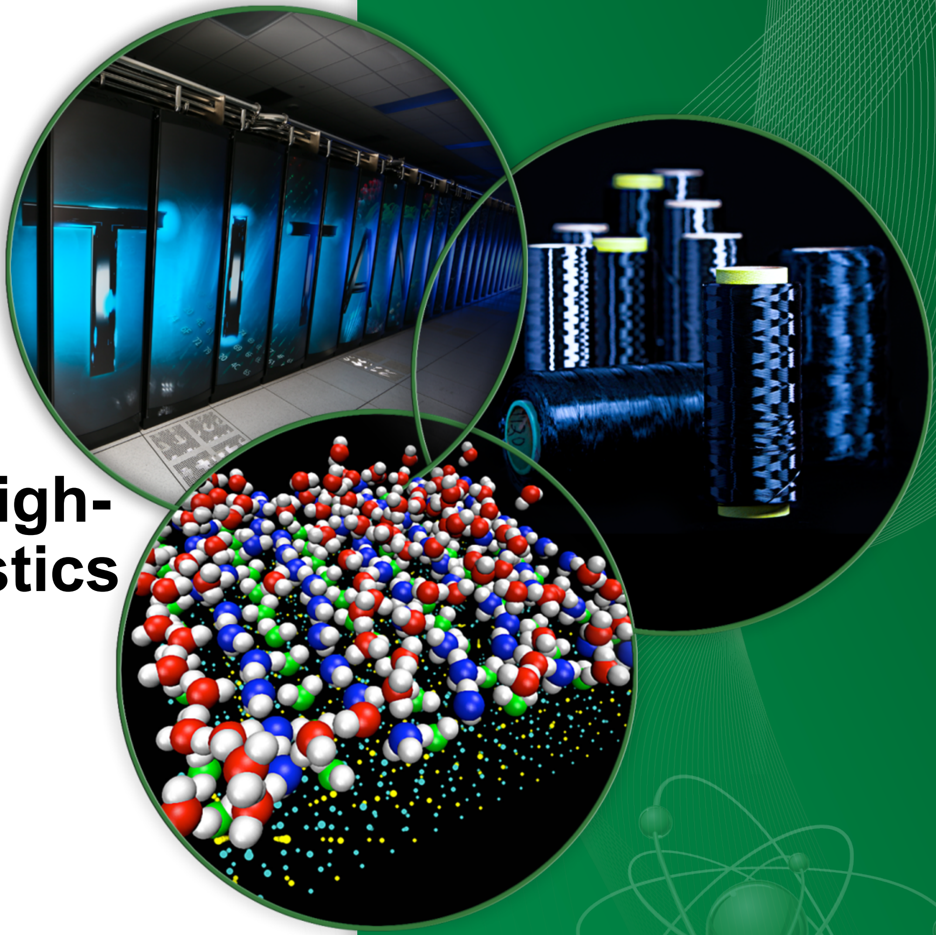
Initial Implementation of a Thomson Scattering Diagnostic for Proto-MPEX

2.2.15



Presented at the:

20th Topical Conference on High-Temperature Plasma Diagnostics

T.M. Biewer[1] and G. Shaw[1,2]

[1]*Oak Ridge National Lab.*

[2]*University of Tennessee-Knoxville*

June 1-5, 2014, Atlanta, GA, USA

ORNL is managed by UT-Battelle
for the US Department of Energy

THE UNIVERSITY of TENNESSEE UT
KNOXVILLE

OAK RIDGE
National Laboratory

Abstract

Thomson scattering (TS) of laser photons from plasma electrons is a relatively common diagnostic technique, utilized in fusion grade plasmas to measure electron velocity distribution functions (due to the Doppler shift imparted to scattered photons from moving electrons) and thereby infer electron temperature and density. In conjunction, Rayleigh scattering (RS) of laser photons from neutral particles can be measured to infer the neutral particle density in the same scattering volume as TS. Since the cross-section for TS (and RS, to a less severe extent) is extremely small, the TS "signal" photons must be discriminated from the "background" large number of injected photons from the laser. This is typically accomplished by minimizing laser background light with light baffling, choice of viewing geometry, beam polarization, and efficient beam dumping. Hence the vast majority of laser photons are not utilized, but are dumped. This laser power (or a fraction thereof) can be harnessed to enable additional laser based diagnostics, such as Laser Induced Break-down Spectroscopy (LIBS). TS, RS, and LIBS measurements can be accomplished with a single laser, if the LIBS impact is time-of-flight delayed relative to the TS and RS measurements.

Laboratory Directed Research and Development (LDRD) funds have been used at Oak Ridge National Laboratory (ORNL) to enable the initial installation of a laser based, Thomson scattering diagnostic on the prototype Material-Plasma Exposure eXperiment (Proto-MPEX). Since LDRD funds are limited in amount and duration, the initial TS system has followed a low cost design and rapid implementation. This paper will discuss the design elements of the initial TS configuration on Proto-MPEX and issues encountered during installation. Avenues of response to system limitations will be discussed, along with considerations for further optimization. The laser system will undergo reconfiguration to enable additional LDRD project milestones, e.g. LIBS.

Acknowledgements

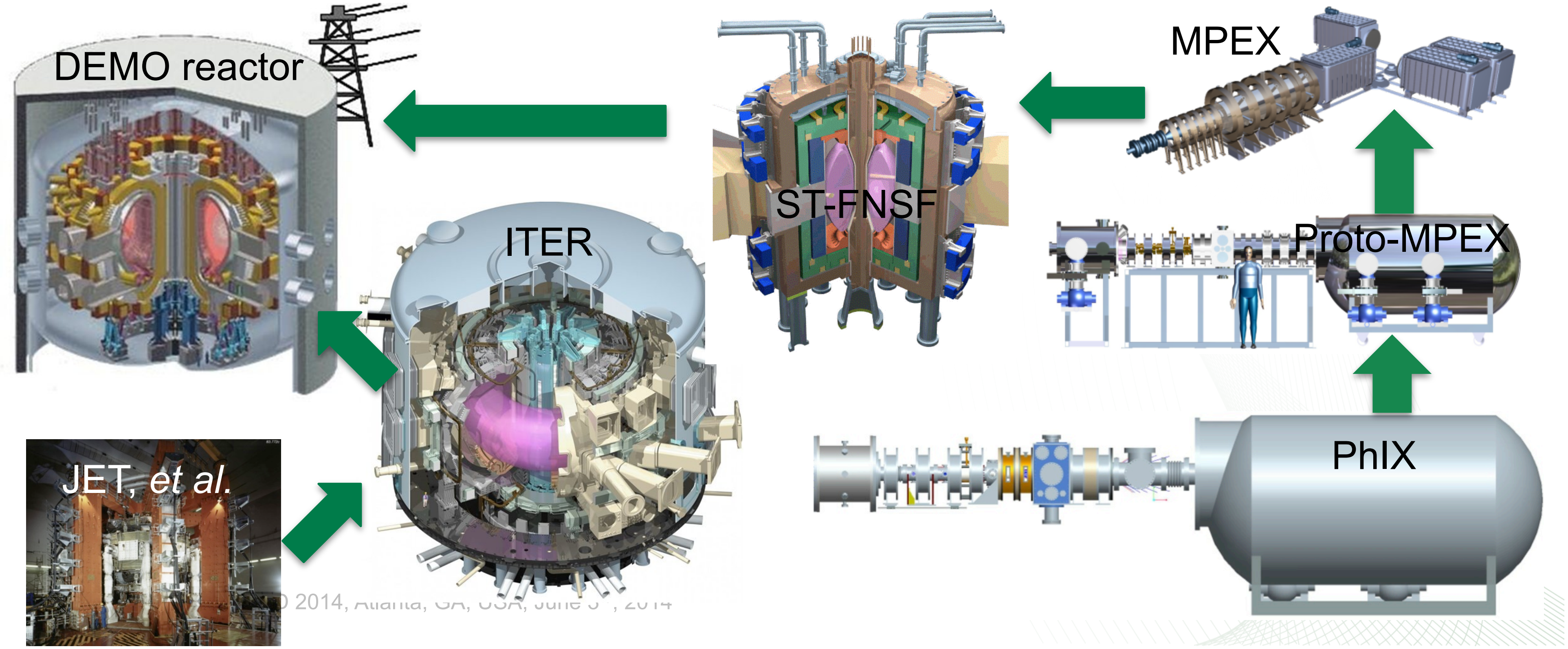
- The authors gratefully acknowledge the help of everyone that contributed to this effort.
- This work was supported by US. D.O.E. contract DE-AC05-00OR22725. Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy.
- Copies of this poster are available for download:
  - http://sprott.physics.wisc.edu/biewer/HTPD2014poster.pdf
- Or write your email address below:

Outline

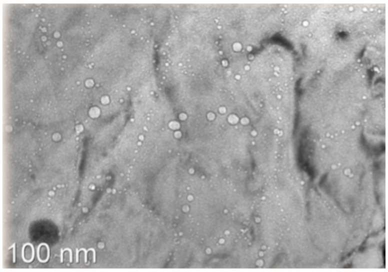
- Motivation for MPEX
  - Fusion Energy and the Plasma Facing Component (PFC) "gap"
  - Address with Plasma-Material Interaction (PMI) science
- Description of Proto-MPEX
- Laser Based Diagnostics on Proto-MPEX
  - Thomson & Raleigh Scattering
  - Laser Induced Break-down Spectroscopy
- Implementation of a Thomson Scattering Diagnostic on Proto-MPEX
- Summary and Future Work

