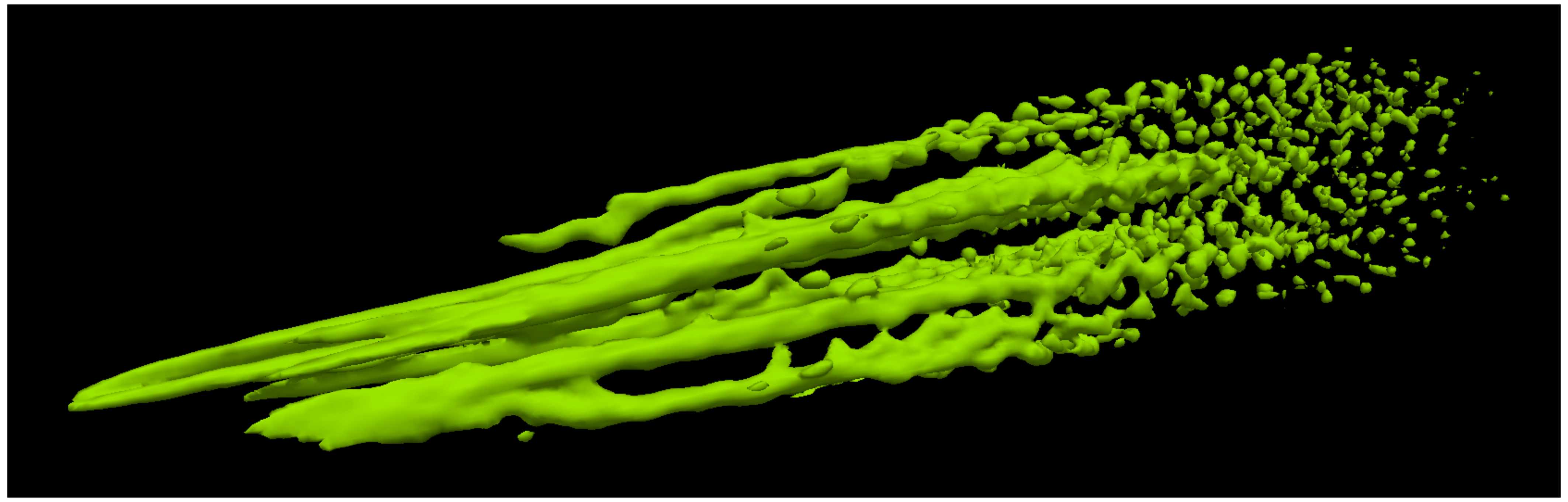
FACET-II Science Workshop, Oct. 29 - Nov. 1, 2019

E-305: Beam filamentation and bright gamma-ray bursts



Principal Investigators:

Sébastien Corde

Ken Marsh

Frederico Fiuza

Collaborators: E-300 collaboration, CEA (France), MPIK (Germany)

The E-305 collaboration and areas of expertise/responsibilities

l'X ÉCOLE POLYTECHNIQUE INSTITUT POLYTECHNIQUE DE PARIS	S. Corde, O. Kononenko, G. Raj, P. San Miguel Claveria
UCLA	W. An, H. Fujii, C. Joshi, K. Marsh, W. Mori, C. Zhang
SLAC NATIONAL ACCELERATOR LABORATORY	C. Emma, F. Fiuza, S. Gessner, M. Hogan, B. O'Shea, D. Storey, V. Yakimenko
	R. Ariniello, J. Cary, C. Doss, K. Hunt-Stone, V. Lee, M. Litos
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG	C. Keitel, A. Sampath, M. Sangal, M. Tamburini
cea	X. Davoine, L. Gremillet
	E. Adli
Stony Brook University	N. Vafaei-Najafabadi

The E-305 collaboration and areas of expertise/responsibilities

Areas of expertise/responsibilities and coordinators

Target assembly and solid targets

(K. Marsh and S. Corde)

PIC modelling - gas

(S. Corde and F. Fiuza)

Gas jets and laser ionisation

(K. Marsh and M. Litos)

PIC modelling - solids

(S. Corde and M. Tamburini)

Electron and gamma diagnostics

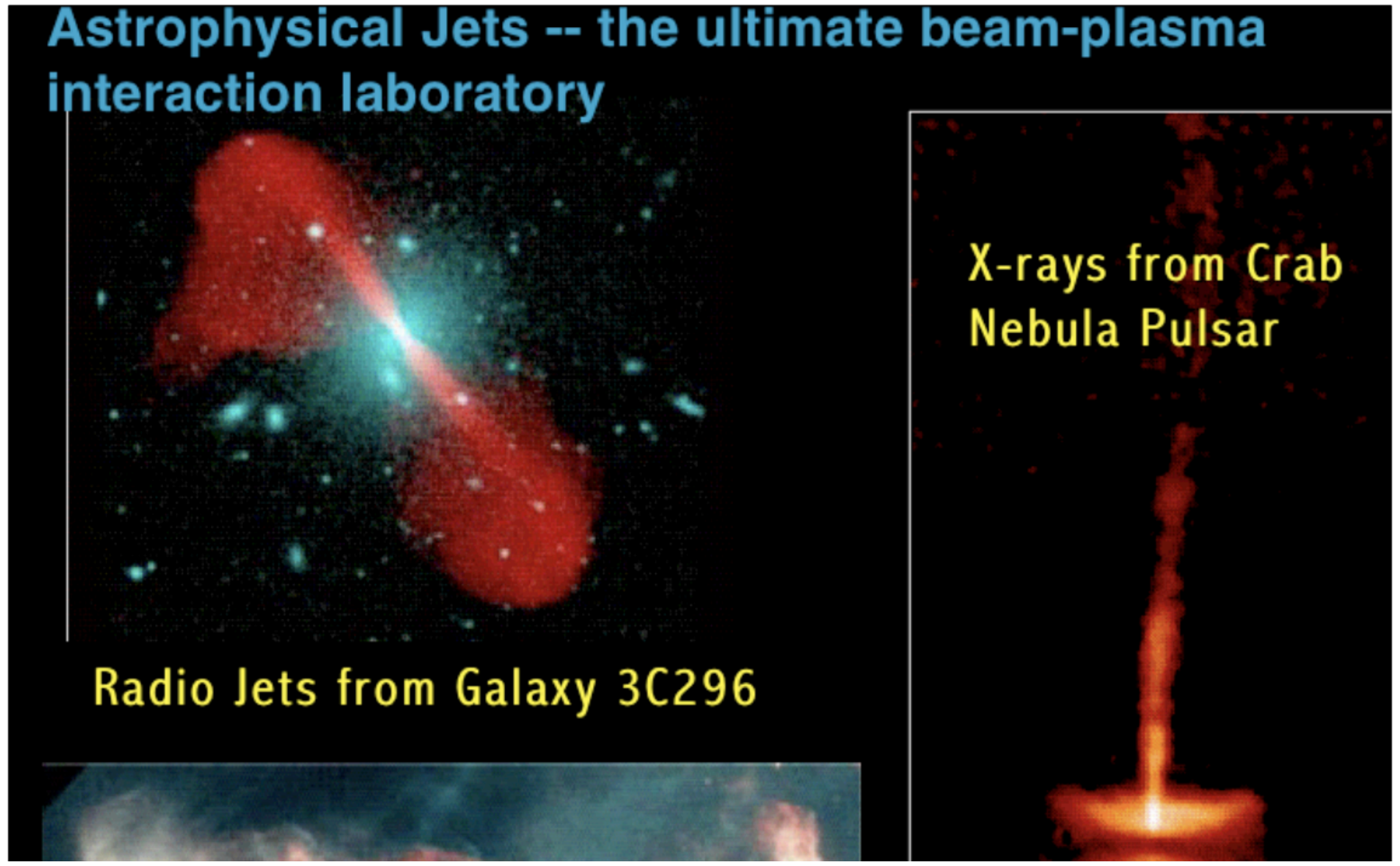
(D. Storey and S. Corde)

PIC modelling - liquid H_2

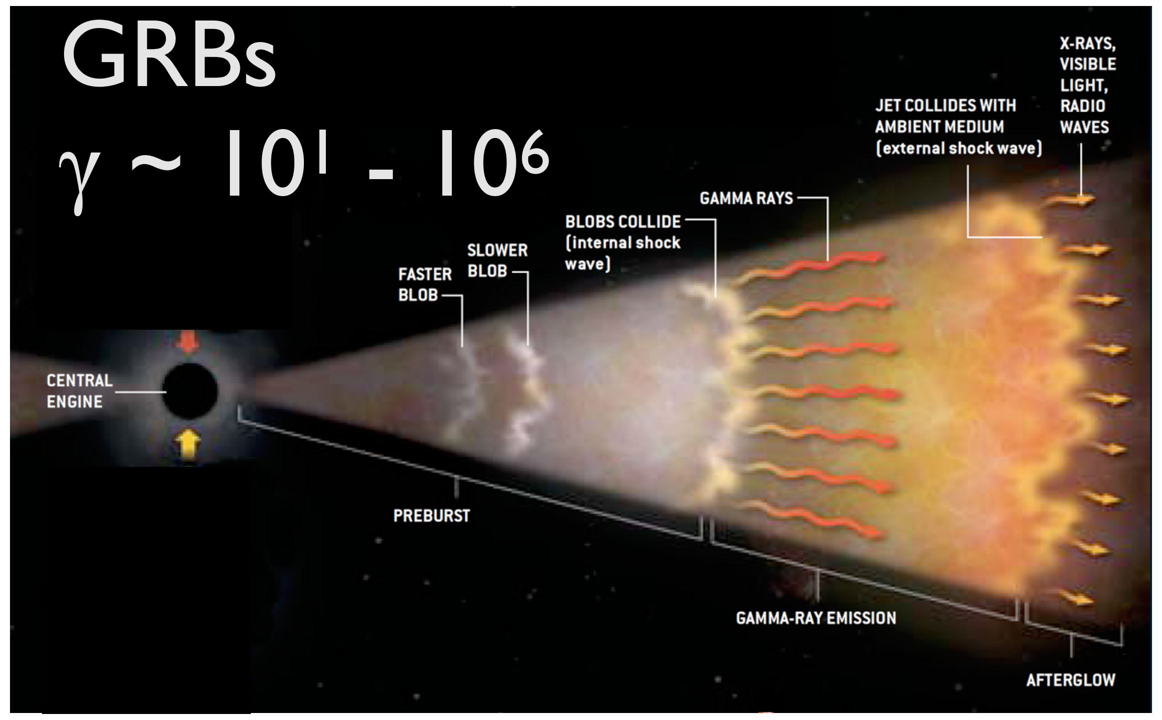
(F .Fiuza)

Motivations for filamentation physics and bright gamma rays

Relativistic streaming instabilities are pervasive in astrophysics

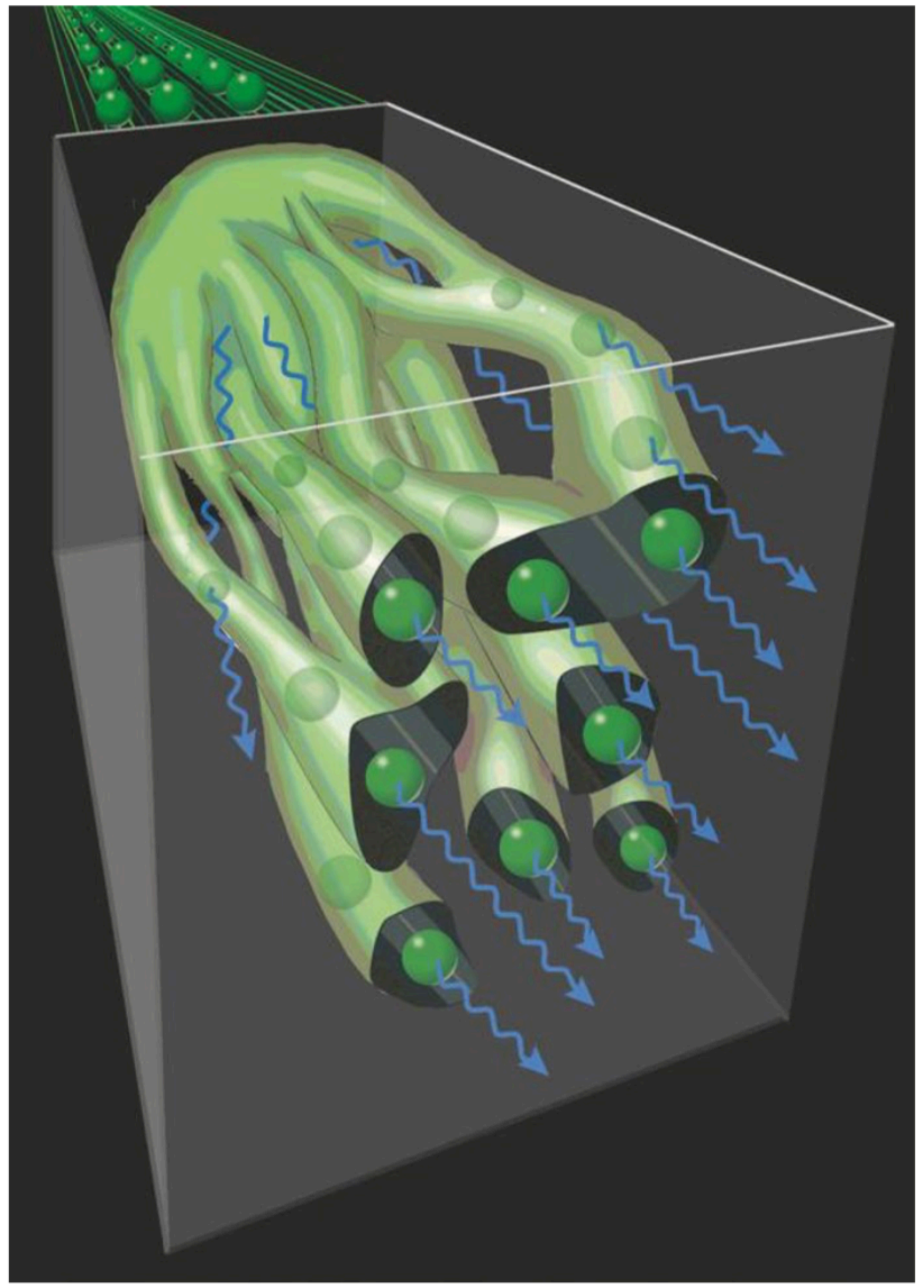


T. Katsouleas, role of Weibel instability in astrophysics and cosmic jets



Current filamentation instability and oblique instabilities are believed to:

- mediate slow down of energetic flows (e.g. in GRBs and blazars)
- mediate shock formation and cosmic-ray acceleration
- determine radiation signatures of energetic environments

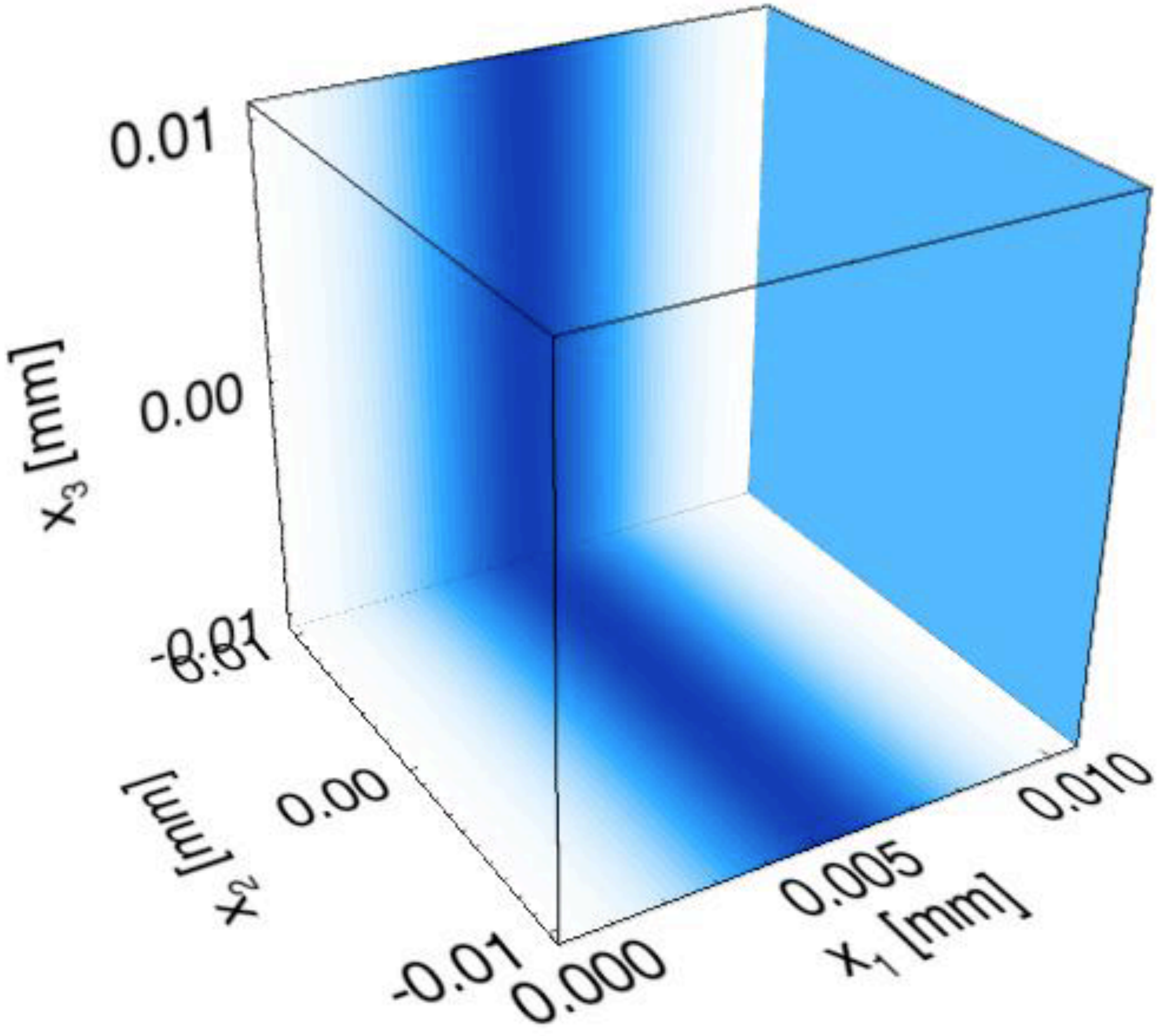


Nature Photon. 12, 314 (2018), Nature Photon. 12, 319 (2018)

- in solids, it has implications for ultrafast condensed matter physics
- in addition to its fundamental importance for astrophysics, it provides a mechanism for energy conversion from particles to EM fields, and to gamma-ray radiation: potential for bright gamma-ray sources
- gamma-ray source with applications to defence, industry, medicine, scientific research

Motivations for filamentation physics and bright gamma rays

In high-density gas jet

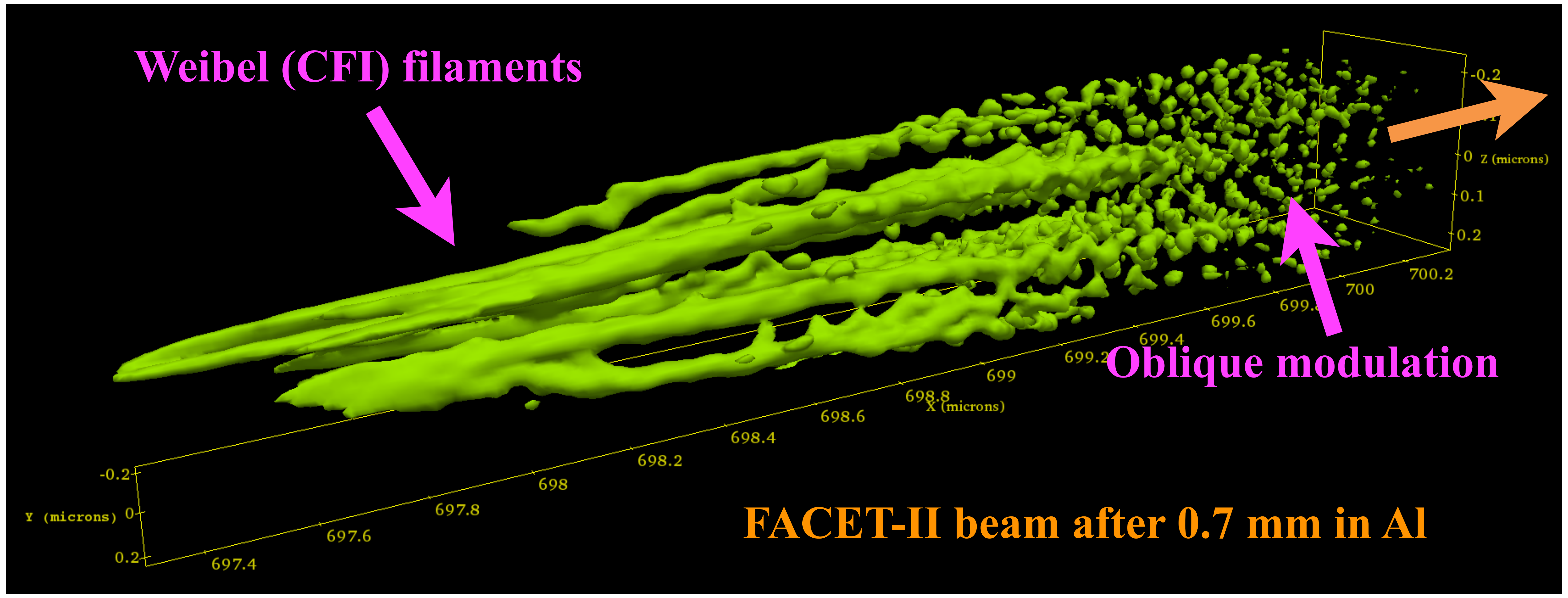


OSIRIS 3D PIC simulation

$n_b = 2 \times 10^{18}\ \mathrm{cm}^{-3}$

$n_p = 10^{20}\ \mathrm{cm}^{-3}$

In solid



CALDER 3D PIC simulation

$n_b = 10^{20}\ \mathrm{cm}^{-3}$

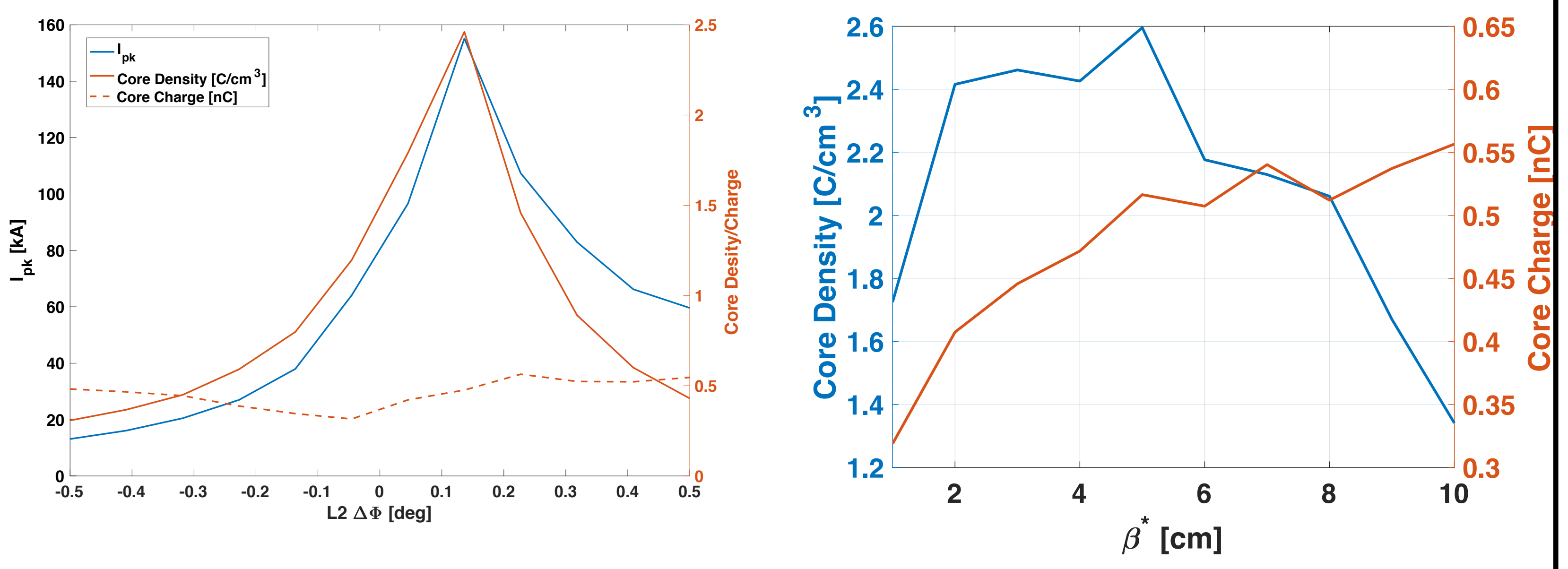
Gamma-ray radiation could approach 1% of initial total beam energy

From the physics to the experiment

Moving to the experiments, solid and high-density cases have very different requirements for hardware, beam optics and diagnostics. They are therefore considered separately.

E305-solid

- Define core as charged contained within FWHM in x, y & z projections (for perfect Gaussian, this would be 36% of total bunch charge)

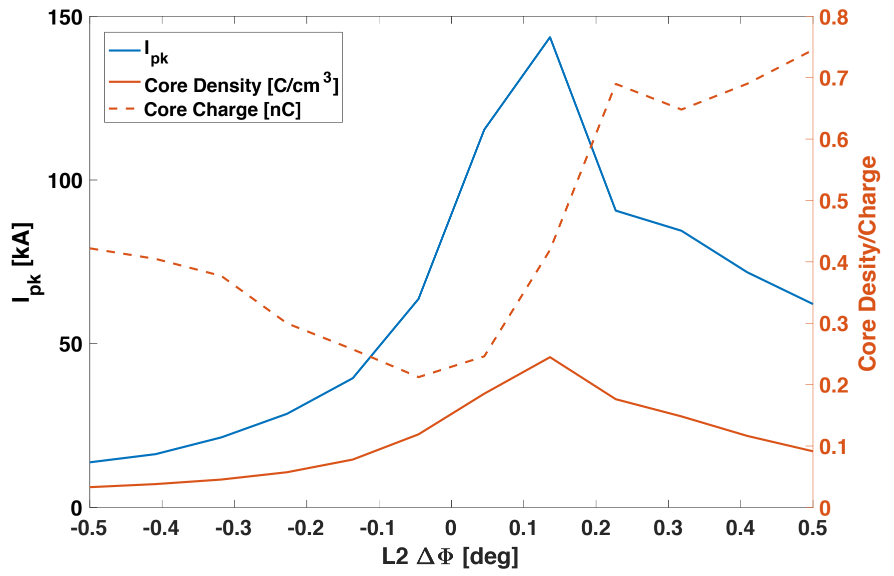


- With no collimation in BC11/BC14 (Q_{bunch} = 2.0 nC)
  - Max core density ~ 2.5 C/cm^3 with β^* = 5 cm
  - 500 pC in core (25% of bunch)

Non-gaussian, 2 nC, 150 kA, 5 cm betas, 1.6e19/cc peak bunch density

E305-gas

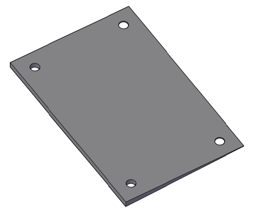
- Define core as charged contained within FWHM in x, y & z projections (for perfect Gaussian, this would be 36% of total bunch charge)



- No BC11/BC14 Collimation (Q_{bunch} = 2.0 nC)
  - β^* = 0.7 m ($\sigma_{x,y}$ = 10 μm at γε=3μm-rad)
  - 700 pC in core for I_{pk}=100kA (35% of bunch)

Gaussian, 2 nC, 100 kA, 10 micron beam size, 70 cm betas

Beam optics developed by Glen White:



	E305-solid	E305-gas
Target:	Wedges 100 microns to 2 mm made of: Al, Mylar, Si, W.	H_2 gas jets, 3-5 mm long, 1e20/cc plasma
Laser ionisation:	No	Yes
Diagnostics:	Gamma rays, electron angular profile, electron spectrometer, transition radiation	Electron angular profile, electron spectrometer, gamma rays, Thomson scattering, transverse shadowgraphy

