Diagnosing Large Beams:
The Particle Tracking Code BBCNI for Negative Ion Beams and its Application to BATMAN Upgrade

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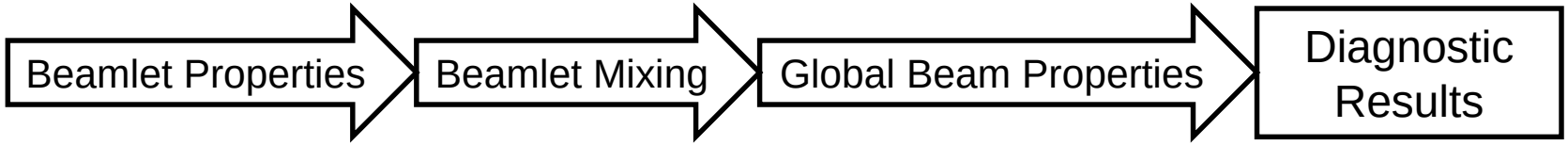
Introduction

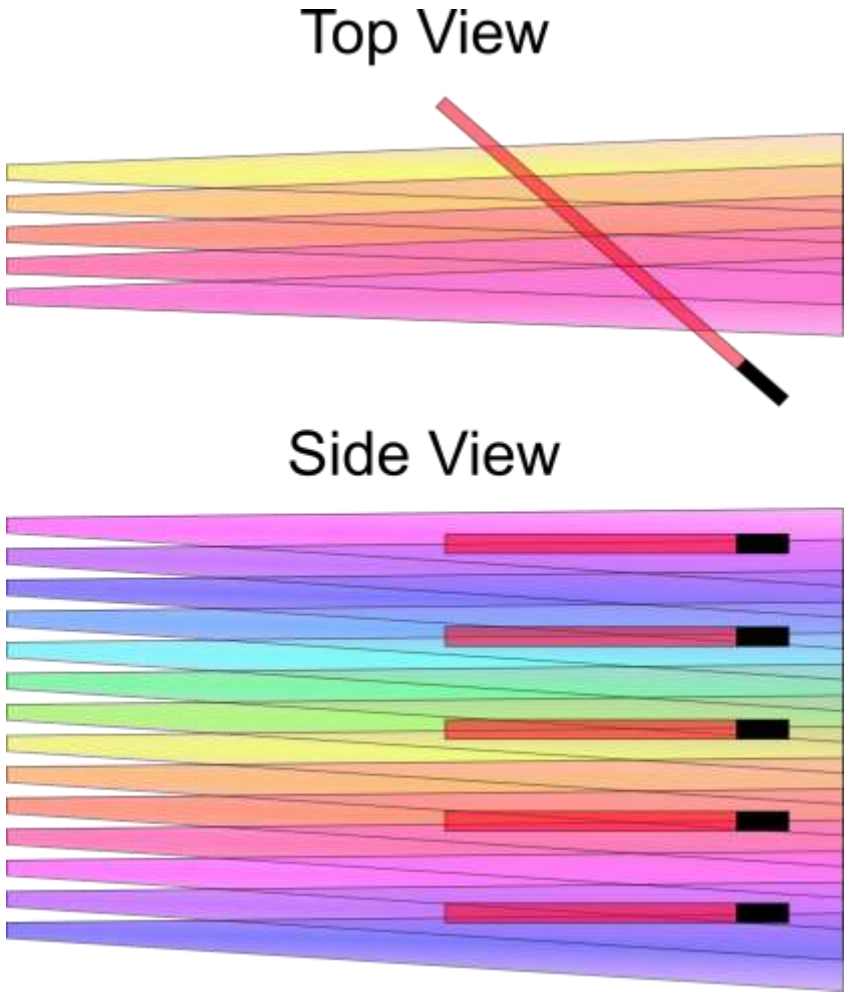
- Understanding of the generation and transport of large ion beams necessary for e.g. NBI on ITER
- ITER target for j_{acc} met in H
  - See Wünderlich **MonO3**
- Improvements still required in beam 'quality'
  - See Bonomo **WedO1**
- Requires implementation and good understanding of beam diagnostics

- High power densities preclude many options for diagnostics
- Limited to beam dumps or passive optical diagnostics
- Diagnostics generally only measure whole beam properties
- Improvements in optics required at beamlet level



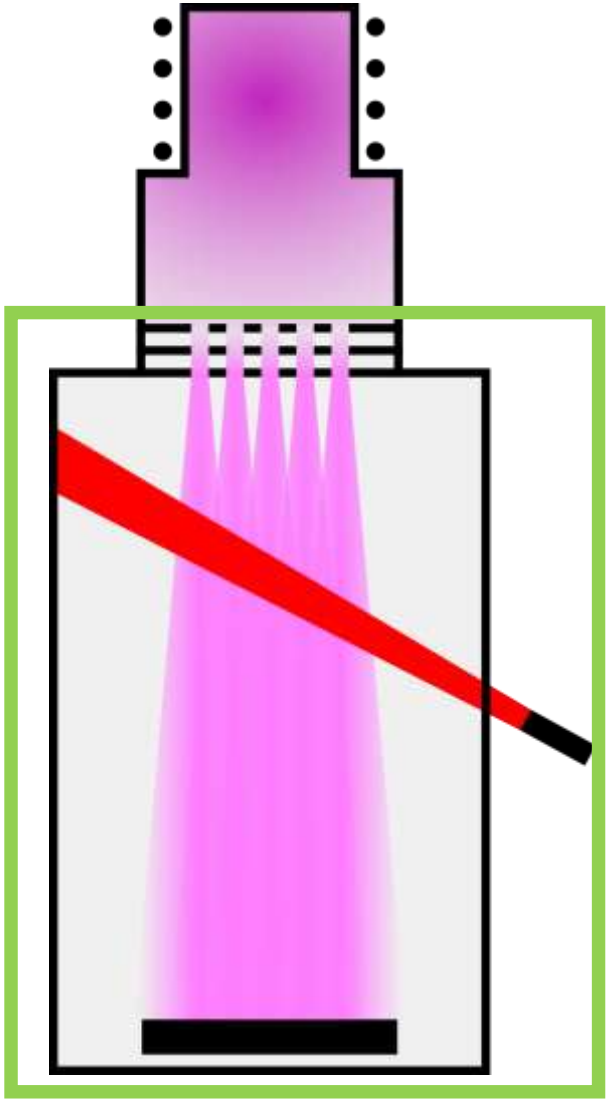
Large Beam Diagnostic Difficulties

- Disentangling actual beam properties from diagnostic data is not easy
- Beam Emission Spectroscopy (BES) particularly tricky:
  - Each beamlet has own properties, own spectrum
  - Measured spectra nontrivial combinations of these
- Calorimeter data only single slice of beam power density
  - Can't know were beam has been or exactly where it's going
- Can get more information by comparing BES and Calorimeter results
  - Results unclear, often disagree …



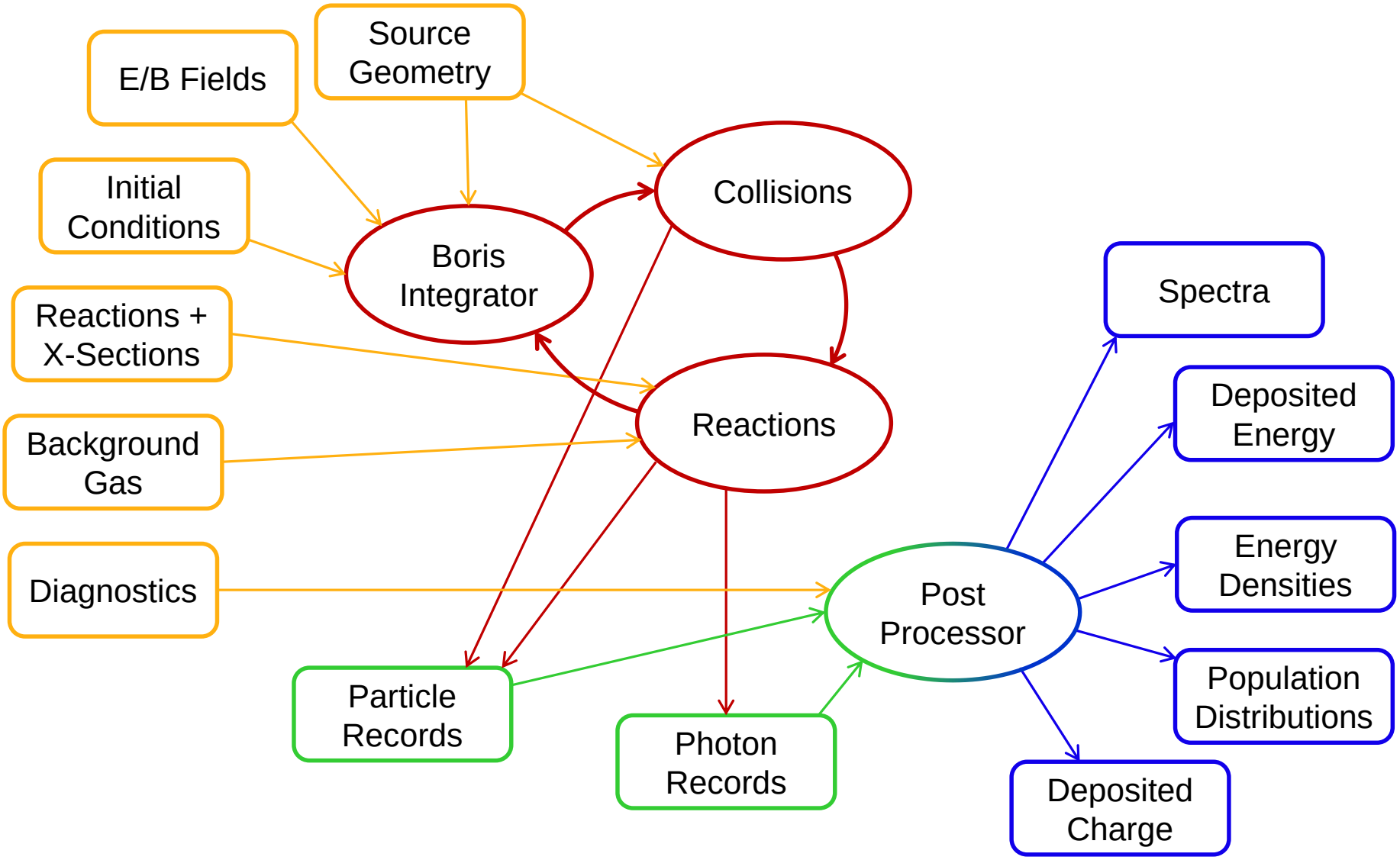
→ Simulation Required

Options for Simulating Diagnostics



- Complex 3D Geometry
  - Multiple, nonuniform, perpendicular magnetic fields
  - Non-trivial arrangement of apertures
- Large scale ranges
  - Beamlet formation needs sub-mm
  - Diagnostics are metres away
  - Energies 1 eV – 1 MeV
- Large domain
- Impractical for PIC
- Particle tracking in pre-calculated fields is a good compromise
- Particle tracking code BBCNI recently undergone dramatic upgrades and enhancements

The Particle Tracking Code BBCNI



BBCNI Inputs and Outputs

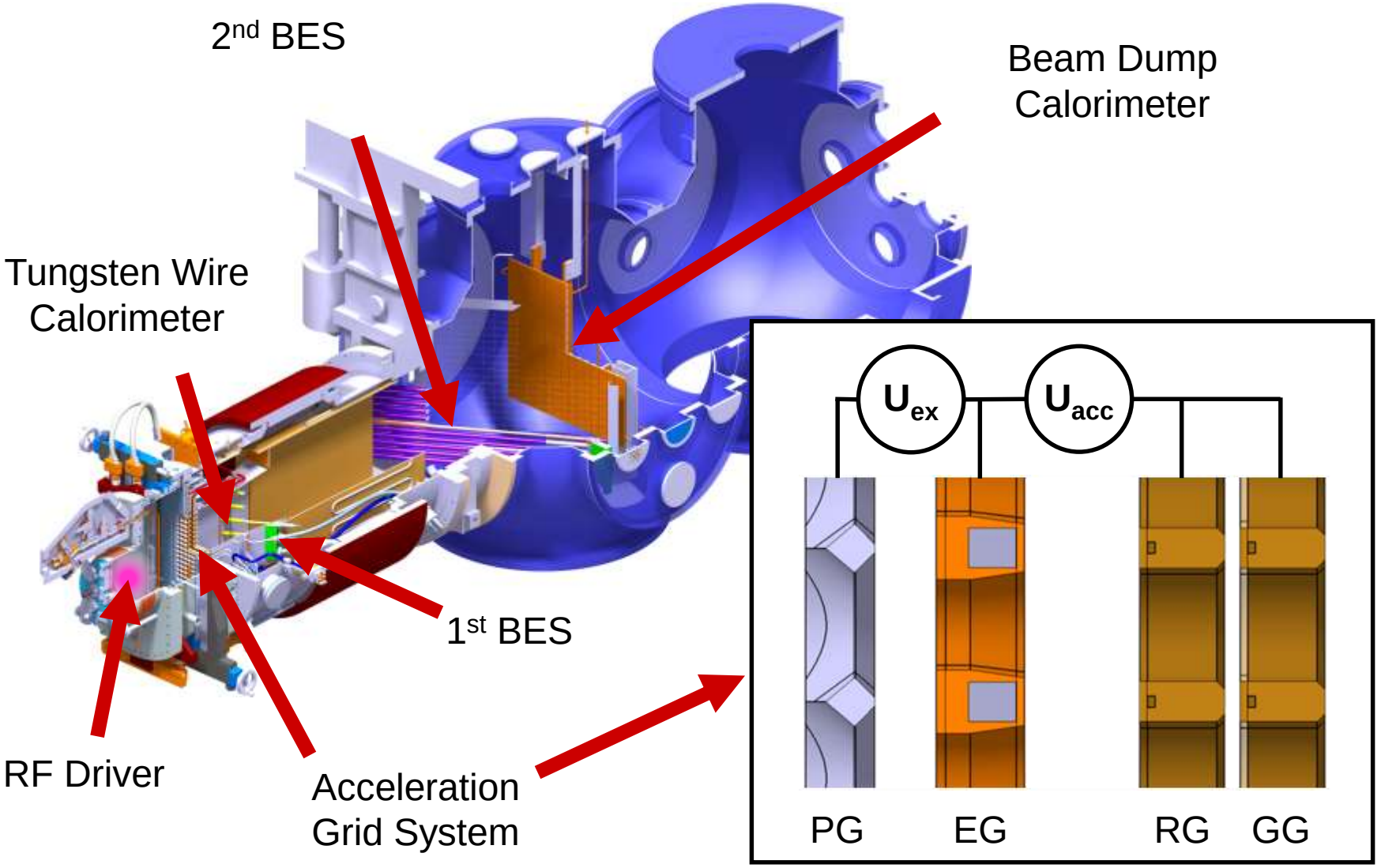
- Particle Tracking is **not** self consistent
  - No beamlet interaction
  - External inputs for fields etc. are required
- E fields from IBSimu[1]
  - Matching initial conditions
- B fields from PerMag[2]/Ansys
- BBCNI is flexible with field inputs
  - Multiple files for each field
  - **Aperture specific E fields**
- Background gas density from in-house gas flow calculation
  - Highest uncertainty here

- Variety of diagnostic outputs – not just recreation of experiment
- Spectroscopy module for BES
- "Diagnostic planes" - energy deposited on/through surfaces
- Energy spectra of particle populations
- **Full traceability** to source particle and aperture

[1] T. Kalvas et al, *Rev. Sci. Instrum.* **81**, 02B703 (2010)

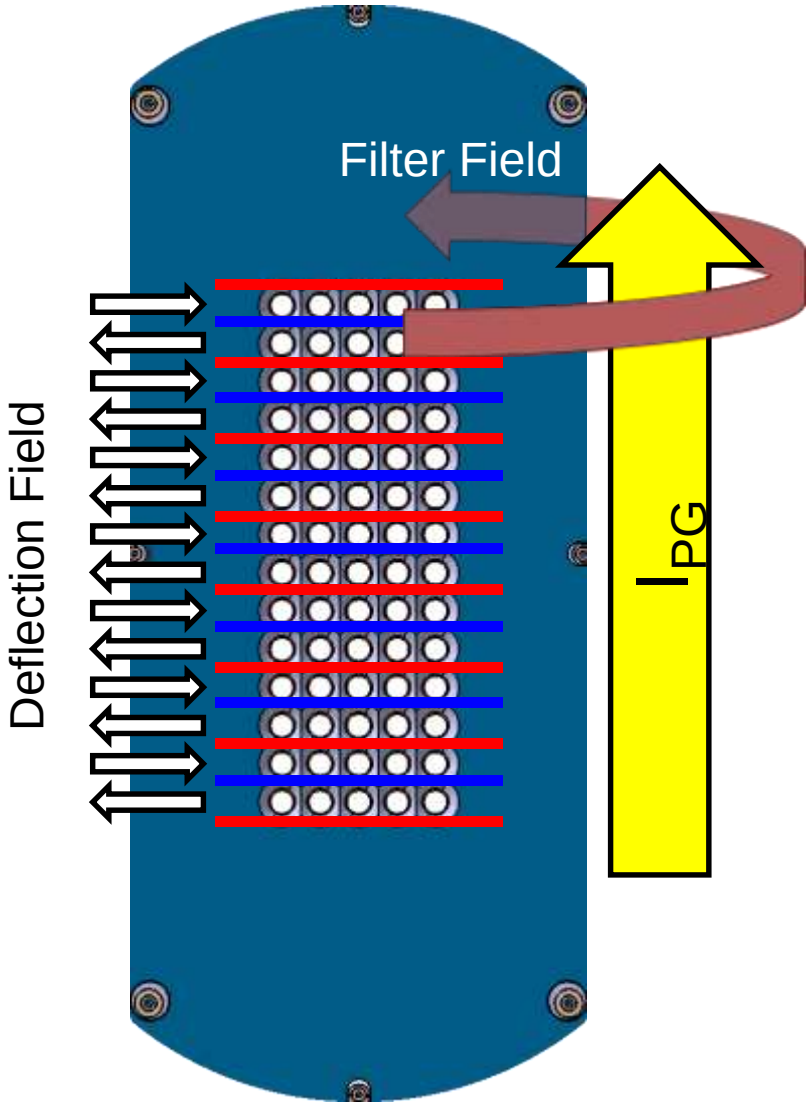
[2] D. Ciric (private communication)

