CALIFES Research Exploitation Workshop

Emittance Growth due to Beam Scattering in Plasma

The Cockcroft Institute of Accelerator Science and Technology

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of Accelerator Science and Technology

Outline

Idea to test

- Emittance and energy spread growth via scattering by plasma ions and electrons.
- Simulations for linear collider based on PDPWFA (500m) are available - relevant to shorter ranges, more significant at lower energy,
- A fundamental measurement: Complementary to our longer term plans: correlation between media (vacuum, gas, plasma) and beam divergence (or even better emittance),
- No need for wakefield generation.

What do we have?

- Partial equipment to build a gas-filled capillary based discharge plasma source,
- Experience in numerical tools (particle interaction with matter and fluid dynamics) and diagnostics,
- Man power.

What do we need?

- Electron beam,
- A touch more equipment on top of existing ones.

ELECTRON-PLASMA SCATTERING

Tracking Scenario

Pre-formed wakefields by LCODE

- Longitudinal (0.5 GV/m) and transverse (0.1 GV/m) fields defined in GEANT4,
- Li (Z = 3, a = 6.941 g/mol), Rb ((Z = 37, a = 85.468 g/mol)) gasses and vacuum were considered,
- Uniform medium: 500m long, 100mm radial extent.

Initial beam

- 10k particles at 10 GeV
- Gaussian distribution for beam size and divergence, with standard deviation of 10μm and 10μrad.

ELECTRON-PLASMA SCATTERING

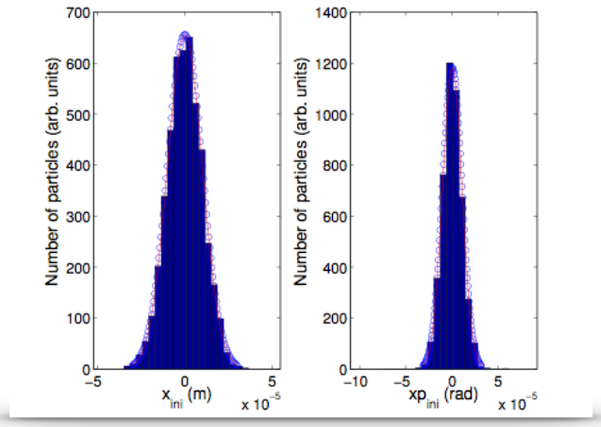
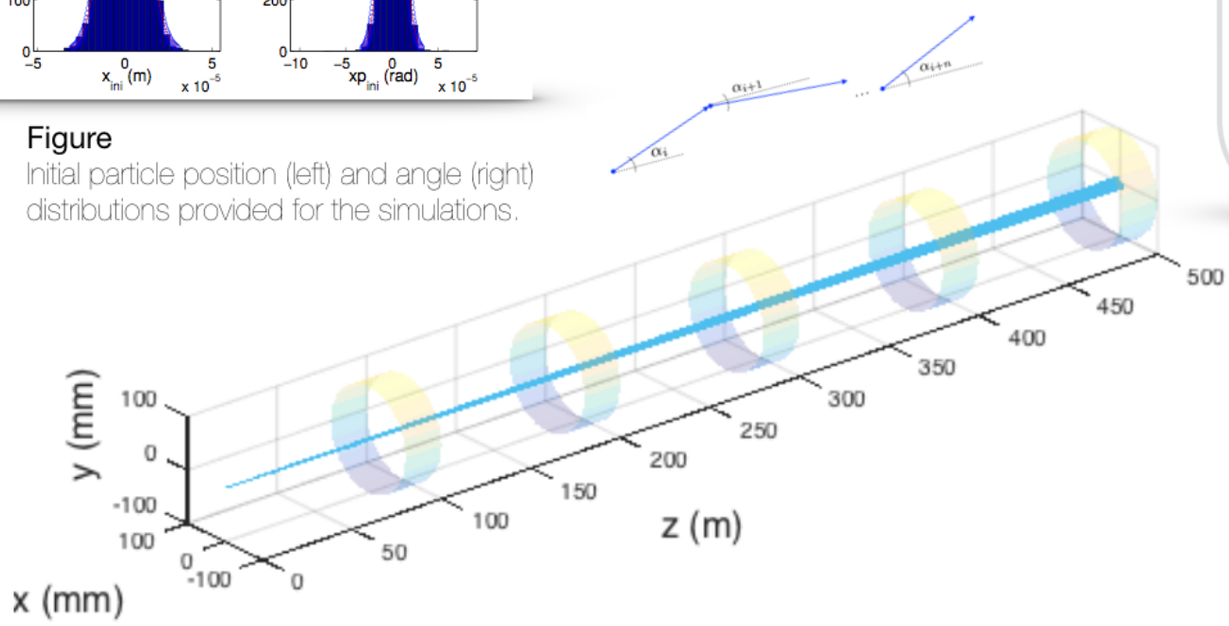


Figure
Initial particle position (left) and angle (right) distributions provided for the simulations.

This 500 m plasma column with 100 mm radius was split into logical sections of 20 m, and the transverse phase space of the beam was reconstructed at the end of each section. For the analysis, primary particle tracks were isolated from possible secondary particles.



Emittance growth due to multiple Coulomb scattering.

$$\Delta\epsilon = \frac{F}{2\gamma'}\left[\sqrt{\gamma_f} - \sqrt{\gamma_i}\right]$$

$$F = 2\pi r_e^2 n\left[\frac{-\pi\sigma_0^2 mc^2}{\lambda_p e E_{z0}\cos(\phi)}\right]^{1/2} ln\left(\frac{\lambda_D}{R}\right)$$

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$$

Reference [8]

$$\epsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\langle x^2\rangle = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2}$$

$$\langle x'^2\rangle = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2}$$

$$\langle xx'\rangle = \sum_{i=1}^{N}(x_i - \langle x\rangle)(x'_i - \langle x'\rangle)$$

A geometric cut was implemented to reject the particle tracks falling outside of the plasma column with a radius of 100 mm. The rms emittance values were calculated and Courant-Snyder parameters were extracted.

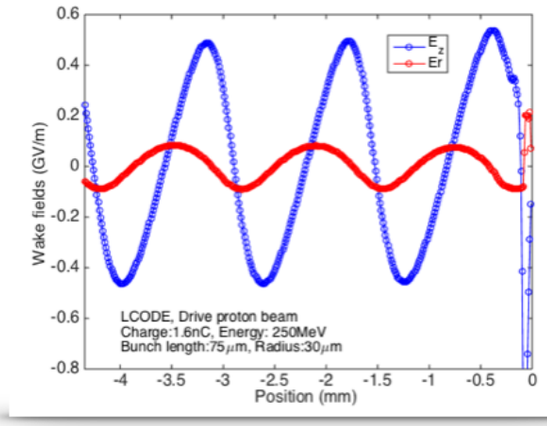


Figure
Longitudinal and radial plasma wake fields due to a proton bunch that is located at zero.

