UCLA

The Photo-ionized Vapor Plasma Source for Plasma Wakefield Accelerator Experiments

1) Plasma Wakefield Accelerator plasma source requirements
2) Heat pipe oven construction and operation
3) Oven temperature profiles.
4) Diagnostics
5) Plasma Formation by UV laser absorption
6) Formation of Tunnel Ionized Plasmas
7) Control System for Lithium Oven
8) Future developments.

Presented by Chan Joshi UCLA
CERN Dec 18 2009

In collaboration with K. Marsh, P. Muggli, S. Wang, and others on E157

1 Plasma Source Design Requirements, for Plasma Wakefield Accelerators

General:

1) Plasma density from 10^{12} to 10^{16} cm^{-3}.

2) Lengths from 1 to 5 meters.

3) 10% or higher ionization fraction.

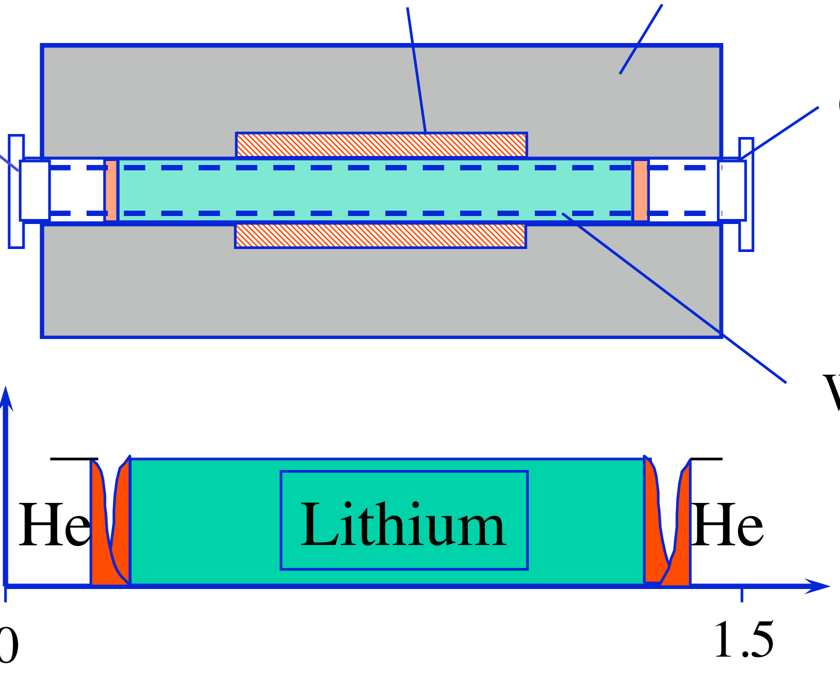
4) Longitudinal homogeneity < 20 %.

5) Radial uniformity.

6) Low Z vapor. Lithium Z = 3. Ionization potential, 5.4 eV. (Could also use Rb or Cs)

Considered Gas discharges, RF discharges, Helicon plasmas, Multiphoton Ionization and Photoionized alkali metal vapor

2 Heat Pipe Oven Source



Helium buffer
gas, both ends

Heater

Insulation

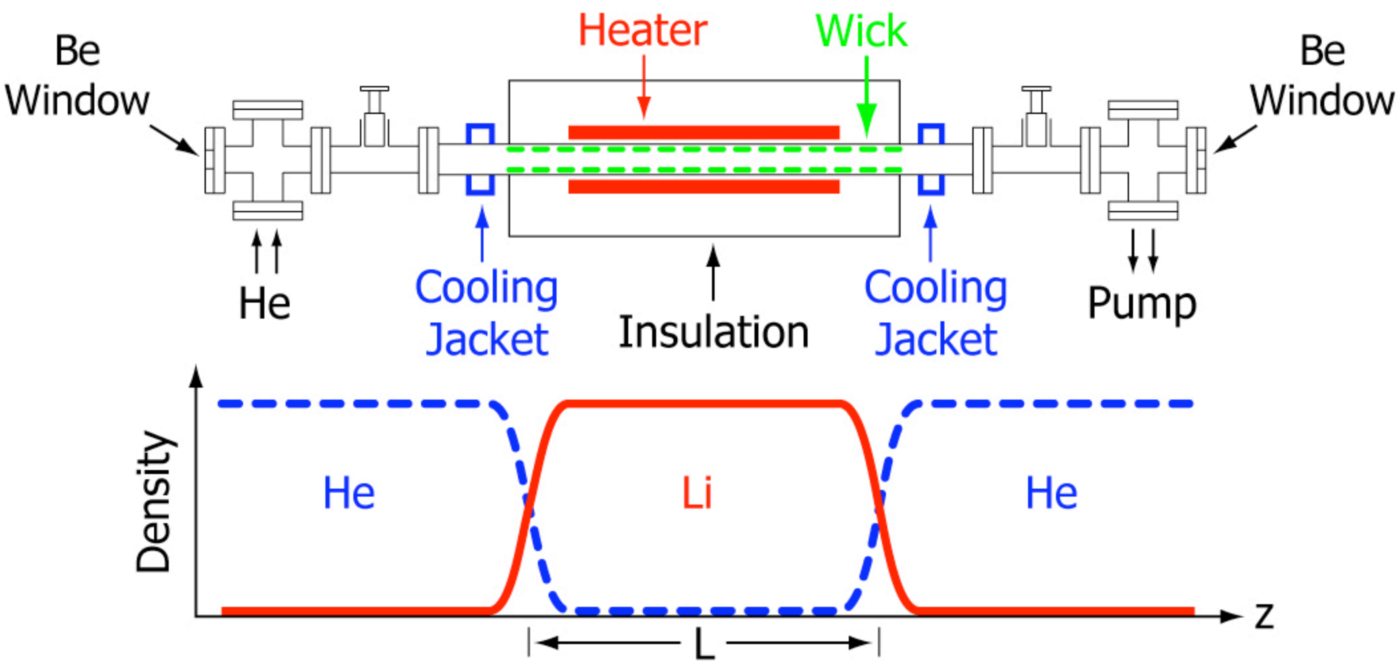
Cooling Water

Wick

Li vapor
pressure

The operating principle of a heat pipe oven vapor source

Lithium Oven Diagram

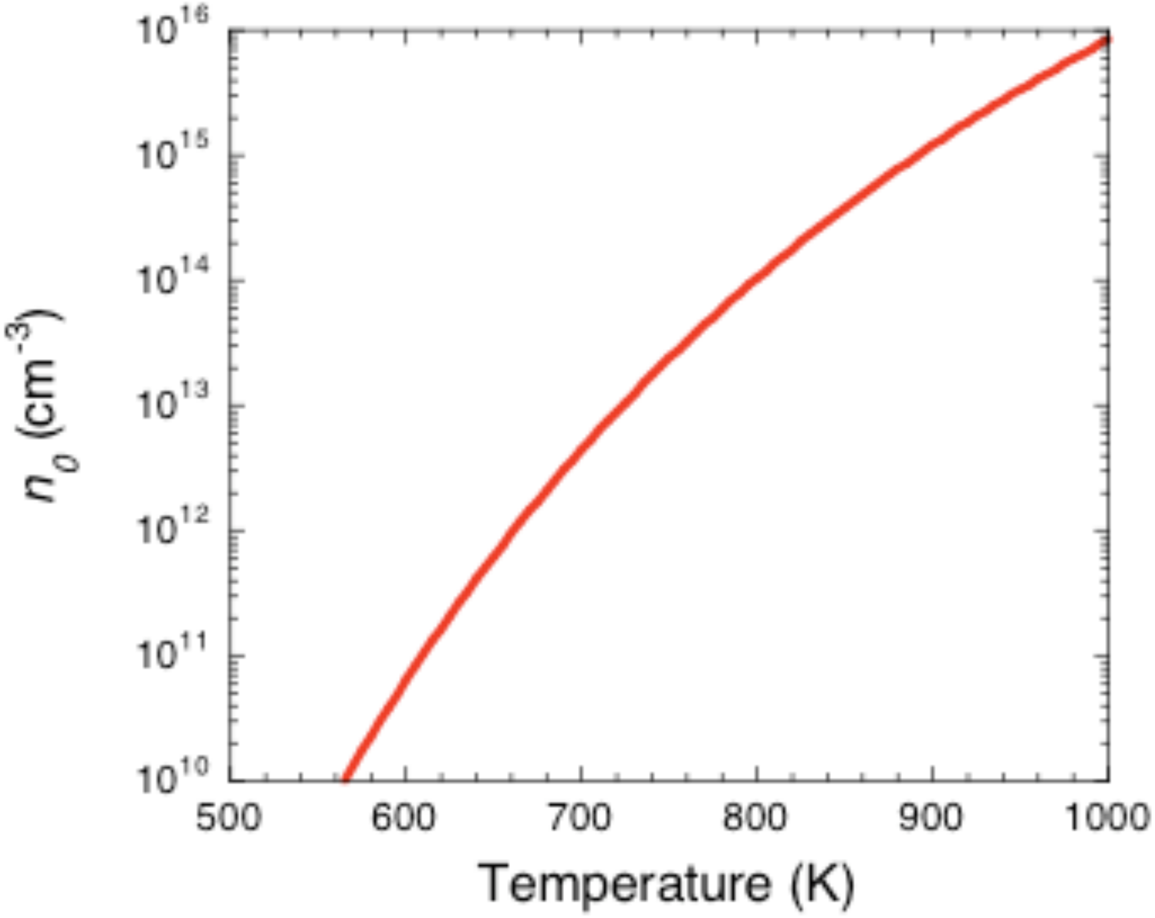


How it works:

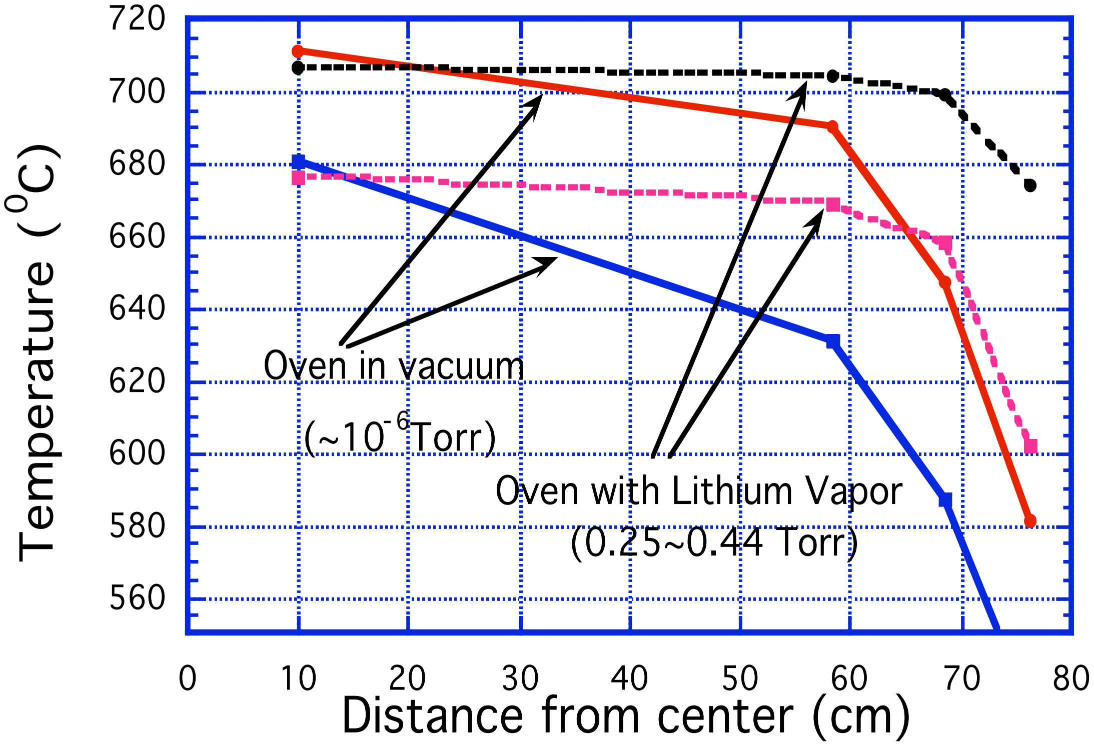
1) Heated to 800^{o}C to vaporize solid Li.
2) Li vapor diffuses out to the He transition region and condenses on wick.
3) The molten Li wicks back to center, vaporizes and begins the process again.

