NSTX-U

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Solenoid-Free Plasma Start-Up & Ramp-Up

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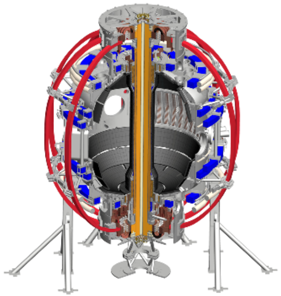
PPPL

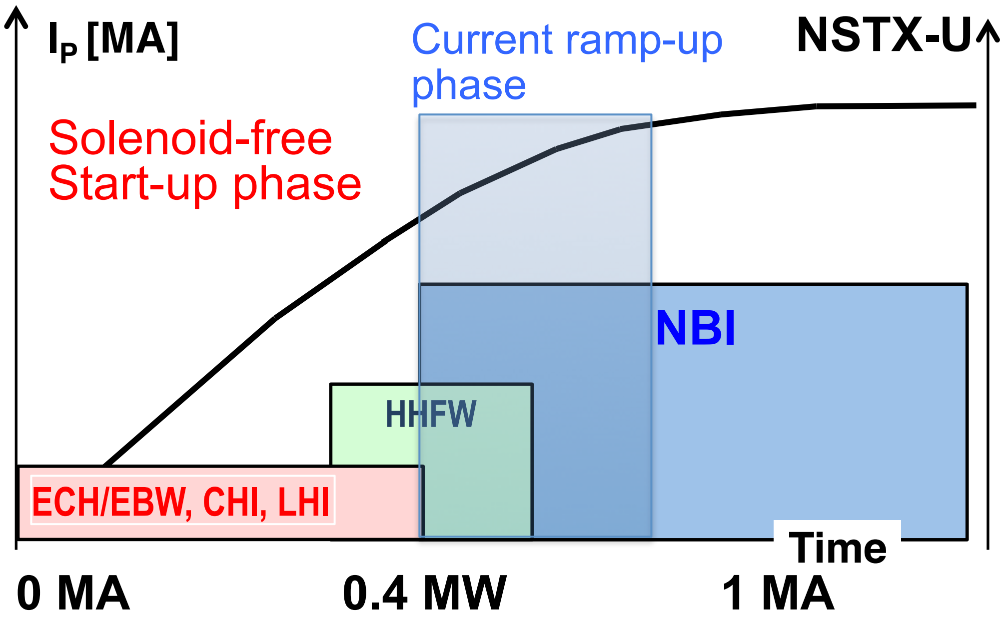


Solenoid-free Start-up and Ramp-up are Critical Issues for Compact ST and Tokamak-based Reactors

- ST has been addressing critical issue of solenoid-free start-up
  - A compact ST has little space for a central solenoid
  - Solenoid-free start-up is also attractive for tokamak designs

- Maximizing solenoid-free start-up currents reduces reliance on less developed non inductive current ramp-up scenarios

- Few MA start-up current is projected for reactors
  - Higher currents may be feasible



ECH / EBW – Utilize 1 – 2 MW 28 GHZ gyrotron
CHI – Coaxial Helicity Injection up to ~ 400 kA
LHI – Local Helicity Injection up to ~ 400 kA
HHFW - ~ 4 MW 30 MHZ high Harmonic Fast Wave
NBI - ~ 10 MW NBI

Solenoid-Free Start-Up / Ramp-Up
Present Plans

- NSTX-U can start with Ramp-Up studies using inductively generated targets with HHFW & NBI, as in original plan.
  - Eventual goal is to transfer this capability to CHI/LHI/ECH started targets when one or more of these are implemented on NSTX-U

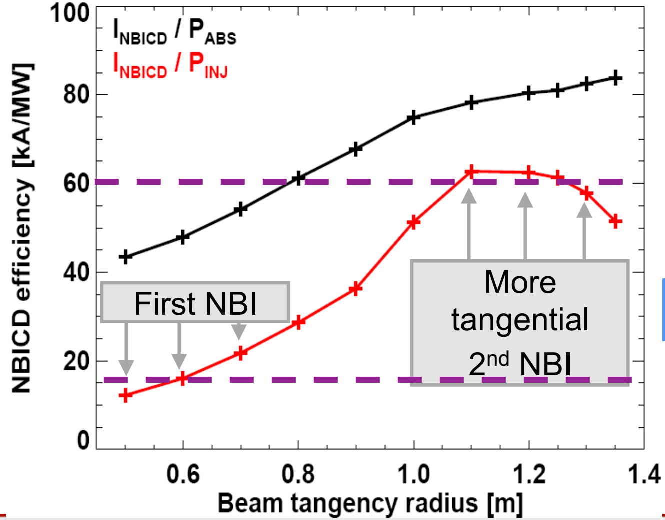
- NSTX-U SFPS experiments deferred in the near term; progress will be made through collaborations and theory/modeling:
  - Supporting ECH / EBW start-up studies being conducted on QUEST
  - Pegasus has been investigating Local Helicity Injection
  - Supporting CHI work being conducted on QUEST in Japan

On NSTX-U, Non-inductive Ramp-Up from ~0.4MA to ~1MA Projected to be Possible With New CS + More Tangential 2nd NBI

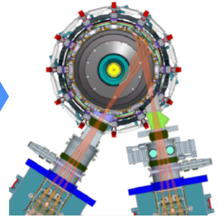
- **2nd NBI provides 3-4x higher CD at low I_P:**
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
    - Will test on NSTX-U during YRS 1 & 2
  - 1.5-2x higher current drive efficiency