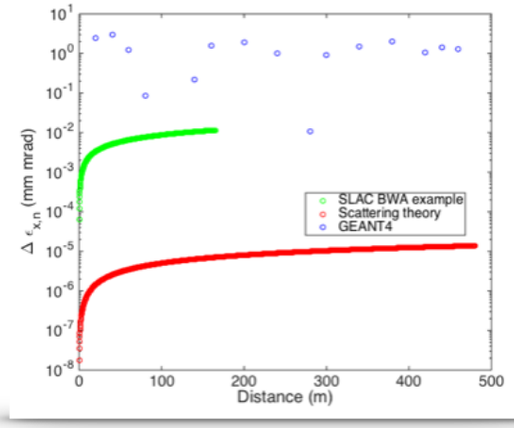
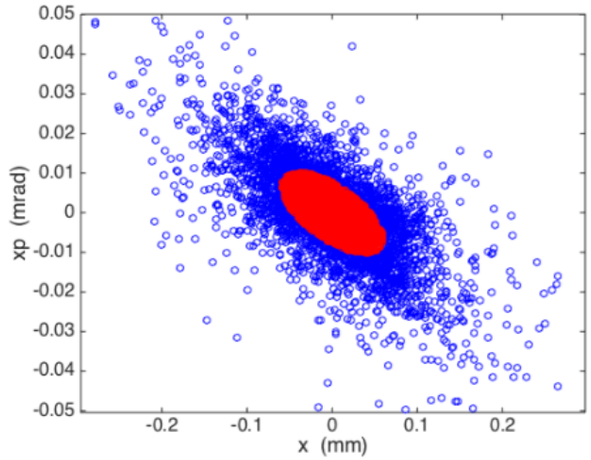
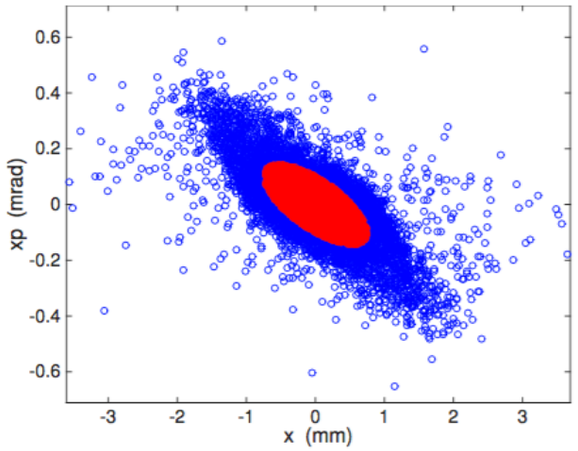


Figure
The evolution of emittance growth throughout a gas column of 500 m according to the theoretical predictions and GEANT4 results.

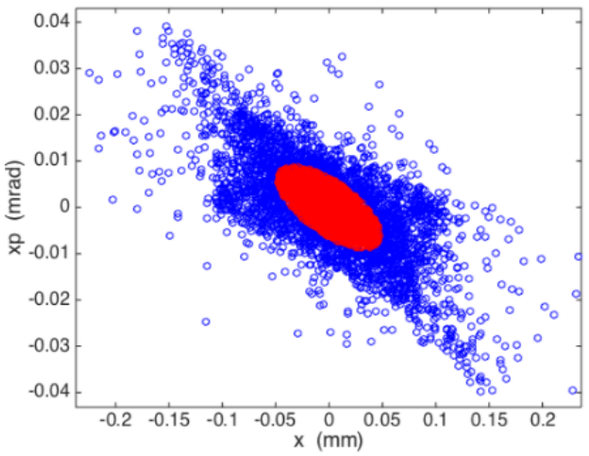
ELECTRON-PLASMA SCATTERING



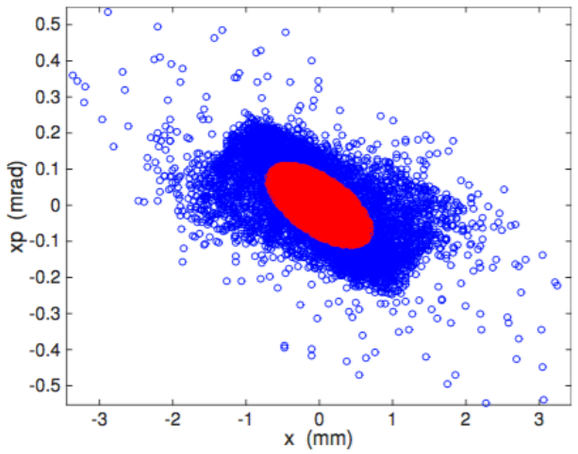
(a) at 100 m in Li gas.



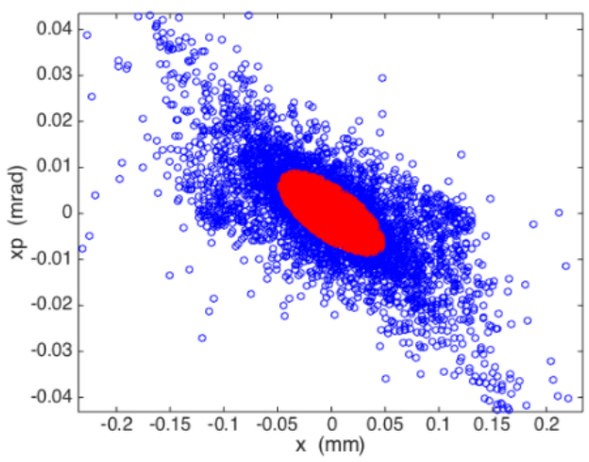
(b) at 100 m, Rb gas.



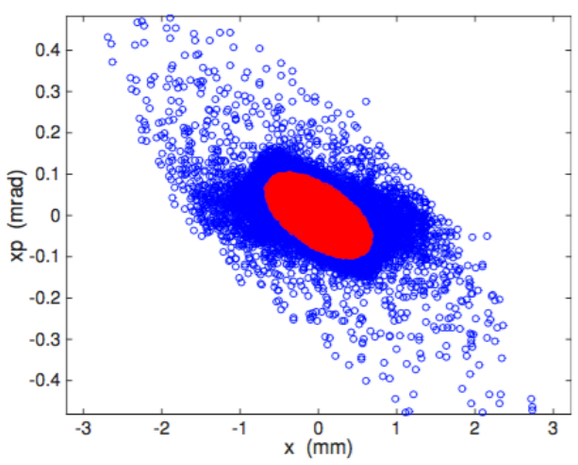
(c) at 200 m, Li gas.



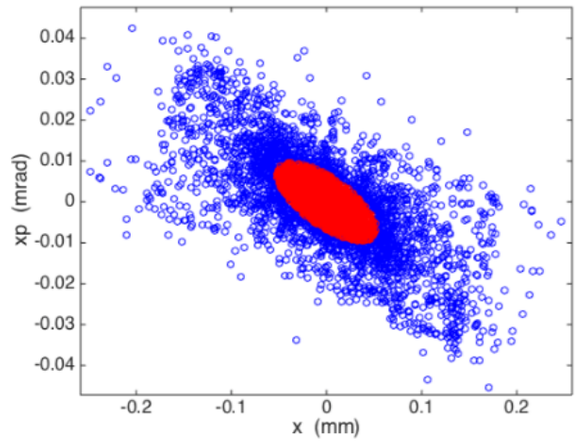
(d) at 200 m, Rb gas.



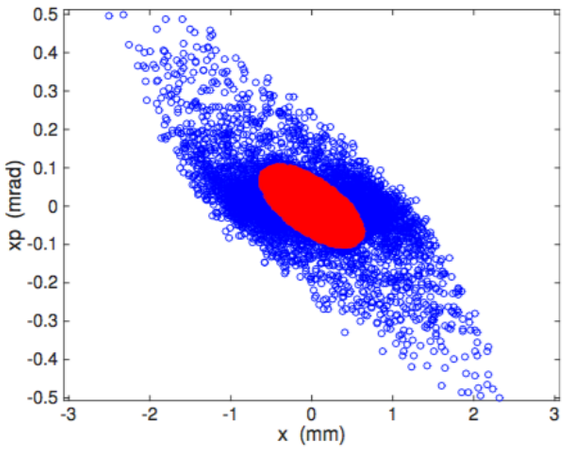
(e) at 300 m, Li gas.



