A long traveling wave tube used to investigate wave-particle interactions in plasmas

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Introduction

- Industrial traveling wave tubes (TWTs): from 2 to 30 cm in length. Mainly used as signal amplifiers for wireless communications, such as space telecommunication

- Some meters long TWTs: used for basic plasma physics research
  G. Dimonte, J. H. Malmberg, Phys. Fluids 21, 1188 (1978)
  F. Doveil et al., Phys. Rev. Lett. 94, 085003 (2005)

- Equations describing TWT are the same characterizing beam-plasma instability in small cold beam limit

- Electromagnetic waves interact with electron beam in vacuum:

  Possible to experimentally mimic beam-plasma system without background plasma effects, and we properly identify effects due to beam dynamics

Motivation

- Wave-particle interactions have many applications in particle acceleration and particle heating
  M. C. de Sousa, I. L. Caldas, *Phys. Plasmas* **25**, 043110 (2018)
  T. M. Corrêa da Silva *et al.*, *Phys. Rev.* E **88**, 013101 (2013)

- Fundamental process in plasmas, particle beams, and accelerators
  P. K. Shukla *et al.*, *Phys. Rep.* **138**, 1 (1986)

- Basis for electromagnetic radiation amplifiers, such as free electron lasers, gyrotrons, TWTs, etc.
  A. S. Gilmour Jr., *Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons* (Artech House Radar Library, Boston, 2011)

Objectives

- Use an upgraded TWT to simulate one-dimensional beam-plasma systems, which represent a paradigm for instabilities in plasmas:

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  - Develop theoretical model for wave propagation

  - Analyze linear and nonlinear effects arising from beam-wave interaction:

    Modulation of electron beam

    Wave growth and saturation

    Development of electron bunches and consequent oscillations in wave amplitude along the device

TWTs used for basic research

- First TWT used for plasma physics research (no longer in operation):
  3 m long – University of California in San Diego
  G. Dimonte, J. H. Malmberg, *Phys. Rev. Lett.* **38**, 401 (1977)
  G. Dimonte, J. H. Malmberg, *Phys. Fluids* **21**, 1188 (1978)

- Second research TWT (upgraded to next item):
  4 m in length – PIIM Laboratory, CNRS and Aix-Marseille University
  C. Chandre *et al.*, *Phys. Rev. Lett.* **94**, 074101 (2005)
  F. Doveil, A. Macor, Y. Elskens, *Chaos* **16**, 033103 (2006)

- Third TWT used for research (presented in this talk):
  4 m in length – PIIM Laboratory, CNRS and Aix-Marseille University
  M. C. de Sousa *et al.*, *Phys. Plasmas* **27**, 093108 (2020)

TWT at PIIM Laboratory

a) TWT structure: (1) helix; (2) electron gun; (3) trochoidal velocity analyzer; (4) movable antenna; (5) glass vacuum tube; (6) slotted rf ground cylinder; (7) main magnetic coil; (8) resistive rf termination to reduce reflections

b) 4 m long TWT: (7) main coil producing magnetic field B_z to confine the beam; (9) rectangular coils generating B_x and B_y for beam tilt correction

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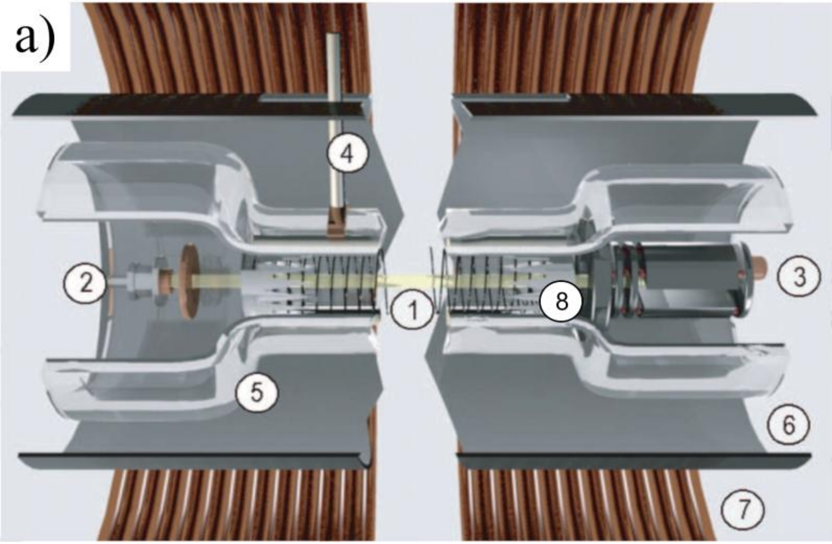