Viable fusion energy source depends on solving “plasma facing component” gap

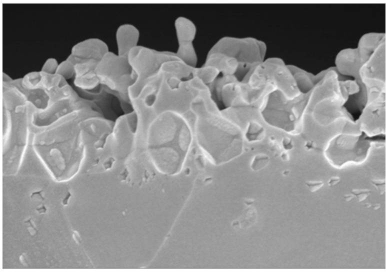
- Fusion needs a PFC solution, which motivates plasma material interaction (PMI) research.
- Research device trajectory (ORNL) for fusion energy:
  - DEMO (goal) ← ITER ← FNSF ← MPEX ← Proto-MPEX ← PhIX



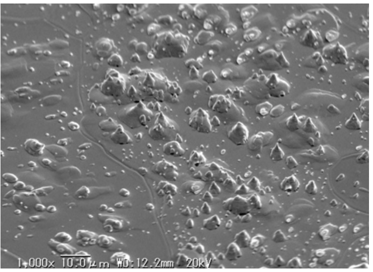
Plasma-Material Interactions



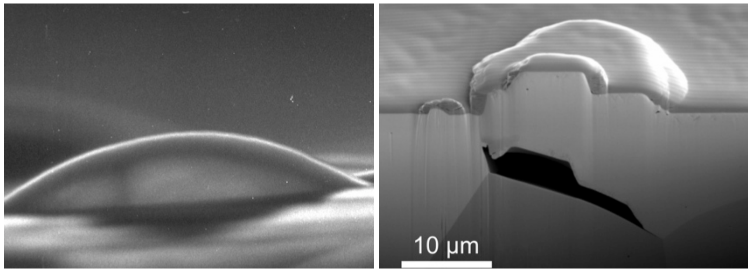
Void formation, 9 dpa



Bubbles in W by He



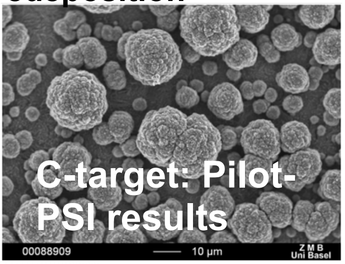
Blisters within grains



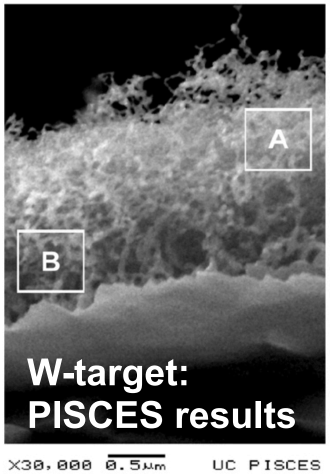
Large Blisters due to voids at grain boundary

- Fusion nuclear environment leads to structural modification of exposed surfaces.
  - Access to irradiated devices extremely limited.
- Even low-temperature plasmas can damage diagnostic probes.
- Reliable, *in-situ* diagnostic techniques needed for plasma measurements and material characterization.

Complex 3D structures form from erosion and redeposition



C-target: Pilot-PSI results



W-target: PISCES results

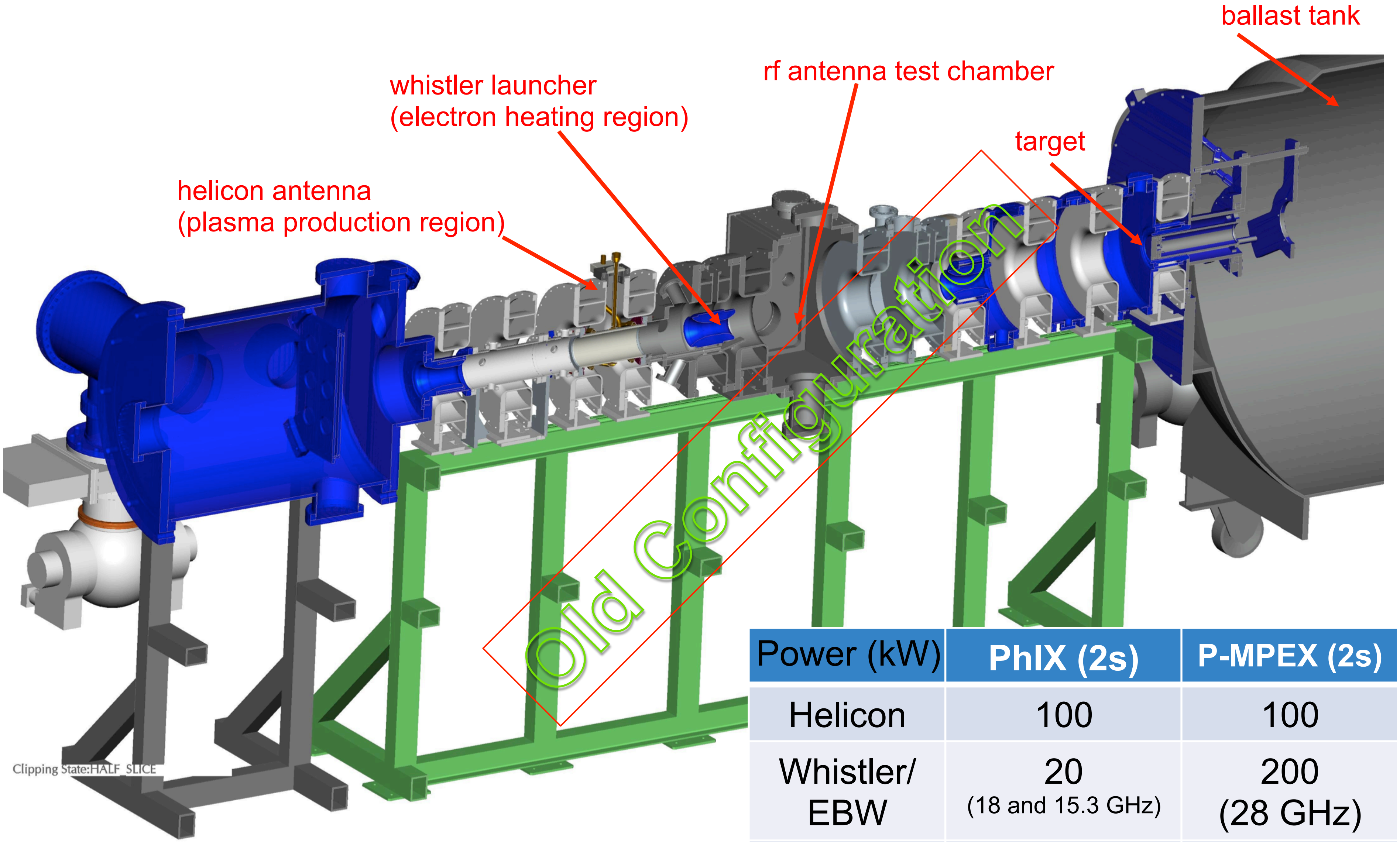
The harsh plasma/nuclear environment necessitates *in-situ*, non-invasive diagnostic techniques

- The high plasma density and temperature found in fusion relevant plasmas requires non-invasive diagnostics for plasma characterization
  - Problem: conventional probes for measuring fundamental plasma parameters burn up
  - Solution: laser-based techniques, such as Thomson scattering, are well-suited for this environment
- *In-situ* techniques for studying target material evolution during plasma exposure are needed
  - The change in material composition during plasma bombardment cannot be captured with *ex-situ* techniques
  - Material mixing and micro-structural changes as a function of time are expected to be important
  - Laser-based techniques (LIBS/LIAS/LIDS) offer many advantages

