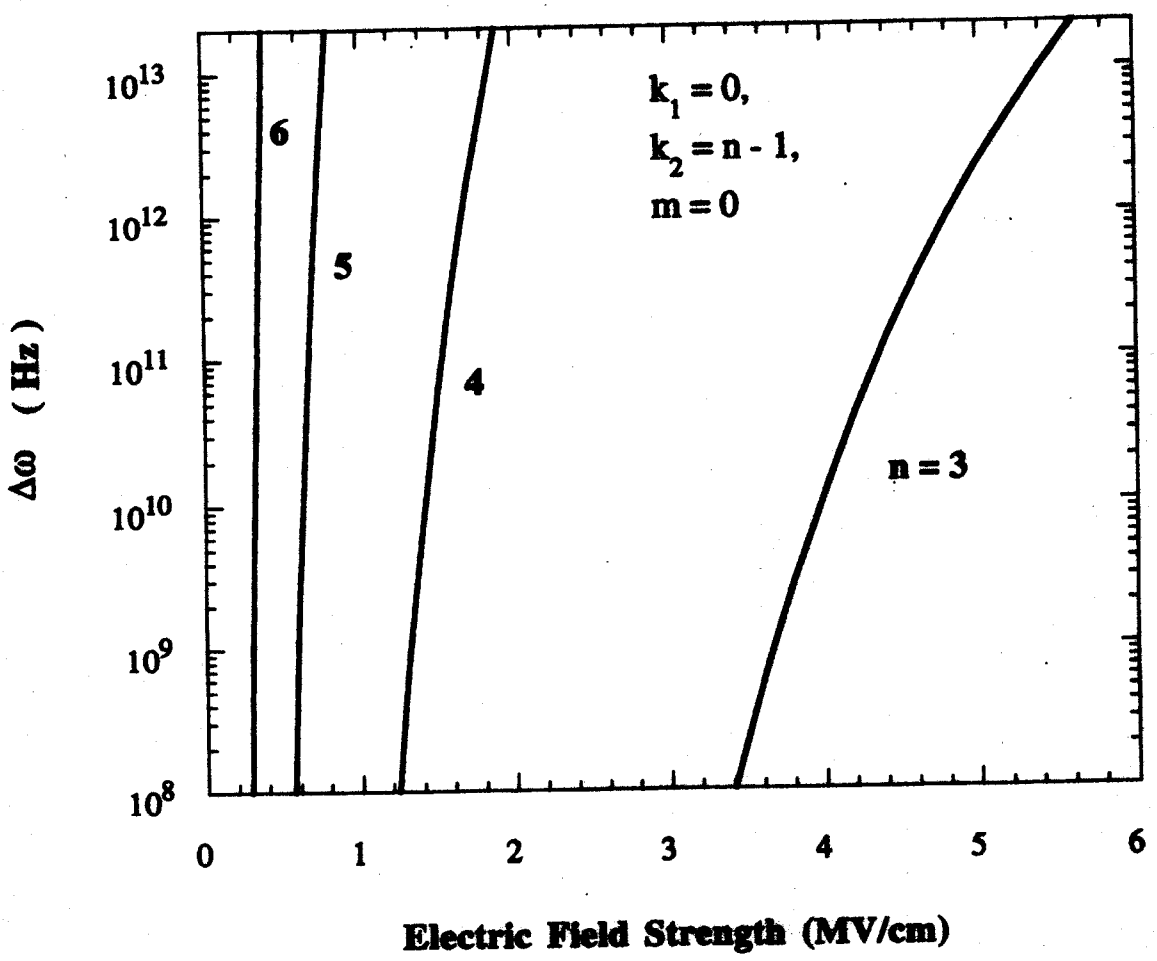
$$W = -\frac{1}{2n^2} + \frac{3}{2}n(k_1 - k_2)E - \frac{1}{16}n^4\left\{17n^2 - 3(k_1 - k_2)^2 - 9m^2 + 19\right\}E^2$$

Level width broadening by Stark Effect;

$$\Gamma = \frac{1}{n^2}\left(\frac{4}{n^3 E}\right)^{1+|m|+2k_2} \cdot \left\{k_2!(k_2 + |m|)!\right\}^{-1} \cdot \exp\left\{-\frac{2}{3n^3 E} + 3(n - 2k_2 - |m| - 1)\right\}$$