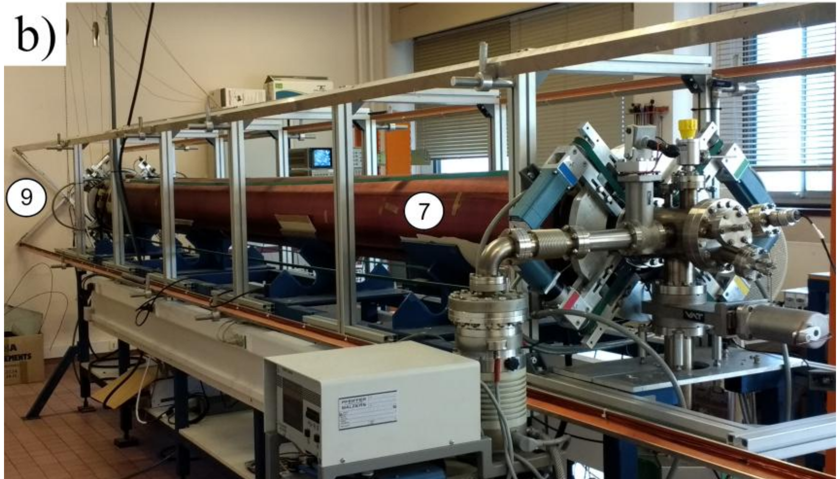

TWT upgrade

- TWTs used for research: specifically conceived to study wave-particle interactions in plasmas
- Long enough for nonlinear effects to take place
- Previous TWTs: helix held inside glass tube by three alumina rods
- Upgraded PIIM TWT: helix wrapped in and rigidly held by dielectric polyimide tape, ensuring nearly constant helix pitch along whole device length
- Results obtained with upgraded helix are much more precise
- New experiments are possible
- The only TWT for plasma physics research currently in operation

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Wave propagation

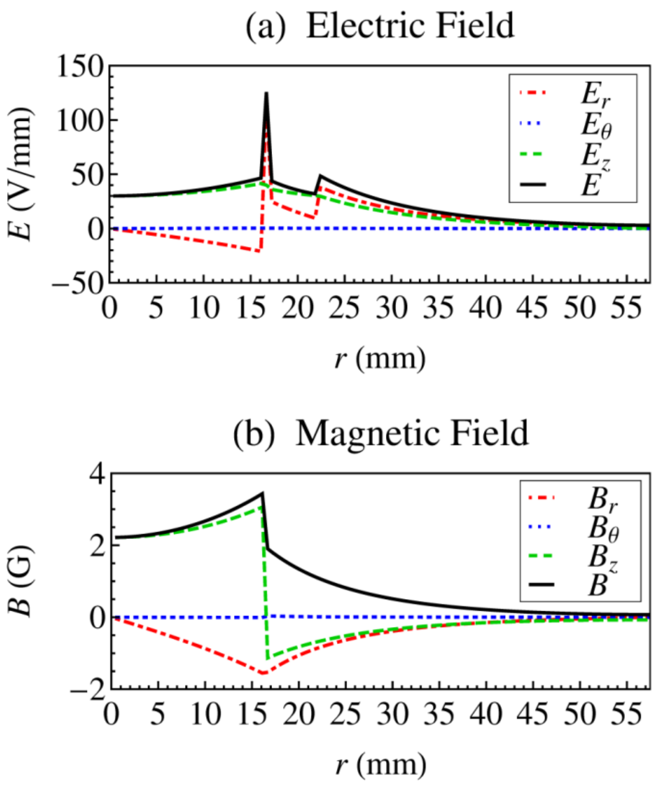
- In [M. C. de Sousa *et al.*, *Phys. Plasmas* **27**, 093108 (2020)], we introduced theoretical model describing wave propagation in upgraded TWT

