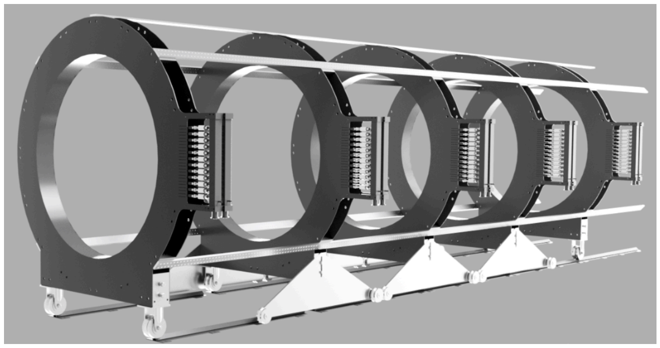
Multiple Coil Arrays - Water-cooled and in-vacuum

Model WE-IVC-6X-300MT · In-Vacuum High-Field Generation for Fusion Plasma & Beam Applications · 0.3 Tesla Field Strength

UHV COMPATIBLE · Six-coil series-connected array · Welded stainless 301 vacuum-rated construction · Internal water-cooled copper windings (6mm channels) · 96 turns × 800A per turn · Parallel cooling manifolds with series electrical architecture

Doc Ref: WE-IVC-6X-300MT · Rev 01 · 2026-03-16

High-Field In-Vacuum Magnetic Field Generation



Woodruff Engineering's In-Vacuum Coil Array System delivers 0.3 Tesla magnetic field generation within ultra-high vacuum environments, making it ideally suited for fusion plasma confinement research, neutral beam ion source development, and vacuum-compatible diagnostic systems where direct magnetic field coupling to plasma or high-energy particle beams is essential. Built around six water-cooled copper coil assemblies with welded stainless steel 301 vacuum-compatible forms, the system generates highly stable magnetic fields from individually controlled coil sections while maintaining vacuum integrity under pulsed high-current operation. Each coil features 92 precision-wound turns of square copper conductor with internal 6mm diameter cooling channels, rated for 800 amperes per turn to achieve the full 300 mT field strength required for plasma shaping, beam steering, and magnetic confinement experiments where external field coils cannot provide sufficient coupling or where space constraints demand in-vessel field generation.

Vacuum-Compatible High-Current Architecture

Each coil assembly features heavy-section square copper windings with integrated internal water cooling, providing direct thermal management of the 77 kA total current (96 turns × 800 A/turn) required for 0.3 Tesla operation while maintaining vacuum compatibility through fully-welded stainless steel construction. The precision-fabricated 301 stainless steel coil forms provide both structural support and magnetic shielding, with all-welded construction ensuring vacuum integrity under thermal cycling and Lorentz forces during pulsed operation. Water cooling is distributed in parallel across all six coil sections through vacuum-rated feedthrough manifolds, enabling independent thermal management of each coil while electrical connections are configured in series for simplified high-current power supply integration. This hybrid manifold architecture—parallel cooling with series electrical connection—optimizes both thermal performance and power delivery, allowing continuous pulsed operation with rapid thermal equilibration between shots while requiring only a single high-current power supply rated for 800 amperes rather than six independent supplies.

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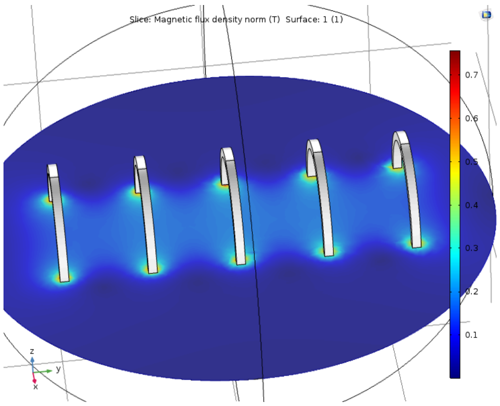
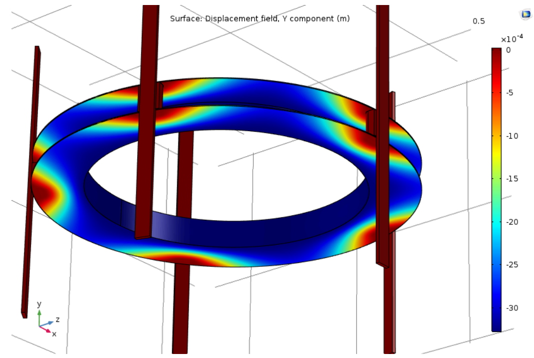
COMSOL simulations of multiple coil array

