The NSTX Program For FY '03 - '04

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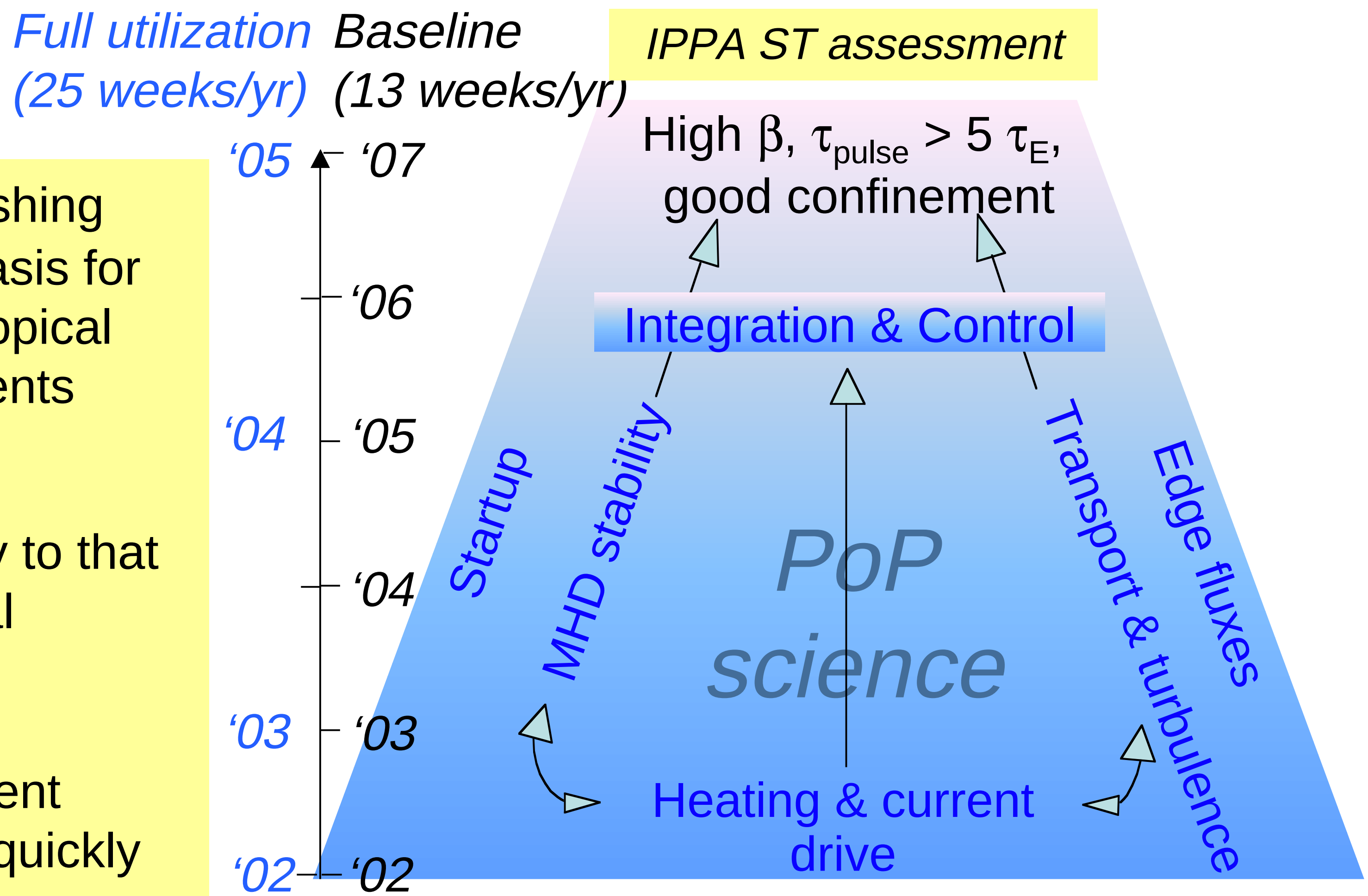
Beyond FY ‘02, the NSTX program will continue its mission of assessing the attractiveness of the ST

IPPA Goal: Assess the attractiveness of the spherical torus

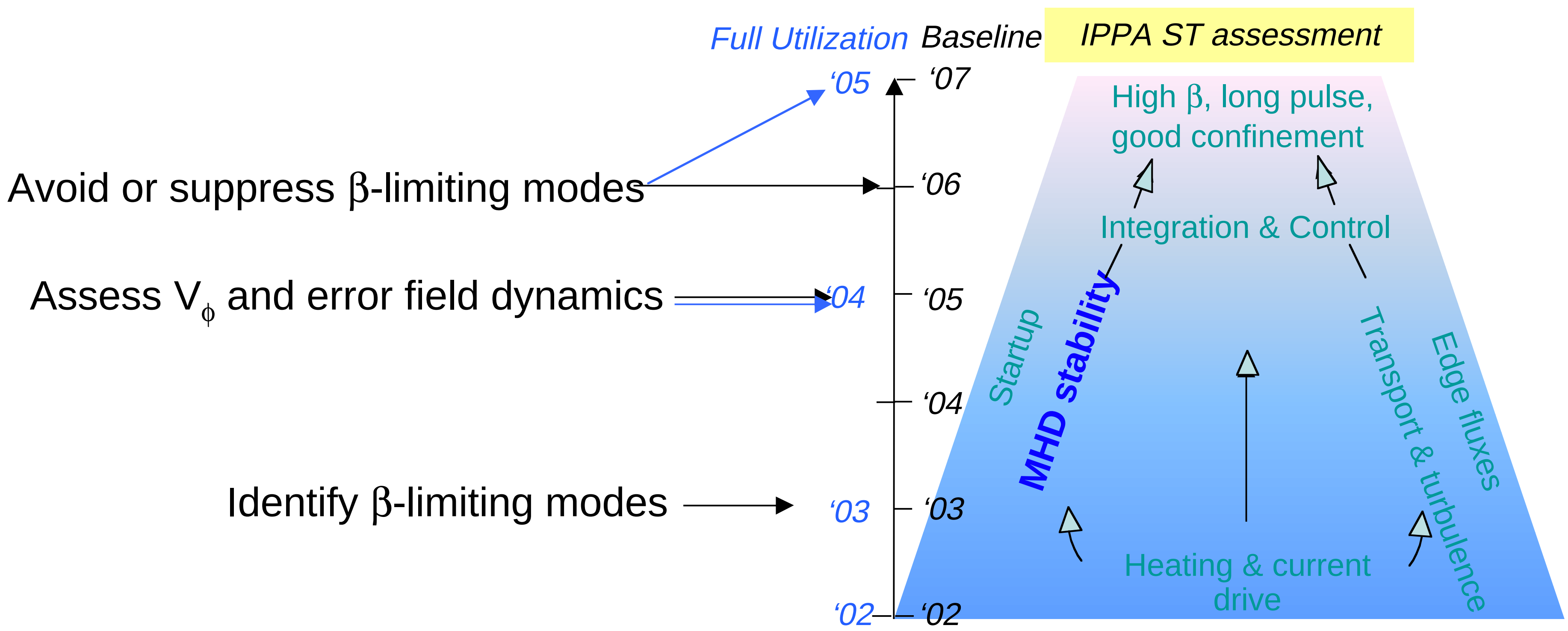
- Central to proof-of-principle mission
- Integration of several major research areas is critical
  - MHD, confinement, RF, non-inductive startup, boundary physics
- Determining ST attractiveness by the end of ‘04 will require full utilization of the facility

Integration of topical science is at the foundation of the NSTX Proof-of-Principle mission

- PoP ⇒ establishing extrapolable basis for integration of topical scientific elements
- ST science is complementary to that of other toroidal concepts
- IPPA assessment reached more quickly with full utilization



