UCLA

SLAC

FACET

FACET II
OCT 2017 Meeting

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Talk Outline

- Matching $\boldsymbol{\beta_m = 1/k_b}$
- Four plasma based experiments
- Focusing, Emittance vs aberrations
- Can we do experiments with thin foil windows?
  - Scattering comparison. Be vs Si_3N_4
  - Matching through a thin scattering foil.
- Plasma Sources cont.
  - Can we make a hydrogen plasma with density ramps?
- Beam-ionization and head erosion in H_2 plasma.
  - Is it possible to beam ionize H_2 plasma?
  - What is required to avoid head erosion?
  - Wake structure, $r_p > R_b$ requirement
- Laser optics
- Differential pumping
- Some testing and commissioning

Why beam matching?

- Why do we need beam matching at FACET?
  - For linear focusing system, normalized emittance is conserved
    - Even though the density or energy might change, ε_n = const.
  - Energy spread causes phase mixing
    - If there was no energy spread there would be no emittance growth.
  - Beam matching prevents emittance growth in finite dE/E beams
  - Matching requirement $\boldsymbol{\beta_m = 1/k_b}$ does not depend on emittance
- Why do we need low emittance?
- Why do we need small beam size? $\sigma_r^2 = \beta\, \varepsilon$
  - Small beam size required $\sigma_r < R_b < r_p$
  - Beam ionized experiments require small σ_r to avoid head erosion
  - $n_b > n_b$ to reach blow out regime

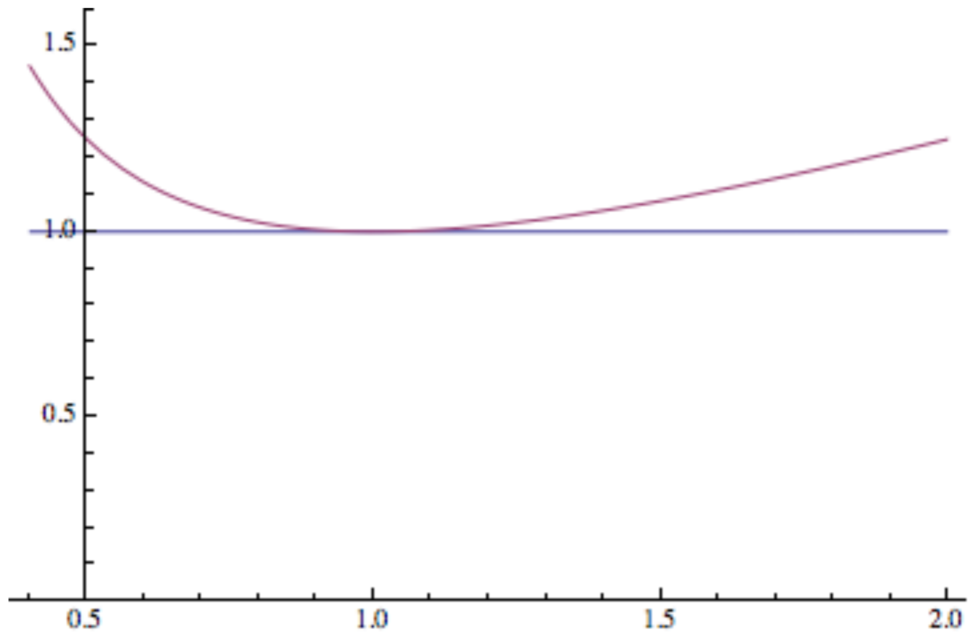
Why beam matching cont.?

- Why do we need density ramps?
  - Conventional lens requires $1/k_b = \beta < .5$ cm
  - Density ramp allows vacuum beta =5 cm
  - Exit ramps prevent emittance growth in vacuum
- What remains is engineering
  - How to make appropriate density ramps?
  - How to avoid chromatic aberrations?
  - Emittance growth in foils verses differential pumping.

Beam matching tolerance

$$\varepsilon_f / \varepsilon_i = ((1+\alpha^2)\beta_m / \beta + \beta / \beta_m) / 2$$

$\varepsilon_f/\varepsilon_i$



β/β_m

$$\alpha = 0$$

Complete decoherence formula, Mehrling PRSTB

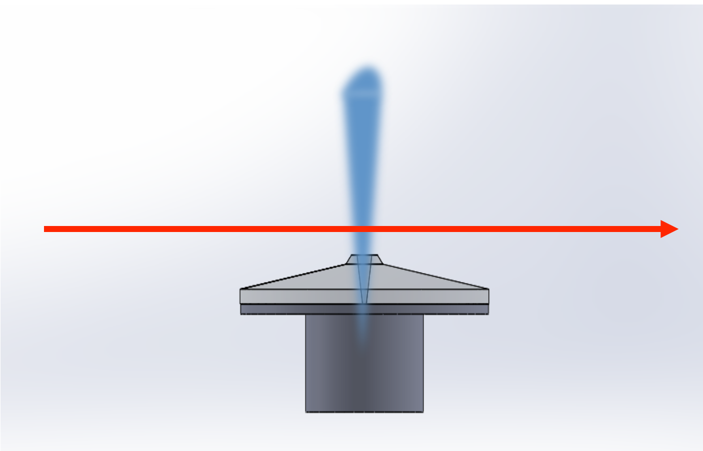
Large emittance growth for mismatched beams seen in Experiment, Theory and Simulation

- For $2x10^{17}$ cm^{-3} $\boldsymbol{\beta/\beta_m}$ was 20 to 50
- For large mismatch, emittance growth $\boldsymbol{\varepsilon_f/\varepsilon_0 \approx \beta/\beta_m/2}$

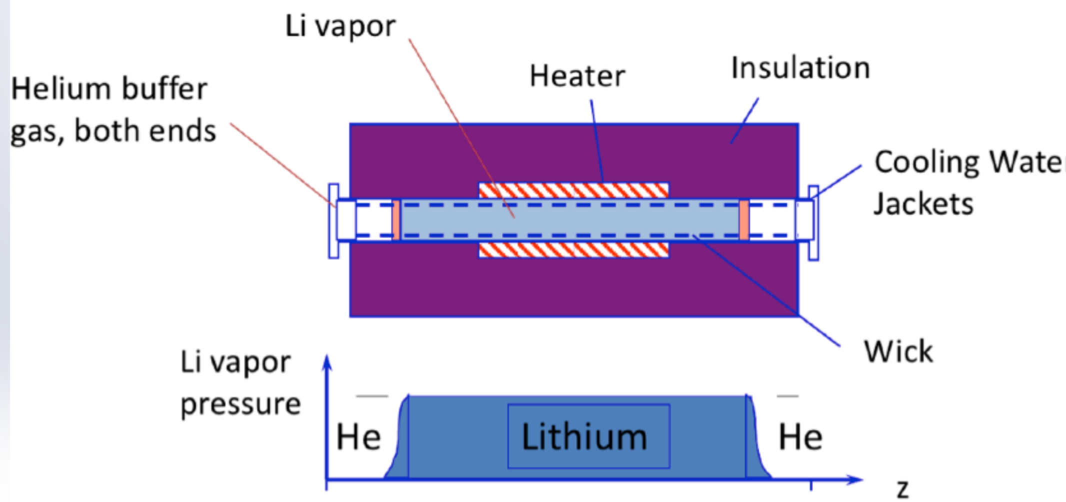
Why use density ramps anyway?

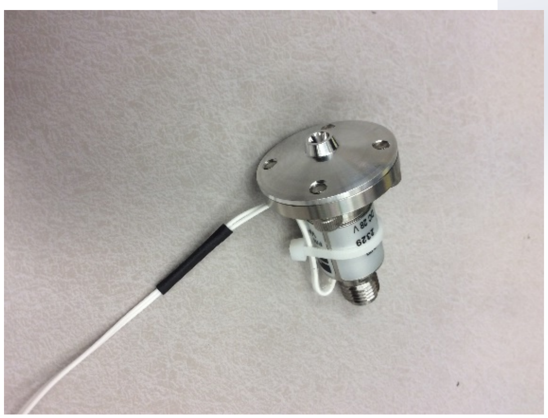
- They are unavoidable in lithium plasma
- Entrance ramp can act as a beam matching section.
- Exit ramp reduces beam divergence
  - The faster the beam diverges (even in vacuum) the more phase rotation of differing energies. Phase mixing causes emittance growth.

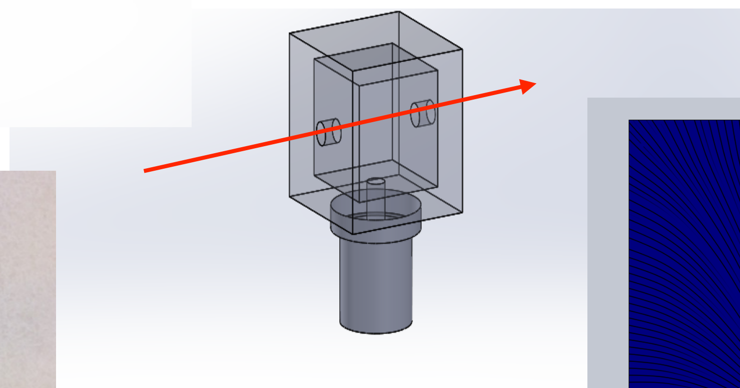
Plasma source designs



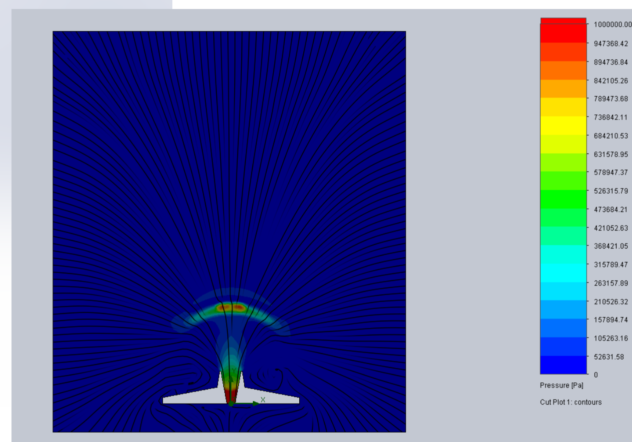
Pulsed valve







Gas cell



Solid works flow

Four prominent plasma based experiments

- Lithium oven plasma experiment
- Hydrogen plasma with matching ramps experiment
- *Extreme Beam*, High density Hydrogen plasma experiment
- Downramp injector experiment

Beams for 10 GeV Facet II PWFA Experiments #1

Lithium oven plasma experiment
Plasma density $4x10^{16}$ (preionized, or beam ionized)
Plasma length ≈ 50 cm

	Drive	Witness
Emittance	< 10 um	< 10 um
Vacuum beta	< 5 cm	< 5 cm
Vacuum σ_r	< 5 um	< 5 um
σ_z	12.8 um	6.4 um
Charge	$1.0x10^{10}$	$3.0x10^{9}$
Current	15 kA	10 kA
Spacing	135 um	

Lithium oven plasma experiment
Natural density ramps (discussed last year)

Helium buffer gas ionization could cause emittance growth
(Might require larger drive beam emittance)
Beam heating modifies oven profile
Limited diagnostic access

Beams for 10 GeV Facet II PWFA Experiments #2

Hydrogen plasma with matching ramps experiment
Plasma density $2x10^{17}$ (if beam ionized)
Best if preionized

	Drive	Witness
Emittance	< 10 um	< 10 um
Vacuum beta	< 2.5 cm	< 2.5 cm
Vacuum σ_r	< 5 um	< 5 um
σ_z	8 um	6.38
Charge	1x10^10	3x10^9
Current	30 kA	10 kA
Spacing	68 um	

Hydrogen plasma with matching ramps experiments
<u>Beam ionized head erosion issues:</u>
Small σ_r < 5 um required for beam ionization
Head erosion requires low emittance < 10 um, high current.
Ionization radius $r_p > R_b$, $R_b \approx 2/k_p$ therefore requires high density