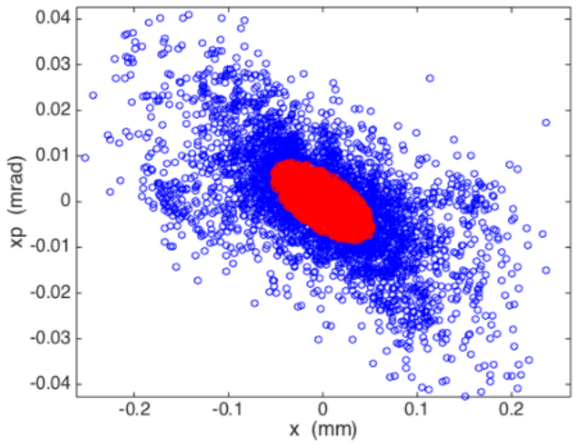
(f) at 300 m, Rb gas.



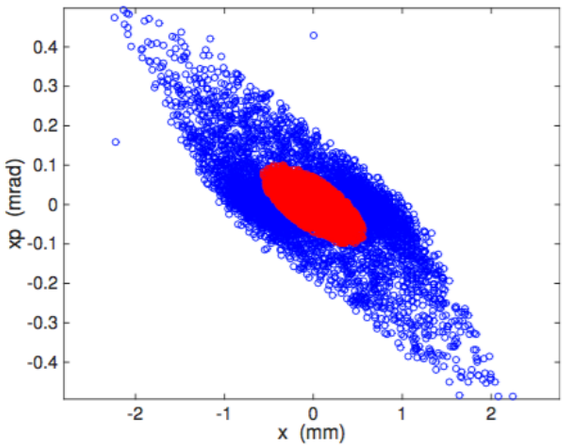
(g) at 400 m, Li gas.



(h) at 400 m, Rb gas.

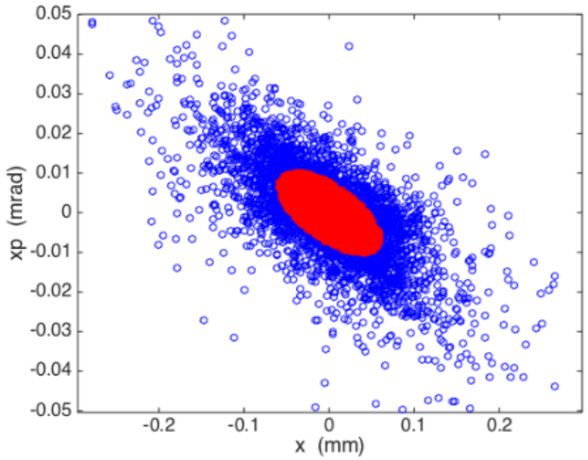


(i) at 500 m, Li gas.

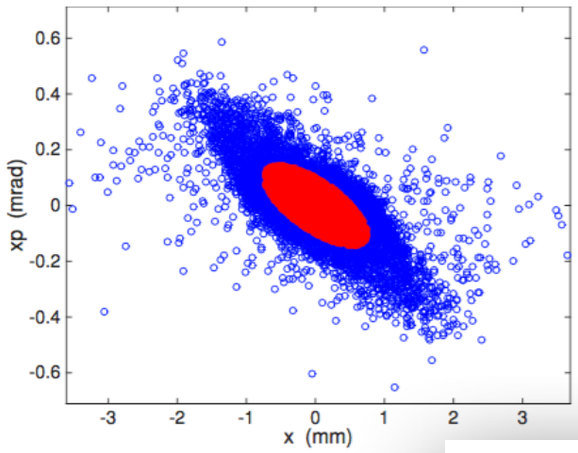


(j) at 500 m, Rb gas.

ELECTRON-PLASMA SCATTERING



(a) at 100 m in Li gas.



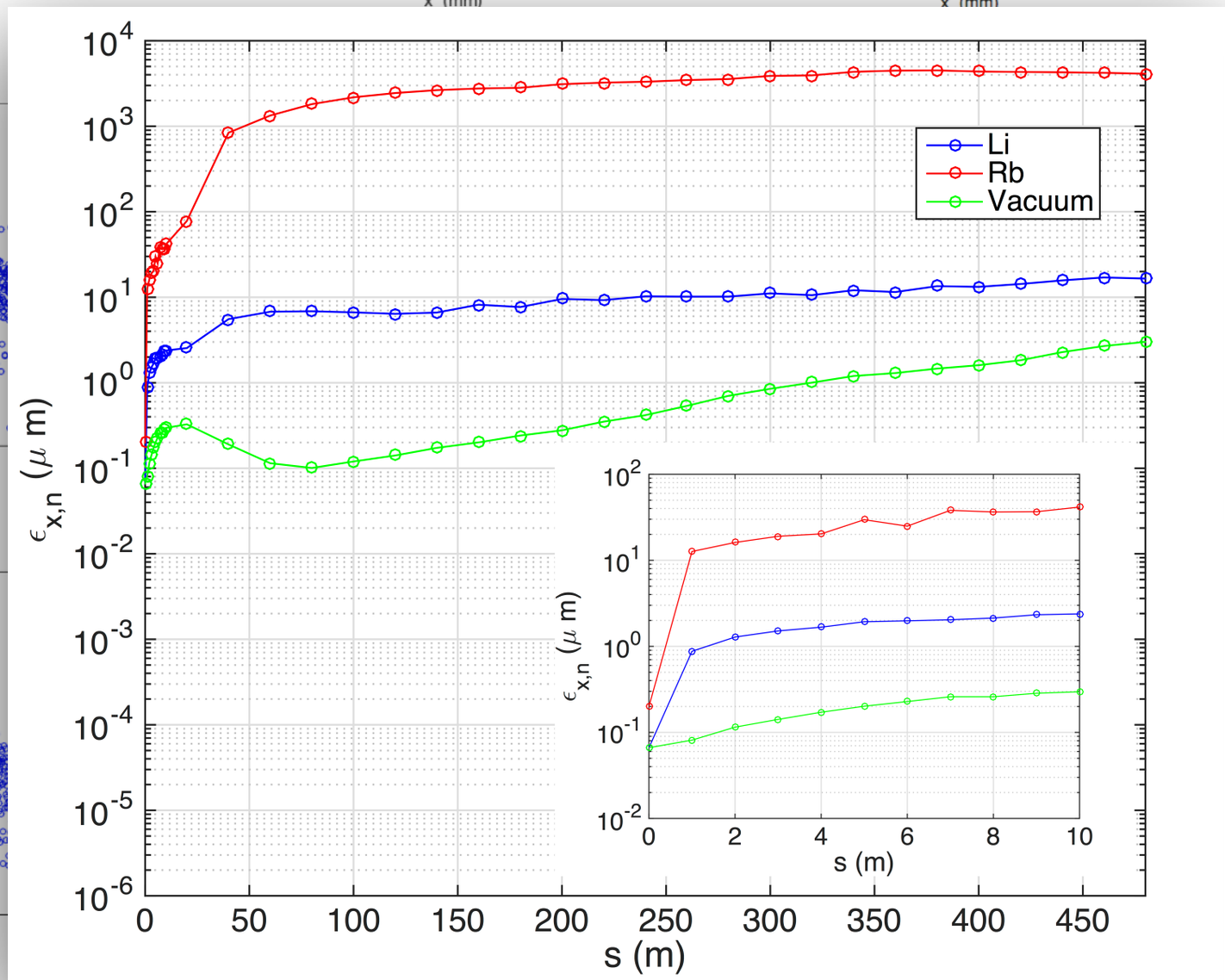
(b) at 100 m, Rb gas.

(c) at 200 m, Li gas.

(d) at 200 m, Rb gas.

(e) at 300 m, Li gas.