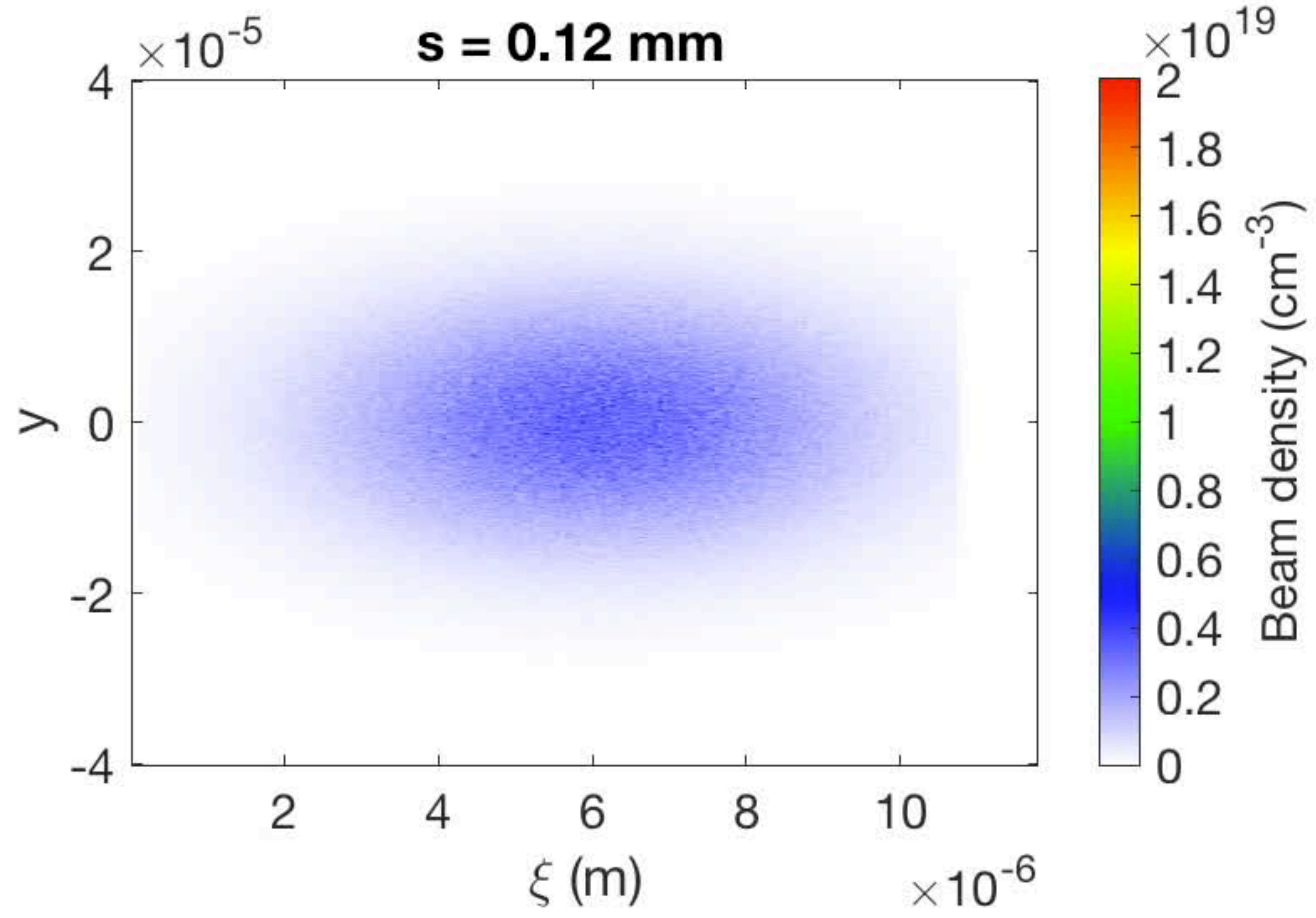
From the physics to the experiment

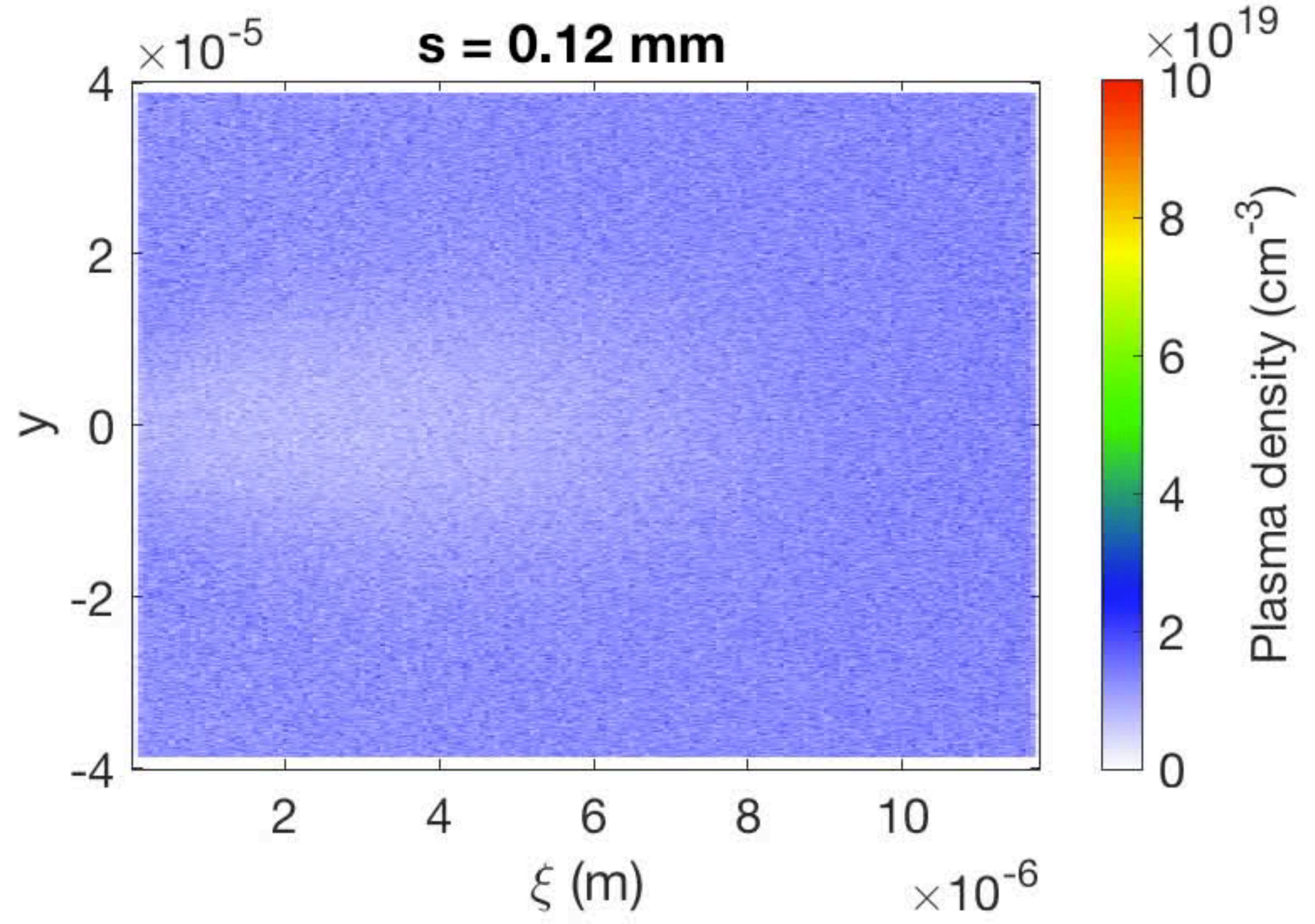
E305-gas

CALDER 3D PIC simulation

Glen White E305-gas beam configuration

Gas jet with 4-mm plateau at 10^{20} cm^{-3} and 1-mm ramps





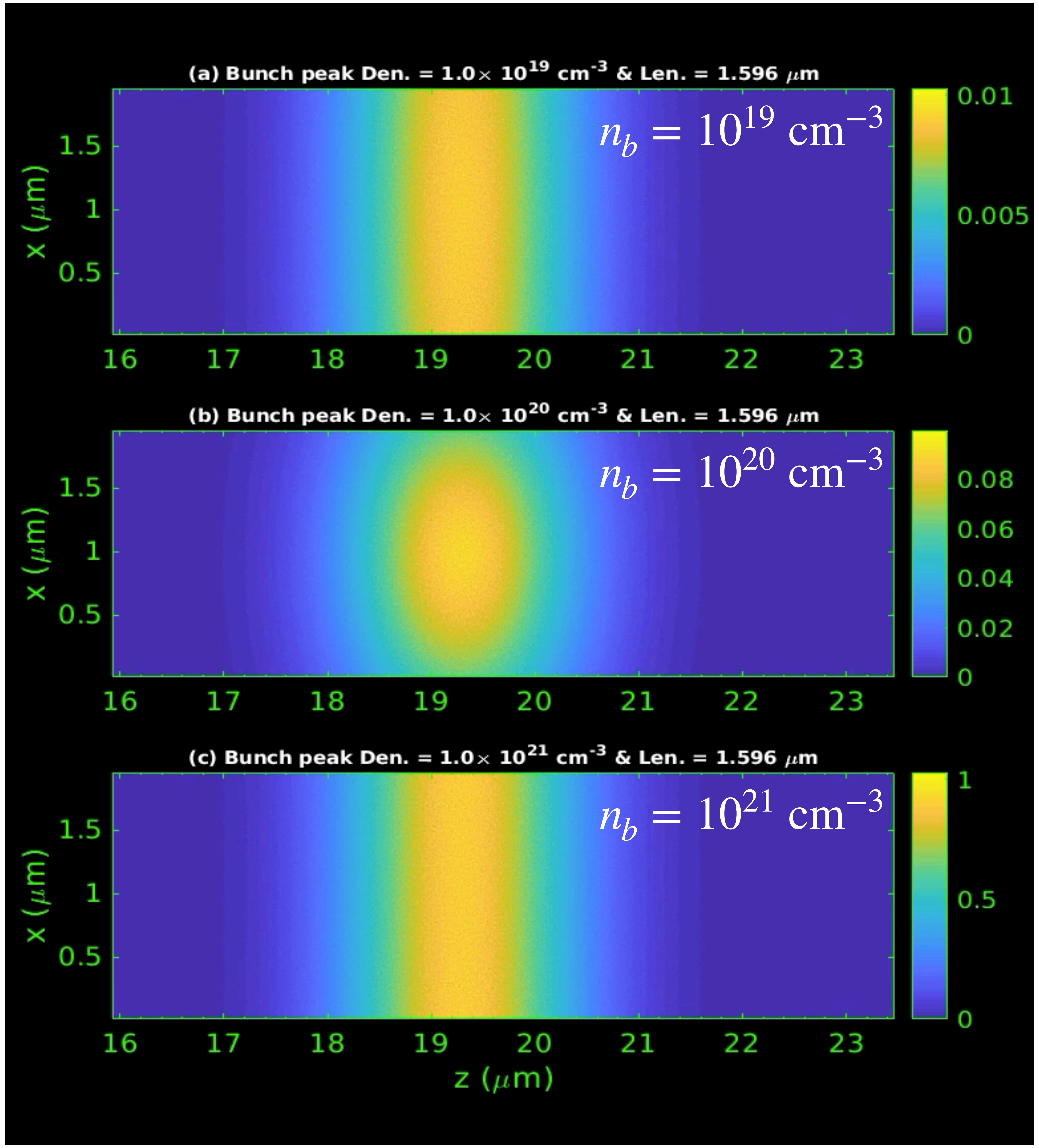
From the physics to the experiment

E305-solid

CALDER 2D PIC simulation

Varying bunch density at 150 kA peak current

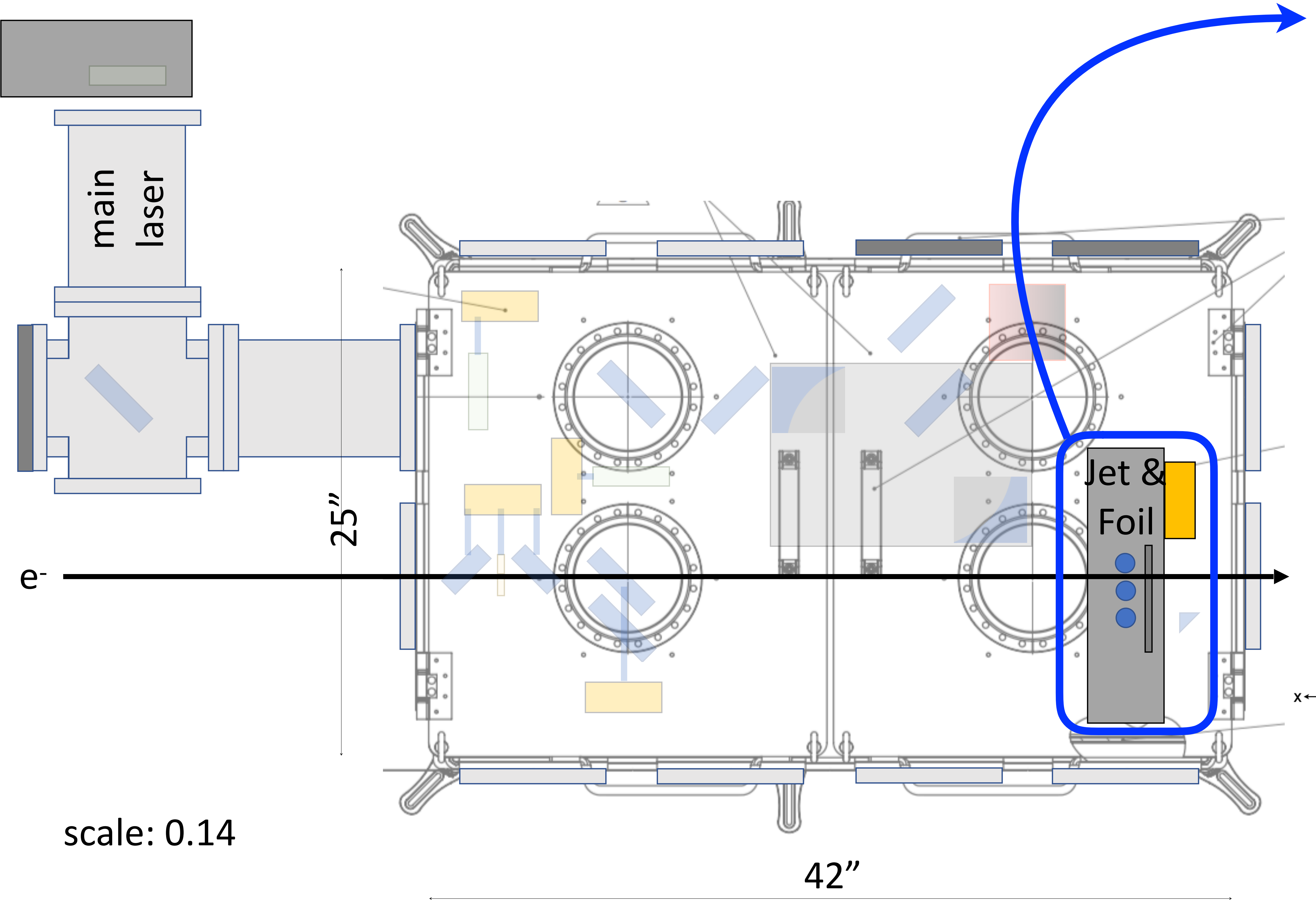
Al solid target



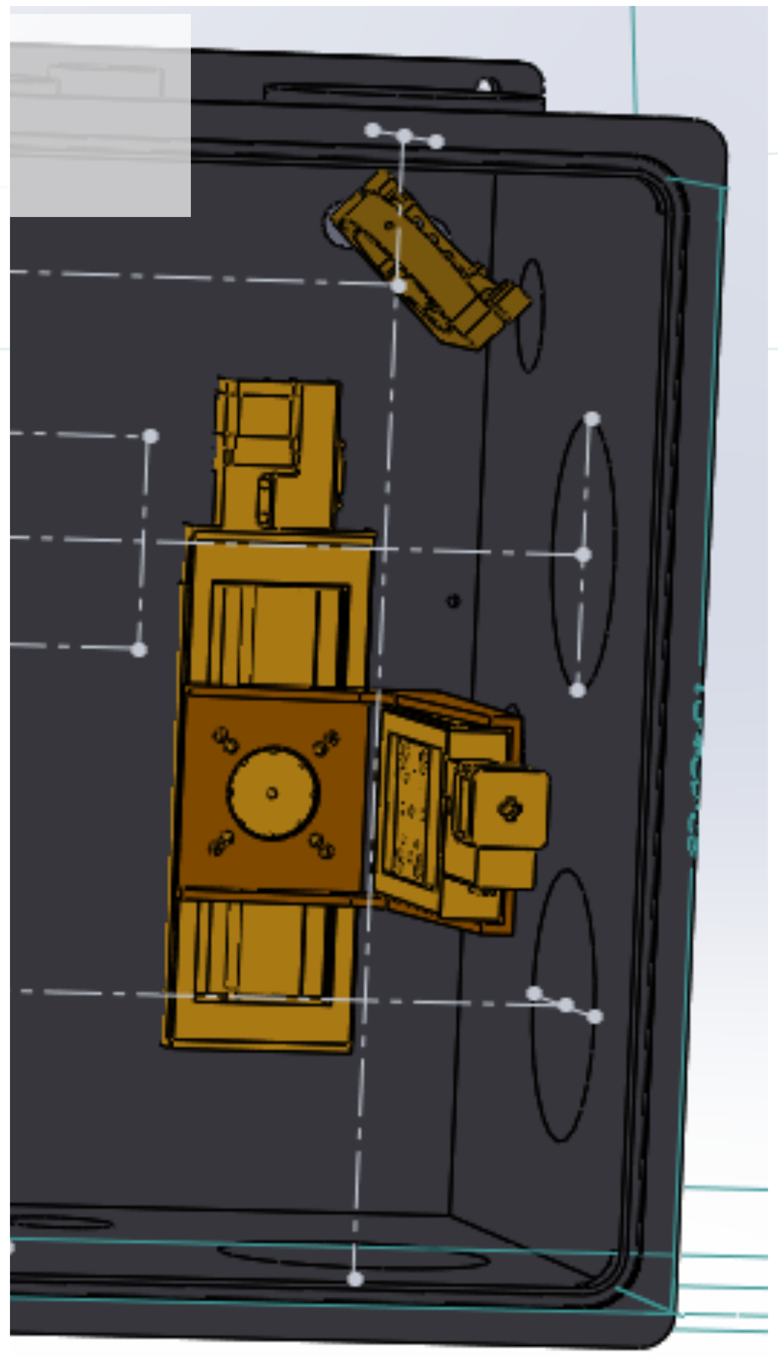
E305-solid

E305-solid: experimental considerations

Installation of solid targets in the “Picnic Basket” chamber

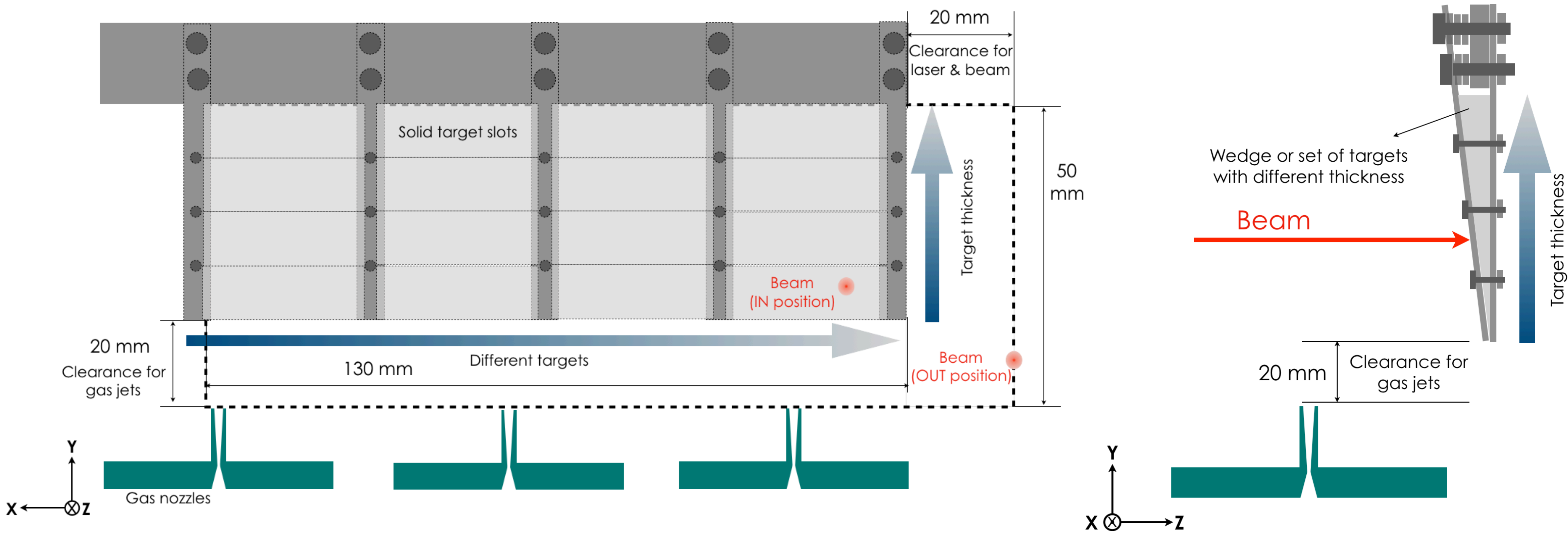


scale: 0.14



- Solid target on two linear stages: UTS 150 mm range for horizontal X, UTS 50 mm range for vertical Y.

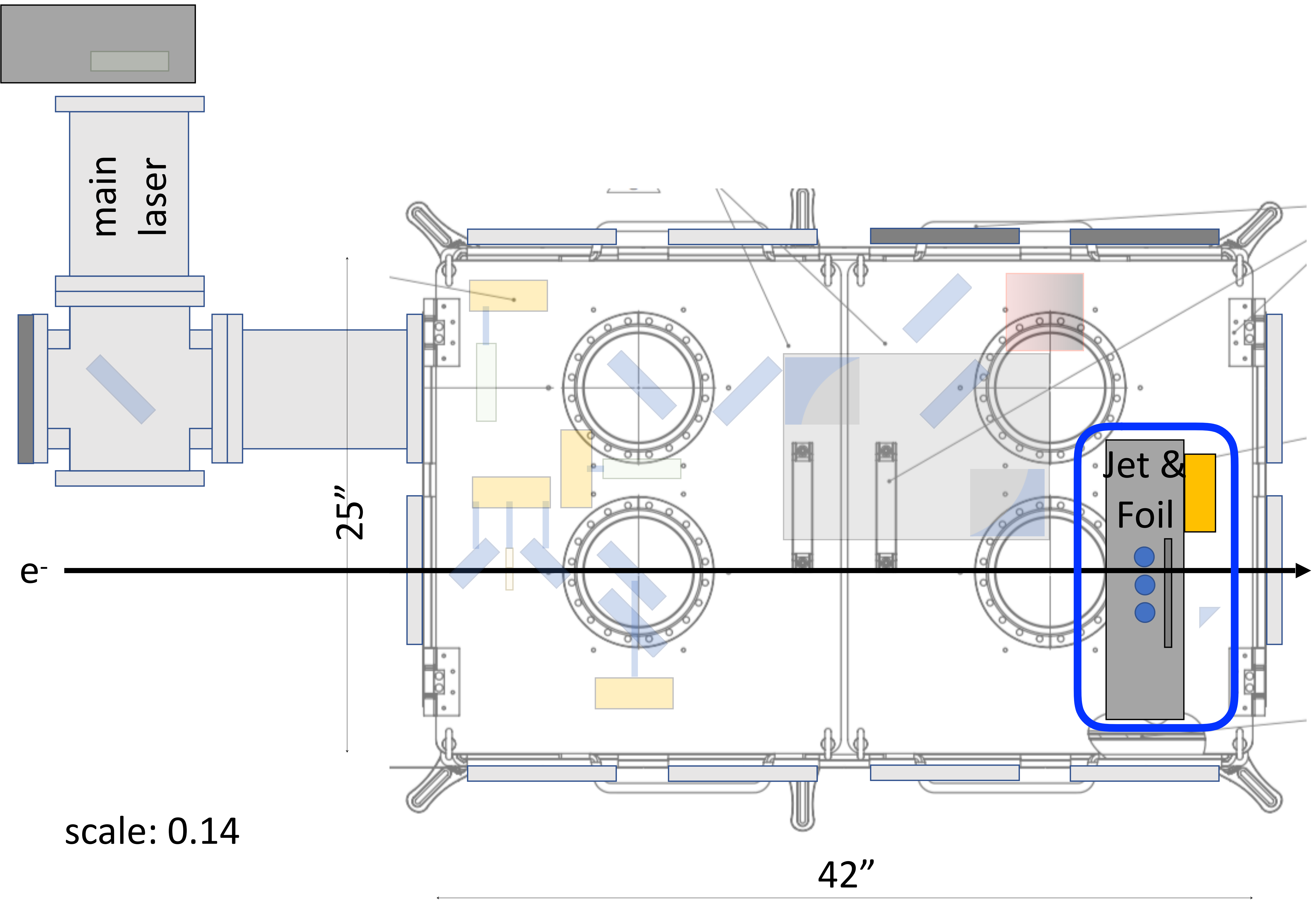
- With 2-cm clearance, rastering surface of 130 mm x 30 mm:



- Preliminary experimental data needed to quantify available number of shots. For 0.2 mm and 1 mm raster steps, we have 4000 and 100 000 shots respectively.

E305-solid: experimental considerations

Installation of solid targets in the "Picnic Basket" chamber



- Solid target is a wedge or stepped foil, with thickness varying from 100 microns to 2 mm, the ideal range identified in our simulations.

- Default material:
  - **Al**: reference case, benchmarking with PIC simulations

- Other materials to be considered in future:
  - Mylar: negligible Bremsstrahlung
  - Si: comparison to Al, conductor vs semiconductor
  - W: effect on positron generation (E-303)
  - C: vary collisionality and growth of Weibel and oblique modes

E305-solid: experimental considerations

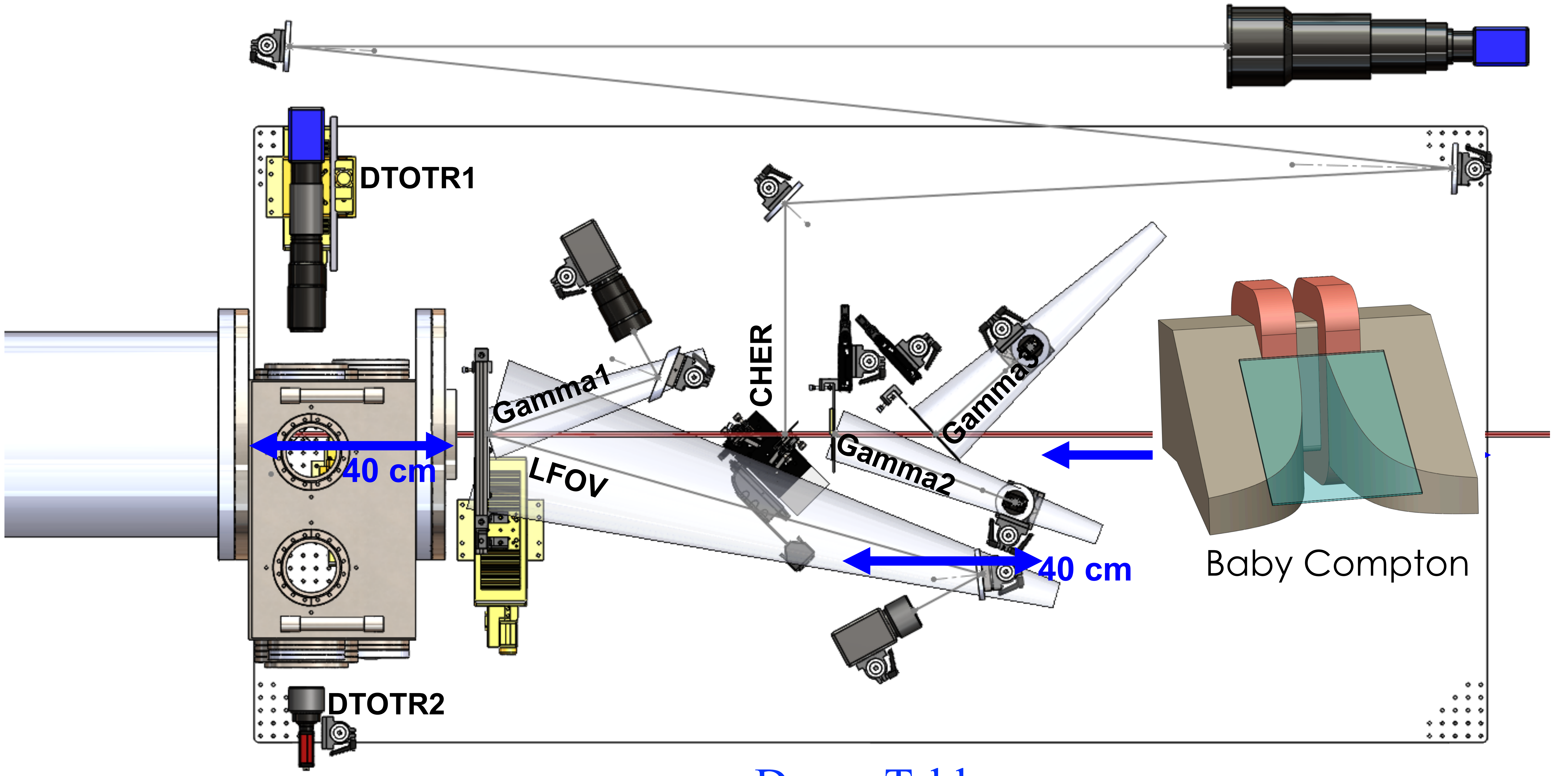
Overview of experimental diagnostics for E305-solid

For day 1:

- Profile monitor before quads for electron angular distribution.
- High-resolution electron energy spectrometer.
- Gamma screens for yield, angular distribution and critical photon energy of gamma-ray beams.