Research Objectives

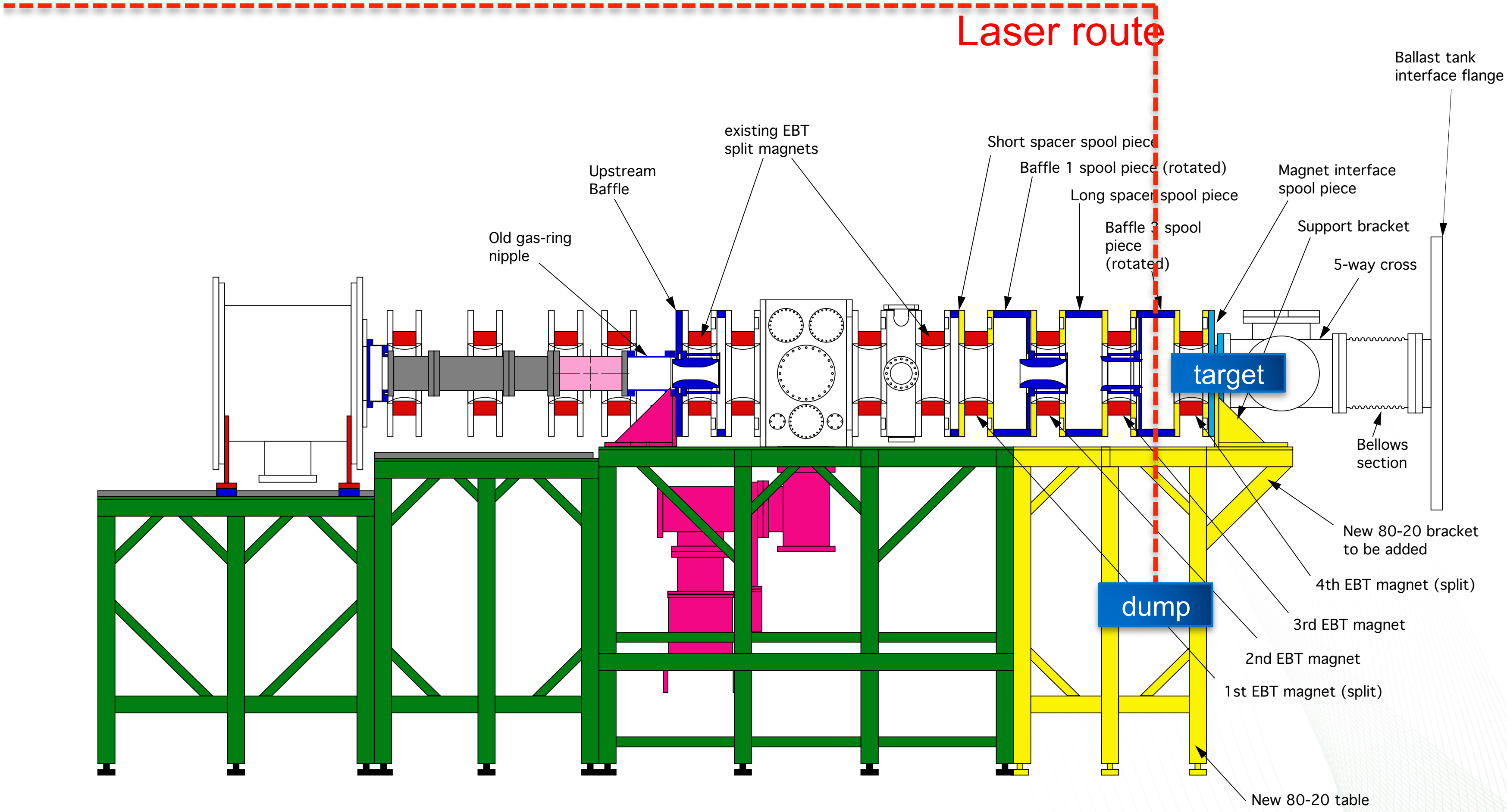
1. Install and operate Thomson Scattering system
   - Determine axial & radial profiles of electron density and temperature
2. Measure target surface erosion dynamics with *in-situ* LIBS technique
   - Determine changes in surface composition versus exposure time
3. Compare *in-situ* LIBS with *ex-situ* LIBS for calibration
   - Needed for detailed signal interpretation
4. Connect surface diagnostics results to Molecular Dynamics simulations
5. Plasma modeling (SOLPS) verification from TS measurements

Proto-MPEX upgrade in FY14

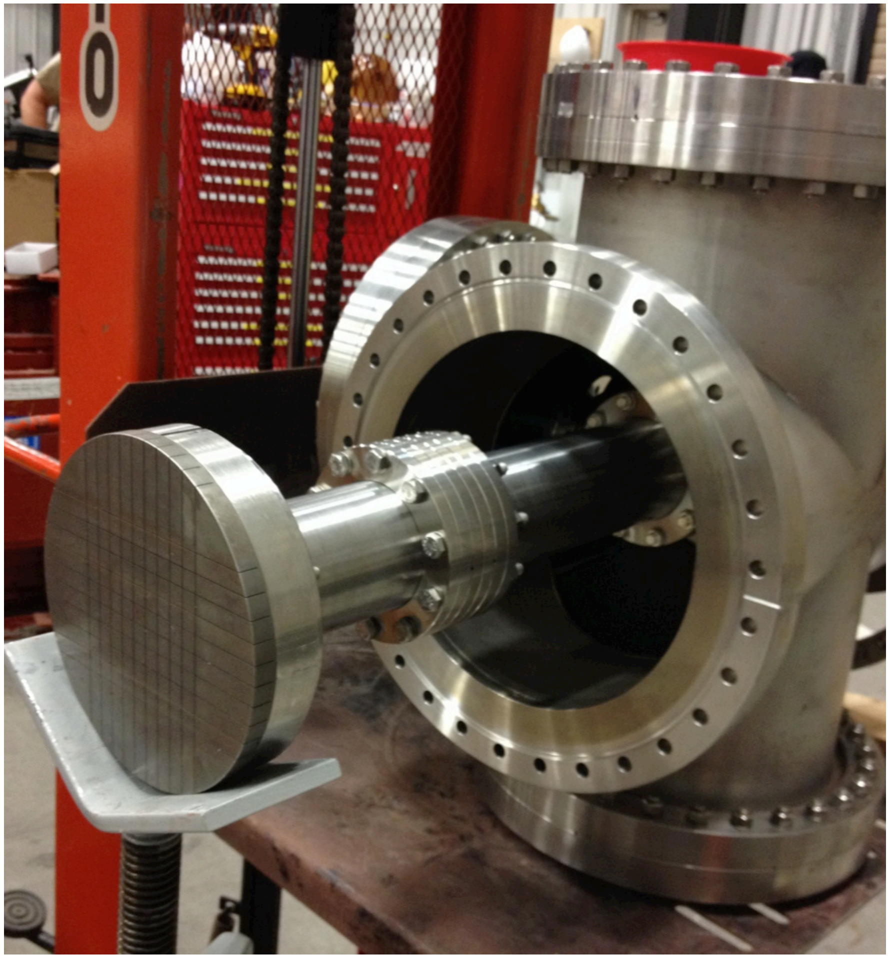


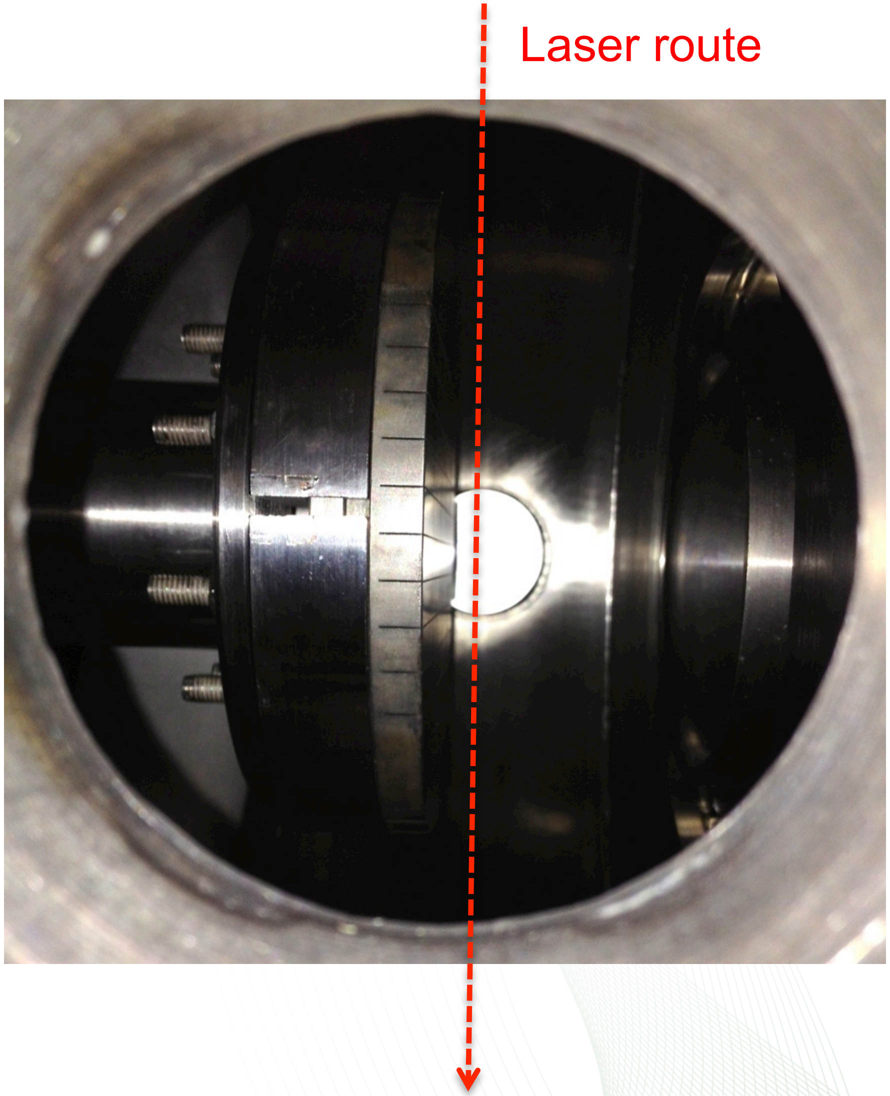
Power (kW)	PhIX (2s)	P-MPEX (2s)
Helicon	100	100
Whistler/ EBW	20 (18 and 15.3 GHz)	200 (28 GHz)
ICH		30 – 200
TOTAL	120	330 – 500

