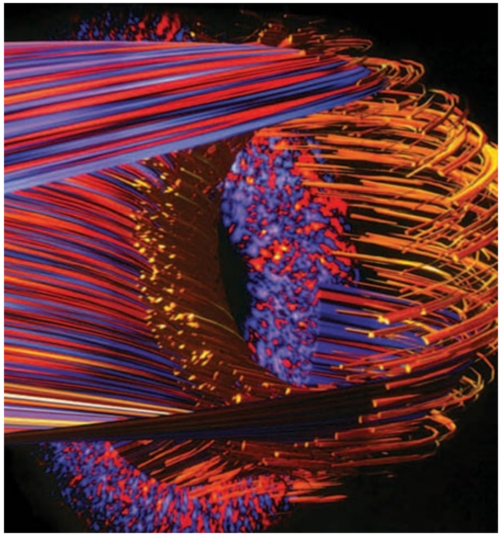
FSP Science Drivers



Presented by Martin Greenwald on behalf of FSP Team

Fusion Simulation Project PAC

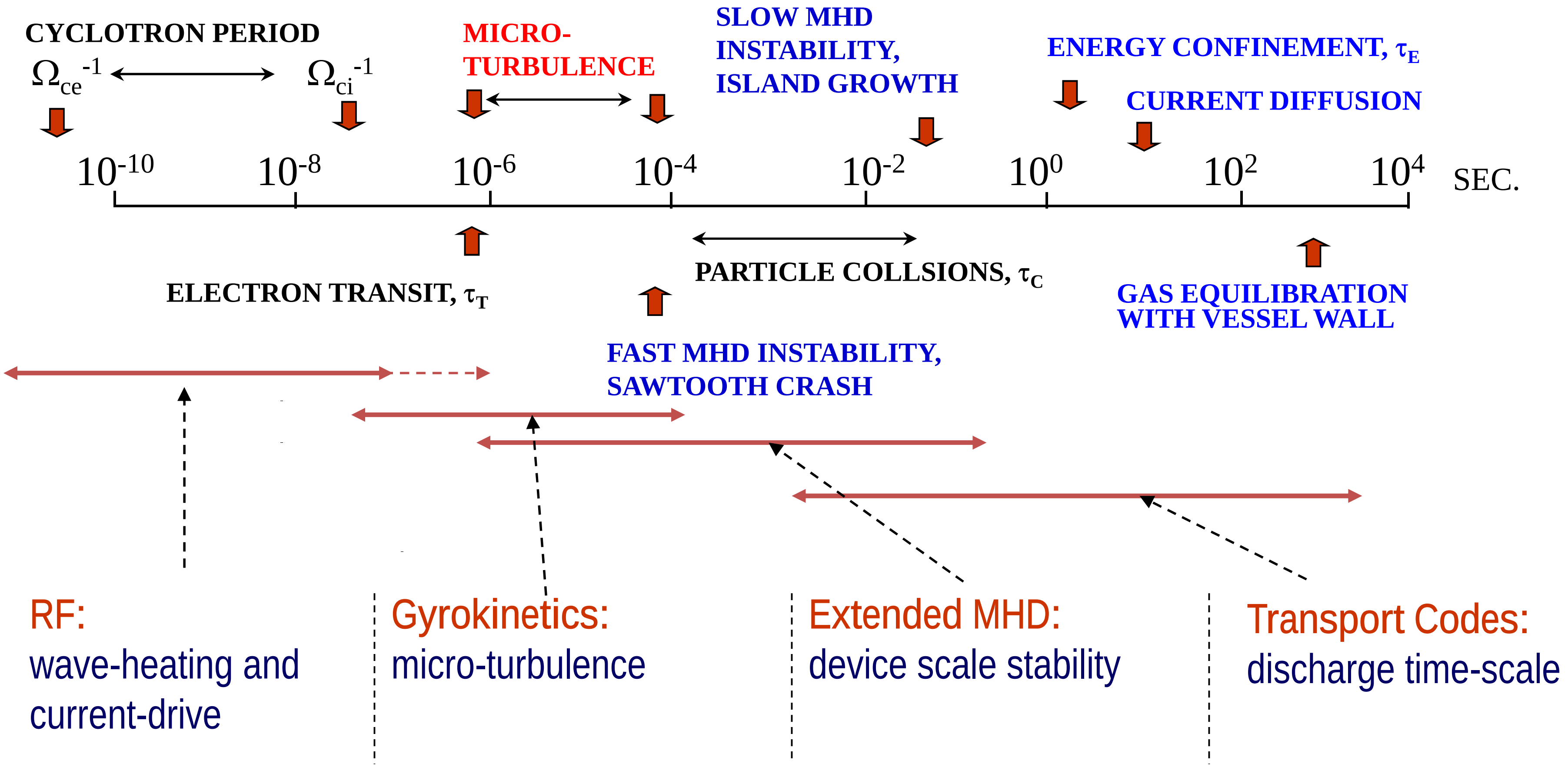
March 25, 2010

Outline

- Introduction and Motivation
- Process of developing plans based on Science Drivers
- Description and Status of Drivers

Science Challenges:

Progress Achieved Historically Through Separation of Physics Domains



CYCLOTRON PERIOD

Ω_{ce}^{-1} ↔ Ω_{ci}^{-1}

MICRO-TURBULENCE

SLOW MHD INSTABILITY, ISLAND GROWTH

ENERGY CONFINEMENT, τ_E

CURRENT DIFFUSION

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} SEC.