E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

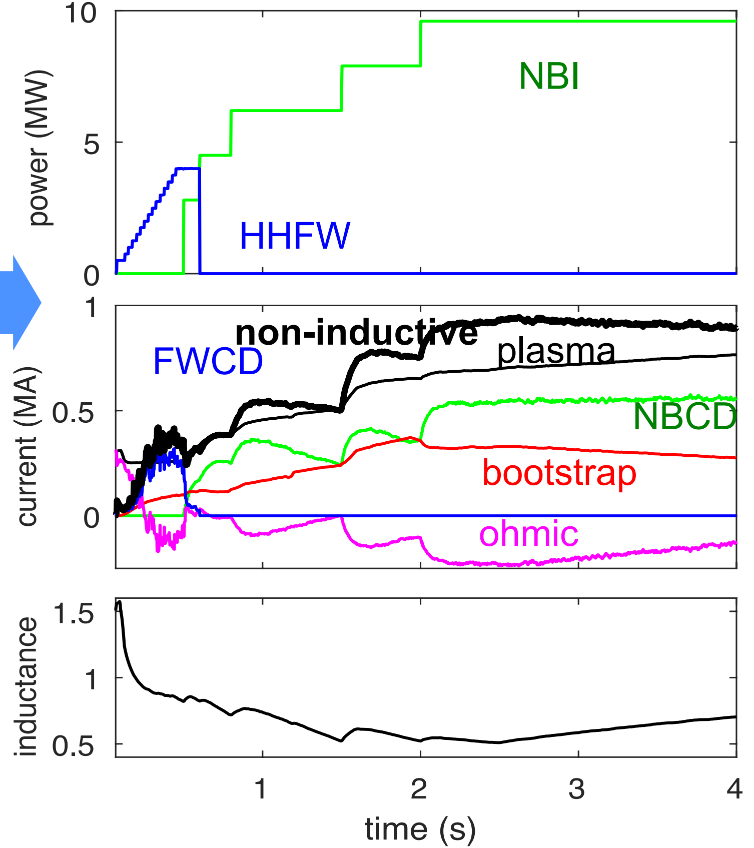
$\overline{n}_e = 2.5\times10^{19} m^{-3}$, $\overline{T}_e$ = 0.83keV



TRANSP Simulations



First NBI   2nd NBI

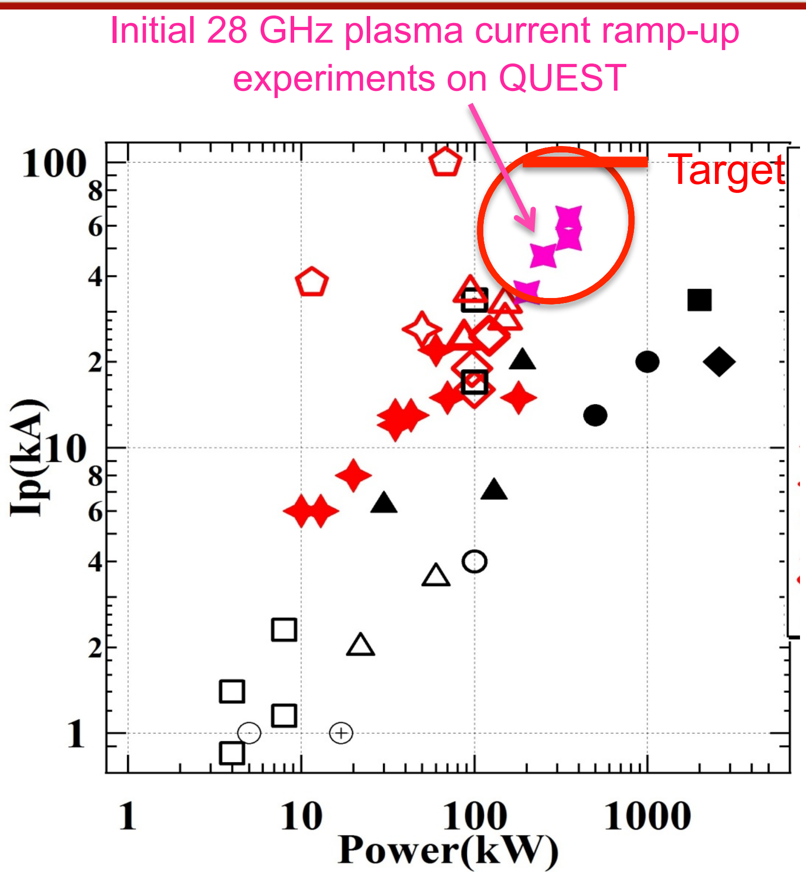


High Current Helicity Injection Start-Up can Reduce Reliance on Less Understood Current Ramp-Scenarios

Method	Device	Current Scaling	Present Demonstrations
ECH / EBW	MAST QUEST	Current scaling not understood	<100 kA on QUEST & MAST (Not coupled to induction)
Local Helicity Injection (LHI) [Small area electrodes / high voltage]	Pegasus	Dynamo Current Drive models need development $\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$	200 kA on Pegasus (Coupled to induction)
Steady State CHI [Large area electrodes / lower voltage]	HIT-II HIST	Dynamo Current Drive models need development	400 kA on NSTX 200 kA on HIT-II (Not coupled to induction)
Transient CHI [Short 2-3ms pulse discharge]	HIT-II NSTX QUEST	Scaling to large devices well understood	200kA on NSTX 100 kA on HIT-II Demonstrated flux saving on NSTX by ramping to 1MA with inductive drive

QUEST Has an On-Going Active Program on ECH
NSTX-U is Contributing via. Theory and Diagnostic Support

