

Final Report for DOE grant # DE-FG03-02ER54686
Roger Raman – PI, University of Washington, Seattle, WA 98195
Grant ending: July 14, 2004

The CT injector originally used for injecting CTs into 1T toroidal field discharges in the TdeV tokamak was shipped PPPL from the Affiliated Customs Brokers storage facility in Montreal during November 2002. All components were transported safely, without damage, and are currently in storage at PPPL, waiting for further funding in order to begin advanced fueling experiments on NSTX. The components are currently insured through the University of Washington.

Several technical presentations were made to investigate the feasibility of the CT injector installation on NSTX. These technical presentations, attached to this document, were:

- [1] Motivation for Compact Toroid Injection in NSTX, NSTX Physics Seminar, April 7, 2003 by R. Raman (attached). Also attached as STI File: Raman_040703.pdf
- [2] Assessment of the Engineering Feasibility of Installing CTF-II on NSTX, April 22, 2003, by R. Raman (attached).
- [3] Assessment of the Cost for CT Installation on NSTX – A Peer Review, May 20, 2003, H.W. Kugel, R. Raman, L. Dudek, F. Jones, L. Roquemore (attached).
- [4] CT Fueling for NSTX Fy 04-08 steady-state operation needs, NSTX Fy 04-08 plans meeting, June 24-26, 2002, R. Raman, T.R. Jarboe, H.W. Kugel.

At the ITPA meeting on Steady-State operations held at GA during October 2003, a presentation was made on CT Fueling [5, also attached as STI File: Raman_100803.pdf]. The summary from this meeting stated: "R. Raman made a presentation on the injection of compact toroids (CT) for fuelling advanced scenarios. The approach appears interesting and a plan for developing this technique was proposed, the first step being a full test on NSTX, which appears essential before considering such a technique for ITER. The group is in favor of this proposal." [6]. The ITPA steady state group, thus, endorsed the proposal to conduct a CT Fueling test on NSTX.

As suggested by the ITPA meeting summary, CT injection experiments on NSTX will make a unique and very important contribution to ITER, while developing needed systems for the ST concept (fueling requirements for steady state high-beta operation and momentum injection capability). This is because no other large machine is at present engaged in such an experiment mainly because no one else has the capability to conduct such an experiment on a near-time scale.

We are at present investigating, through PPPL, the possibility of re-assembling the CT hardware in a test lab at PPPL.

The US is currently the world leader in CT Fueling technology and because of NSTX, is in a unique position to conduct the required next-step experiments on a near time scale, as reflected by the endorsement from the ITPA summary [6]. Eventually such a system is also needed for the ST concept.

Recent References:

- [1] Motivation for Compact Toroid Injection in NSTX, NSTX Physics Seminar, April 7, 2003 by R. Raman (attached).
- [2] Assessment of the Engineering Feasibility of Installing CTF-II on NSTX, April 22, 2003, by R. Raman (attached).
- [3] Assessment of Cost for CT Installation on NSTX – A Peer Review, May 20, 2003, H.W. Kugel, R. Raman, L. Dudek, F. Jones, L. Roquemore (attached).
- [4] CT Fueling for NSTX Fy 04-08 steady-state operation needs, NSTX Fy 04-08 plans meeting, June 24-26, 2002, R. Raman, T.R. Jarboe, H.W. Kugel.
- [5] R. Raman, Fueling requirements for steady-state, high bootstrap current fraction discharges, ITPA Meeting on Steady State and Energetic Particles Working Group, General Atomics, October 8-10, 2003.
- [6] Annual report of the ITPA Steady State and Energetic Particles Working Group (2003), Page 9, section 9 of the file ITPATGSSO&EP_2003_annual_rep.d



Assessment of the Engineering Feasibility of Installing CTF-II on NSTX

In partial fulfillment of work commissioned by
DOE grant No. DE-FG03-02ER54686

Roger Raman
University of Washington, Seattle
and the NSTX Research Team

CT Engineering Review Meeting
Princeton Plasma Physics Laboratory

April 22, 2003

Raman, CT Tech. Rev. 4/22/03

Chronology of collaborator Compact Toroid Fueling presentations at NSTX Research Forums

	<i>U - Washington</i>	<i>UC - Davis</i>
Dec. 1997	R.Raman-1st pres. Action: submitted proposal to DOE	D.Hwang-1st pres. Action: submitted proposal to DOE
Jan. 1999	R.Raman -2nd pres.	D.Hwang-2nd pres.
Jan. 2000	R.Raman - 3rd pres. (in Advanced Concepts)	
Jan. 2001	R.Raman - 4th pres. (in Heat., CD & Fueling) & 5th pres. (in Transport & Turbulence) Action: submitted 2nd proposal to DOE	
Nov. 2001	R.Raman - 6th pres. (in Boundary Physics)	
June. 2002 5yr Res. Plan. Meet.	R.Raman - 7th pres. (in Boundary Physics) R.Raman - 8th pres. (in Integrated Scenario Dev.)	
July. 2002	Action: submitted 3rd proposal to DOE. Result: <i>Approved by DOE for CT injector Relocation & Evaluation</i>	

Outline of Talk

- Proposed Installation Plans
- CT Injection Plan time-line
- Installation cost estimates (H.W. Kugel)
- Conclusions

A CT is accelerated to high velocity and injected into the target plasma to achieve deep fueling

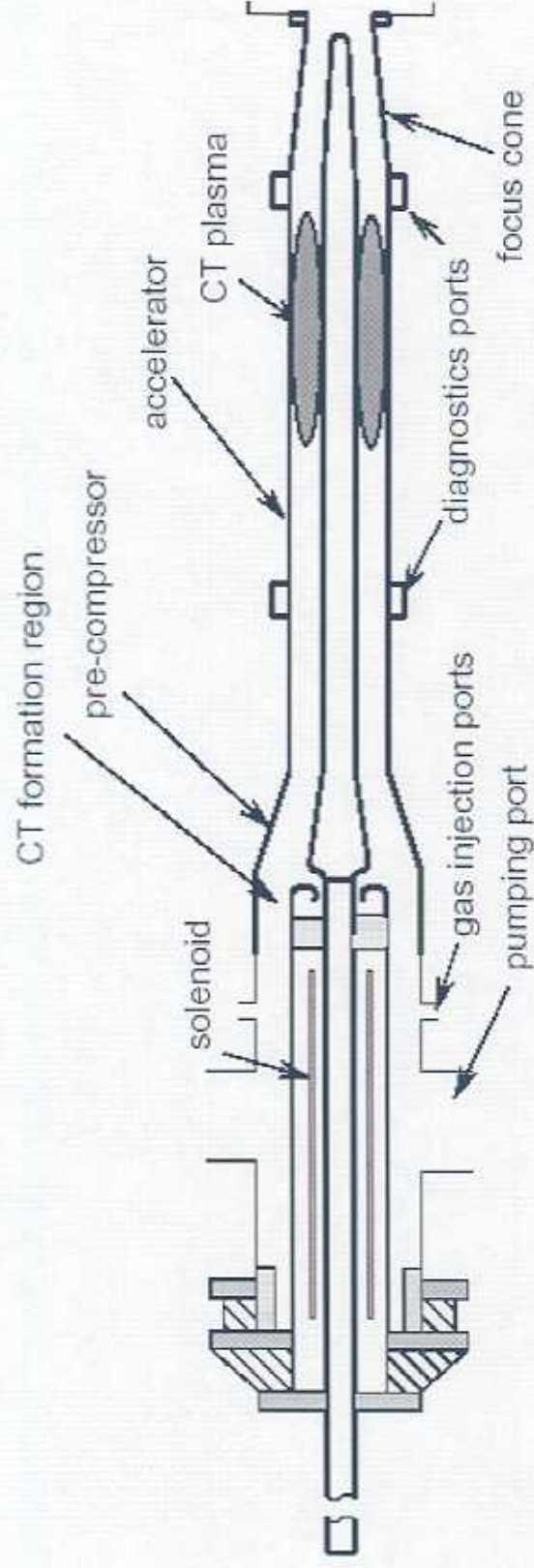


Compact
Toroid (CT)



Tokamak Plasma

A CT Fueler forms and accelerates CTs in a coaxial rail gun in which the CT forms the sliding armature

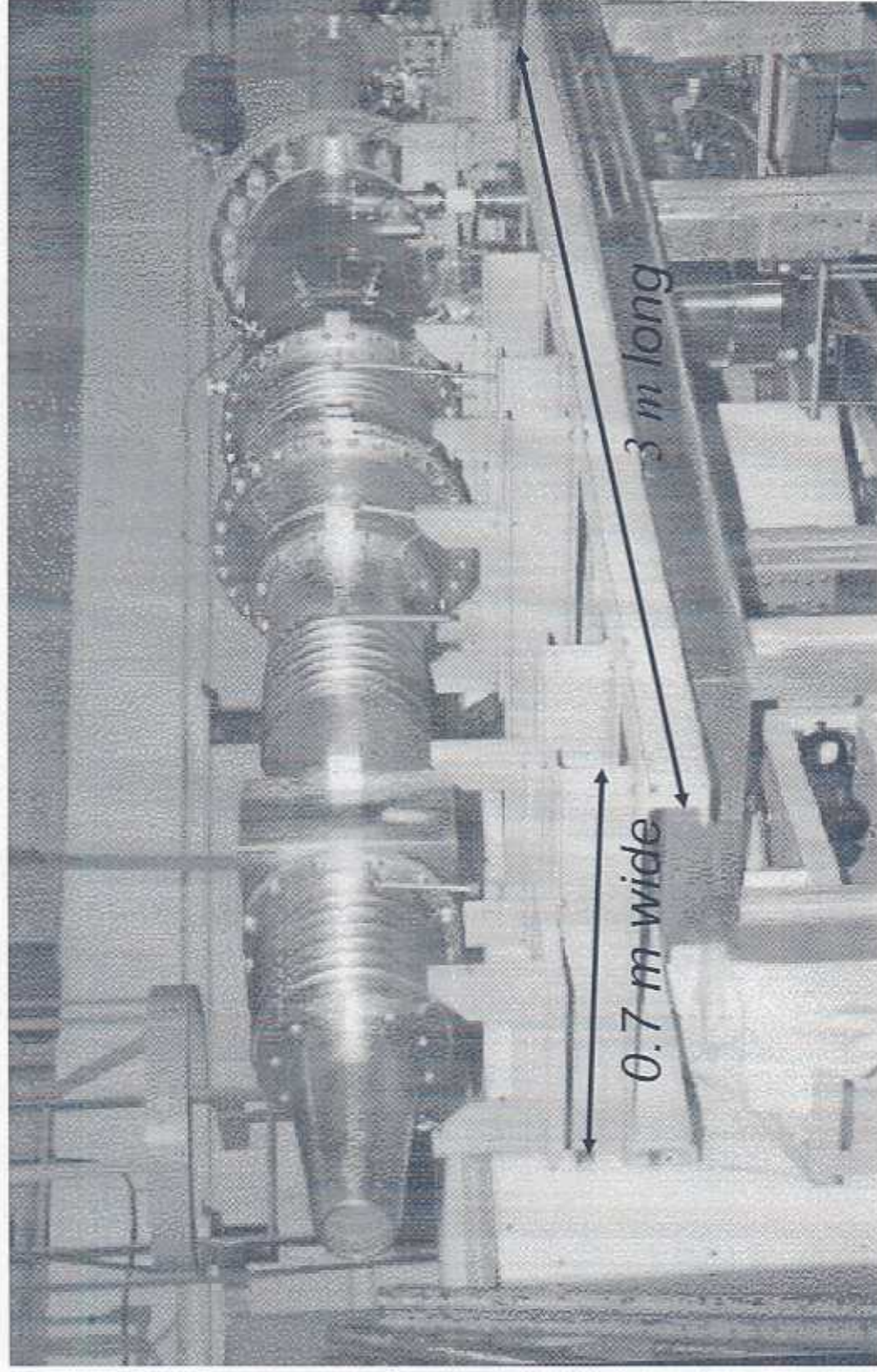


Raman et al., Fusion Techn., 24, 239 (1993)