Good diagnostic access
Locate in picnic basket?
Differential pumping

Beams for 10 GeV Facet II PWFA Experiments #3

***Extreme Beam*, High density Hydrogen plasma experiment**

Plasma density > $1x10^{20}$

Plasma length ~ 1 cm

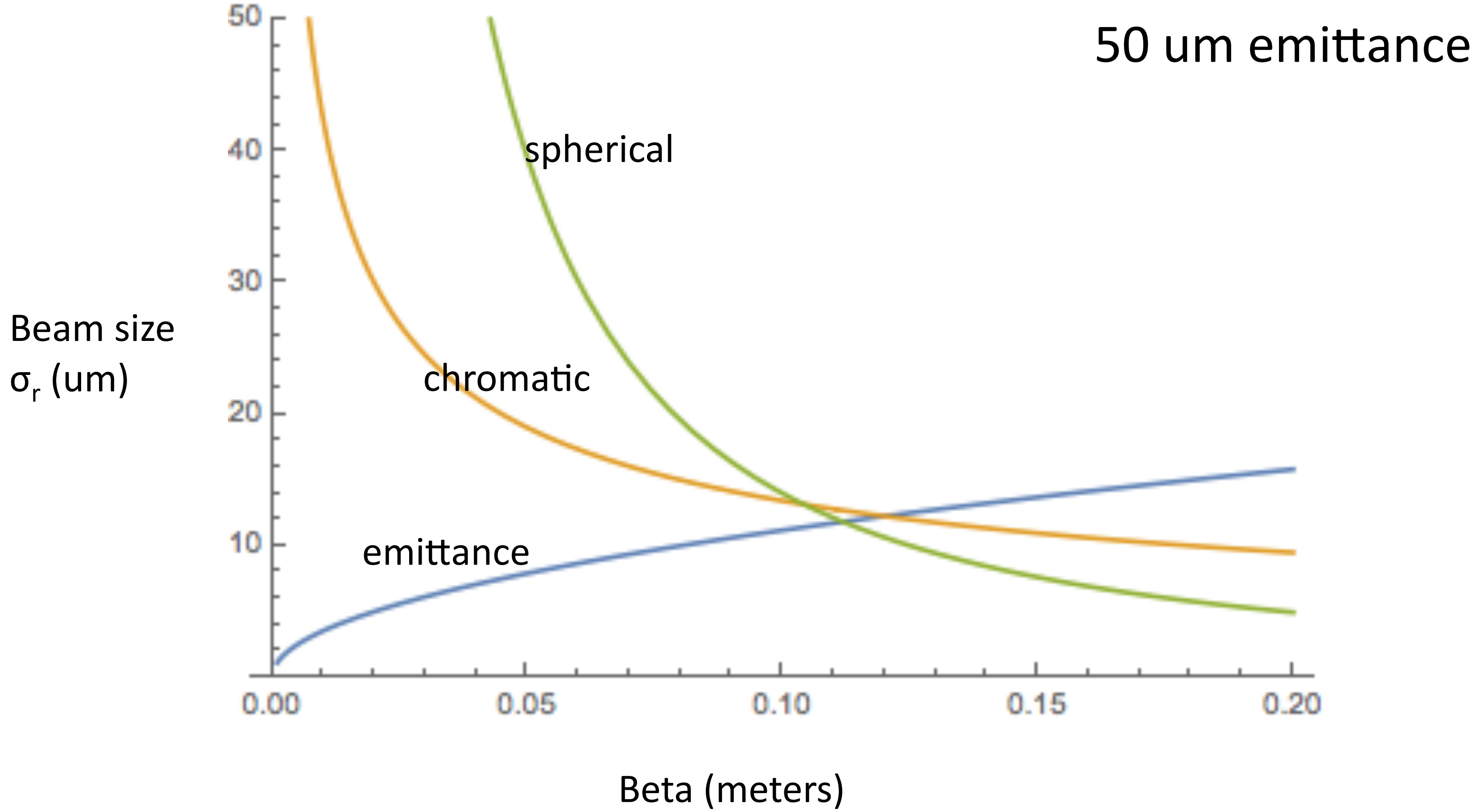
	Drive	Witness
Emittance	3 um	3 um
Vacuum beta (not matched)	~ 1 cm	~ 1 cm
Vacuum σ_r	~1 um	~1 um
σ_z	< 1 um	< 1 um
Charge	$7.5x10^8$	$3.1x10^8$
Current	18 kA	7 kA
Spacing	3 um	

Beams for 10 GeV Facet II PWFA Experiments #4

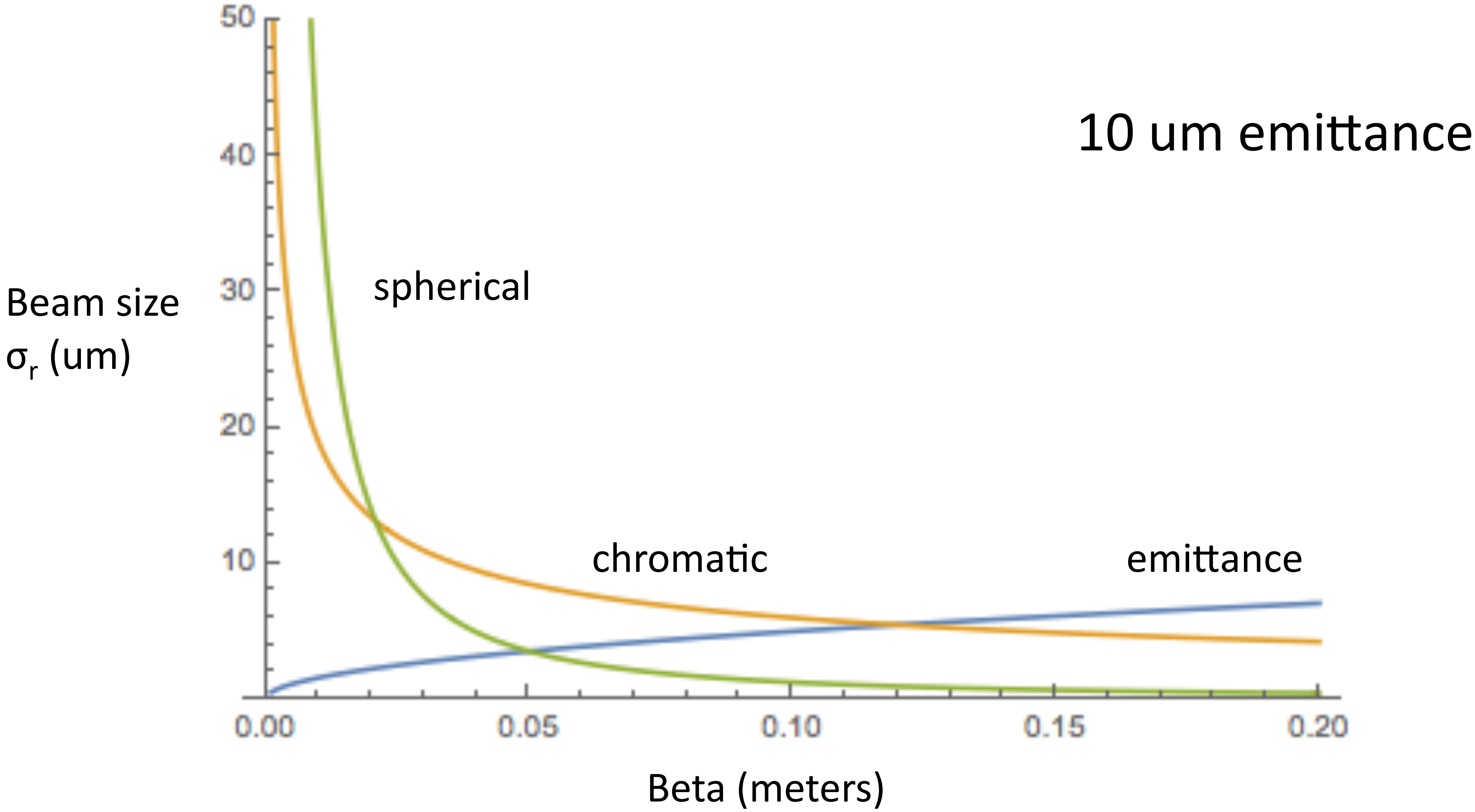
Downramp injector experiment
Plasma density ~$1.5x10^{18}$
Plasma length < 1 cm

	Drive	Trapped beam from PIC
Emittance	< 5.3 um	80 nm
Vacuum beta (not matched)	< 5 cm	
Vacuum σ_r	< 5.3 um	.2 um
σ_z	~5.0 um	1.3 um
Charge	$1.0x10^{10}$	$8.8x10^{8}$
Current	35 kA	14 kA
Energy	10 GeV	620 MeV

Beam size FACET I parameters



Beam size FACET II parameters



Optimize the IP area for small betas

- Beam matching and small betas
  - Smaller initial emittance reduces aberrations
  - Move plasma closer to final quads?
- To reduce emittance growth in foils
  - Optimize window design and location
  - Differential pumping

FACET2 with Foil Windows?

- Difficult to keep $\varepsilon_n < 10$ um with Be windows
- Windowless set up requires 10^{-9} diff pumping to protect linac
- Consider 1 um thick Silicon Nitride windows, Si_3N_4

Emittance growth in foils

Coulomb scattering formula*

$$\theta = 13.6\sqrt{l / l_r}\,2 / \gamma (1 + .038 \ln(l / l_r))$$

l_r = radiation length

*Valid for $10^{-3} < l / l_r$

$$\varepsilon^2 = \varepsilon_0(\varepsilon_0 + \beta_0\theta^2)$$

$$\beta^2 = \beta_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$

$$\alpha^2 = \alpha_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$

Comparison of Be to Si_3N_4

Foil	density	Thick um	Rad Length cm l/l_r	Emitttance um	MP deg C	Hazzard	Price
Be	1.88	50	35.28, 10^{-4}	16	1287	High	$1000+
Si_3N_4	3.44	.5 to 1.0	~10, 10^{-6}	2.4	1900	Low	$500

The Coulomb formula should be checked against GEANT

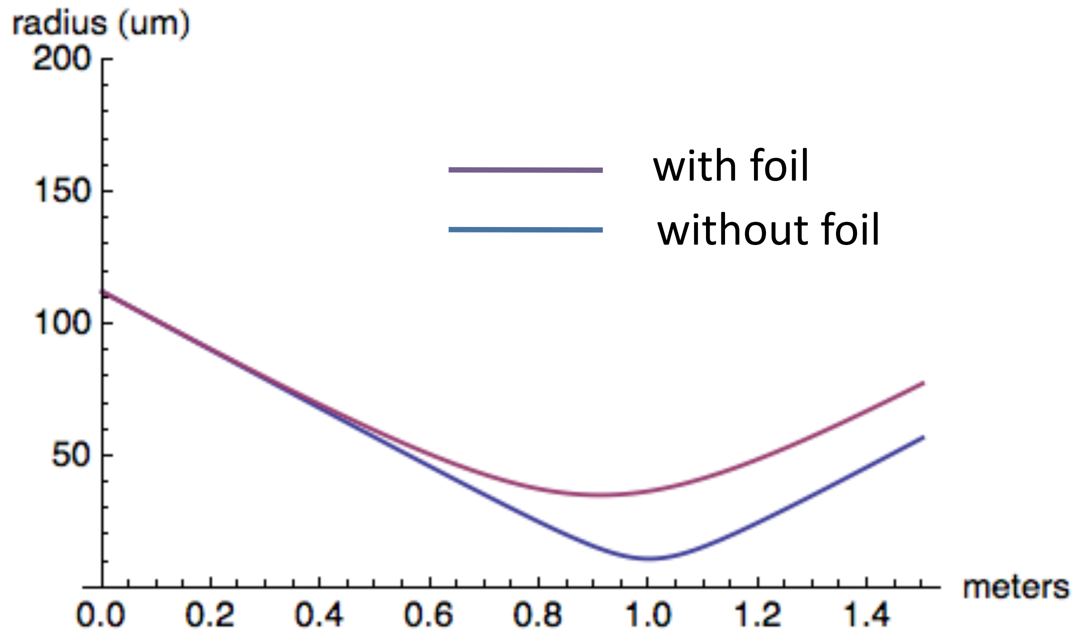
Illustration of Beam propagation through thin foil in vacuum