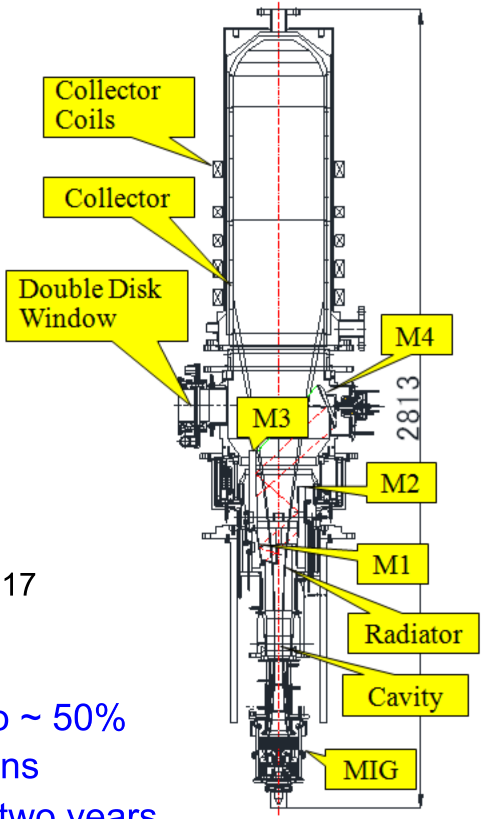
- Current efficiency increased from 66kA/270kW to 85kA/230kW using new wave guides and polarizer
- Further polarizer improvements should enable higher power (available up to 400 kW) operations.
- Model validation of non-thermal electron tail created by the ECCD being carried out by PPPL researchers (Bertelli, Poli, Taylor)
- X-ray camera from PPPL together with modeling to improve understanding of physics of ECCD (Delgado-Aparicio)

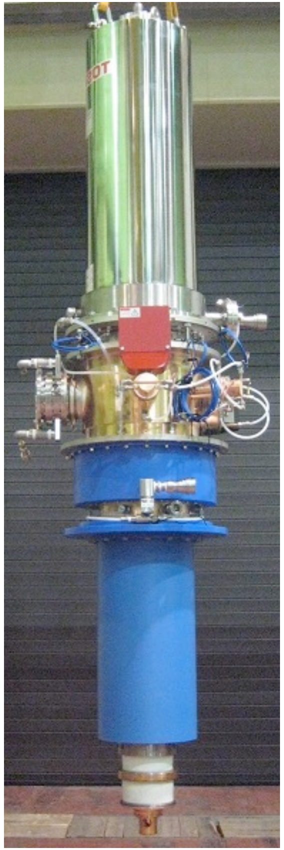


28GHz-34.8GHz Two Frequency Gyrotron Development by University of Tsukuba, Japan

28 GHz 2 MW Dual-frequency Gyrotron			
Frequency	28 GHz		34.77 GHz
Output Power	2 MW	0.4 MW	1 MW
Pulse Width	3 s	CW	3 s
Output Efficiency	50% (with CPD)		
Beam Voltage	80 kV	70 kV	80 kV
Beam Current	70 A	20 A	40 A
MIG		triode	
Cavity mode	$TE_{8,5}$		$TE_{10,6}$
Output mode	Gaussian like		
Output Window	Sapphire Double Disk		
Collector	Depressed Collector		
	Sweeping coils		

T. Kariya, NF 2017





- High power test to be conducted in 2018 for > 1.5 MW at 28 GHz.
- CPD (Cathode Potential Depressor) increased the tube efficiency to ~ 50%
- Double disk window developed for long-pulse/steady-state operations
- High power tube should be technically available for NSTX-U within two years

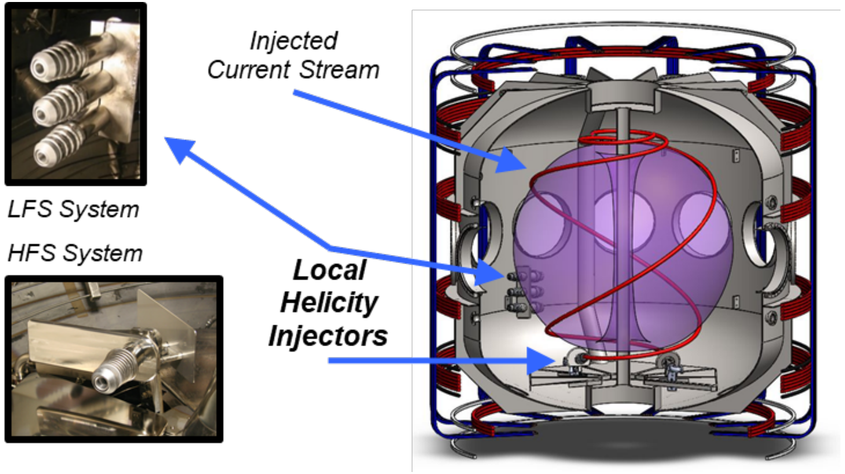
Local Helicity Injection (LHI) Providing High-I_p Start-Up being Developed on PEGASUS ST (Univ. of Wisconsin)

- LHI provides non-solenoidal startup and sustainment:
  - $I_p \leq$ 0.2MA to date (with less than 8 kA of injected current)
  - Inboard and outboard injection location investigated

- LHI also enables access to interesting physics regimes:
  - The current drive mechanism does appear to fundamentally be due to edge localized reconnection activity
  - Strong edge drive provides access to low ℓ_i and very high β_T plasmas at relatively high I_p discharges at very low B_T