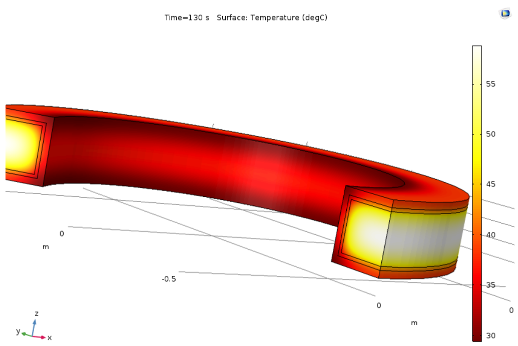
Magnetic modeling



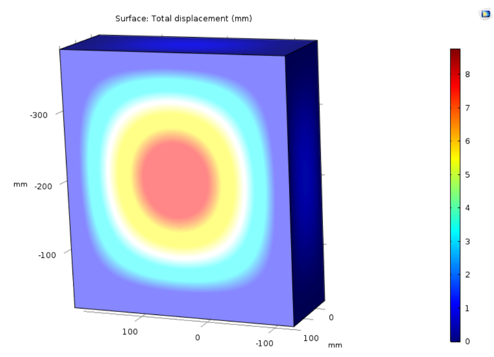
Stress Analysis



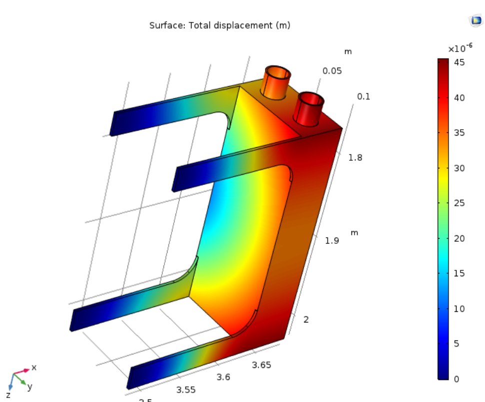
Thermal modeling



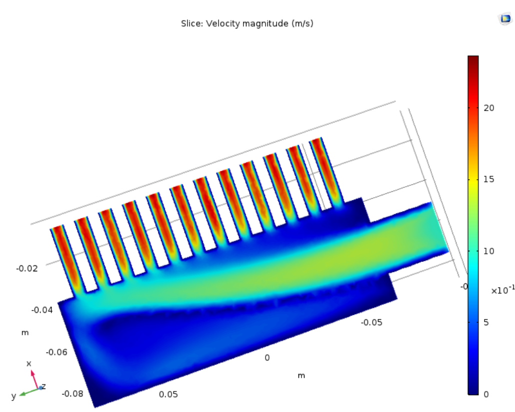
Pressure vessel modeling



Stress modeling



Fluid modeling



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MODEL WE-IVC-6X-300MT

In-Vacuum High-Field Coil Array — UHV-Compatible 300 mT Generation

COIL SPECIFICATIONS

Coil Configuration	In-vacuum linear array (6 coils) *Series electrical connection, parallel water cooling*
Operating Environment	Ultra-high vacuum (UHV) compatible *Designed for ≤10^{-8} Torr operation*
Turns per Coil	96 turns *Precision-wound square copper conductor*
Operating Current	800 A per turn *77kA total current per coil (96 turns × 800 A)*
Magnetic Field Strength	0.3 Tesla (300 mT) *Maximum field at design current*
Conductor Type	Square copper with internal cooling *6 mm diameter internal water channels*
Coil Former Material	Welded stainless steel 301 *All-welded construction for vacuum integrity*
Insulation System	Vacuum-compatible high-temperature *Rated for UHV thermal cycling*
Coil Spacing Range	Zero separation to Helmholtz configuration *Magnets designed for direct contact or optimal spacing*
Axial Length per Coil	Custom (application dependent) *Optimized for field uniformity and Lorentz force management*