ELECTRON TRANSIT, τ_T

PARTICLE COLLSIONS, τ_C

GAS EQUILIBRATION WITH VESSEL WALL

FAST MHD INSTABILITY, SAWTOOTH CRASH

RF:
wave-heating and current-drive

Gyrokinetics:
micro-turbulence

Extended MHD:
device scale stability

Transport Codes:
discharge time-scale

- **A similar approach divides the problem spatially between Core, Pedestal, Boundary Layer, Plasma Wall Interactions**
- **However, this approach is fundamentally limited and inadequate!**

Accurate Modeling Requires Going Beyond This Historical Paradigm

- **Clean separation is only an ideal - Overlap in scales (time and space) often means strong ordering is not possible.**
- **Additional physics enters (Nuclear reactions, atomic physics, neutral transport, radiation transport, plasma-material interactions)**
- **We've provisionally identified 6 “Science Drivers” which exemplify and span these two challenges**
  - Boundary Layer, including turbulence, atomic physics and plasma-wall interactions
  - Pedestal, transport barrier, profile structure, relaxation mechanisms (ELMs)
  - Core Profiles: Nonlinear turbulence and MHD
  - Wave particle interactions including fusion products and RF
  - Disruption avoidance, detection and mitigation
  - Whole device modeling

Science Drivers – Motivation

- **The Science Drivers are a set of compelling scientific problems chosen to focus FSP's design and initial implemenation**
- **These could also be described as a set of evolving use cases**
- **Further, the drivers**
  - Define and exercise the required range of capabilities
  - Produce useful tools for the broader fusion community
- **Criteria**
  - Clear need for multi-scale, multi-physics integration
  - Importance and urgency for the fusion program
  - Readiness and tractability
  - Opportunities to open up new lines of research

Science Drivers and the Program Definition Process

- **Multi-step process for developing program plans for each driver**
  - For each, teams have developed “science development roadmaps”, a step by step plan for adding scientific capabilities.
  - We are in the process of including components and framework requirements.
  - Verification and Validation needs will be defined for each.
  - Schedule and resource requirements can then be estimated.
  - Result is a detailed program plan for each drive.r
- **Program is rationalized across all drivers**
  - Schedule and priorities adjusted to mesh development elements and to match anticipated funding profiles.
  - Major deliverables and milestones defined.
- **Result is an overall FSP program plan**

Community Input

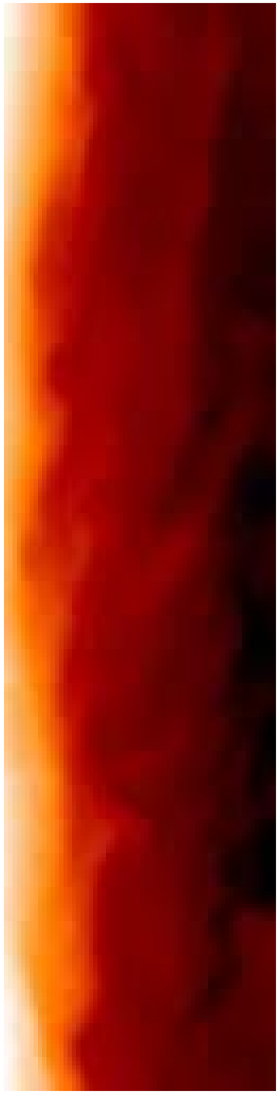
- Work rests on previous community efforts and ongoing outreach activities
  - MFE Research Needs Workshop 2009 (ReNeW)
  - FESAC panel report on Priorities, Gaps and Opportunities 2008
  - “FES Grand Challenges and Computing at the Extreme Scale” 2009
  - TTF, BPO, ITPA activities
  - Outreach as previous noted (GA, PPPL, MIT, LLNL, LANL, U.Md., U.S. Japan workshop on integrated modeling)
- Approximately 35 people contributed to development of science drivers, more still through the March FSP Workshop. Interactions will be ongoing...
- Wiki provides opportunity for community to observe and engage in development of FSP science program http://fspscidri.web.lehigh.edu/index.php/Main_Page

Roadmaps Are Step By Step Plans For The Development Of Scientific Modeling Capabilities

A few more notes:

- They show the sequence in which capabilities arrive. Work must typically begin well in advance.
- Achieving the capabilities outlined in the roadmaps will require coordinated efforts by the FSP partnering with theory, SciDAC and experiments.
- They do not promote or describe particular implementations.
- Science Drivers are summarized in workshop talks at https://ice.txcorp.com/trac/fspfrmwrkplan/wiki/FspPlanningAgenda
- The FSP team, working with the community is in the process of defining component and framework requirements for each.
  - Talks by John and Xianzhu will outline progress in each area