The BATMAN Upgrade Test Facility

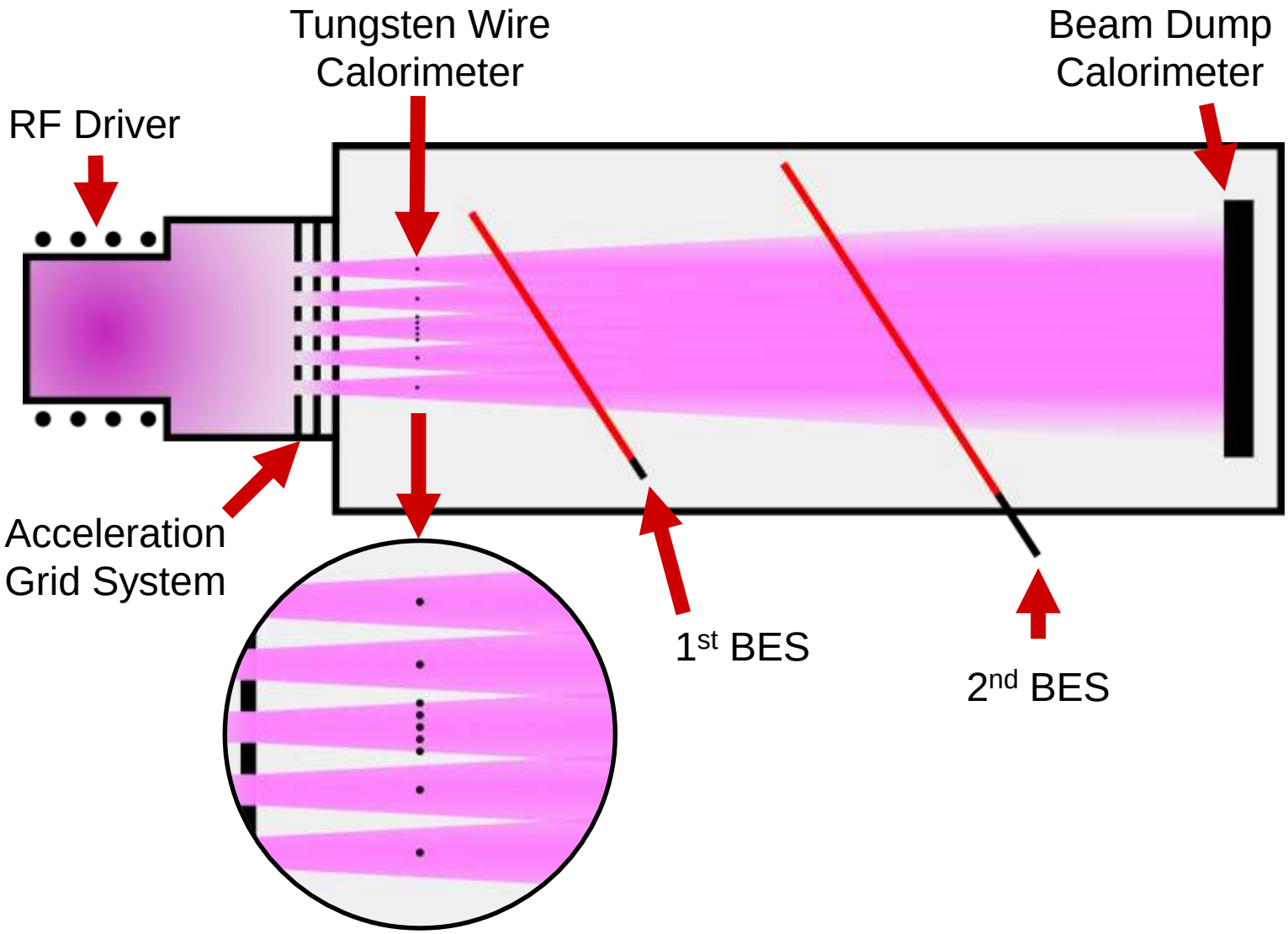


Samples of Diagnostic Capabilities

- Sample simulation of BATMAN Upgrade (BUG)
  - U_{ex} = 5.7 kV
  - U_{acc} = 20 kV
  - p = 0.4 Pa
  - j_{ex} = 12.8 mA·cm^{-2} ← **Homogeneous**
- Fields present:
  - Filter field from 2.2 kA flowing vertically through PG
  - Deflection field from permanent magnets in EG
  - Specific E fields for each aperture
- BBCNI Run
  - All 70 apertures (5×14)
  - 100k particles per aperture → 7M initial particles
  - 1hr10 runtime on 16 cores



Diagnostics Overview



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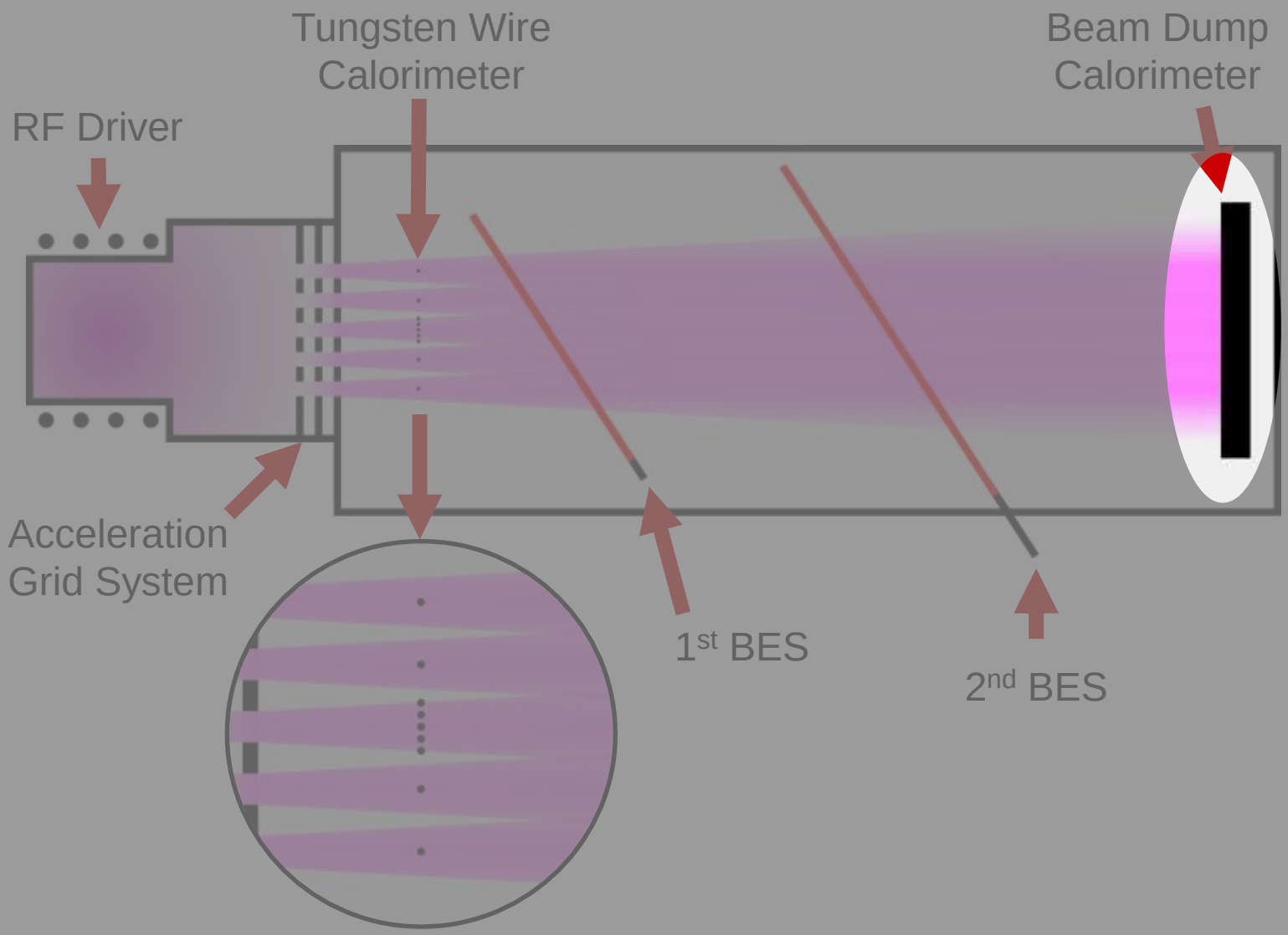
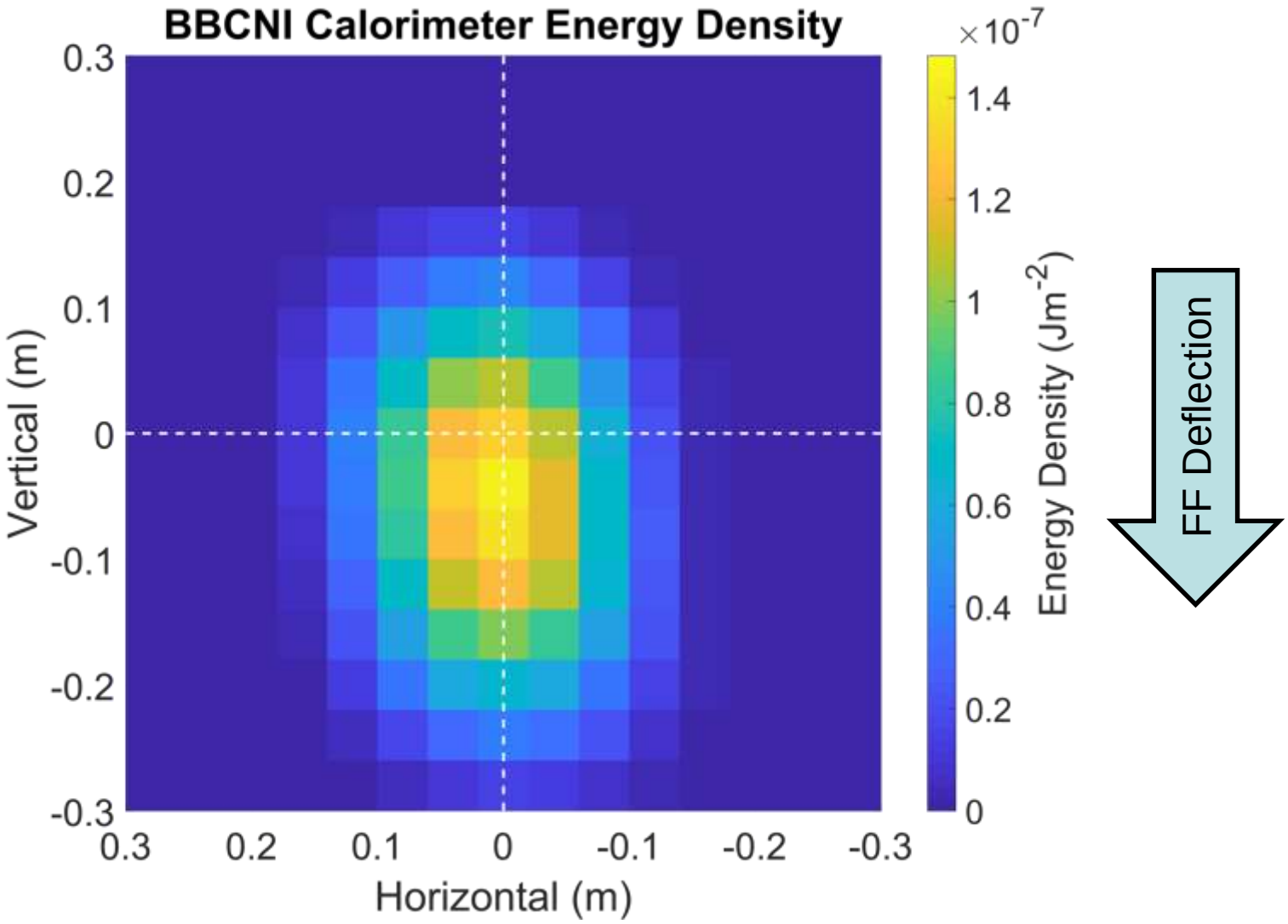


Beam Energy Density



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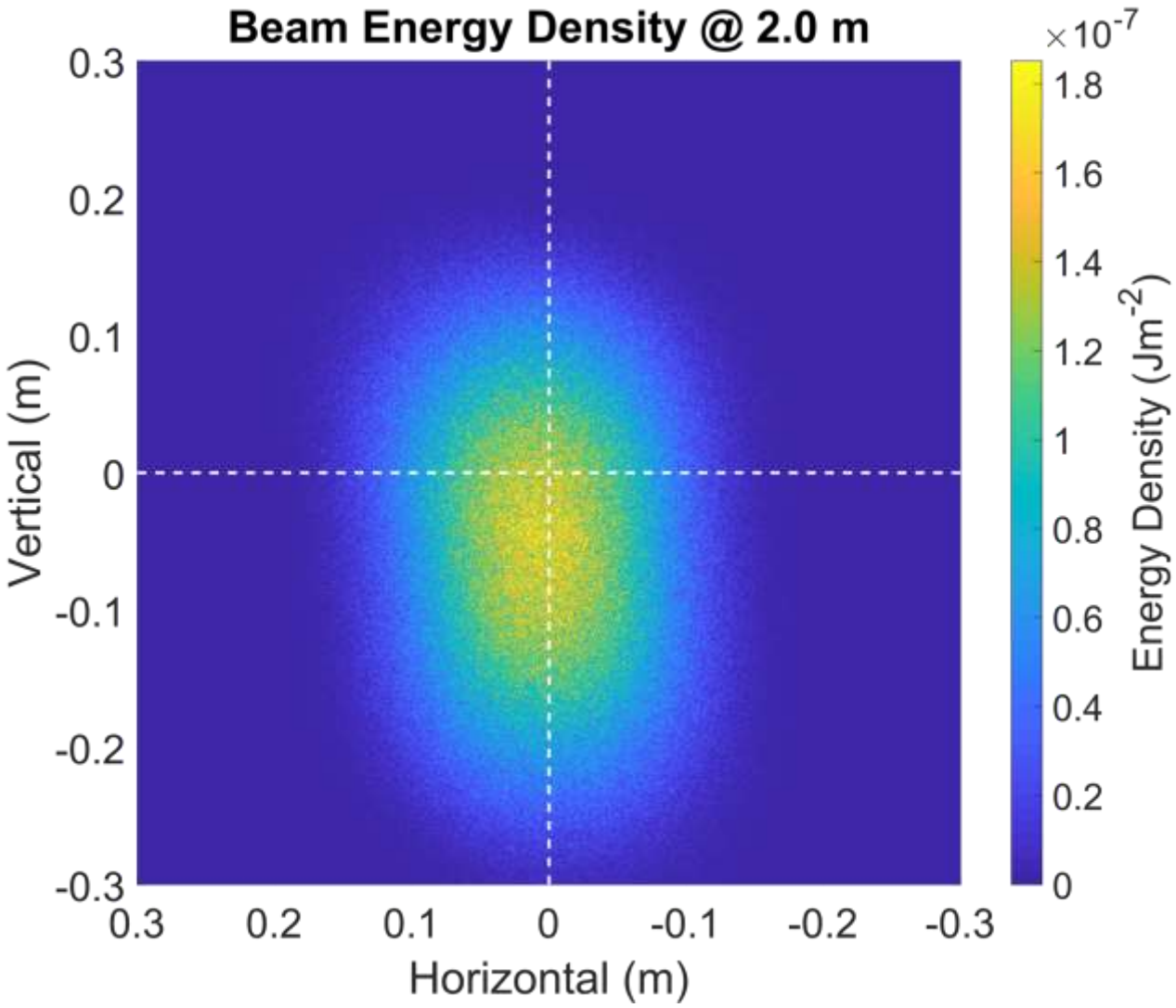

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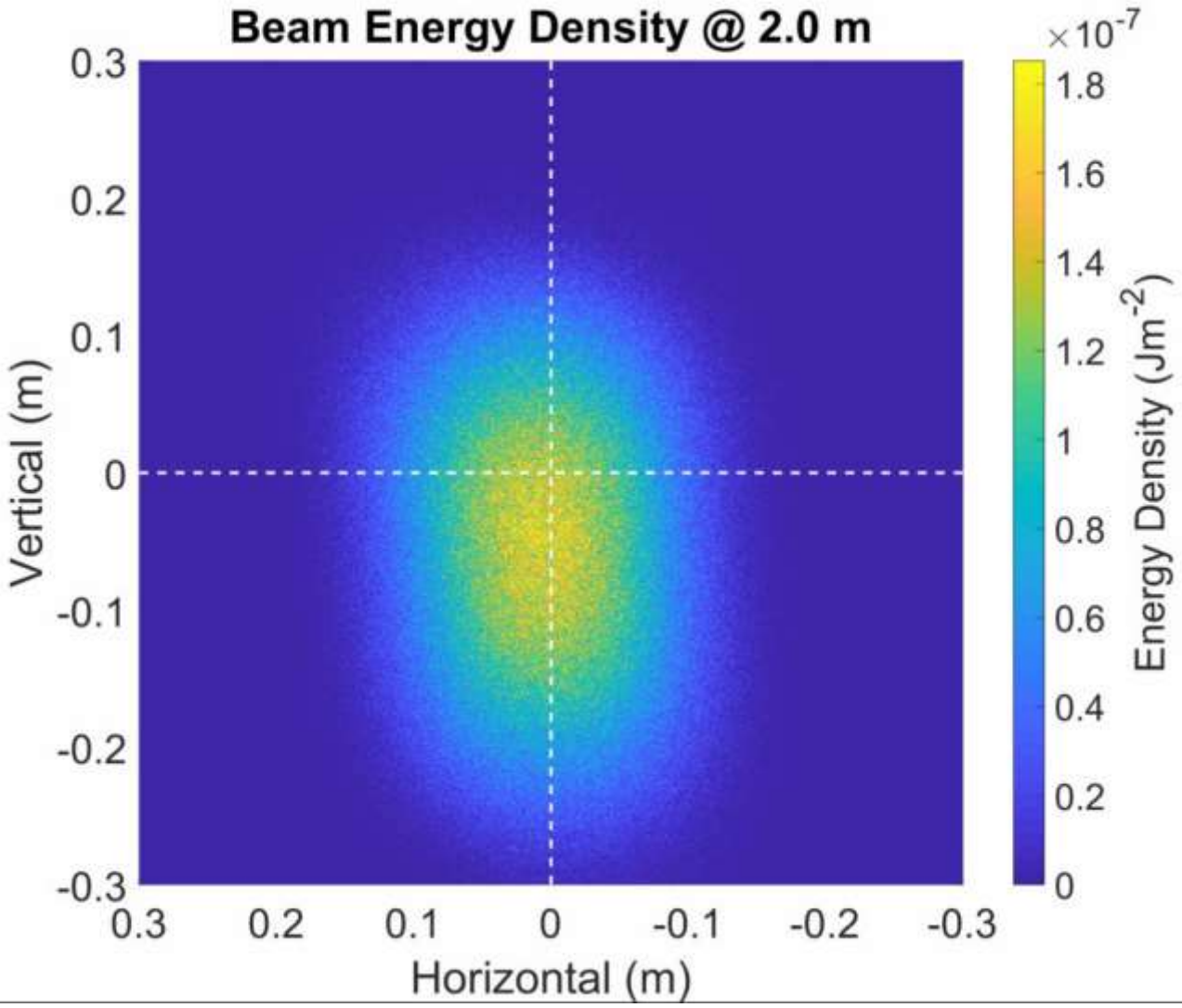