ELECTROMAGNETIC PERFORMANCE

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Field Strength (Single Coil)	0.3 Tesla (3000 Gauss) *At 77 kA total current (96 turns × 800 A)*
Field Uniformity	Configuration dependent *Optimized for zero-spacing or Helmholtz configuration*
Array Configuration Options	Variable spacing: 0 to R (Helmholtz) *R = coil radius for optimal uniformity*
Lorentz Force (Adjacent Coils)	Calculated for zero-spacing worst case *Structural bracing designed to withstand maximum attractive/repulsive forces*
Total Ampere-Turns	76,800 AT per coil *460,800 AT total for 6-coil array*
Field-Current Linearity	Linear to rated current *No saturation in non-magnetic construction*

LORENTZ FORCE ANALYSIS AND STRUCTURAL DESIGN

Force Calculation Basis	Maxwell stress tensor analysis *Validated for coil-to-coil spacing from 0 to R (Helmholtz)*
Maximum Axial Force	Calculated for zero-spacing configuration *Attractive force between adjacent coils at full current*
Maximum Radial Force	Hoop stress on coil windings *Outward expansion force from self-field*
Structural Bracing	Coil-to-coil mechanical coupling *Magnets braced against each other for force distribution*
Support Structure	Welded stainless steel 301 framework *Designed for worst-case Lorentz loads with safety factor*

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Thermal Expansion Allowance	Calculated for 100°C temperature rise *Clearances maintain vacuum integrity during thermal cycling*

VACUUM FEEDTHROUGH SYSTEM

Electrical Feedthroughs	High-current vacuum-rated *800 A per conductor, series connection reduces feedthrough count*
Feedthrough Configuration	Series electrical topology *Single high-current input/output per array (not per coil)*
Vacuum Rating	UHV-compatible to 10^{-8} Torr *Helicoflex or copper gasket seals*
Water Feedthroughs	Parallel cooling manifold system *Independent inlet/outlet per coil for balanced thermal management*
Coolant Connections	12 total water feedthroughs *6 inlet + 6 outlet for parallel coil cooling*
Feedthrough Material	Stainless steel 316L or Conflat-compatible *Bakeable to 200°C for vacuum conditioning*
Leak Rate	$<10^{-9}$ mbar·L/s per feedthrough *Tested under thermal cycling and current loading*

WATER COOLING SYSTEM (VACUUM-COMPATIBLE)

Cooling Architecture	Parallel flow distribution *All six coils cooled independently for balanced thermal management*
Internal Cooling Channels	6 mm diameter per conductor *Integrated into square copper winding*
Coolant Flow Rate	5-10 L/min per coil (30-60 L/min total)

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	Adjustable for thermal load and duty cycle
Coolant Type	Deionized water *Resistivity >1 MΩ·cm to prevent electrical leakage*
Inlet Temperature	15-25°C recommended *Facility chilled water or recirculating chiller*
Maximum Temperature Rise	30-50°C at rated current *Depends on pulse duration and duty cycle*
Flow Monitoring	Flow switches on each coil circuit *Automatic current shutdown on low flow*
Thermal Sensors	RTD or thermocouple embedded in windings *Real-time temperature monitoring and data logging*
Manifold Design	External vacuum feedthrough distribution *Minimizes in-vacuum plumbing complexity*

POWER SUPPLY AND CONTROL

Power Supply Type	Single high-current DC supply *800 A rated for series-connected array*
Operating Current	800 A DC *Constant current regulation required*
Operating Voltage	Application dependent *Determined by total series resistance of 6 coils + cabling*
Current Regulation	±0.1% stability *Closed-loop feedback for field stability*
Pulse Duration	1 second to continuous *Limited by thermal management and duty cycle*

