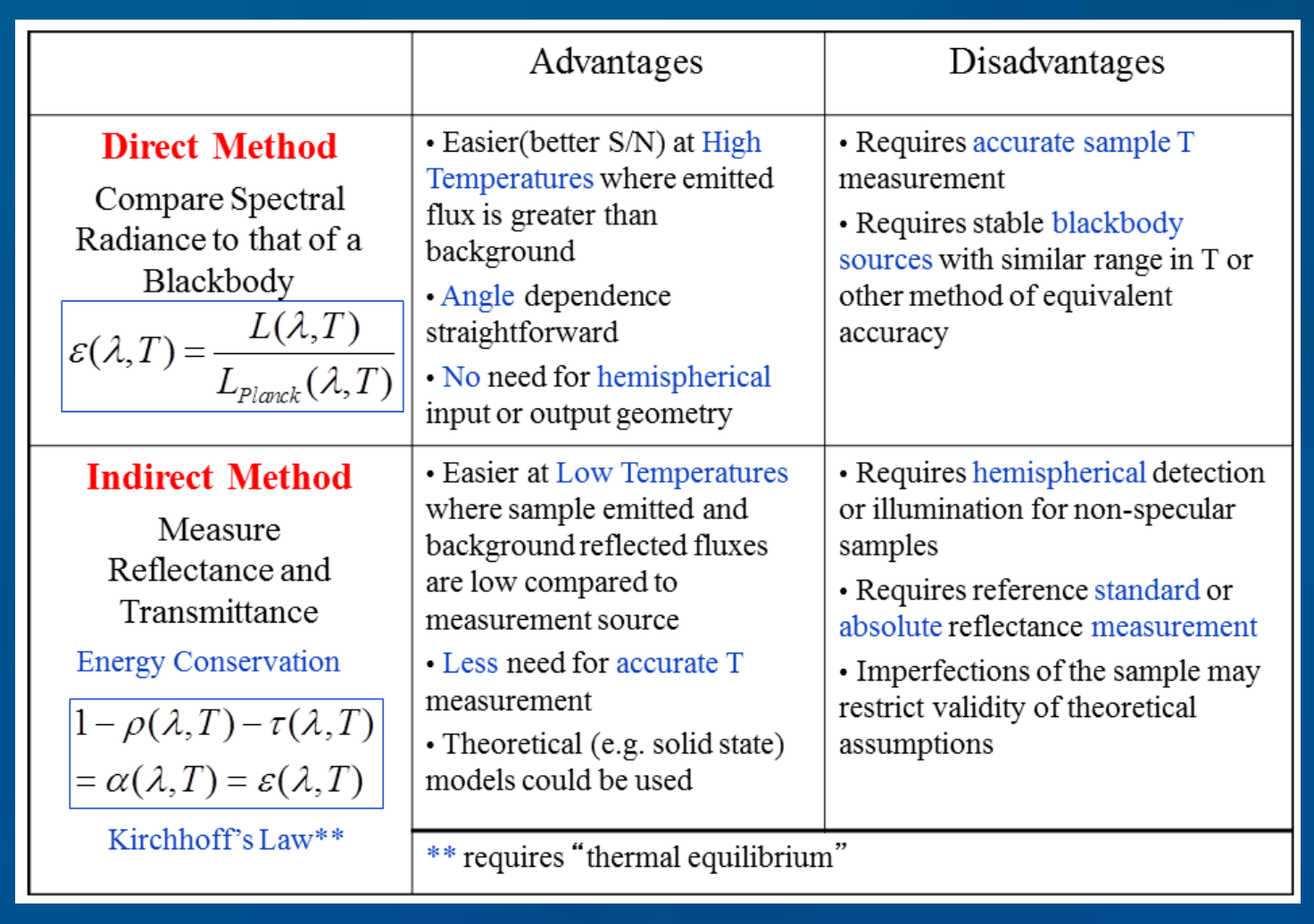
Temperature & **E**mittance of **M**elts, **P**owders and **S**olids

Additive Manufacturing and other applications, involving directed energy beams to selectively melt or sinter materials, can benefit from better understanding of emissive properties of materials in solid, powder and liquid states, as well as improved techniques for real time temperature determination.

To address these priority needs, AMMT Testbed incorporates TEMPS, a system for characterizing the optical and radiative properties of metallic, polymer and ceramic materials in solid, powder and molten states at temperatures up to 3300 K at static as well as dynamic conditions of the heated zone.

Emissivity Realization Options



	Advantages	Disadvantages
Direct Method Compare Spectral Radiance to that of a Blackbody $\varepsilon(\lambda,T)=\frac{L(\lambda,T)}{L_{Planck}(\lambda,T)}$	• Easier(better S/N) at High Temperatures where emitted flux is greater than background • Angle dependence straightforward • No need for hemispherical input or output geometry	• Requires accurate sample T measurement • Requires stable blackbody sources with similar range in T or other method of equivalent accuracy
Indirect Method Measure Reflectance and Transmittance Energy Conservation $1-\rho(\lambda,T)-\tau(\lambda,T)=\alpha(\lambda,T)=\varepsilon(\lambda,T)$ Kirchhoff's Law**	• Easier at Low Temperatures where sample emitted and background reflected fluxes are low compared to measurement source • Less need for accurate T measurement • Theoretical (e.g. solid state) models could be used	• Requires hemispherical detection or illumination for non-specular samples • Requires reference standard or absolute reflectance measurement • Imperfections of the sample may restrict validity of theoretical assumptions
	** requires "thermal equilibrium"	

HYBRID METHOD (Pierluigi Testa, Rome University, 1975):

- INDIRECTLY measure EMITTANCE (reflectance) at a SINGLE λ*
  - (a) Measure RADIANCE T at λ*
  - (b) Calculate TRUE SURFACE TEMPERATURE at λ*
- DIRECTLY Measure EMITTANCE across the spectral range