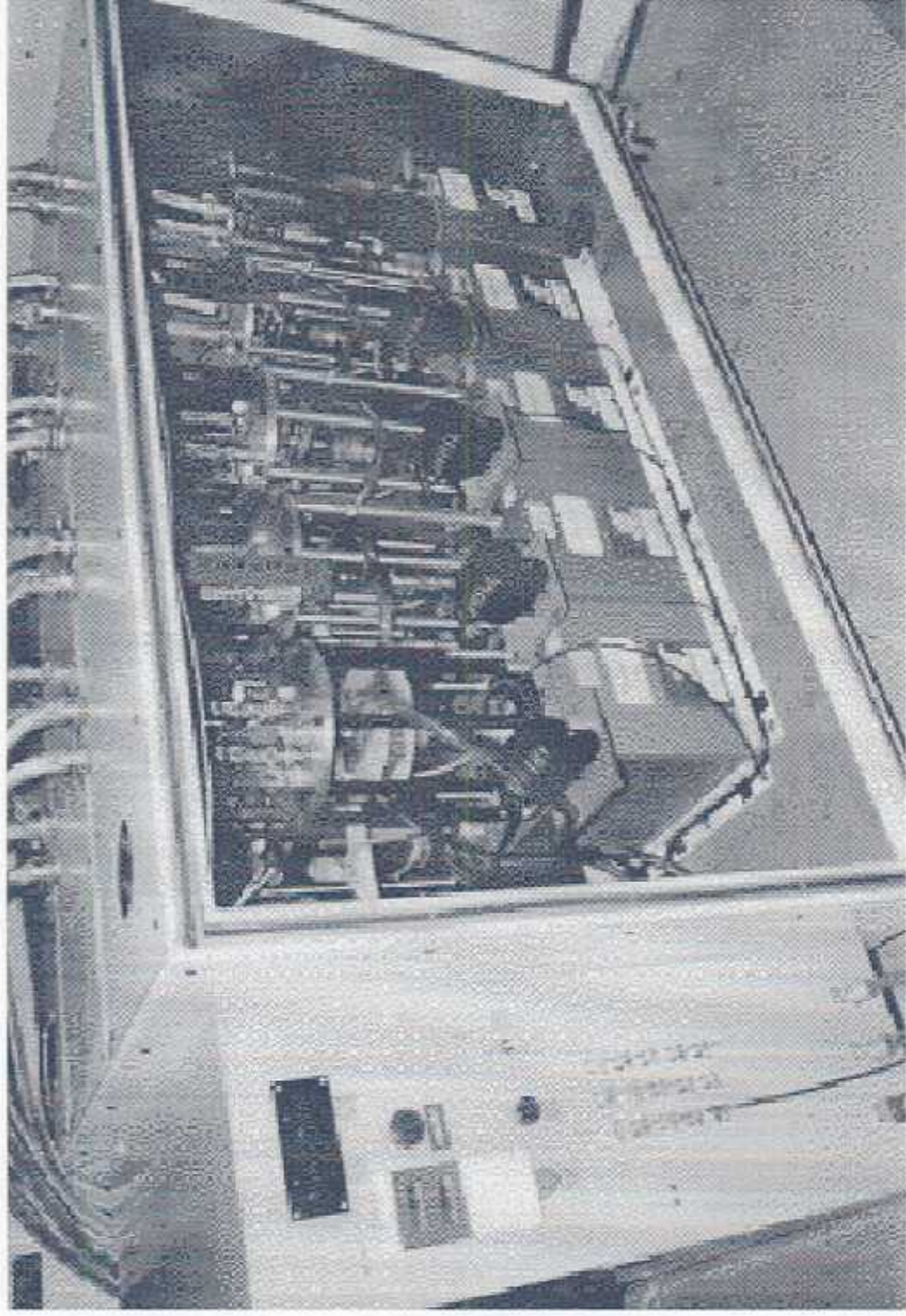
Amount of gas injected controls CT density
Applied voltage controls CT velocity
Control system specifies fuel deposition location for each pulse

Raman, CT Tech. Rev. 4/22/03

The CTF-II injector at PPPL



The CT Formation bank power supply (110VAC input)



Raman, CT Tech. Rev. 4/22/03

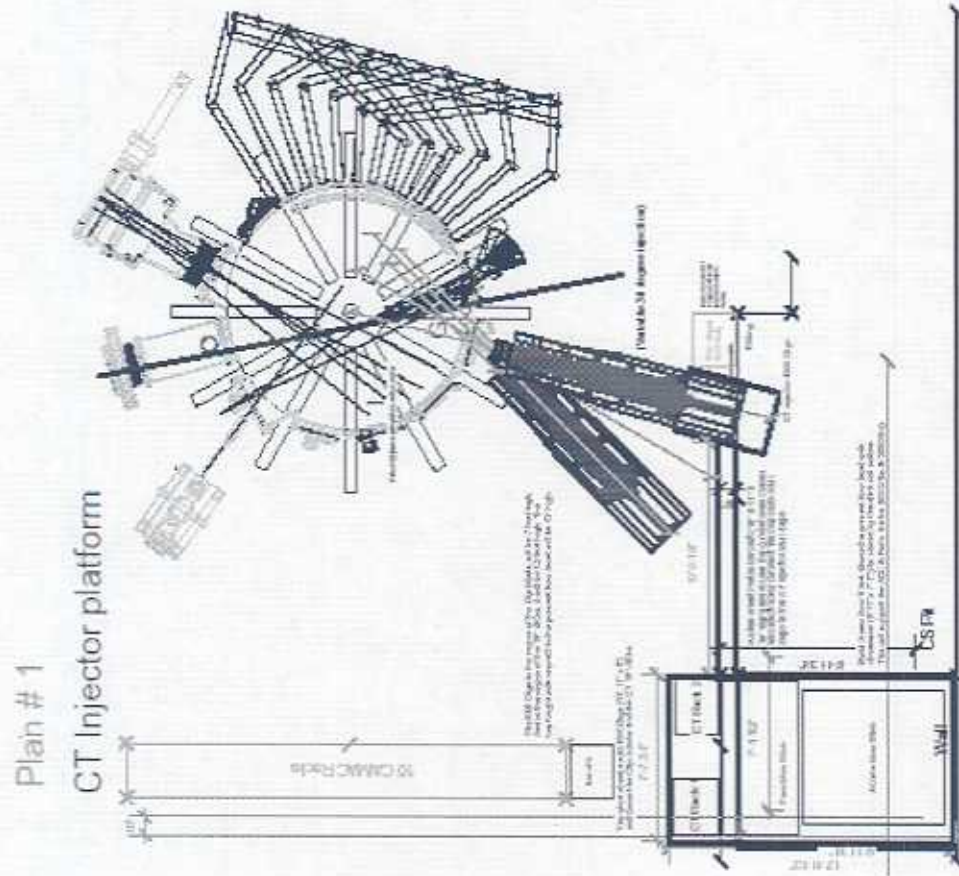
The ability to inject CTs immediately enhances NSTX experimental capability

- Immediate enhancement to NSTX experimental capability
 - Precise H-mode initiation capability valuable for on-going XPs
 - Leads to Electron Transport Barrier studies
 - Prompt density injection to avoid locked modes
 - Clarification of the edge barrier seen during Neon injection
 - Transport studies by isotopic impurity tailoring
 - He ash removal studies
- Other Possibilities
 - Momentum injection studies for transport barrier sustainment
 - Local current injection studies for suppression of NTMs
 - Reconnection studies are an important aspect of PPPL research

Objectives for CT Injection proposal

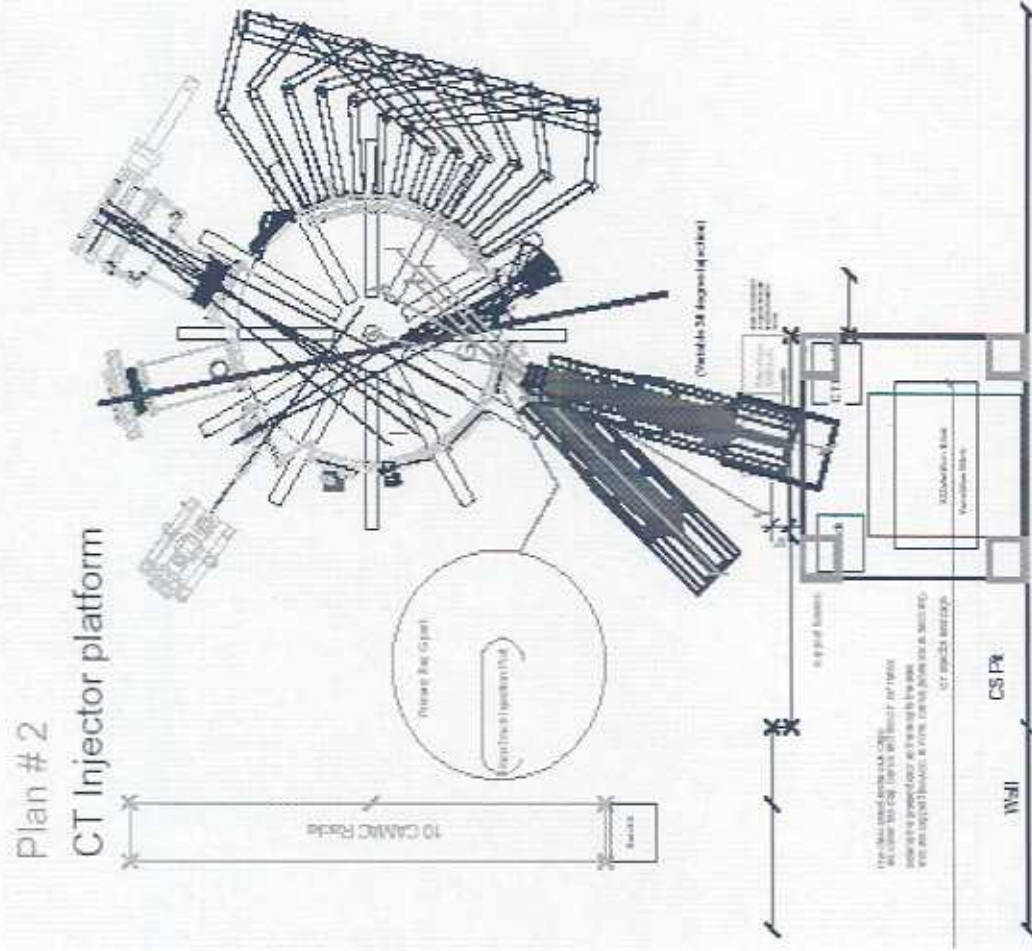
- Induce toroidal rotation or H-mode (during year-1)
- Establish CT parameters for controlled deep fuelling (during years 2 and 3)
 - Data needed for multi-pulse injector
- Use CT as a tool for other NSTX XPs (years 2 and beyond)

