Diagnostic Neutral Beam and Beam-Based Diagnostics to Study Non-Inductive Startup Techniques

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PEGASUS-III Toroidal Experiment

Layout Slide (Include for Posters)

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

Diagnostic Neutral Beam and Beam-Based Diagnostics to Study Non-Inductive Startup Techniques

PEGASUS-III	Beam-Based Diagnostics Being Developed	Arc Plasma Source Characterization	Neutral Beam Systems Under Development
PEGASUS-III: A Spherical Tokamak Dedicated to Investigating Non-Solenoidal Plasma Startup and Current Drive	MSE Diagnostic	DNB Ion Source Designed to Support These Diagnostics	Accelerator Grid Power Supply Constructed
Need to Understand Plasma Evolution During Startup and Hand-off	Ion Spectroscopy Diagnostic (ISD) Implemented in Pegasus	Arc Source Parameter Space Explored	PLECS Simulation Meets Performance Requirements
Magnetic Reconnection from DC Helicity Injection Heats Ions	Filtered Photodiode Array	Anode-Cathode Fueling Ratio Shown to Impact Arc Stability	Power Supply Development is Progressing
Electrodes and Antennae can Source Impurities to the Plasma	Beam-Diagnostics Geometry Summary (more discussion needed)	Source Plasma Expansion Characterized	DNB Deployment Planned for 2020

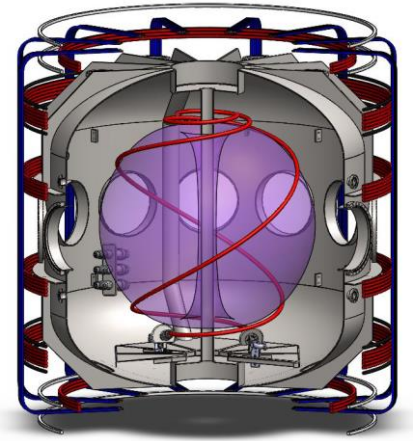


PEGASUS-III

PEGASUS-III: A Spherical Tokamak Dedicated to Investigating Non-Solenoidal Plasma Startup and Current Drive

Phase 3 Objective ⟶ use a single device to evaluate viable current drive techniques:

Pegasus Phase-2



Local helicity injection (LHI)

Coaxial helicity injection (CHI)

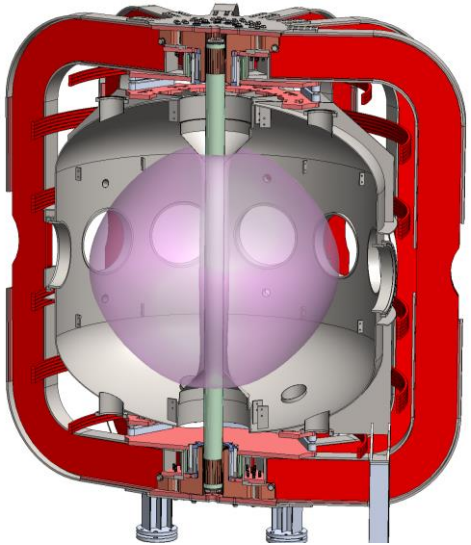
EBW RF-heating & drive

Poloidal induction

Neutral Beam Current Drive, *etc.*

Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm²]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
ΔT_{bundle}	< 10°C	< 20°C
R_0 [cm]	45	45
A	1.15–1.3	1.18–1.35

Pegasus Phase-3



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UNIVERSITY of WASHINGTON

OAK RIDGE National Laboratory

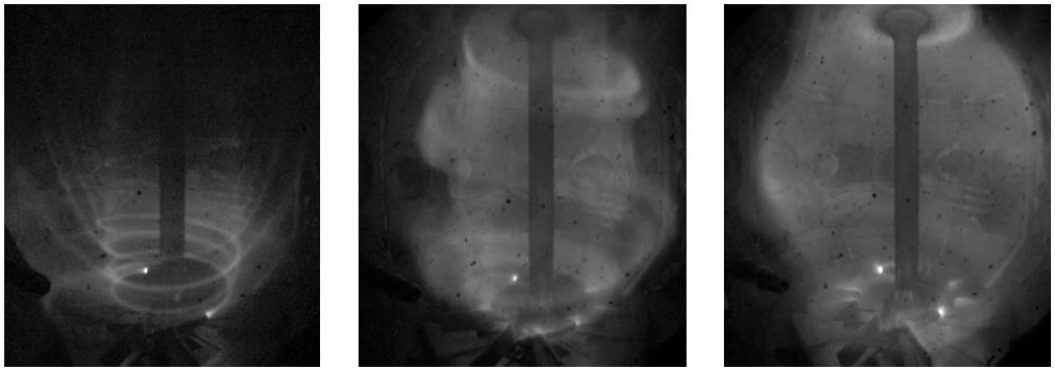
PPPL

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New Diagnostics are Required to Understand Plasma Evolution During Startup and Hand-off