Science Driver: Plasma Boundary Layer

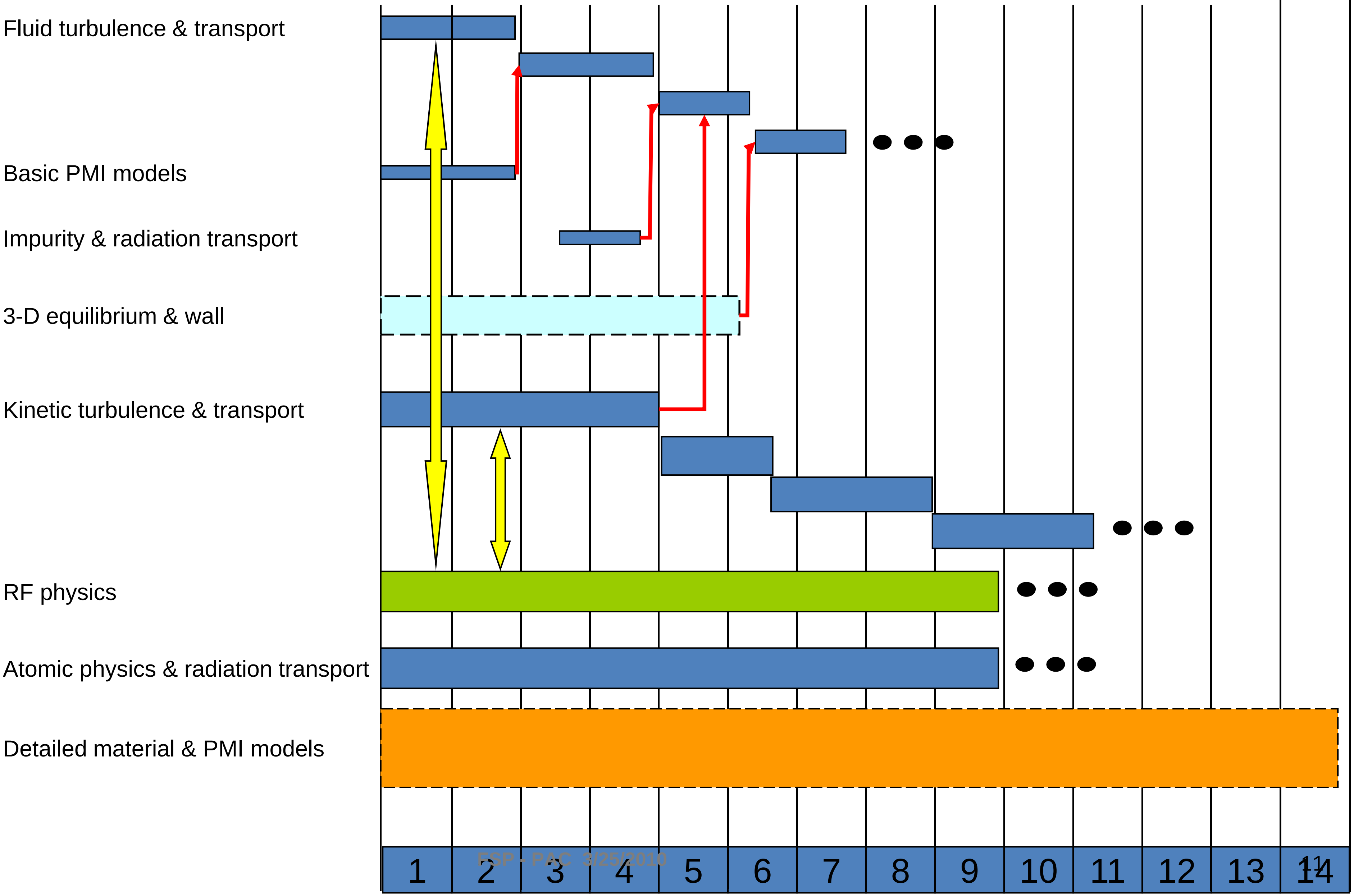


- Crucial unresolved scientific issues for fusion.
  - Heat and particle loads
  - Erosion of first wall & impurity generation
  - Tritium fuel cycle – retention in first wall
- Key Challenges
  - Self-consistent solution of coupled plasma turbulence, macro-stability, neutral transport, atomic physics, plasma-wall interactions, materials chemistry and morphology
  - Lack of spatial scale separation (gradients, gyro-radius, neutral mfp, photon, mfp), scrape-off layer (SOL) coupling to pedestal
  - Magnetic topology: open and closed field lines, 3D geometry
- Payoff
  - Predict heat loads for divertor design and operational strategies
  - Minimize erosion via material choice and wall design/plasma shape
  - Predict tritium retention and optimize removal strategies

Simplified Plasma Boundary Layer Roadmap

1. 3D fluid turbulence/2D transport coupled to models for collisional transport, neutral dynamics and impurity radiation
2. Include reduced model for plasma wall interactions, including chemical and physical erosion, wall-temperature dependent retention and recycling
3. Include physics for impurity transport, radiation and simple models of radiation transport
4. Include kinetic plasma turbulence and transport calculations
5. Include 3D equilibrium and wall geometry effect, include models for sheath behavior at all angles of incidence and kinetic parallel transport.
6. Add multi-scale plasma-wall models – molecular dynamics ⇒macroscopic
7. Include RF effects, edge absorption, plasma response to local heating, effects of fluctuations on wave propagation, treatment of RF sheaths
8. Include more complete treatment of radiation transport, more detailed models of atomic and molecular physics.

