Partially–Grounded Depressed Beam CollectorΩ for O-MBK and Beyond

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Abstract:
To address RF source inefficiency, we present a design of an L-band multi-beam klystron with a new type of depressed collector. It comprises a grounded element, a magnetic lens, and an electrode held at negative potential. This collector allows recovery of a larger portion of energy in the spent electron beams than could a conventional depressed collector, and will increase the tube efficiency towards 80 percent in a single stage.

Summary:
A high-power single-stage Partially-Grounded Depressed Collector (PGDC) for the 2.5-MW, 60-kV, L-band multi-beam klystron (MBK) is being developed [1]. A single-stage PGDC obtains high energy recovery - comparable to that of a four-stage conventional depressed collector - through use of a grounded collector portion that absorbs reflected low-energy electrons, preventing their return to the MBK cavities or cathode. Further, a steep gradient in applied magnetic field near the voltage gap before the depressed collector-electrode, together with space charge, imparts transverse deflection to beam electrons and provide trapping of electrons against leaving the collector. Theory and simulations for a beam that upon exit from the output cavity has a prescribed energy distribution, predict an increase in the 65% intrinsic MBK efficiency to up to 80%. The layout for a single-stage depressed collector is relatively simple; adding additional stages is estimated to result in greater efficiency enhancement: e.g., 4 stages would yield an 87% net tube efficiency. The principles invoked in this project for a 60-kV, 12 A per beam-let, 6 beam-let MBK should be applicable for other high-power linear beam tubes, such as conventional klystrons, IOTs, and travelling-wave tubes.

... depressed collector (DC) is a component used to recover unexpended power from a spent electron beam after it emerges from the output cavity;

--- increases the tube efficiency;
--- reduces the waste heat.

... known techniques to design:

(a) shaping applied electric and magnetic fields to guide electrons along trajectories to specific areas within the collector [2, 3]*;
(b) employing asymmetry in the collector geometry to prevent back-streaming of reflected primary and secondary electrons [4, 5];
(c) applying transverse magnetic fields to reduce back-streaming [6, 7]; and
(d) using materials of low secondary emission coefficient [8, 9].

* see reference section at the end of the presentation
Presented beam collector some of the above mentioned techniques;

PGDC = “partially grounded depressed collector”…

...comprises a grounded element (b:1), a magnetic lens (b:2), and an electrode (b:3) held at negative potential. (Space-charge effects are absolutely important too!)

Figure. Schematics of linear beam microwave tubes (a) without DC, (b) with PGDC, and (c) with two-stage DC
Figure (left) Layout of a PGDC, and (right) static electric potential and magnetic field distributions along each beam-let axis within the depressed collector as configured to work with the O-MBK (will be presented momentarily).
6-beamlet O-MBK demonstrated [10] good performance achieving nearly 60% efficiency and producing 2.86 MW output at 60 kV in 15 µs-long pulses at a 60 Hz prf.

**Figure.** (a) a 3D cut-away view of Omega-P’s recently-built 1.3 GHz O-MBK; (b) photo showing the tube before it was inserted into the coil-assembly. (c) the assembled setup at the CPI test site; (d) the 6 beam-let gun of the 1.3 GHz, 60 kV MBK during cathode tests; and (e) the tube’s beam collector (shown without external cooling casing), showing one channel for each beam-let.
**Figure** Performance of the Omega-P 1.3 GHz, 60 kV O-MBK are shown, via typical traces of gun voltage (yellow); current (blue), output power (green), and input power (magenta). Here the output power trace is \( \sim 12 \) µs long.
Figure. An example of a family of transfer curves for the coil settings that minimized the body-interception.

Transfer curve: Output-power vs Input Power

BASELINE: O-MBK

After optimization

F=1.3GHz, PRF = 60 Hz
10 μsec RF

Steep slope moved to
~3.5W
@ 60kV

No steep slopes above 2.5W when
working @ 59kV and below

56kV
58kV
59kV
60kV

2.5 MW
2
1.5
1
0.5

500
1000
3000

![Graph showing transfer curves for different voltages and powers.](image-url)
Figure. Example of investigations of the bell-jar shape of the dependence of the output-power vs. the RF frequency at 60kV vs. different coil settings.

Even if the slope is sharp, it was moved away from 1.3 GHz by 1.5 MHz... and... in addition we see the power-output is still above 2.5 MW.
For O-MBK $V_e = 21kV; \ V_m = 3 \ kV$

If $V_C$ is set to be $V_m$, then $I_C = I_B$

$\eta_C = 14.3\% \ \text{and}$

$\eta_t \rightarrow 68\%$

Regime of “simple” DC

The tube efficiency is

$$\eta_t = \frac{I_B(V_B - V_e)}{I_B V_B - I_C V_C} = \frac{\eta_e}{1 - \eta_c(1 - \eta_e)}$$

where the RF circuit efficiency $\eta_e$ without the DC is defined as $\eta_e = 1 - V_e/V_B$ and the collector efficiency $\eta_c$ is defined as $\eta_c = I_C V_C/I_B V_e$. 
Increase $V_C$ above $V_m$ but remember that

$$I_C = \int_{V_C}^{\infty} J(V) dV$$

where $J(V)$ is the beam-distribution vs. voltage (energy)
Different distributions have been studied

