Multi-MA Reflex Triode Research†

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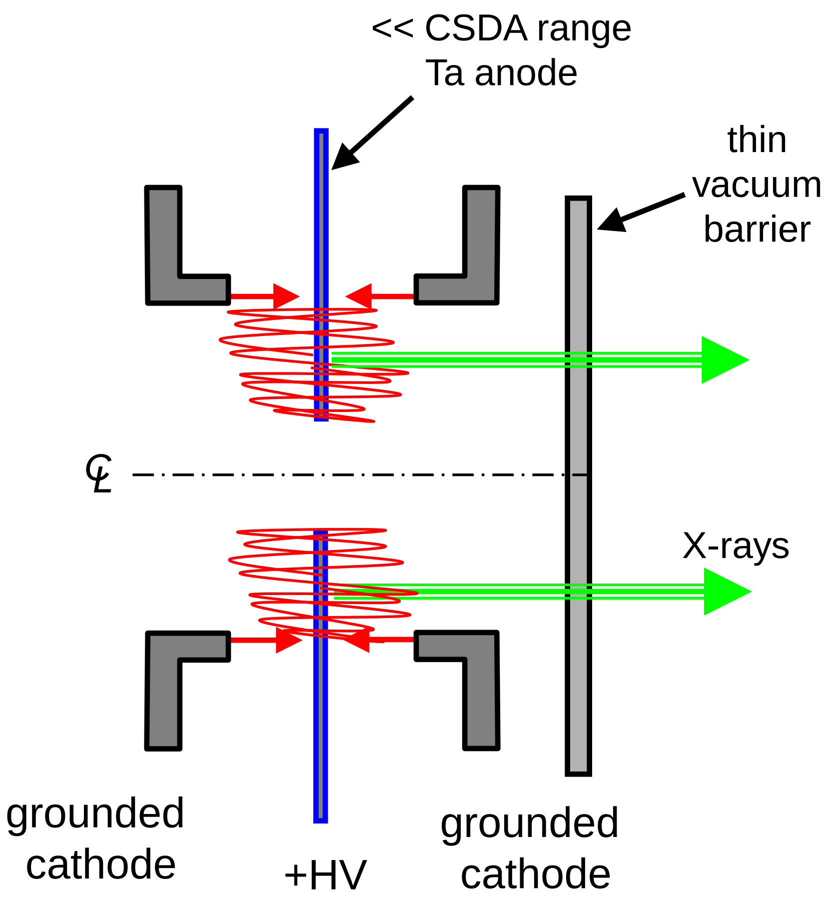
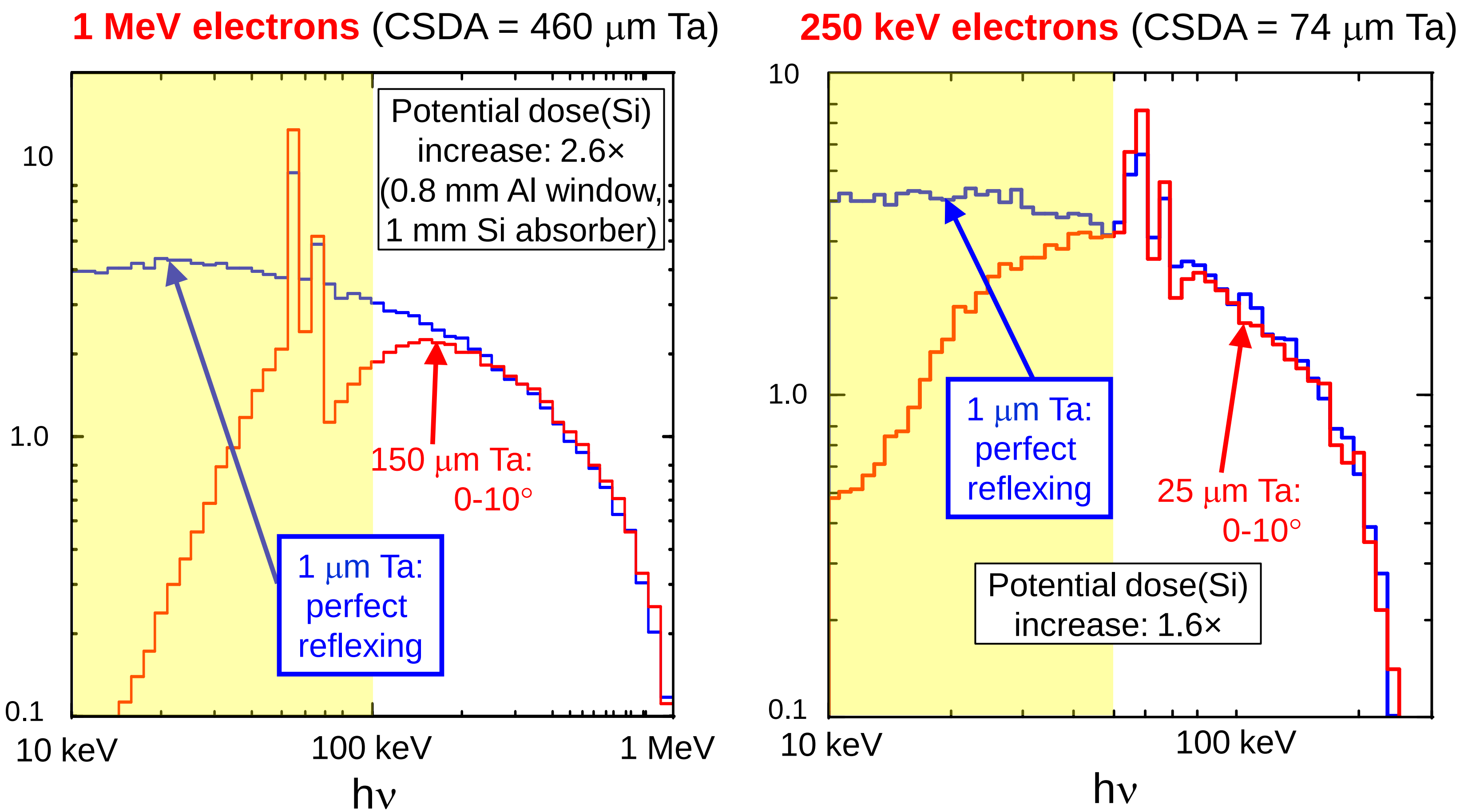
The Reflex Triode can efficiently produce and transmit medium energy (10-100 keV) x-rays



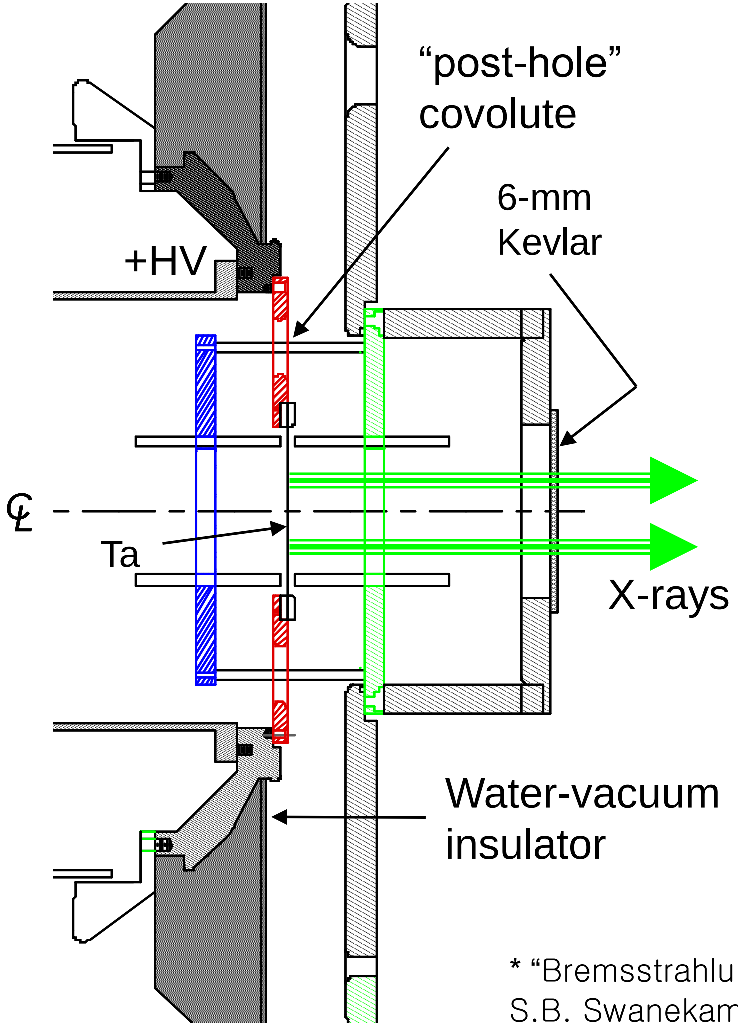
- Triode: two grounded cathodes, +HV anode
- Electrons (250 keV-1 MeV) attracted to +HV tantalum anode
- Electrons pass through tantalum ("reflex") many times before stopping
- X-ray transmission increased by reducing tantalum thickness
- Vacuum window transmission increased using low-Z, thin material (< 1 mm aluminum)
- X-ray output (dose, dose rate) **proportional to electron current** for fixed voltage and pulse length

