Status & Plan for Discharge Plasma Source R&D at IST

AWAKE Collaboration meeting, CERN, 06 Oct. 2023

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AWAKE Team

Electron-positron plasmas in extreme conditions

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- Discharge plasma source
- Recent results
- Mid term plans

DPS test lab @ IST (since 2018)

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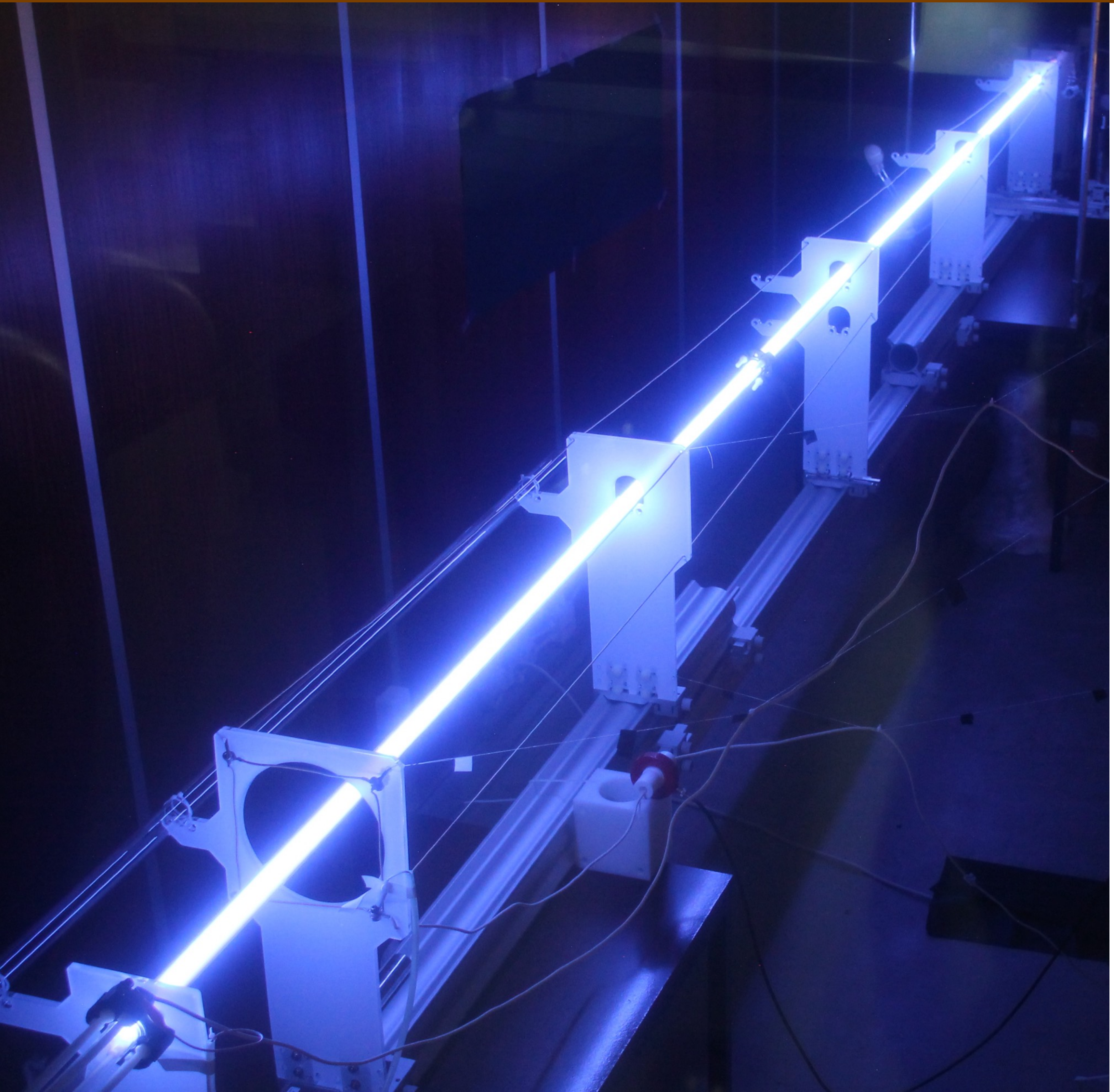

Support R&D of DPS Electrical kit

5 m long tube (longest possible)

25 mm diameter (as in CERN DPS tube)

Currently an ignition + heating circuit

made of old prototype modules …

… but all made aiming 0.1 % reproducibility

Presently working towards increasing the precision of interferometric measurement of plasma density

Previous setup not adequate for reproducible operation (e.g. manual gas injection, chronic gas leaks)

New gas injection system made the gas pressure reproducible to ~0.1% (in range 5 - 50 Pa Argon)

Electron-positron plasmas in extreme conditions

- Discharge plasma source
- **Recent results**
- Mid term plans

Better control and reproducibility of gas injection system

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Gas/vacuum system

Primary dry pump (UP = 4 Pa)

Regulator fixed to 1.1 Bar

2 injection valves w/ 2.5 ccm in between

3 puffs of 2.5 ccm into tube 5 l … 150 Pa in tube

Pump to desired pressure (5 - 50 Pa)

Borosilicate tube … H2 contam. after discharge

Reproducibility tests … pump + new gas for each discharge

Future … quartz + continuous flow w/ leaks

New automatic pump and gas injection…

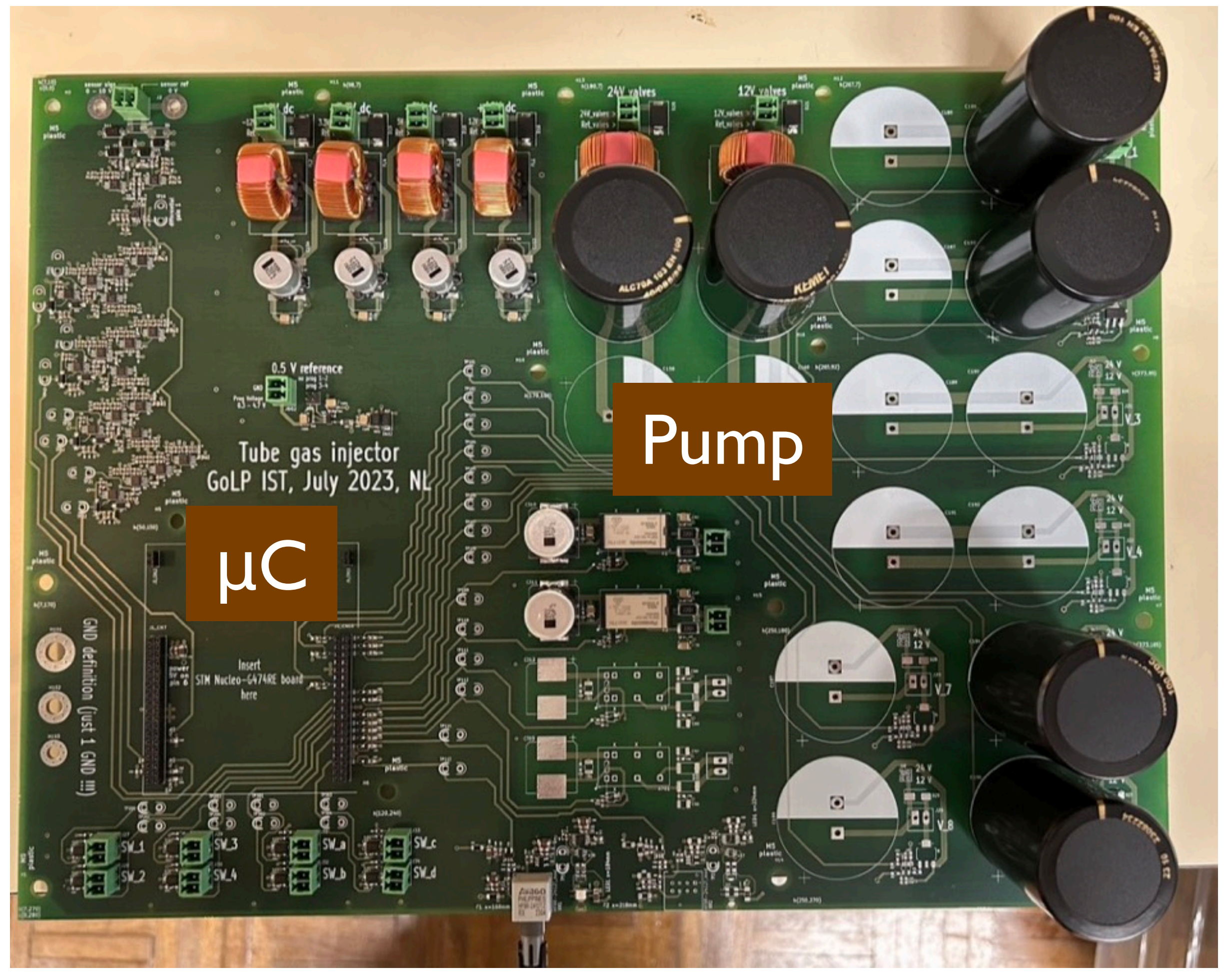
… ~ 0.8 % pressure reproducibility

… w/ discharges (work in progress)

PS

G1

G2

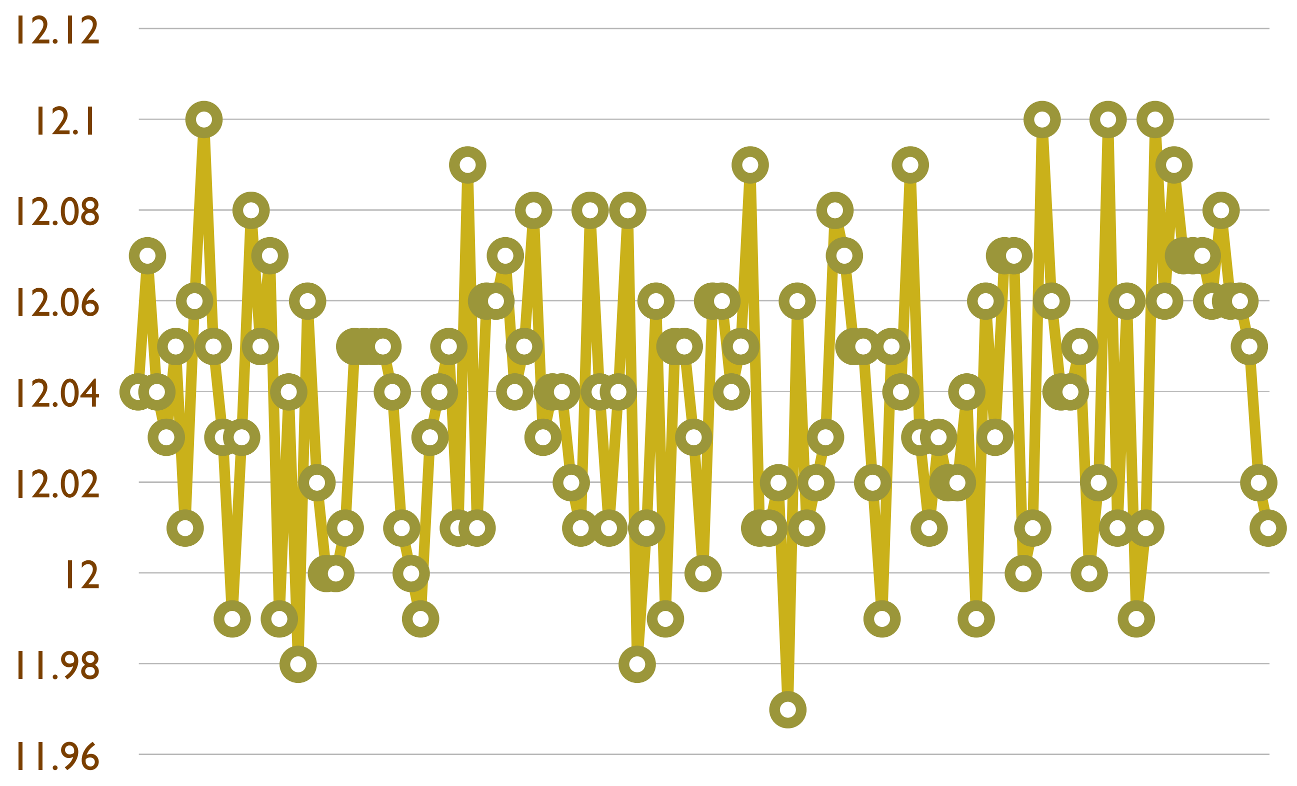


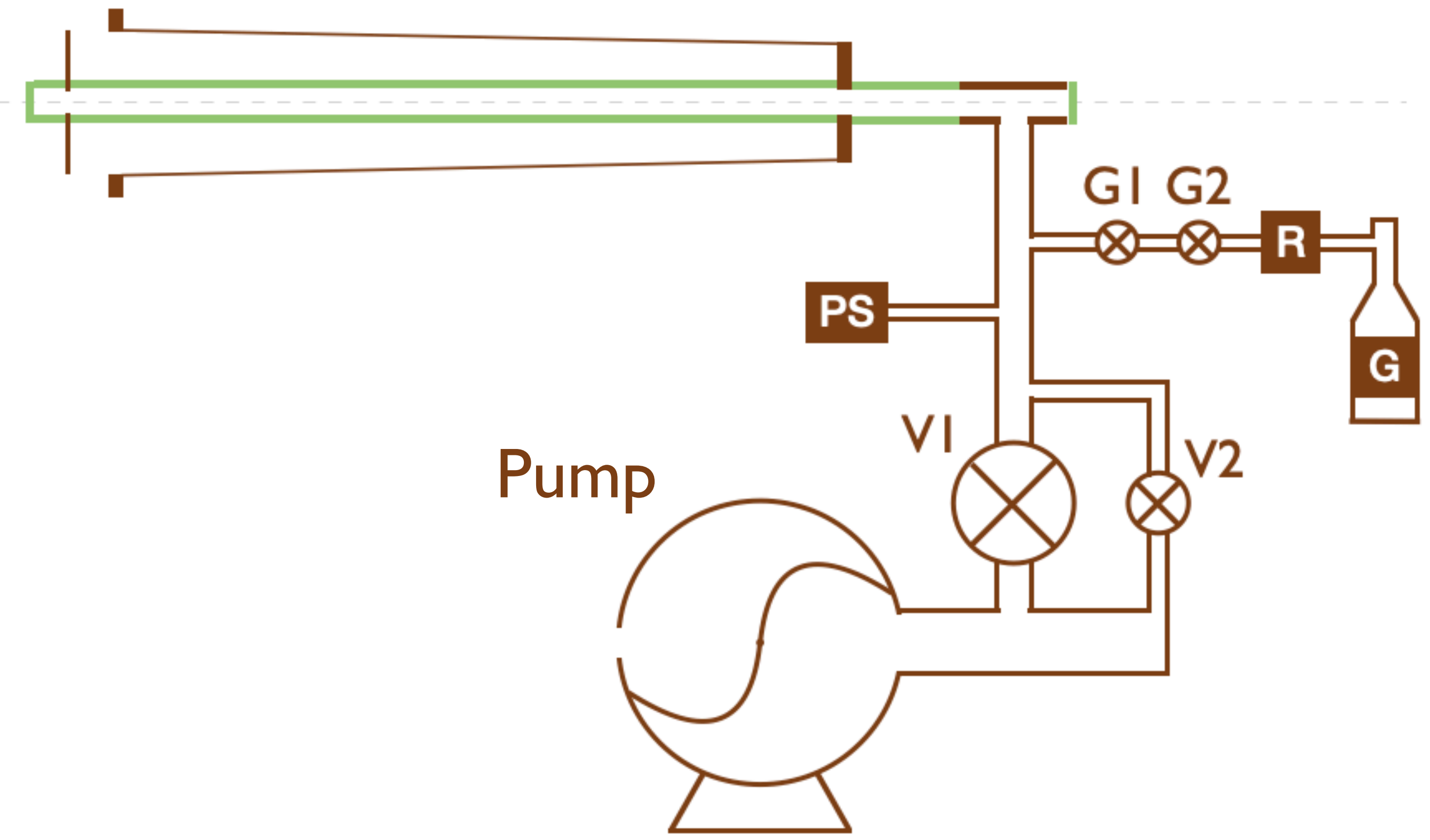
V1

V2

Press programming

Remote start





121 discharges

Programmed to 12.0 Pa

P average = 12.04 Pa

max - min = 0.13 Pa (1.08 %)

Tests after calibration 0.1% to 0.5%

Irregular manual operation

…

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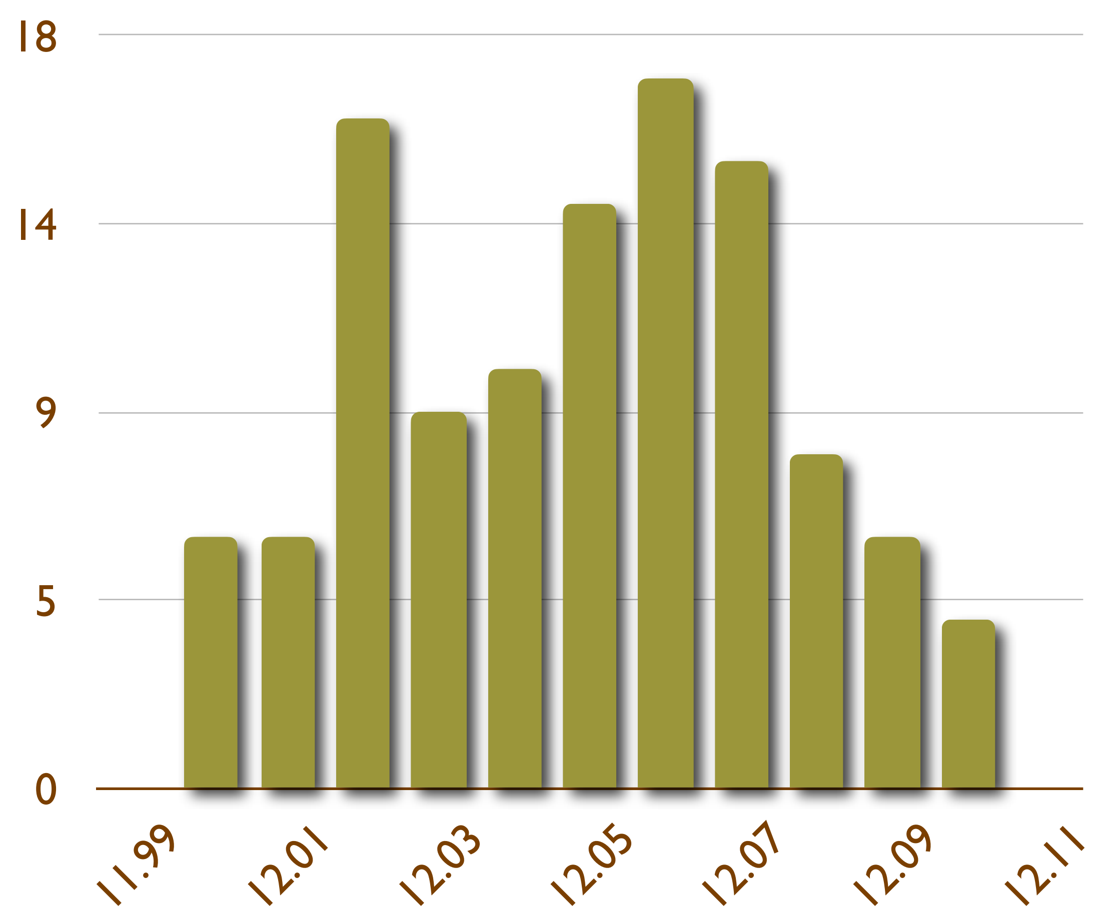

