Klynac: a combined resonant klystron and linac architecture

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September 23, 2024

Outline

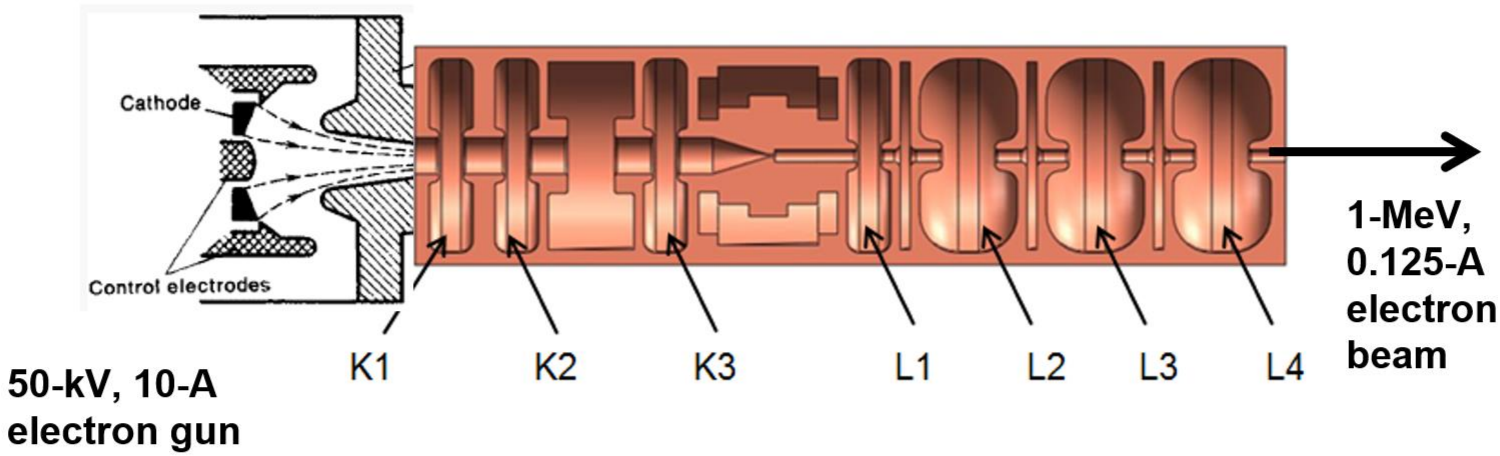
- Klynac
  - Basic description
    - Single resonant structure/bi-resonant structure
    - Tuned on resonance/tuned off resonance
  - Summarize earlier work and the KlyLac work at RadioBeam (Smirnov)
  - Summarize LANL work on our preferred klynac architecture
- Electrostatic potential depression for enhanced e-beam bunching
  - Original application to IOT
  - Application to high-efficiency klystron
  - Application to shorten bunching section in compact accelerators

Acknowledgements: **Dave Schwellenbach** (original klynac idea); **Kimberley Nichols** and **Alex Malyzhenkov** (original LANL collaborators); **Jim Potter** (designed the RF cavity); and University of Maryland collaborators (**Noah Hoppis** and **Tim Koeth**)

Special recognition: **Petr Anisimov** (detailed klynac tuning) and **Haoran Xu** (electrostatic potential depression development)

Klynac architecture

K refers to a klystron cavity
L refers to a linac cavity



Can be a single RF structure (which builds up from noise) or the klystron input cavity can be a separately driven cavity (we know how that variant works)

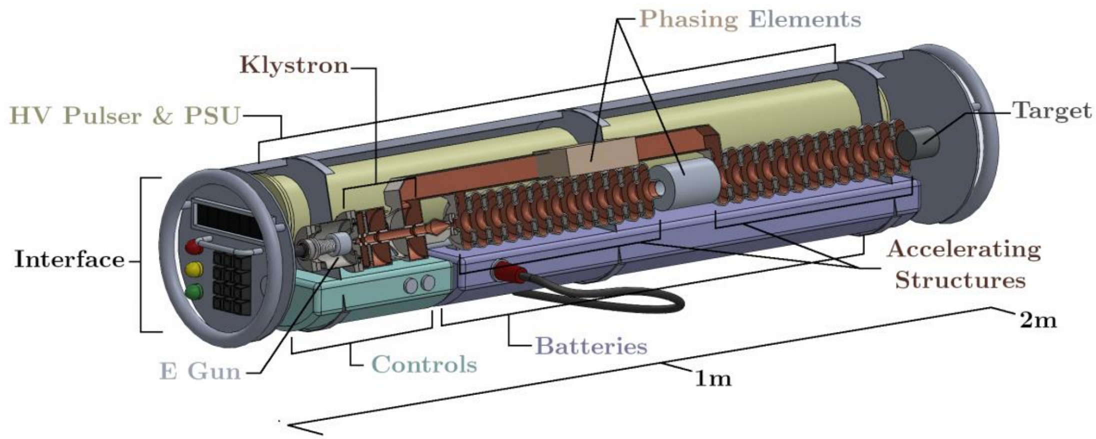
Advantages: lower cost, lower weight, smaller size, and lower temperature sensitivity

Rough power balance

- Use an electron gun with a μP of about 1
- Assume 50% extraction efficiency in the klystron (250 kW for image above)
- Assume 50% beam loading (125 kW beam power)
- (25% overall efficiency)

Klynac has a broad design range – we've made designs for several different parameters

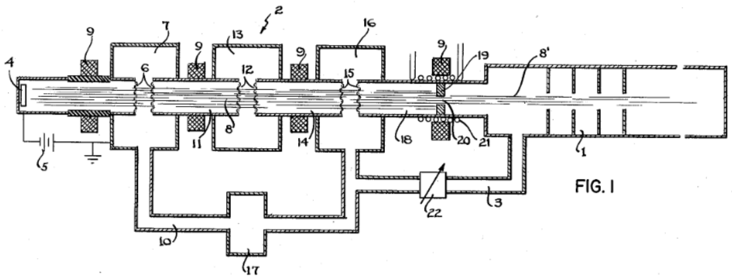
E-gun voltage	E-gun current	E-beam energy	E-beam current
50 kV	10 A	1 MeV	125 mA
75 kV	21.3 A	10 MeV	40 mA
80 kV	25 A	5 MeV	100 mA



10-MeV design with University of Maryland
(image above is the integrated design by Noah Hoppis)

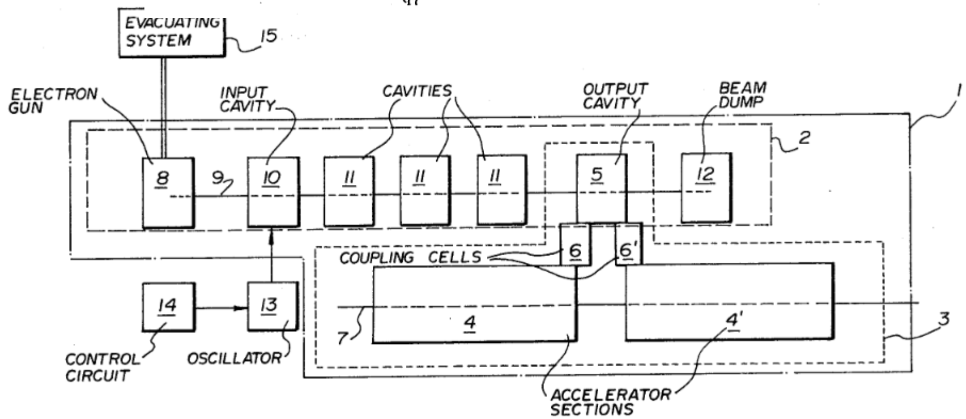
Earlier related work

Nygard, 1960



"Compact linear accelerator"
Patent 2,922,21, filed Oct 28, 1954

Schriber, 1977



"Klystron-resonant cavity accelerator system" Patent 4,027,193

Xie, 2003

5054 Rev. Sci. Instrum., Vol. 74, No. 12, December 2003

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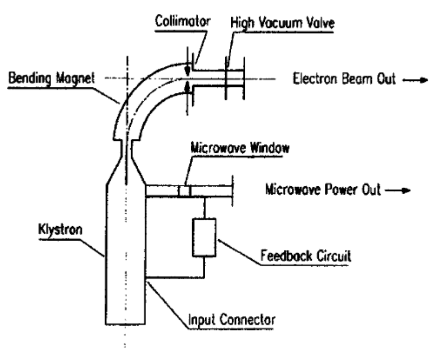

FIG. 1. Layout of the main components of the combined source.

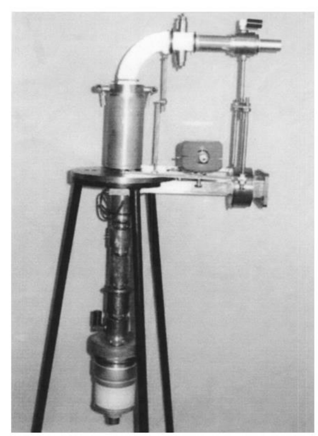

FIG. 8. External view of the klystron, which produces both microwave power and electron bunches.

"A combined source of electron bunches and microwave power", *RSI*, **74**, 5053 (2003)

The KlyLac

Closely related concept, differences are:

- Klystron cavities are uncoupled
- Klystron output cavity is coupled to linac section
- Feedback from linac section to klylac input cavity

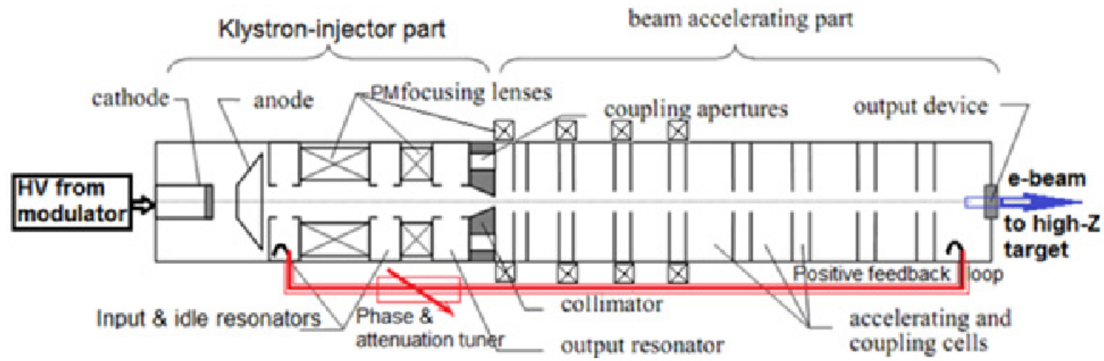

Figure 1: Simplified schematics of the compact X-ray source for borehole logging using "KlyLac" concept enhanced with a positive feedback loop.

THPVA147 Proceedings of IPAC2017, Copenhagen, Denmark

KlyLac CONCEPTUAL DESIGN FOR BOREHOLE LOGGING*

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Abstract

Linac-based system for borehole logging exploits KlyLac approach combing klystron and linac sharing the same electron beam, vacuum volume, and RF network. The conceptual design tailors delivering 3.5-4 MeV electrons within 3.5 inch borehole at ambient temperatures 150 degrees C to replace ^{137}Cs, >1 Ci source used in borehole logging. The linac part is based on a very robust, high group velocity, cm-wave, standing wave accelerating structure. The design concept features i) self-oscillation analog feedback that automatically provides modal stability; ii) ferrite-free isolation of the klystron; and iii) long accelerating section with large (0.3%) frequency separation between adjacent modes; and iv) low-voltage klystron.

considerable adaptation of the linac technology to design a linac for logging [4].