- Amplitude of each component of (a) electric and (b) magnetic fields through radial plane in slow wave structure for wave at 30 MHz

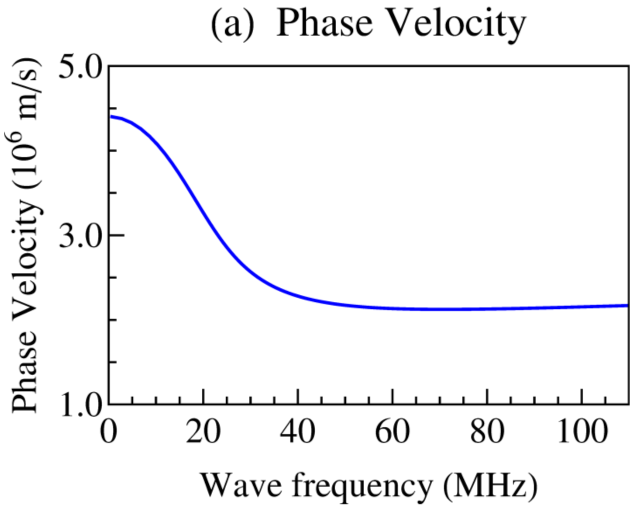
- Near axis ($r = 0$ mm): electric and magnetic fields present only longitudinal components; electrons interact with electrostatic field similar to the ones in plasmas

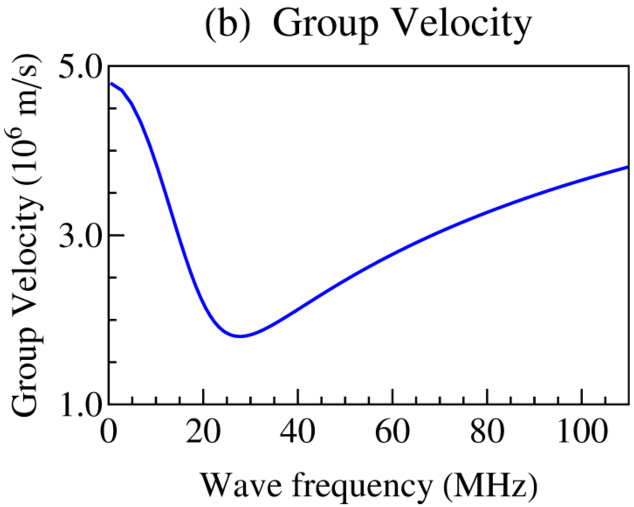
- Close to helix ($r = 16.355$ mm): total amplitudes reach maximum value

- Near ground cylinder ($r = 57.5$ mm): all field components decay to zero



Wave propagation





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- Phase velocity: decreases rapidly for frequencies $0 < f < 40$ MHz; constant for $f > 50$ MHz
- Group velocity: presents a minimum around $f \sim 27$MHz

Wave propagation

- Excellent agreement between theoretical model and experimental data

- Temporal signal registered by oscilloscope for propagating wave at 30 MHz along the axial direction z of the TWT