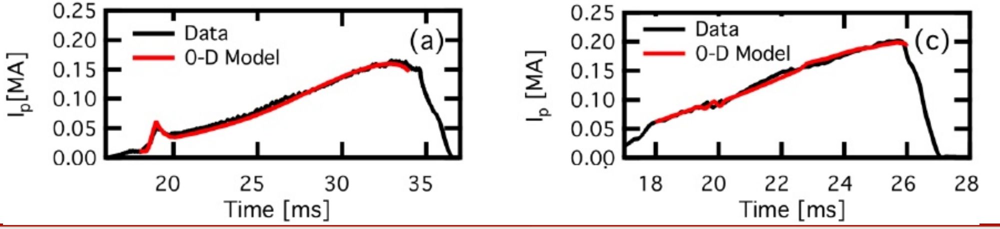
J.A. Reusch,et. al, PoP (submitted)

LHI Injector Geometries Vary Dominant Drive on PEGASUS

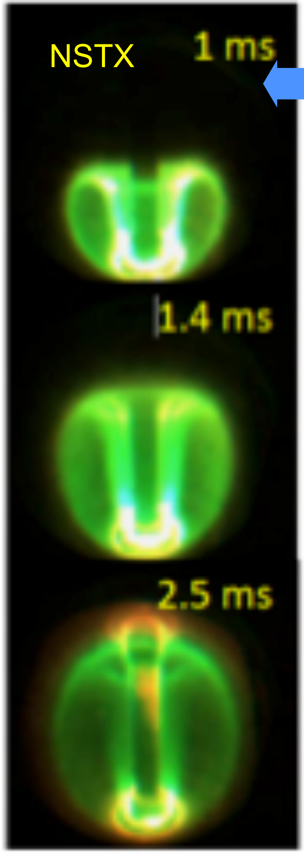


LHI-Driven I_p ~ 0.2 MA Scenarios Test Predictive $I_p(t)$ Model

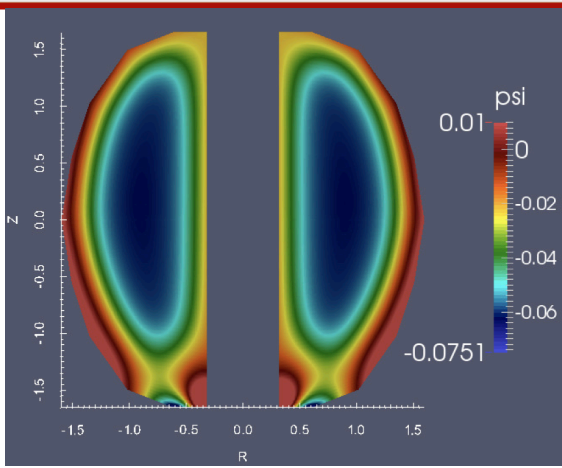
Outboard: V_{IND} Dominant *Inboard: V_{LHI} Dominant*

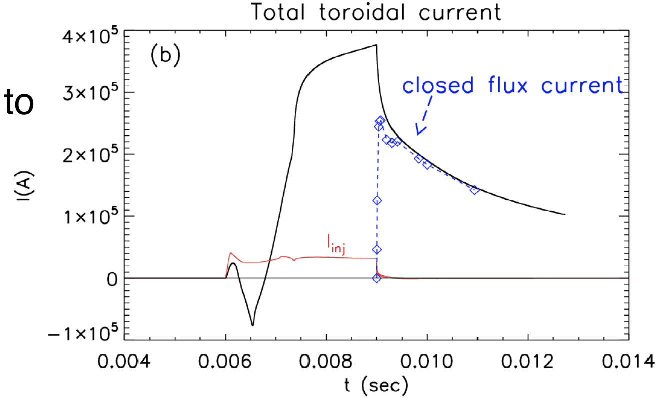


Transient CHI: High Fraction of Open to Closed Flux Conversion in NIMROD Simulations & in Experiments