- Core $|B|$ and $\tilde{B}$ measurements
- Density profiles
- Impact of impurities
- Ion temperatures and heating mechanisms

LHI Startup in Pegasus (up to 200kA I_p)



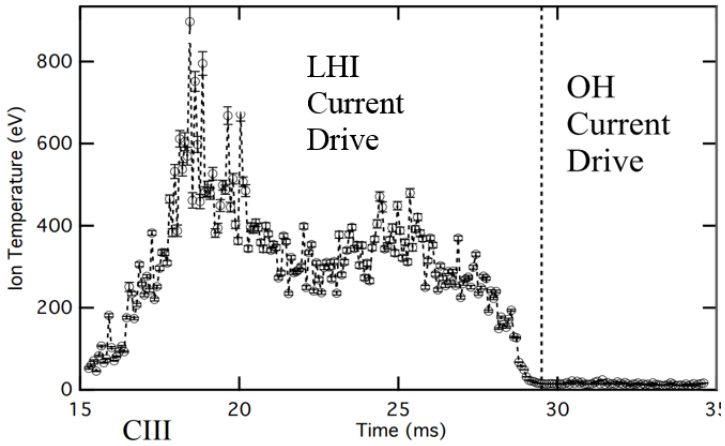
Initial Injection | Transition | Relaxed Plasma

Understanding these aspects informs predictions of:

- Performance scaling to larger experiments
- Compatibility with steady state CD systems

Local Ion Temperature Measurements are Needed for Equilibrium Reconstruction and Reconnection Analysis

Anomalous Ion Temperatures Observed During LHI



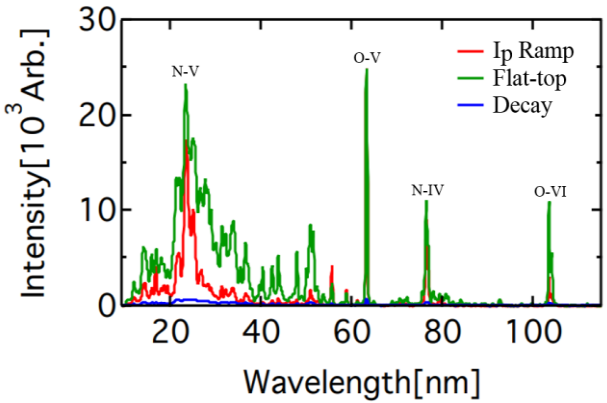
- LHI drives helicity by injecting current in the plasma edge
- Helicity transport to the core requires a change in magnetic field structure
- Magnetic reconnection events preferentially heat ions
- Local impurity T_i measurements can locate reconnection activity

$T_i(r,t)$ measurements:

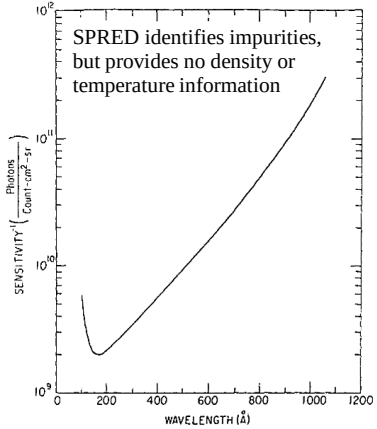
- Provide ion pressures and equilibrium constraints
- Support studies of reconnection ion heating

Impurity Density Measurements are Needed to Understand Impurity Sourcing by Electrodes and Antennae

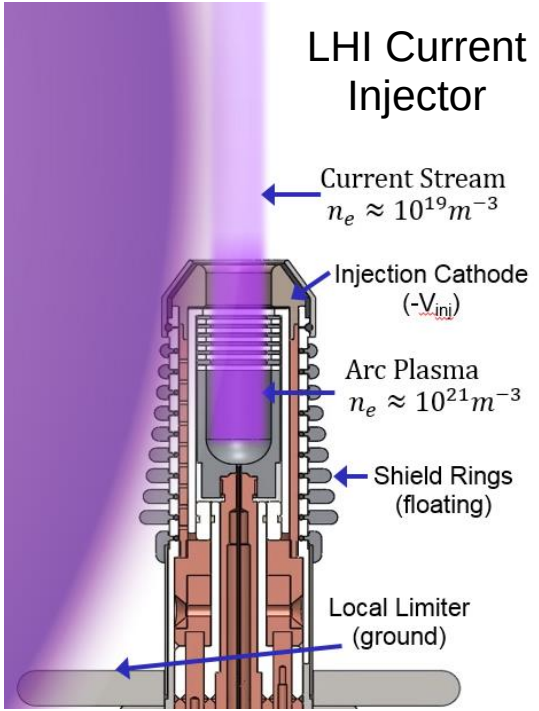
VUV Spectrum Identifies Impurities During LHI



Sensitivity Curve for Similar SPRED Spectrometer



LHI Current Injector



Impurity behavior during non-solenoidal startup needs characterization:

- LHI and CHI: electrodes and injectors contact plasma; impact of current streams on vessel
- RF: high power density on launchers, waveguides contact plasma

Goal: Demonstrate acceptable impurity concentrations for I_p sustainment

B.C. Stratton, *et al.*, Review of Scientific Instruments 57, 2043 (1986)

Beam-Based Diagnostics Being Developed

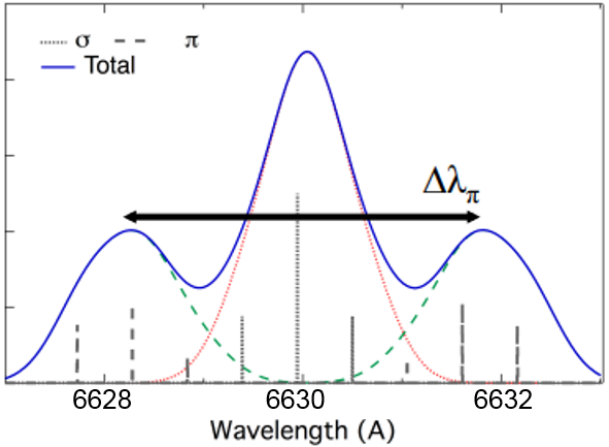
A High Energy DNB Enables MSE Diagnostic on PEGASUS-III

- At ~.6T and 80kV, we can resolve MSE splitting
- Requires <1% fluctuation in beam energy
- Requires a spectral resolution of ~.5Å

With an MSE diagnostic, we obtain:

- $|B|(r,t)$ which constrains equilibrium reconstructions in an ST with high paramagnetism (~1.4)
- Core $\tilde{B}$ measurements if noise levels permit
- Current profile comparisons for different CD techniques

Modeled MSE Spectrum for 80kV DNB at .6T



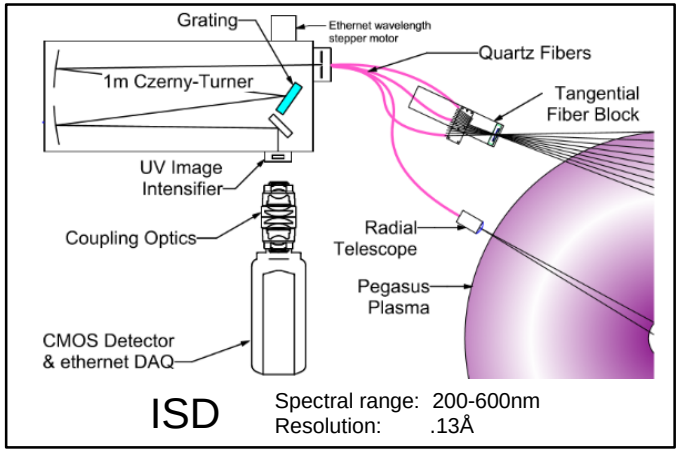
Beam divergence and energy fluctuations contribute to line broadening

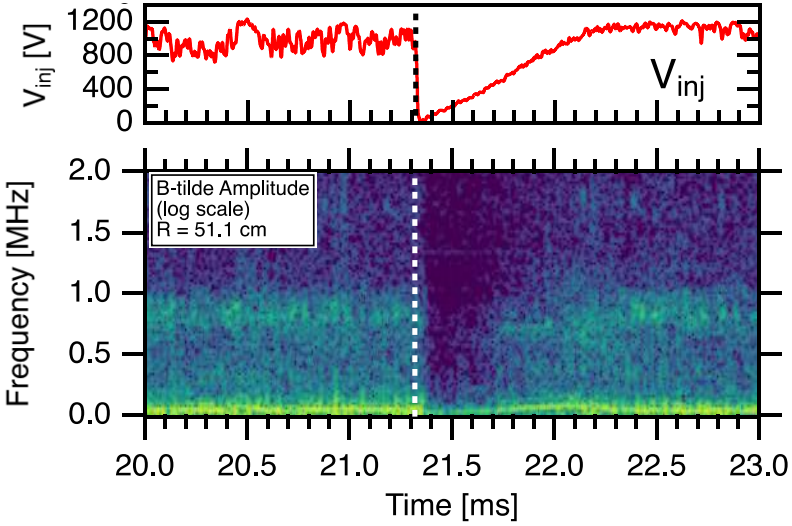
D.S. Thompson, *et al.*, Plasma Sources Sci. Technol. 19 (2010) 065016

CHERS Expands the Measurement Capabilities of the Ion Spectroscopy Diagnostic (ISD) on PEGASUS

Measure impurity T_i , n_i , and v_ϕ profiles to:

- Determine local ion pressure
- Characterize impurity content and behavior
- Study anomalous ion-heating