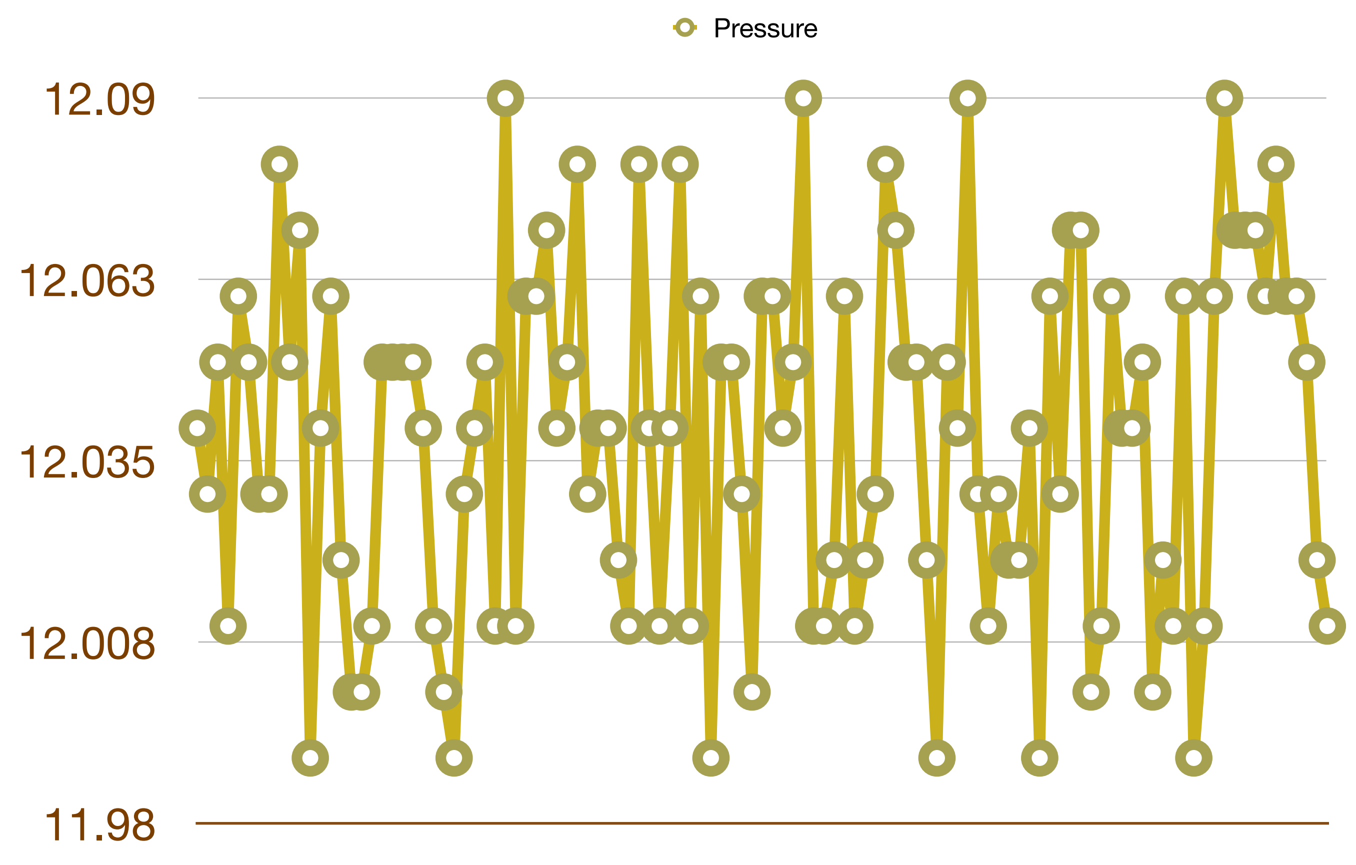

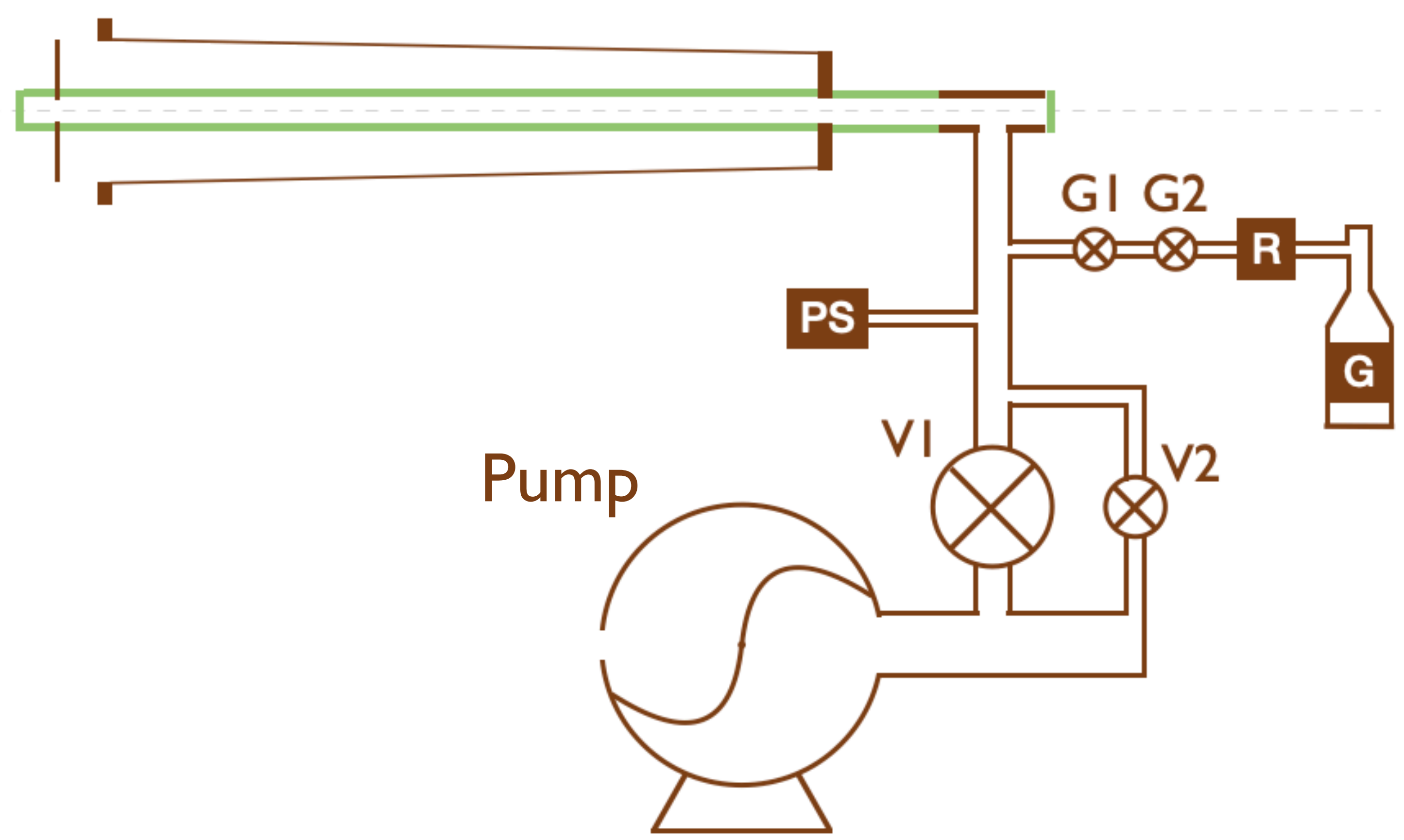

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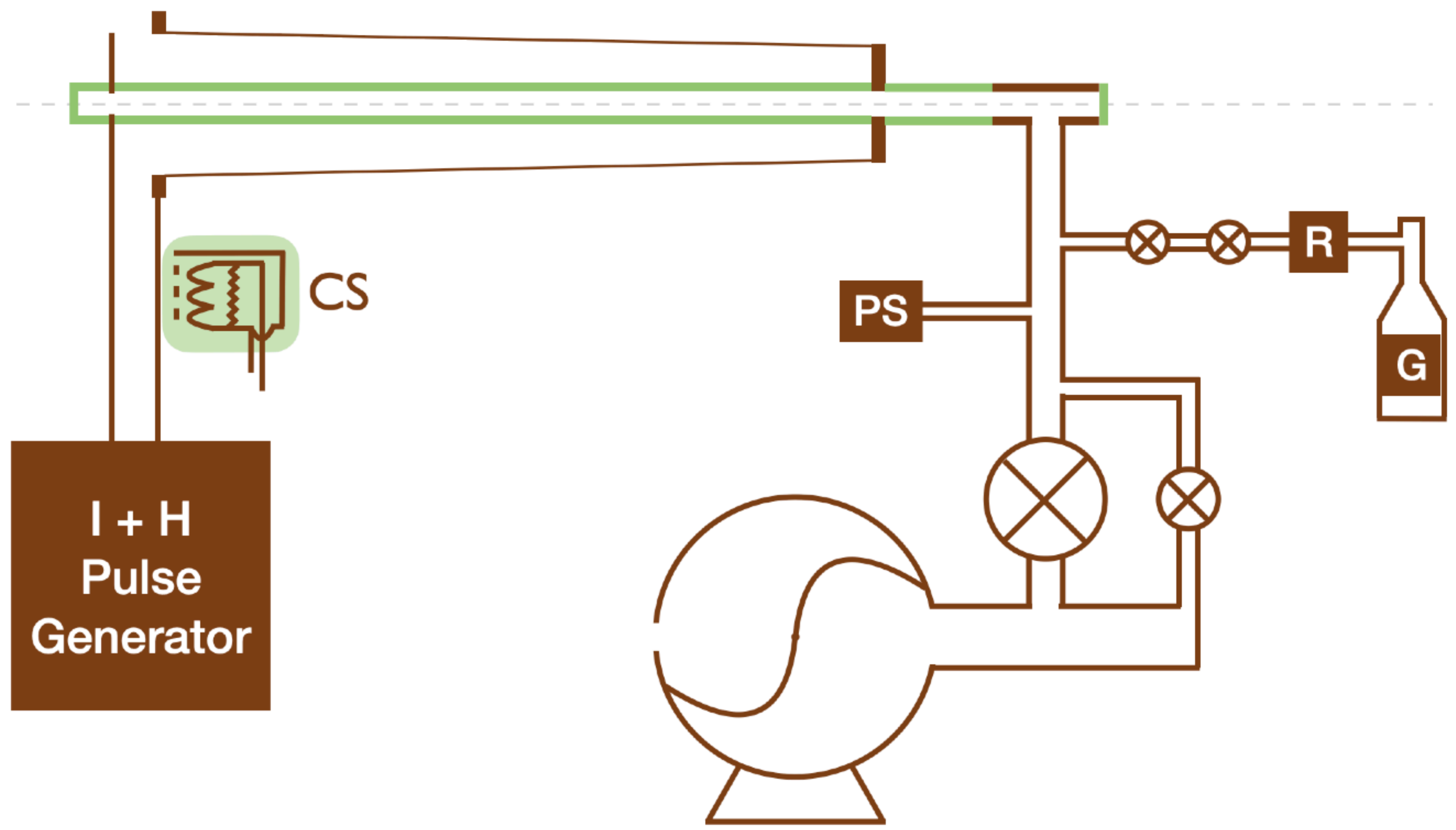
Exclusion thermal outliers →(0.8%)

Thermal control not main var. source

Thermal ctrl. essential for 0.1% op.

Current reproducibility



120 discharges

CS Bergoz current transformer

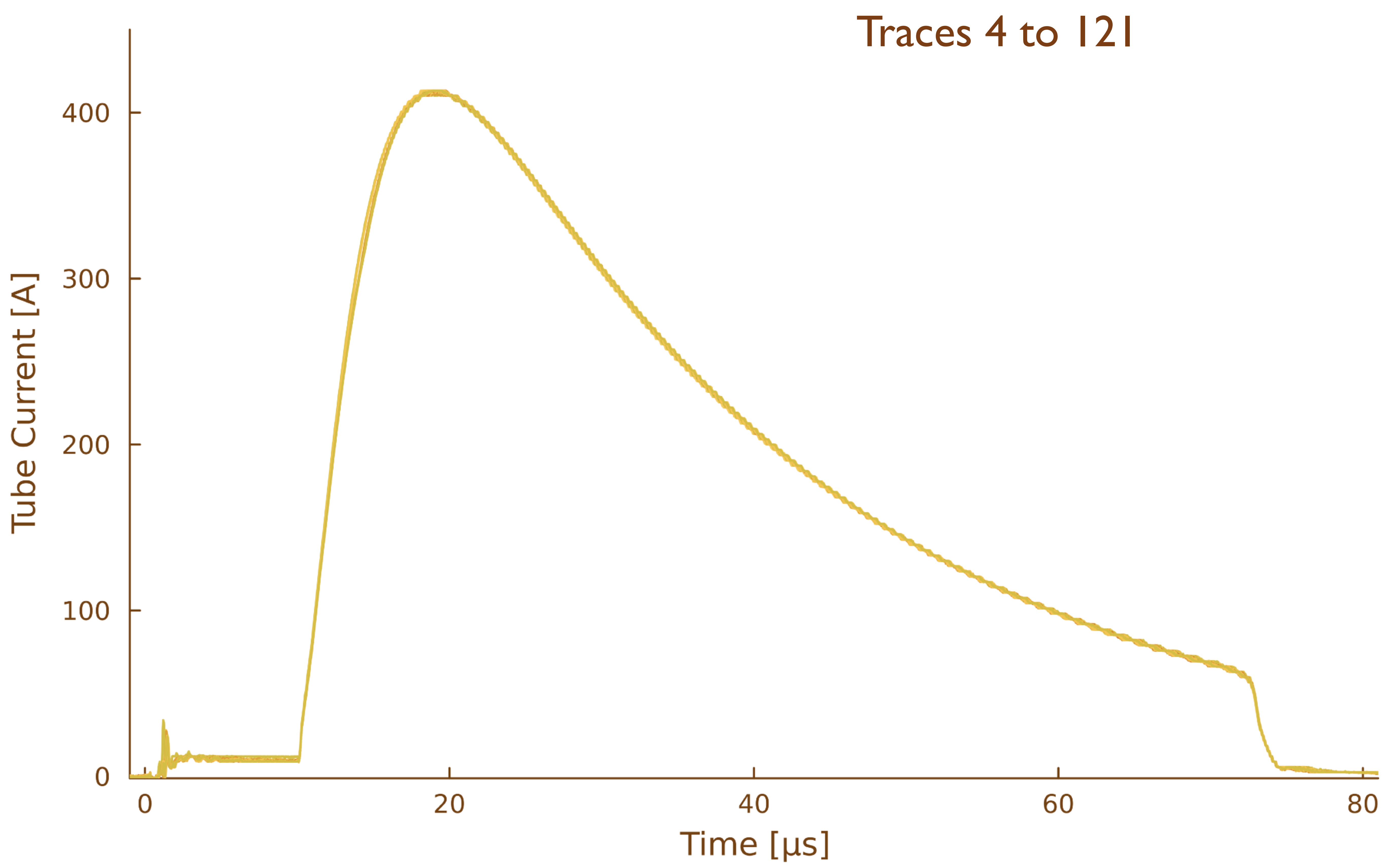
Delay between shots 75 - 440 s

Short delays …

→ lower tube gas density
(for same measured pressure)

→ lower plasma resistance

→ higher tube current
(for same V_{heat})



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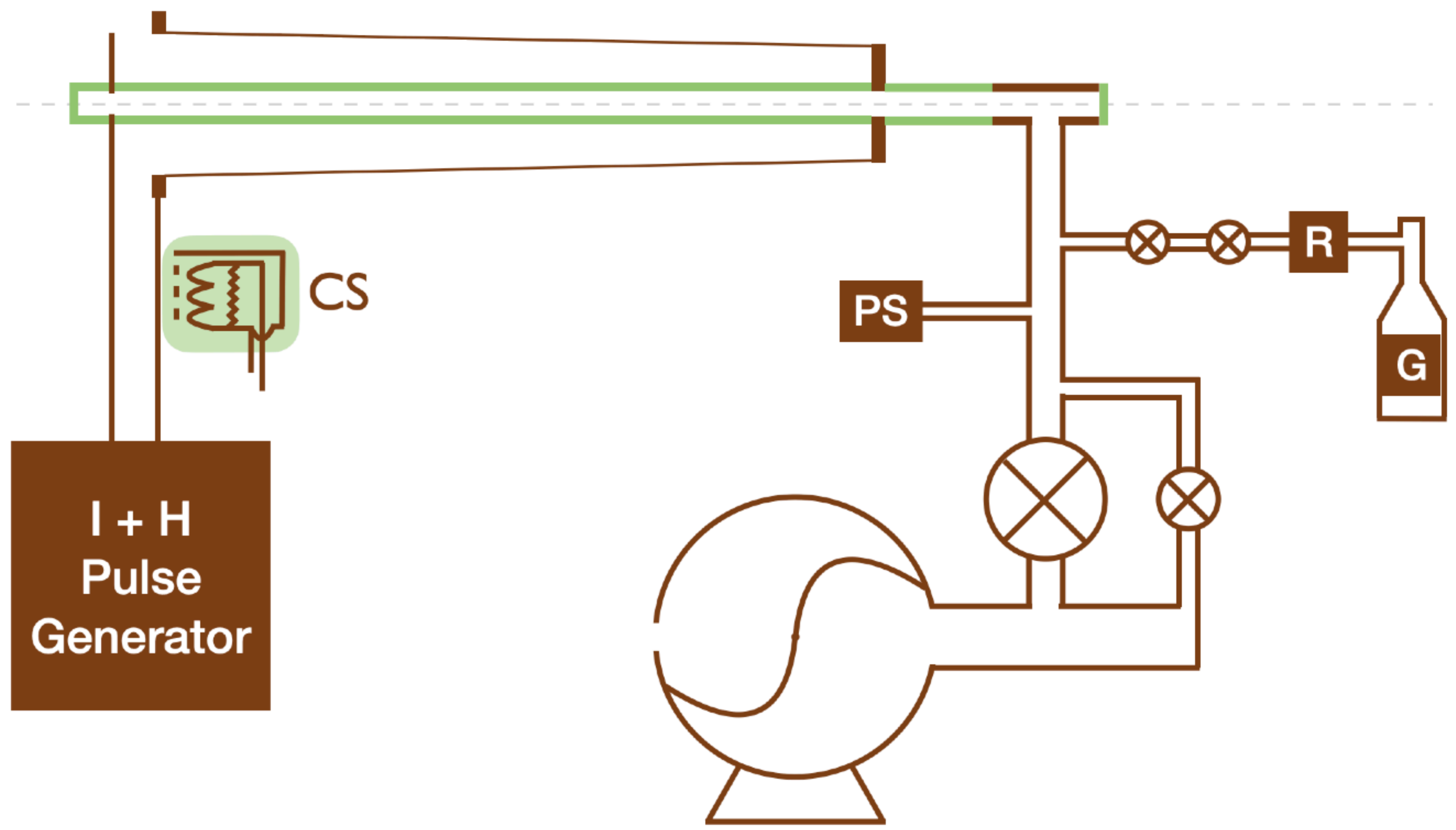

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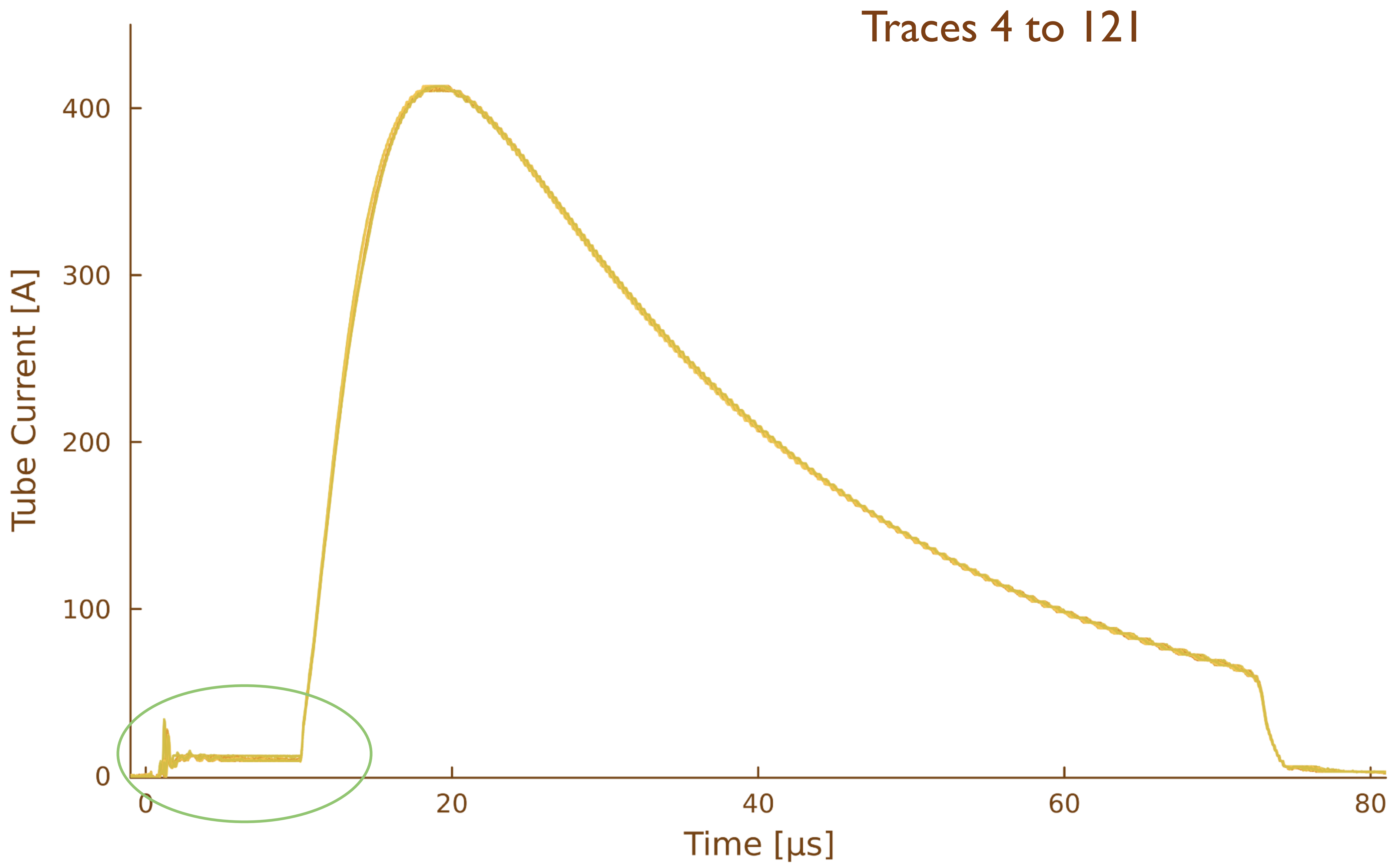

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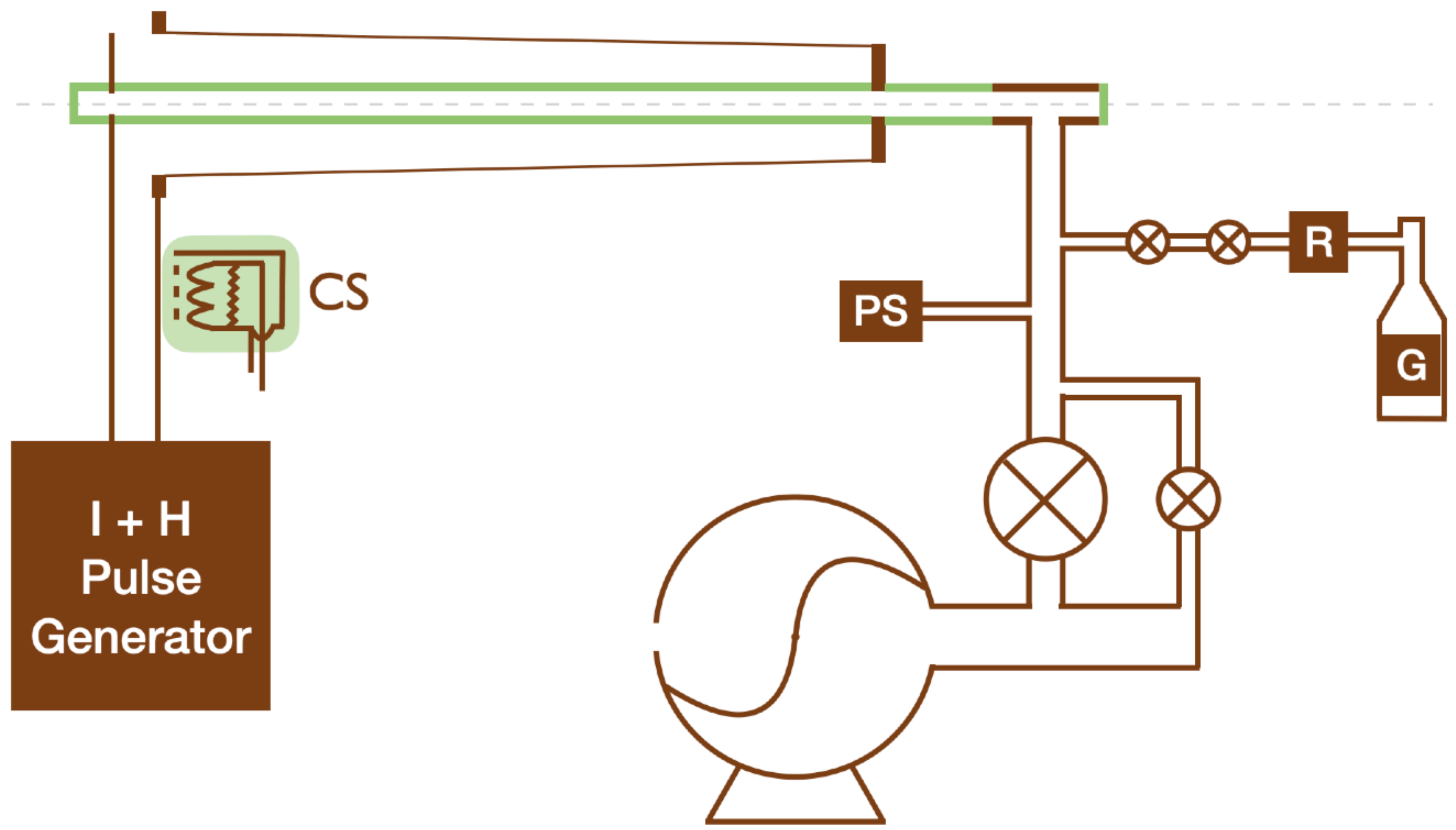

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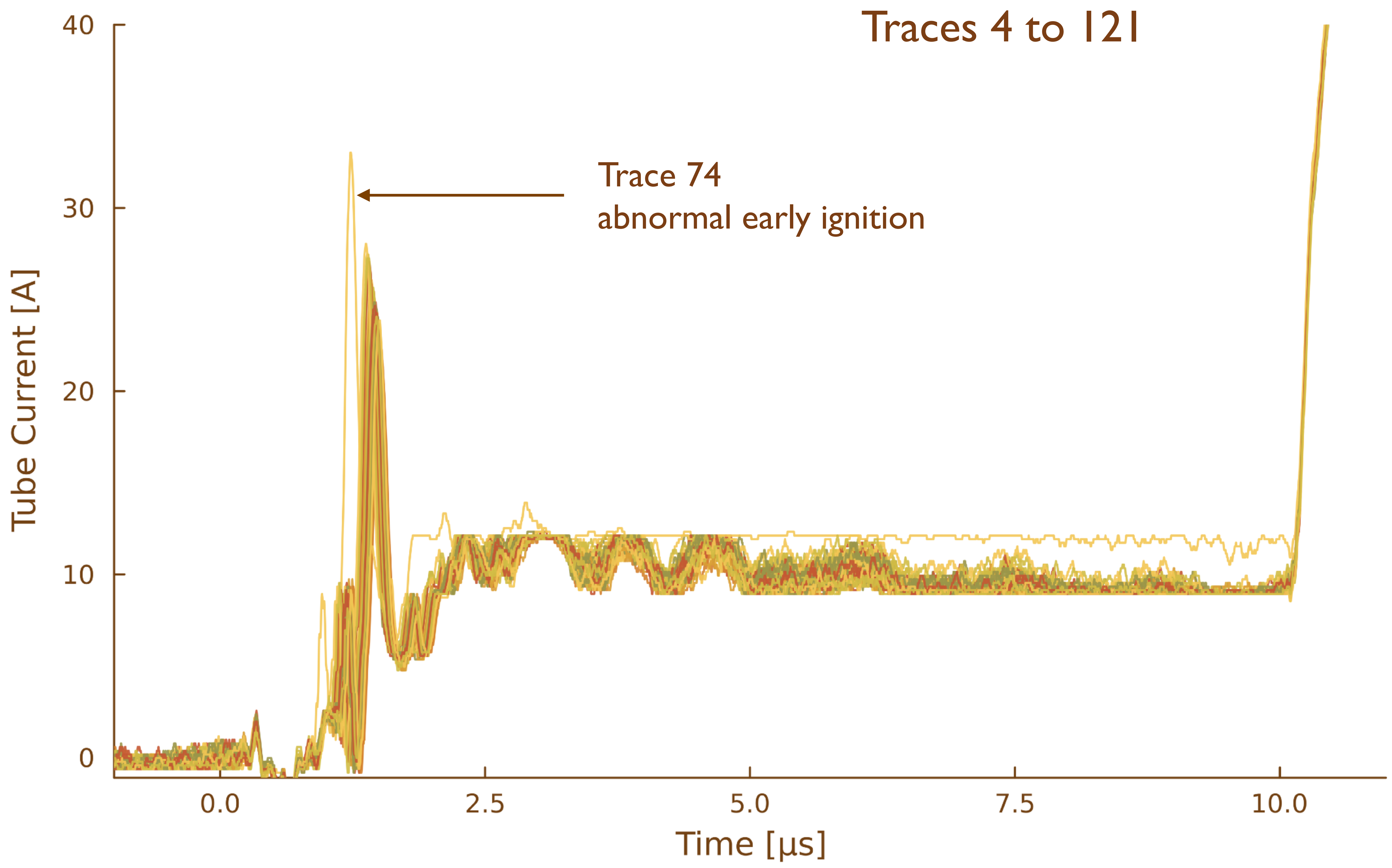

