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Zerronox Corporation: Using pulsed electron beams for the removal of carbon dioxide, nitrogen oxides and other emissions from power plants

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Pulsed Electron Beam

Removal of Carbon Dioxide, Nitrogen Oxides and Other Emissions From Power Plants

ZERRONOX CORPORATION

APRIL, 2016

- Leadership
- Value Proposition
- PEB Technology
- Emission Removal
- Summary

Leadership: Stephen Kennedy, CEO

Stephen Kennedy

- Founder/CEO of Zerronox
- Business Executive focusing on early-stage technology companies
  - Siimpel [CEO]: Camera modules using MEMS for mobile phones – JPL
  - Picolight [Bus Mgr & CFO]: Fiber opto-electronic transceivers using vertical cavity lasers for GB and 10GB communications
  - EpiWorks [CEO]: High-speed wireless GaAs and InP compound semiconductors
  - Utilities, Inc. [COO]: Water and environmental technologies
  - Pfizer [Engineering Manager]: Magnetic oxides for analog data storage
- Education:
  - B.S. Chemical Engineering: Rose-Hulman Institute of Technology
  - MBA: Northwestern University (Kellogg Business School)

Leadership: John Sethian, CTO

Dr. John Sethian - Zerronox CTO and Technical Lead

- Naval Research Laboratory (NRL) from 1977-2015
  - Former Head, Electron Beam Science and Applications, Plasma Physics Division
  - Manager of NRL team of engineers and large multi-institutional programs
  - Chief scientist and developer of the PEB process
  - Conceived of the NOx removal approach
- Fellow of the American Physical Society
- Awards:
  - Four NRL invention/technology transfer awards and three NRL publication awards
  - Fusion Power Associates Leadership Award
  - American Nuclear Society's Annual Outstanding Achievement Award
  - Navy Meritorious Civilian Service Award
- Education:
  - A.B. in Physics: Princeton University
  - Ph.D. in Applied Physics: Cornell University

Development Team Members

ONSITE AT NRL		
Dr. Matt Wolford	Program Head	NRL
Matt Myers	Pulsed Power/E-beam physicist	NRL
John Dubinger	Senior Technician	NRL
Dr. Frank Hegeler	E-beam/plasma physicist	NRL
Dr. John Giuliani	E-beam Driven Chemistry modeling	NRL
Areg Mangassarian	Electronics Engineer	SAIC
OFFSITE		
Silicon Power (formerly APP)	Advanced solid state Pulsed Power	

- NRL has 2200 employees, including 750 PhDs
- NRL Team has expertise for a wide range of technologies, e.g. chemistry, mechanics, computer modeling, etc.
- Zerronox currently engages the NRL, Silicon Power and other firms as outside contractors

Pulsed Electron Beam – Value Proposition

- PEB approach pioneered by Naval Research Laboratory
  - Platform technology developed over the past 15 years with $150M
  - Projected 5x to 10x cost savings over conventional technology
  - Experiments confirm CO_2 converted to CO, methanol and hydrogen
    - Synfuels to be used for higher value products or re-routed to boiler
  - NOx removal demonstrated and optimized at the NRL
    - Removes up to 98-99% of NOx by varying the energy deposited
  - Can be applied to removal of other emissions such as Hg or SOx
  - Can be applied to emissions generated by any fossil fuel
    - For example, gas or diesel turbines
  - Estimated power requirements
    - NOx removal of 80% using 2-3% plant power (proven)
    - CO_2 removal of 50-100% estimated at 5-15% plant power (estimated)