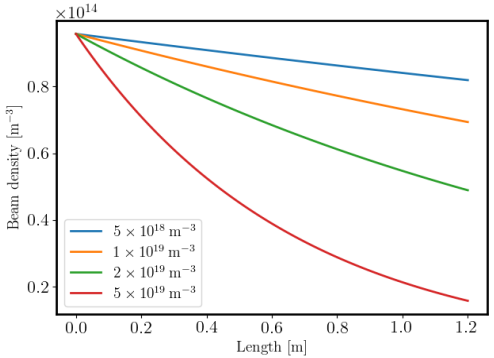




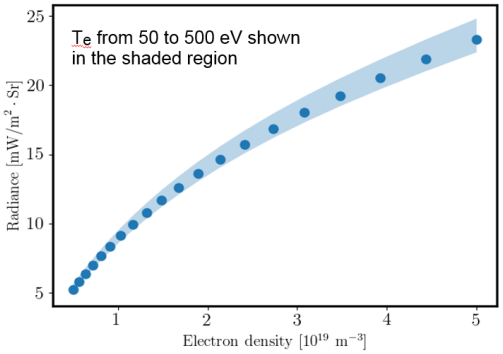
- Ion-heating dominated by reconnection events
- Reconnection events correlated to high frequency $\tilde{B}$
- High frequency $\tilde{B}$ quickly ceases when V_{inj} is removed
- Bulk T_i determined by measuring equilibration T_i of impurities after removing V_{inj}

Analysis of Beam Atom Emissions Yields Plasma Density Profiles

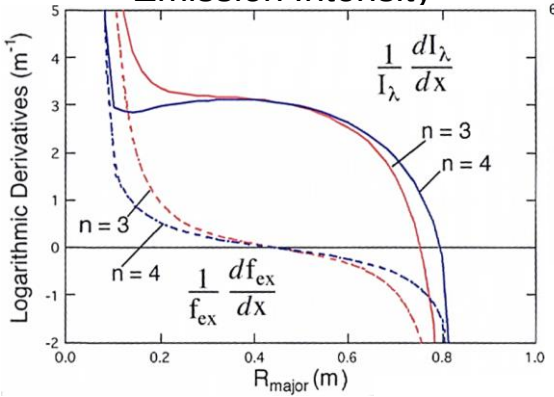
Modeled Beam Attenuation



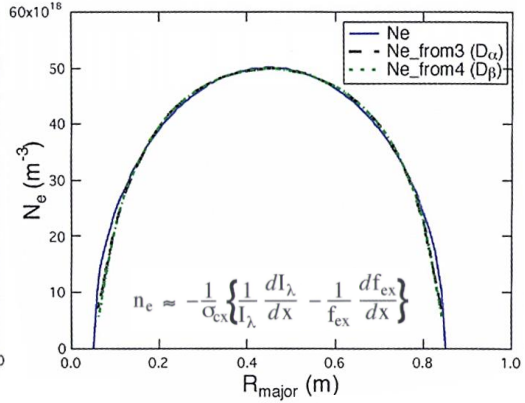
Modeled H-alpha Radiance



Logarithmic Derivative of Emission Intensity



Plasma Density Profile

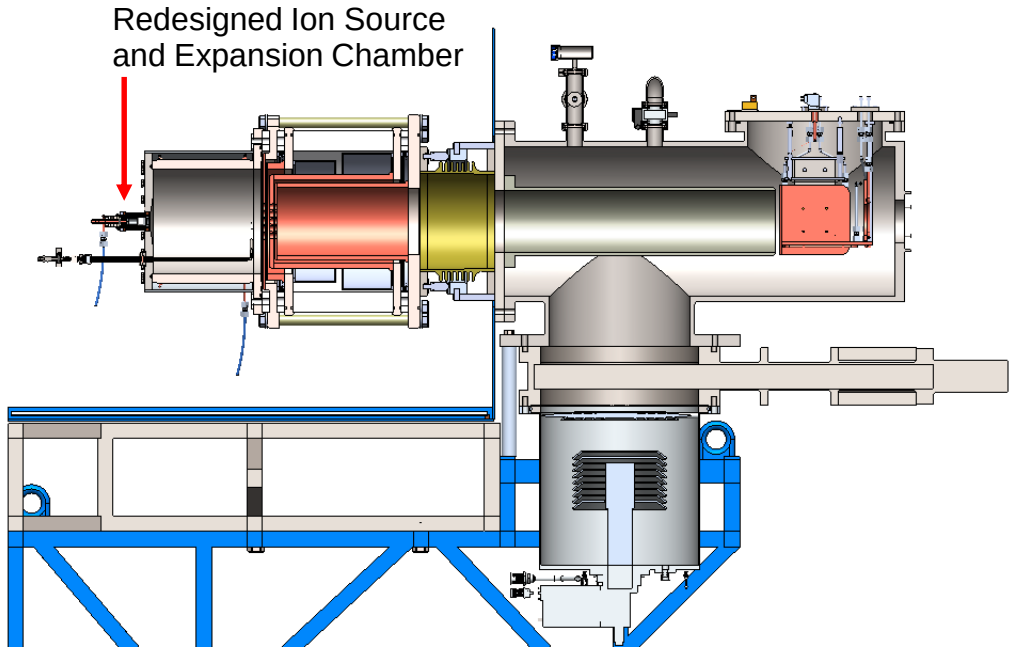


- H^0 beam atom bound electrons are excited by collisions
- Radiance mostly depends on beam density and plasma density
- Logarithmic derivative of intensity can be used to calculate the plasma density profile
- Beam emission analysis can determine $n(r,t)$ without calibration