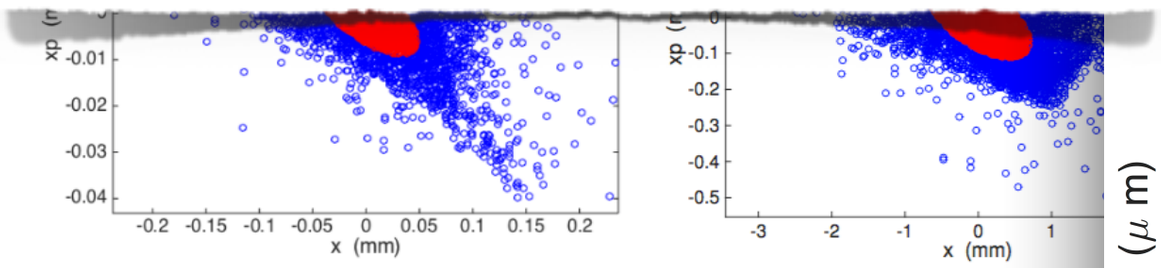
(f) at 300 m, Rb gas.



ELECTRON-PLASMA SCATTERING

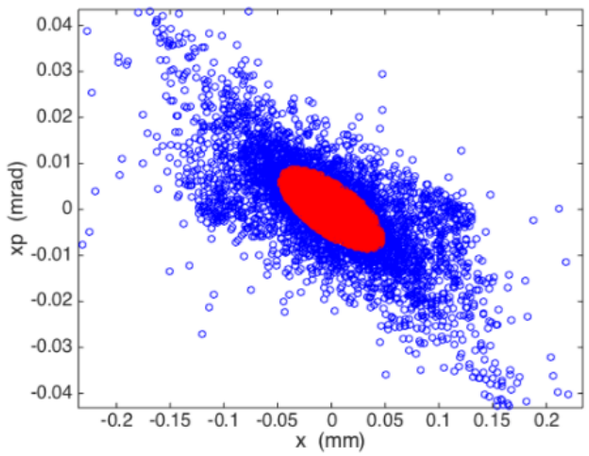
According to the simulations, the largest growth is induced by the multiple scattering of the beam particles by plasma particles. Rb gas yields two orders of magnitude larger emittance growth (41 mm mrad/m) than Li gas (0.5 mm mrad/m) in average over 500 m, as expected, since the scattering cross section is proportional to the square of the atomic number. Both cases are compared to the vacuum case where beam travels through vacuum under the effect of the transverse and longitudinal wakefields, and an average emittance growth of 6 nm/m was calculated due to effects other than scattering such as plasma-beam mismatch.

O. Mete et al.,
Physics of Plasmas 22, 083101 (2015).

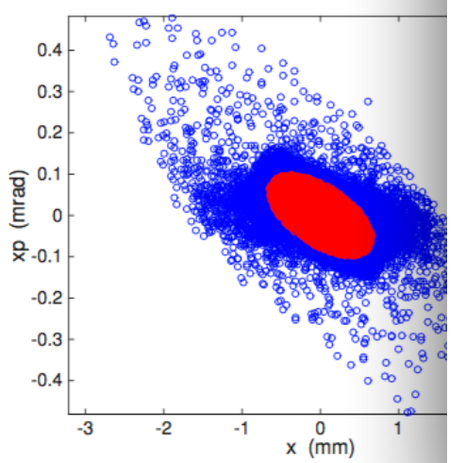


(c) at 200 m, Li gas.

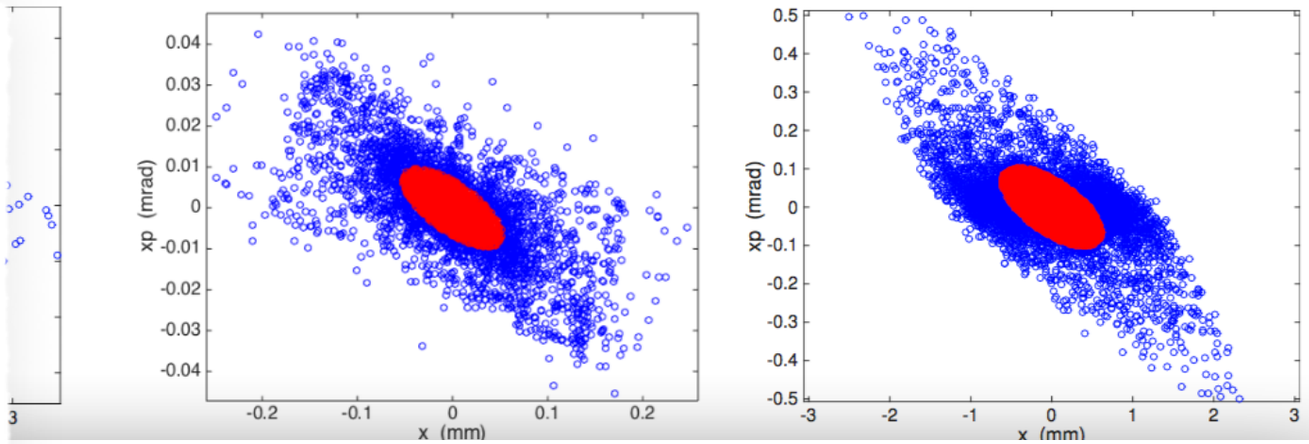
(d) at 200 m, Rb gas.

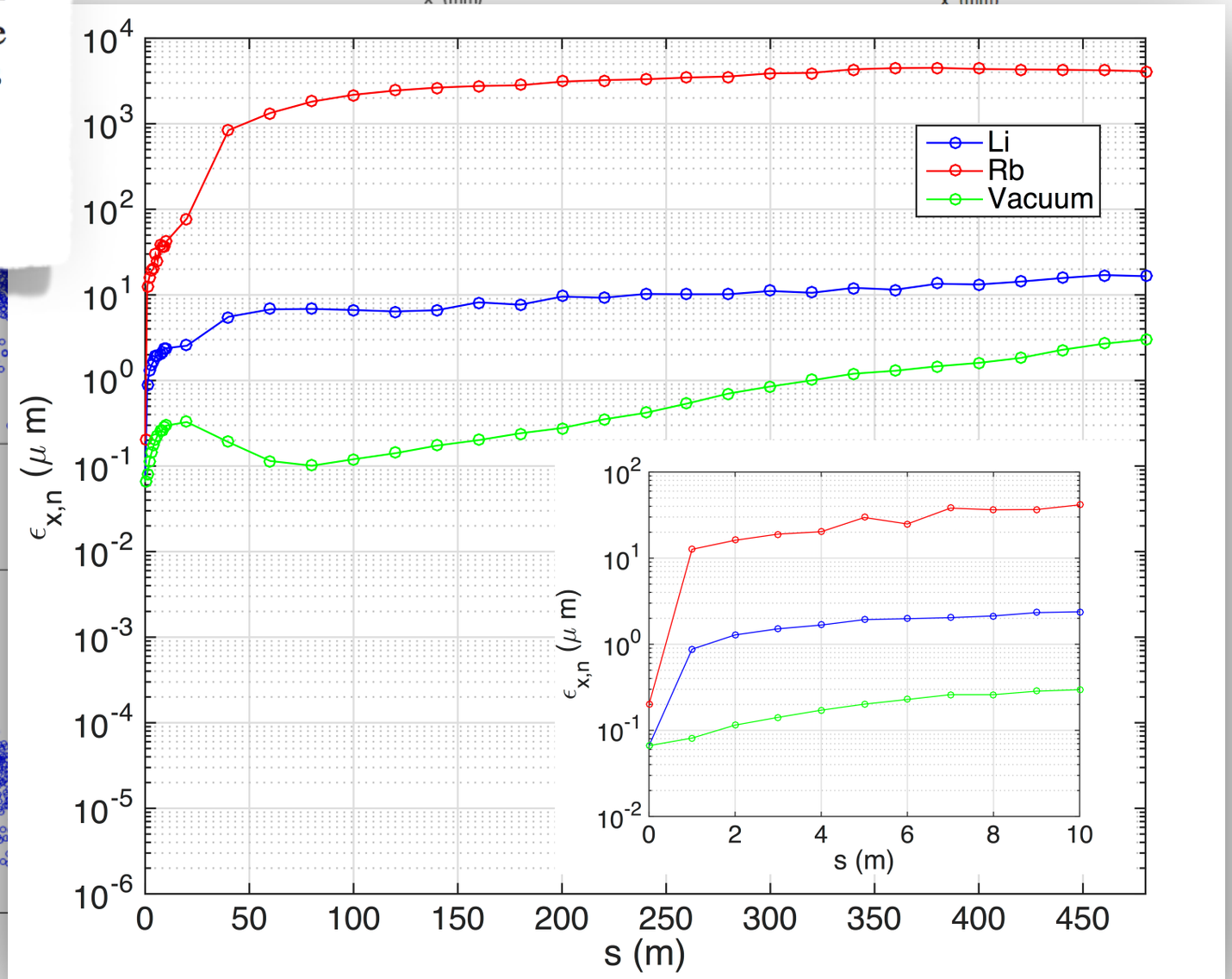


(e) at 300 m, Li gas.