- Black solid line indicates theoretical phase velocity obtained from model

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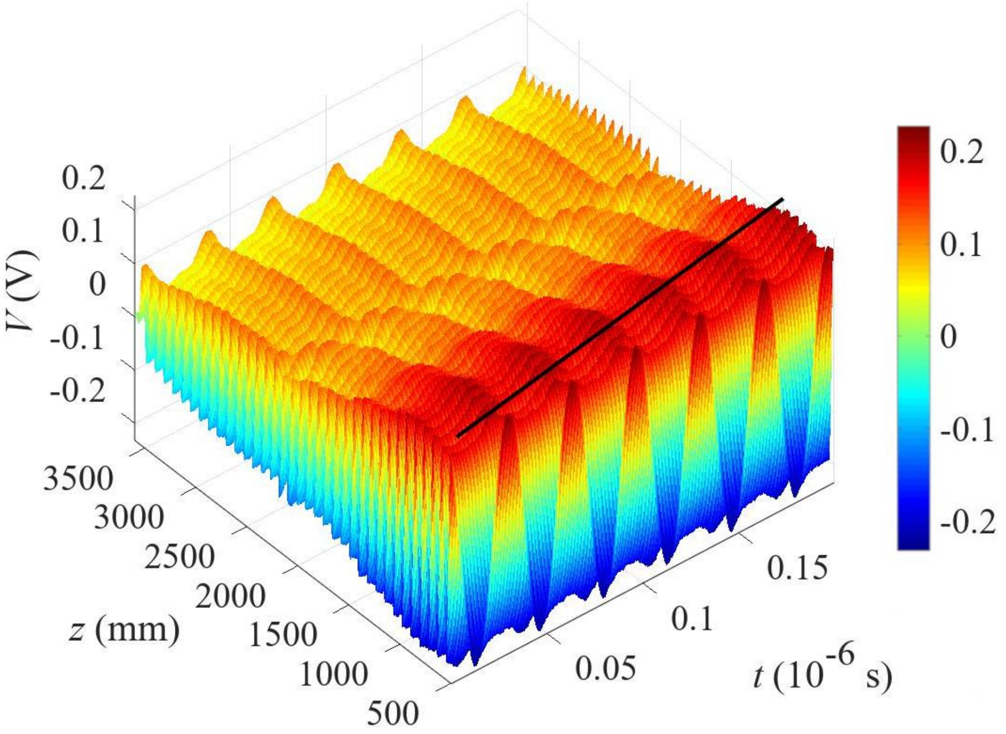
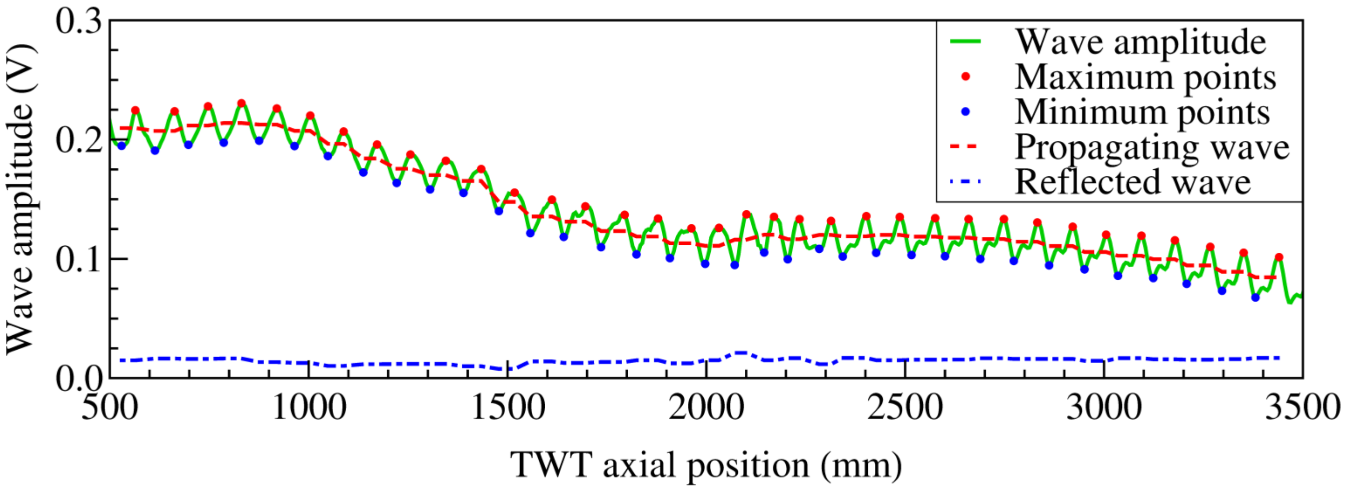