Installation Concept A

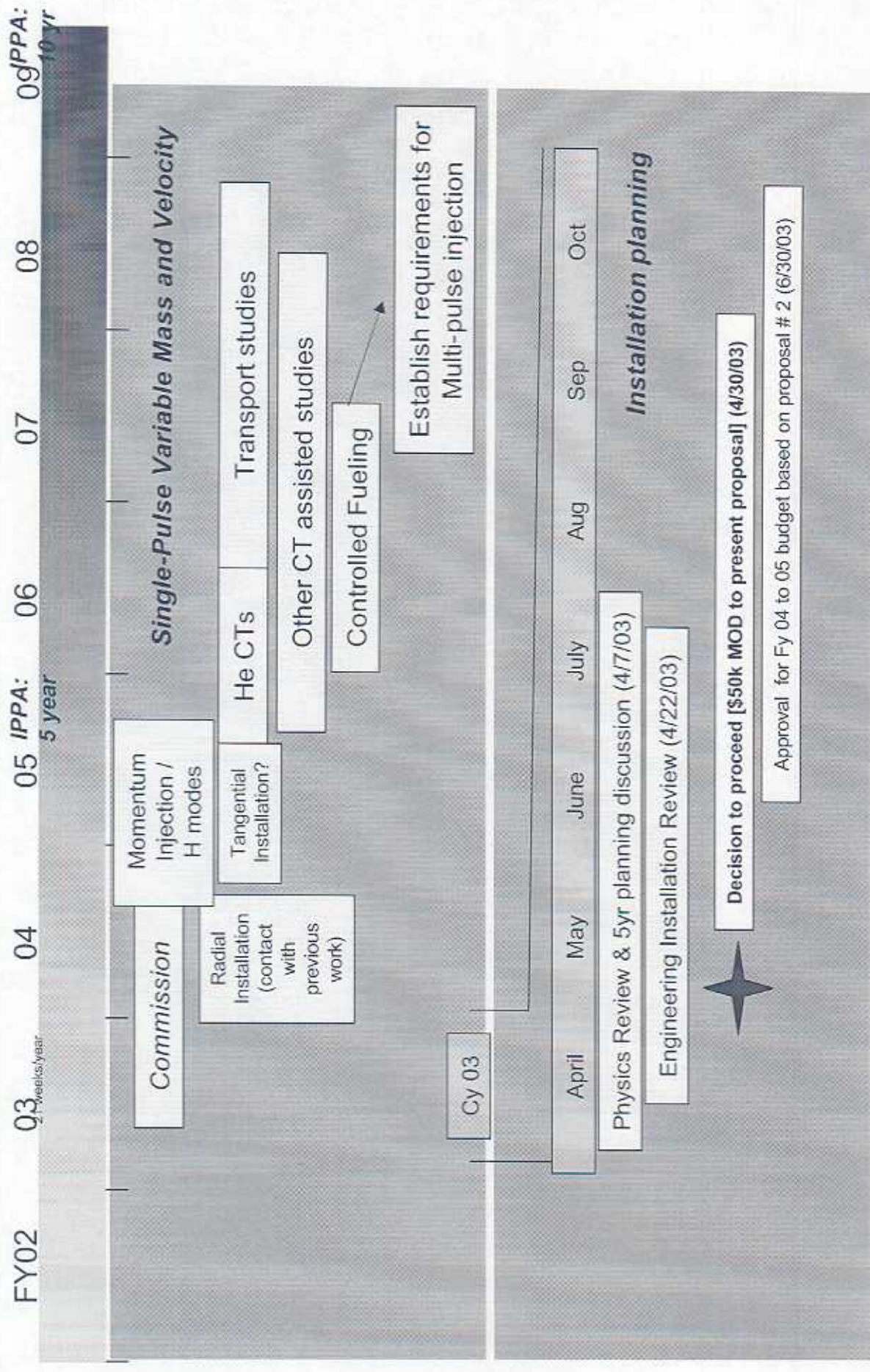


Raman, CT Tech. Rev. 4/22/03

Installation Concept B



- Efficient use of space above water skid
- Increases free space
- Save \$20k in cables



Raman, CT Tech. Rev. 4/22/03

CT_timeline_042203

Conclusions

- CT Injection will enhance NSTX experimental capability
- CT relation to NSTX 5yr plan discussed (4/7/03)
- Variable angle injection is possible for about additional \$50k - \$100k
- First year to be spent on commissioning and initial experiments
- Second year and beyond will see the CT used as a tool for other NSTX XPs
- Action Needed
 - May decision to proceed
 - UW proposal request for Fy03 funds to initiate work
 - Approval of UW Proposal No. 2 for Fy 04 and 05 funds

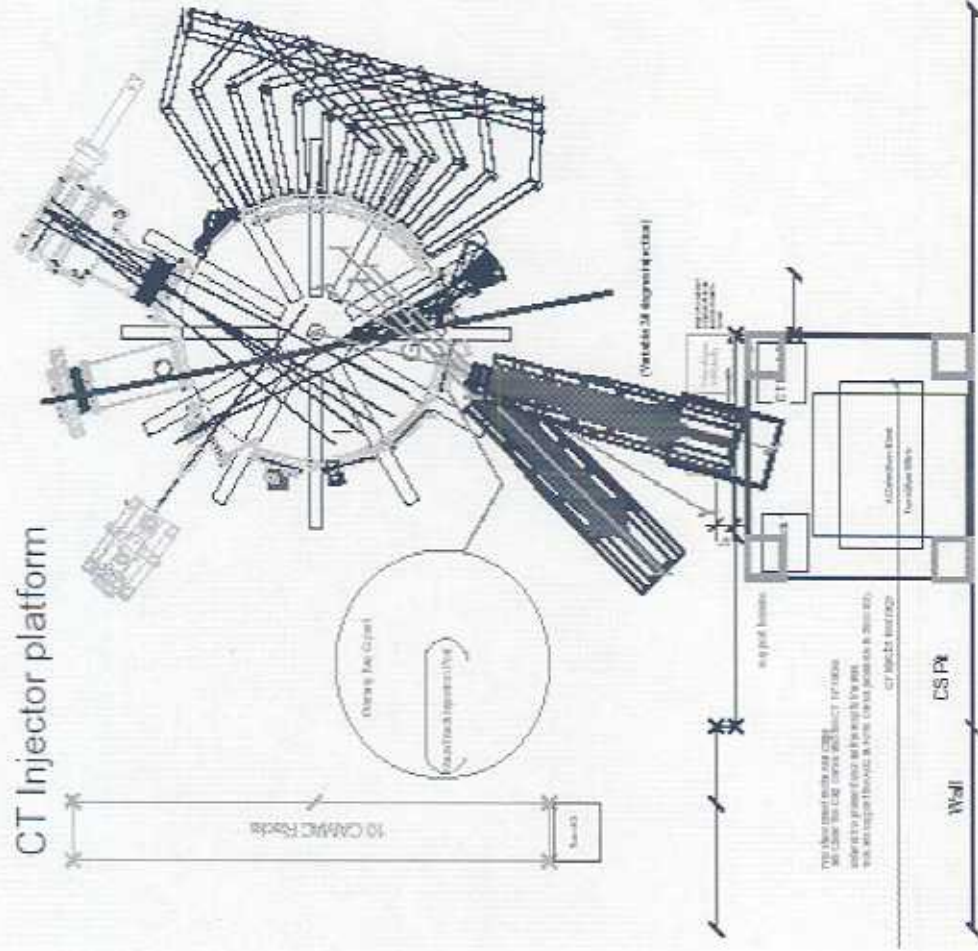
Assessment of Cost for CT Installation on NSTX

**In partial fulfillment of work commissioned by
DOE grant No. DE-FG03-02ER54686**

H.W. Kugel, R. Raman, L.Dudek, F.Jones, L. Roquemore

May 20, 2003

Bay-G Installation Concept



- Efficient use of space above water skid
- Increases free space
- Save \$20k in cables

CT Mechanical Installation Cost Estimate

(Improves Diagnostic Space and Vessel Maintenance Safety)

L.Dudek, 5/16/03

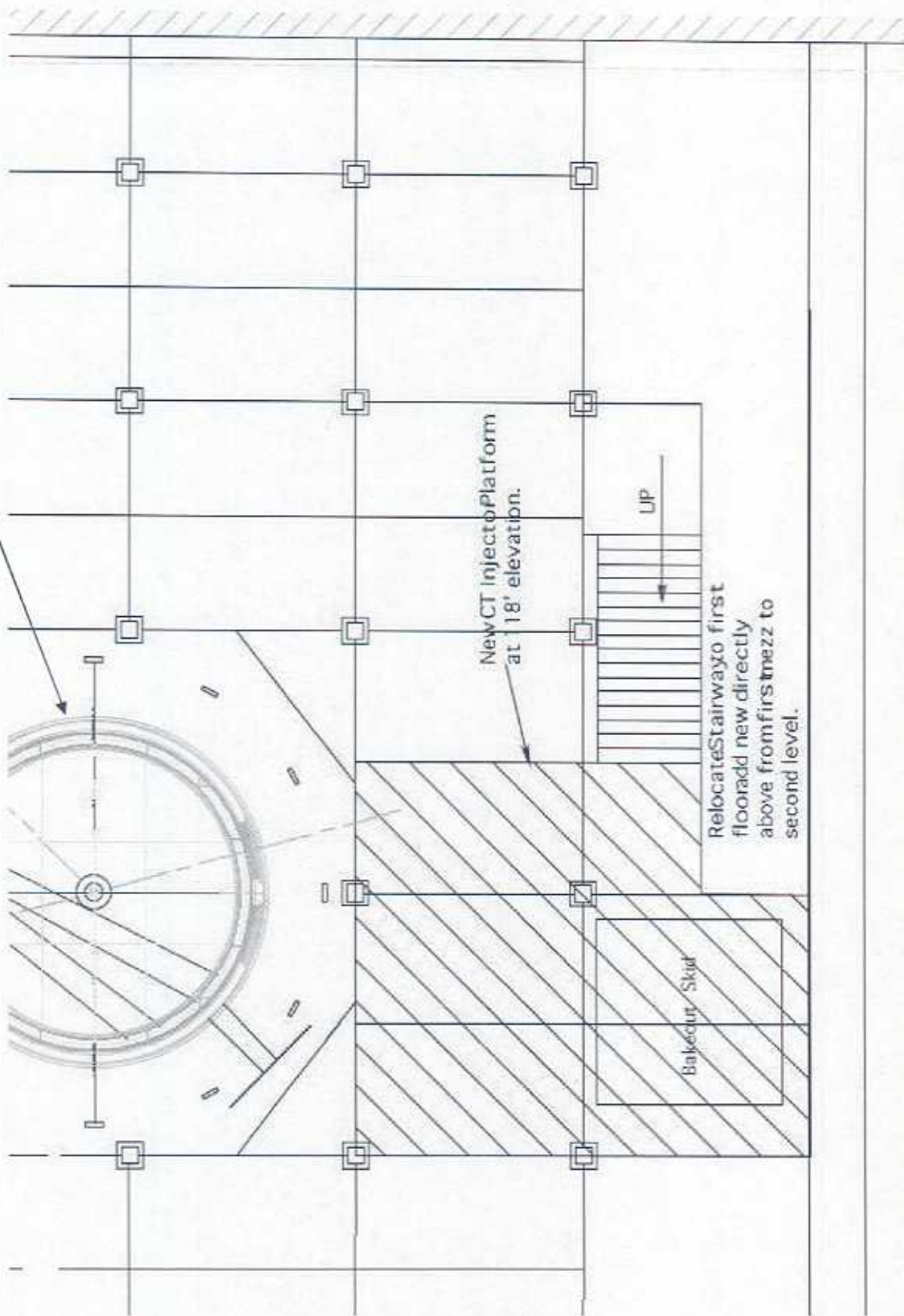
Date: Fri, 16 May 2003 15:16:22 -0400
Subject: CT Platform Estimate
Cc: "KEMP STEPHEN G." <SKEMP@pppl.gov>
To: KUGEL HENRY <HKUGEL@pppl.gov>
From: Larry Dudek <dudek@pppl.gov>

Henry,

Attached is an estimate and sketch for the CT injector platform. Note that the platform is larger than that presented at the review but it will tie into the existing RF platform on the East side of the machine and give better access to the machine for maintenance and installation. Platform cost came to \$63,500 with contingency.

Larry

NSTX



TOTAL JOB WITH G&A & BURDEN \$36,600																			
BUREN =																			
HOURLY RATES =																			
TASK DESCRIPTION																			
41MS	40MS	STK	EMEM	EMSN	EMTB	EA	EAEN	EAOM	EE	EEEN	EEES	EEETB	EECEM	TASKC=	TASKC=	TASKC=	TASKC=	TASKC=	TASKC=
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1 Stairway	1500																		
2 Handrail	500																		
3 Angle 3"	150																		
4 Lbeam 4250 / 20	1000																		
5 Plate	200																		
6 200 / Column	1200																		
7 Wood 300 Section	925																		
8 O-10 Insulators	100																		
9 Handrails	500																		
10																			
11																			
12 Labor to fabricate columns / beams / deck prep																			
13 Labor to install platform																			
14 Grounding																			
15																			
16																			
17																			
18																			
19																			
20																			
21																			
22																			
23																			
24																			
25																			
26																			
27																			
28																			
29																			
30																			
Date of Rates 5/03																			
Rev Date 5/03																			
TOTAL MAN WEEKS																			
EM DIVS W/O BUR & G&A																			
EA DIVS W/O BUR & G&A																			
EE DIVS W/O BUR & G&A																			
*** DIV																			
***** DIV																			
41 MRS W/O G&A																			
40 MRS																			
STOCK W/O G&A																			
ASSIGNMENTS																			
TOTAL HRS UNASSIGNED																			

CT Electrical Installation Cost Estimate (Pg.1)

F. Jones, 5/06/03

X-Sender: fjoness@pobox.ppppl.gov
Date: Tue, 06 May 2003 14:46:08 -0400
To: hkugel@pppl.gov
From: Frank Jones <fjoness@pppl.gov>
Subject: electrical estimate for Compact Torus (CT) Injector on NSTX
Cc: jchrzanowski@pppl.gov, jsiegel@pppl.gov

Henry

This is the electrical estimate for Compact Torus (CT) Injector on NSTX. The estimate does not include platform modifications or routing from racks/power supplies.
Total cost not including G & A \$44,200.00 [Total Loaded cost ~\$53.9K]

Materials:

\$11,000.00 @ building steel [loaded ~ \$11K x 1.32 = \$14.5K]
or

\$14,000.00 @ Diagnostic ground [loaded ~ \$14K x 1.32 = \$18.4K]
power blocks, junction box, 2- safety switches, 1-50a, 480v breaker, 1-100a, 240v breaker,
1- 100a panelboard with branch breakers, 10-120v-15a receptacles, 3 -240v-15a receptacles, 4-
120v-30a receptacles
2 power strips, 17 receptacle boxes, wireway, conduit, wire 1/0, 3/c#12 & 3/c#10, 1-480v
delta to 208v-y, 30 kva transformer,
bare & insulated ground wire, connectors, strut, hilti's and misc. hardware.