These Diagnostics can be Implemented on PEGASUS-III with an Appropriate Neutral Beam

DNB from PBX received from PPPL:

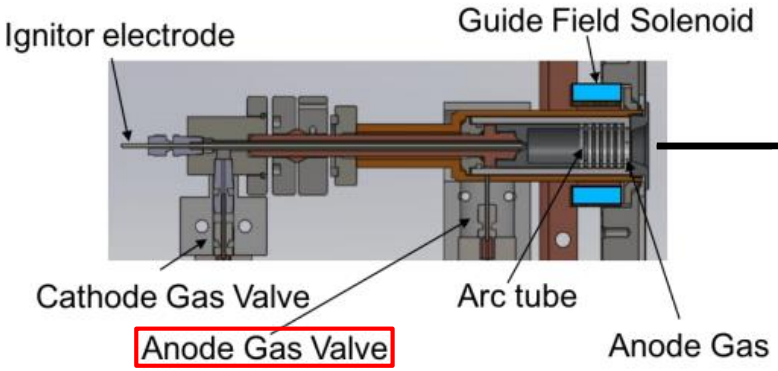
- 2.5A of H^0 current at 80kV
- >6 $\frac{mA}{cm^2}$ at beam focus
- ~9cm maximum diameter
- 100ms pulse length
- ≤ .5° beam divergence



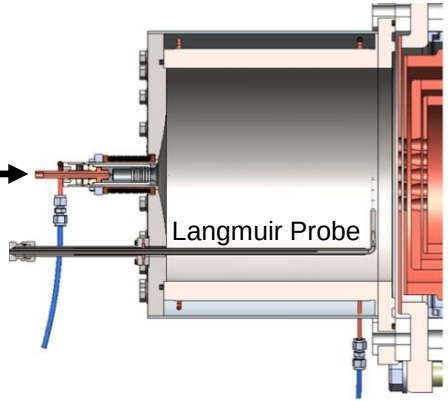
Arc-Plasma Ion Source Characterization

DNB Ion Source Redesigned to Support These Diagnostics

Filament Source Replaced by
Washer-Stack Arc Plasma Source



Expansion Chamber



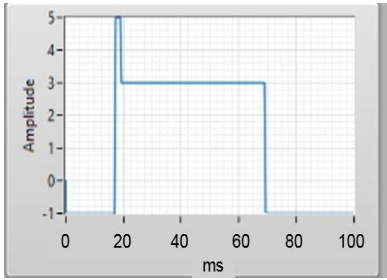
DNB performance constraints require an ion source with:

- High T_e to maximize full energy component
- Stable n_e and T_e to minimize fluctuations in beam parameters
- Fine control of fueling rates to tune beam parameters

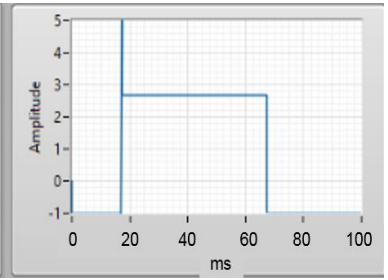
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Sufficient Anode Fueling Shown to Stabilize Arc