(f) at 300 m, Rb gas.





ELECTRON-PLASMA SCATTERING

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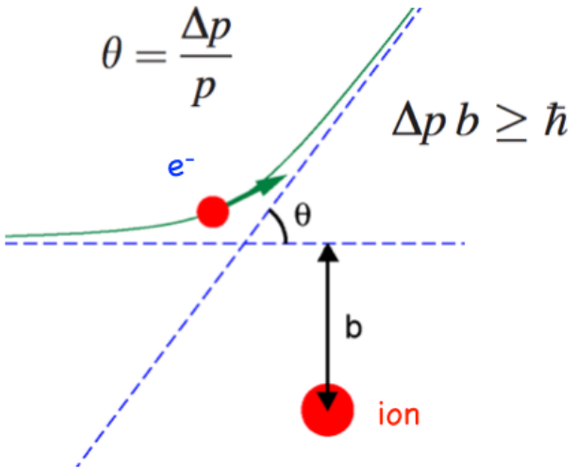


$$\theta_{min,max} = \frac{\hbar}{p\, b_{max,min}}$$

Minimum impact factor, can be related to the effective Coulomb radius of the nucleus, R for neutral gas (ion impact is larger than neutral atom case - due to the potential including the electronic structure of the ion).

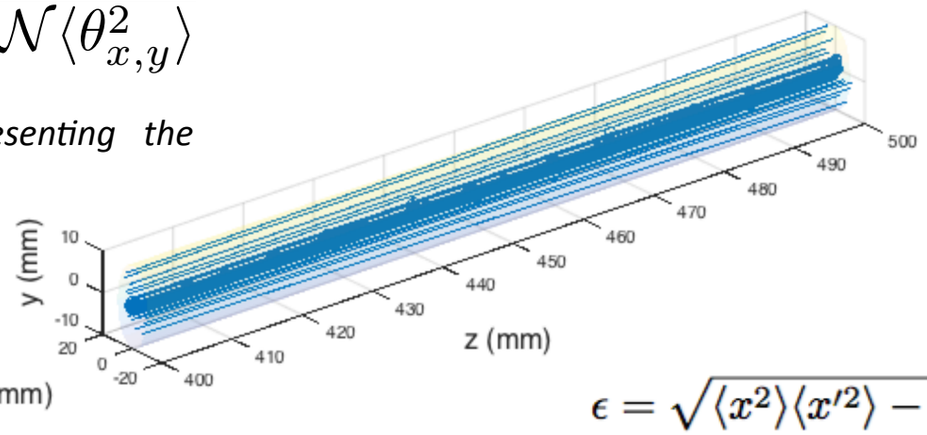
Simulations might overestimate θmax.

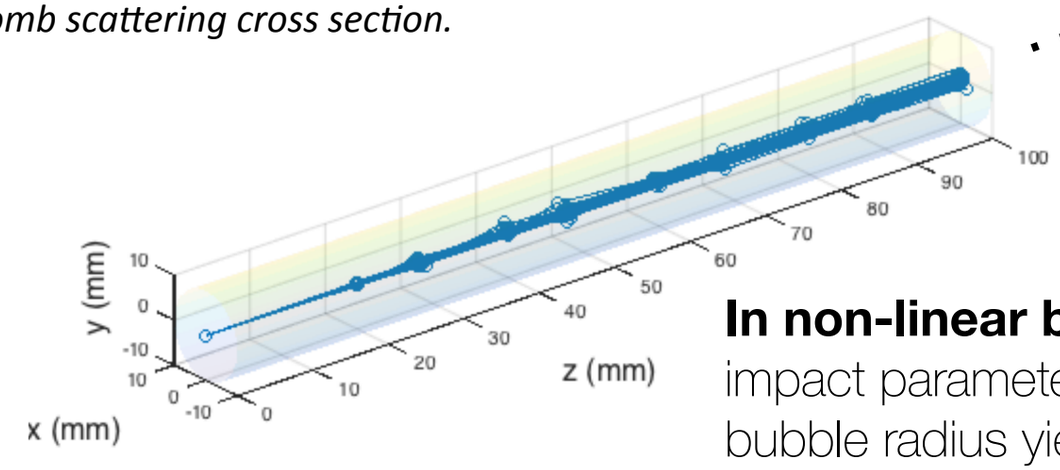
$$\frac{d\sigma}{d\Omega} \approx \left(\frac{2Zr_0}{\gamma}\right)^2 \frac{1}{(\theta^2 + \theta_{min}^2)^2}$$

Coulomb scattering cross section.

$$\Delta\epsilon_{n,x,y} = \frac{\gamma\beta_{x,y}}{2}\overline{\mathcal{N}\langle\theta_{x,y}^2\rangle}$$

Diffusion equation representing the emittance growth.

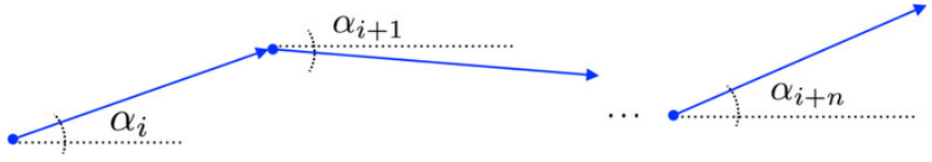




In a fully ionised plasma, maximum impact parameter corresponds to the plasma Debye length.

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$$

In non-linear bubble regime, maximum impact parameter will be defined by the bubble radius yielding much smaller scattering angles.



$$\epsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\langle x^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2$$

$$\langle x'^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2$$

$$\langle xx'\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)(x'_i - \langle x'\rangle)$$