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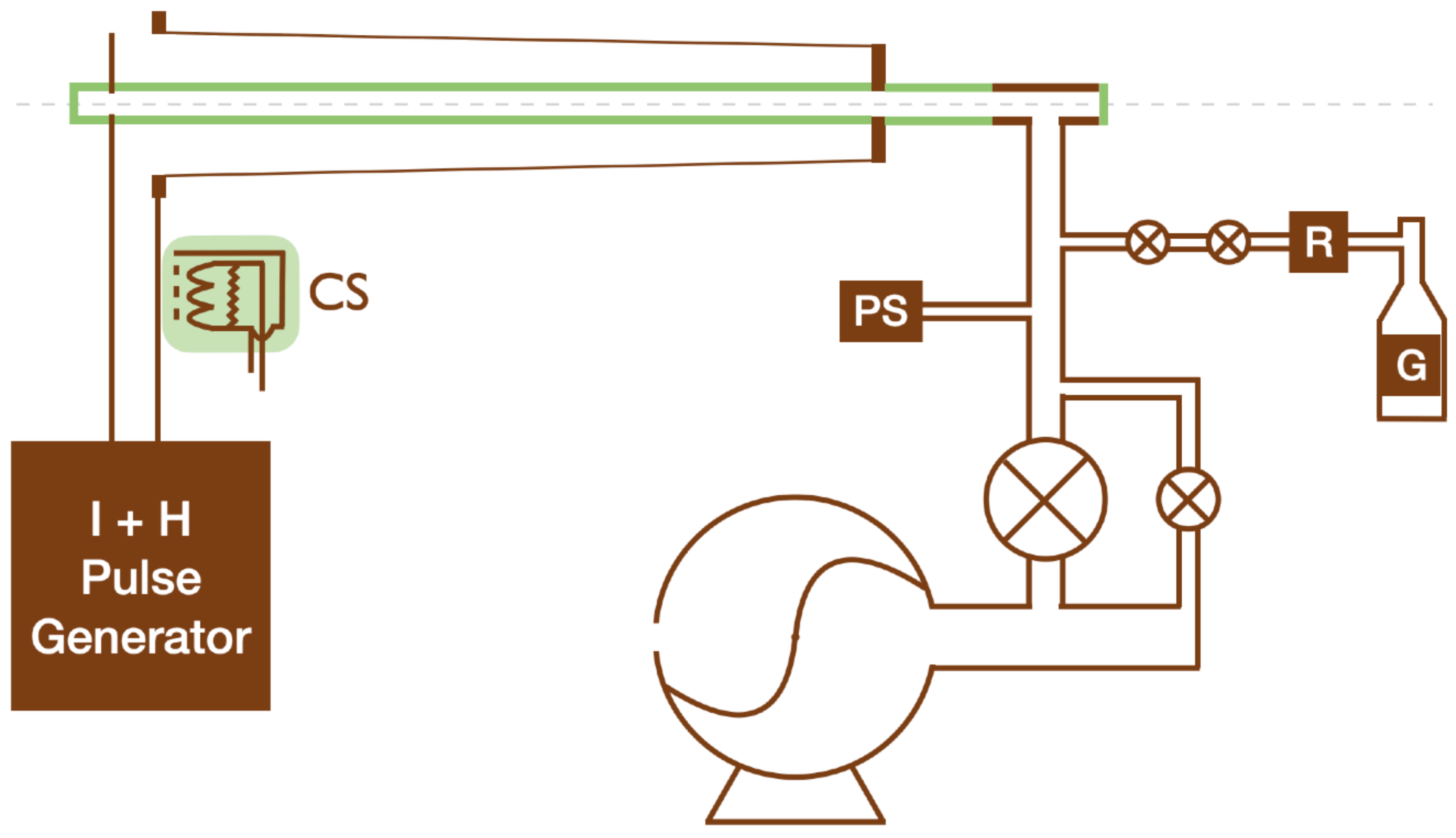

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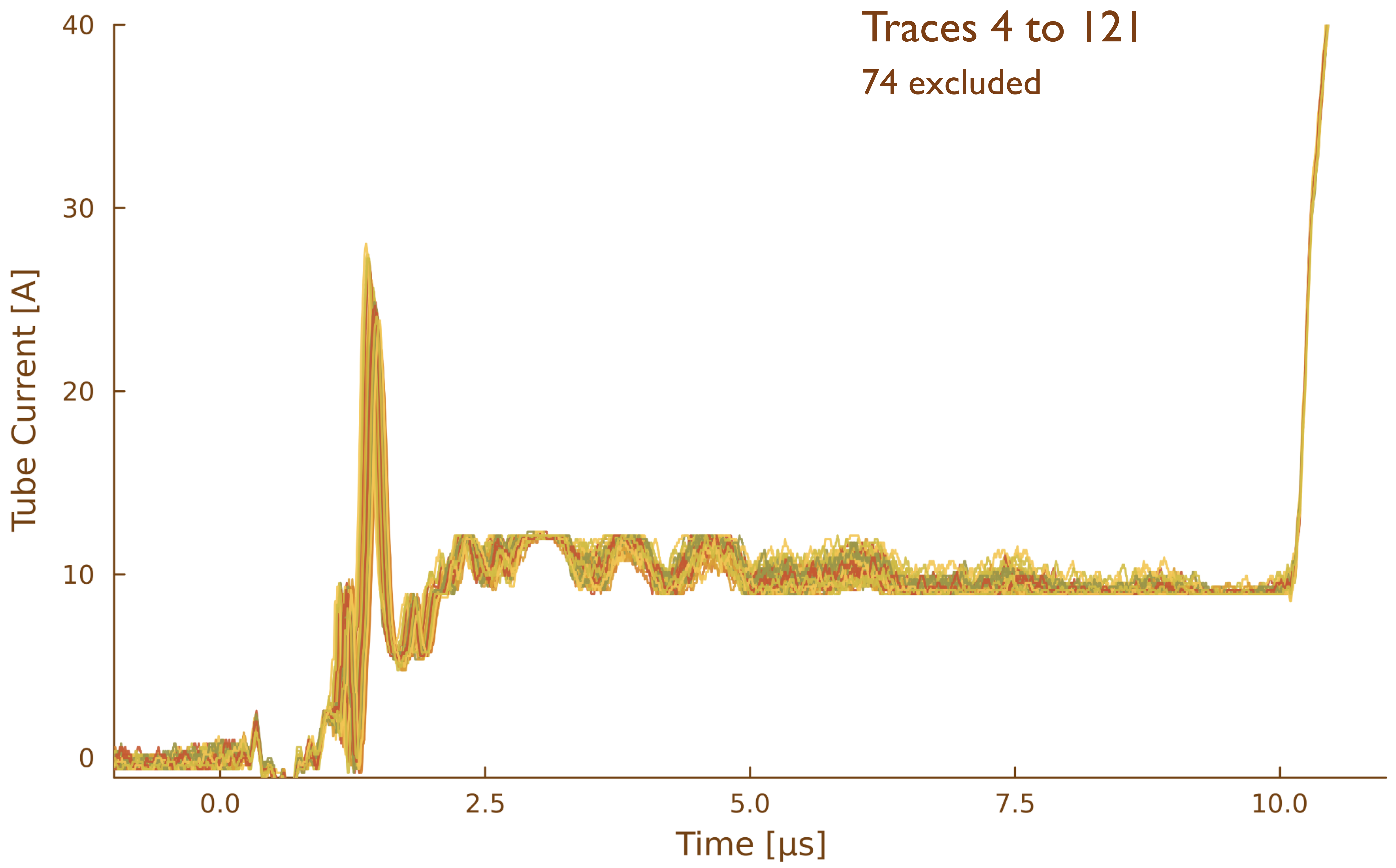

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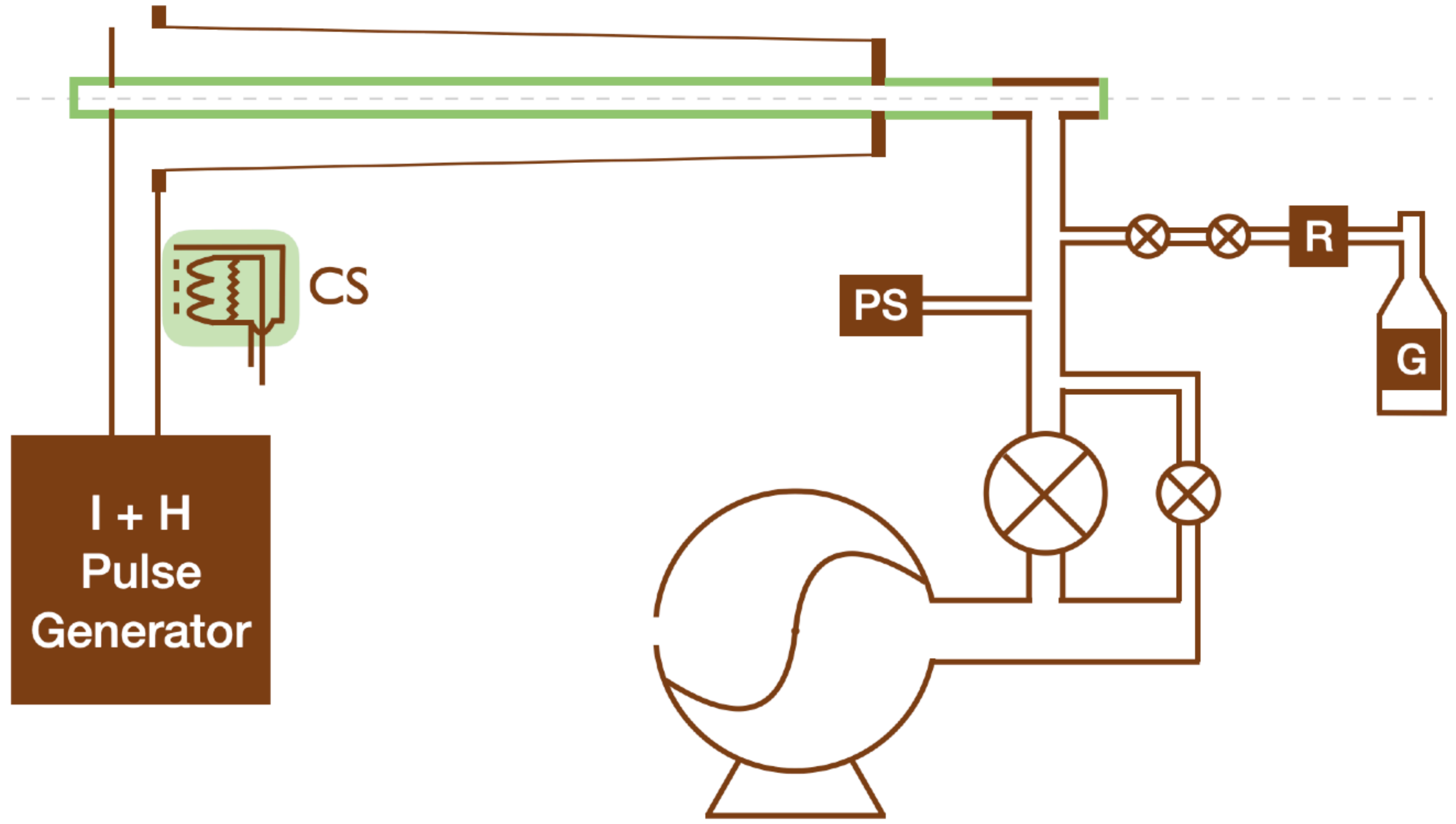

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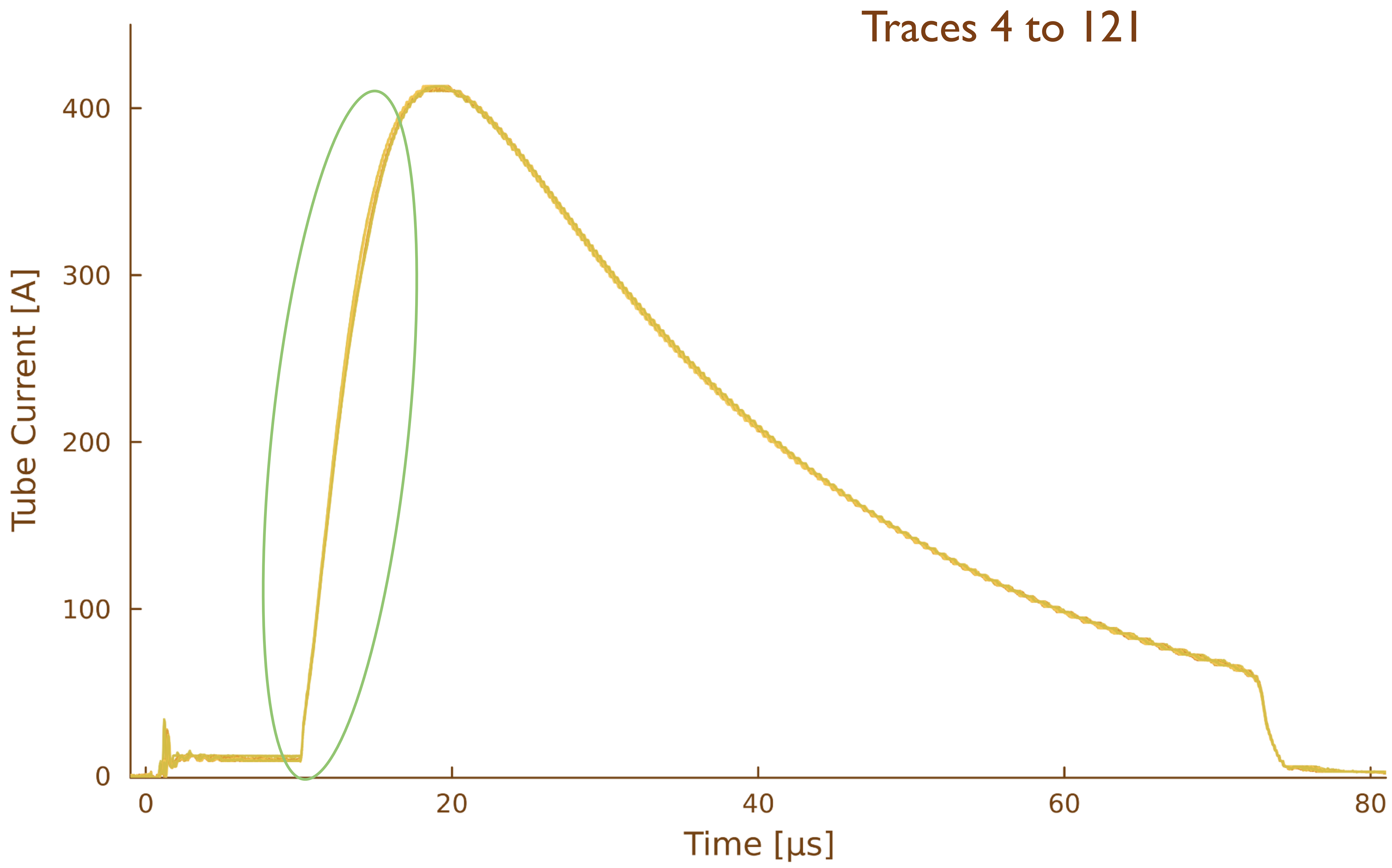

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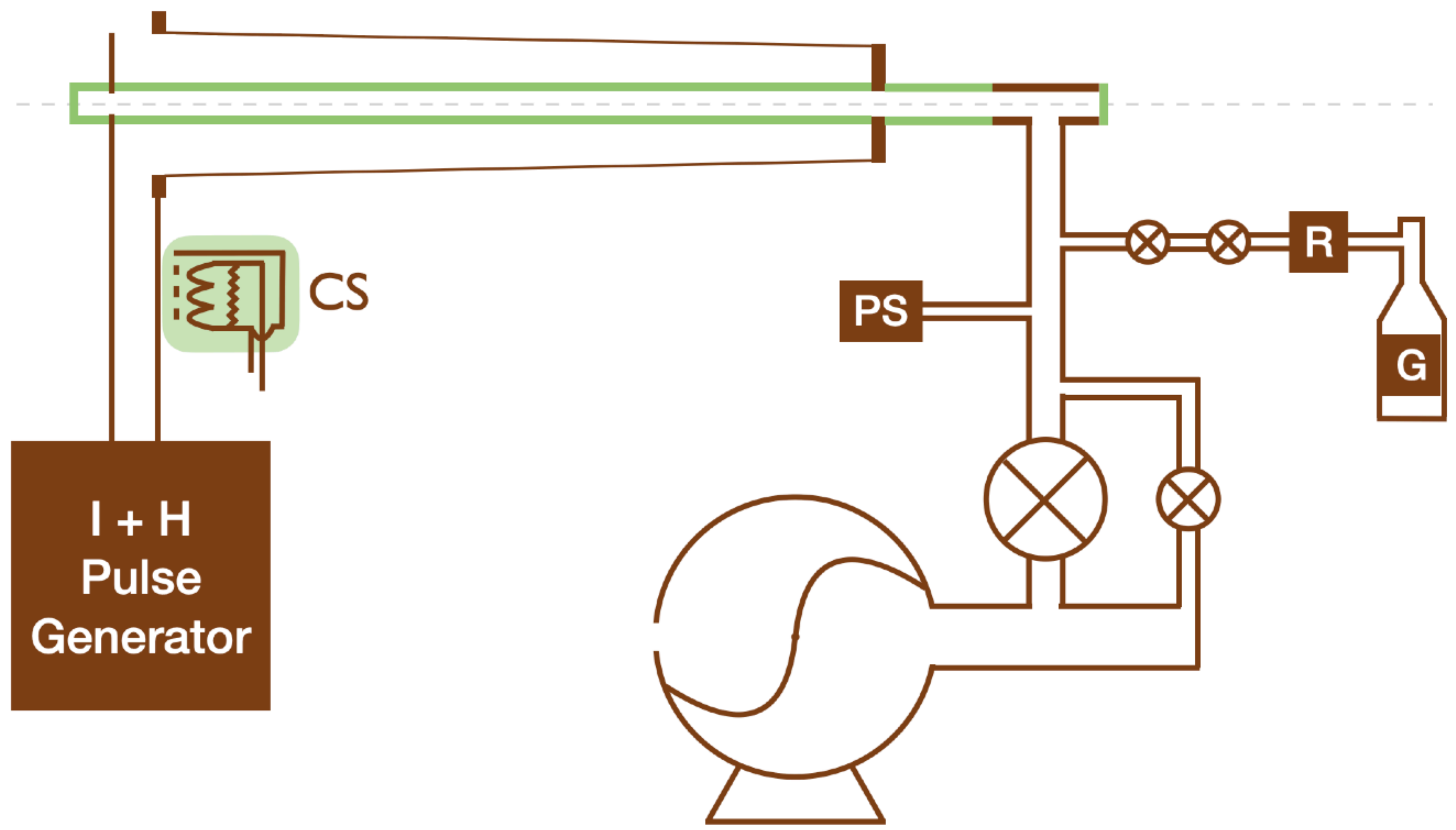

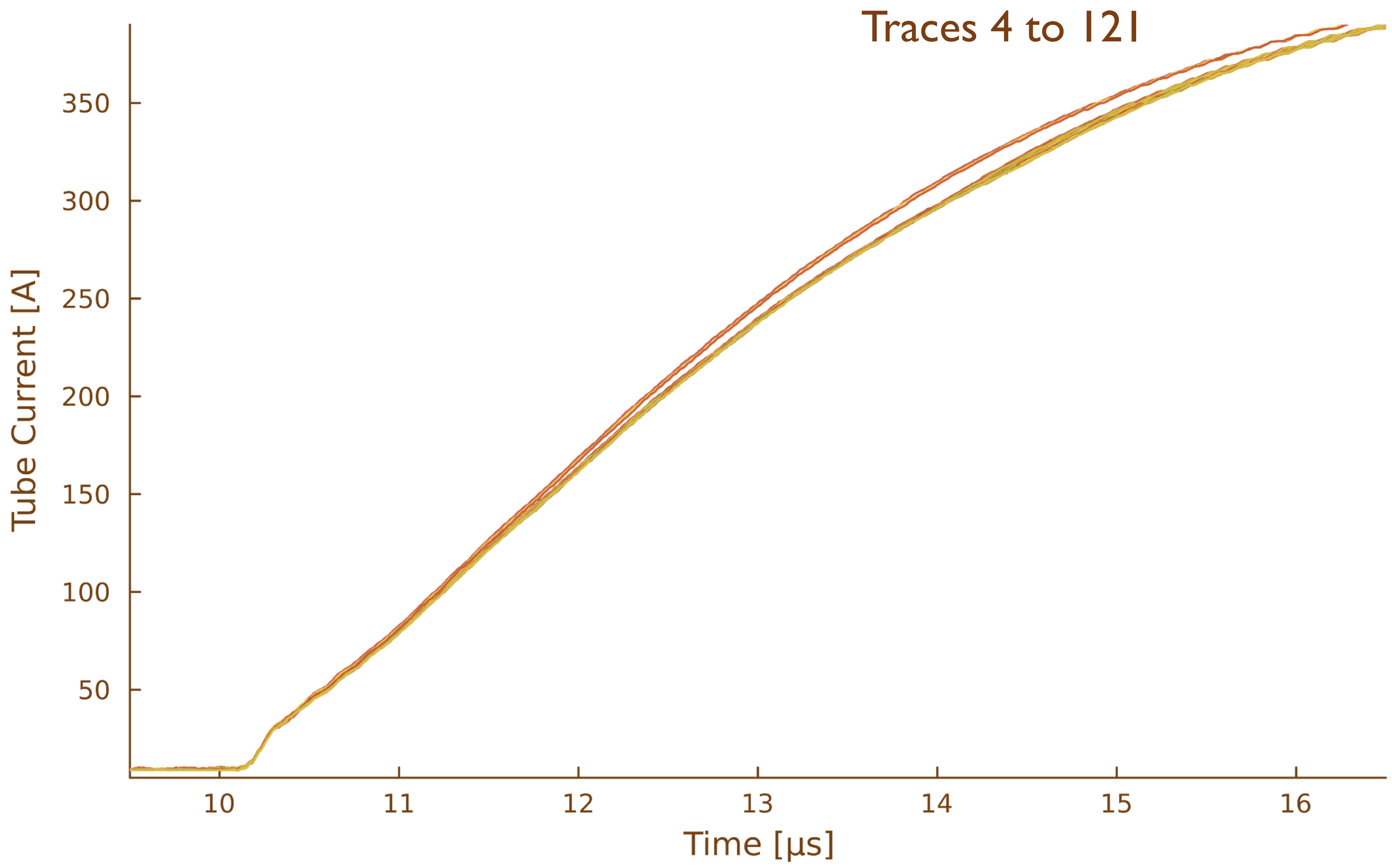

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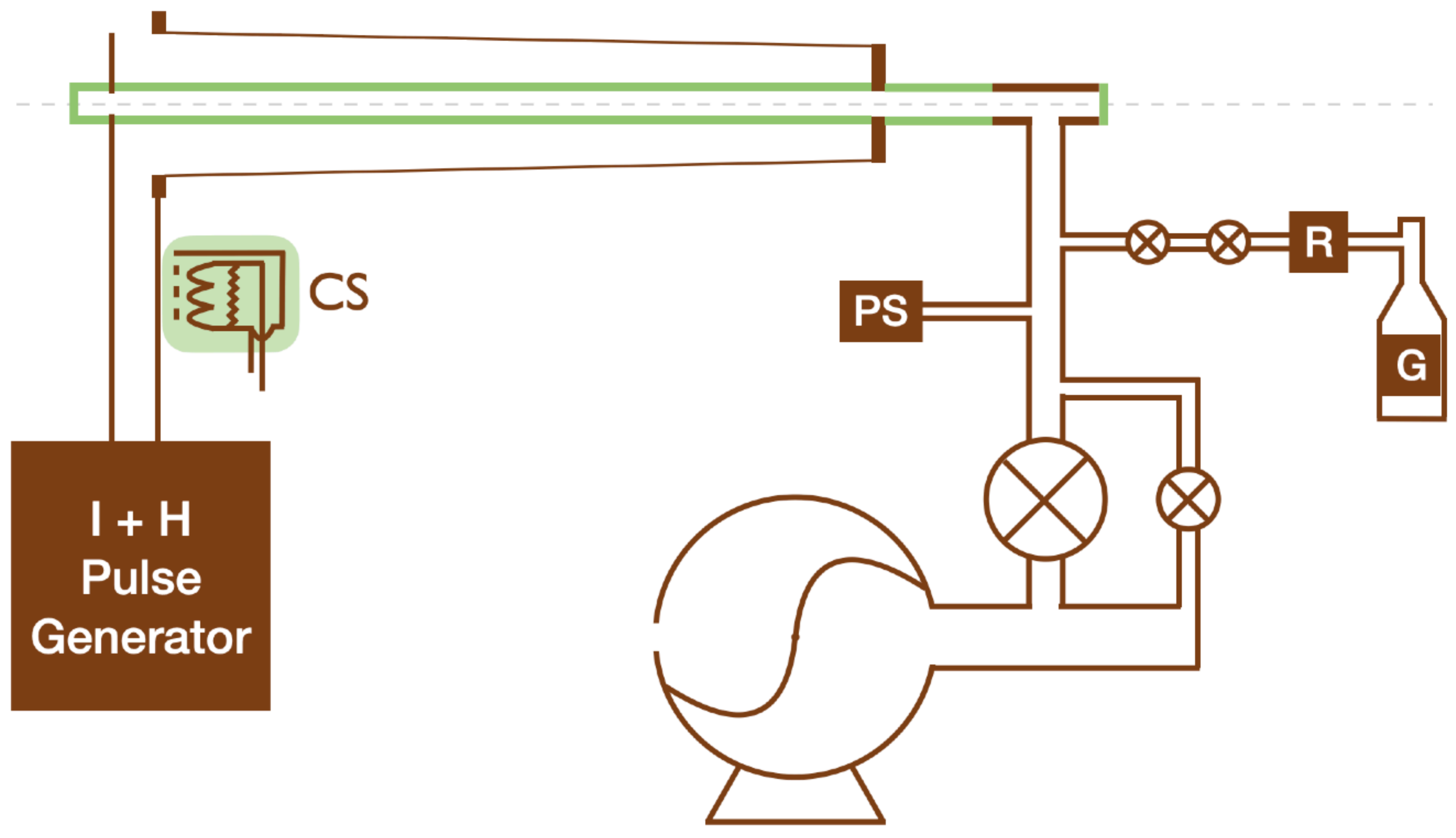