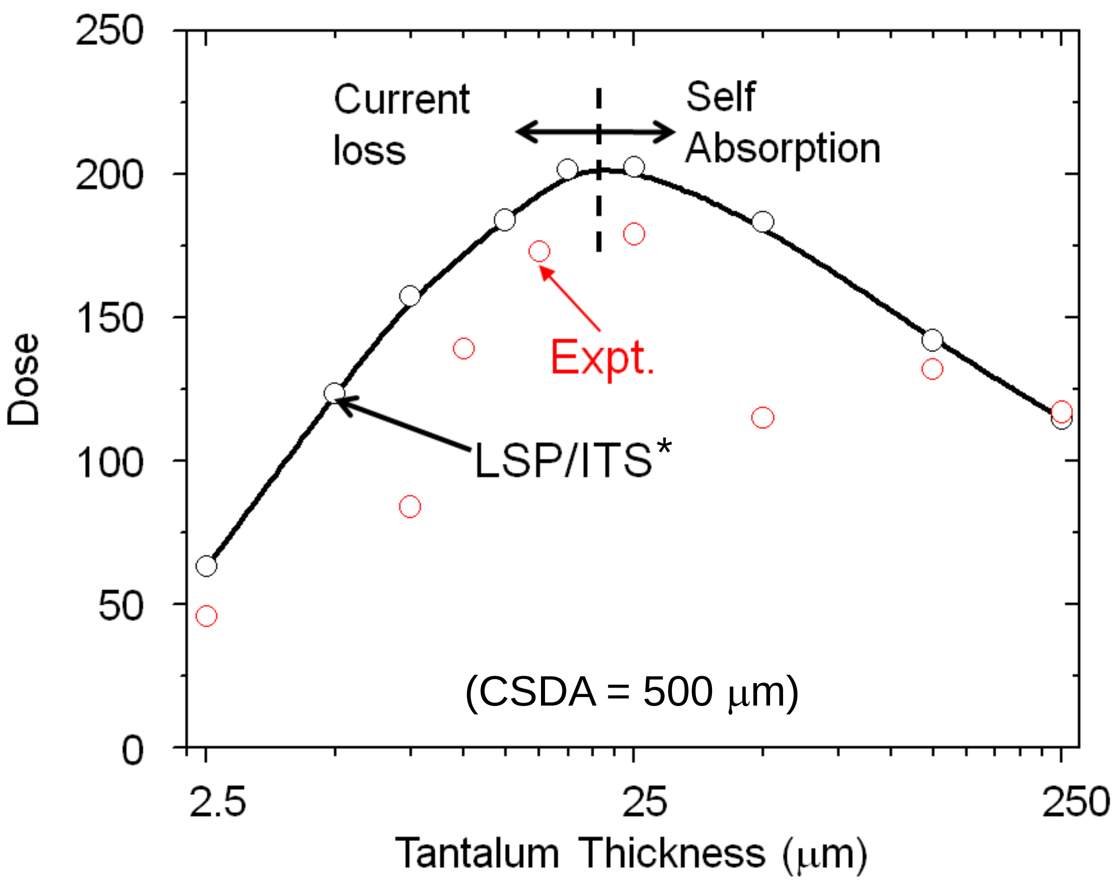
Perfect reflexing through thin converter can increase transmission of 10-100 keV x-rays

X-ray energy spectra (eV/eV-C) transmitted through tantalum



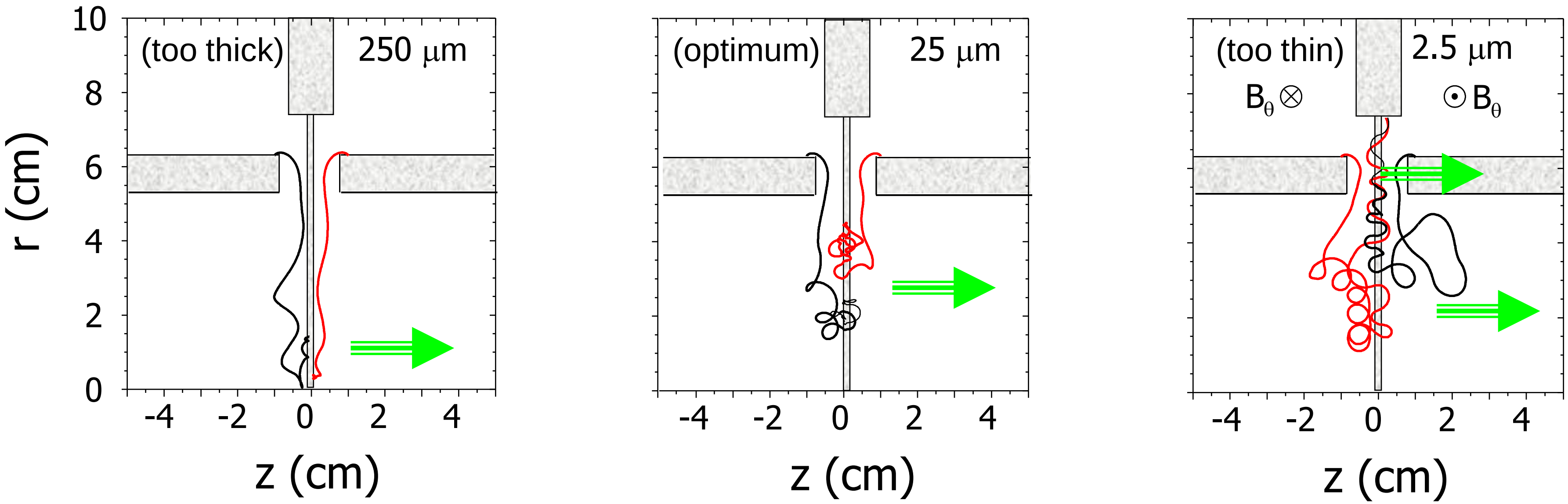
Gamble II experiment at 1 MV, 1 MA, 60 ns: maximum dose with 25 micron tantalum





* "Bremsstrahlung Target Optimization for Reflex Triodes," S.B. Swanekamp, B.V. Weber, S.J. Stephanakis, D. Mosher, and R.J. Commisso, Phys. Plasmas 15, 2008

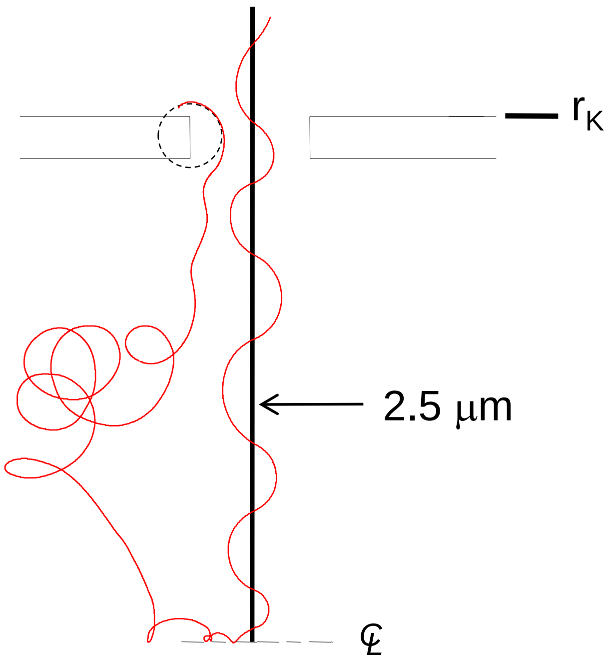
Electron orbits depend on the foil thickness