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Ramp Rate	Programmable 0-800 A *Controlled ramp to minimize voltage transients and mechanical shock*
Protection Systems	Overcurrent, overtemperature, flow interlock *Automatic shutdown on fault conditions*
Control Interface	Analog 0-10V or digital (Modbus/Ethernet) *Integration with facility control systems*

MECHANICAL SPECIFICATIONS

Coil Former Construction	Welded stainless steel 301 *All-welded for vacuum integrity, non-magnetic*
Support Structure	Integrated inter-coil bracing *Distributes Lorentz forces across array*
Weld Quality	Full-penetration TIG welds *Vacuum-qualified, leak-tested to <10^{-9} mbar·L/s*
Surface Finish	Electropolished or passivated *Low outgassing for UHV compatibility*
Alignment Features	Precision-machined mounting interfaces *Repeatable installation and field alignment*
Total Weight	Approximately 800-1200 kg *Depends on coil size and support structure (6-coil array)*
Handling Features	Integrated lifting points *Crane-ready for vacuum vessel installation*

VACUUM COMPATIBILITY AND MATERIALS

Vacuum Rating	UHV-compatible ≤10^{-8} Torr

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	Suitable for fusion plasma vessels, ion sources, beam lines
Bakeout Temperature	150-200°C *All materials rated for vacuum conditioning*
Outgassing Rate	<10^{-10} mbar·L/s/cm² (after bakeout) *Electropolished stainless, low-outgassing insulation*
Materials (Vacuum-Exposed)	Stainless steel 301/316L, copper, alumina *All UHV-compatible, non-magnetic where possible*
Leak Testing	Helium mass spectrometry *Each coil and feedthrough individually tested*
Thermal Cycling Qualification	100+ bakeout cycles validated *Maintains vacuum integrity under operational thermal loads*

PERFORMANCE SPECIFICATIONS

Field Strength (Per Coil)	0.3 Tesla (3000 Gauss) *At rated 76.8 kA (96 turns × 800 A)*
Combined Field (6-Coil Array)	Configuration dependent *Uniform zone or gradient field based on coil spacing*
Field Stability	<0.5% over continuous operation *With active cooling and current regulation*
Thermal Drift	<1% field change over thermal equilibration *Minimized by parallel cooling architecture*
Rise Time	<10 seconds to full field *L/R time constant (inductance/resistance limited)*
Duty Cycle	Application dependent *Continuous DC or pulsed based on thermal management*

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Operational Lifetime	>10,000 thermal cycles *Designed for long-term fusion research campaigns*

KEY FEATURES

Ultra-High Vacuum Compatibility: All-welded stainless steel 301 construction with vacuum-qualified materials achieves ≤10^{-8} Torr operation. Electropolished surfaces and low-outgassing insulation ensure compatibility with fusion plasma vessels, ion sources, and particle beam vacuum systems.

High-Field Generation: 0.3 Tesla (3000 Gauss) per coil with 92 precision-wound turns carrying 800 amperes per turn. Total 76.8 kA per coil enables strong magnetic field generation for plasma confinement, beam steering, and diagnostic applications requiring in-vacuum field coupling.

Integrated Internal Cooling: Square copper conductors with 6mm internal water cooling channels provide direct thermal management of high-current windings. Parallel cooling manifold architecture enables independent thermal control of each coil while series electrical connection simplifies power delivery and reduces vacuum feedthrough count.

Lorentz Force Management: Structural design validated for operation from zero coil separation to Helmholtz configuration. Inter-coil bracing distributes attractive and repulsive forces across the array, while welded stainless construction provides mechanical rigidity under worst-case Lorentz loads during pulsed high-current operation.

Series-Parallel Hybrid Architecture: Series electrical connection of six coils requires only a single 800A power supply and minimizes high-current vacuum feedthroughs (critical for leak-free UHV operation). Parallel water cooling ensures balanced thermal management across all coils, preventing hot spots and thermal drift during extended operation.

Vacuum Feedthrough Integration: High-current electrical feedthroughs (800A rated) and vacuum-compatible water feedthroughs (12 total for parallel cooling) maintain UHV integrity while delivering power and cooling to in-vessel coils. All feedthroughs helium leak-tested to <10^{-9} mbar·L/s and rated for thermal cycling during vacuum bakeout.