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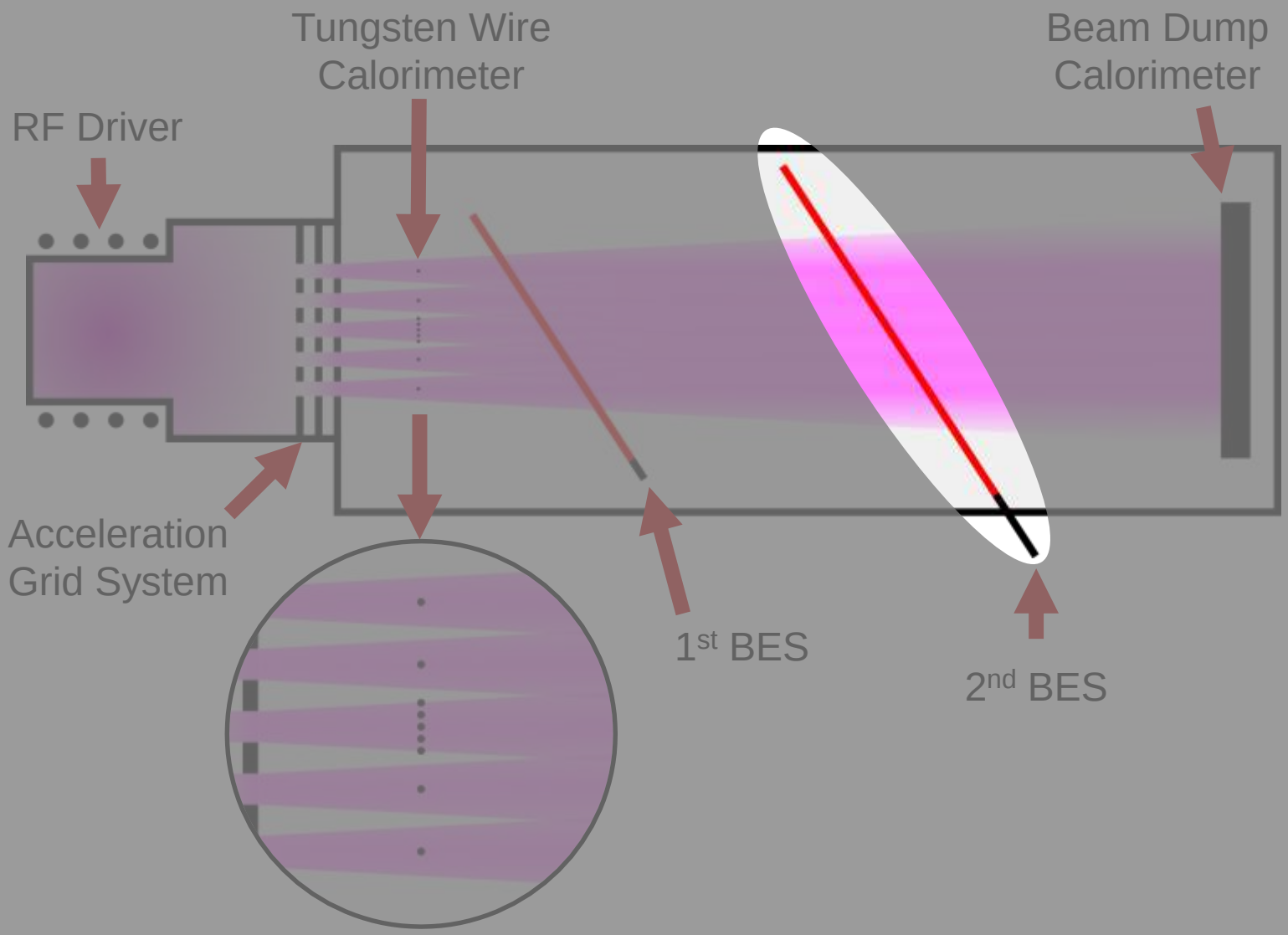
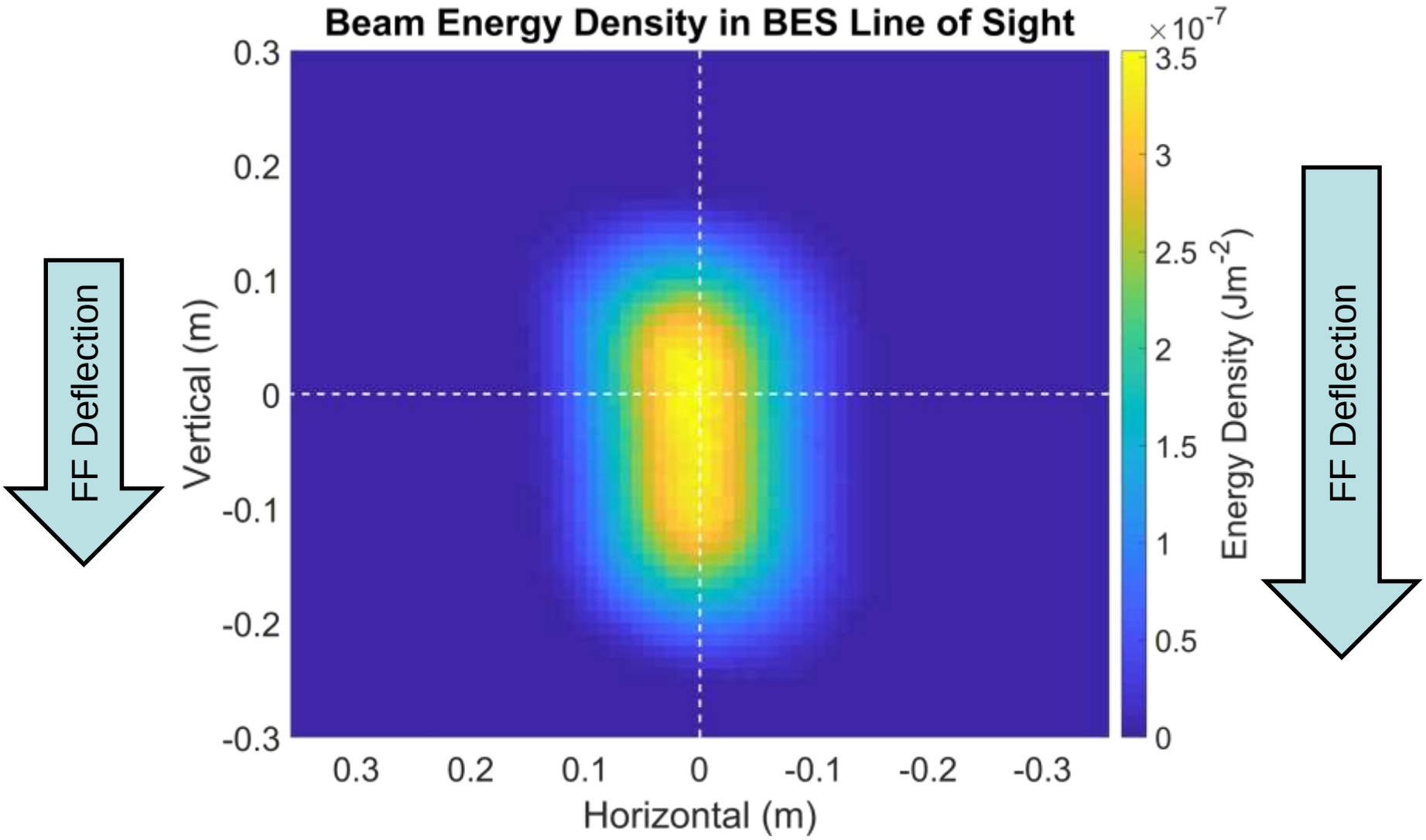


Beam Energy Density – BES Plane



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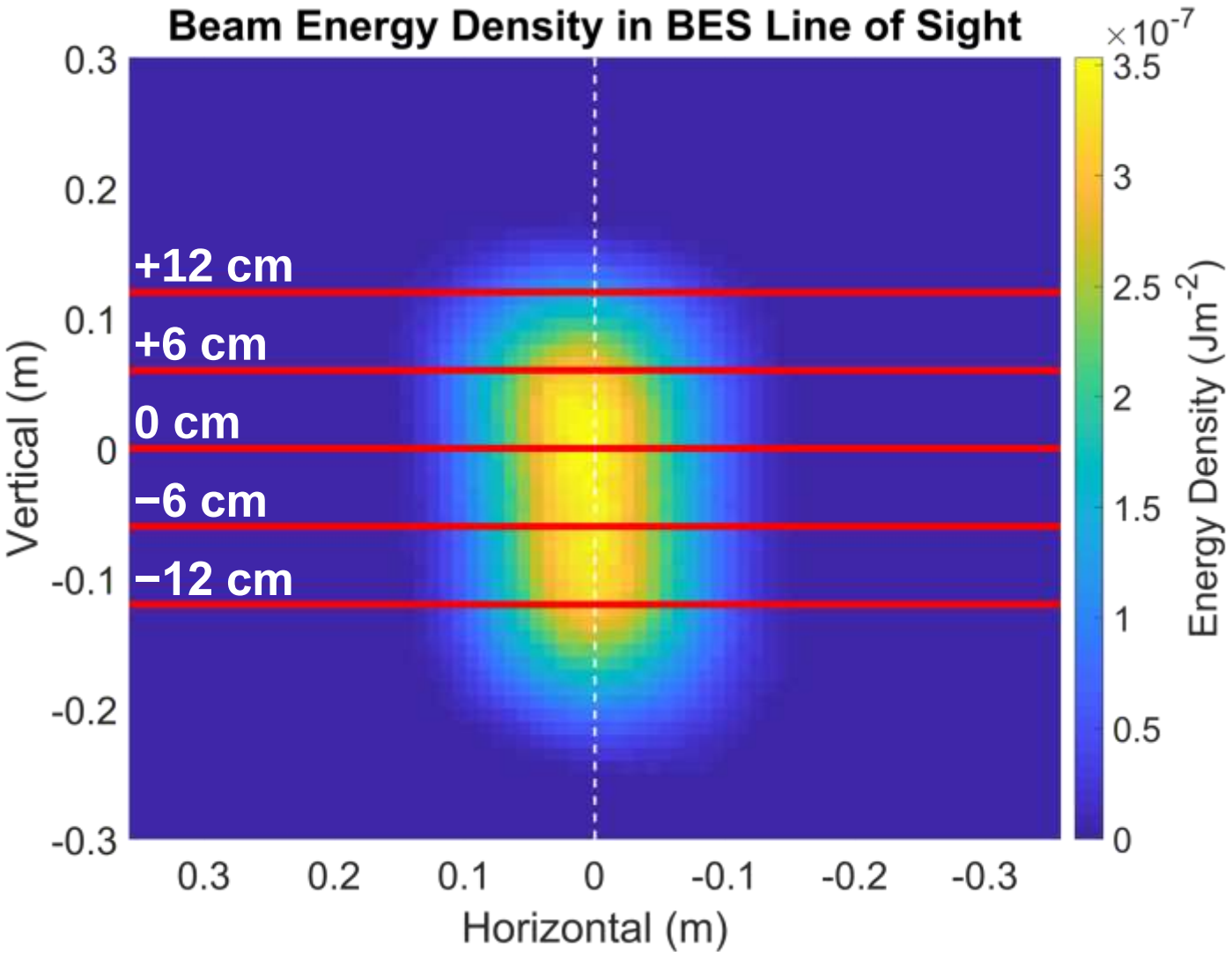
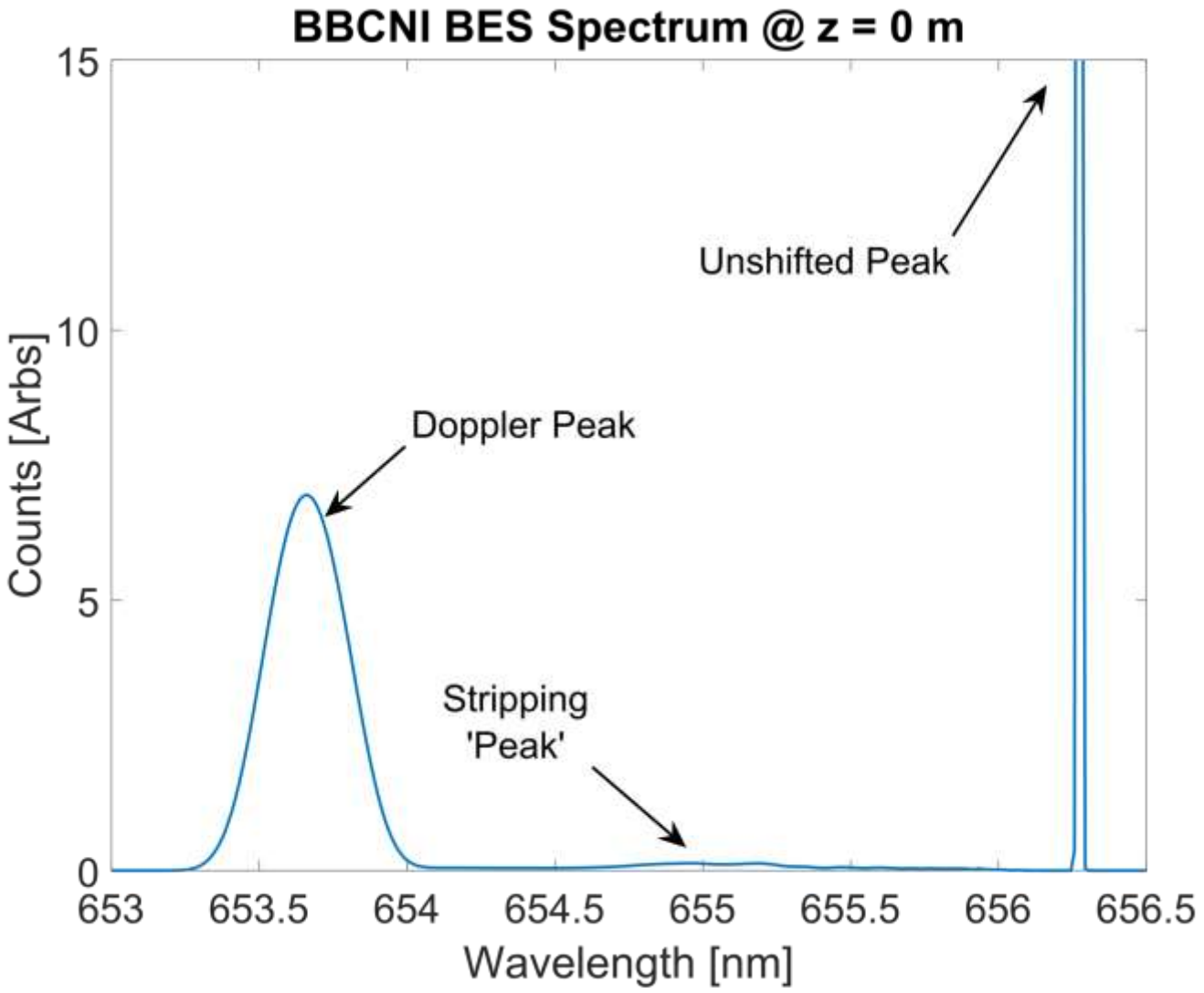