Change in beam parameters at the foil

$$\varepsilon^2 = \varepsilon_0(\varepsilon_0 + \beta_0\theta^2)$$

$$\beta^2 = \beta_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$

$$\alpha^2 = \alpha_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$



Θ = 35 urad
ε_0 = 50 mm-mrad
ε_s = 164 mm-mrad

at plasma entrance
β = 10 cm
β_s= 30 cm

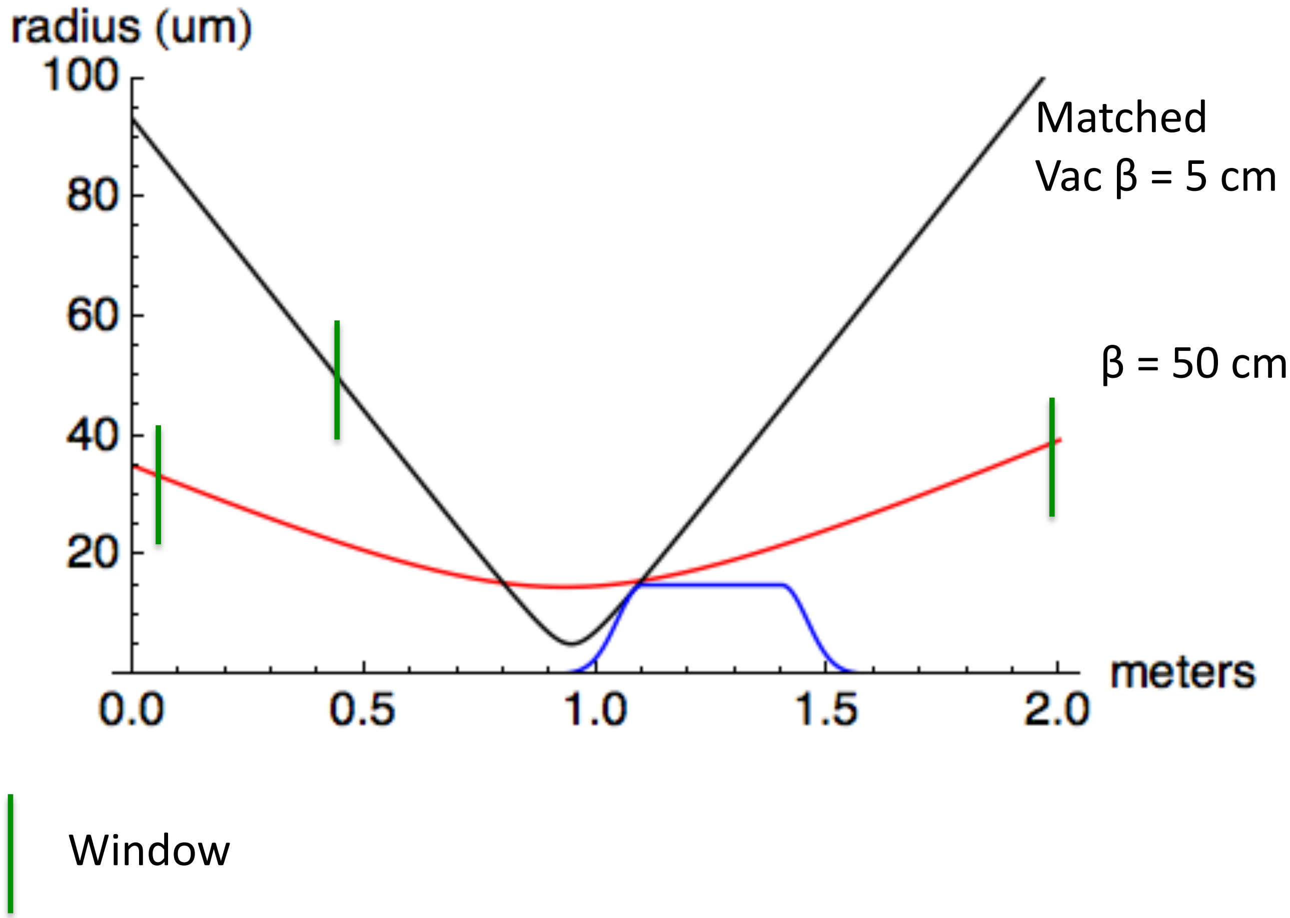
σ_r = 11 μm
σ_s = 35 μm

Beam matching through a thin scattering element

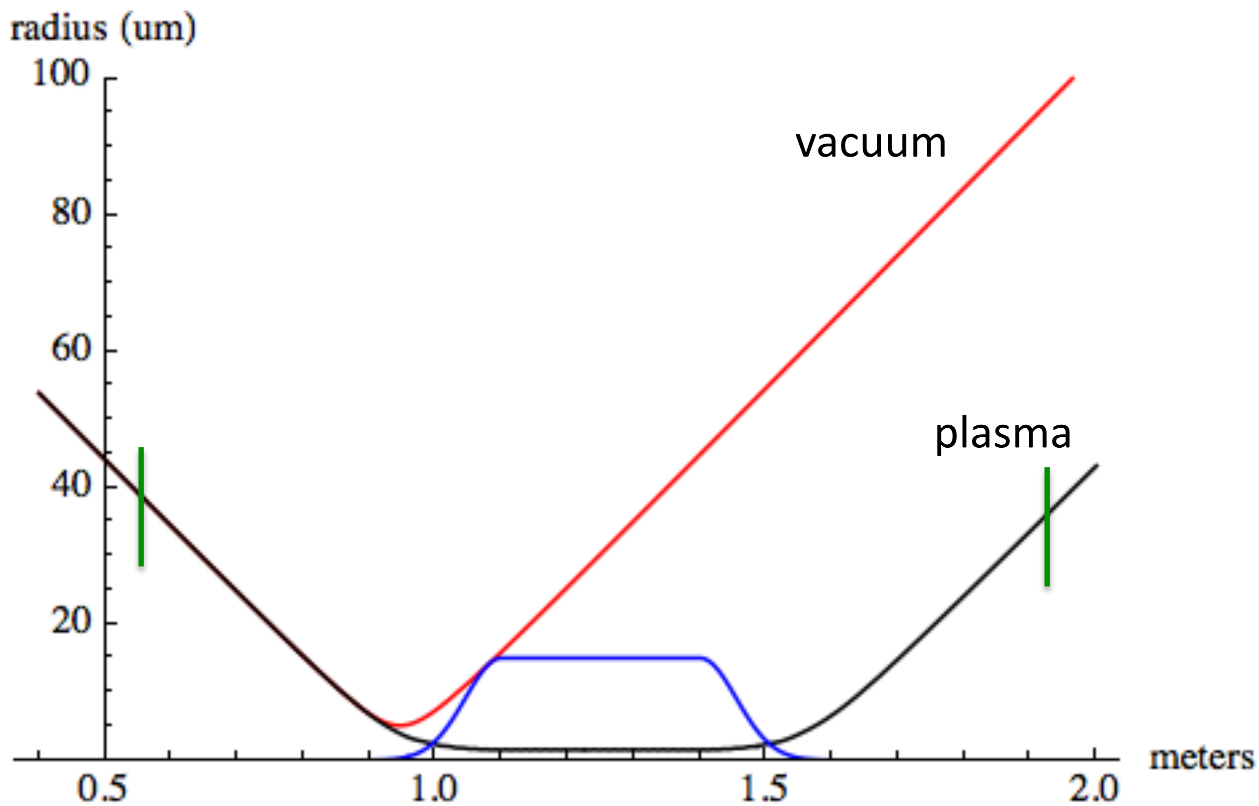
1. Start with matched beam at plasma
2. Propagate beam back to foil; $\beta_0 = \beta_m(1+z^2/\beta_m^2)$
3. Calculate new beam parameters at foil; $\varepsilon_0\beta_0 = \varepsilon_s\beta_s$
4. **Focusing condition at plasma, foil removed is $\beta_f = \beta_m\varepsilon_0/\varepsilon_s$**
5. Inserting foil will make beam matched

6. Beam parameters can be checked using 3 or 4 screen method
7. With foils in, quad scan could produce errors

Large β can have small beam size on windows causing damage (envelope shown in vacuum)



Matched beam Facet2
Where to put entrance and exit windows?