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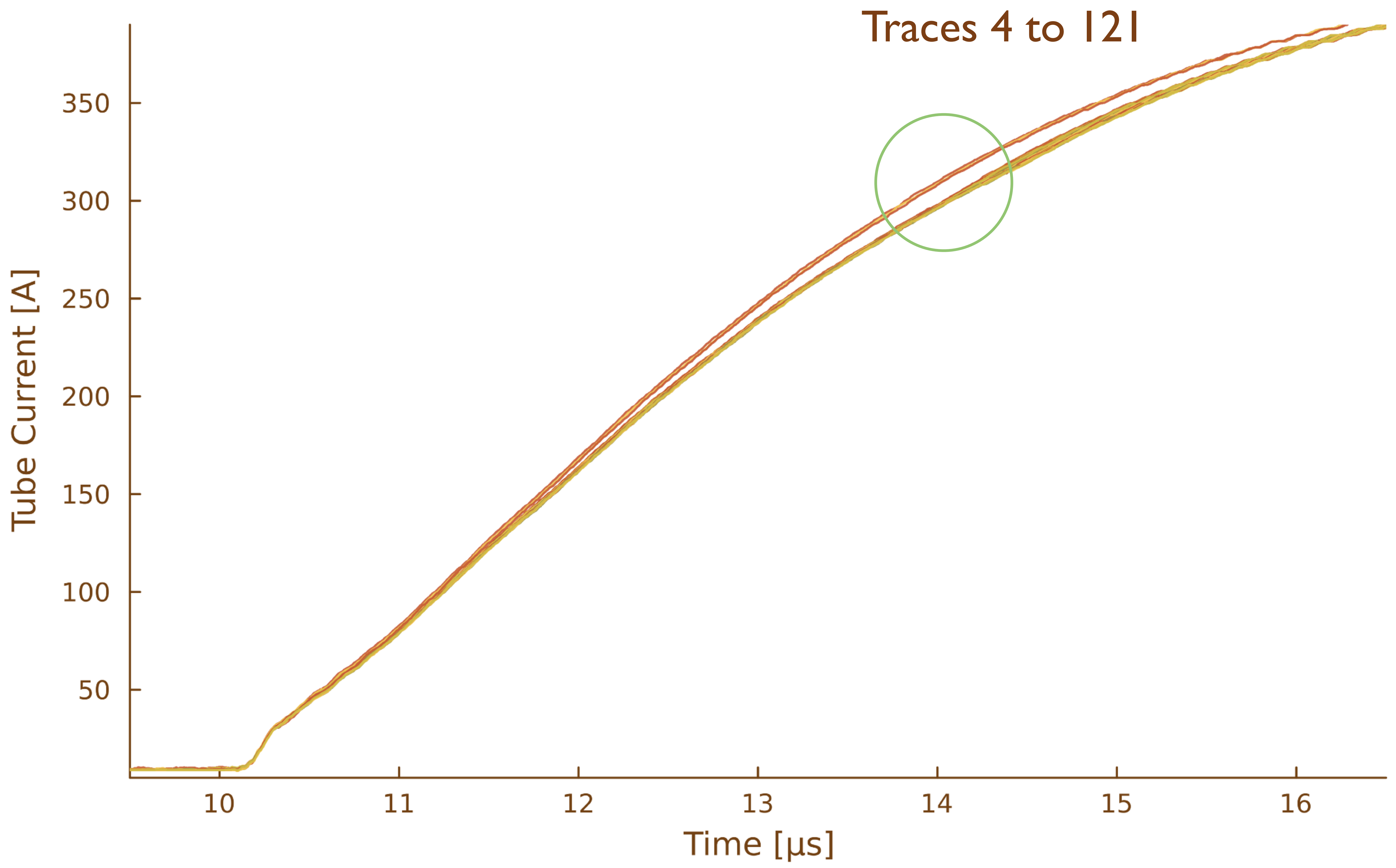

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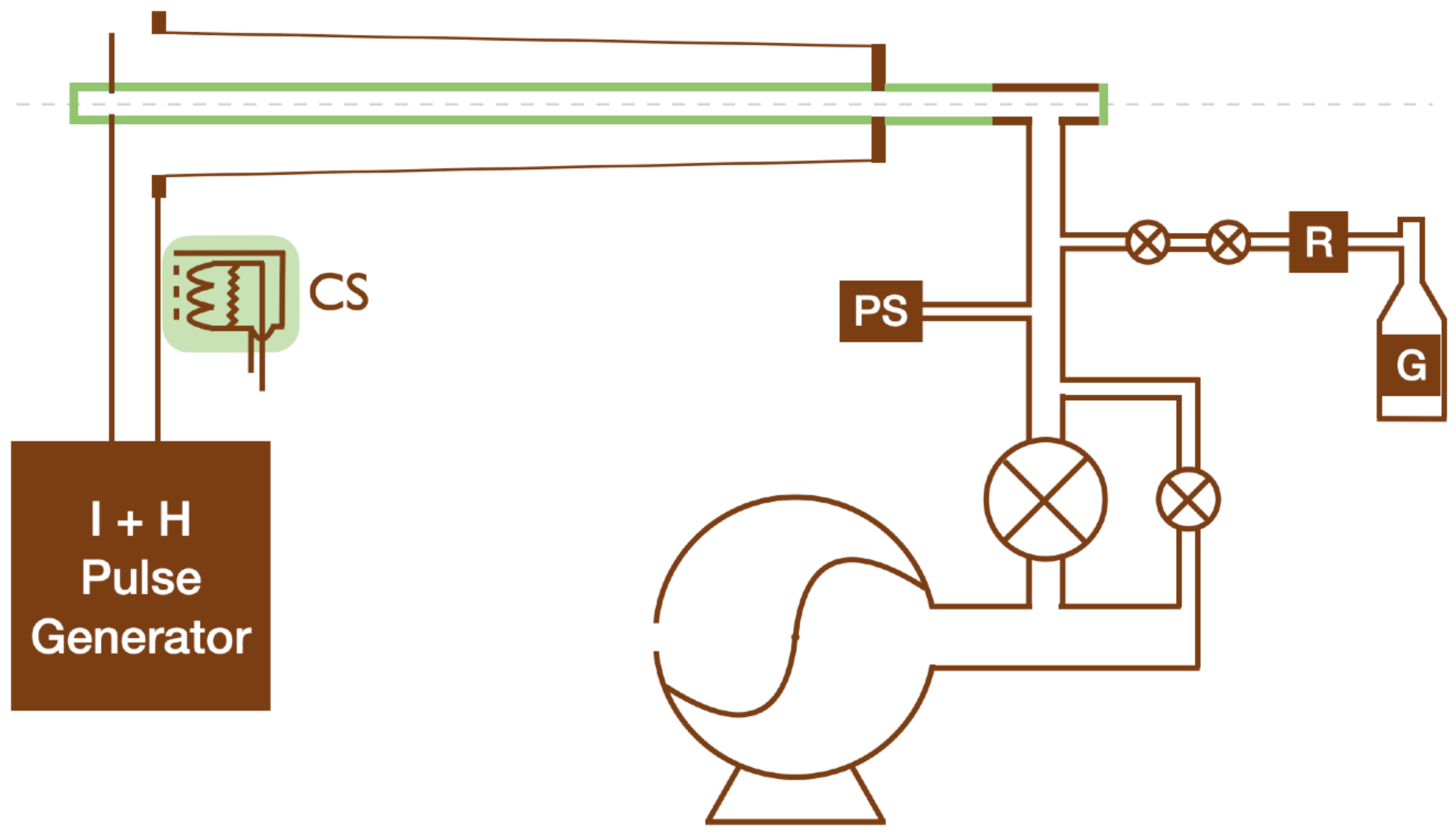

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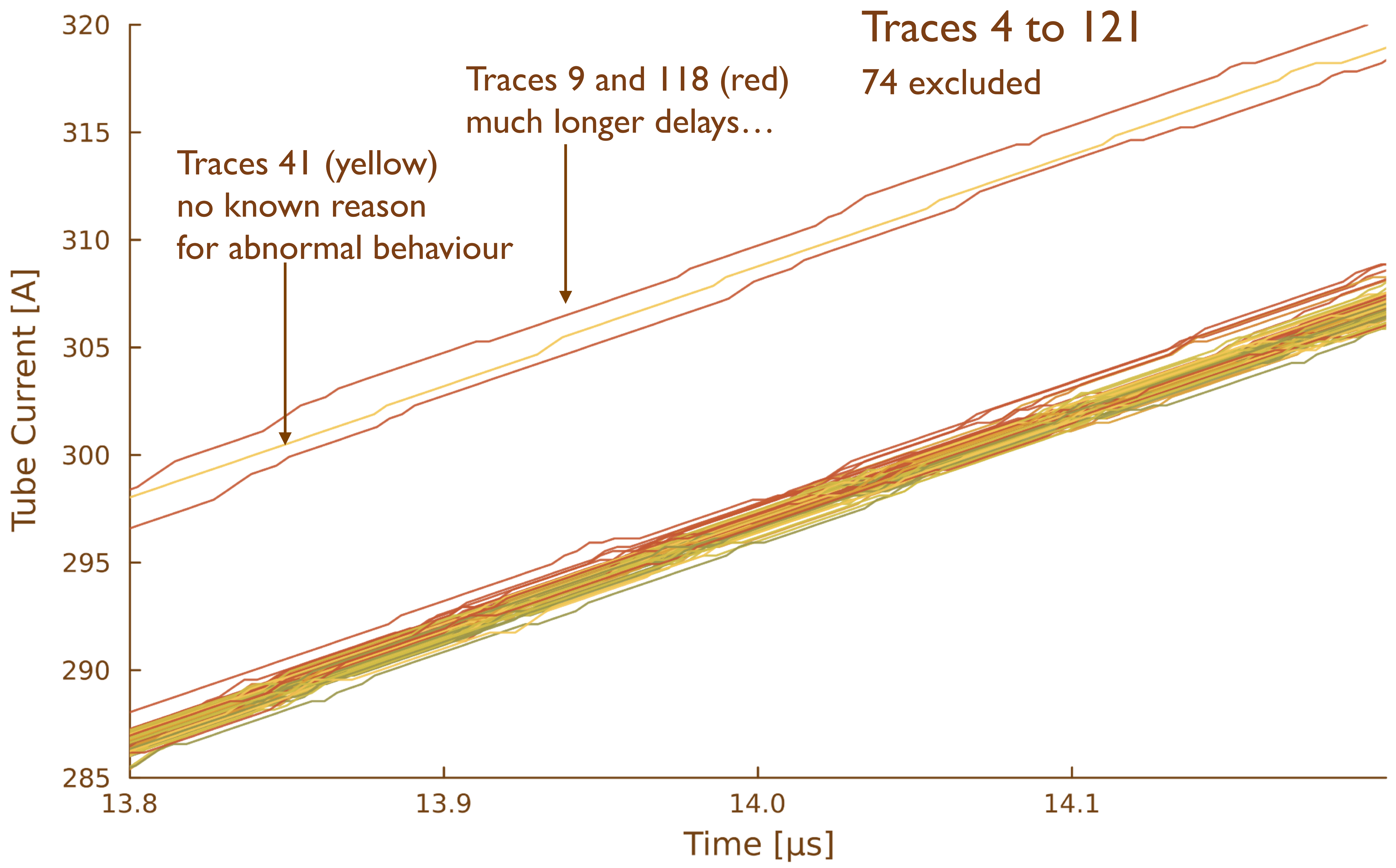

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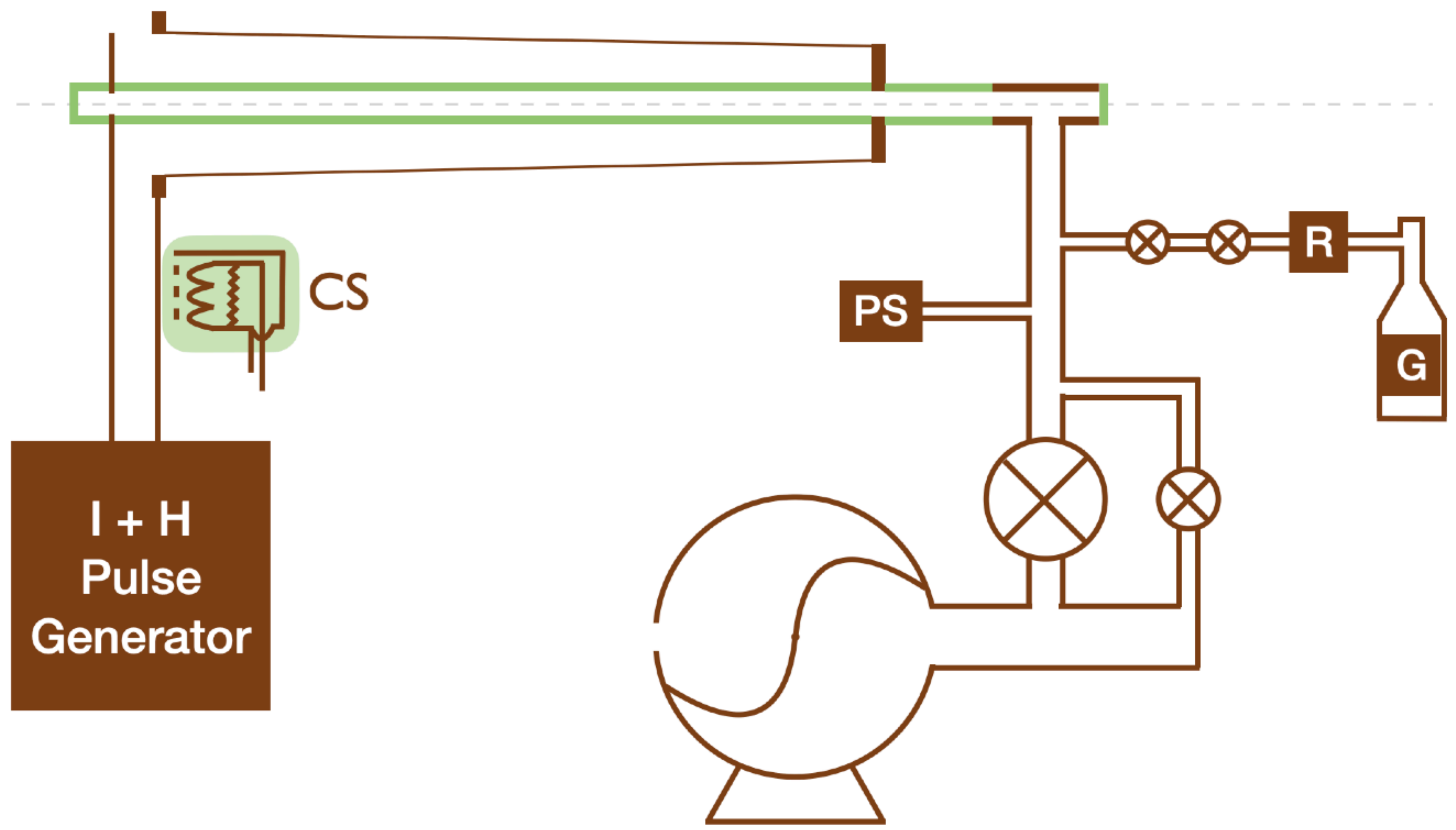

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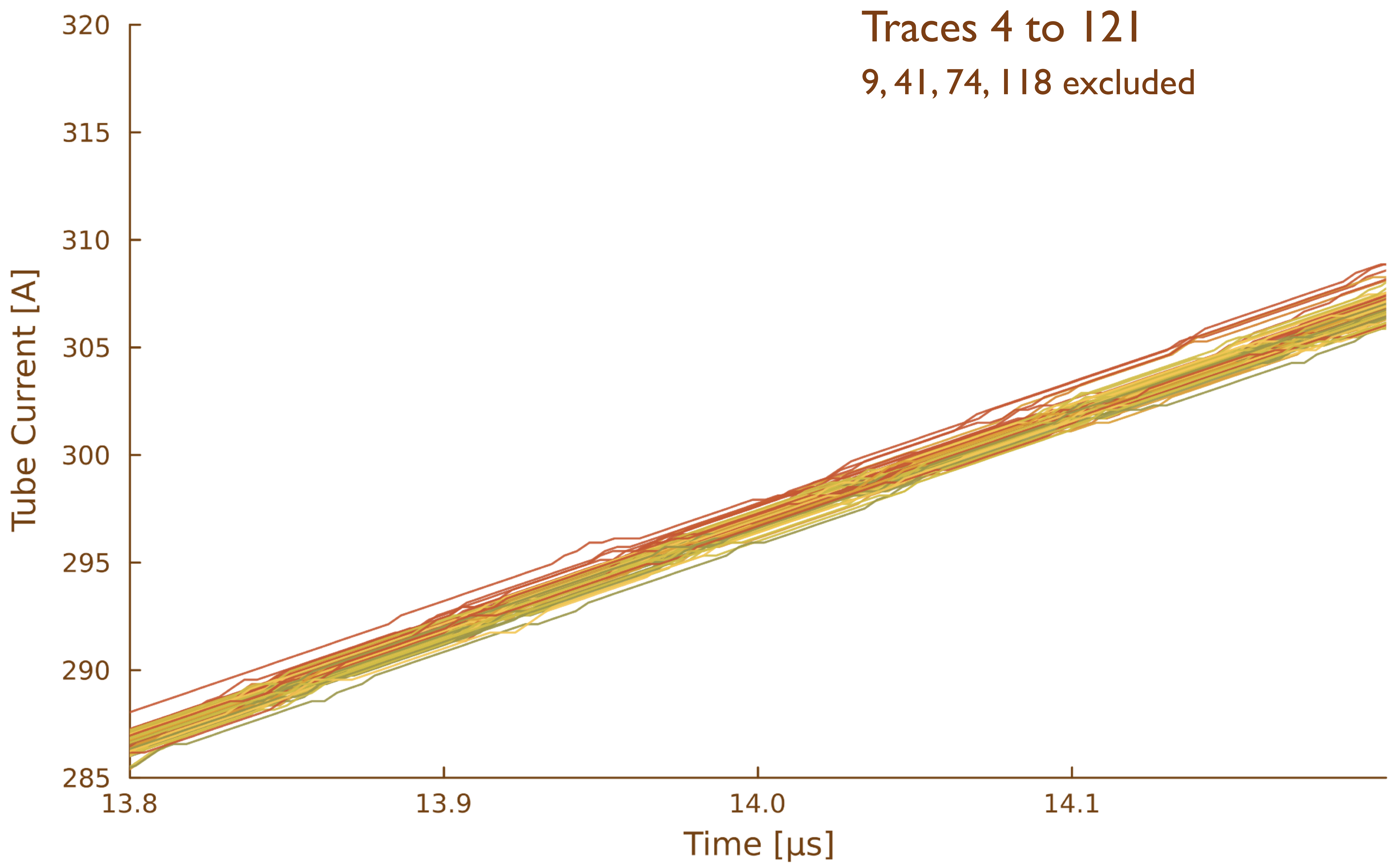

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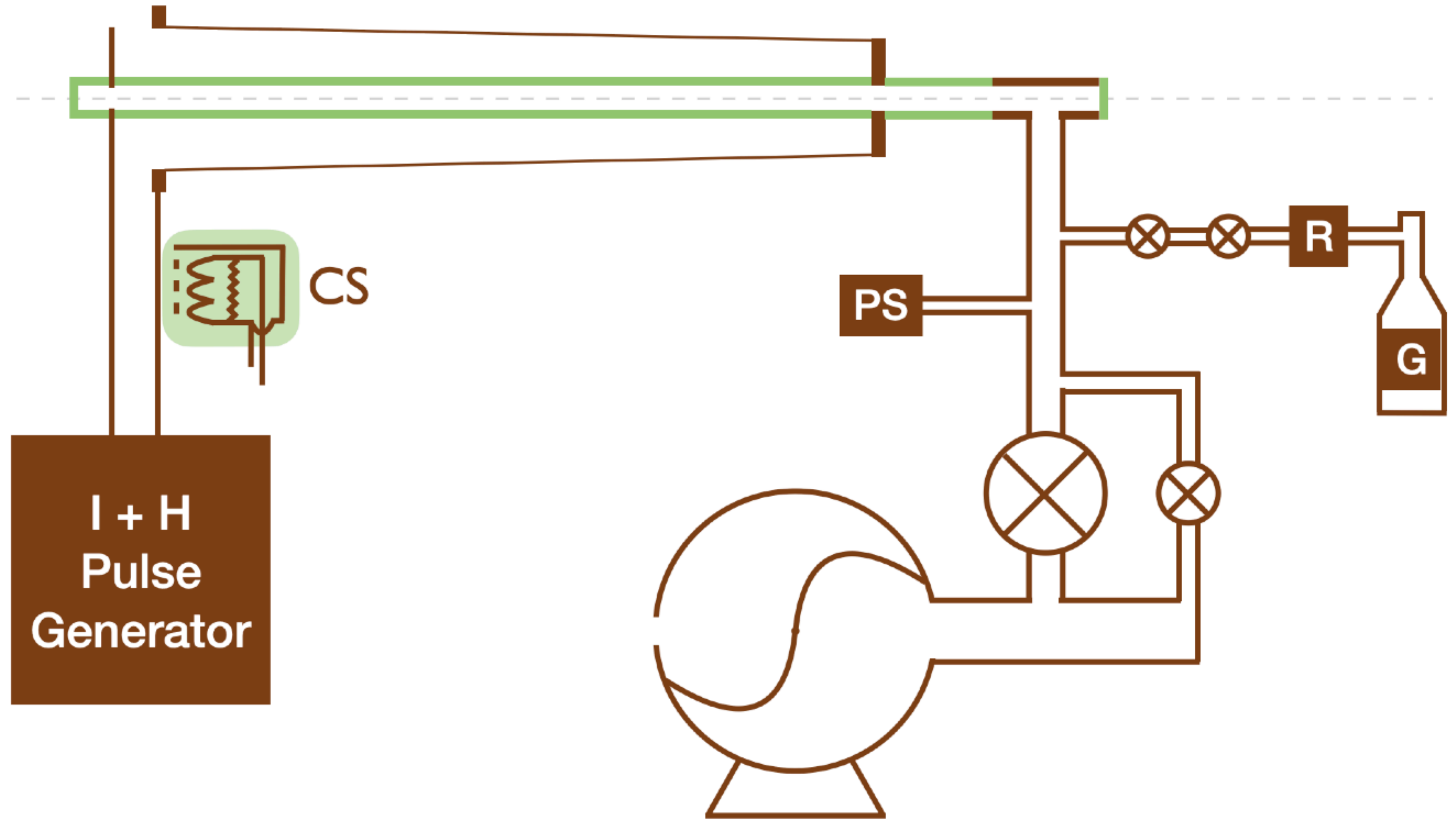

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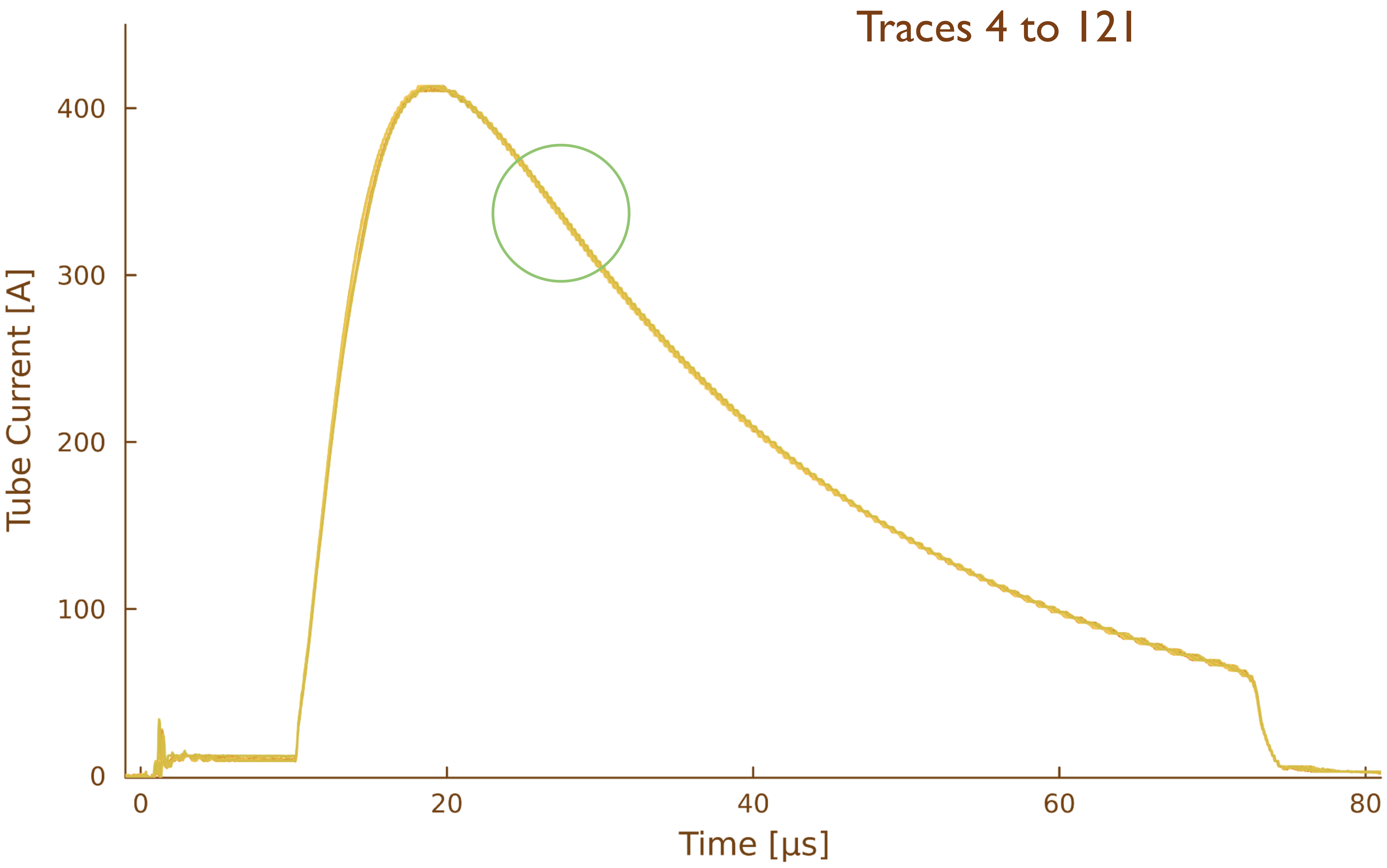