Capillary Based Discharge Plasma Source

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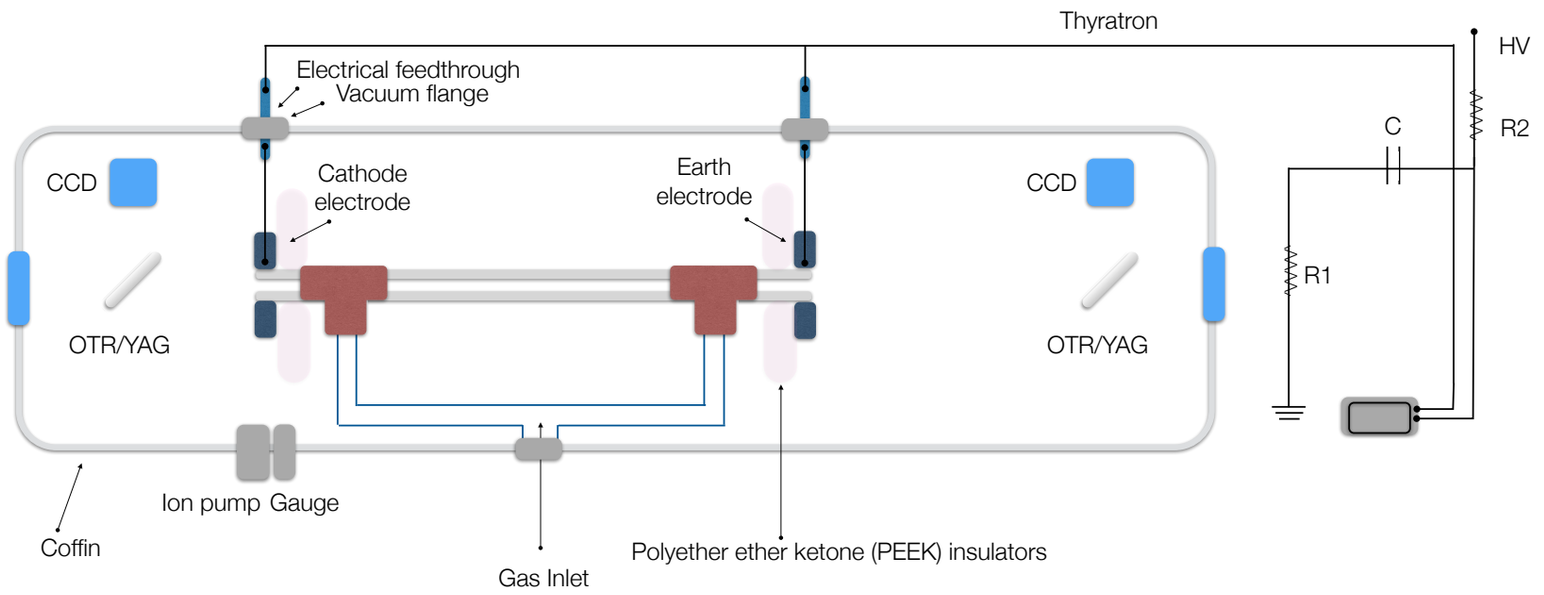

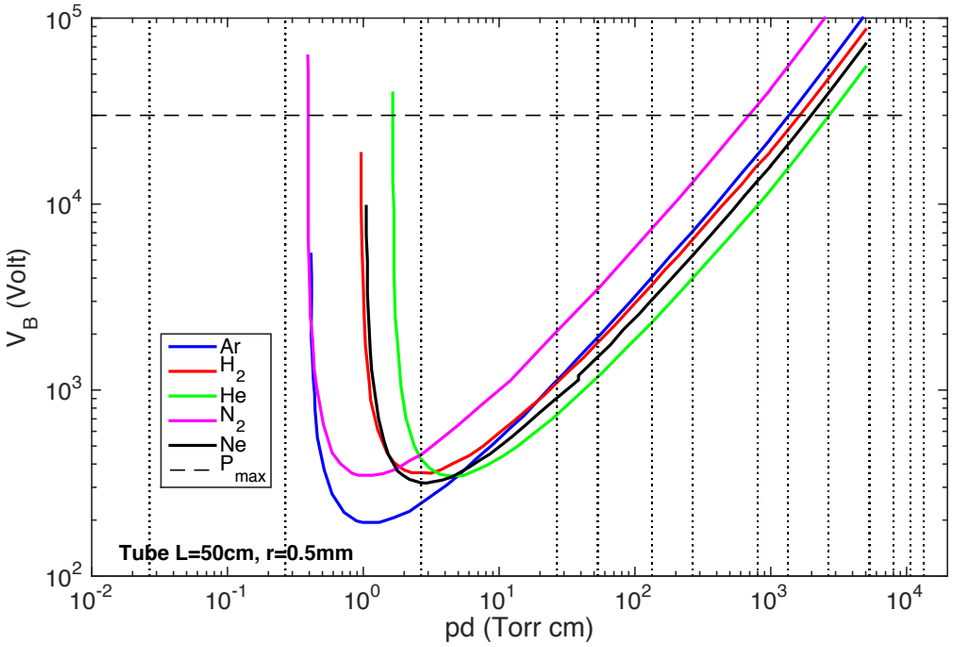

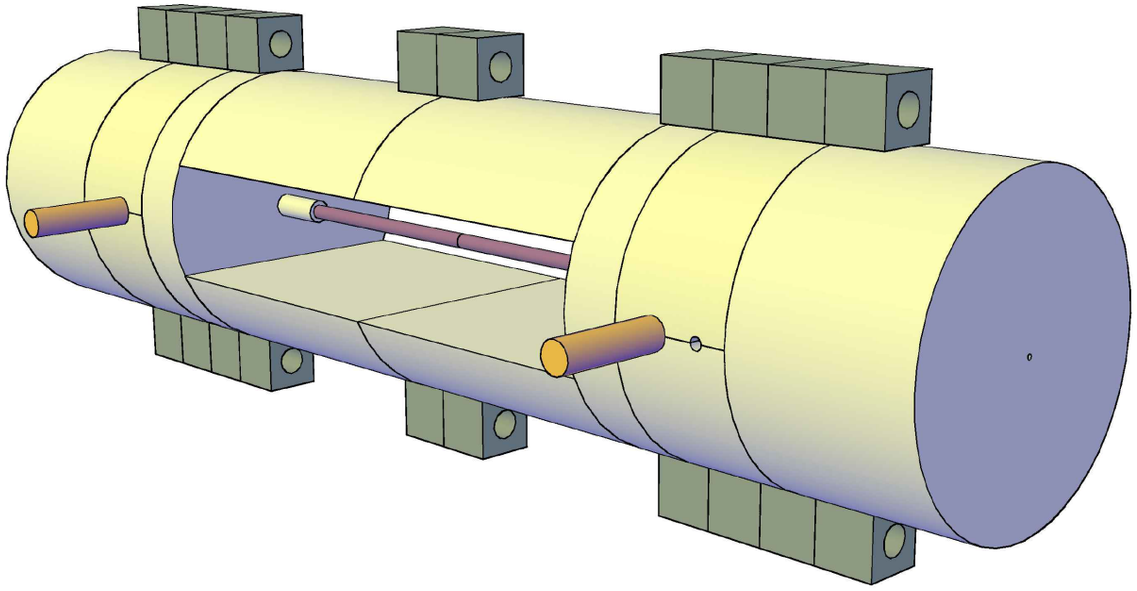

n (m^{-3})	Pressure (mbar)	Pd (5 cm) (mm mbar)	Pd (10 cm) (mm mbar)	Pd (50 cm) (mm mbar)
1×10^{17}	0.000533	0.002665[a]	0.00533[a]	0.02665[a]
1×10^{18}	0.00533	0.02665[a]	0.0533[a]	0.2665[a]
1×10^{19}	0.0533	0.2665[a]	0.533	2.665
1×10^{20}	0.533	2.665	5.33	26.65
2×10^{20}	1.067	5.335	10.67	53.35
5×10^{20}	2.7	13.5	27	135
1×10^{21}	5.33	26.65	53.3	266.5
3×10^{21}	16	80	160	800
5×10^{21}	26.7	133.5	267	1335
1×10^{22}	53.33	266.65	533.3	2666.5
2×10^{22}	106.67	533.35	1066.7	5333.5[b]
3×10^{22}	160	800	1600	8000[b]
4×10^{22}	213	1065	2130	10650[b]
5×10^{22}	266.7	1333.5	2667	13335[b]

[a]No discharge can occur due to low pressure. [b] No discharge can occur due to power limit.

Collaboration with Nelson Lopes et al.?

10^{13}-10^{17}cm^{-3} is theoretically possible.

6x10^{14}cm^{-3} used in the simulations.