Earlier Facility Limitations and New Opportunities

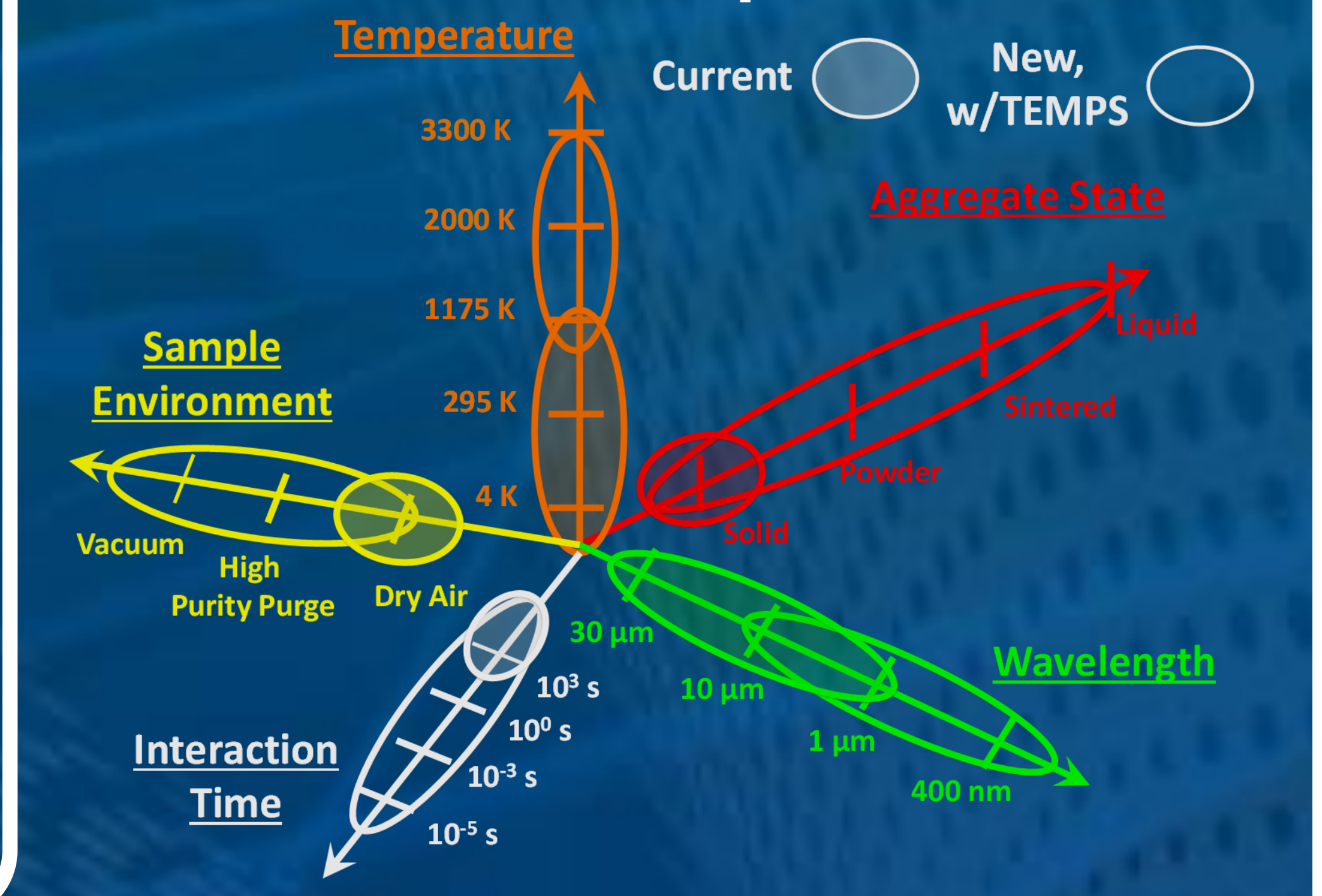
- Limited T Range (resistive heating)
  - -Use Laser Heating
- Sample Containment
  - -Use local heating (variation of a "Cold Skull")
- Long Dwell Time at High T (sample degradation)
  - -Use Scanning Laser Beam + Fast Spectrometer
- Only Solid Samples (no melts or powders)
  - -Use center-mount virtual sphere reflectometer
- Limited T Range for Reference Sources
  - -Use Solid State / Laser Sources

Anticipated Impact and Beneficiaries

Promote Innovation via better Non-Contact Thermometry, Radiative Transfer Analysis and Process/Target Engagement Control in:

- Laser-Based Additive Manufacturing and Material Processing Technologies
- Refractory and Composite Materials for aerospace, nuclear reactors and thermionic systems
- Directed Energy Systems and their counter-measures

Measurement Capabilities



Dynamic Meltpool Emissometry (DyME)

- Treats moving melt pool or hot spot as a static target; reduces contamination & evaporation due to the small heat affected zone
- Reflectance and emittance measurements utilize a shared optical path with heating and probing lasers.
- Path integration leads to several seconds of total measurement time and enables good signal-to-noise ratio