Integrated Boundary Layer (SOL), Divertor, Plasma Wall Interactions Time Line



Fluid turbulence & transport

Basic PMI models

Impurity & radiation transport

3-D equilibrium & wall

Kinetic turbulence & transport

RF physics

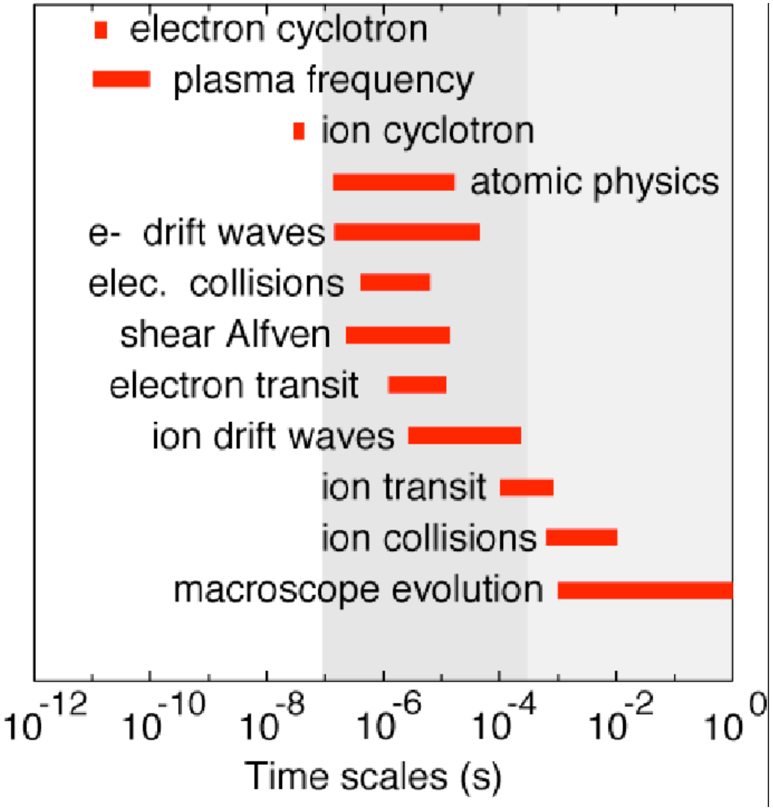
Atomic physics & radiation transport

Detailed material & PMI models

1 2 3 4 5 6 7 8 9 10 11 12 13 14

Science Driver: Pedestal

- **Key Scientific Issues**
  - Bifurcation thresholds, barrier structure and relaxation mechanism
- **Challenges**
  - Perturbations are not small
  - Pedestal is both collisional and collisionless, coupling to SOL
  - Multi-physics, interactions with neutrals, impurities, radiation
  - Self-stabilization mechanisms
    - o Bifurcations (L-H transitions)