Electric Field Strength (V/cm)
10^7
10^6
10^5
(d)
(c)
(b)
(a)
(a) 0.8GeV
(b) 1.0GeV
(c) 1.3GeV
(d) 2.0GeV
0
0.5
1
1.5
2
Magnetic Field Strength (Tesler)


0
-0.5
-1
-1.5
-2
-2.5
Energy (eV)
n = 6
n = 5
n = 4
n = 3
(m = 0)
E c
10^4
10^5
10^6
10^7
Electri field strength (V/cm)


10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
$\Delta\omega$ (Hz)
6
5
4
$k_1 = 0,$
$k_2 = n - 1,$
$m = 0$
n = 3
0
1
2
3
4
5
6
Electric Field Strength (MV/cm)

7, Resonant Photoionization

Ionization Cross Section; $\sigma_i = \sigma_{kn}\eta_i, \quad \eta_i \cong 1$

Transition Cross Section; $\sigma_{kn} = \frac{g_n}{g_k}\frac{\lambda_{kn}^2}{2\pi}\frac{A_{nk}}{\Delta\omega_a^{kn}},$

Saturation Energy Density; $\Phi_S^{kn} = \frac{\hbar\omega_{kn}}{\sigma_{kn}},$

Necessary Energy Density of Laser during Interaction Period; $\Phi_{kn} = \frac{\Phi_S^{kn}}{\Delta\omega_a^{kn}\tau_{\text{int}}^{PRF}}$

Transition cross section

$$\sigma_{kn} = \frac{g_n}{g_k} \frac{\lambda_{kn}^2}{2\pi} \frac{A_{nk}}{\Delta\omega_a^{kn}}$$

$$\frac{g_n}{g_k} \frac{\lambda_{kn}^2}{2\pi} \cdots\cdots \textit{statistical factor}$$

$$A_{nk} \cdots\cdots \textit{Einstein coefficient (transition probability)}$$

$$\frac{1}{\Delta\omega_a^{kn}} \cdots\cdots \frac{1}{\textit{levelwidth}} = \textit{level lifetime}$$

Atomic Data and Nuclear Data Tables, Vol. 28, No. 2, March 1983

TABLE III. Transition Probabilities in sec^{-1} for $n'k' \rightarrow nk$ and $n' \rightarrow nk$ Transitions
$2 \leq n \leq 11$, $-(n'-1) \leq k' \leq n'-1$, $1 \leq n \leq 5$, $0 \leq k \leq n-1$