CT Electrical Installation Cost Estimate (Pg.2)

F. Jones, 5/06/03

Eng., Design and Drafting documentation:

20 man days approx. $14,000.00 + G \& A$ [loaded ~ 20 MD x 8 Hrs/D x 4100/Hr = \$16K]

New drawings:

physical drawing with elevation detail, panel schedule, panel locator drawing, shutdown instruction drawing, power cnd

Revised drawings:

NSTX AC PWR Block Diagram, East wall bus dwg., platform grounding, heating system ac power Installation/related documentation:

Requisitions for materials, Installation procedure, equipment labels, lift review, flame permit, test cell work permit, ecn

Construction cost:

40 man days labor approx. $\$19,200.00 + G \& A$ [loaded~40MD x 8Hrs/D x \$73/hr = \$23.4K]

Test cell work permit, shut down NSTX vessel heating system, cut existing conduit and cable feed to the heating system,

install junction box and power blocks, deliver and lift xfmr onto platform, install two disconnects/breaker assemblies,

install xfmr, assemble & install panelboard, install 19 branch breakers, install ground system (requires cadweld), flame permit,install two racks (lift required), electrical safety, Q.C and AC power review

[Total Loaded cost ~\$53.9K]

Bay-G Port Cover Modification

Cost Estimates

L. Roquemore, 5/16/03

- **Option A**

- Radial Injection - No Cost, Use existing port previously installed for radial CT injection

- **Option B**

- Tangential and Radial Injection - 19k engineering (3MWks) + 6k machining = \$25k

Candidate Location

for Off-Line Testing in FY03

- **Neutral Beam Power Conversion Building**
- **TFTR DNB Rectifier Room**
 - **Significant Power**
 - **Terminated Fiber Optics to Nearby Control Room**
 - **Convenient Pump Exhaust**
 - **Safety Enclosure with X-ray Shielding**
 - **Nearby Control Room**
 - **Nearby Computer Division Junction Area**
 - **Nearby Shops and Expert Personnel**

Fy 03 CT installation cost for Univ.of Washington (~\$50k MOD to existing proposal)

- Univ. of Washington manpower support 4 weeks: \$15k - \$20k
 - Unpack and clean the items
 - Identify components
 - Plan for final assembly
 - Reducing UW support to ~\$10k will increase preparation time from 4 weeks to about 12 weeks
 - Graduate student cost for 0.5 yrs ~\$17k
 - Raman/Jarboe partial cost ~\$5k
 - Travel cost ~\$5k
- Miscellaneous cost for supplies: \$18k
 - Replace internal seals in the oil-free pump - \$2k
 - Replace all seals on the injector - \$6k
 - Other Misc. small supplies: \$5k
 - Other contingency: \$5k

Fy 03 CT installation cost for PPPL (~\$2.4k)

- Assist with injector assembly (~2.4k)
 - 1 PPPL technician help for 3days (with crane operation help for about 3hr/day)

Fy 04 cost for UW as per proposal # 2 (~\$150k)

- Miscellaneous supplies: **\$76k**
 - Replace ignitron switches - \$20k
 - Replace ceramic break/bellows - \$6k
 - Fast Digitizers: ~ \$15k
 - New power cables for power supply: \$15k
 - Other Misc. hardware costs - \$20k
- Full graduate student cost \$35k
- Part time cost cost for Raman/Jarboe: \$25k
- Travel cost: \$14k

Fy 04 CT installation cost for PPPL (~\$90.7k)

- Interface to NSTX
 - 3 technicians for 3 days: \$7.2k
- PPPL Control Engineering help (~\$20k)
 - P. Sichta / R. Gernhardt: PLC/timing signals & control (\$10K M&S + \$10K Engineering)
- New platform for CT, MSE and safety
 - \$63.5k (Ref: L. Dudek)

Fy 04 or 05 CT power feed cost for PPPL
(~\$53.9k, Re: F. Jones)

- Materials: \$14.5k
- Engineering & Design (20 Man days): \$16k
- Construction (40 Man days): \$23.4k

Consumables needed

- Small D2 , He cylinder for plasma fuel
- Compressed air to activate pneumatic valves
- Small SF6 cylinder for solenoid insulation
- Cleaning solvents: Methanol (3 gallons)
- Cleaning solvent: Acetone (3 gallons)
- Large cylinder of Ar/O2 and Ar/SF6 for switches

Electrical power near the power supplies

- 120VAC x 15A - 10 outlets
- 120VAC x 30A - 4 outlets
- 240VAC x 15A X 1-phase x 3 outlets
- Two 19 inch racks without power
- Two CAMAC crates
- A separate ground - this is simply a long (20 meters) thick copper cable that will be connected to the standard NSTX ground. All CT components will be grounded to the other end of this long cable

CT injector controls (Vacuum system)

- Valve 1. TIV
- Valve 2. CT Turbo gate valve
- Valve 3. CT Roughing pump valve
- Valve 4. Bypass valve-1
- Valve 5. Bypass valve-2

- These are ON/OFF type control signals
- Interlock valves 1 and 2 to Ion Gauge Controller pressure signals

Fast time scale trigger signals (+/- 200ns)

1. Solenoid trigger (@ t=-0.5 to -2.5 ms)
2. Gas valve trigger (@ t = -200 to -800 μ s)
3. Formation bank trigger (@ t = -10 to +10 μ s)
4. Acceleration bank trigger (@ t = -10 to + 30 μ s)
5. Second gas valve control (@ t = -200 to -800 μ s)
6. Third gas valve control (@ t = -200 to -800 μ s)

Injector operation sequence (step 1: program the voltage and trigger timings)

- Ensure TIV is open
- Read programmed Gas valve, Solenoid bank, Formation bank and Acceleration bank voltages
- Read programmed Gas valve, Solenoid bank, Formation bank and Acceleration bank trigger times

Injector operation sequence (step 2: Prepare the power supplies for charging)

- Energize the STAND-BY relays in each of the four power supplies
- Energize the CHARGE-ENABLE relays in each of the power supplies
- Energize solenoid valve in the Accelerator bank to fill rail-gaps to required gas pressure based on a voltage/gas pressure table. Monitor the rail gap pressure (1-10 VDC signal out) and turn off the solenoid valve when the pressure gets to the specified value.

Injector operation sequence (step 3: Energize the power supplies)

- Provide 1-10 volt DC control signal to each if the four power supplies to charge the DC power supplies to the required value.
- Monitor the power supply output voltage from the 1-10 VDC signal out from the power supplies. Prior to installation on NSTX a small TV camera interface is needed to visually monitor the power supply voltages from the front panel display. A fiber-optic based power supply discharge capability is needed, as a back-up Manual Dump.

Injector operation sequence (step 4: Discharge the power supplies and return system back to a safe state)

- Provide the fast trigger signals to each of the power supplies at the desired times as previously described.
- After the shot, open the vent valve in the acceleration bank to vent the rail gaps.
- After 1 minute close the vent valve in the acceleration bank.
- Close the charge enable and stand-by relays in the power supplies.

Summary of control signals

Total signals	Related system	Signal Type
5	Vacuum system	ON/OFF
6	Input to Injector	0-10 VDC
6	Output from Injector	0-10 VDC
6	Power supply triggers	5V TTL, 200ns resolution
5	Injector control	ON/OFF

Summary of NSTX Installation Costs

- Tech labor FY03 - \$2.4k
- Mechanical FY04 - \$63.5k*
- Tech labor FY04 - \$7.2k
- Bay-G Port Cover FY04
 - Option A (radial) - \$0
 - Option B (tangential & radial) - \$25k
- Controls FY04 - \$20k
- Electrical FY04 or FY05- \$53.9k
- Total \$147k (Option A)-radial
\$172k (Option B)-tangential and radial

* Includes modifications required for MSE & Machine Top Safety

Summary and conclusions

Cost	UW	PPPL
Fy 03	\$50k MOD	\$2.4k
Fy 04	\$150k	<\$144.6k (A-radial)* or \$169.6k (B-tangential & radial)*

* \$53.9 k could be moved into FY05.

- A \$1.5M CT Injector is in storage at PPPL
- Enhances Experimental Operations for small cost

Appendix I - CHIT Resolution

CHIT	Comment/Concern/Recommendation	Response
1	Tangential injection will have significant impact on other diagnostics at Bay G – possibly very expensive -D. Johnson	Tangential injection installation is more difficult compared to radial injection. To touch base with previous work, radial injection may be an easier way to start. There will be cost associated with modifying the Bay G flange and a solution needs to be found for interference with LIF MSE. -R.Raman <i>The cost of modifying the Bay-G port cover for tangential and radial injection is estimated to be</i> <i>\$19K (3 MWks engineering) + \$6K (machining) = \$25K</i> <i>-L. Roquemore 5/16/03</i>
2	Need to focus on tangential injection to enable momentum injection and plasma momentum transport studies as this still allows fueling to plasma core. -M.Peng	We would like to inject tangentially, but because of cost issues, tangential injection installation is more difficult compared to radial injection. To touch base with previous work, radial injection maybe an easier way to start. Please also see the response to Chit 1. -R.Raman
3	Need to review safe use of oil at high temperatures with safety. -L. Dudek	We agree. The oil circulates in a cavity which is surrounded by a 1/2-inch thick stainless steel wall and it is at ambient pressure. It has been safely operated in this manner for about 2 years with no issues. -R.Raman

CHIT	Comment/Concern/Recommendation	Response
4	Need to review impact of injector on egress paths with Ray Jeanes. -L. Dudek	Either access behind the CT should be provided, or a ladder type assembly would be needed to go over the injector to the other side. -R. Raman
5	Milestones should be established for the lab test as a prelude for installation work on NSTX. -D. Johnson	The milestone will be to get the injector functional and to finish the injector / NSTX control interface work. -R. Raman
6	Frank Jones should provide an estimate of AC power both for laboratory (if necessary) and NSTX test cell installations since costs will be significant. -D. Johnson	Refer to F. Jones estimate 5/6/03: \$44,200 not including G&A. [Loaded: \$53.9K] -H. Kugel

CHIT	Comment/Concern/Recommendation	Response
7	This system has very significant impact both in terms of needed space and in terms of support needed. An assessment should be done of usefulness of a single CT injector. A single CT injector will have a few percent perturbation on density and toroidal velocity relative to high power NBI. An injector capable of repetitive CTs would be needed for more significant perturbations. Consideration should be given to the development of multi-pulse capability in the lab before a installation on NSTX. -D. Johnson	A single CT injector will make immediate contributions to NSTX experimental capability. These include (1) reliable H-mode initiation for on going XPs, (2) Prompt fueling method to avoid locked modes, (3) Improve present understanding of barrier seen during Neon injection and others. Cost is the primary issue with a multi-pulse injector. Single pulse experiments will provide the needed data for significantly reducing the cost associated with the power supplies needed for multi-pulse operation. -R. Raman
8	a) Sufficient space (3 feet) in front of any electrical equipment needed per codes b) What are the failure modes? Any concerns/interlocks? c) Isolation requirements of electrical power input? d) Is vacuum pump electrical feed included? -S. Ramakrishnan	a) Thank you for code regulations information. 3 feet requirement will be met. b) If power supplies charge above set values then both an automatic and manual abort capability is needed in the control software and the hardware. All capacitors are enclosed within a metal cage. The system was designed and built to industrial standards by a pulsed power company in California. During routine operation all power supplies will be interlocked through the test cell door. c) An isolation transformer is needed for the CT power feeds. d) Vacuum pump electrical power will be drawn from the main CT outlets. -R. Raman