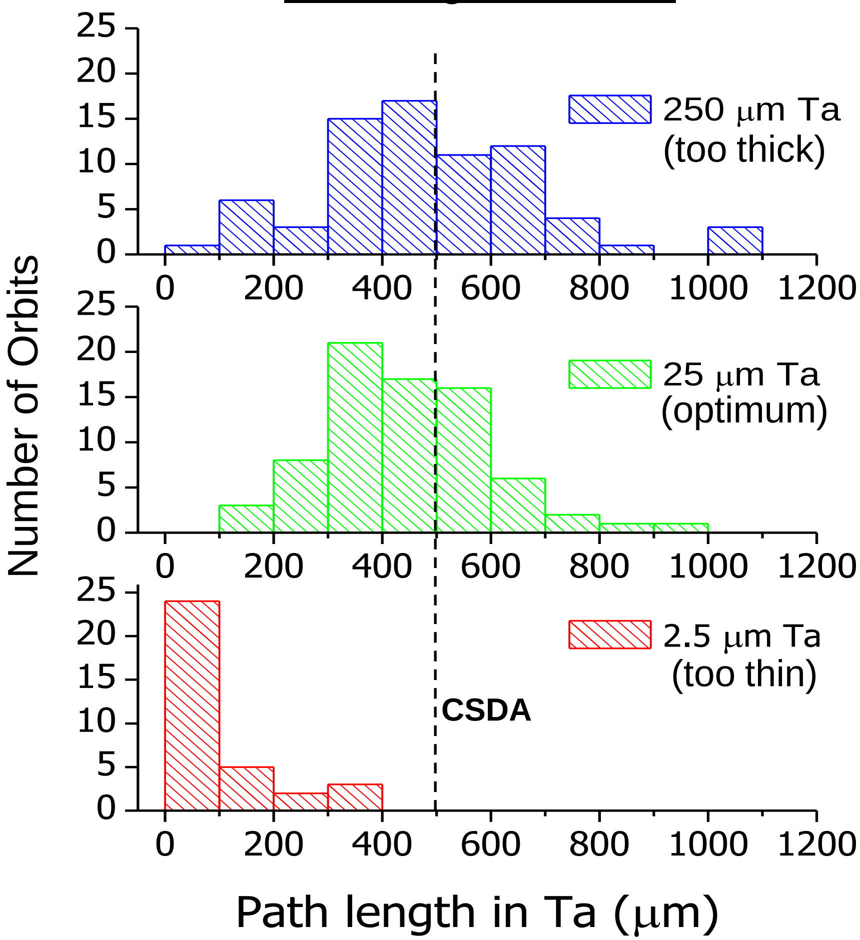
- (calculated orbits near the time of maximum dose rate)
- Electrons flow radially inward and first interact with the foil at small radius
- Energy deposition is more diffuse for thinner foils consistent with x-ray images
- For very thin foils electrons migrate outward beyond the cathode radius

Electron orbits from LSP used to calculate path length inside tantalum

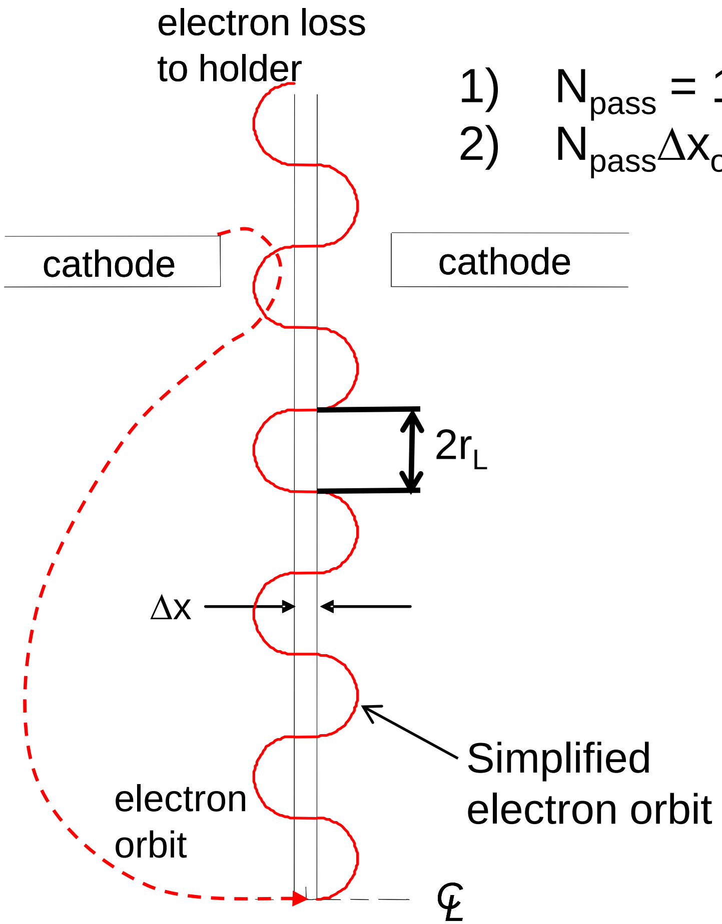
Calculate path length of electrons inside tantalum for $r < r_K$



