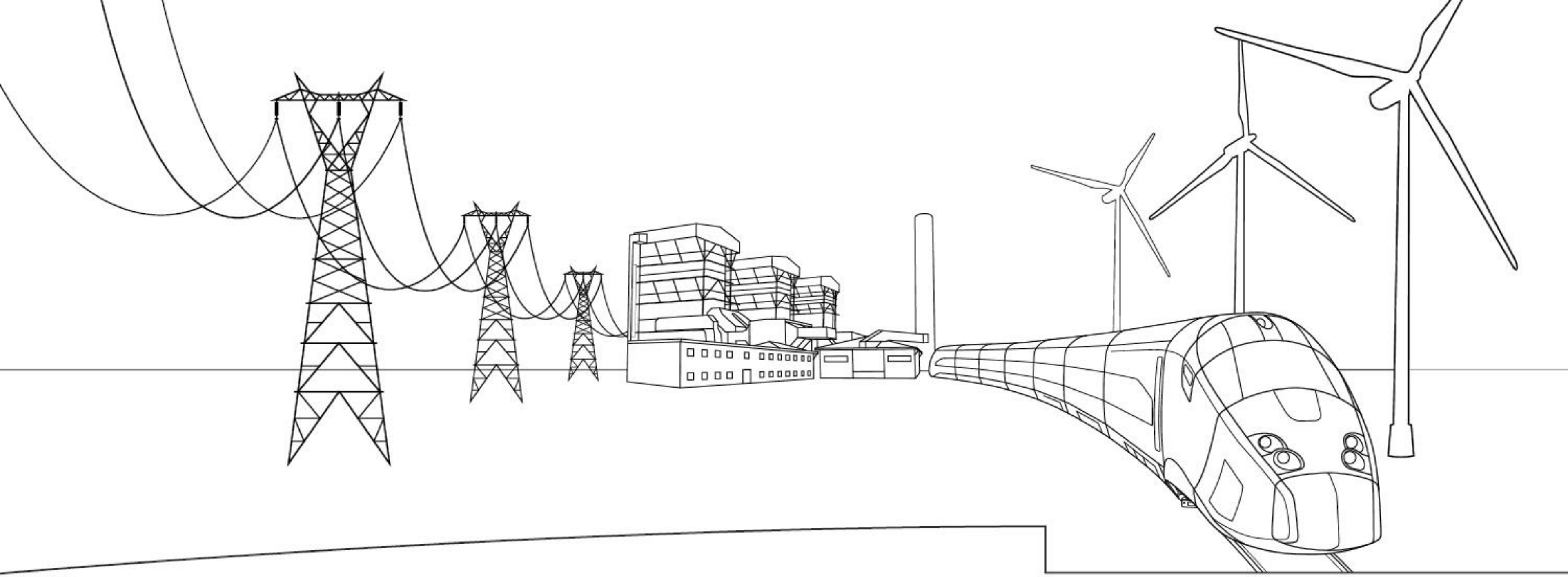

POWER SYSTEM FOR FUSION RESEARCH

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PPPL Princeton NJ

01/15/2014

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The presentation materials are extracts from published papers by PPPL staff - C. Neumeyer , S. Ramakrishnan & others

Shaping the future

POWER SYSTEM FOR FUSION RESEARCH

- **FUSION RESEARCH**
- FUSION RESEARCH CENTERS IN THE WORLD
- FUSION RESEARCH IN PRINCETON
- NSTX in Princeton
- DCCTs USED IN POWER LOOPS

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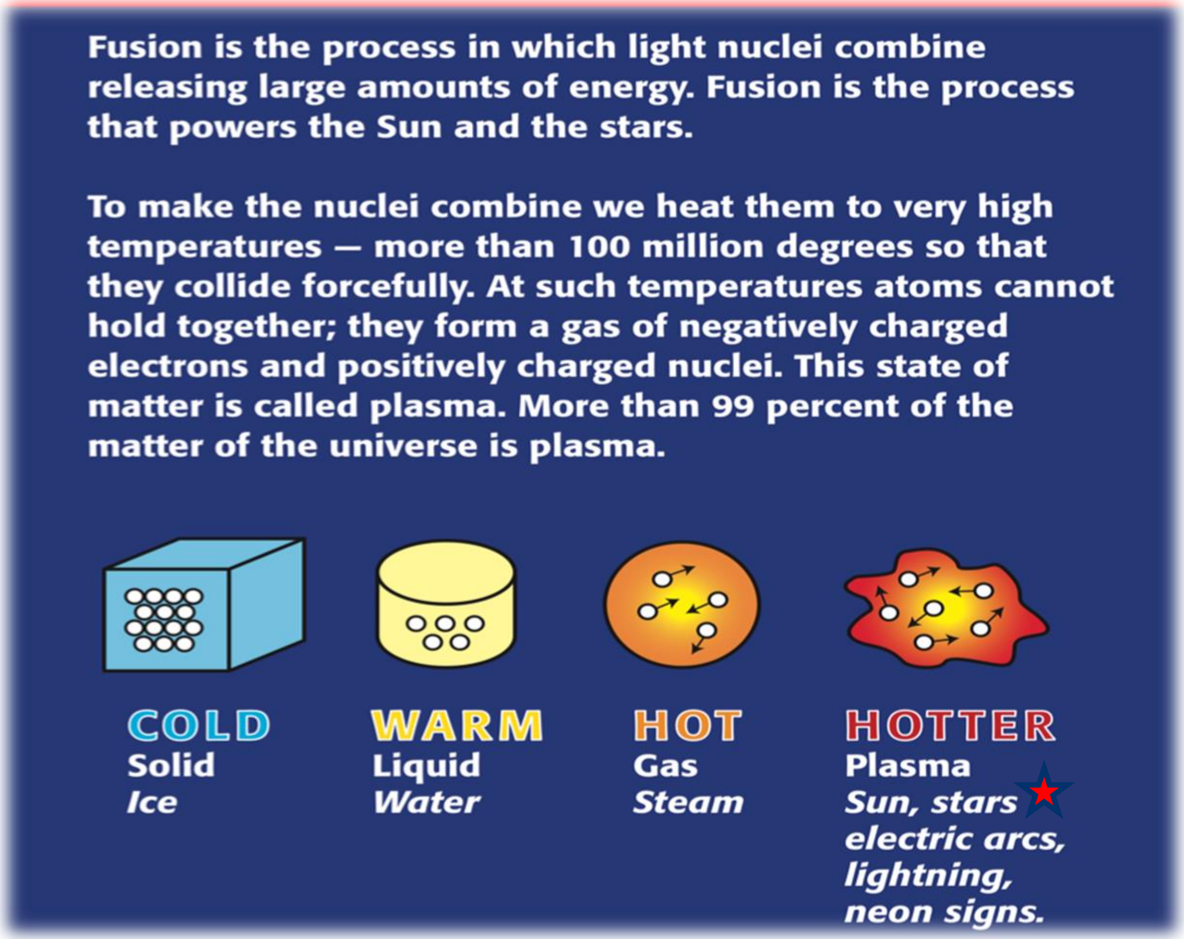
What is Fusion

- Fusion



Fusion is the process in which light nuclei combine releasing large amounts of energy. Fusion is the process that powers the Sun and the stars.

To make the nuclei combine we heat them to very high temperatures — more than 100 million degrees so that they collide forcefully. At such temperatures atoms cannot hold together; they form a gas of negatively charged electrons and positively charged nuclei. This state of matter is called plasma. More than 99 percent of the matter of the universe is plasma.

COLD	WARM	HOT	HOTTER
Solid	**Liquid**	**Gas**	**Plasma**
Ice	***Water***	***Steam***	***Sun, stars ★ electric arcs, lightning, neon signs.***

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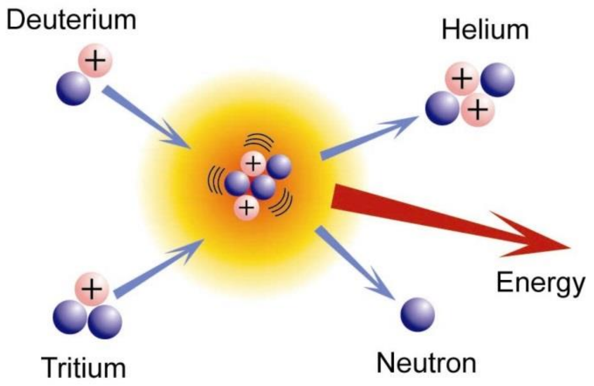
FUSION CONCEPTS

- Research Started in 1951 in Princeton
  - Soon after the H2 bomb test
- KEY CONCEPTS
  - D-D and D-T reactions

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + \mathrm{n} $$



  - Plasma heating – Ohmic, Neutral Beam, and RF
  - High temperatures needed: plasma
  - Fuel unlimited: ^{2}H in seawater
  - Little radioactive waste
  - Containment
    - Magnetic
    - Inertial
  - Fusion Power Generation unlikely for next couple of decades

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Power System for Fusion Research