CHIT	Comment/Concern/Recommendation	Response
9	Existing Bay G port cover has 1mm radial interferometer on mid-plane flange and tangential bolometer on flange proposed for tangential CT injection. These interferences have to be resolved even before MSE-LIF issue is addressed. -R. Kaita	Radial Injection requires no modification. Tangential and radial injection requires a Bay-G port cover modification to accommodate the requirements. -H.Kugel
10	Assumptions used in arriving at cost of platform are questionable (eg use of existing platform design). This is likely too low and should be reevaluated. -D. Johnson	Refer to Mechanical Installation Cost Estimate and innovative design \$63,500 (with contingency) - L. Dudek 5/16/03.
11	Platform for power supplies needs to be engineered to support the weights (spans on beams are greater, columns are taller) -L. Dudek	Refer to Mechanical Installation Cost Estimate and innovative design \$63,500 (with contingency) - L. Dudek 5/16/03.
12	Need to add fire sprinkler system under platform (check with R Jeannes) -L. Dudek	Refer to L. Dudek conceptual design 5/16/03

CHIT	Comment/Concern/Recommendation	Response
13	Mechanical drawing estimate looks light. CT installation 1 Asm. drawing 1 design drawing (platform mods to adapt to NSTX) 3 design drawings (vac. interface) power platform 1 Asm. drawing 3 Asm. drawing Looks more like 6 Man Weeks of drawing (assuming some old platform drawings are used.) -L. Dudek	Refer to Mechanical Installation Cost Estimate and innovative design. \$63,500 (with contingency) - L. Dudek 5/16/03.
14	A copy of the power system operating manual should be given to S. Ramakrishnan to see if there is any problem involved in installing it in the test cell. -M.Ono	1. Provide an AC Contactor (208V 60Hz., single phase) on the input side of the charging power supply in the 19" Rack. This Contactor shall be automatically arranged to drop off if the Test Cell Doors are opened. (Don McBride is requested via this email to implement (when the system is installed inside the Test Cell) a scheme similar to the Vessel Isolating and Grounding Switch.) 2. The positive side of the Cap Bank is always kept grounded since this is a grounded system and not a floating one. The Negative side is connected to ground in series with a 10K resistor, via a Dump switch. It is necessary to provide a hard ground on the Negative side also. This can be done in two stages as follows: Stage 1: Dump energy via the 10k resistor. Stage 2: After the Caps are discharged (typically a few milliseconds) provide a timed relay to completely short & ground the Cap- bank. The above grounding scheme shall be automatically accomplished when the Test Cell is accessed. S. Ramakrishnan 5/20/03

CHIT	Comment/Concern/Recommendation	Response
15	In case of an earthquake there will be a shearing load on the proposed platform support post. Some one such as Bob Parcels should verify that this is not an issue. -M. Ono	Refer to Mechanical Installation Cost Estimate and innovative design. \$63,500 (with contingency) - L. Dudek 5/16/03.
16	Henry Kugel should look into if there are any issues related to OSHA rules. -M. Ono	Concur. This has been included in the electrical and mechanical cost estimates. Additional reviews of possible issues will occur during the Work Planning Process and the respective Design Reviews. -H. Kugel



Motivation for Compact Toroid Injection in NSTX

In partial fulfillment of work commissioned by

DOE grant No. DE-FG03-02ER54686, for the proposal

Assessment of the feasibility of using the CTF-II injector on NSTX

Roger Raman

University of Washington, Seattle

and the NSTX Research Team

NSTX Physics Meeting

Princeton Plasma Physics Laboratory

April 7, 2003

Raman, NSTX Phys meet., 4/07/03

Chronology of collaborator Compact Toroid Fueling presentations at NSTX Research Forums

	<i>U - Washington</i>	<i>UC - Davis</i>
Dec. 1997	R.Raman-1st pres. Action: submitted proposal to DOE	D.Hwang-1st pres. Action: submitted proposal to DOE
Jan. 1999	R.Raman -2nd pres.	D.Hwang-2nd pres.
Jan. 2000	R.Raman - 3rd pres. (in Advanced Concepts)	
Jan. 2001	R.Raman - 4th pres. (in Heat., CD & Fueling) & 5th pres. (in Transport & Turbulence) Action: submitted 2nd proposal to DOE	
Nov. 2001	R.Raman - 6th pres. (in Boundary Physics)	
June. 2002 5yr Res. Plan. Meet.	R.Raman - 7th pres. (in Boundary Physics) R.Raman - 8th pres. (in Integrated Senario Dev.)	
July. 2002	Action: submitted 3rd proposal to DOE. Result: <i>Approved by DOE for CT injector Relocation & Evaluation</i>	

The ability to inject CTs significantly expands NSTX experimental capability

- Precise H-mode initiation capability valuable for on-going XPs
- Electron Transport Barrier studies
- Clarification of the edge barrier seen during Neon injection
- Transport studies by isotopic impurity tailoring
- He ash removal studies
- Prompt density injection to avoid locked modes
- Reconnection studies - an important aspect of PPPL research
- Momentum injection studies for transport barrier sustainment
- Precise density profile control needed for NSTX SS discharges
- Local current injection to suppress NTMs
- Reduced divertor pumping requirements
- Possible extension of density limits
- Disruption mitigation by high-z plasma injection

Acknowledgements

For support during the past several years

Prof. Thomas R. Jarboe (Univ. of Washington)

Dr. Henry W. Kugel (PPPL)

Outline of Talk

- Description of a CT Injector
- Motivation for CT Injection
- Experimental results
- Proposed research plan on NSTX
- The CTF-II injector in storage at PPPL
- Summary and conclusions

A Compact Toroid (CT) is a self-contained toroidal plasma with embedded magnetic fields

Two types of CTs

- A Spheromak has comparable poloidal / toroidal fields and about 10% beta
 - Technology easily adaptable to high rep-rate operation
 - Electrode based CT formation requires attention to electrode tech.
- A Field Reversed Configuration (FRC) has only poloidal field (if it is not accelerated) and about 50% beta
 - Considerably challenging pulsed power technology
 - Inductive formation but CTs longer in length than Spheromaks

Very Early Work on CT Injection

- Perkins (LLNL) and Parks (GA) proposed concept for fueling
-[Perkins, Ho, Hammer, NF 28, 1365 (1988) & Parks, Phys. Rev. Lett. **61**, 1364 (1988)]
- Hammer and Hartman (LLNL) developed the accelerator concept
-[Hammer and Hartman, Phys. Rev. Lett., **61**, 2843 (1988)]
- First tokamak fueling (CT size < Tok. size)
-[Raman et. al., Phys. Rev. Lett. **73**, 3101 (1994)].

A CT is accelerated to high velocity and injected into the target plasma to achieve deep fueling



Compact
Toroid (CT)



Tokamak Plasma

CT Penetration time: few μs

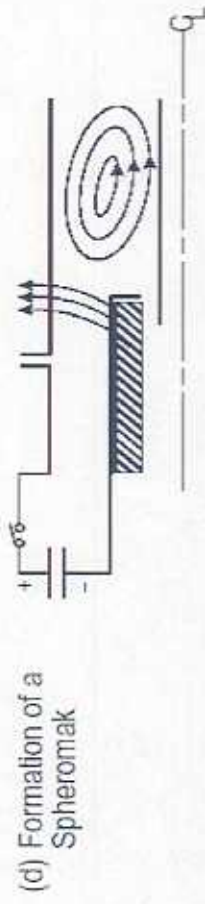
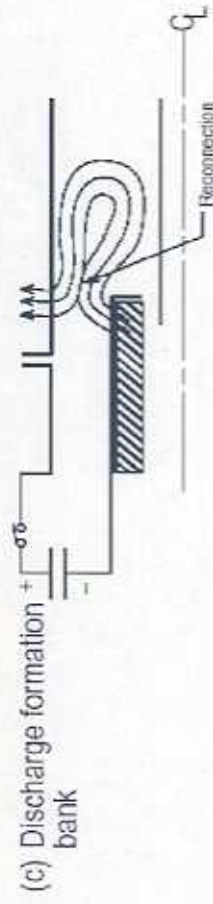
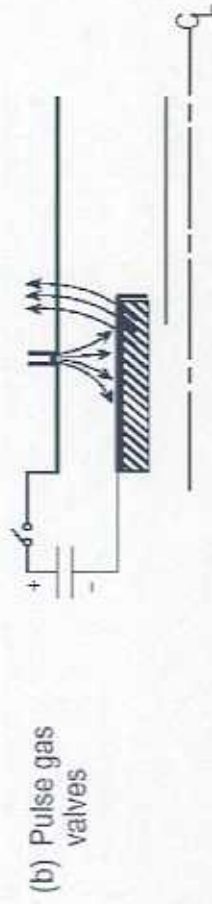
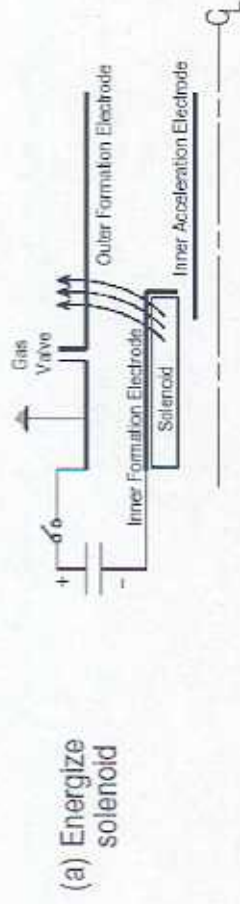
CT Dissociation time: $< 100 \mu\text{s}$

Density Equilibration time: $250 - 1000 \mu\text{s}$

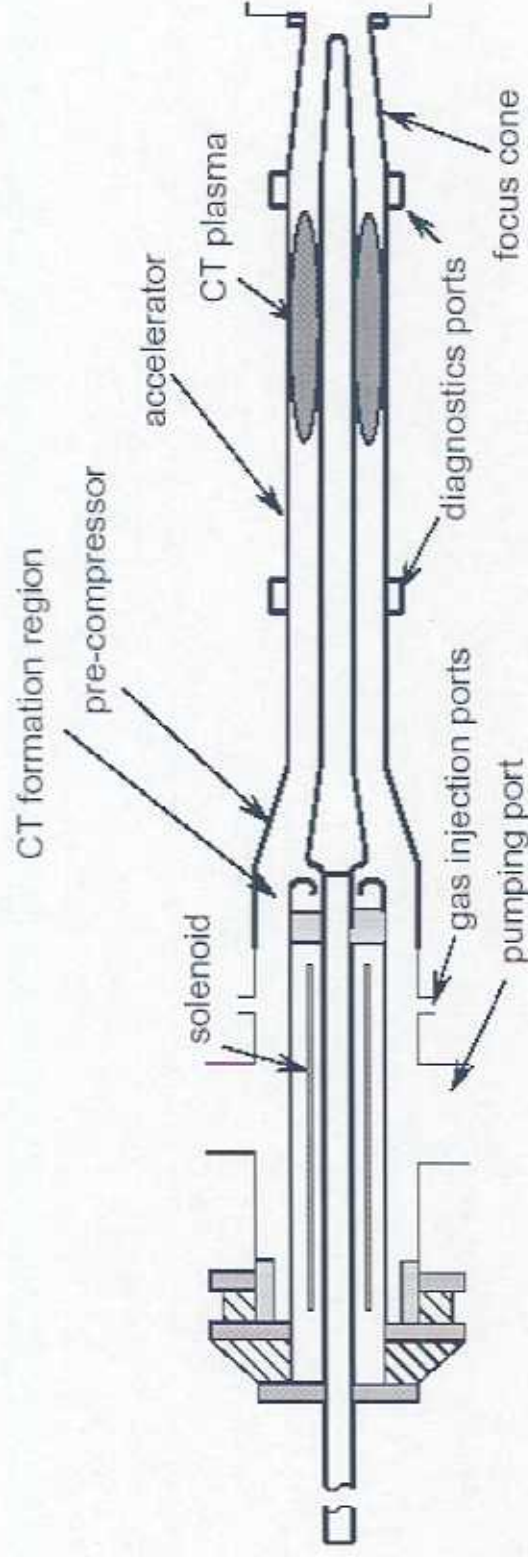
Variable Penetration depth: edge to beyond the core