Path length statistics

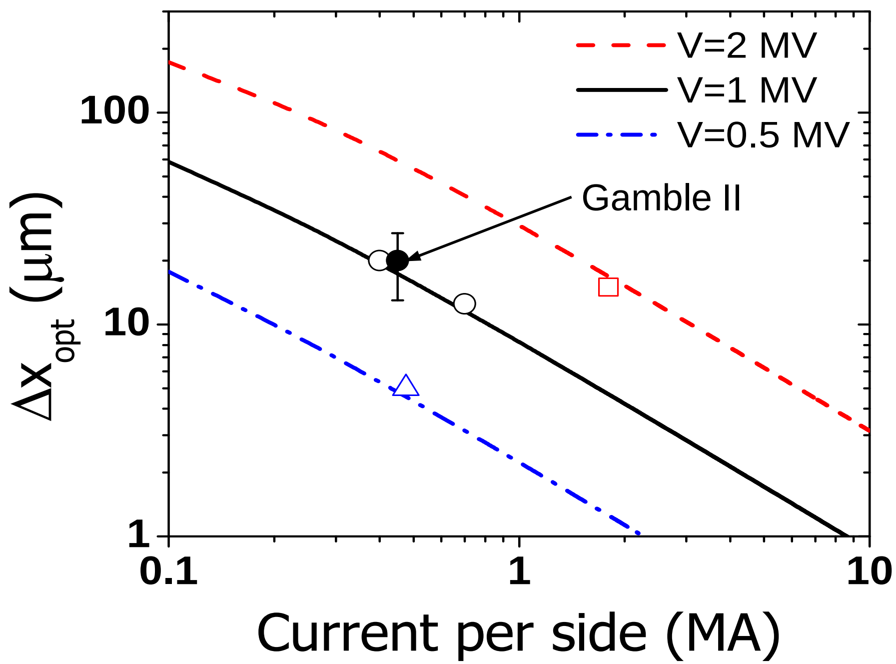


A simple formula predicts the optimum foil thickness for reflexing converters

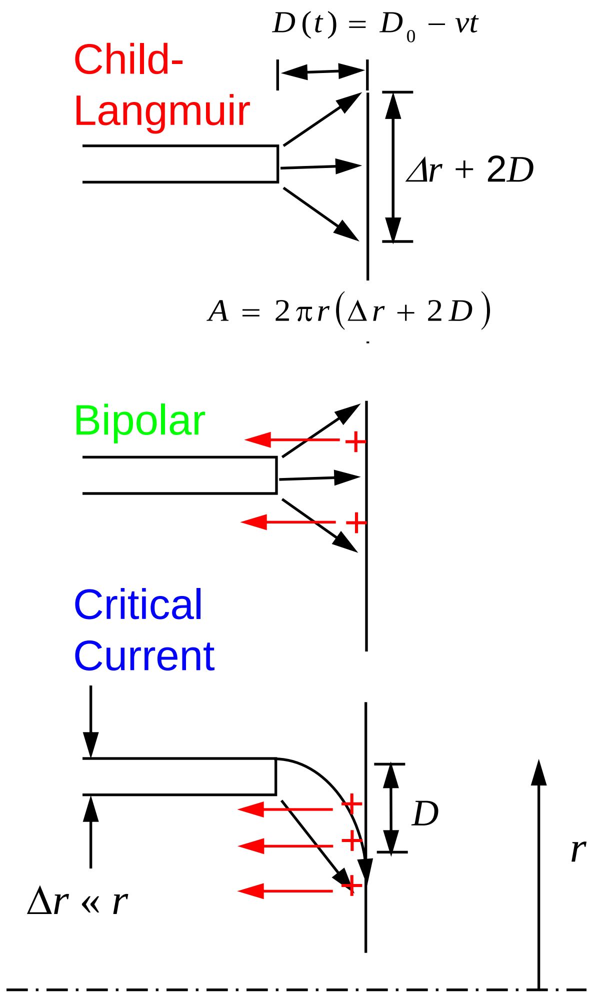


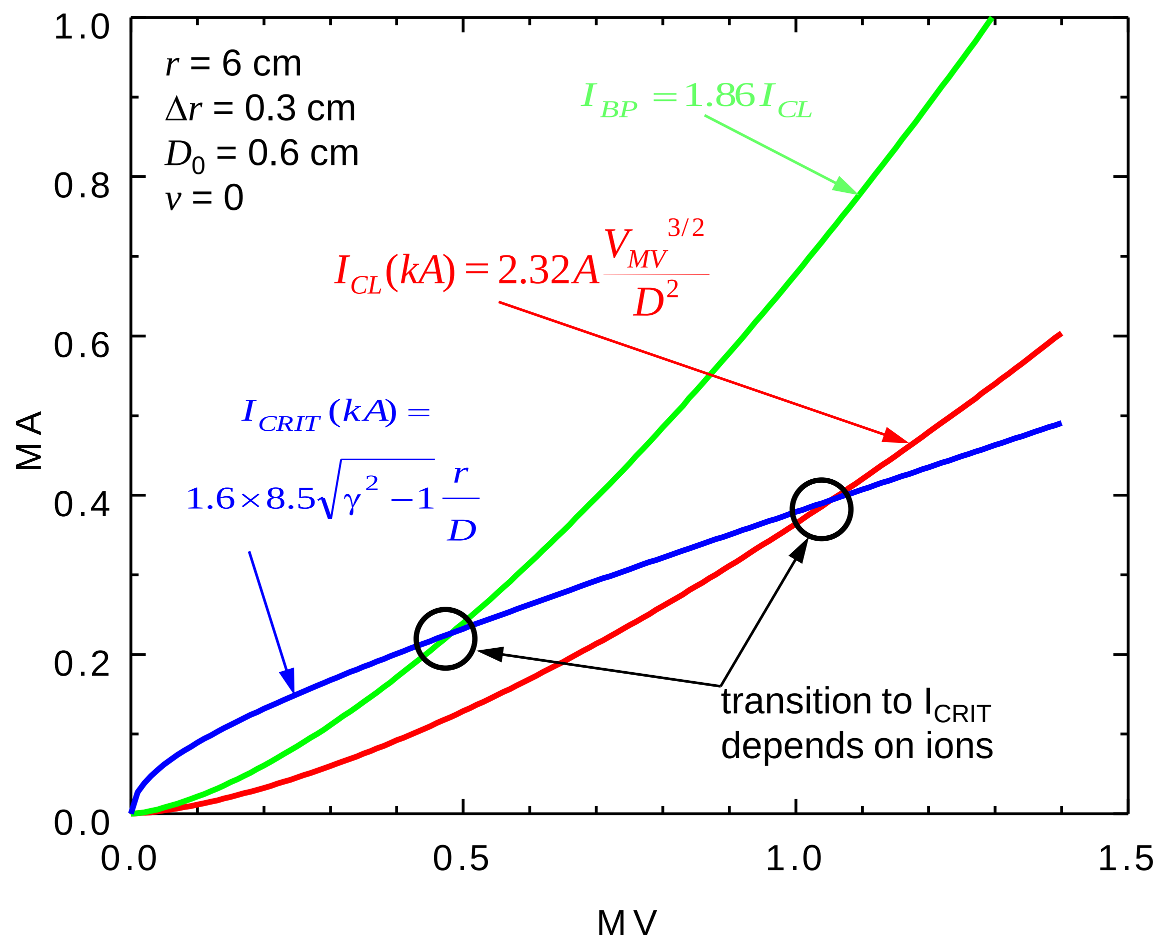
1) $N_{pass} = 1 + r_K/(2r_L)$
2) $N_{pass}\Delta x_{opt} = R_{CSDA}/3$

$$\Delta x_{opt} = (R_{CSDA}/3)\left(1 + \frac{I/I_0}{\left(\gamma^2 - 1\right)^{1/2}}\right)^{-1}$$



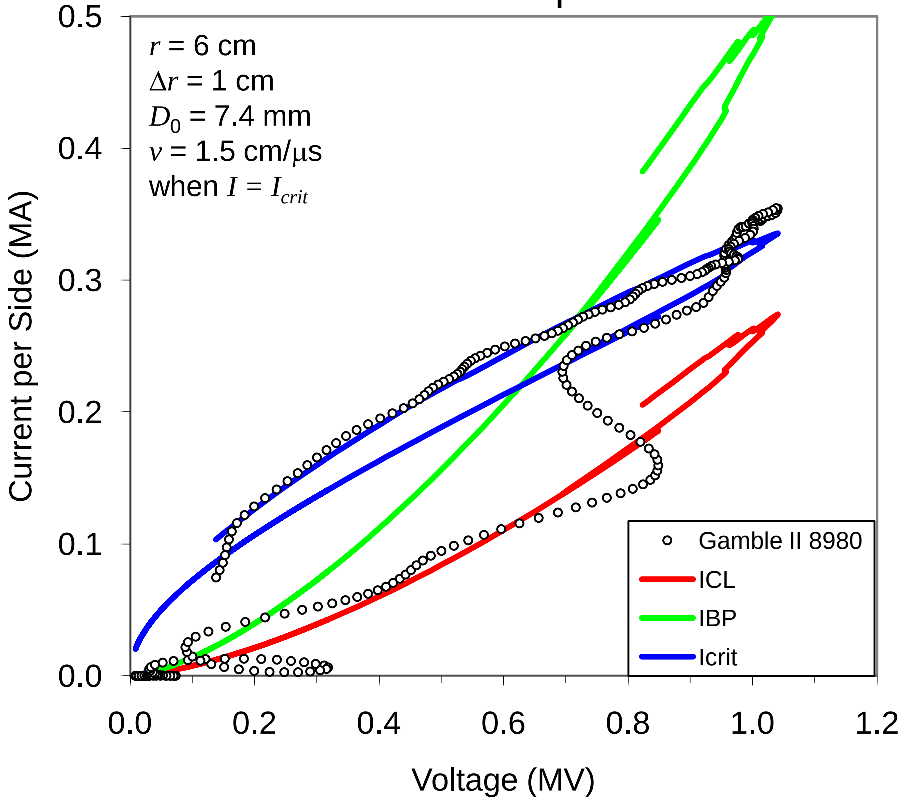
The I(V) characteristics of the diode can be understood using simple models



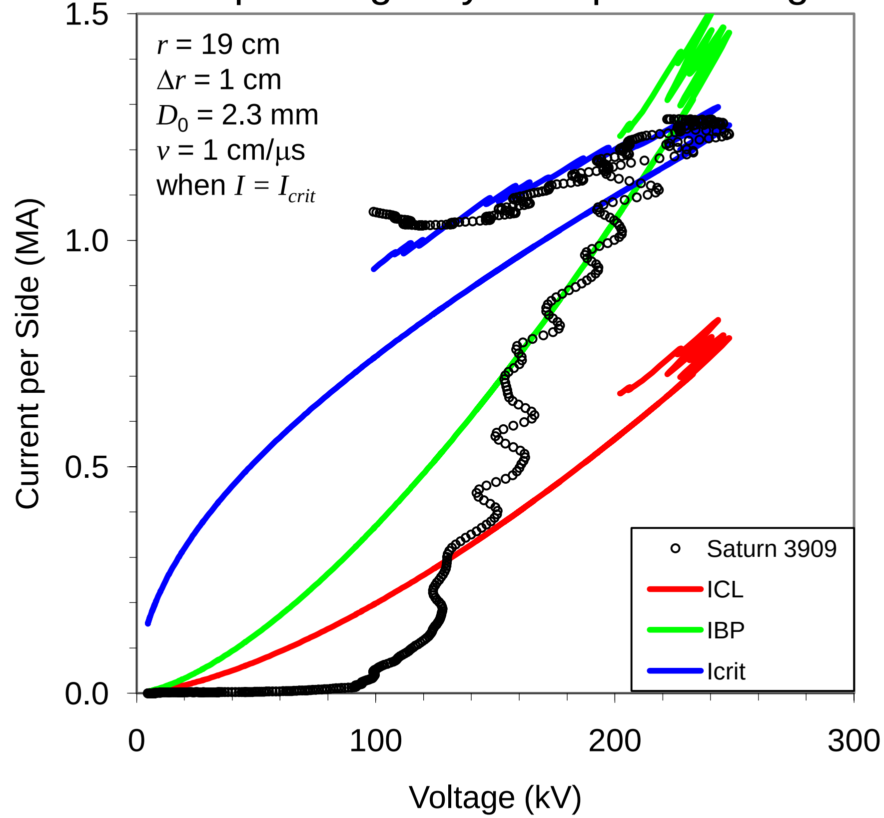


Critical current dominates high voltage triodes, bipolar current is more important at low voltage