Integrating MHD science with control strategies is key to establishing physics basis



- ★ Arrows point to target completion dates of task

MHD science directly relevant to practical, long pulse integration goal

Active major areas that are planned emphases in ‘03 - ‘04

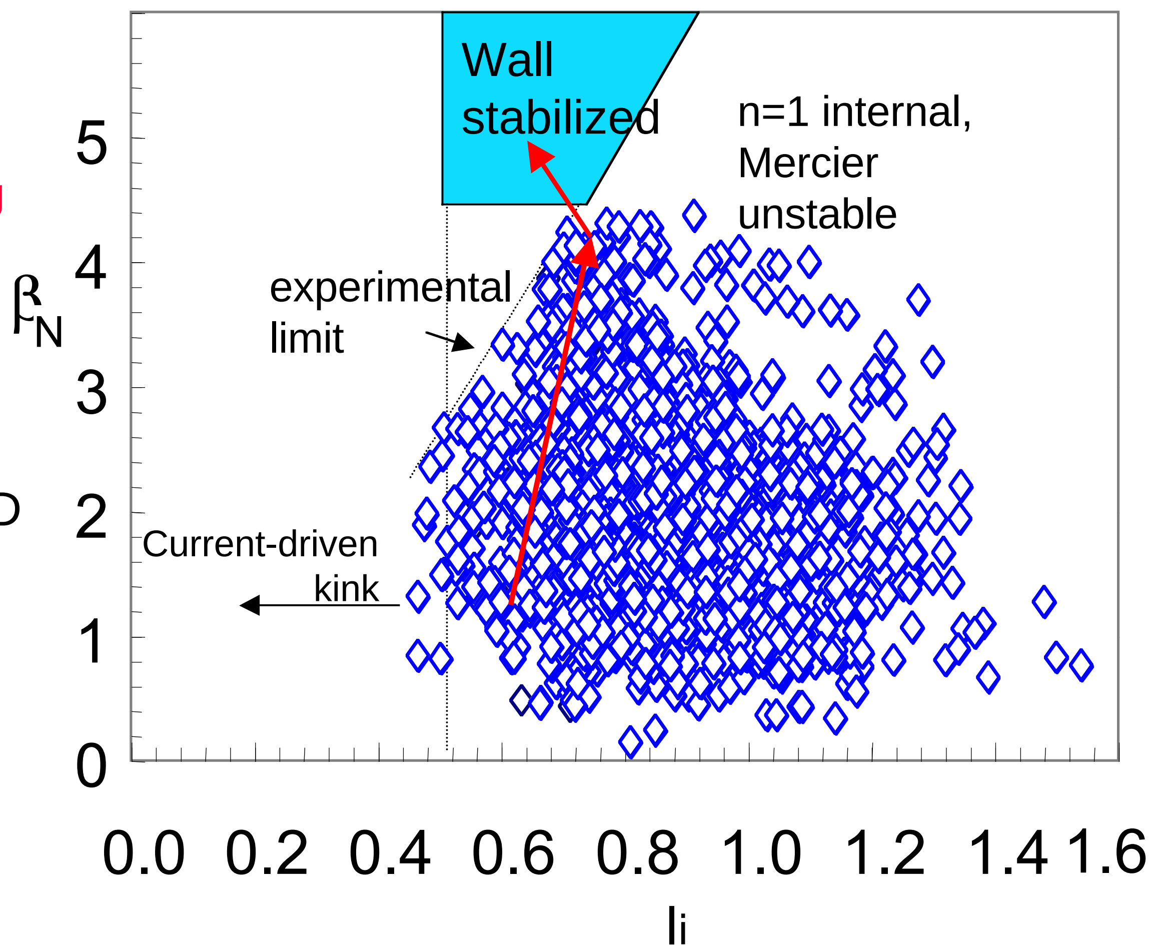
- Pressure driven ideal/resistive wall modes & fast β collapses
- Tearing modes and beta saturation
- Fast MHD: CAE, and impact on heating
- Locked modes, error fields, reconnection events

Less explored areas where attention will continue or increase

- Reduction of sawtooth size
- ELM character, influence on divertor heat fluxes and core

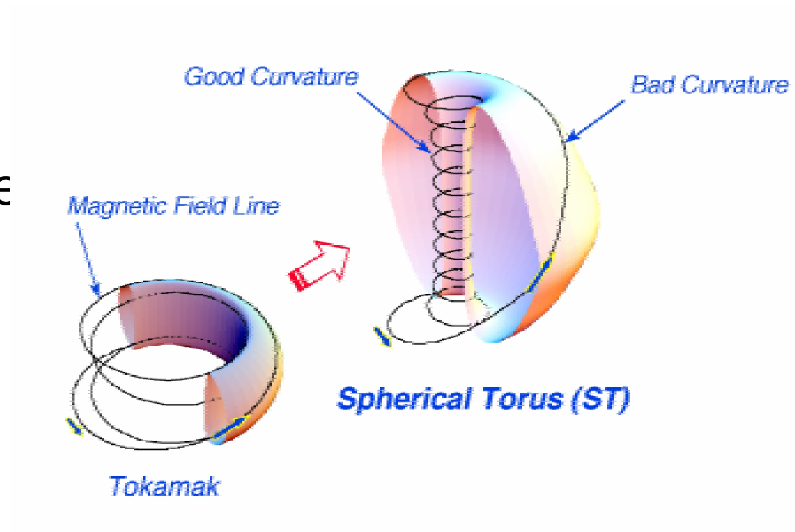
Developing a path to go beyond no-wall limit is a challenge for integrated research

- Beyond no-wall limit ⇒ need high β_N to take advantage of wall or active fast coils
  - ST ideal modes develop strong ballooning only at high β_N compared to moderate A
- For high β_N, need low l_i, broad P(r)
  ⇒ Current drive, transport, MHD intimately linked
- Experimental limit corresponds to n = 1 no-wall beta limit



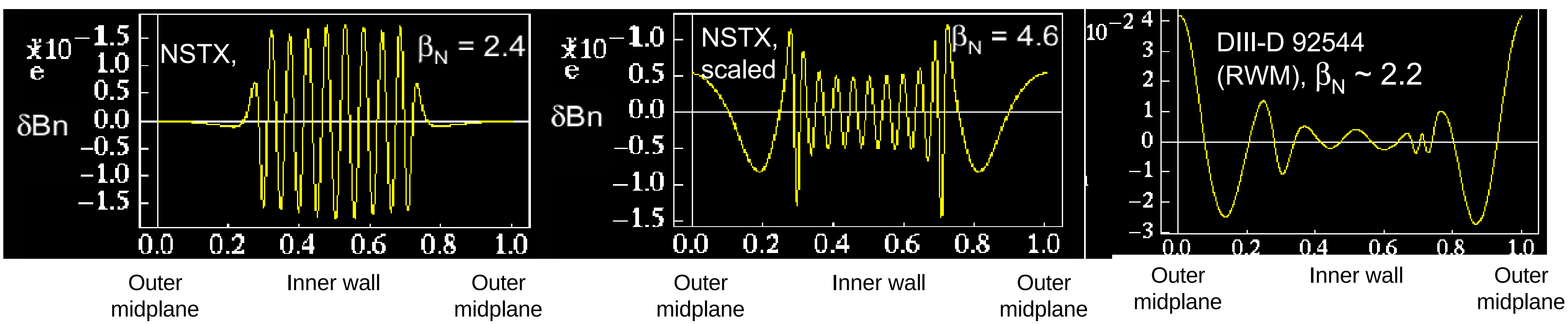
Ideal instability mode structure takes on ballooning character only at higher β_N