Layout for Proto-MPEX with measurements in plasma expected in ~July 2014



Proto-MPEX solid W target installed





Validate plasma models used in design of MPEX

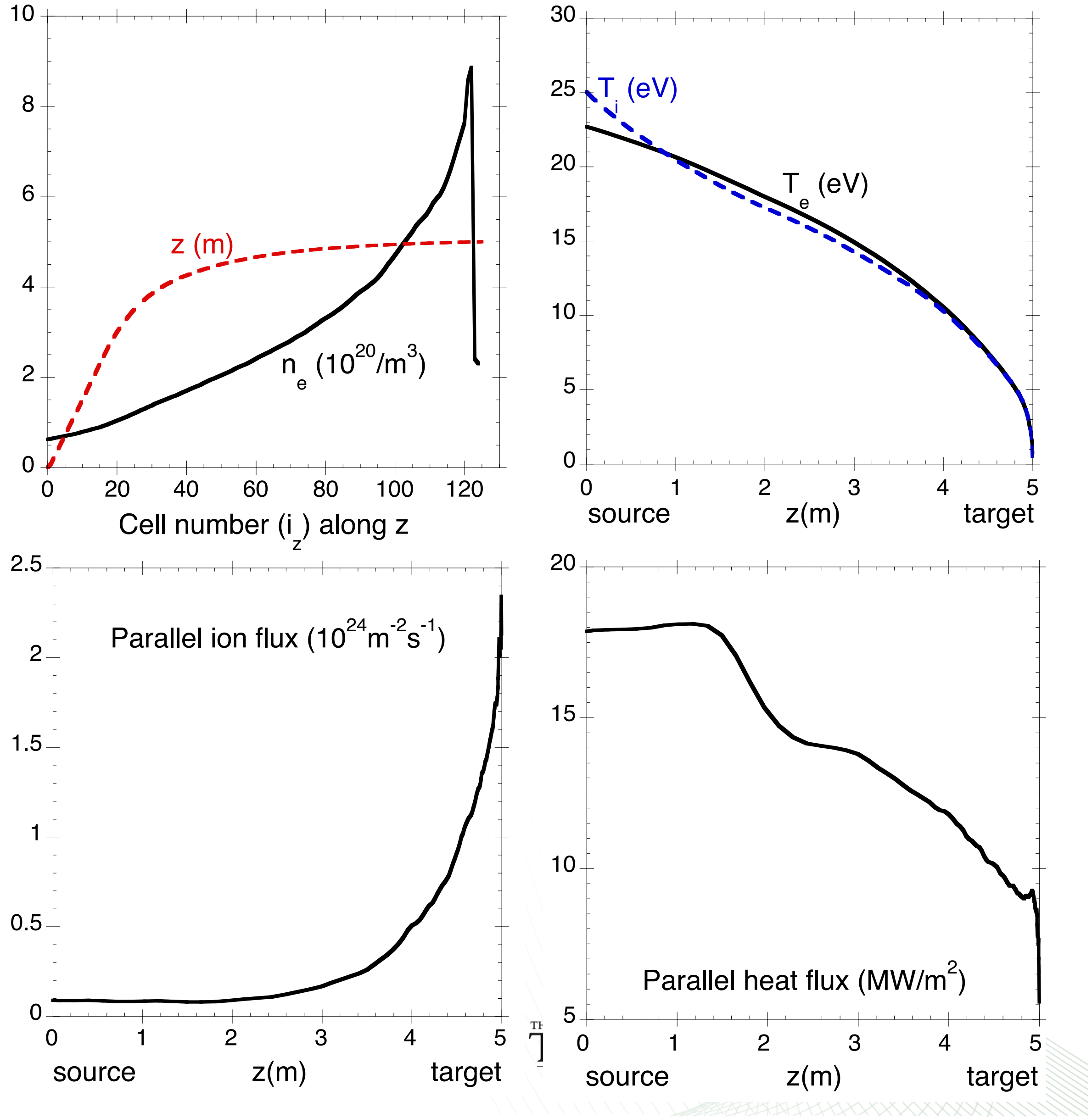
B2-Eirene: fluid model for plasma transport (B2) coupled to Monte-Carlo code for neutrals (Eirene)

ITER-relevant parameters appear feasible

- power fluxes of 10 MW/m^2
- ion fluxes of 10^{24} m^{-2}s^{-1},
- densities of ~ 10^{21} m^{-3}
- temperatures of 1 – 2 eV

Achieving these parameters depends critically on the “strength” of the axial gradients as the plasma reaches the target.

<u>Need TS measurements!</u>



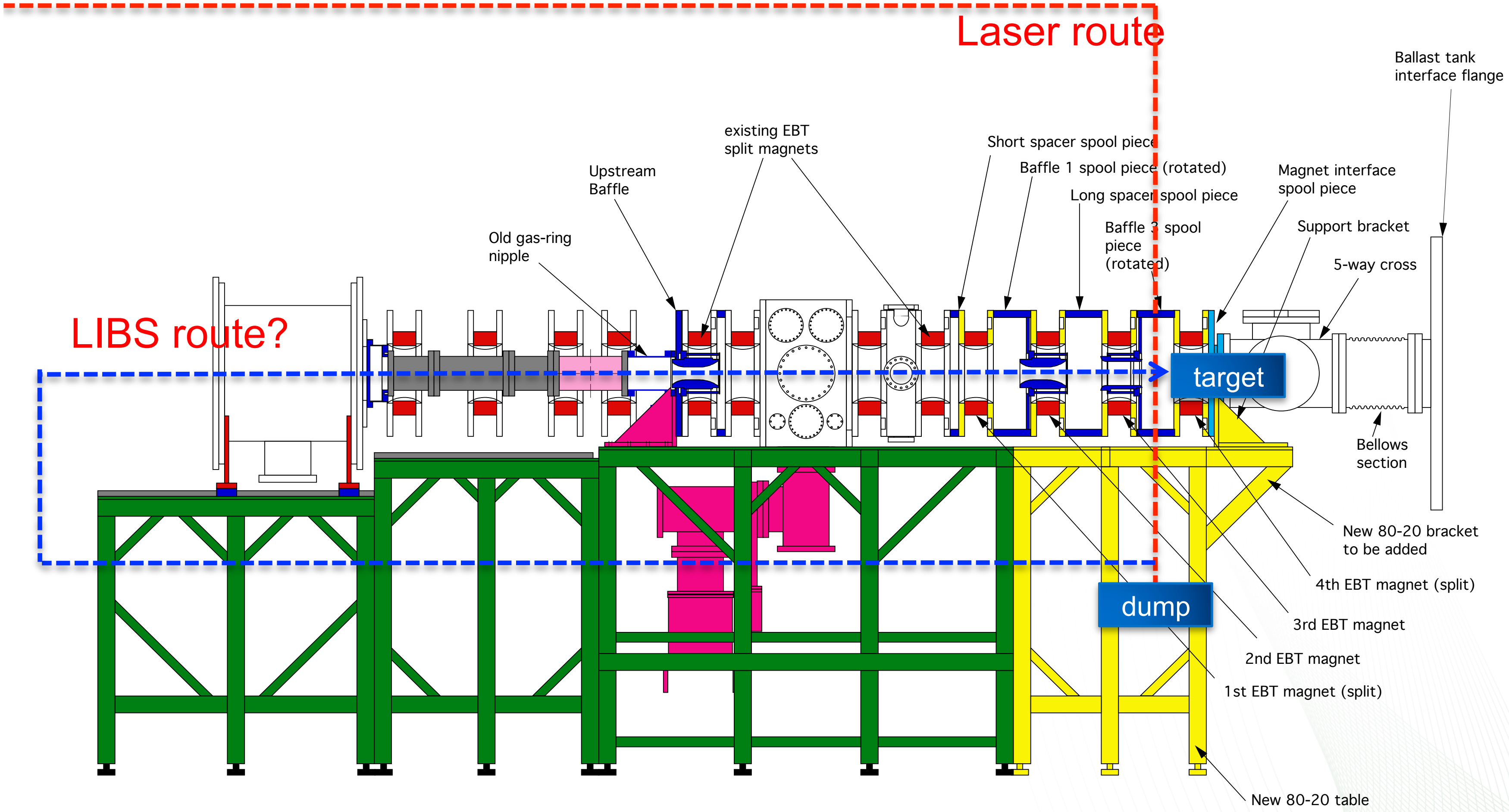
Non-invasive laser scattering for plasma diagnosis will be used

- Thomson Scattering: laser light scatters off (plasma) e^-; measured spectrum representative of electron velocity distribution: density (n_e), temperature (T_e)
- Rayleigh Scattering: laser light scatters off neutral gas; measured spectrum representative of neutral gas density (n_0)
- High-powered Nd:YAG laser common to both, frequency doubled to 532 nm to bring measurements into visible range.
- F&MNSD owns iCCD camera, high-throughput transmission grating spectrometer, gratings, other hardware.
- Need high-powered Nd:YAG laser ($120k budgeted in FY13)
- Axial and radial n_e, T_e profiles are possible.

Laser probe for *in-situ* surface diagnosis will be used.