Gamble II triode data follow I_{crit} after V exceeds 800 kV: Beam should pinch

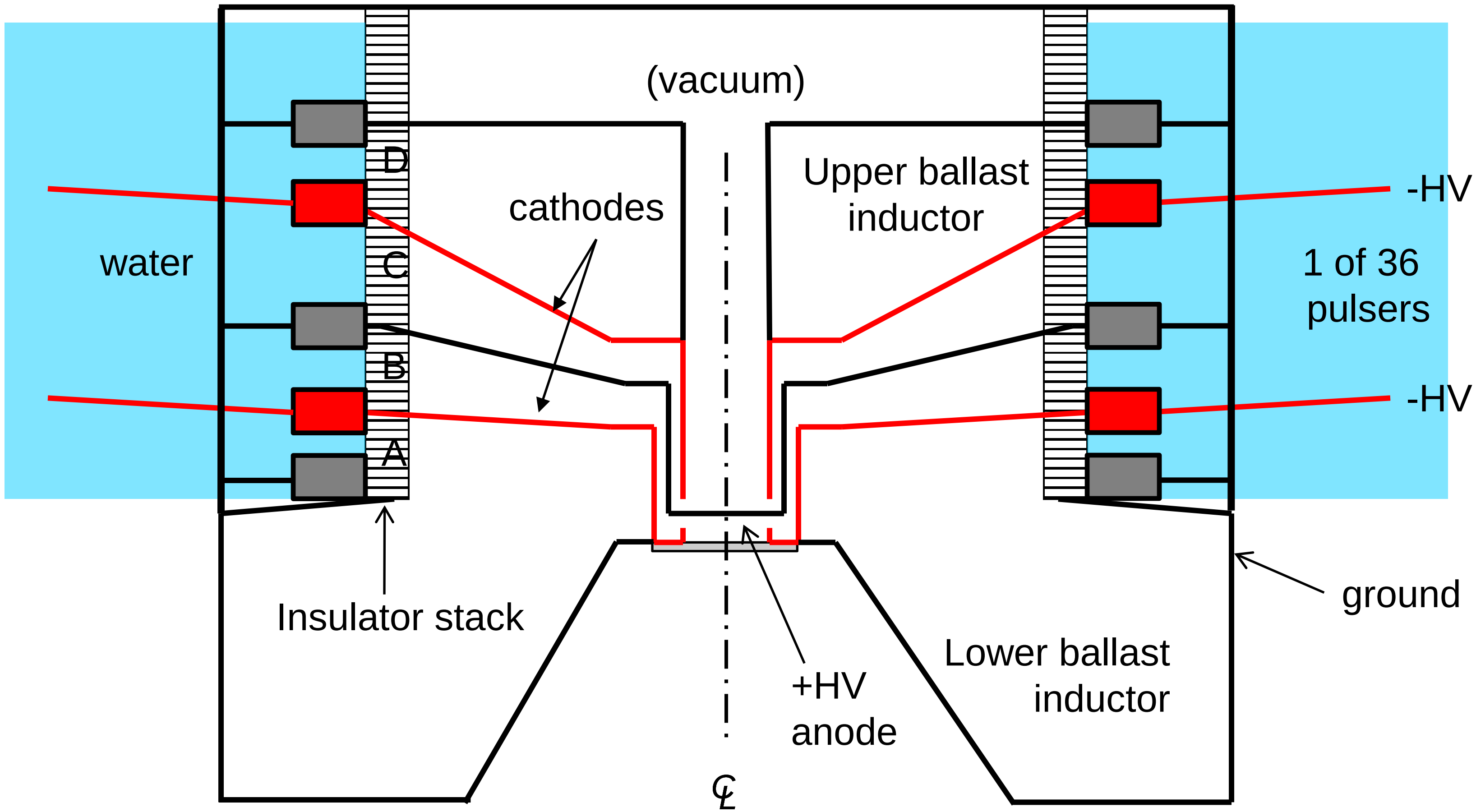


Saturn triode data follow space-charge-limited emission until V exceeds 210 kV: Beam pinching only after peak voltage

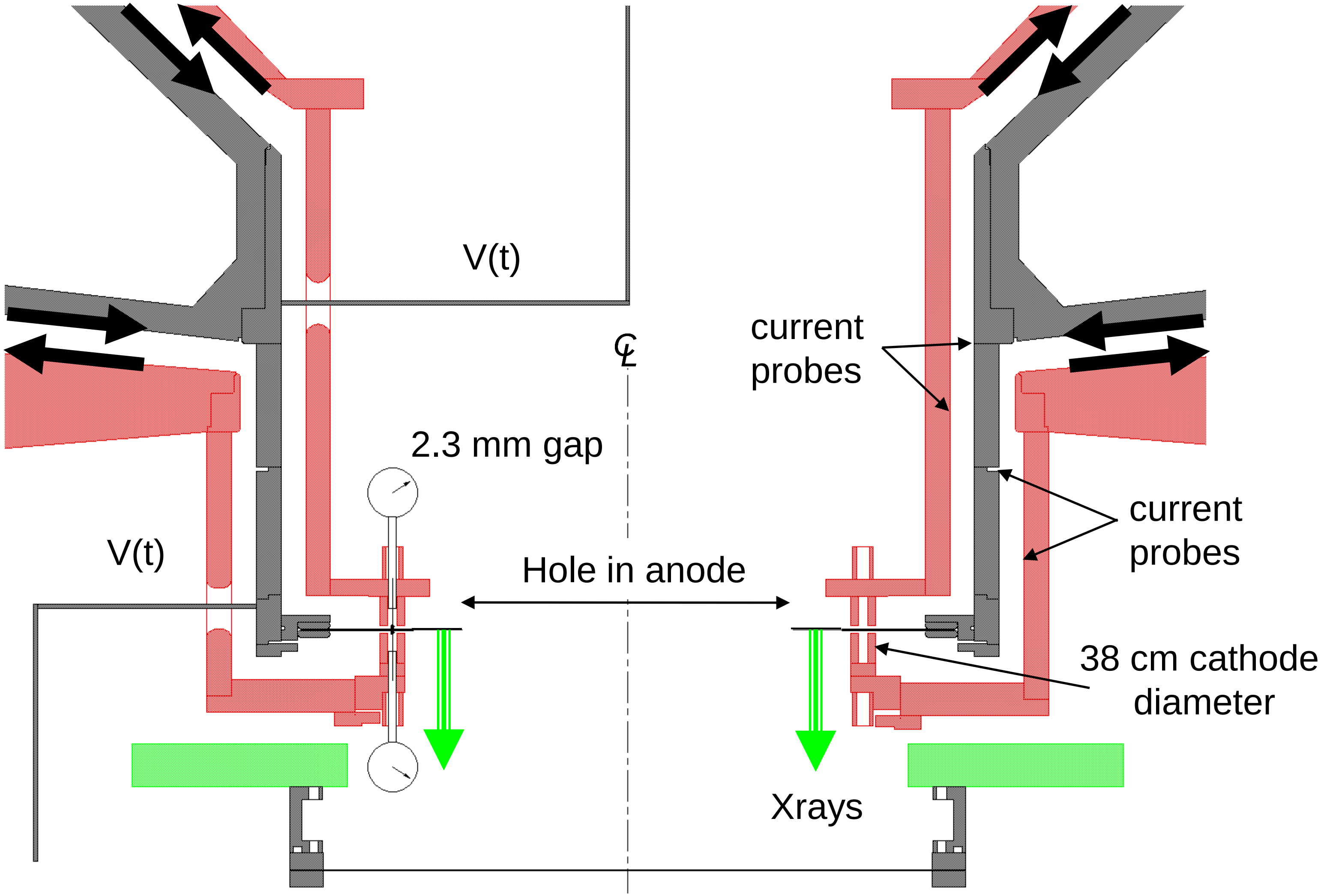


Higher current (2.5 MA), lower voltage (250 kV) triodes are being tested on Saturn at Sandia