Wave propagation



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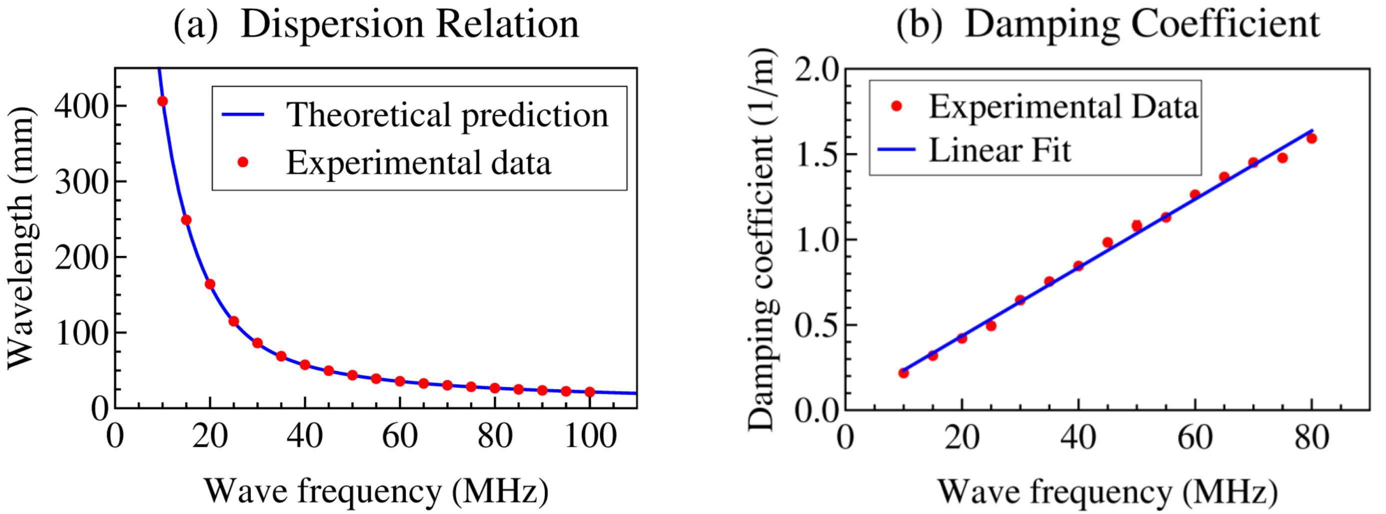
- Fast Fourier Transform (FFT) (green curve) of temporal signal shown in previous slide
- Presence of 60 MHz harmonics for z > 1600 mm
- Total signal (green) decomposed into propagating (red) and reflected (blue) waves

Wave propagation



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- Error bars are within the marker size
- Upgraded TWT is very precise: it is possible to obtain accurate experimental data, and to carry out new experiments that require fine adjustment of parameters