Field Configuration Flexibility: Coil spacing adjustable from direct contact (zero separation) to Helmholtz configuration (separation = radius) enables uniform field zones, gradient fields, or custom magnetic topologies. Mechanical design accommodates reconfiguration for different experimental requirements while maintaining structural integrity under Lorentz forces.

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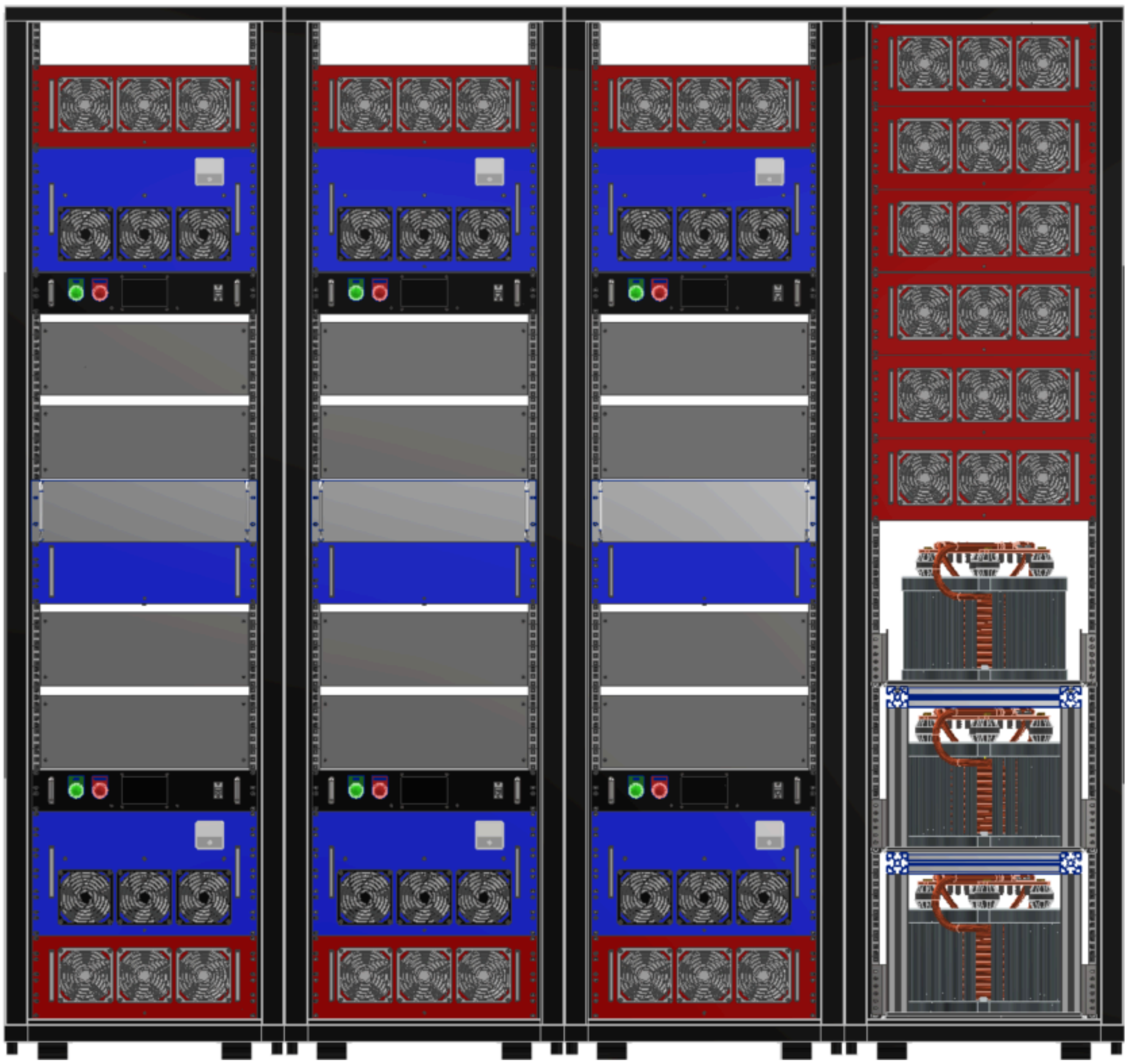
Power supply