- Ballooning needed for efficient wall or coil coupling
- Different mode structure expected compared to moderate aspect ratio tokamak experience
  - An expression of field line differences
- Ballooning on NSTX expected at higher β_N than DIII-D



Bialek, Paoletti, Sabbagh (Columbia)

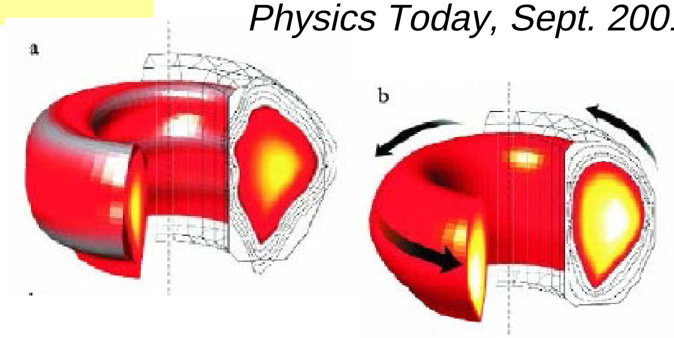
Results from VALEN code analysis



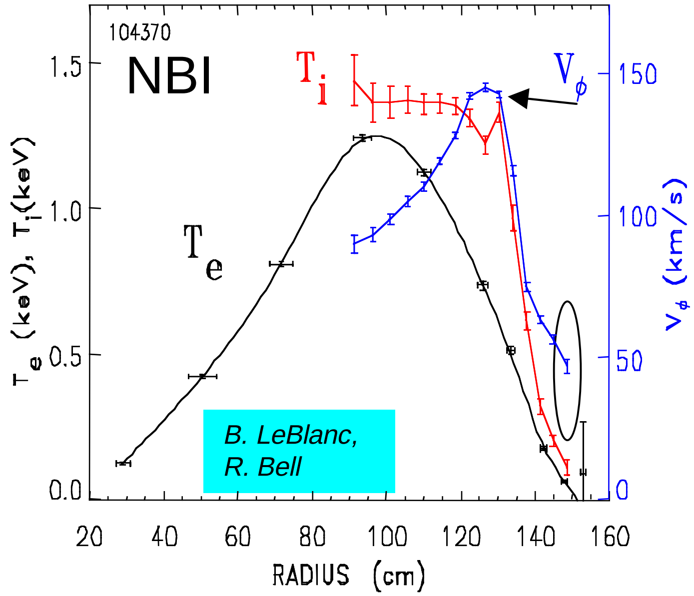
Hardware approach for RWM control strategy starts with dynamic error field control

FY '04 Milestone (baseline), FY '03 (full utilization): Assess dynamics of rotation and error fields

DIII-D
Physics Today, Sept. 2001



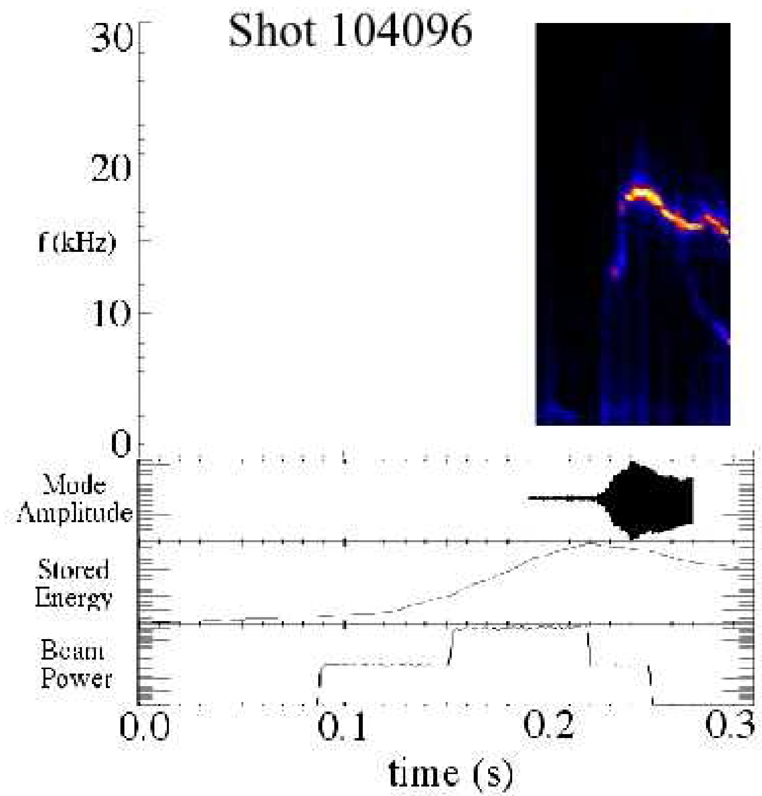
- Can NSTX stay above ω_{crit} required to stabilize modes? Is naturally high edge rotation a help? Does this extrapolate?
  - Diagnostics: Improved V_ϕ, locked mode coils, toroidally displaced USXR arrays, magnetics sensors
  - Deploy MSE CIF '03
  - Analysis with VALEN, GATO, PEST
  - 3-D MHD: M3D, NIMROD
- First step: Assess and deploy new error field control system in '03 (Full utilization)
- Vary error field and driven rotation, assess implications for fast mode control



NTM's are another possible candidate for mode control on NSTX

FY '04 Milestone (baseline), FY '03 (full utilization): Assess EBW current drive requirements

- NTM's observed lead to beta saturation
- Can EBW drive current in an island and hold off the NTM growth?
  - Motivated in part by DIII-D/ASDEX-U ECH successes
- More detail in RF part of this talk



NTM research: Fredrickson, Gates

Research on fast MHD, including role in ion heating, will likely continue

- Investigate role of CAE modes in heating: high leverage if true
  - $V_{beam} >> V_{Alfven}$
  - New phenomena: fast ion/magnetosonic wave/thermal ion interactions