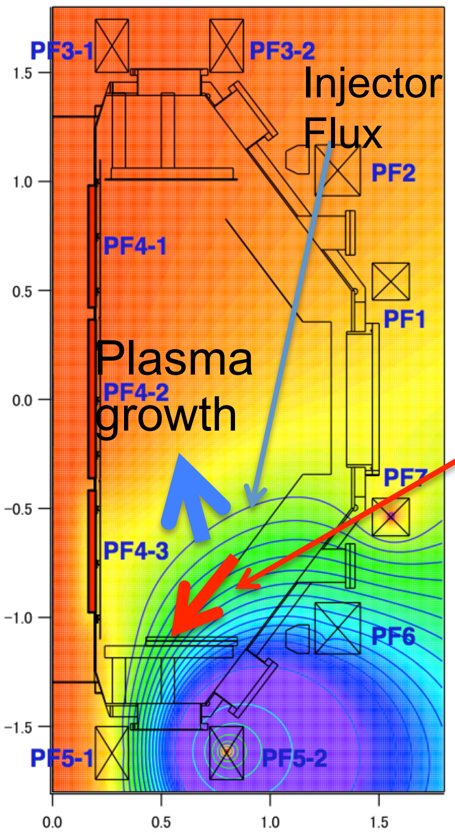


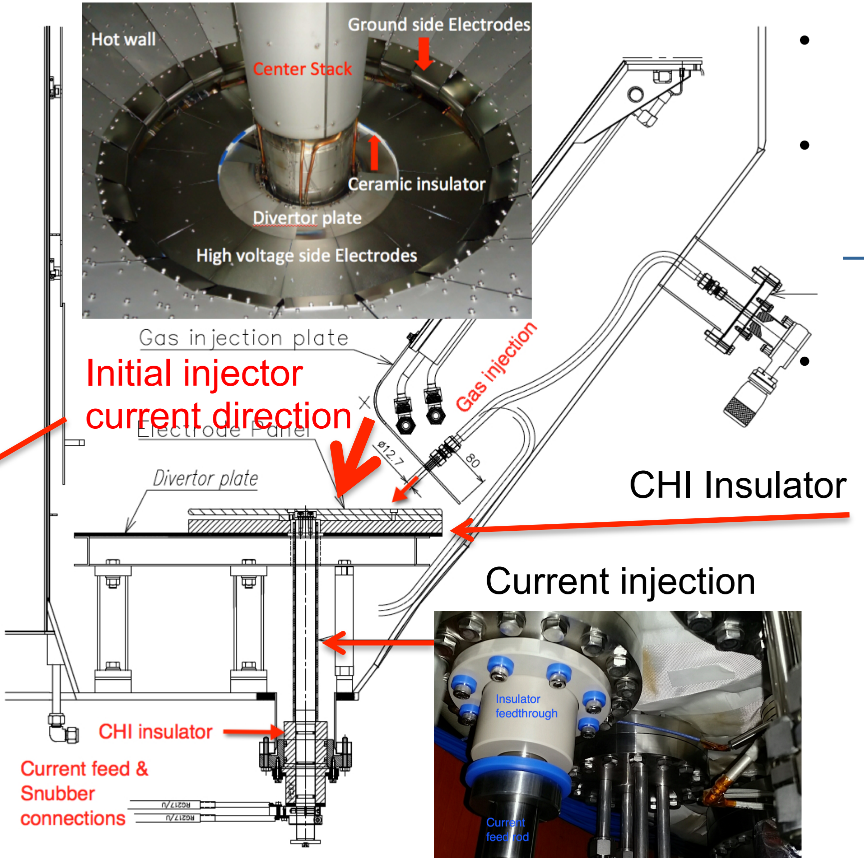
- Transient CHI injects poloidal magnetic flux from divertor area into vessel on a 1-3ms time scale
  - Injector flux shaping and injector current ramp-down causes open flux to form closed flux surfaces (like in a soap bubble)
- Promising PoP level tests on NSTX-U motivated us (during the NSTX-U construction period) to examine and develop CHI implementation concepts for a reactor (R. Raman, et al., Fus. Sci. Technol. **68**, 674 (2015))
- Encouraged QUEST to implement & test reactor-relevant CHI capability
- Significantly ramped up computational modeling work to understand CHI scaling
- Theory and NSTX-U/HIT-II Experimental work has resulted in simple scaling relation for transient CHI to project to reactor scale devices ($I_p \propto$ Injected flux)



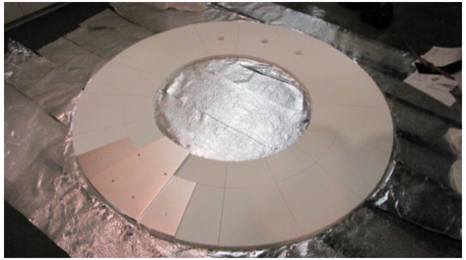


QUEST (in Japan) is Developing Reactor-Relevant CHI Configuration & Will Test ECH Heating of a Transient CHI Plasma