- A high-powered laser (i.e. the Nd:YAG also used for TS measurements) can be utilized for *in situ* characterization of material surfaces.
- Laser Induced Break-down Spectroscopy (LIBS)
  - With or without B-field, the laser pulse vaporizes sample surface <u>and</u> forms a plasma from the resulting gas, emitting light which is observed to characterize the constituents of the (vaporized) sample.
- Laser Induced Ablation Spectroscopy (LIAS)
  - Similar to LIBS, but with external plasma source (i.e. PhIX).
- Laser Induced Desorption Spectroscopy (LIDS)
  - Similar to LIAS, but with laser pulse spread-out in time so that sample surface is locally heated rather than vaporized.
- LID-Quadrupole Mass Spectroscopy (LID-QMS)
  - Similar to LIBS/LIDS, but with Residual Gas Analysis (RGA) replacing optical spectroscopy; sample line-of-sight not required.

Potential layout for LIBS beam to enable t.o.f. delay relative to TS measurement



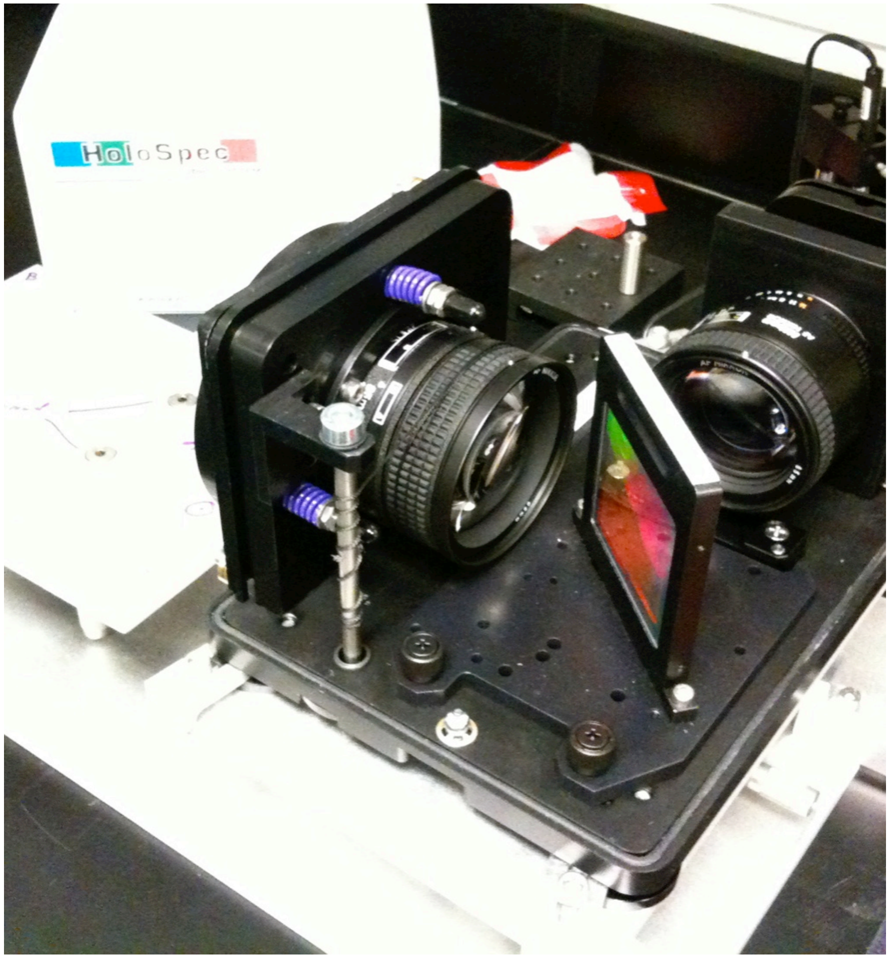
Ex-situ LIBS key to *in-situ* characterization

- *In-situ* LIBS/LIDS/LIAS/LID-QMS . . . measurements can be directly compared to *ex-situ* LIBS/etc. measurements.
  - LIBS laboratory available for measurements in Biosciences Division at ORNL; included in LDRD proposal.
- *Ex-situ* LIBS measurements can be compared to more detailed *ex-situ* characterization methods, e.g. electron microscopy, depth profiling, positron annihilation spectroscopy, etc.
  - Surface analysis capability in Materials Science Division.
- Links PMI science in Proto-MPEX to world-leading surface analysis at ORNL.

LDRD benefited from "early" purchase of high energy laser.

- Newport (Spectra Physics) Quanta Ray Pro 350 (10 Hz)
- Nd:YAG laser purchase accelerated into FY13 LDRD close-out funds.
- Motivated dedicated lab space, and cut "wait time."
- Has been delivered and staged; water, power, N_2, and "safety" in progress.
- "Highest energy laser at ORNL." (~1.4 J at 532 nm)

Spectrometer available at ORNL



- Kaiser Optical Systems: Holospec f/1.8 (~$7k)
- Short focal length (curved image plane).
- Transmission grating, high throughput, fixed wavelength
  - "low" dispersion: ~$3k
  - "high" dispersion: ~$7k
- 85 mm input lens
- 85 or 58 mm output lens (have), also 50 mm lens at JET
- Mounting hardware (have)

CCD cameras at ORNL

ICCD: PI PIMAX3, 1024

- Bought for this purpose
  - 45% QE at 532 nm: Gen III, $47k
- 2 ns minimum exposure
- 13 micron pixel, 13 mm chip
  - 85 mm lens
    - 10x 1 mm fiber
    - 17x 600 micron fiber
  - 58 mm lens
    - 15x 1 mm fiber
    - 25x 600 micron fiber

EMCCD: PI PhotonMAX 512b

- Returned from Tore Supra
- 95% QE at 532 nm
- 1.5 ms minimum exposure
- 16 micron pixel, 8 mm chip
  - 85 mm lens
    - 7x 1 mm fiber
    - 11x 600 micron fiber
  - 58 mm lens
    - 10x 1 mm fiber
    - 17x 600 micron fiber

Available fiber bundles

2x10, "low disp", 1 mm fibers

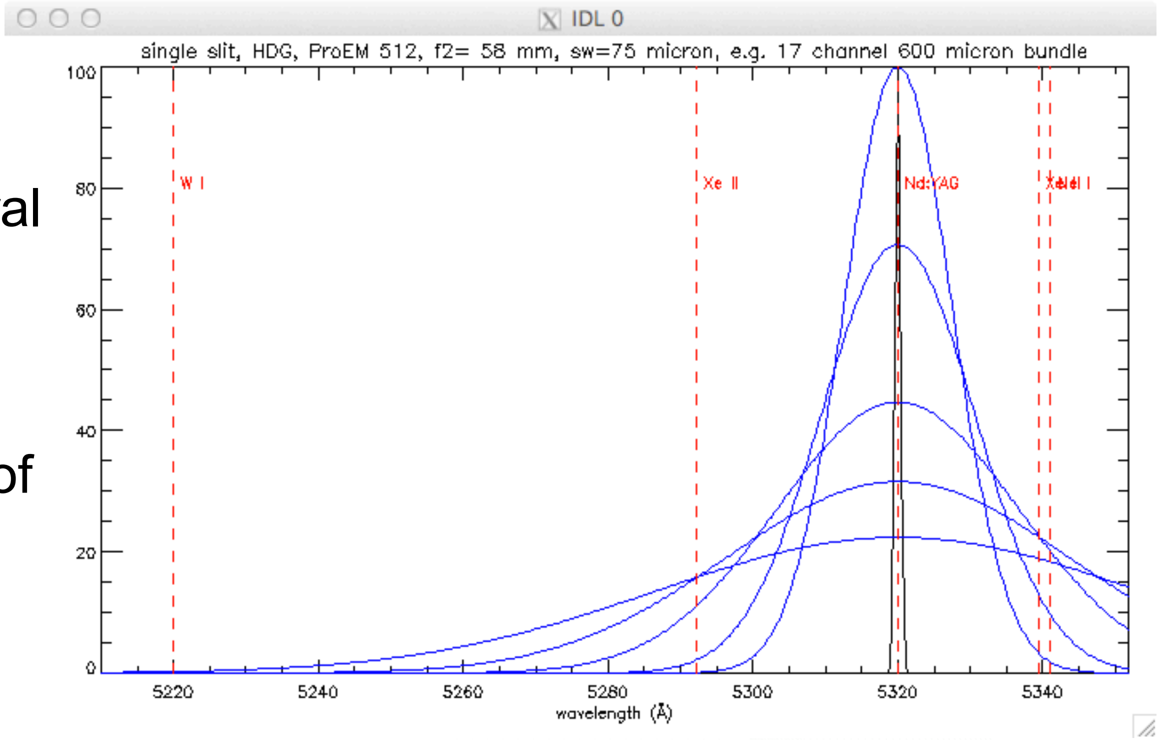
- Returned from JET (in storage for 2+ years)
- Entrance slits: 150, 250, 400 microns
- 2m long, SMA termination
- 532 nm "HSG" grating ~$3k
- Need (else 10 channels only) narrow BP filter to separate 2 columns ($3k?)
- 3x more light/channel (1mm v. 0.6 mm)

1x17, "high disp", 0.6 mm fibers

- To be fabricated for purpose.
- Entrance slits: 75, 150, 250 microns
- 7m long, SMA termination
- 532 nm "HDG" grating ~$7k