Capillary Based Discharge Plasma Source

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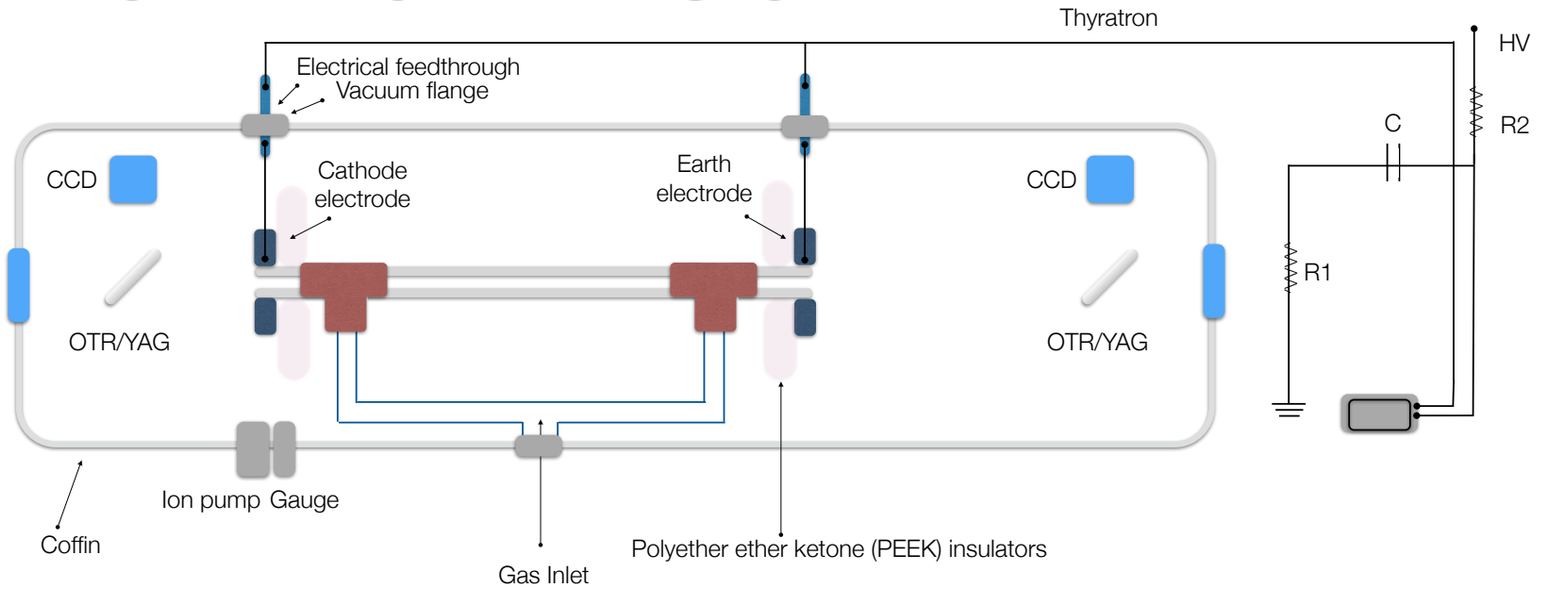
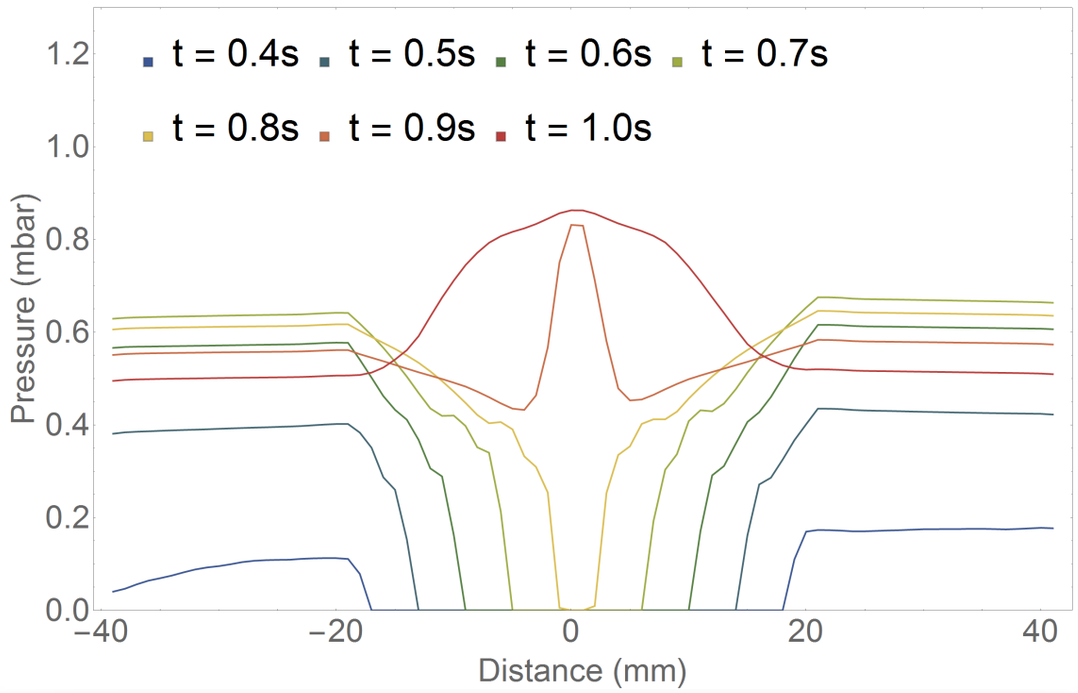
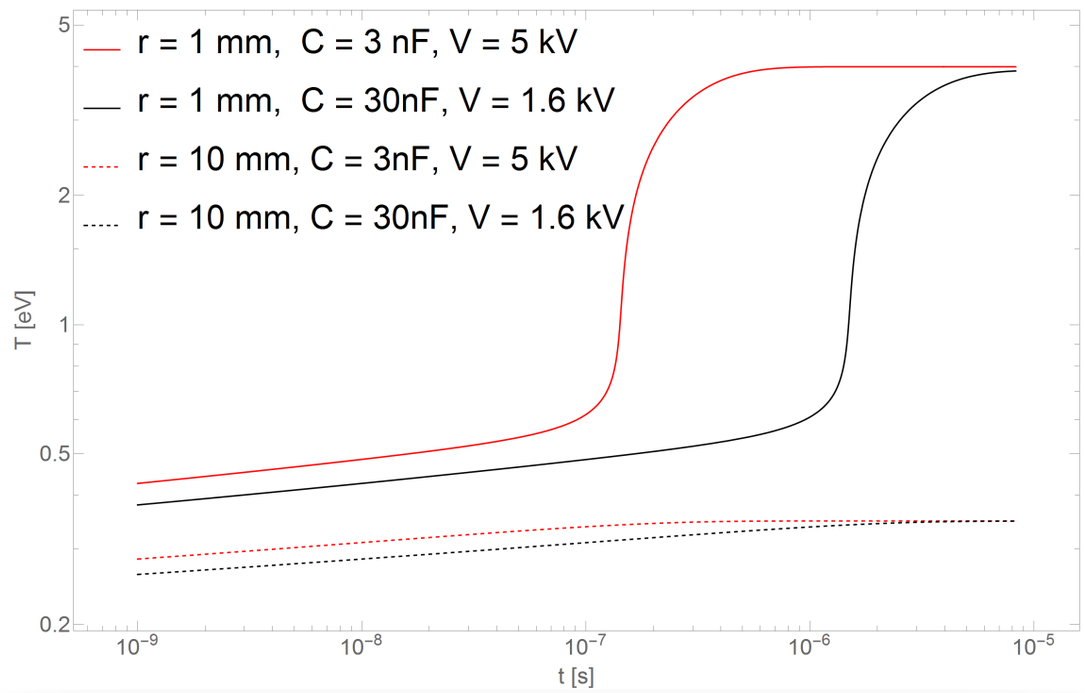
NUMERICAL DESIGN



Plasma temperature can be measured with optical spectrometry by using a diffraction grating and a CCD camera.