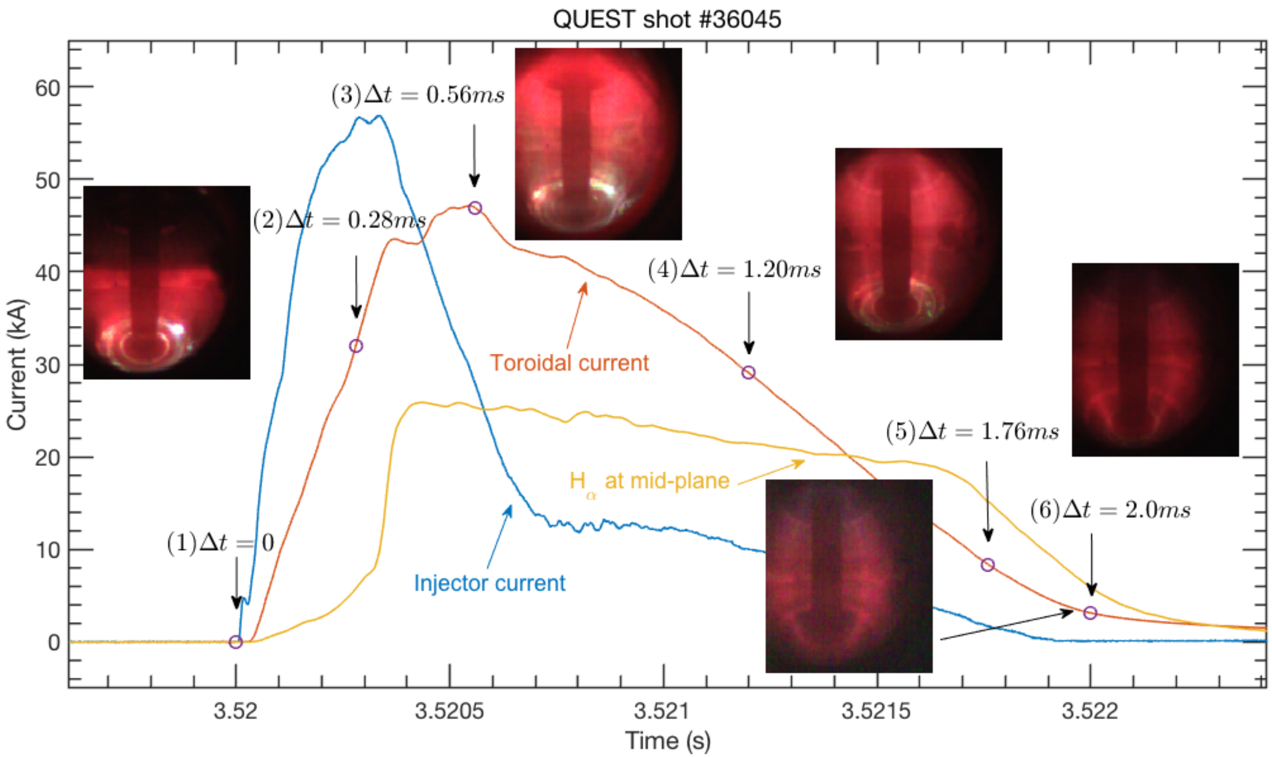


- In reactor concept insulator can be shielded from neutrons
- Insulator not part of vacuum boundary as on NSTX
  - Needs experimental test / verification
- CHI system on QUEST is similar in concept to the one planned for NSTX-U



QUEST CHI is a NSTX-U CHI Team Led Effort

Transient CHI Discharges Successfully Established in QUEST



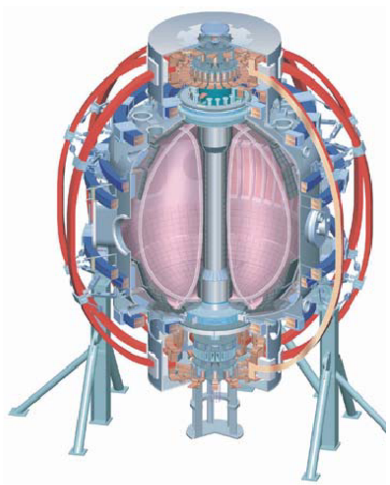
ECH heating to be tested during 2018

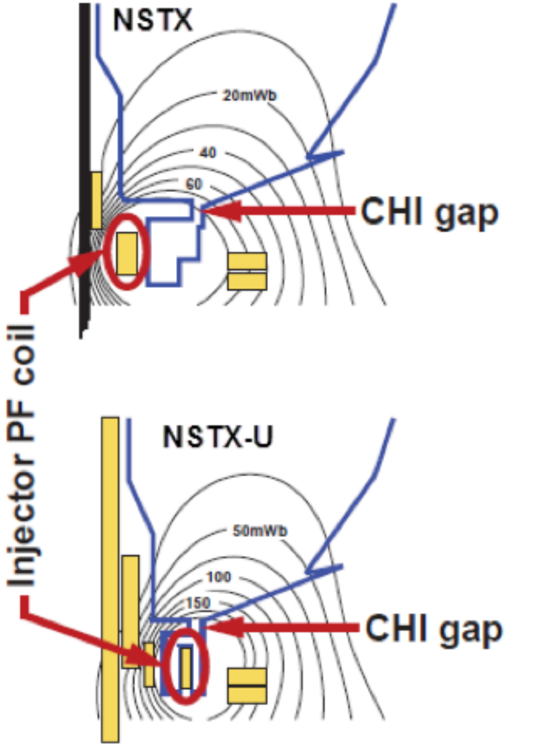
Solenoid-Free Start-Up / Ramp-Up
NSTX-U Plans Utilize Multiple Facilities

- NSTX-U Ramp-Up studies will continue using inductively generated targets with HHFW & NBI, as in original plan.
- NSTX-U solenoid-free start-up activities will be conducted in other ST facilities in the near term:
  - Supporting CHI work being conducted on QUEST in Japan
  - Supporting ECH / EBW start-up studies being conducted on QUEST
  - Pegasus is studying LHI
- Preparation toward NSTX-U CDRs:
  - NSTX-U ~ 1.5 MW, 28 GHz gyrotron CDR completed
  - NSTX-U reactor-relevant CHI CDR to be ready in ~ 3 years via QUEST and other experiments/modeling