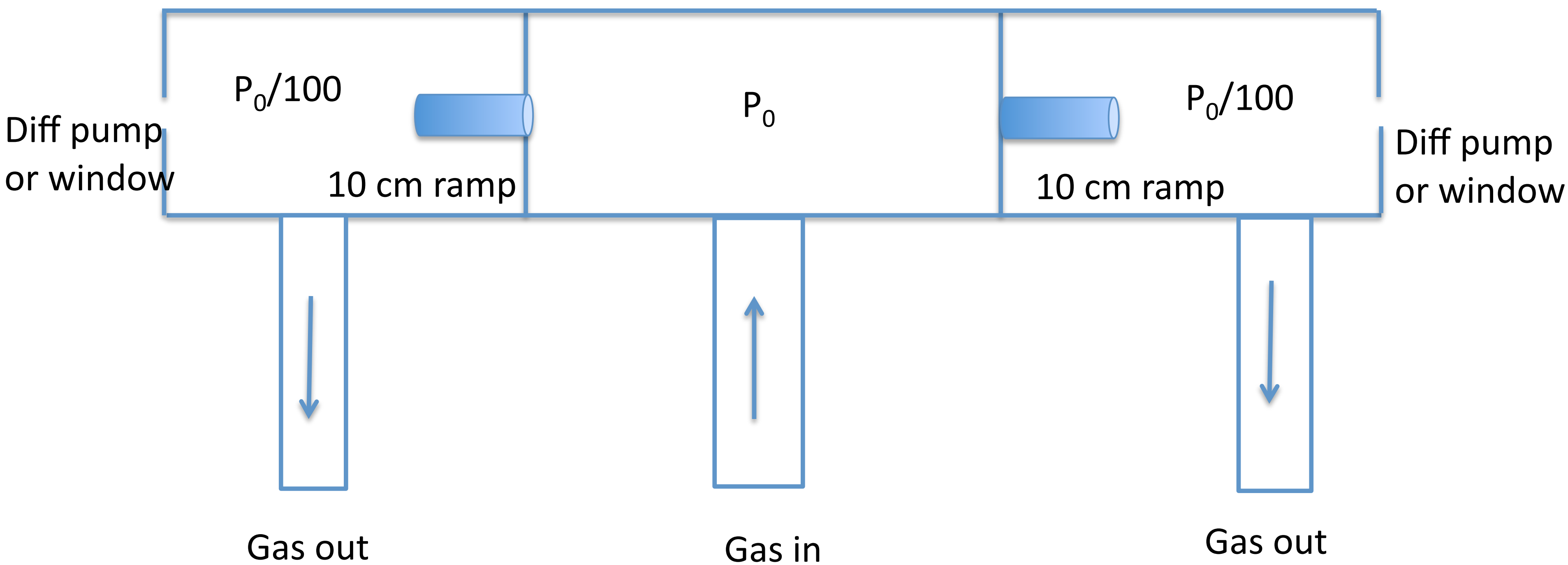
Beta vac= 5 cm
n=5x10^16

Advantages of H_2 plasma sources

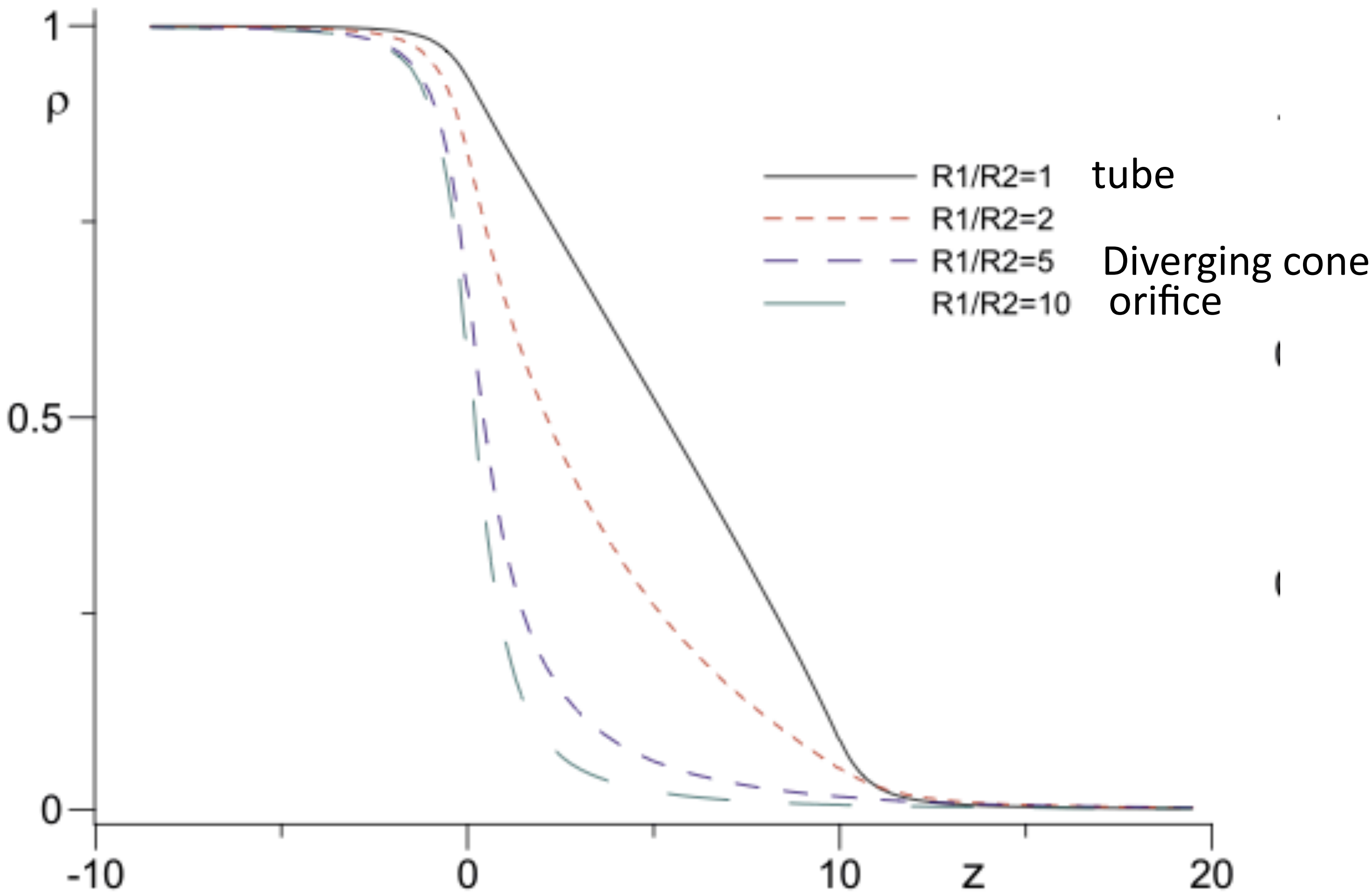
- Control of plasma density and length.
- Density ramps can be tailored.
- Ideal single species ionization.
- Allows full diagnostic access.
- Gas heating is a problem.
  - This could be as high as 2500 W average
  - Large gas flow can be recirculated

Tailored 30 cm H2 plasma

Density ramps created by diverging conical pipe

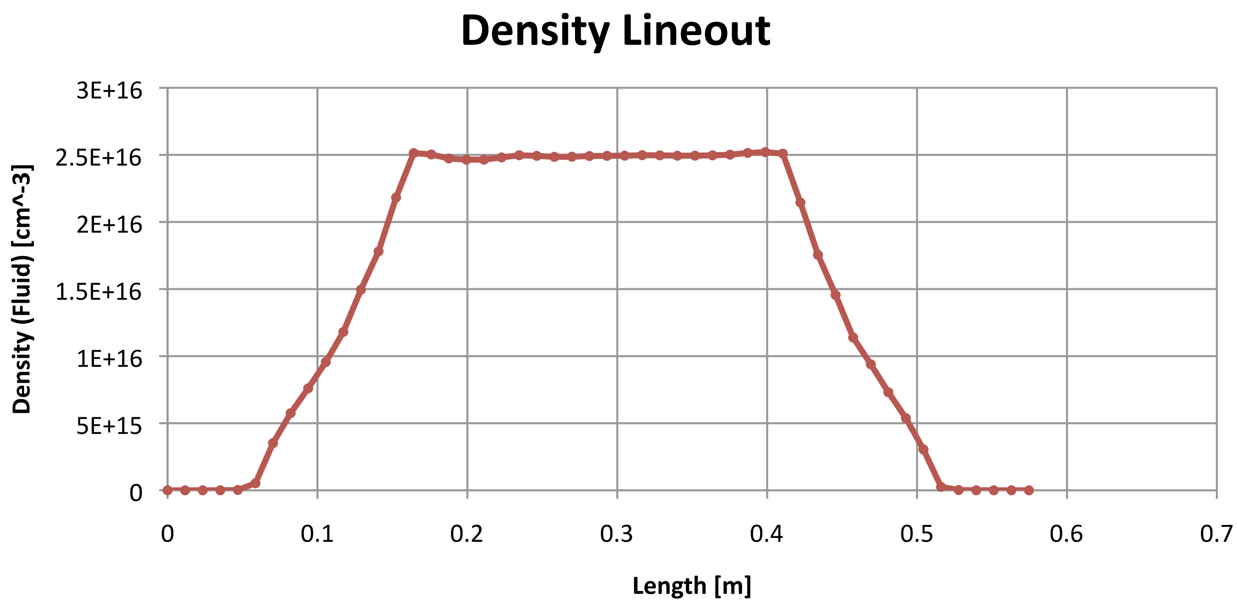


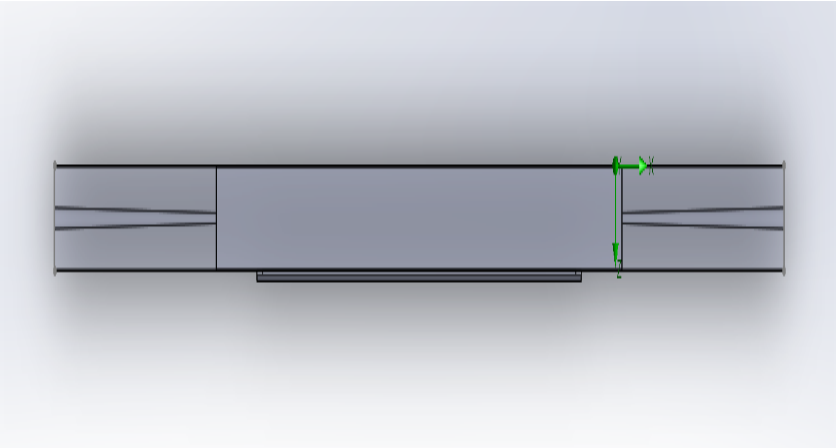
Gas flow through diverging conical pipe, Titarev, V. A.



(a) density

25 cm H_2 cell with 10 cm matching ramps (SolidWorks Flow WIP)





H_2 plasma concerns

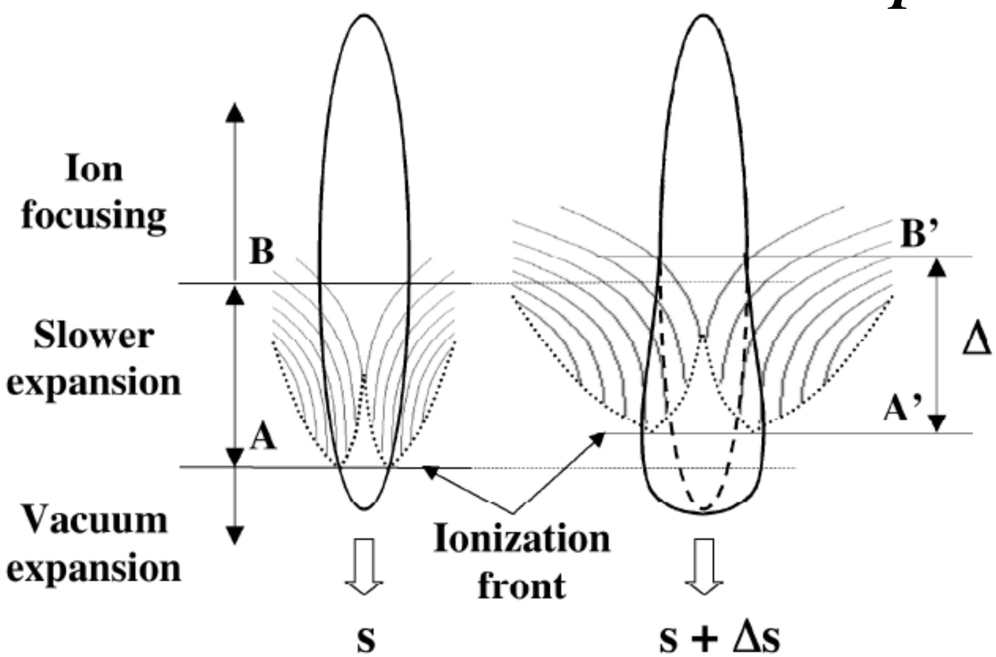
- For $r_p > R_b$, Beam ionized requires high density plasma $2x10^{17}$ cm^{-3}
- Head erosion -> low emittance, high current, small beam size
- Laser ionized is best if $r_p > R_b$
  - Can we ionize hydrogen cell? Yes, 3-4 meter focal length axilens

Head Erosion in Self Ionized Plasma

$$L_{HE} \sim \sigma_z / v_{etch}$$

$$v_{etch} \sim \frac{\varepsilon_N}{\gamma} \frac{1}{I^{3/2}} eV^{1.73}$$

$$I \sim N_c / \sigma_z$$



M. Zhou thesis, Ian Blumenfeld thesis

Head Erosion concerns for FACET2

- $L_{HE} \sim \gamma$
- Required < 10 um emittance to avoid HE in H_2
- High current helps but,
  - For fixed charge $L_{HE} \sim 1/\sigma_z^{1/2}$
  - For fixed current $L_{HE} \sim \sigma_z$
- L_{HE} > Beam depletion length, (25 cm)

Head Erosion Length in H_2 at FACET2

$$L_{HE} = \sigma_z / v_{etch}$$

$$I = eN_c / (2\pi)^{1/2} \sigma_z / c$$

$$v_{etch} = A \frac{\varepsilon_N}{\gamma} \frac{1}{I^{3/2}} eV^{1.73}$$

$$A = 2.4 \times 10^9$$

$$\varepsilon_n = 10 \mu m$$

$$N_c = 1 \times 10^{10}$$

$$\sigma_z = 8 \mu m$$

$$I = 24 kA$$

$$eV = 15$$

$$L_{HE} = 23 cm$$

Experimental area footprint

- How to shorten distance from quads to IP?
- Optimize vacuum window location
- Picnic basket creates extra distance from quads to IP. Should it be reconfigured?
- Gas cells and jets can be placed in picnic basket.
- Accommodate laser and pre-ionized plasmas
  - Laser focusing optics

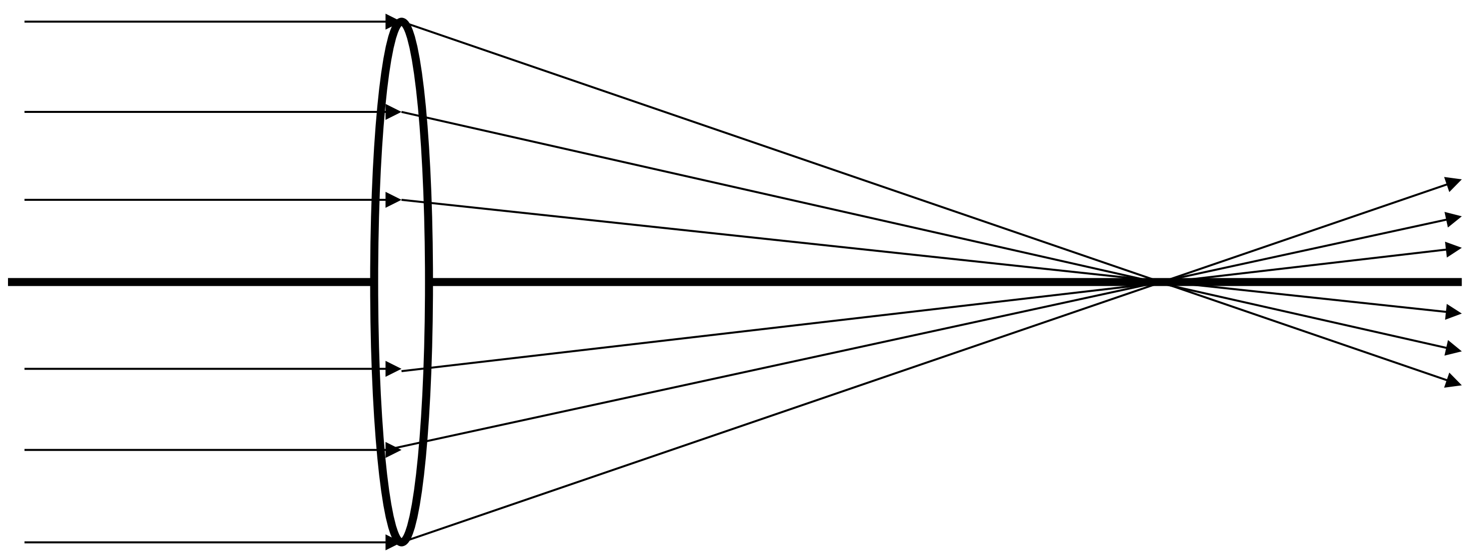
Laser focusing optics for pre-ionized meter scale plasma