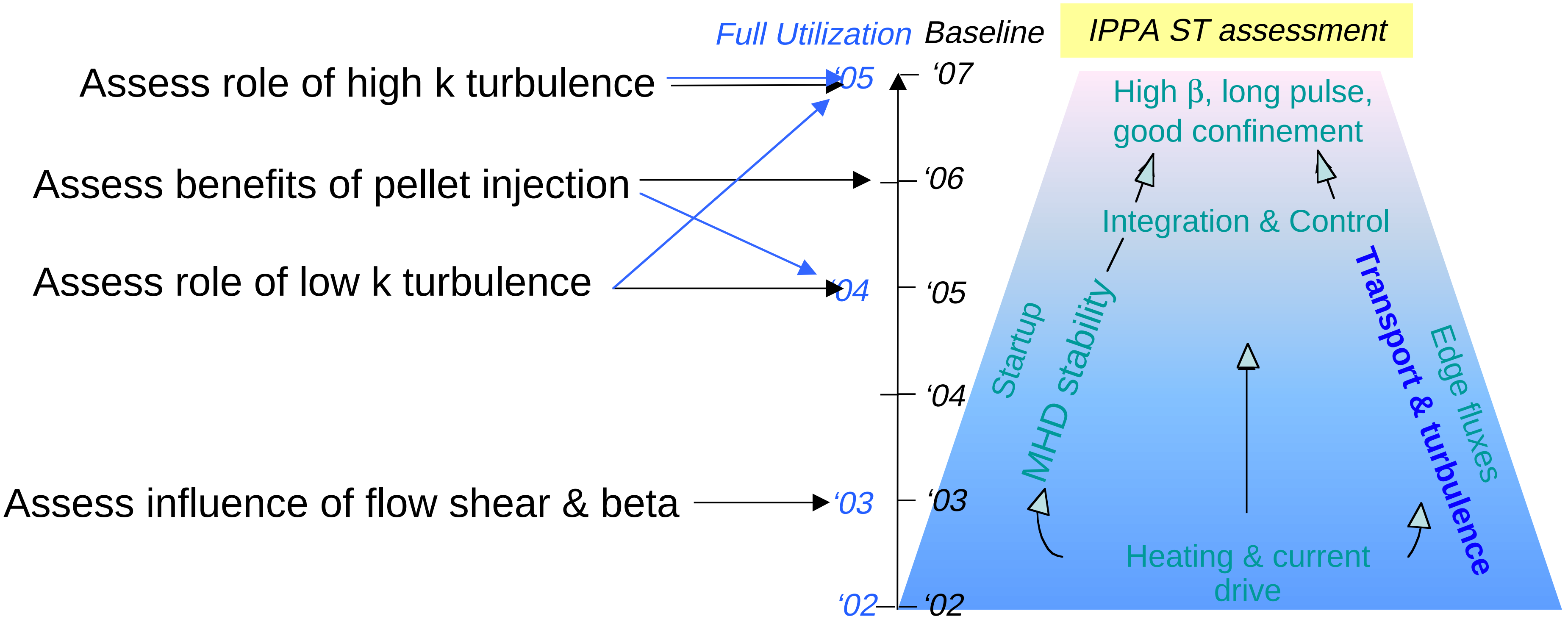
Gates, Gorelenkov, White

- Details of research in FY '03 & '04 depend on outcome of FY '02 research on search for modes > ω_{ci}
  - Use new HF Mirnov coils

- Clear predictions on differences in TAE mode structure between moderate and low A
  - Joint first experiment with DIII-D to be executed this FY

Heidbrink, UC Irvine

For IPPA assessment, establishing science of confinement trends is required

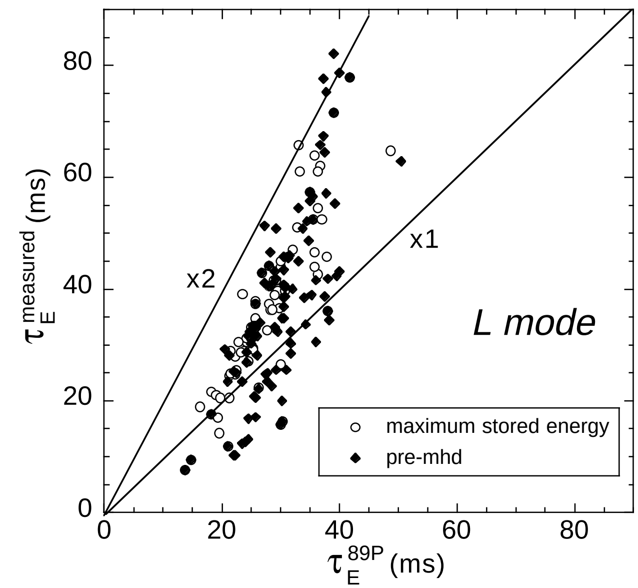


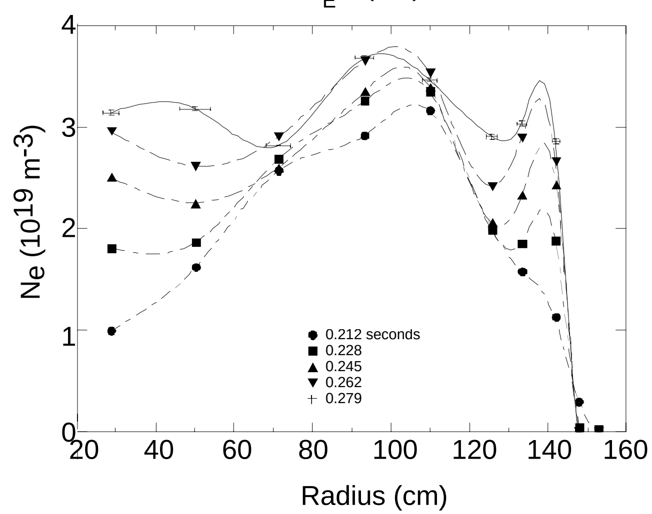
- Pellet injection, H mode, and q profile changes are tools for P(r) modification through modification of the transport

Understanding confinement trends has important practical implications, high physics leverage

IPPA Goal 1.1: Advance transport physics based on understanding of turbulence & turbulence dynamics

- Favorable confinement scaling: important if extrapolable
  - If H mode provides further enhancement and is stable at high β, implications are deep
- Form physics basis for assessment: establish physics behind the trends
  - Favorable τ_E scaling
  - P_{th}^{LH} ~ 800 kW, >> scaling prediction
- Deviations from moderate-A $\Rightarrow$ teach something important for tokamak as well as ST transport?





Transport research aims to identify effects of high beta, low aspect ratio, and to develop tools

Areas where study has begun and will continue

- MHD/transport connection: possible CAE heating
- Ion, electron thermal transport
  - Electrons very stiff; ions transport likely low
- Impurity particle transport

Areas where emphasis will increase in FY '03 - '04

- L-H physics; role of strong poloidal damping
- Turbulence measurements, core and edge
- Pressure profile modification
  - H modes, pellets, q profile mods (with early HHFW heating)

Full utilization will enable maturation & full impact of these studies

Turbulence studies provide unique opportunities for toroidal physics and for connections to other fields

- Low k: routinely suppressed?
  - core low k capability coming on line now (reflectometry; UCLA)
    - Correlation lengths end of this FY; $\Delta n/n$ brought on line next FY
  - opportunity for advanced low k imaging (proposed)

- High k: mode is expected to be larger than in tokamak, easier to detect, can be spatially resolved. Robustly unstable in analysis
  - Key to understanding differences in ion and electron channels
  - high k milestone for '06 (baseline), '04 (full utilization)

- Flow shear, q profile effects
  - CIF MSE deployed in '03
  - LIF MSE separates E_r, J effects '05 (baseline), '04 (full utilization)

- V_θ CHERS deployed in FY '05 (baseline), FY '04 (full utilization)

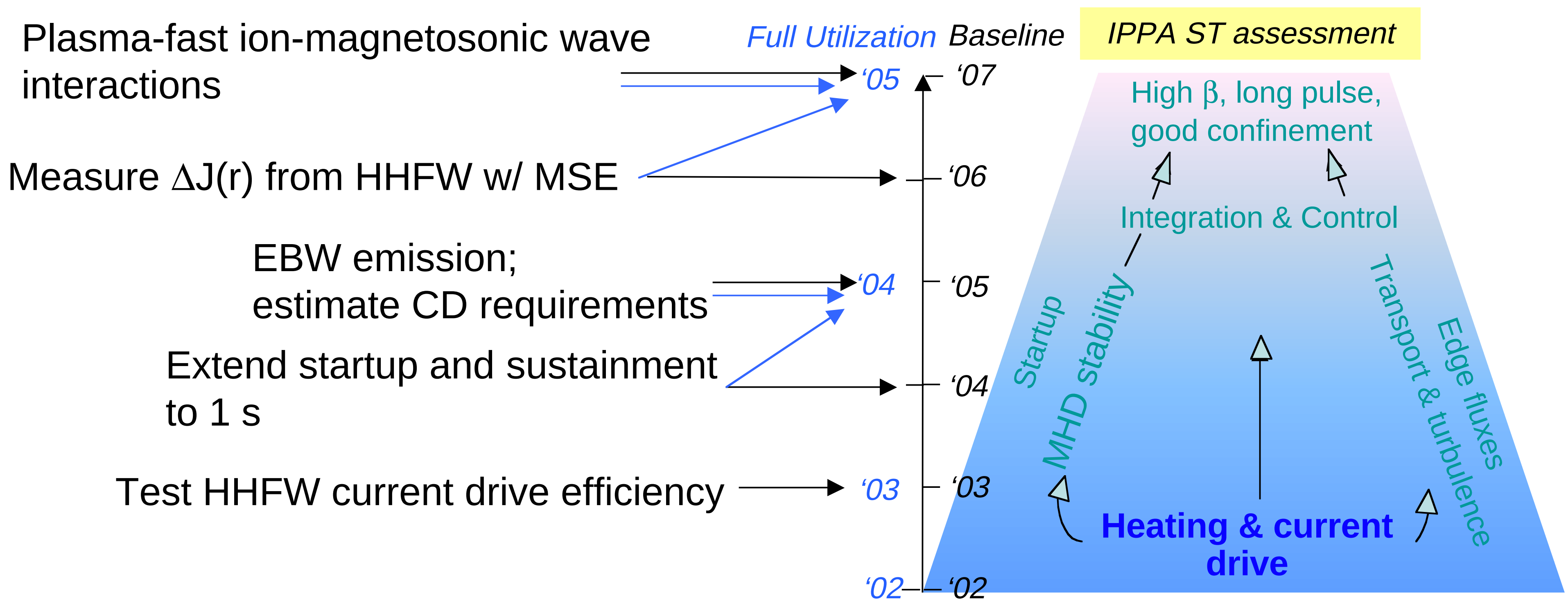
- High beta: exaggerated electromagnetic effects
  - Link with astrophysics turbulence where $\beta > 1$