RF linacs using conventional technology remain too large and sensitive to background to operate remotely in harsh environment of deep borehole wells at temperatures as high as 150°C and in presence of vibrations (with accelerations 2G and above). The conventional linacs with their automatic frequency control (AFC) system, ferrite-based circulator, and magnetron are not suitable.

KlyLac concept [5,6,7,8] offers an alternative, rugged approach to this problem. Both KlyLac and KlyNac [9,10] concepts are based on a combination of klystron and linac sharing the same vacuum envelop and electron beam source.

The goal of the development is to conceptually design a

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Klynac architecture types

- Simplest architecture and least susceptible to temperature variations is a single resonant structure
  - Conceptually simple
  - Easy to make high-power designs
  - How (if) it turns on is not simple
- In 2019 we reported on our analysis for a “bi-resonant” klynac architecture, where the first cell is a separate resonant cavity
  - It will turn on and will be stable, but will require a separate input drive that follows the frequency of the rest of the klynac

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Bi-resonant klynac

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A R T I C L E   I N F O

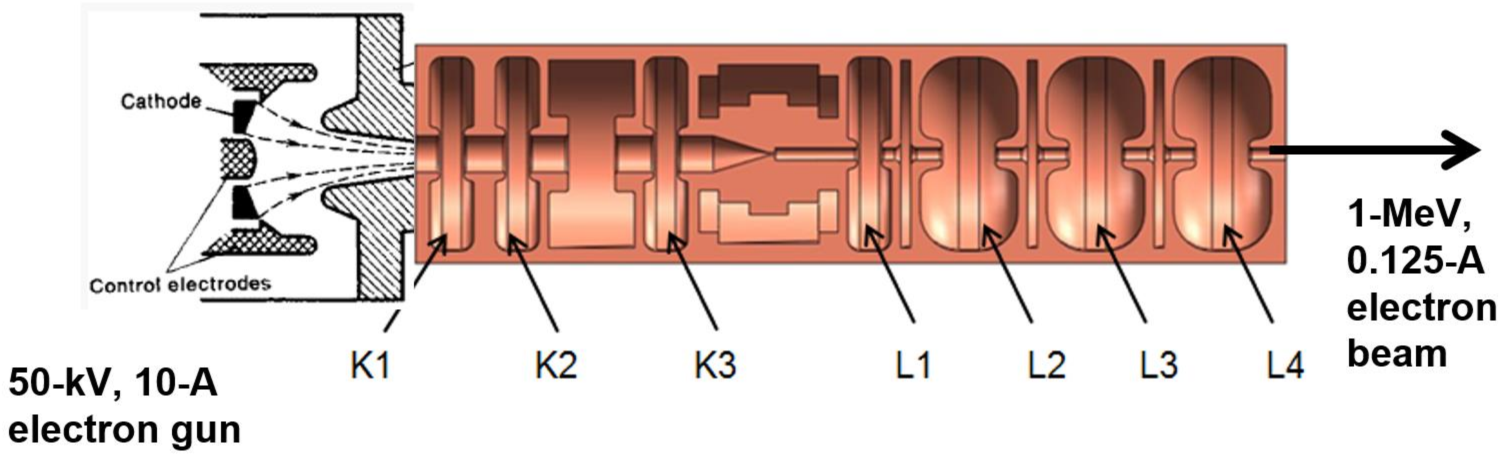
Keywords:
Electron accelerator
RF source
Klystron
Linac

A B S T R A C T

Here we present the first analysis of a new device called the bi-resonant klynac, which is a combined klystron and linac. In a bi-resonant klynac, all RF cells, except for the cell that acts as the input for the klystron section, belong to a single resonant circuit. This resonant coupling configuration leads to increased operational stability and can tolerate significant temperature variations. In this paper, a basic analysis of this device is presented, including discussions of how it operates and of the advantages of resonantly coupling the RF generation directly to the linac. We additionally describe the approach used to numerically model the klynac and we include detailed simulations of a 50-kV, 10-A klynac that produces a 1-MeV, 0.1-A output beam. This type of device may be especially useful for situations where an electron beam is needed at low cost.

LANL bi-resonant klynac

K refers to a klystron cavity
L refers to a linac cavity



Independent first cavity, driven externally with 500 W

All other cavities in a $\pi/2$ mode (successive K, L cavities 180^o out of phase)

L2-L4 identical, with identical field amplitudes (L1 much lower field amplitude – factor of ε)

K1 drive frequency same as frequency of K2-L4 cavity

Alternative approach: K1-K2-K3 one cavity and K4-L1-L2-L3-L4 second cavity

- Eliminates need for external drive
- Reduces temperature stability, may not have frequency match between cavities

Temperature stability

Greater temperature stability was initial motivation for developing the klynac

Estimates below assume:

- 1-m long, 30-kg klynac
- Cooling from forced air through radial cooling fins
- Power loss leads to 0.2^{o} C temperature variation per W of lost power
- Beam powers/power lost below correspond to 5% amplitude variations (equations for field amplitude variations from Wangler's book)

Architecture	Maximum beam average power
Klystron/linac cells not coupled	2 W
Klystron/linac cells coupled, not $\pi/2$ mode	150 W
Klystron/linac cells coupled, $\pi/2$ mode	600 W

Klynac governing equations

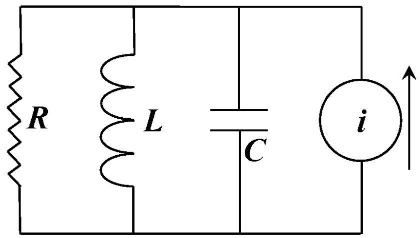
Steady-state power balance:

$$Power\ generated\ in\ klystron = Ohmic\ losses + power\ in\ linac\ beam$$

$$0 = \eta I_0 V_0 - (3+\varepsilon^2)\frac{V_L^2}{Z_L} - (3+\varepsilon) I_L T_L V_L$$

Steady-state circuit model for K2-L4 cavity:

(need a self-consistent definition of $V_{circuit}$)



$$V_{circuit}(t) = Z_{circuit} i_{ind,1}(t)$$

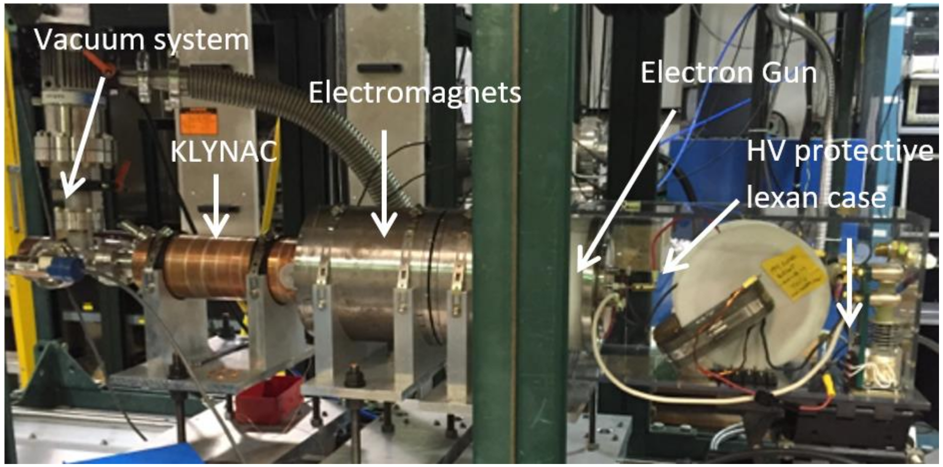
$$i_{ind}(t) V_{circuit}(t) = \sum_{cavity\ n} \int_{V_n} \vec{J}(t) \cdot \vec{E}_n(t)$$

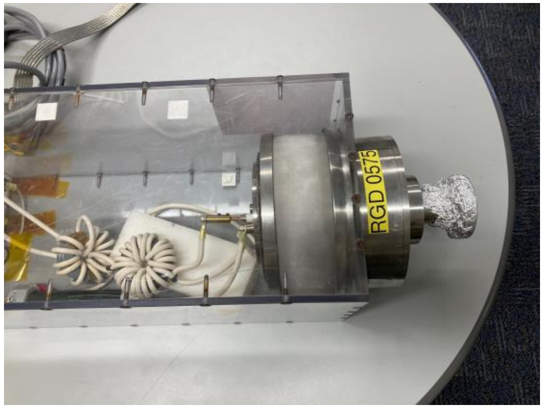
$$\frac{1}{Z_{circuit}} = \frac{1}{R} + j\omega C + \frac{1}{j\omega L} = \frac{1}{R} + j\left(\frac{f}{f_0} - \frac{f_0}{f}\right)\frac{1}{R/Q}$$

We built a klynac but it didn't turn on

We built a klynac with a single resonant circuit obeying the steady-state equations, before we understood the complexities with that design

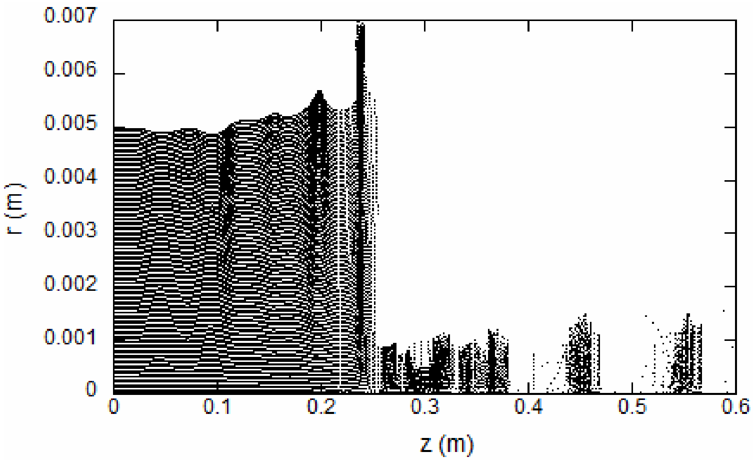
(To be fair, our modulator had troubles achieving 50 kV and we stopped the testing before we fixed it)



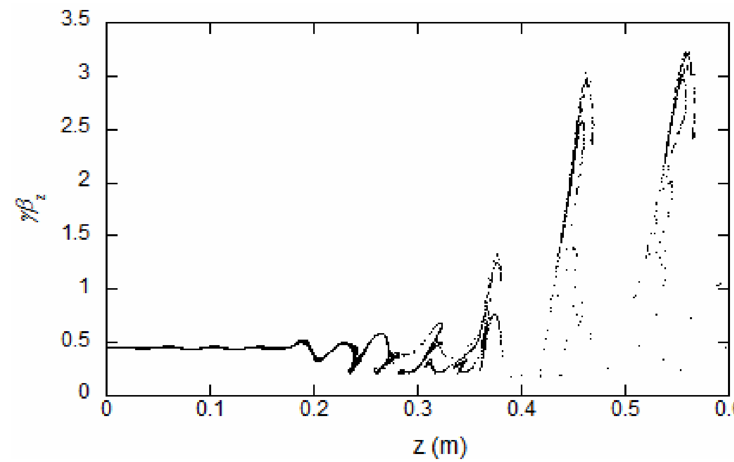


50-kV, 10-A e-gun

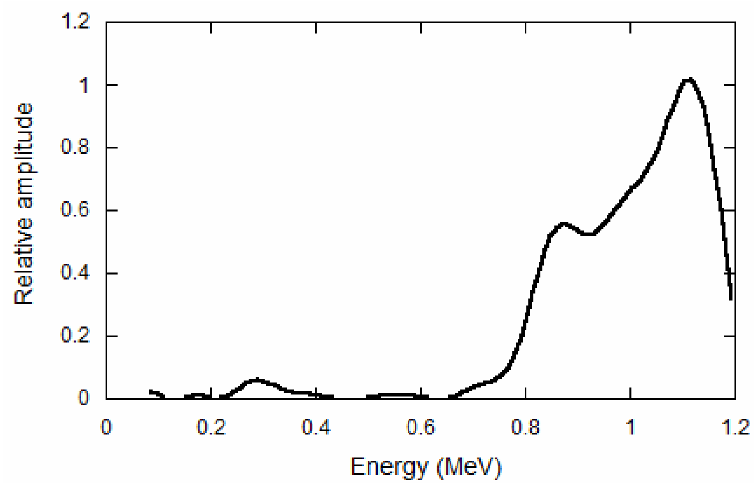
Modeling results for 1-MeV bi-resonant klynac



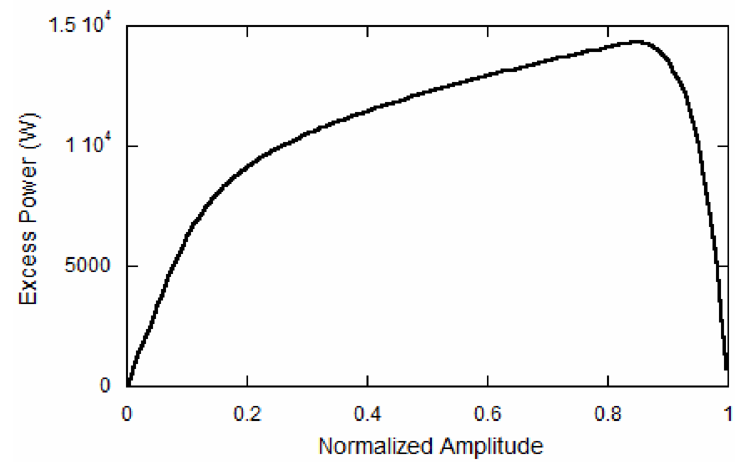
r-z transport



$\gamma\beta_z$-z transport



Final energy spectrum – rms energy spread is 4.3%



Excess power is needed for the device to turn on – easy to understand for the bi-resonant architecture

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Turn on

Bi-resonant structure with K2-L4 cavity on resonance: showed in paper that will turn on smoothly

Bi-resonant structure with K2-L4 cavity off resonance: should also turn on smoothly

Single resonant structure: will need to frequency hop as it turns on

Need to solve this equation to know if it can:

$$\left(\omega_0 - \frac{j\omega_0}{Q_m}\frac{d}{dt} + \frac{d^2}{dt^2}\right) q_m(t) = \frac{1}{\varepsilon_0} i_{ind}(t) \int_\Gamma \hat{a}_m \cdot d\hat{l}$$

where mode *m* has vector potential $\vec{A}_m = q_m(t)\hat{a}_m(\vec{r})$

Electrostatic potential depression (EPD)

- Funded by U.S. DOE/Stewardship program
  - Project was to design a high-efficiency klystron (>80%), we proposed doing so using the electrostatic potential depression method.
- Accomplishments
  - Theoretical investigation complete, work published in *IEEE Trans Electron Devices*.
  - Experiment design, mechanical design and fabrication, low-power test, setup assembly complete.
  - A high-efficiency (83%), compact (0.65 m), 956.2-MHz klystron architecture design complete.

1930 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 68, NO. 4, APRIL 2021

High Efficiency Compact Microwave Sources Using Electrostatic Potential Depression

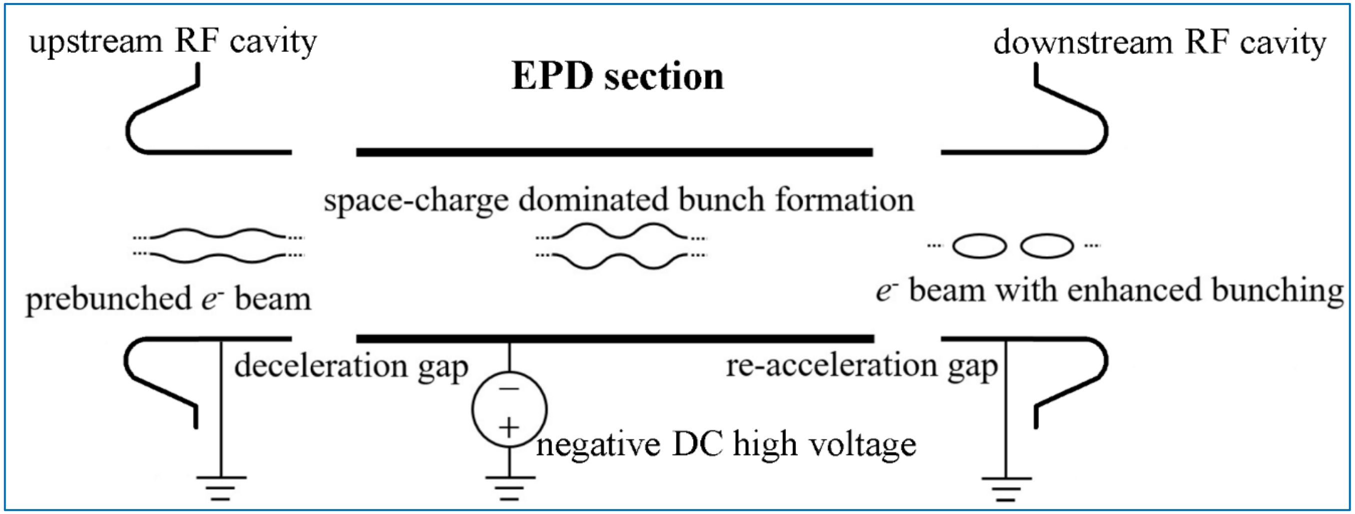
Haoran Xu, Quinn R. Marksteiner, and Bruce E. Carlsten, *Fellow, IEEE*

***Abstract*—In this article, we report theoretical and design studies on the application of an electrostatic potential depression (EPD) on two types of traditional microwave sources, the klystron and the inductive output tube (IOT), both operating in the UHF band. The EPD is implemented by a section of the metallic beam pipe on which a direct current (dc) negative high voltage is applied. Inside the EPD section, the modulated electron beam develops into bunches over a very short longitudinal distance, indicating a possible design approach for a compact device. With the application of an EPD, the peak value of the first harmonic current in a microwave tube can be further increased compared to that in a conventional design, suggesting higher circuit efficiency. As the electron beam leaves the EPD section, the reacceleration of the beam provides a longitudinal cooling effect. With the addition of an EPD, circuit power extraction efficiency above 80% is achieved in both the modified design of the IOT and the novel conceptual circuit design of the klystron.**

the DBA, each with 48-μs pulses at an output power level of 20 MW and at a repetition rate of 50 Hz [4]. Meanwhile, the research and development activities are ongoing for high-efficiency microwave sources for another major facility, the European Spallation Source (ESS) [5]. Instead of the option of an MBK, the 84 high-β superconducting accelerator cavities are planned to be powered by a high-efficiency multibeam inductive output tube (MB-IOT). Each MB-IOT outputs 1.2 MW of RF power at 704.42 MHz with a duty factor of 4%–5%. The ESS MB-IOT and the CLIC DBA MBK have similar levels of average output power, and even a small increase in their efficiencies can make a great improvement in power and energy savings for these facilities with enormous power consumption.

Among the modern electron beam bunching techniques, core oscillation method (COM) [6], [7], core stabilization

Features of electrostatic potential depression (EPD)

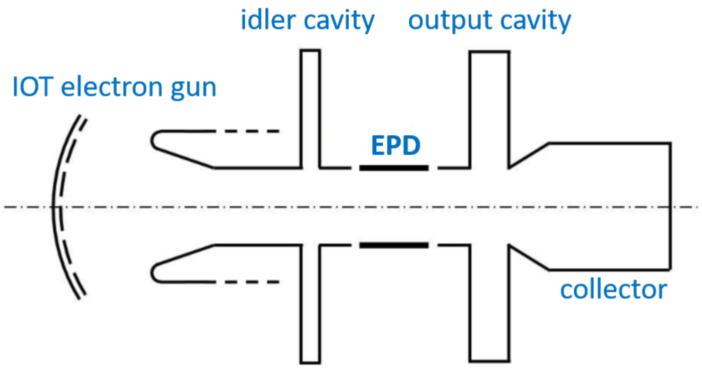


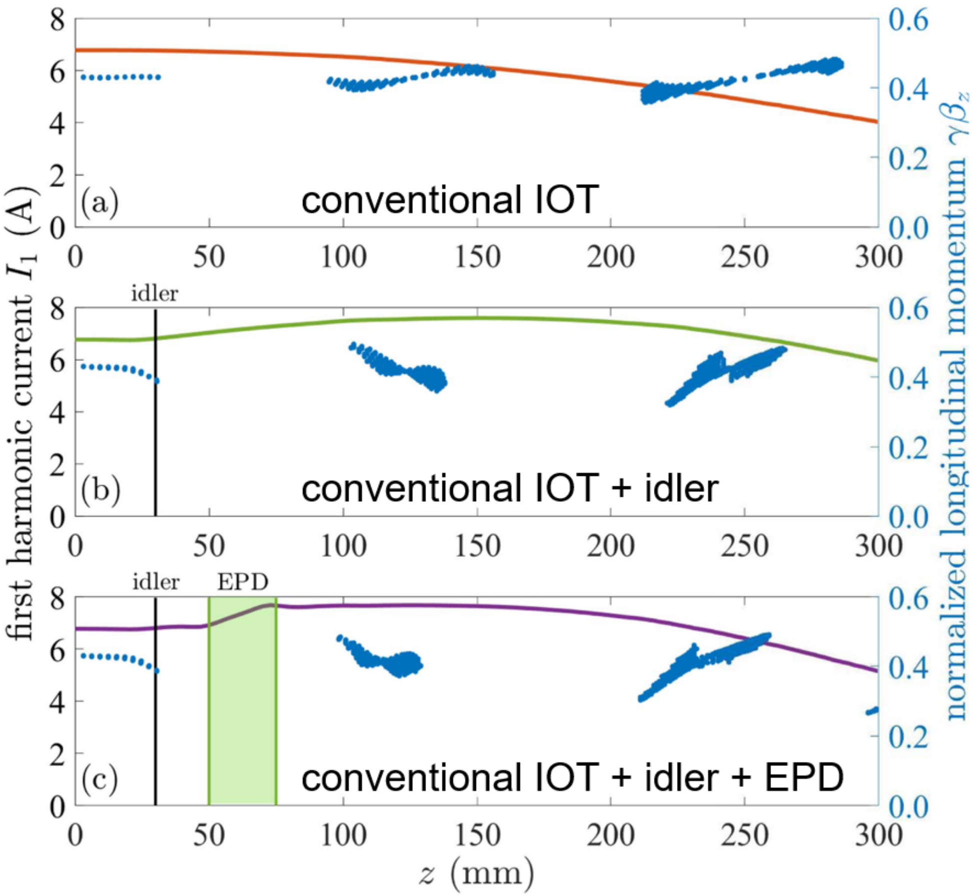
- **Enhanced bunch formation**
  - Deceleration → enhanced bunch formation → re-acceleration
  - Space charge aids bunch formation (but need to be careful)
- **Compactness**
  - Beam velocity significantly slowed down for bunching development
- **Reduced energy spread**
  - RF modulation homogenized by the enhanced space charge effect.
  - Need a lower velocity modulation plus there is longitudinal cooling by re-acceleration – beam ends up more monoenergetic which preserves bunching