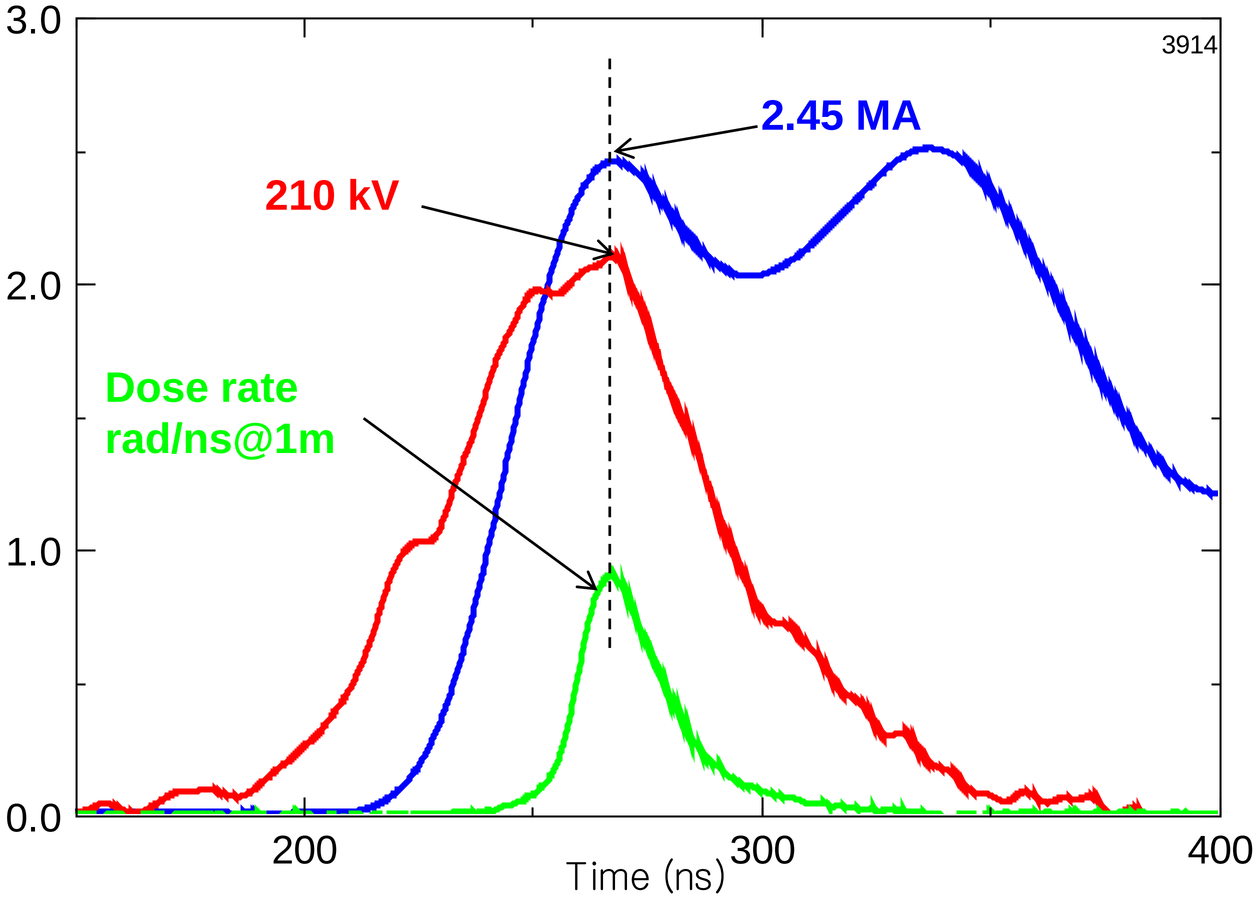
Polarity "inversion" in vacuum using ballast inductors



Small, precise, anode-cathode gaps enable low impedance operation

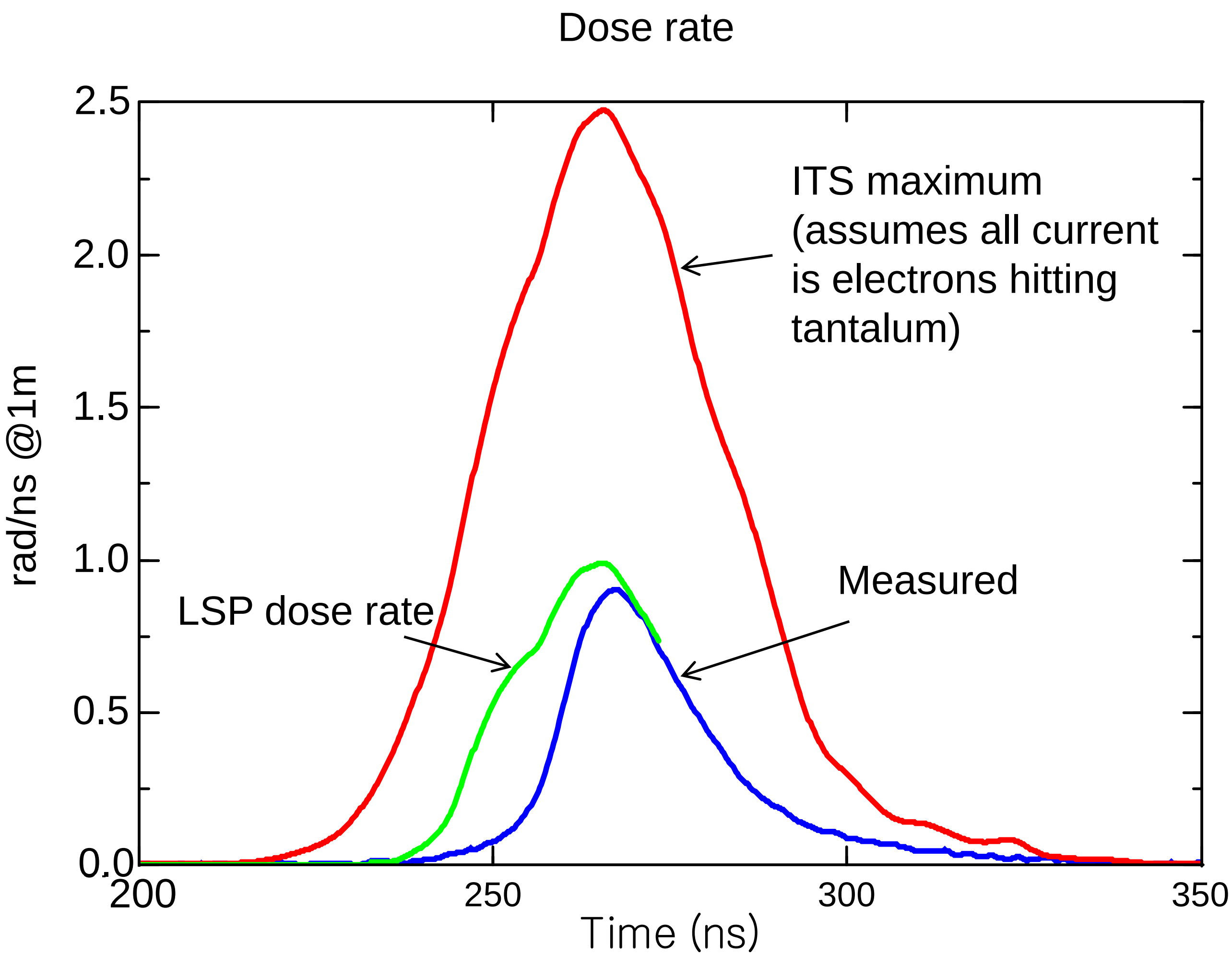


Sample Saturn results at 2.5 MA, 250 kV



- 18 of 36 Saturn modules charged, other 18 connected as parallel loads
- 2.3 mm anode-cathode gaps
- Current begins after voltage exceeds 75 kV
- Dose rate signal starts later than current
  - X-rays shadowed by lower cathode
  - Beam not strongly pinched

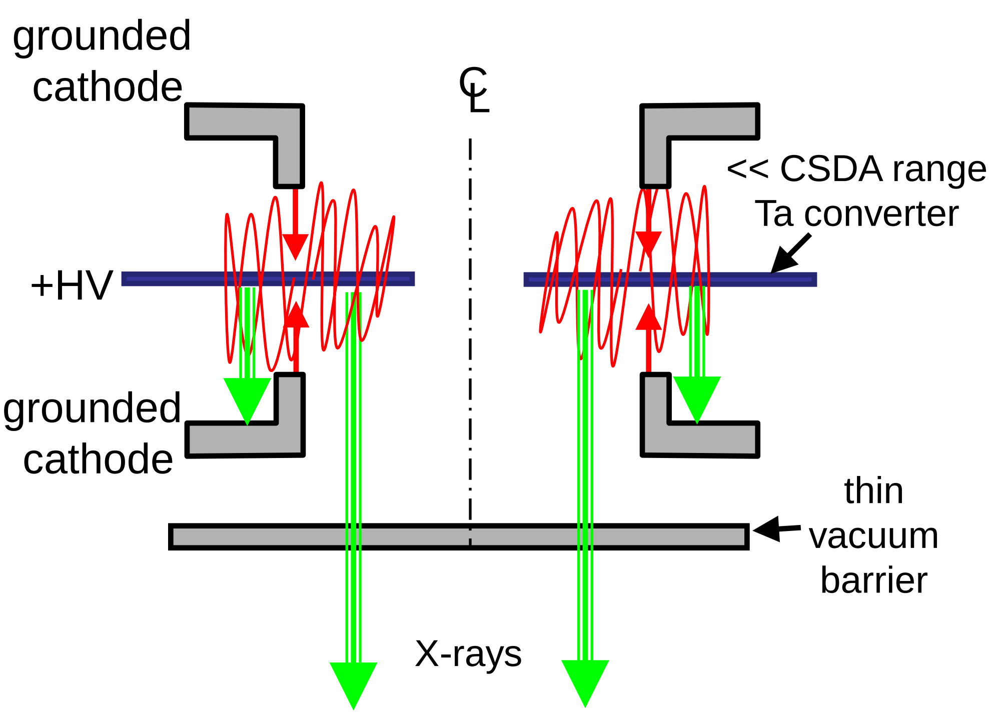
Saturn dose rate could be about two times greater