The long-pulse and scientific goals place high demands on tool development

Milestone FY ‘05 (baseline), FY ‘03 (full utilization): assess benefits of pellet injection

- Tools for modifying P(r) likely required if path to high β is to be found
- Experiments say: most efficient way to modify P(r) and J(r) is by modifying the transport
  - Shear layer at edge triggers broad H mode profile
  - Reverse shear makes ITBs more likely in tokamaks, with strong modification of P(r)
  - Pellets can yield pressure changes by triggering drop in χ, D
- Can we reap confinement benefits of H mode or ITB and remain stable?
- Off-axis HHFW a tool for modifying P(r) as well

HHFW, EBW science is central to developing control strategies



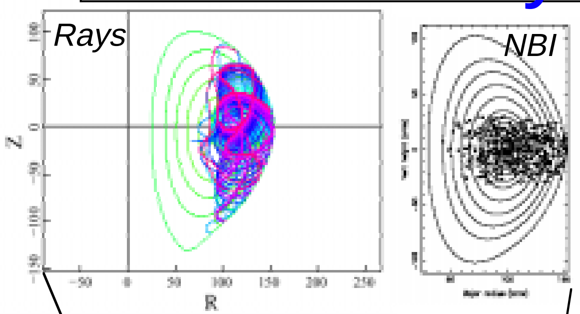
- Strongly linked with MHD and transport topics

Plans for diagnosing and controlling CD with HHFW current are in place

- Recall FY '02: surface voltage changes in long pulse with HHFW
- Pitch angle changes: FY '03 will permit the first measurements of changes driven by HHFW
  - CIF MSE deployed at start of FY '03
  - Measurement resolution target: ΔI_p ~ 1.5 kA within half-radius, assuming no E_r complication
- LIF MSE: FY '05 (baseline), FY '04 (full utilization)
  - E_r, J(r) effects on MSE signal will be separated
- Full utilization of control system and phased array will enable start of feedback control studies of CD & heating in '03
  - HHFW phase control coupled with rtEFIT and feedback on l_i

Benchmarking with advanced theory and data key to understanding HHFW

Approach: *benchmark and test* faster models against most sophisticated theory and measurements



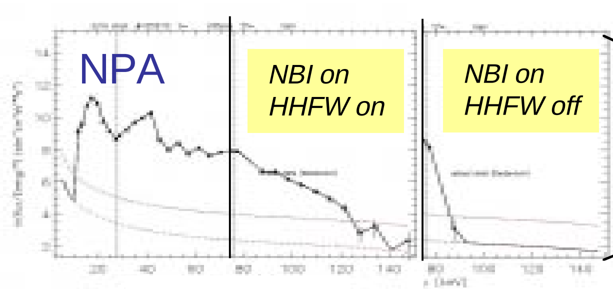
GENRAY CQL3D

Benchmark with complete wave theory
AORSA-2D (Batchelor, Jaeger, ORNL) (SciDAC)

Faster model: Ray tracing
GENRAY (Harvey, CompX)
CURRAY (Mau, UCSD);
HPRT (Rosenberg, P.U., Menard)

Analysis of transport, current drive
TRANSP

Faster model: Full wave
TORIC (Bonoli, MIT);
METS (Phillips; SciDAC)



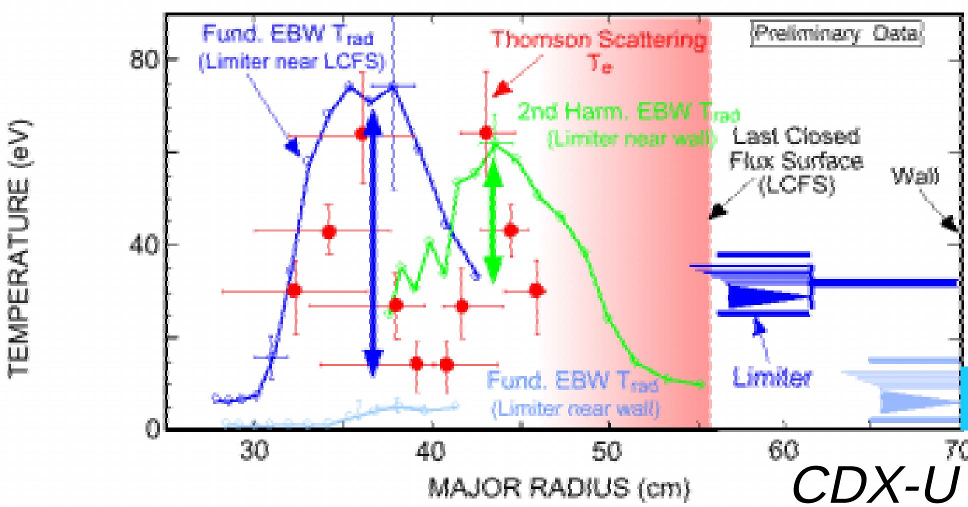
Energy (keV)

Benchmarking with NSTX Data
Wave-particle interactions
Source measurements

EBW studies will form basis for current drive tools for startup, possible NTM control

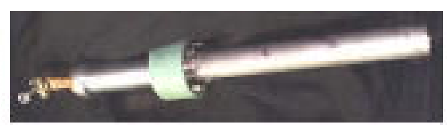
FY '04 milestone (FY '03 enhanced): Estimate current drive requirements for EBW

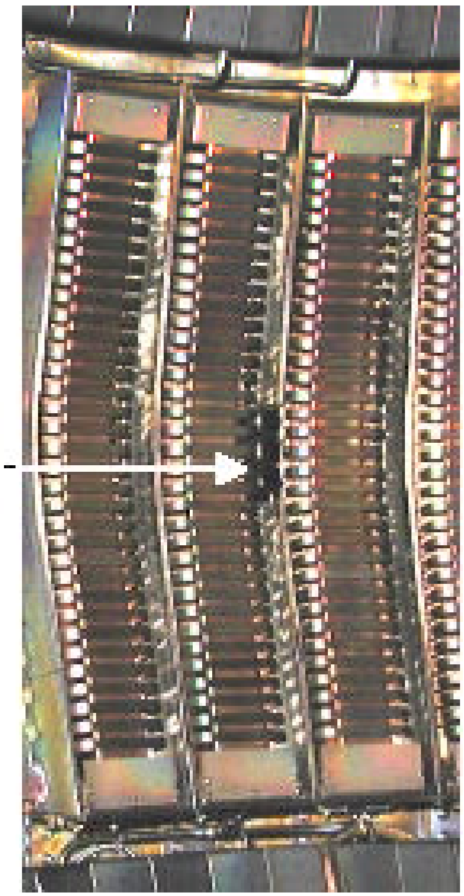
- Install horns with controllable density gradients to assess coupling
  - Demonstrated on CDX-U
- Possible NTM control, plasma startup tool