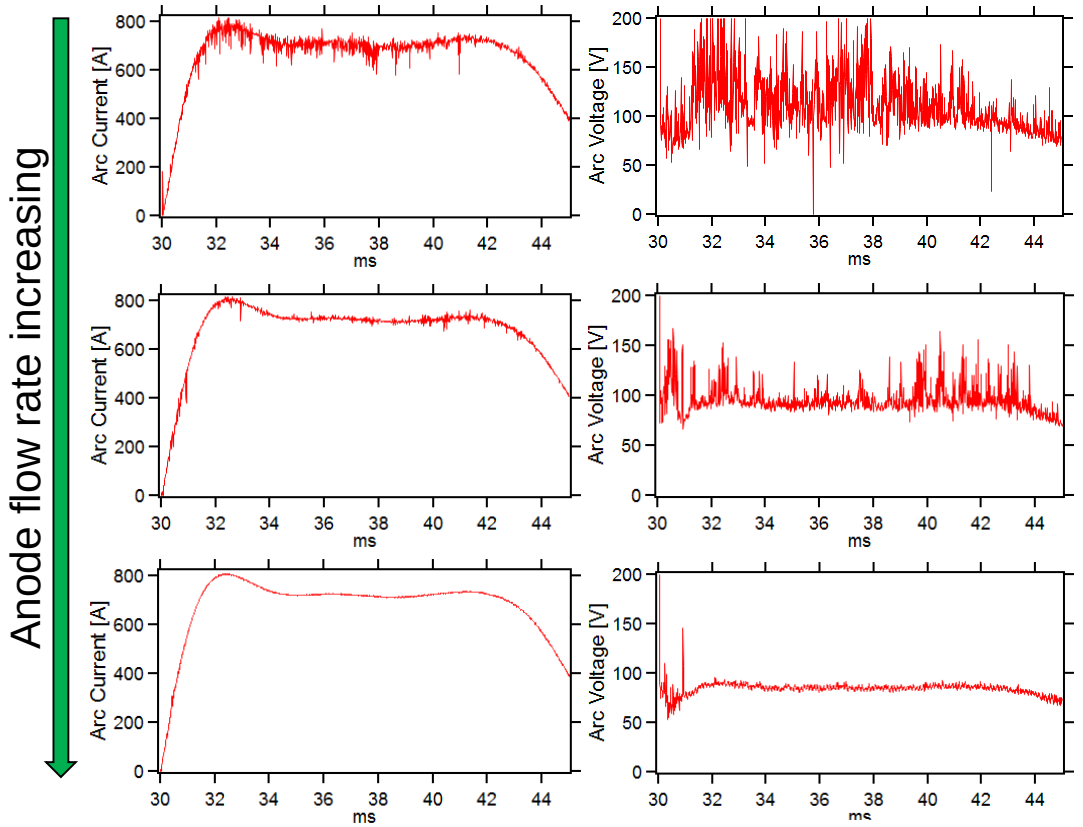
Cathode PEV Voltage



Anode PEV Voltage



- Piezoelectric valves (PEV) provide fine control of anode and cathode flow rates
- Quick gas puff ensures breakdown, followed by constant flow rates
- 2000V spark ionizes the arc channel, pulse-forming network sustains arc

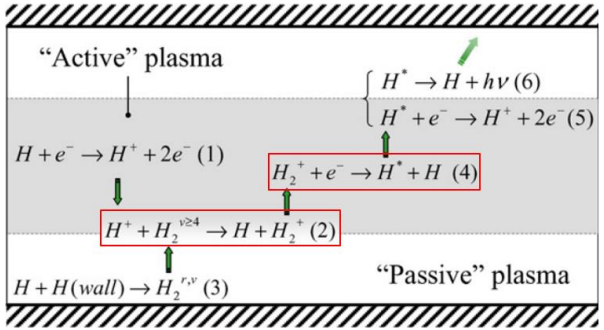


Minimal increase in anode-cathode fueling ratio suppresses arc instability

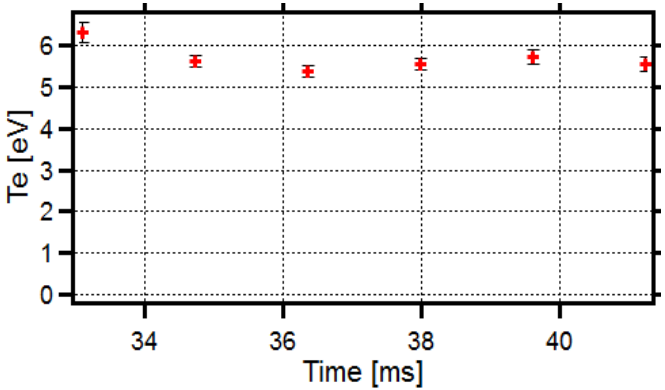
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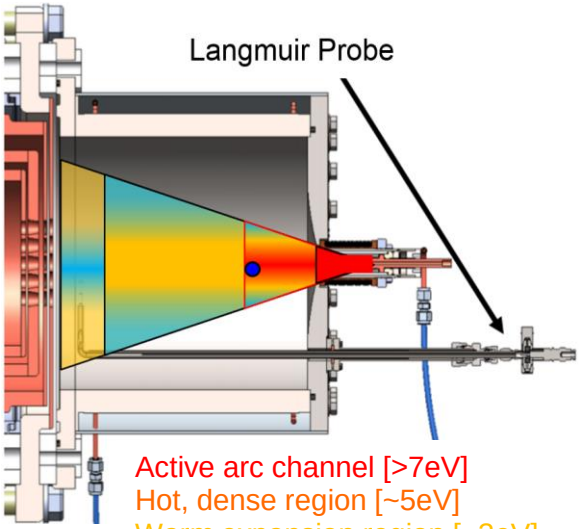
Source T_e Increased to Maximize Full Energy Component