See page 226 for Explanation of Tables

	A. n = 1, k = 0													
n' \ k'	-n'+1	-5	-4	-3	-2	-1	0	1	2	3	4	5	n'-1	Mean
2							6.27+8	3.13+8						4.70+8
3							0.00	8.37+7	8.37+7					5.58+7
4							1.36+7	1.14+6	2.05+7	3.07+7				1.28+7
5							0.00	5.16+6	1.15+6	6.88+6	1.38+7			4.13+6
6							1.69+6	5.64+4	2.26+6	8.46+5	2.82+6	7.05+6		1.65+6
7							0.00	8.83+5	8.83+4	1.10+6	5.89+5	1.33+6	3.98+6	7.57+5
8							3.93+5	7.02+3	4.92+5	8.85+4	5.90+5	4.10+5	2.41+6	3.87+5
9							0.00	2.41+5	1.38+4	2.89+5	7.72+4	3.38+5	1.54+6	2.14+5
10							1.28+5	1.42+3	1.53+5	1.64+4	1.79+5	6.38+4	1.03+6	1.26+5
11							0.00	8.62+4	3.19+3	1.01+5	1.64+4	1.15+5	7.19+5	7.84+4
	B. n = 2, k = 0													
3							5.14+7	1.62+7	5.05+5					2.44+7
4							0.00	8.17+6	5.16+6	4.30+5				4.41+6
5							1.99+6	1.68+5	2.06+6	2.02+6	2.84+5			1.29+6
6							0.00	8.09+5	1.84+5	6.74+5	9.19+5	1.84+5		4.90+5
7							3.17+5	1.24+4	3.57+5	1.40+5	2.63+5	4.66+5	1.21+5	2.19+5
8							0.00	1.72+5	2.04+4	1.71+5	9.78+4	1.17+5	8.25+4	1.10+5
9							8.50+4	1.92+3	9.64+4	2.08+4	8.81+4	6.73+4	5.77+4	6.02+4
10							0.00	5.35+4	3.88+3	5.38+4	1.81+4	4.82+4	4.14+4	3.52+4
11							3.03+4	4.45+2	3.41+4	4.68+3	3.35+4	1.49+4	3.04+4	2.17+4
	C. n = 2, k = 1													
3					1.40+4	2.25+5	3.41+6	2.72+7	2.36+7					9.85+6
4				2.69+4	1.61+5	7.25+5	9.67+5	8.06+4	7.90+6	9.70+6				2.01+6
5			2.56+4	9.09+4	1.95+5	1.02+5	1.10+5	8.09+5	1.78+4	2.92+6	4.62+6			6.20+5
6		2.04+4	5.11+4	6.13+4	1.02+4	6.54+4	1.23+5	1.63+4	5.00+5	6.13+4	1.28+6	2.47+6		2.42+5
7	1.55+4	2.97+4	2.15+4	3.57+2	3.35+4	3.05+4	1.67+4	1.10+5	5.16+2	3.00+5	7.14+4	6.29+5	1.44+6	1.10+5
8	1.16+4	8.07+3	1.91+2	1.70+4	7.80+3	1.28+4	2.87+4	4.60+3	8.42+4	9.20+2	1.84+5	6.54+4	8.94+5	5.57+4
9	8.73+3	7.02+2	8.77+3	1.88+3	8.45+3	1.03+4	4.38+3	2.68+4	8.13+2	6.11+4	3.18+3	1.16+5	5.84+5	3.07+4
10	6.63+3	4.66+3	3.62+2	5.34+3	3.81+3	3.73+3	9.32+3	1.66+3	2.24+4	1.48+1	4.39+4	4.66+3	3.98+5	1.80+4
11	5.09+3	3.01+1	3.35+3	1.40+3	2.81+3	4.15+3	1.54+3	8.89+3	5.03+2	1.80+4	1.31+2	3.16+4	2.80+5	1.12+4

Since the present calculation is based on first-order perturbation theory, results are valid if the applied electric field is much smaller than the atomic field. On the other hand, from the point of view of observation, the Stark-level spacings must be much larger than the fine-structure splittings. For the case of a hydrogen-like atom, we must then have

$$\frac{Z^4\gamma^2}{n^3(j+1/2)}\,\mathrm{Ryd} \ll eaF \ll \frac{Z^2}{n^2}\,\mathrm{Ryd}, \qquad (1)$$

where F is the applied field, e is the absolute value of an electron charge, a and j are the atomic radius and angular-momentum quantum number, and γ is the fine-structure constant. Equation (1) can be written alternatively as

$Z=1.\ n=5$

4.1×10^6 V/cm

$$1.37\times10^5\,\frac{Z^6}{n^5(j+1/2)}\,\frac{\mathrm{V}}{\mathrm{cm}} \ll F \ll 2.57\times10^9\,\frac{Z^4}{n^4}\,\frac{\mathrm{V}}{\mathrm{cm}}. \qquad (2)$$

The first calculation on the intensity of Stark-level transitions in atomic hydrogen was done by Schroedinger[2] and Epstein,[3] and the results have been put to extensive experiment tests.[4] Bethe[5] and Bethe and Salpeter[6] have given the transition probabilities, lifetimes, and statistical and dynamical intensities involving the first three energy levels of atomic hydrogen.

Underhill[7] and Underhill and Waddell[8] have calculated the oscillator strengths for all possible transi-

number, the state of an atom in an electric field is completely specified. The energy levels in the linear Stark effect depend on n and k, and m is a degenerate quantum number. In this way k is the counterpart of the angular-momentum quantum number l in a field-free atom, except that the energy levels of atomic hydrogen are degenerate with respect to l, while in an electric field the energy levels depend on k.

In this paper this point of view is adopted, and transition probabilities, lifetimes, and branching ratios are expressed in terms of the quantum numbers n and k.

In the following section, necessary formulas for the transition probabilities and branching ratios are given, and the relationships between these quantities and statistical and dynamical intensities are defined. Symmetries and selection rules are discussed, and an analytical formula for the number of the spectral lines for transitions between arbitrary n' and n is given. Tables for the transition probabilities, lifetimes, and branching ratios are given at the end of the paper.