At later stage:

- Gamma Compton spectrometer by UCLA (J. Rosenzweig et al.)
- Transition radiation diagnostics to uncover temporal and spatial modulations of electron beam

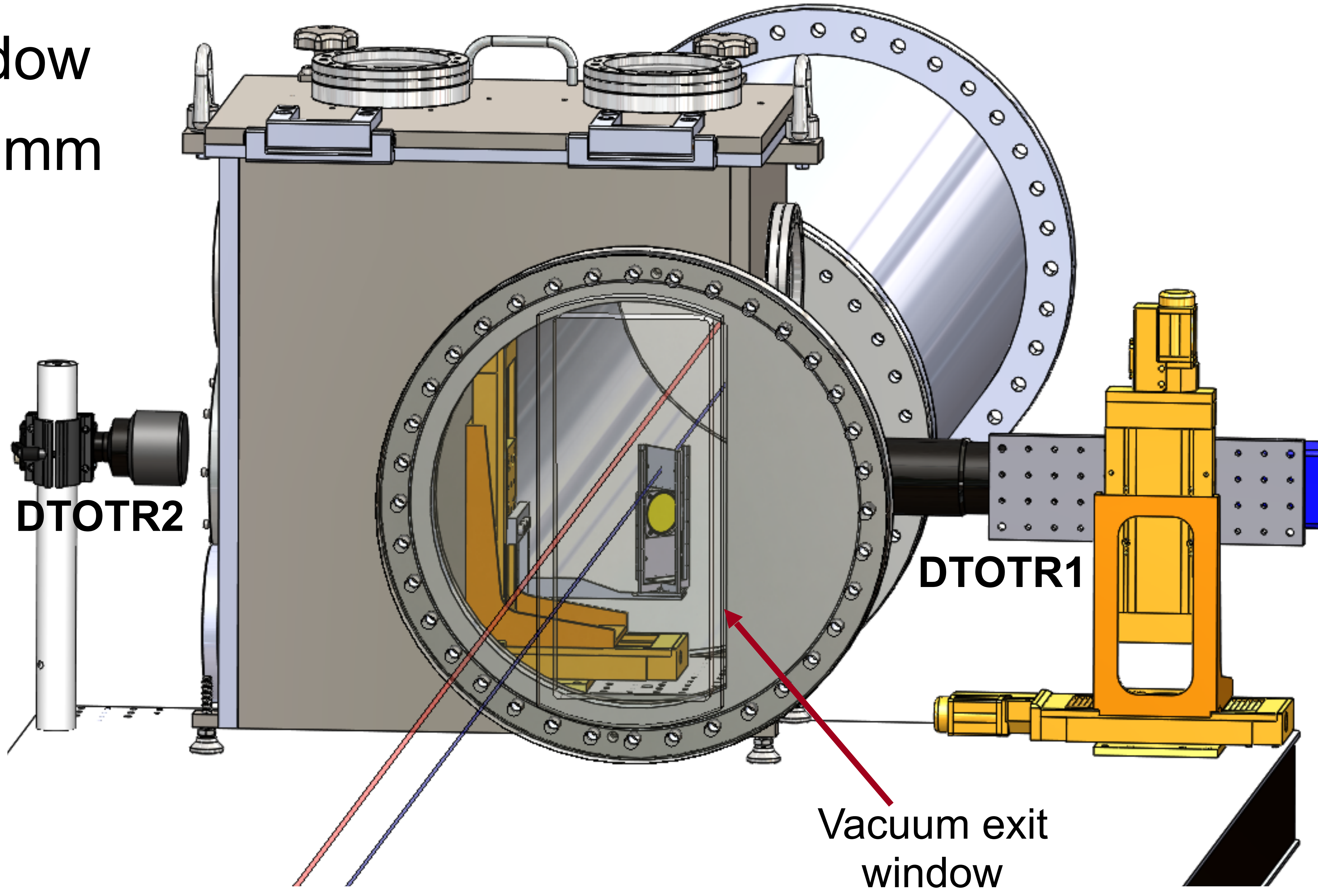


Dump Table

E305-solid: experimental considerations

DTOTR — High resolution electron profile monitor / energy spectrometer

- Located on the dump table, downstream of the reimaging spectrometer
- In vacuum, just prior to the aluminum vacuum exit window
- Nominal dispersion at the dump table: $D_0 = 60$ to 70 mm



DTOTR1 – high resolution

- OTR from 0.5 mm polished Ti target
- 7.0 x 8.4 mm^2 field of view
- Resolution optimized:
  - Imaging resolution: $\sigma_{res,y} = 4.5$ µm
  - Energy resolution: $\sigma_{res,E}(E) = \dfrac{E\sigma_{res,y}}{D(E)} \sim 1$ MeV

DTOTR2 – brighter, larger field of view

- OTR or 50 µm thick YAG:Ce
- 26 x 39 mm^2 field of view → $\sigma_{res,E} \sim 10$ MeV resolution

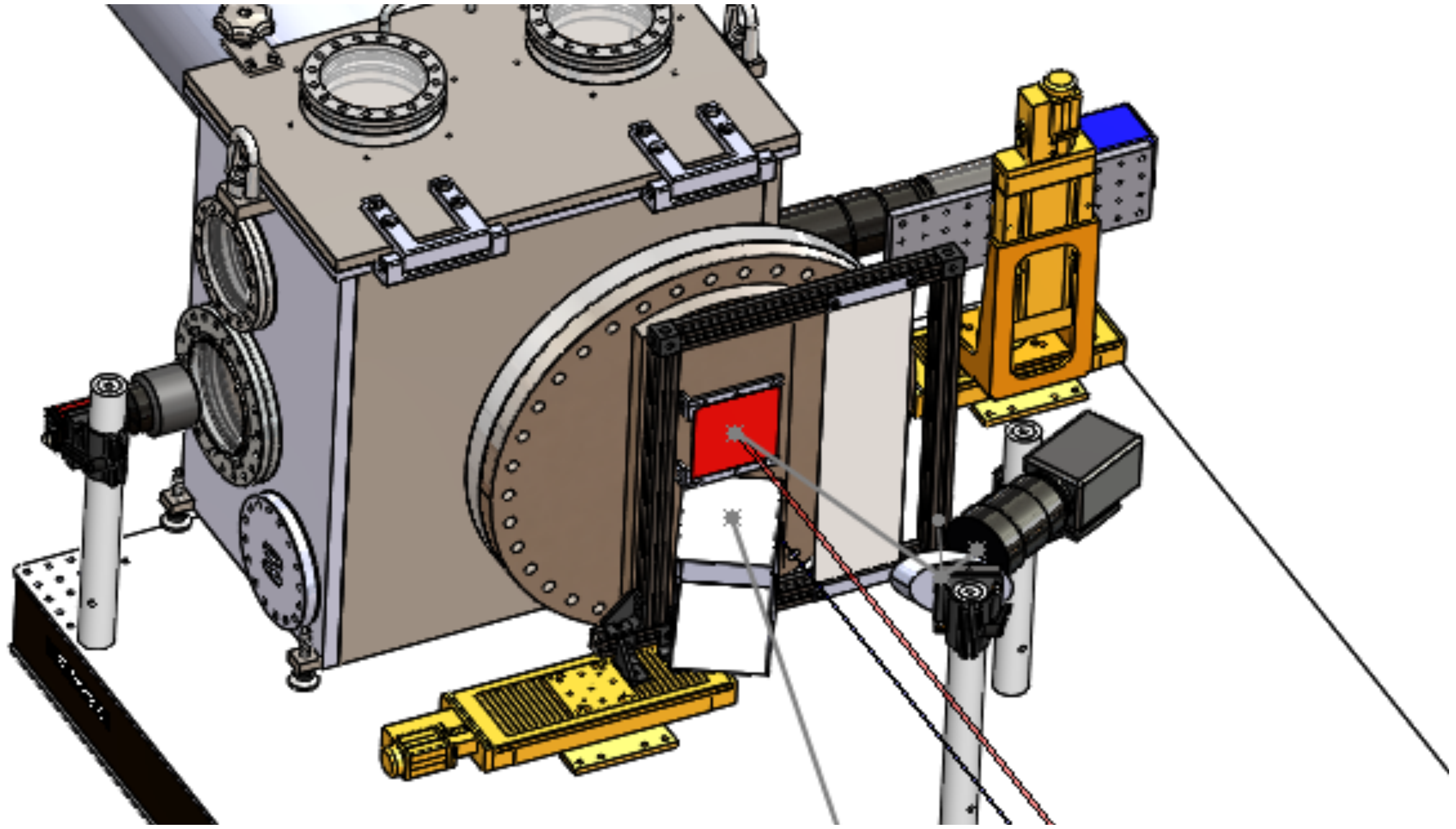
E305-solid: experimental considerations

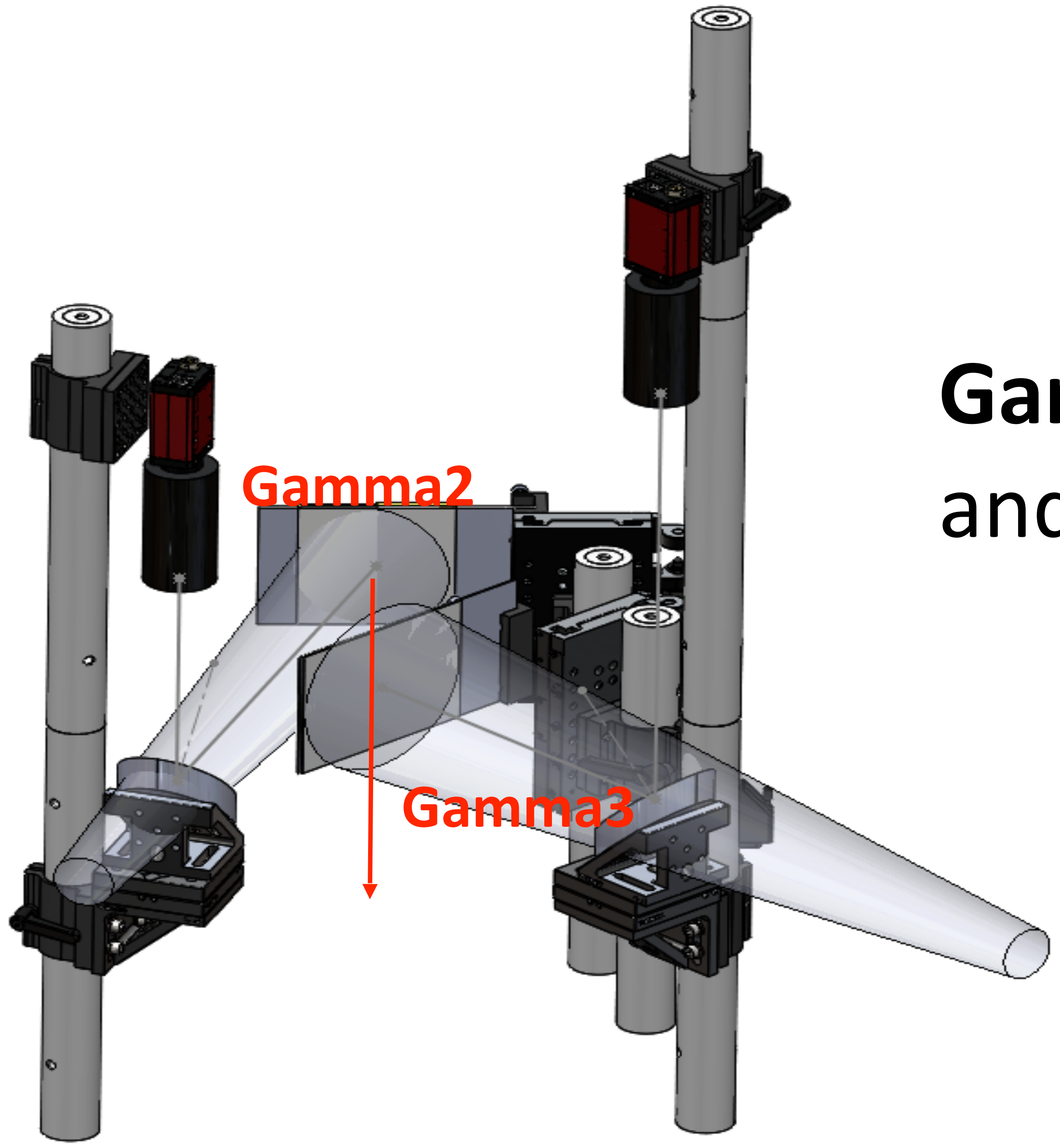
Gamma screens

Gamma1: photon profile monitor

Two scintillator set-ups:

- Pixelated CsI Array
- DRZ screen + W converter



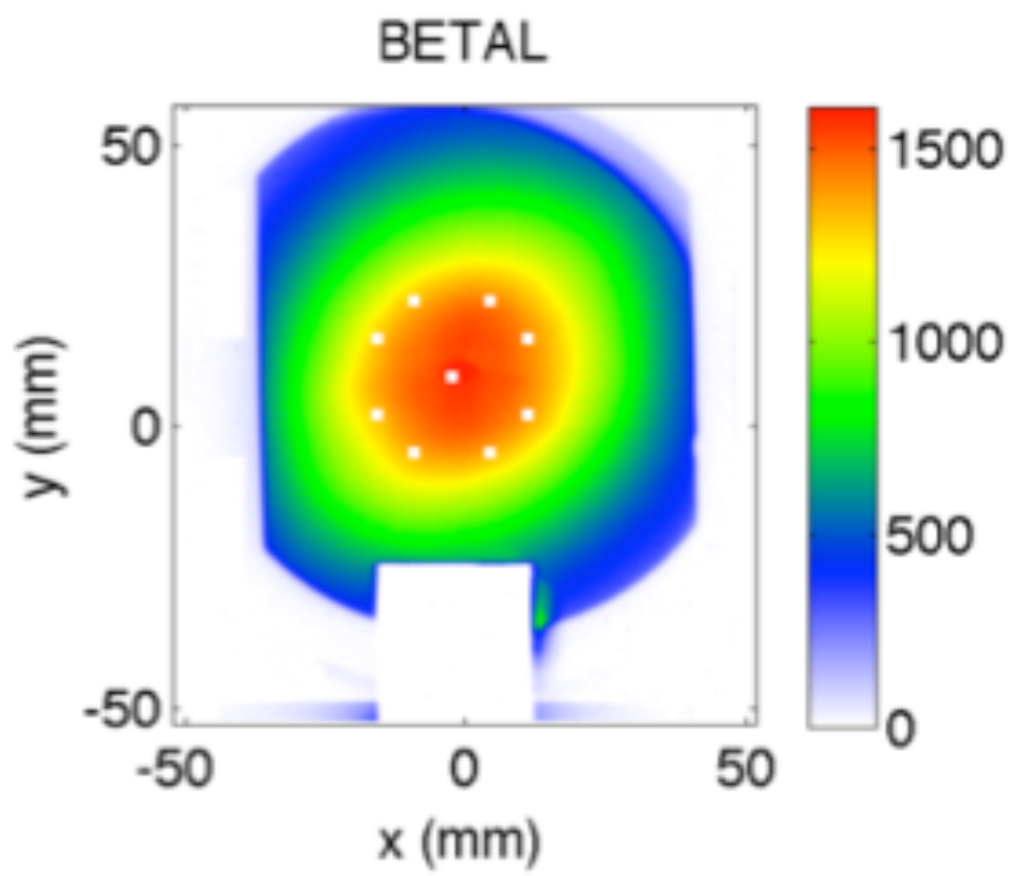


Gamma2/3: Photon spectral information by measuring conversion (Gamma2) and transmission (Gamma3) of gammas through a set of converters-filters.

Filters set-up:

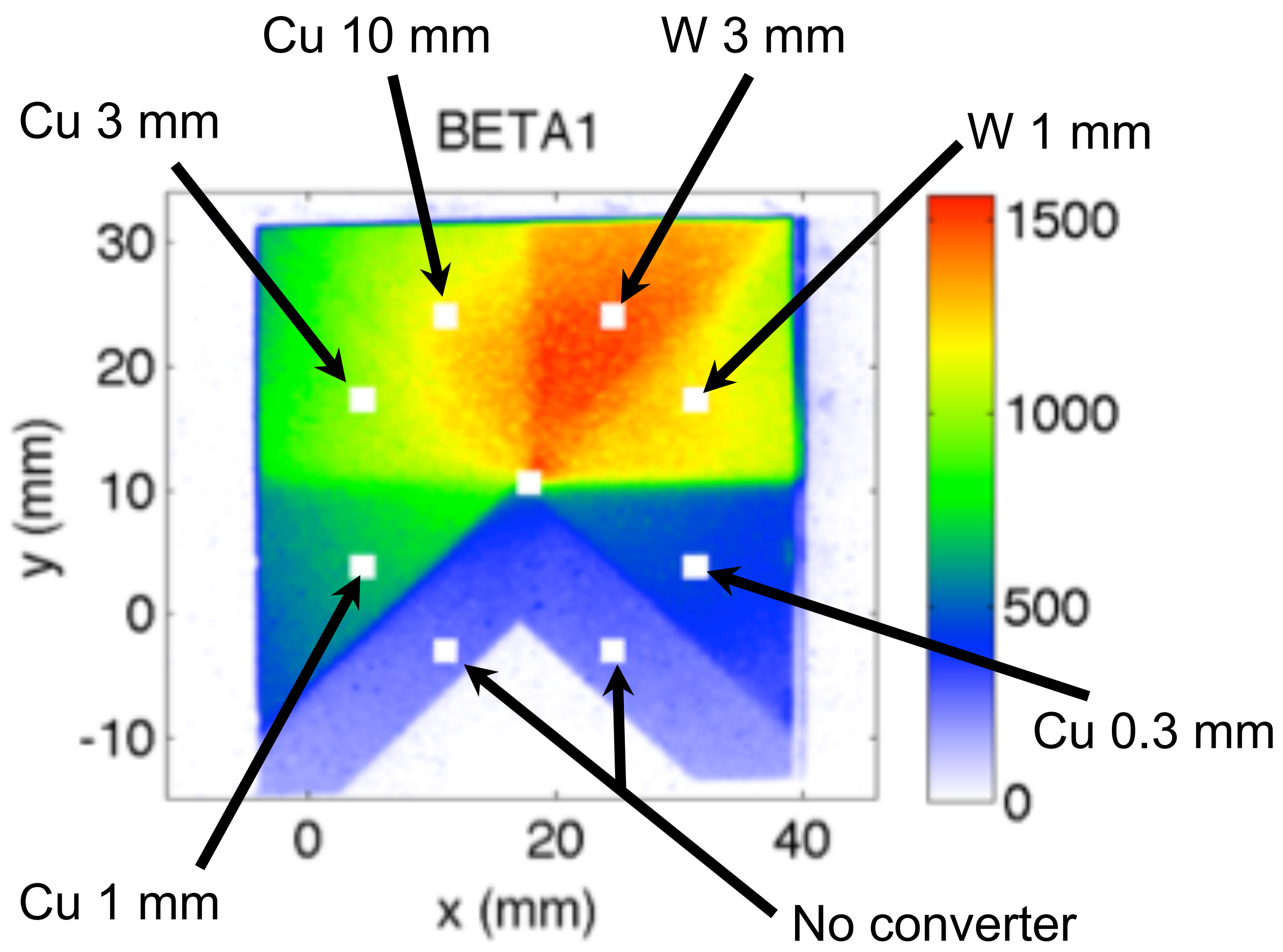
- Step filters: transmission (50-100's keV) and conversion (100's keV-10's MeV)
- Ross filters: energy bands (<100 keV)

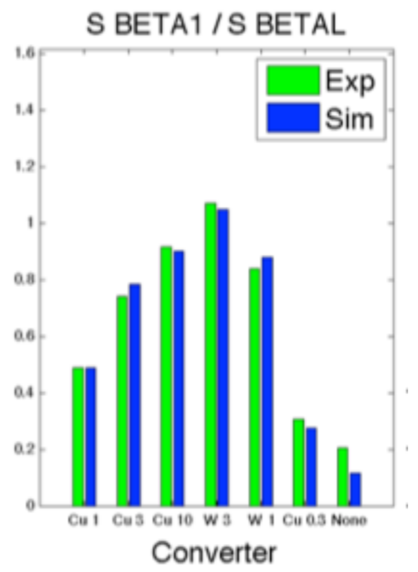
E305-solid: experimental considerations



GAMMA1 screen
= LFOV screen

Convertor foils:



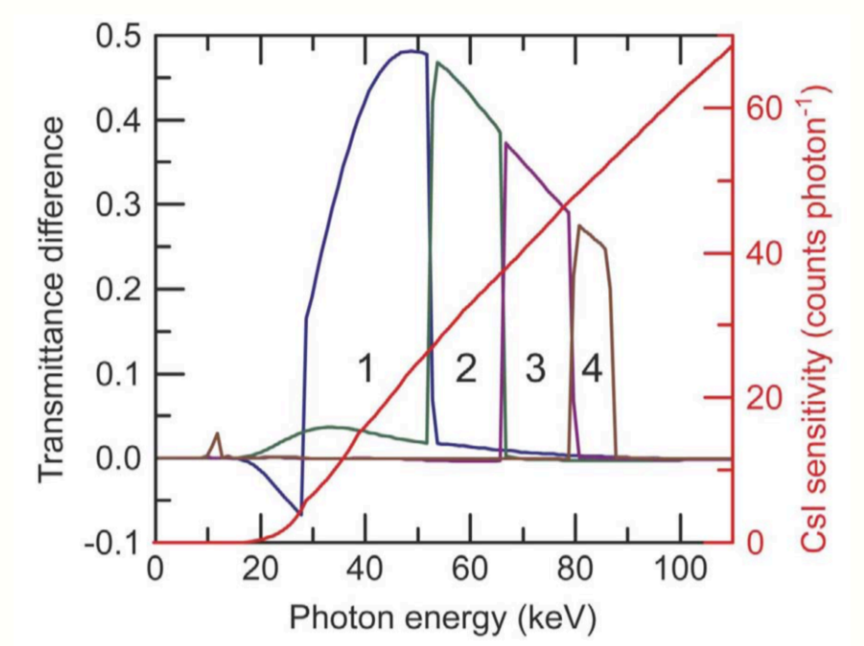


$$\frac{dW}{d\omega} = A\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(\xi)d\xi$$

$$E_c = \hbar\omega_c$$

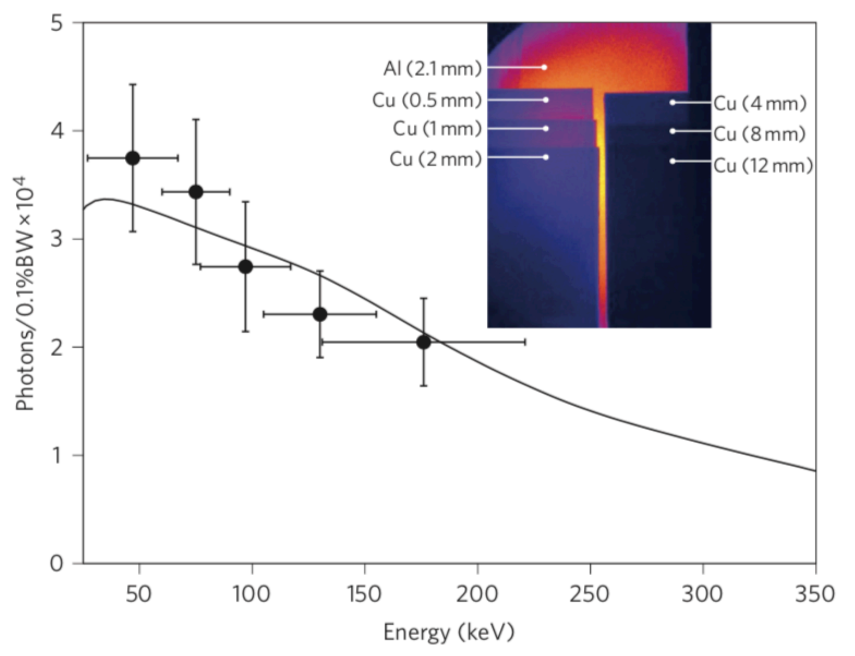
Ec fit = 13.2 MeV

Ross filters:



Nature Photon.
8, 28 (2014)

Step filters:



Nature Photon.
6, 308 (2012)

GAMMA1

GAMMA2

GAMMA3

E305-solid: support from theory and simulations

Goals:

- to provide guidance to the experimental programme
- to support experimental findings

Challenges:

- High plasma density and long propagation distance
- Collisional
- Many physical modules needed: binary collisions, collisional ionisation, field ionisation, bremsstrahlung, synchrotron)
- Three-dimensional problem

Benchmarking between two teams and PIC codes:

- CEA/LOA: CALDER
- MPIK: SMILEI (previously EPOCH)

One remaining question from last year:

- Finite beam size

Parameters: 10 GeV, 0.46 μm beam size (RMS), 0.48 μm bunch length (RMS), 10^{21} cm^{-3} bunch density (8 times smaller charge than nominal beam)

E305-solid: support from theory and simulations

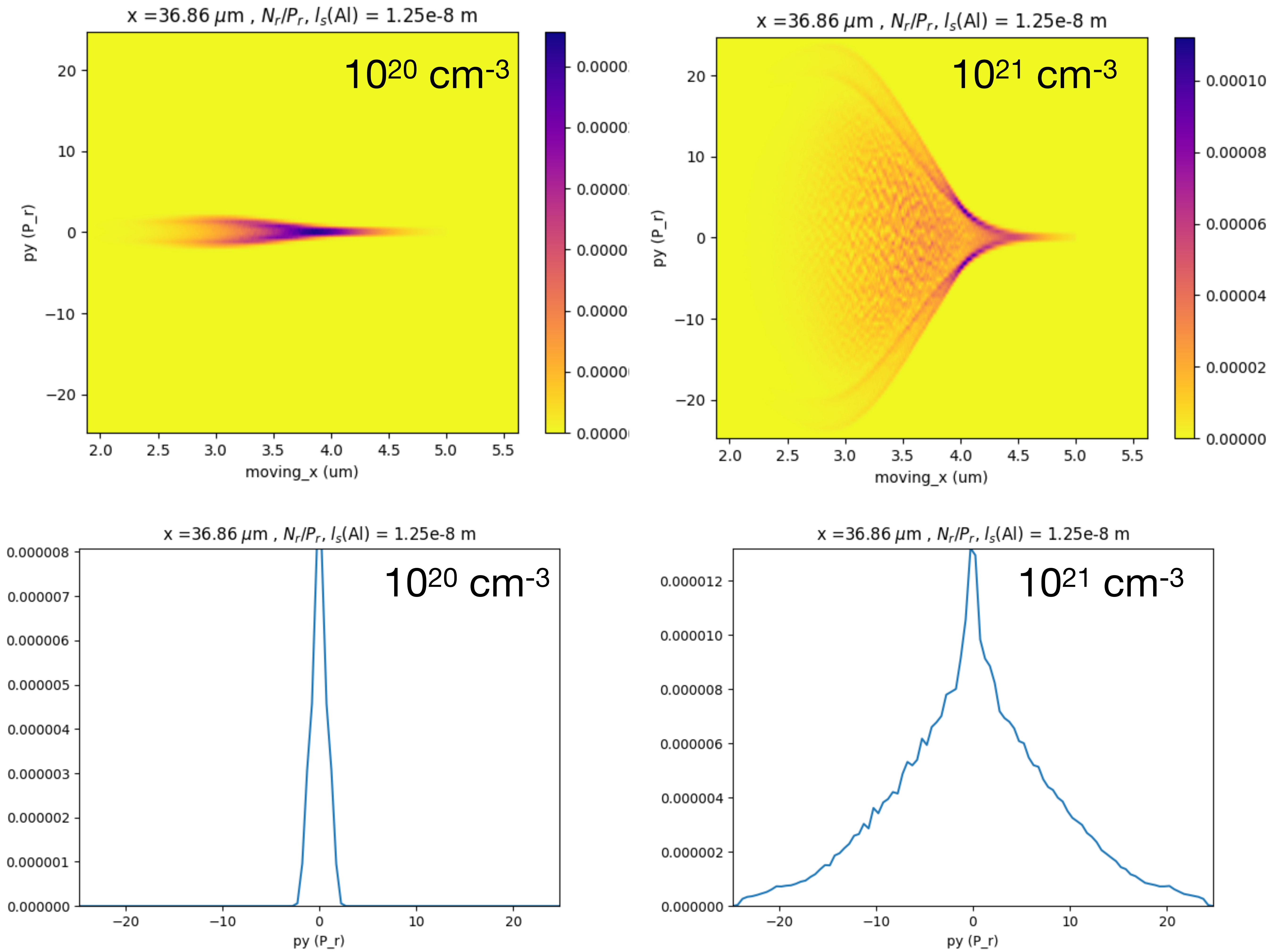
Max-Planck-Institut für Kernphysik Heidelberg

M. Tamburini et al.

SMILEI 2D PIC simulations

Cold beam:
- zero initial emittance

Finite beam size effects at high bunch density:
- result into transverse momentum gain due to magnetic field in target and self-field reflection
- can lead to beam pinching



E305-solid: support from theory and simulations

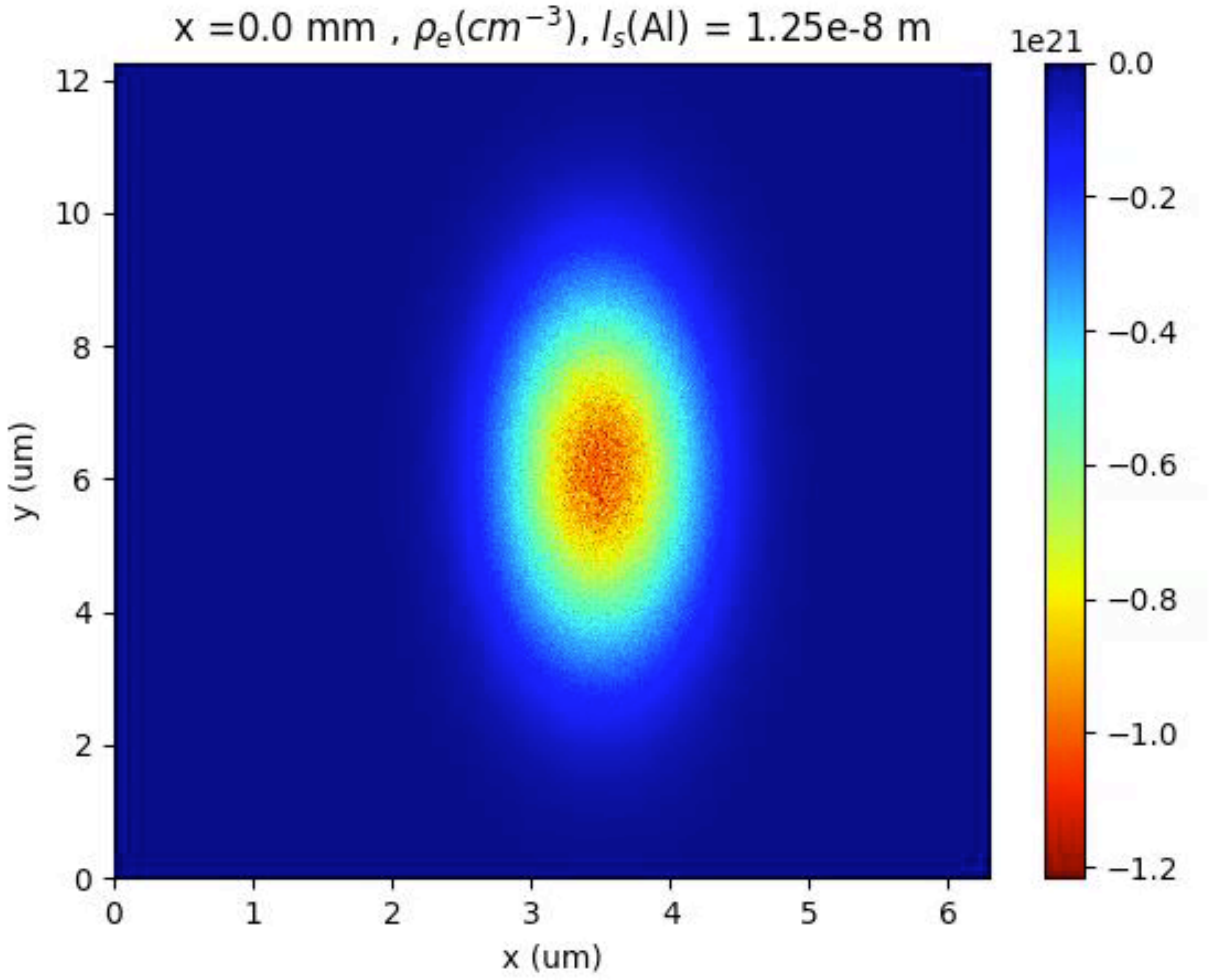
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

M. Tamburini et al.

SMILEI 2D PIC simulations

Cold beam:
- zero initial emittance

With x4 beam size and 1e21/cc bunch density:
- slight initial beam pinching followed by filamentation