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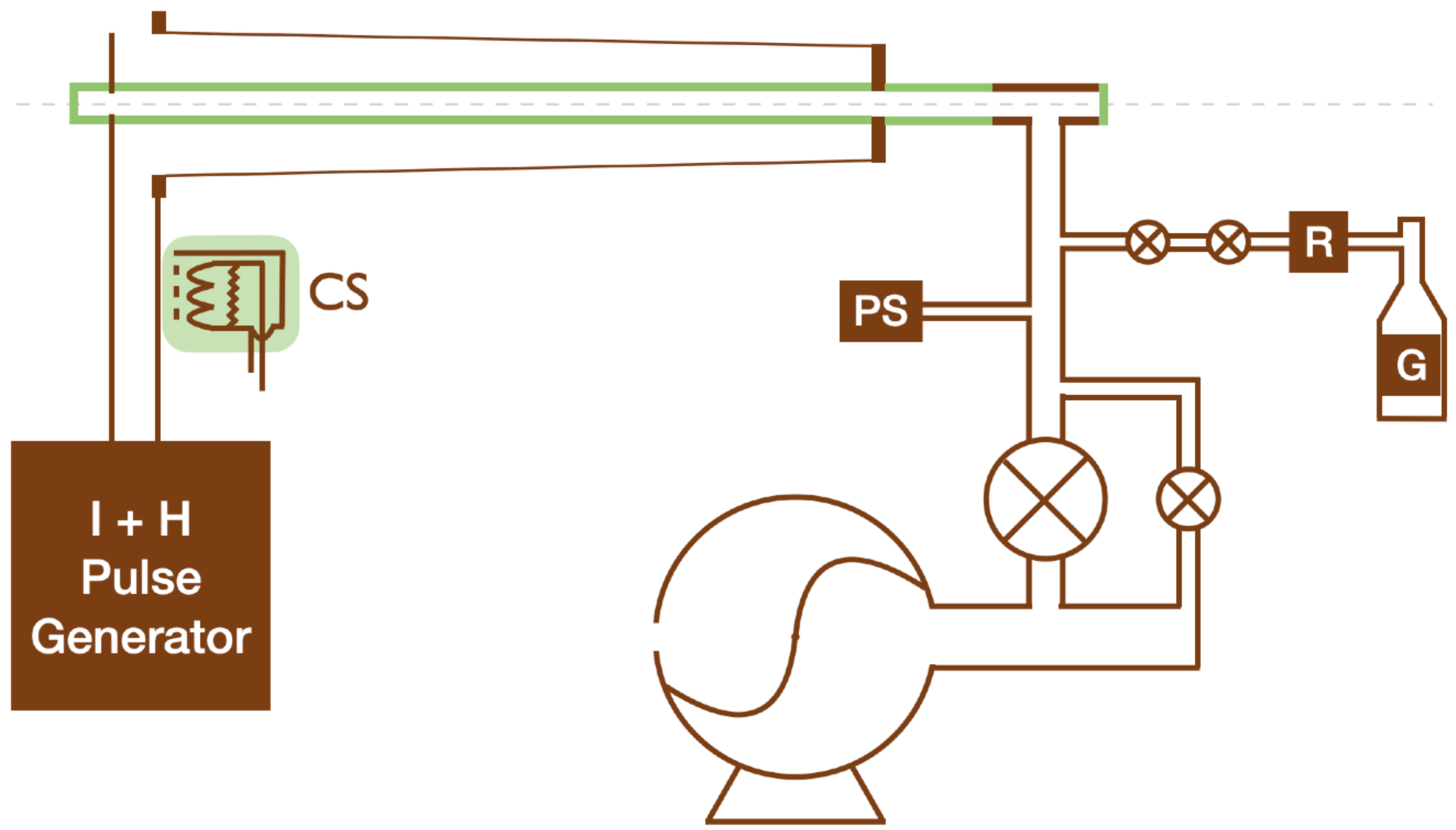

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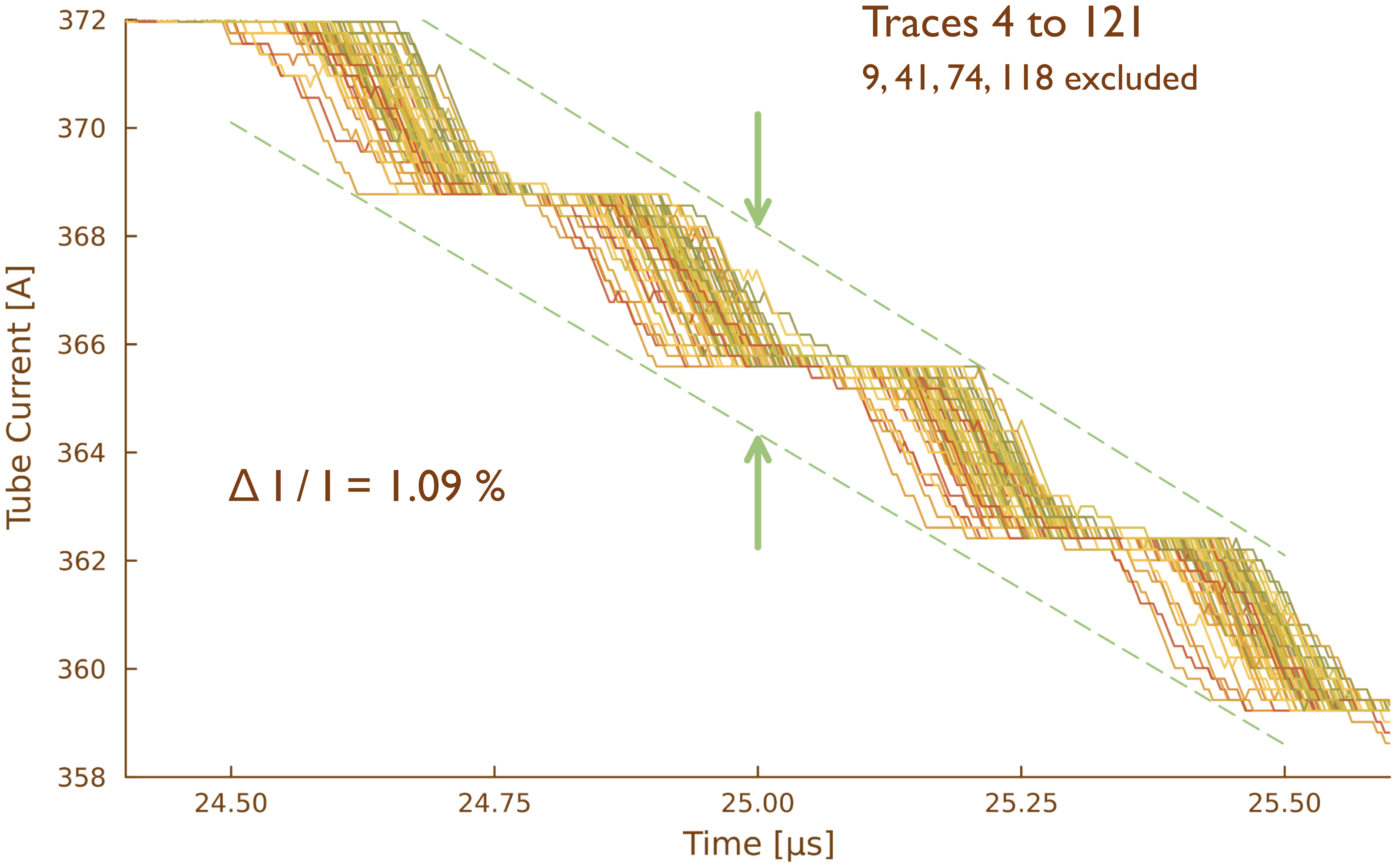

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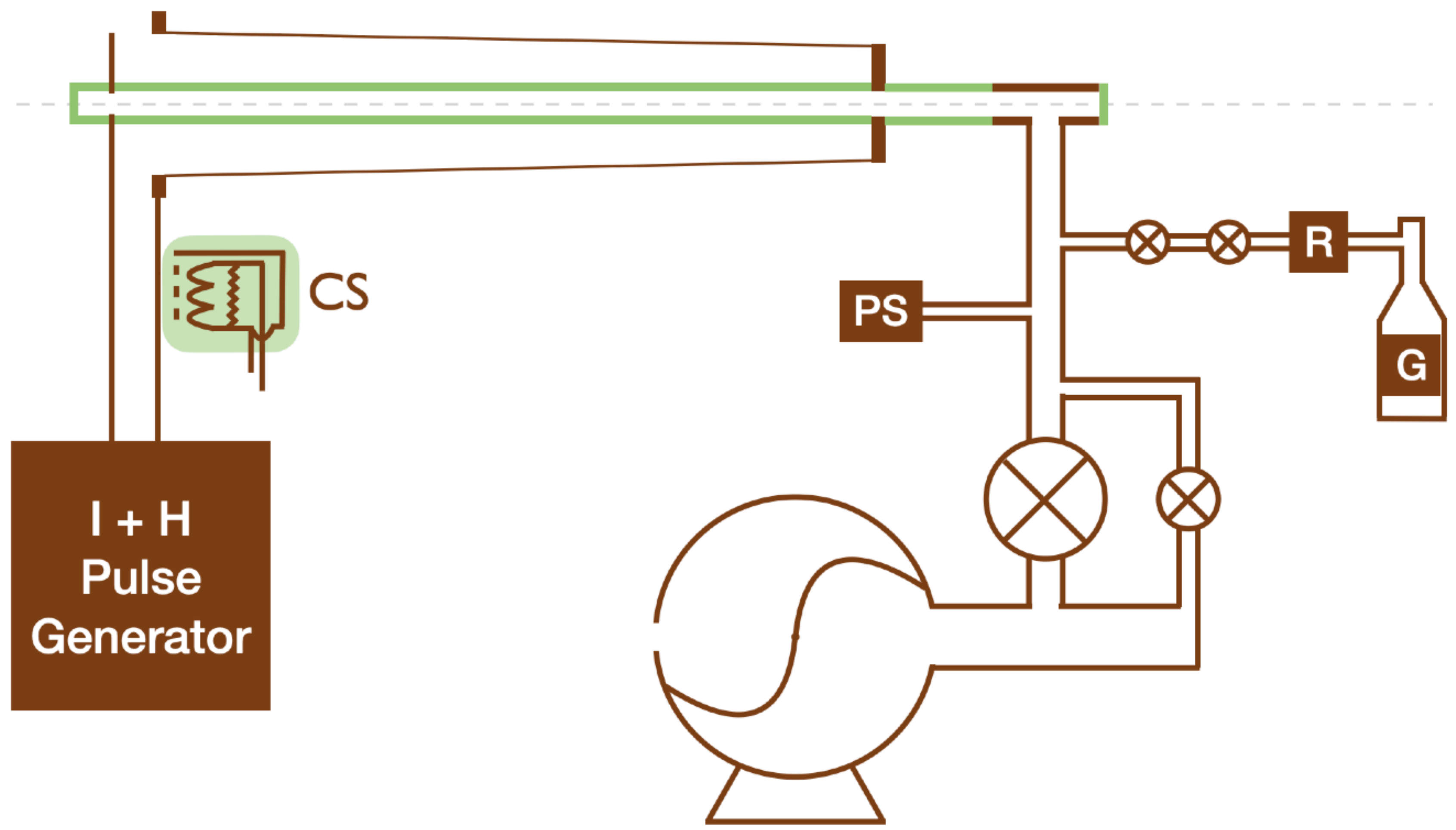

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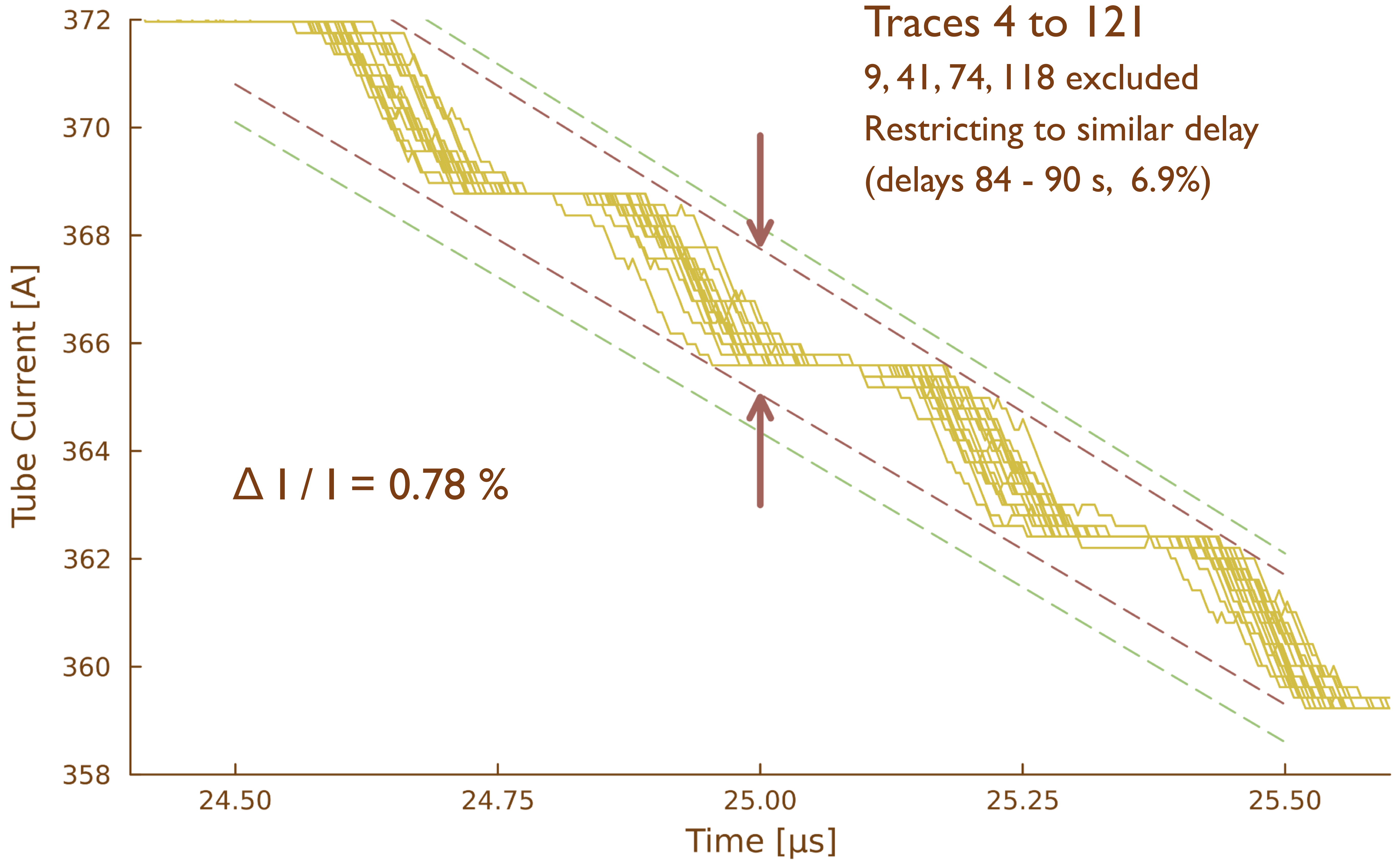

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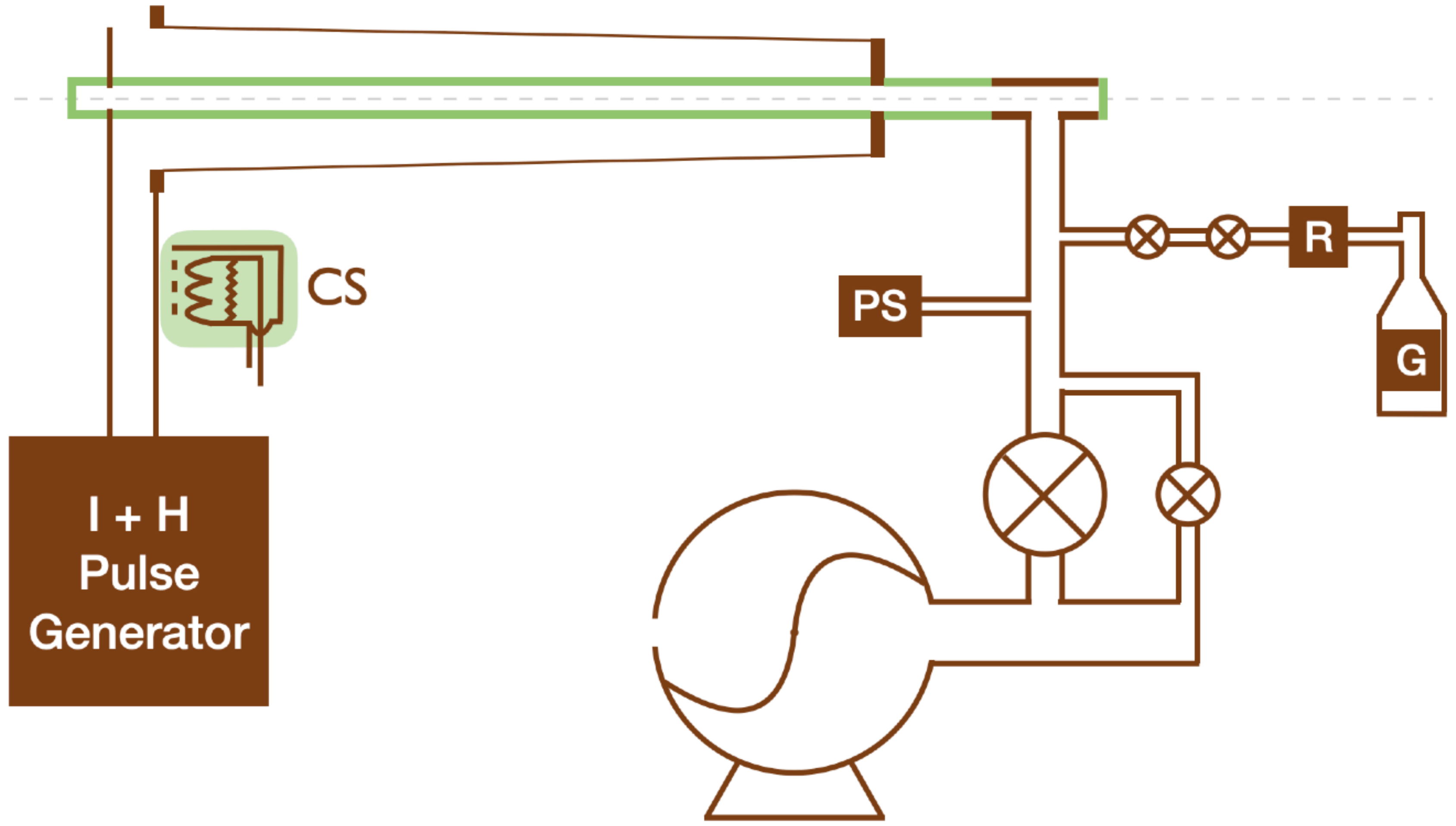

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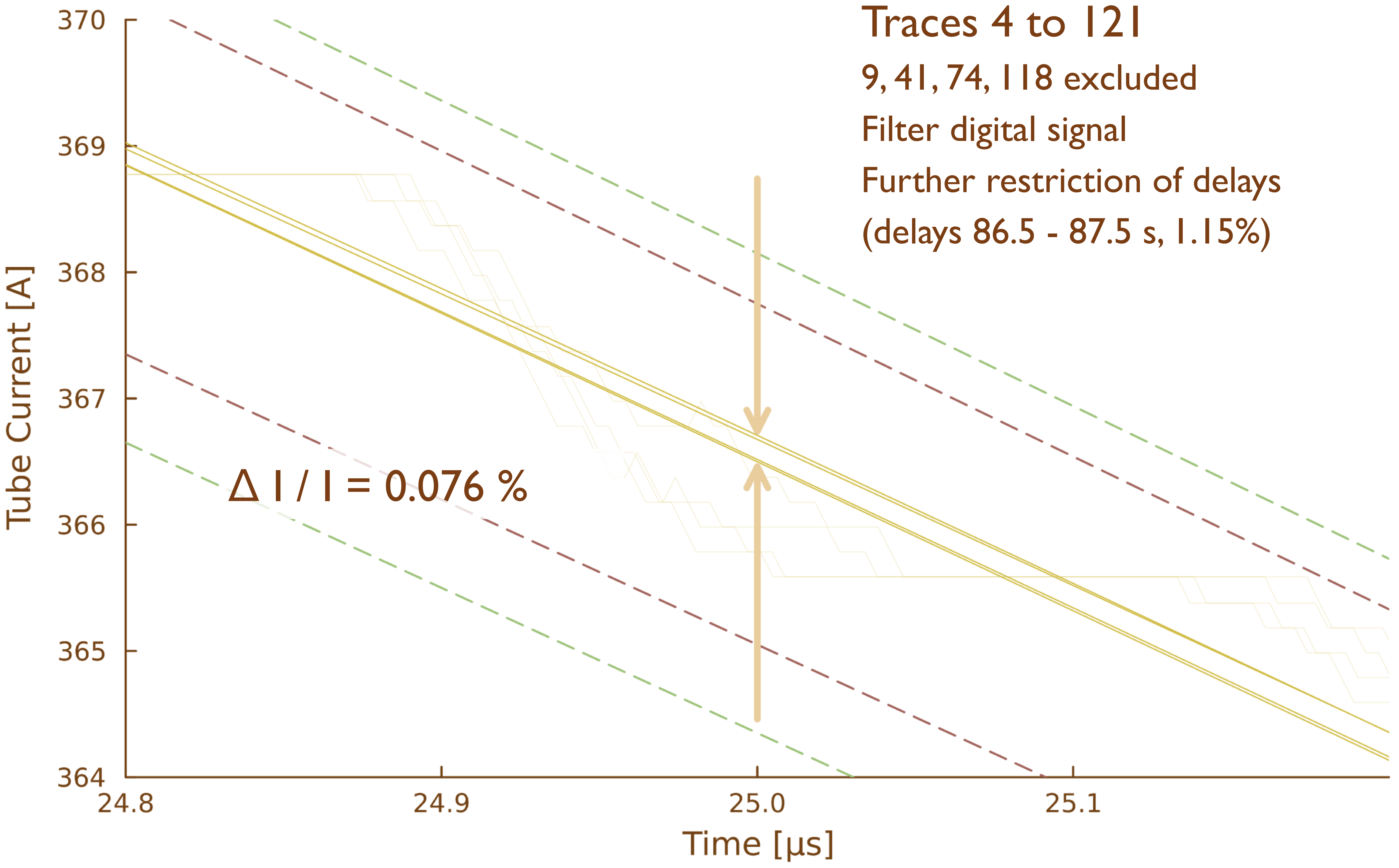

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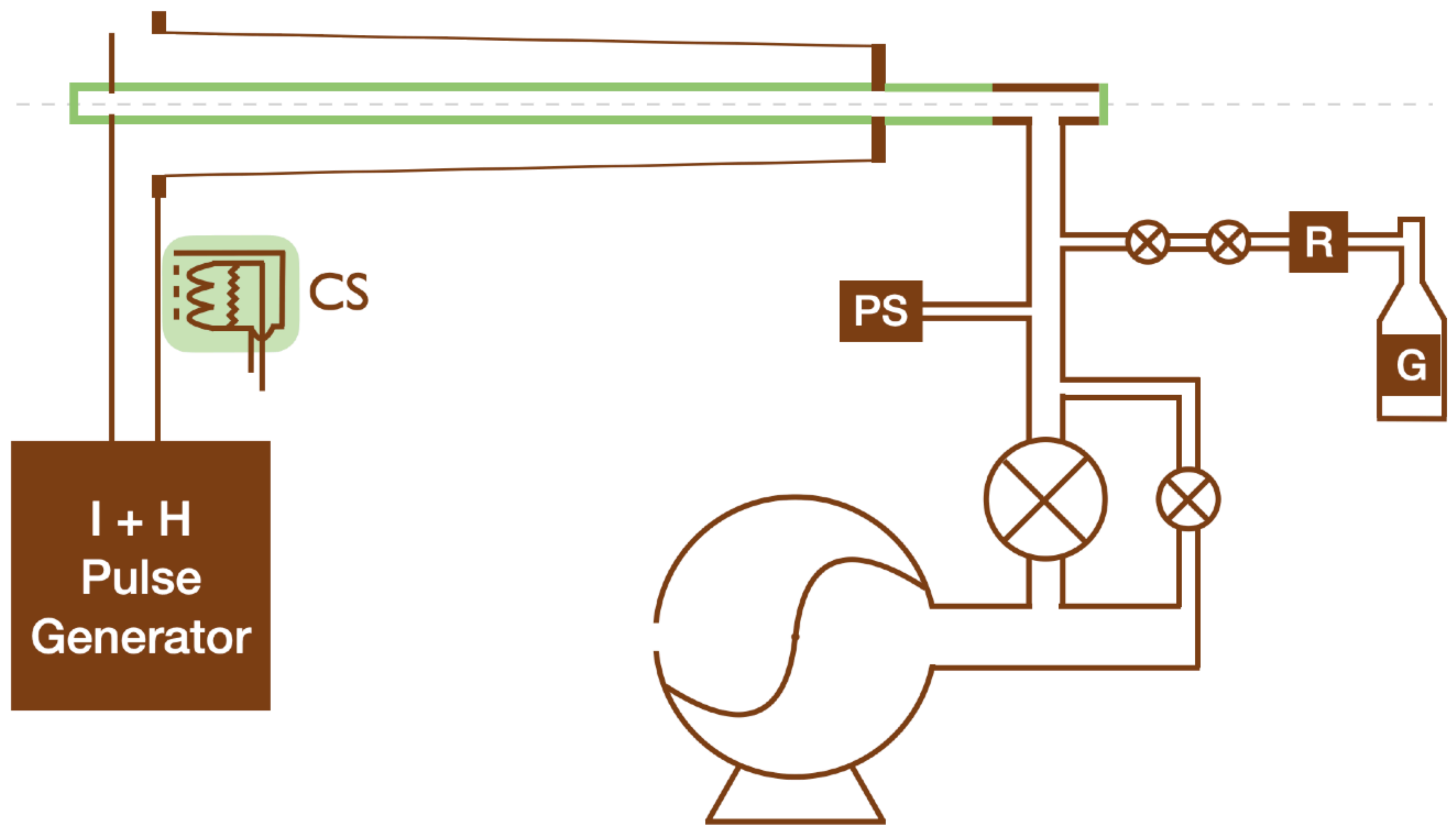