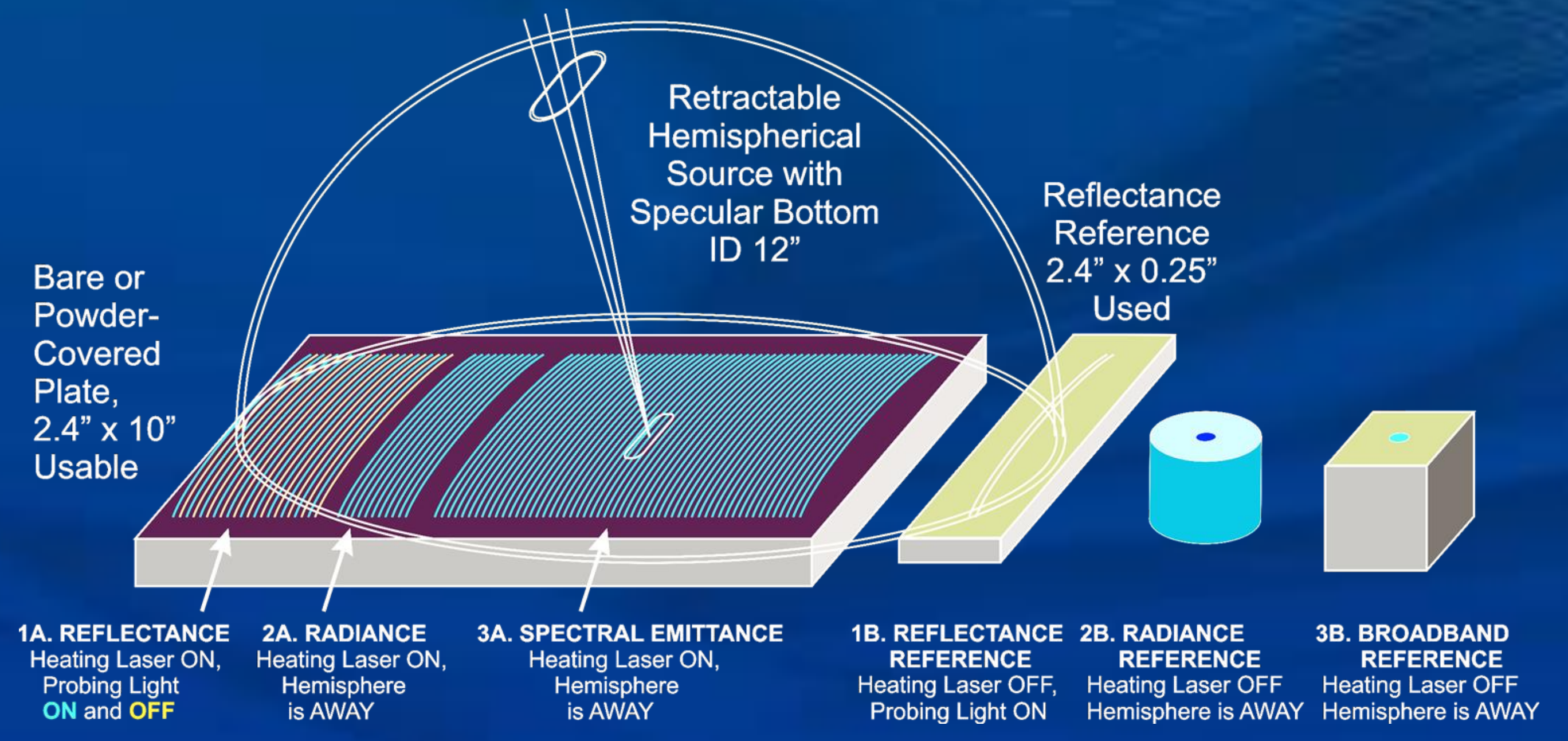
ADVANTAGES

- Very few model assumptions
- Polymers, ceramics and metals
- Powders, solids and melts
- Very high T's possible
- Wide spectral coverage

LIMITATIONS

- T uniformity across FoV
- Triggering and integration
- Imaging is very demanding
- Plume effects
- Highly reflective materials

Hybrid Method: New Realization



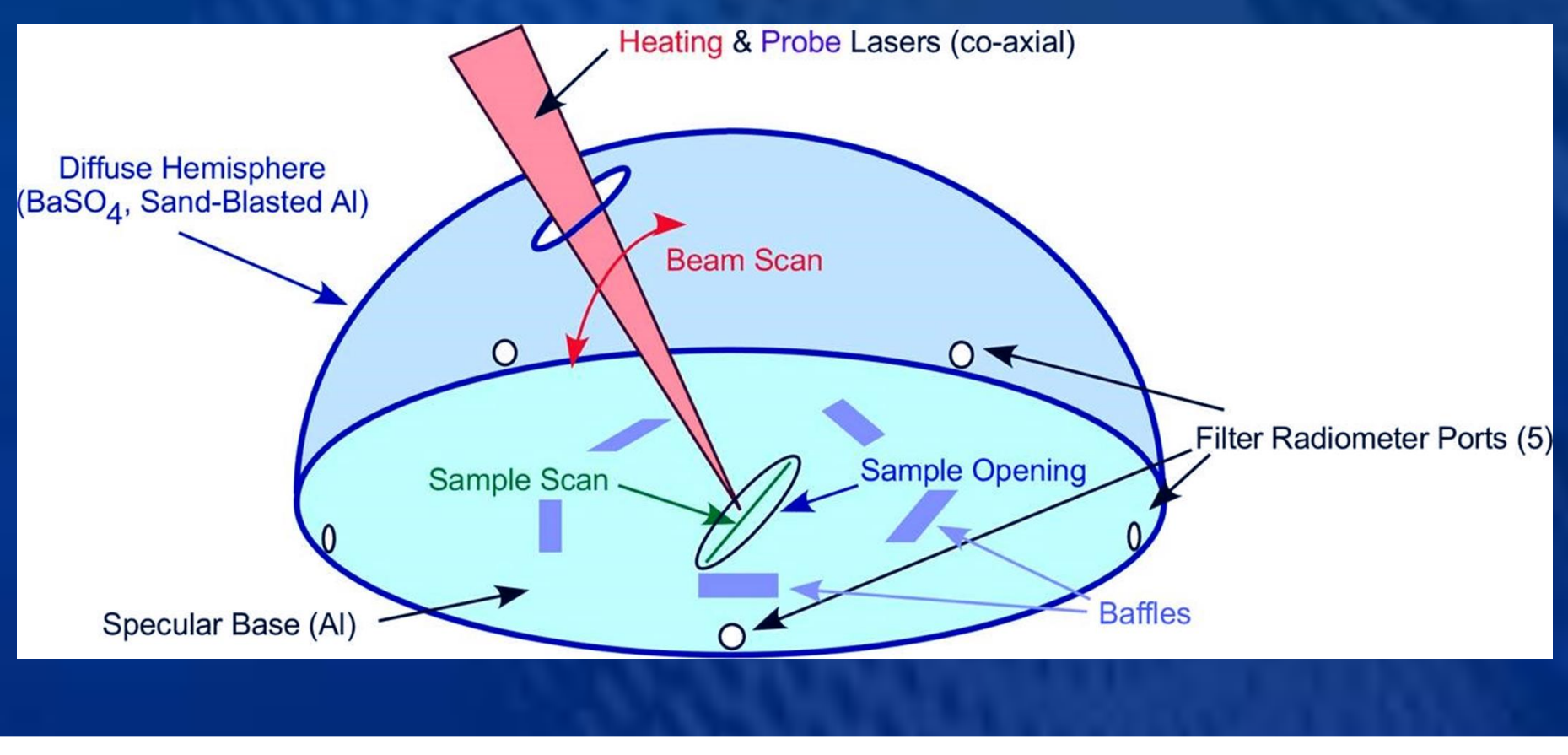
1A- 1B Measure reflectance/emittance at single wavelength with filter radiometer