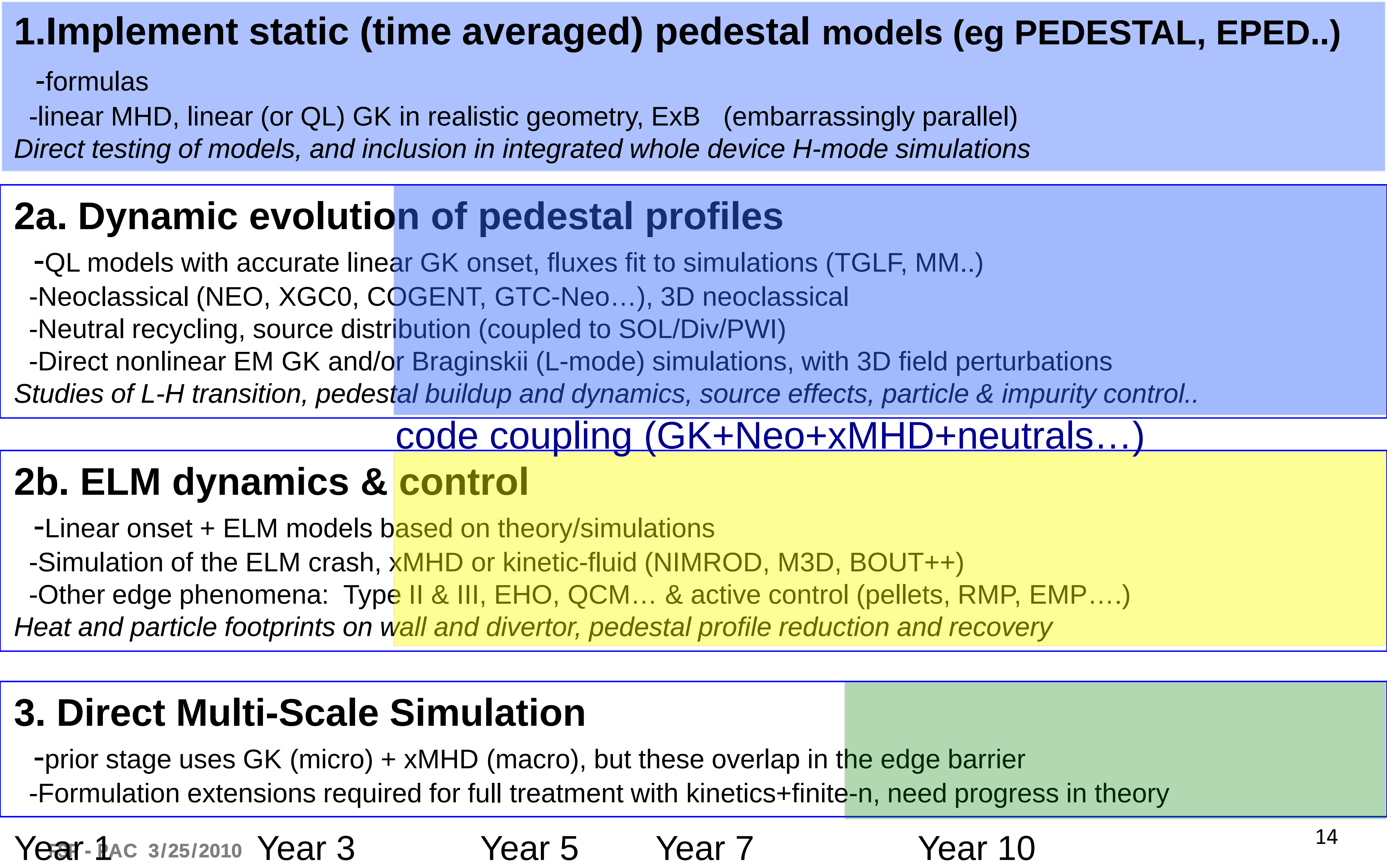


- **Payoff**
  - Predictability of plasma confinement regime (threshold for edge barrier)
  - Predictability of boundary conditions for core plasma - pedestal height
  - Control of pedestal relaxation – avoid regimes with strong ELMs

Simplified Pedestal Roadmap

1. Implement existing time averaged pedestal models based on linear constraints (stability) and experimental validation
2. Directly calculate linear constraints (e.g. peeling-ballooning, KBM), including realistic geometry, initially with extended MHD, later full gyrokinetic (GK) calculations for KBM. Incorporate ExB shear stabilization.
3. Develop dynamical "quasi-linear" models using accurate representation of linear onset of various modes (ETG, TEM, ITG, KBM...). Include accurate calculations of neoclassical transport
4. Implement fluid and/or kinetic models of neutral recycling, fueling and density evolution
5. Direct nonlinear electromagnetic gyrokinetic simulation of turbulent transport coupled to neoclassical and sources
6. Model ELM crash dynamics
7. Include 3D effects – extended MHD + parallel transport.
8. Direct multi-scale simulation, formulation for finite n needs new theory

Possible Roadmap for FSP Pedestal Science Driver



1.Implement static (time averaged) pedestal models (eg PEDESTAL, EPED..)

-formulas

-linear MHD, linear (or QL) GK in realistic geometry, ExB (embarrassingly parallel)

Direct testing of models, and inclusion in integrated whole device H-mode simulations

2a. Dynamic evolution of pedestal profiles

-QL models with accurate linear GK onset, fluxes fit to simulations (TGLF, MM..)

-Neoclassical (NEO, XGC0, COGENT, GTC-Neo…), 3D neoclassical

-Neutral recycling, source distribution (coupled to SOL/Div/PWI)

-Direct nonlinear EM GK and/or Braginskii (L-mode) simulations, with 3D field perturbations

Studies of L-H transition, pedestal buildup and dynamics, source effects, particle & impurity control..

code coupling (GK+Neo+xMHD+neutrals…)

2b. ELM dynamics & control

-Linear onset + ELM models based on theory/simulations

-Simulation of the ELM crash, xMHD or kinetic-fluid (NIMROD, M3D, BOUT++)

-Other edge phenomena: Type II & III, EHO, QCM… & active control (pellets, RMP, EMP….)