$n_b = 10^{21}\ \mathrm{cm}^{-3}$

E305-solid: support from theory and simulations

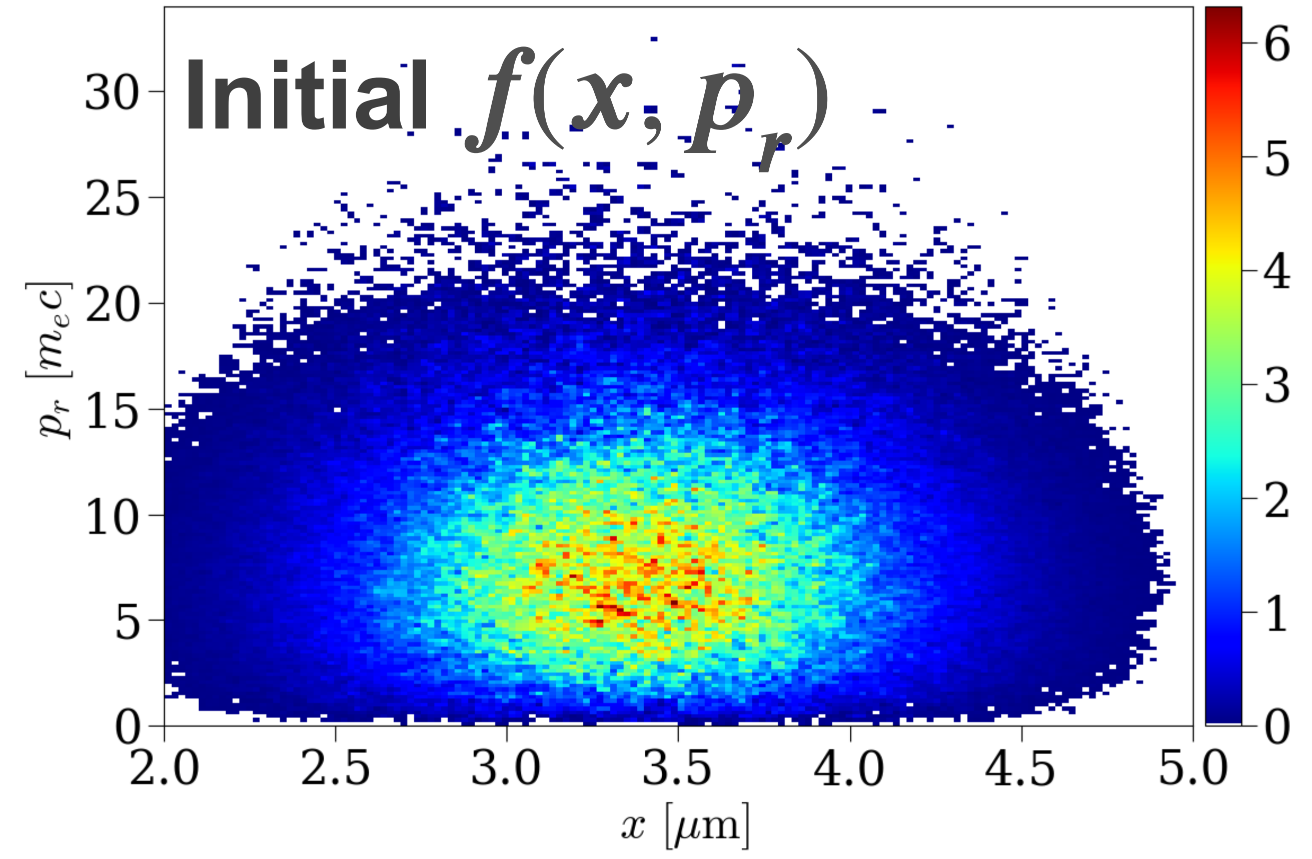
G. Raj and S. Corde

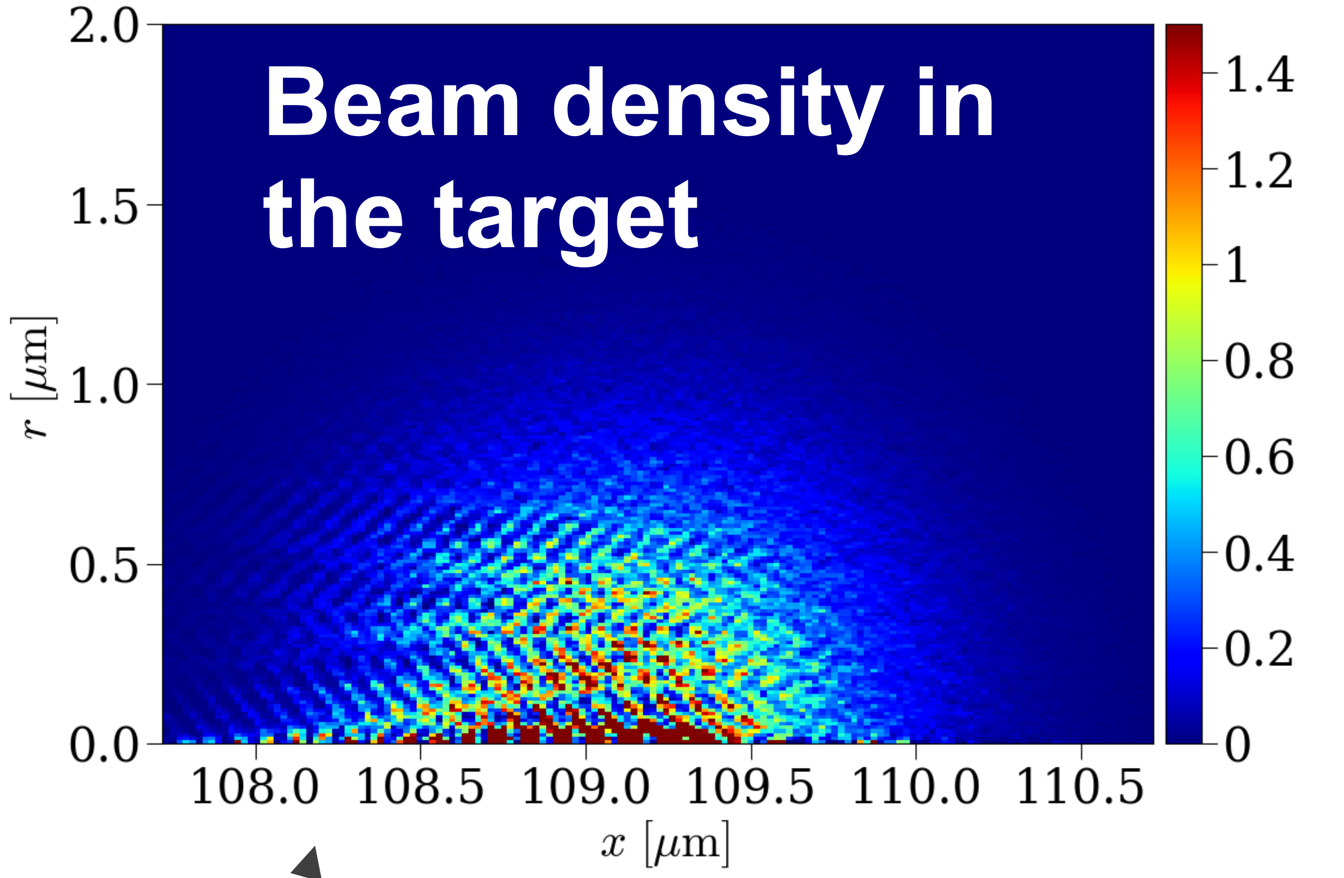
X. Davoine

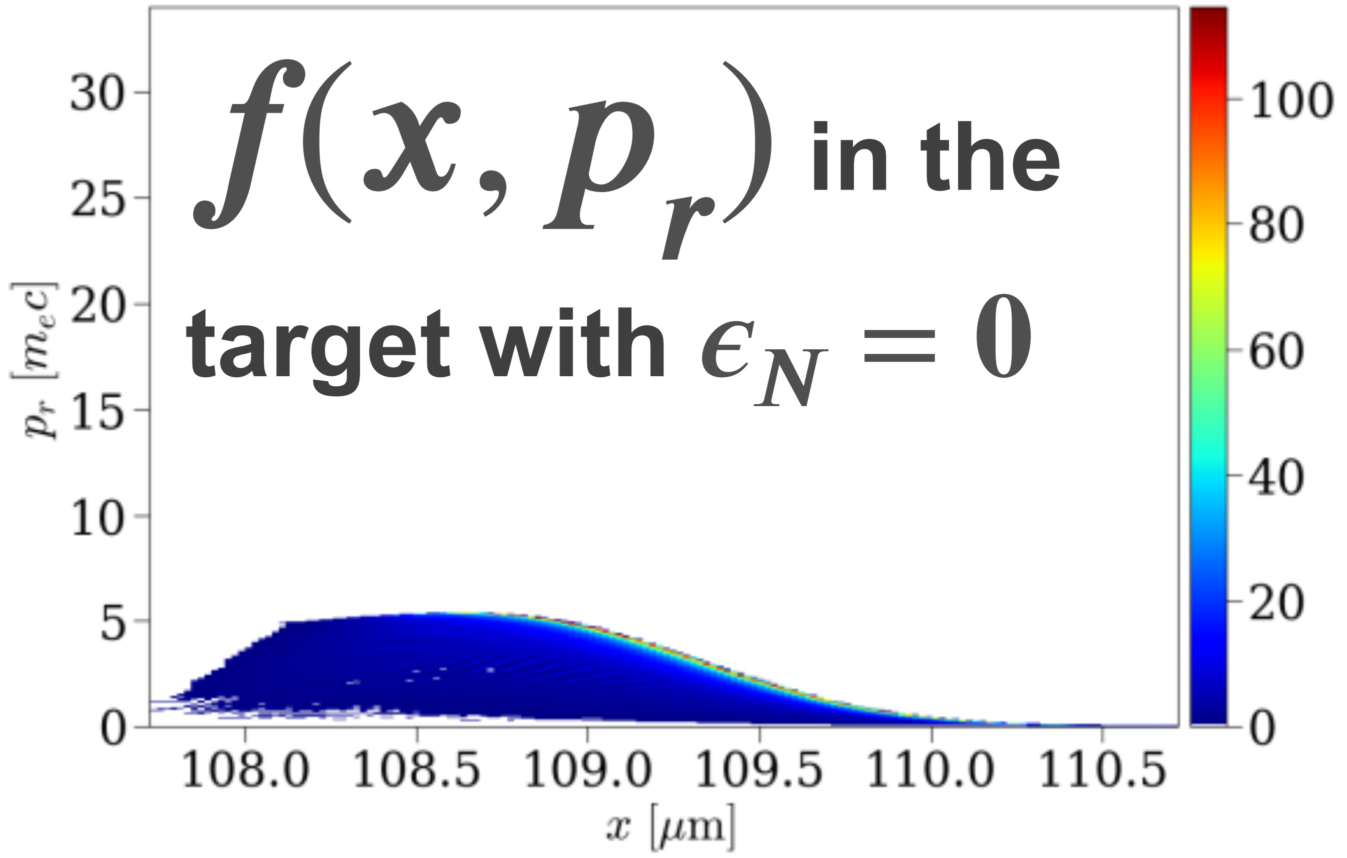
Observations:
- the reflection of the beam self-field induce a focusing force and a transverse momentum gain.
- finite emittance of 3 mm.mrad: the transverse momentum gain due to self-field reflection is smaller than the initial momentum spread, the focusing effect is reduced.

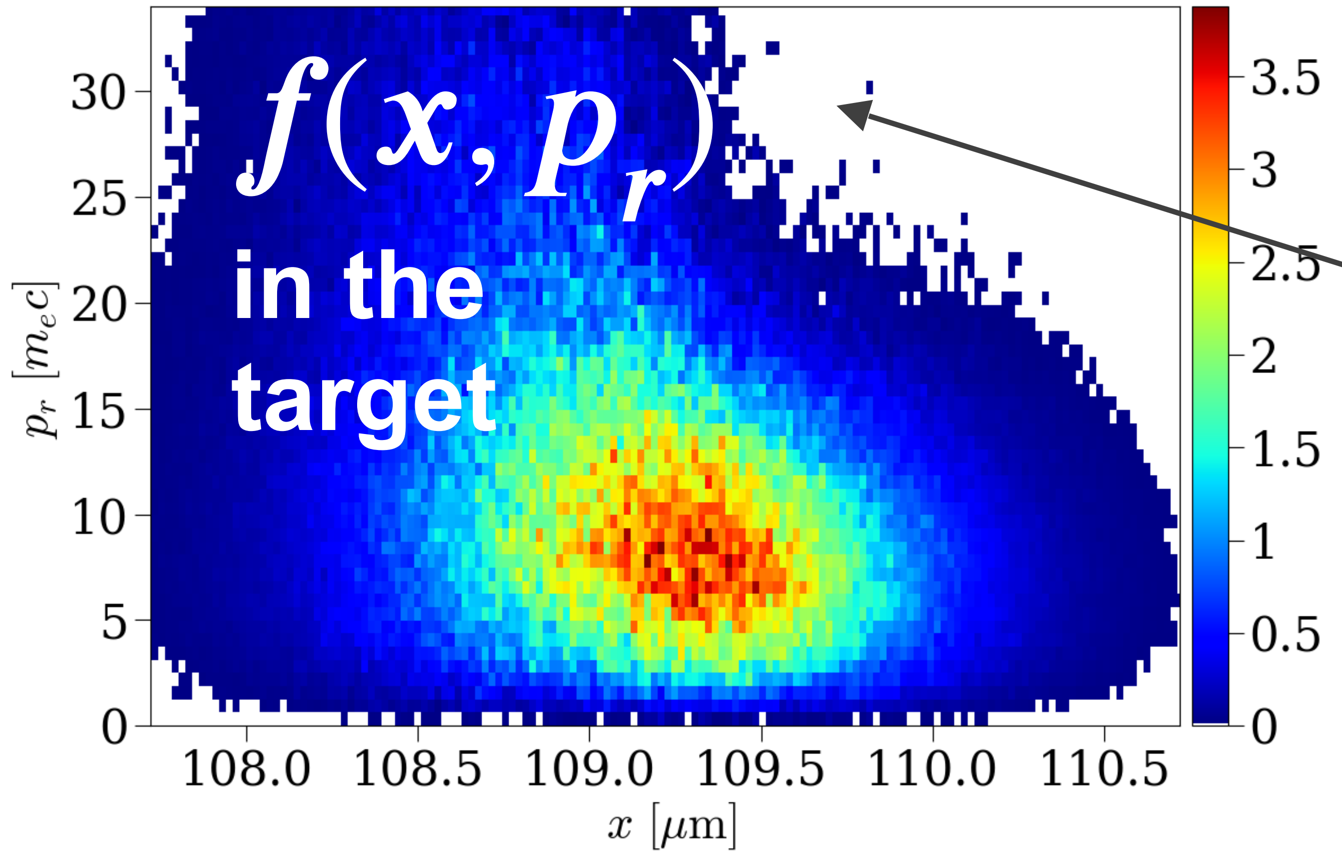
CALDER-Circ PIC simulations

Beam emittance:
- zero or 3 mm.mrad









Momentum gain and density modulation due to the oblique instability.

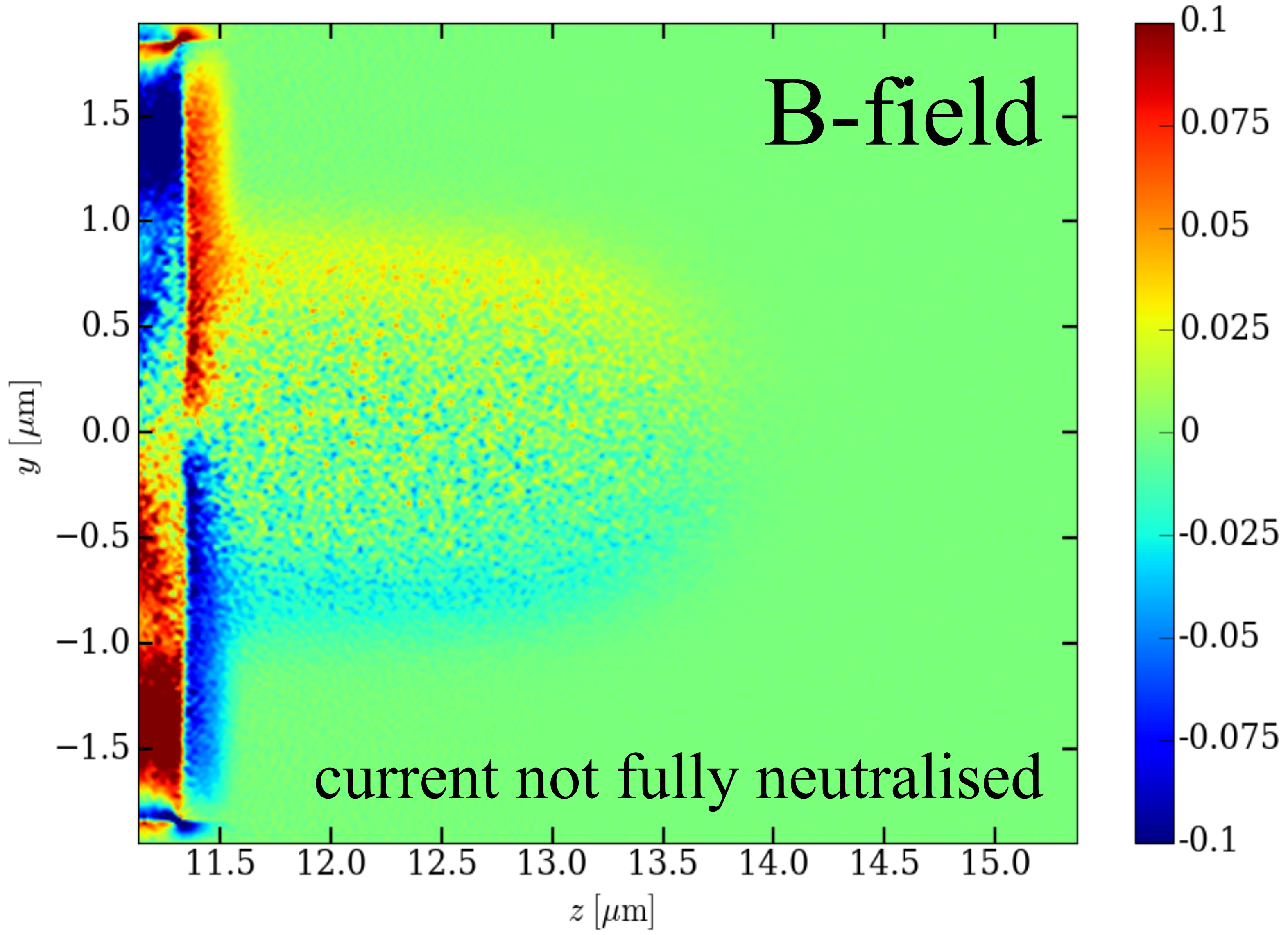
E305-solid: support from theory and simulations

G. Raj and S. Corde

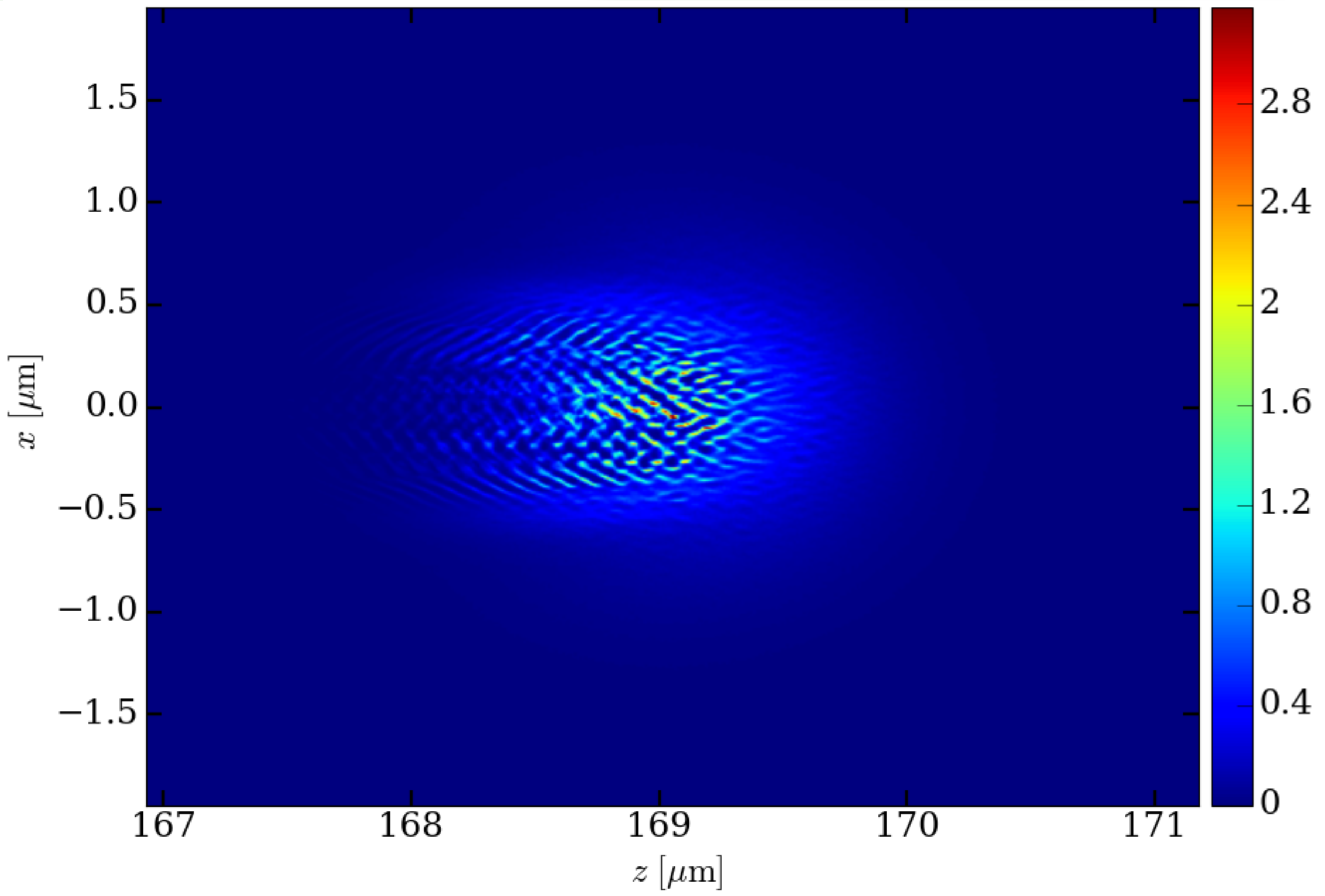
X. Davoine

CALDER **3D** PIC simulations

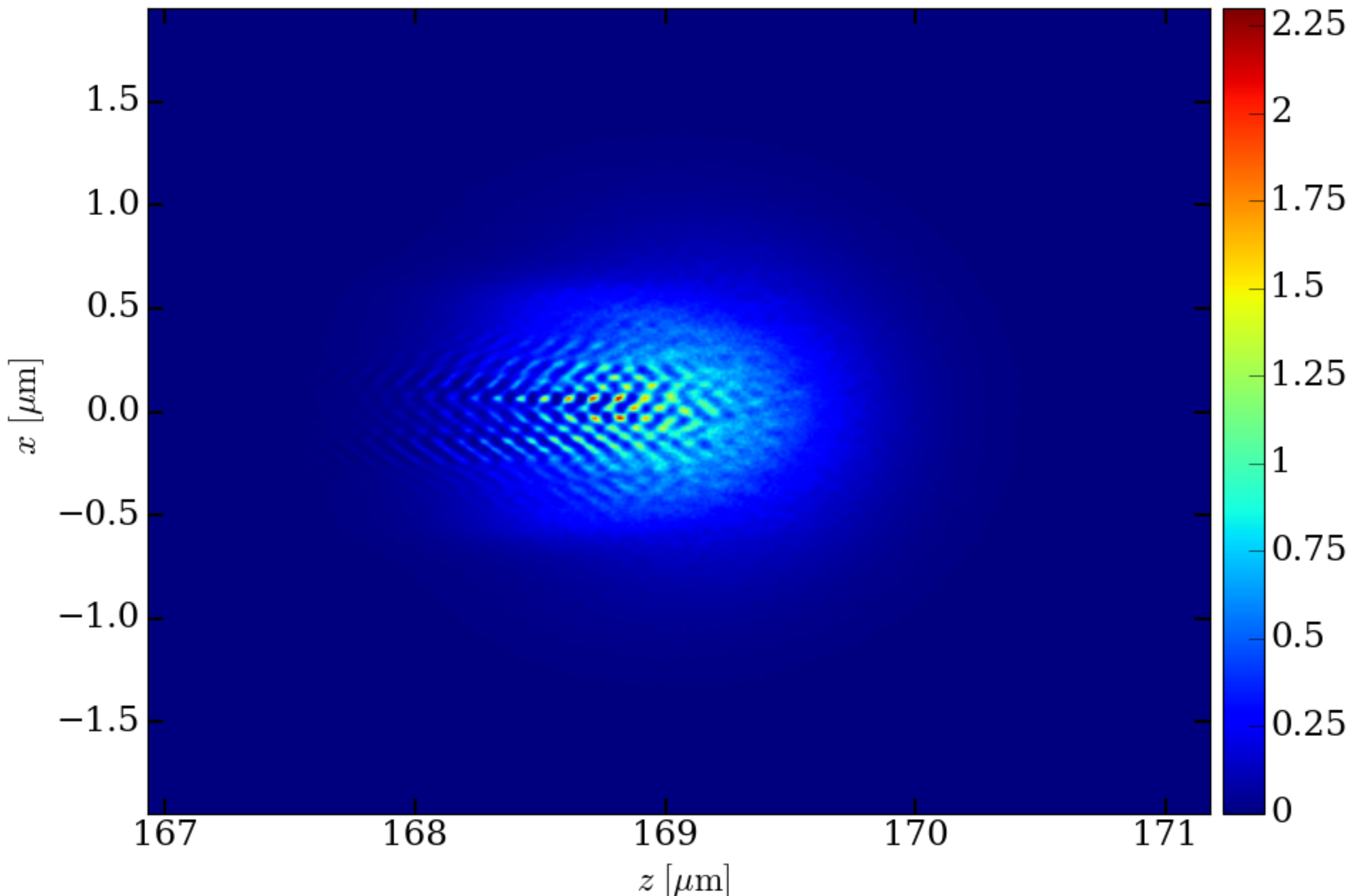
Beam emittance:
- zero or 3 mm.mrad


B-field

current not fully neutralised



zero emittance



3 mm.mrad

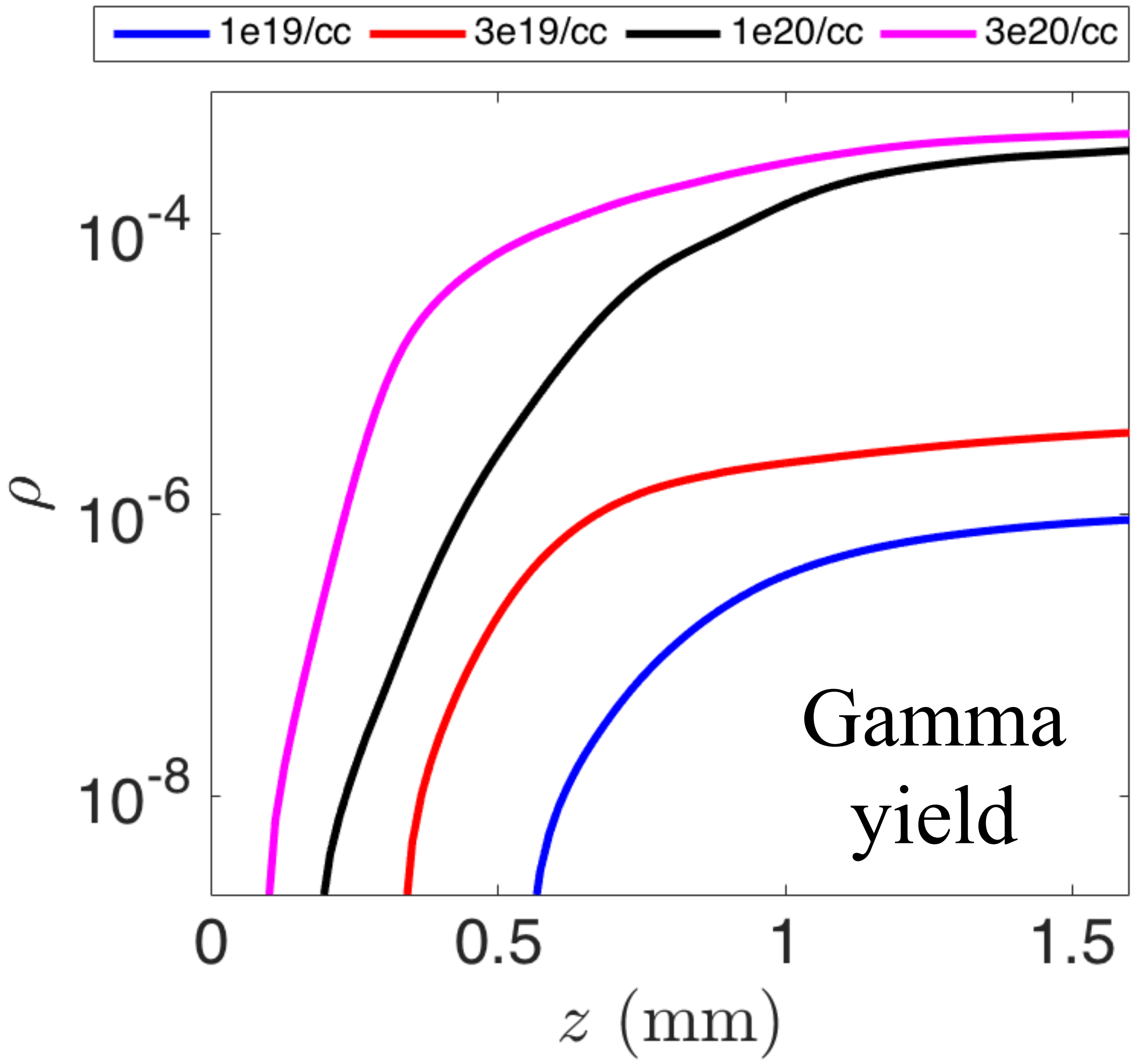
E305-solid: goals and observables for phase 1

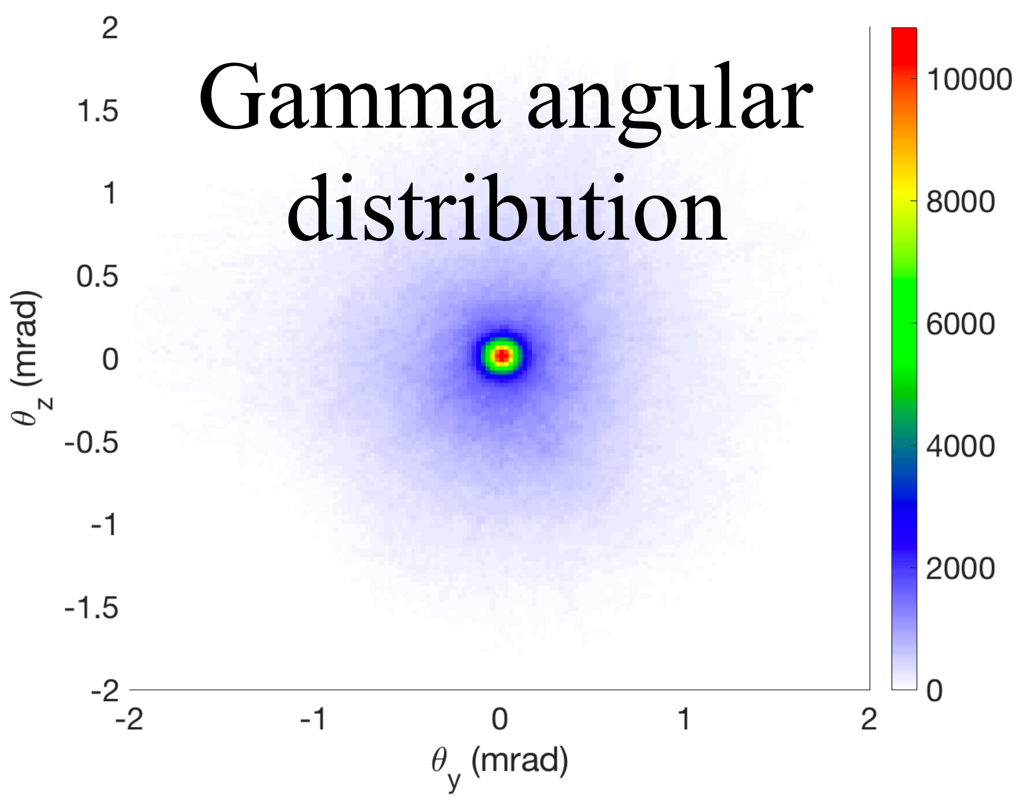
Two high-level goals (defining success):