Dominant Particle Interactions



T_e(t) 6cm from Arc Channel





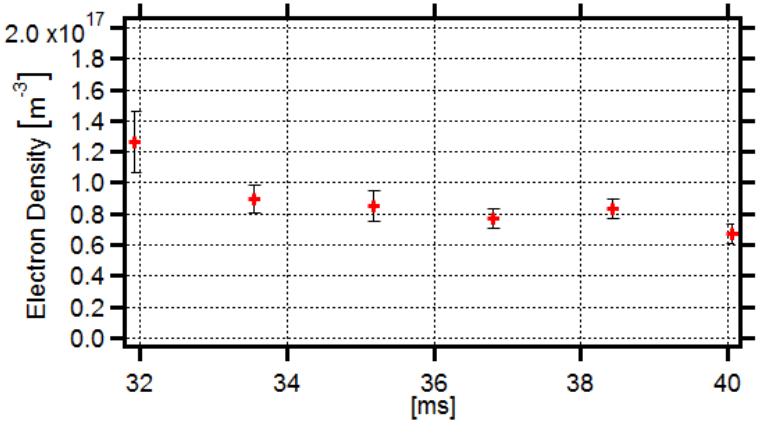
T_e and n_e in the arc-channel are favorable for producing atomic H ions:

- Dissociation rate for H_2 peaks at T_e ~13eV
- Molecular assisted recombination rate decreases as T_e increases from 1.5eV
- Density decrease from expansion reduces volume recombination rate

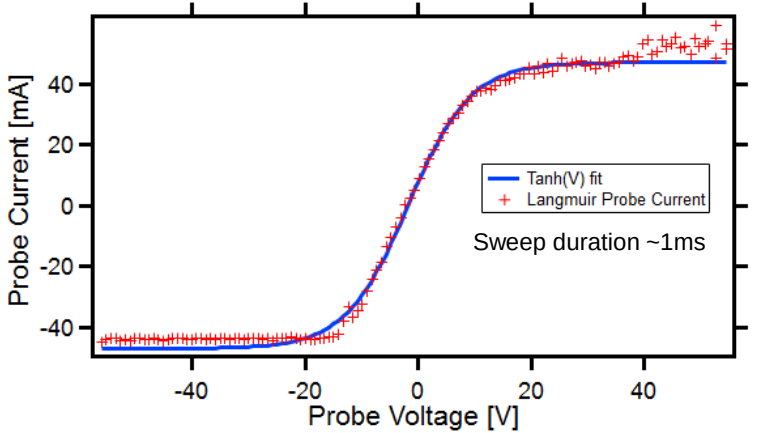
n_e decreases from ~10^{21}m^{-3} in the arc-channel ~10^{17}m^{-3} at the grid

Target Density Maintained at Extraction Grid

$n_e(t)$ 4cm from First Grid



Example Langmuir Probe Sweep



- 3A of extracted current requires a steady density of ~10^{17} m^{-3} at the grid
- Stable target densities at maximum T_e have been demonstrated