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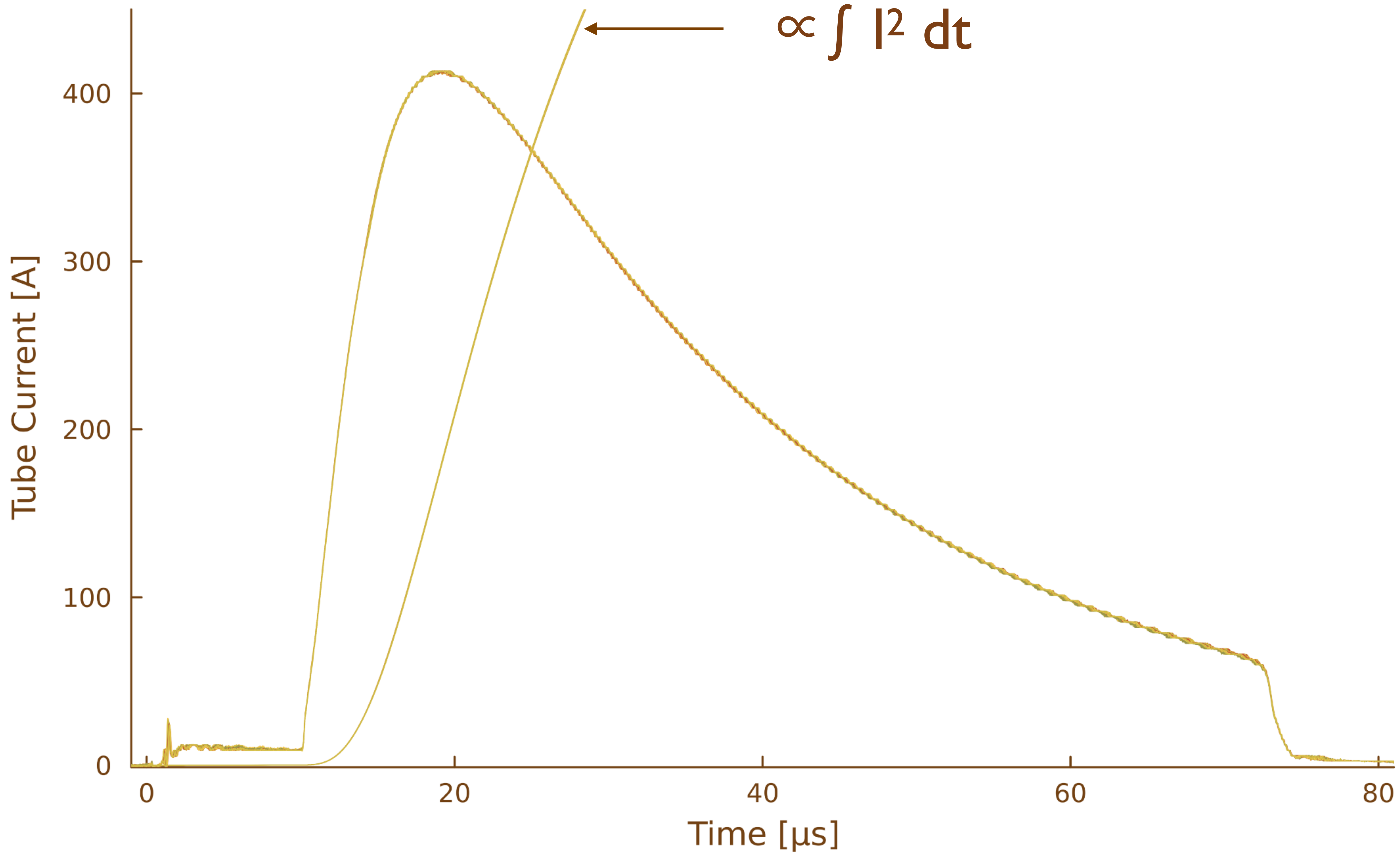
Traces 4 to 121

9, 41, 74, 118 excluded



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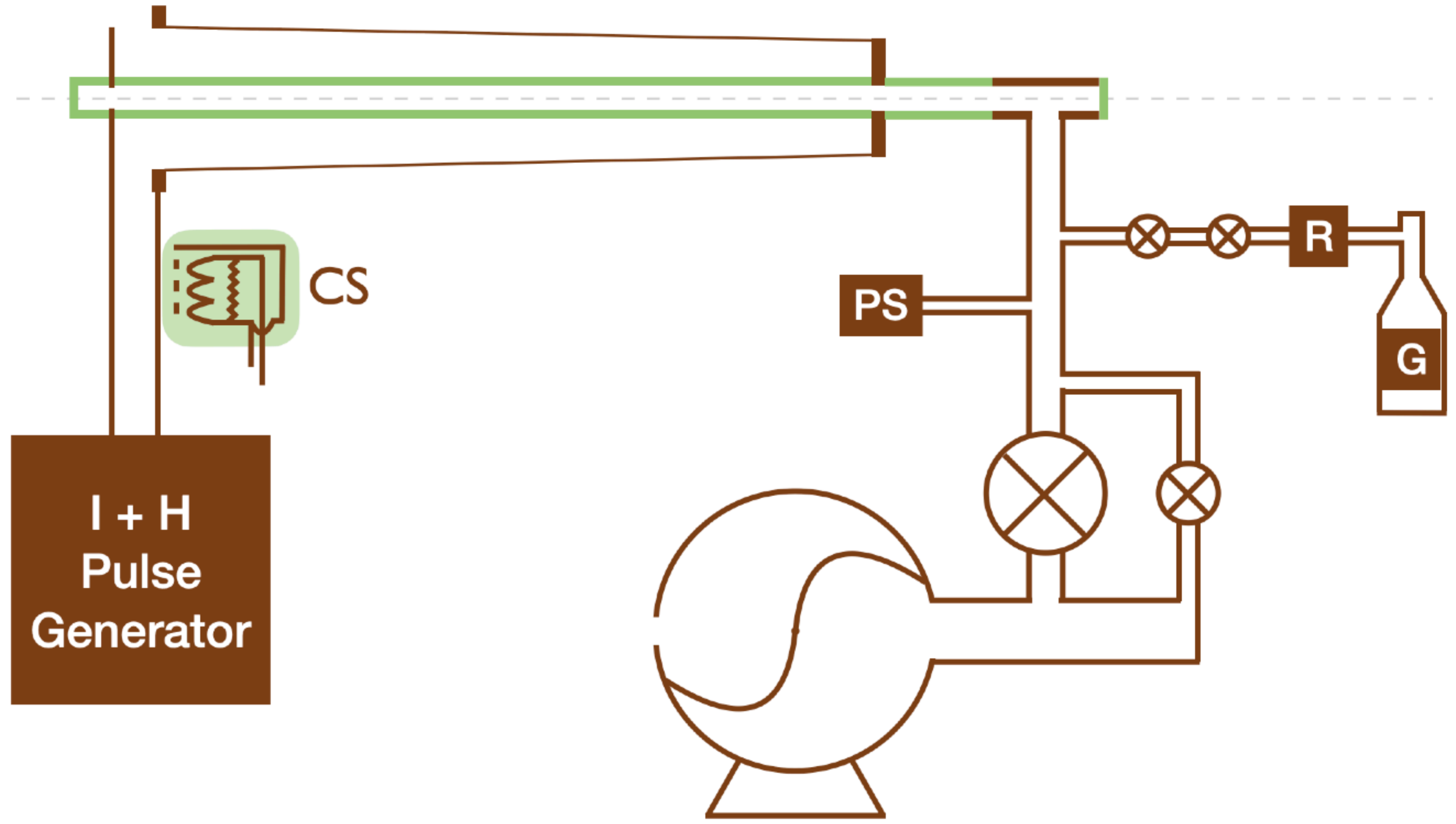

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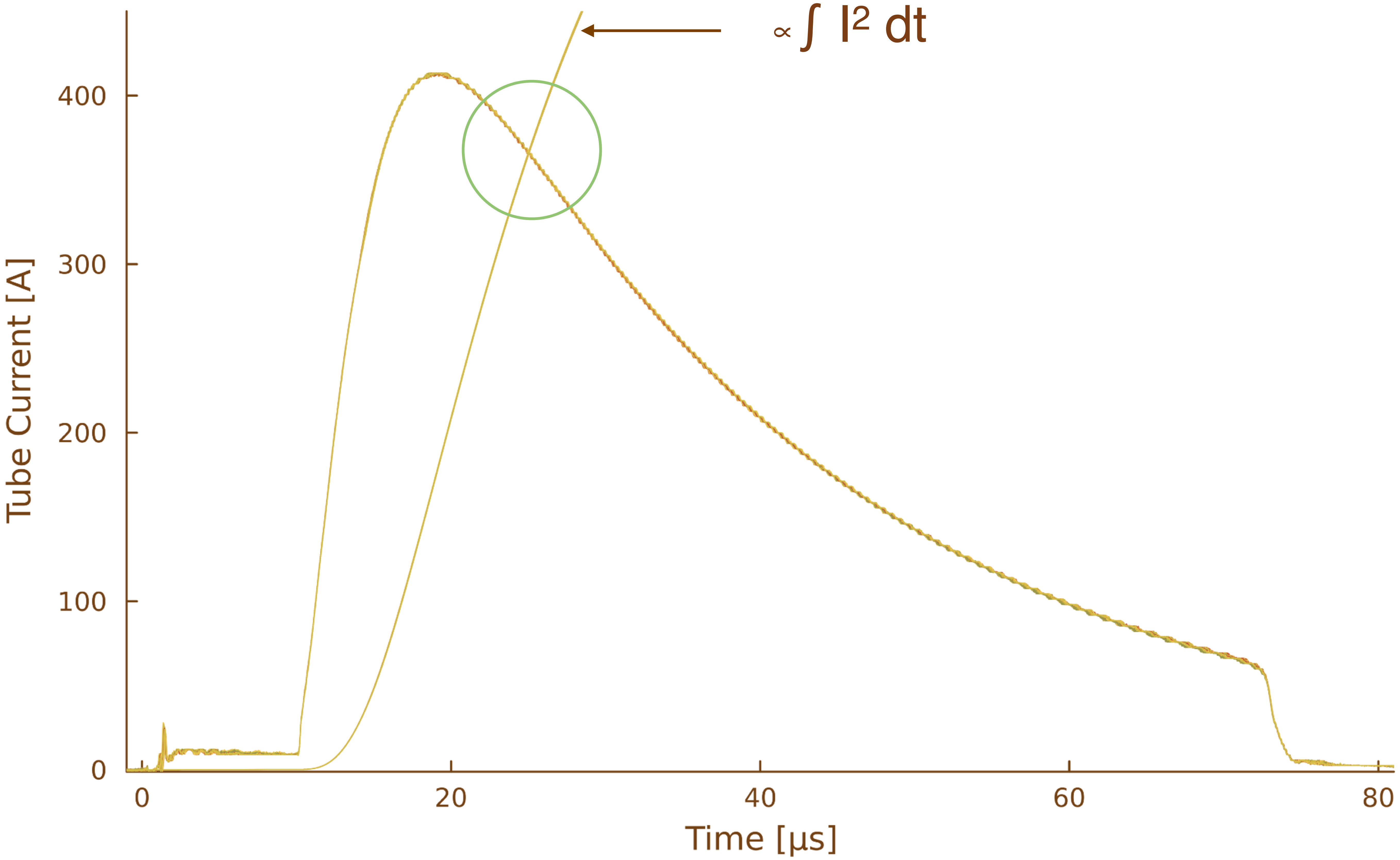

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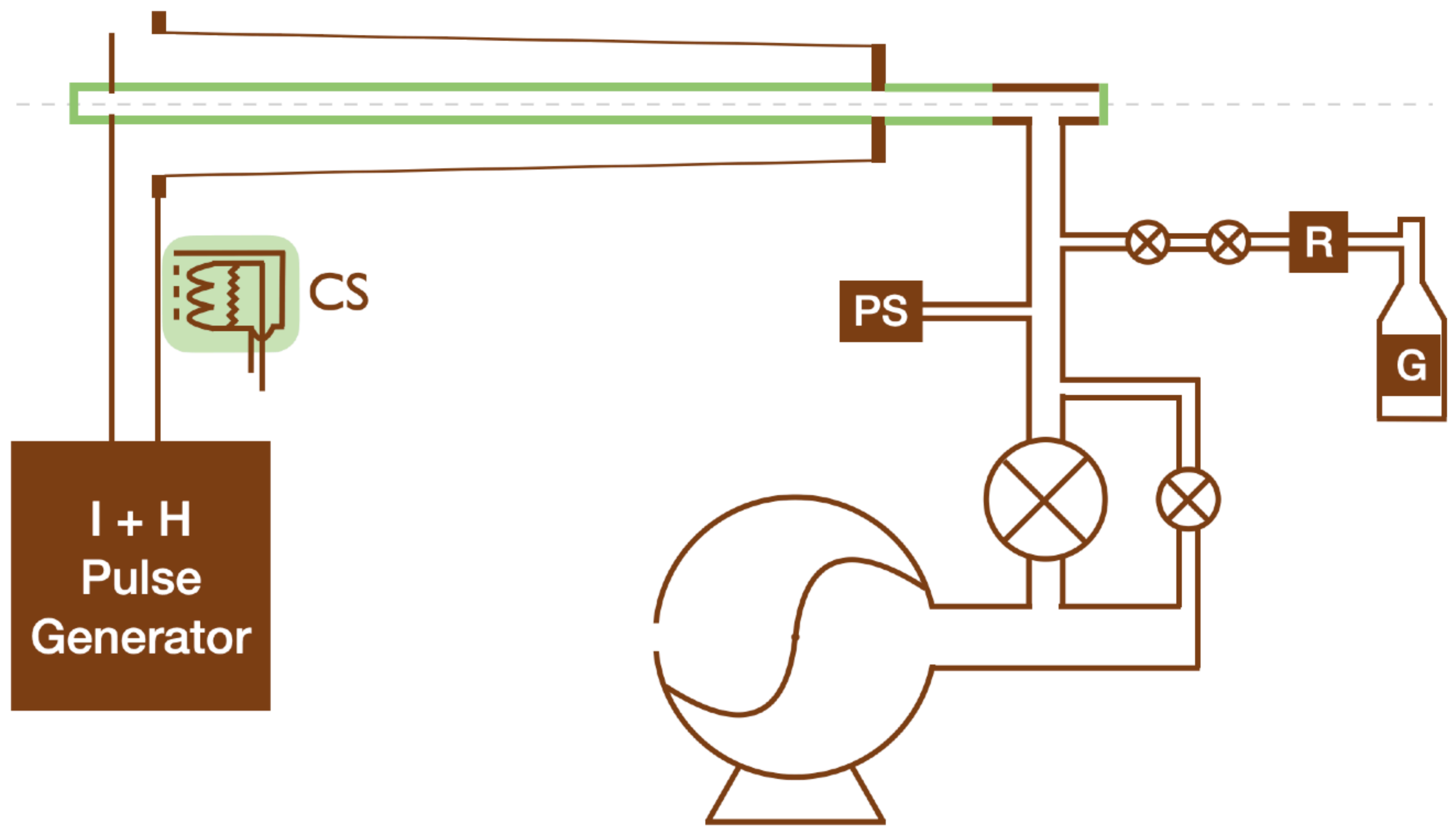

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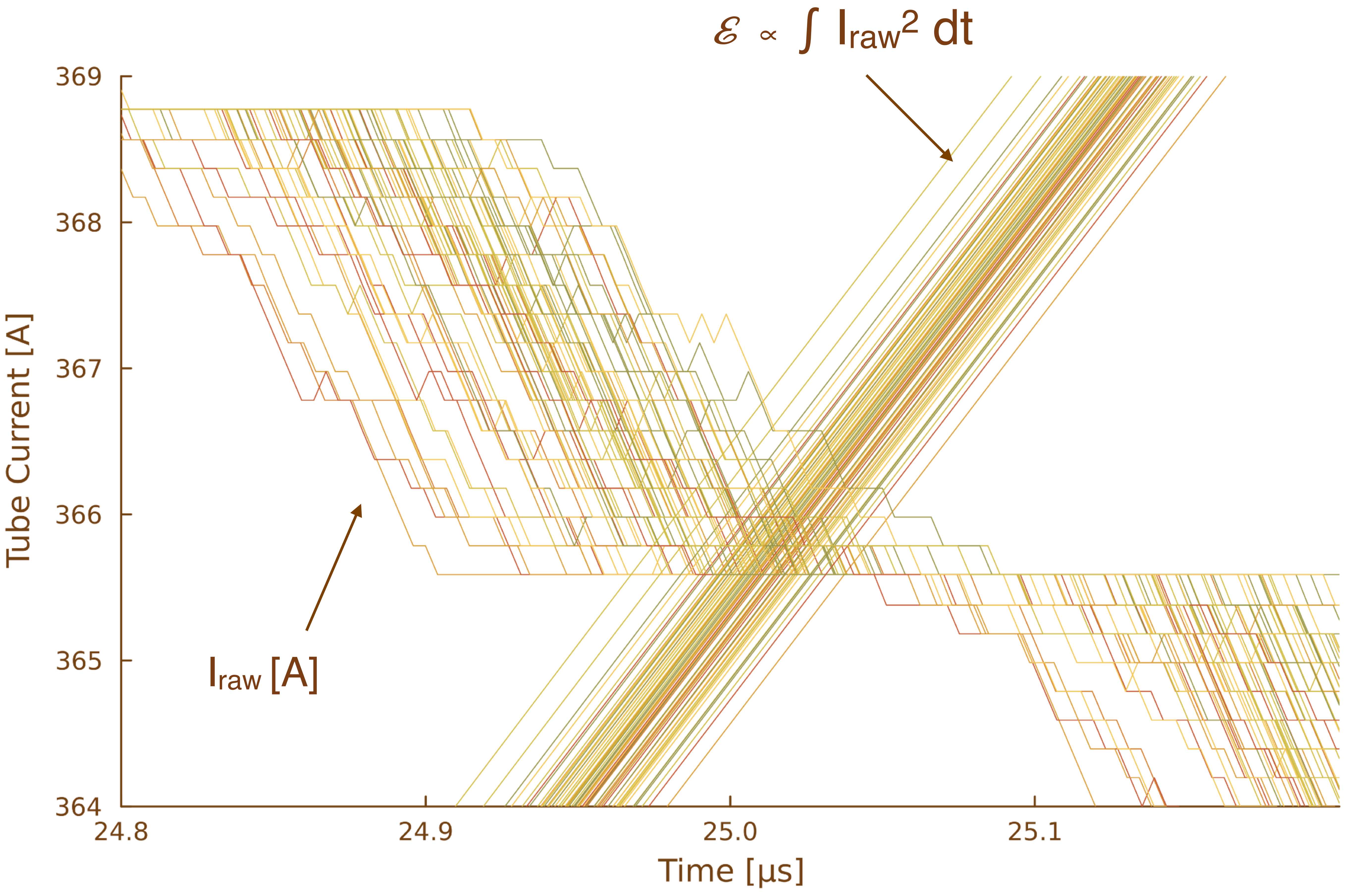

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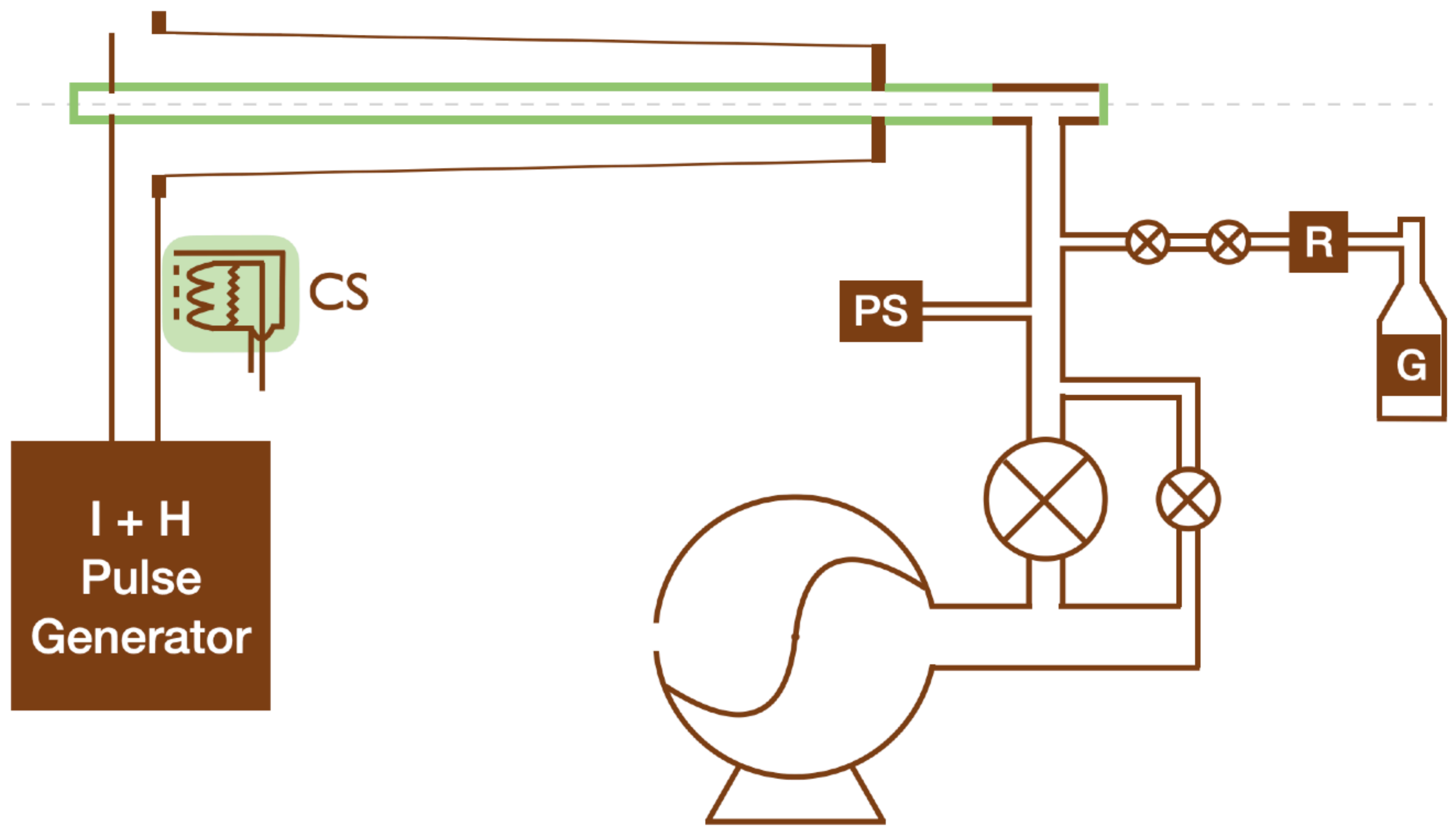

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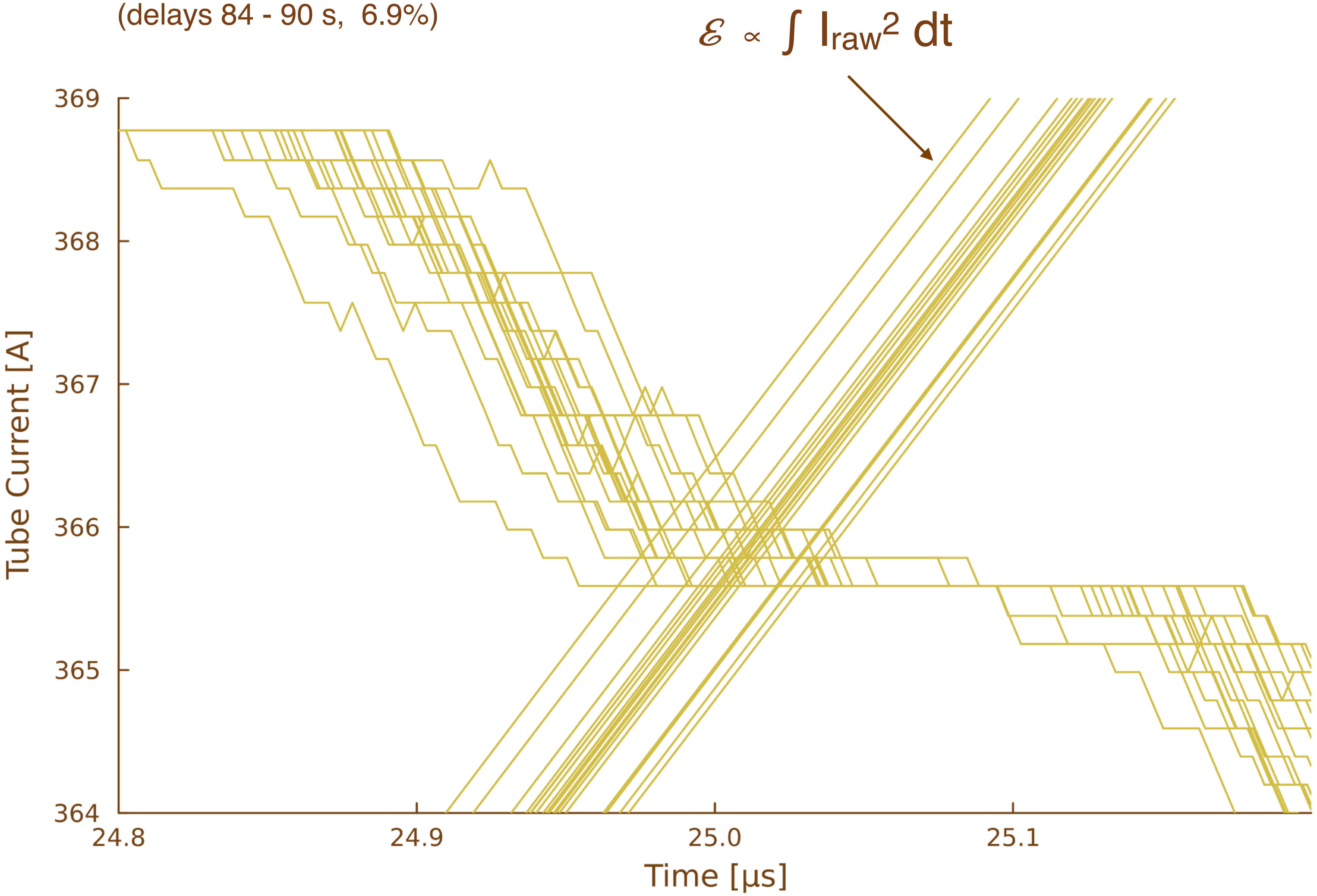
Restricting to similar delay