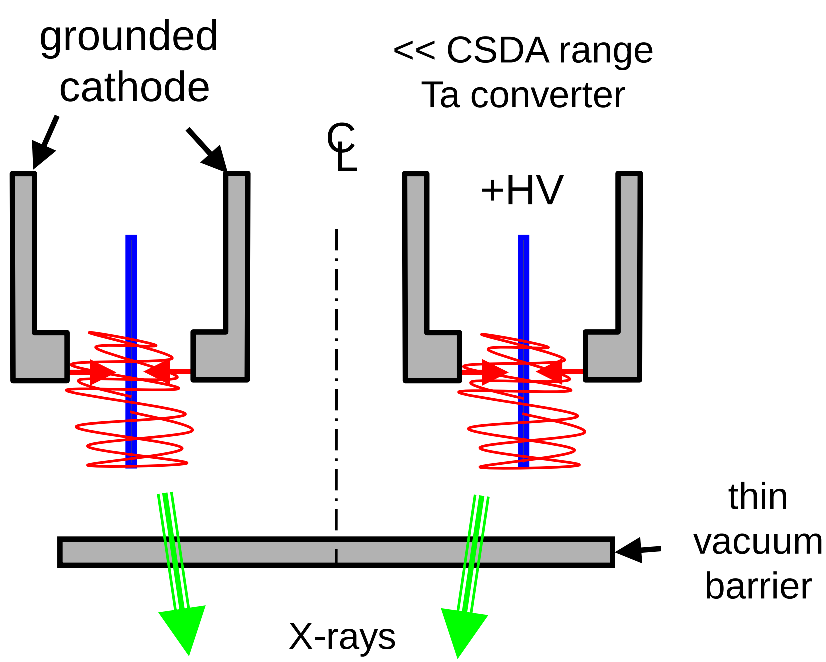
- Reasons why measured dose rate is 2.7 times less than ITS maximum
  - Ion current
  - Electrons miss tantalum
  - X-rays shadowed by cathode
  - 40-56% of current makes useful x-rays
- LSP dose rate close to measurements
  - Only half of current propagates inward to tantalum

Cylindrical triode* may improve x-ray transmission

Saturn triode

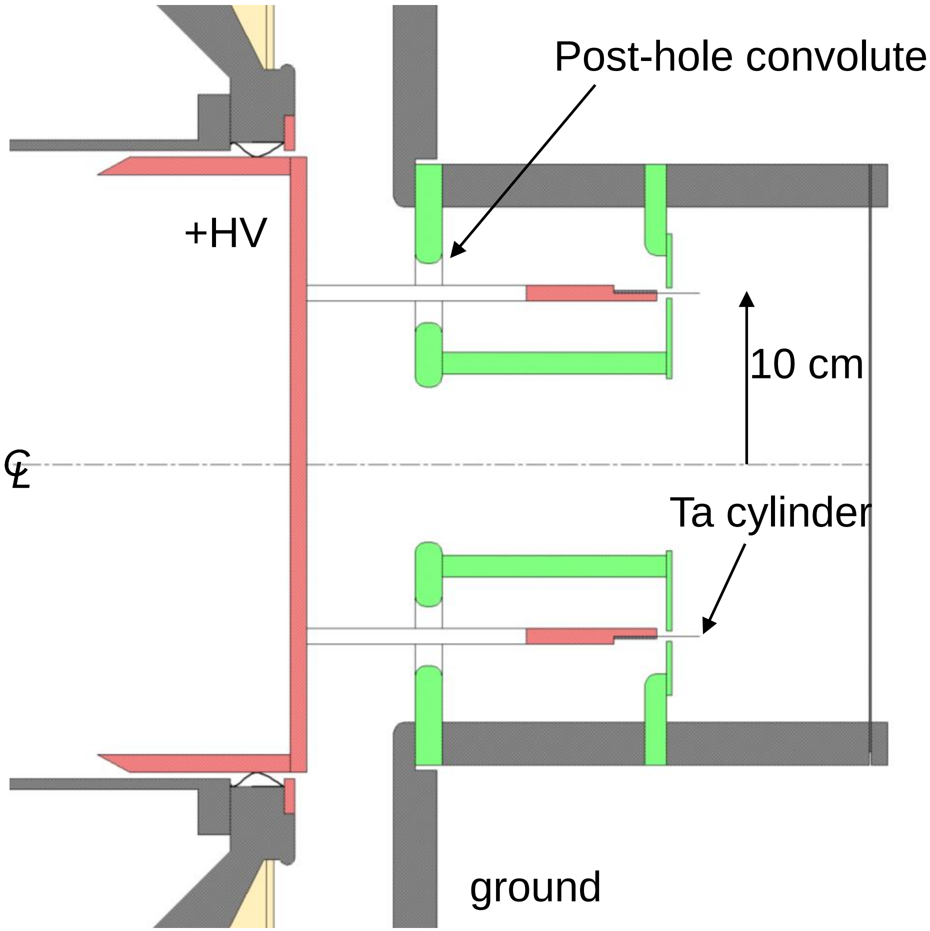


Cylindrical triode



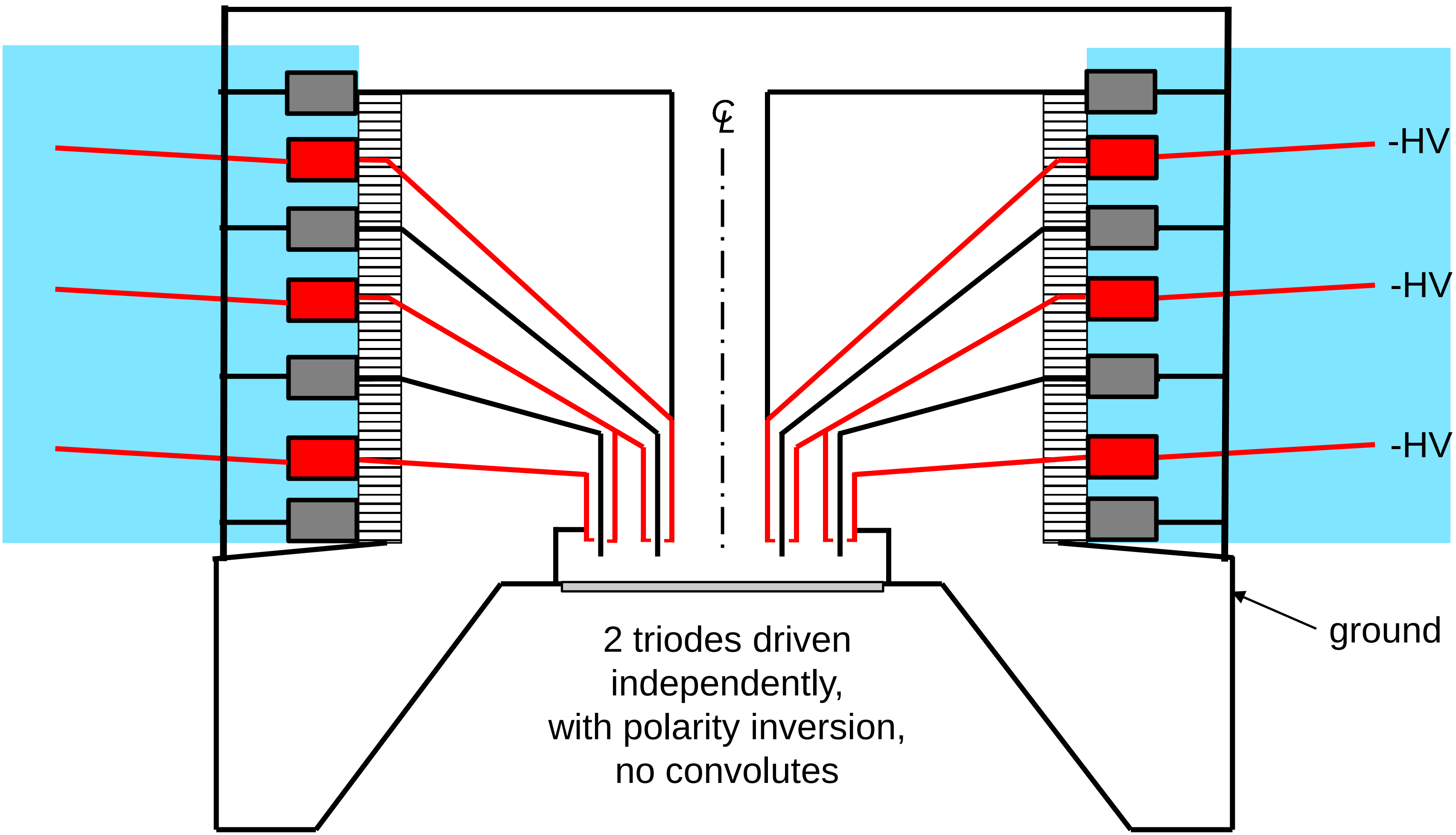
* T.W. L. Sanford and J.A. Halbleib, G. Cooperstein, and B.V. Weber, "Potential Enhancement of Warm X-Ray Dose from a Reflexing Bremsstrahlung Diode", IEEE Trans. Nucl. Sci. NS-42, 1902 (1995).