See the WE-MPSU-320 for an example PSU unit for this magnet set



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IN-VACUUM HIGH-FIELD COIL SYSTEMS — Product Variants

UHV-Compatible Magnetic Field Generation • Welded Stainless Steel 301 • Internal Water Cooling • Series/Parallel Architecture

MODEL	BORE DIAMETER	TURNS	CURRENTPER TURN	FIELD STRENGTH	TOTAL AMPERE-TURNS	WEIGHT PER COIL	FUSION APPLICATIONS	LEADTIME
WE-IVC-300-300MT ⭐	300mm (12")	96 turns	800 A	0.3 T (3000 G)	73.6 kAT	80 kg	Diagnostic calibrationNBI ion source R&D Small tokamak diagnostics	16 wks
WE-IVC-400-250MT	400mm (16")	80 turns	800 A	0.25 T (2500 G)	64 kAT	120 kg	Mid-scale diagnostic arrays Plasma-facing component tests Beam deflection studies	18 wks
WE-IVC-500-200MT	500mm (20")	72 turns	800 A	0.2 T (2000 G)	57.6 kAT	180 kg	Extended diagnostic volumes Component exposure testing FRC edge field studies	20 wks
WE-IVC-800-150MT	800mm (31")	60 turns	800 A	0.15 T (1500 G)	48 kAT	350 kg	University tokamak fringe fields Divertor region testing Large NBI component testing	22 wks
WE-IVC-1000-120MT	1.0 m (39")	54 turns	800 A	0.12 T (1200 G)	43.2 kAT	550 kg	Mid-size tokamak auxiliaries FRC formation coils Plasma shaping studies	24 wks
WE-IVC-1500-100MT	1.5 m (59")	50 turns	800 A	0.1 T (1000 G)	40 kAT	900 kg	DIII-D-class auxiliaries Edge field control Diagnostic access ports	26 wks
WE-IVC-2000-80MT	2.0 m (79")	45 turns	800 A	0.08 T (800 G)	36 kAT	1500 kg	Large tokamak trim coils Vertical field correction Plasma position control	28 wks
WE-IVC-2500-70MT	2.5 m (98")	42 turns	800 A	0.07 T (700 G)	33.6 kAT	2200 kg	ITER-scale port plugsIn-vessel correction coils Feedback control systems	32 wks
WE-IVC-3000-60MT	3.0 m (118")	40 turns	800 A	0.06 T (600 G)	32 kAT	3200 kg	Main chamber auxiliaries Error field correction RWM stabilization coils	36 wks
WE-IVC-4000-50MT	4.0 m (157")	38 turns	800 A	0.05 T (500 G)	30.4 kAT	5500 kg	Stellarator auxiliary coilsLarge-bore trim fields Plasma shaping at scale	40 wks
WE-IVC-5000-40MT	5.0 m (197")	36 turns	800 A	0.04 T (400 G)	28.8 kAT	8500 kg	ITER in-vessel coils JT-60SA auxiliaries DEMO program R&D	48 wks
WE-IVC-6000-35MT	6.0 m (236")	34 turns	800 A	0.035 T (350 G)	27.2 kAT	12,000 kg	Major tokamak EFC systemsIn-vessel RMP coils Plasma-facing trim fields	52 wks
WE-IVC-7000-30MT	7.0 m (276")	32 turns	800 A	0.03 T (300 G)	25.6 kAT	16,500 kg	DEMO-scale in-vessel coils Fusion pilot plant auxiliaries Extreme-scale stellarators	56 wks
WE-IVC-8000-25MT	8.0 m (315")	30 turns	800 A	0.025 T (250 G)	24 kAT	22,000 kg	National lab mega-tokamaks Fusion power plant prototypes Custom mega-scale research	64 wks
WE-IVC-10000-20MT	10.0 m (394")	28 turns	800 A	0.02 T (200 G)	22.4 kAT	35,000 kg	Maximum-scale in-vessel coils Commercial fusion reactors Dedicated facility custom build	72 wks