Some of the formulations necessary for this paper have been given previously by the author[12] in a paper on transition probabilities in field-free hydrogen-like atoms. We designate this paper by I for reference.

FORMULATION

Electric-Dipole Matrices and Branching Ratios

Due to the spherical symmetry of the atomic Hamiltonian in the absence of an electric field, the

TABLE I. Transition Probabilities in Atomic Hydrogen (in sec^{-1}) for Transitions $n'l' \rightarrow n$ and $n' \rightarrow n$

See page 7 for Explanation of Tables

n'ℓ' \ n	1	2	3	4	5	Total	Lifetime (sec)
20	0.0					0	∞
21	6.27+8*					6.27+8	1.60-9
Mean	4.70+8					4.70+8	2.13-9
30	0.0	6.32+6				6.32+6	1.58-7
31	1.67+8	2.25+7				1.90+8	5.27-9
32	0.0	6.47+7				6.47+7	1.55-8
Mean	5.57+7	4.41+7				1.00+8	1.00-8
40	0.0	2.58+6	1.84+6			4.42+7	2.26-7
41	6.82+7	9.67+6	3.41+6			8.13+7	1.23-8
42	0.0	2.06+7	7.04+6			2.77+7	3.61-8
43	0.0	0.0	1.38+7			1.38+7	7.25-8
Mean	1.28+7	8.42+6	8.99+6			3.02+7	3.31-8
50	0.0	1.29+6	9.05+5	6.45+5		2.84+6	3.52-7
51	3.44+7	4.95+6	1.79+6	9.26+5		4.21+7	2.38-8
52	0.0	9.43+6	3.39+6	1.54+6		1.44+7	6.96-8
53	0.0	0.0	4.54+6	2.59+6		7.13+6	1.40-7
54	0.0	0.0	0.0	4.26+6		4.26+6	2.35-7
Mean	4.13+6	2.53+6	2.20+6	2.70+6		1.16+7	8.65-8
60	0.0	7.35+5	5.07+5	3.58+5	2.68+5	1.87+6	5.35-7
61	1.97+7	2.86+6	1.03+6	5.40+5	3.39+5	2.45+7	4.08-8
62	0.0	5.15+6	1.88+6	8.84+5	4.89+5	8.40+6	1.19-7
63	0.0	0.0	2.15+6	1.29+6	7.35+5	4.17+6	2.40-7
64	0.0	0.0	0.0	1.37+6	1.11+6	2.48+6	4.03-7
65	0.0	0.0	0.0	0.0	1.65+6	1.65+6	6.08-7
Mean	1.65+6	9.74+5	7.79+5	7.72+5	1.03+6	5.21+6	1.93-7

8, Necessary Laser Power Density in Lab Frame

Necessary Energy Density of Laser during Interaction Period;

$$\Phi_{kn}^{L} = \frac{\Phi_{kn}}{\gamma(1+\beta\cos\alpha)}$$

Laser Power Density;

$$I_L = \frac{\Phi_{kn}^{L}}{\tau_{\text{int}}}$$

Table 1. Photo-ionization via Broad Stark State; (n=5, k_1=0,k_2=4,m=0)

Interaction Length = 30cm

T (GeV)	0.800	1.000	1.300	2.000	H^0 kinetic energy
β	0.842	0.875	0.903	0.948	
γ	1.853	2.066	2.386	3.132	
[Bρ] (Tm)	4.881	5.657	6.778	9.288	Magnetic Rigidity
$\gamma(1+\beta)$	3.412	3.873	4.551	6.099	α=0
(Part. Rest Frame)					
$\Delta\omega_D$ (10^{13} s^{-1})	1.65	1.71	1.81	1.86	Doppler Broadening for $\Delta p/p$ = 0.001
τ_{int}^{PRF}($10^{-9}s^{-1}$)	0.642	0.554	0.462	0.337	τ_{int}^{LF}/γ
$\Phi_{100,5\text{-}40}$ (10^{-6} joule/cm^2)	1.59	1.84	2.20	3.02	$\Phi_s^{100,5\text{-}40}$=0.173(Joul/cm^2) $\Delta\omega_a$=1.7×10^{13} s^{-1}
(Lab. Frame)					
$\lambda_{1,5}^{LF}$ (nm)	327.9	372.2	437.4	586.2	$\lambda_{1,5}^{PRF}$ = 96.1 nm
$\Phi_{100,5\text{-}40}$(LF) (10^{-7} joule/cm^2)	4.65	4.75	4.84	4.95	$\Phi_{100,5\text{-}40}/\gamma(1+\beta)$
τ_{int}^{LF} (10^{-9}s)	1.19	1.14	1.10	1.06	l = 30c m
I^{Laser}(L.F.) (kW/cm^2)	3.91	4.15	4.39	4.69	$\Phi_{100,5\text{-}40}$(LF)/ τ_{int}^{LF}
B^{Stark} (T)	0.171	0.148	0.123	0.090	E = 0.8 × 10^6 V/cm