- Transmitting optics cause pulse and wavefront distortion
- Conventional lens
- Axicon lens
- Kinoform
- Axilens

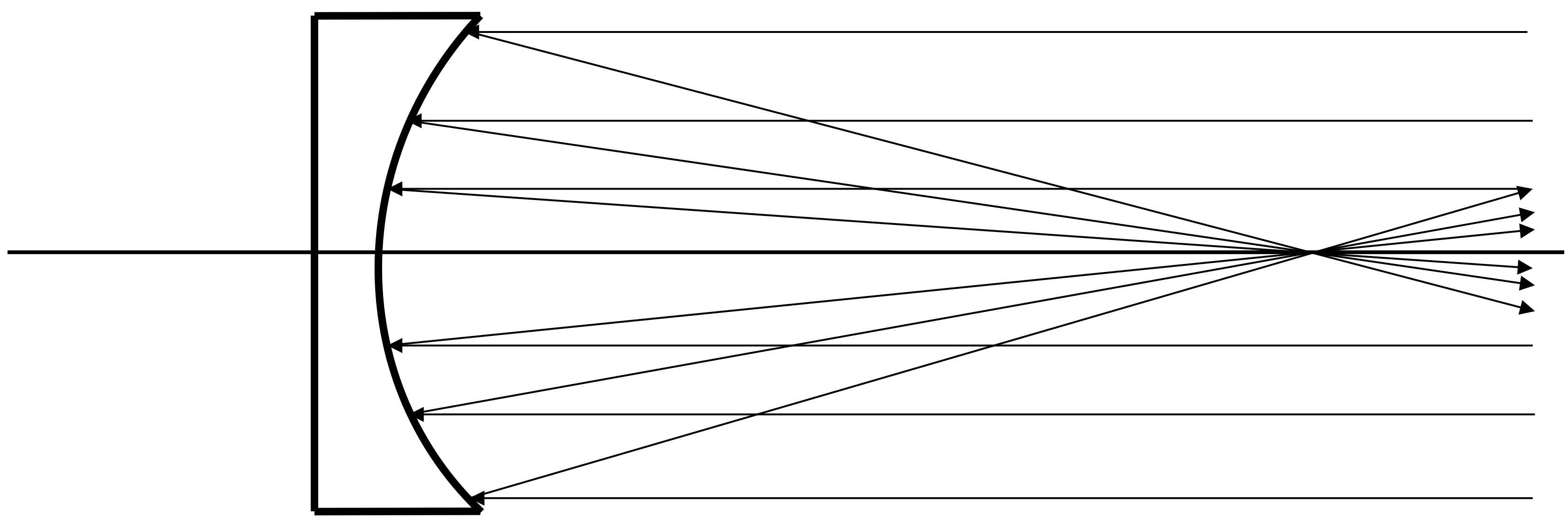
Propose use of Reflective optics

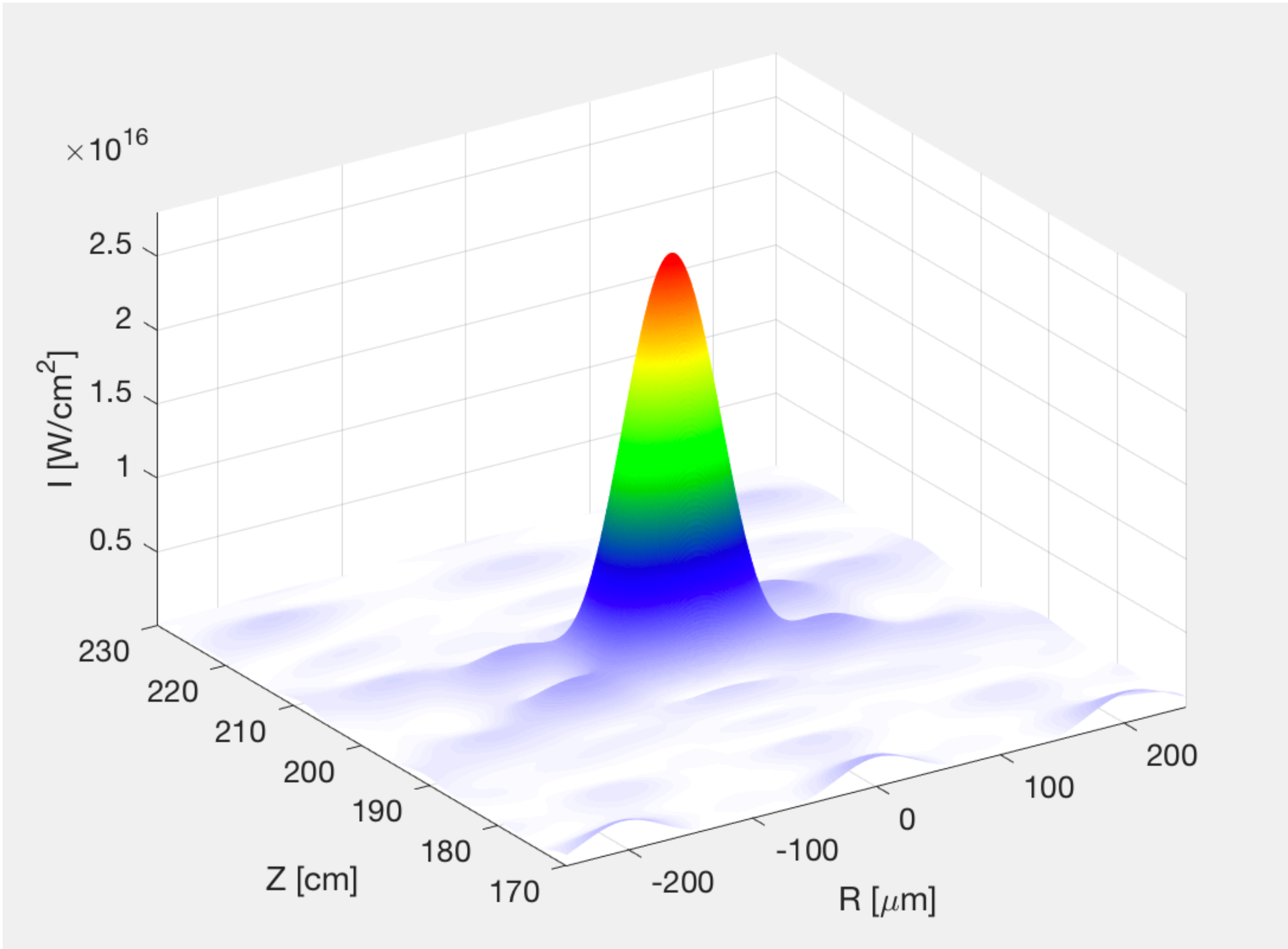
- Reflective axicon
- Two reflective axicons
- Reflective kinoform
- Reflective kinoform 45 degree