EPD-assisted IOT

Modified 956.2-MHz IOT

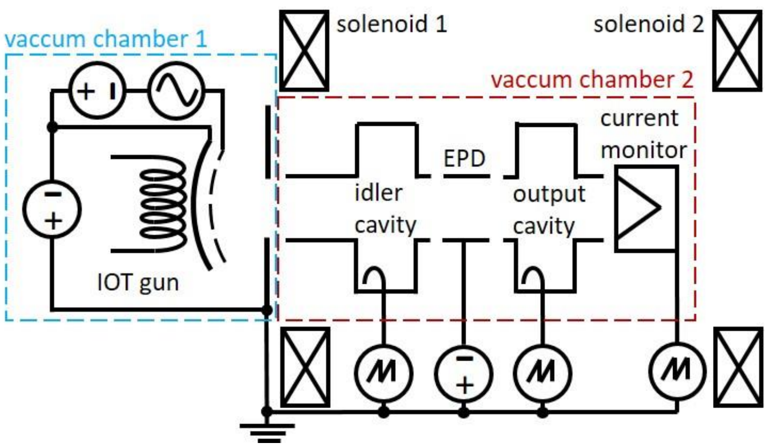
- 45 kV, 4.0 A.
- One idler cavity and one EPD section added to a conventional IOT.
- Particle-in-cell simulations in TUBE and CST.
- Efficiency increased from 77% to 84%.

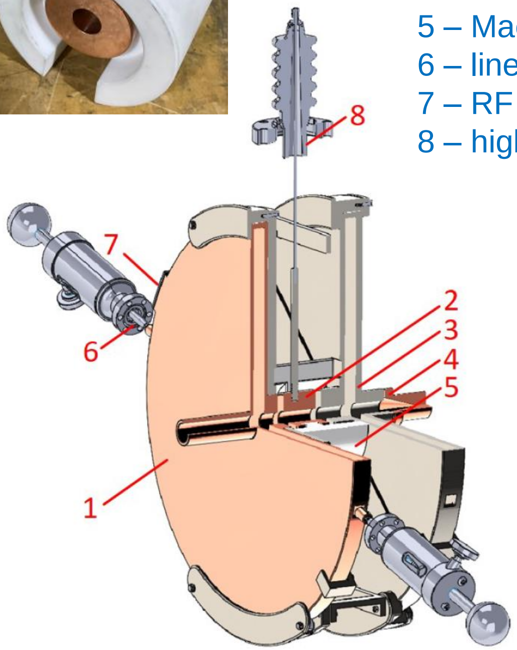




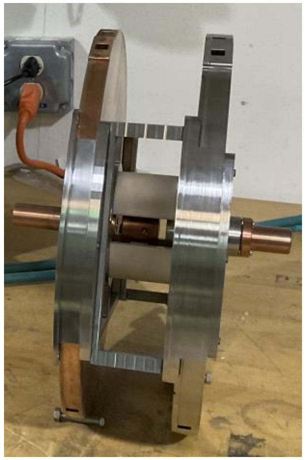
IOT experiment at University of Maryland (using the Naval Research Laboratory IOT)

- **Navel Research Laboratory 700-MHz IOT**
  - 20-30 kV, 0.55/2.2-A average/peak current.
- **Goal**
  - To demonstrate the increase of the bunching level (first harmonic current) by the EPD unit.