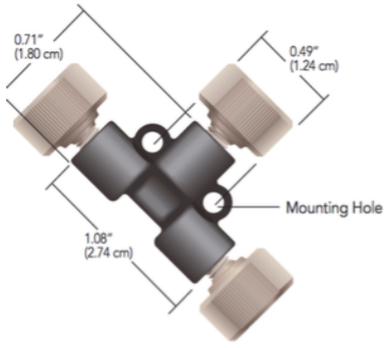




Capillary Based Discharge Plasma Source

Existing Equipment

HV powering, connectors, tubes and auxiliary equipment, vacuum chamber.



Power Source FR30P10.0F22	Glassman
Thyratron CX1622	AEP International
Trigger assembly MA2709A	AEP International
HV electrical feedthrough FHP30-C1-40CF	LewVac
Power in-line connector FHP-BECU-3IL-CON (10/pk)	LewVac
Alumina ceramic beads CB-AL2.7 (45/pk)	LewVac
Glass capillary 1ID1.2OD100Z (pack of 25 tubes)	CM Scientific
Glass capillary 1ID1.2OD300Z (pack of 25 tubes)	CM Scientific
Glass capillary 1.5ID1.8OD100Z (pack of 25 tubes)	CM Scientific
Glass capillary 1.5ID1.8OD300Z (pack of 25 tubes)	CM Scientific
Glass capillary 2ID2.4OD100Z (pack of 25 tubes)	CM Scientific
Glass capillary 2ID2.4OD300Z (pack of 25 tubes)	CM Scientific
Varian Torr Seal	Agilent Technologies
PEEK Tee connectors	Sigma
PEEK nuts and ferrules	Sigma
Vacuum chamber	CI + Kurt J Lesker

Equipment Still Needed for Scattering Tests

CCD Camera and auxiliary optics equipment	?
OTR screens for interferometer	Custom
Linear motion actuators	VacGen
Screen holders	University Workshop
Hydrogen gas cylinder (99.999%, 57L)	Fisher Scientific
Gas accessories	Fisher Scientific
Macor Machinable Glass Ceramic	Precision Ceramics
Precision ceramic machining	TBC
Miscellaneous tubing and fittings for gas to capillary	CM Scientific and Agilent

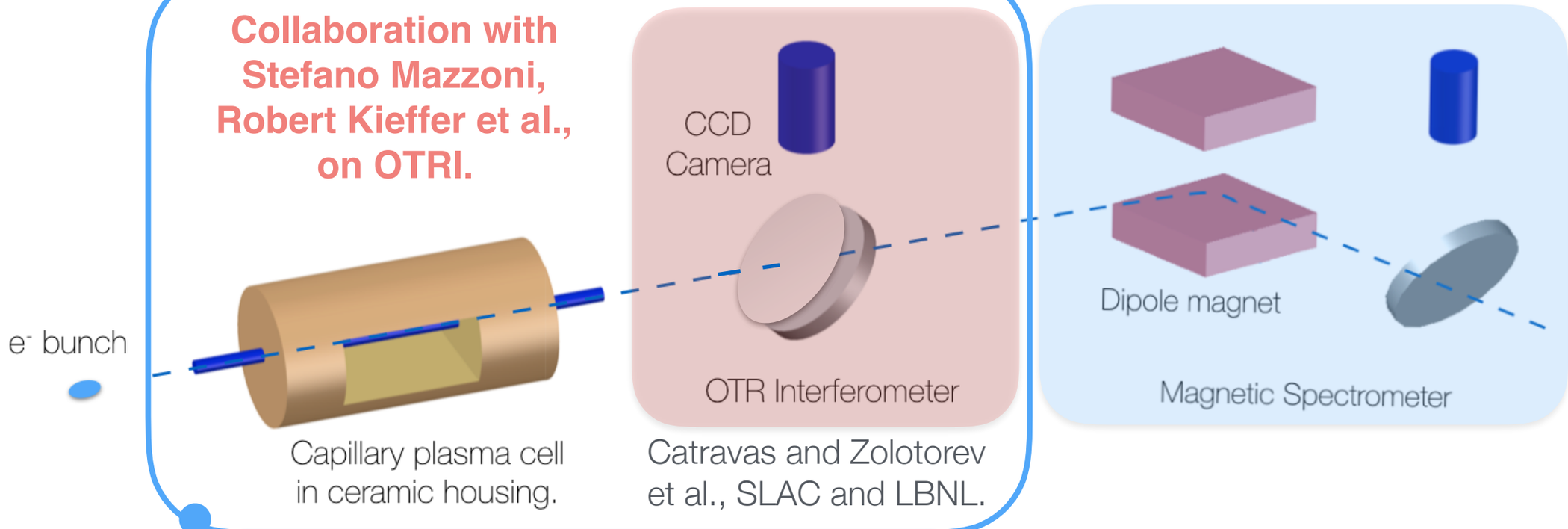
ELECTRON-PLASMA SCATTERING

Experimental Scenario for CALIFES

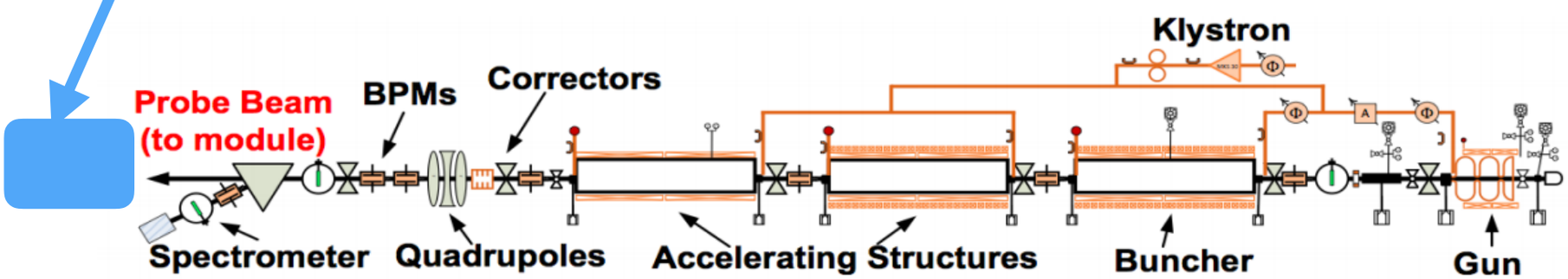
- Measure divergence single shot with OTRI for vacuum, gas and plasma with a variety of densities over many shots. Any correlation?
- Repeat the exercise for energy spread?

- A **spectrometer** after the experimental module area would be useful for energy spread growth studies.
- **Quad scan** after the experimental modules?

Collaboration with Stefano Mazzoni, Robert Kieffer et al., on OTRI.



Spectrometer and/or quadscan?



Conclusions

CALIFES is a strong asset to investigate emittance growth due to beam-plasma scattering for its flexibility as an R&D beamline and its timeline.

Objectives

- Setting up and testing the discharge source - target $6x10^{14}cm^{-3}$ (a larger range is theoretically possible)
  - Optimise capillary size to match the beam size (30kV HV source, flexible geometry),
  - Basic plasma measurements such as temperature…
- High statistics data to explore correlation between beam divergence and scattering media (vacuum, gas and plasma).
  - Scattering is still relevant for short plasma lengths, at lower energy effect will be even more significant.
- Modelling plasma in GEANT4 and scattering simulations in VSIM under way, computational fluid dynamics.

Cockcroft Contribution

- Powering, tubing equipment and experimental chamber is available,
- Man power: Academics, post docs and PhD students, LTAs,

Required from CERN

- 2-3 years intermittent beam time of CALIFES,
- Minor additional equipment, perhaps can be recuperated from CTF3,
- Overlap with OTRI proposal in instrumentation session, why not incorporating two together?

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References

[1] T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

[2] S.P.D. Mangles et al., Nature 431, 535 (2004).

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