Lens

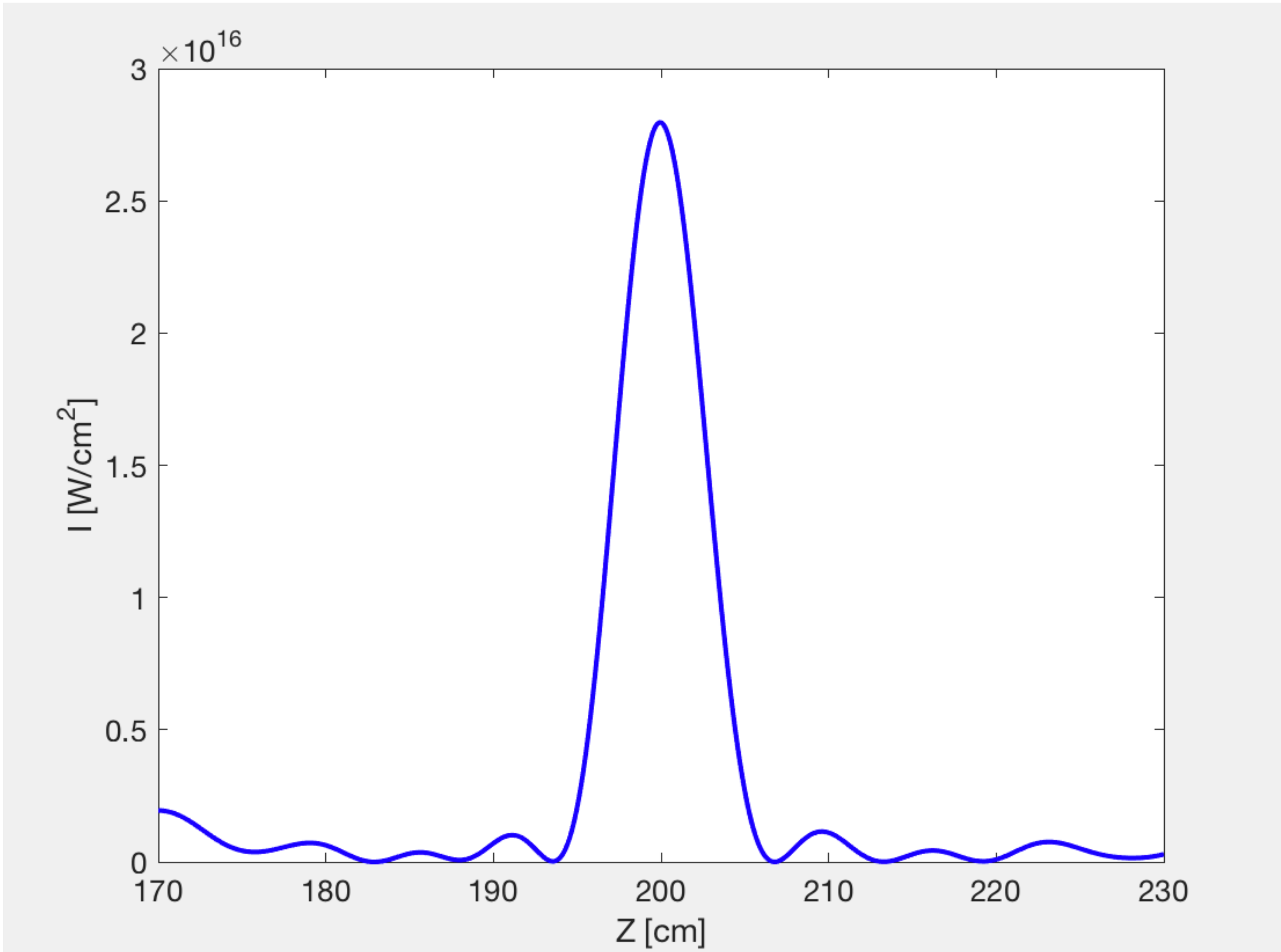


Concave Mirror

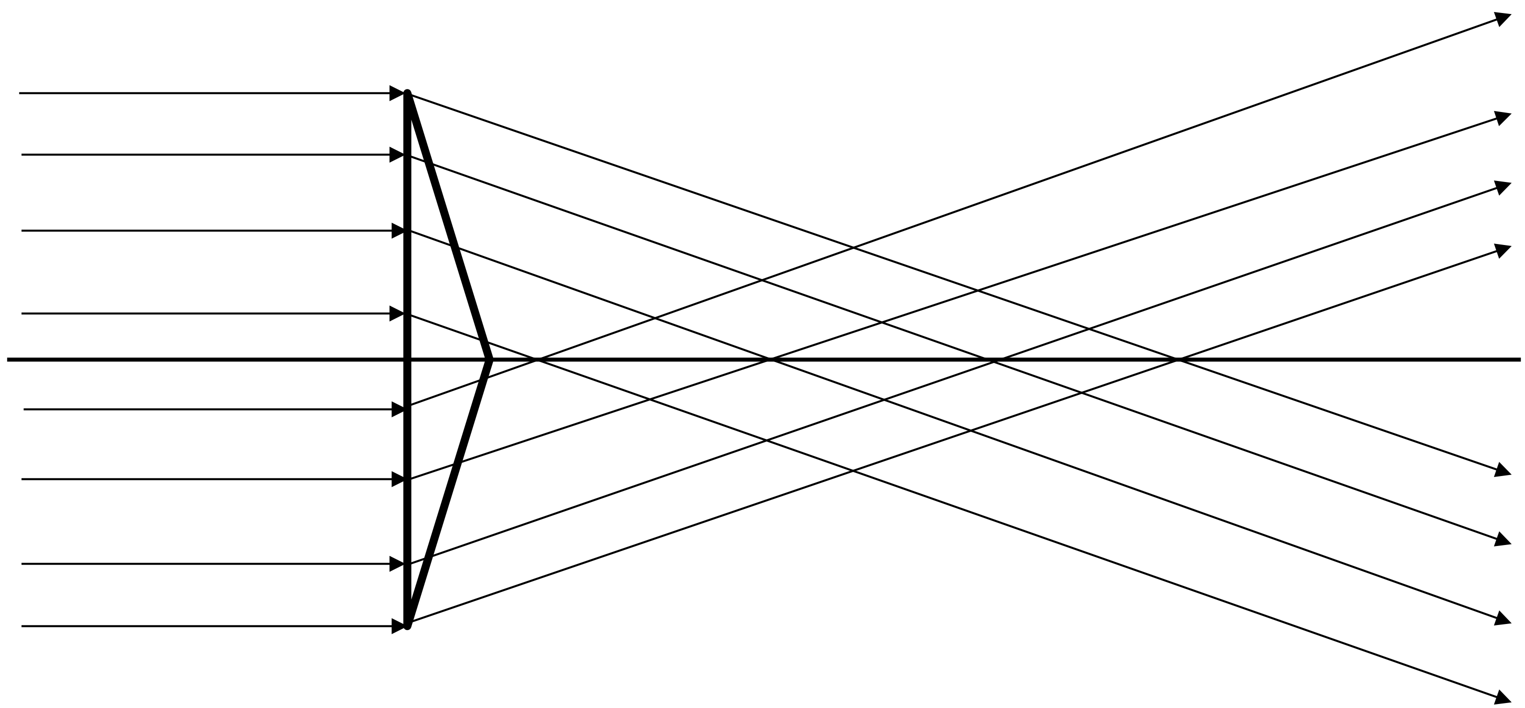




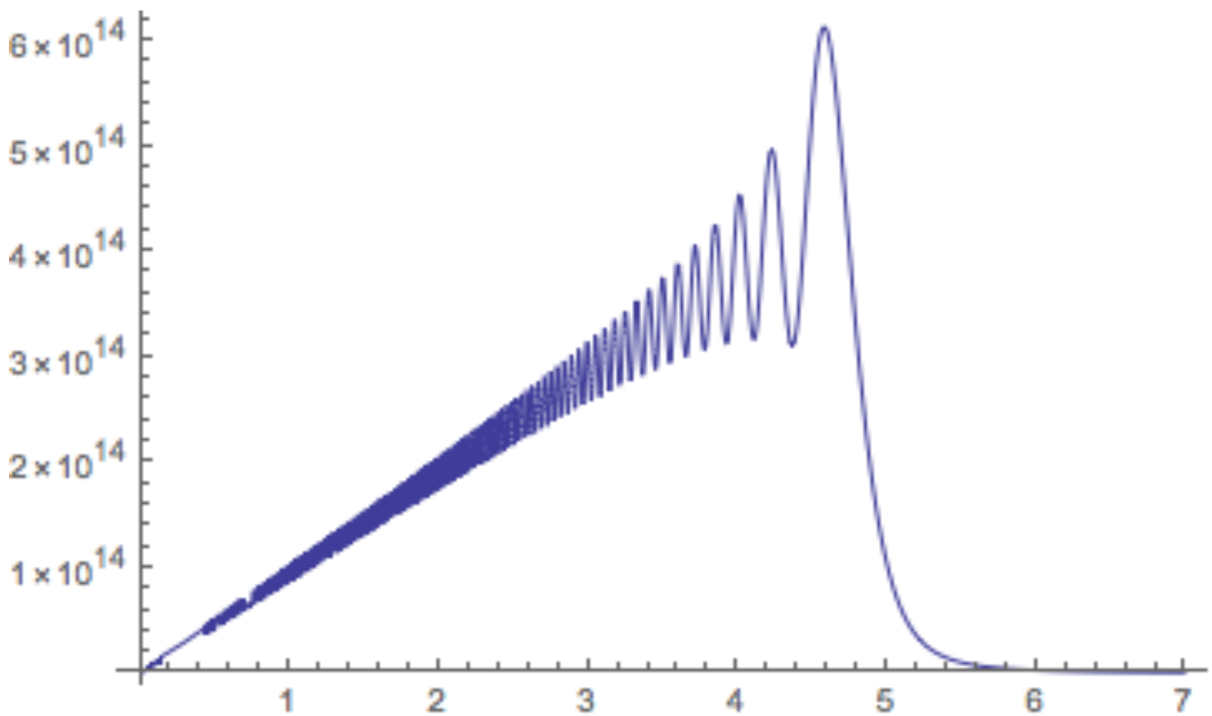
×10^16
2.5
2
1.5
1
0.5
I [W/cm^2]
230
220
210
200
190
180
170
Z [cm]
-200
-100
0
100
200
R [μm]


×10^16
3
2.5
2
1.5
1
0.5
0
I [W/cm^2]
170
180
190
200
210
220
230
Z [cm]