Simulated BES Spectra



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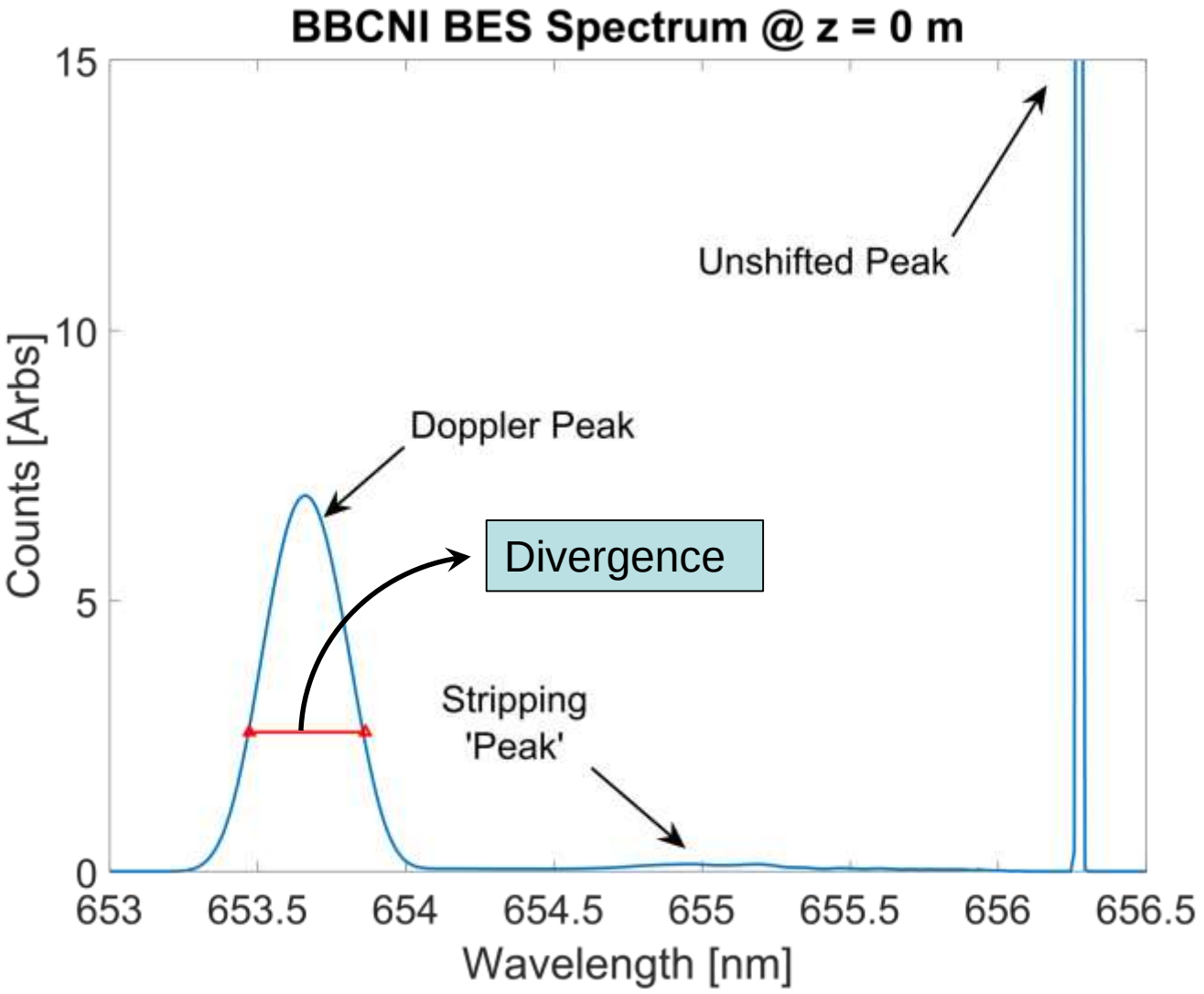
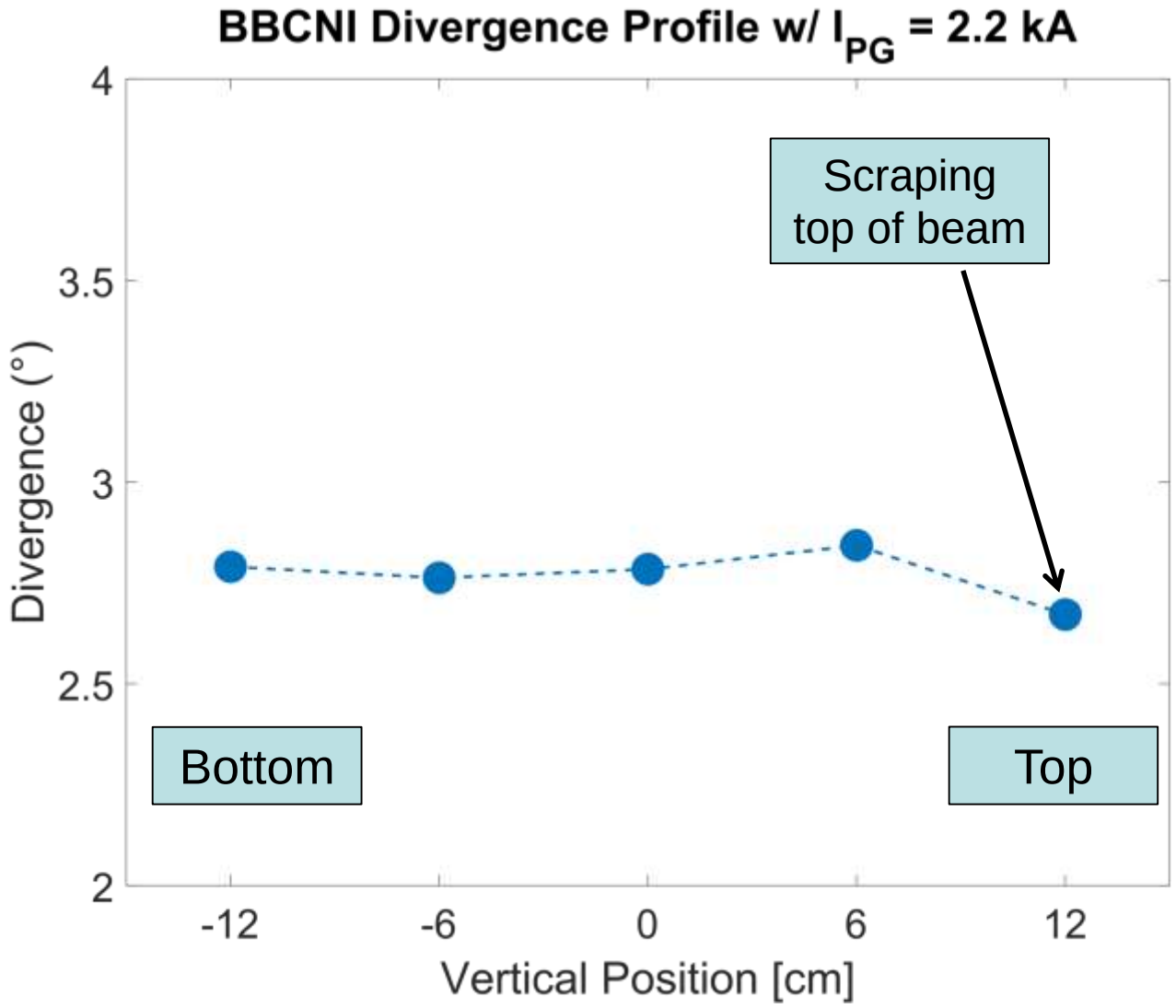
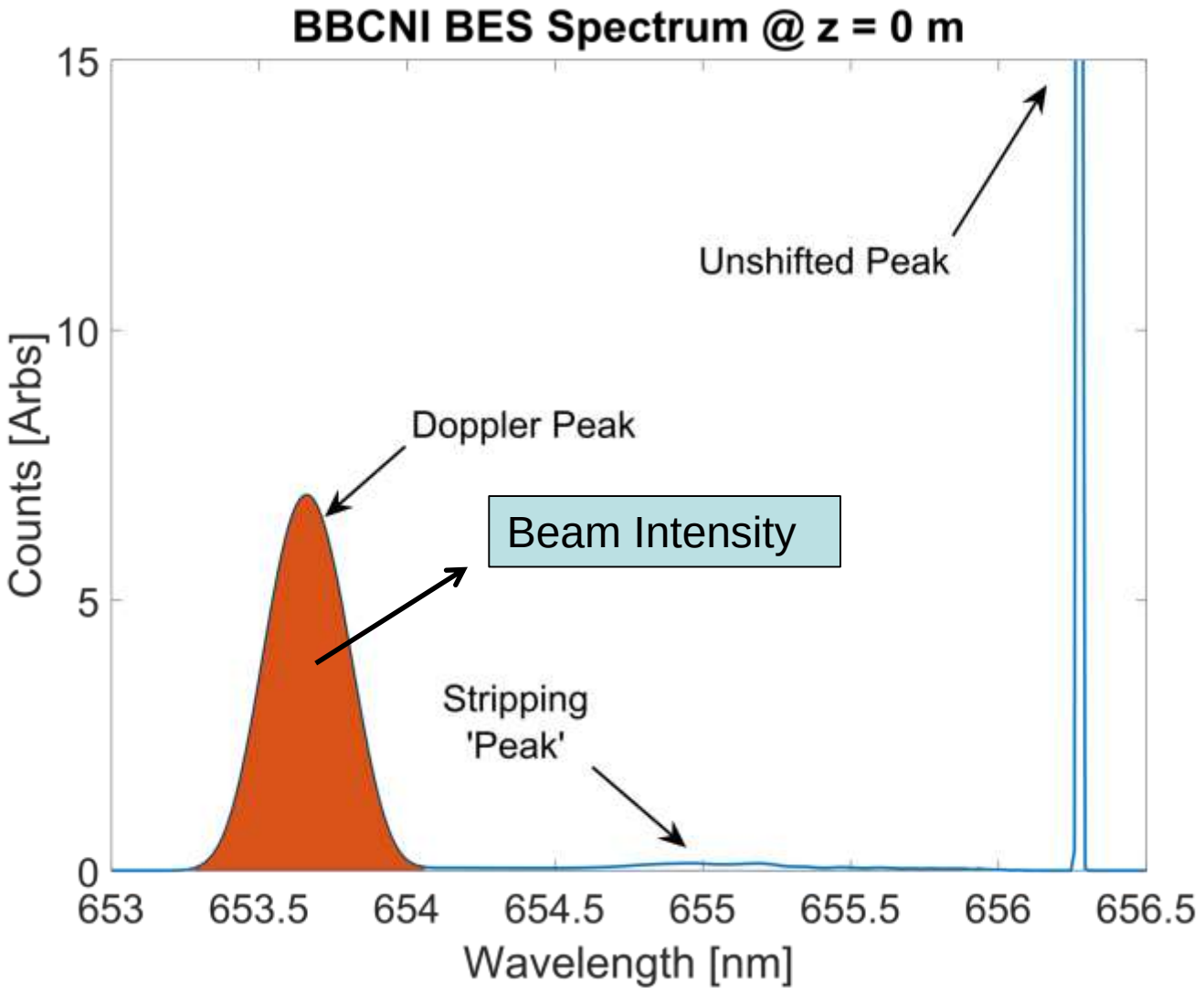