CDX-U

Horn installed behind HHFW Antenna (emission & 15 kW tests)





~ 1 MW 28 GHz design, end of '03

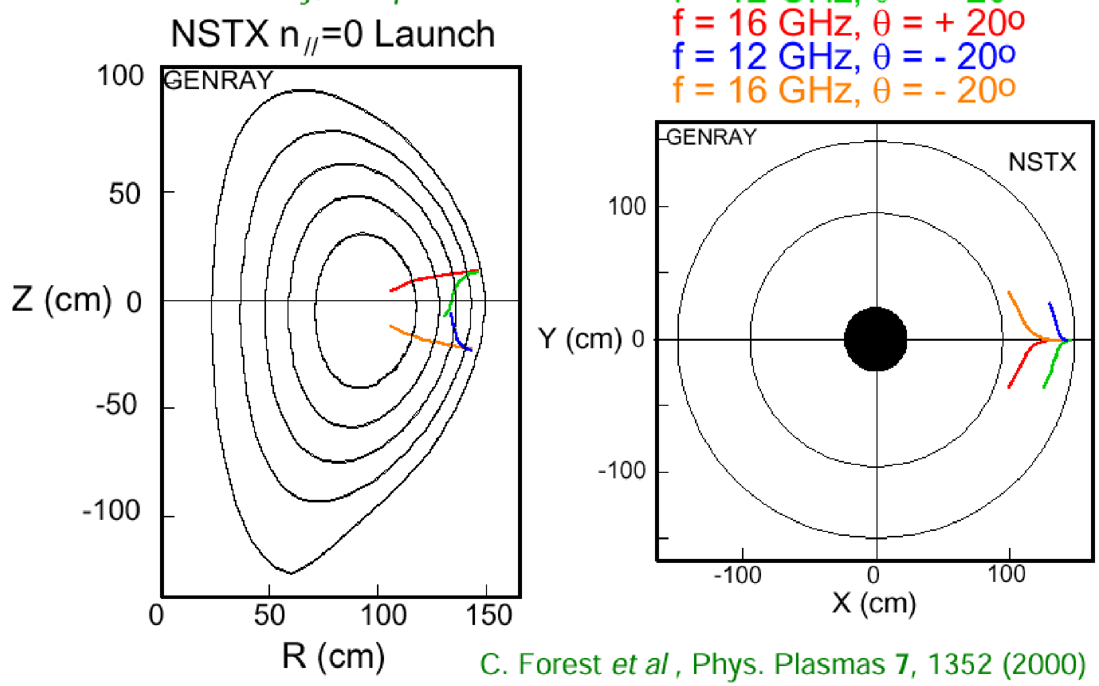
Jones, Taylor, Efthimion

Analysis and receiver measurements will be used to develop EBW launch scenarios

- EBW has several potential uses, each with a different launch requirement

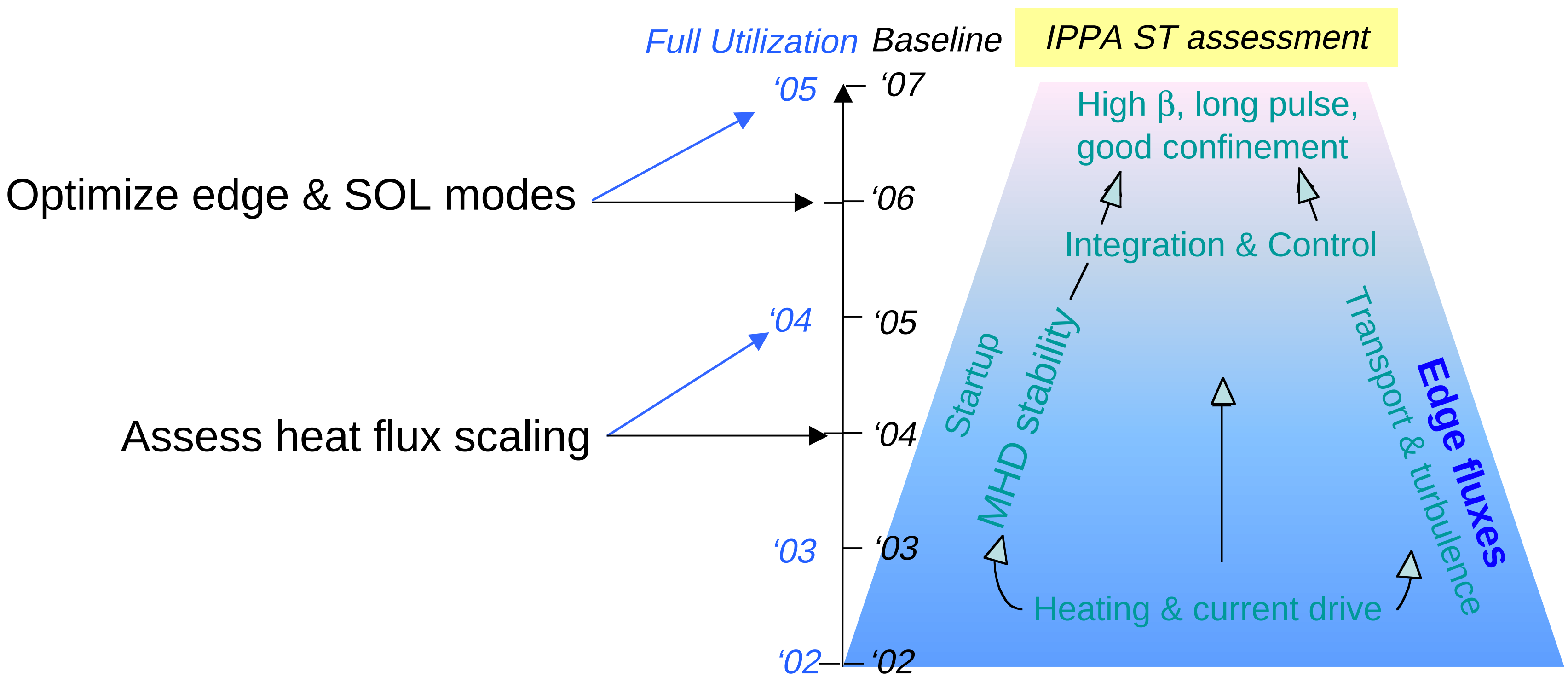
⇒ Exp't and theory assessment needed
  - Off-axis CD for NTMs
  - Startup

GENRAY - *B. Harvey, CompX*



C. Forest *et al* , Phys. Plasmas **7**, 1352 (2000)

Heat and particle control may play a role in achieving NSTX's long pulse integration goal



- Present plasma facing components may be stressed by long pulses with auxiliary heating

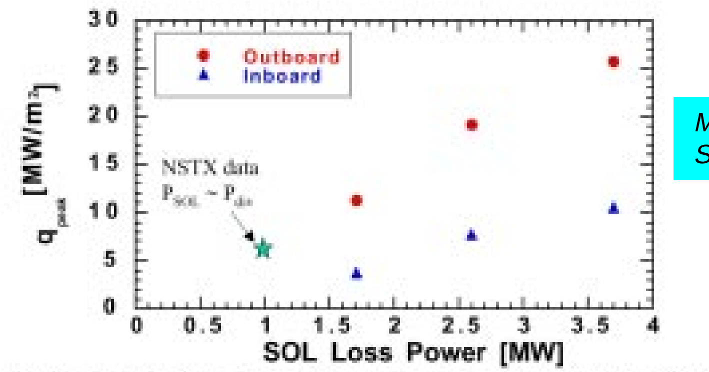
Boundary physics assessment key to assessing viability of edge divertor solutions