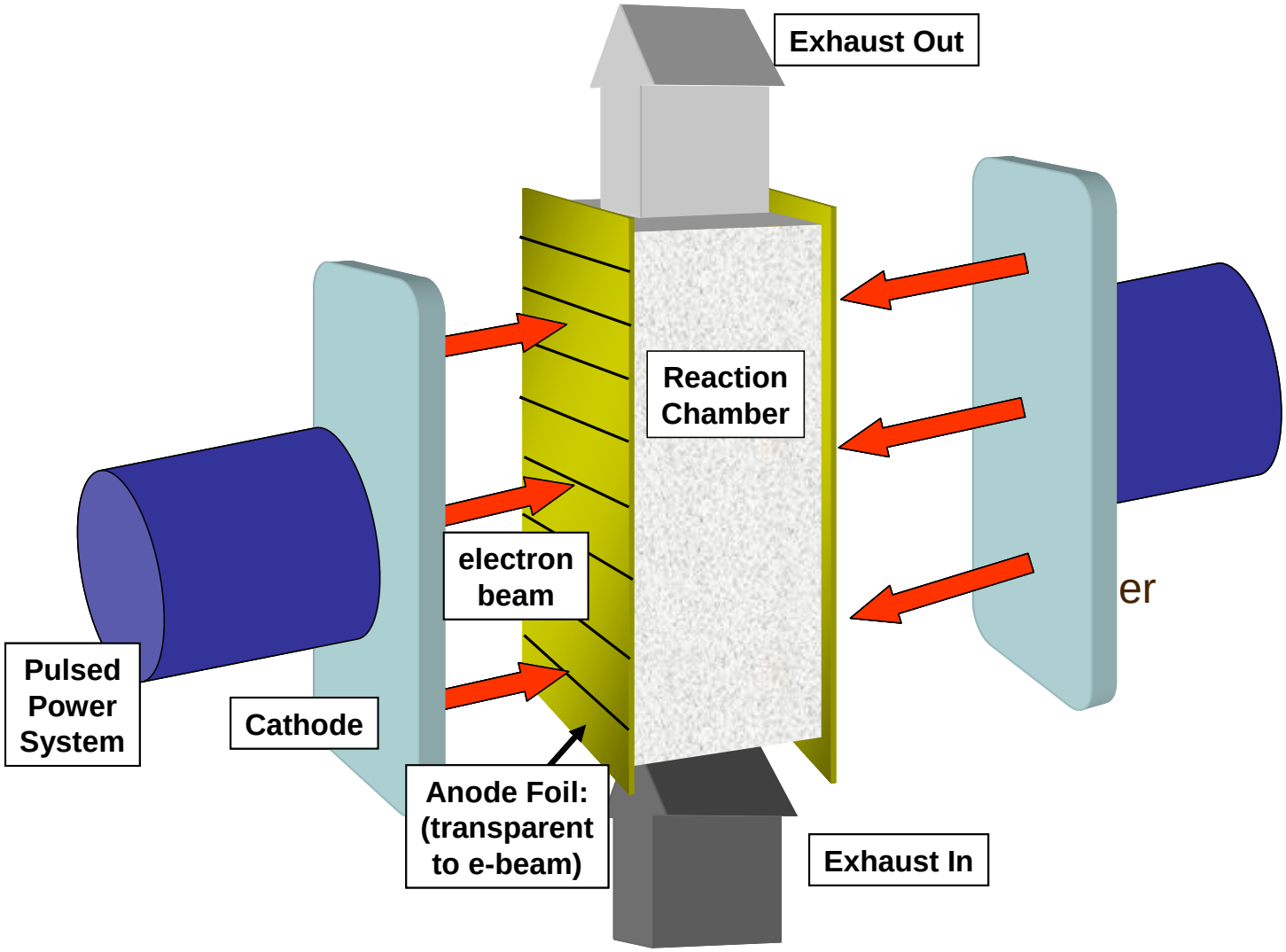
Electron Beams Break Chemical Bonds

PEB is analogous to electric car technology, i.e., uses physics rather than chemistry. There is no need for high temperatures or reagents.

Incandescent bulb:
Current heats filament to 2300 °C
Generates light, but most energy goes into **heat**