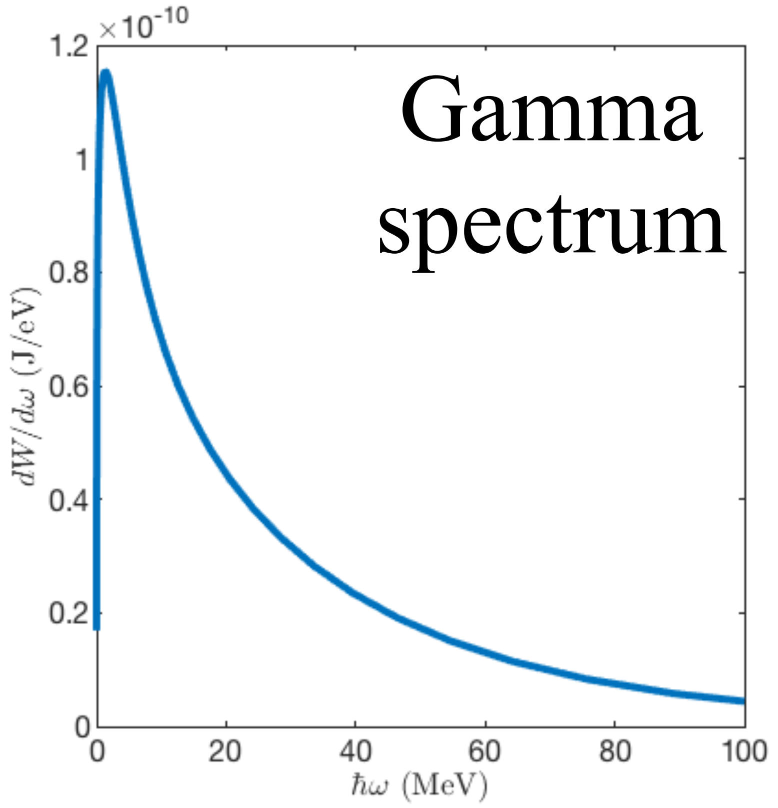
1) Characterisation of interaction of FACET-II beams with solids
2) Evidence of collective beam-plasma interaction (if achieved beam density is sufficient)

Main observables:

1) Gamma-ray yield, exponential growth with target thickness
2) Gamma angular and spectral distribution: benchmarking of gamma properties versus PIC simulations
3) Electron angular and spectral distribution, to check consistency with beam-solid modelling



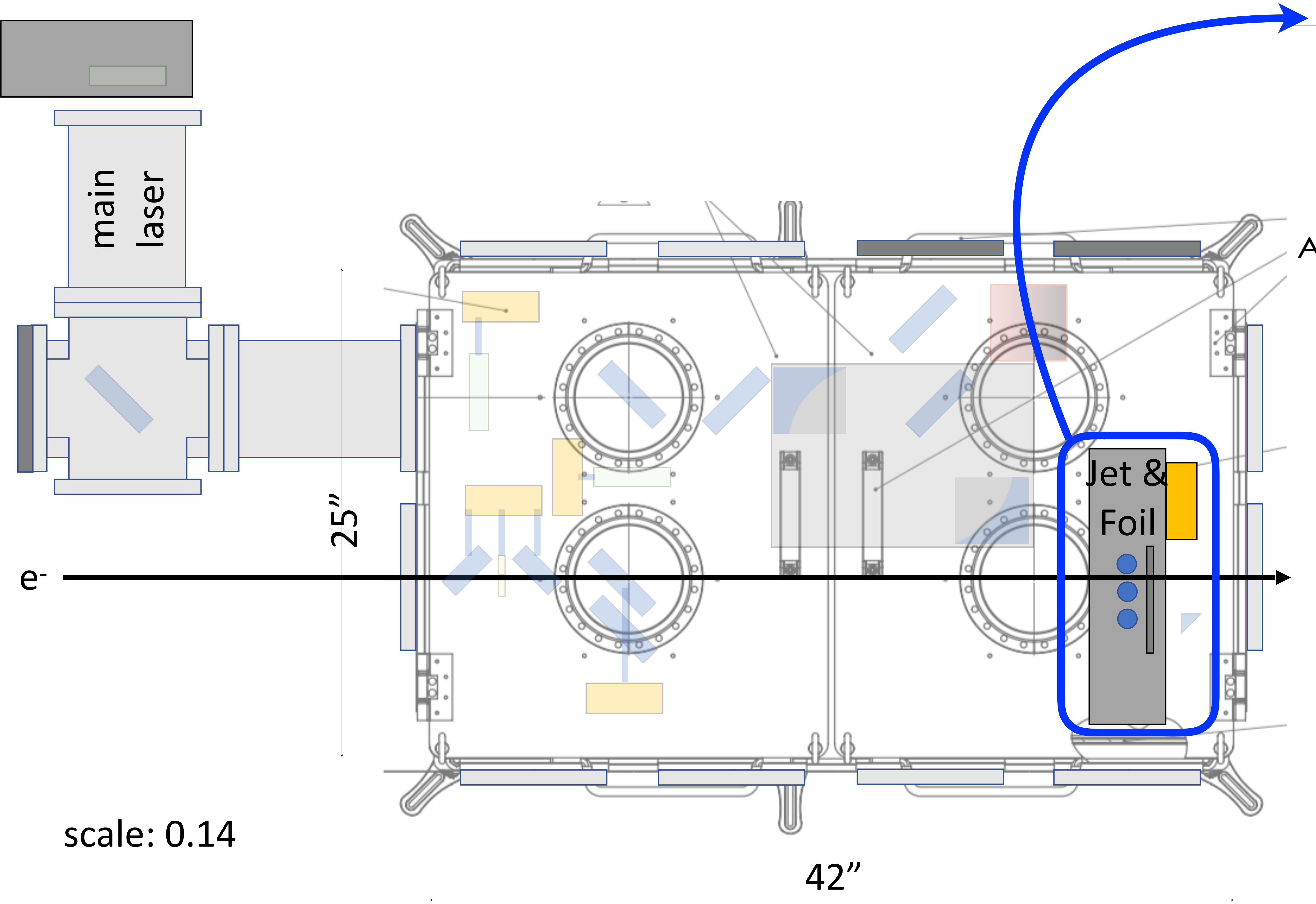




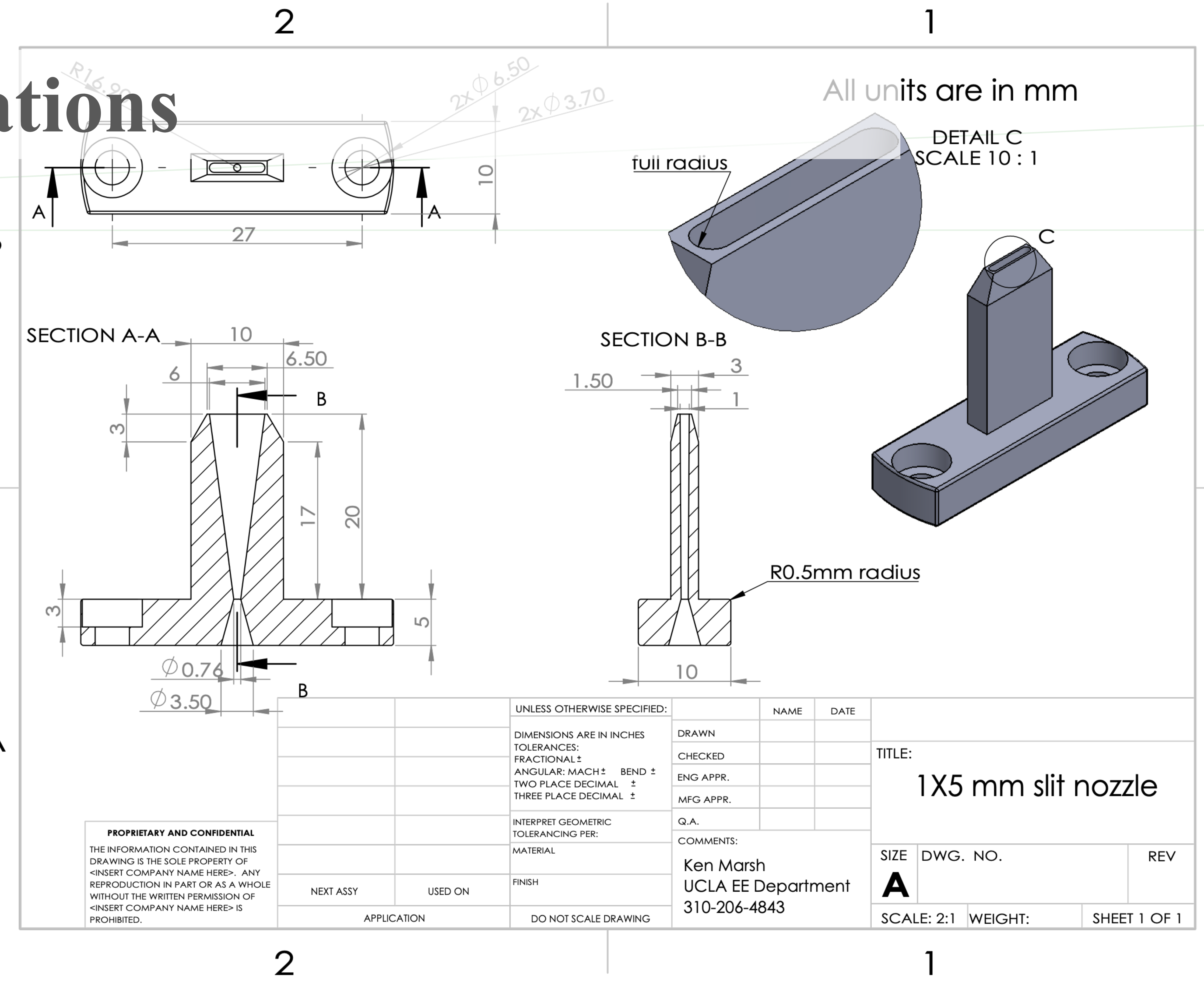
E305-gas

E305-gas: experimental considerations

Installation of gas jets in the "Picnic Basket" chamber



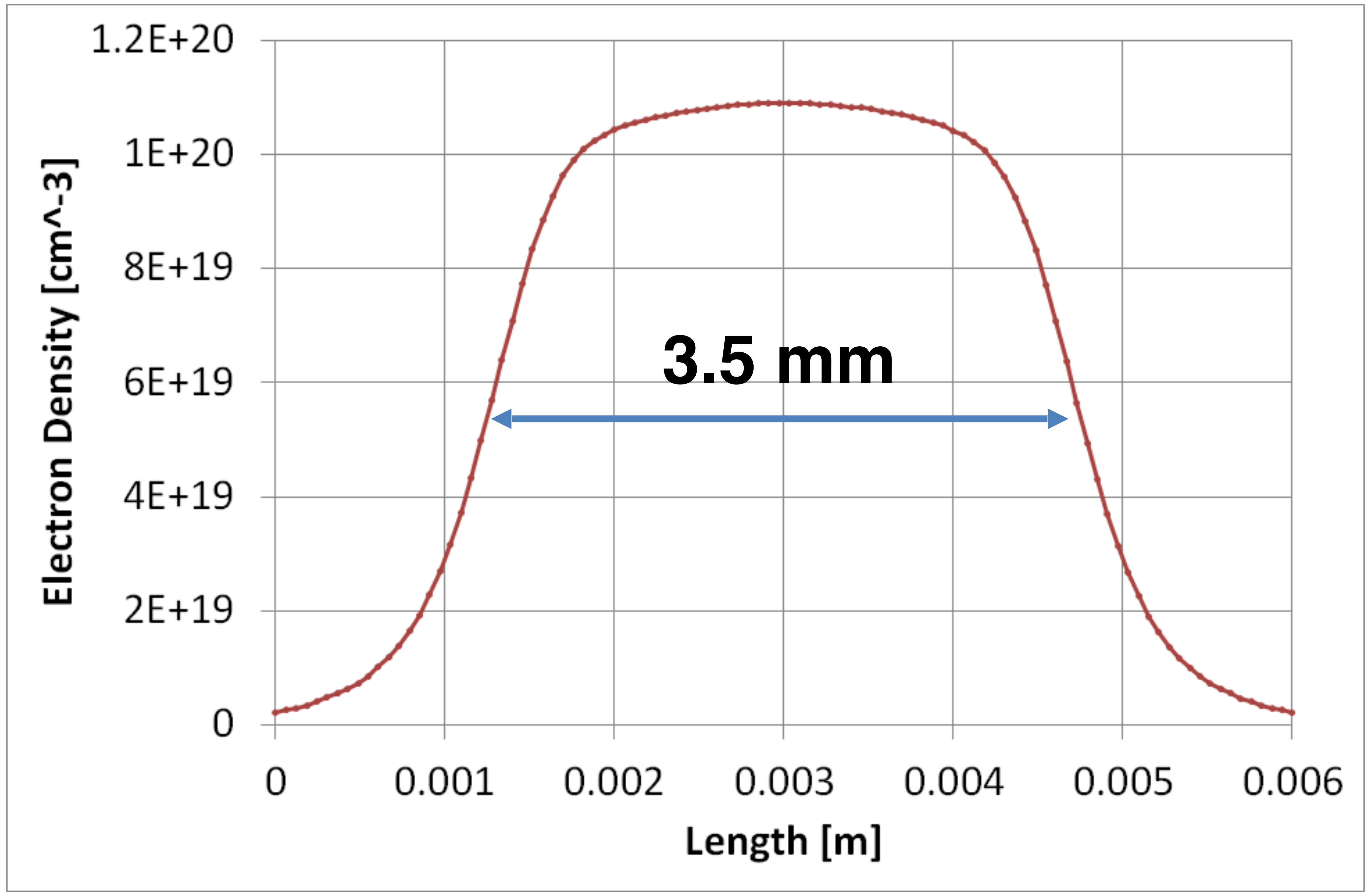
scale: 0.14



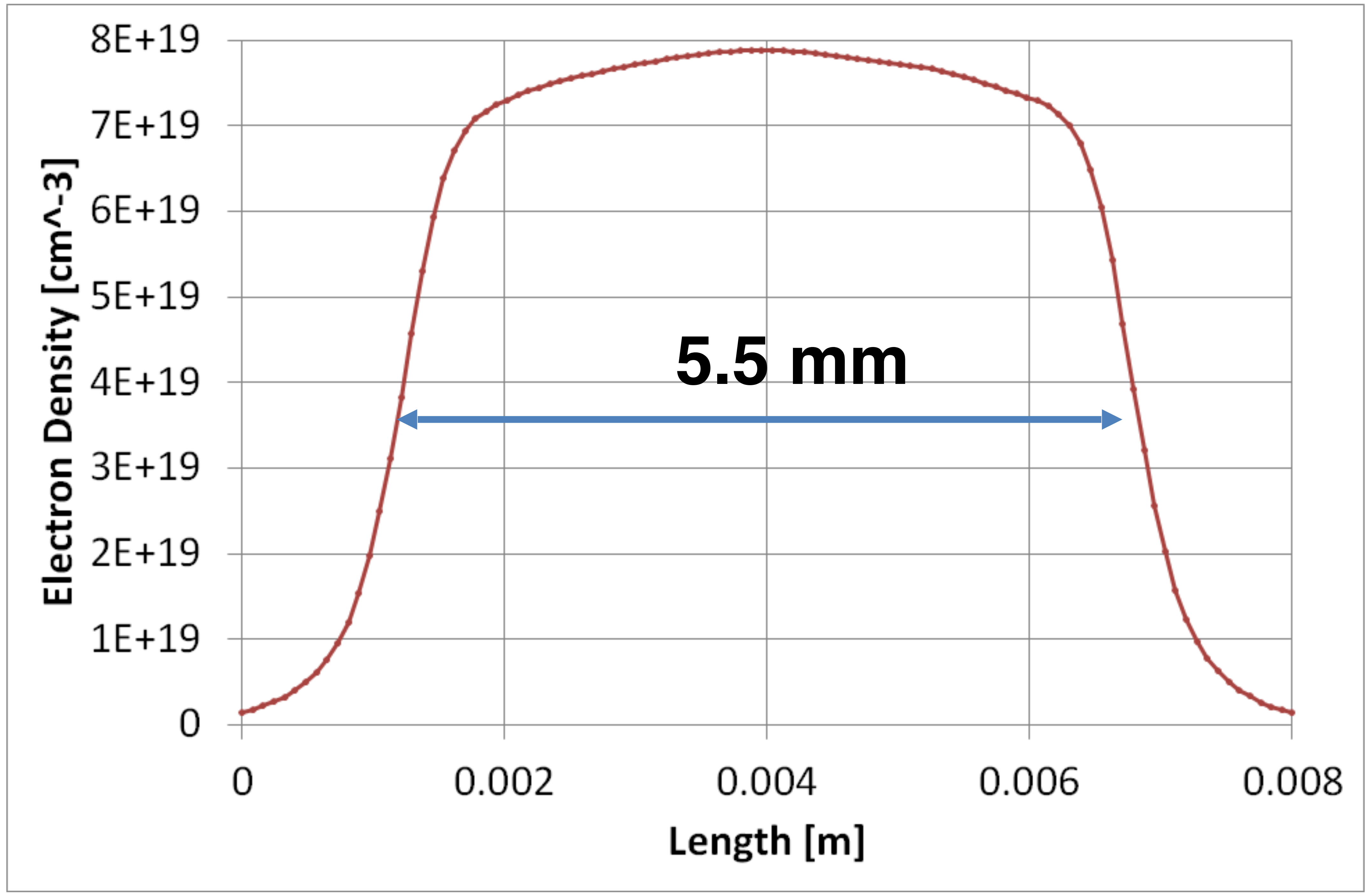
- Entrance diameter: 3.5 mm
- Minimum diameter: 0.76 mm
- Exit size:
  - 1 mm x 6 mm
  - 1 mm x 4 mm
  - 5 mm round
  - 3 mm round

E305-gas: experimental considerations

- 1 mm x 4 mm nozzle



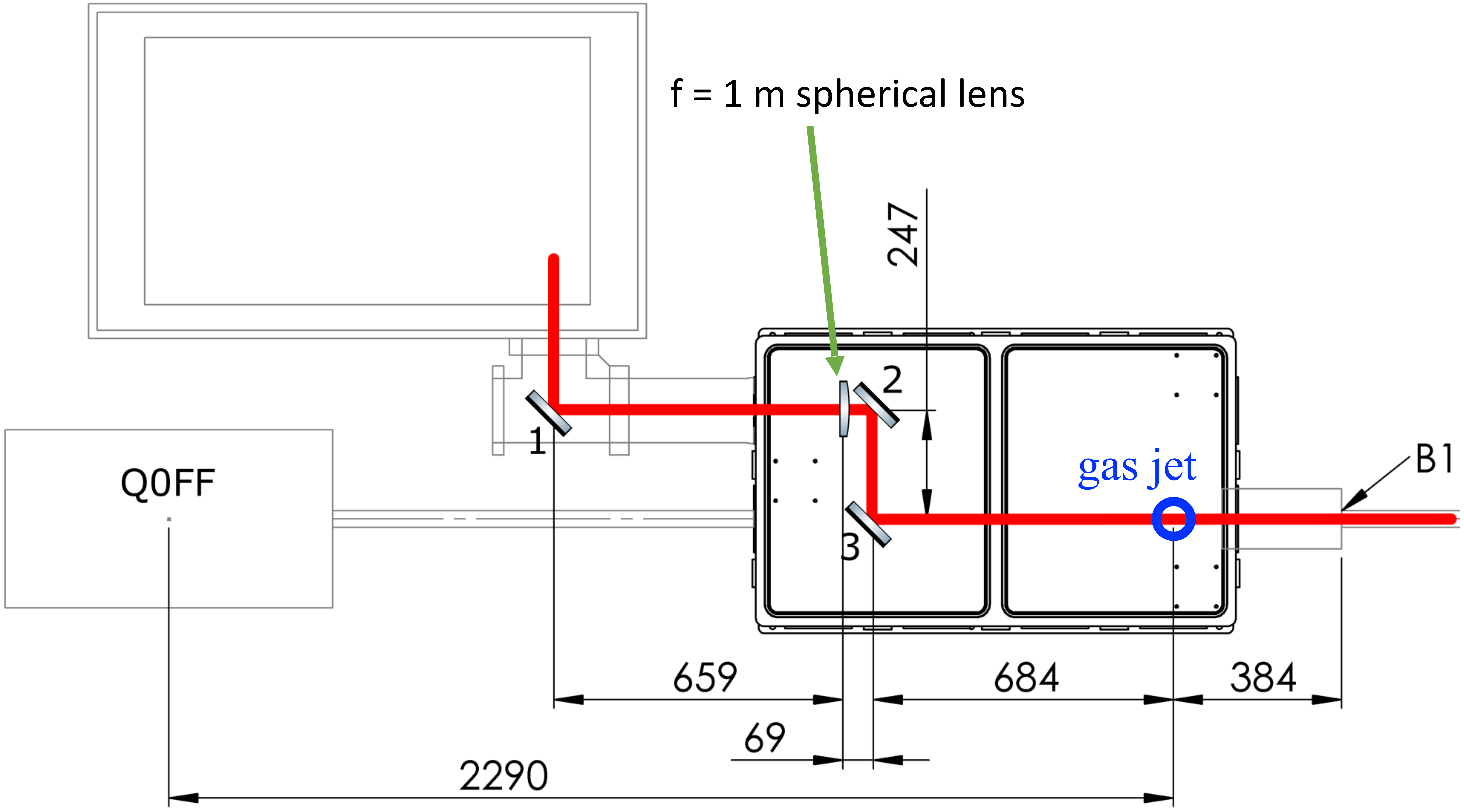
- 1 mm x 6 mm nozzle



- Simulated gas density profile 2 mm above nozzle exit, for 1250 psi backing pressure of H_2.
- Nozzles in hands and currently being tested at UCLA (K. Marsh et al.).
- Solenoid valve and controller in hands, H_2 1250 psi gas line to pass safety review and to be implemented.

E305-gas: experimental considerations

Laser ionization - optical layout



Optical setup

The focusing optic is a 1-m focal length spherical lens located just upstream of mirror 2.

The plasma is formed in front of the last window in the picnic basket 384 mm upstream of B1.

B1 is the aperture between the oven mover bellows and the bypass line.

B2 is the worst-case aperture in the bypass line and is located 200 mm downstream of B1.

E305-gas: experimental considerations

Laser ionization - generated plasma

Laser Parameters

Laser energy:	150mJ
Pulse duration:	70fs
Wavelength:	796nm
Beam width:	40mm FWHM
Beam profile:	Super Gaussian
Focal length:	1.0m
Mask diameter:	1cm

Energy budget

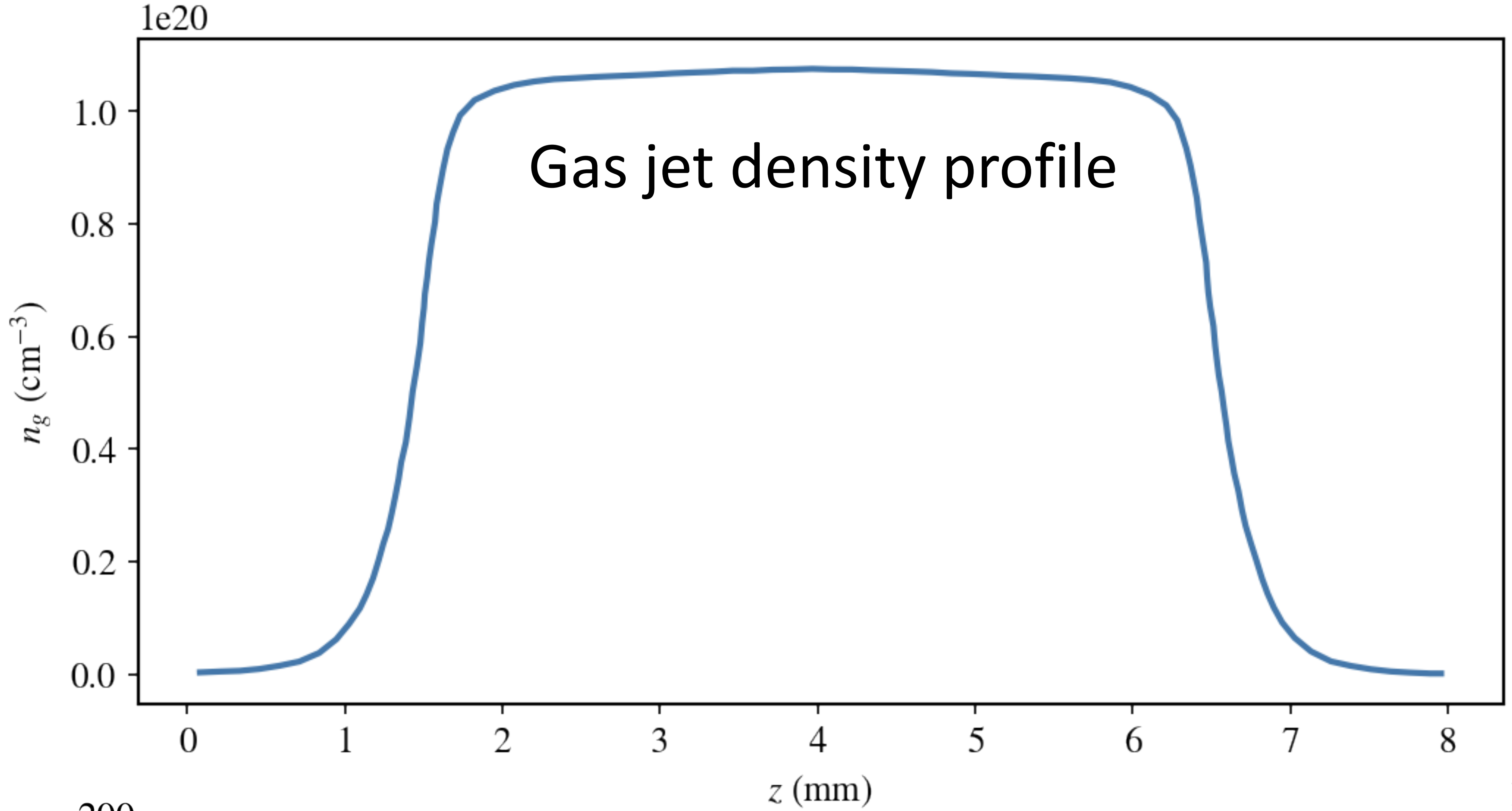
Energy to ionize:	34.7mJ
Plasma heating energy:	44.9mJ
Energy after optics:	120mJ
Energy lost to mask:	8mJ
Required energy:	150mJ

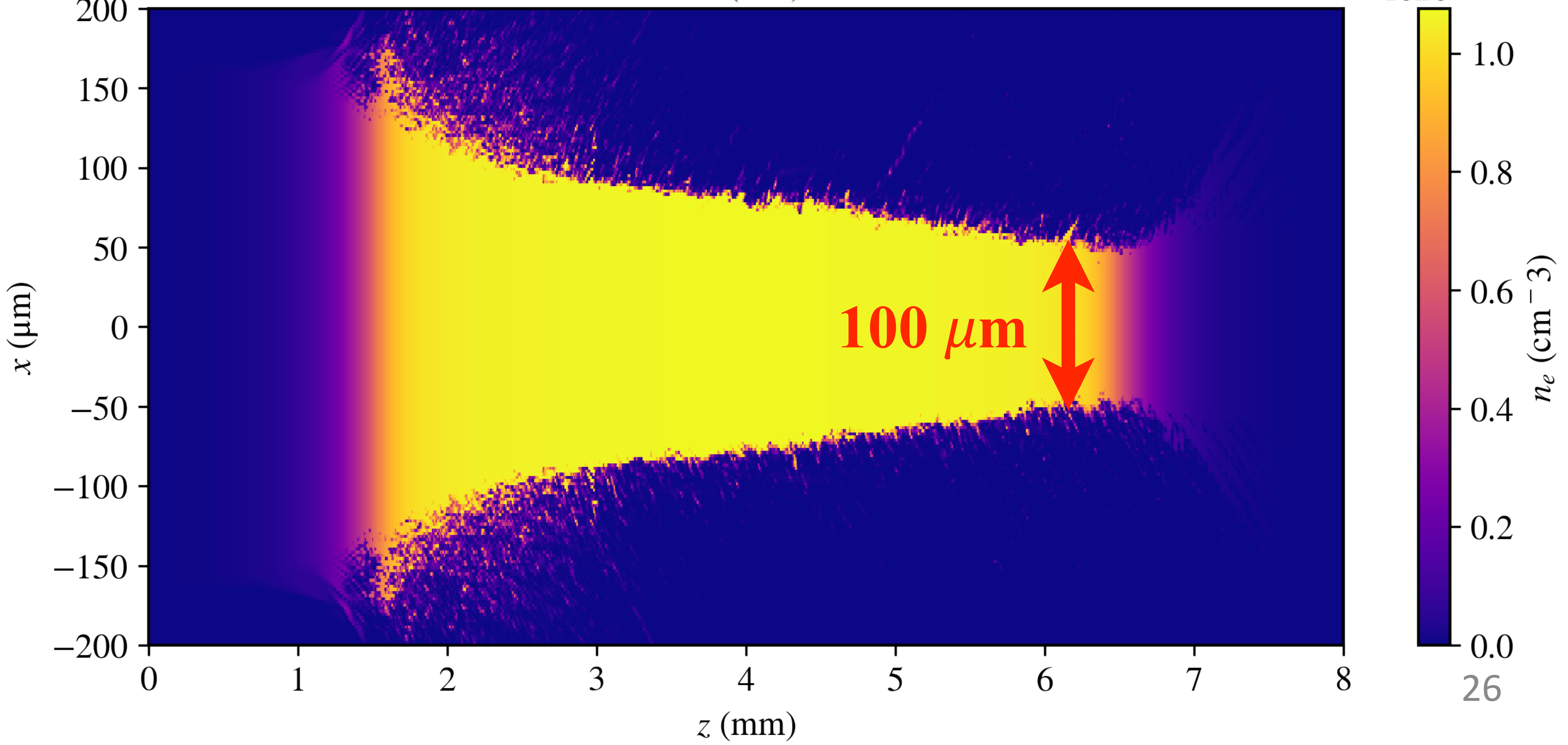
Laser refraction simulation

Split step Fourier based code from CU Boulder (R. Ariniello).

Energy loss due to ionization and plasma heating.

No dispersion, no self-focusing.