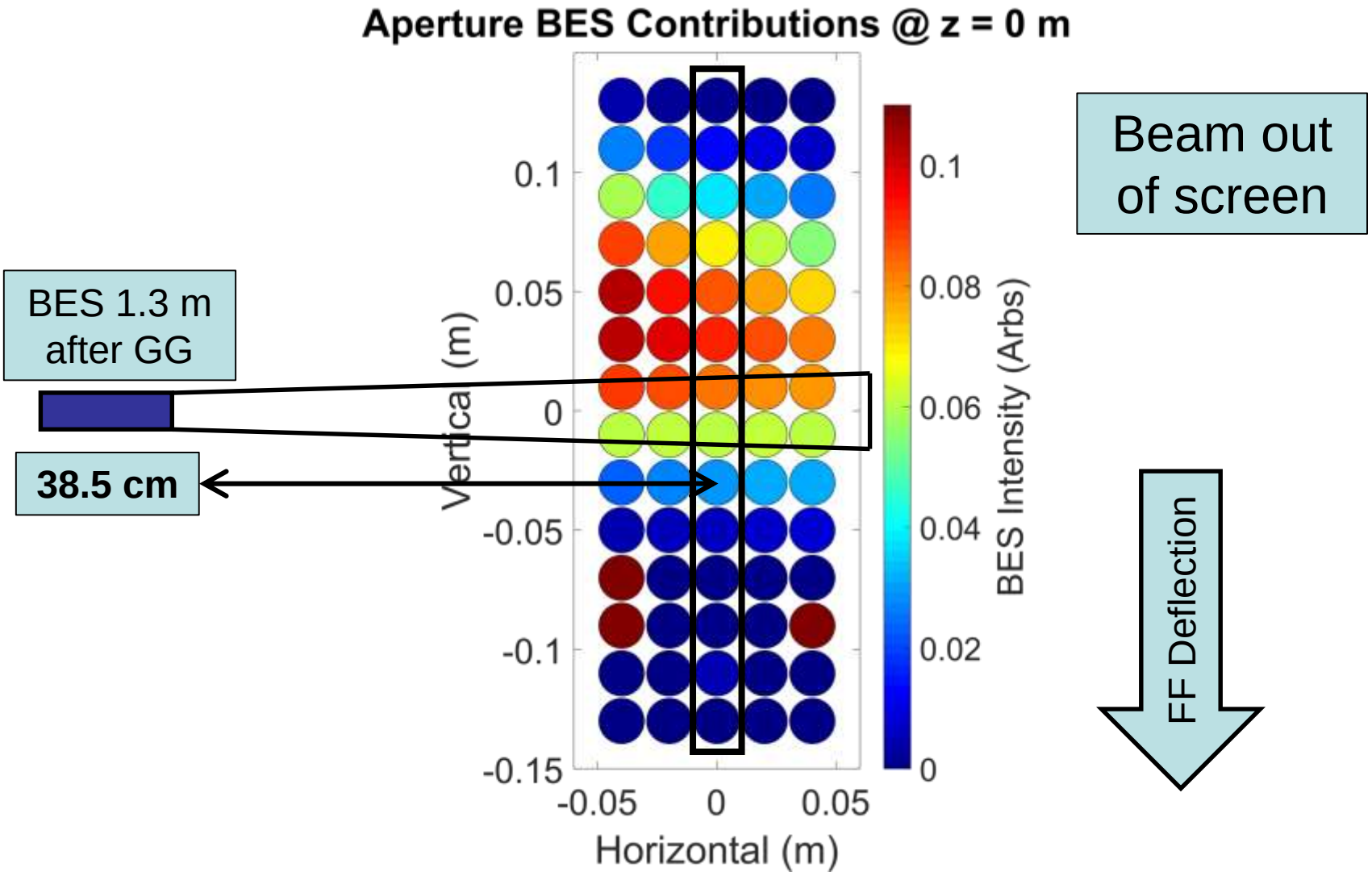
Simulated BES Spectra Divergence



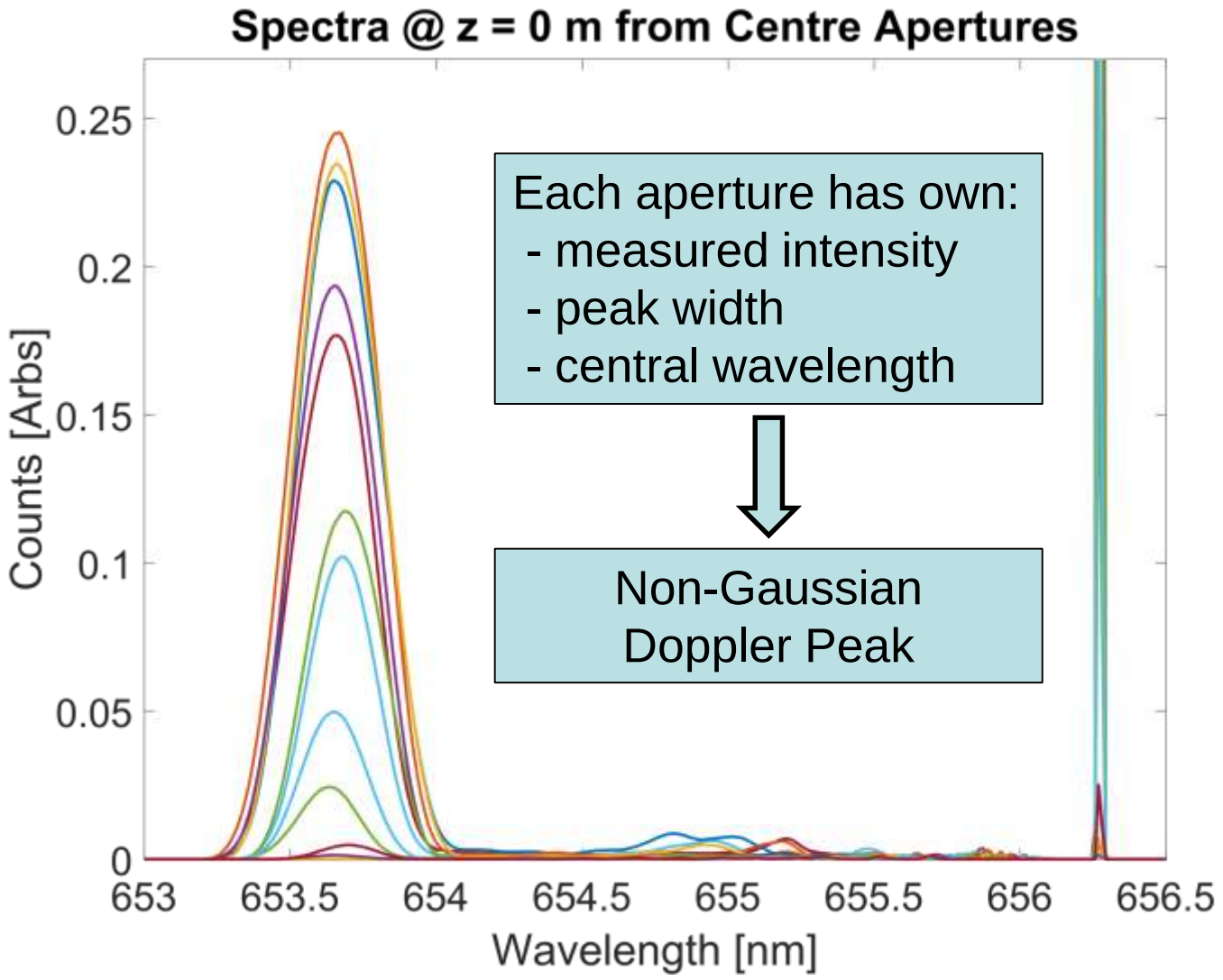
Simulated BES Spectra



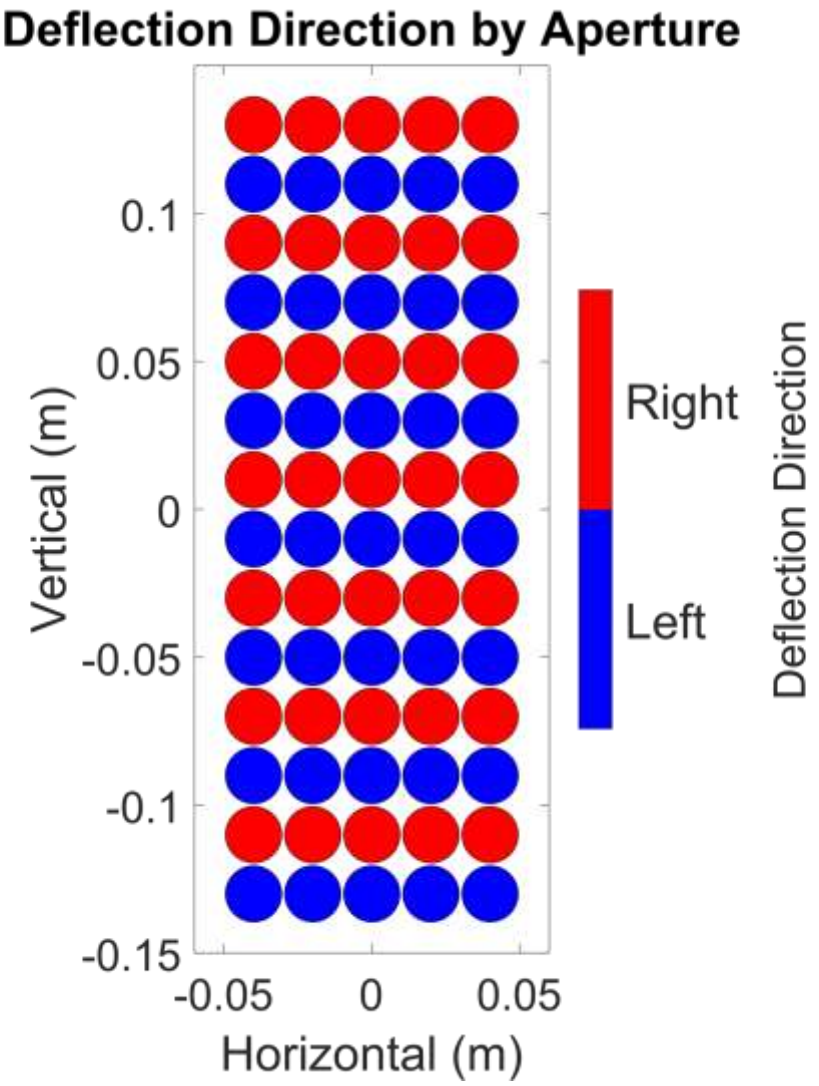
Individual BES Contributions



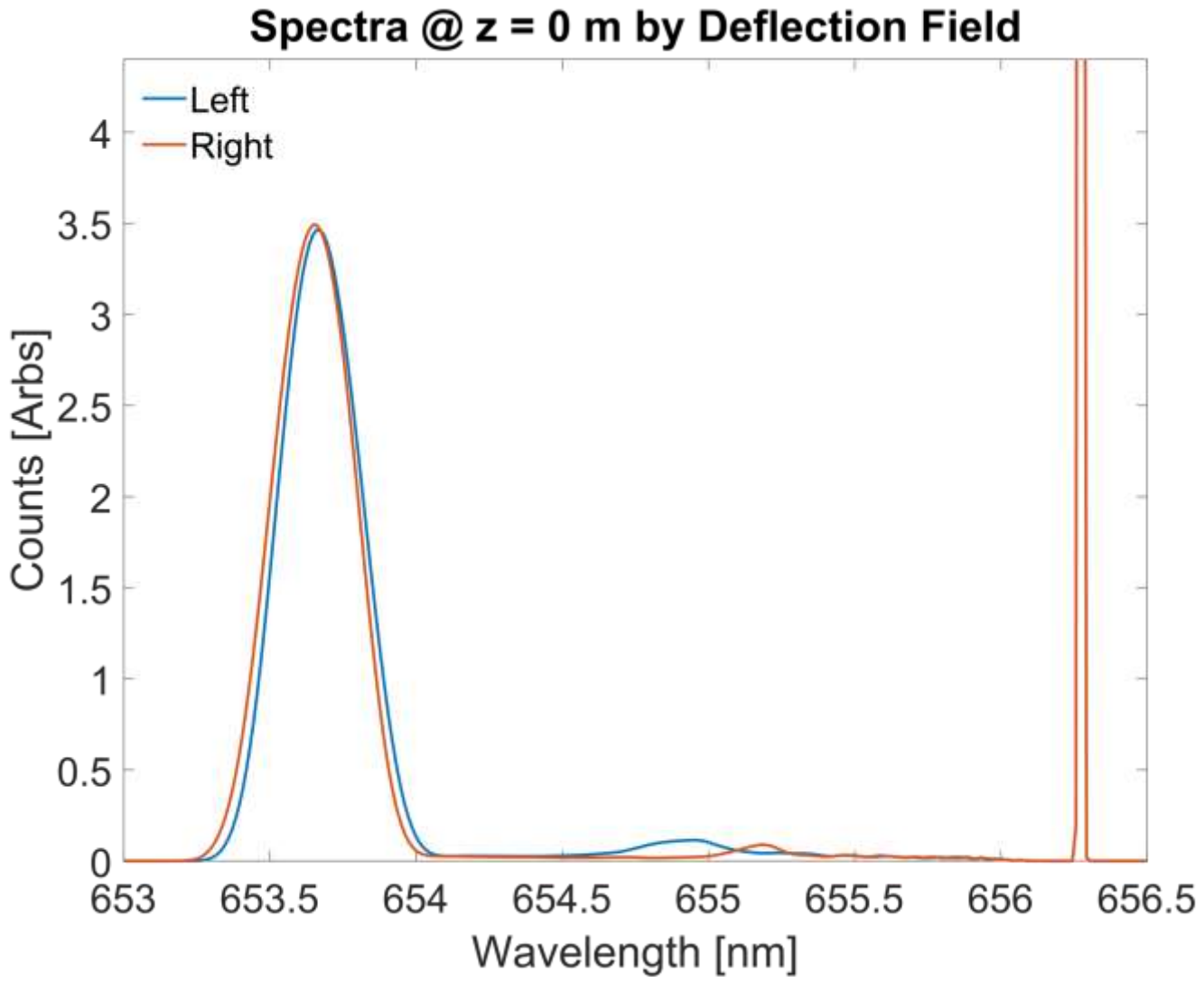
Individual BES Spectra



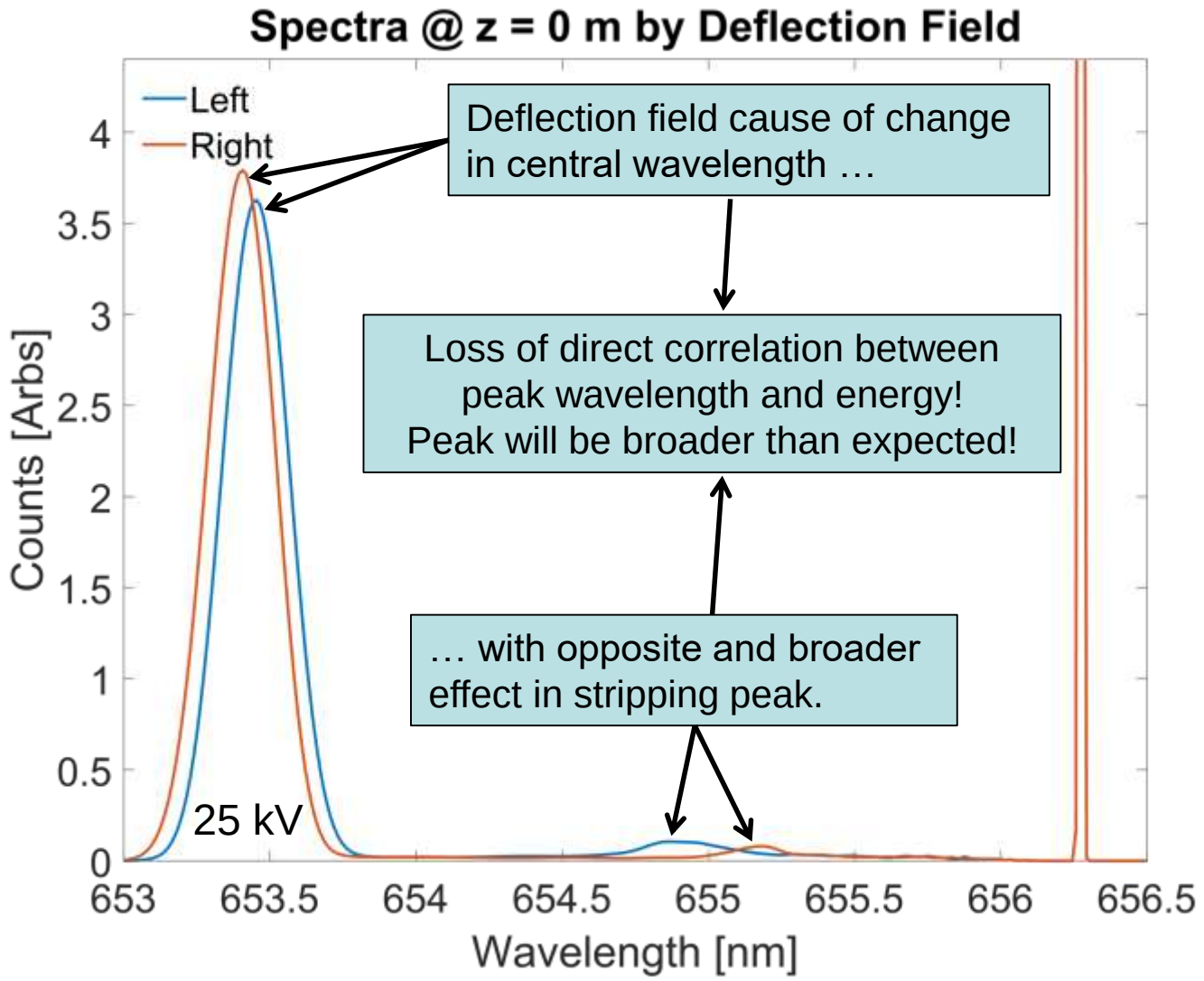
Aperture Deflection Direction



BES Spectra by Aperture Deflection

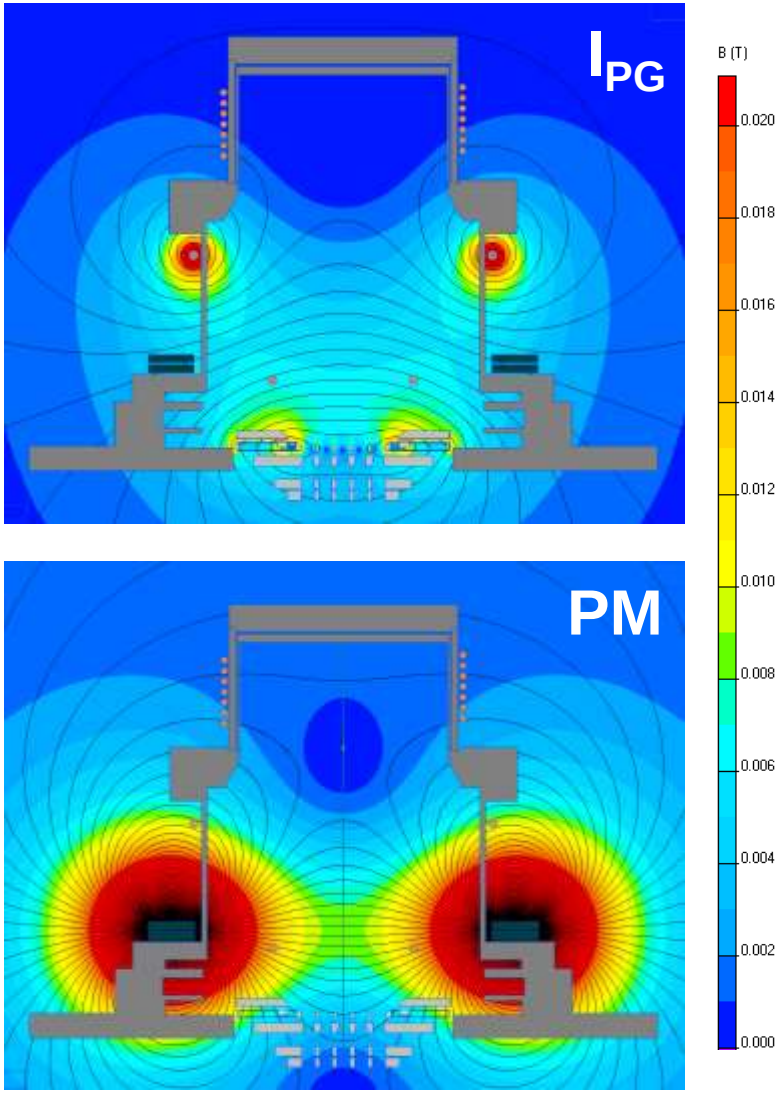


BES Spectra by Aperture Deflection

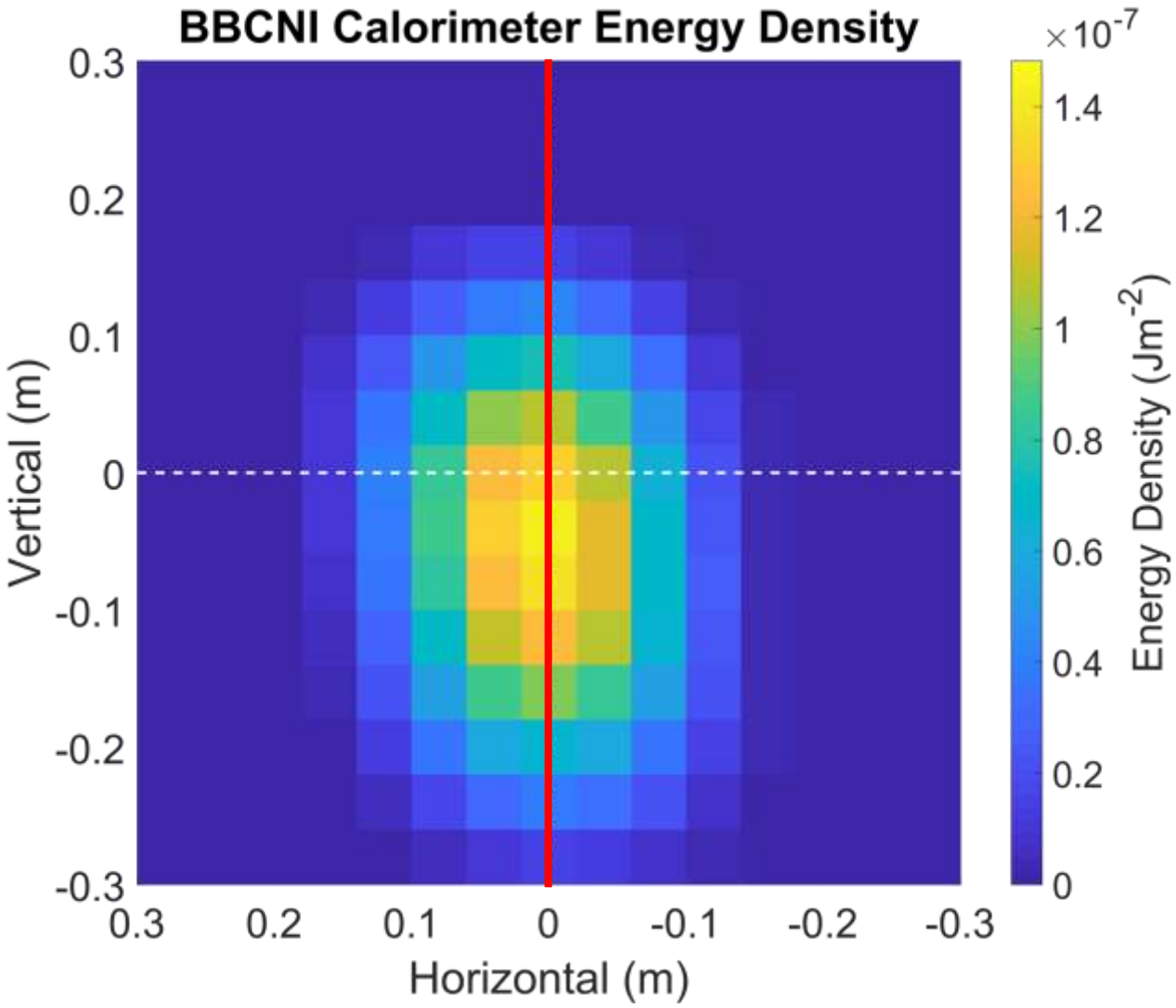


BATMAN Upgrade Comparison

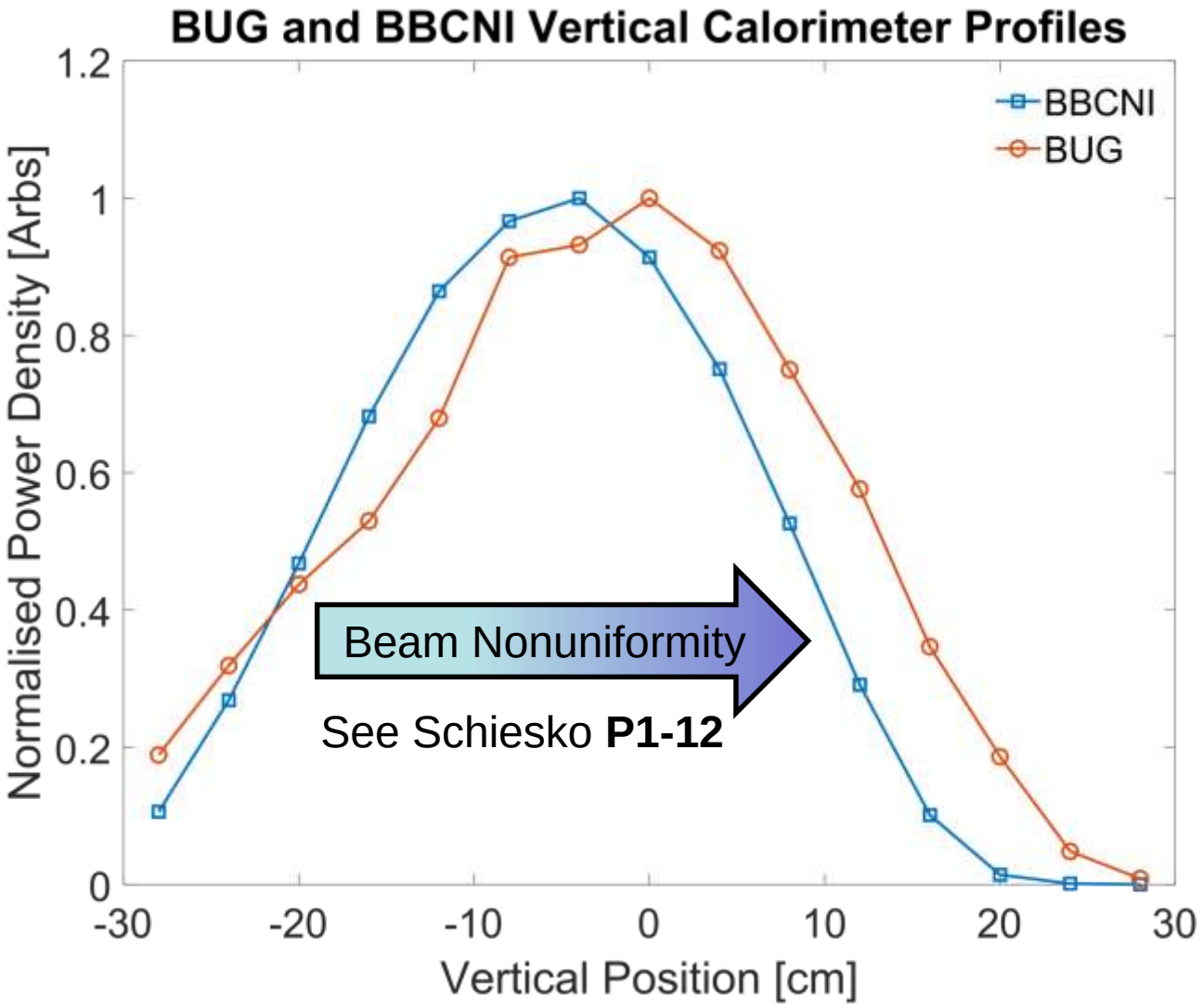
- As part of commissioning and conditioning process, two scans of U_{acc} performed
- Two different filter fields
  - I_{PG} = 2.2 kA
  - Permanent Magnets (PMs)
- Constant Parameters:
  - U_{ex} = 5.7 kV
  - p = 0.4 Pa
  - P_{RF} = 55.6 kW
  - $j_{ex} \approx 12.8\ mA \cdot cm^{-2}$ (I_{PG})
    $\approx 13.7\ mA \cdot cm^{-2}$ (PMs)
- U_{acc} increased from 8 kV until breakdowns occurred
- **Not** indicative of optimum source performance



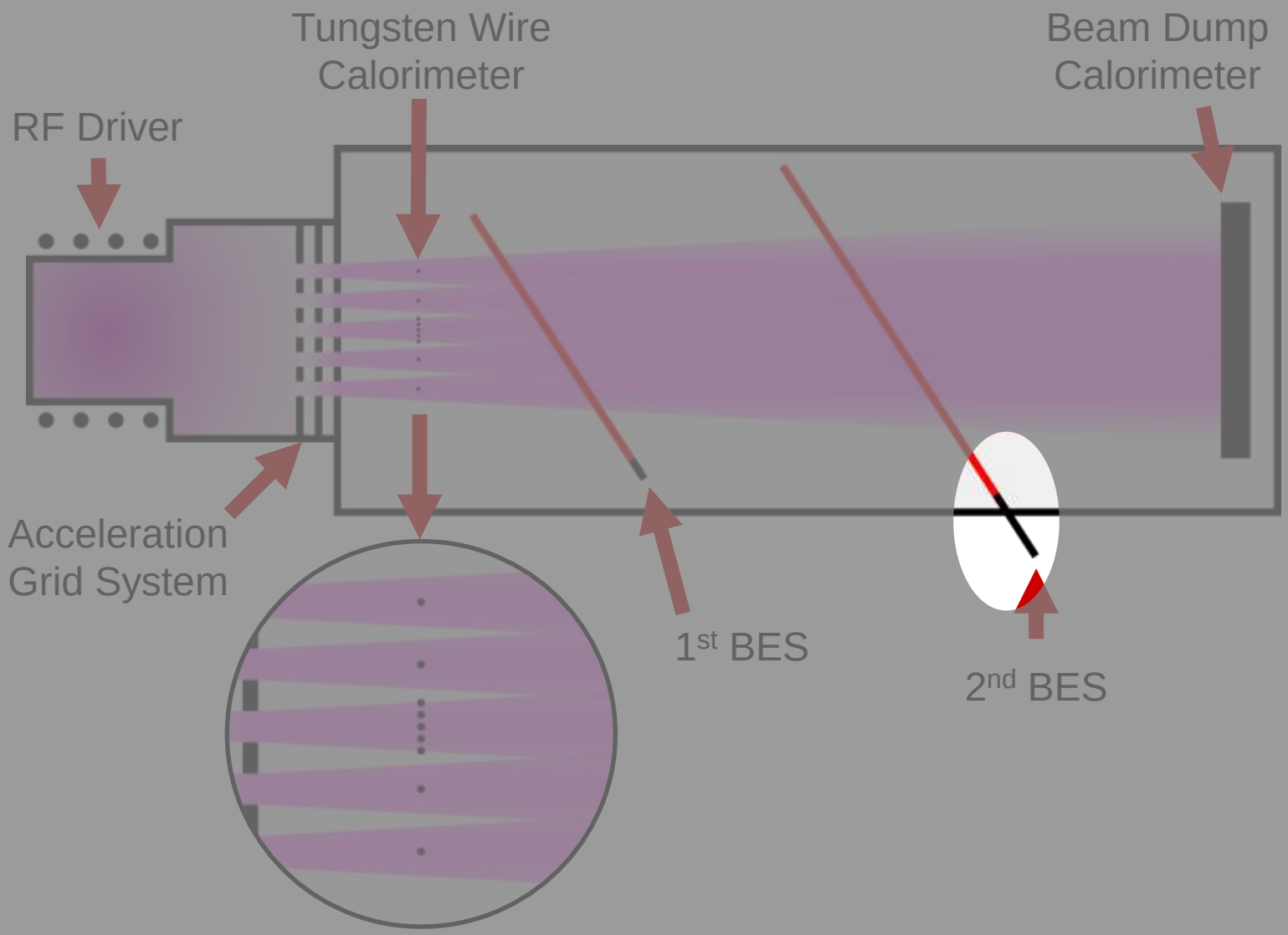
Simulated Calorimeter Image



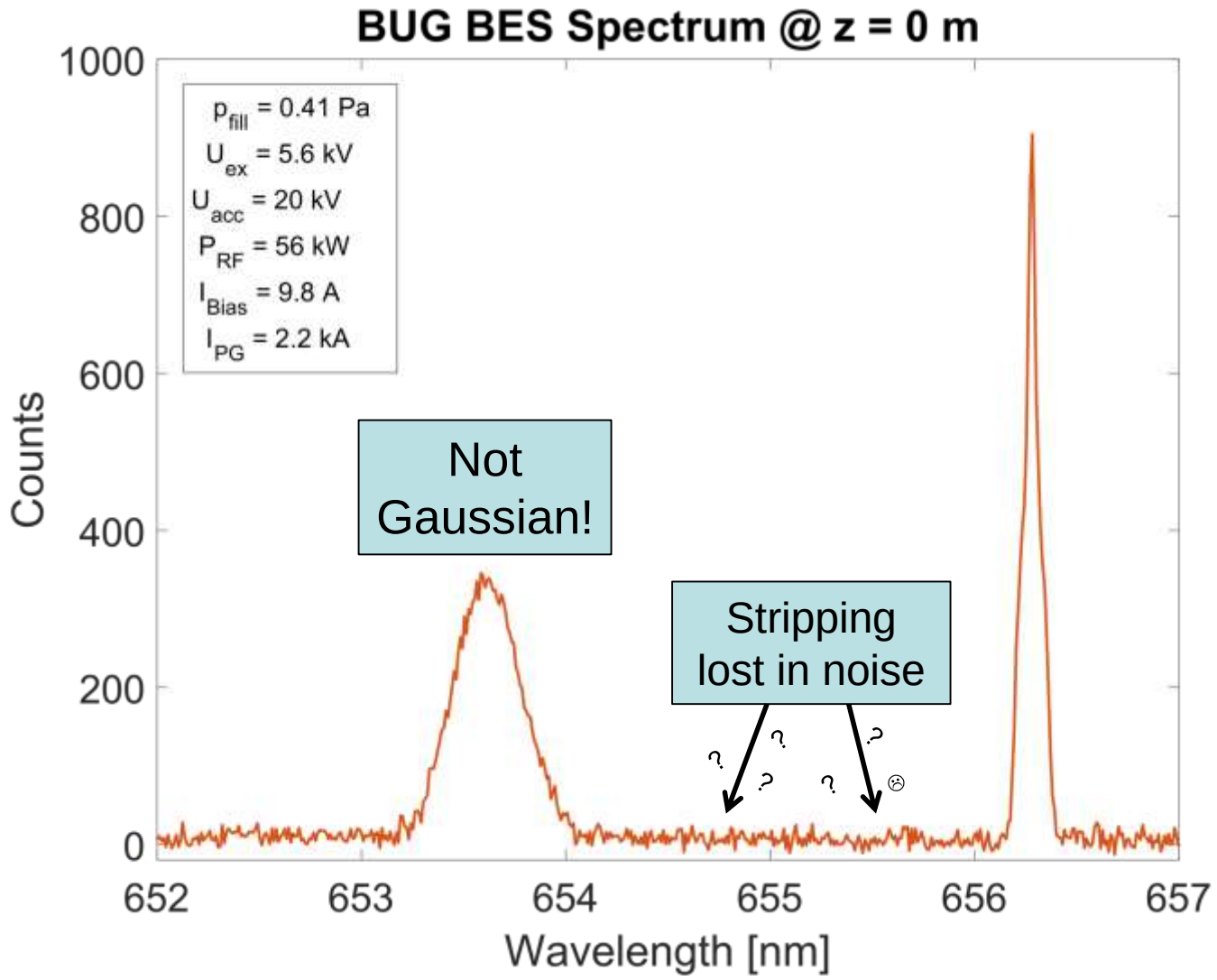
Calorimeter Vertical Profile



Diagnostics Overview



Experimental BES Spectrum



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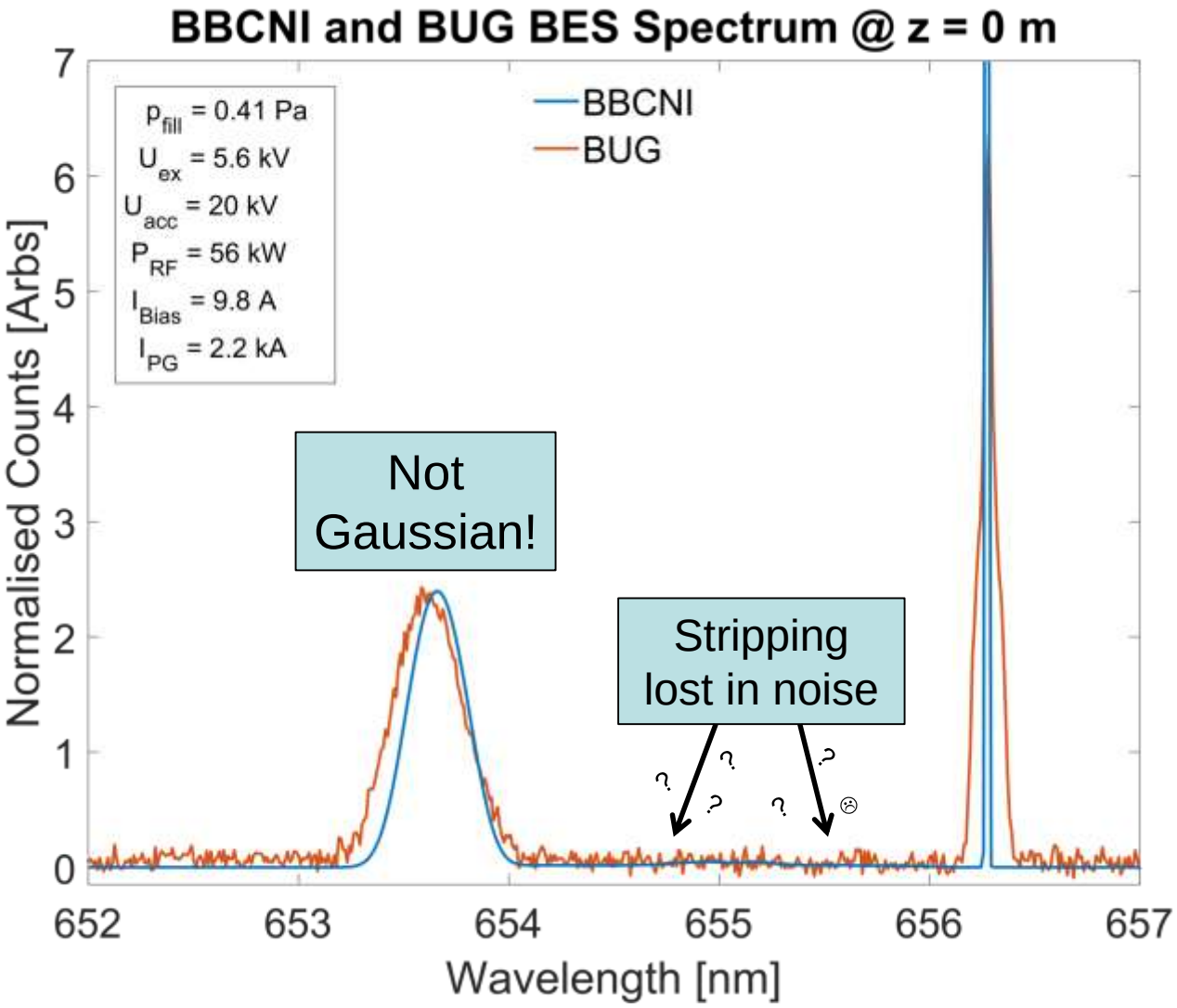
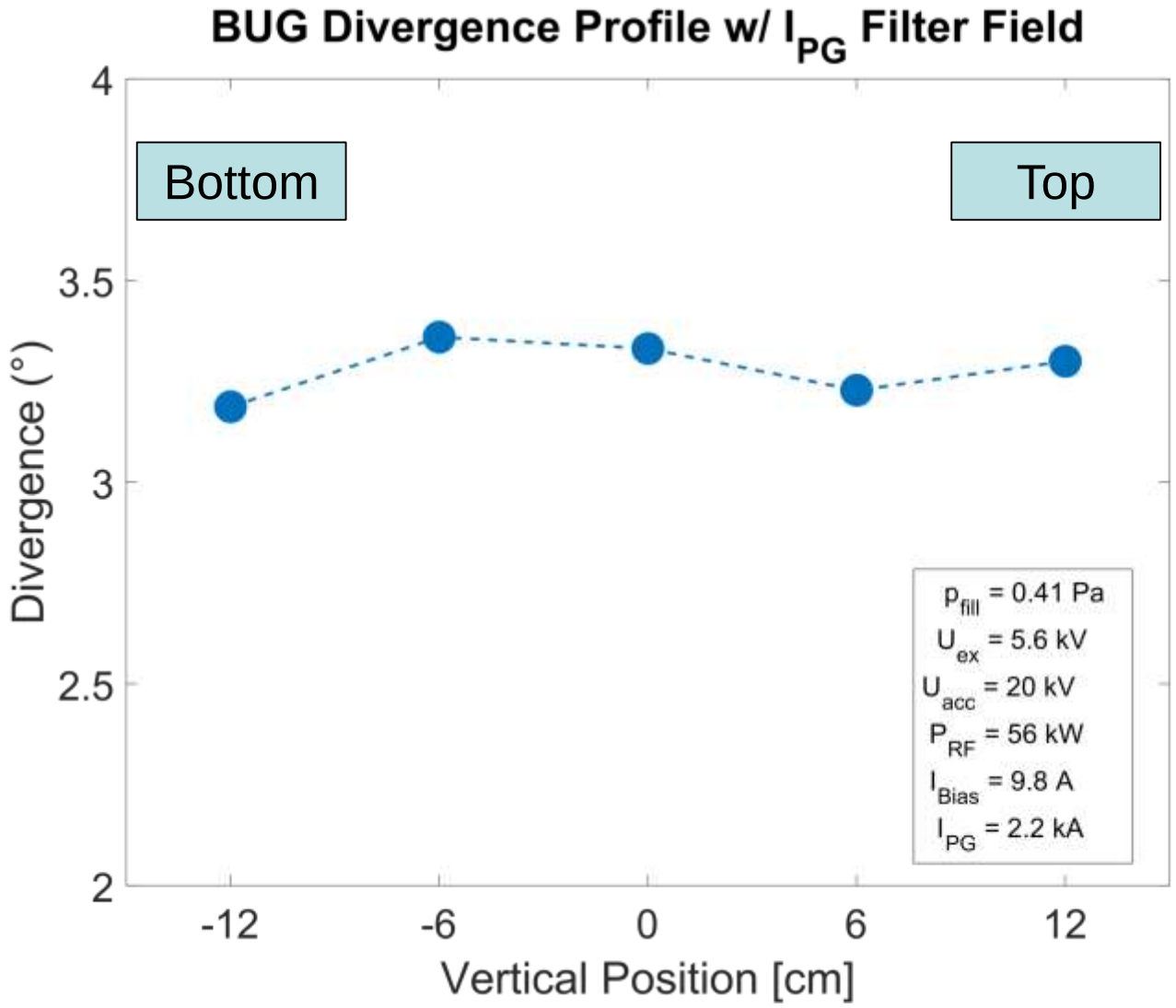
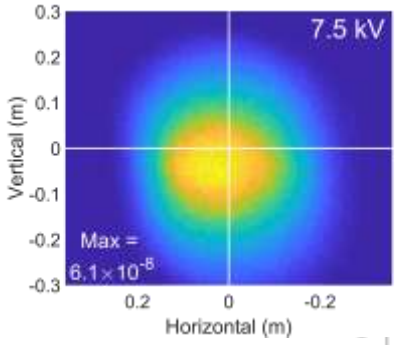
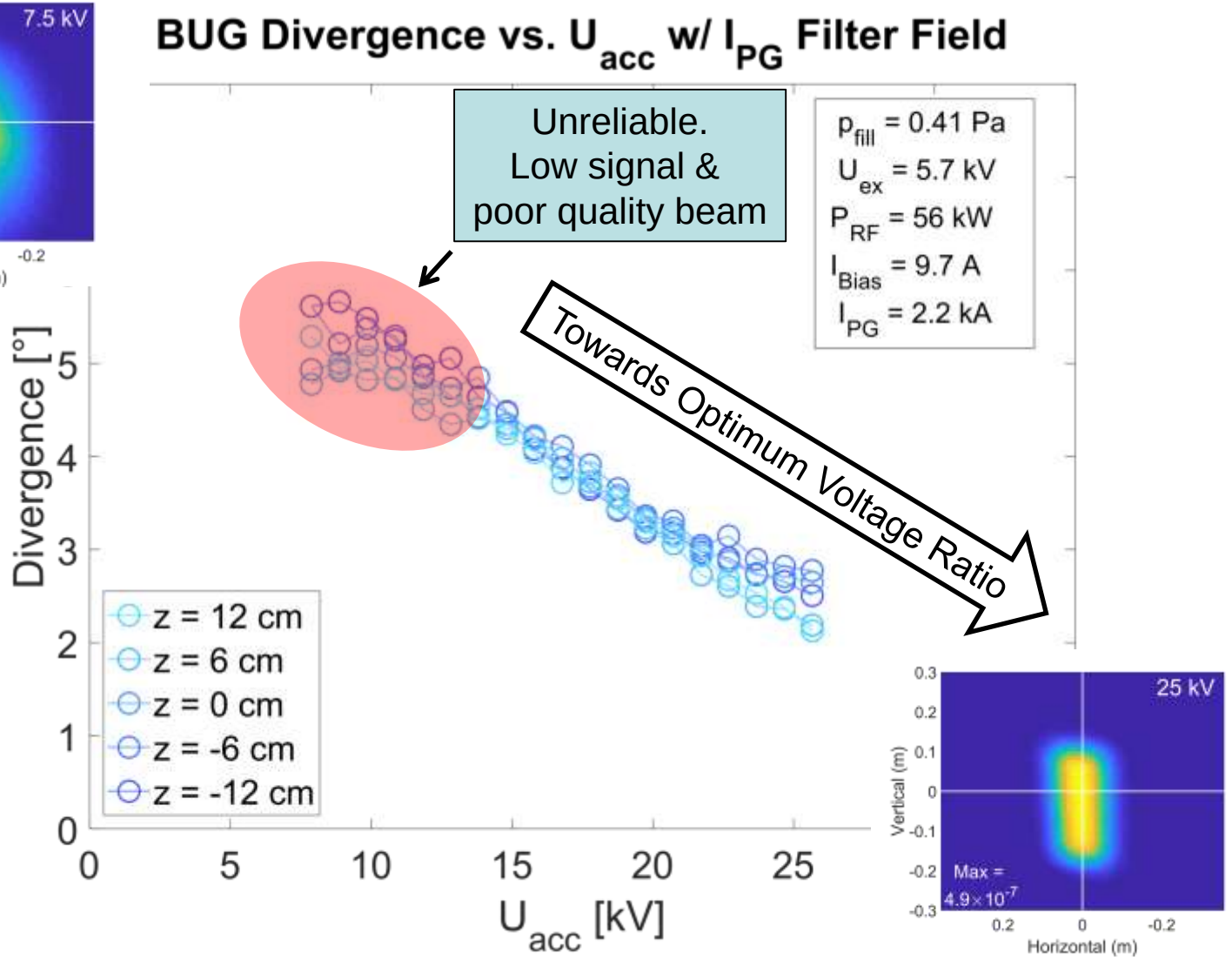


Experimental Divergence Profile

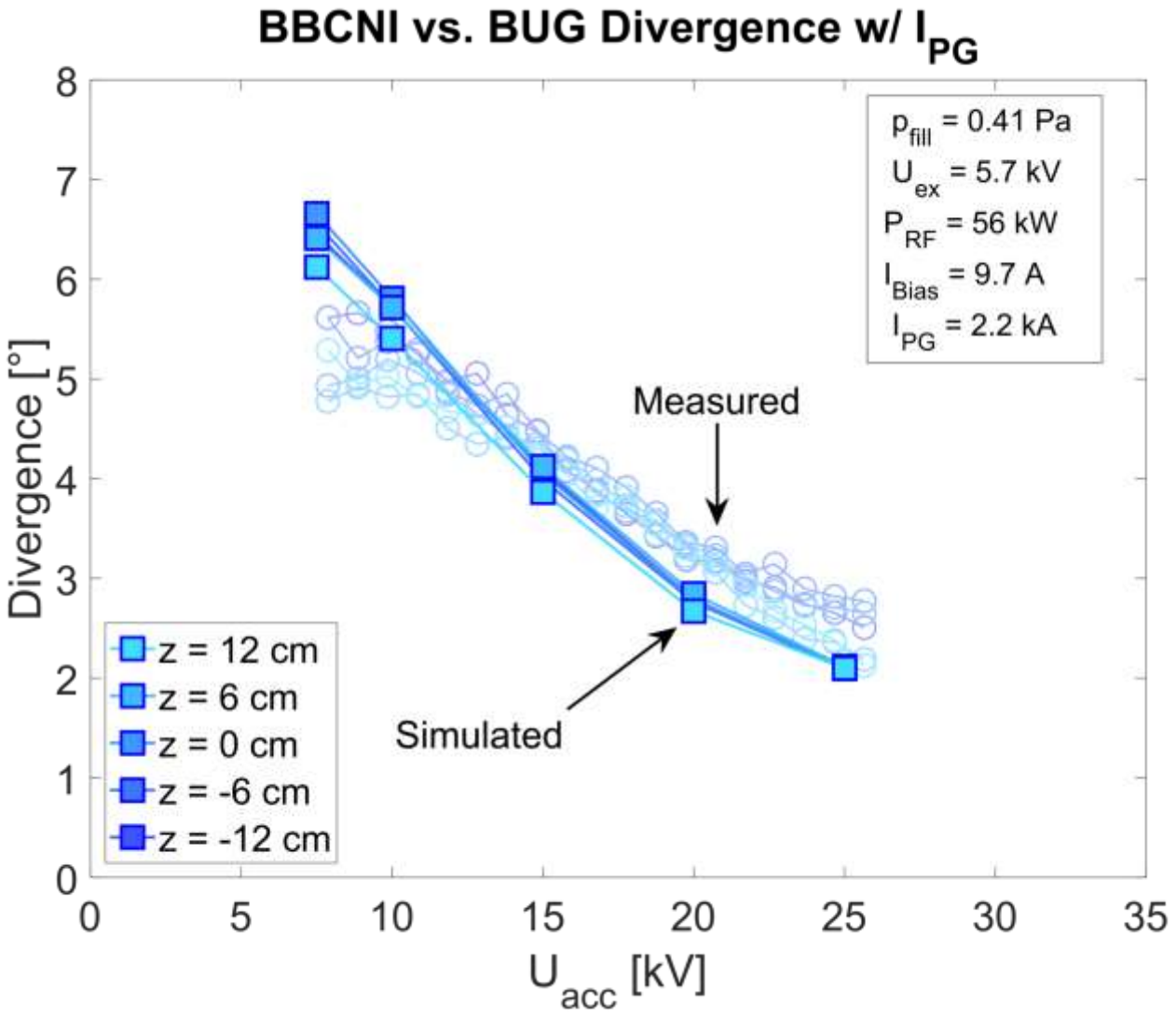


Divergence vs. U_{acc} (I_{PG})

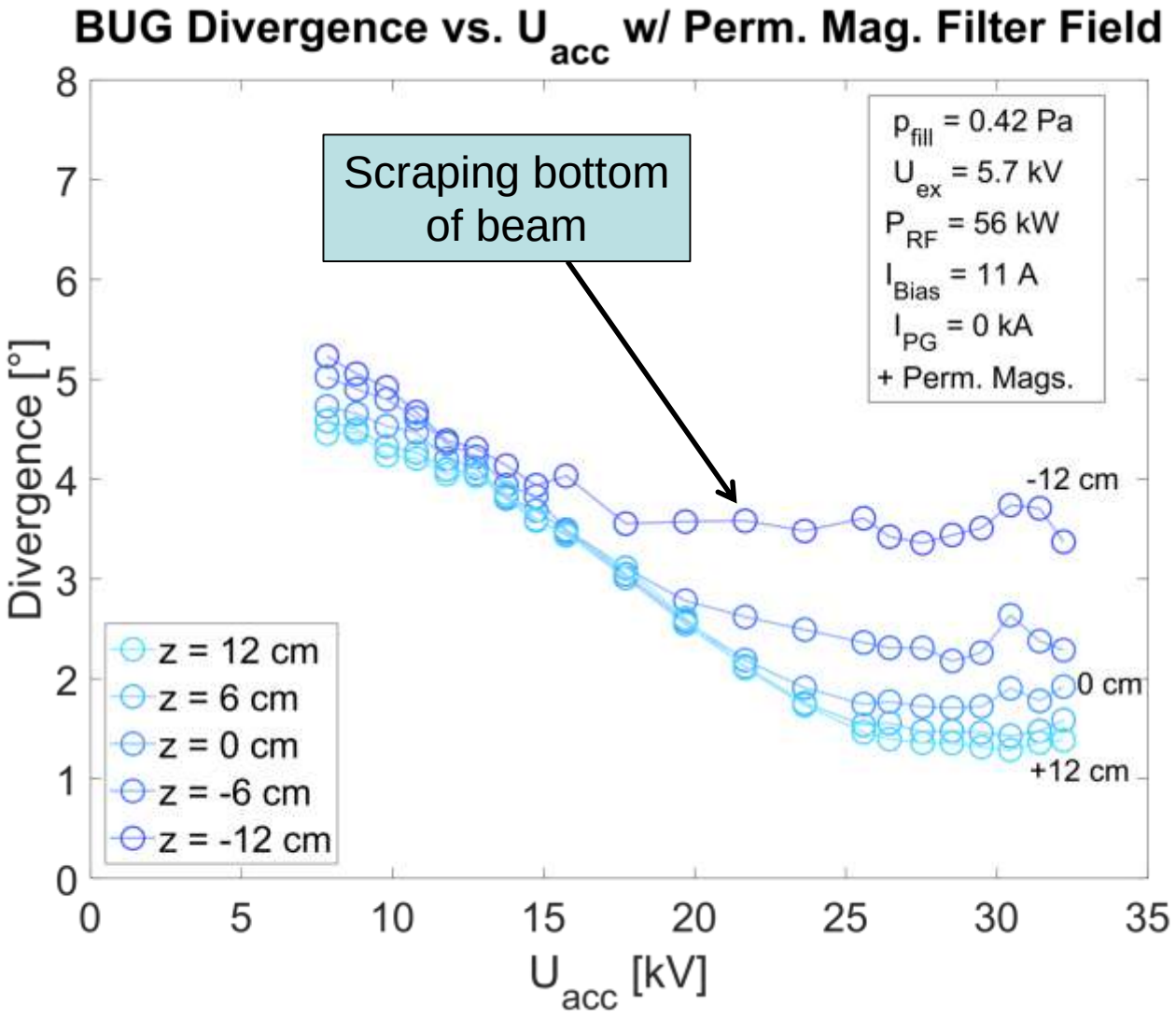




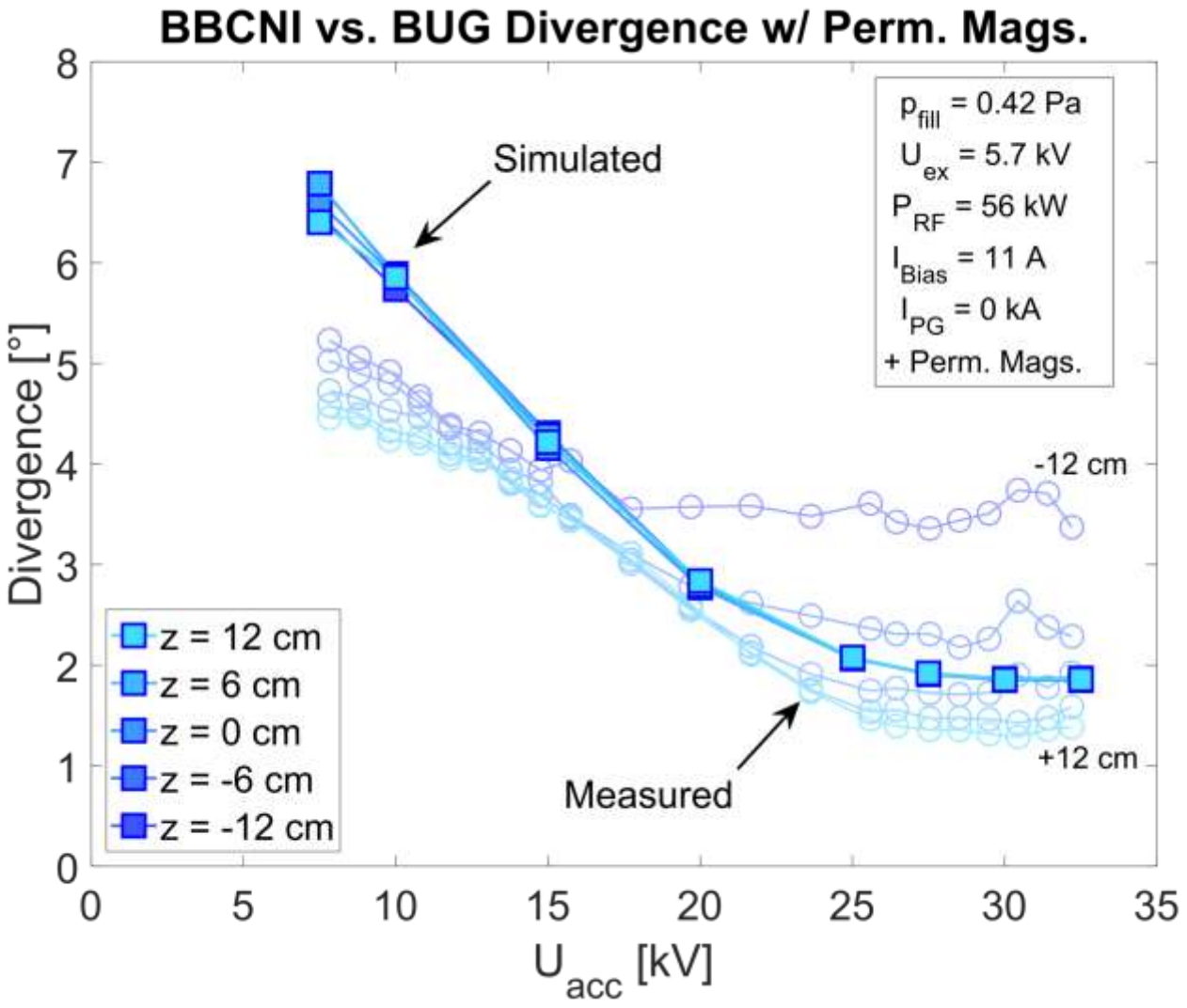
Divergence vs. U_{acc} (I_{PG})



Divergence vs. U_{acc} (PMs)



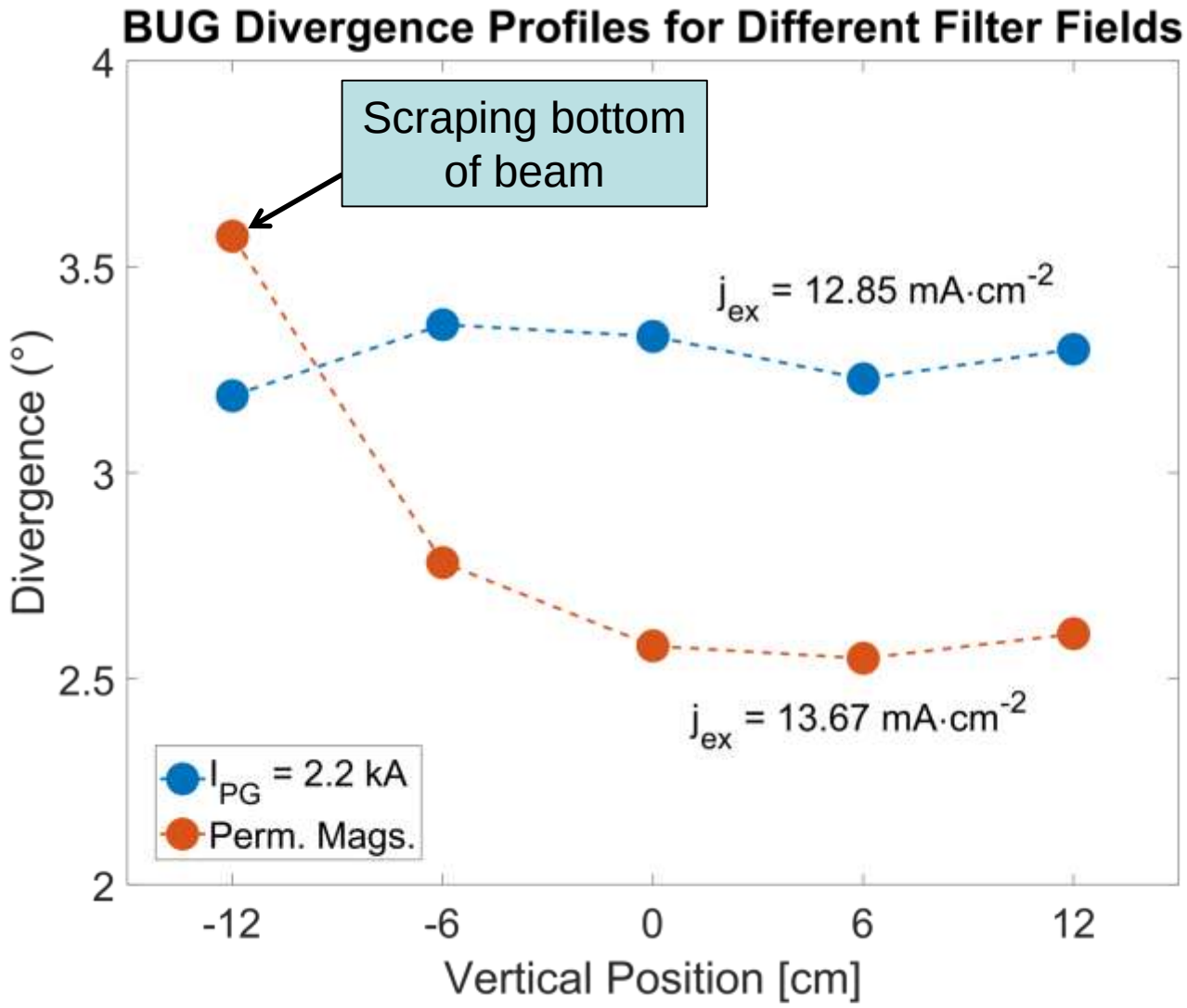
Divergence vs. U_{acc} (PMs)



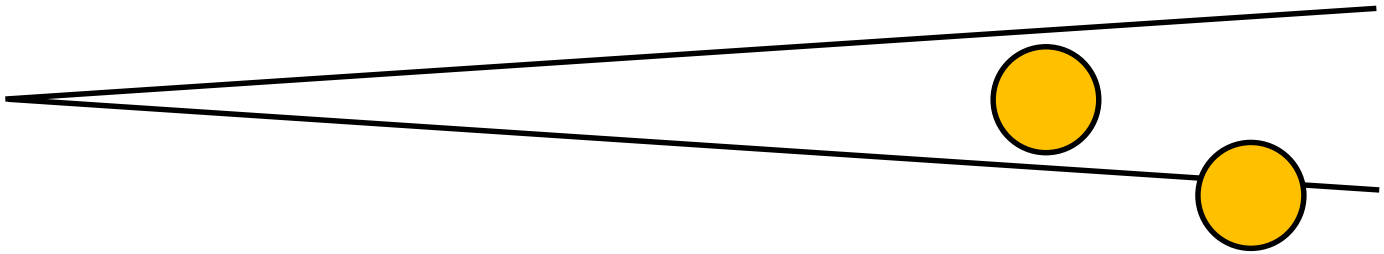
Conclusions

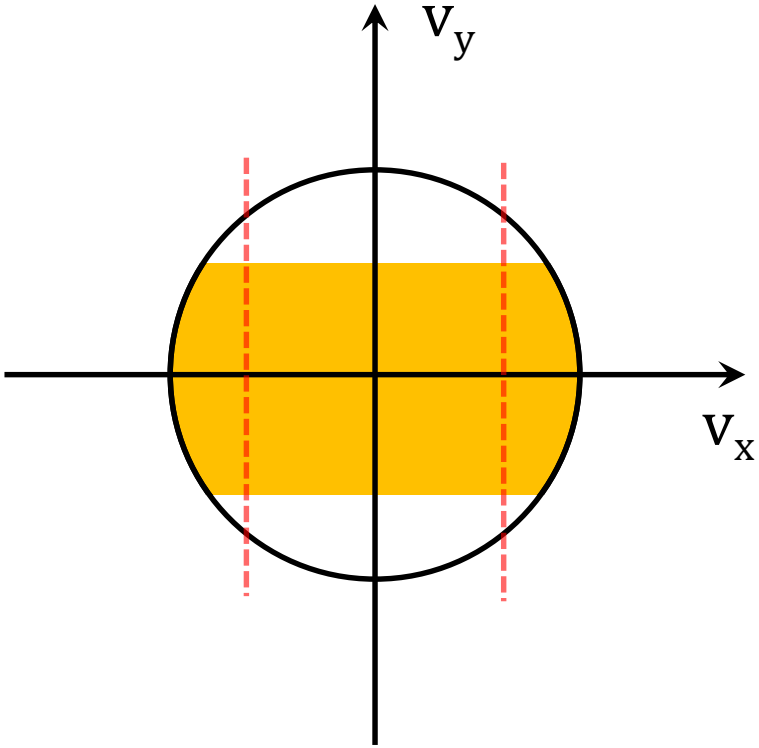
- Advances in generation of large ion beams requires improved understanding of beam physics
- Links between diagnostic results and actual beam properties not trivial
- **Bigger beams → bigger problems**
- **Forward calculation** of diagnostics critical for understanding results
- BBCNI can recreate diagnostic results (and more) from **particle level data**
- Shown to conform with experimental results across parameter ranges
- Will supplement experimental results and investigate underlying causes
- Planned upgrades:
  - **Inhomogeneous current extraction**
  - Application to ELISE

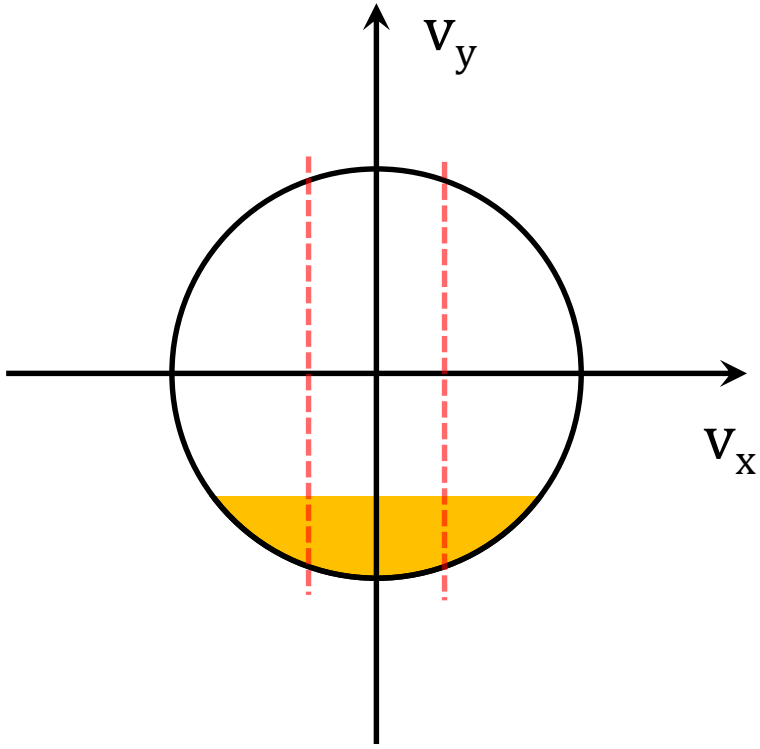
Divergence Profiles I_{PG} vs PMs



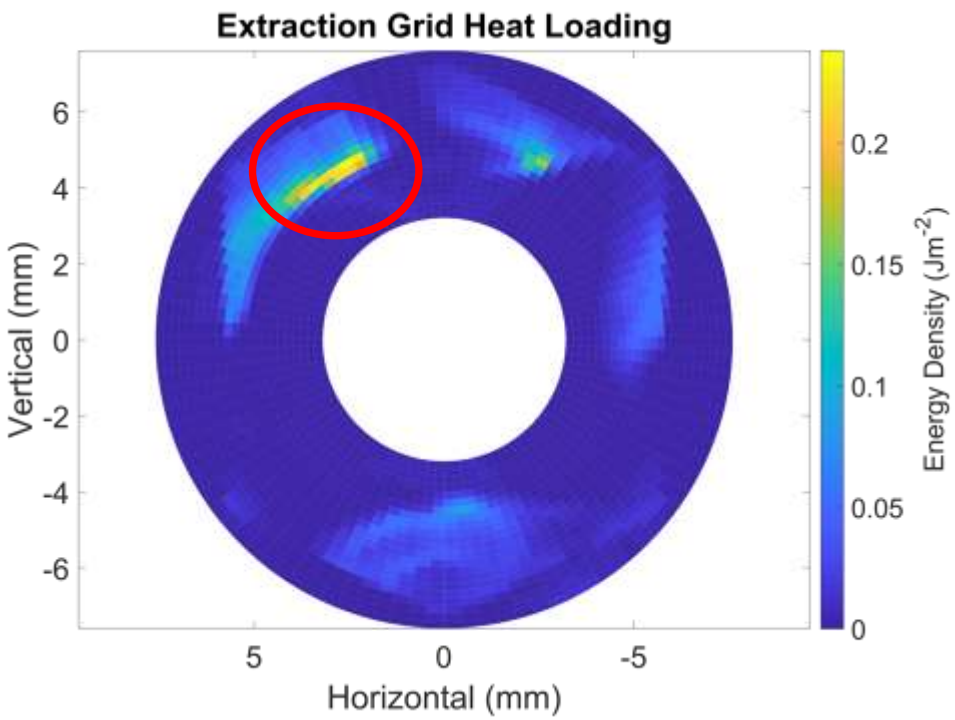
Velocity Sampling

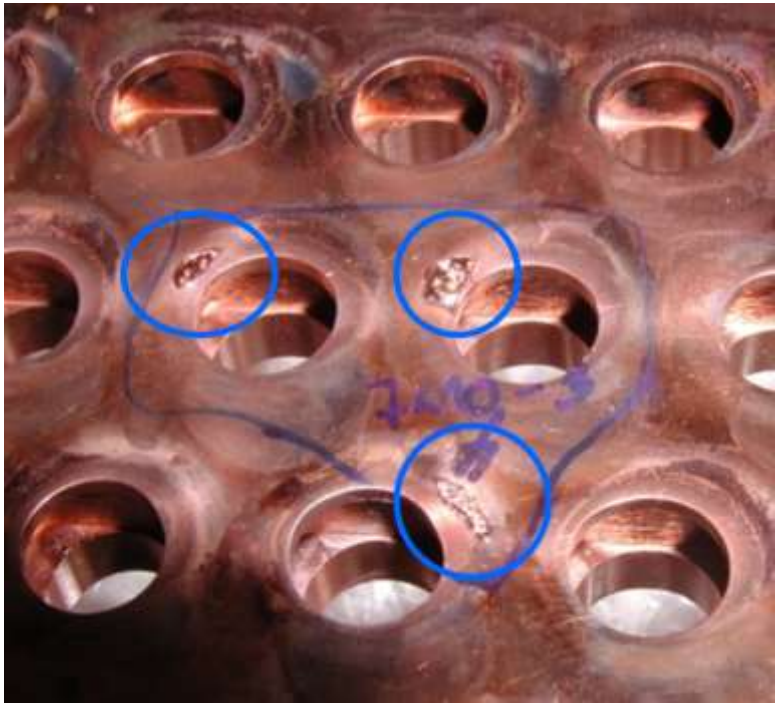


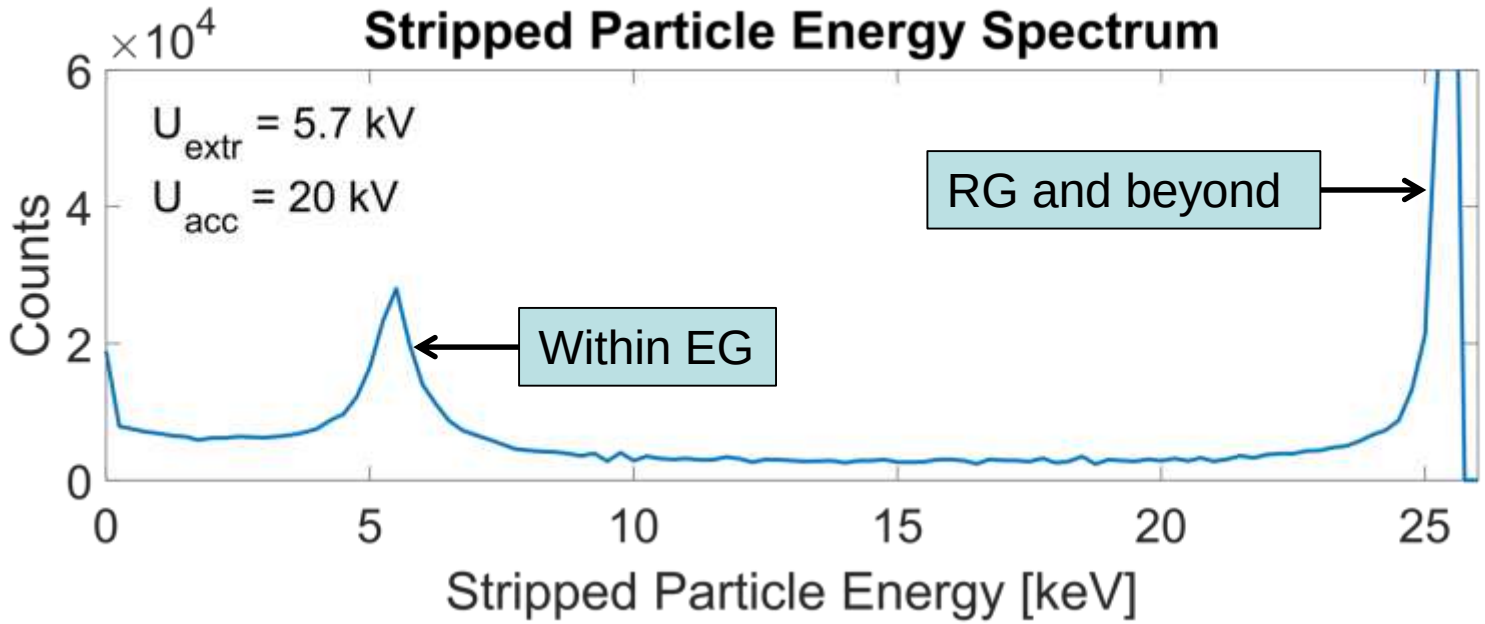


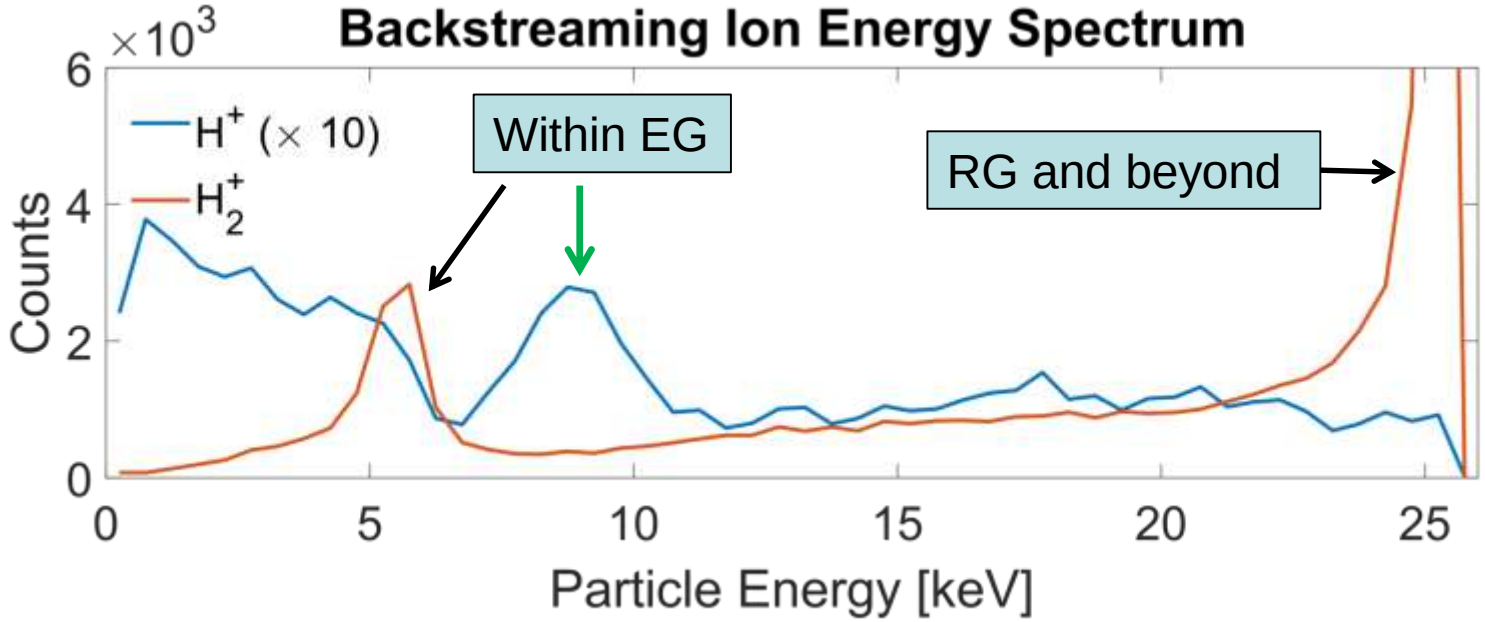


Co-extracted e^- Melt Spots

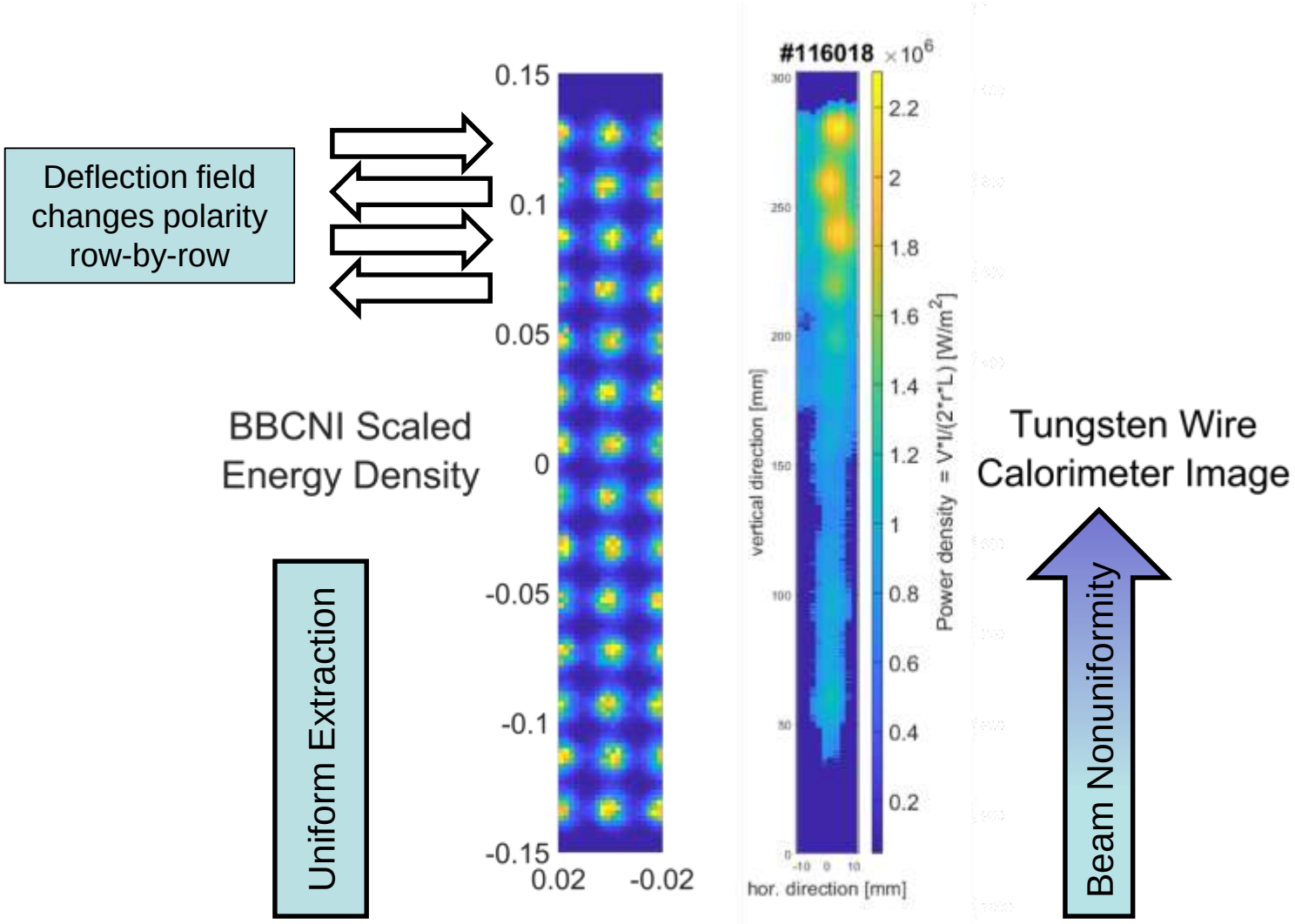




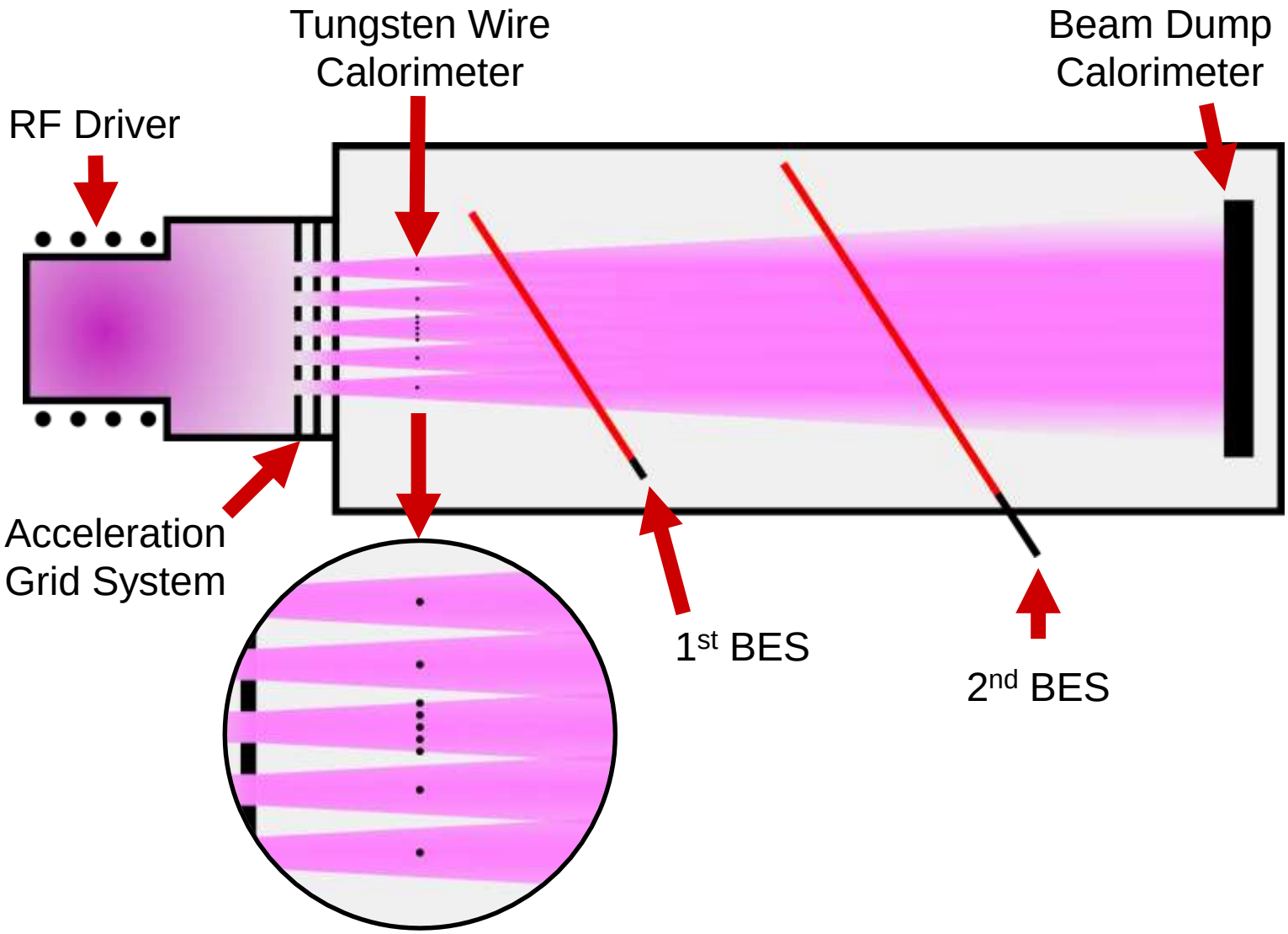
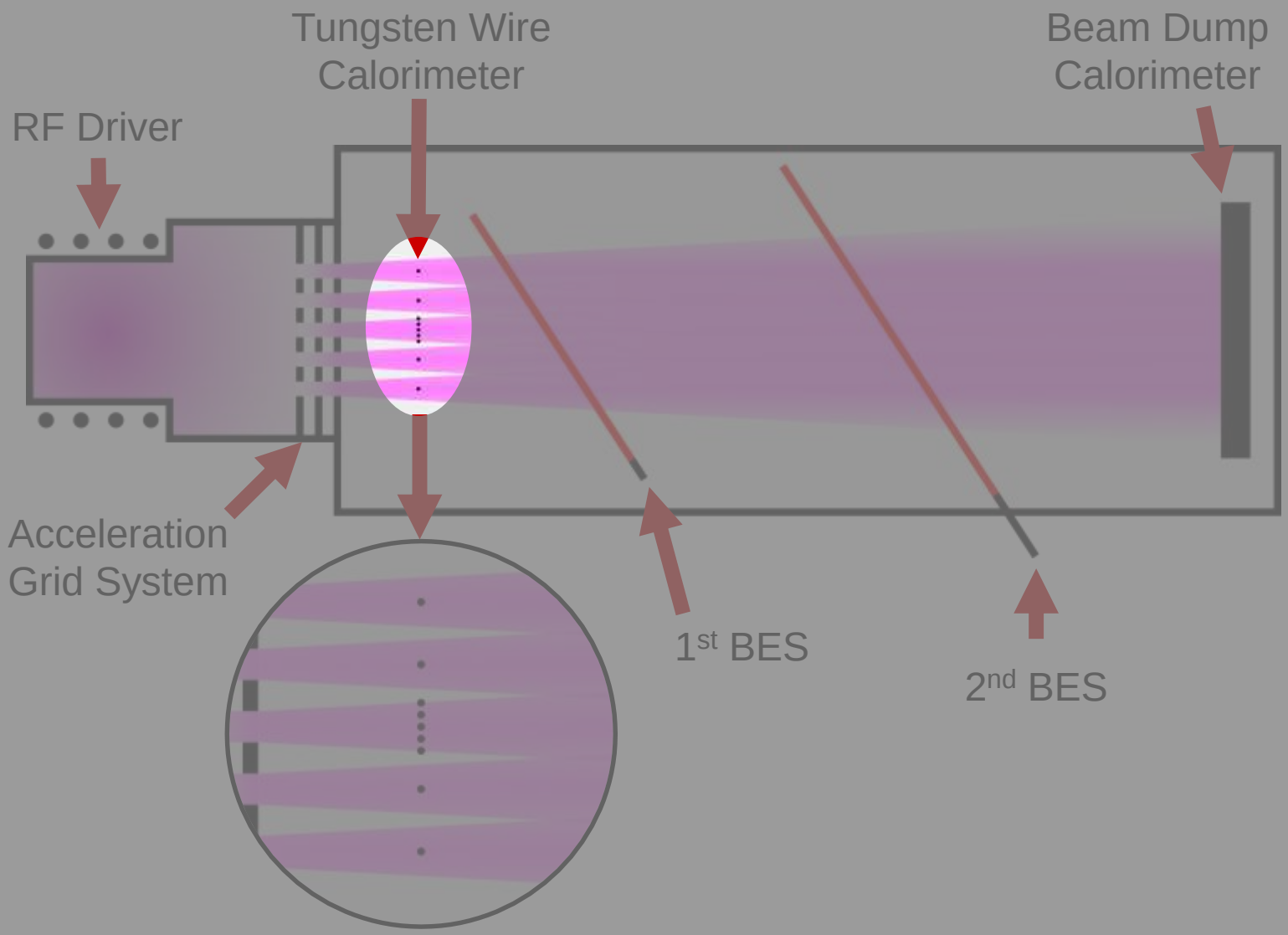

Stripped Particle Energy Spectrum
×10^4
6
4
2
0
Counts
U_extr = 5.7 kV
U_acc = 20 kV
RG and beyond
Within EG
0
5
10
15
20
25
Stripped Particle Energy [keV]


Backstreaming Ion Energy Spectrum
×10^3
6
4
2
0
Counts
H+ (× 10)
H2+
Within EG
RG and beyond
0
5
10
15
20
25
Particle Energy [keV]

Tungsten Wire Calorimeter



Diagnostics Overview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