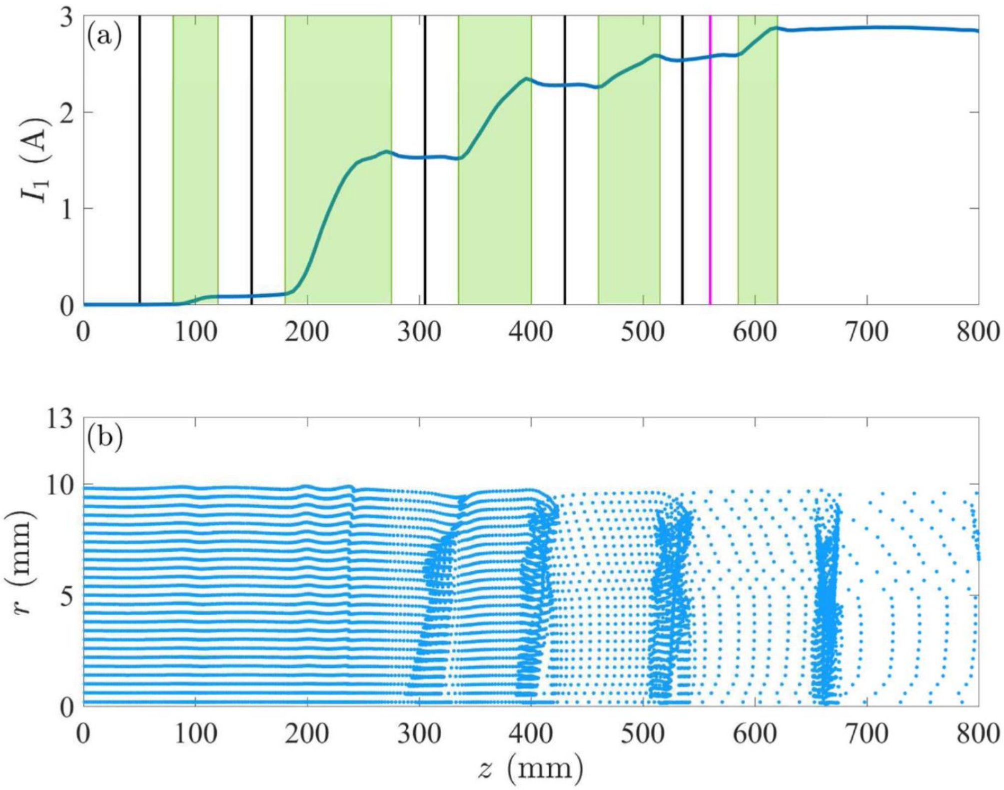


1 – idler cavity
2 – EPD section
3 – output cavity
4 – current monitor
5 – Macor spacers
6 – linear motion feedthrough
7 – RF coupler port
8 – high voltage feedthrough



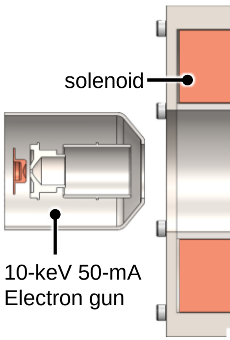
EPD-assisted high-efficiency klystron

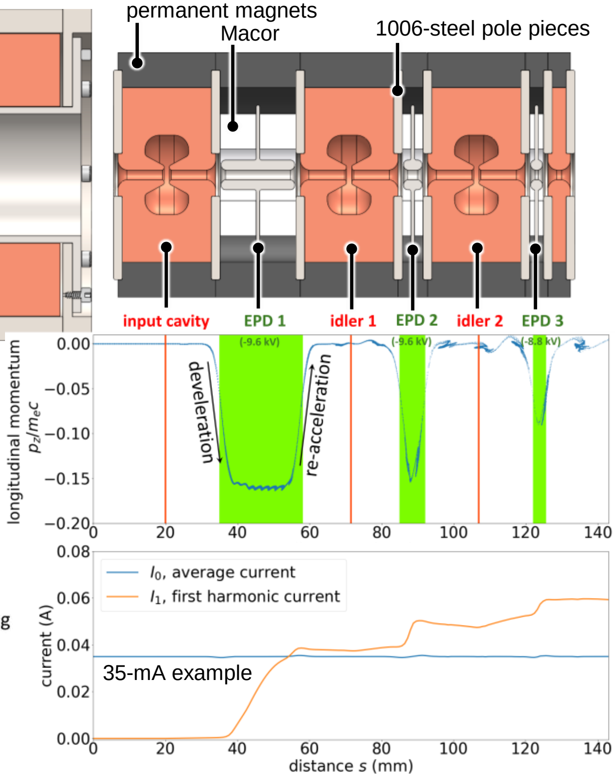
- **956.2-MHz multi-cavity klystron**
  - 80 kV, 2.0 A (0.09 μPerv).
    - Higher perveance calls for an annular electron gun.
  - 83% efficiency.
  - 0.65-m circuit length.
  - Core-oscillation method klystron.
    - 5.8-m circuit length without EPD.
  - Architecture
    - Input cavity and four idler cavities.
    - Five EPD units, each downstream of an RF cavity.
    - One second harmonic cavity.

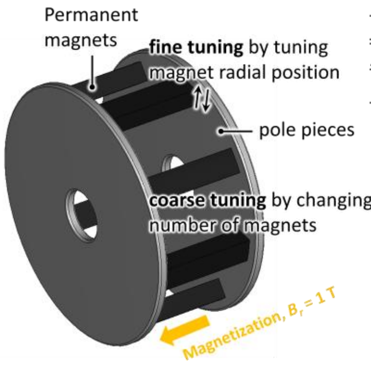


Haoran is now developing a compact buncher for compact accelerators using EPD

- Bunching DC electron beam into 5.7-GHz rep-rate bunches.
- For compact RF electron accelerators.
  - Compactness: EPD approach**.
  - Minimizing beam waste: Ballistic + nonlinear space-charge bunching.
  - Minimizing power consumption: Tunable periodic permanent magnet focusing***.
- Experimental demonstration in FY25







*) H. Xu *et al.*, *IEEE Trans. Electron Device*, 68(4), pp. 1930-1936, 2021.
**) M. Sanchez Barrueta, *abstract #285 for LINAC 2024*, 2024.
***) K. A. Shipman *et al.*, *in Proc. IPAC 2024*, no. MOPC41, 2024.

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Summary

- We've discussed the klynac architecture and related architectures
- The klynac can be singly resonant or bi-resonant
  - We know how to make a bi-resonant klynac work and it can have 25% overall efficiency
  - A single resonant cavity klynac will likely be able to have higher overall efficiency
- Klynac has compactness and temperature stability advantages, particularly in the $\pi/2$ mode

- *Further work needs to be done to understand the turn-on of a singly-resonant structure and to evaluate the relative strengths/weaknesses of all the different variants (including the KlyLac)*

- We also discussed using electrostatic potential depression to enhance the efficiency of klystrons and IOTs
- We are now extending this technology to compact accelerators