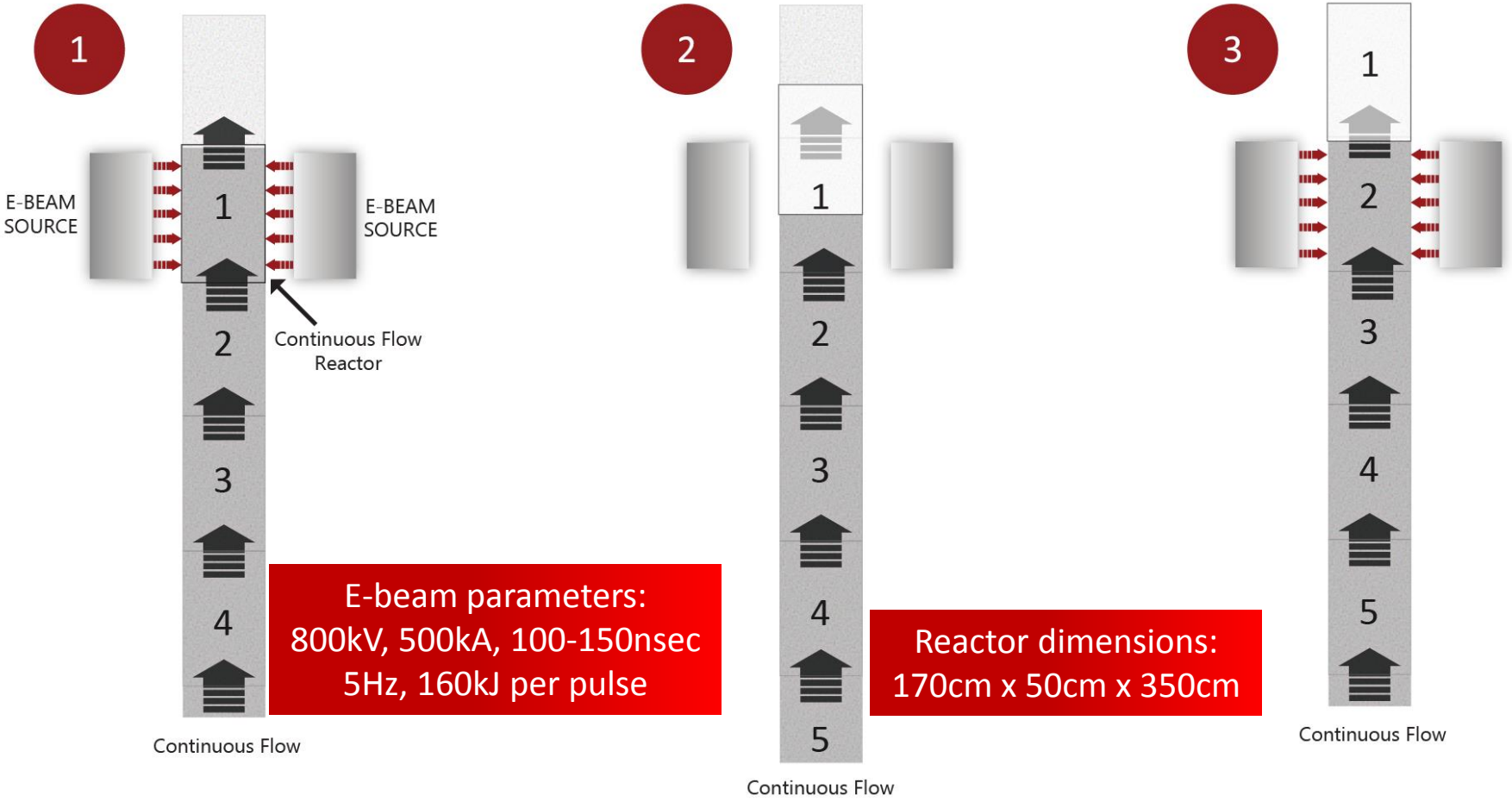
Compact Fluorescent:
Electrons excite molecules in gas
>>Most energy goes into light

Main Parts of an Electron Beam Driven Reaction System



Pulse Rep Rate/ Residence Time:
Flue Gas Flows Continuously Past Reaction Chamber

Each pulse exposes a "new" fill of flue gas to pulsed e-beam
Residence time in reaction chamber is large relative to 100 nsec pulse



Reaction Chamber

- PEB Reaction Chamber
  - E-beam delivers hundreds of billions of watts of power
  - Pulse duration is less than one-millionth second
  - Residence time for emission conversion is large relative to pulse length
    - Residence time of approximately one-tenth second
    - Each pulse is similar to taking a picture
    - Five pulses per second (5Hz)
  - Optimal amount of energy in the shortest amount of time maximizes conversion of emission compounds
    - Single, short pulsed e-beam is ideal, as opposed to long pulse or continuous e-beam
  - Double-sided exposure provides for uniform deposition
  - Modular design will fit any size power plant