Raman, NSTX Phys meet., 4/07/03

CTs formed in a magnetized Marshall gun on fast ($\sim 10 \mu\text{s}$) time scales



A CT Fueller forms and accelerates CTs in a coaxial rail gun in which the CT forms the sliding armature



Raman et al., Fusion Techn., 24, 239 (1993)

Amount of gas injected controls CT density
Applied voltage controls CT velocity
Control system specifies fuel deposition location for each pulse

Raman, NSTX Phys meet., 4/07/03

CT Injection has the potential to meet future NSTX fueling needs

- Future NSTX high β , high bootstrap fraction plasmas require optimized profiles
- During high performance steady state non-inductive operation, optimized profiles must be maintained
- Fueling such discharges requires the prompt injection of small amounts of fuel where needed and as often as needed

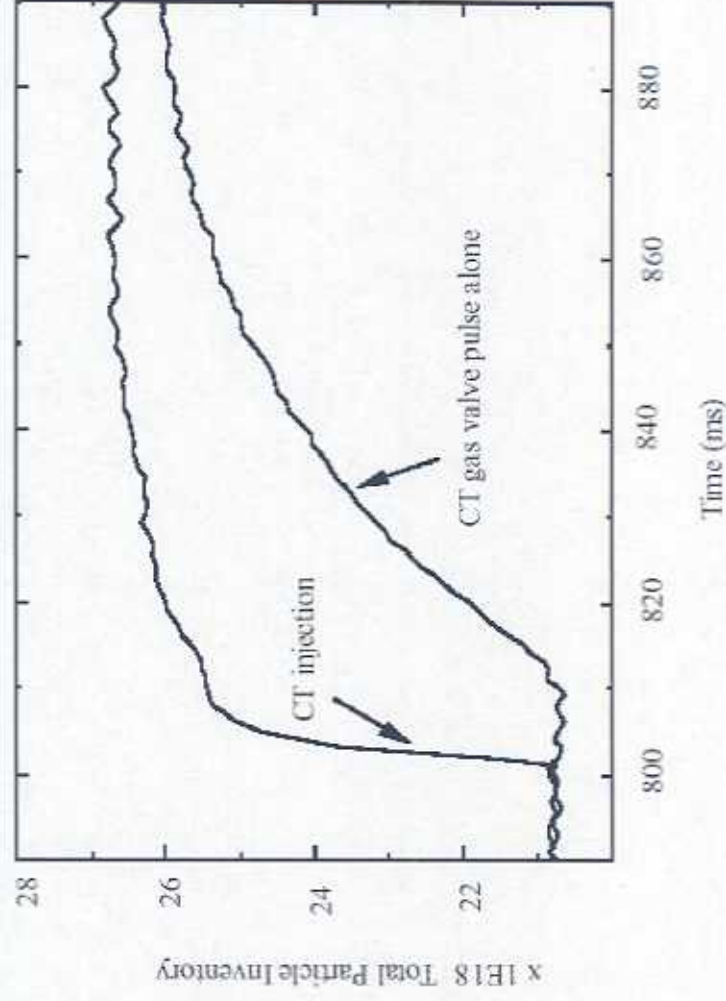
*There is no existing fueling system
to meet this requirement*

Raman, NSTX Phys meet., 4/07/03

IPPA goals relevant for CT Fueling

- 3.4.1.2 Fueling Technologies: "Develop systems and fueling techniques that are capable of providing a reliable, flexible particle source for controlling core plasma density and density gradients at acceptable fueling efficiencies; ..."
- Under the description of Section 3.4.1 Plasma Technologies: "The main issues for fueling technologies are to *understand and exploit advanced fueling physics (such as high field side launch) and demonstrate the performance (i.e., pellet speeds, density of compact toroids and repetition rates) required to effect adequate control of the density profile shape and high fueling efficiency*"

TdeV tokamak discharges beneficially fueled by CTs,
without causing any adverse perturbation



TdeV

$R = 0.86\text{m}$

$a = 0.25\text{m}$

$B_T = 1.4\text{T}$

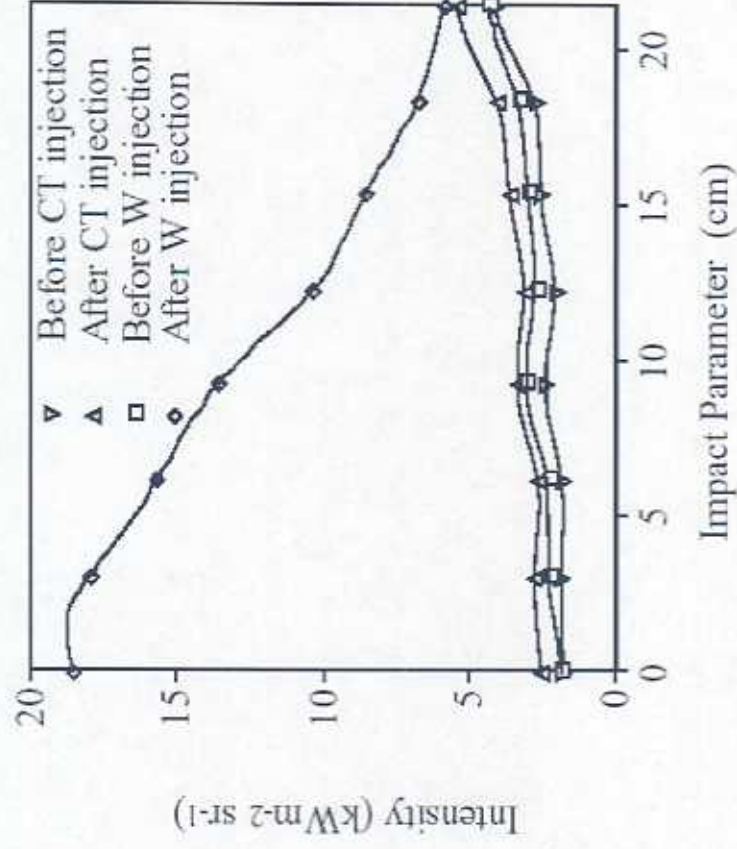
$I_p = 160\text{kA}$

R. Raman et al, NF 37, 967 (1997)

No development work needed to beneficially add fuel to NSTX

Raman, NSTX Phys meet., 4/07/03

No evidence for metallic impurity contamination of TdeV



R. Raman et al, NF 37, 967 (1997)

Raman, NSTX Phys meet., 4/07/03

Edge fueling of diverted discharges triggers improved confinement behavior

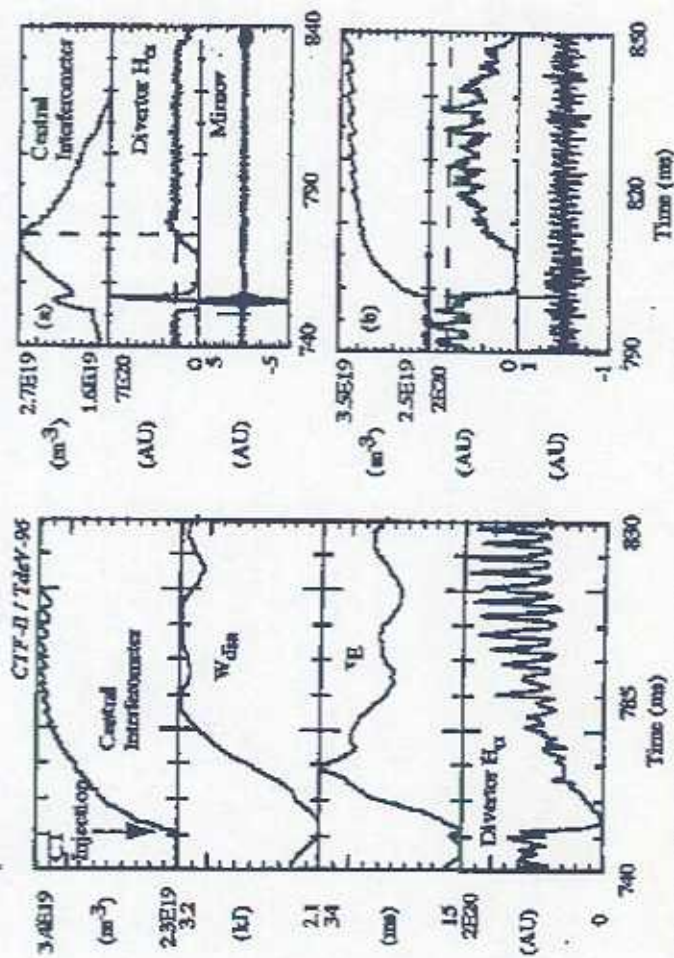


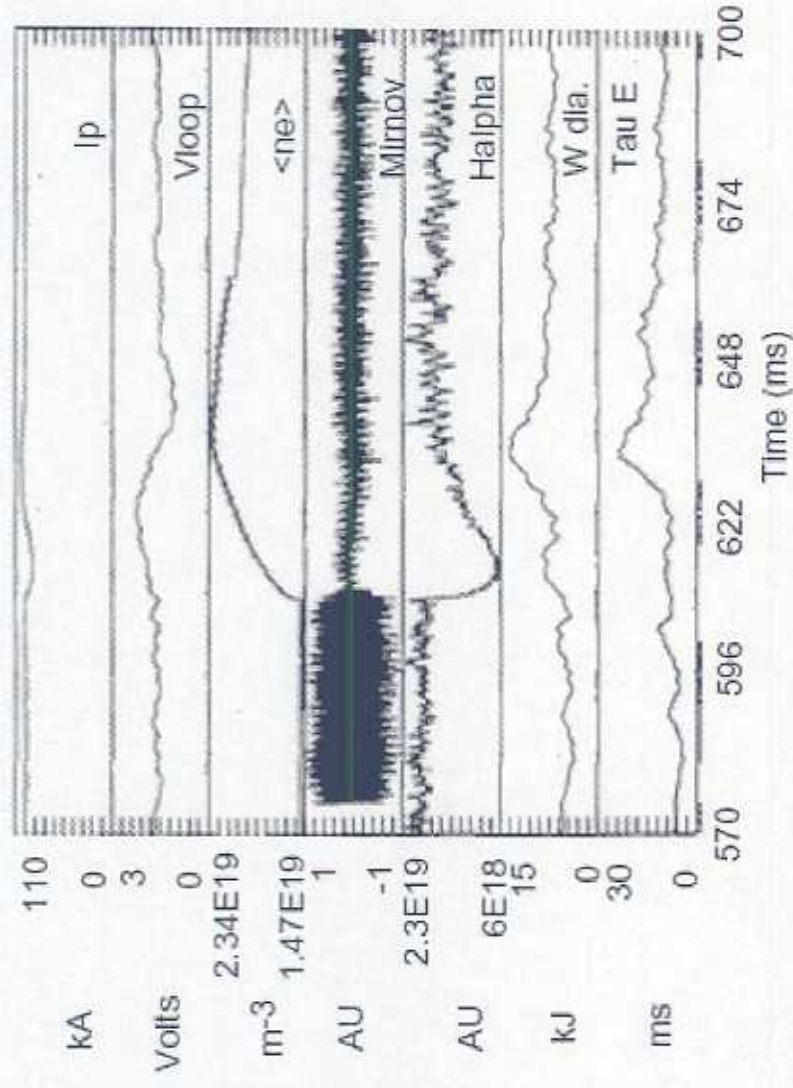
Figure 5: Example of improved confinement discharge from the CTF-II/TdV-96 run. $B_T = 1.5$ T, $I_p = 170$ kA, $T_e(t) = 900$ eV, single null discharge. Beyond $t = 785$ ms, the oscillation amplitude in the divertor H_α signal increases.

Figure 6: (a) The density signal continues to rise for as long as the H_α signal stays depressed. A single ELM is observed. (b) In this case, the H_α signal never quite reaches the pre-CTI injection level while the density signal continues to gradually increase. No ELM feature is seen in this and in most CTI injection discharges.