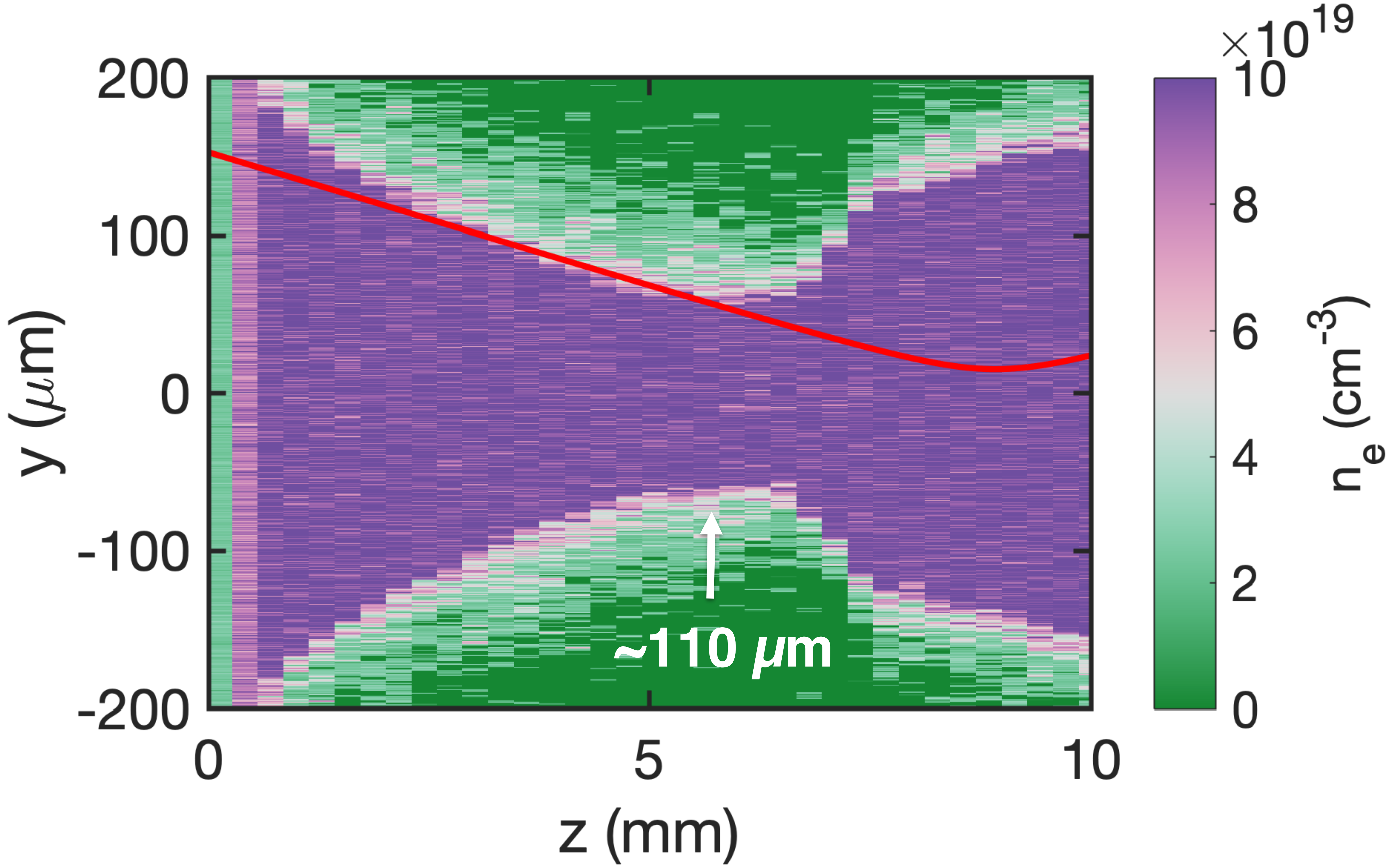


E305-gas: experimental considerations

Laser ionization - generated plasma

Laser Parameters

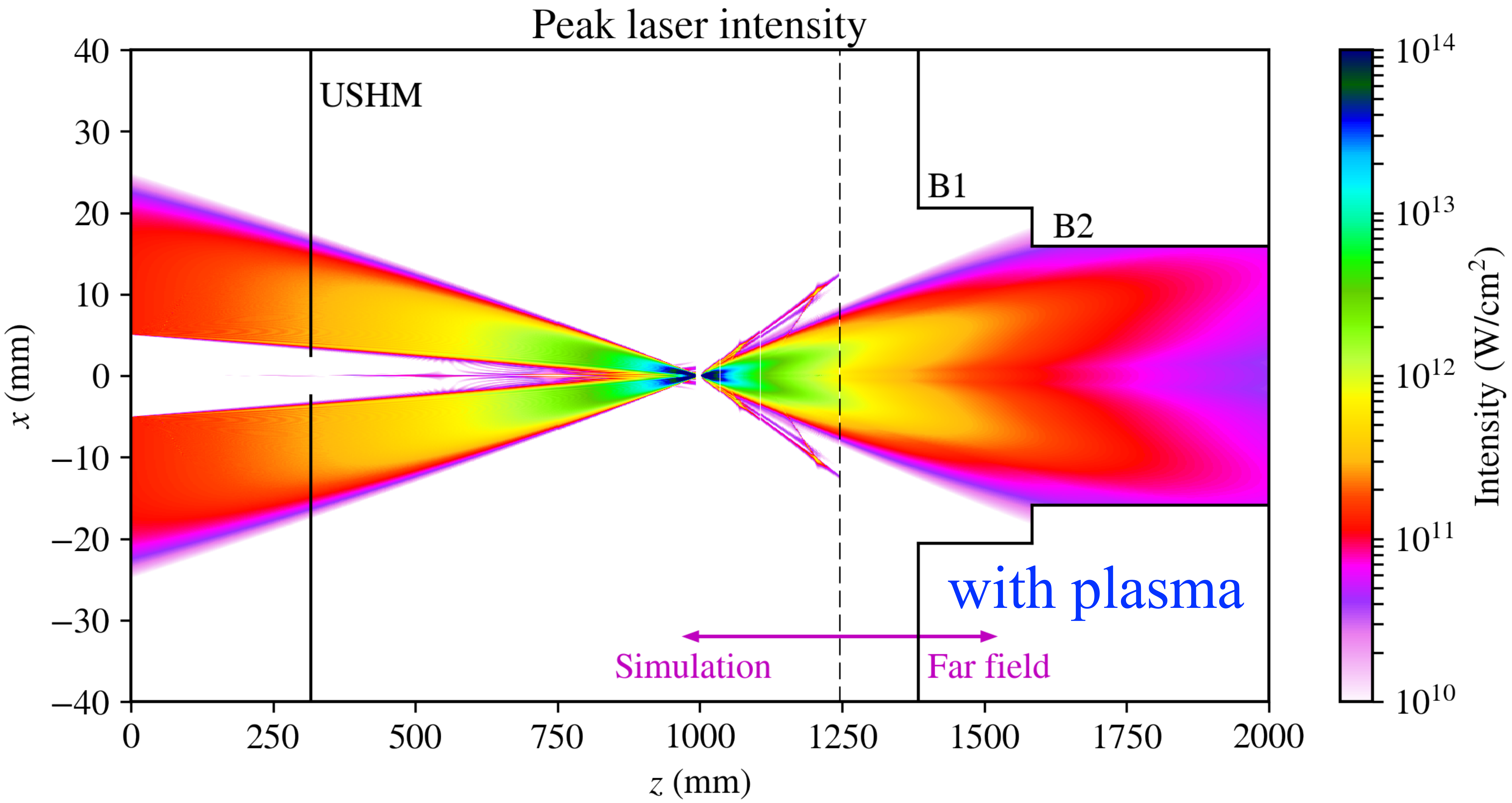
waist $w_0 = 15\ \mu m$
24 mJ, 80 fs, $a_0 = 0.2$



Laser refraction simulation
2D OSIRIS simulation by UCLA (C. Zhang).
No energy loss due to ionization,
Plasma heating underestimated in 2D,
Dispersion and self-focusing included.

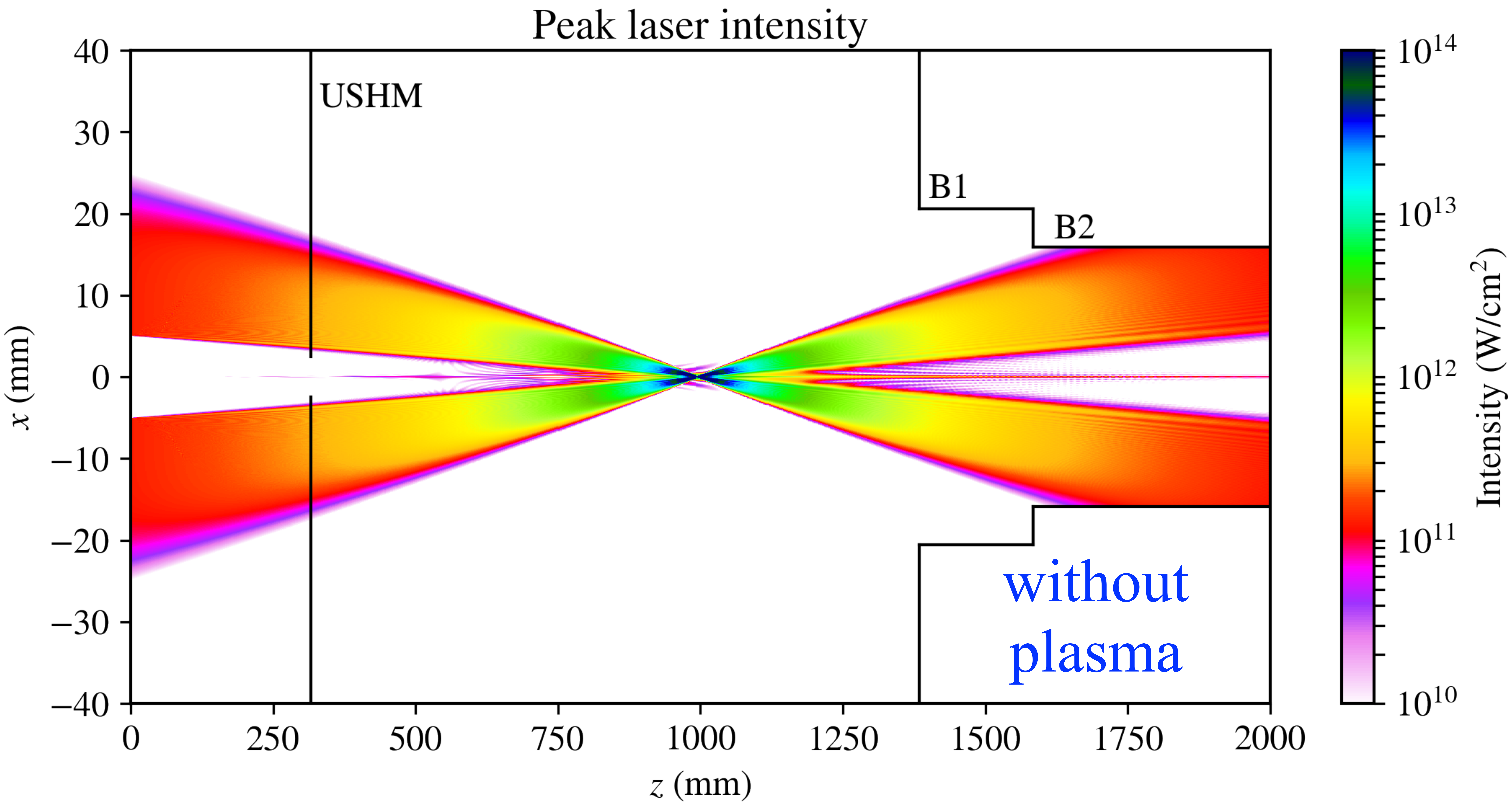
E305-gas: experimental considerations

Laser ionization - laser intensity map



E305-gas: experimental considerations

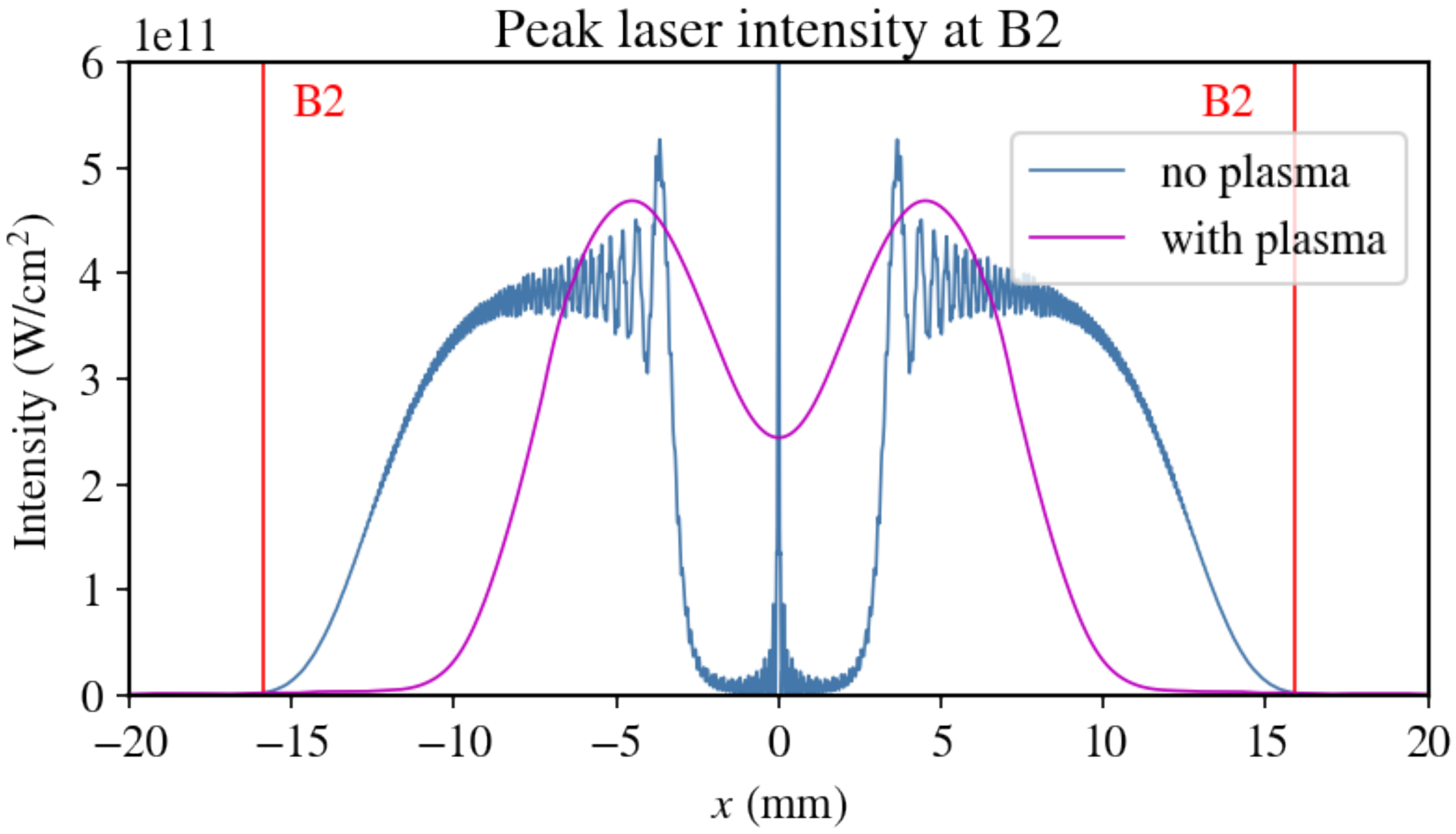
Laser ionization - laser intensity map



without plasma

E305-gas: experimental considerations

Laser ionization - transverse intensity at aperture B2

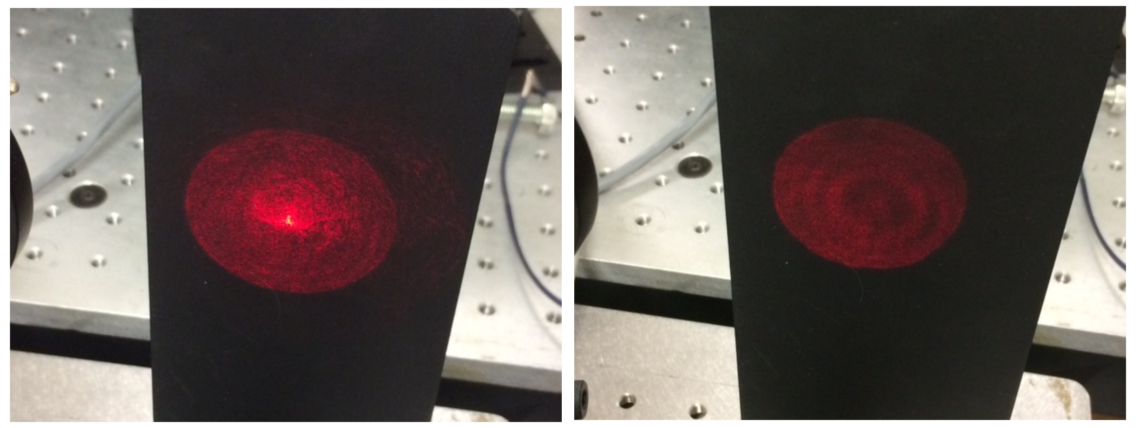


E305-gas: experimental considerations

Laser dump

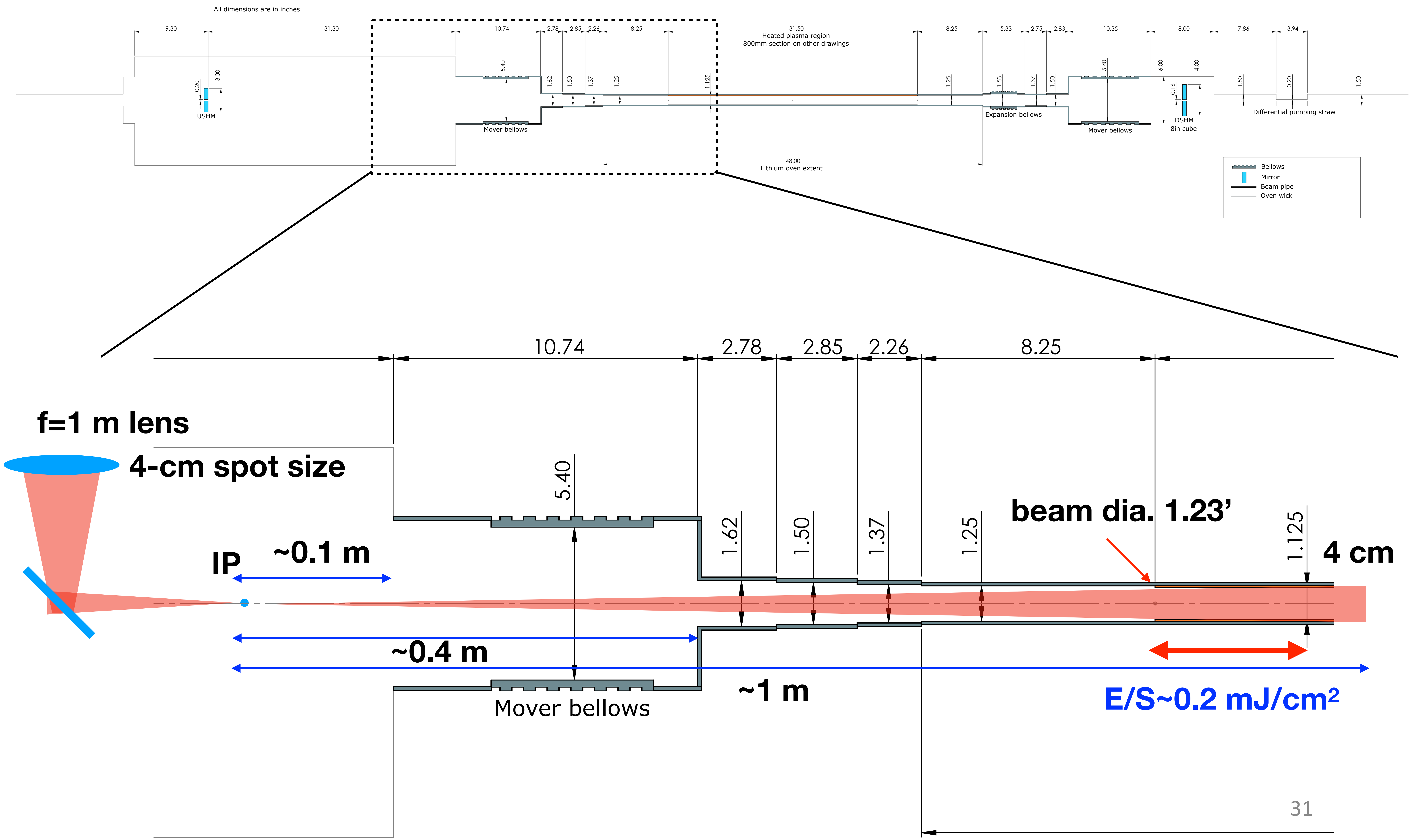
Laser starts hitting the bypass tube where its diameter is <1.25'. Because of the small divergent angle, the areal energy density deposited on the tube is small: ~0.2 mJ/cm².

Laser through bypass line:



Without internal protection

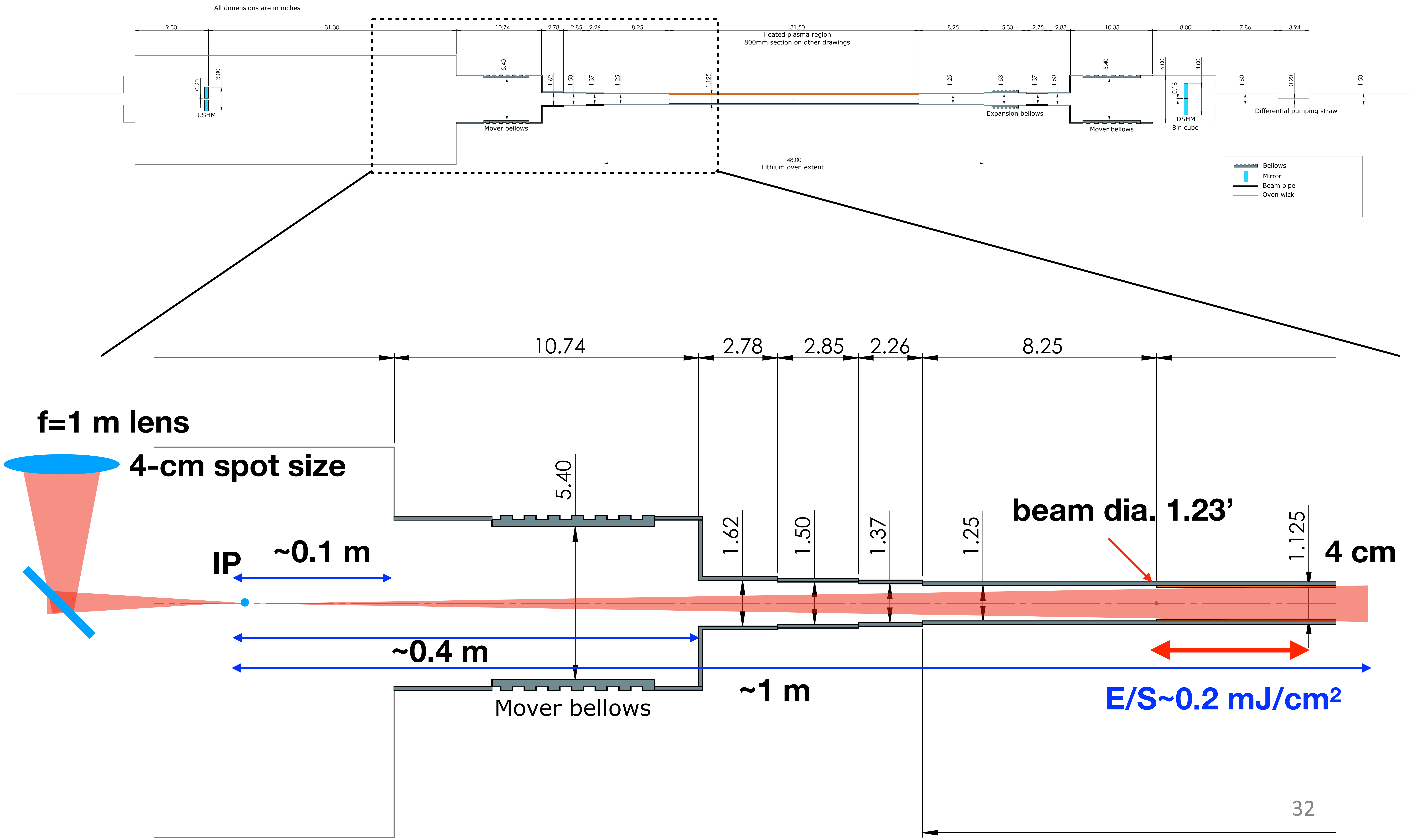
With internal protection

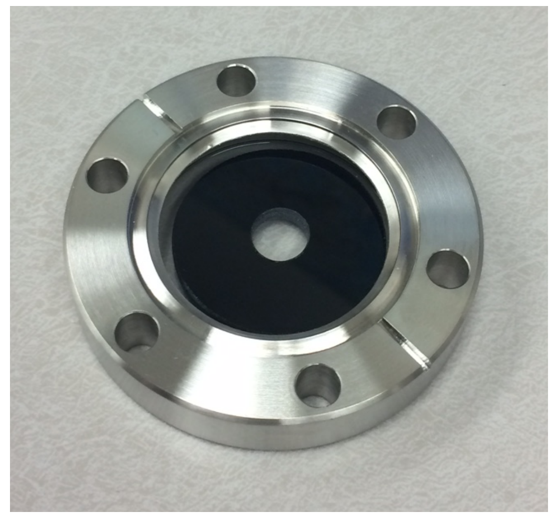


E305-gas: experimental considerations

Laser dump

Laser starts hitting the bypass tube where its diameter is <1.25’. Because of the small divergent angle, the areal energy density deposited on the tube is small: ~0.2 mJ/cm².





Example of laser dump element: ND filter beam dump in 2.75” CF double-sided flange

E305-gas: experimental considerations

Experimental diagnostics for E305-gas

For day 1: same as E305-solid

- Profile monitor before quads for electron angular distribution.
- High-resolution electron energy spectrometer.
- Gamma screens for yield, angular distribution and critical photon energy of gamma-ray beams.

At later stage:

- Gamma Compton spectrometer by UCLA (J. Rosenzweig et al.)
- Thomson scattering to uncover temporal and spatial modulations of electron beam
- Optical transverse shadowgraphy

E305-gas: goals and observables for phase 1

E305-gas objectives (defining success):

1) First tests of beam-plasma interaction with 100 kA beams and laser-ionised high-density gas (> 5 10^{19} cm^{-3})
2) Benchmark against theoretical and numerical predictions, especially verifying trends of observables vs plasma density and beam size in blowout and filamentation regimes

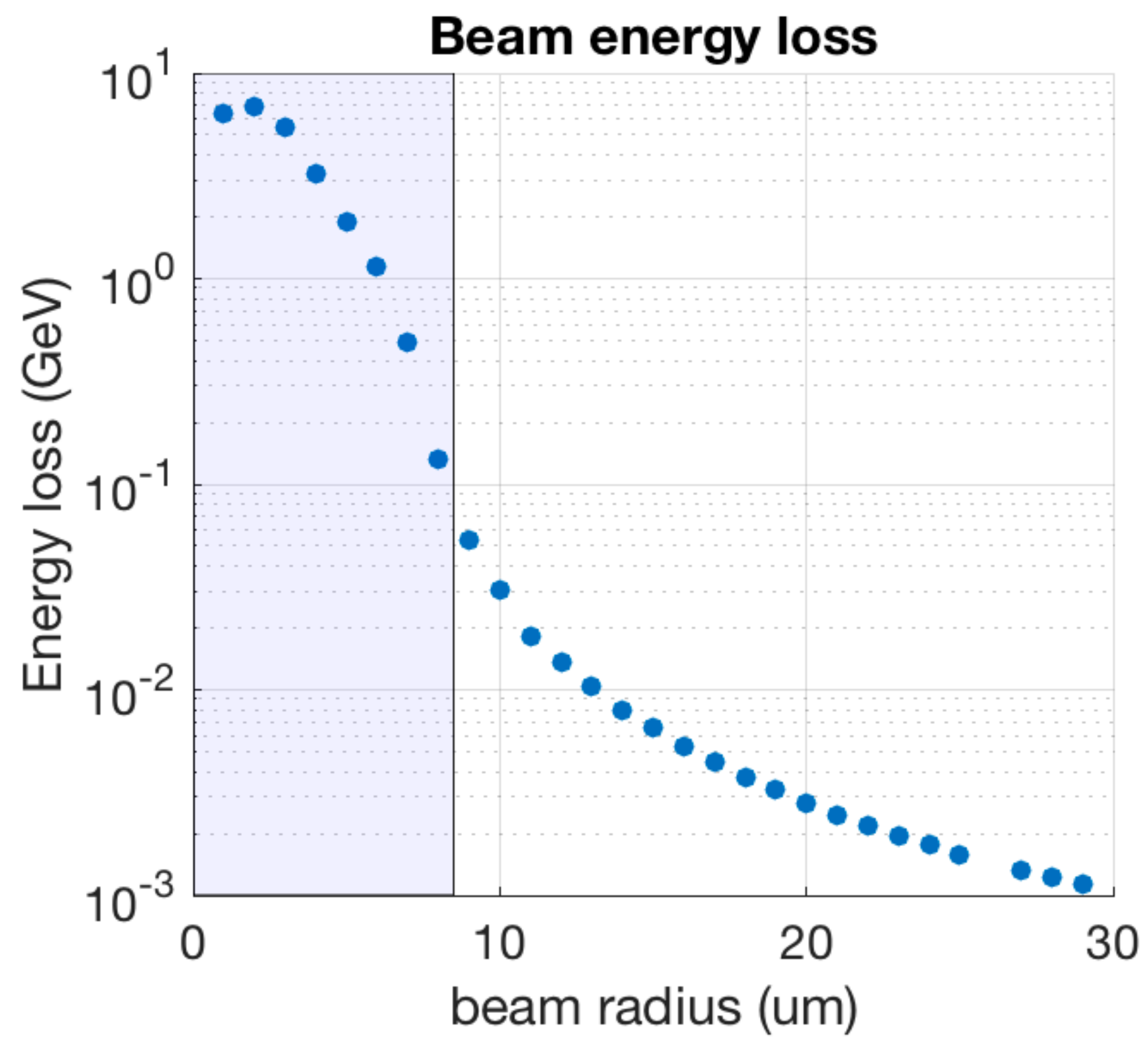
Main observables:

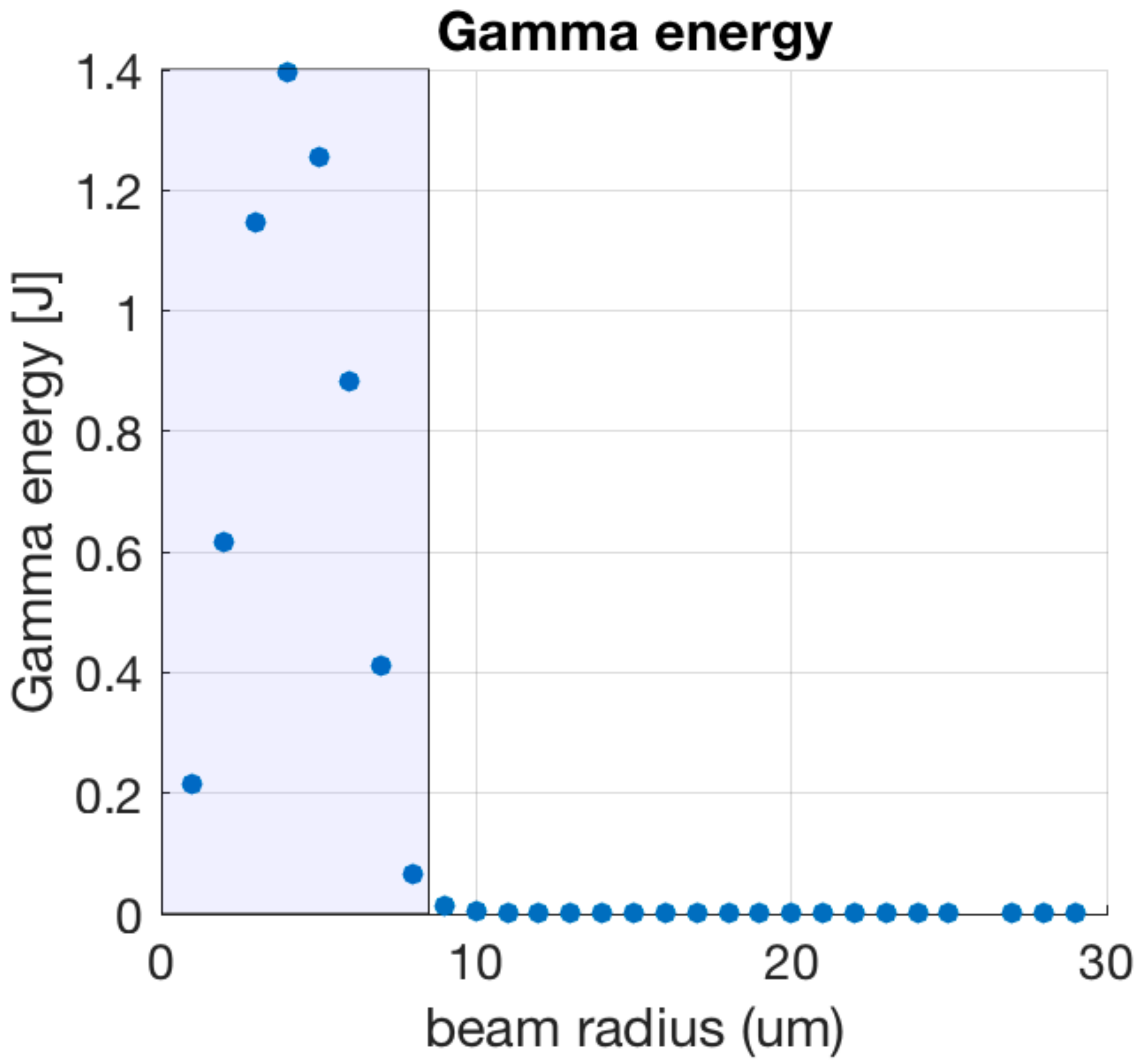
1) Gamma-ray yield
2) Gamma angular and spectral distribution
3) Electron angular and spectral distribution

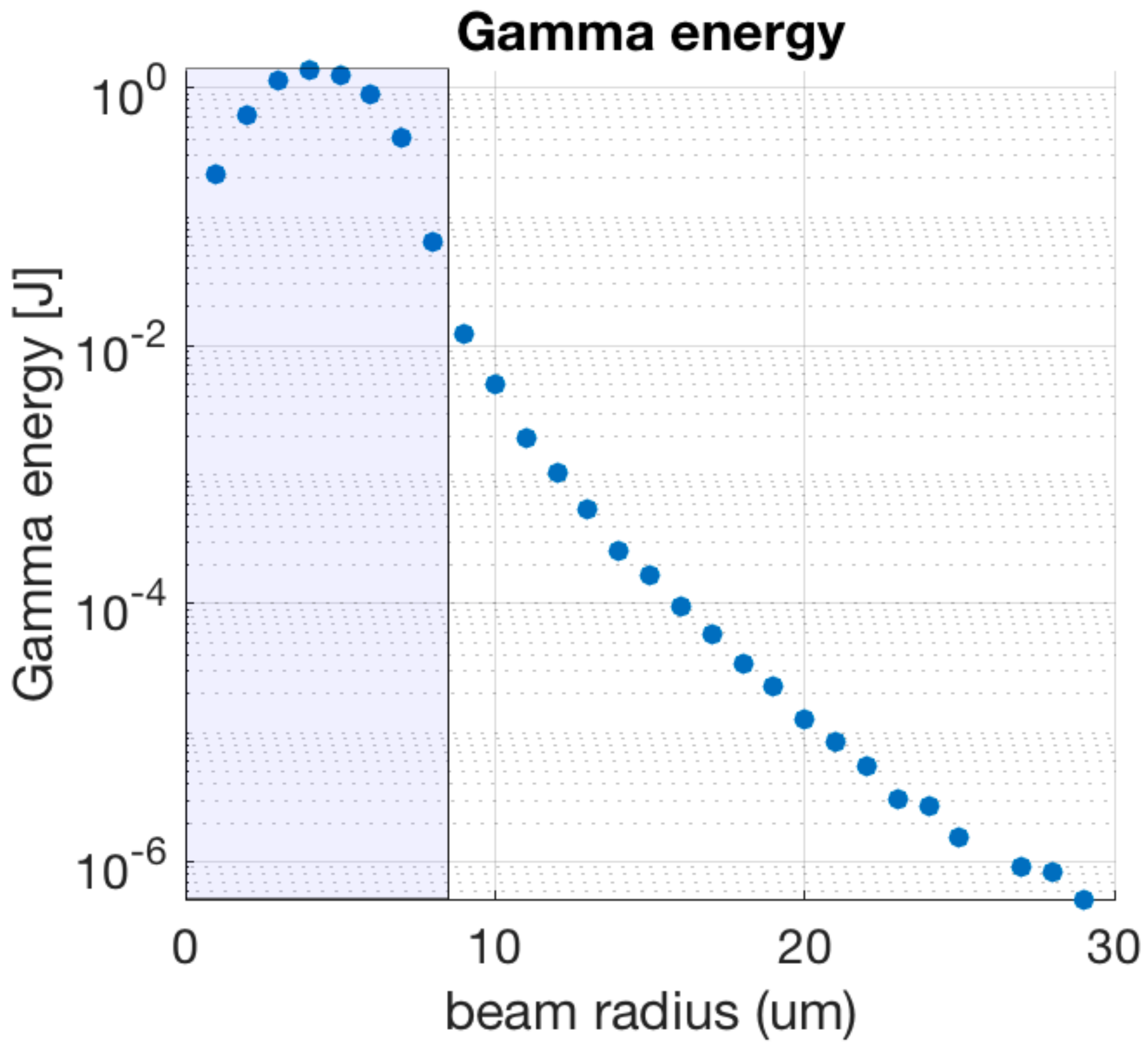
E305-gas: goals and observables for phase 1

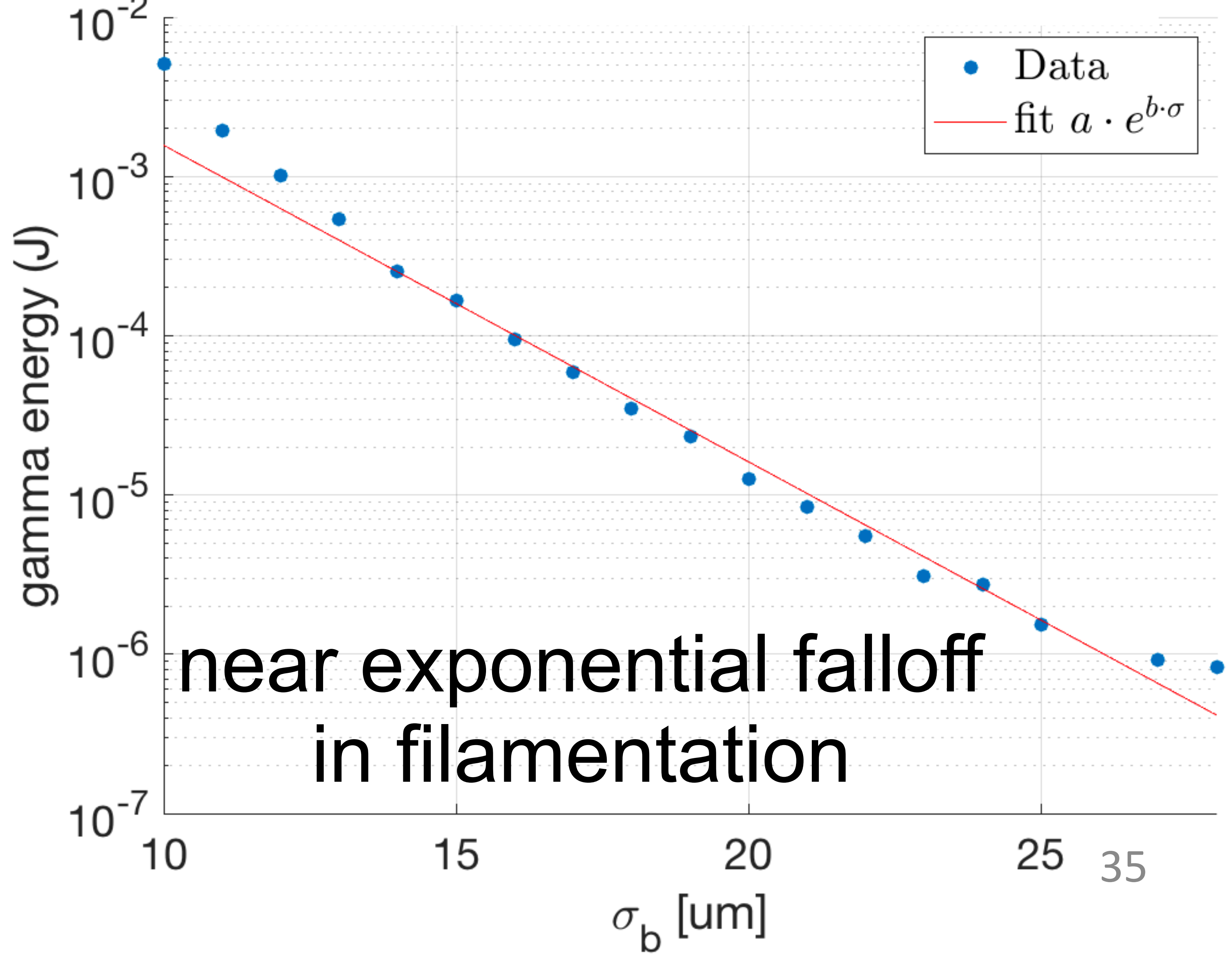
🟦 Blow out

$$n_p = 10^{20}\ \text{cm}^{-3}$$







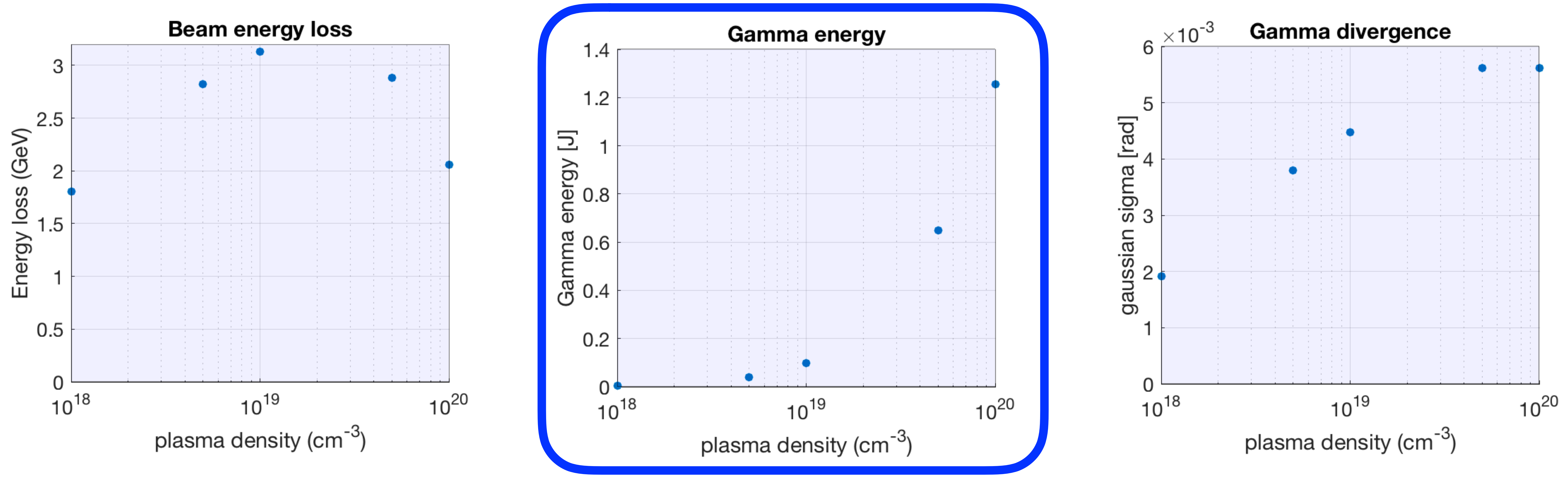


near exponential falloff in filamentation

E305-gas: goals and observables for phase 1

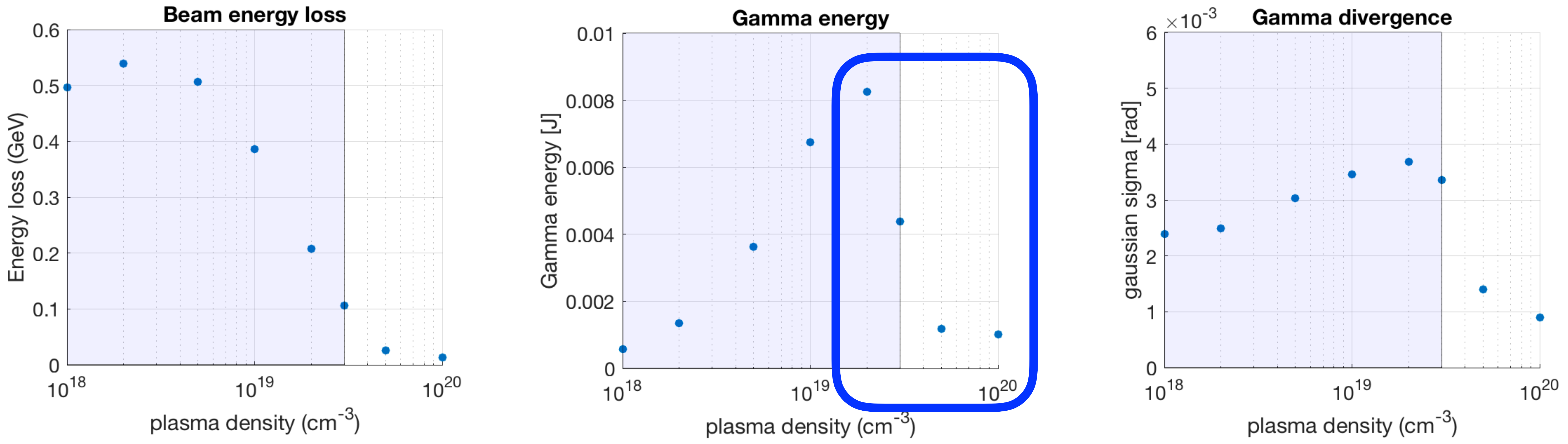
Blow out

$$\sigma_r = 5\ \mu\text{m}$$



Gamma energy always increase with n_p when in blowout

$$\sigma_r = 12\ \mu\text{m}$$



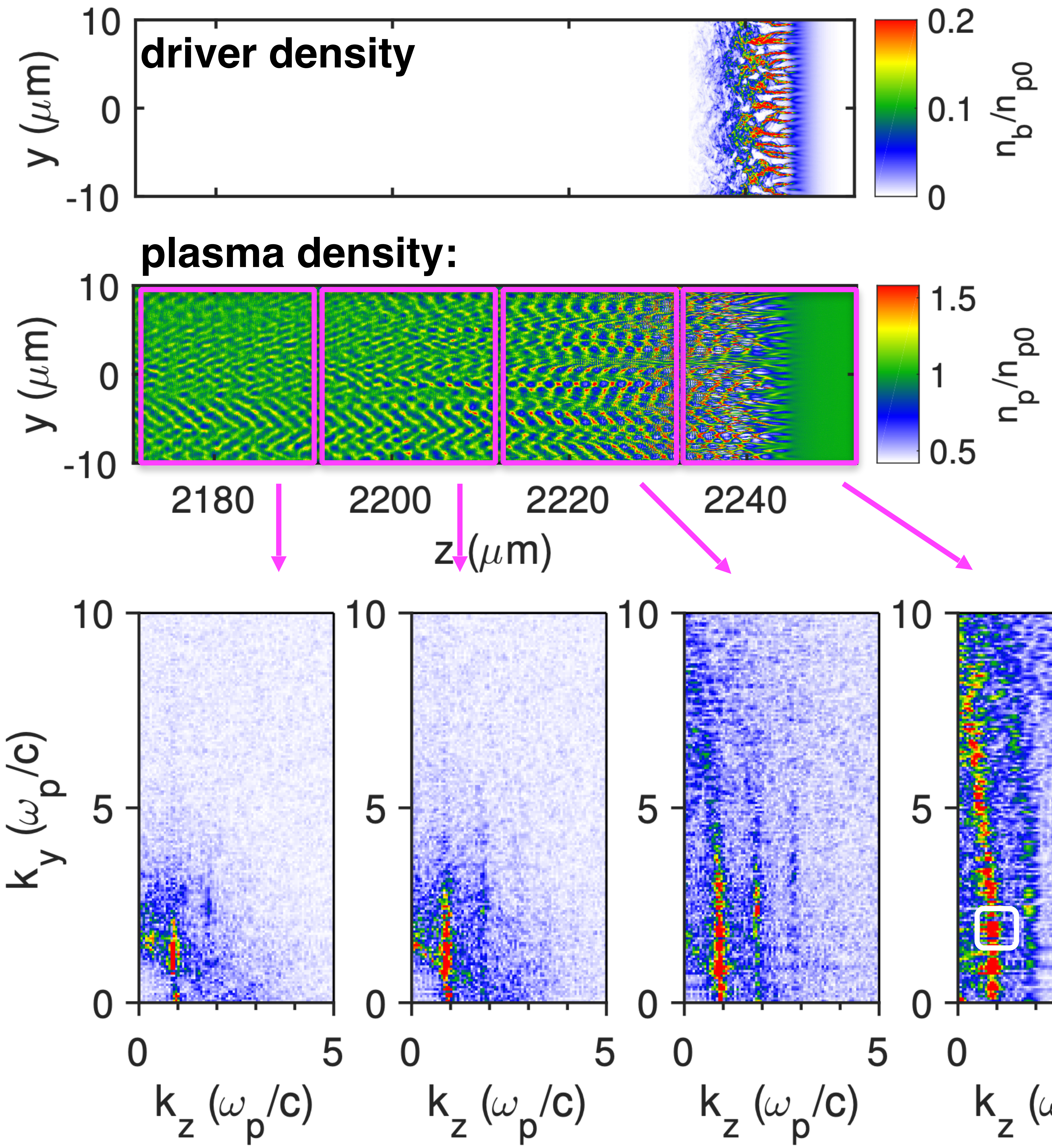
Sharp decrease in gamma energy when transitioning to filamentation

Thank you for your attention

Back-up

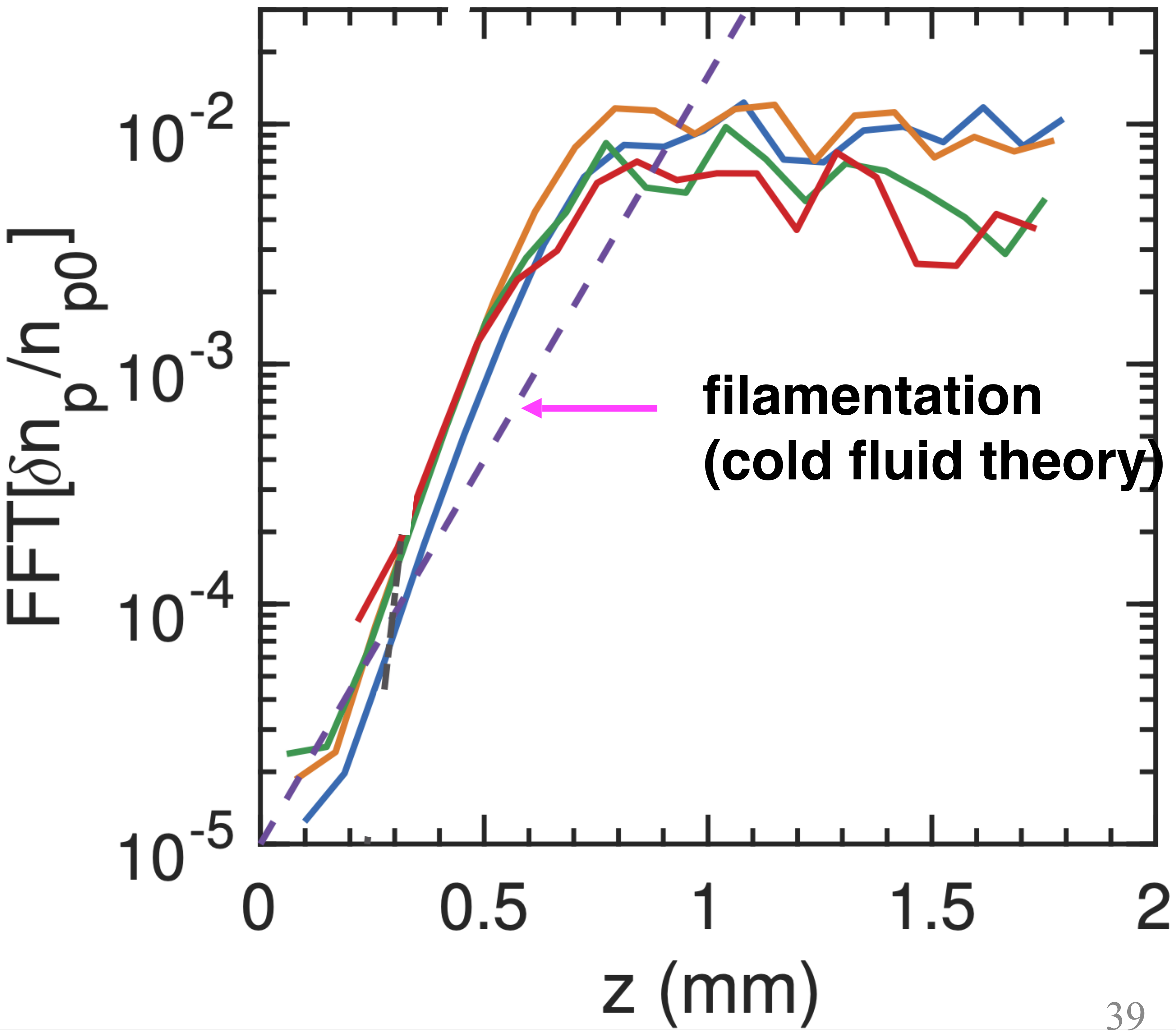
Probing current filamentation instability using Thomson scattering

UCLA



nb=3e19 cm^{-3}, σ_z=2.8 μm
np=3e20 cm^{-3}, 20 eV
256 particles/cell
e-e collisions included

density fluctuation at kz=kp, ky=2kp:



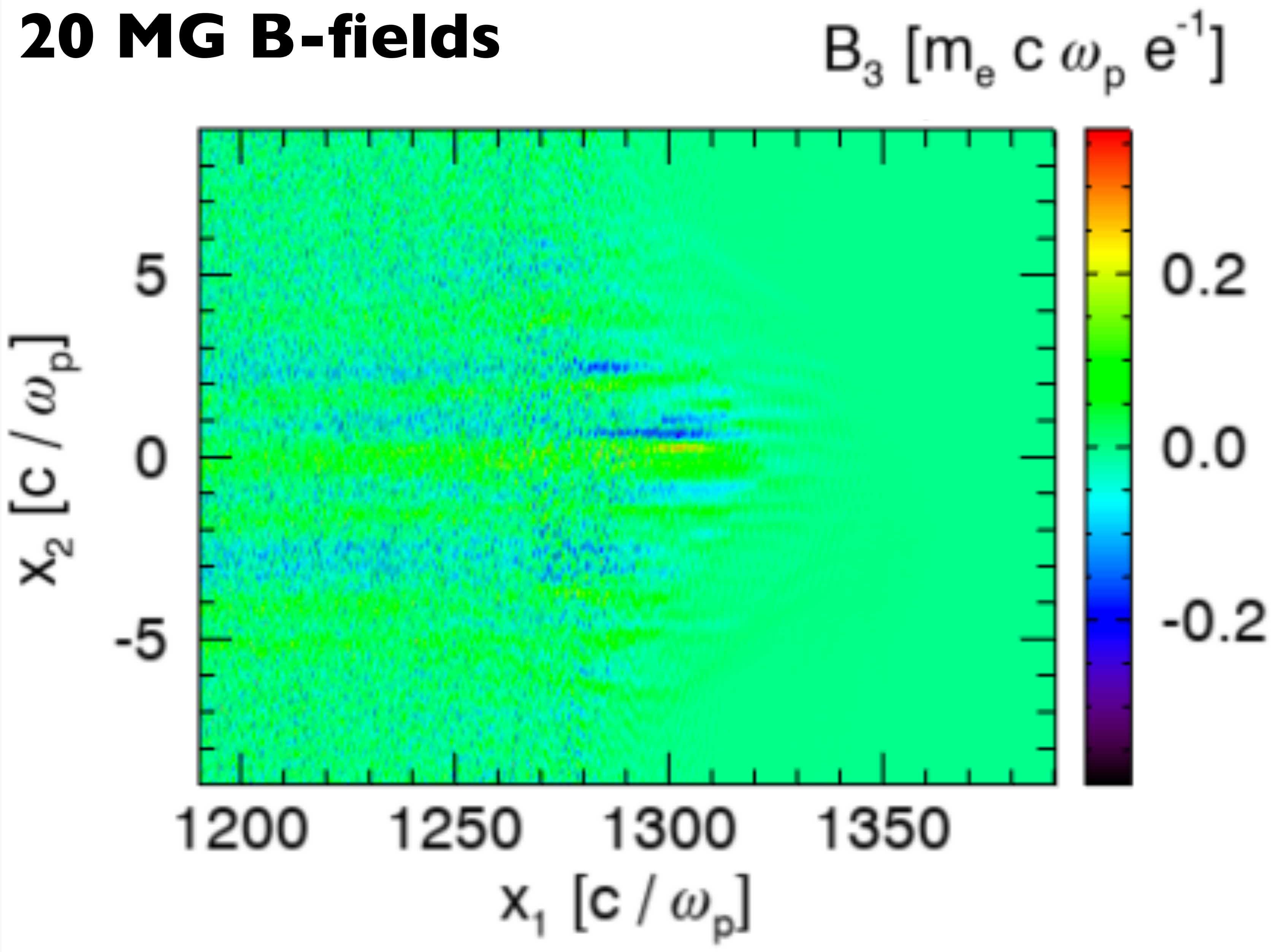
filamentation (cold fluid theory)

Significant filamentation and radiation emission predicted for liquid jet targets

Results from 2D OSIRIS simulations of FACET-II e-beam with 10^{21} cm^{-3} ($\sigma_z = 4.8$ µm, $\sigma_\perp = 0.4$ µm) propagating on liquid H_2 jet

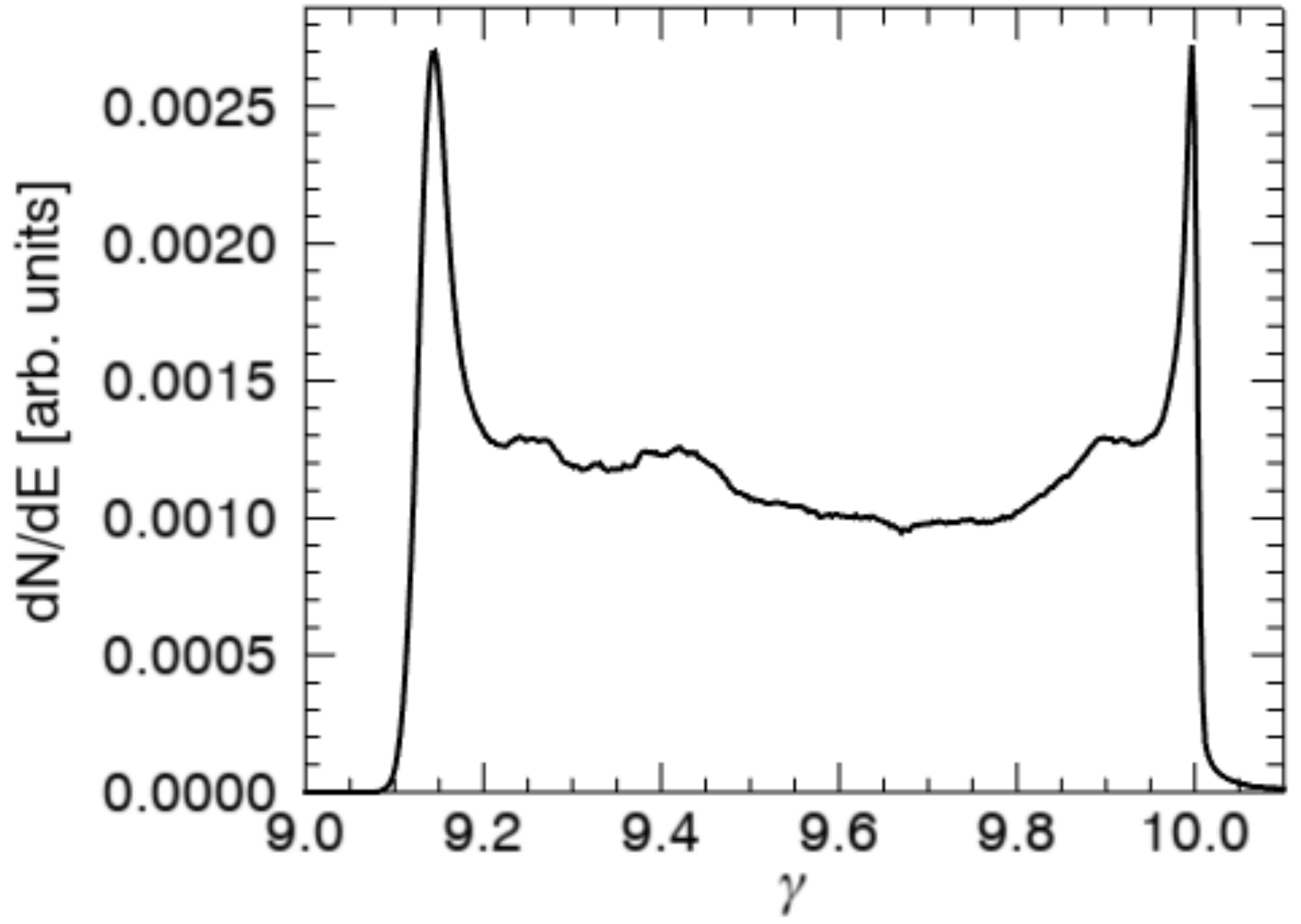
Filamentation instability is dominant

20 MG B-fields



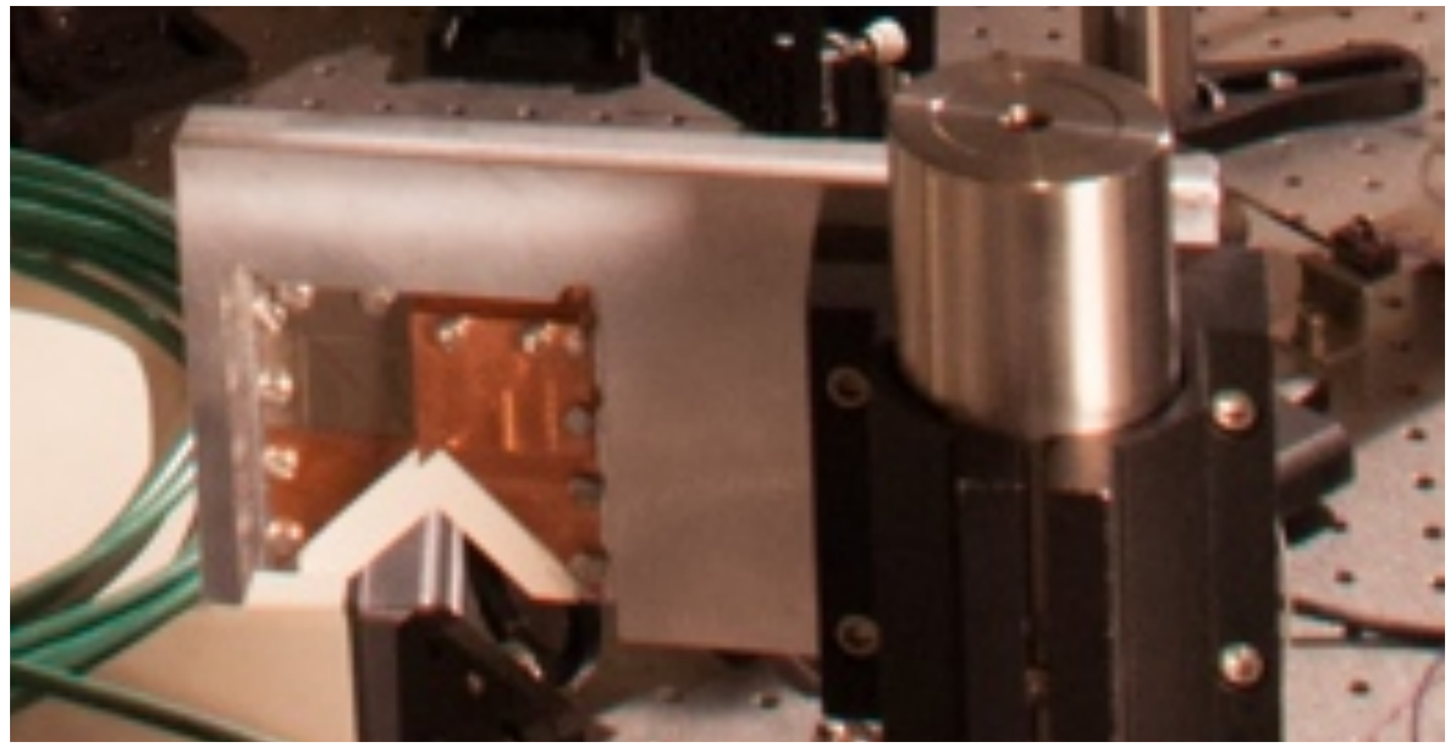
e-beam spectrum after 200 µm

5% beam energy lost



H_2 jet with 100 µm size allows study of filamentation instability with good energy conversion into γ-rays (~1%)