2A – 2B Measure radiance at same wavelength with filter radiometer, Calculate T

3A-3B Measure spectral radiance with spectrometer, Calculate spectral emittance

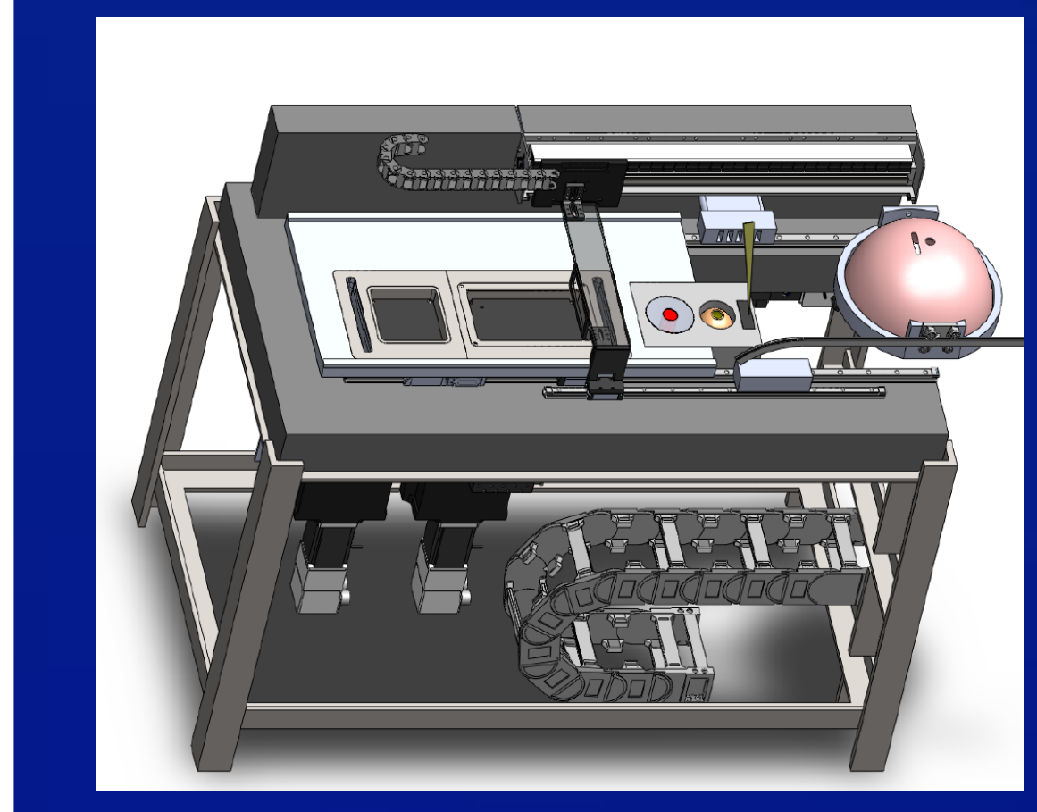
Virtual Integrating Sphere Reflectometer (VIS)

- ➢ Directional-Hemispherical Reflectance (DHR):
  - Probe laser light incident on sample at near-normal
  - Reflected light is sampled by radiometers viewing VIS wall
- ➢ S/N Advantage: sample emitted light has same throughput as probe laser reflected light



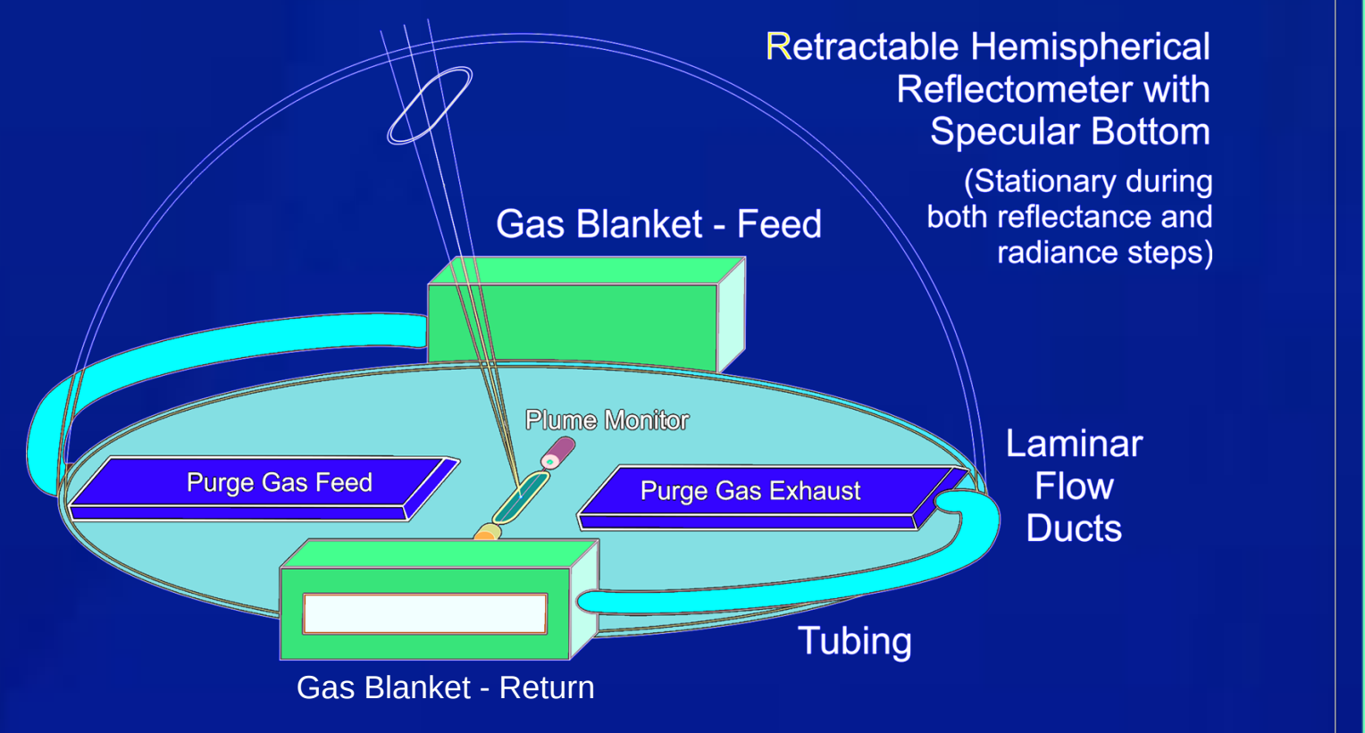
Implementation Features

- Scanning Laser Emissometer with Inline Broadband Metrology (DyME Method)
- Novel Center-Mount Reflectometer (folded virtual sphere) VIS
- Constant Optical Path Trajectory (maintain imaging quality across the spectrum)
- Separate Sample Tray/Heater for large laser beam and long interaction mode (sub-seconds and longer)



Standards Module and Reflectometer

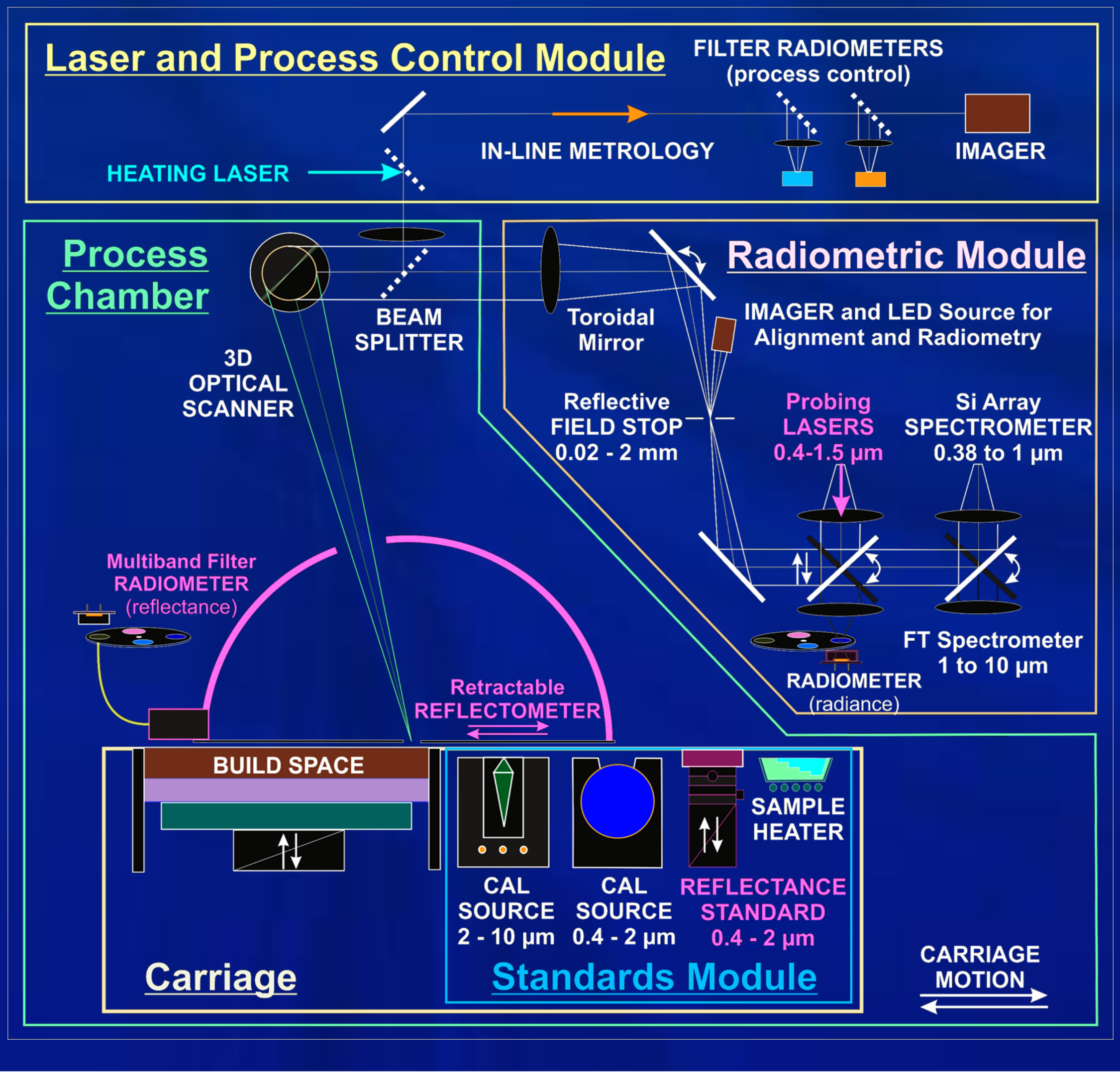
Gas Blanket for DyME (Both Reflectance and Radiance Steps)



Gas Blanket and Plume Evaluation Setup

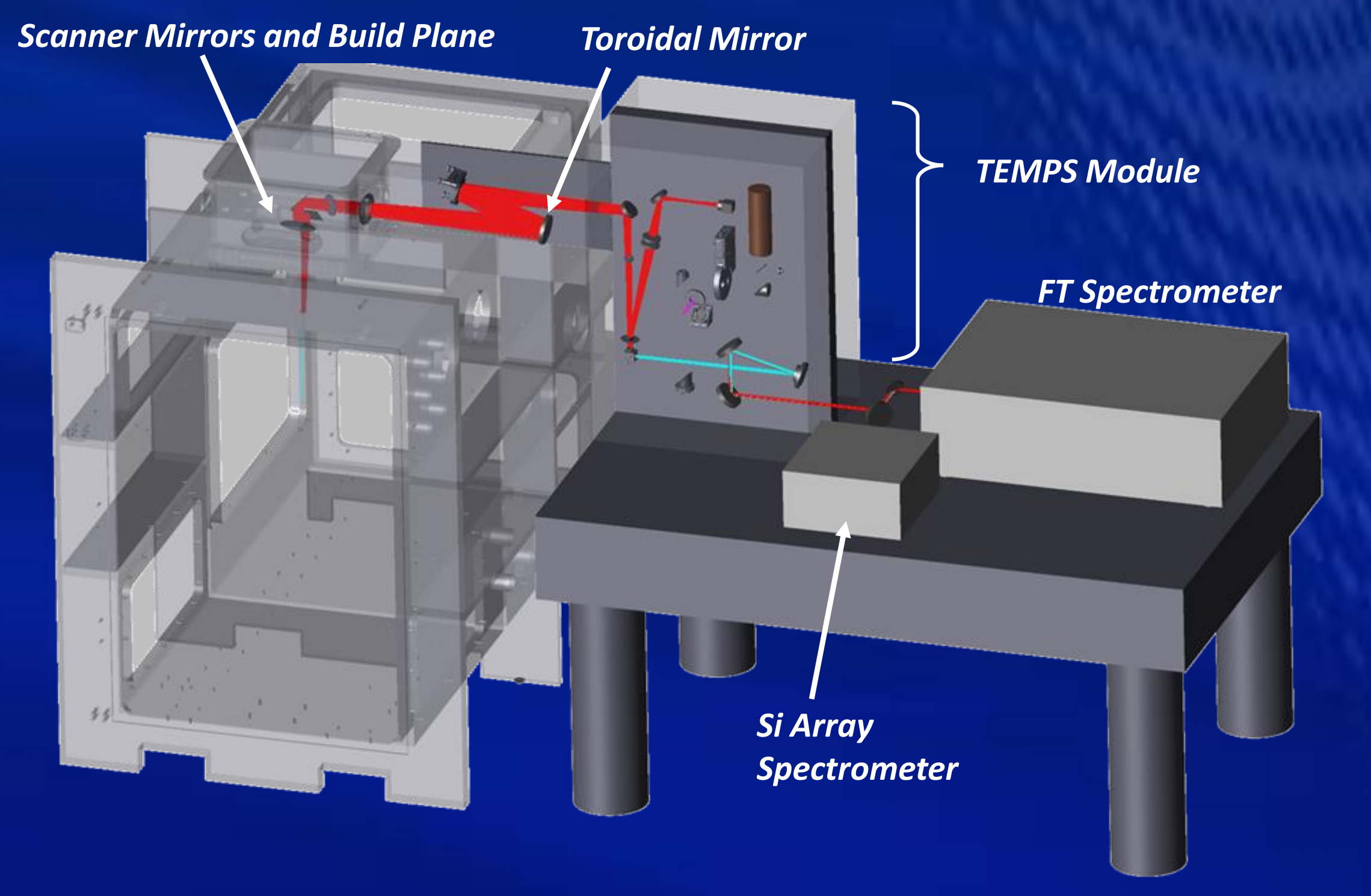
Key TEMPS Components:

Reflectometer, Standards and Radiometric Modules



Future Studies for Uncertainty Evaluation

- Imaging artifacts due to out-of-field scatter
- Temperature distribution across the FoV
- Plume, surface layer ablation, plasma absorption effects
- Thermodynamic equilibrium conditions

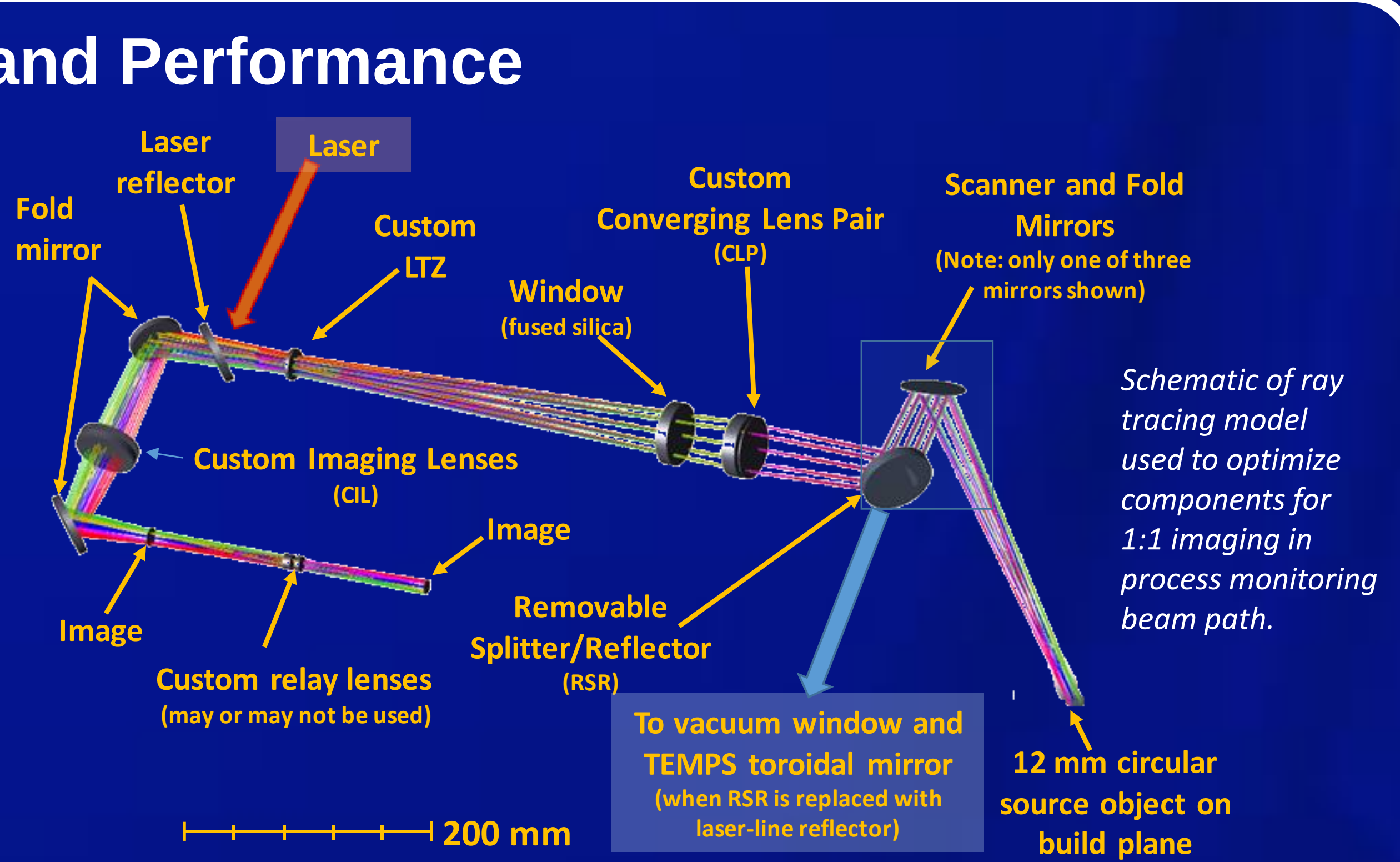


Radiometric Module and Light Path

AMMT Optical Path and Performance

The optical system for laser injection and in-line process monitoring within the system control module is shown on the top right diagram.

Imager is aligned co-axially with the laser to capture 'stationary' images of the melt pool.



Schematic of ray tracing model used to optimize components for 1:1 imaging in process monitoring beam path.