Carbon Dioxide Abatement

- CO_2 Abatement: Four Potential Processes
  - Process I: Use PEB to ionize CO_2 to form CO_2^+ or CO_2^{++}
    - Break CO_2^+ or CO_2^{++} apart using catalysts or reagents
    - React with hydrogen or methane to form synfuels
    - Estimated power usage of 10-15% for 50% CO_2 conversion
  - Process II: Use PEB to form either carbonates or hydrocarbons
    - Will likely require salts, ammonia, urea or perhaps catalysts
  - Process III: Use PEB to cluster CO_2 to form $(CO_2)^n$
    - Explore process using higher gas temperatures rather than condensation
    - Dispose of solid $(CO_2)^n$ by binding or coating with other chemicals
    - Requires very low energy: plant power for 100% CO_2 conversion at less than 5%
  - Process IV: Use PEB to gasify coal directly
    - Convert coal to synfuels or marketable hydrocarbons
    - Convert to H_2 at an estimated cost of $1-2 per kilogram
  - Cost efficiencies for CO_2 abatement would be similar to NOx removal

Comparison: SCR and PEB 600MW Boiler Capacity

Technology	SCR	PEB
Capital Cost	$200-250M[1]	$50-85M[2]
Annual Operating Cost	$20-25M[1]	$3-5M
Catalyst/Reagent	Vanadium, titanium or zeolite catalysts. Ammonia reagents	None
By-Products	Ammonium Nitrate	N_2 and O_2
Estimated Power Requirements	TBD	2-3%[3]

[1]Estimated from the UAR Group Study – 2010

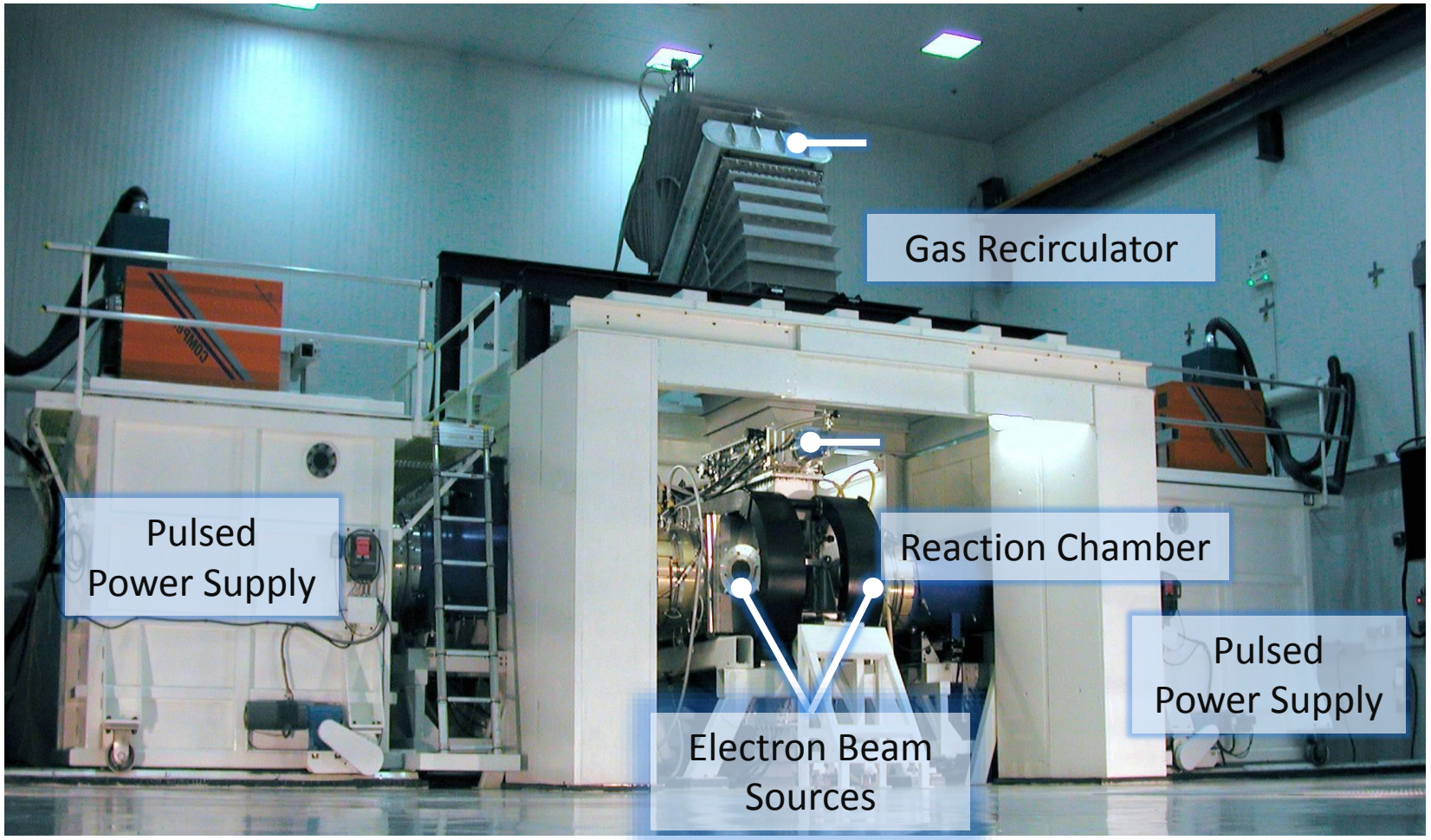
[2]Assume 2x gain from physics plus 2-3x efficiency = 4-6x total improvement