Heat and particle footprints on wall and divertor, pedestal profile reduction and recovery

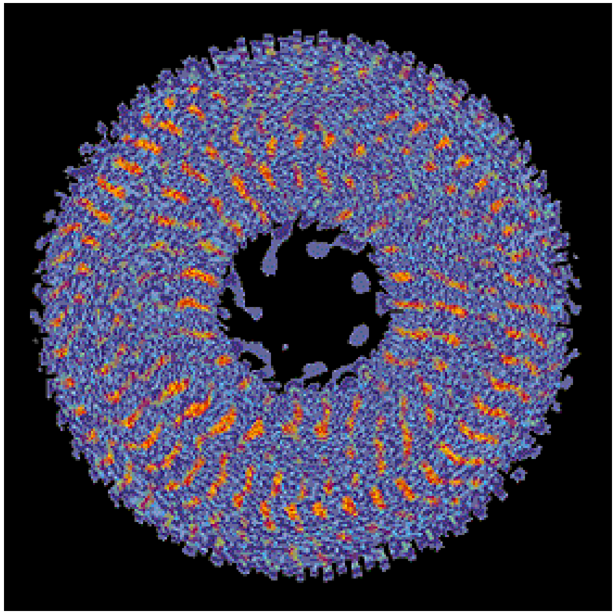
3. Direct Multi-Scale Simulation

-prior stage uses GK (micro) + xMHD (macro), but these overlap in the edge barrier

-Formulation extensions required for full treatment with kinetics+finite-n, need progress in theory

Science Driver: Core Profiles, Nonlinear Turbulence & MHD

- **Key Scientific Issues**
  - Prediction of all core profiles, including internal transport barriers
- **Challenges**
  - Self-consistent, global solutions of micro-and macro-nonlinear dynamics on transport time scales including effects of 3D field structures on turbulence.
  - Meso-scale phenomena (between gyro-orbit and device size), overlap with MHD scales



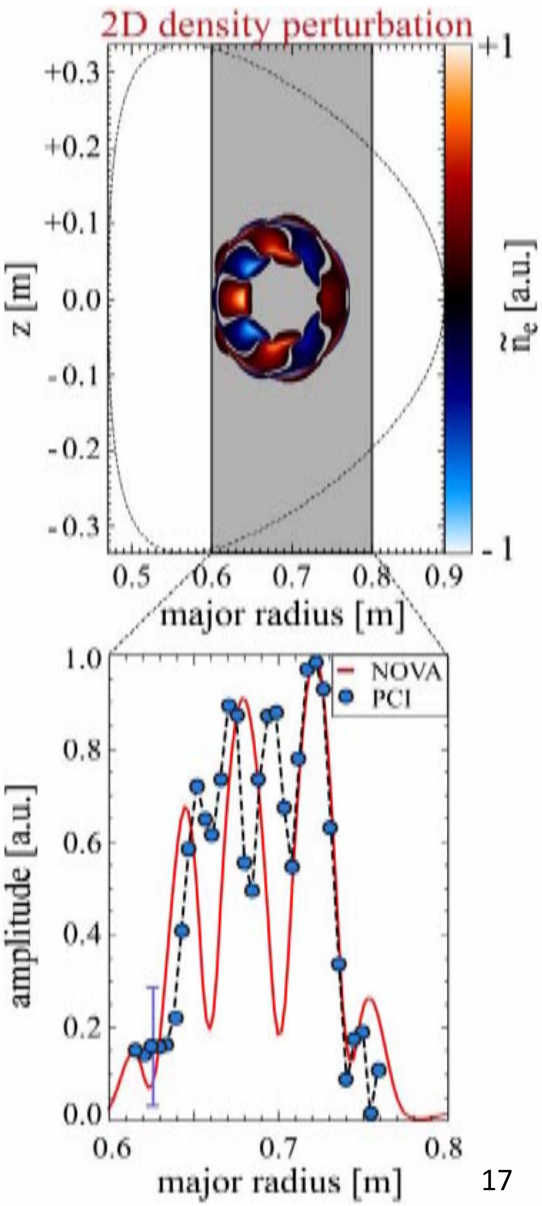
- **Payoff**
  - Predictability of plasma profiles for temperature, density, rotation, current.
  - Prediction of operational limits (plasma pressure) and performance (fusion yield, bootstrap current)
  - Ability to extrapolate to future devices

Simplified Core Profiles Roadmap

1. Start with a detailed comparison of current first-principles and reduced transport models through experimental validation.
    - Address discrepancies in models of electron transport.
2. Evaluate current approaches to full radius and long-time simulations via local models.
3. Include appropriate GK formulations for calculation of momentum transport, radial electric field.
4. Develop approach to extract information from global simulations to allow prediction of profile evolution for temperature, density and momentum
5. Treat meso-scale phenomena on transport time scales. Model interactions with neoclassical tearing modes (NTM) & other MHD and micro-turbulence - Include treatment of evolving 3D equilibria.
6. Characterize and incorporate boundary condition between the core and pedestal including fluctuations and flows.

Science Driver: Wave Particle Interactions

- **Scientific Issues**
  - Fusion products - alpha particles are born at 3.5 MeV, plus superthermal particles from RF or Beam heating and current drive.
  - Thermalization without loss is essential
  - Fast particles represent potent source of free energy for instabilities
- **Key Challenges**
  - Self-consistent description of phase space distribution on long time scales (energy confinement or slowing-down, orders of magnitude longer than time scales for underlying wave-particle interactions (Alfvenic)
  - Strong nonlinearities and mutual coupling to transport through pressure, velocity and current profiles and fluctuation spectra
- **Payoff**
  - Predictable steady-state burning-plasma performance