R. Raman et al., Proceedings of the 24th EPS Conf. p 283, 9-13 June 1997, Barchinagarden, Germany 1997

Raman, NSTX Phys meet., 4/07/03

Edge fueling of limited plasmas also shows a sharp reduction in Mirnov coil oscillations



CT induced confinement improvement also seen on STOR-M*

STOR-M

$$R = 0.46 \text{ m}$$

$$A = 0.12 \text{ m}$$

$$I_p = 20 \text{ kA}$$

$$B_T = 1 \text{ T}$$

C. Xiao, A. Hirose, R. Raman, 2001,
Compact Torus Injection Experiments
in the STOR-M Tokamak,
Proc. of 4th Symp. on Current Trends in
International Fusion Research:
Review and Assessment
(Washington D.C., March 12-16, 2001,
in print)

* Recent similar results on JFT-2M

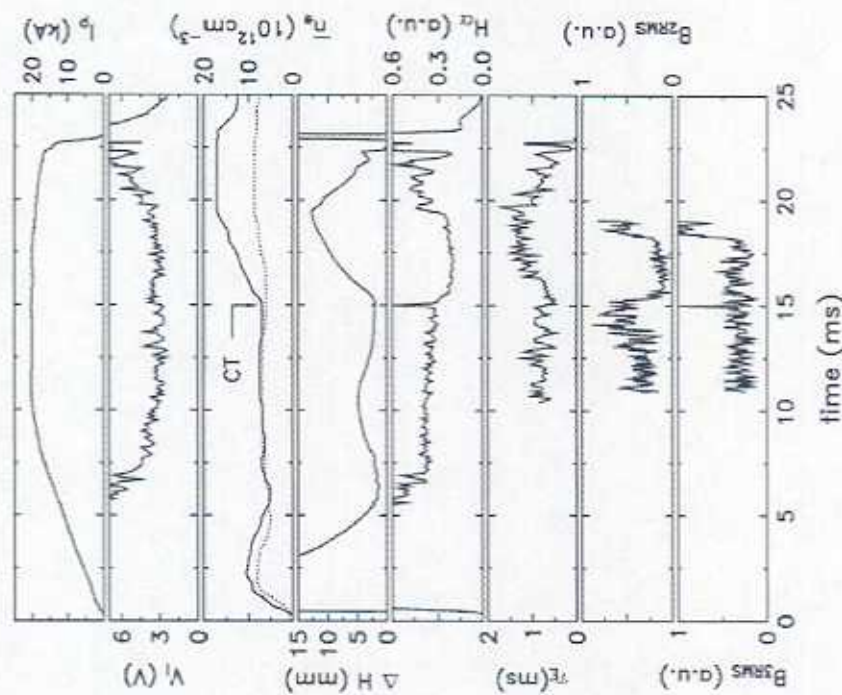
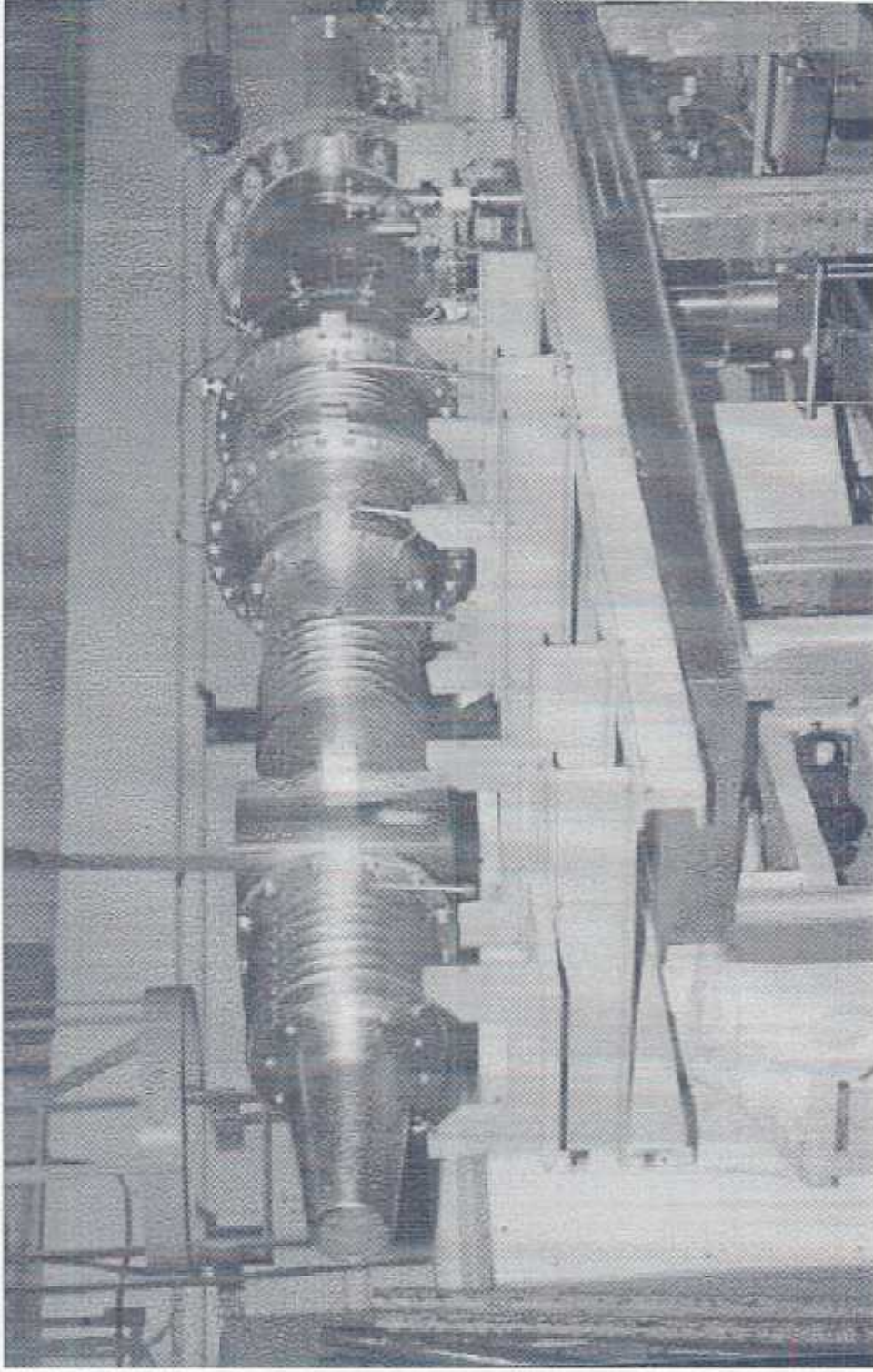


Figure 3. Tokamak plasma parameters during a discharge with CT injection at $t = 15$ ms. Shown are from top to bottom: plasma position, loop voltage, line averaged electron density, horizontal plasma position, H_α signal, energy confinement time, $m = 2$ Mirnov coil oscillations and $m = 3$ Mirnov coil oscillations. The dotted line shows the electron density with gas puffing in the injector, but without CT discharges.

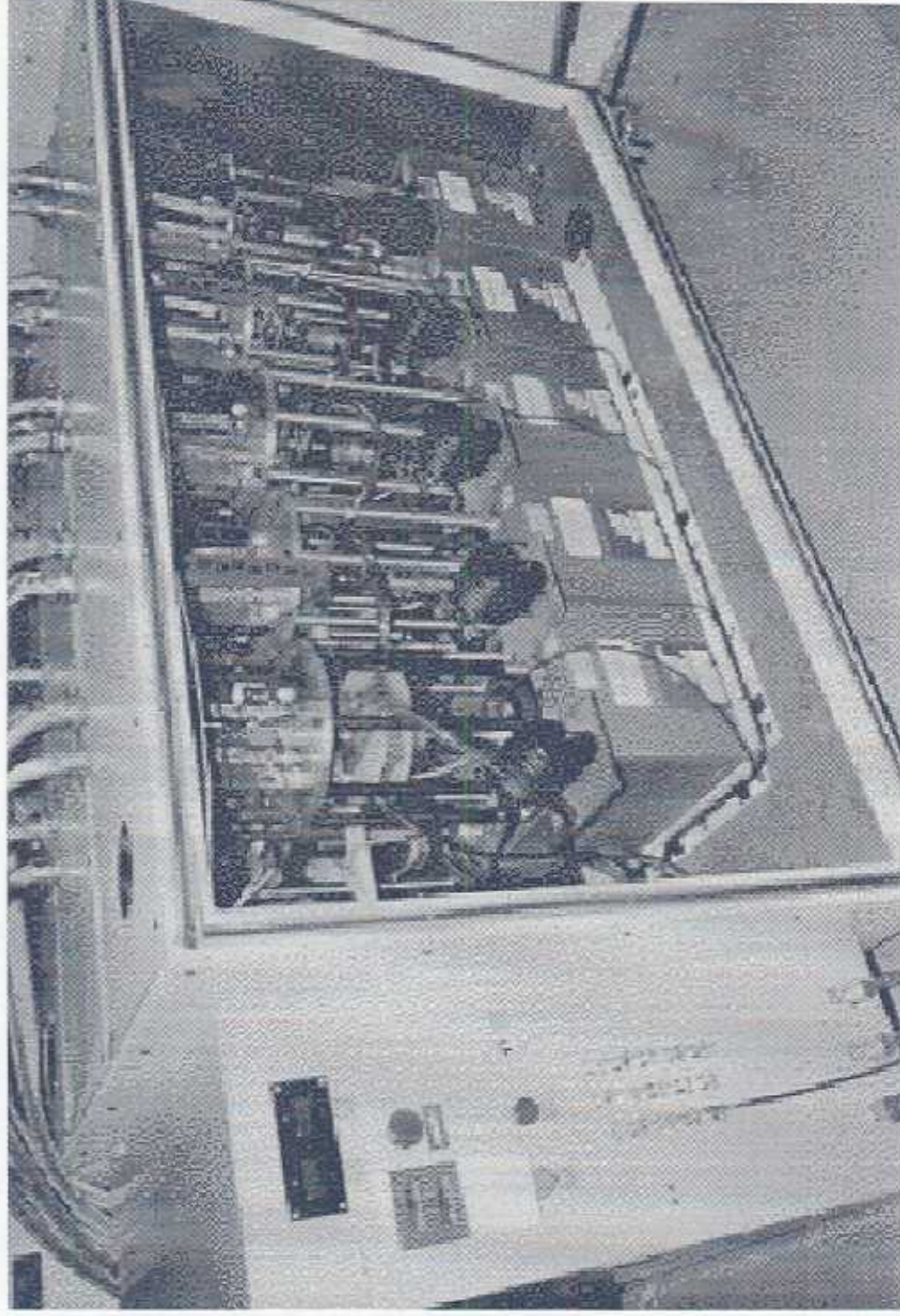
Raman, NSTX Phys meet., 4/07/03

The CTF-II injector



Raman, NSTX Phys meet., 4/07/03

The CT Formation bank power supply (110VAC input)

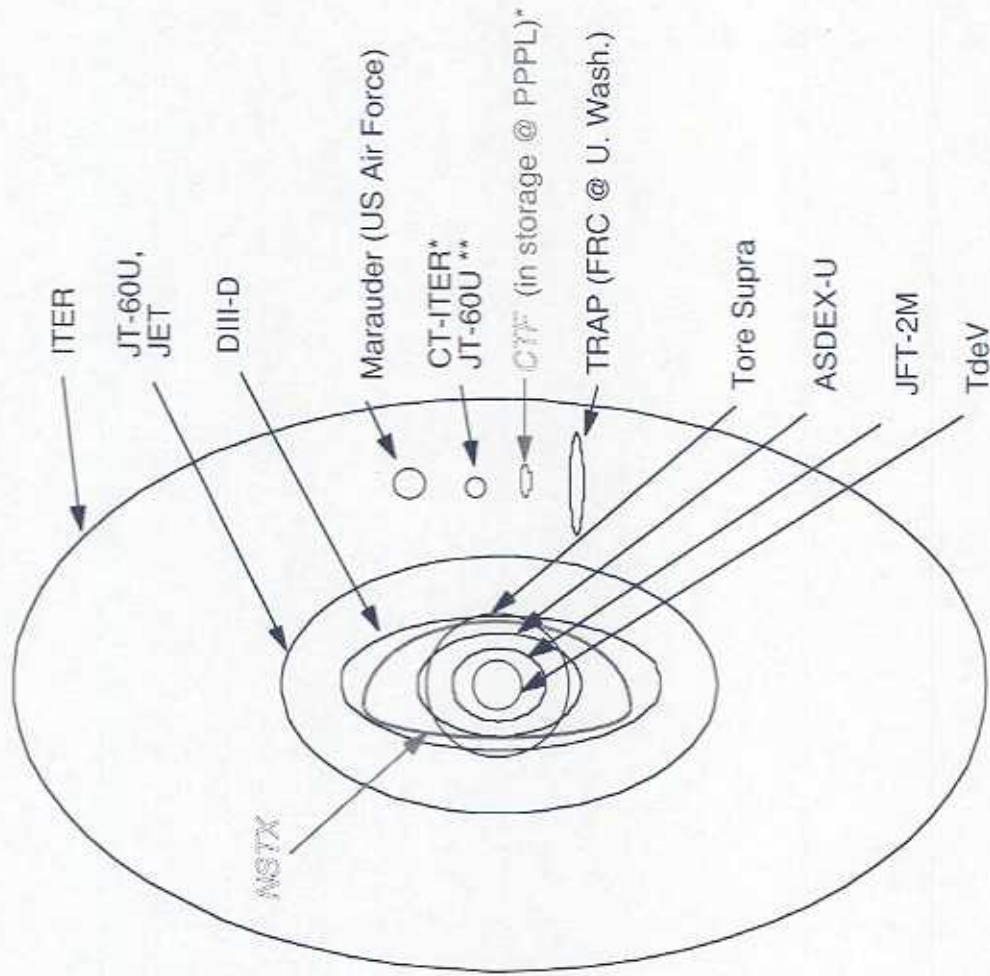


Raman, NSTX Phys meet., 4/07/03

Two primary objectives for proposal

- Reliable initiation of H-modes and large surface area H-modes (during year-1)
- Establish CT parameters for controlled deep fuelling (during years 2 and 3)
 - Data needed for multi-pulse injector

Previous experiments too small to study localized core fueling



Relative sizes of various target plasmas and CTs.