⭐ *WE-IVC-300-300MT: Reference design — 300 mT validated architecture*

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Scaling Architecture Notes:

• Turn Count Optimization: Higher turn counts (92) for compact systems maximize field strength; reduced turn counts (28-40) for large-bore systems balance field generation with Lorentz force management and fabrication complexity.• Constant Current Architecture: All variants designed for 800 A per turn, enabling standardized power supply infrastructure and vacuum feedthrough designs across the product range.• Field Strength Scaling: Field decreases with increasing bore size due to geometric dilution and practical limits on total ampere-turns. Compact systems (0.3 T) suitable for strong field applications; large systems (0.02-0.05 T) optimized for trim/correction fields in major fusion devices.• Weight Scaling: Weight increases approximately as diameter^3 due to increased conductor mass, structural reinforcement for Lorentz forces, and larger stainless steel vacuum vessel requirements.• Cooling Scaling: Water flow requirements scale with coil size and heat load. Compact systems: 5-10 L/min per coil; large systems: 20-50 L/min per coil to maintain thermal stability during pulsed operation.

Common Features Across All Variants:

• Welded Stainless Steel 301 Construction: All-welded vacuum-compatible coil formers and support structures• Internal Water Cooling: 6mm diameter cooling channels integrated into square copper conductor• Series Electrical Connection: Simplified power distribution, reduced vacuum feedthrough count• Parallel Water Cooling: Independent thermal management per coil for balanced heat extraction• UHV Compatibility: Designed for $\leq 10^{-8}$ Torr operation with bakeable to 200°C• Lorentz Force Analysis: Structural design validated for zero spacing to Helmholtz configuration• Vacuum Feedthrough Integration: High-current electrical and water feedthroughs, helium leak-tested• Precision Alignment Features: Machined mounting interfaces for repeatable installation• Modular Design: Coils can be configured individually or as multi-coil arrays• Factory Testing: Helium leak testing, pressure testing, electrical continuity, insulation resistance

Application Segmentation by Scale:

COMPACT SYSTEMS (300-500mm): Diagnostic Calibration & Component Testing

High field strength (0.2-0.3 T) enables magnetic diagnostic calibration, neutral beam ion source development, and plasma-facing component exposure testing. Compact size allows benchtop integration or small vacuum chamber installation for R&D laboratories and university tokamak programs.

MID-SCALE SYSTEMS (800mm-1.5m): Research Tokamak Auxiliaries

Moderate field strength (0.1-0.15 T) suitable for university and mid-size tokamak fringe field generation, FRC formation coils, and edge field control. Weight range (350-900 kg) allows crane installation without requiring specialized heavy-lift equipment.

LARGE-SCALE SYSTEMS (2-4m): Major Tokamak Correction & Control

Field strengths (0.05-0.08 T) optimized for error field correction, plasma position control, and resistive wall mode stabilization in large tokamaks (DIII-D class and above). Weight range (1.5-5.5 tons) requires facility crane infrastructure but remains manageable for installation in existing vessels.

MEGA-SCALE SYSTEMS (5-7m): ITER-Class In-Vessel Coils

Field strengths (0.03-0.04 T) designed for in-vessel correction coil systems in ITER, JT-60SA, and DEMO program devices. Weight range (8.5-16.5 tons) requires dedicated installation procedures and vacuum vessel modifications for integration. Lead times reflect extensive engineering, FEA validation, and mock-up testing.

ULTRA-LARGE SYSTEMS (8-10m): Commercial Fusion Reactor Scale

Field strengths (0.02-0.025 T) represent the practical limit for in-vacuum coil systems at commercial fusion power plant scale. Weight range (22-35 tons) requires specialized installation equipment and facility modifications. These systems are custom-engineered for specific fusion reactor designs and require extensive collaboration with facility engineering teams. Lead times include full-scale prototype validation and testing programs.