[3]Shown in tests at NRL

Economic payback is approximately 2.5 -3.0 years

NRL Electron Beam Facility

PEB System for Developing and Optimizing Emission Removal Process

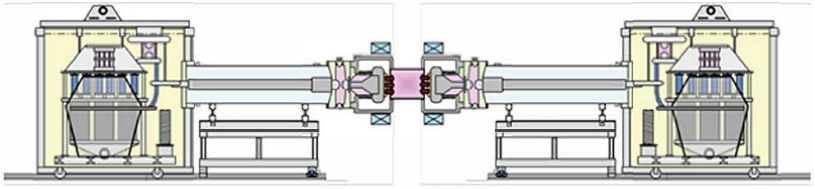


Prototype for Field Testing (Possible Configuration)

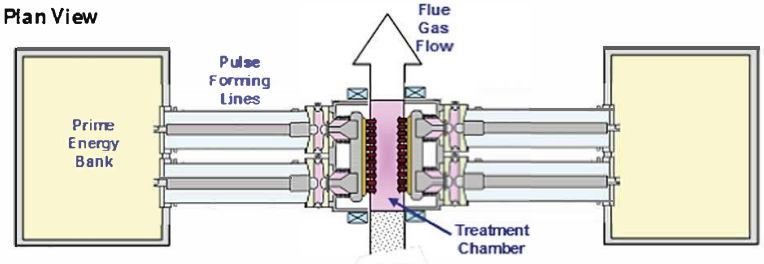
Prototype Pulsed Electron Beam system for emission control

- **Capable of being tested/evaluated at power generation plants**
- **Capable of removing NOx to less than 30 ppm**
- **Capable of reducing other emissions**
- **Scalable to full size system. Twelve full size systems required for 600 MWe (Notional concept will be finalized upon completion of testing)**

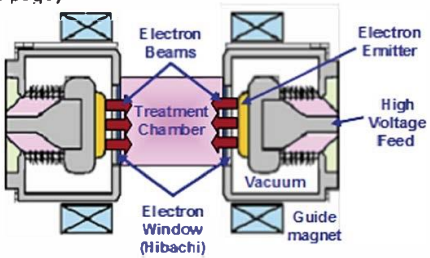
Elevation View



Plan View



Close up of e-beam source and treatment chamber (Elevation View):
(gas flow is into the page)