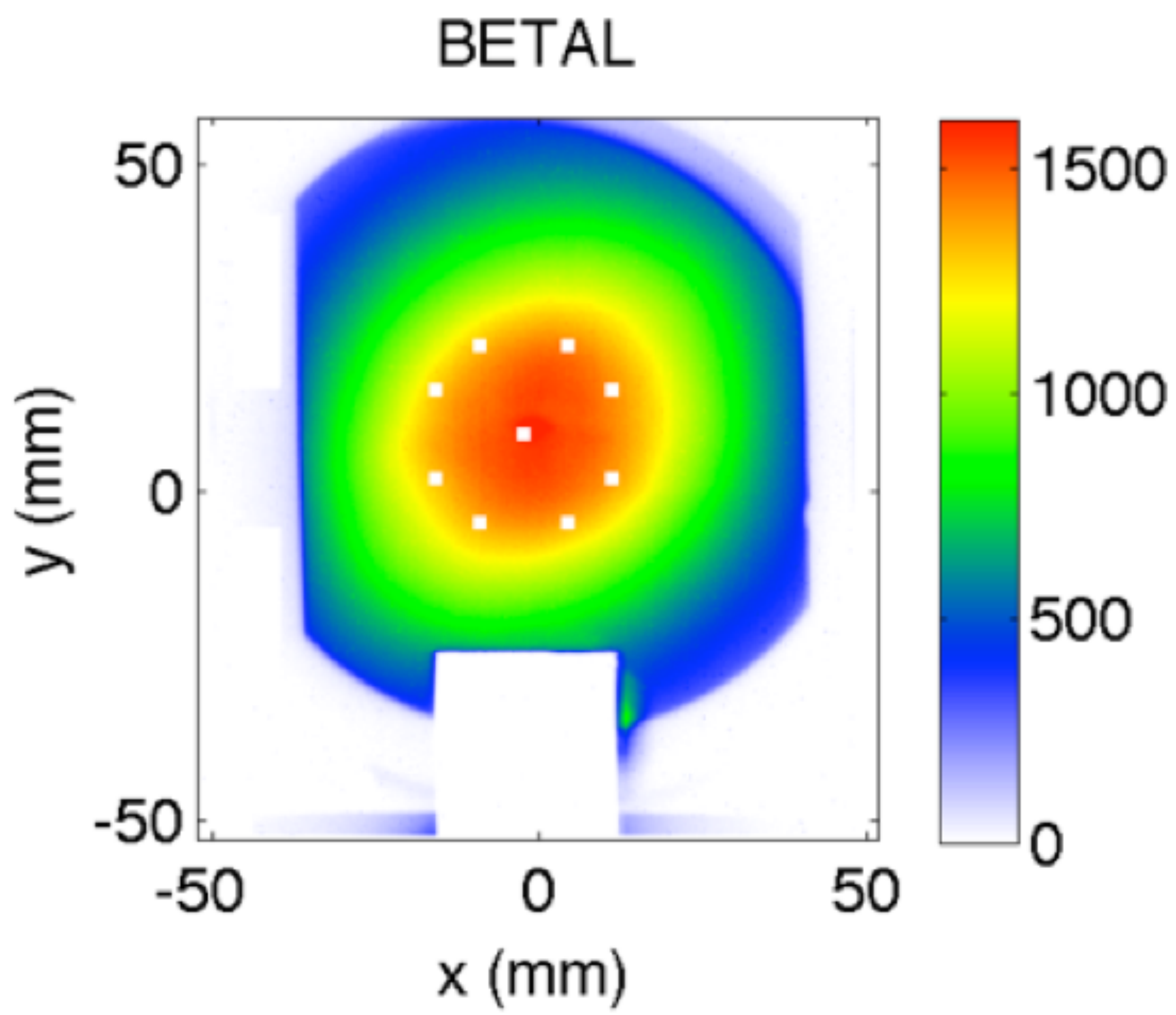
FACET-I gamma-ray detection (S. Corde FACET-II Science Workshop 2016)

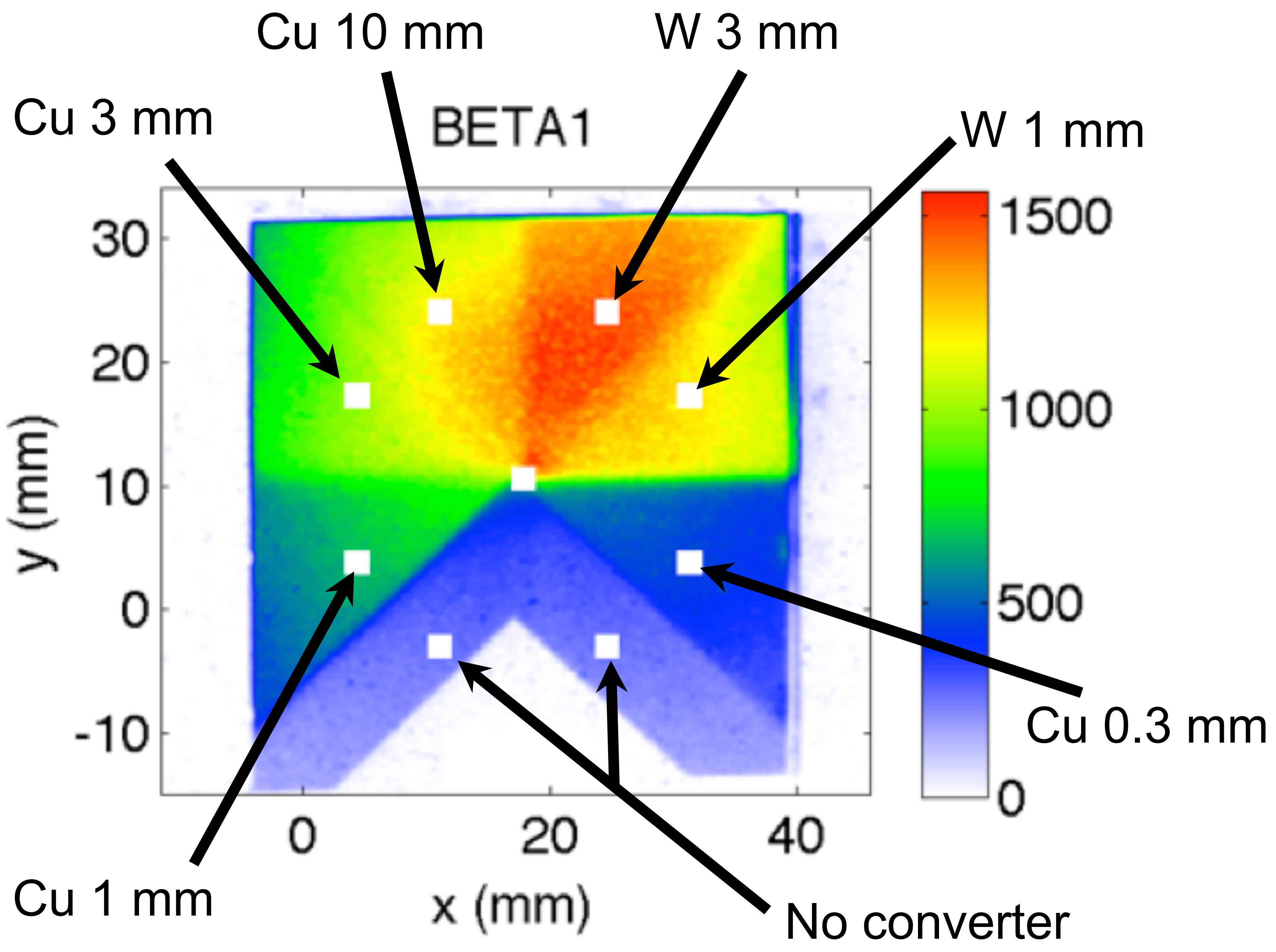


Sextufilter:

A set of filters, made of Cu and W with thicknesses ranging from 0.3 to 10 mm, is used to characterize the spectral distribution of the gamma-ray beam.

Single shot measurement!





FACET-I gamma-ray detection (S. Corde FACET-II Science Workshop 2016)

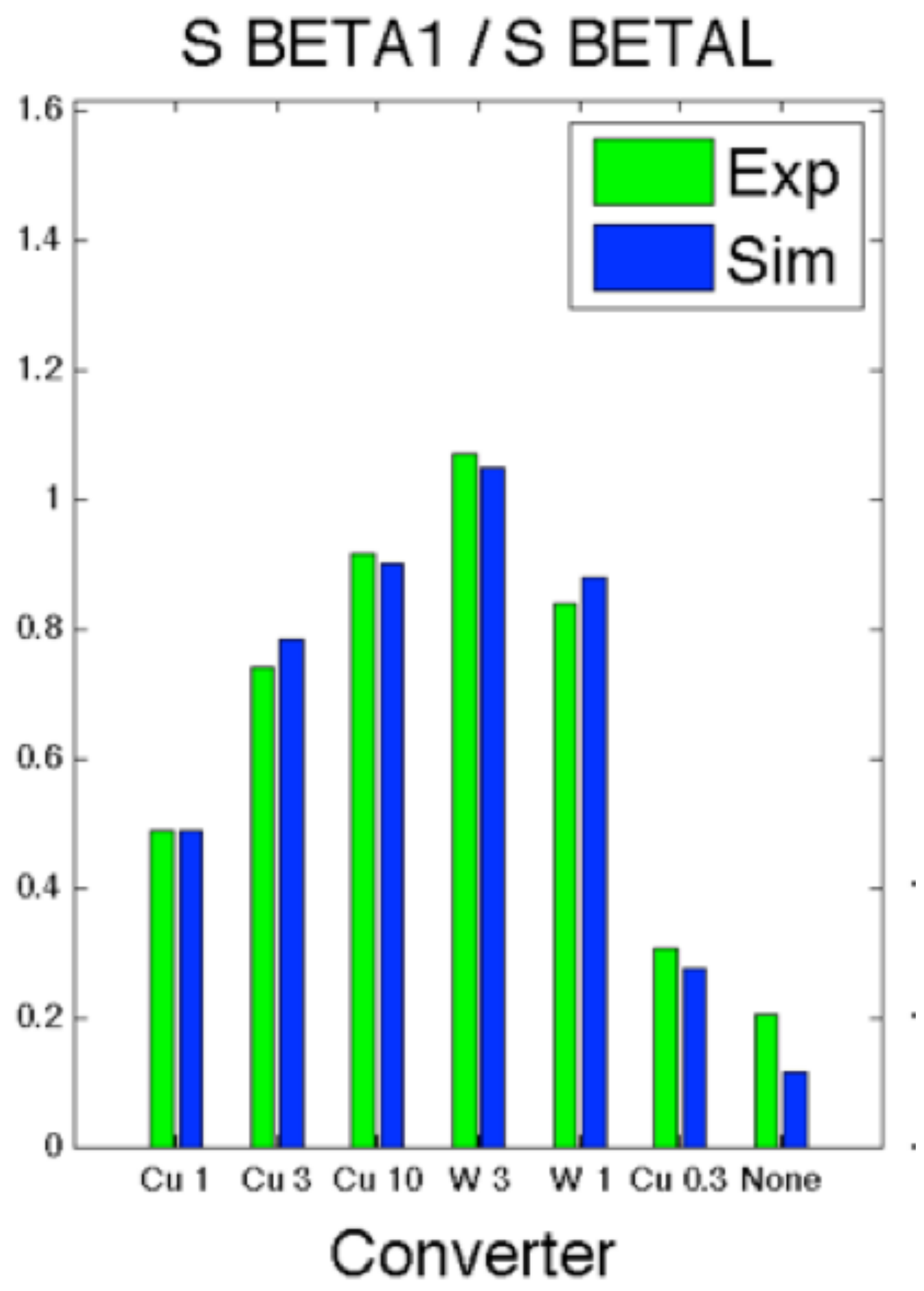
Synchrotron spectrum:

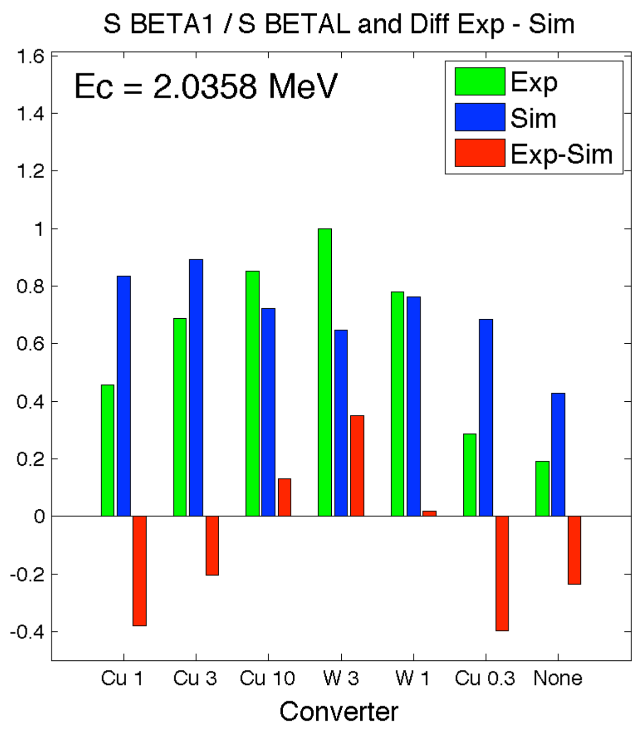
$$\frac{dW}{d\omega} = A\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(\xi)d\xi$$

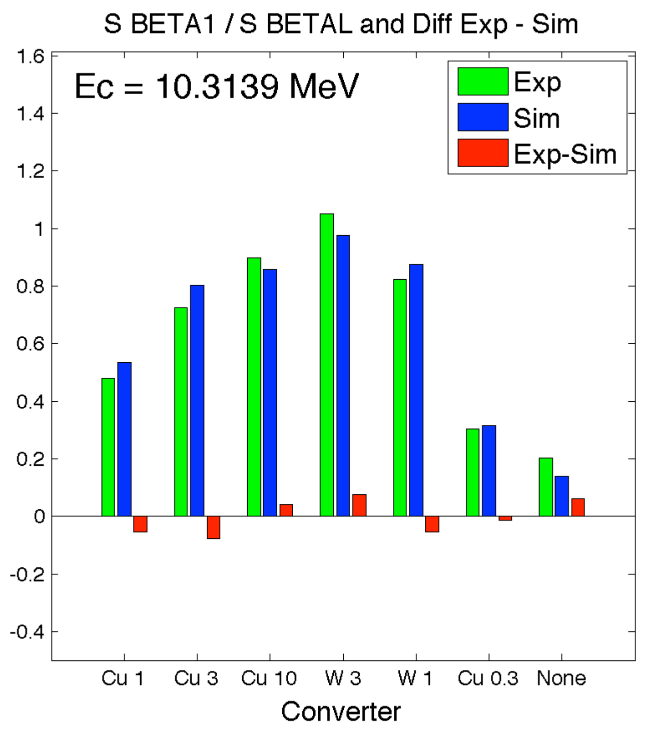
$$E_c = \hbar\omega_c$$

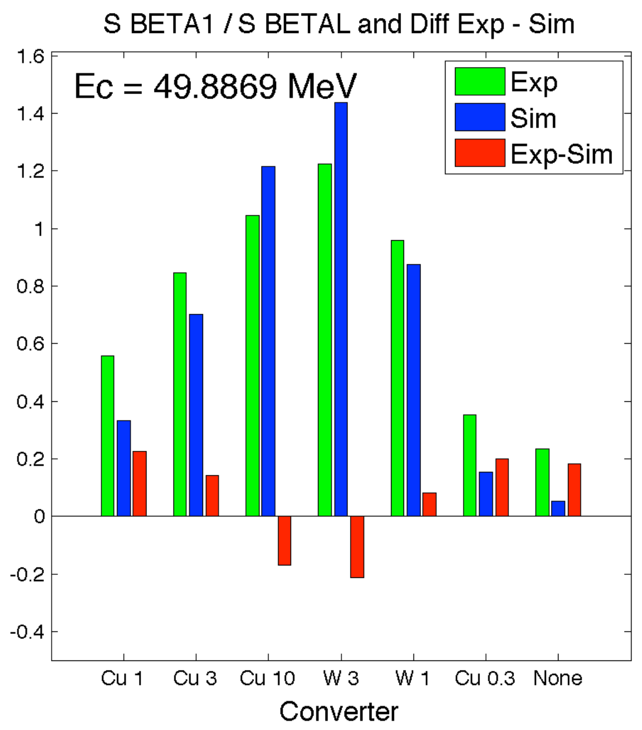
Critical energy fit:

Fit the measured signals behind each filter to the predicted signals from Monte Carlo simulations for different photon critical energies.



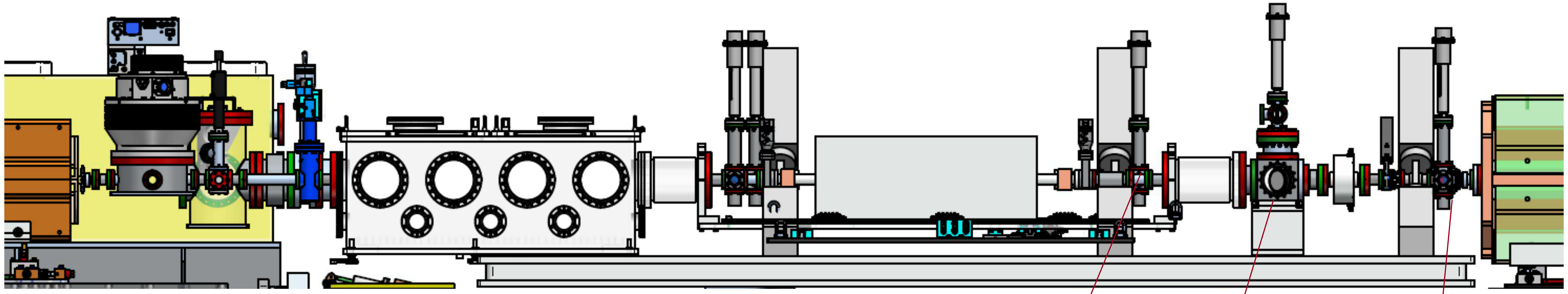






E_c fit = 13.2 MeV

Temperature of IP2A screen for E305 w. gas target

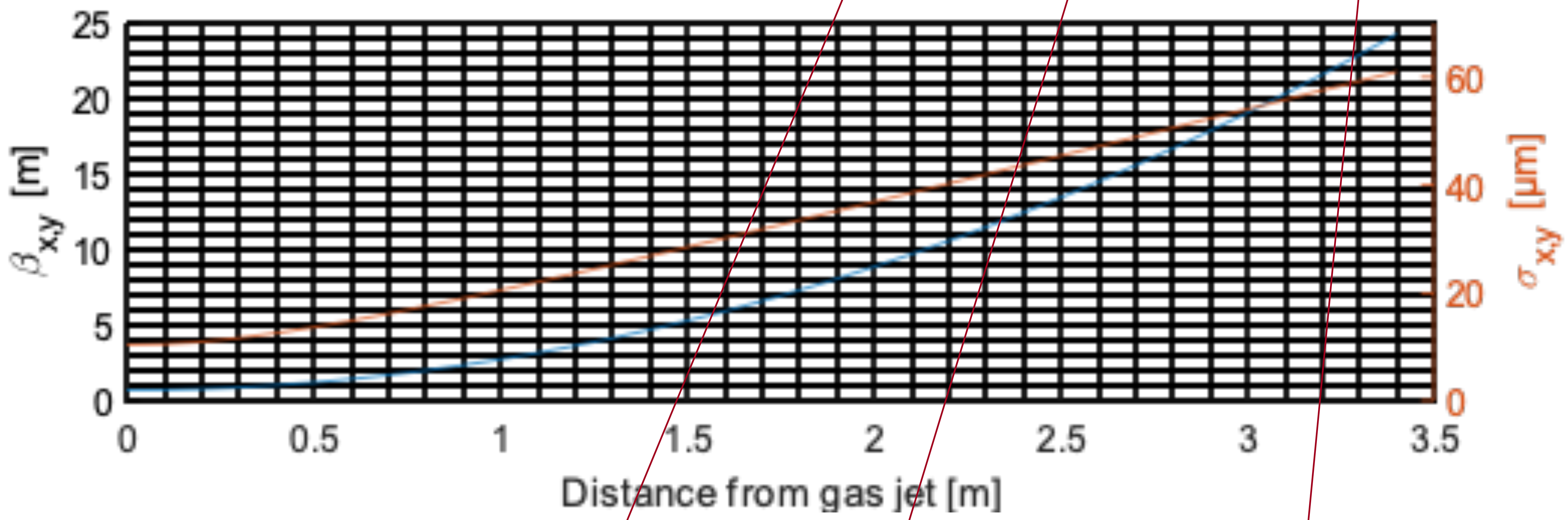


Beam parameters:

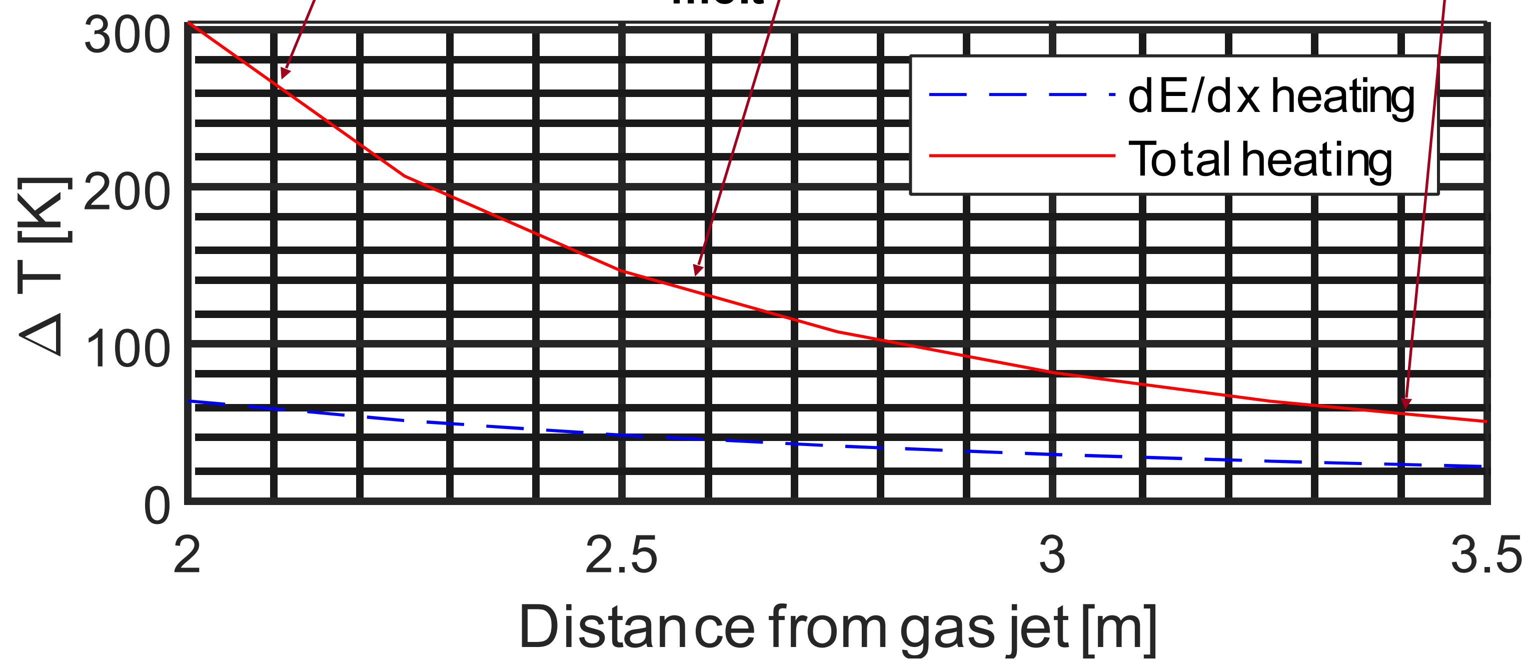
- $\beta = 70$ cm in picnic basket
- $q_b = 2$ nC, $I_{pk} = 100$ kA, $\epsilon_n = 3$ μm

Two modes of temperature rise:

- dE/dx: $\Delta T_b = \dfrac{\frac{dE}{dX}\ N_e}{2\pi\ \sigma_x \sigma_y\ c_p}$
- Ohmic heating: SLAC-PUB-15729
  - Temperature rise from image currents induced on metal surface



$T_{melt} = 1668$°C

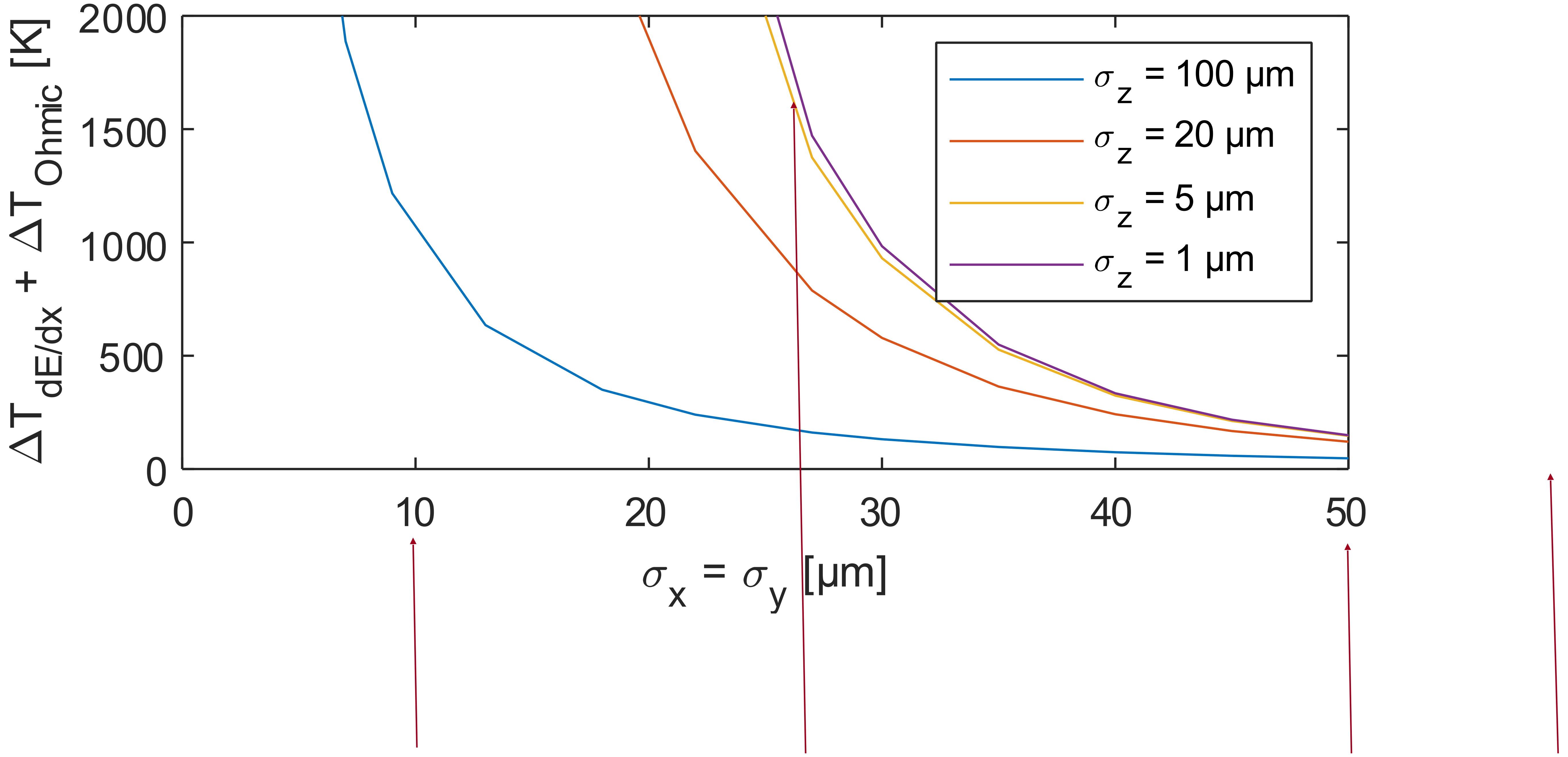


Screen at IP2A is $\ll T_{melt} = 1668°$C → <u>IP2A is safe to use</u>

- $\underline{\Delta T_{dE/dx} + \Delta T_{ohm} \cong 50°}$C
- Note: Ohmic heating stays roughly the same for 200 kA

General Ohmic heating results:

For round 2 nC beam: $\sigma_x = \sigma_y$



Beam size at IP = 10 µm

Ti foil melts at σ_x~25µm

Beam size at DSTOR = 50 µm

Beam size at IP2A = 60 µm