<table>
<thead>
<tr>
<th>Current Distribution</th>
<th>$J(V; V_0)V_0/I_B$</th>
<th>$V_0^*$</th>
<th>$V_c$ (kV)</th>
<th>$\eta_t$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>1</td>
<td>$2(V_e - V_m)$</td>
<td>20</td>
<td>79</td>
</tr>
<tr>
<td>Linear</td>
<td>$\frac{V_{\text{max}} - V}{V_{\text{max}} - V_m}$</td>
<td>$3(V_e - V_m)/2$</td>
<td>19</td>
<td>77</td>
</tr>
<tr>
<td>Un-shifted Gamma</td>
<td>$V e^{-V/V_0}/V_0$</td>
<td>$V_e/2$</td>
<td>17</td>
<td>76</td>
</tr>
<tr>
<td>Un-shifted Maxwell</td>
<td>$\sqrt{4V/\pi V_0}e^{-V/V_0}$</td>
<td>$2V_e/3$</td>
<td>18</td>
<td>75</td>
</tr>
<tr>
<td>Shifted Gamma</td>
<td>$\frac{V - V_m}{V_0}e^{-\frac{V - V_m}{V_0}}$</td>
<td>$(V_e - V_m)/2$</td>
<td>16</td>
<td>77</td>
</tr>
</tbody>
</table>

The optimal tube efficiencies all appear to be above 75% for a single-stage PGDC independent of the specific spent beam distribution.

* Distribution scaling-parameter, adjusted so as to have the full current be $I_B$
**Shifted Gamma distribution** leads to a prediction of a collector efficiency $\eta_C = 44\%$ and a net tube efficiency of $\eta_t = 76.8\%$. 

**O-MBK**: Histogram of electron energies entering the collector. Red curve: shifted gamma distribution curve fitted to the histogram. Insert: energies versus time in the spent beam and the minimum beam energy $V_m = 3\ kV.$
Figure. Comparison of overall efficiencies among the RF circuit (no DC, black curves), the conventional SDC (green curve), the conventional MSDC (blue curve), and our proposed PGDC (red curve). The conventional MSDC is modeled as a four-stage DC with voltages $-3$, $-10$, $-30$, and $-60$ kV for each stage, with a maximum efficiency of 80%.
Figure: the net tube efficiency $\eta_t$ with PGDC versus the spent beam voltage spread at different beam-to-RF efficiencies $\eta_e$. The voltage spread is normalized to the average spent beam voltage $V_e$. The red dotted curve shows the depressed collector efficiency $\eta_c$ for the case of a uniform distribution of spent beam current. The smaller the voltage spread, the higher will be the net tube efficiency.

...balance the RF circuit efficiency and spent beam voltage spread.

\[ \eta_c \]

\[ \eta_e = 67\% \]

\[ \eta_e = 60\% \]

\[ \eta_e = 50\% \]
**Figure (left)** Layout of a PGDC, and **(right)** static electric potential and magnetic field distributions along each beam-let axis within the depressed collector as configured to work with the O-MBK.
PGDC efficiency versus DC voltage.
Blue curve = reflected current.
Red curve = collector efficiency.
Green curve = total tube efficiency.
PGDC efficiency versus DC voltage.
Blue curve = reflected current.
Red curve = collector efficiency. Green curve = total tube efficiency.
O-MBK case w/ PGDC

no secondary emission

Spent-beam trajectories; (space charge effects are included)
O-MBK case w/ PGDC

**no secondary emission**

**(top)** Histogram of electron final positions.

**(bottom)** Average power density distribution on the collector inner surface in the PGDC with DC voltage at $-15$ kV, space-charge effects included,

\[ P_{\text{peak}} \approx 75 \text{ W/cm}^2 \]
O-MBK case w/ PGDC

secondary emission is ON

...the secondary electrons are well constrained inside the collector.
O-MBK case w/ PGDC

unmodulated beam (no input RF)

\[ P_{\text{peak}} \sim 180 \text{ W/cm}^2 \]
Figure as appears in [1]: PGMSDC total tube efficiency $\eta_t$ (solid curves) and collector efficiency $\eta_c$ (dotted curves) versus the last stage voltage $V_n/V_0$, with single (purple curves), two (blue curves), three (green curves), four (red curves), and higher stages (brown curves), where the RF circuit efficiency without DC $\eta_e$ is set at 65% and the spent beam is taken to have a gamma distribution For four stages, the PGMSDC tube efficiency is predicted to be 87%.
Aim of the project is to develop a cost-effective PGDC to boost the efficiency of O-MBK above 75%, or even to 80%.

The key components include a grounded element, a magnetic lens, and an electrode held at negative potential. (Space-charge effects are absolutely important too!)
References


The purpose of this year’s Working Group 3 is to discuss recent advances in achieving higher gradients and better acceleration efficiency in externally powered structure-based accelerators, both laser driven and microwave. The capability to accelerate particles at higher accelerating gradients with less power is essential for reduction of size and cost of future accelerators for DOE missions and industry. This includes the future multi-TeV e+e- collider for High Energy Physics, free-electron lasers (FELs) for Basic Energy Sciences and National Security, and industrial accelerators for Energy and Environmental Applications. The working group welcomes presentations on the following topics:

1. Recent developments in novel accelerating structures over the range of frequencies from microwaves to Terahertz and optical spectrum.
2. Demonstration of high (100 MV/m and above) accelerating gradients in structures.
3. Recent advances in understanding the breakdown phenomenon at different frequencies and materials and other limitations to the accelerating gradient, such as pulse heating.
4. Investigations of new structures’ geometries, and new materials (normal conducting, superconducting, and dielectric).
5. Novel fabrication technologies for accelerating structures that cannot be fabricated by conventional means (such as additive manufacturing and micromachining).
6. Advances in other externally-driven accelerating schemes such as inverse free-electron lasers (IFELs).
7. RF source development with the emphasis on high efficiency and high average power; the talks on integrated RF sources from the AC line to the accelerator structure are particularly welcome.
8. Challenges in simulation of novel accelerating structures and breakdown phenomena and higher order mode damping in novel structures.

The group will also try to address issues such as increasing wall-plug-to-beam efficiency, and multi-stage prototyping for a multi-TeV e+e- collider and X-ray FELs.