ADVANTAGES

- ***Abundant Fuel Supply***
- **Deuterium – inexhaustible supply from sea water (1 part/ 6,500 H_2O)**
- **Tritium – produced from Lithium, thousands of years supply**
- **No Risk of Nuclear Accident**
- **No meltdown possible**
- **Large uncontrolled release of energy impossible**
- **No Air Pollution of Greenhouse Gases**
- **Reaction product is Helium**
- **Minimal or No High Level Nuclear Waste**
- **Careful material selection should minimize waste caused by neutron activation**

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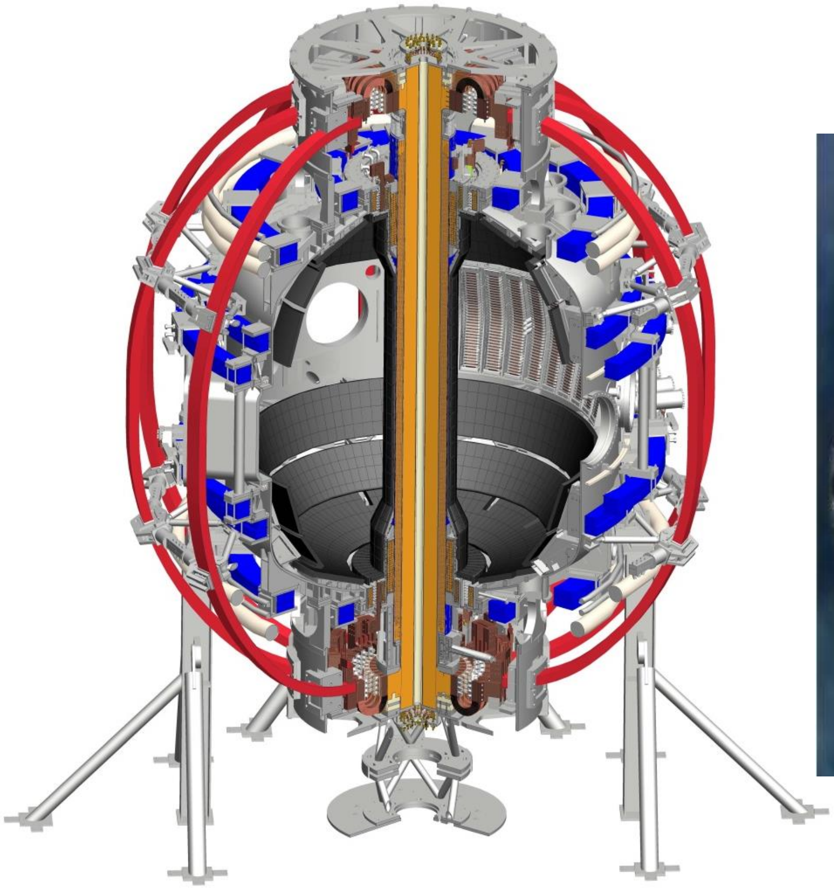
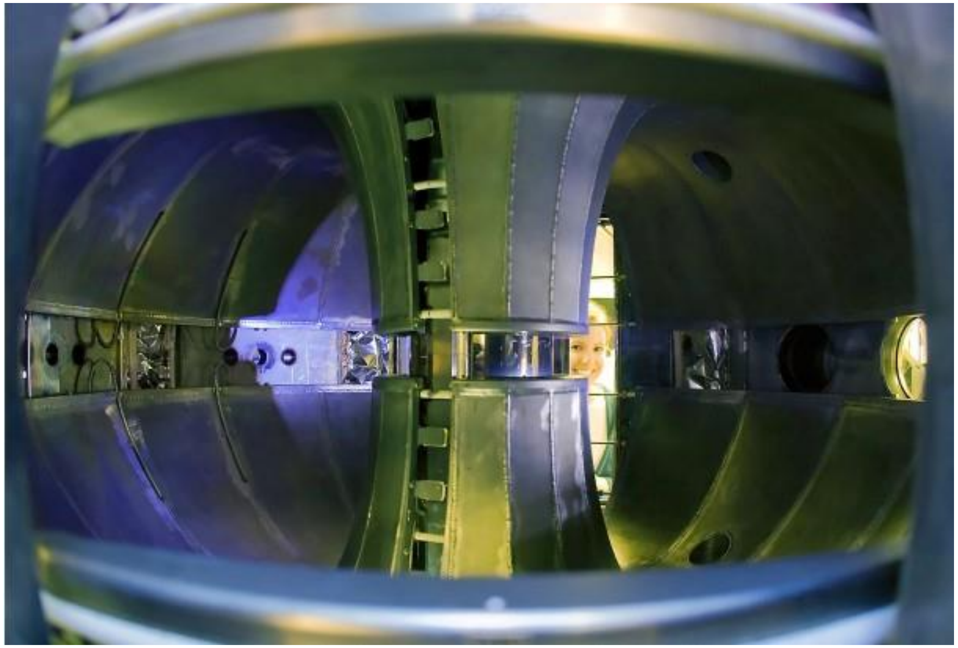
National Spherical Torus Experiment in PPPL





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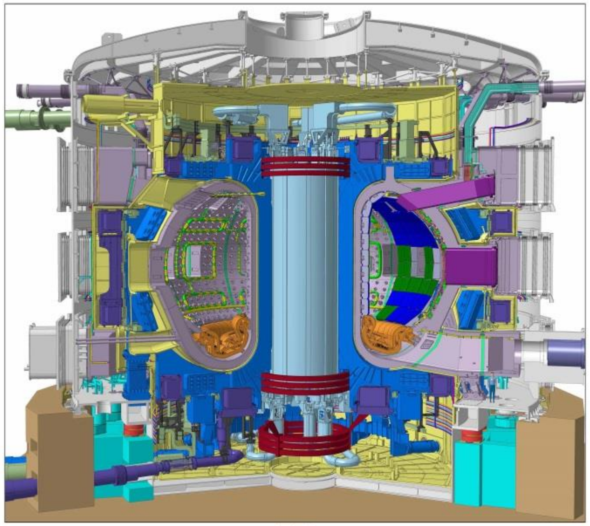
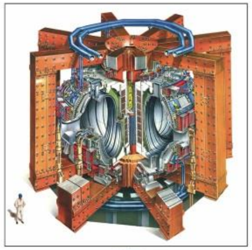
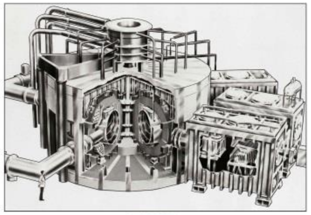
Comparison of Fusion Research Devices in the World



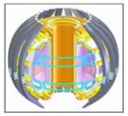
ITER



JET



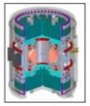
TFTR



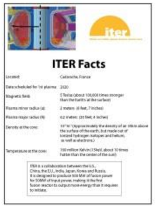
DIII-D

QUASAR

NSTX



Alcator C-Mod



ITER Facts

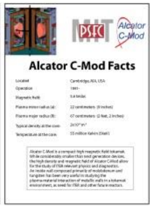
Joint European Torus (JET) Facts

Tokamak Fusion Test Reactor (TFTR) Facts

DIII-D Facts

QUASAR / NCSX Facts

NSTX-U Facts



Alcator C-Mod Facts

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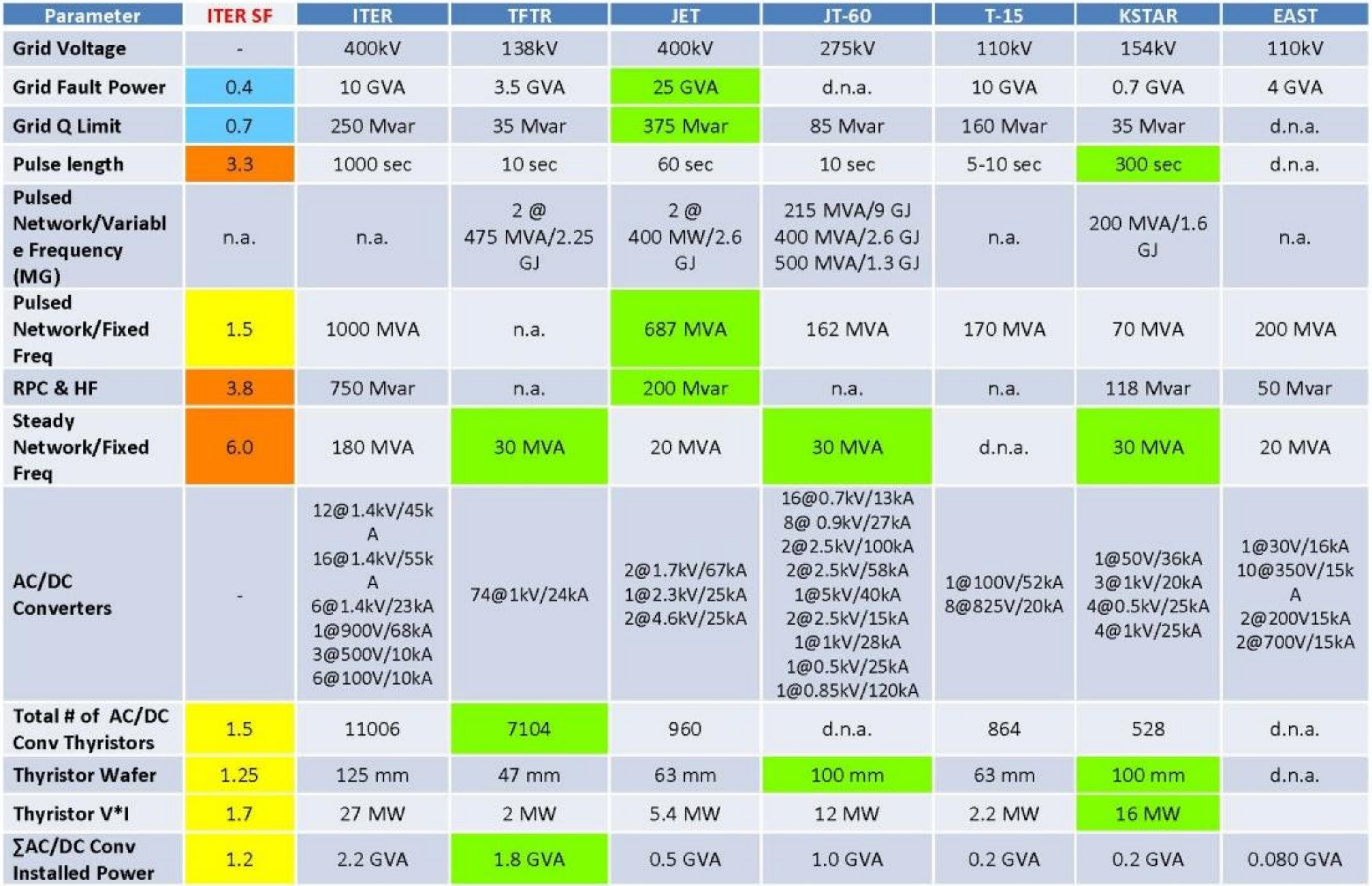
Power System for Fusion Research

Fusion Devices in the World



Parameter	ITER SF	ITER	TFTR	JET	JT-60	T-15	KSTAR	EAST
Grid Voltage	-	400kV	138kV	400kV	275kV	110kV	154kV	110kV
Grid Fault Power	0.4	10 GVA	3.5 GVA	25 GVA	d.n.a.	10 GVA	0.7 GVA	4 GVA
Grid Q Limit	0.7	250 Mvar	35 Mvar	375 Mvar	85 Mvar	160 Mvar	35 Mvar	d.n.a.
Pulse length	3.3	1000 sec	10 sec	60 sec	10 sec	5-10 sec	300 sec	d.n.a.
Pulsed Network/Variable Frequency (MG)	n.a.	n.a.	2 @ 475 MVA/2.25 GJ	2 @ 400 MW/2.6 GJ	215 MVA/9 GJ 400 MVA/2.6 GJ 500 MVA/1.3 GJ	n.a.	200 MVA/1.6 GJ	n.a.
Pulsed Network/Fixed Freq	1.5	1000 MVA	n.a.	687 MVA	162 MVA	170 MVA	70 MVA	200 MVA
RPC & HF	3.8	750 Mvar	n.a.	200 Mvar	n.a.	n.a.	118 Mvar	50 Mvar
Steady Network/Fixed Freq	6.0	180 MVA	30 MVA	20 MVA	30 MVA	d.n.a.	30 MVA	20 MVA
AC/DC Converters	-	12@1.4kV/45kA 16@1.4kV/55kA 6@1.4kV/23kA 1@900V/68kA 3@500V/10kA 6@100V/10kA	74@1kV/24kA	2@1.7kV/67kA 1@2.3kV/25kA 2@4.6kV/25kA	16@0.7kV/13kA 8@ 0.9kV/27kA 2@2.5kV/100kA 2@2.5kV/58kA 1@5kV/40kA 2@2.5kV/15kA 1@1kV/28kA 1@0.5kV/25kA 1@0.85kV/120kA	1@100V/52kA 8@825V/20kA	1@50V/36kA 3@1kV/20kA 4@0.5kV/25kA 4@1kV/25kA	1@30V/16kA 10@350V/15kA 2@200V15kA 2@700V/15kA
Total # of AC/DC Conv Thyristors	1.5	11006	7104	960	d.n.a.	864	528	d.n.a.
Thyristor Wafer	1.25	125 mm	47 mm	63 mm	100 mm	63 mm	100 mm	d.n.a.
Thyristor V*I	1.7	27 MW	2 MW	5.4 MW	12 MW	2.2 MW	16 MW	
∑AC/DC Conv Installed Power	1.2	2.2 GVA	1.8 GVA	0.5 GVA	1.0 GVA	0.2 GVA	0.2 GVA	0.080 GVA

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Power System for Fusion Research

Fusion Devices in the World – Contd.

Parameter	ITER SF	ITER	TFTR	JET	JT-60	T-15	KSTAR	EAST
SNU DC Circuit Breaker	-	5 @ 45kA/8.5kV 2@45kA/6kV 1@35kA/8.5kV	6 @ 24kA/25kV	2 @ 80kA/20kV	92kA/25kV	10kA/3kV	6 @ 25kA/3kV 2 @ 25kA/5kV 2 @ 20kA/5kV	15kA/2.4kV
∑SNU V*I	0.8	2.2 GVA	3.6 GVA	3.2 GVA	2.3 GVA	0.03 GVA	0.45 GVA	0.03 GVA.
∑SNU Energy	22.4	8500 MJ	55 MJ	320 MJ	35 MJ	d.n.a.	3 MJ	d.n.a.
FDU DC Circuit Breaker	-	9@68kA/10kV 12@55kA/10kV	n.a.	n.a.	n.a.	6 @ 6kA/0.5kV	8 @ 25kA/3kV 3 @ 20kA/3kV	2 @ 14.3kA/2kV
∑FDU V*I	16.3	12.7 GVA	n.a.	n.a.	n.a.	0.02 GVA	0.8 GVA	0.06 GVA
∑FDU Energy	70.0	56 GJ	n.a.	n.a.	n.a.	0.79 GJ	0.25 GJ	0.3 GJ
TF Stored Energy	7.5	41 GJ	1.4 GJ	5.5 GJ	2.6 GJ	0.4 GJ	0.5 GJ	0.4 GJ

Switching Network Unit (SNU)

Fast Discharge Unit (FDU)

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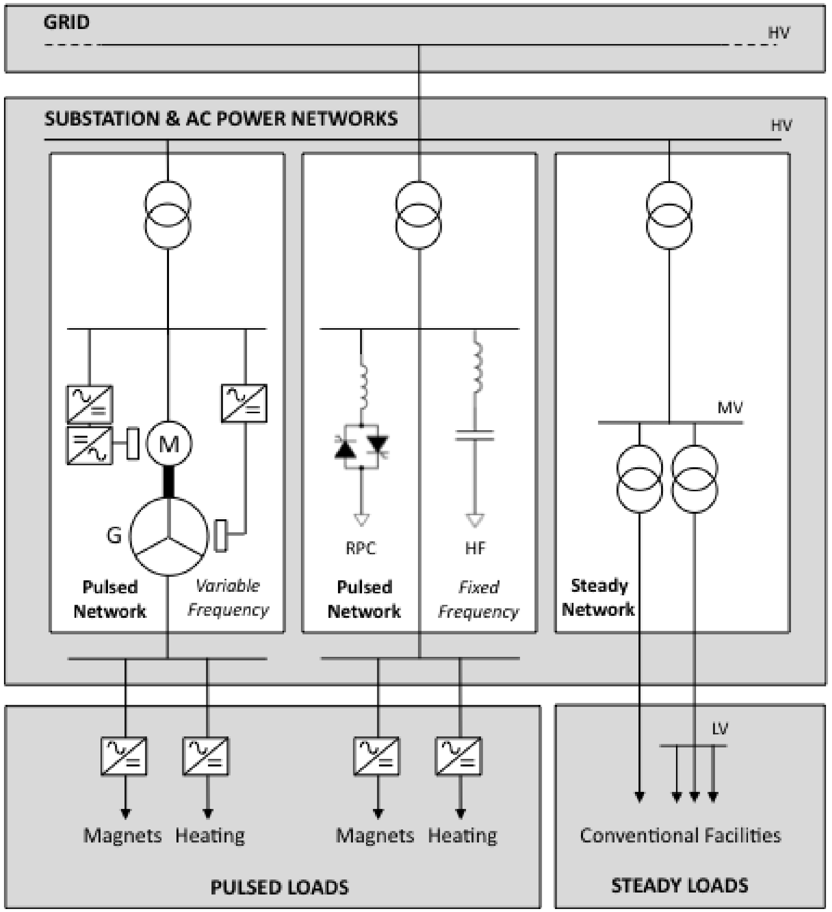
Power System for Fusion Research

Typical AC System



- **Grid** –AC transmission grid provides the input power source.
- **Pulsed Network/Variable Frequency** – receives low level of power from the grid, stores energy between pulses, and delivers a high level of active (P) and reactive power (Q) during pulses, typically using a motor – generator (MG) system with variable frequency output.
- **Pulsed Network/Fixed Frequency** – delivers a high level of P and Q during pulses, directly from the grid. Reactive Power Compensation (RPC) controls net Q and Harmonic Filtering (HF) filters harmonic currents.
- **Steady Network/Fixed Frequency** –receives power from grid and delivers to medium voltage (MV) and low voltage (LV) conventional steady-state facility loads.
- Conventional CTs in use for feeders
- Protective relays tested for variable frequencies

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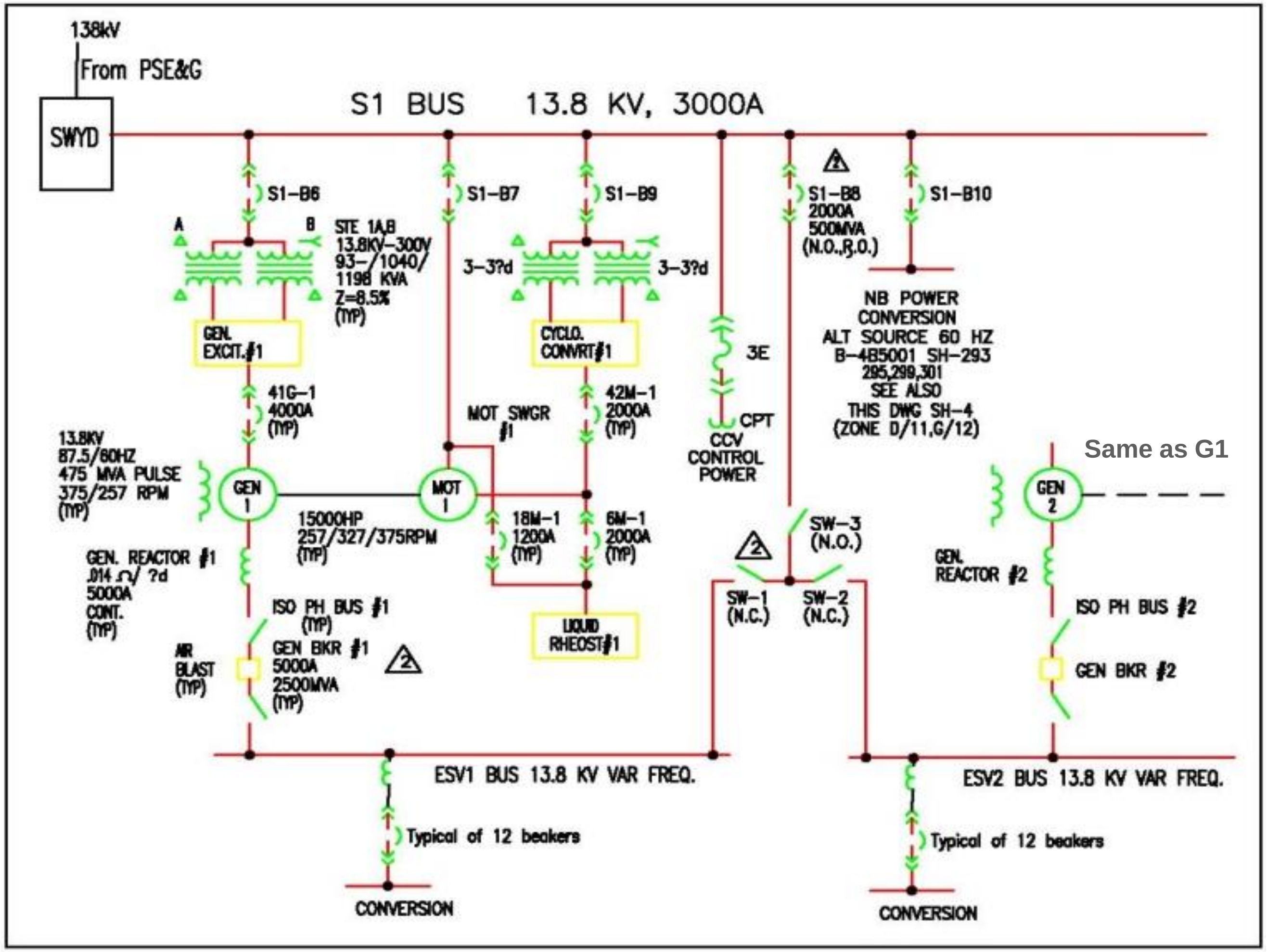
Experimental AC System in PPPL Princeton



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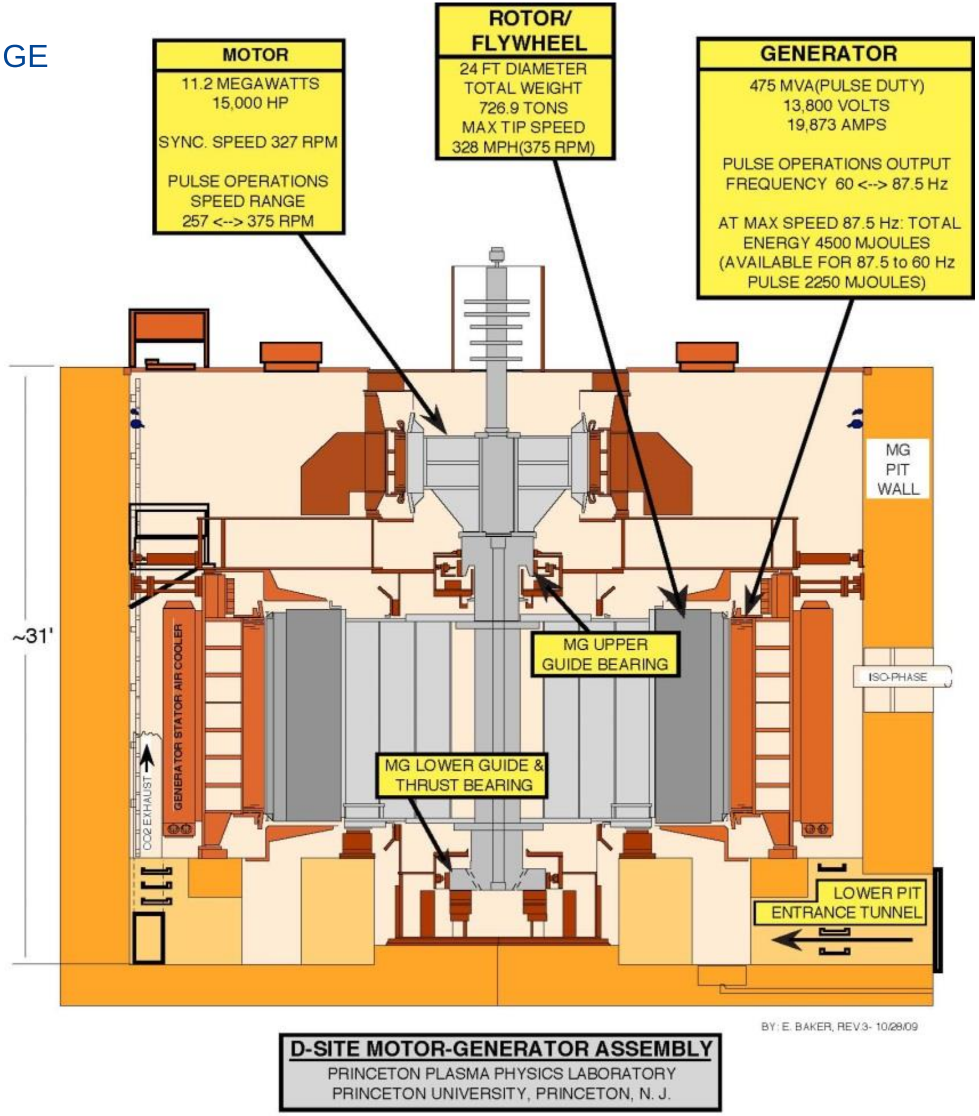
Power System for Fusion Research

PPPL MG – Supplied by GE



MOTOR
11.2 MEGAWATTS
15,000 HP

SYNC. SPEED 327 RPM

PULSE OPERATIONS
SPEED RANGE
257 <--> 375 RPM

ROTOR/ FLYWHEEL
24 FT DIAMETER
TOTAL WEIGHT
726.9 TONS
MAX TIP SPEED
328 MPH(375 RPM)

GENERATOR
475 MVA(PULSE DUTY)
13,800 VOLTS
19,873 AMPS

PULSE OPERATIONS OUTPUT
FREQUENCY 60 <--> 87.5 Hz

AT MAX SPEED 87.5 Hz: TOTAL
ENERGY 4500 MJOULES
(AVAILABLE FOR 87.5 to 60 Hz
PULSE 2250 MJOULES)

D-SITE MOTOR-GENERATOR ASSEMBLY
PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY, PRINCETON, N. J.