High Finesse FP Cavity

Wave Length	**532 ~ 355nm**
Length	**~ 6m**
Diameter of Stored Beam	**~10mm**
Power density of Stored Beam	**~10kW/cm^2**
Finesse	**factor×10^4**
Environment	**Vacuum**

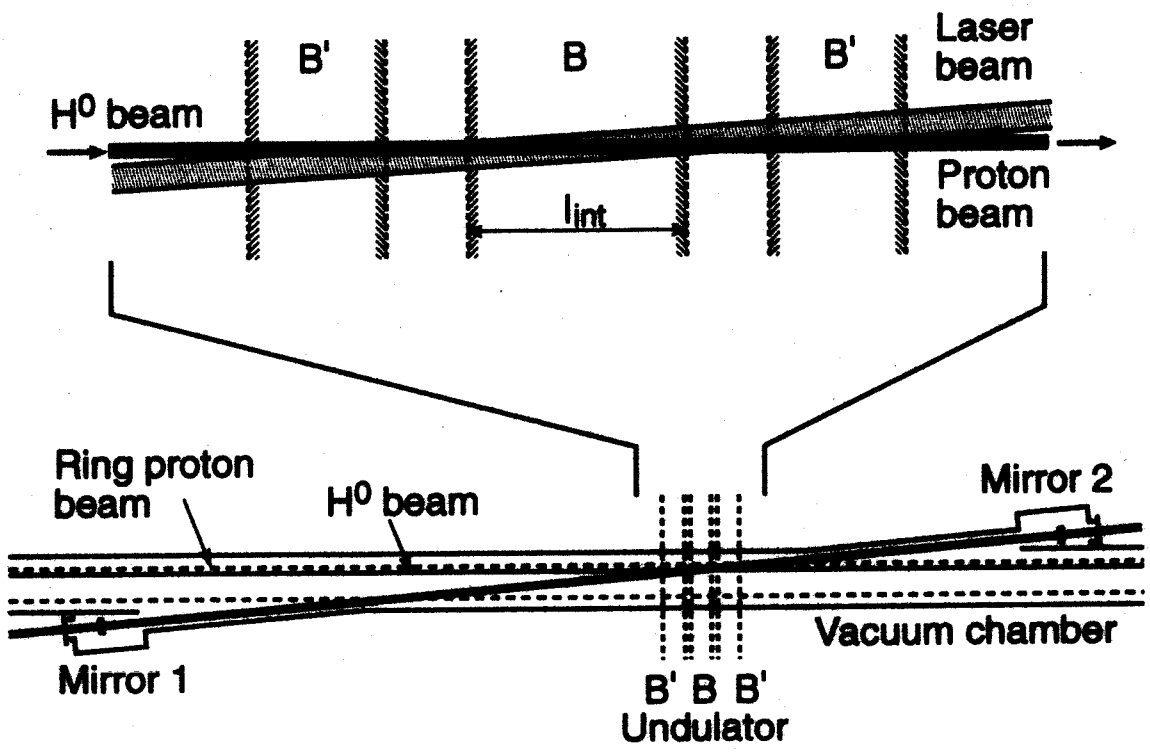
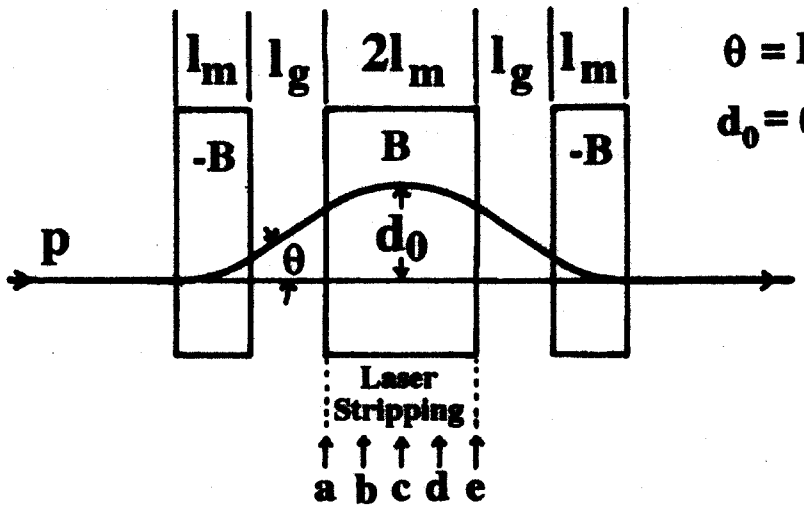