TS spectral simulation

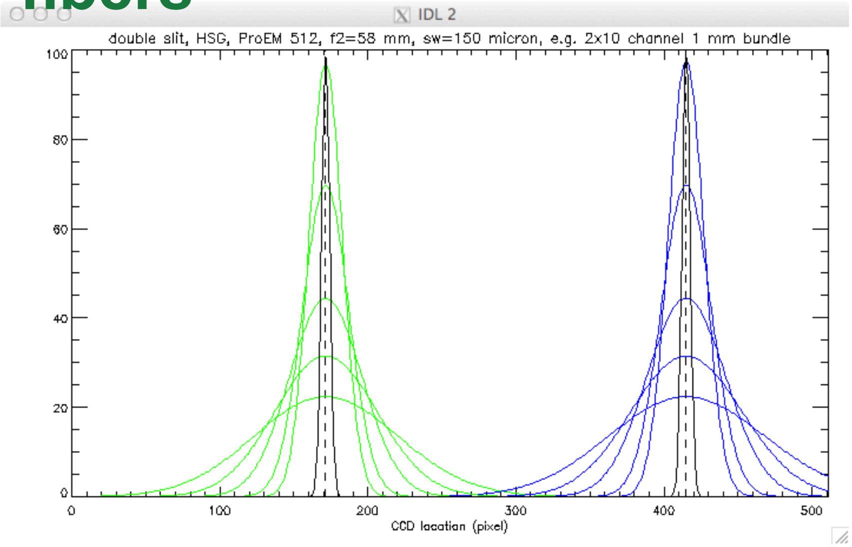
- Xe I "pen lamp" lines convenient for calibration
- W I (522 nm) within spectral range (simultaneous OES measurement)
- Realistic instrument function represents width of neutral (Rayleigh) scattering peak in TS spectrum.



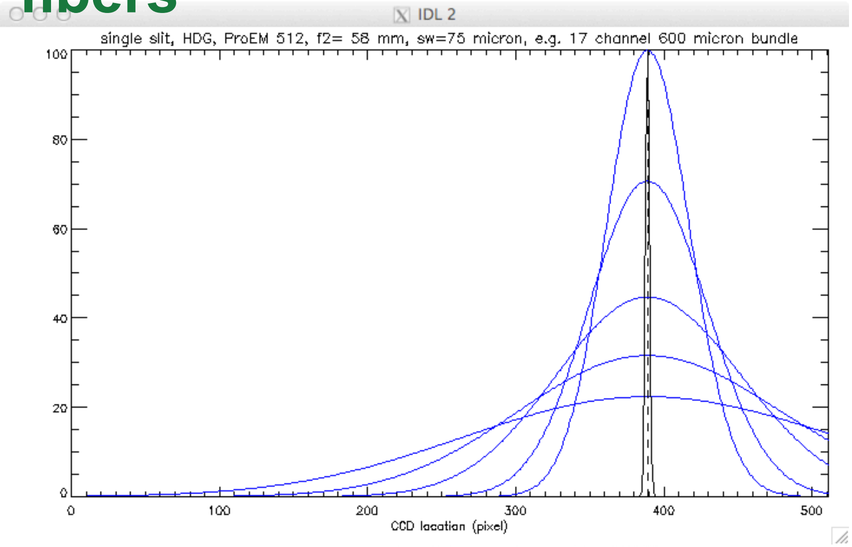
- T_e spectra (blue) for 1, 2, 5, 10, 20 eV at constant n_e

Multi-channel design reduces cost

2x10, “low disp”, 1 mm fibers

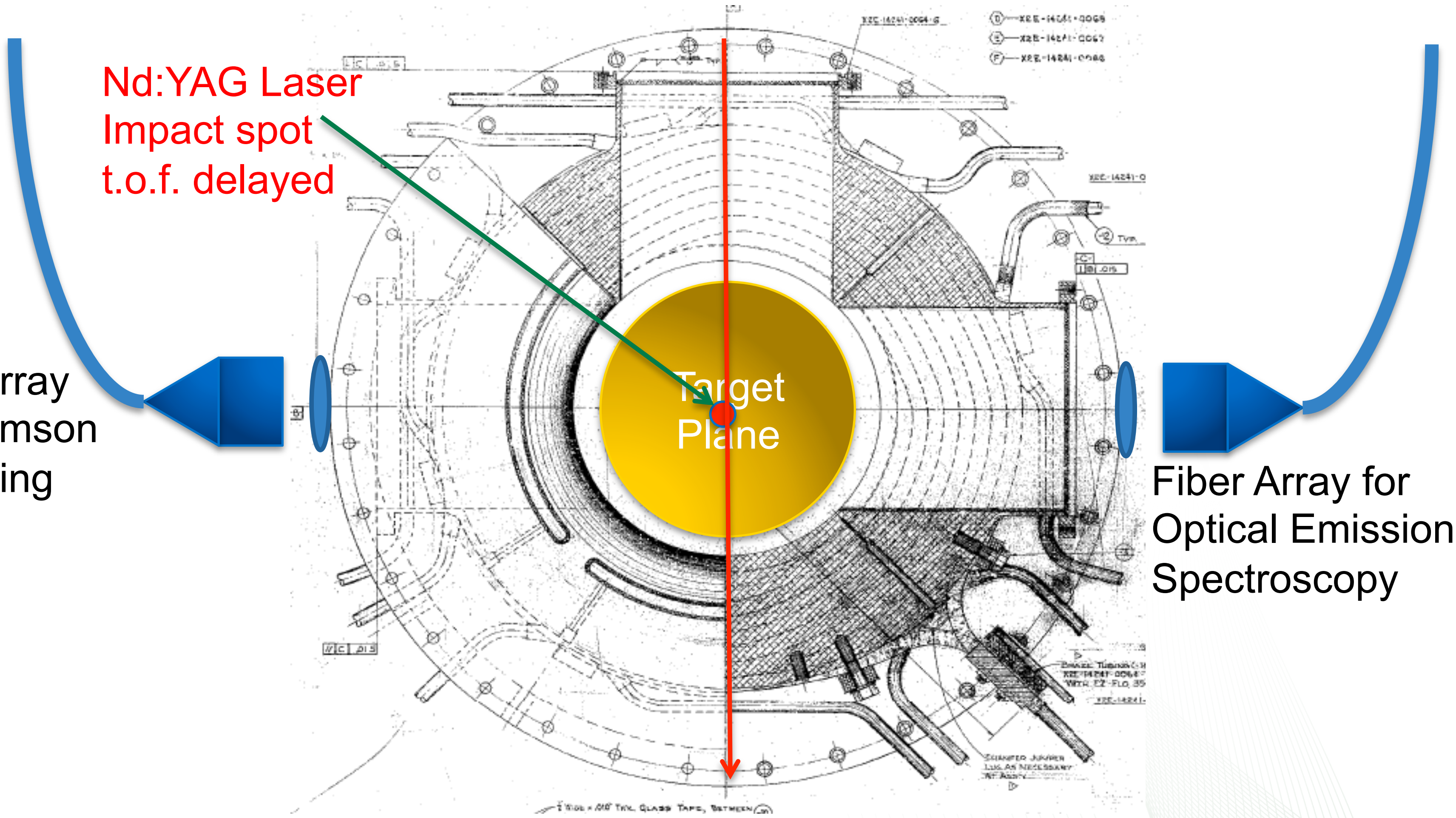


1x17, “high disp”, 0.6 mm fibers



- Figures show the simulated spectra on the image plane (CCD chip), utilizing the detection hardware described on the previous slide.
- Nd:YAG laser line (black) convolved with realistic instrument function
- TS spectra (green & blue) for 1, 2, 5, 10, & 20 eV plasmas at constant (arb.) e^- density

Observation geometry for TS and LIBS?