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Power Supply and Cooling Infrastructure:

• Power Supply Current: All variants designed for 800 A series connection (single high-current supply)• Power Supply Voltage: Scales with array size due to increased resistance ($V = I \times R_{total}$)• Total Power: Compact systems 50-200 kW; mid-scale 200-800 kW; large-scale 1-3 MW; mega-scale 3-8 MW• Cooling Flow: Compact 30-60 L/min total; mid-scale 100-300 L/min; large 500-1500 L/min; mega 2000-5000 L/min• Feedthrough Count: 2 electrical (in/out) + 12 water (6 coils × 2) for 6-coil array regardless of size• Control System: PLC-based with Ethernet/Modbus interface, EPICS-compatible for facility integration

Lead Time Determinants:

• Engineering & FEA: Lorentz force analysis, thermal modeling, vacuum compatibility validation (2-8 weeks)• Procurement: Stainless steel plate, square copper conductor, vacuum feedthroughs (4-12 weeks)• Fabrication: TIG welding, leak testing, conductor winding, assembly (8-32 weeks, scales with size)• Testing: Helium leak test, pressure test, electrical test, FAT (2-6 weeks)• Large Systems (>5m): Mock-up testing, installation procedure development add 8-16 weeks• Custom Engineering: Facility-specific integration, mounting design, cooling manifolds add 4-12 weeks

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Coil Arrays

Technical Specification Form

Please complete all sections below. This information will be used to prepare a detailed quotation and ensure the system meets your requirements. If you have questions about any specification, contact us at sales@woodruffeng.com

CUSTOMER INFORMATION

Organization / Institution	
Contact Name	
Email Address	
Phone Number	
Shipping Address	

SYSTEM CONFIGURATION

Number of Coils	
Inner Coil Diameter	_________ mm (Typical range: 1000–10000mm)
	Outermost coil diameter: _________ mm
Coil separation	☐ Standard Helmholtz (d = R) ☐ Custom (specify): _______

FIELD REQUIREMENTS

Maximum Field (Continuous Operation)	_________ mT (Typical range: 10–200mT continuous)
Peak Field(Pulsed, if needed)	_________ mT at _________ % duty cycle

WORKING VOLUME & UNIFORMITY

Required Uniform Volume(diameter or radius)	_________ mm (Typically 30–50% of innermost coil diameter)
Field Uniformity Specification	☐ <0.5% ☐ <1% ☐ <2% ☐ Other: _____%
Uniformity measured over:	☐ Central sphere ☐ Central cylinder (1-axis) ☐ Other:

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OPERATING FREQUENCY & POWER SUPPLY

Operating Mode	☐ DC only ☐ AC capable ☐ Both
If AC capable, frequency range:	DC to __________ Hz (Typical: DC–100Hz or DC–1000Hz)
Waveform Requirements	☐ DC ☐ Sine ☐ Triangle ☐ Square ☐ Arbitrary
Power Supply Preference	☐ Woodruff Engineering supply ☐ Customer-provided
If customer-provided:	Current capability: __________ A Voltage: __________ V

COOLING & INSTALLATION

Cooling Method	☐ Air-cooled ☐ Water-cooled ☐ Forced air
If water-cooled:	Available water flow: ________ L/min Pressure: ________ PSI
Mounting Configuration	☐ Benchtop ☐ Floor-standing ☐ Custom frame
Access requirements	☐ Horizontal bore ☐ Vertical bore ☐ Both (3-axis)

SPECIAL REQUIREMENTS & NOTES

Computer Control Interface	☐ Not required ☐ USB ☐ Ethernet ☐ RS-232
Control Software	☐ Standalone GUI ☐ LabVIEW compatible ☐ Python API
Field Sensors / Feedback	☐ Open-loop ☐ Closed-loop (Hall probe feedback)
Budget Range (optional)	$ __________ to $ __________
Target Delivery Date	__________ (Typical lead times vary between 8–26 weeks)

Additional Requirements or Notes:

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SUBMISSION

Please email this completed form to: sales@woodruffeng.com

We will review your specifications and provide a detailed quotation within 3–5 business days. If clarification is needed on any requirements, we will contact you directly.

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