B'
B
B'
Laser beam
H0 beam
Proton beam
lint
Ring proton beam
H0 beam
Mirror 2
Vacuum chamber
Mirror 1
B' B B'
Undulator

Fig. 5

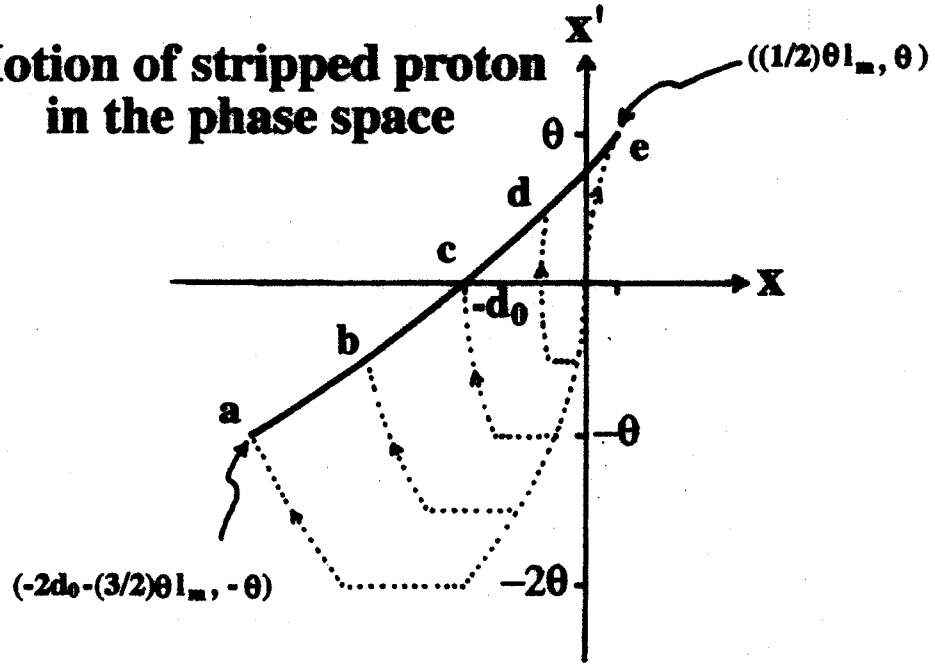
Emittance Growth due to Laser Stripping in Undulator