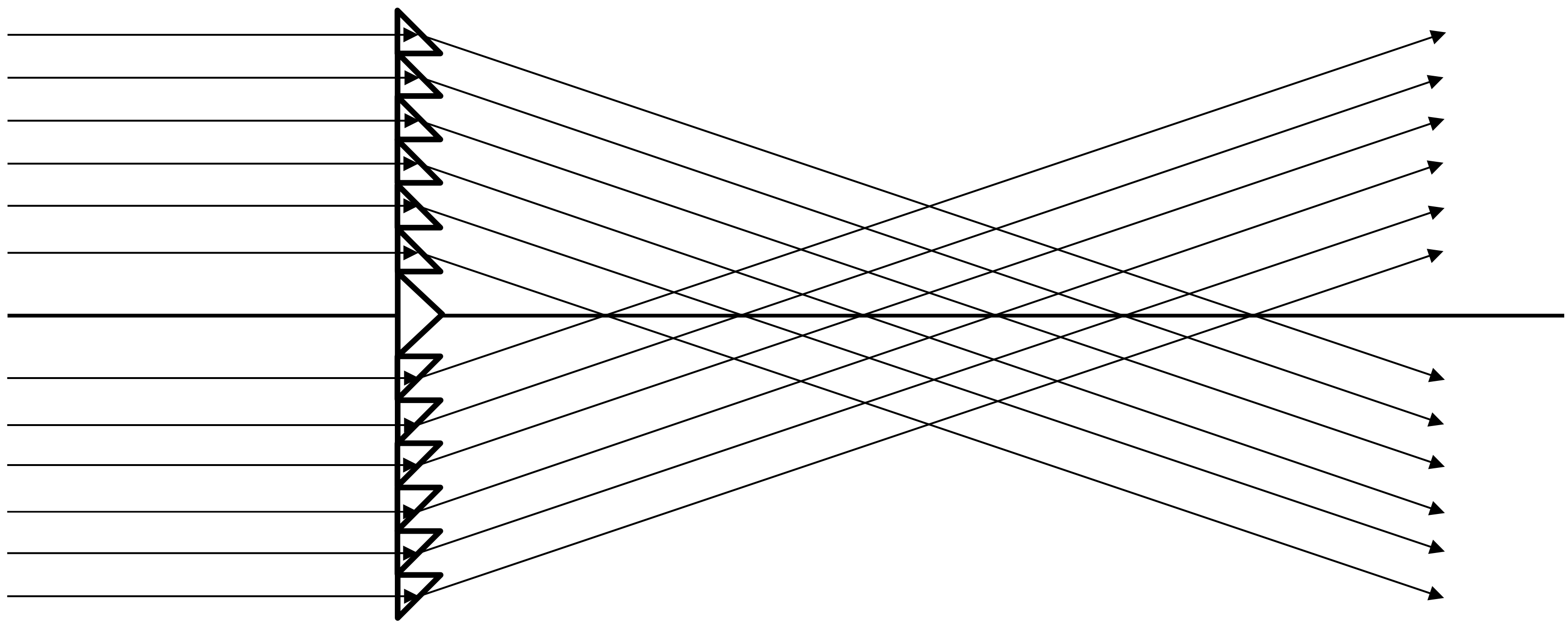
Transmitting Axicon



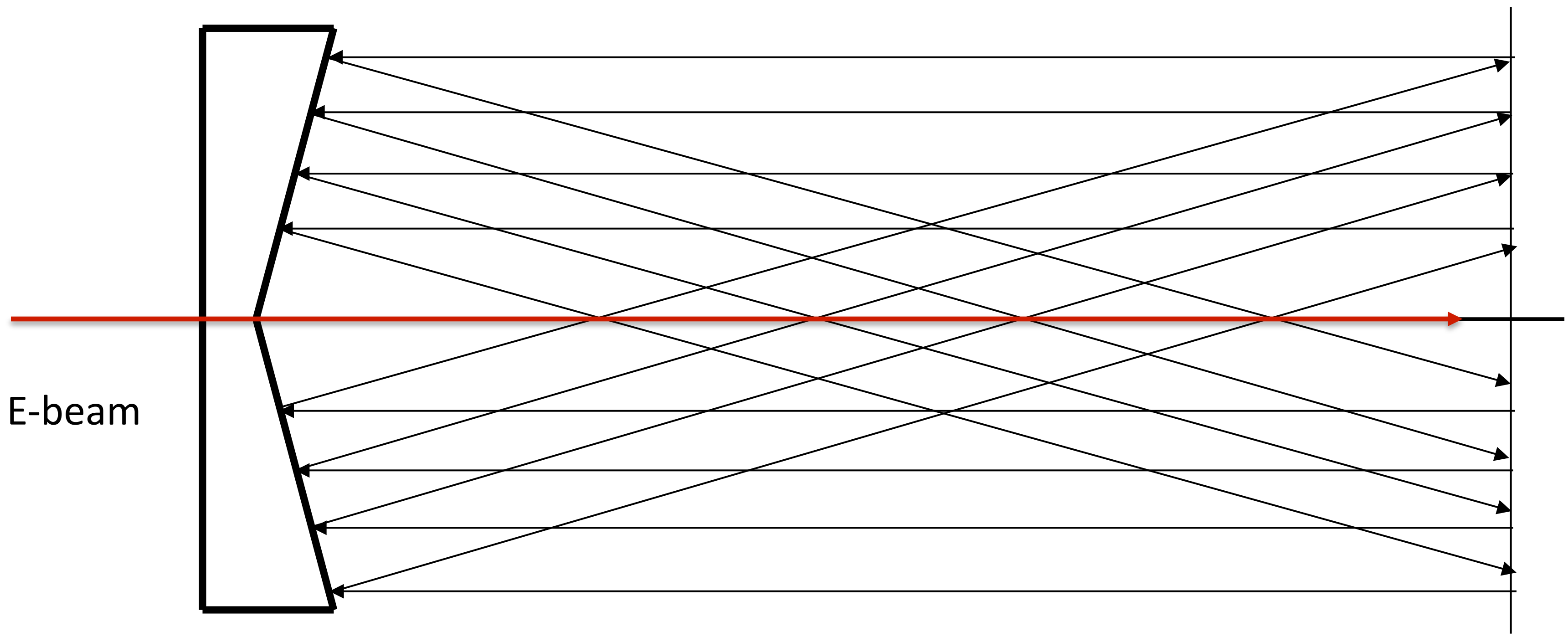
Axicon intensity profile



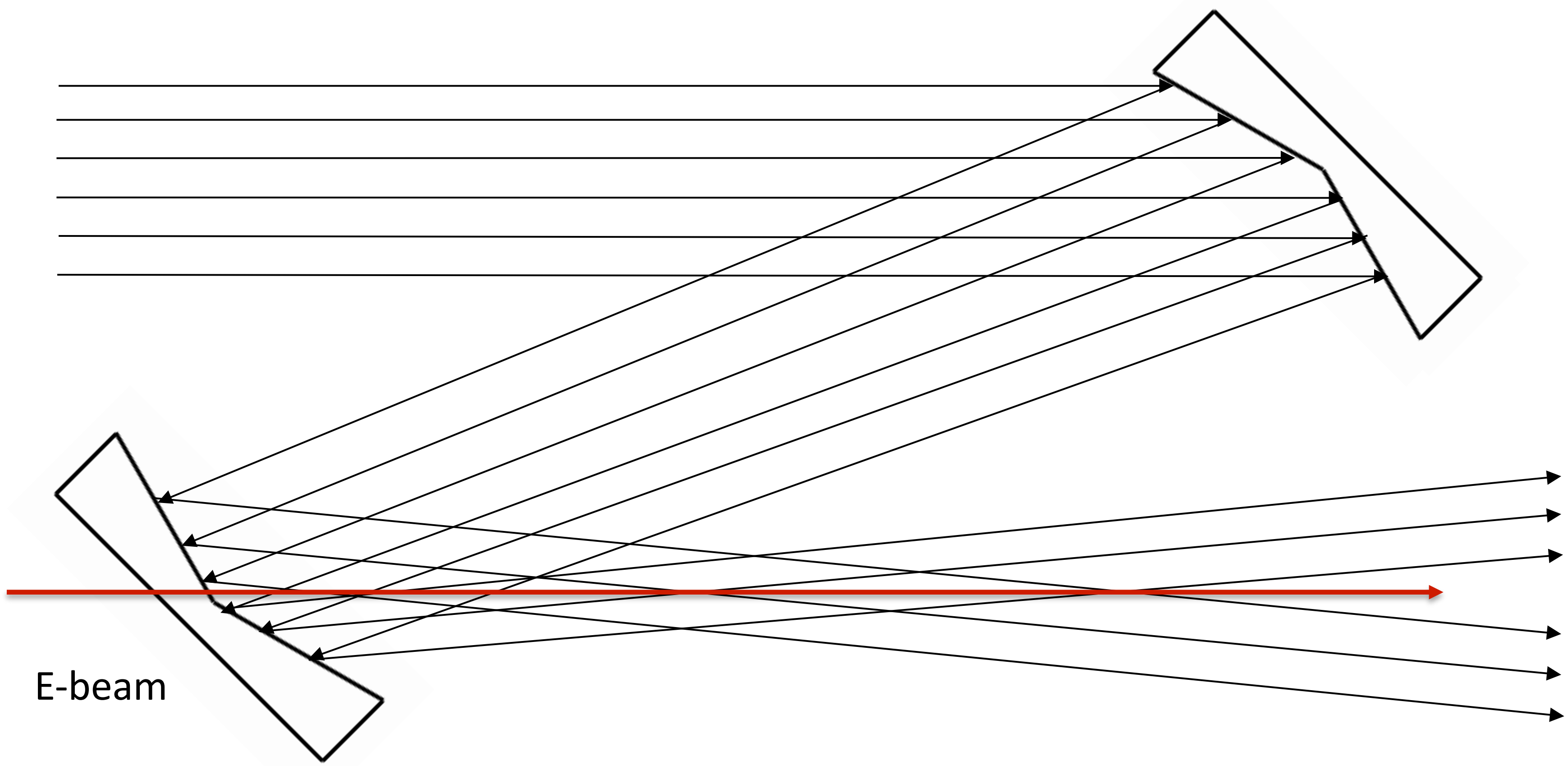
Transmitting Kinoform and Axilens



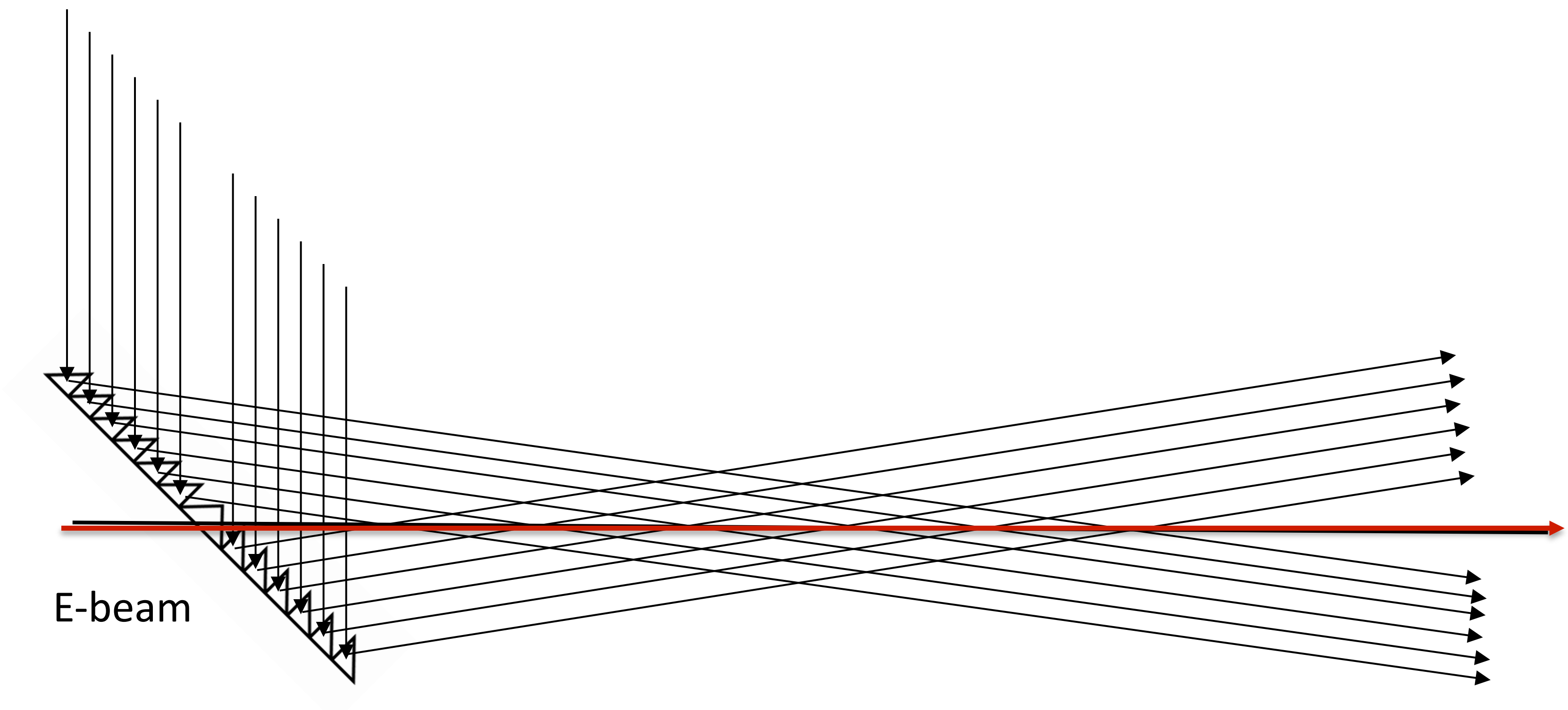
Reflecting Axicon



2 Reflecting Axicons



45 deg Reflecting Kinoform



Applied Optics, Vol 42, January 2003

Differential pumping basics

- In steady state the following equations holds for calculating conductance if

  $P_1 >> P_2$

  - Conductance of an orifice

    $C\left[\frac{L}{s}\right] = 20A$

  - Conductance of a pipe

    $C\left[\frac{L}{s}\right] = 135\frac{d^4}{l}\overline{p} + 12.1\frac{d^3}{l}\left(\frac{1+192d\overline{p}}{1+237d\overline{p}}\right) \quad \overline{p}[mbar] = \frac{P_1 + P_2}{2}$

From conductance, we can calculate the pumping speed:

$$S\left[\frac{L}{s}\right] = C\left(\frac{P_1}{P_2}\right)$$

$Q=P_2S=P_1C$ Flow rate

- S - Pump speed
- C - Aperture conductance
- Q - PV flow (Pump throughput)
- P_1 - High pressure side
- P_2 - Low pressure side
- A - Area of orifice in cm^2
- d - Diameter of hole/pipe in cm
- $\overline{p}$ - Pressure average

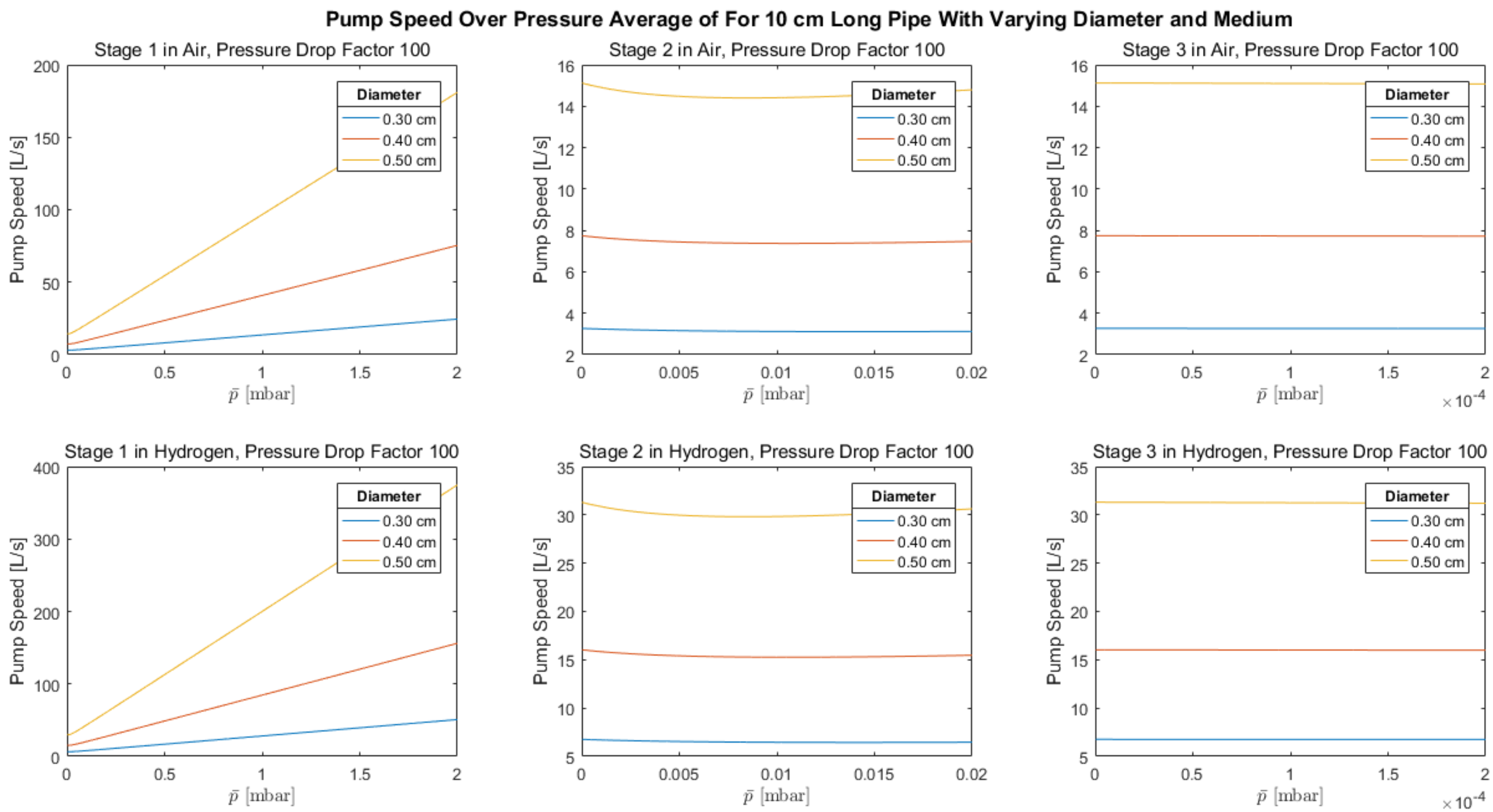
Conductance factors of gases

Gas (20 °C)	Molecular flow	Laminar flow
Air	1.00	1.00
Oxygen	0.947	0.91
Neon	1.013	1.05
Helium	2.64	0.92
Hydrogen	3.77	2.07
Carbon dioxide	0.808	1.26
Water vapor	1.263	1.73