A CTF sized CT will do far more localized fueling on a NSTX sized plasma

*R. Raman and P. Gierszewski, Fusion Engin. And Design, **39-40**, 977 (1998)

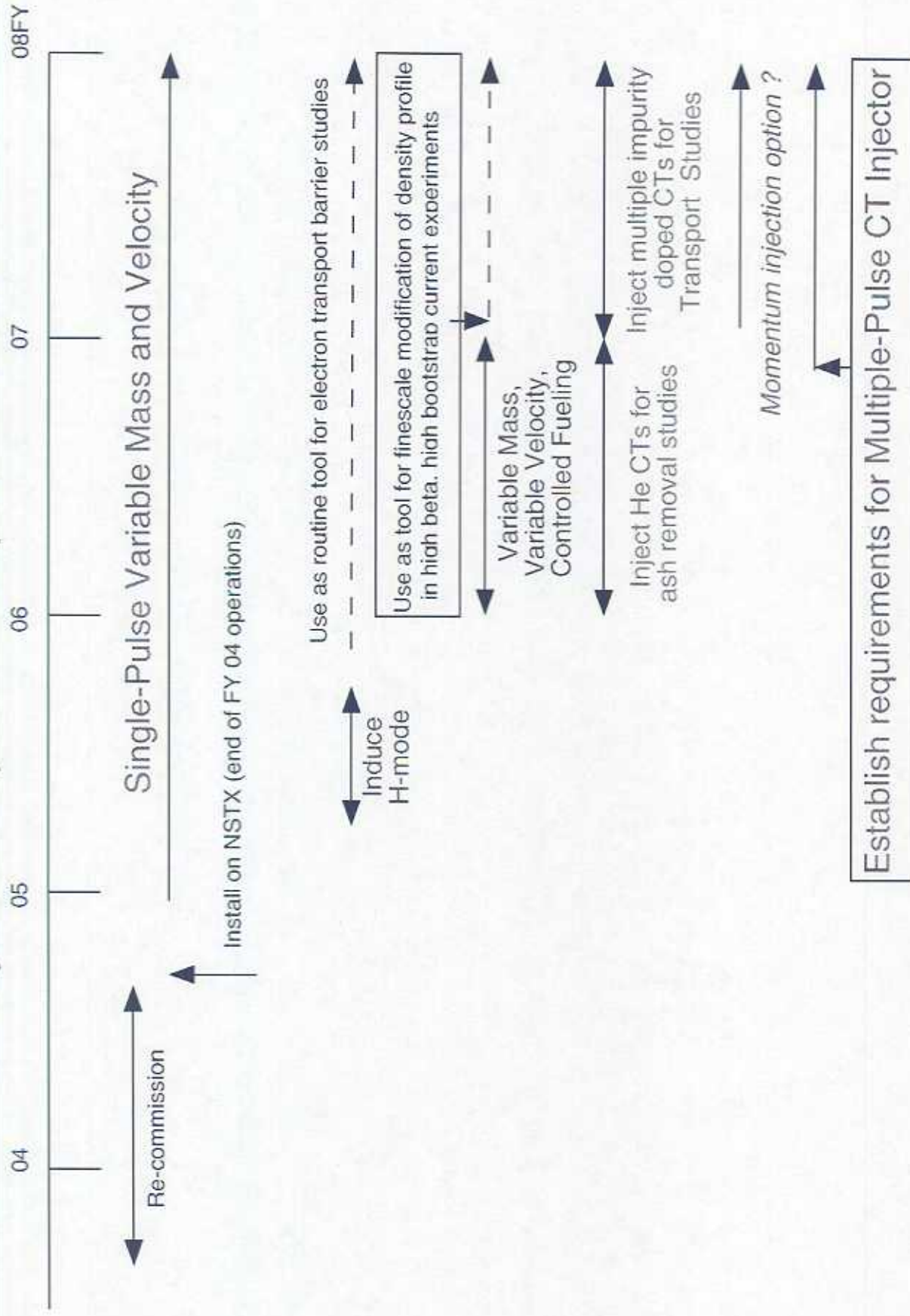
R. Raman and K. Itami, Journal of Plasma and Fusion Research, **76, 1079 (2000)

*Will cost >\$1.5M and 2-yr to build it from scratch

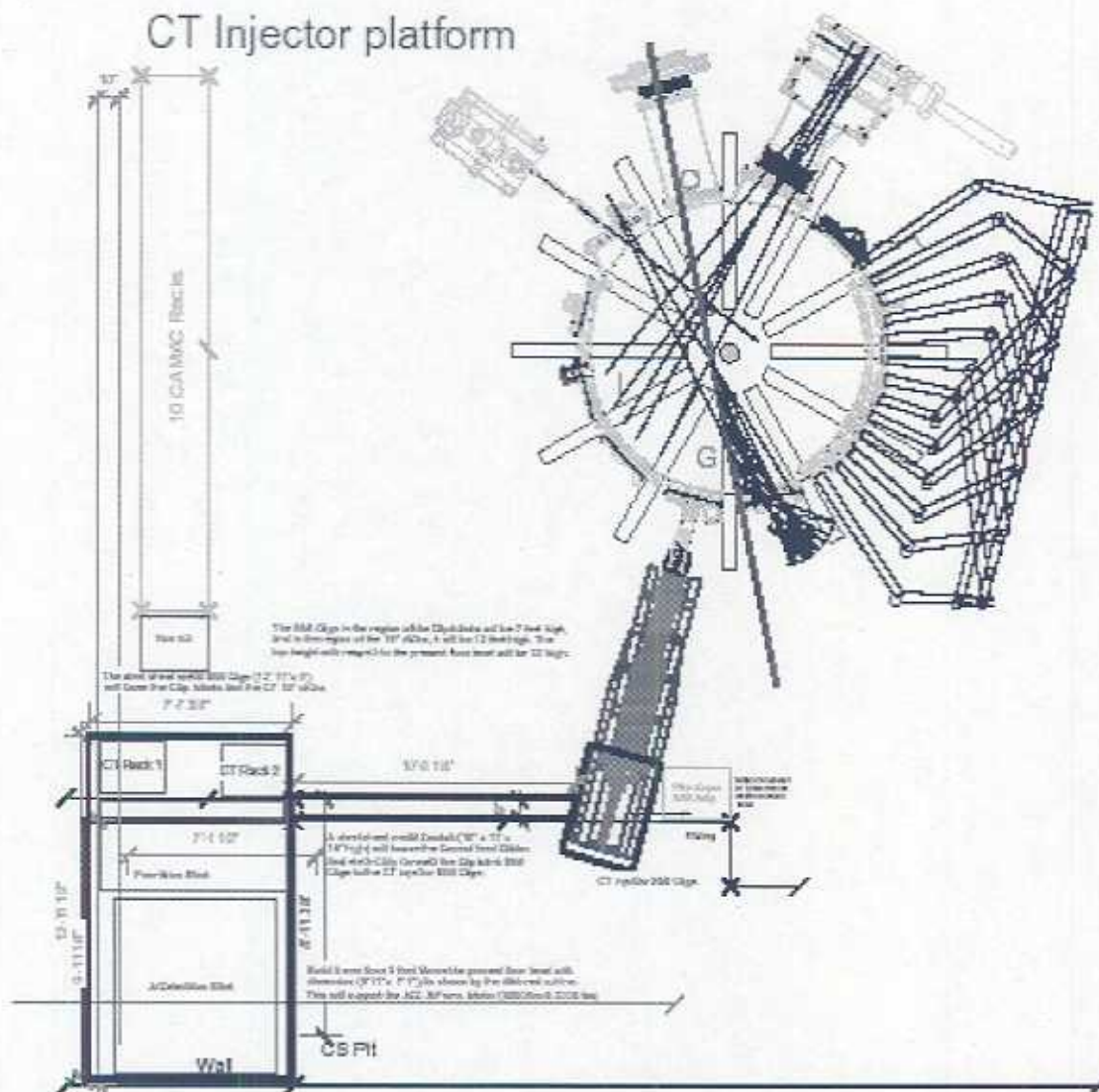
Secondary objectives

- Inject He CTs for He ash removal studies
- Inject Ne (or other impurity) doped CTs for transport studies
- Investigate capability for future tangential injection for momentum injection

CT Injection experimental plan on NSTX



Installation Concept



Raman, NSTX Phys Meet.
4/7/03

Boundary Physics 5-Yr program reviewer recommendations (Bruce Lipschultz)

- Comments on talk and program writeup (continued)
 - Cryopump justification and priority is not clear - make a decision
 - Cryopump is not obviously needed for density control per se.
 - However, the ability to 'dictate' a specific density in a given shot may be worthwhile - but has to be put in the context of progress in other areas.
 - Other aspects of fueling need to be clarified as well (e.g. pellets vs CTs)
 - Radial transport
 - Again, NSTX is in a potential position to make unique contributions
 - The basic diagnostic elements for attacking this are either there or in progress
 - A clear cohesive program bringing these diagnostics (and more importantly people) together is needed.
 - The effect on the wall (and impurities) may be very significant for an ST,

ST is a new class of plasma configuration, new technologies may be better suited to help the ST achieve its potential performance capability

	CT	Pellet
Particle invent. perturbation for deep fueling	Few % - will not destroy optimized profiles, allows precision fueling capability to adjust profiles	Typically 50% on DIII-D - large pellets needed to deposit small fraction of fuel in core
Penetration governing param.	$\alpha 1/B^2 \Rightarrow$ much easier penetration in ST as B^2 in NSTX is 2% of DIII-D	Te, fast electrons - similar to tokamak
Optimal injector location	Outboard mid-plane - tangential injection will impart momentum	‘True’-Inboard mid-plane - improbable in a ST as even DIII-D does not use ‘True’ inboard mid-plane
Real time density feedback control capability	Yes - potential for fuel deposition location specification on each pulse using control system request	Improbable because large pellets fuel entire discharge and mechanical nature of injector.

Other remarks

- A reactor will not use NBI & Alpha power is isotropic $\Rightarrow$ No momentum injection
- In a high β , high f_{BS} reactor some auxiliary current drive is needed

This leaves excellent density profile control as the method of choice to optimize reactor performance and to sustain transport barriers

Conclusions

- Excellent density profile control will enable STs to reach their highest potential
- Fueling SS discharges is much more difficult than fueling transient discharges. The needed fueling capability does not exist. Yet, the NSTX program plan calls for SS pulses with high beta and high bootstrap current drive
- The CT injection concept has the potential to meet this need, but data is needed from a single pulse injector
- The CT is also a source of momentum input and has the potential to sustain transport barriers
- A single pulse CT can make additional immediate contributions to the NSTX program
 - Precise H-mode triggering capability is useful for present XPs
 - Core injection of Neon will clarify transport issues
 - Injection of He CTs will enable He-ash removal studies