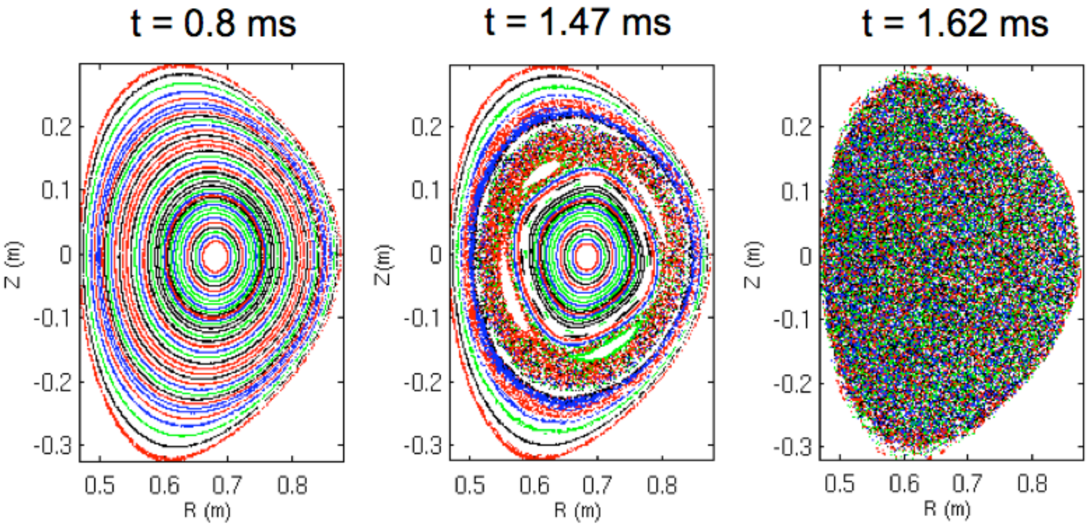


Simplified Wave-Particle Interactions Roadmap

1. 2 fluid and gyrokinetic models for FLR effects on Alfvenic eigenmodes
2. Develop “edge to core” wave coupling and propagation, perhaps by coupling finite-element and spectral codes.
3. Calculate nonlinear evolution and transport of fast ions in field of Alfvenic instabilities calculated via linear eigenmodes. Extend to mode saturation time scale.
4. Include finite Larmour radius effects into ICRF-energetic particle interaction.
5. Address effects of edge instabilities on coupling and propagation of short wavelength modes (LHRF).
6. Incorporate reduced models of energetic particle modes and transport into RF models.
7. Develop kinetic closure for MHD hierarchy to describe stabilization of neoclassical tearing modes and sawteeth
8. Deploy more complete, self-consistent calculation of nonlinear evolution of fast ion distribution on slowing-down or transport time scales.

Science Driver: Disruption Avoidance and Mitigation

- **Scientific Issue**
  - Needed to predict, avoid and mitigate effects of disruptions which include severe heat loads, JxB forces, run-away electron generation
- **Key Scientific Challenges**
  - Strongly nonlinear MHD, with large Lundquist number ($\tau_{\text{magnetic diffusion}}/\tau_{\text{Alfven}}$)
  - Coupling to plasma pressure & current, atomic physics, neutral and impurity transport, radiation transport, relativistic electron transport
  - Coupling to electromagnetic model of machine (complex wall geometry, power supplies coils, control systems, etc., diagnostics)
- **Payoff**
  - Minimize impulsive loads to material components
  - Reliable steady-state operation