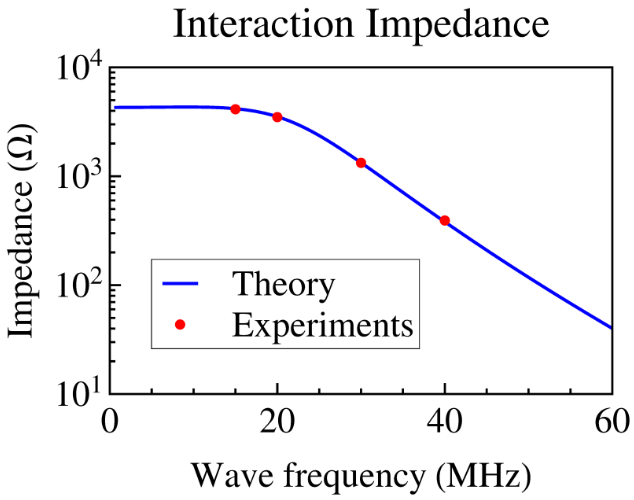
Beam-wave interaction

- Mainly characterized by interaction impedance, or coupling impedance: coupling between electron beam and wave electric field E_z in direction beam propagates

- Very good agreement between theory and experiments: robustness of theoretical model and accuracy of experimental measurements for upgraded TWT

- Higher frequencies: electromagnetic field gets more concentrated near helix and far from beam

- Impedance strongly decreases with wave frequency: coupling between particles and waves is less efficient above 20 MHz



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Beam-wave interaction: Beam modulation

- Electron gun generates initially monokinetic beam

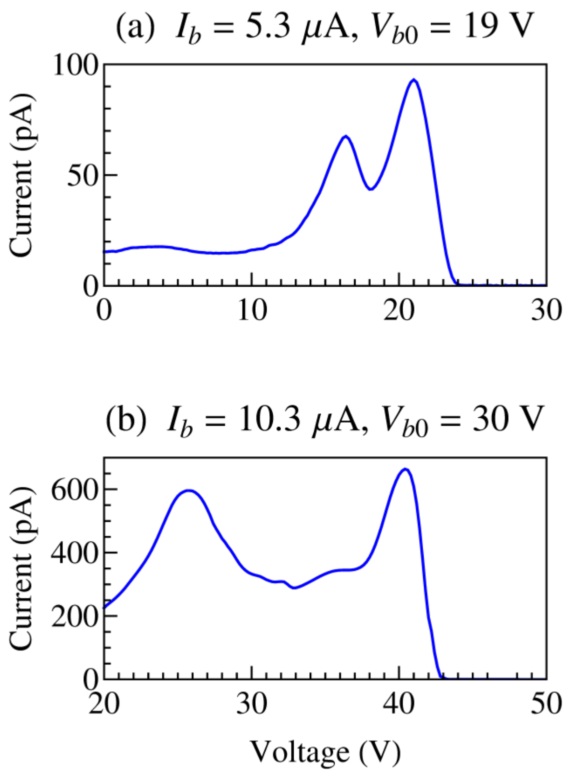
- (a) 30 MHz wave, initial beam voltage V_{b0} = 19 V (beam velocity v_{b0} approximately equal to wave phase velocity v_φ)
  After interaction with wave: 2 peaks in distribution function, V_{b-} = 16.4 V and V_{b+} = 21 V

- (b) 15 MHz wave, initial beam voltage V_{b0} = 30 V ($v_{b0} < v_\varphi$)
  After interaction with wave: 2 peaks, V_{b-} = 25.6 V and V_{b+} = 40.4 V (v_b close to v_φ)

- Difference between peaks: estimate wave amplitude disregarding damping effects

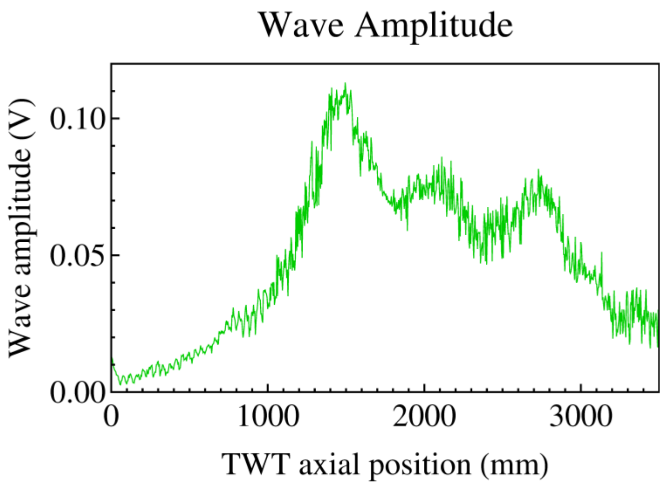
$$V_0 = \left(\sqrt{V_{b+}} - \sqrt{V_{b-}}\right)\left|\sqrt{V_{b0}} - \sqrt{V_{b\varphi}}\right|$$