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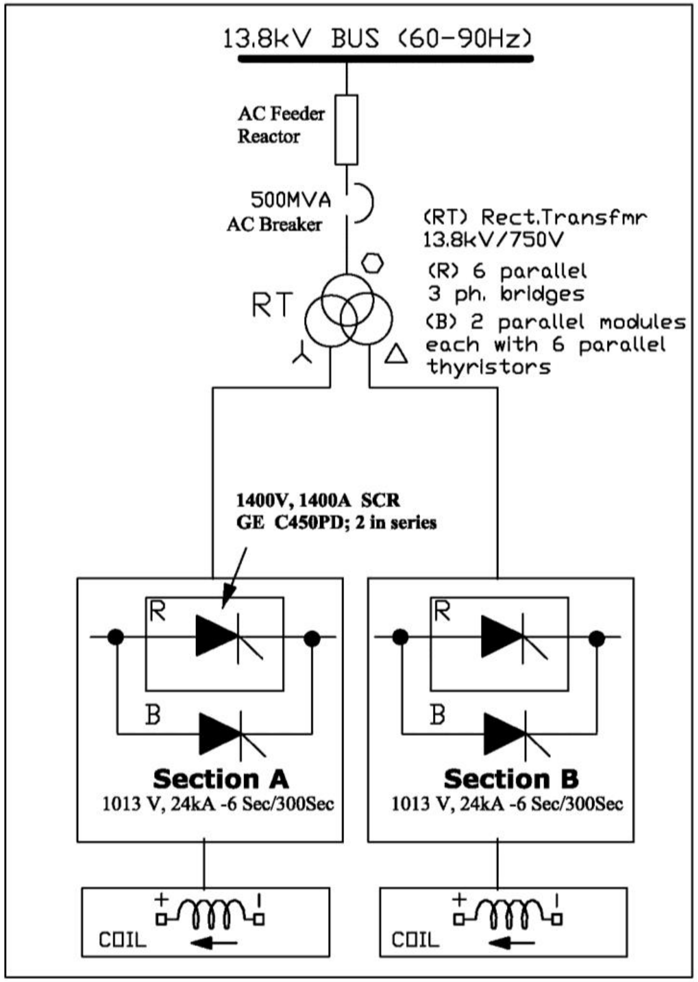
Power System for Fusion Research

Typical Conversion System in PPPL

- Three Winding Transformer feed the Rectifiers
  - These have polygonal primaries
  - Total of 37 Units of this rating
  - Effective 24 pulse rectification possible by series/parallel operation
  - Conventional CTs on AC side
  - DCCTs are typically Hall effect type
  - Some fiber DCCTs are also used.
  - DCCT accuracy typically 0.1%



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PPPL Pwr. Supply Bldg

PPPL Thyristor Rectifiers

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Power System Equipment

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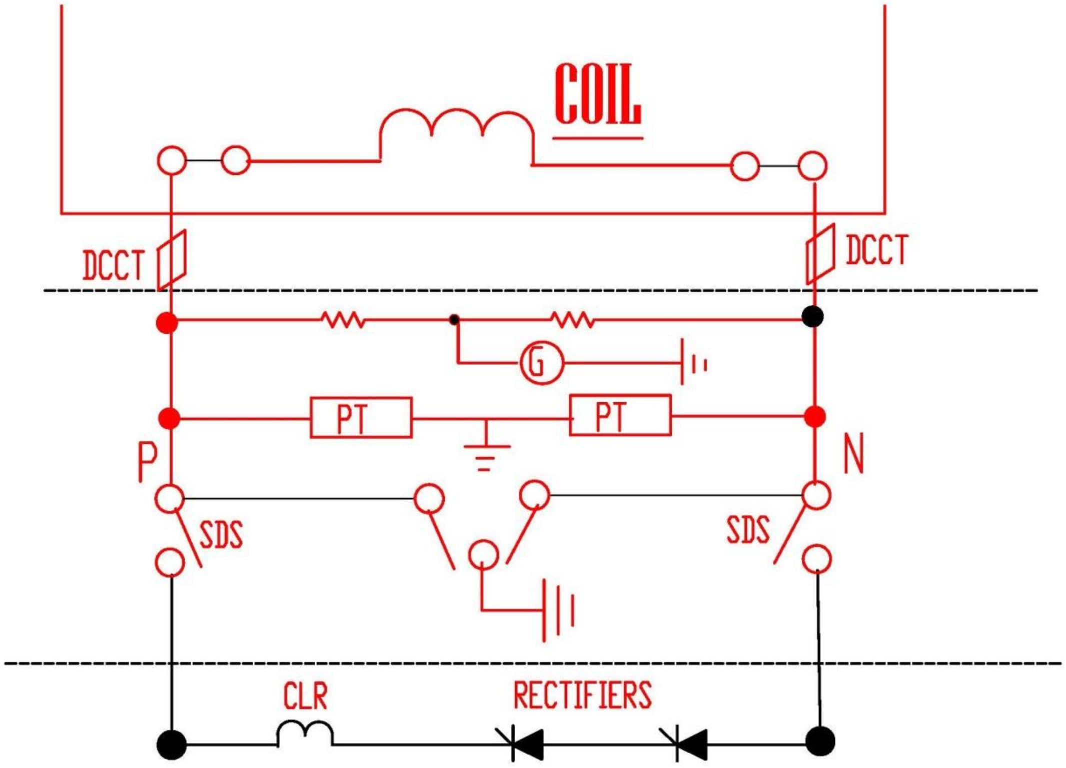

TYPICAL COIL CIRCUIT

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POWER SYSTEM FOR FUSION RESEARCH

NSTX in PPPL

-The National Spherical Torus Experiment (NSTX) designed & installed in existing facilities at Princeton Plasma Physic Laboratory (PPPL) in 1999.

-Most of the hardware, plant facilities, auxiliary sub-systems, and power systems originally used for Tokamak Fusion Test Reactor (TFTR) have been used with suitable modifications to reflect NSTX needs.

-At present, the NSTX power system is feeding thirteen (13) circuits from the Power converters.

-An upgrade of the NSTX center stack is being executed and will be commissioned in 09/2014. This has a much higher Toroidal Field Current from 71.2kA to 129.8kA, and required major configuration changes including doubling the number of parallel strings of rectifiers along with associated power loop changes. Also, three additional coils are to be installed in the machine.

-The control and protection of the rectifiers have to be replaced to reflect state of the art features to enhance the performance.

The main power supply systems for NSTX upgrade are for the Toroidal Field (TF), Poloidal Fields (PF) with twelve individual circuits), the Ohmic Heating Solenoid (OH) coil circuit, the Coaxial Helicity Injection (CHI) system, and the Resistive Wall Mode Coils (RWM). Table 1 gives the details of the NSTX coil system circuits for the upgrade mode. All the DC power loops are kept floating.

The Coaxial Helicity Injection (CHI) system is retained. For CHI operation, the vacuum vessel is divided into two electrically separate parts. These act as the two electrodes for the CHI. Thus the vessel sections are also required to float during CHI operation.

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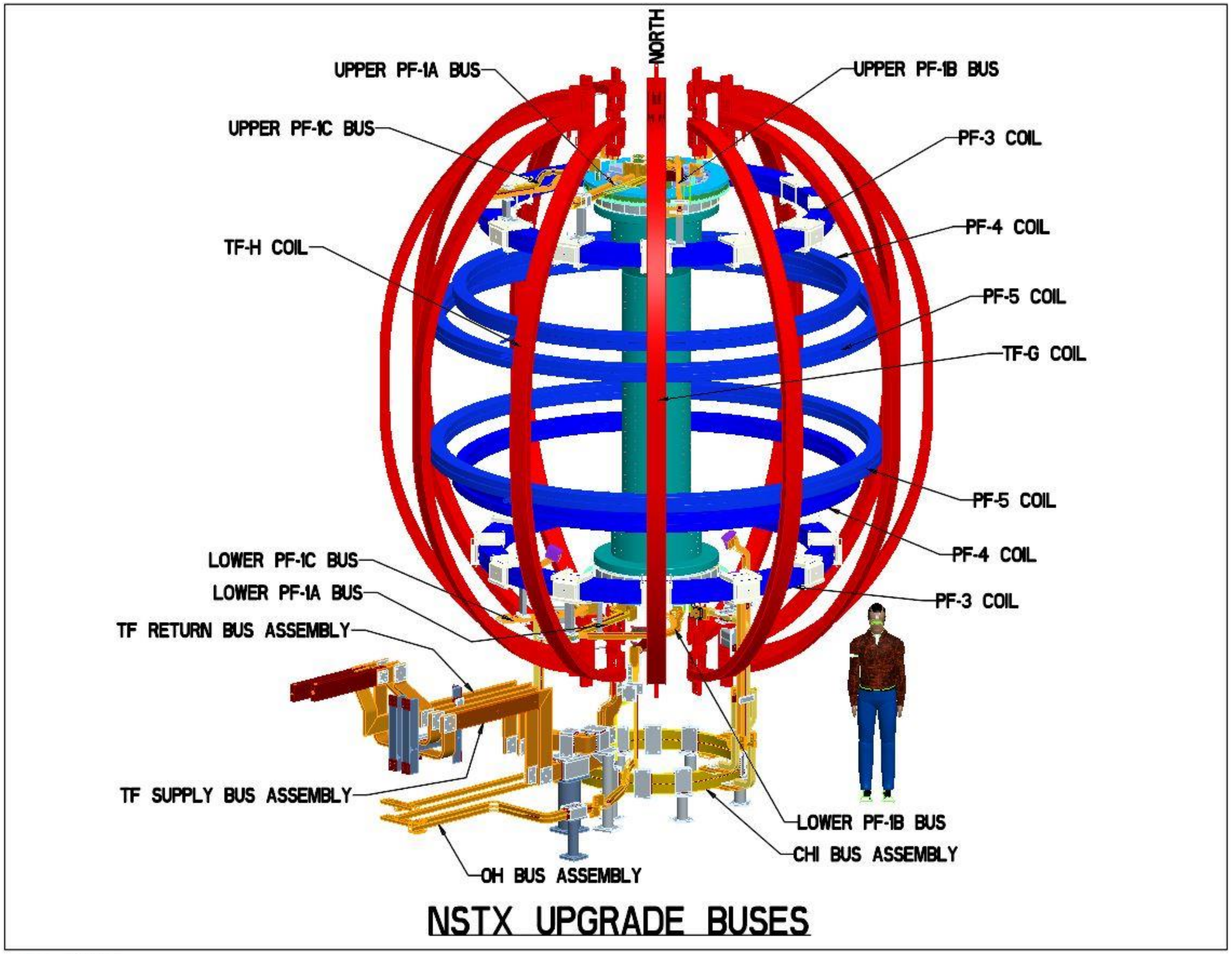
Power System for Fusion Research



NSTX UPGRADE BUSES

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POWER SYSTEM FOR FUSION RESEARCH

NSTX-U Coil Circuits

1	**TF**	**7.08**	**2400**	**1200**	**U**	**8**	**1**	**130**	**0**	**7061**	**9985**	**Increased current**
2	OH	1.474	2400	1200	B	2	6	24	-24	595	841	**Change CLR**
3	PF1aU	5.5	2400	1200	B	2	1	18	-7	862	1219	**Eliminate ripple reactor**
4	PF1aL	5.5	2400	1200	B	2	1	18	-7	862	1219	**Eliminate ripple reactor**
5	PF1bU	2.104	2400	1200	U	1	1	13	0	385	544	New
6	PF1bL	2.104	2400	1200	U	1	1	13	0	385	544	No Change
7	PF1cU	4.341	2400	1200	U	1	1	16	0	680	962	New
8	PF1cL	4.341	2400	1200	U	1	1	16	0	680	962	New
9	PF2U	5.5	2400	1200	U	1	1	15	-11	718	1016	No Change
10	PF2L	5.5	2400	1200	U	1	1	15	-11	718	1016	No Change
11	PF3U	5.5	2400	1200	B	2	2	12	-16	766	1083	No Change
12	PF3L	5.5	2400	1200	B	2	2	12	-16	766	1083	No Change
13	PF4	5.5	2400	1200	U	1	2	16	0	766	1083	No Change
14	PF5	5.5	2400	1200	U	1	3	24	0	1149	1625	No Change
15	RWM	5.5	2400	1200	B	1	1	3.3	3.3	158	223	No Change

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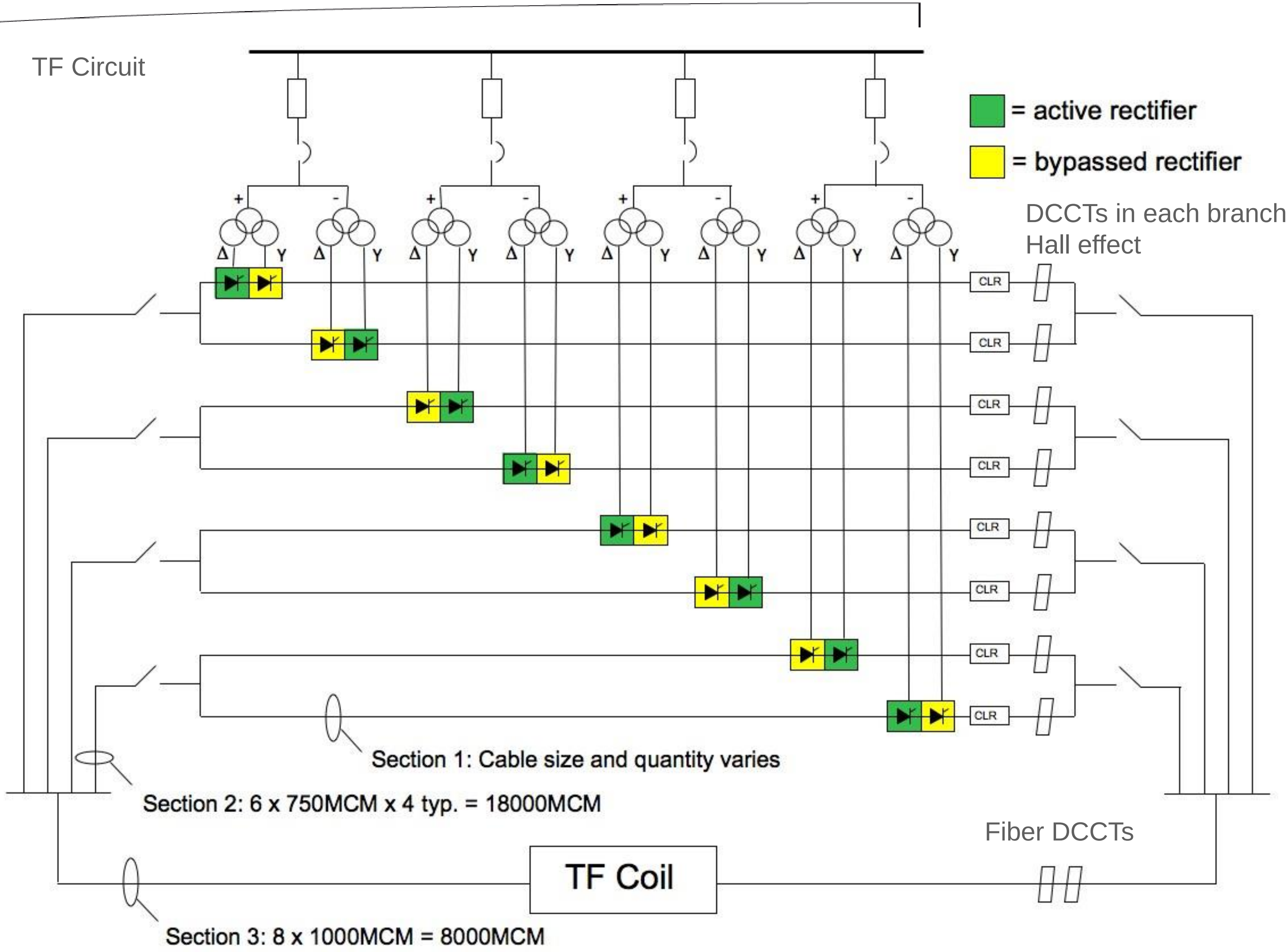

TF Circuit

🟩 = active rectifier

🟨 = bypassed rectifier

DCCTs in each branch
Hall effect

Section 1: Cable size and quantity varies

Section 2: 6 x 750MCM x 4 typ. = 18000MCM

Fiber DCCTs

TF Coil

Section 3: 8 x 1000MCM = 8000MCM

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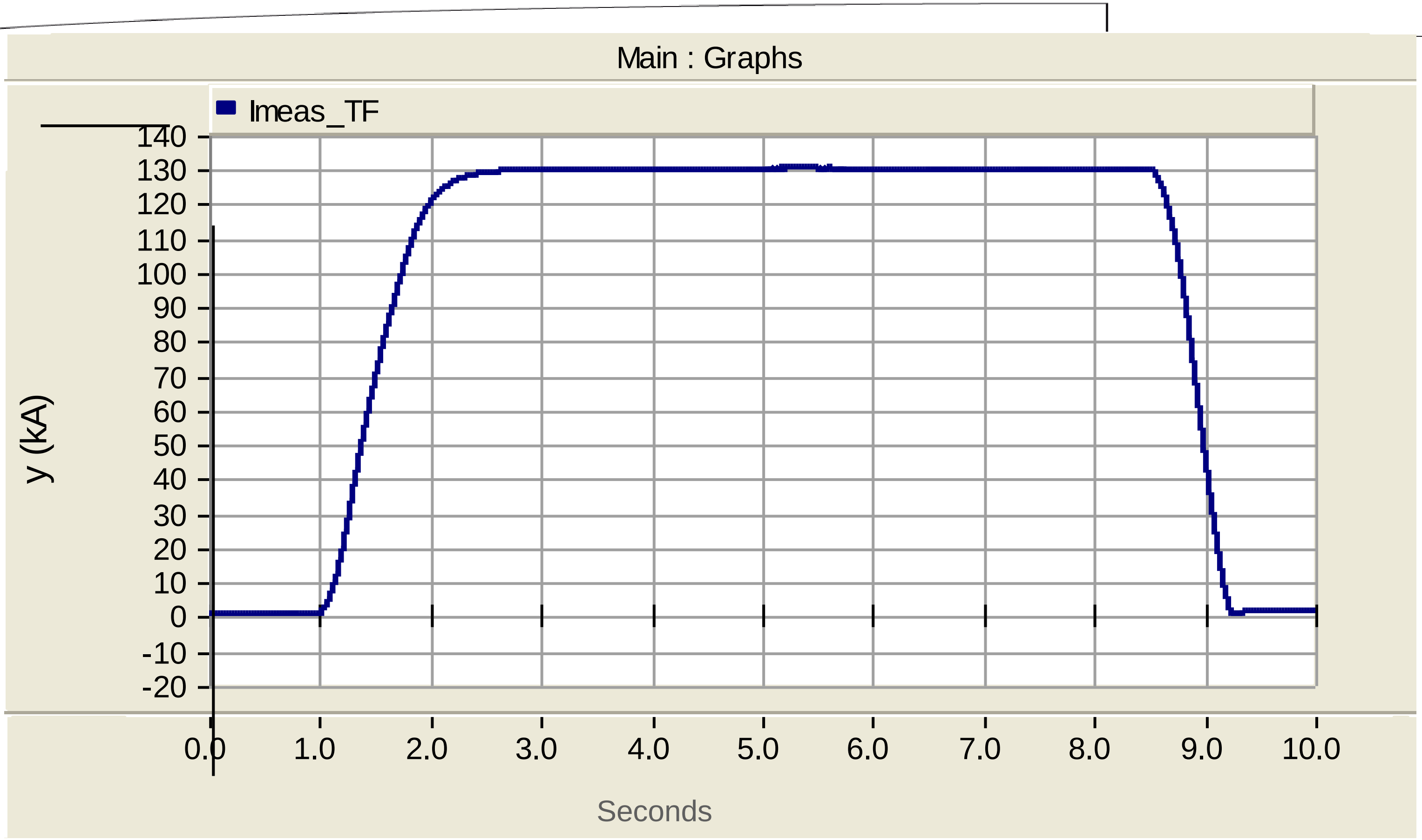
POWER SYSTEM FOR FUSION RESEARCH



Typical projected current in TF coils

Fiber DCCTs supplied by Dynamp installed

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Power System for Fusion Research

DCCTS USED IN PPPL PRINCETON

- Different Types of DCCTs used
  - Rogowski coils to measure plasma current up to one megamp – Built in-house (3 units)
  - Standard shunts with fiber optic transmitters – (4 units – transmitters built in-house)
  - Coaxial shunts with fiber transmitters as needed – (6 units were in service for TFTR)
  - Misc. dccts
    - ADM units supplied originally by Halmar Electronics – total of 30 units
    - LEM units – 12 units
  - Fiber optic dccts. (Total of 6 units)
  - Time response important in some applications

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+150/-150kA DCCT installed in TF Circuit

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A unique application of a COSI DCCT

- TF pulsed current is 129.8kA for 7.04 seconds every 1200 seconds in the final phase
- There are twelve TF bundles each with three turns
- Each bundle will have a max. current of 390kA during the pulse

- Keeping the above factors in view following is proposed:
    - Use a fiber optic current DCCT sensor
    - Run the sensor fiber around the machine (at the top or bottom of the machine) such that the sensor fiber is placed in clockwise direction in one bundle and in the anticlockwise direction in the next bundle.
    - Thus the resultant current sensed is zero under normal operating condition.
    - If a turn to turn fault develops in any one bundle the resultant current will be 130kA as sensed by the fiber. This will initiate a trip.
    - See the sketch

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- The COSI fiber DCCT can be used for this application.
- Manufacturer of this DCCT is Alstom type A, COSI-CT-F3 – Open Loop
- This is +50/-50kA unit with a 50 meters long sensor fiber.
- Provide the required loops around the machine as per sketch
- Proposed to keep the trip setting around 50Amps (10mV)

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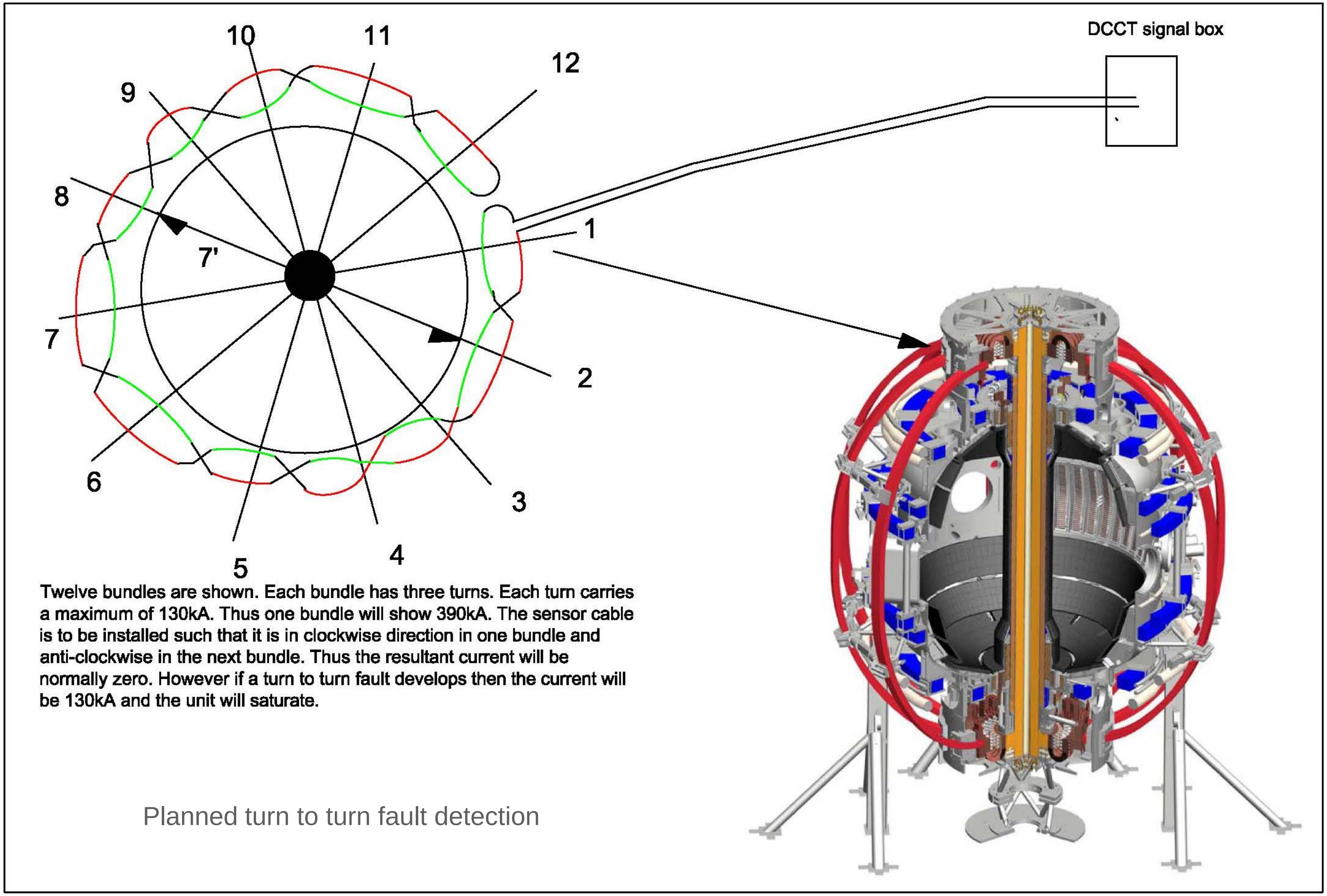

Twelve bundles are shown. Each bundle has three turns. Each turn carries a maximum of 130kA. Thus one bundle will show 390kA. The sensor cable is to be installed such that it is in clockwise direction in one bundle and anti-clockwise in the next bundle. Thus the resultant current will be normally zero. However if a turn to turn fault develops then the current will be 130kA and the unit will saturate.

Planned turn to turn fault detection

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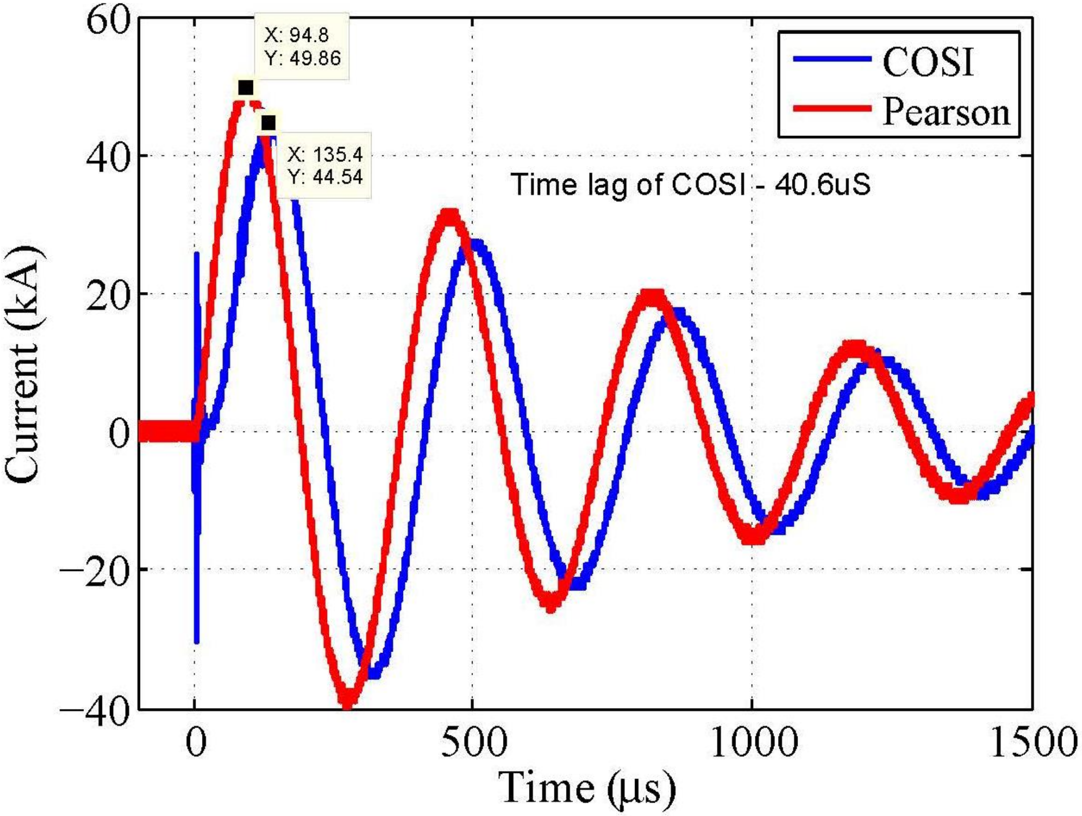
Tests on COSI DCCTs in PPPL Princeton

- COSI with 50 meter sensor tested in PPPL
- Clarifications and support was extended by Jim Blake and others in ALSTOM Phoenix.
- Cap banks used for the Experiment
- Rate of change of current > 500 Amps / microsecond
- Time lag without filters 41us approximately
  - Per Jim Blake (Alstom) this is expected.



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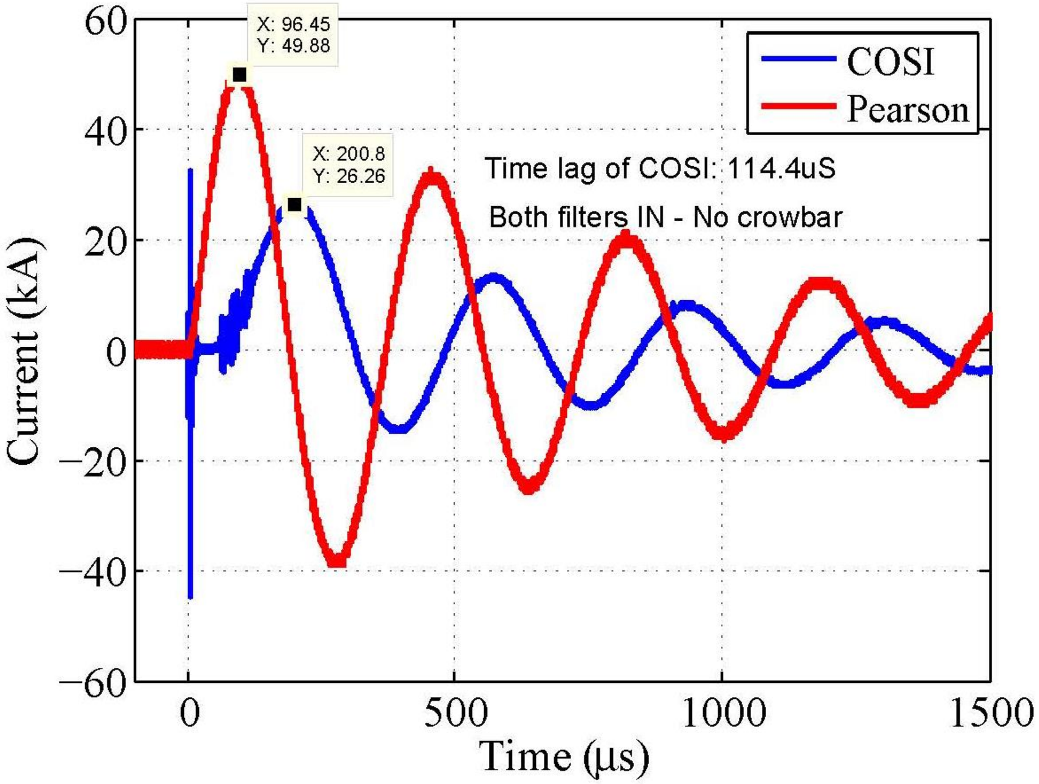
COSI Tests in Princeton

- Time lag with filter 110us approx.



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Conclusion

- Fusion research principles outlined
- International effort to explore fusion for eventual alternative to power
- Overview of Fusion research in PPPL
- Typical Power systems for Fusion research – AC & DC systems
- CTs used in power system
- A unique application of COSI in PPPL
- COSI tests for time response given

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Acknowledgement

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The contents of this presentation are extracts from already published articles and internal reports within PPPL.

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1. S. Ramakrishnan et al – “Power System for NSTX upgrade” Symposium on Fusion Engineering 2013.

2. C. Neumeyer et al –” ITER Power Supply Innovations & Advances” Symposium on Fusion Engineering 2013.

3. PPPL internal presentations on Fusion

4. Input from Jim Blake of Alstom on COSI dccts

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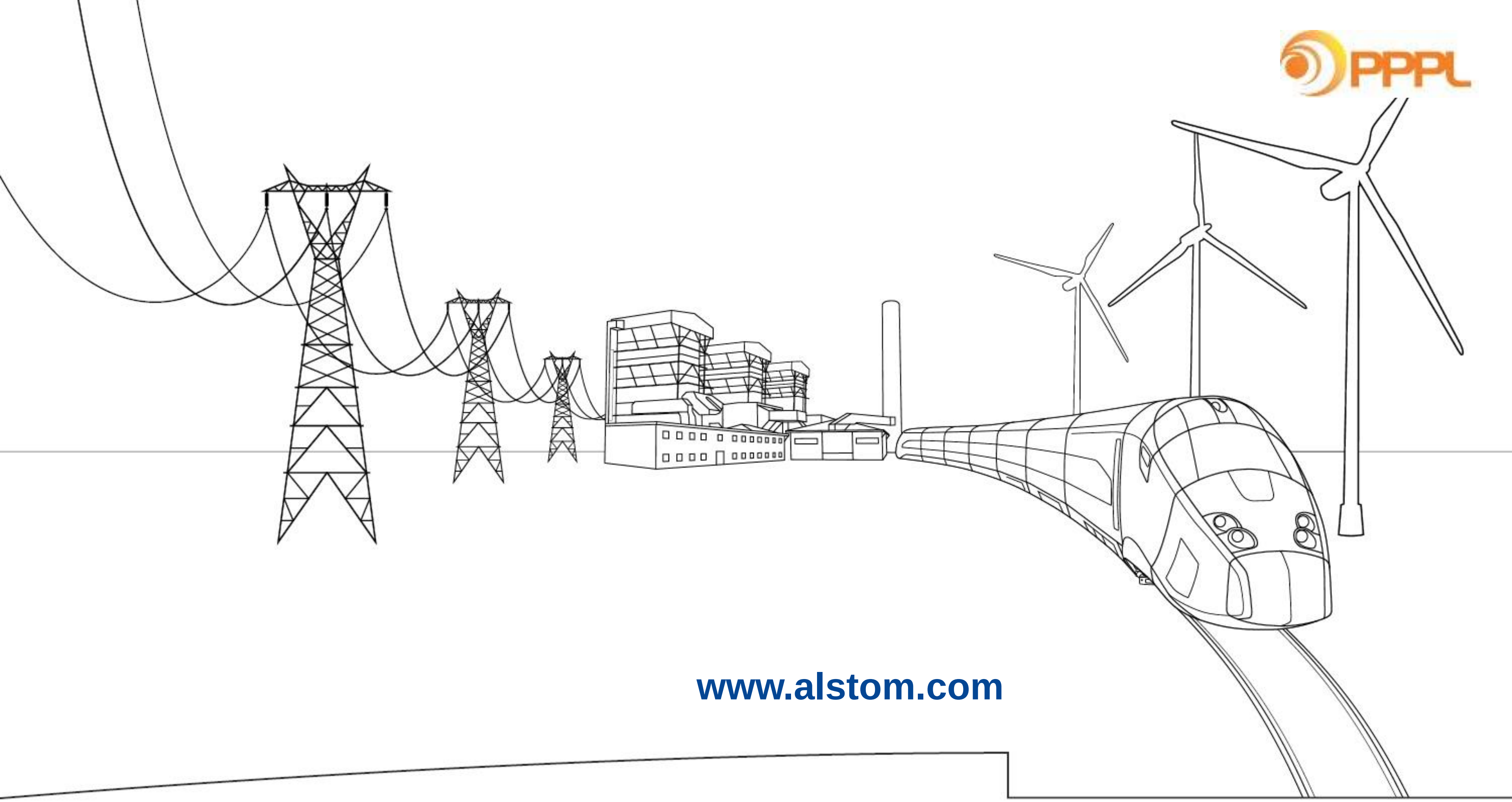

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