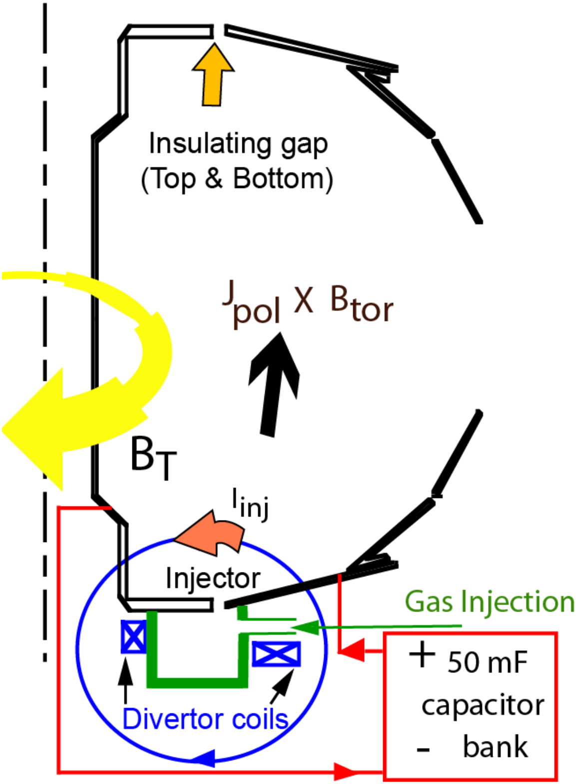
Back-Up Slides

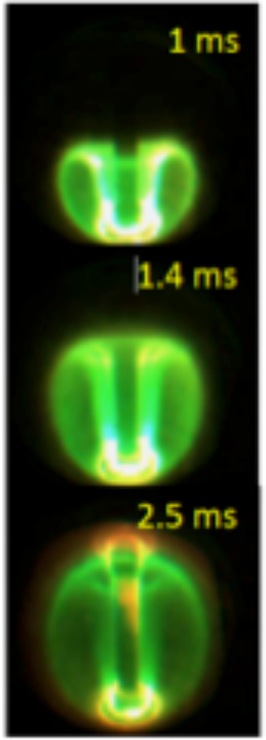
Transient CHI Start-Up



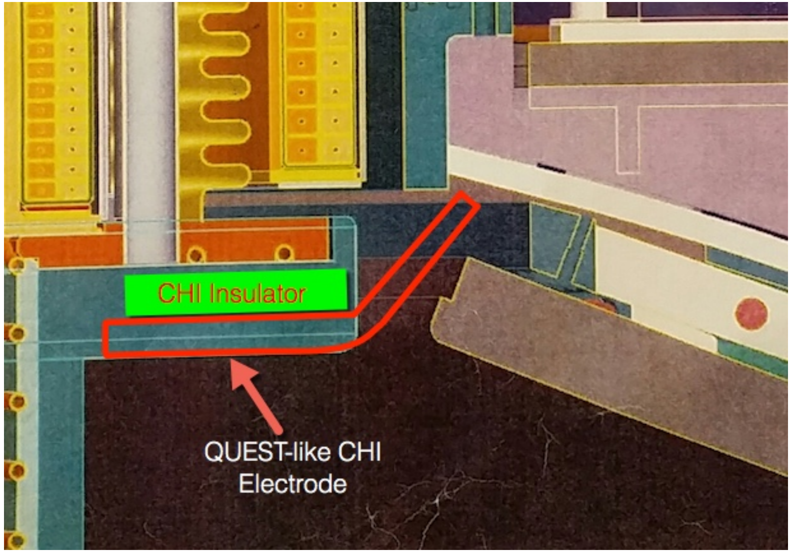


Inj. Flux in NSTX-U > enclosed flux in 1MA plasma





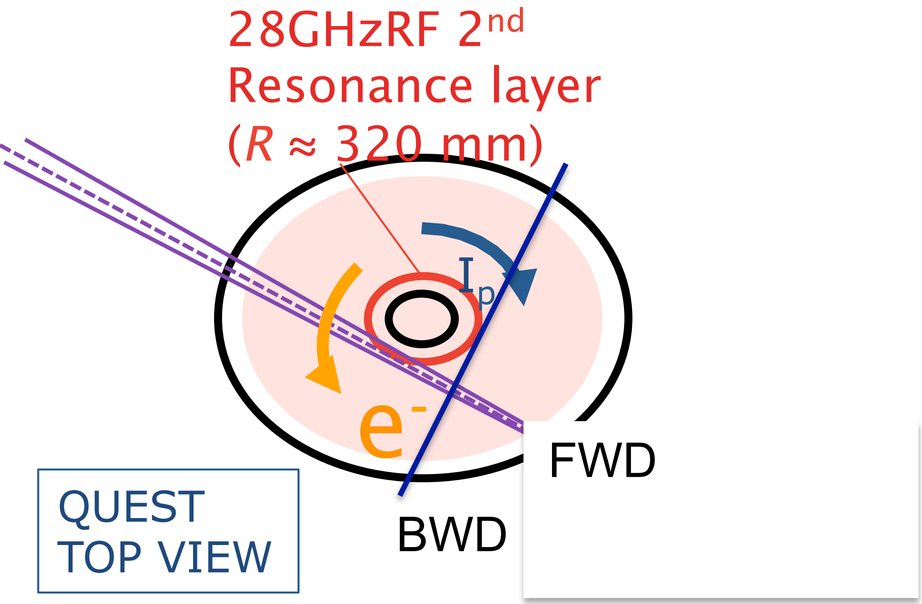
CHI start-up to ~0.4MA is projected for NSTX-U, and is projected to scale favorably to next-step STs

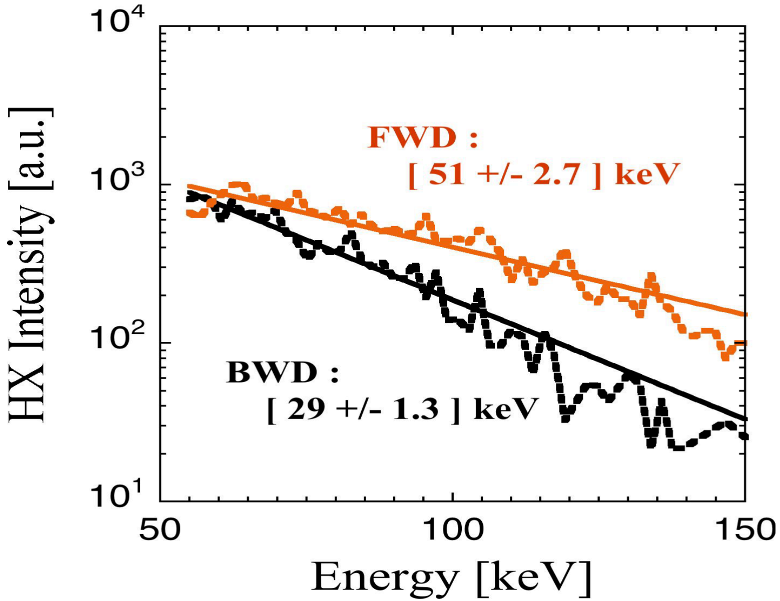


- Conceptual concept for "QUEST– like" CHI electrode in NSTX-U upper divertor
- Utilizes full injector flux capability in NSTX-U
  - I_p > 400 kA
  - 1MA Start-up potential

Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Aspect ratio: A	1.30	1.50	1.50	1.70
Elongation: κ	2.6	2.8	3.1	3.3
Major radius: R_0 [m]	0.86	0.93	1.2	2.2
Minor radius: a [m]	0.66	0.62	0.80	1.29
Toroidal field at R_0: B_T [T]	0.55	1	2.2	2.4
TF rod current: I_{TF} [MA]	2.4	4.7	13.2	26.4
Toroidal flux: Φ_T [Wb]	2.5	3.9	15.8	45.7
Reference maximum sustained plasma current: I_{PS} [MA]	1	2	10	18
Start-up plasma normalized internal inductance: l_i	0.35	0.35	0.35	0.35
Injector flux footprint: d [m]	0.6	0.56	0.73	1.17
Injector flux for projecting start-up current: ψ_{inj} [Wb]	0.047	0.10	0.66	2.18
Bubble-burst current: I_{bb} [kA]	3.3	9.0	79	165
Injector current: I_{inj} [kA]	4.0	10.8	95	198
Start-up plasma flux: ψ_p [Wb]	0.04	0.08	0.53	1.74
Start-up plasma current achieved or projected: I_P [MA]	0.20	0.40	2.00	3.60
Current multiplication: I_P / I_{inj}	50	37	21	18
Multiplication limit: Φ_T / ψ_{inj}	53	38	24	21
Injector current density [kA/m^2]	4.9	12	63	39

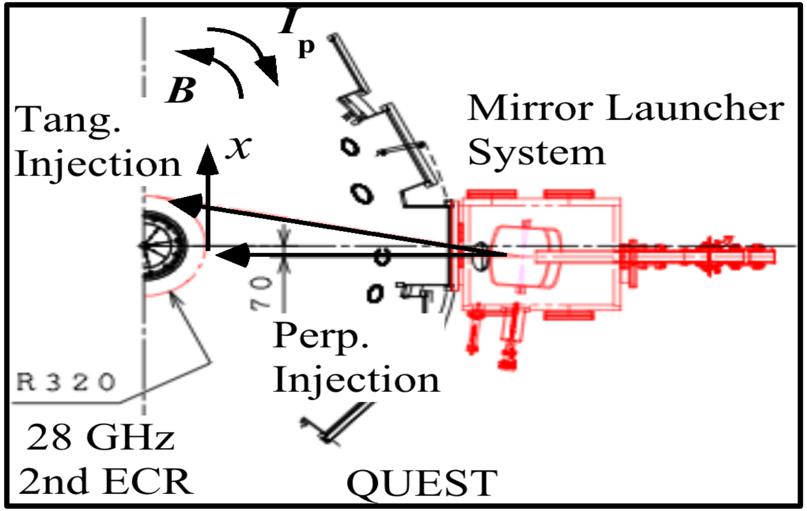
QUEST ECH current start-up generates forward fast electrons NSTX-U plans to install x-ray camera to elucidate ECCD physics



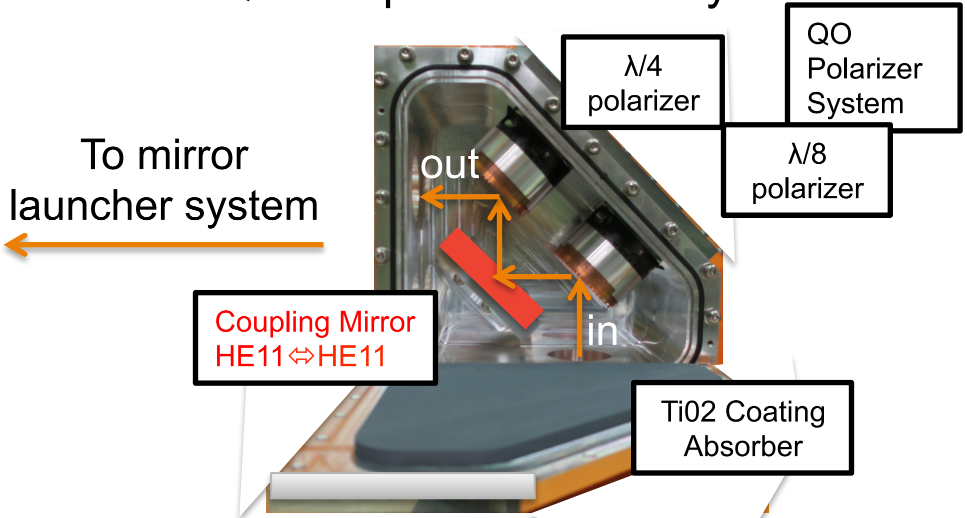


- NSTX-U multi-energy soft x-ray camera to be used to measure the QUEST ECH induced high energy electrons with high spatial and time resolutions.
- Developing a new synthetic diagnostic tool for multi-energy soft x-ray camera with UT.
- On-going modeling with GENRAY and CQL3D for ECH fast electron generations.

QUEST New ECH Beam Steering, Focusing and Polarization Capability Enabled High Current Access and Physics Study



Quasi-optic Polarizer System



- Steering and focusing mirror launcher system together with quasi-optic waveguide enables incident polarization, $N_{//}$, and deposition profile scanning
- ECH power is presently limited by arcing in the quasi-optic waveguide. Improvements are being made for next campaign for higher power (and higher current) operations.
- Current ramp-up and sustainment mechanisms will be also investigated via parameter scanning.