- (a) V_0 = 0.0036 V; (b) V_0 = 1.07 V



Beam-wave interaction: Wave growth and saturation

- Initial beam velocity slightly higher than wave phase velocity
- Wave receives momentum and energy from beam, its amplitude increases (0 < axial position z < 1500 mm)
- Operation mechanism for industrial TWTs used as signal amplifiers
- PIIM TWT is long enough for development of electron bunches after wave saturates (z > 1500 mm)
- Electrons are trapped by wave, moving back and forth in its potential
- Momentum and energy conservation implies that wave amplitude oscillates along TWT



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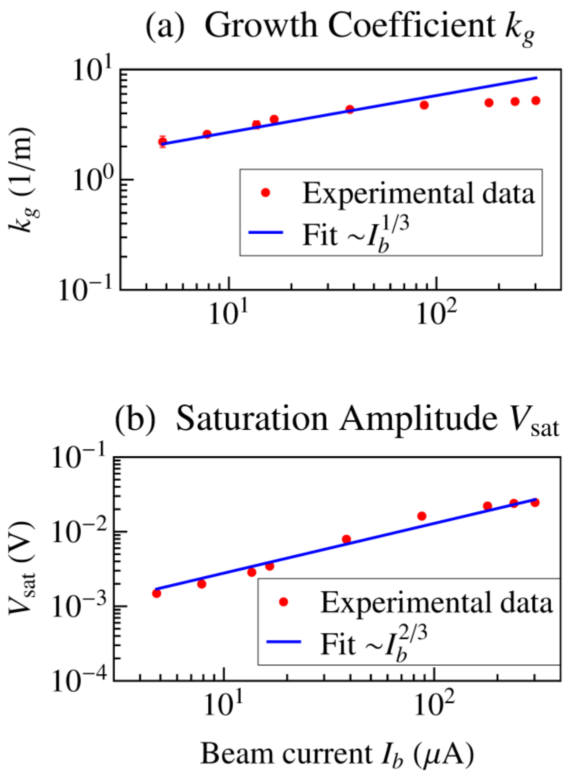
Beam-wave interaction: Wave growth and saturation

- 40 MHz wave in figures
- Wave amplitude grows exponentially as $V \sim e^{k_g z}$
- For $I_b \lesssim 100\mu A$: growth coefficient and saturation amplitude increase with beam current
- Experimental data (red dots) agree very well with theoretical predictions (blue solid curve) $k_g \sim I_b^{1/3}$ and $V_{sat} \sim I_b^{2/3}$ (wave saturates due to nonlinear development of electron bunches trapped by wave potential)
- For $I_b \gtrsim 100\mu A$: nonlinear space charge effects become important, parameters deviate from linear prediction, tending to constant value



Beam-wave interaction: Pierce linear parameters

- Four Pierce linear parameters:

  Completely characterize linear regime of interaction between waves and beam in TWT