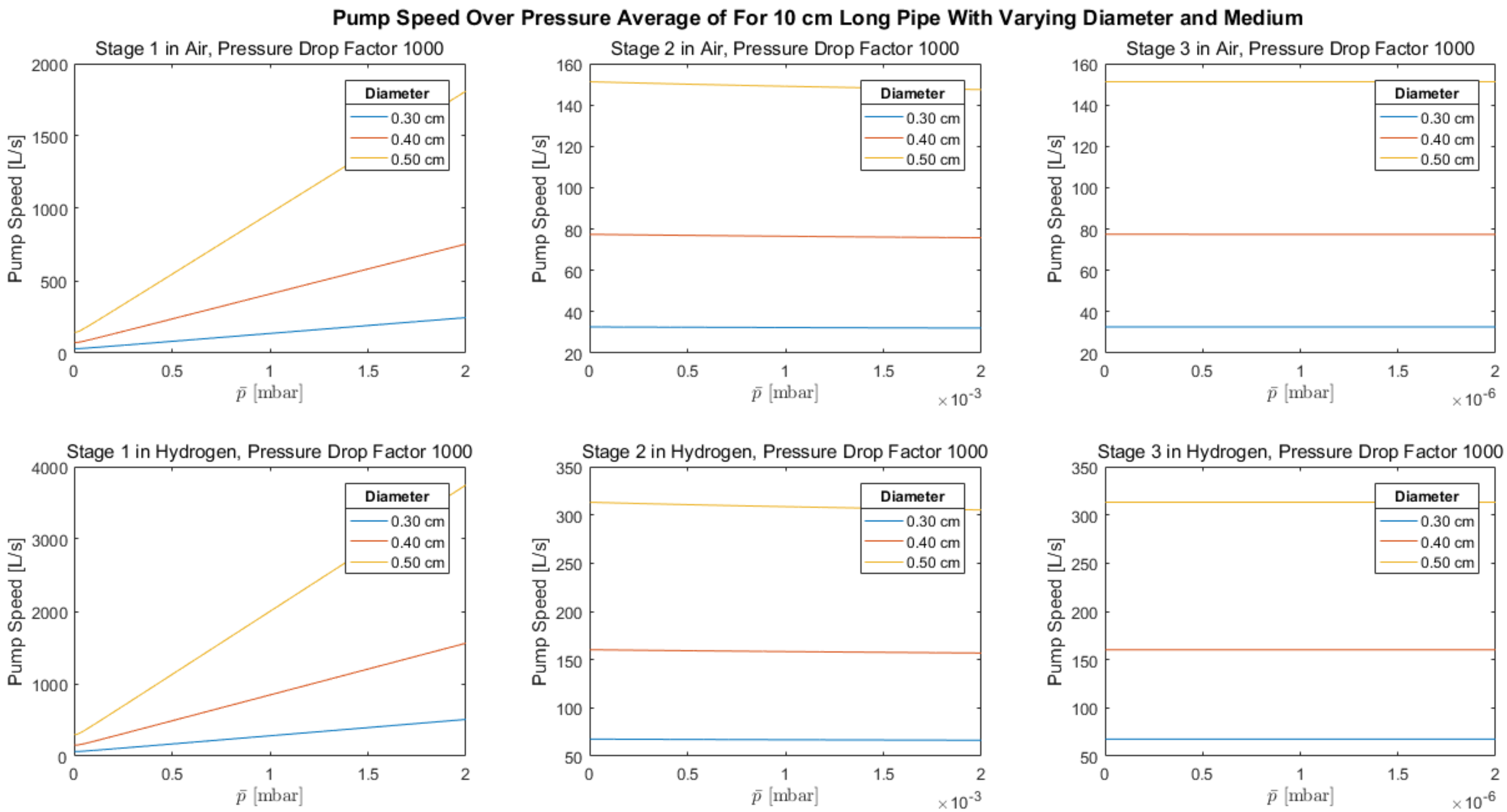
Table 1.1 Conversion factors (see text)

When working with other gases it will be necessary to multiply the conductance values specified for air by the factors shown in Table 1.1.

Calculation Through Pipe (100x)



Calculation Through Pipe (1000x)



Gas Flow Technology

- Gas flow requirements. How much gas?
  - Pulsed, cells and jets < 100 scfh
  - Oven with diff pumping < 100 scfh
  - H_2 with ramps < 10 scfh
- Recirculating H_2 or He?
- Can differential pumped Helium be used with lithium oven?
  - Look a flow patterns in Solidworks Flow. WIP
- Si_3N_4 solves a lot of problems, if it holds up!

Some hardware beam testing and commissioning

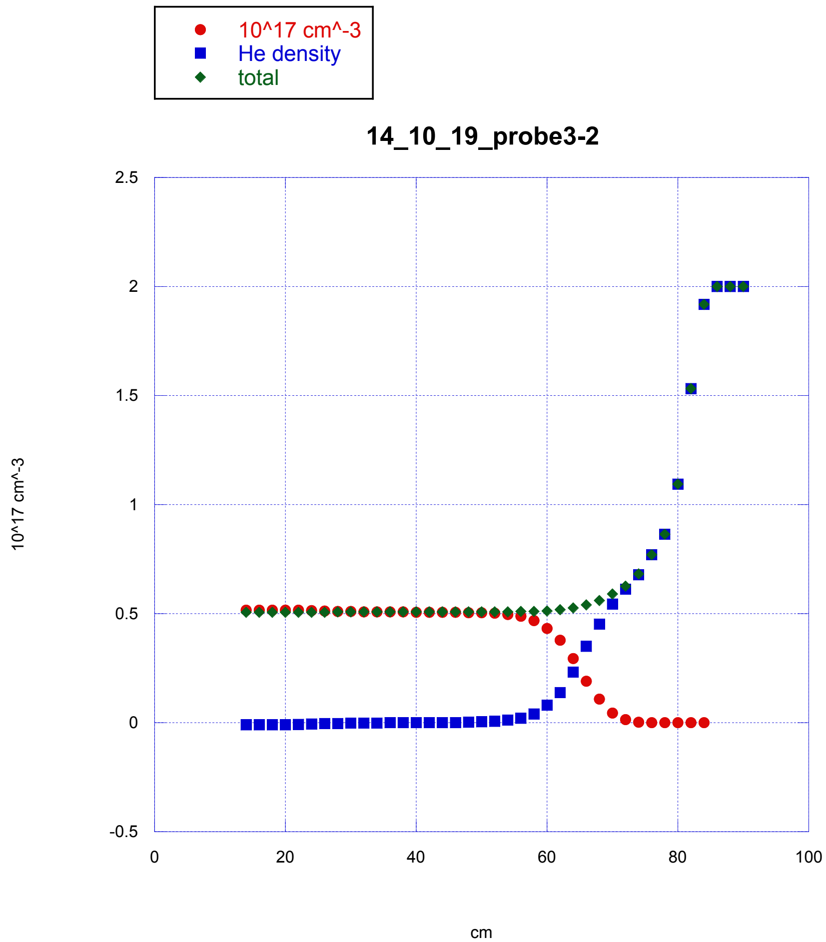
- Study 30 kA beam damage to, windows, OTR foils and apertures
- Be vs Si_3N_4 foils damage test
- Emittance growth from foils and neutral gases, H_2 and He
- Gas control systems, differential pumping
- Beam ionize H_2 plasma
- H2 gas cell damage testing
- Beam Emittance diagnostics?
  - Multiscreen beam characterization with foils
- All beam diagnostics
  - High current beams

The End

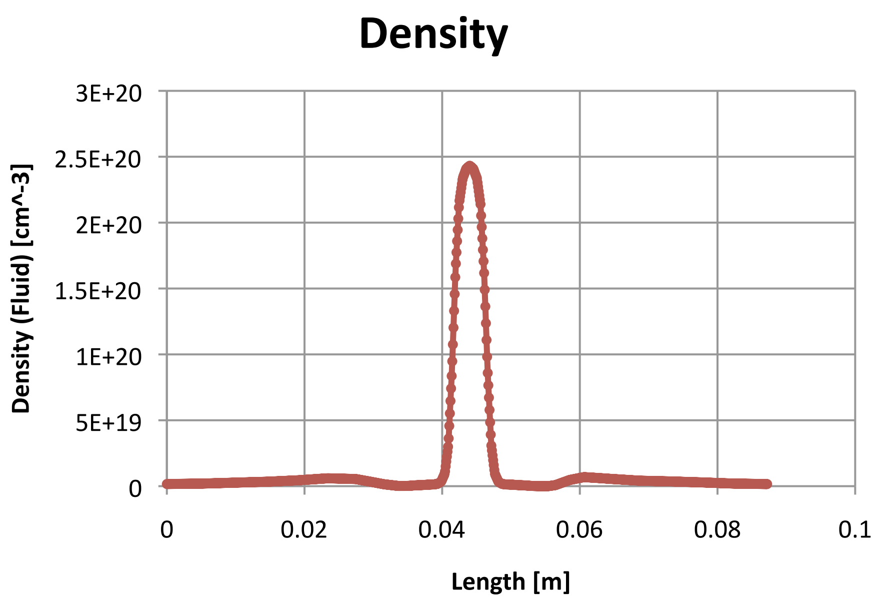
Laser technology

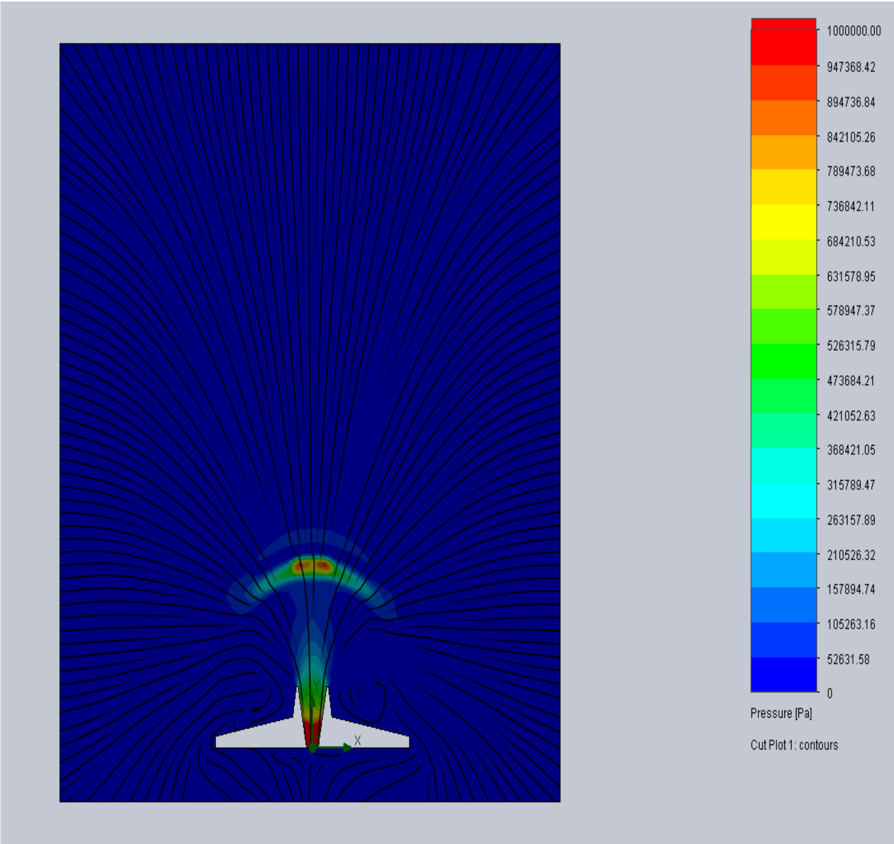
- More power for ionization of H2, see Shaper
  - 10x ionization threshold
- Plasma homogeneity
  - Laser profile correction
  - Measure phase front with Phasics
  - Correct with deformable mirror
- Measured too much pulse distortion due to short pulses in transmitting optics
  - Wedges cause spatial chirp
  - SPM
    - Use fabs for beam splitters
    - Enlarge beam
  - SPM changes phase front and therefor bessel profile
    - This was tested at ucla, see ppt
    - Plasma in glass asts like lens
- Beamsplitters can change the laser spectral shape
- Avoid thick transmitting optics in laser room
- All RP attenuator issues, new design
- Laser beam profile improvement to make uniform plasma
- Laser beam dump not required if diff pump
- SiN3 windows could be far DS without significant emittance growth

The helium wall



Gas Jet 10^20 density





- 2mm bottom hole
- 5mm top hole
- 8mm height
- Lineout taken at 1.2 mm above exit

Beam ionized H2 plasma