$\theta = Bl_m/(B\rho)$

$d_0 = \theta(l_m + l_g)$

Motion of stripped proton in the phase space



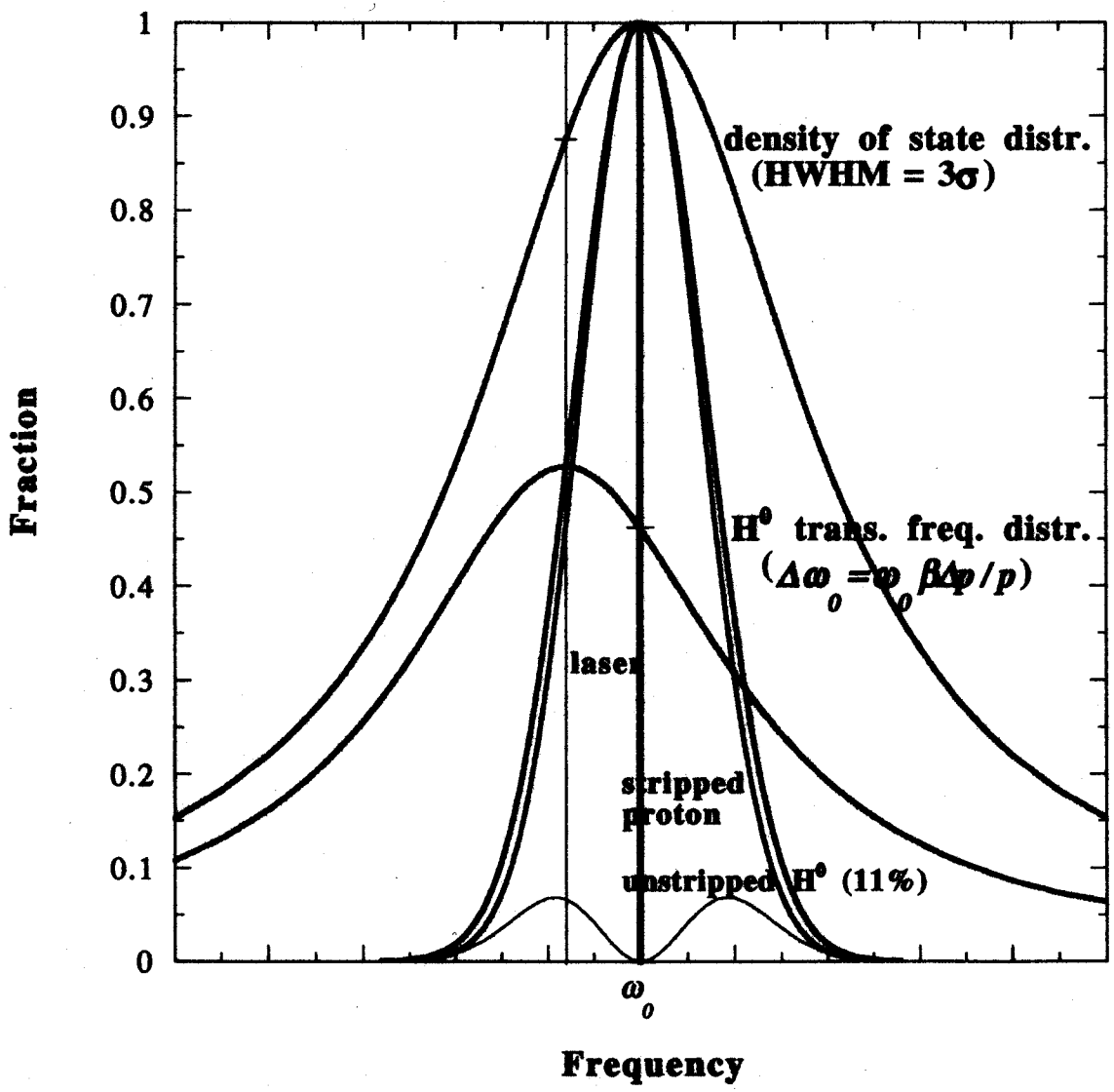
Example; 2GeV H^0 by 532 nm laser

$(B\rho) = 9.3\text{Tm}$, $B = 0.09\text{T}$, $l_m = 0.15\text{m}$, $l_g = 0.1\text{m}$

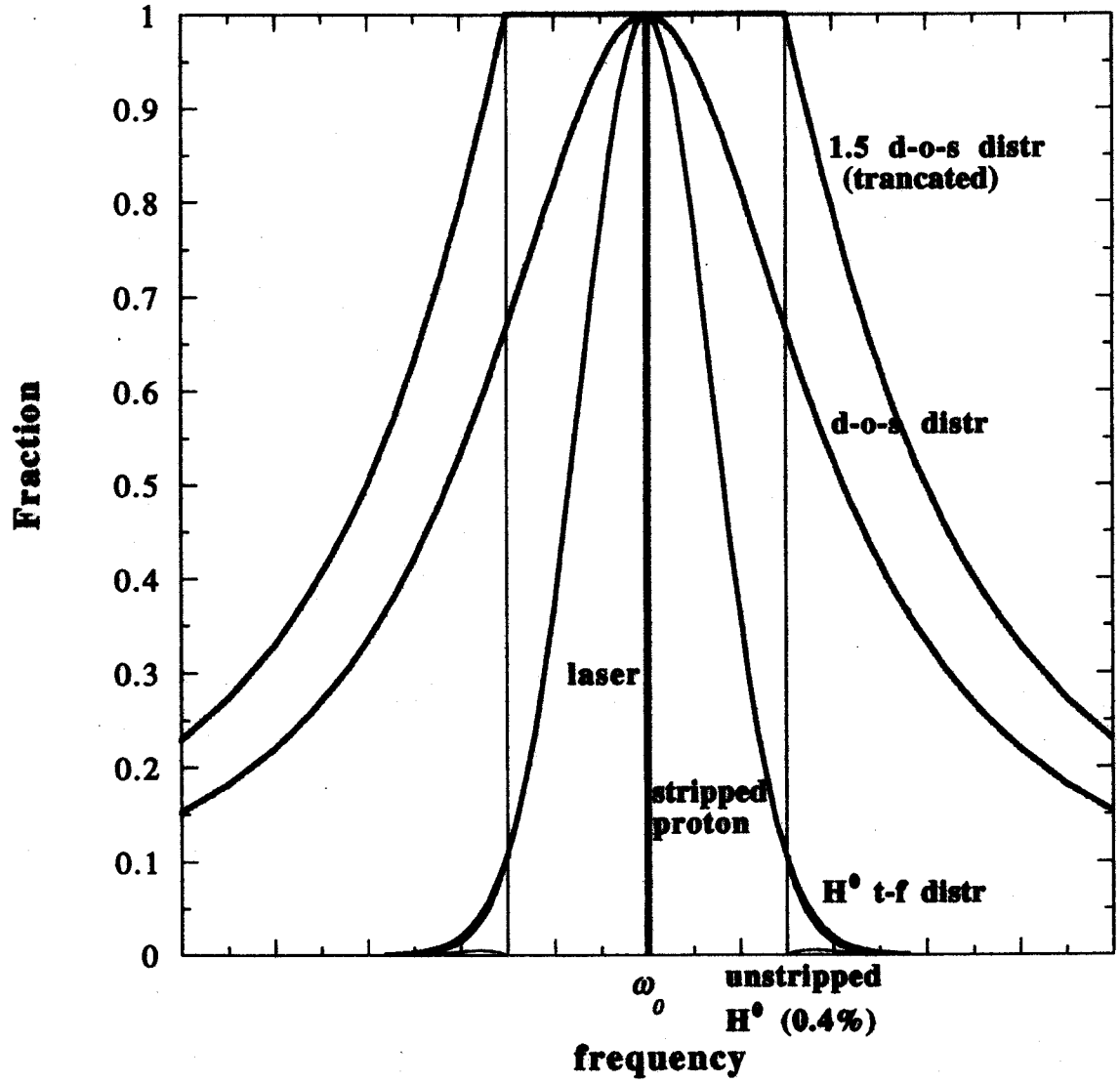
$\theta = 1.45$ mrad

$2d_0 + (3/2)\theta l_m = 1.05$ mm

Effect of Level Broadening



(1.5 higher laser power)



Summary

1. It is possible to charge-exchange H^- beams to proton beams using combination of Lorentz stripping and pumping-up of H^0 atoms to an excited state with n no less than 3 by intense laser beam.

2. The most serious problem is that the transition frequency spreads as broad as 10^{13} Hz according to the momentum spread of H^0 beam.

3. Of three schemes proposed at ICFA-HB2002 to overcome this problem, the scheme using static excitation of a broad Stark state has a merit of long interaction time. Interaction time of the scheme is hundreds times longer than other two schemes.

4. For 1 GeV H^0 beam, and using a broad Stark state with quantum number set (5, 0, 4, 0), laser wavelength, magnetic field and laser power density necessary for the laser stripping are 372 nm, 0.15 T and 4.2 kW/cm^2, respectively.

5. By means of combining an undulator and a high finesse Fabry-Perot resonator, laser stripping via a broad Stark state is considered to be applicable to an accelerator.

6. High finesse Fabry-Perot resonator for a laser wavelength of 372 nm needs development to realize, but is considered enough realizable by extending existing technique for 1,064 nm laser.

7. We must take sufficient care of emittance growth accompanying with stripping in magnetic field and reduction of stripping efficiency due to level broadening.