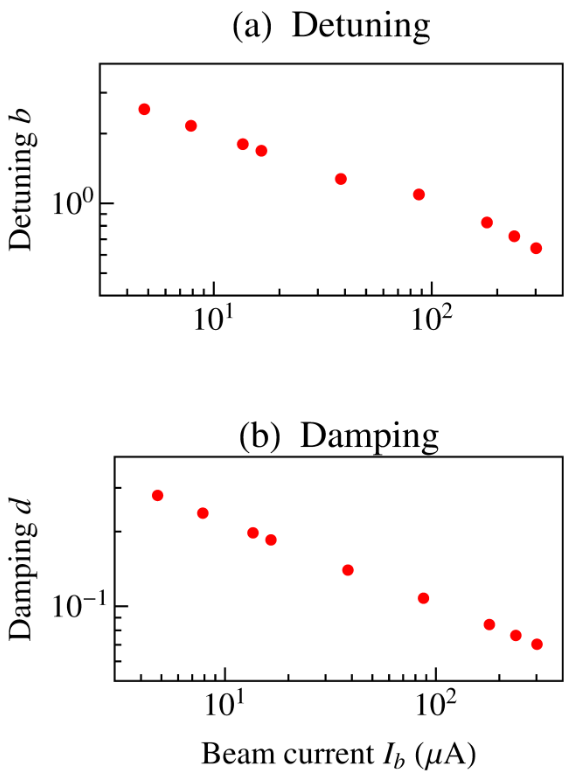
  J. R. Pierce, *Traveling Wave Tubes* (Van Nostrand, New York, 1950)

- Detuning parameter b:

  Measures normalized difference between initial beam velocity and wave phase velocity in absence of electrons

- Damping parameter d:

  Damping rate of slow wave structure in absence of electrons normalized with wave frequency, initial beam velocity, and gain parameter



Beam-wave interaction: Pierce linear parameters

- Gain parameter C:

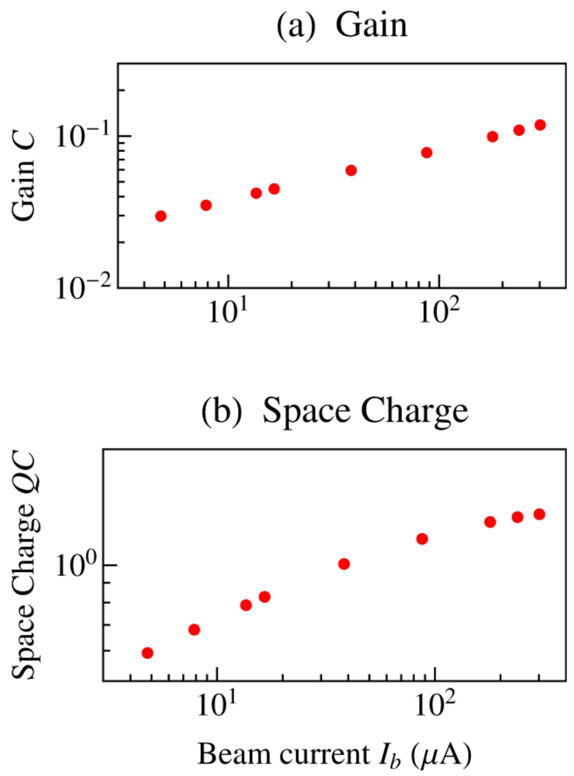
  Defines wave gain as it interacts with beam

  High currents: wave extracts more energy and momentum from beam, resulting in higher growth coefficient and saturation amplitude

- Space charge parameter QC:

  Accounts for TWT geometry, and repulsive electrostatic force between beam electrons

  Sufficiently high currents: electrostatic force acting on beam electrons increases, nonlinear effects caused by beam space charge become important and predictions of linear theory lose accuracy



Conclusions and perspectives

- Upgraded TWT: accurate experimental data agree very well with theoretical predictions

- Possible to mimic beam-plasma system with low noise; analyze nonlinear effects after saturation

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- Possible to mimic beam-plasma system with low noise; analyze nonlinear effects after saturation

- New experiments are possible in upgraded TWT:
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  Pulsed beam instead of continuous one

  Synergy between chaos and self-consistent effects

  Warm beams to investigate quasilinear theory predictions for chaotic diffusion of electrons in broad wave spectrum

- Experimental data used to benchmark numerical model DIMOHA

Thank you!

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