Cylindrical triode design will be tested at ½ scale on Gamble II



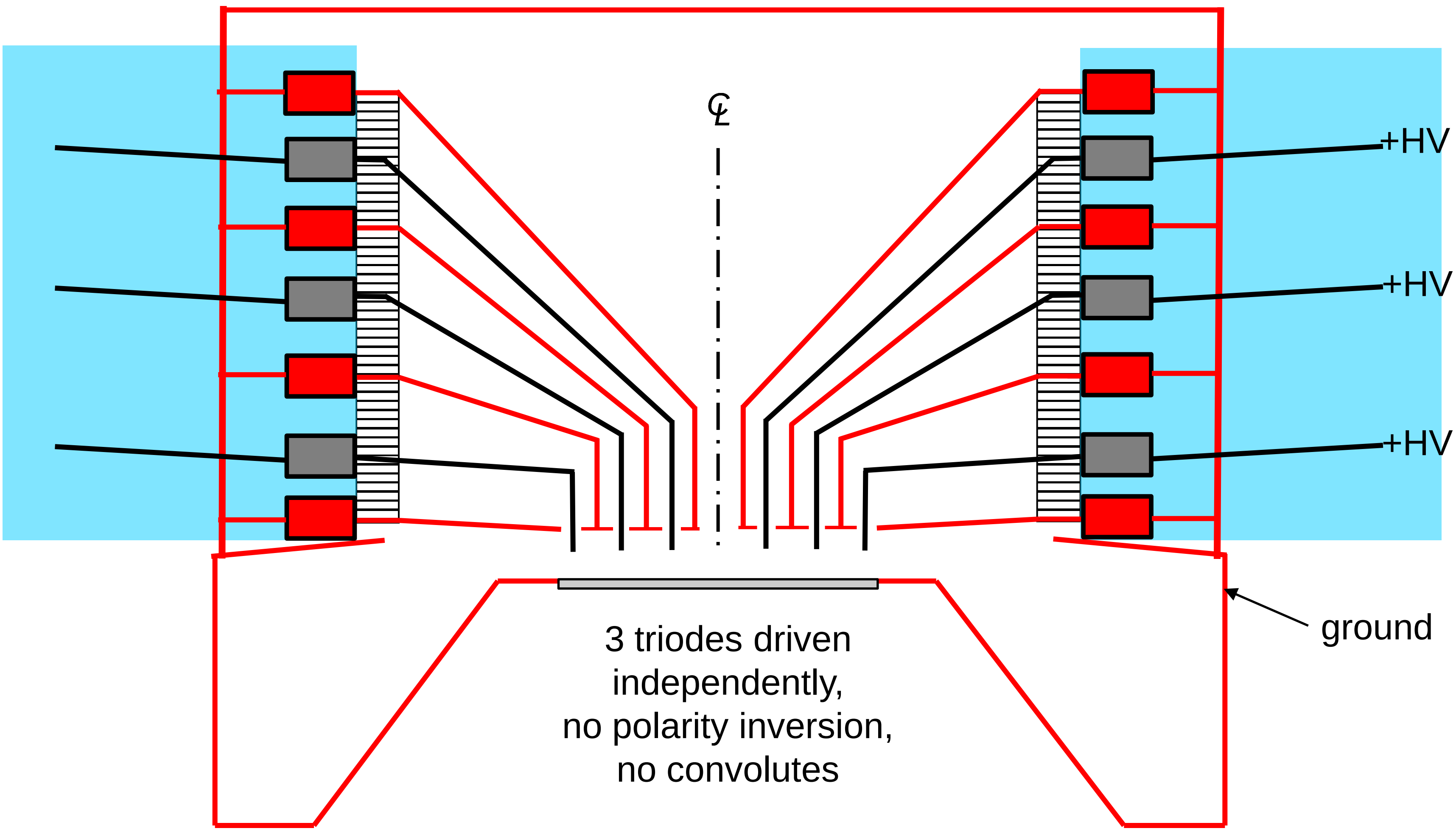
- Half scale of Saturn triode
  - 10 cm radius converter
  - 1.3 MA, half of Saturn current (with 18 modules)
  - Same AK gap (2.3 mm)
  - Same B field & voltage
  - Beam dynamics should be the same
- If practical, could be implemented on Saturn
  - straightforward to do 2 in parallel
  - 3 in parallel require positive polarity
  - Could be connected in series

For higher current on Saturn, could use two cylindrical triodes* in parallel

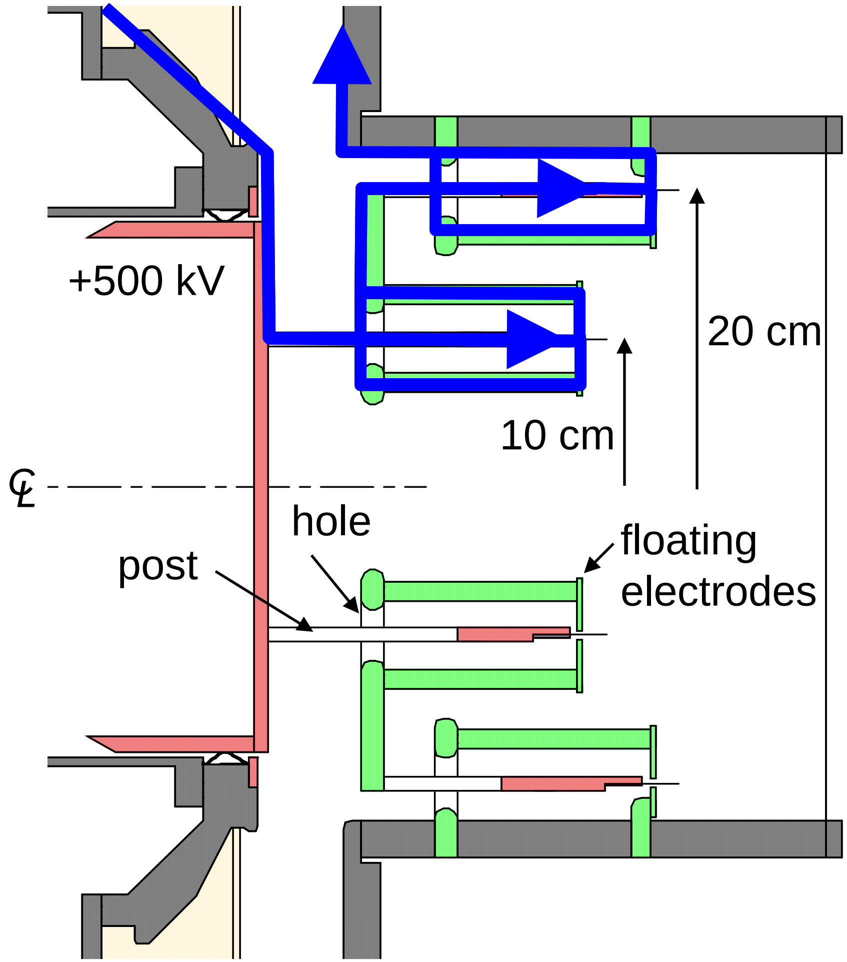


* T.W. L. Sanford and J.A. Halbleib, G. Cooperstein, and B.V. Weber, "Potential Enhancement of Warm X-Ray Dose from a Reflexing Bremsstrahlung Diode", IEEE Trans. Nucl. Sci. NS-42, 1902 (1995).

3 triodes in parallel require positive polarity operation



"Triodes in series" would improve matching low impedance triodes to generator



- Generator current flows through both triodes
  - 250 kV at each triode, 500 kV total
  - Need to support floating electrodes (insulator stack?)
- On Saturn with 18 modules
  - 4Ω/18 = .22 Ω driver impedance
  - 250 kV/2.5 MA = 0.1 Ω each triode
  - 2 triodes in series matches generator
- Practical issues
  - Alignment, setup, electron losses
  - Could be tested on Gamble II

Conclusions

- Physics of reflex triodes from Gamble II experiments (1 MA, 1 MV)
  - Converter thickness 1/20 of CSDA range optimizes x-ray dose
  - Simple model based on electron orbits predicts optimum thickness from LSP/ITS calculations and experiment
  - I(V) analysis: beam dynamics different between 1 MV and 250 kV
- Multi-MA triode experiments on Saturn (2.5 MA, 250 kV)
  - Polarity inversion in vacuum
  - No-convolute configuration, accurate gap settings
  - About half of current produces useful x-rays
  - Cylindrical triode one option to increase x-ray transmission
- Potential to increase Saturn current toward 10 MA, maintaining voltage and outer diameter
  - 2 (or 3) cylindrical triodes in parallel
  - Triodes in series to improve matching
  - These concepts will be tested first on Gamble II