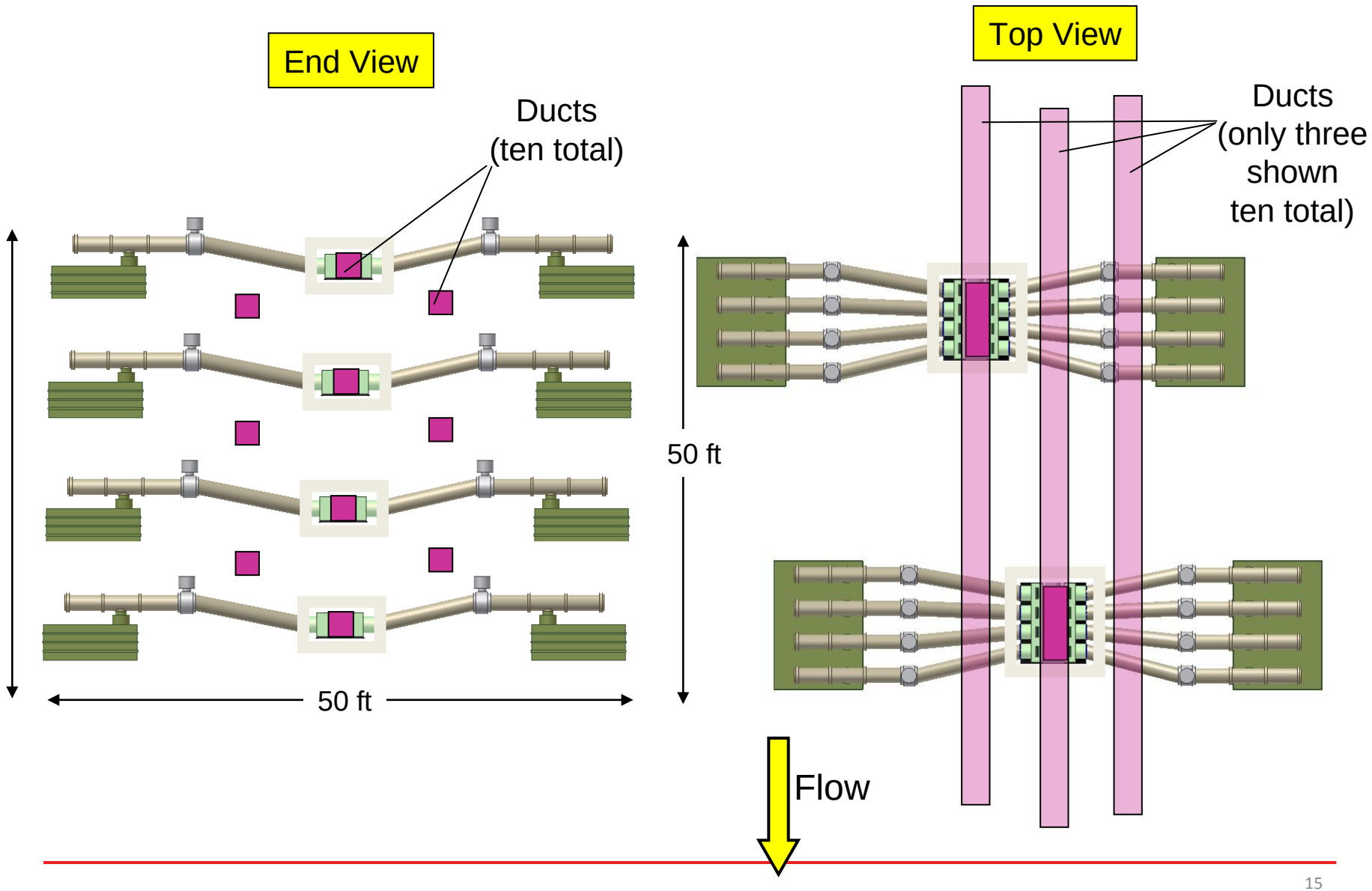


Nominal system parameters (will be finalized upon completion of testing):

Capable of treating 9000 cu ft/min = 1/18 full system size (12 full systems needed for 600 MWe)

Voltage:	500,000 Volts	Length:	40 ft
Current:	100,000 Amps x 2	Height:	8 ft
Pulse Length	140 nsec	Width:	10 ft
Repetition Rate	5 Hz	(May be smaller, depends on pulse width)	

Conceptual Design for PEB System on Power Plant



- Next Steps
  - Further develop and optimize CO_2 processes
  - Build and test prototype system on power plants
    - Two years: Detailed schedule with costs and Gantt Chart
    - Projected to treat 3-5MW of flue gas
  - Evaluate PEB potential for removal of other emissions
    - SOx and Hg oxidation
  - Continue market development
  - Commercialize worldwide

Contact Information

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