Nd:YAG beamline

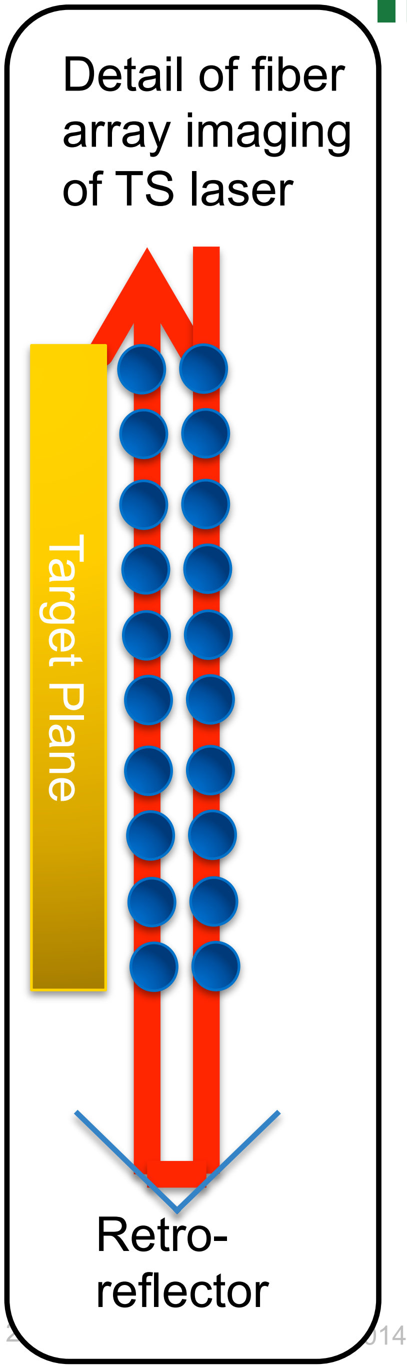
Nd:YAG Laser
Impact spot
t.o.f. delayed

Fiber Array
for Thomson
Scattering

Target
Plane

Fiber Array for
Optical Emission
Spectroscopy

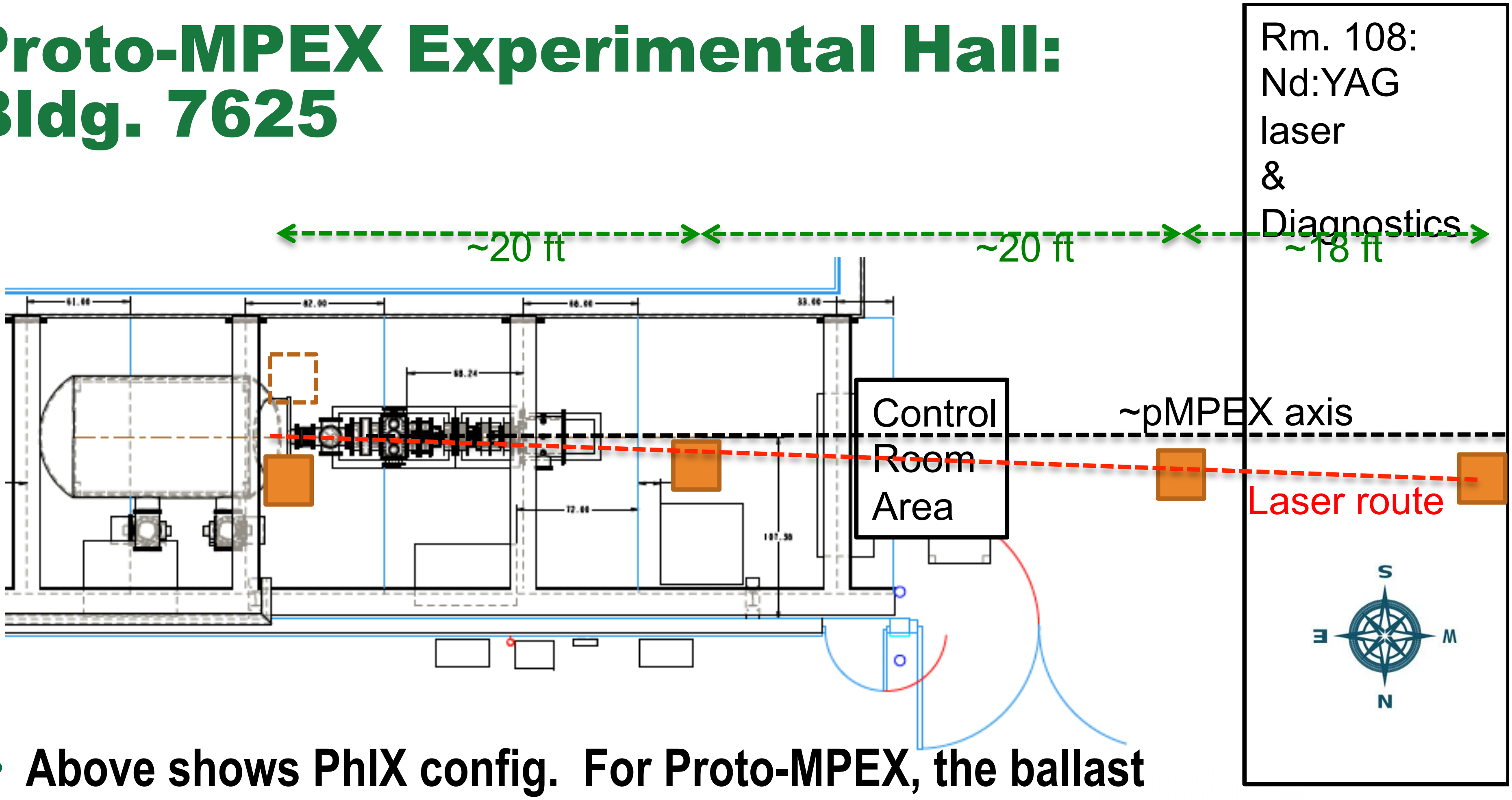
Innovative & Low Cost Design



Detail of fiber array imaging of TS laser

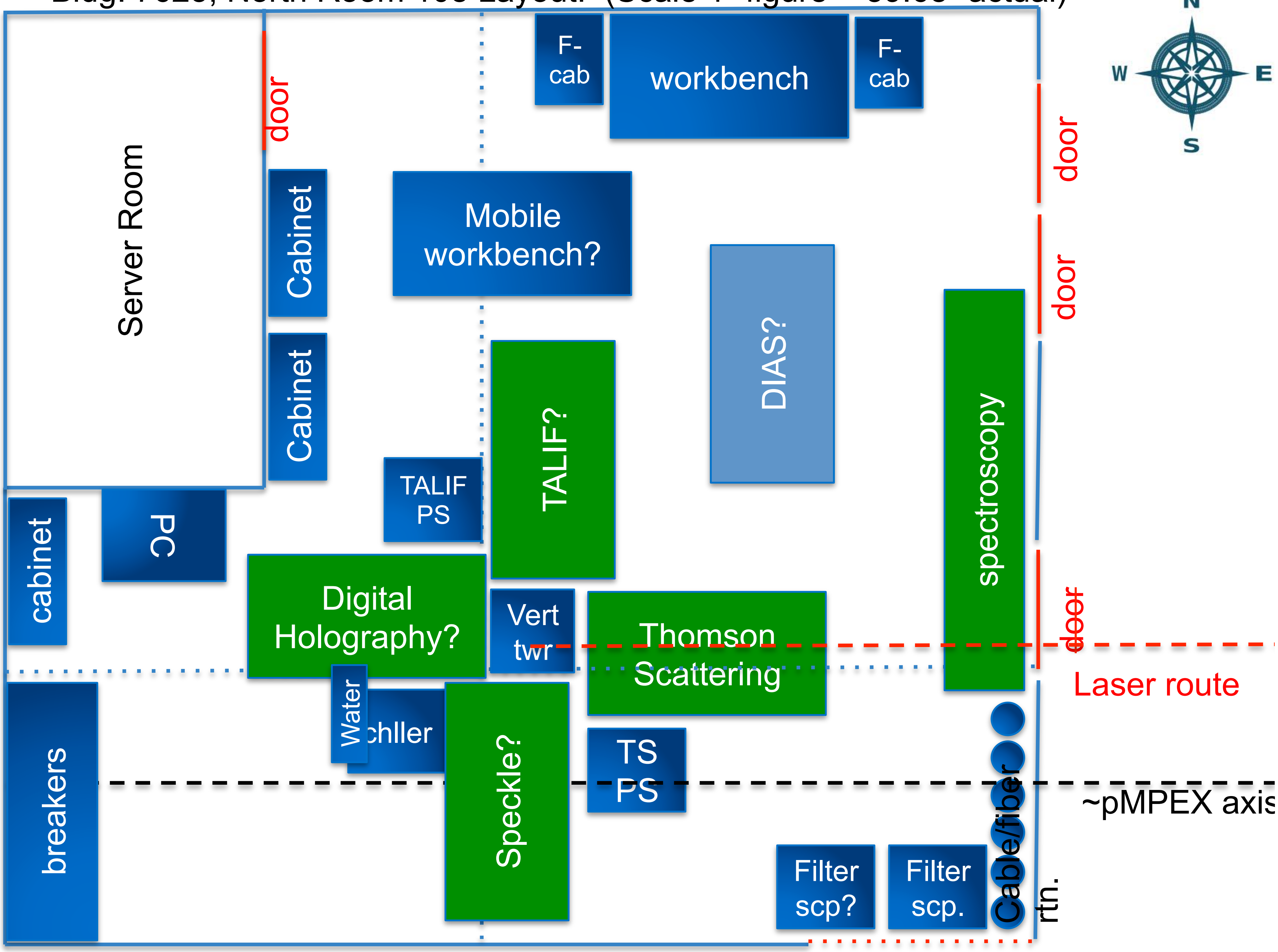
- Double passing an off-set Nd:YAG laser allows for “true,” simultaneous (~1 ns) 2D TS measurements of n_e, T_e, n_0
  - “2D TS” at C-Mod utilized beam steering between laser pulses (20 ms bet. pulses)
  - “2D TS” at ASDEX utilized 6 radial staggered lasers, fired sequentially (2 μs bet. pulses)
- Accomplished on a single spectrometer & detector eases alignment/calibration and reduces cost
  - “2D TS” at C-Mod utilized 6 spectrometers
  - “2D TS” at ASDEX utilized 16 spectrometers and 6 lasers

Proto-MPEX Experimental Hall: Bldg. 7625



- Above shows PhIX config. For Proto-MPEX, the ballast tank moves to the east ~2ft. Target plane approximate.
- 2x2 ft tower footprints shown in orange.
- **Red laser route** for vertical Proto-MPEX crossing; east-most tower may need to be a “bridge.”