(delays 84 - 90 s, 6.9%)



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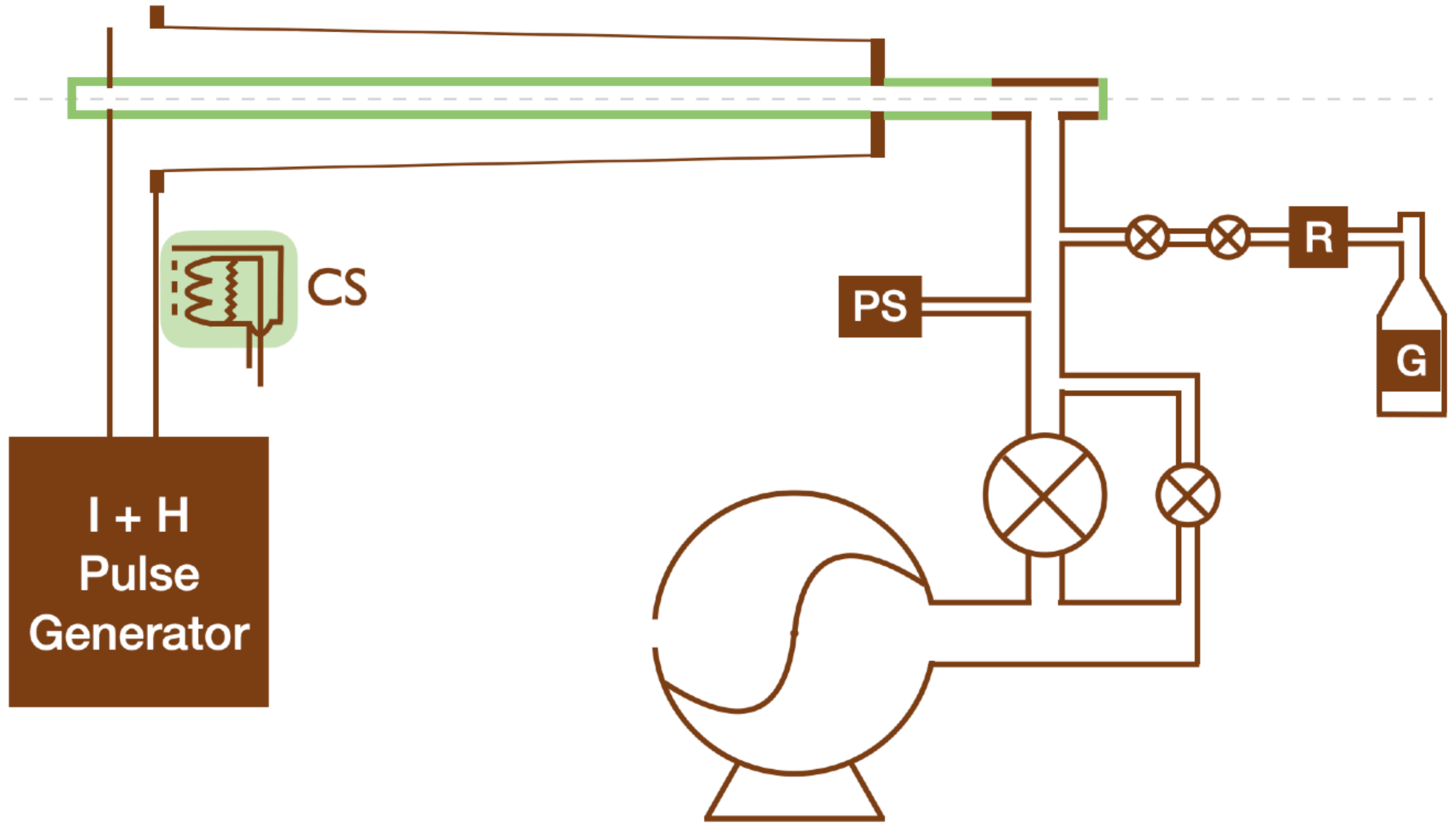

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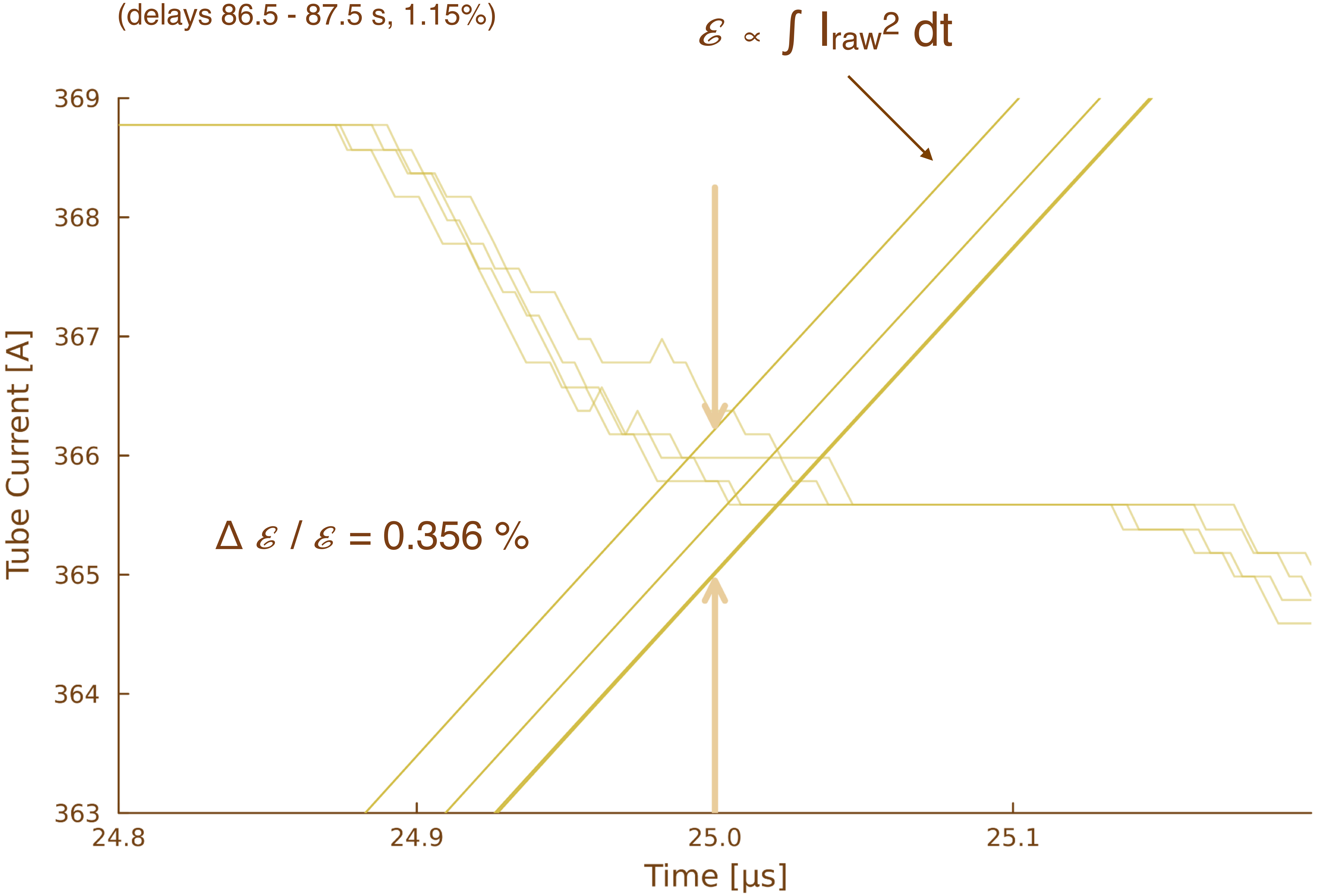
Further restriction of delays

(delays 86.5 - 87.5 s, 1.15%)



Current reproducibility

These measurements suggest…

→ current reproducibilities < 0.5% are currently achievable

→ variation of current correlates with delay between discharges

→ further reduction require…

… strict temperature control of all relevant tube sections

… higher precision pressure sensors and current signal digitiser

Further work

→ new control system with fixed rep. rate measurements (not planned)

→ force tube temperature with external flow of hot water (planned 2024)

Interferometry for … time resolved axial integrated density

Time resolved axial integrated density

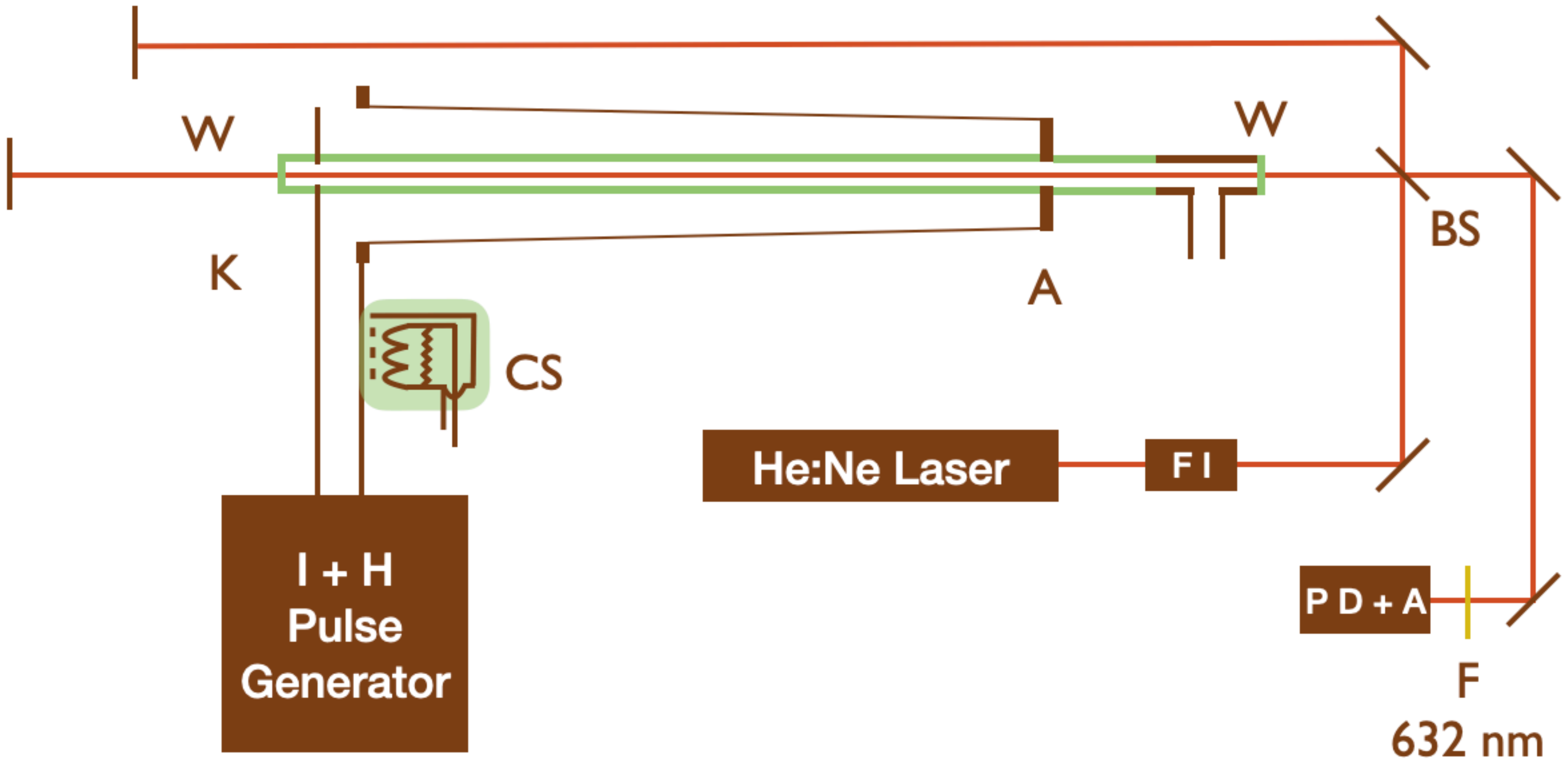
Michelson topology

5 m plasma + double pass

1 fringe shift = cm^{-3}

Measurements done at fixed parameters…
… P = 12 Pa (Argon)
… Delay heater-ignition = 10 μs
… Heating pulse duration = 60 μs (noise red.)

~ kHz seismic oscillations present
(actually used in data analysis)



Interferometry … plasmas + building vibrations + G Waves

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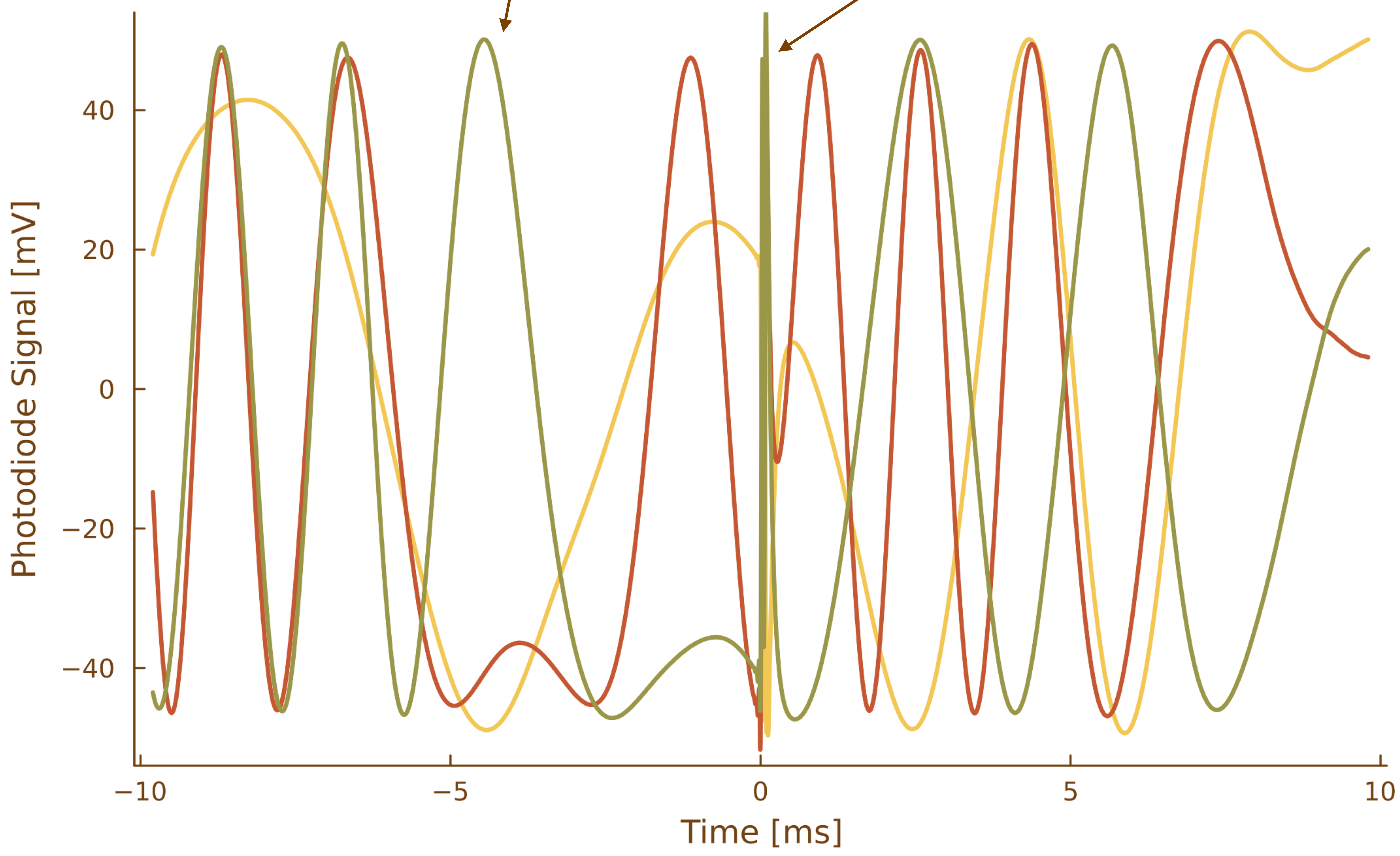
Traces 22 42 78
Delays 80 91 112 (s)

Seismic oscillations*
… provide first signal normalisation

Plasma



* Buterword filter w/ 25.0 kHz cutoff + Monot. piecewise cubic interp. w/ 2.0 µs steps
(plasma oscillations not resolved)
Offset -50.0 mV

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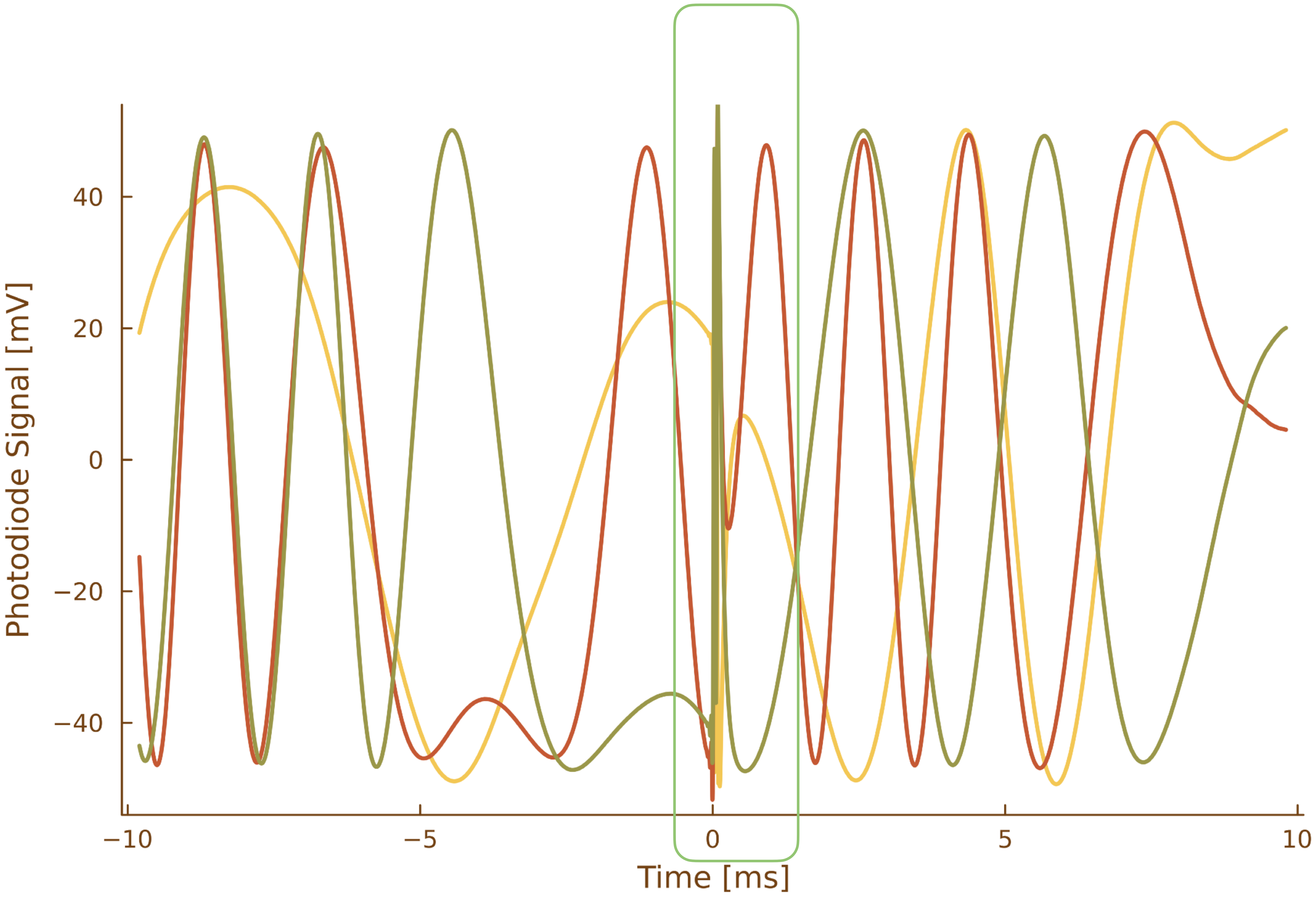

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Interferometry … raw signal from photodiode + amplifier

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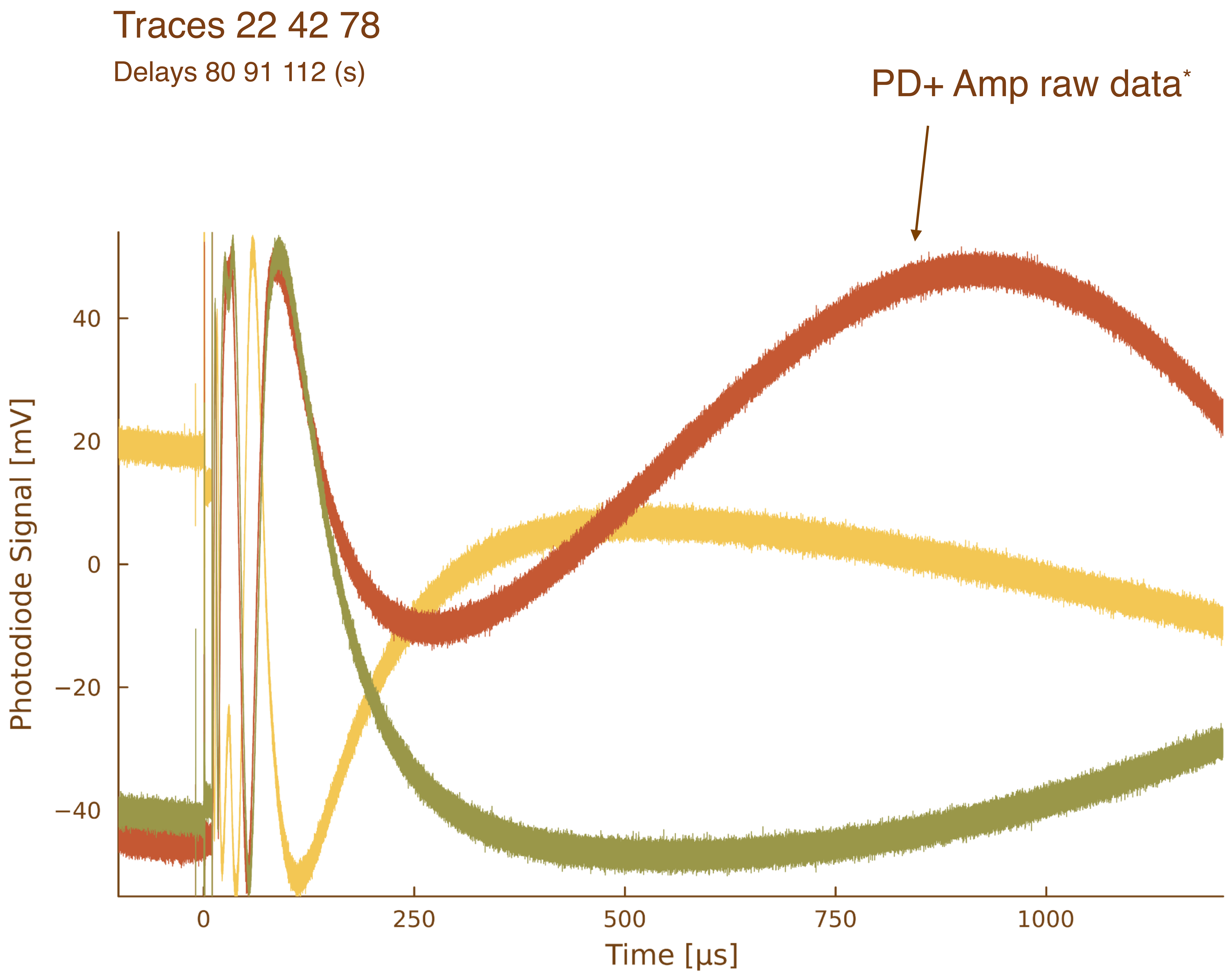
He:Ne CW Laser power ~ 1 mW

PD amp (Thor. PDA10A2) gain ~ 5 kV/A (150 kHz)