Source is ready to be deployed and optimized for beam parameters

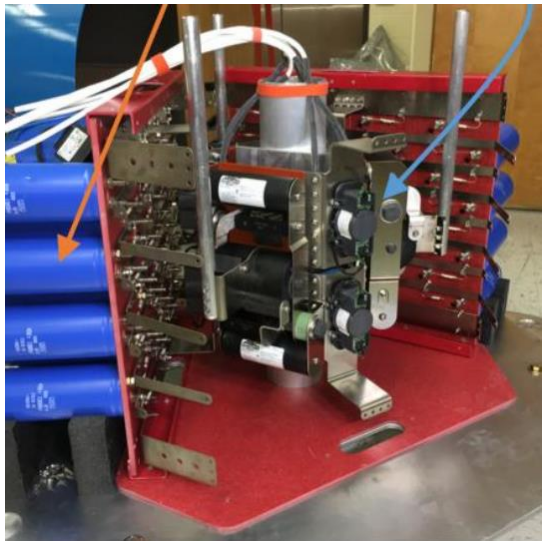
Neutral Beam Systems Under Development

DNB Performance Constraints Require a Novel Accelerator Grid Power Supply

80kV resonant DC-DC converter power supply

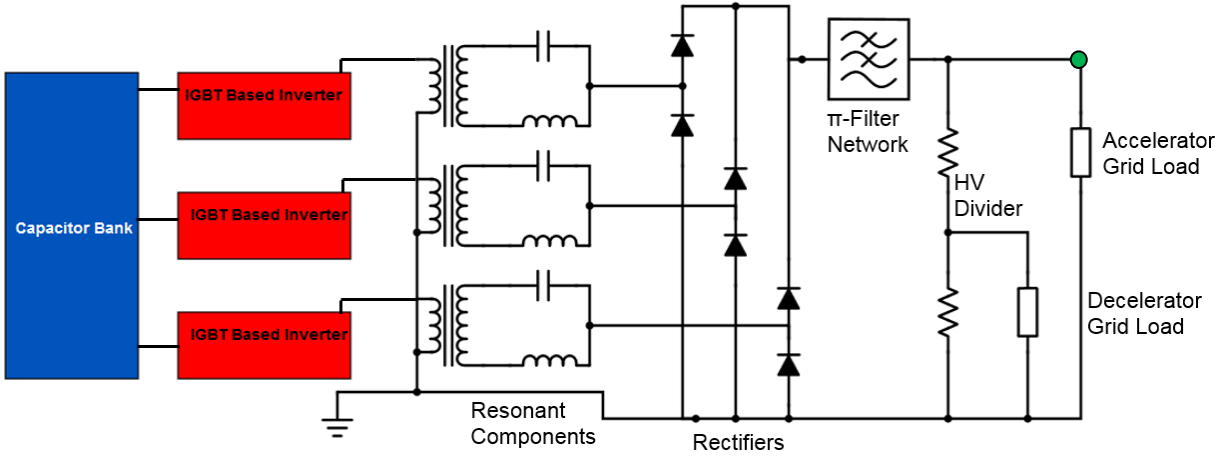
- Low output ripple (<1%)
- Designed for 4A 100ms pulses
- Fast rise/fall times (<200μs)
- Inherent fault protection
- Low stored energy (<120kJ)
- Switching frequency sets system gain
- FPGA and IGBT control

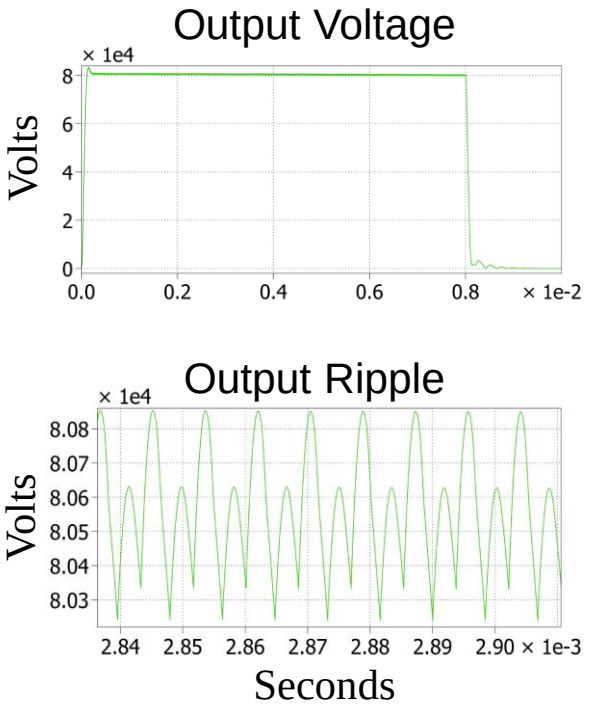
Stored Energy IGBTs





3-Phase Resonant DC-DC Converter Meets Performance Requirements in Simulation



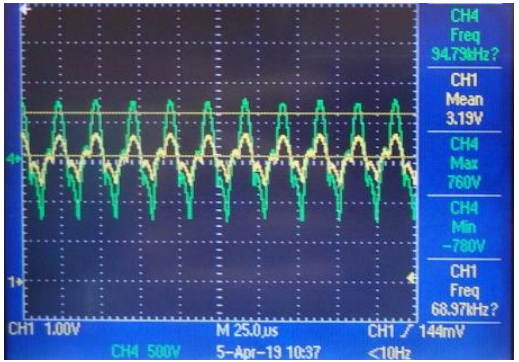


- 4A DC at 80kV
- Ripple <1% (<800V)
- Rise/fall time <200μs

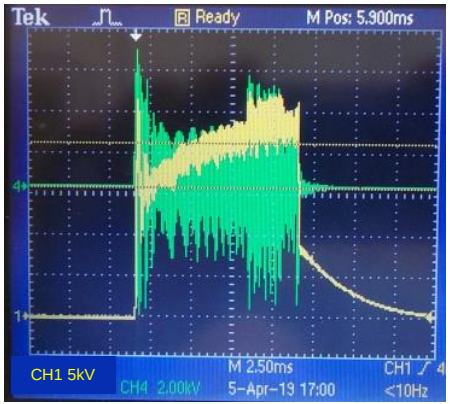
3-Phase Resonant Converter Power Supply Constructed and Being Tested

- Resonant 3-phase converters require precise balancing of resonant components
  - <.1nF difference results in large phase imbalance
  - Capacitors typically have higher capacitance than nominal
  - Resolved by measuring capacitors and selecting from batch to match impedances
- Next Steps:
  - Fabricate and install internal insulation
  - Install π-filter network and test up to 80kV

Phase Imbalance on Low-Voltage Discharge



Unfiltered 20kV Discharge (yellow trace)



DNB Installation Planned for 2020

1. Resolve 80kV supply arc-overs
2. Install filter and test 80kV supply
3. Fire the DNB, characterize:

   Power

   Energy fraction

   Divergence
4. Prepare control systems for PEGASUS integration
5. Shutdown, construction, install beam
6. Commission DNB on PEGASUS-III

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