Disruption Avoidance, Mitigation and Effects Roadmap

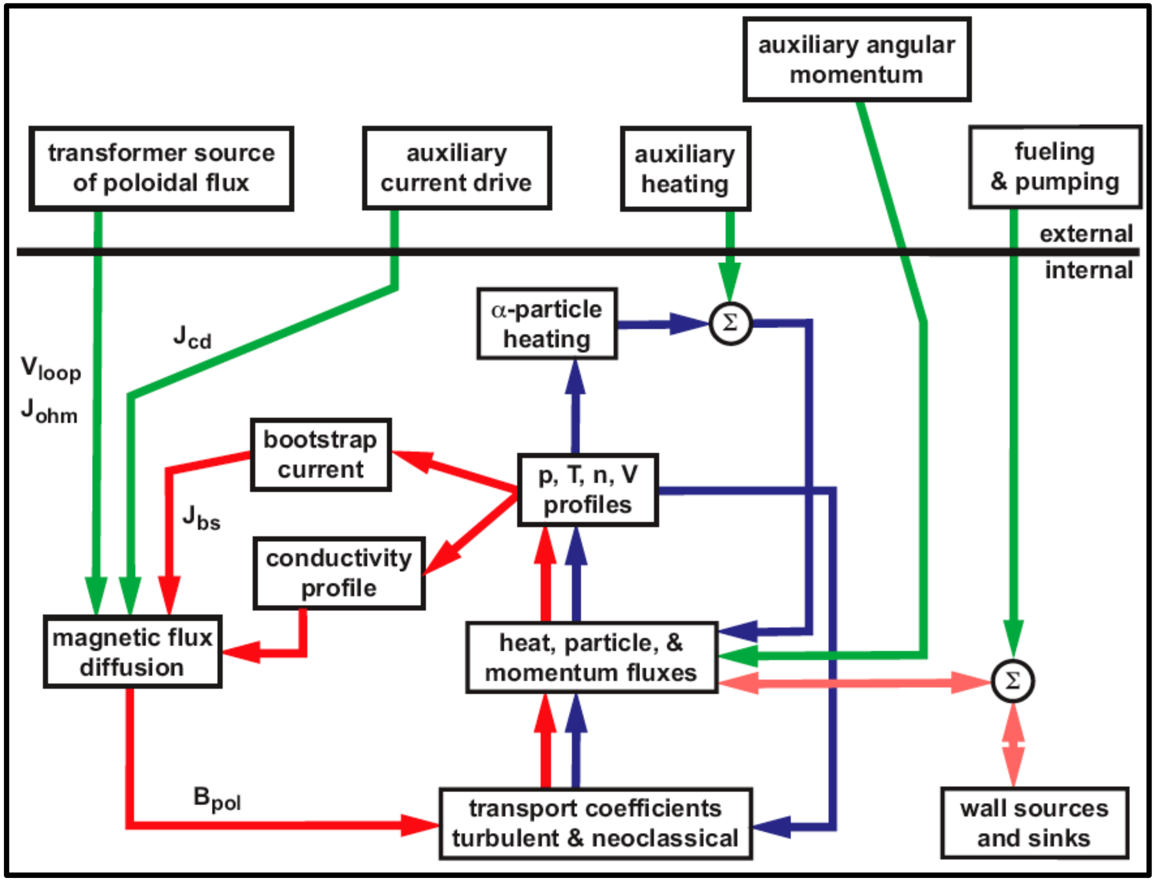
1. Start with existing extended MHD codes, free-boundary disruption models
2. Couple three-dimensional MHD fields with Fokker-Plank modeling of runaway electron generation and transport in stochastic, time-varying fields.
3. Couple three-dimensional MHD fields with external codes to study effects on material wall and detailed force analyses.
4. Use reduced models for plasma-material boundary interactions including sheath model, impurities and radiation losses and couple to MHD calculations.
5. Use improved models for plasma-material boundary interactions including reduced wall models, dust, and radiation transport
6. Use improved modeling of gas jet and pellets for disruption mitigation.
7. Include improved models for electron and ion (thermal and super-thermal) transport in stochastic field
8. Implement self-consistent coupling of extended MHD models with codes that model PMI and structural forces.
9. Develop Kinetic-MHD hybrid models
10. Develop better whole-device techniques for studying disruption onsets and effects, including integration with 3D modeling

Further Integration

- **Over time, science driver paths will begin to merge**
  - Pedestal integrated with Boundary Physics
  - Pedestal integrated with Core
  - Wave-particles models including effects of micro-turbulence
  - Etc., etc.
- **From the start, we envision full integration (whole device modeling) at various, but increasing levels of physics fidelity.**
  - To begin, reduced models will be required for many phenomena.
  - Over time better models will need to be made available.
    - We will need to support development of a range of models, balancing fidelity and computational speed.
  - Frameworks should support flexible mix of models employing different levels of accuracy, computation on widest range of platforms.

Science Driver: Whole Device Modeling

- Challenges
  - integration of all relevant physical models
  - How to couple and integrate advanced, high-fidelity physics components?
  - When necessary, how to produce accurate and computationally tractable reduced models?
- Payoff
  - Scenario design for existing and planned machines (especially ITER)
  - Reliable design of future devices



Simplified Whole Device Modeling Roadmap

1. Implement reduced plasma models for all relevant phenomena in quiescent, axisymmetric equilibrium, including off-line verification and validation of reduced models against experiments and high-fidelity codes.
2. Establish mechanisms for coupling to high-fidelity models running on parallel architectures during time-dependent simulations. Start with turbulence models.
3. Implement tight-coupling between core and edge plasmas including pedestal, scrape-off layer and plasma-wall interactions.
4. Include high-fidelity models for interactions between fast and thermal particles, waves, instabilities and turbulence.
5. Implement 3D free boundary equilibrium that can handle magnetic islands, stochastic regions, RF, nuclear and atomic physics modules.
6. Include nonlinear extended MHD models for disruptions, sawteeth, ELMs, etc.

Continuing Activities

- Science driver teams will continue to refine approaches to address these critical issues.
- At the same time they will continue to work with the components, frameworks, verification and validation groups to develop concrete plans.
  - Science driver work will be increasingly coordinated with these groups.
- We need to ensure that proposed solutions remain well aligned with principal science challenges.
- Outreach will also continue.

Summary

- We believe that the current science drivers address a critical set of physics issues that are appropriate for the FSP.
- Each entails ambitious, scientific challenges of importance for ITER and for future reactors.
- Each requires significant physics integration.
- For each, we have defined an initial development roadmap which will be elaborated iteratively, by the whole FSP team, to produce detailed program plans.
- We would expect these to evolve over the life of the FSP.
- Creating the overall FSP program plan will require adjusting priorities and schedules to mesh development elements and to fit assumed funding profiles.