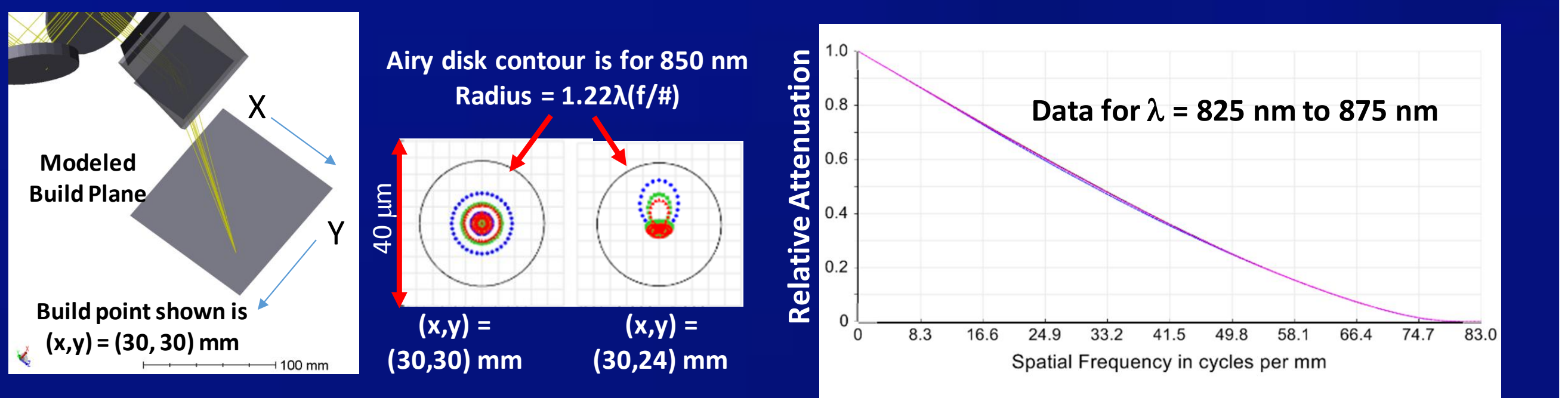
System Optimization

Objective: Optimize imager performance at 850 nm

Constraints: Attain <150 µm FWHM laser spot at 1070 nm

Variables: LTZ, CLP, and CIL lens curvature, glass type, distance

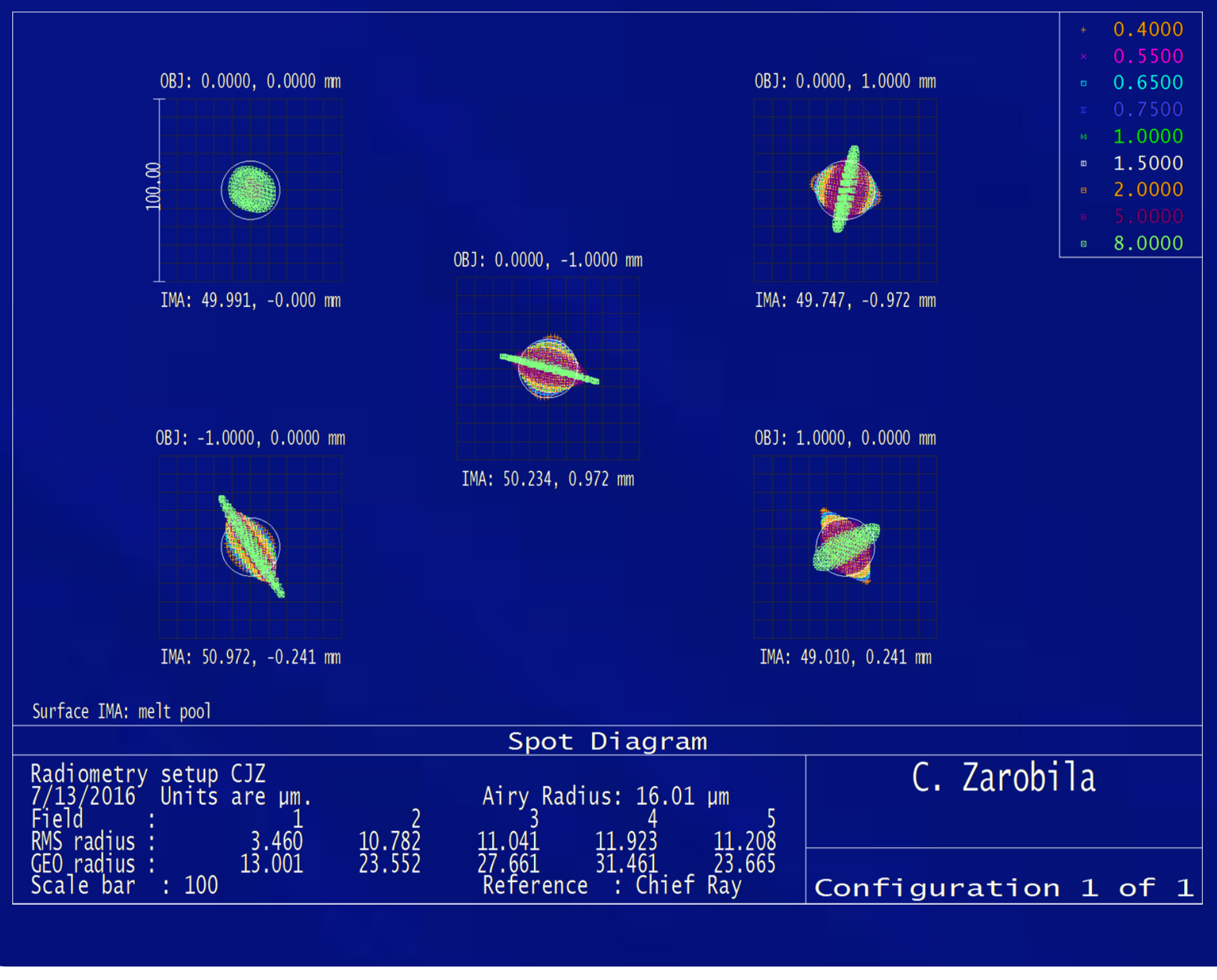
Result: MTF 64 cycle/mm



Left to Right: Coordinates in optical model, spot diagram for modeled imager performance, and modeled imager MTF estimating 64 cycle/mm resolution.

TEMPS Optical Path and Performance

- Reflective mirrors with protected silver coating to avoid chromatic aberrations
- diffraction limited performance on-axis over the full wavelength range (.38 µm to 10 µm)
- Near-diffraction limited performance over a 2 mm diameter field of view.



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Radiometry setup CJZ
7/13/2016  Units are µm.                Airy Radius: 16.01 µm
Field      :          1          2          3          4          5
RMS radius :      3.460     10.782     11.041     11.923     11.208
GEO radius :     13.001     23.552     27.661     31.461     23.665
Scale bar  : 100                 Reference  : Chief Ray
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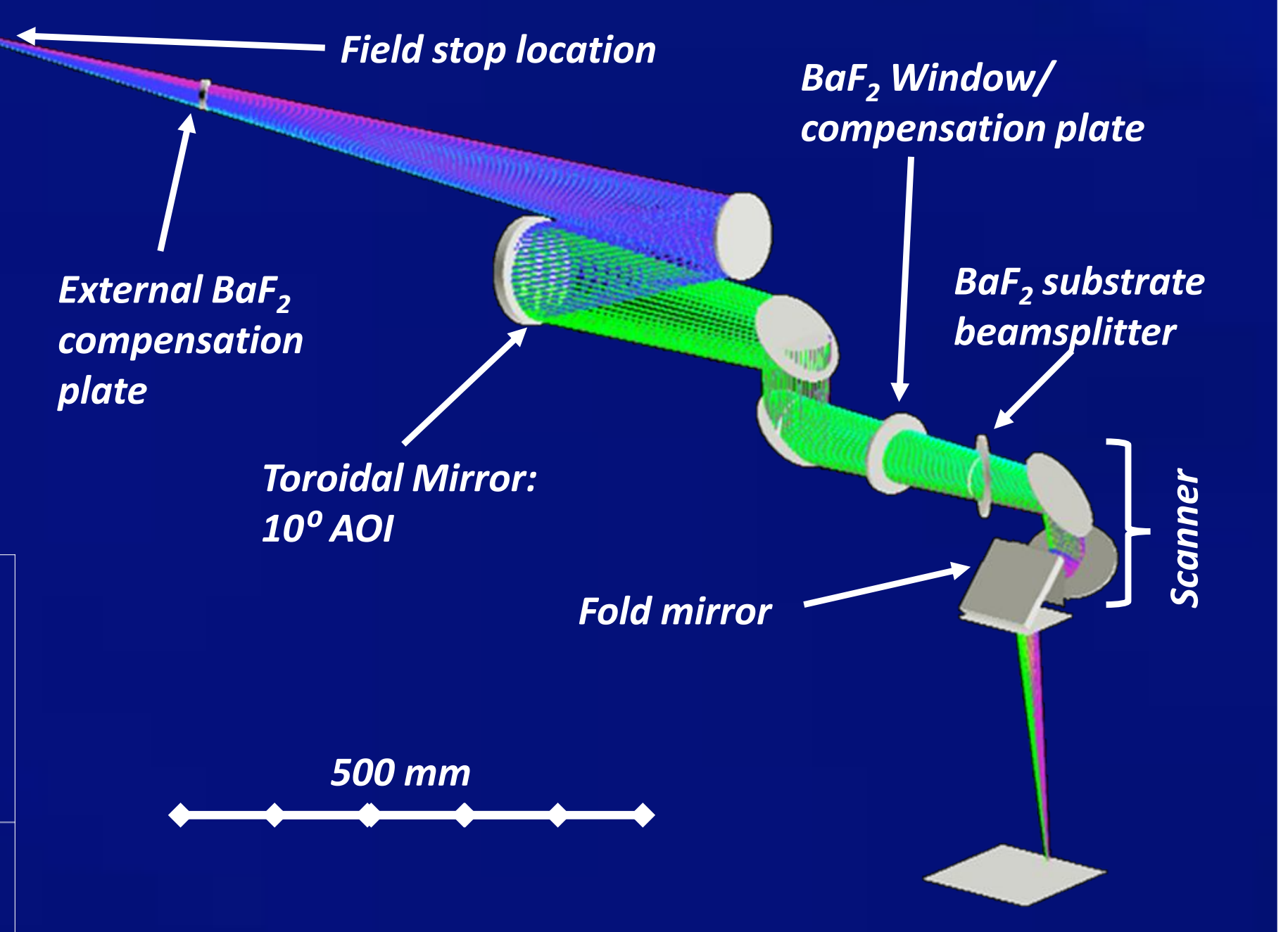

Three flat BaF_2 plates:

- nearest to the scanner acts as a beamsplitter with a front surface reflecting the fiber laser;
- The 2nd provides a gas seal and partial compensation for the chromatic aberration caused by the beamsplitter plate
- The 3rd provides the remainder of the chromatic aberration compensation.