Signal to noise ratio ~ 1



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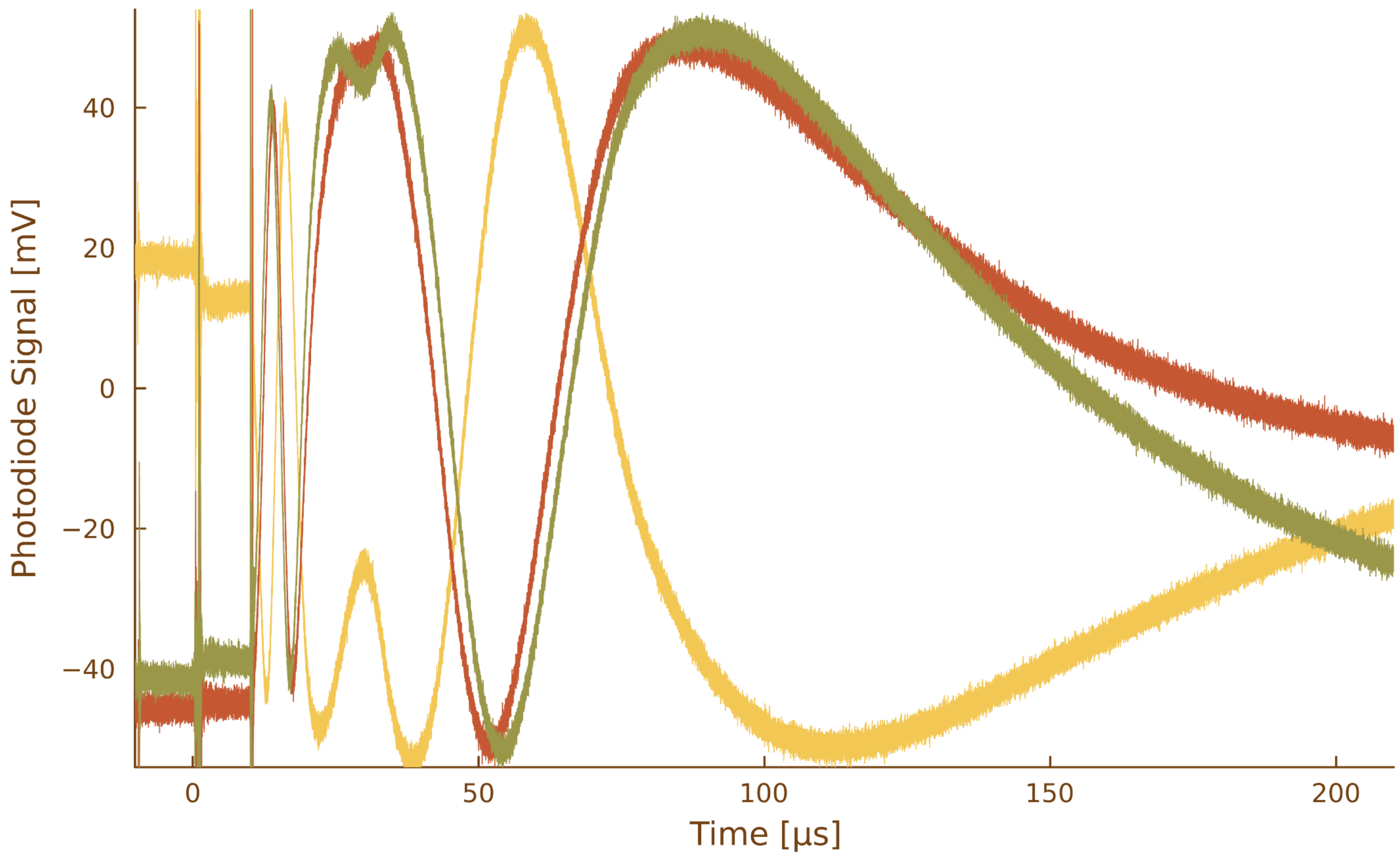

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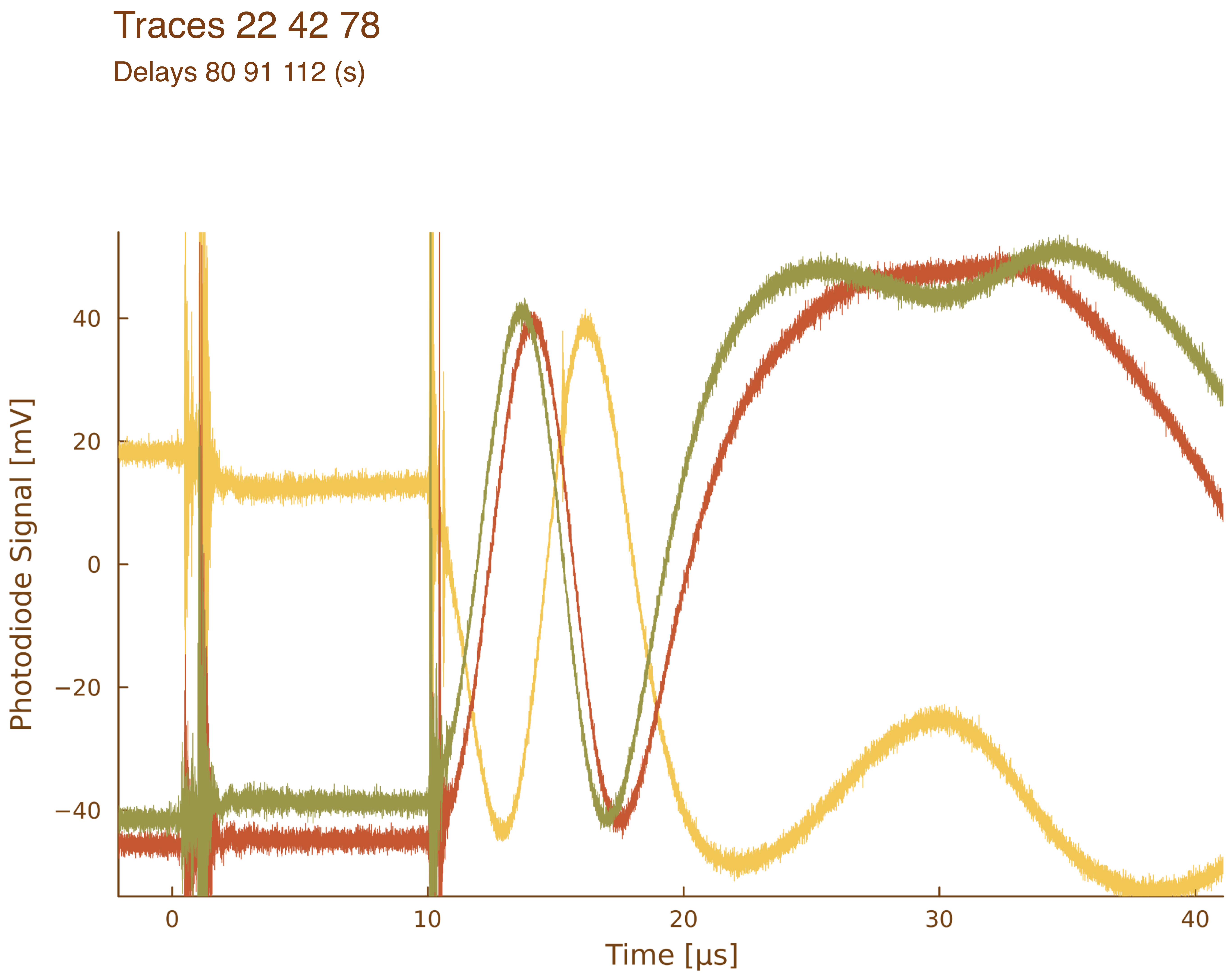


* Offset -50.0 mV

Interferometry … signal affected by EM noise

Time resolved axial integrated density

Michelson topology

5 m plasma + double pass

1 fringe shift = cm^{-3}

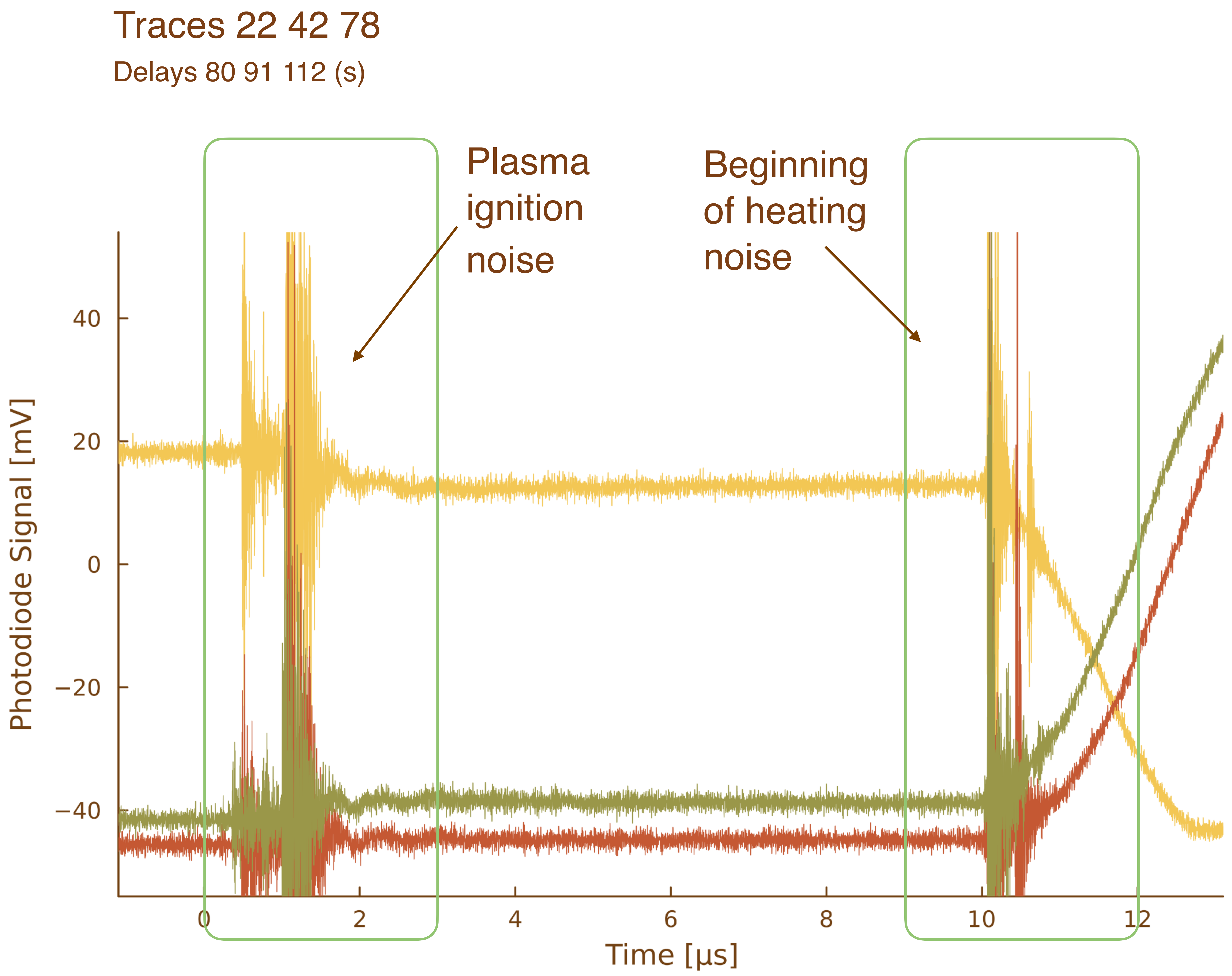
Measurements done at fixed parameters…
… P = 12 Pa (Argon)
… Delay heater-ignition = 10 µs
… Heating pulse duration = 60 µs (noise red.)

~ kHz seismic oscillations present
(actually used in data analysis)

He:Ne CW Laser power ~ 1 mW

PD amp (Thor. PDA10A2) gain ~ 5 kV/A (150 kHz)

Signal to noise ratio ~ 1



* Offset -50.0 mV

Interferometry … noise filtering (average w/ excl + BW filtering)

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Time resolved axial integrated density

Michelson topology

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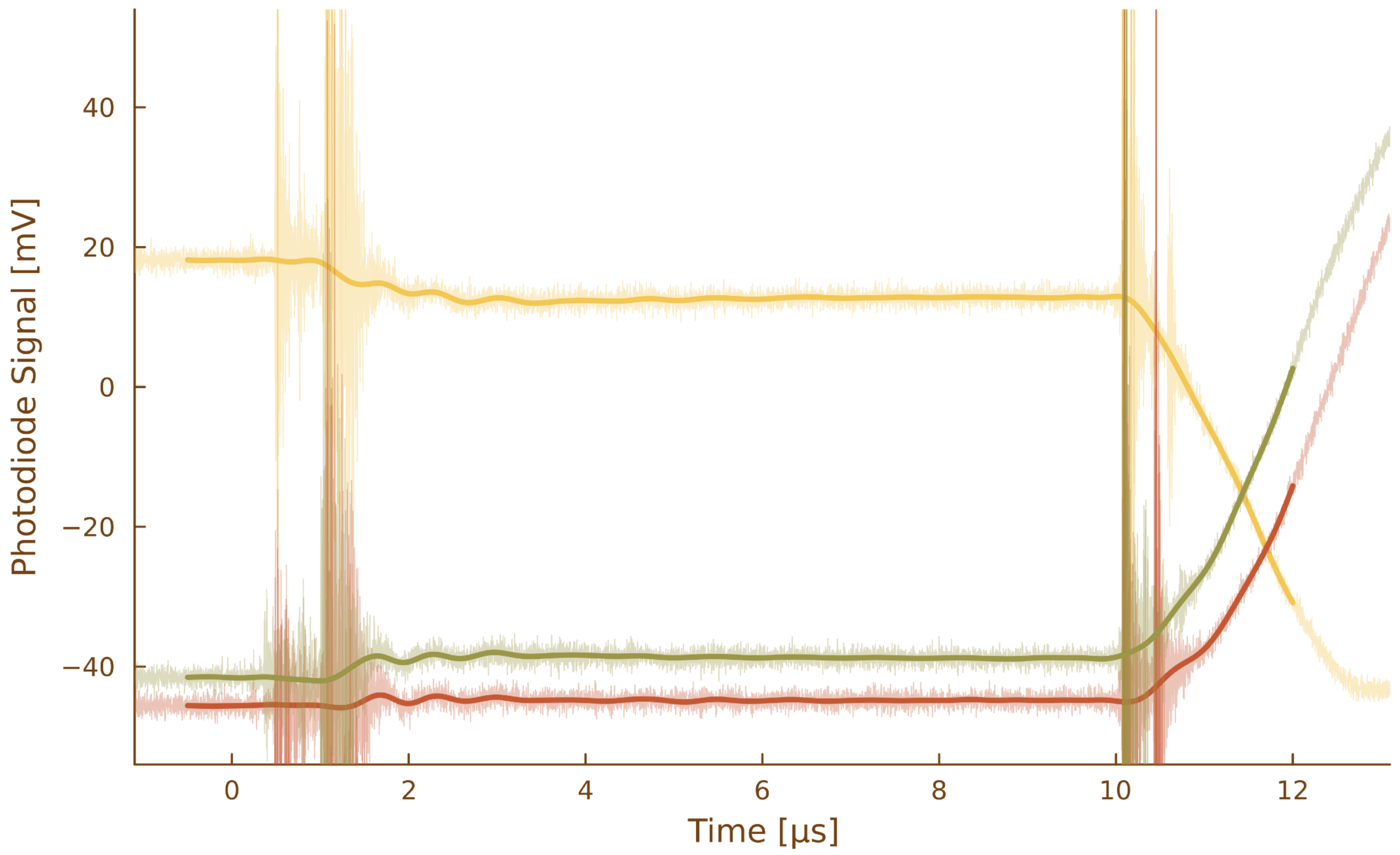
Signal to noise ratio ~ 1

Average w/ exclusion + BW filtering + interp. 10 ns

Traces 22 42 78
Delays 80 91 112 (s)



* Offset -50.0 mV
Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes
Step 2: Buterword filtering with cut-off at 2.0 MHz
Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … noise filtering (average w/ excl + BW filtering)

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Traces 22 42 78

Delays 80 91 112 (s)

BW filter w/ cutoff 2 .0 MHz

* Offset -50.0 mV

Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes

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Interferometry … noise filtering (average w/ excl + BW filtering)

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Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … BW cut-off frequency adjustment

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Traces 22 42 78

Delays 80 91 112 (s)

BW filter w/ cutoff 2 .0 MHz

Stagnation point zone…

Arc Sin very sensitive to oscillations near limits…

Cut-off frequency need to be reduced…

* Offset -50.0 mV

Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes

Step 2: Buterword filtering with cut-off at 2.0 MHz

Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … BW cut-off frequency adjustment

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Traces 22 42 78
Delays 80 91 112 (s)

BW filter w/ cutoff 350 kHz

Stagnation point zone…
Arc Sin very sensitive to oscillations near limits…
Cut-off frequency need to be reduced… to 350 kHz

* Offset -50.0 mV
Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes
Step 2: Buterword filtering with cut-off at 350 kHz
Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … BW cut-off frequency adjustment … everywhere

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* Offset -50.0 mV

Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes

Step 2: Buterword filtering with cut-off at 2.0 MHz

Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … BW cut-off frequency adjustment … everywhere

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Traces 22 42 78

Delays 80 91 112 (s)

* Offset -50.0 mV

Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes

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Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … the plasma is a time variable negative lens …

43 Traces

Multiple delays

* Offset -50.0 mV

Step 1: Average w/ radius 60 points (@ 2 ns sampling) w/ exclusion 2 x 30 extremes

Step 2: Buterword filtering with cut-off at 2.0 MHz

Step 3: Monot. piecewise cubic interpolation w/ 10.0 ns steps

Interferometry … the plasma is a time variable negative lens …

43 Traces

Multiple delays

* Smoothness of the top and bottom spline was further adjusted…

… from 5.0 to 3.0 aiming to reduce the impact of the last normalisation

… next slide contains the traces normalised with splines of smoothness 3.0

Interferometry … plasma lensing (almost) compensated

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43 Traces

Multiple delays

Still minor imperfections
left for final normalisation

43 traces not ideal for this method …
… (120 - 150 likely ideal for highest precision)

* Smoothness of the top and bottom spline was further adjusted…
… from 5.0 to 3.0 aiming to reduce the impact of the last normalisation
… this slide contains the traces normalised with splines of smoothness 3.0

Interferometry … plasma lensing (almost) compensated

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27 Traces

Multiple delays

Needs further work…

… the plasma duration is not fixed …

(no consequence on previous plasma)

Interferometry … plasma lensing (almost) compensated

TÉCNICO LISBOA

27 Traces

Multiple delays

Interferometry … plasma lensing (almost) compensated

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27 Traces

Multiple delays

Uncoloured …

… means very long delay to previous shot

Interferometry … plasma lensing (almost) compensated

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25 Traces

Multiple delays

Interferometry … plasma lensing (almost) compensated

5 Traces (# 57 60 61 93 94)

Delays from 84 to 90 sec

(same delay restriction as for currents a few slides ago)

Δ n_e / n_e = 0.381%*

(Assuming no error on diagnostic…)

(Error still to be quantified …

… expected low on stagnation point due to nearby peaks)

* Could be further reduced….

…. the bottom trace is delay extreme

Interferometry … plasma lensing (almost) compensated

2 + 9 Traces (# 97 101 + # 22 23 26 37 38 45 56 73 74)
Delays from 76 to 84 + 93 to 96 s

$\Delta n_e / n_e = 0.993\%$ (for pop. 93 - 96 s… ~3.2%)

(Assuming no error on diagnostic…)

Current reproducibility

These (preliminary) measurements suggest…

→ density reproducibilities <= 1.0% seem currently achievable

→ density likely more affected by rep. rate variations than current …

… depends more on the neutral density …

→ further reduction require…

… strict temperature control of all relevant tube sections

… higher precision pressure sensors and current signal digitiser

… more stable and powerful laser

Further work

→ further improvement of setup and data analysis (soon)

→ quadrature interferometer (more precise density retrieval) (planned 24)

→ force tube temperature with external flow of hot water (planned 2024)

Electron-positron plasmas in extreme conditions

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- Discharge plasma source
- Recent results
- Mid term plans

Mid term plan: focus on plasma source(s) for Run 2-C

Main requirements	Density step , plasma gap, beam quality	DPS …
2 plasmas: SM + Acceleration @ same density Beam superposition (e-beam + SM p-beam) at beginning of acceleration section SM section < 10 m Acc section ≥ 10 m Plasma e-density 1e14 - 1e15 cm-3	Density step on SM section … … essential to preserve wakefield amplitude Gap between SM and Acc plasmas … … detrimental for wakefield amplitude Injection through solid window … … detrimental for electron beam quality	… can be used in SM section (SM e-seeding) … can be used in Acc section … compact DPS anodes minimize gap … same gas volume for SM and Acc sections … beam injection via pinhole … transparent … plasma light diagn. possible

SM section …

… controllable thermal density step

… SM seeding w/ e-beam

Plasma gap …

… e-beam injection

… possible integrated design
to minimize gap length

Acc section …

… single discharge section ≥ 10m *

… double plasma ≥ 20m **

… multiple double plasmas (no length limit)***

* 10 m single plasmas demonstrated (May 2023 AWAKE DPS test)
> 10 m may require new heater modules running > 8 kV
** Double plasmas with common cathodes dem. (May 2023 AWAKE DPS test)
*** Full length DPS scalability not yet demonstrated (Oct 2023)

Tentative DPS centric scheme for Run 2-C*

*** (very) preliminary CAD design …
… w/ B = 1T, 80 MeV e-beam angle 30º, …
… suggest an integrated gap section with L ≤ 25 cm possible w/ DPS

* Recovered from presentation at "Plasma sources meeting" - CERN 2023-08-29

** Density steps up to 10% produced by sleeve with flow of water at controlled temperatures above room temperature…
… water flow requirement significantly reduced by second sleeve with quiet air (not in scheme)

Tentative DPS centric scheme for a Run 2-C

* P. Muggli suggestion…

… preliminary calculations suggest diff pump with a small turbo molecular pump will preserve accelerator vacuum

** interferometry likely essential in tunnel for more permanent setup

Tentative IST plan for next funding cycle (24-26) …

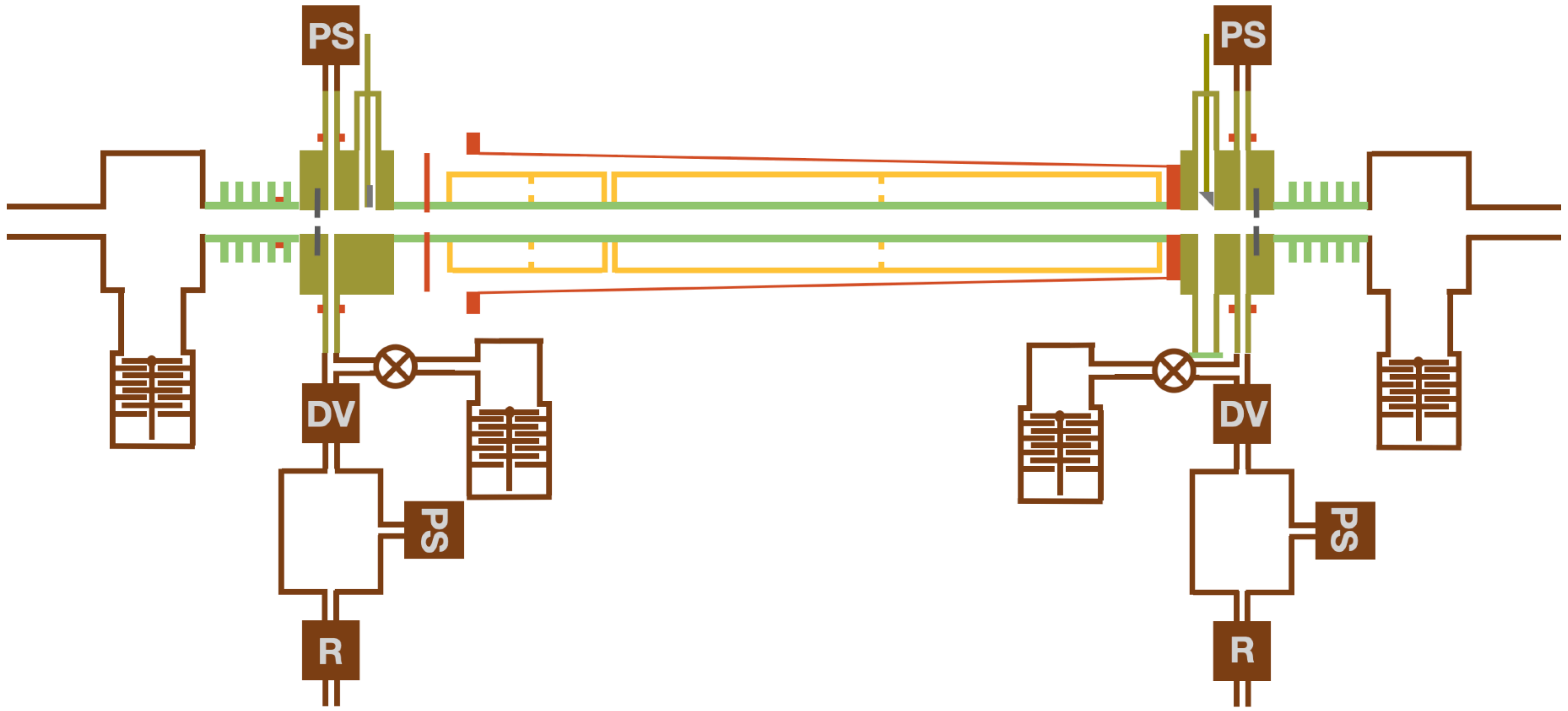
New test bench for R&D on DPS critical aspects for Run 2

Temperature control of …
… tube, gas feed and gas measurement

High precision plasma density diagnostics

High purity tube for more precise plasma density

Improve manufacturability of electrical kit



Some critical points to address

Development of tube warm water sleeves

Safe discharges w/ leaking holes …
… near the cathode

Interferometry compatible with particle beams on tube

Consistent operation at high density reproducibility

Manufacturability of dielectric tube end pieces

Find the limits of the electrical kit

Automatic operation of the DPS

Best effort to measure longitudinal uniformity