FY '03 Milestone: assess heat flux scaling

- Heat flux handling will be an issue in NSTX for 5 s pulses for higher powers (> 5 MW)
  - Possibly an issue for lower powers, depending on SOL transport
  - Perhaps an issue for 2 s pulses as well
- An extrapolable understanding of heat flux scaling will require
  - measurements of rate and character (e.g. bursty?) of cross-field transport with edge probes (UCSD)
  - use of these data in analysis codes (UEDGE, B2.5, DEGAS)
- Density control will likely become an important issue for the long term
  - Particle control tool needs: to be assessed in FY ‘03; possibly deploy cryopumps in ‘05
  - Pellet injector an important component of this
    - Deploy ‘03, full utilization; ‘05, baseline

Understanding of fluxes requires assessment of edge transport characteristics

- Understanding of cross-field transport in SOL is critical for proper modeling of heat fluxes

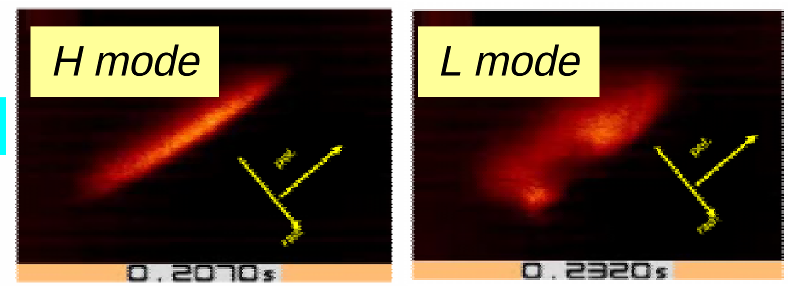


b2.5 code, 4 m^2/sec cross-field transport, deuterium radiation

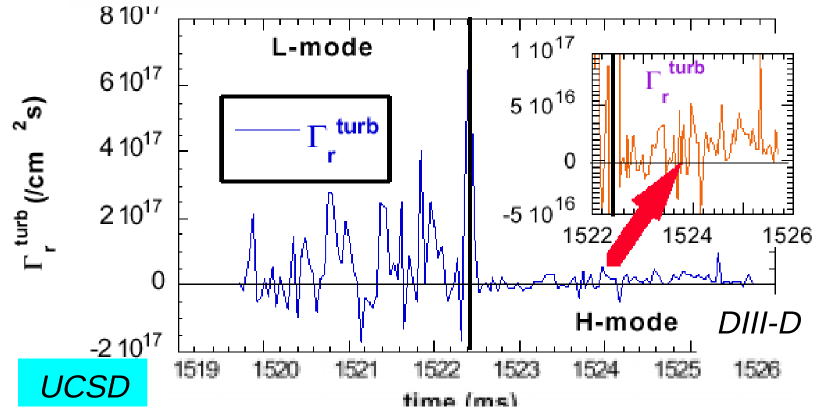
Maingi, ORNL; Stotler

- Edge probe (UCSD), fast LANL camera will allow studies of convective cross-field transport evens ("bursty"; "blobs").
  - What is the impact on heat flux handling requirements?

LANL

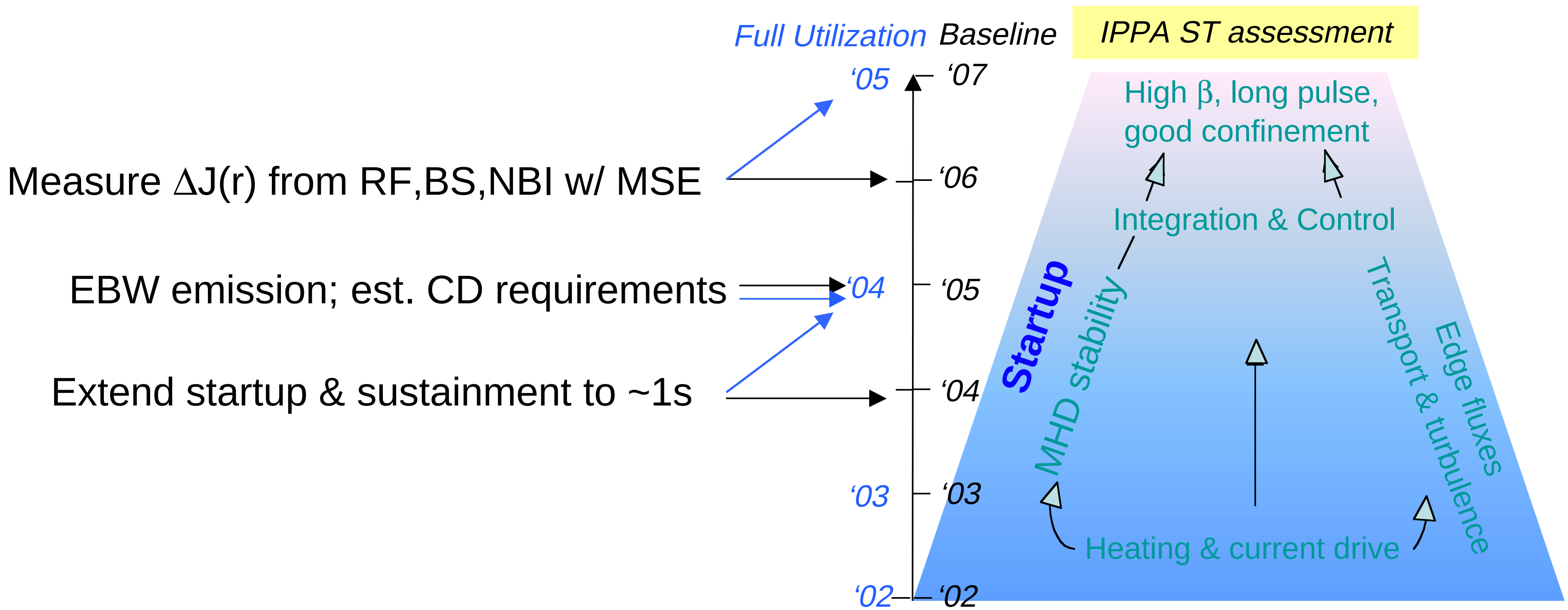


- FY '03, full utilization: diagnostics for heat fluxes from "fast" events
  - e.g. fast IR camera for ELMs, reconnection events



UCSD

CHI, EBW are the primary candidates for non-inductive startup scenarios



- 1 second startup/sustain milestone (end of '03) may draw on CHI,HHFW at low density, NBI, and/or bootstrap
- Full facility utilization gives run time for control scenario development

Coaxial Helicity Injection will benefit from improved absorber design and analysis

Goal, FY '03: 500 kA w/CHI, handoff to other current drive mechanism

- CHI control with upgraded control system to be attempted in '02
- Improved insulator being designed: aim is to reduce arcs
  - Deploy in FY '03
  - Additional absorber null coils

Raman, Nelson, Jarboe, U. Washington

Analysis plans:

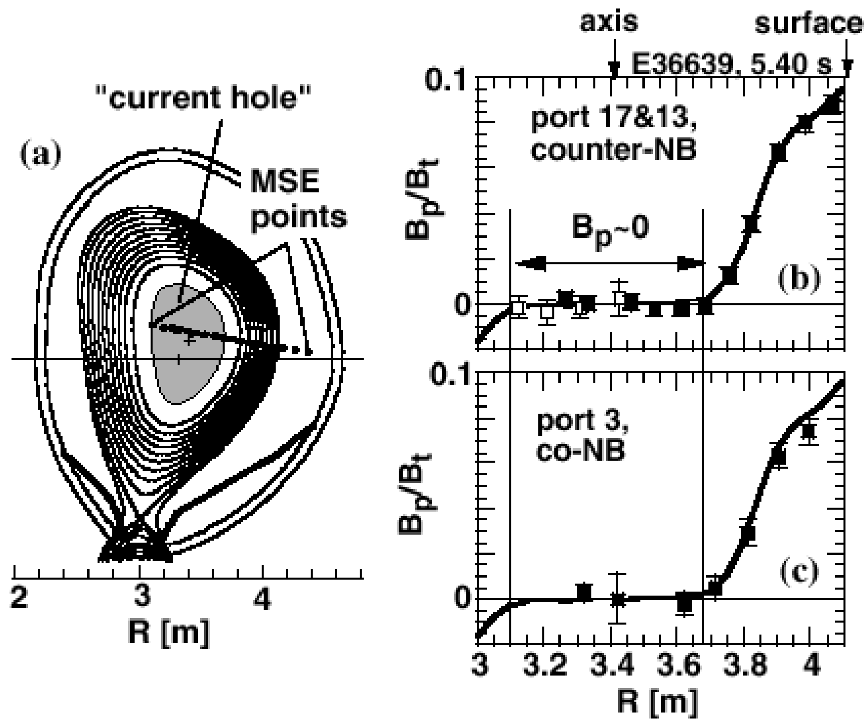
- 3-D MHD analysis tools developed to develop physics basis for CHI (X. Tang)
- EFIT being modified to account for open field line currents in scrapeoff (L. Lao, M. Schaffer, GA)
- TSC being developed to scope out operating scenarios

Other tools for startup assistance are being explored

- EBW, as previously discussed
  - Rich area for collaboration (Pegasus, W7-AS)
  - Major effort on MAST
- Ramping of poloidal field coils
  - Analog of MAST induction/compression
  - Collaboration
- Bootstrap current

Recent research regarding current “holes” may have important implications for NSTX startup

- Normal expectation: back-emf from development of bootstrap current would drive negative current near axis: but J ~ 0 observed
- If J ~ 0 is observed in NSTX core with strong current ramp as bootstrap develops, V-s may be saved



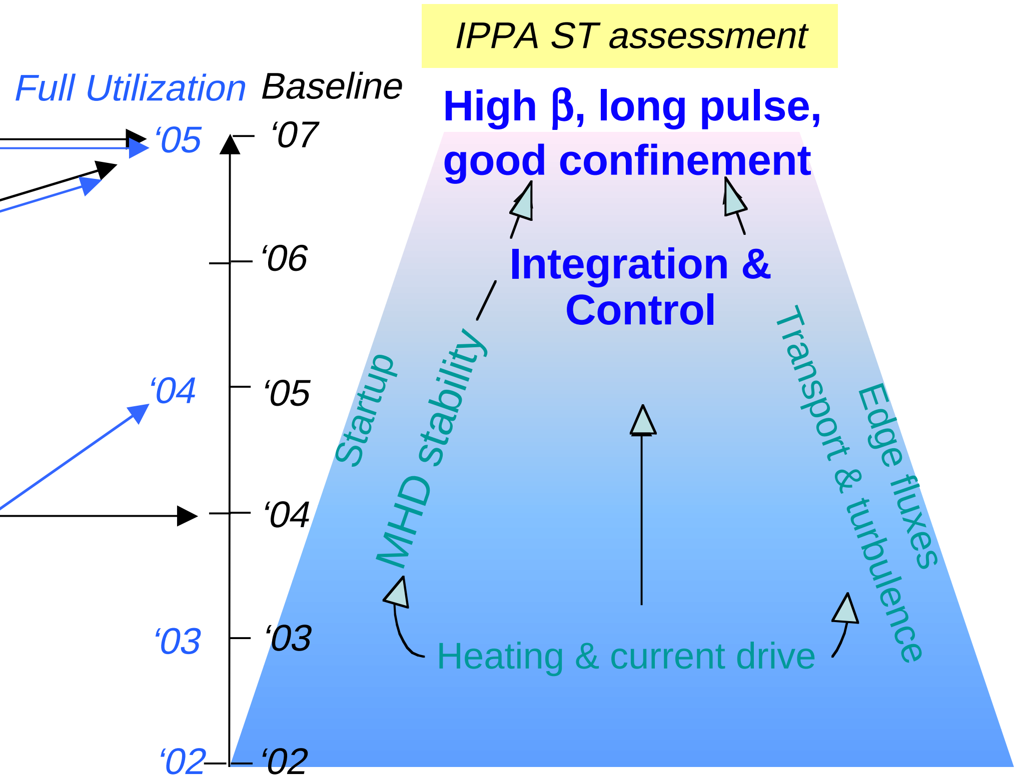
From Fujita et al., PRL 87, Dec. 10 2001
Also, JET: Hawkes, Stratton, et al., PRL 87, Sept. 10 2001

Integration of topical areas requires advanced control capability in addition to mastery of topical science

Integrate mode control of high β, high τ_E for 5 τ_E

Characterize plasma-fast ions-wave interactions

Integrate passive high β, high confinement for 5 τ_E; Extend startup & sustainment to 1 s



Very flexible control system will be in place

Development of control capability & feedback algorithms requires full utilization of the facility

The long-pulse integration goal draws on each area of topical research

- With high confinement, do the transport and fueling sources yield a pressure profile compatible with MHD stability?
- Is there a path to a high beta, mode stabilized regime? Are the proposed strategies for mode stabilization effective?
- Can current be driven where needed to sustain a given high β, high τ_E plasma?
- Can v-s be preserved in the startup to enable long enough pulse?
- Will the density and heat flux control be sufficient to manage a long pulse?

An integrated understanding of magnetosonic wave-fast ion-thermal plasma interactions may have significance for ST attractiveness

CAEs and HHFWs are magnetosonic oscillations

- Fast ion/CAE/thermal ion coupling
  - Fast ions (>> V_{alfven}) generate CAE's
  - If CAE's heat thermal ions stochastically, this has important implications for ST attractiveness
- HHFW/fast ion interactions
  - Coupling already observed
  - Effectiveness of electron current drive will depend in part on this physics
  - Implications for interactions with alphas?
- How does this science influence our choice of operating scenario?

Goal: develop a complete enough understanding of magnetosonic wave-fast ion-thermal plasma interactions to help clarify the most attractive operating regimes

The NSTX program is aimed at meeting the IPPA ST assessment

- Assessment on attractiveness will be based on successful integration of many topical science areas
  - The interplay between MHD, transport, RF, boundary physics, CHI is key
- Full utilization of the facility will enable meeting the ST assessment by the end of '04.
  - Integration of high beta, long pulses, high τ_E for 5 τ_E
  - Demonstration of extrapolable startup solution
  - Understanding of extrapolable wall flux solution

    Lack of full utilization will delay the assessment by at least two years
- The topical science areas give to and draw upon other areas of toroidal plasma science

RF research in several areas will continue to be key, and needs have been identified

- HHFW heats effectively; can it drive current?
- Evidence for HHFW interaction with fast ions found (Rosenberg (Ph.D. Thesis), Medley)
  - Important for assessing CD efficiency
  - New phenomena: magnetosonic wave/fast ion interaction
- EBW emission consistent with strong L_n dependence near upper hybrid layer (Jones, Taylor, Efthimion)
- EBW as a tool for NTM control, plasma startup will be investigated
  - with analysis and with research on CDX-U and on Pegasus