- Be (low-Z) windows separate the He from the FFTB beam line vacuum.
- The He pressure determines the Li vapor density, and the heater power determines the Li vapor length

Temperature Dependence of Vapor Pressure of Lithium



3 Oven temperature profiles with and without lithium.



There are 4 thermocouples located inside along the oven to monitor the lithium temperature. From the vapor pressure tables we can obtain the lithium vapor density.

4 Lithium vapor density diagnostics:

UV Energy Absorption : Nonresonant

$$E_{\text{transmitted}} = E_{\text{incident}}\, e^{-\sigma n_0 L}$$

Ionization cross section $\sigma = 1.8\times10^{-18}$ cm^2

$$\Rightarrow \quad n_0 L = -\frac{1}{\sigma}\ln\left(\frac{E_{transmitted}}{E_{incident}}\right)$$

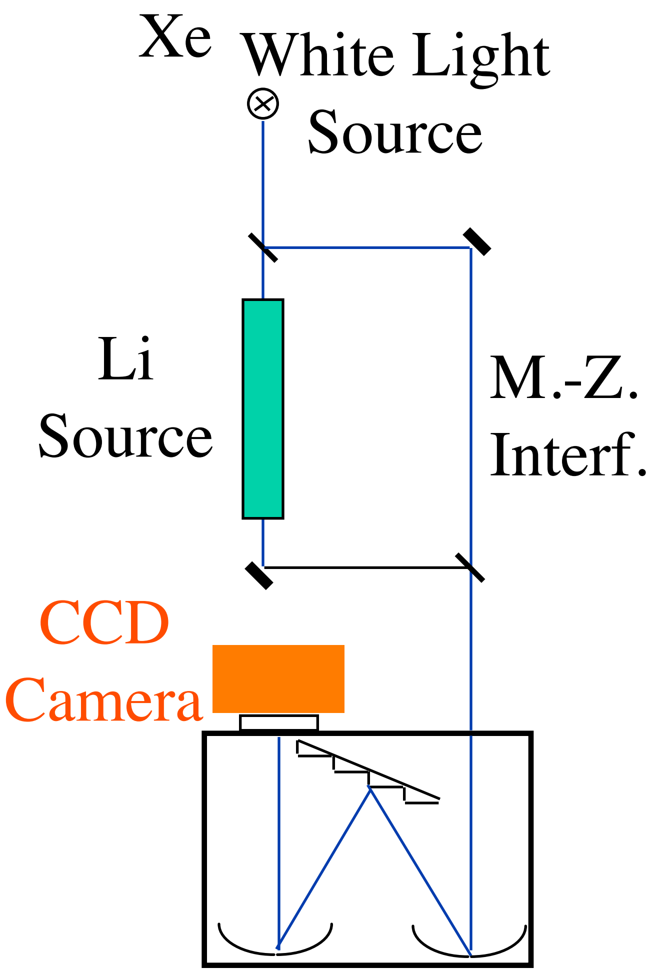
Hook Method : Resonant (Marlow, Appl. Opt. 6, 1715, 1967)

Li has an absorption line from the ground state $\lambda_0 = 670.785$ nm
Use white light to measure the real and imaginary part of the
Index of refraction in the vicinity of the resonant transition.

$$\mathrm{Re}\quad n(\lambda) \cong 1 + \frac{n_0 f r_0 \lambda_0^3}{4\pi(\lambda - \lambda_0)}$$

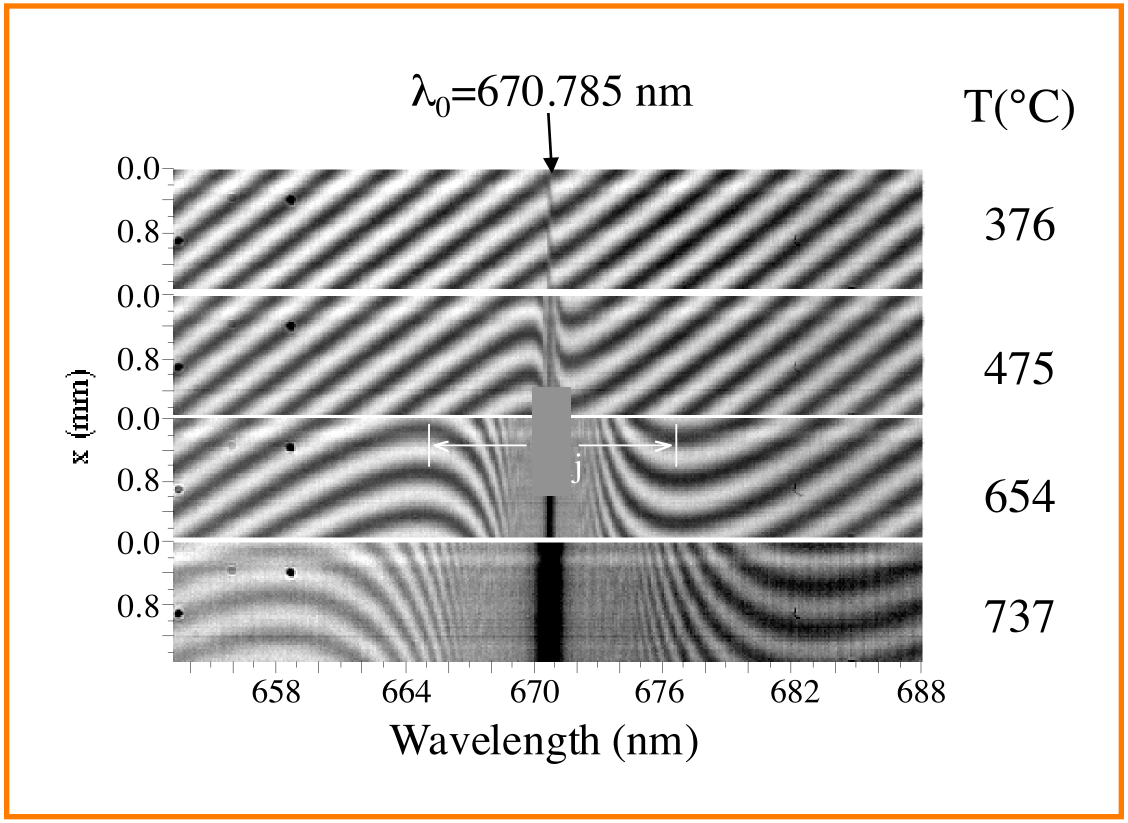
$n(\lambda)$, refractive index,
r_o, classical electron radius,
f, oscillator strength,
n_0, vapor density

Experimental Set Up of Hook Measurement of Vapor Density



¼ m Imaging Spectrograph

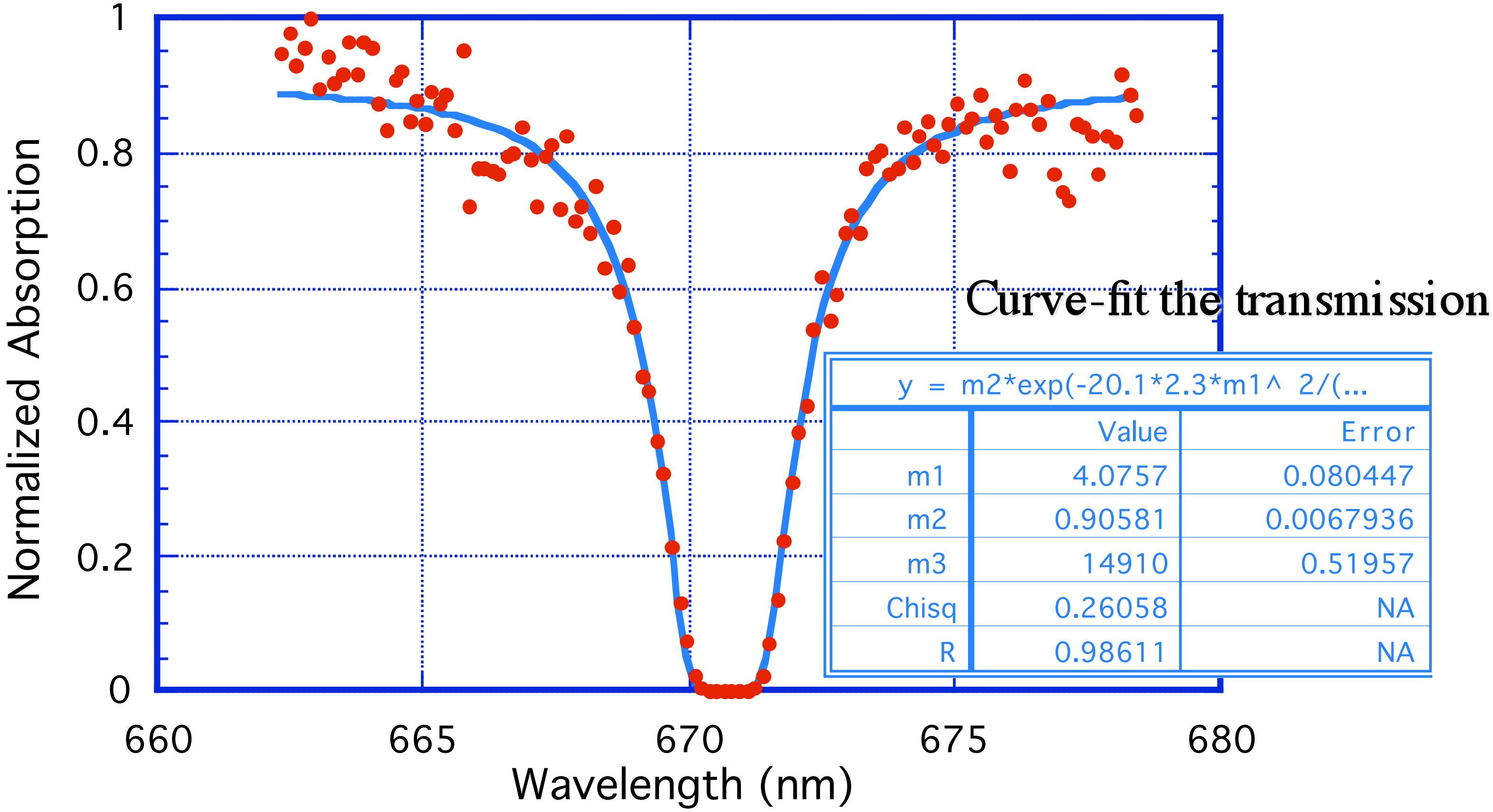
1200 Grooves/mm



$$n_0 L = \frac{\pi k}{r_0 \lambda_0^3 f}\Delta^2$$

Δ, hook separation,
k, the fringe number.

White light absorption measurement



Curve-fit the transmission

y = m2*exp(-20.1*2.3*m1^ 2/(...

	Value	Error
m1	4.0757	0.080447
m2	0.90581	0.0067936
m3	14910	0.51957
Chisq	0.26058	NA
R	0.98611	NA

There are three to-be-fit parameters. m1 is neutral density in the unit of (*10^{15}cm^{-3}). m2 is the normalized factor, m3 is the absorption center in unit of (cm^{-1}).

White Light Absorption Measurement

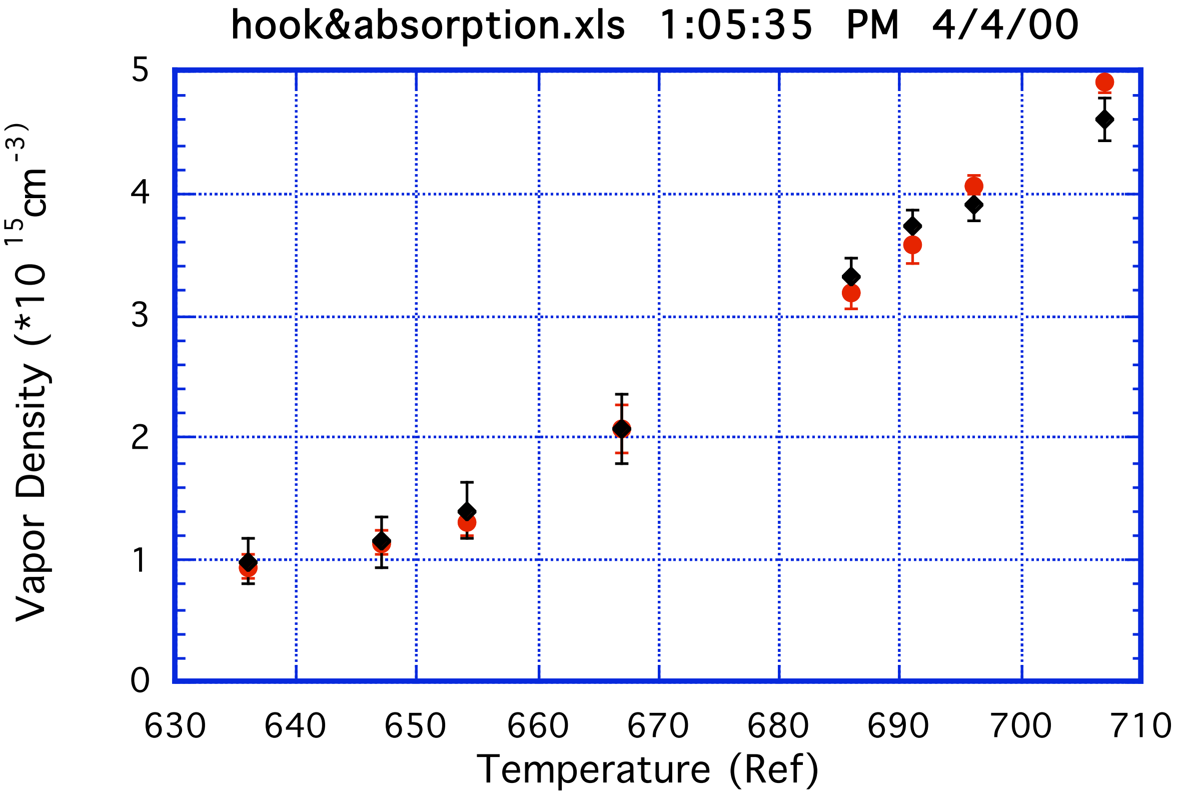
$$I = I_0 \cdot e^{-\alpha \cdot L}$$

$$\alpha = \frac{0.5 n_{vapor} \cdot r_0 \cdot f \cdot \Delta\nu}{(\nu - \nu_0)^2 + (\frac{\Delta\nu}{2})^2}$$

$$\Delta\nu = K \cdot r_0 \cdot f \cdot n_{vapor} / \nu_0$$

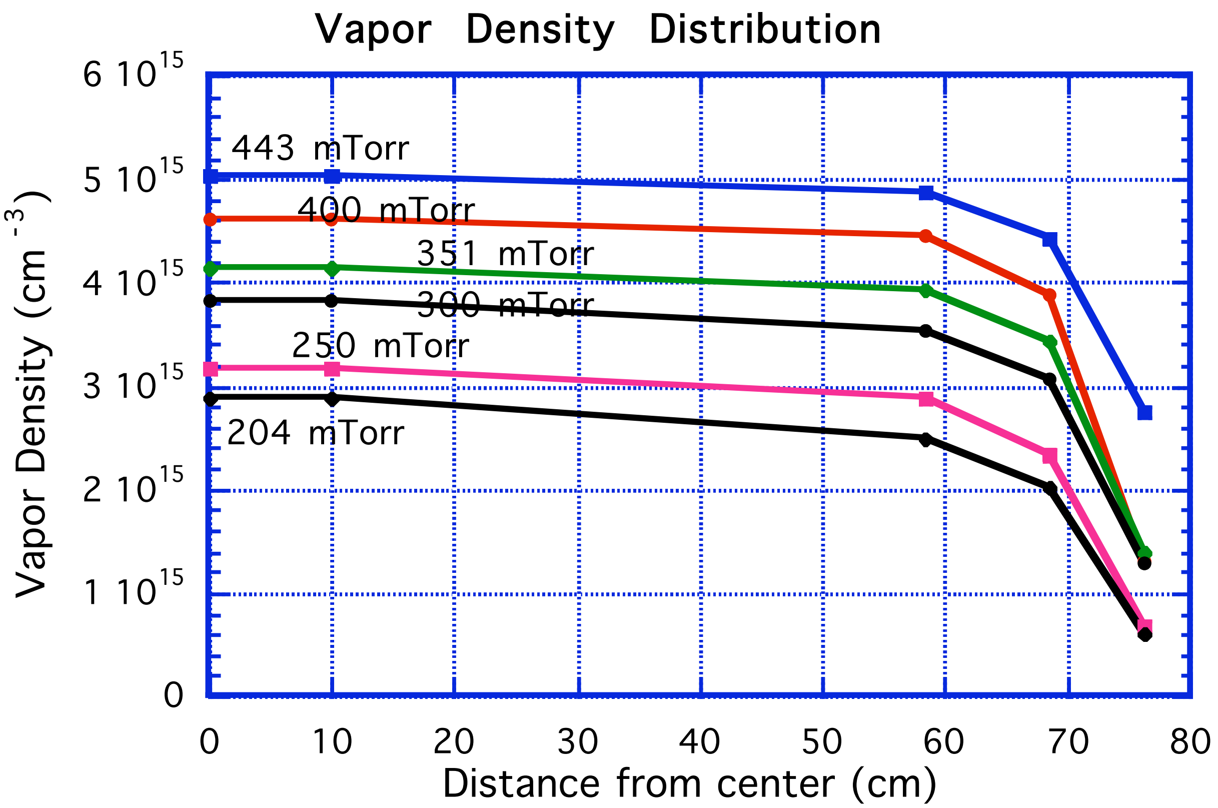
$$K = 1.33$$

Comparison of vapor density measurement from hook method and white light absorption measurement.



Good agreement with the hook method allowed us to use white light absorption to monitor the oven neutral density during the run.

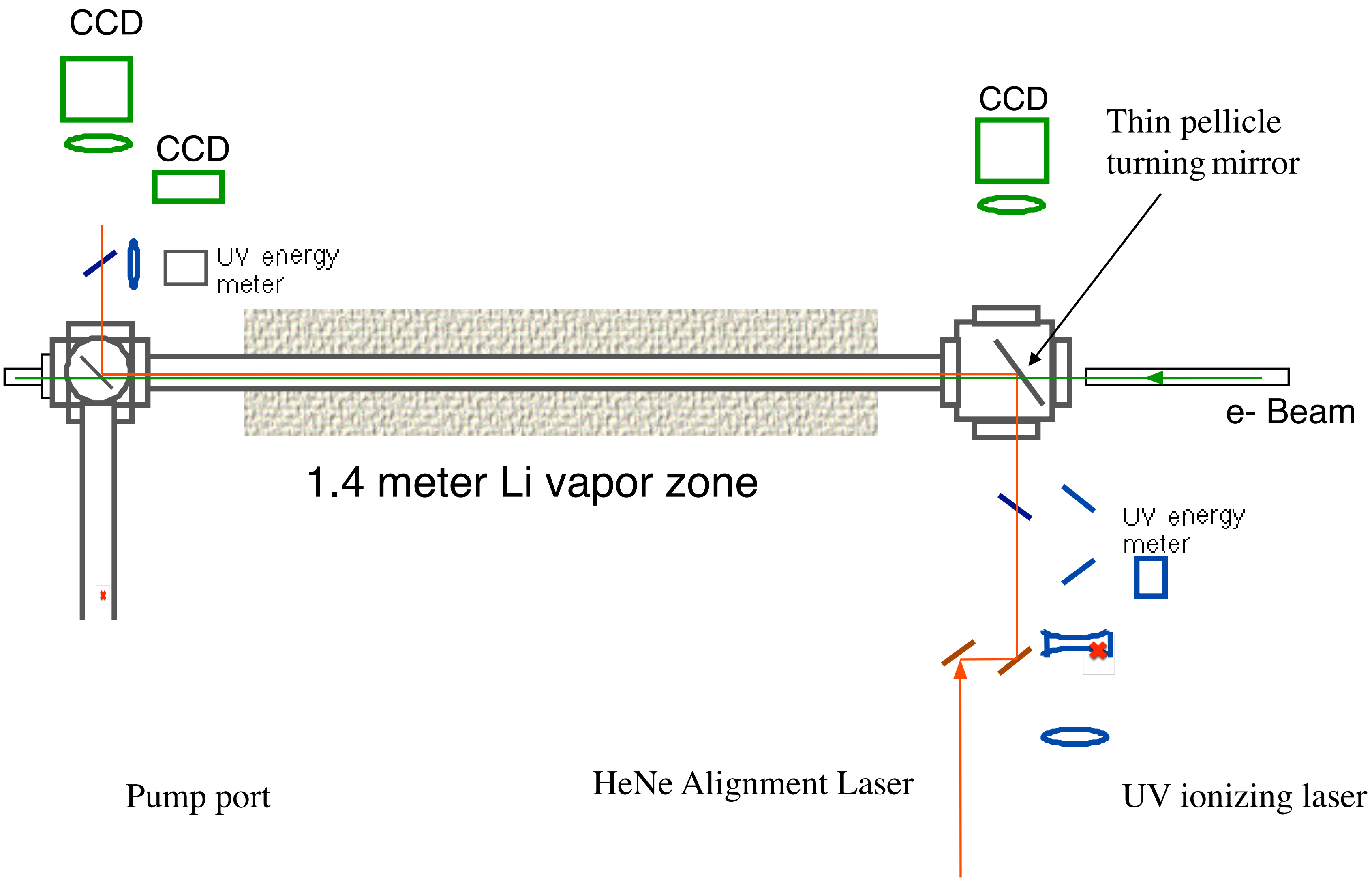
Vapor density distribution along the oven for different buffer gas pressures.



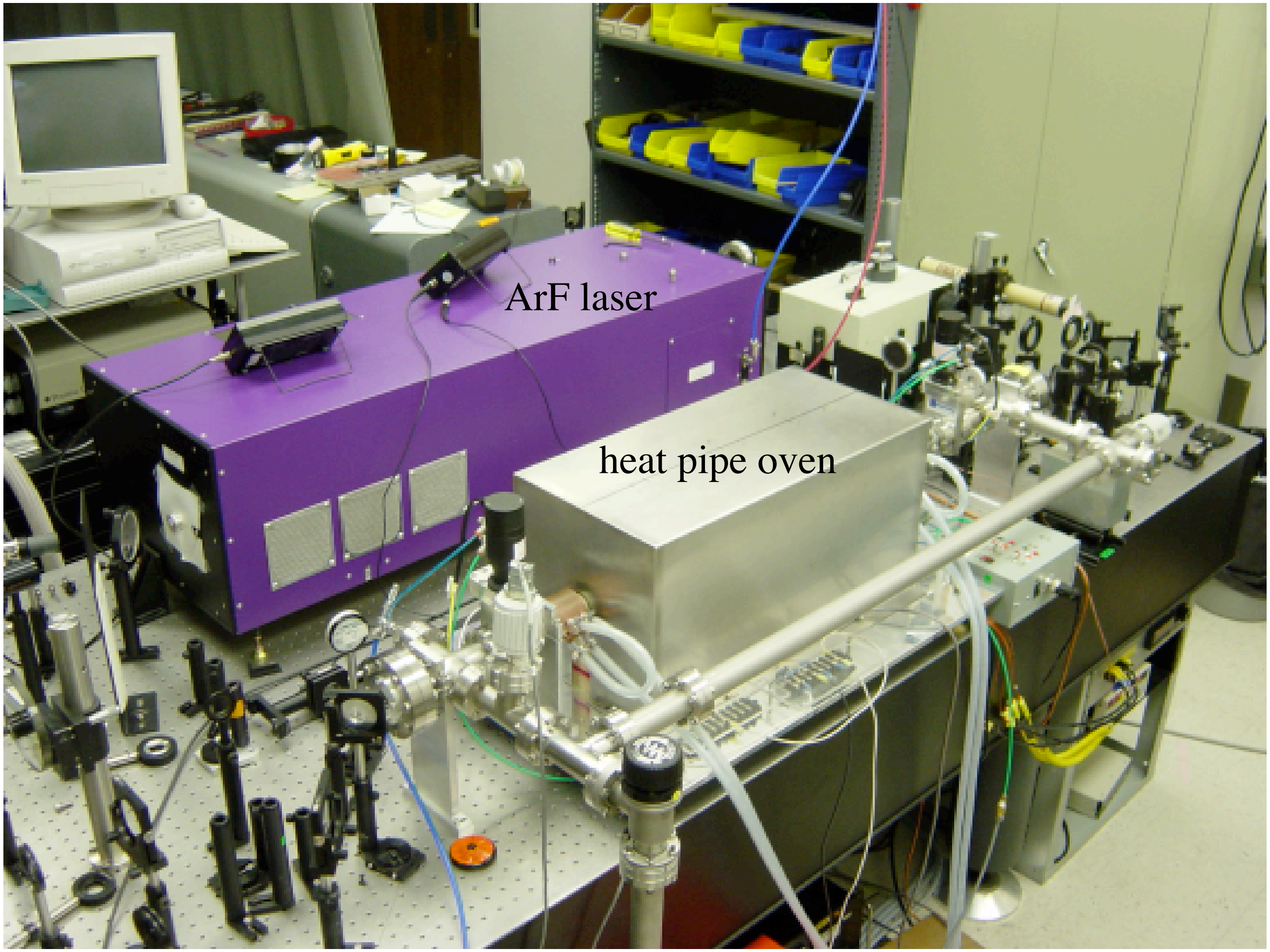
The range of densities was chosen for application to E-157.

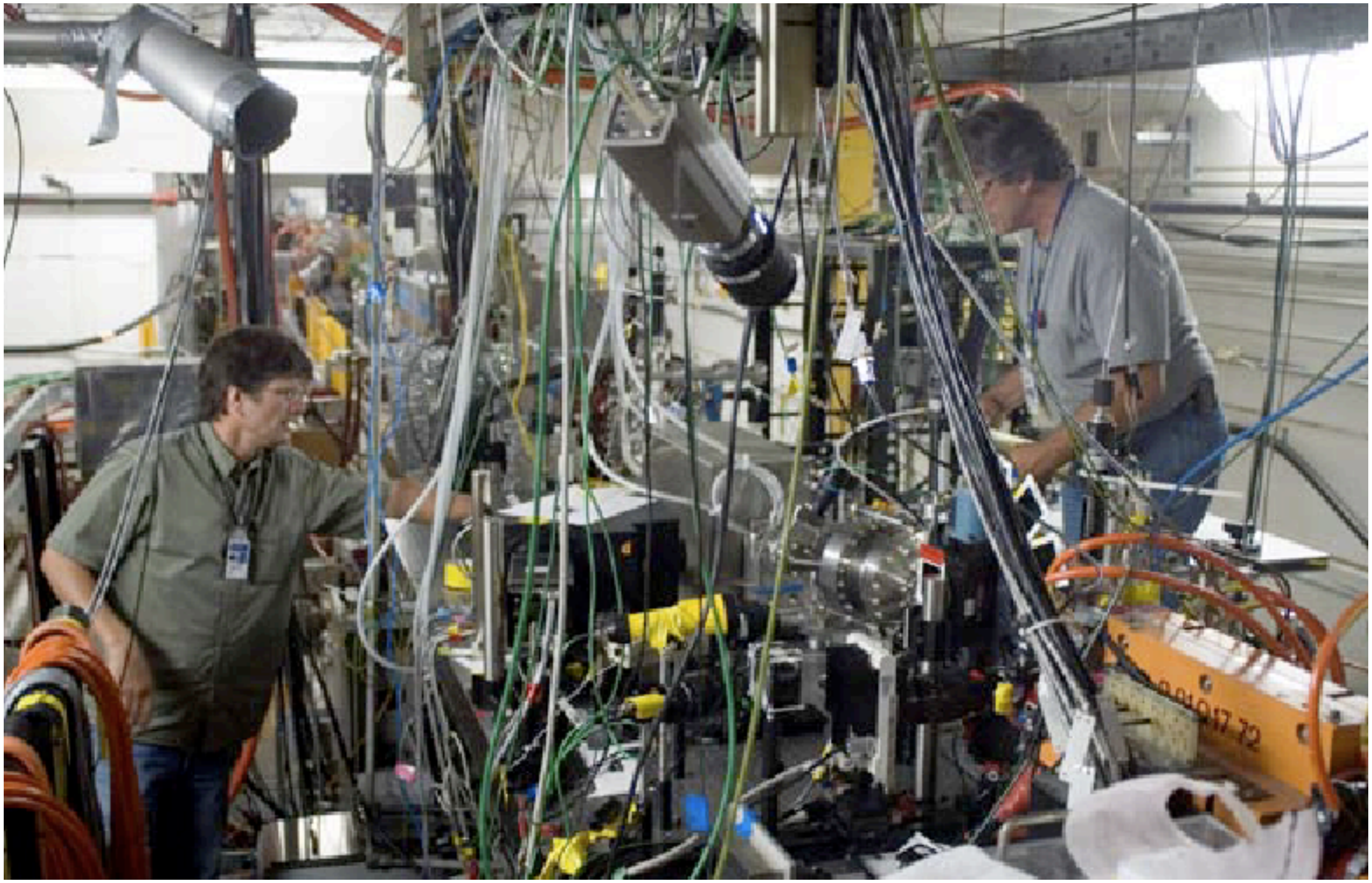
5 Plasma Formation by Single Photon Ionization

The lithium is ionized by an ArF excimer laser with approximately 100mj/cm^2



UV Ionized Lithium Plasma Source and Diagnostics





Life of an experimentalist

From: Chan Joshi, UCLA Personal archives

UV Laser Ionization and Plasma Density Measurements

The UV laser energy per cm^2 is absorbed by the lithium vapor according to,

$$F(z)=F_0 S(z) \mathrm{Exp}[-n_0 \sigma z] \quad (\text{joules/cm}^2)$$

where S(z) is the laser profile in vacuum and σ is the photoionization cross section.

The electron density profile for single photon ionization is given by,

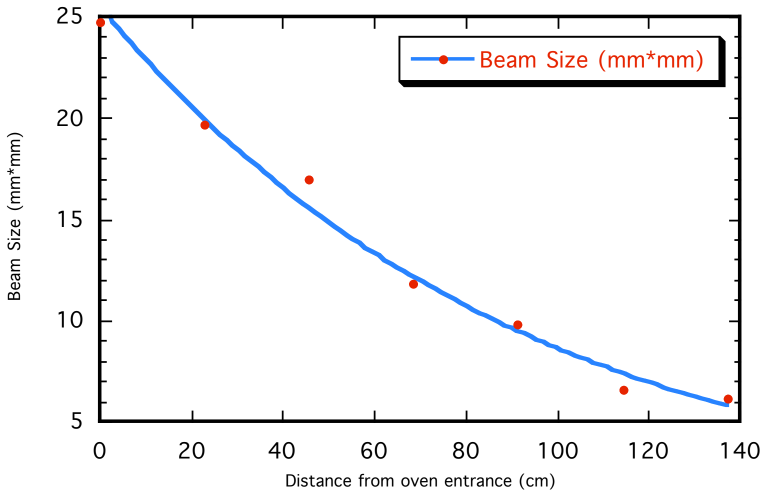
$n_e(z)=n_0(1-\mathrm{Exp}[-F(z)\,\sigma/h\nu])$ and approximately by,

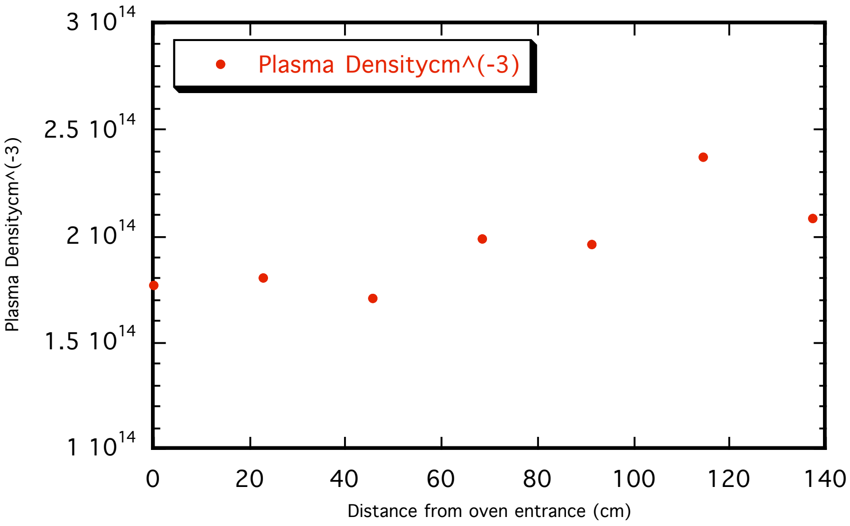
$$n_e(z) \cong n_0\, F(z)\, \sigma/h\nu.$$

It can be seen that the plasma density is proportional to laser flux and the uniformity depends on the laser profile. S(z) is chosen to compensate for absorption by adjusting the laser focusing profile.

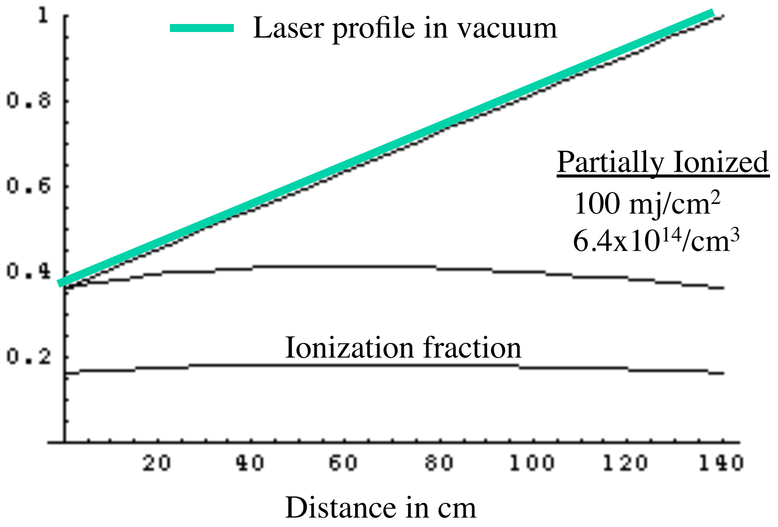
Plasma Density Profile Measurement

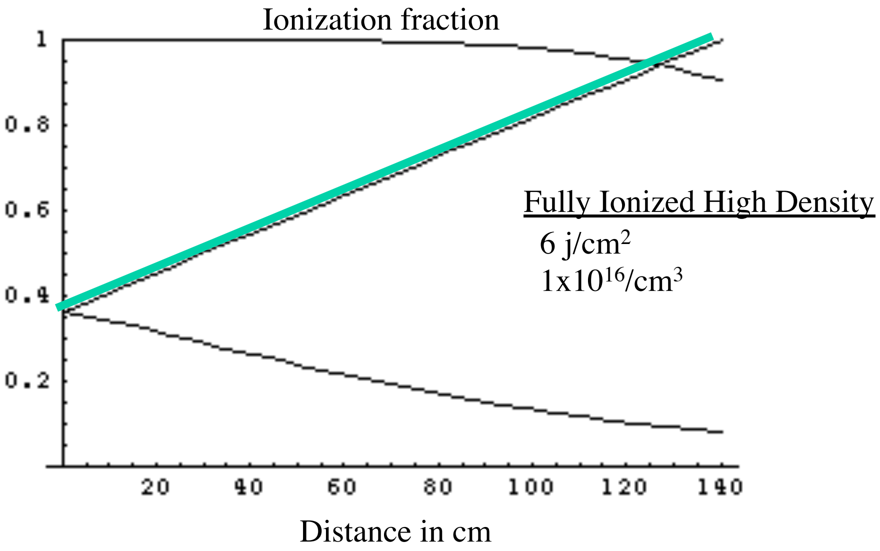
By measuring the laser profile in vacuum, S(z), and knowing vapor density of the lithium we can obtain the plasma density profile.

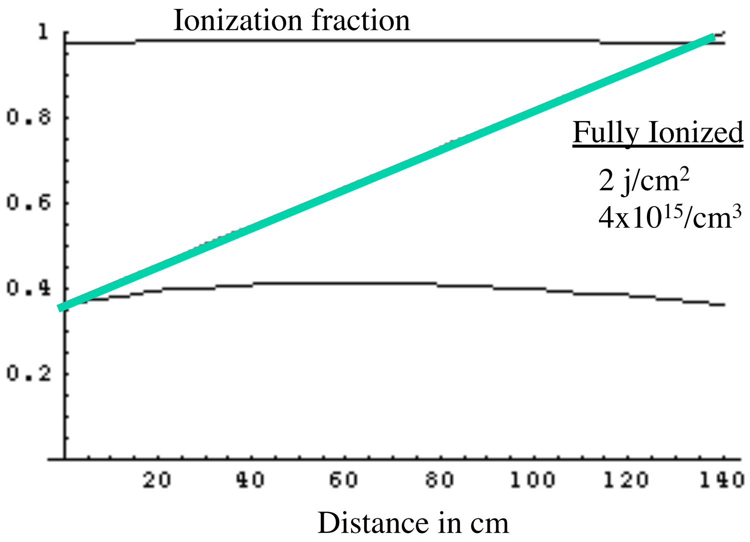




Feasibility of Producing Very Uniform High Density Plasmas with UV



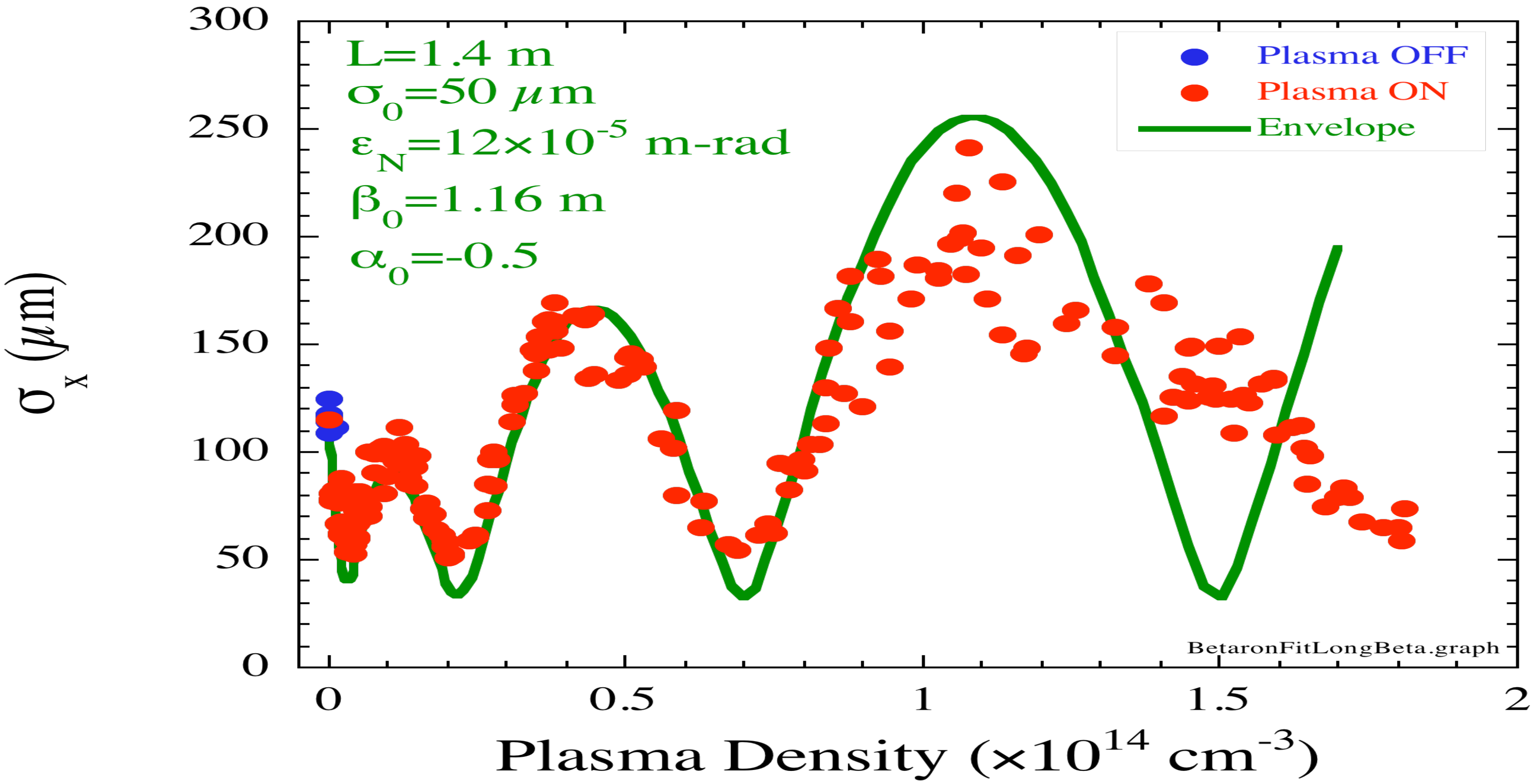




By fully ionizing the vapor, very uniform plasma profiles can be produced, however this requires high laser energy flux.

Resonant laser-driven ionization is a viable remedy which is the subject an SBIR proposal to be discussed by Jerry Hoffman.

Envelope Oscillation data showing confidence in density measurement



6 Formation of Tunnel Ionized Plasmas

- Low first ionization potential
  For rapid ionization.

- High second ionization potential
  Secondary ionization could be problem with trapped electrons and other wake field dynamics.

- Low atomic number
  To reduce impact ionization.

- Homogeneous density
  The gas cell has a more homogeneous density profile compared to metal vapors in a typical heat pipe design.

Table of Ionization Thresholds and Related Quantities For Gases Used

Gas	IP (eV)	n	E_{thres} (GV/m)
H	13.6	1.00	21
H2	15.4	.938	25
He	24.5	.746	54
He+	54.4	1.00	150
Li	5.39	1.59	4.3
Li+	75.5	.848	255
Xe	12.13	1.06	17
Xe+	21.21	1.6	30
Xe++	32.1	1.95	49
NO	9.25	1.21	10
N	14.5	.97	23
O	13.6	1.00	21

Secondary Ionization Mechanisms

(With respect to parameters for last run)

Sources of localized high fields for secondary tunnel ionization

- Wake amplitude, Ez, 10-100 GV/m
- Beam pinch points, Er > 100 GV/m
- Ion column, Er > 10 GV/m

Sources of impact ionization $n_e = n_g(1\text{-Exp}(-n_b \sigma_i ct))$

Beam electrons at 28.5 GeV

$\sigma_i = 2.6\text{x}10^{-23}\ \text{m}^2$

$n_e/n_g \sim .0003$

Blow out plasma electrons at ~1 MeV

$\sigma_i = 3\text{x}10^{-21}\ \text{m}^2$

$n_e/n_g < .05$

Photo ionization from synchrotron x-rays

Radial Electric Field of a Gaussian Shaped Electron Beam

$$E_r = \frac{eN_c(1 - \mathrm{Exp}(-r^2/2\sigma_r^2))\mathrm{Exp}(-z^2/2\sigma_z^2)}{(2\pi)^{3/2}\varepsilon_0\sigma_z r}$$

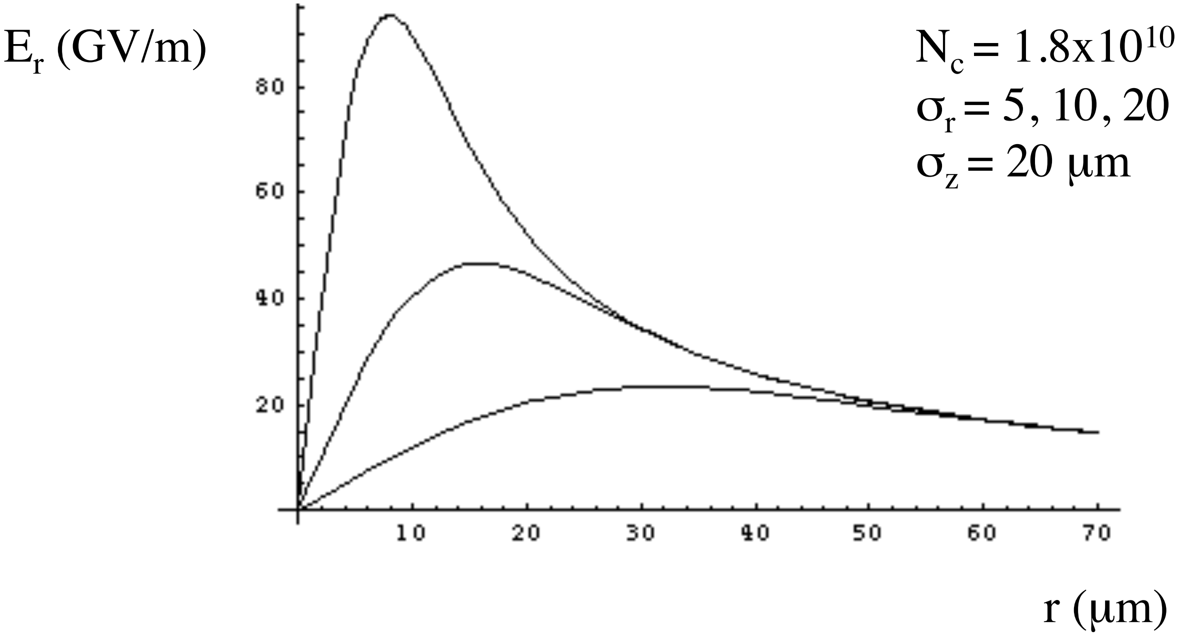
N_c = number of electrons per bunch
σ_r = rms beam size
σ_z = rms bunch length

E_r is maximum at $z = 0$ and $r = 1.59\sigma_r$ and given by;

$$E_{max}(\mathrm{GV/m}) = 5.2\times10^{-19}N_c/\sigma_r\sigma_z$$

Because we ionized hydrogen we know $\sigma_z < 20\ \mu\mathrm{m}$

Plot of beam radial field $E_r(r, z = 0)$ vs r (μm)

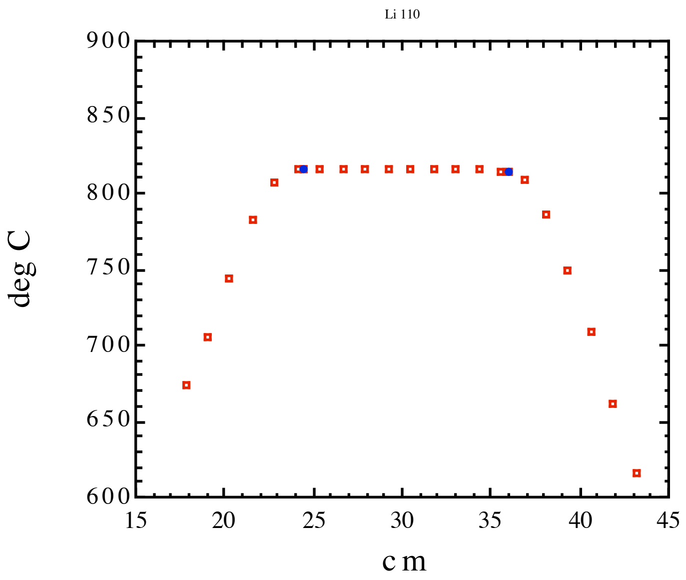


$N_c = 1.8\mathrm{x}10^{10}$
$\sigma_r = 5, 10, 20$ μm
$\sigma_z = 20$ μm

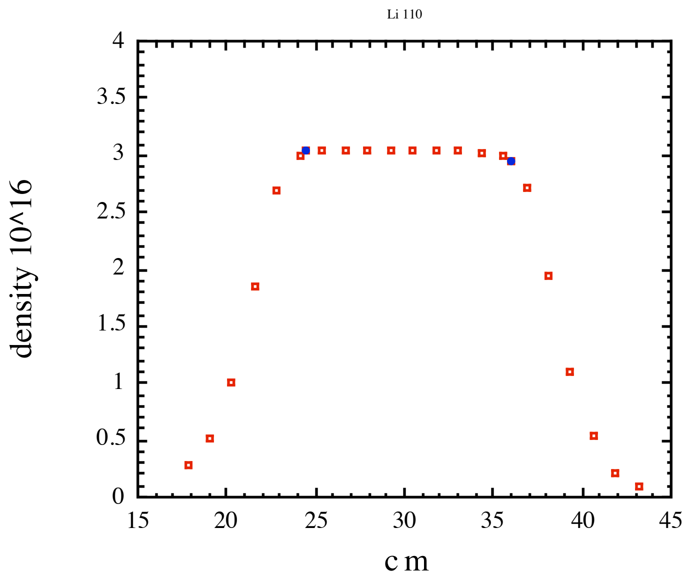
As the beam focuses, σ_r can reach <1 μm and $E_{max} = 470$ GV/m.
This will lead to further localized ionization.

Heat Pipe Oven Temperature and Density Profile

Heat pipe ovens produce very uniform density columns due the the excellent heat conductivity of the alkali vapors. Especially lithium.



Measured oven temperature profile



Oven temperature converted to density profile from empirical formula

Tunneling Ionization Theory

The ADK tunneling ionization rate equation (from Bruwiler)

$$W(s^{-1}) = 1.5\times 10^{15}\frac{4^n\xi(eV)}{n\Gamma(2n)}\left[20.5\frac{\xi^{3/2}(eV)}{E(GV/m)}\right]^{2n-1}\mathrm{Exp}\left[-6.83\frac{\xi^{3/2}(eV)}{E(GV/m)}\right]$$

Where, E =E(r, t) is the electric field, ξ is the ionization potential of the atom or molecule, and n is the effective principle quantum number, $n \approx 3.69Z/\xi^{1/2}(eV)$
n = 1 gives Landua's tunneling formula.

The plasma density as a function of r and t can be solved numerically using;

$$dN/dt = -WN, \quad N = N_0 - N_e$$

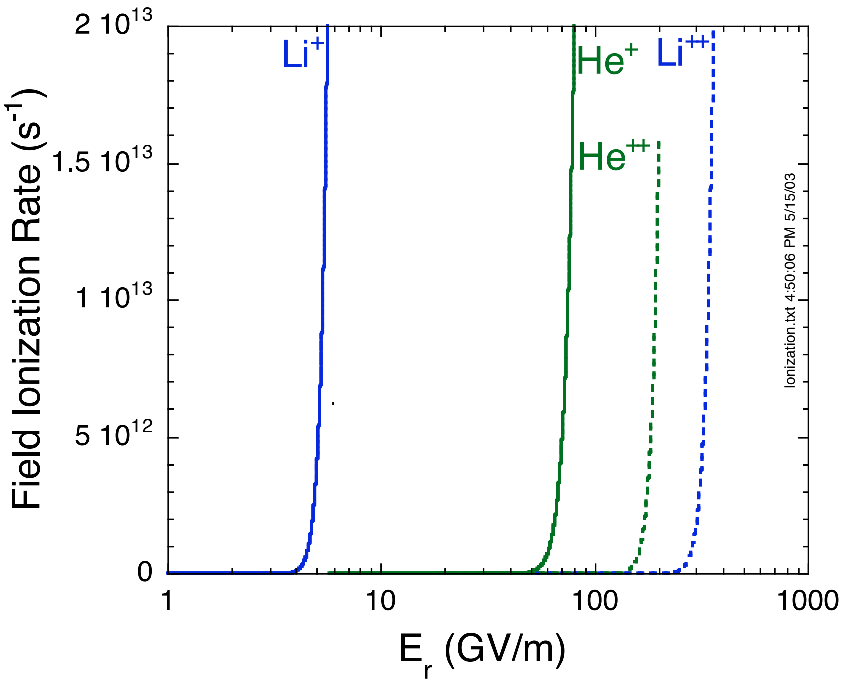
$$N_e(r, t) = N_0(1-\mathrm{Exp}(-F))$$

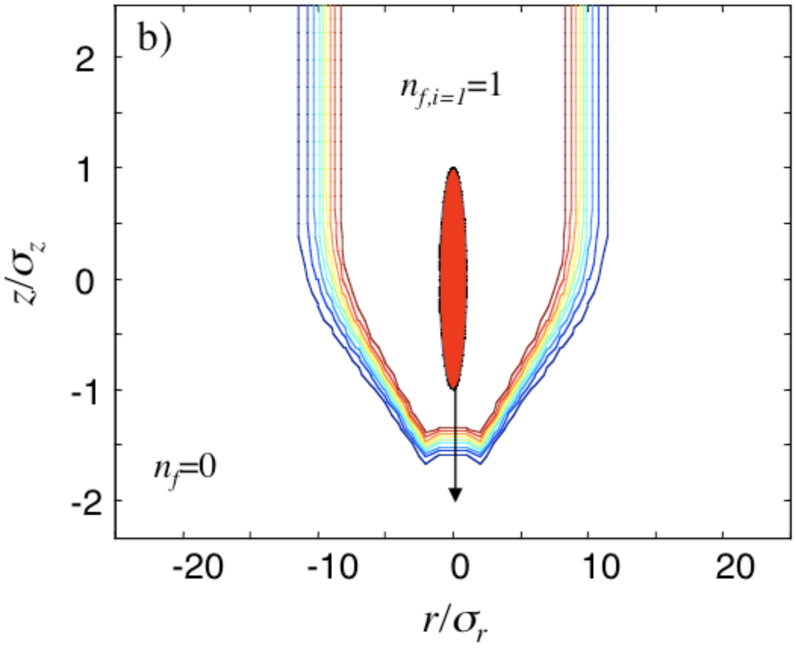
$$F = \int W dt$$

Tunneling Ionization

Plot of ionization rate vs electric field

Plot of ionization fraction contours from 0 to 1



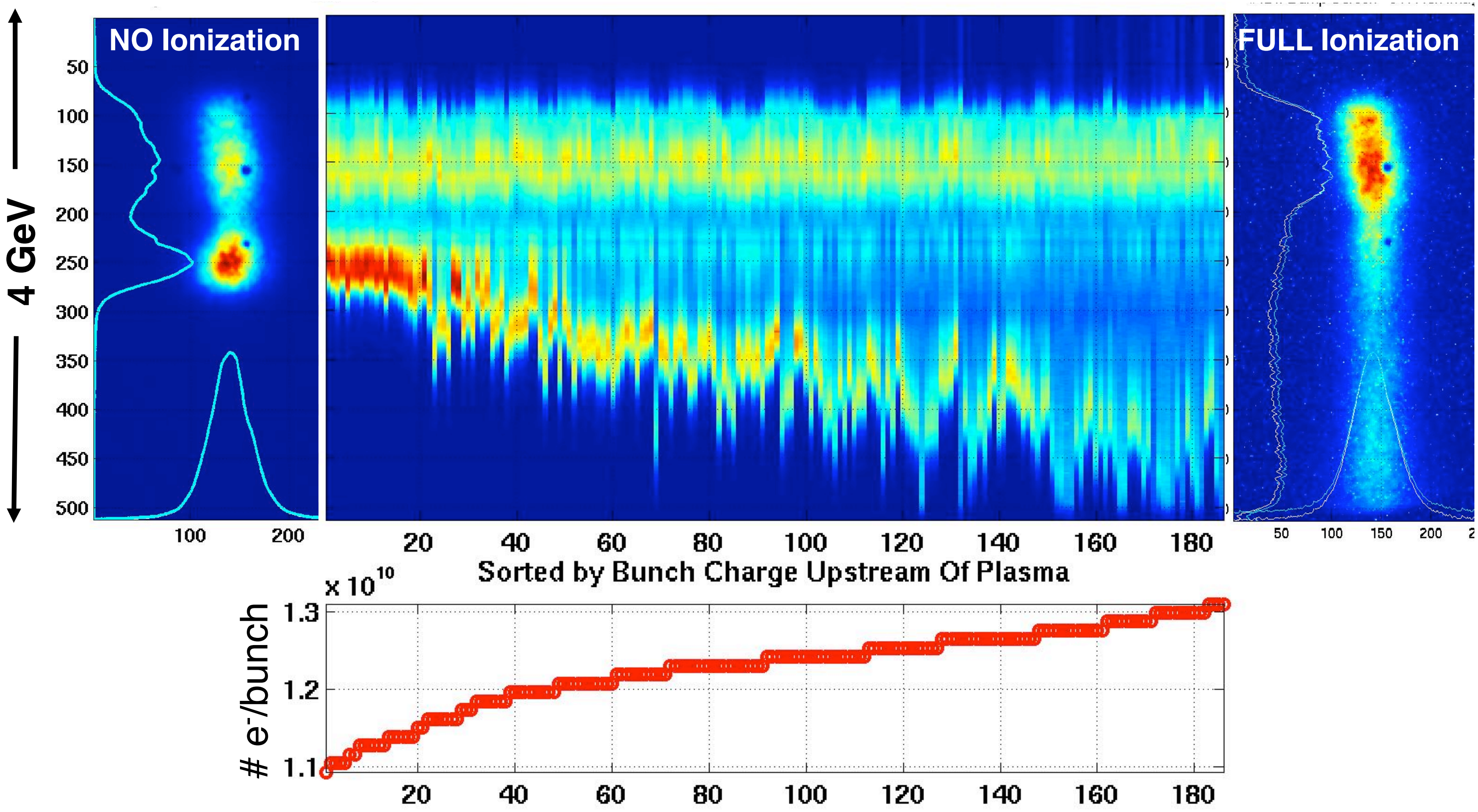


$N=2\times10^{10}$, $\sigma_r = 25\ \mu m$, $\sigma_z = 12\ \mu m$ in Li, $E_{r.max} \approx 35$ GV/m

Energy Loss as a Function of Beam Charge

$\sigma_z \approx 100\ \mu\text{m},\ n_e \approx 8\text{x}10^{15}\ \text{cm}^{-3}$

> 3 GeV/m Energy Loss in Beam Ionized Plasma



7 Control System for Lithium

SRS 630 Brent

Heater Voltage 115.10

Heater Current 6.94

Oven Pressure 330.00

Oven Lookup Table 2

Pressure (mTorr) 351.00

Current (A) 6.97

Hook nL (10^17) 5.65

Vapor Density 4.13

Step 24

Who's on Shift Sho & Seung

Update Min 5.00

Lithium Oven Interlock Overview

Faults

Pressure in oven exceeds 600 mT (oven leak).
Pressure falls below 200 mT (Helium loss).
Leak detected in FFTB beam line.
Water cooling jacket exceeds 30 degrees C.
Thermal coupler exceeds 710^0 C.

Action in all cases

SLAC controls shut down beam.
Oven gate valves close.
Heater power shuts off either by interlock or manually.

Investigate

If fault occurs, cool down oven to room temperature (5+ hours).
Keep oven gate valves closed.
Fix leak or reason for failure.
Go to oven start up procedure

Special Case

Closing oven gate valves, while beam is on, will shut down beam.

CONCLUSIONS

Heat pipe ovens are excellent sources of uniform alkali vapor columns in the density range from 1e14-1e18 cm-3.

The vapors are confined by an inert gas which forms a boundary layer with a scale-length of 15 cm-5 cm.

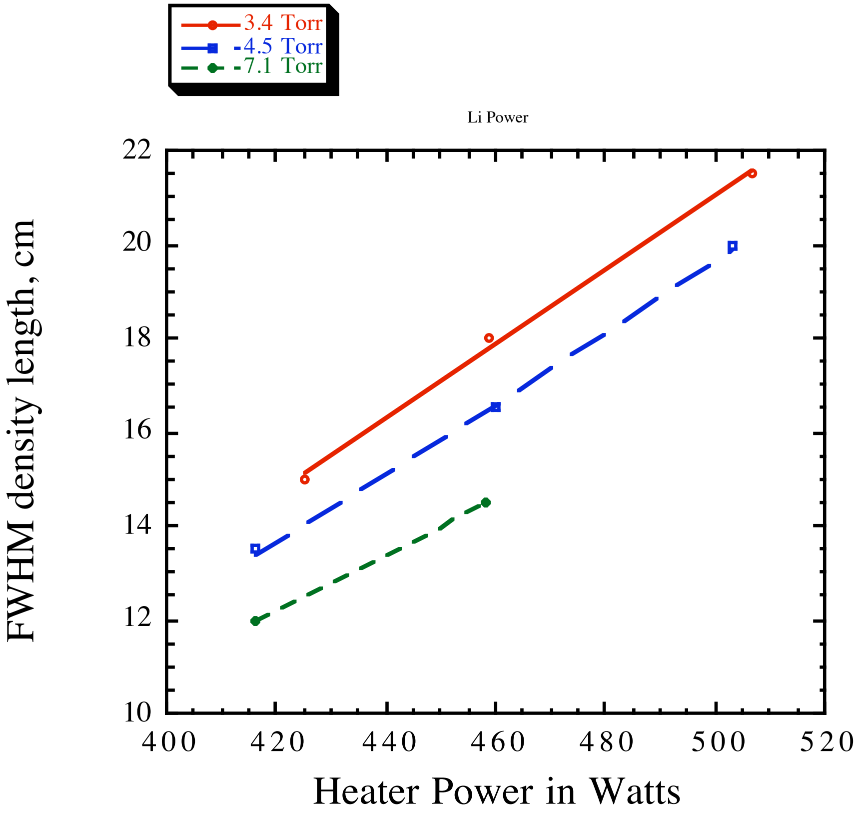
Single photon ionization can be used to produce relatively uniform 10cm -5m long plasmas in the density range from 1e11-1e15 cm-3 .

Using self fields of intense beams fully ionized, uniform plasma columns are produced .

Heat pipe ovens can be operated over a large range of density and length

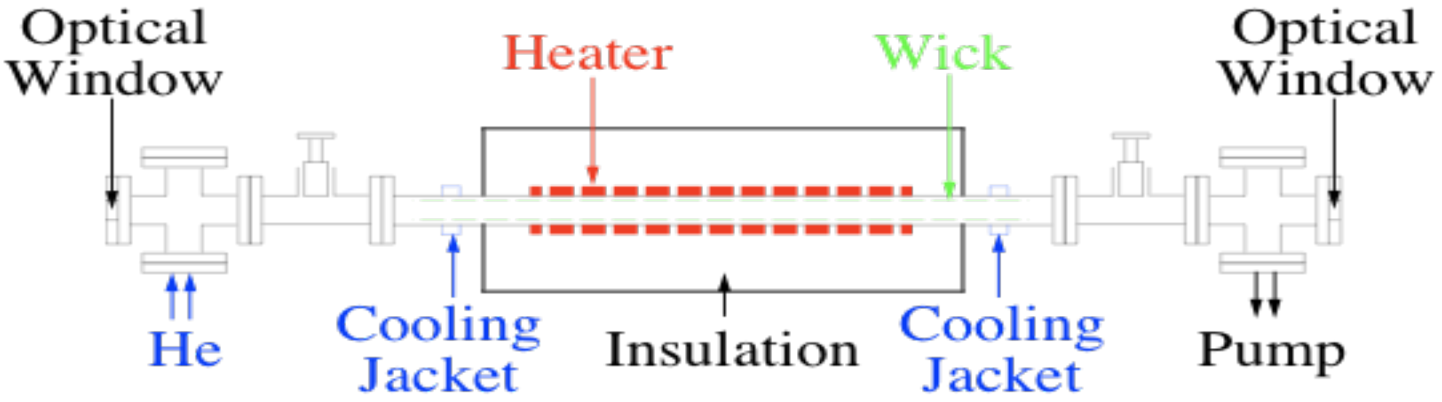
In the heat pipe oven mode, the vapor density can be changed by adjusting the buffer gas pressure.

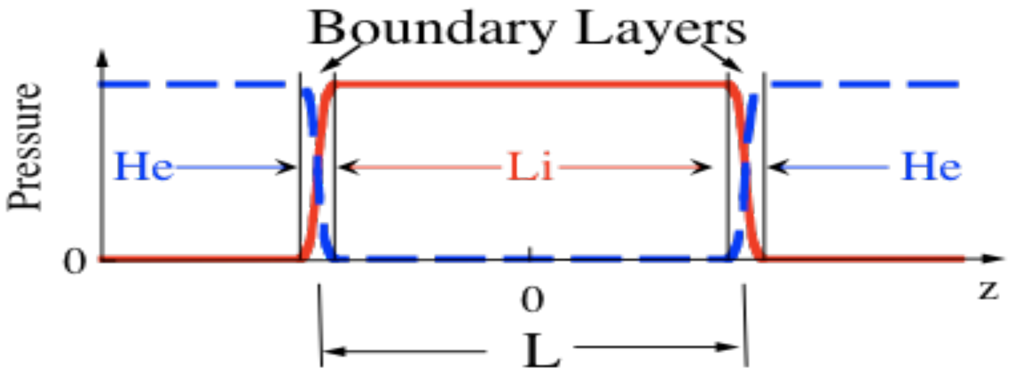
The vapor zone length can be adjusted linearly with the heater power



LITHIUM PLASMA SOURCE

FPAH151





- n_0(Li) ↔ P_{He}
- L ↔ Heating Power

:

- $n_{Li}<5\times10^{15}$ cm^{-3}
- $L\approx1.4$ m

\+ uv laser ionization =

- $n_e<5\times10^{14}$ cm^{-3}
- $L\approx1.4$ m

- Other atomic vapor, other ionization schemes

PLASMA PARAMETERS

- Ionization: single photon ionization

$$N, E(z) = N_0, E_0 \exp(-n_0 \sigma_i z)$$

$$n_e = -\frac{N(z+dz) - N(z)}{A dz} \rightarrow n_0 E_0 \frac{\sigma_i}{h\nu} \frac{\exp(-n_0 \sigma_i z)}{A(z)}$$

$n_0=4.4\times10^{15}$ cm^{-3}
$\sigma_i=1.8\times10^{-18}$ cm^2
$A=0.12$ cm^2
$E_0=3.7$ mJ
L=1.4 m

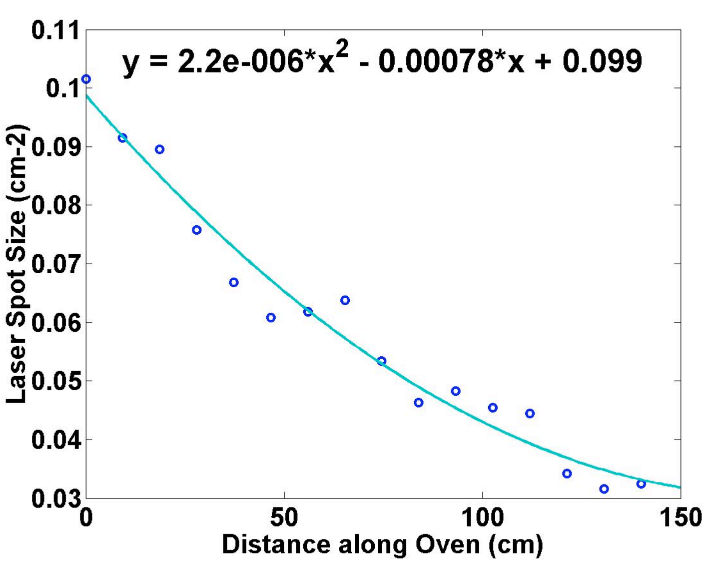
→

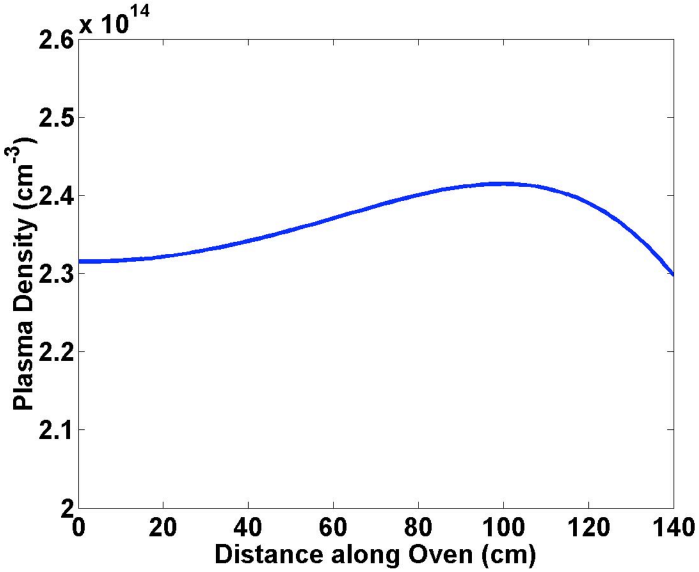
$n_e(z=0)=2.32\times10^{14}$ cm^{-3}

$\exp(-n_0\sigma_i L)=0.33$

→

Focused
UV Beam

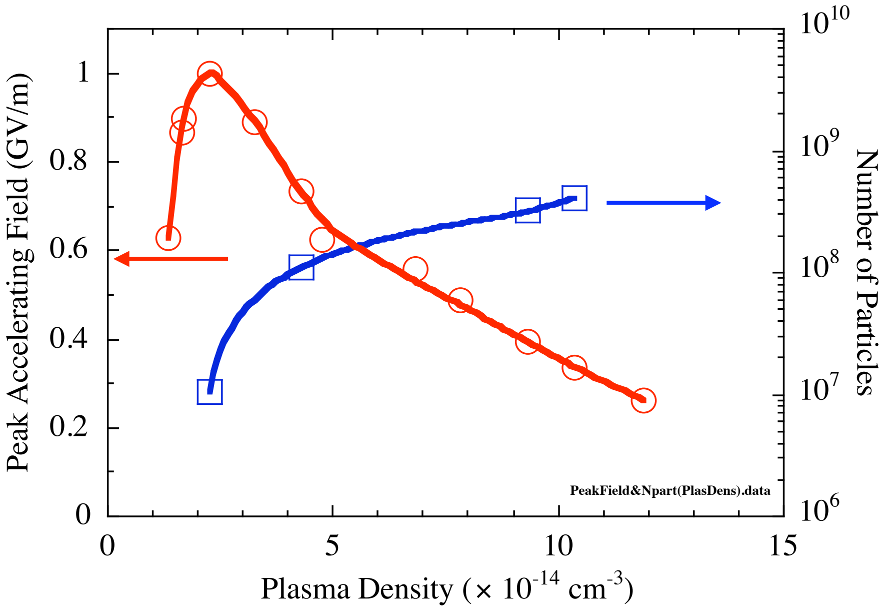


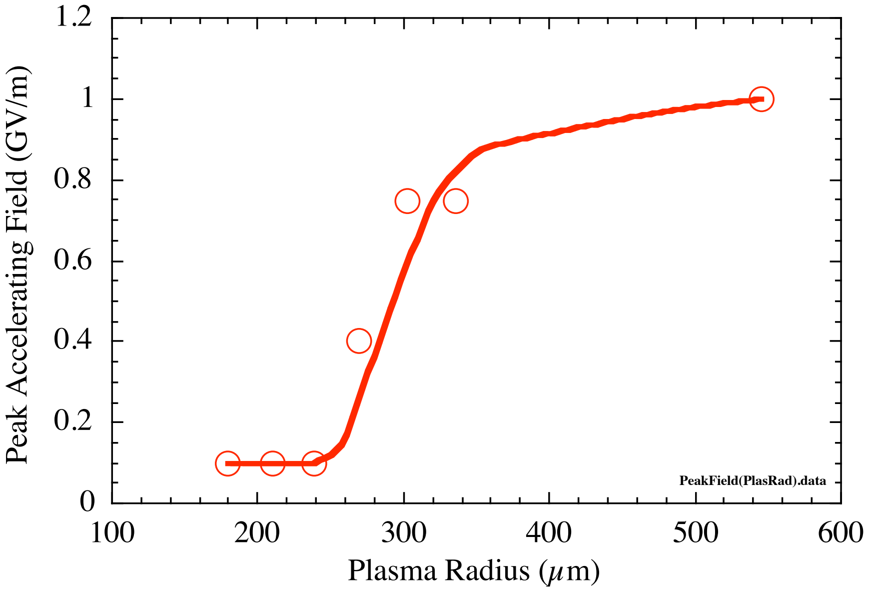


- Uniform Plasma!

PLASMA REQUIREMENTS

2-D PIC Simulations: $N = 4\times10^{10}$, $\sigma_z = 0.6$ mm, $\sigma_r = 75\ \mu$m



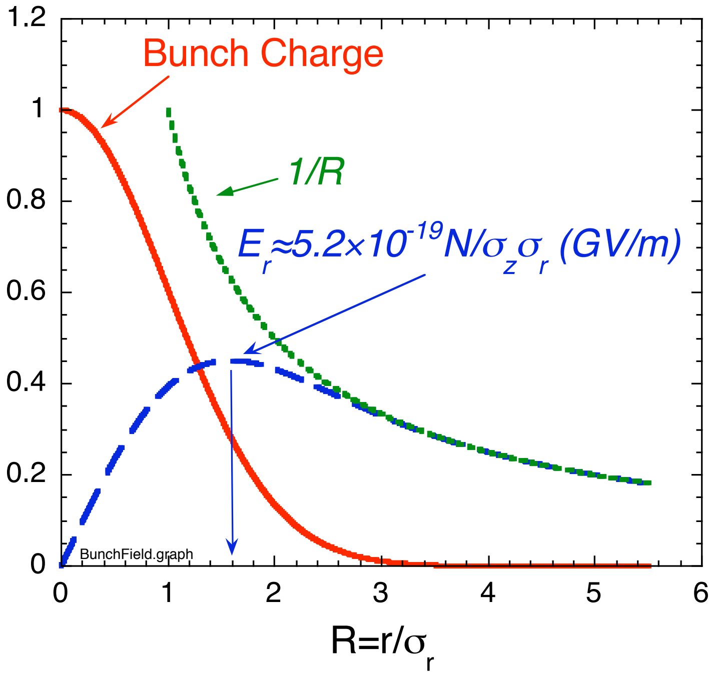


- Plasma density $1.5\text{-}2.1\times10^{14}$ cm^{-3}
- Plasma radius > 400 μm
- $L \approx 1.4$ m, $\Delta n_e/n_e < 25\%$, $n_e/n_0 > 10\%$

e$^-$-BEAM FIELD-IONIZATION

Gaussian beam electric field:

$$E_r(r,z) = \frac{1}{(2\pi)^{3/2}} \frac{e}{\varepsilon_o} \frac{N}{\sigma_z \sigma_r} \frac{\left(1 - e^{-r^2/2\sigma_r^2}\right)}{r/\sigma_r} e^{-z^2/2\sigma_x^2}$$



$E_{r.max} \approx 2.6$ GV/m for $N = 1\times10^{10}$, $\sigma_r = 20\ \mu$m, $\sigma_z = 100\ \mu$m

Ionization rate (ADK model):

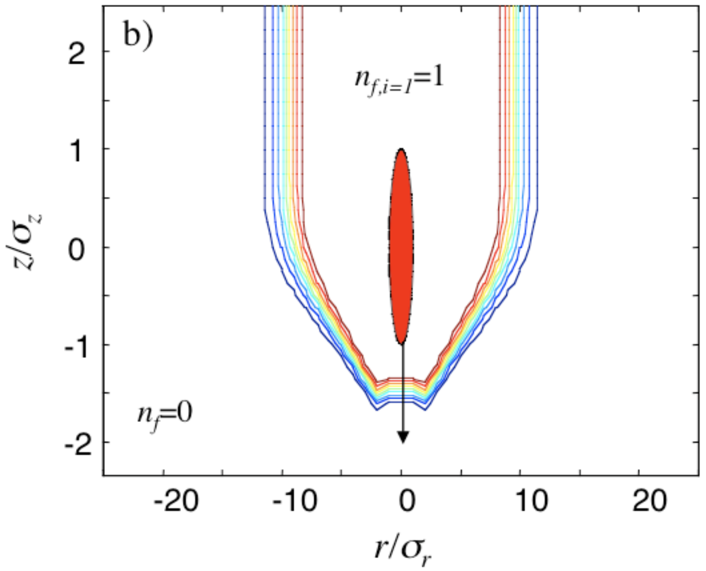
$$W\left[s^{-1}\right] \cong 1.52\times10^{15} \frac{4^{n^*}\xi_i}{n^*\Gamma(2n^*)} \left(20.5\frac{\xi_i^{3/2}}{E}\right)^{2n^*-1} e^{\left(-6.83\frac{\xi_i^{3/2}}{E}\right)}$$

ξ_I= ionization potential = 5.45 eV for Li

E= electric field in GV/m

n^*=effective quantum number $=Z/(2\xi_I)^{1/2}$

$N = 2\times10^{10}$, $\sigma_r = 25\ \mu$m, $\sigma_z = 12\ \mu$m in Li, $E_{r.max} \approx 35$ GV/m



- Threshold process
- Short bunches can field-ionize their own plasma and create their own accelerating structure (E-164X, after-burner?)

see for example D. Bruhweiler et al., Phys. of Plasmas to be published, and P.Muggli et al, AAC-2002 Proceedings