Bldg. 7625, North Room 108 Layout: (Scale 1” figure = 39.68” actual)



Towers 1 – 4 “installed”

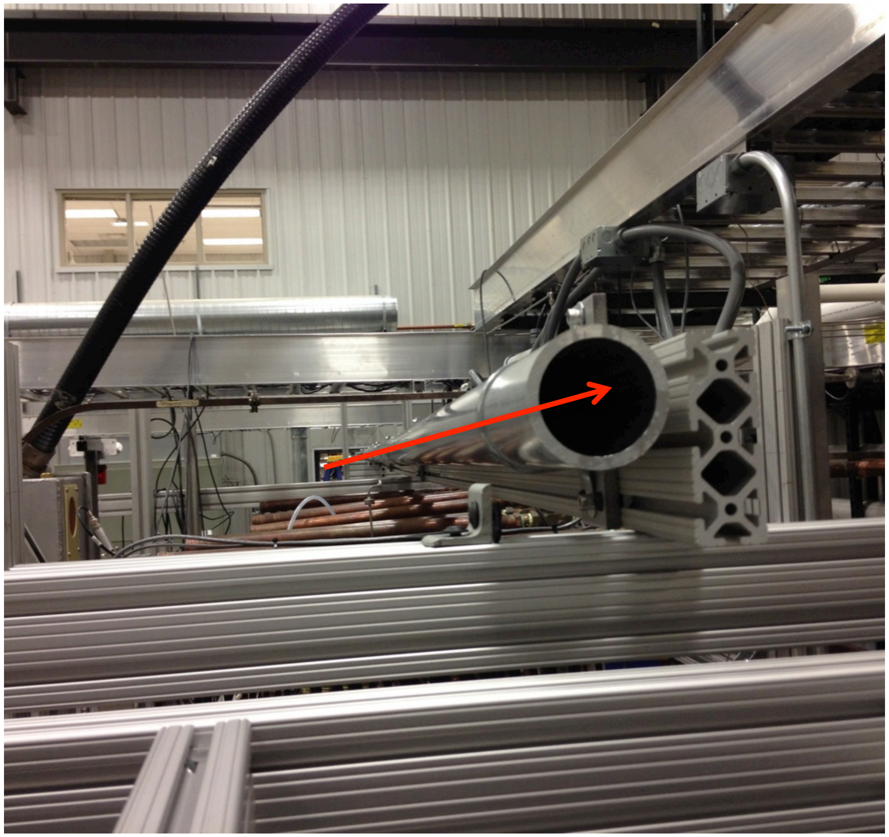
Tower 1 in laser room

Tower 2 (pre-revision)

Tower 3 (pre-revision)

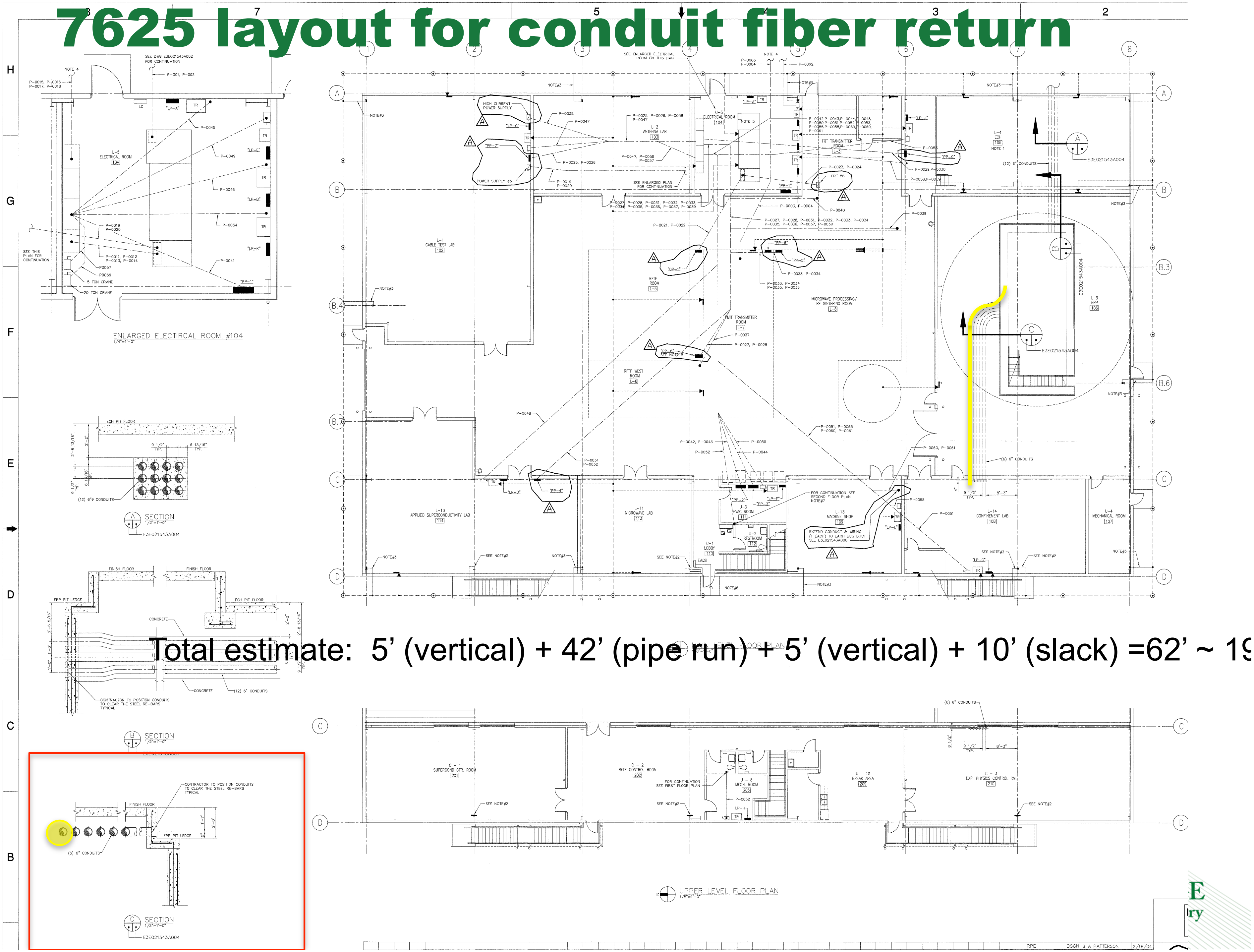
HeNe beam delivered to target plane

YAG beam enclosure pipe installed and "aligned" over 60 ft.



Tower 4: HeNe spot arrives at vertical turn (to traverse Proto-MPEX)

7625 layout for conduit fiber return



Total estimate: 5’ (vertical) + 42’ (pipe run) + 5’ (vertical) + 10’ (slack) =62’ ~ 1

Research Objectives (from LDRD pitch)

1. Install and operate Thomson Scattering system
   - Determine axial and radial profiles of electron density and temperature
2. Measure target surface erosion dynamics with *in-situ* LIBS technique
   - Determine changes in surface composition versus exposure time
3. Compare *in-situ* LIBS with *ex-situ* LIBS for calibration
   - Needed for detailed signal interpretation
4. Connect surface diagnostics results to Molecular Dynamics simulations
5. Plasma modeling (SOLPS) verification from TS measurements

Roles of the Research Team (mod)

- T. Biewer: PI; project management, TS installation
- J. Caughman, R. Goulding: Proto-MPEX operation
- M. Martin, R. Martin, K. Leonard: *ex situ* surface analysis & guidance on *in situ* LIBS implementation
- J. Rapp, J. Lore: PMI guidance and plasma modeling
- B. Wirth, G. Shaw: MD simulations + experimental work for PhD thesis
- Budget:
  - FY13 $141k: $120k Nd:YAG, $21k staffing
  - FY14 $236k: $25k hardware, $201k staffing, $10k travel
  - FY15 $363k: $25k hardware, $328k staffing, $10k travel

Summary (from LDRD pitch)

- Actualizing magnetic fusion as an energy source requires solutions to the plasma facing component "gap" due to plasma-material interaction effects.
- ORNL has invested in a strategy (mainline tokamak plasma physics research) of unique linear plasma sources to test PMI and PFC.
  - PHIX ➔ Proto-MPEX ➔ MPEX ➔ FNSF ➔ ITER ➔ DEMO
- *In situ*, laser based diagnostics are needed for plasma and material surface characterization on Proto-MPEX. (This work)
- FY14 Goals: Utilize high-powered Nd:YAG laser for: 1) multi-channel TS & RS measurements of n_e, T_e, n_0 of plasma, 2) LIBS implementation for *in situ* material surface measurements.
- FY15 Goals: Expose material surface to quantified plasma flux in Proto-MPEX and compare *in situ* LIBS data to *ex situ* LIBS data and other detailed analysis; comparison of MD simulation models and verification of plasma simulation models.

Current activities

- Modifying lab space RSS for “Class 4” laser ops.
- Writing Standard Operating Procedures.
- Writing Alignment Procedures.
- Seek approval for Work Plan to enable Vendor “installation” of Nd:YAG, including water, air, power.
- Aiming [pun intended] to have laser operational for TS measurements in Proto-MPEX “first plasma” July 2014.
- Transition to LIBS attempt ~Fall 2014.

Reprints

- Copies of this poster are available online:
  - http://sprott.physics.wisc.edu/biewer/HTPD2014poster.pdf
- Or, write your name and email address below: