MuCol

# High Efficiency Klystrons for MuCol

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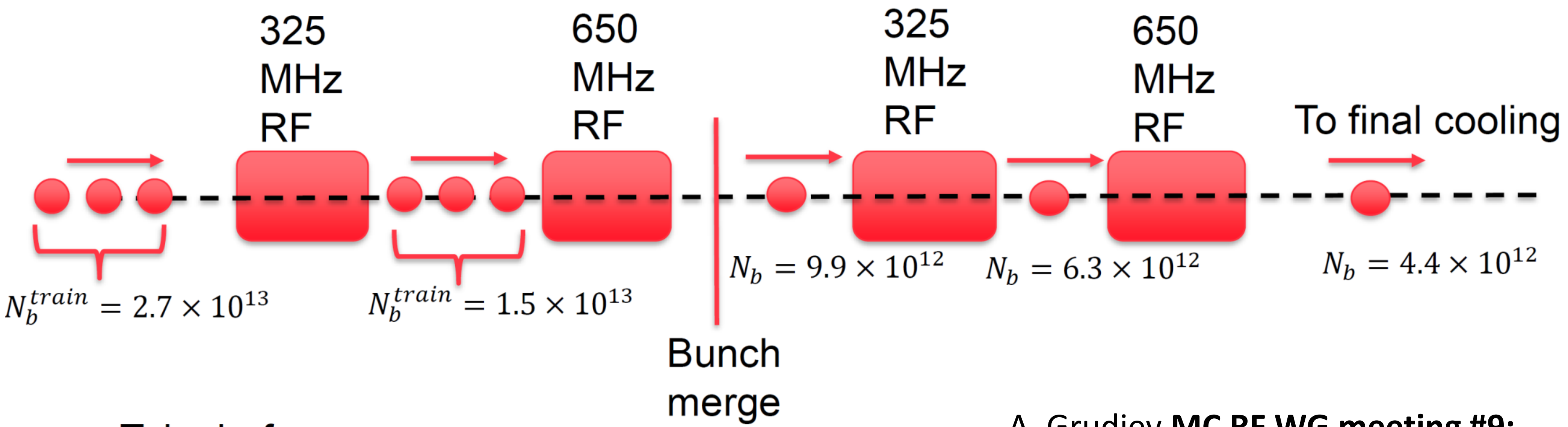
# Cooling channel: beam parameters



325 MHz RF

650 MHz RF

325 MHz RF

650 MHz RF

To final cooling

$N_b^{train} = 2.7 \times 10^{13}$

$N_b^{train} = 1.5 \times 10^{13}$

Bunch merge

$N_b = 9.9 \times 10^{12}$

$N_b = 6.3 \times 10^{12}$

$N_b = 4.4 \times 10^{12}$

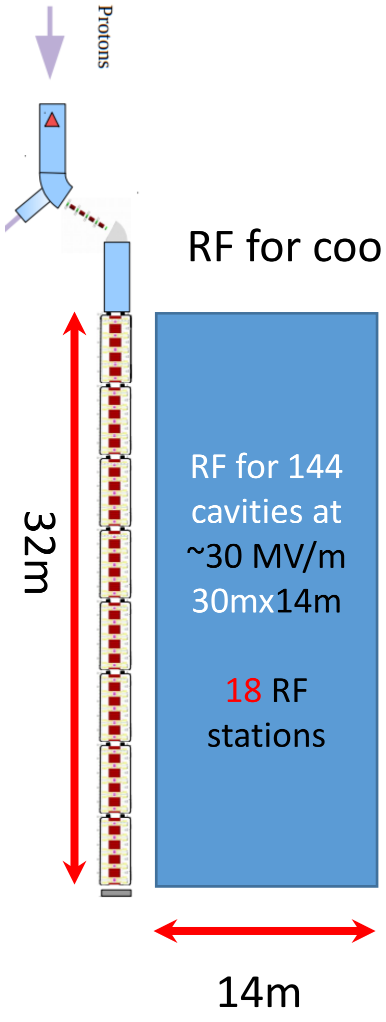
Take before merge
$N_b^{train} = 2 \times 10^{13}$
for simplicity

A. Grudiev **MC RF WG meeting #9:**
March 22

# Muon cooling demonstrator layout
# High peak power klystron: 24 MW

A. Grudiev and R. Losito
**MC RF WG meeting #5:**
Sept 21

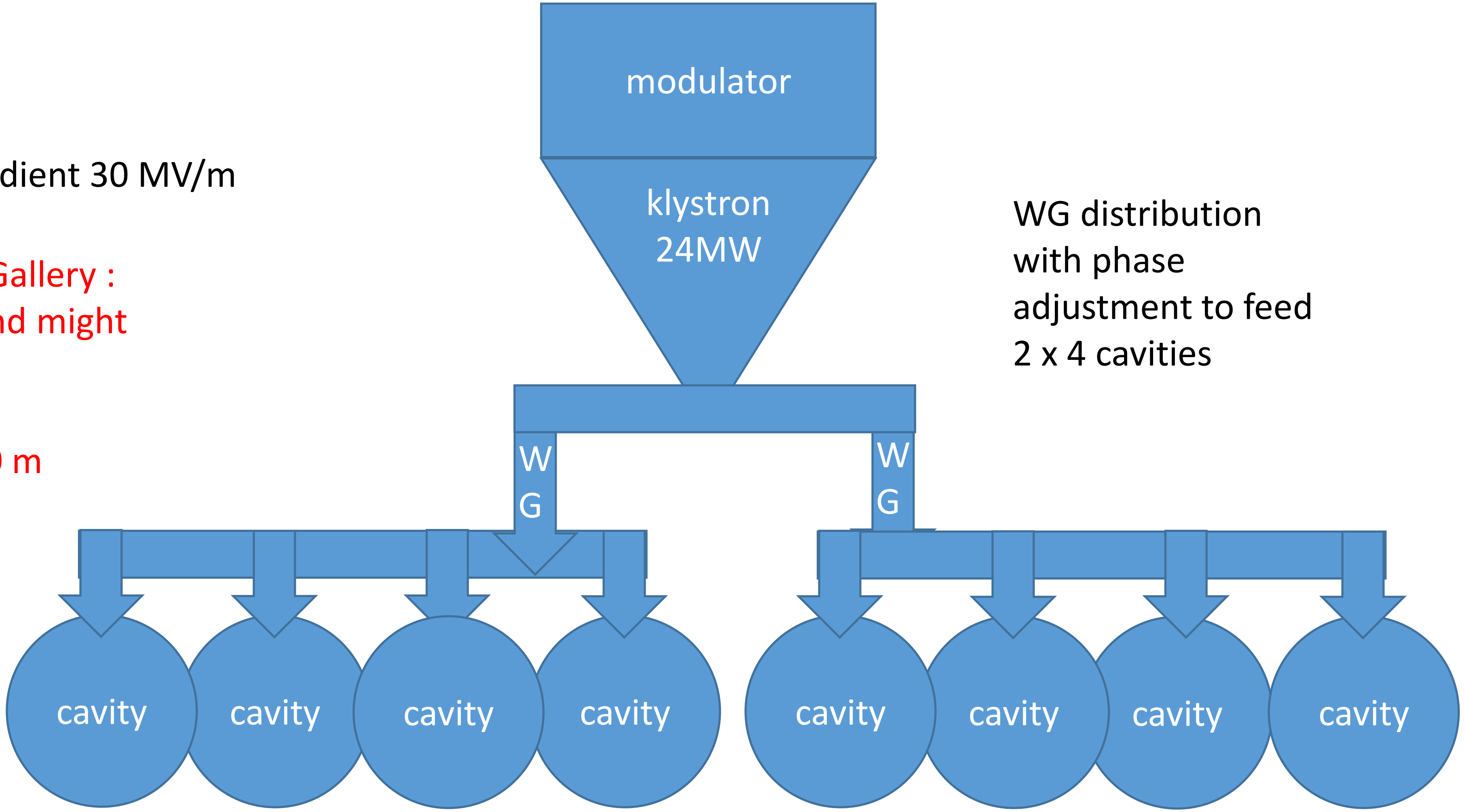
RF for cooling: Max. gradient 30 MV/m



RF for 144 cavities at ~30 MV/m 30mx14m

18 RF stations

Building -> Gallery : (underground might be possible)
30m x **15m**
Height: 8-10 m



WG distribution with phase adjustment to feed 2 x 4 cavities

# Existing tubes

While tubes >24 MW exist they are all above 3 GHz

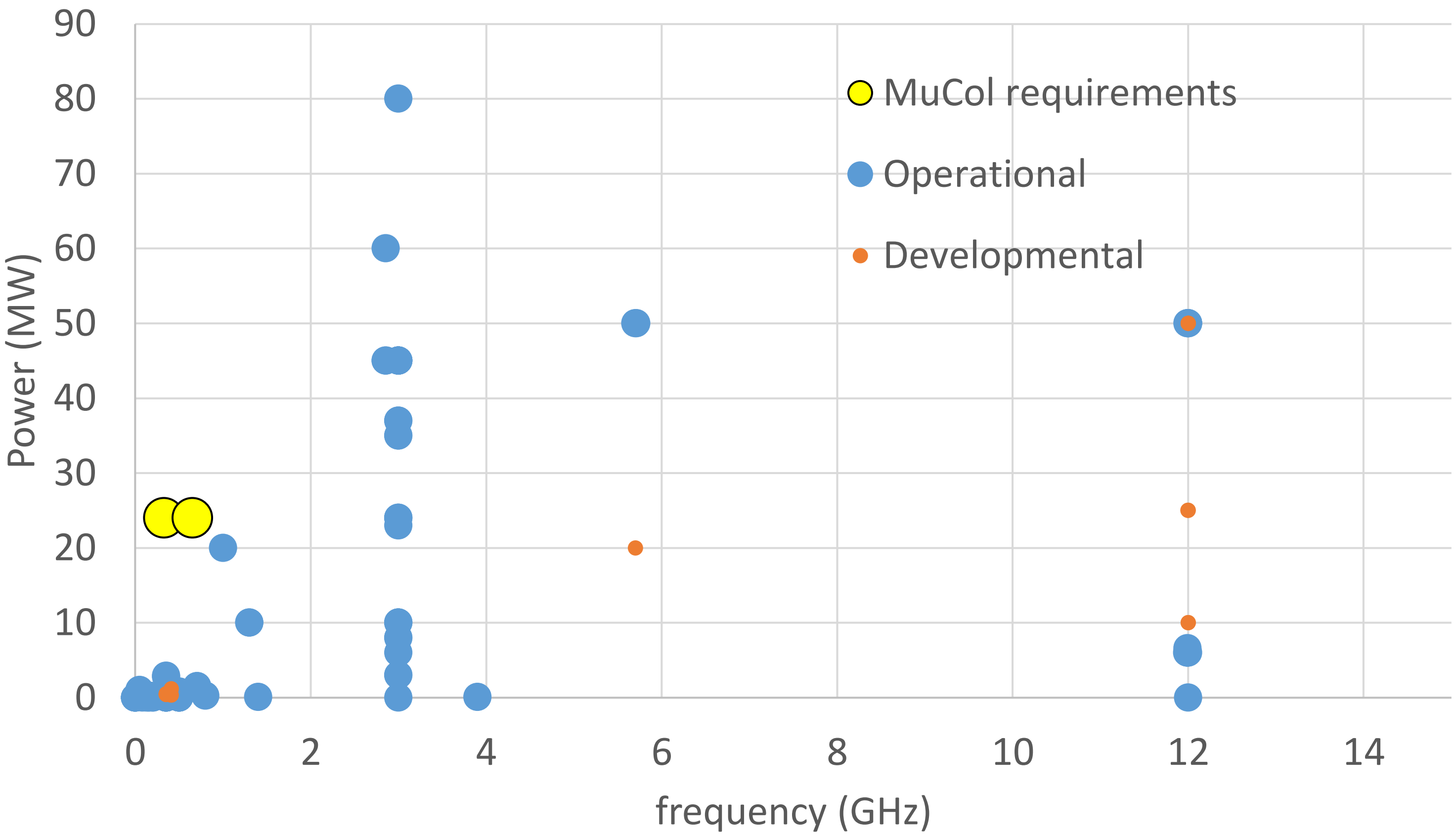
There are 10-20 MW tubes developed for CLIC drive beam and ILC at 1-1.3 GHz

Nothing of this power exists at 325 or 650 MHz

Issue is typically that to get high power means high voltage which makes the tubes longer

For scaling at low frequency this used to not be feasible as length is inversely proportional to frequency for constant beam

New developments may change that........



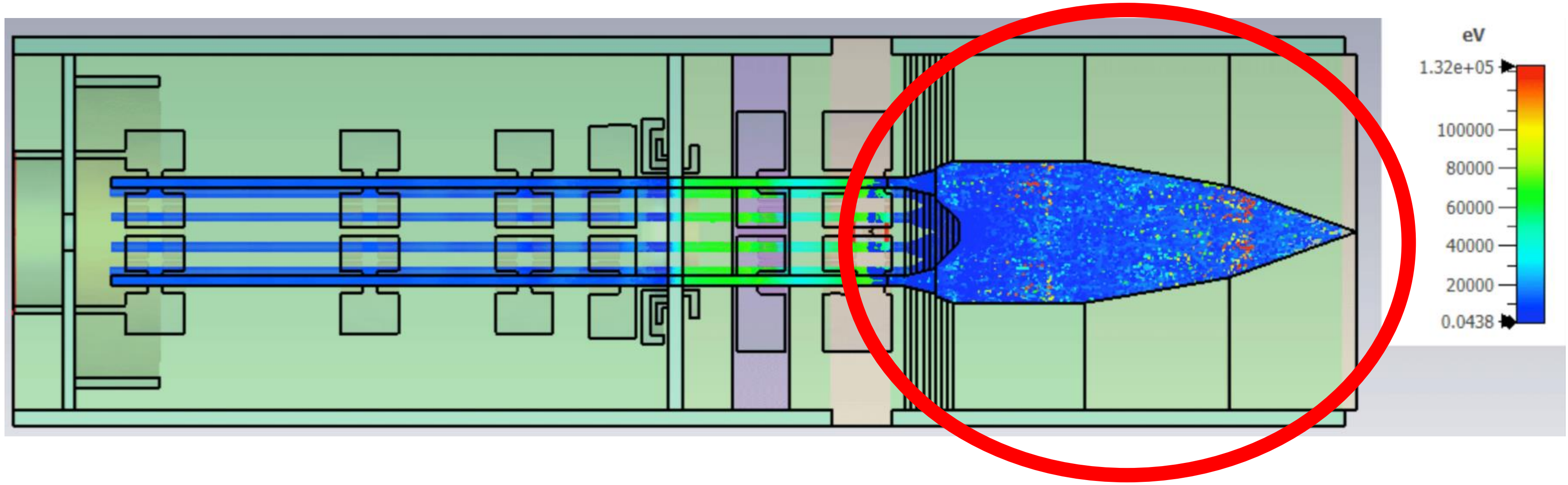
# High power L-band Multi Beam Klystrons (MBK). Commercial tubes.

Frequency: **1.0 GHz**
Peak RF power: 20 MW
Efficiency: 70%

Frequency: **1.3 GHz**
Peak RF power: 10 MW
Efficiency: 65%

# Collector

- A large chunk of a klystron's length is the collector
- In DC mode the collector must absorb the entire beam power, and dissipate the heat load without heating up too much
- The Canon E37503 had a max heat load of 300 kW and was 1.5m long (ie half the tubes length)
- The DC heat load for the muon collider klystron is sub-5 kW and hence a much shorter collector can be used (30 cm may be fine).



# Scaling Klystrons (PSP)

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 66, NO. 2, FEBRUARY 2019 1075

Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons

Jinchi Cai, Igor Syratchev, and Zening Liu

- Key numbers in klystron scaling is the electron wavelength, Beta, and the bunching parameter, A,

$$(\beta_e = \omega/v_e).$$

$$A = \frac{I_0}{U_0^{\frac{3}{2}}} \frac{\eta_0 U_e^{1/2}/\pi}{\gamma^2(\gamma+1)^{\frac{3}{2}}} \sum_{n=1}^{\infty} \frac{r_c^2}{r_b^2} \left[ \frac{2}{\mu_{0n}^2} \frac{J_1(\mu_{0n} \frac{r_b}{r_c})}{J_1(\mu_{0n})} \right]^2 .$$

- If we scale a klystrons voltage, current, or frequency certain relationships need be maintained

$$\begin{aligned} U_0 I_0 &= \text{constant} \\ f(\beta_e z) &= \text{constant}, \quad \sqrt{A}\beta_e L_{\text{drift}} = \text{constant} \\ \frac{1}{\rho Q} \frac{1}{|M(\beta_{e0})|} \frac{1}{N_b I_0} &= \text{constant} \\ \frac{n\omega - \omega_0}{\rho \omega_0} \frac{1}{|M(\beta_{e0})|} \frac{1}{N_b I_0} &= \text{constant}. \qquad (12) \end{aligned}$$

- In our case scaling from 1 GHz to 350 MHz, while keeping A constant would mean the length increases by a factor of 3

# Scaling the Canon tube to 0.7GHz, 24MW and 30 µsec.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**Canon E37503**
**6 beams MBK**

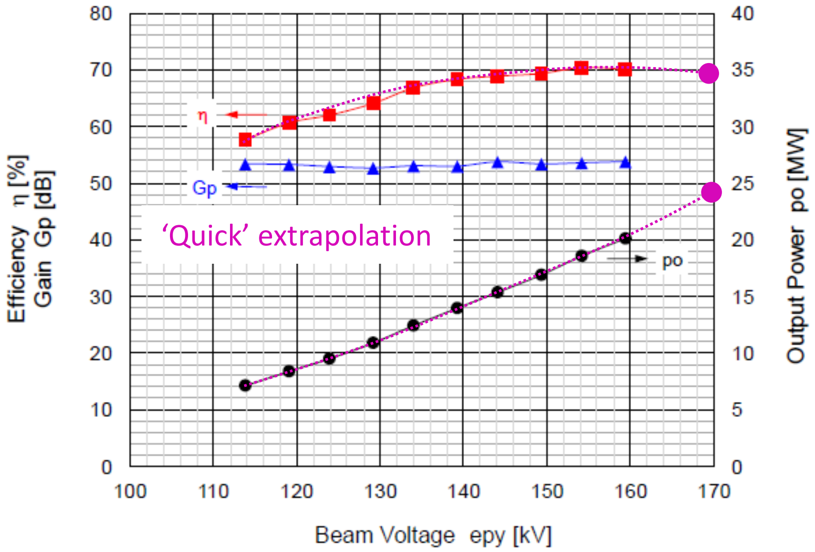
| | |
|---|---|
| **F=** | **999,5 MHz** |
| **P max=** | **20.2 MW** |
| **T =** | **150 µsec** |
| **V=** | **159.4 kV** |
| **I total =** | **180 A** |
| **Eff.=** | **70.5 %** |
| **uP=** | **0.47 µAxV$^{-3/2}$/beam** |
| **Gain =** | **53.9 dB** |
| **P$_{average}$ (50Hz)=** | **150kW** |

**Mu-tube, 0.7 GHz**
**6 beams MBK**

| | |
|---|---|
| **F=** | **700 MHz** |
| **P max=** | **24 MW** |
| **T =** | **30 µsec** |
| **V=** | **171 kV** |
| **I total =** | **200 A** |
| **Eff.=** | **70.0 %** |
| **uP=** | **0.47 µAxV$^{-3/2}$/beam** |
| **Gain =** | **53.9 dB** |
| **P$_{average}$ (5Hz) =** | **3.6kW** |

To our experience such a scaling is a ‘low’ risk development:

- For the fixed micro perveance, the tube length is proportional to the frequency
- Lower cathode current density (55%) and increased life time.
- Much lower average power (simpler collector)
- Marginal (~10%) increase of the modulator voltage and current.



**Cost and schedule:**

- The CLIC tube prototypes were designed/built about 10 years ago; Canon: **iiiii** and Thales : **iiiiii**. Mu-tube cost will be within this range, as the companies shall do it not from scratch, but could scale it from exiting ones. *Though, today there is no market for such devices, thus the cost of ‘unique’ prototype could be even higher.*
- Similar to the CLIC tubes, it will take about 24 month to design, built and test the first Mu-tube prototype. Additional budget will be needed for the testing infrastructure (like RF loads etc.).

# How do we reduce the size?

- Drift scales proportional to the bunching parameter, A, and the beam velocity.
  - We can use a higher beam voltage

$$\sqrt{A}\beta_e L_{\text{drift}} = \text{constant}$$

- Bunching parameter is given by

$$A = \frac{I_0}{U_0^{\frac{3}{2}}} \frac{\eta_0 U_e^{1/2}/\pi}{\gamma^2(\gamma+1)^{\frac{3}{2}}} \sum_{n=1}^{\infty} \frac{r_c^2}{r_b^2} \left[ \frac{2}{\mu_{0n}^2} \frac{J_1(\mu_{0n}\frac{r_b}{r_c})}{J_1(\mu_{0n})} \right]^2 .$$

- We could increase beamlet current (use less beams) but then the voltage needs to decrease
- Or the filling factor can be changed but this is only a 25% change.

# Two-Stage Multi Beam Klystron (TS MBK) technology.

## Specific features

1. Bunching at a low voltage (high perveance). Very **compact RF bunching circuit.**
2. Bunched beam acceleration and cooling (reducing $\Delta p/p$) along the short DC voltage post-accelerating gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

## Additional advantages:

1. For pulsed tubes, the second HV stage can be operated in DC mode. Thus simplifying the modulator topology. (cost/volume) and increasing the modulator efficiency.
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.

## Drawbacks:

1. Reflected electrons from the output cavity and collector shall be **avoided at any cost.**
2. RF radiation into DC gap has to be sealed.
3. Requires special HV isolated RF feedthrough to inject RF signal into input cavity.

**GOOD FOR:**

FCC hh ee he

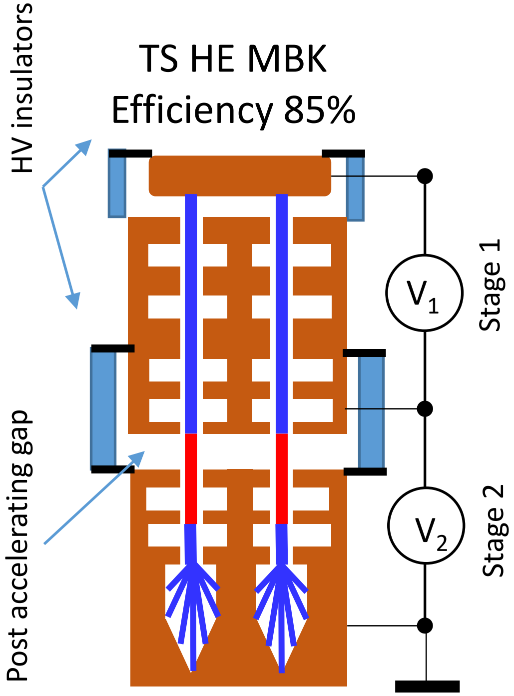
ilc

International MUON Collider Collaboration

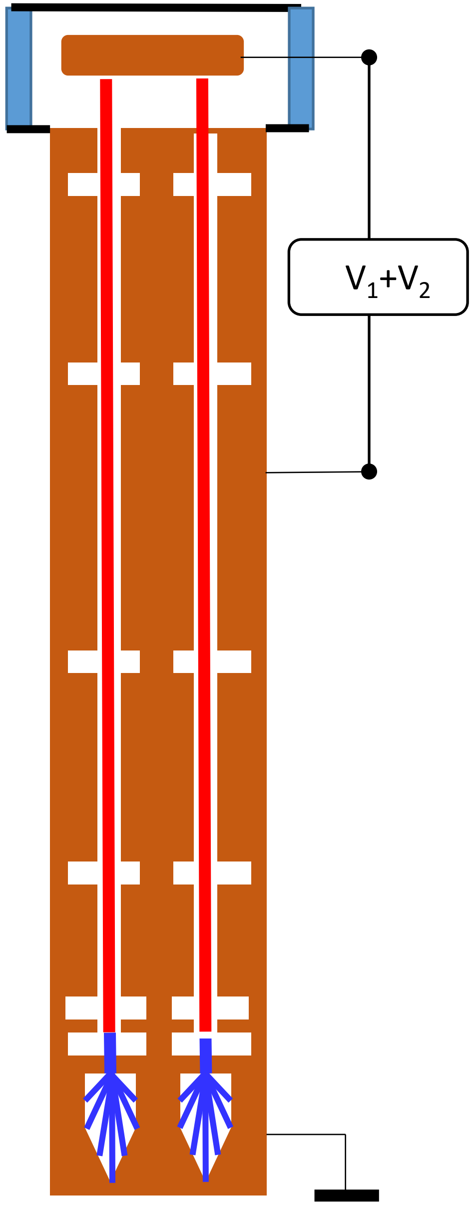
CLIC

CEPC

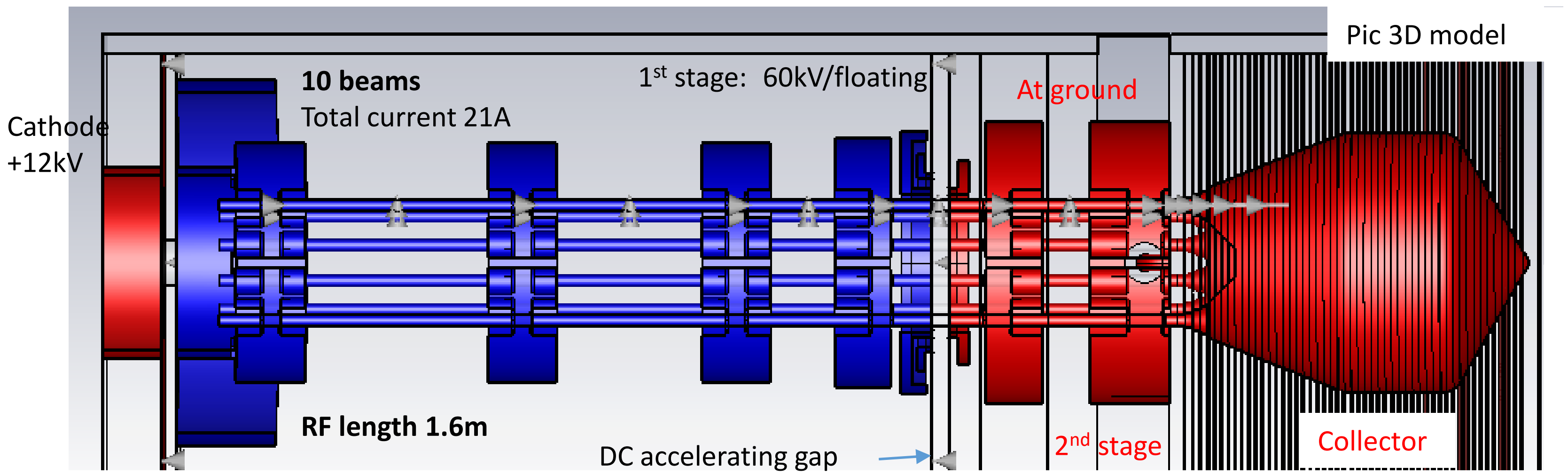
TS HE MBK
Efficiency 85%

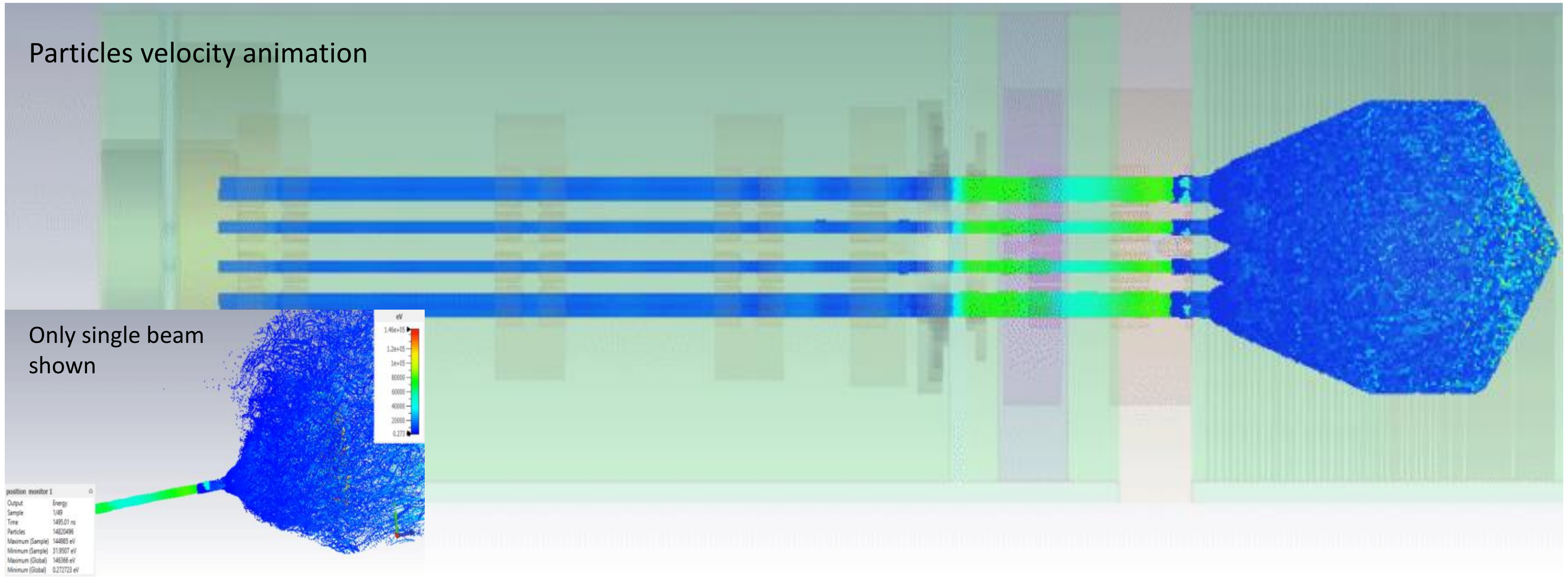


Commercial HE MBK
Efficiency 70%

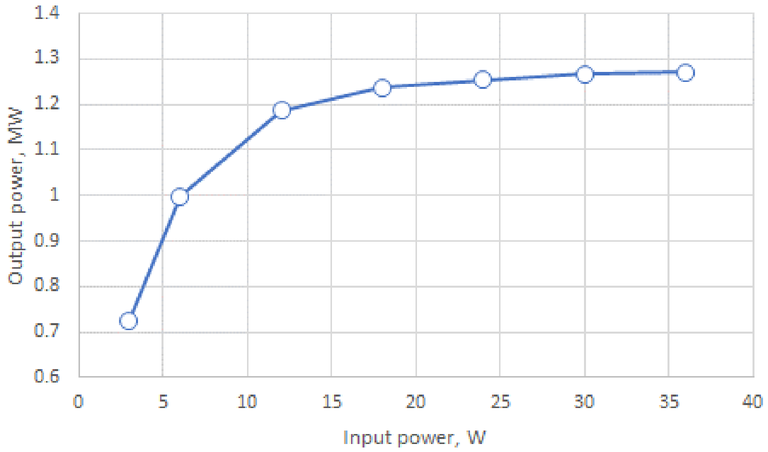


# FCC Two-stage MBK klystron: **CW, 400MHz, 1.28MW.**





Power gain curve at nominal voltage (PIC results)



- **Very Efficient: 84%**
- **Compact: ~2.5m length in total**
- **Low voltage: 60kV+12kV**
- **High saturated power gain: 46dB**

# CLIC Two-stage MBK klystron: **Pulsed, 1.0 GHz, 24 MW**

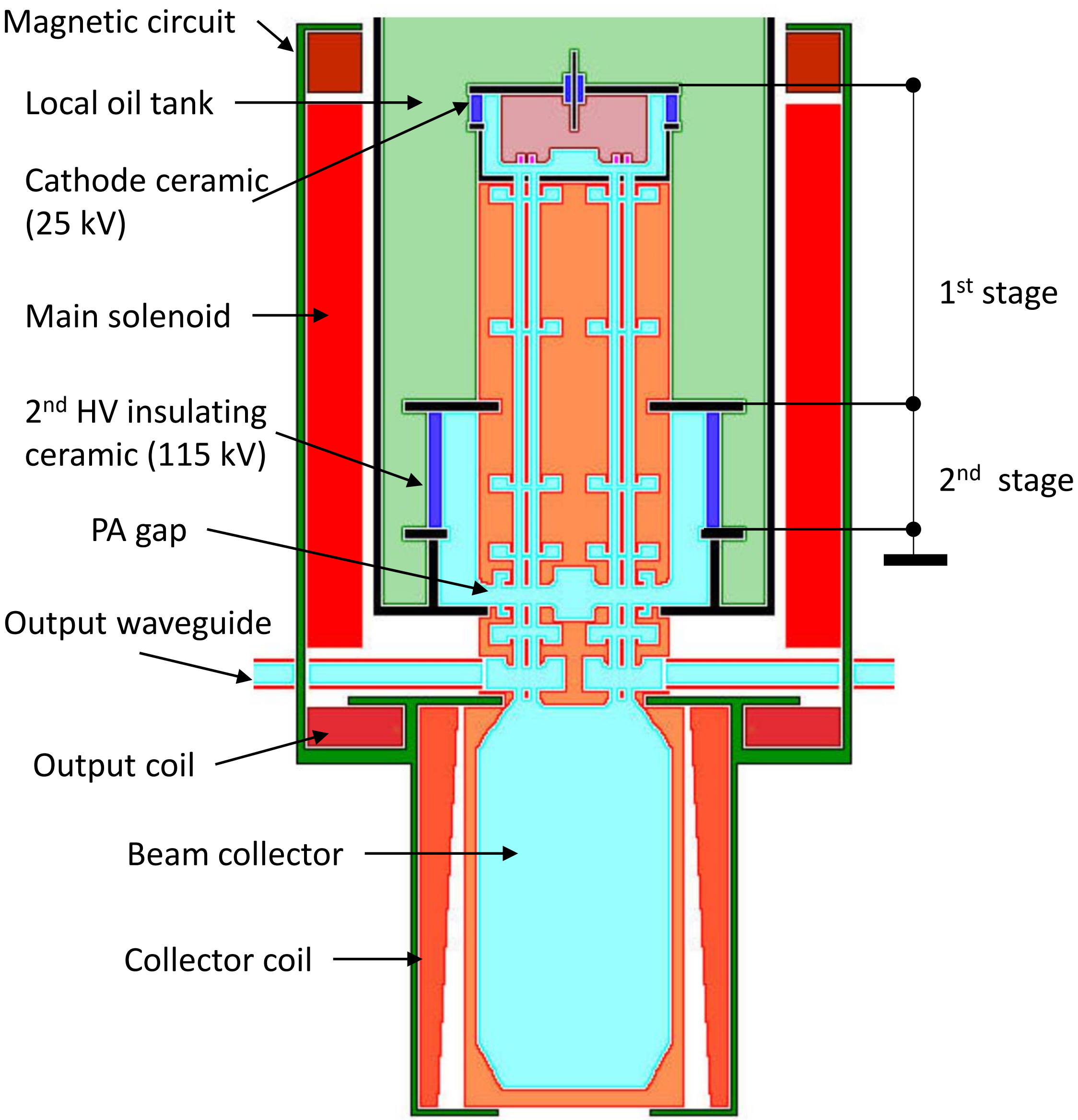
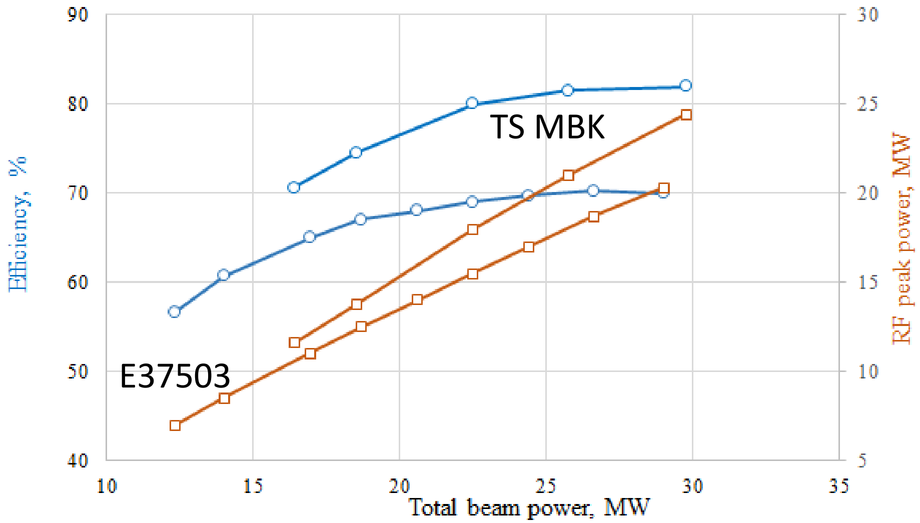
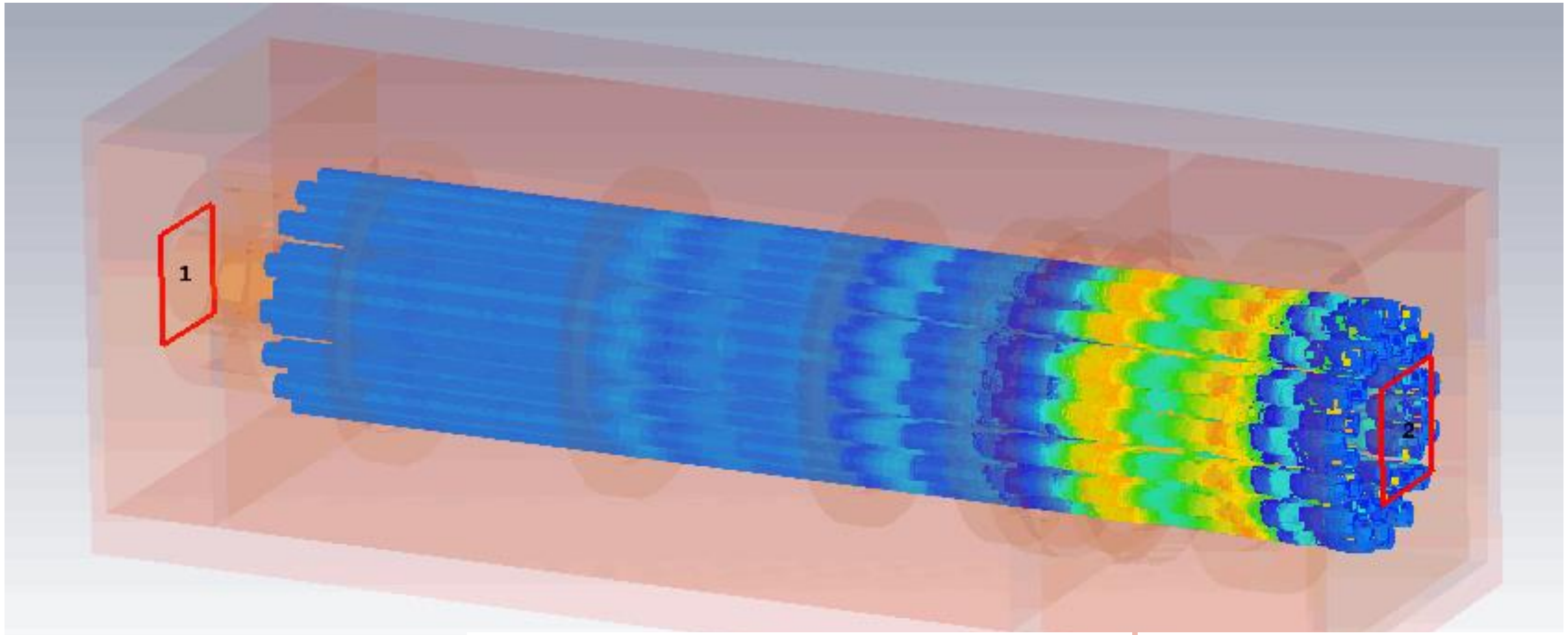


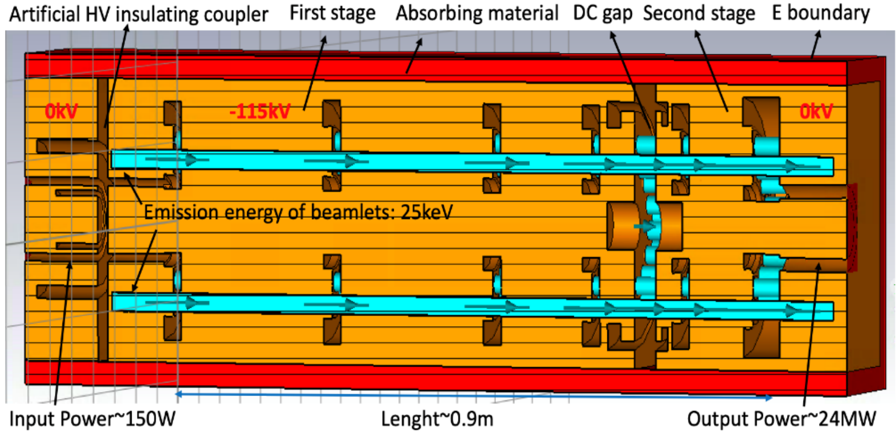
TABLE I. DESIGN AND SIMULATED PARAMETERS (CST/3D) OF THE CLIC TS MBK AND CANON MBK E3750 CATALOGUE DATA

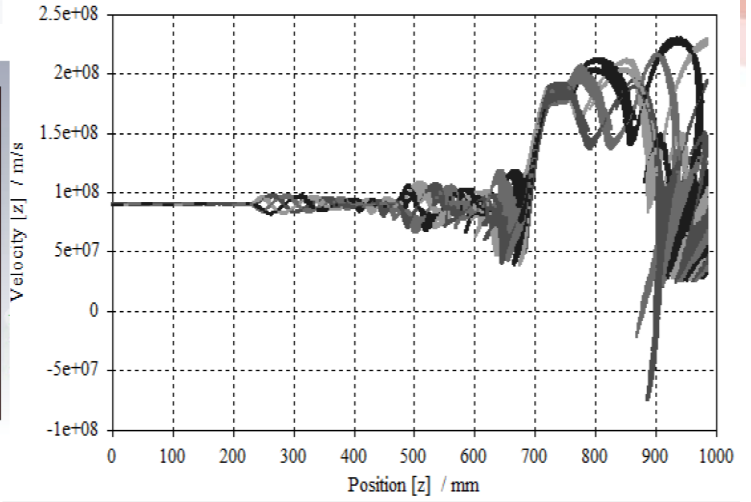
| Parameter | TS MBK | E37503 | Unit |
|---|---|---|---|
| Operating frequency | 1000 | 1000 | MHz |
| Voltage at the 1st stage | 25 | 160 | kV |
| Voltage at the 2nd stage | 140 | | |
| Total beam current | 212 | 180 | A |
| Number of beamlets | 30 | 6 | |
| Number of cavities | 6 | 6 | |
| Perveance at the 1st stage | 1.77 | 0.47 | $\mu A/V^{3/2}$ |
| Perveance at the 2nd stage | 0.133 | | |
| Output RF power | 24.1 | 20 | MW |
| Saturated power gain | 52 | 54 | dB |
| Saturated efficiency | 82 | 70 | % |
| Length of RF circuit | 900 | 1500 | mm |

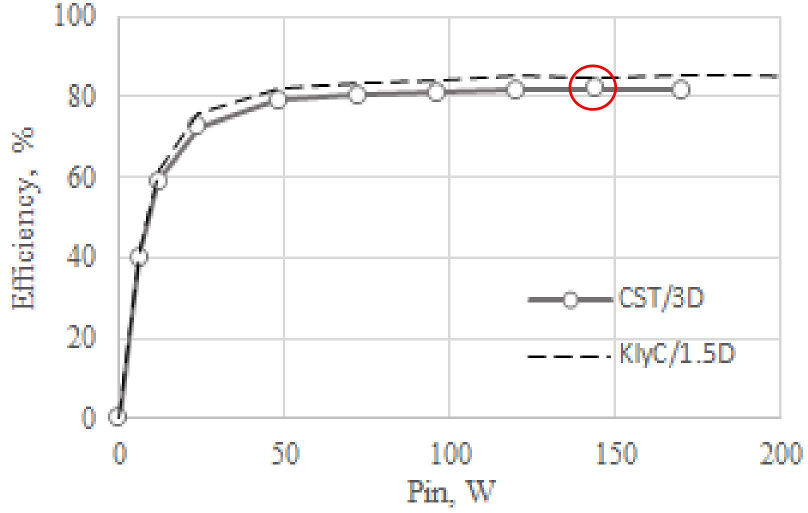


# CLIC Two-stage MBK klystron: **Pulsed, 1.0 GHz, 24 MW**



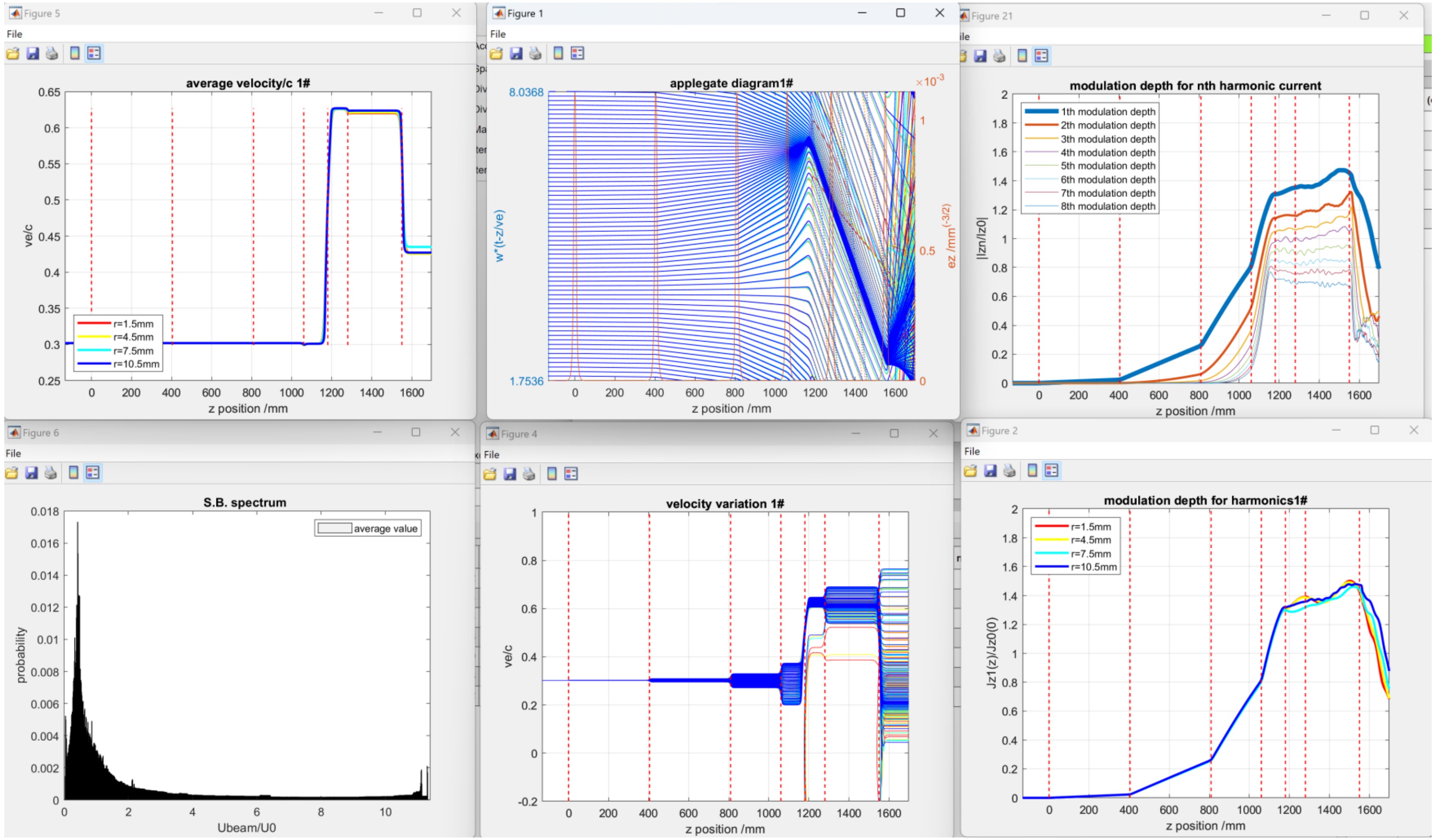






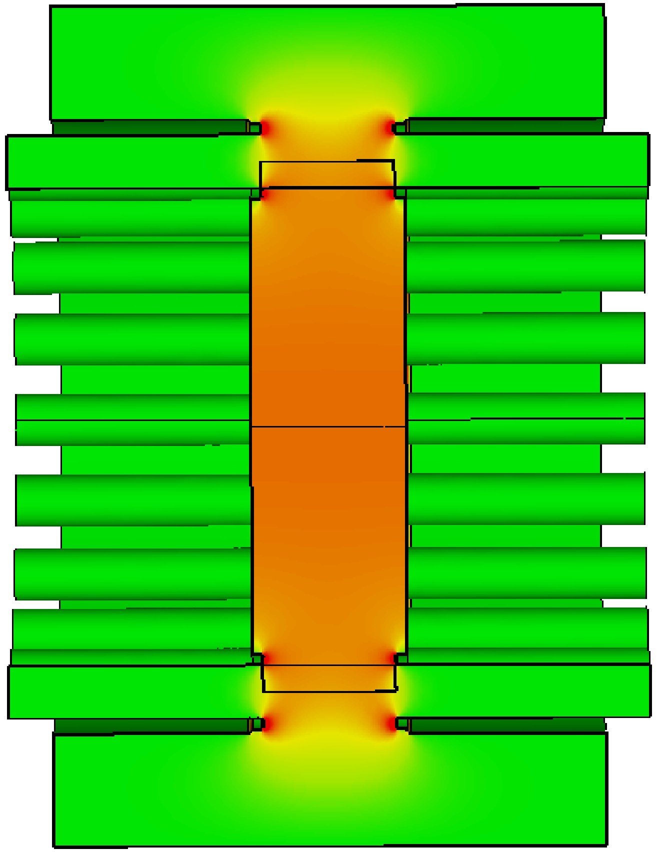
# Example 352 MHz

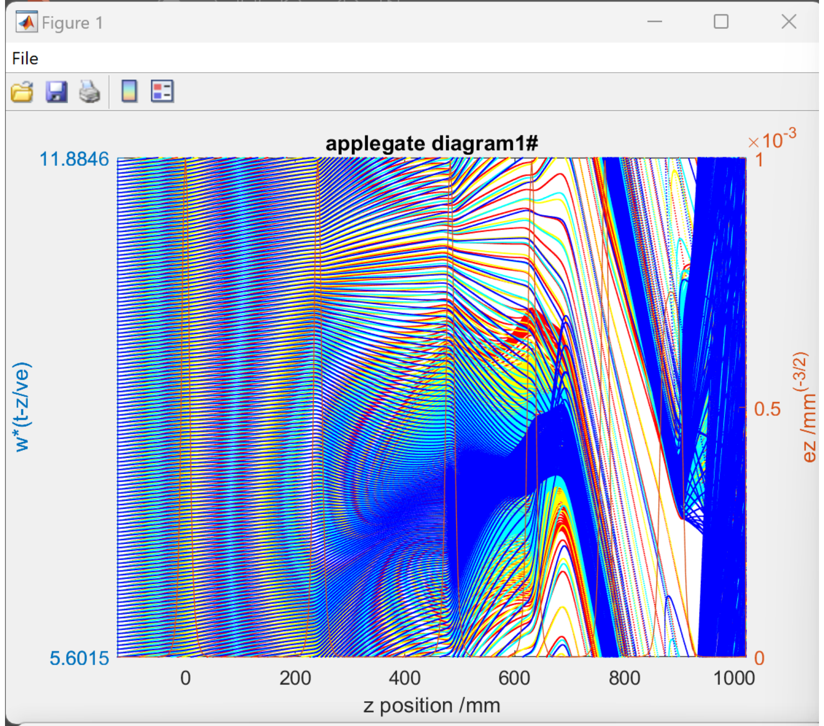
- (Incomplete) design of a 12 MW 352 MHz klystron.
- RF circuit is 1.55 meters long, total length inc. collector will be around 2 m
- Further work needed to get to 24 MW by adding more beamlets (CLIC was 30 this is only 20) and improving efficiency

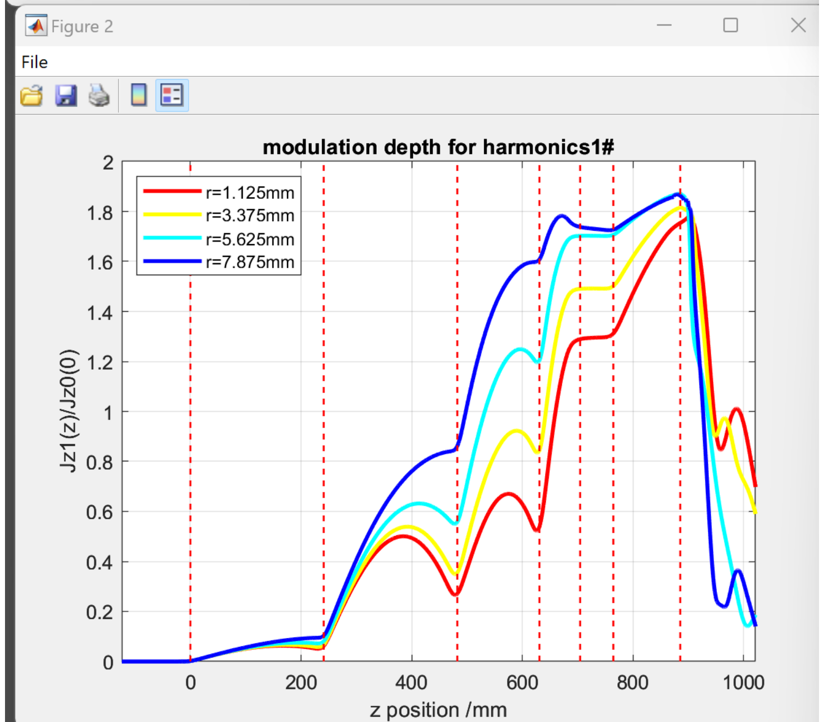


# Scaling CLIC Klystron to 400 MHz

- High efficiency klystrons always have long gaps to allow bouncing electrons. This allows a larger gap voltage to flatten the develeration.
- At 400 MHz a comparable long gap would have 2.5 times more voltage at the same field.
- We will require low external Q's on the output gap to keep the voltage low.

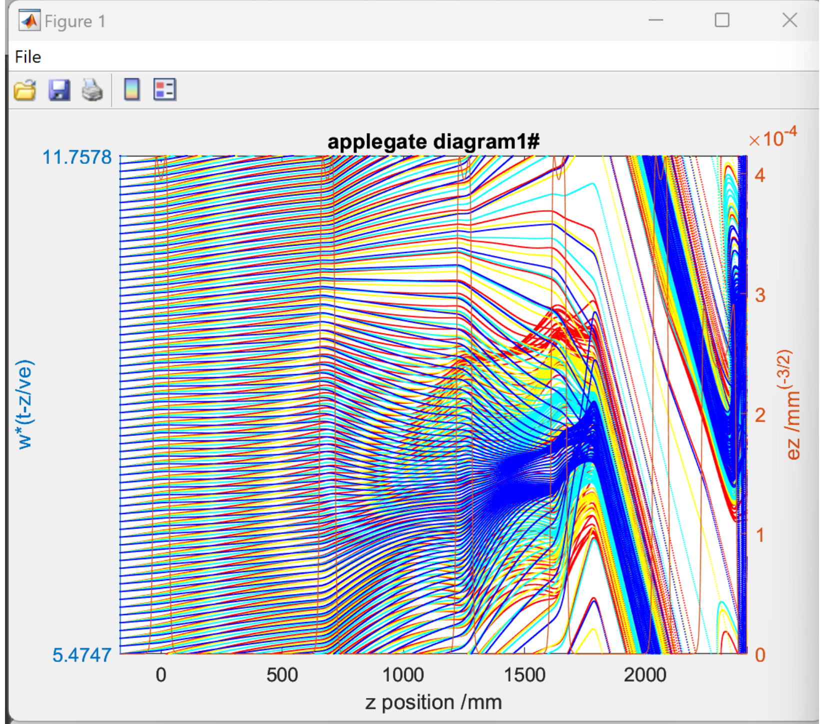


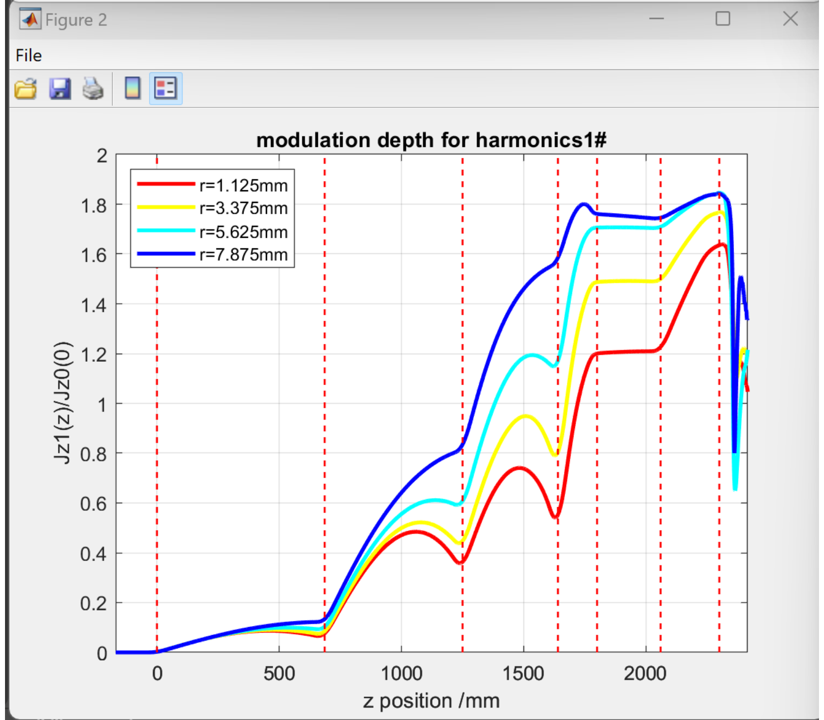




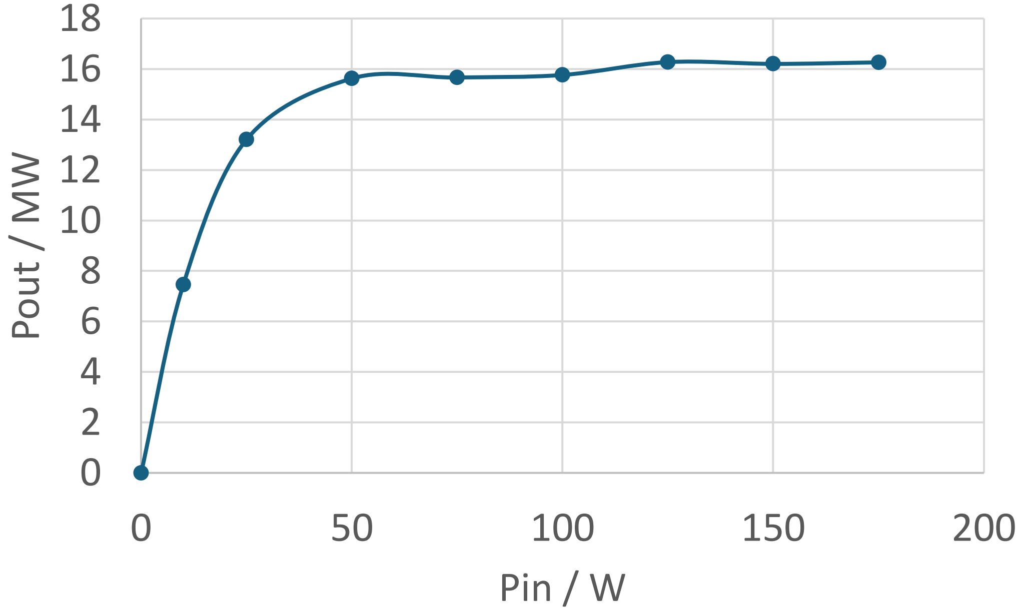
# 20 beam version

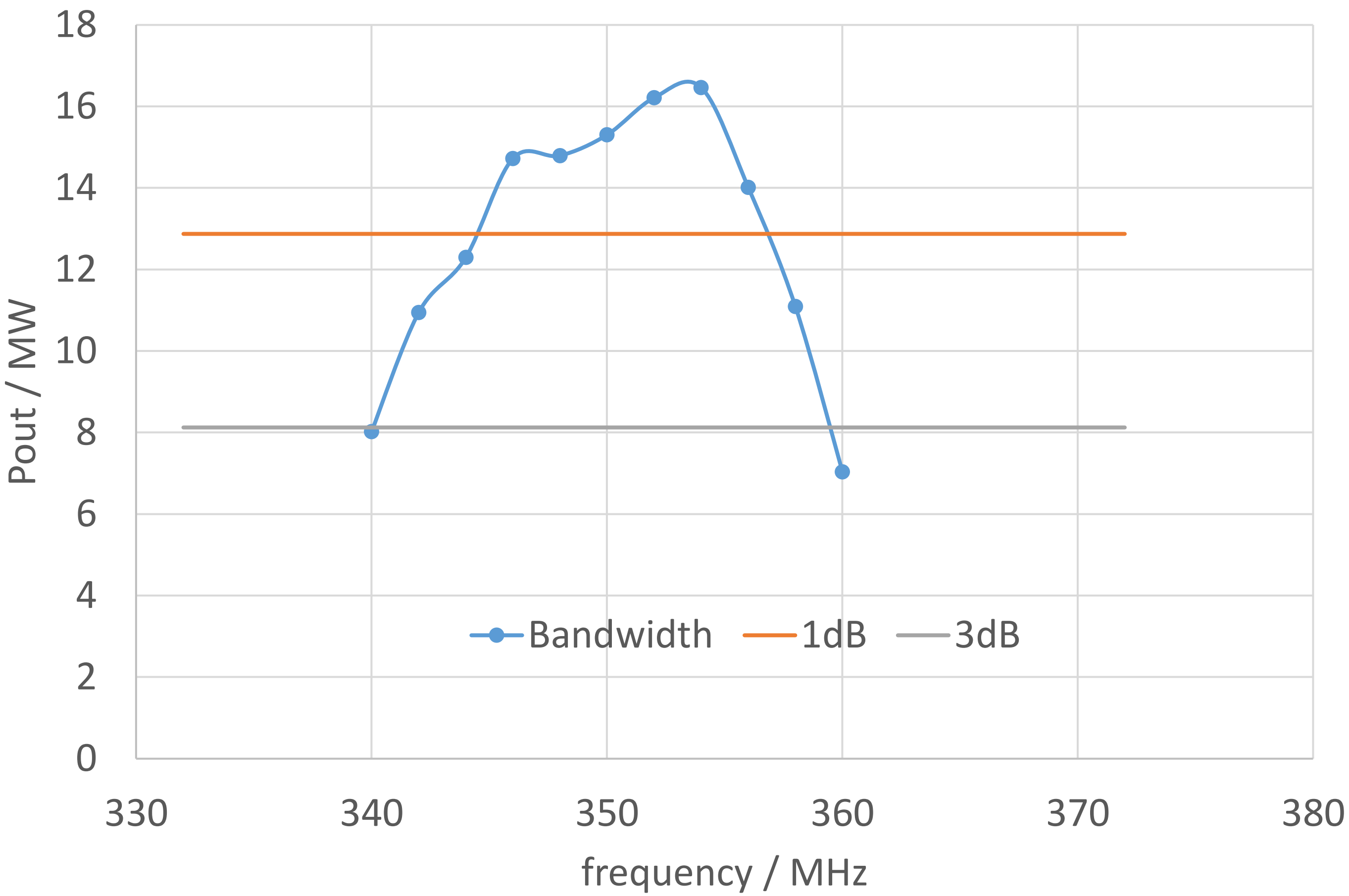
- CLIC is on left, Muon on right
- Not identical but very similar
- Needed some tweaking of frequencies and spacing as gap profile is different





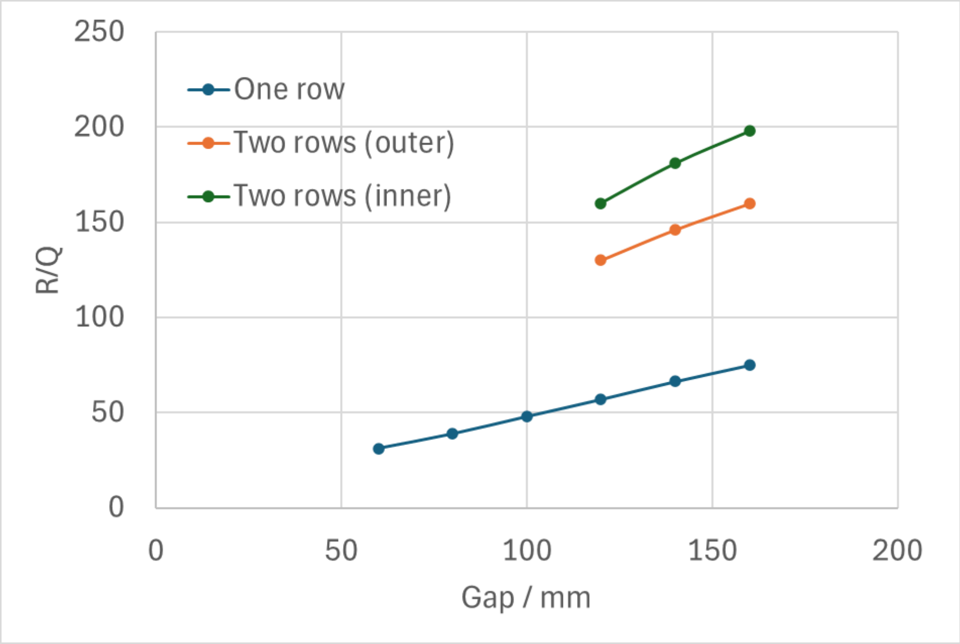
# Band and gain

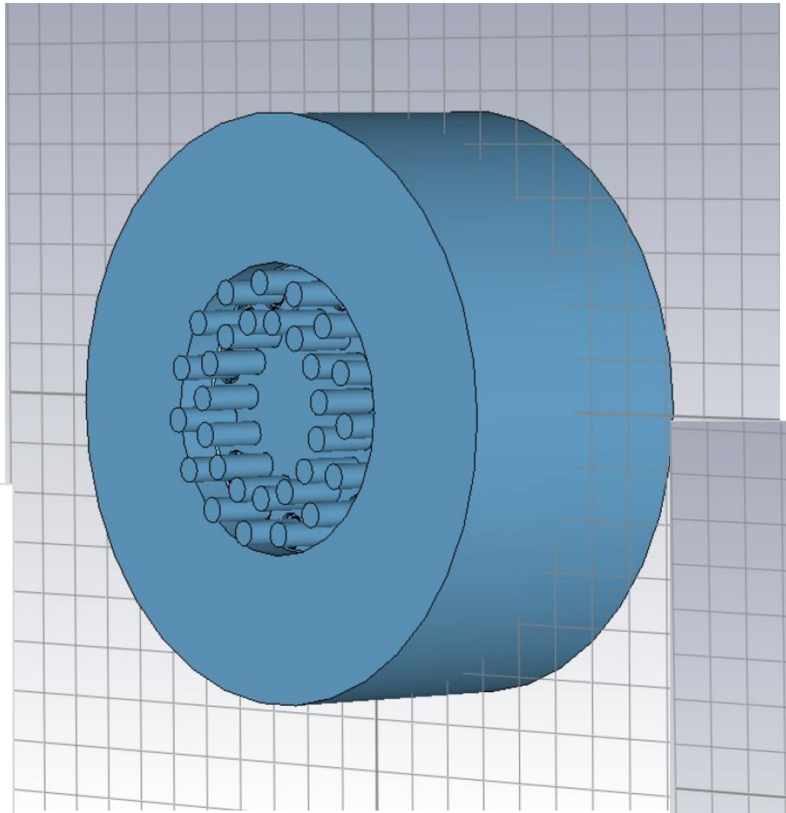




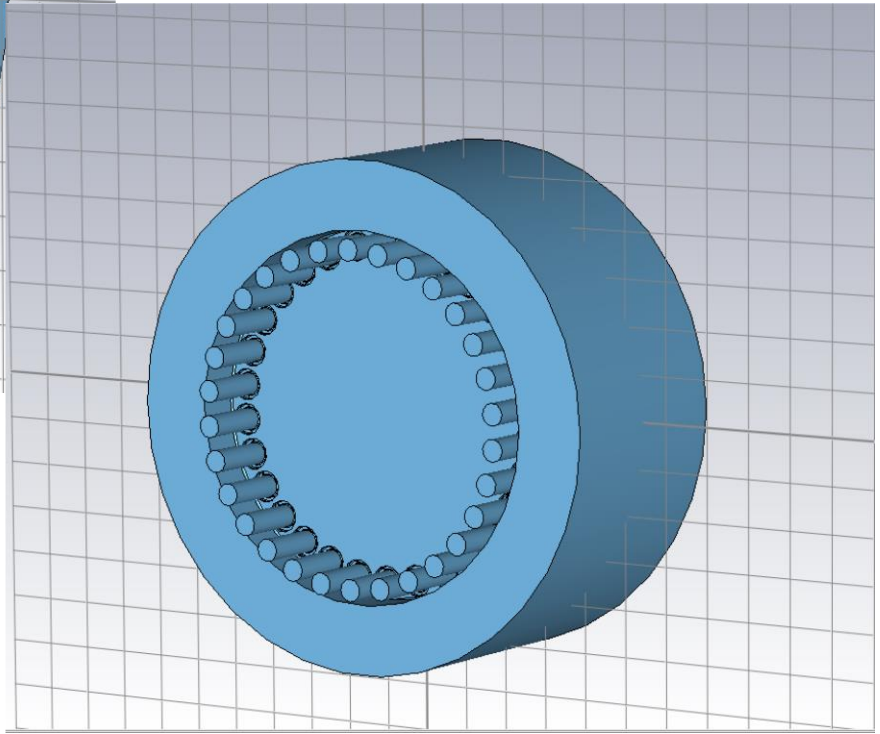
# 30 beams: 1 or 2 rows of beams?

- To fit in 30 beams we can have two rows of 15 or one row of 30



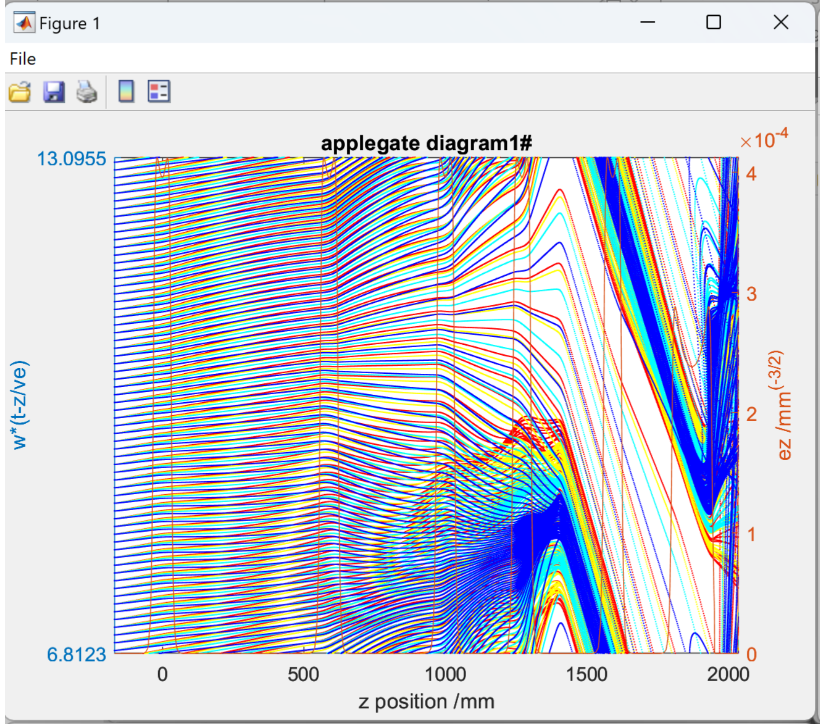


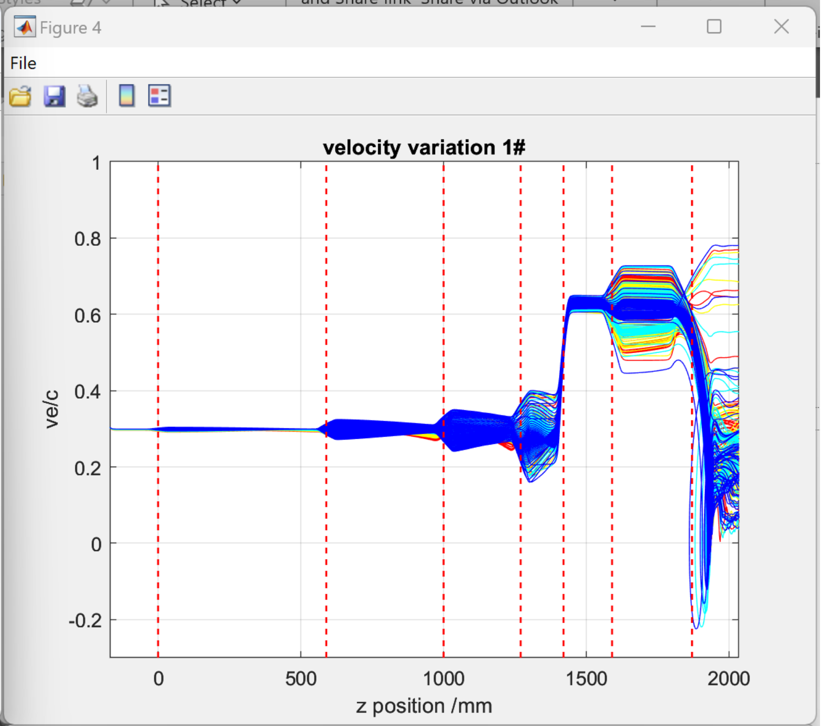
- One row needs a large aperture which lowers the impedance.
- Two rows means a different impedance

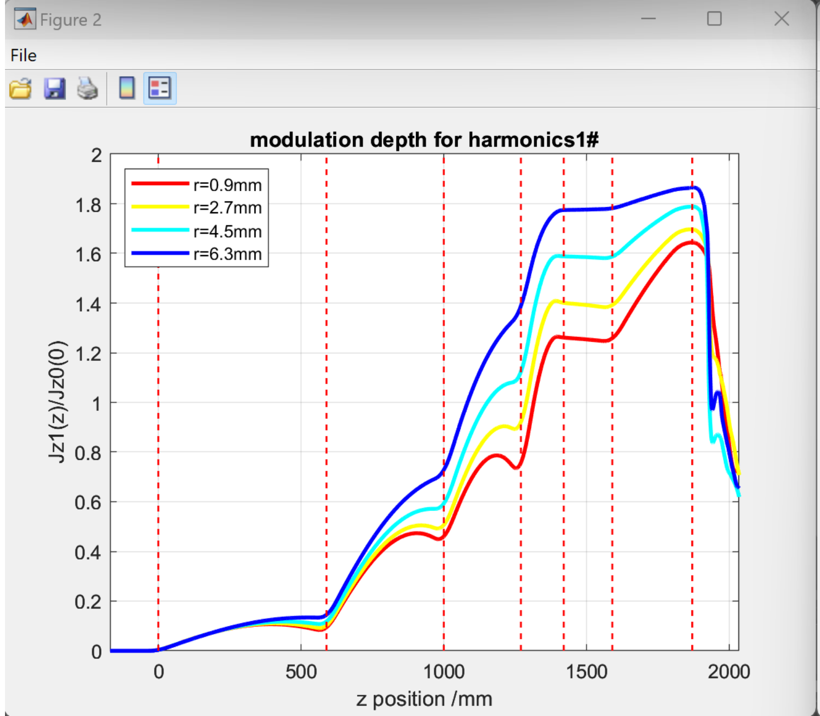


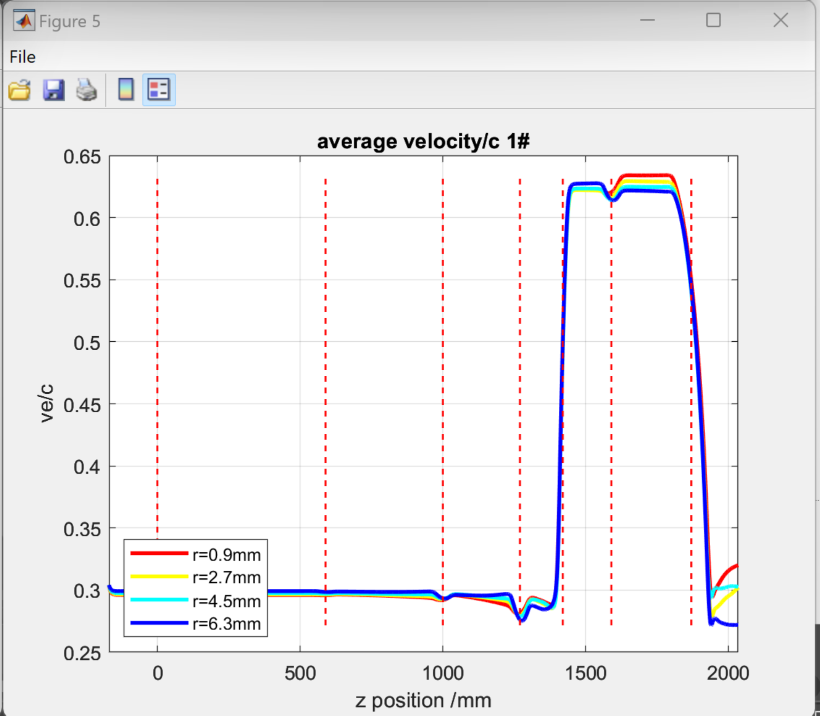
# 30 beam version

- Two rows high impedance
- 24.1 MW 83% efficiency

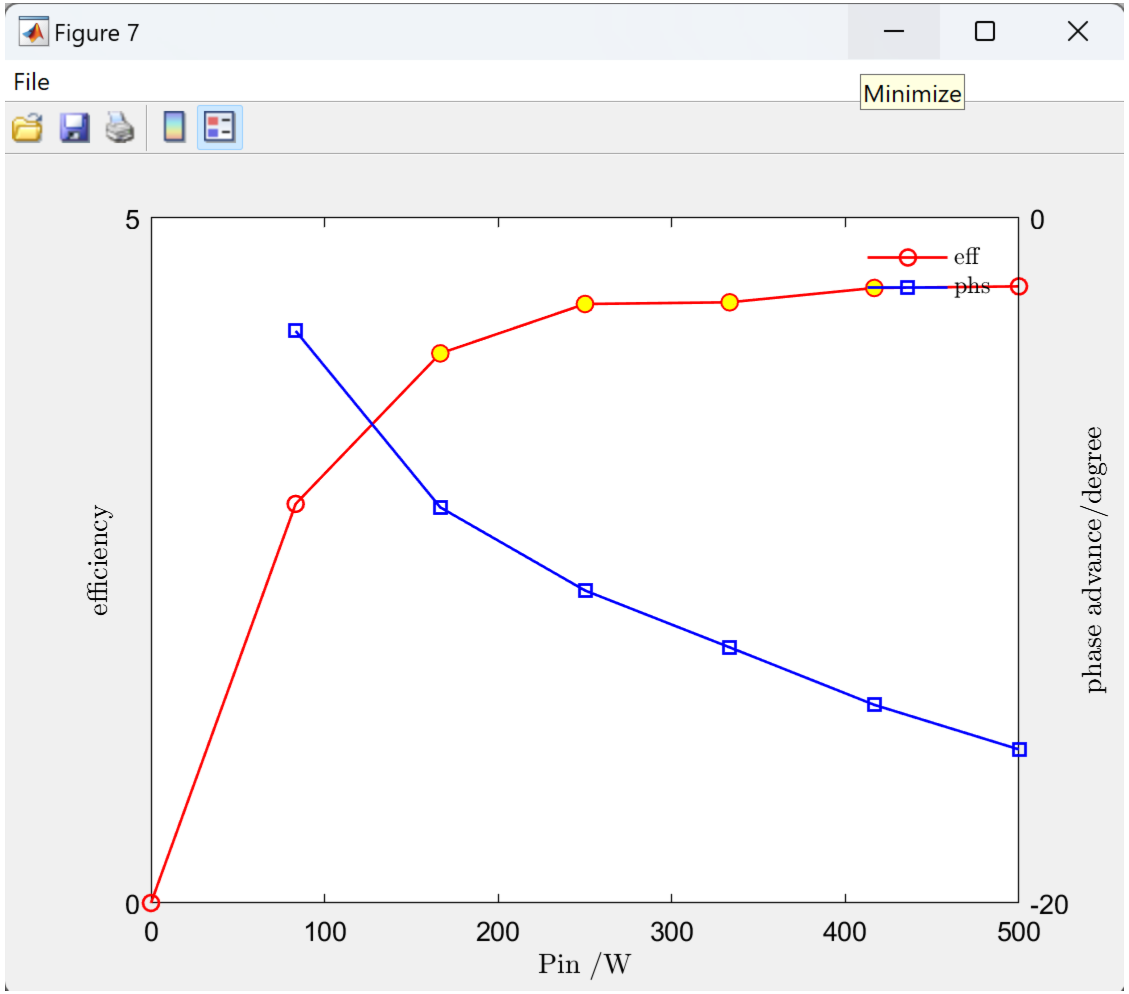


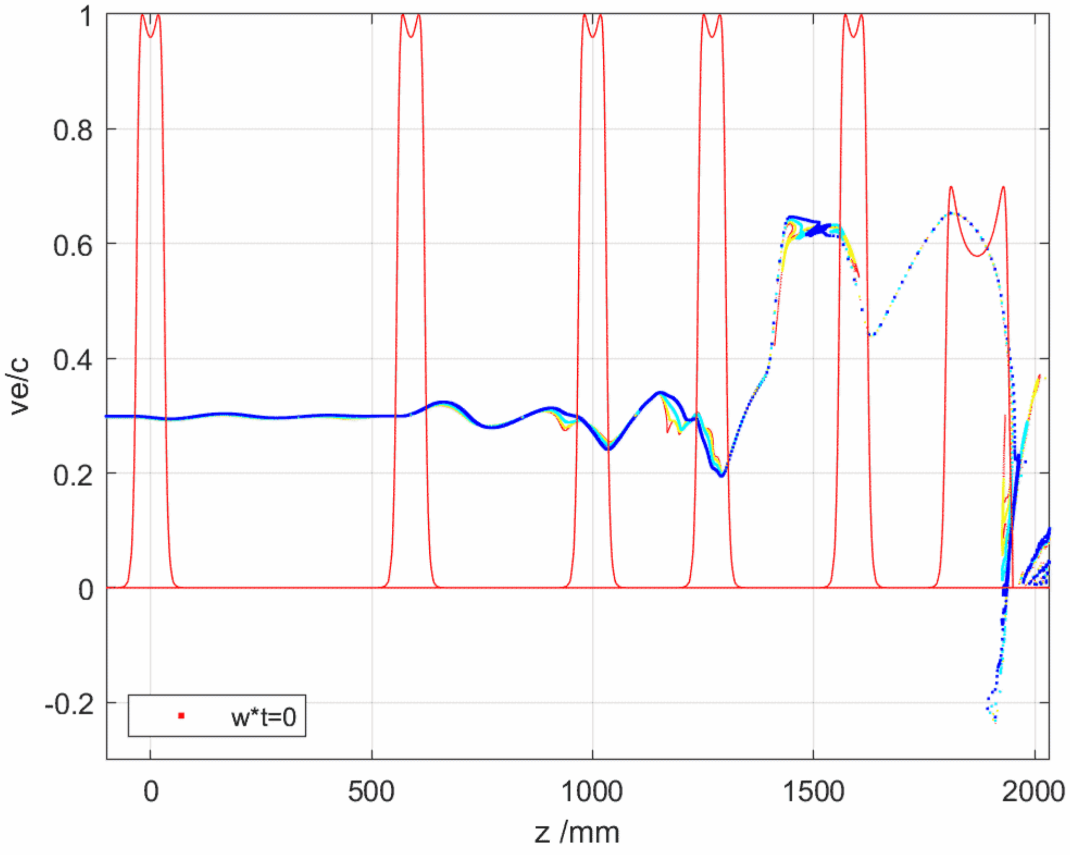






# Reflected electrons

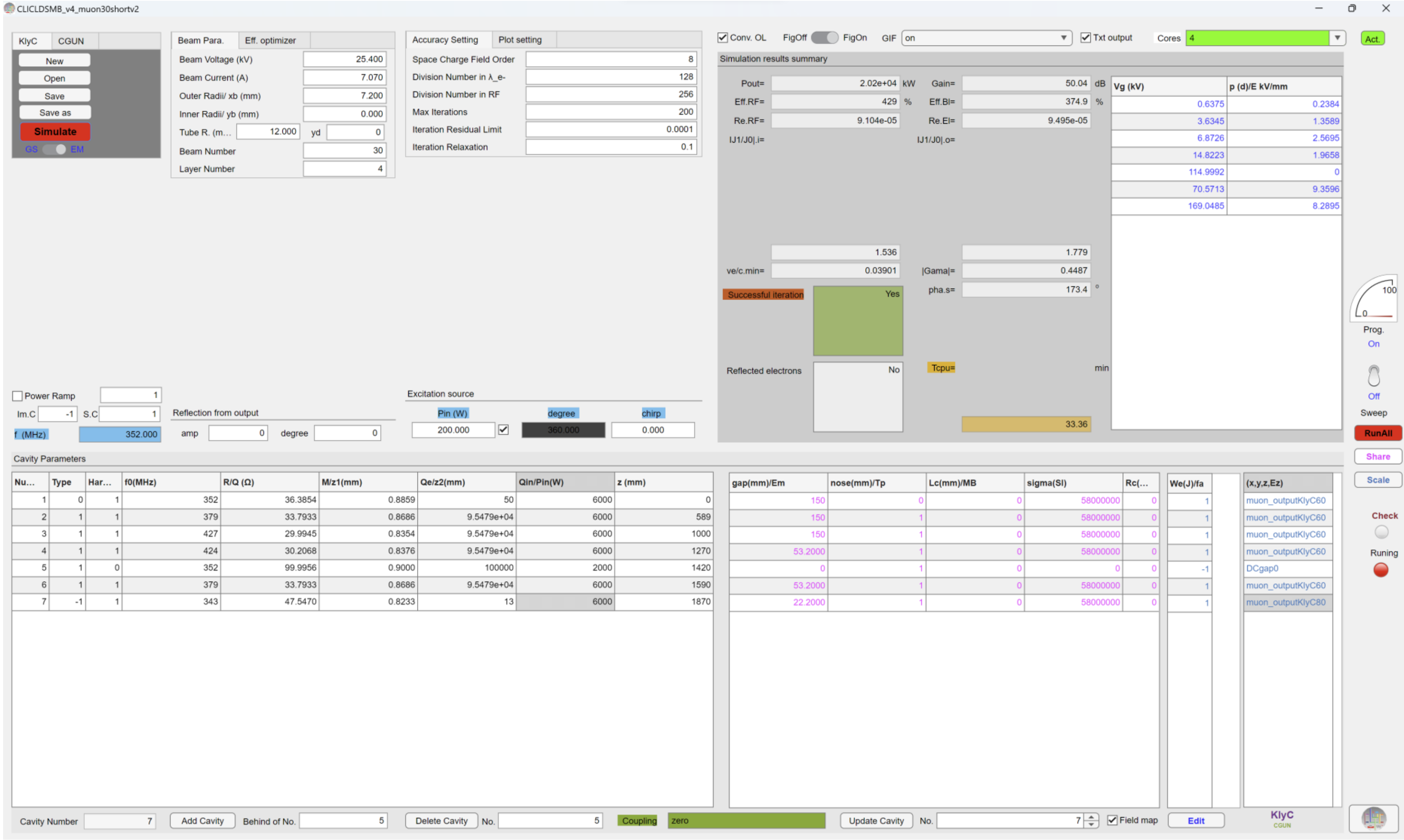




At lower input powers the beam is decelerated for the bounce, but doesn’t get reaccelerated enough to escape leading to reflected electrons. Need to vary the gap

# Shorter output gap (100->80 mm) big drop in power

- A shorter gap gets rid of the reflected electrons but the bounce is required for HE so efficiency drops
- Only 20 MW



Beam Voltage (kV) 25.400
Beam Current (A) 7.070
Outer Radii/ xb (mm) 7.200
Inner Radii/ yb (mm) 0.000
Tube R. (m… 12.000 yd 0
Beam Number 30
Layer Number 4

Space Charge Field Order 8
Division Number in λ_e- 128
Division Number in RF 256
Max Iterations 200
Iteration Residual Limit 0.0001
Iteration Relaxation 0.1

☑ Conv. OL
GIF on
☑ Txt output
Cores 4

Simulation results summary

Pout= 2.02e+04 kW
Gain= 50.04 dB
Eff.RF= 429 %
Eff.Bl= 374.9 %
Re.RF= 9.104e-05
Re.El= 9.495e-05
lJ1/J0|.i=
lJ1/J0|.o=
1.536
1.779
ve/c.min= 0.03901
|Gama|= 0.4487
pha.s= 173.4 °
Successful iteration Yes
Reflected electrons No
Tcpu= 33.36 min

| Vg (kV) | p (d)/E kV/mm |
|---|---|
| 0.6375 | 0.2384 |
| 3.6345 | 1.3589 |
| 6.8726 | 2.5695 |
| 14.8223 | 1.9658 |
| 114.9992 | 0 |
| 70.5713 | 9.3596 |
| 169.0485 | 8.2895 |

☐ Power Ramp 1
Im.C -1 S.C 1
f (MHz) 352.000

Reflection from output
amp 0 degree 0

Excitation source
Pin (W) 200.000 ☑
degree 360.000
chirp 0.000

Cavity Parameters

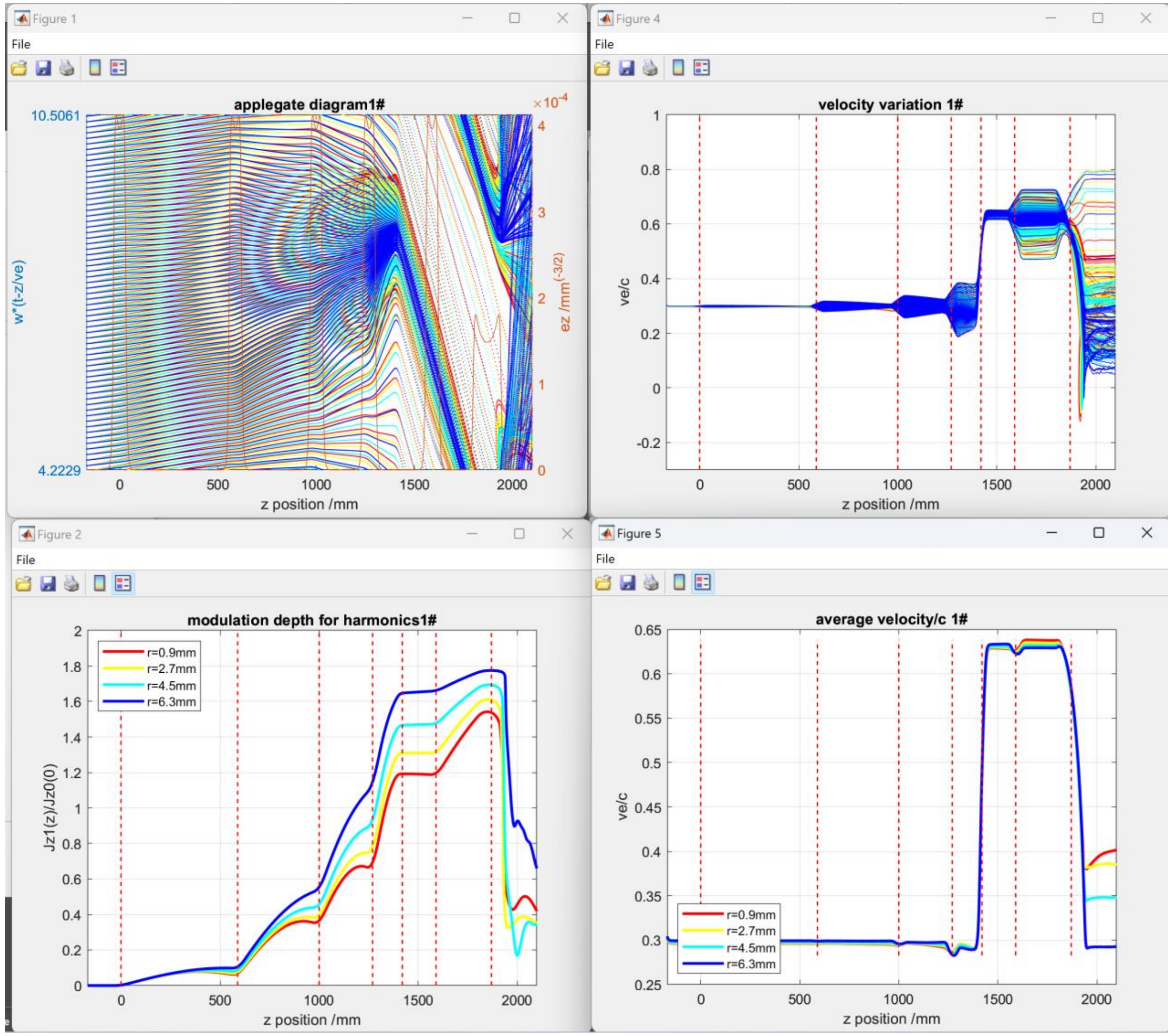
| Nu… | Type | Har… | f0(MHz) | R/Q (Ω) | M/z1(mm) | Qe/z2(mm) | Qin/Pin(W) | z (mm) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 352 | 36.3854 | 0.8859 | 50 | 6000 | 0 |
| 2 | 1 | 1 | 379 | 33.7933 | 0.8686 | 9.5479e+04 | 6000 | 589 |
| 3 | 1 | 1 | 427 | 29.9945 | 0.8354 | 9.5479e+04 | 6000 | 1000 |
| 4 | 1 | 1 | 424 | 30.2068 | 0.8376 | 9.5479e+04 | 6000 | 1270 |
| 5 | 1 | 0 | 352 | 99.9956 | 0.9000 | 100000 | 2000 | 1420 |
| 6 | 1 | 1 | 379 | 33.7933 | 0.8686 | 9.5479e+04 | 6000 | 1590 |
| 7 | -1 | 1 | 343 | 47.5470 | 0.8233 | 13 | 6000 | 1870 |

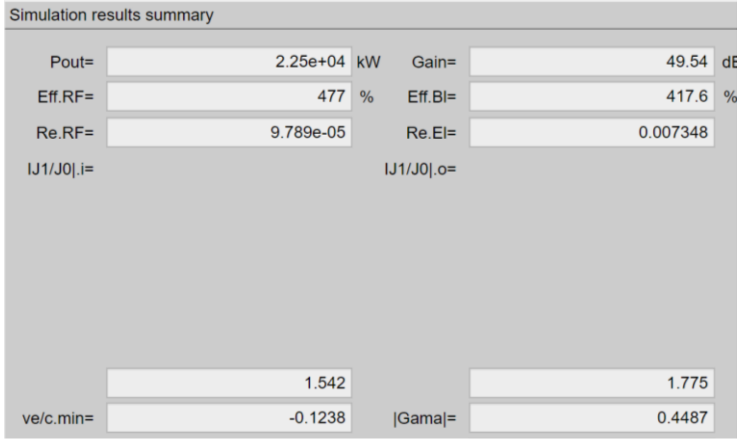
| gap(mm)/Em | nose(mm)/Tp | Lc(mm)/MB | sigma(SI) | Rc(… | We(J)/fa | (x,y,z,Ez) |
|---|---|---|---|---|---|---|
| 150 | 0 | 0 | 58000000 | 0 | 1 | muon_outputKlyC60 |
| 150 | 1 | 0 | 58000000 | 0 | 1 | muon_outputKlyC60 |
| 150 | 1 | 0 | 58000000 | 0 | 1 | muon_outputKlyC60 |
| 53.2000 | 1 | 0 | 58000000 | 0 | 1 | muon_outputKlyC60 |
| 0 | 1 | 0 | 0 | 0 | -1 | DCgap0 |
| 53.2000 | 1 | 0 | 58000000 | 0 | 1 | muon_outputKlyC60 |
| 22.2000 | 1 | 0 | 58000000 | 0 | 1 | muon_outputKlyC80 |

Cavity Number 7
Behind of No. 5
No. 5
Coupling zero
No. 7
☑ Field map

# Larger gap 100->140 mm but also went to single row to decrease R/Q and increase Q

- Efficiency has improved and slowest electron velocity has increased

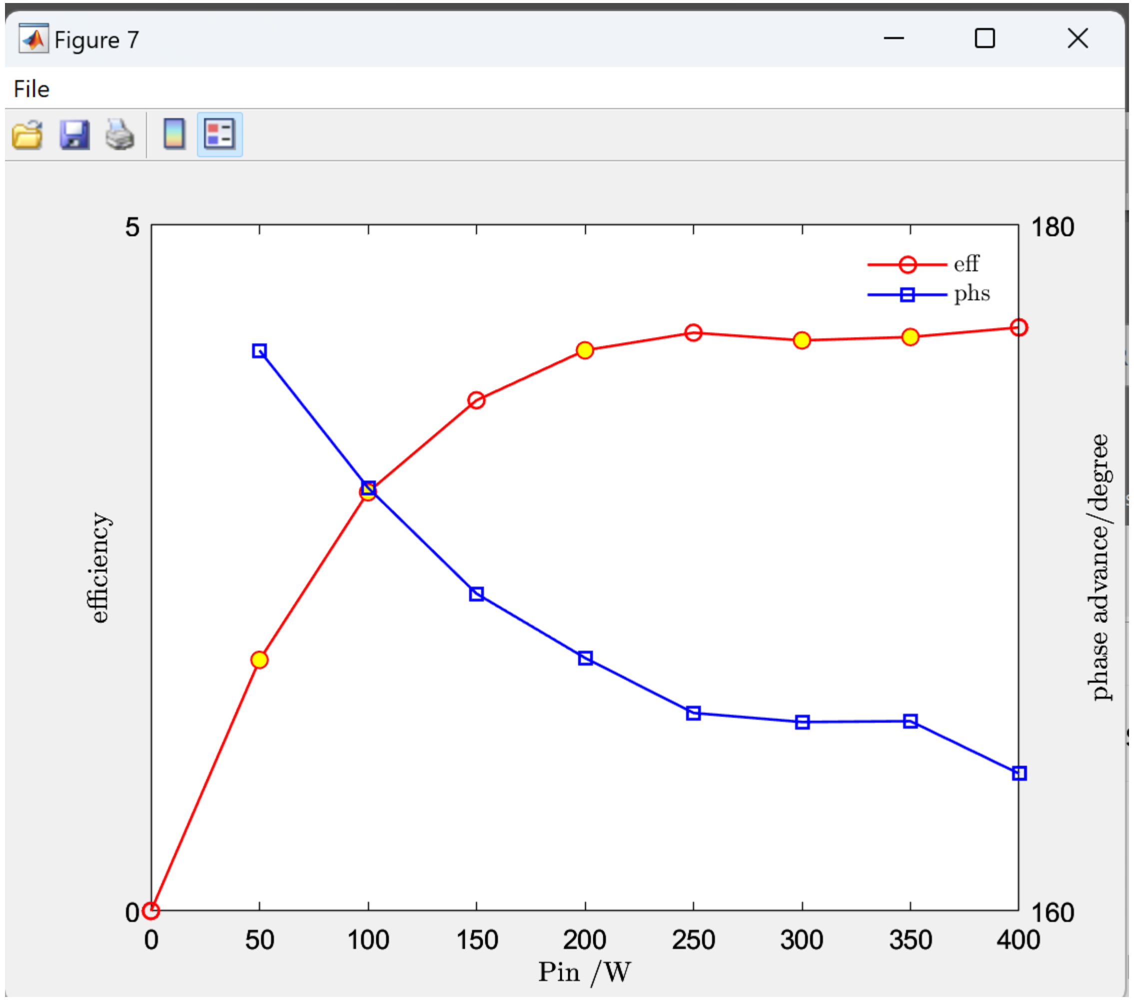




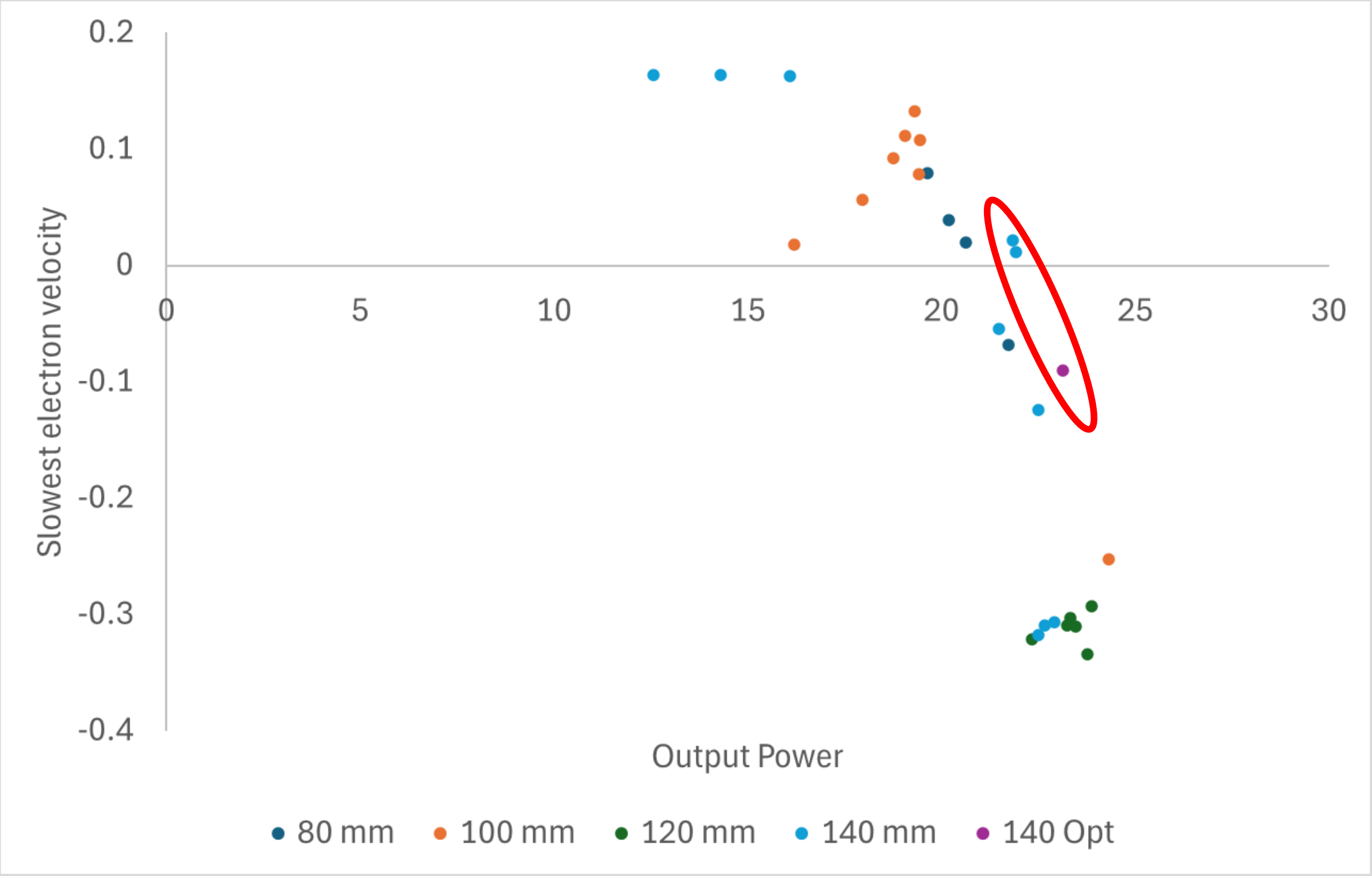
Simulation results summary

| | | | | | |
|---|---|---|---|---|---|
| Pout= | 2.25e+04 | kW | Gain= | 49.54 | d |
| Eff.RF= | 477 | % | Eff.Bl= | 417.6 | % |
| Re.RF= | 9.789e-05 | | Re.El= | 0.007348 | |
| IJ1/J0\|.i= | | | IJ1/J0\|.o= | | |
| | 1.542 | | | 1.775 | |
| ve/c.min= | -0.1238 | | \|Gama\|= | 0.4487 | |

# Still getting reflected electrons



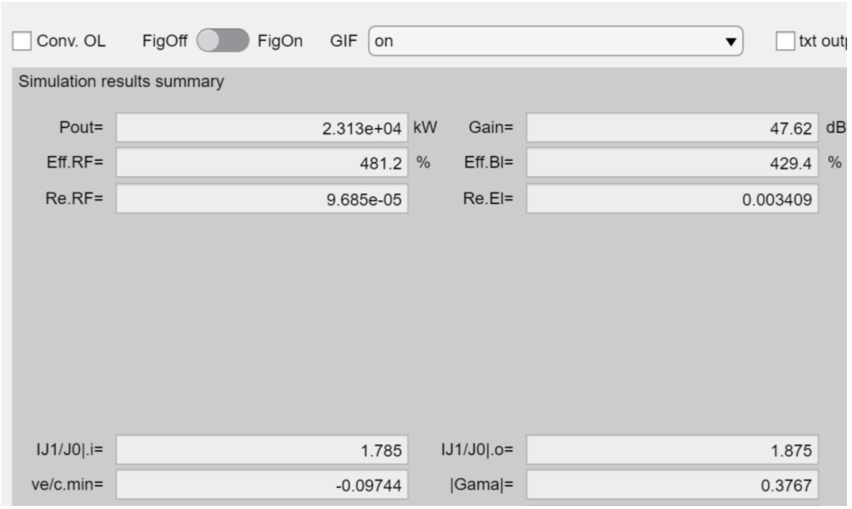
# Pareto front Power versus min vel.



- Optimizing the output cavity tends to keep a linear relationship between power and electron velocity
- Two outliers seem to break that
- Let KLyC optimizer play with the bunch hing circuit

# KlyC optimiser

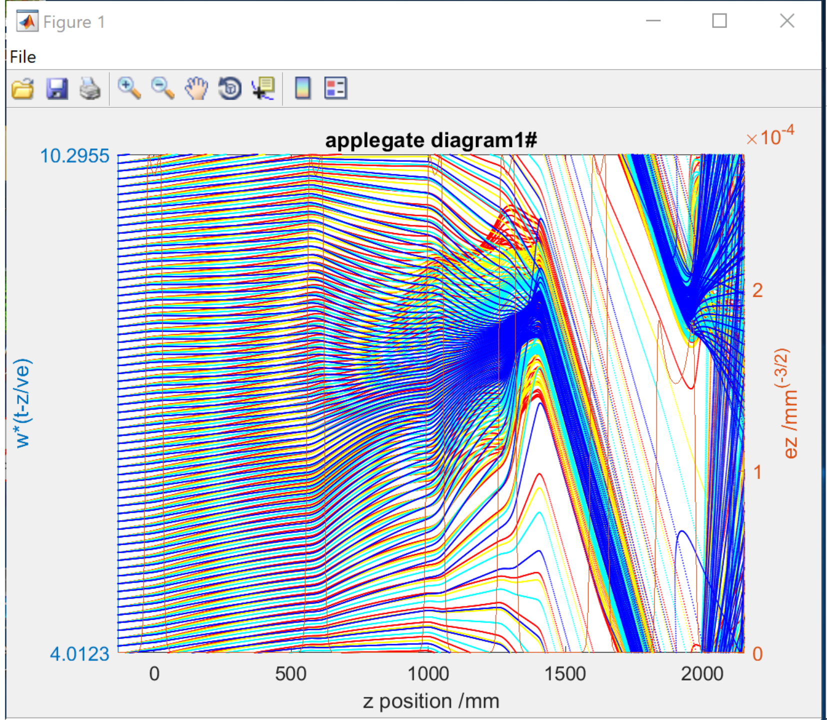
- KlyC optimizer has got it back to 78% efficiency and 23.13 MW
- Min electron velocity increased to -10%c
- Significantly less stratification and not currently at saturation (ran out of time)

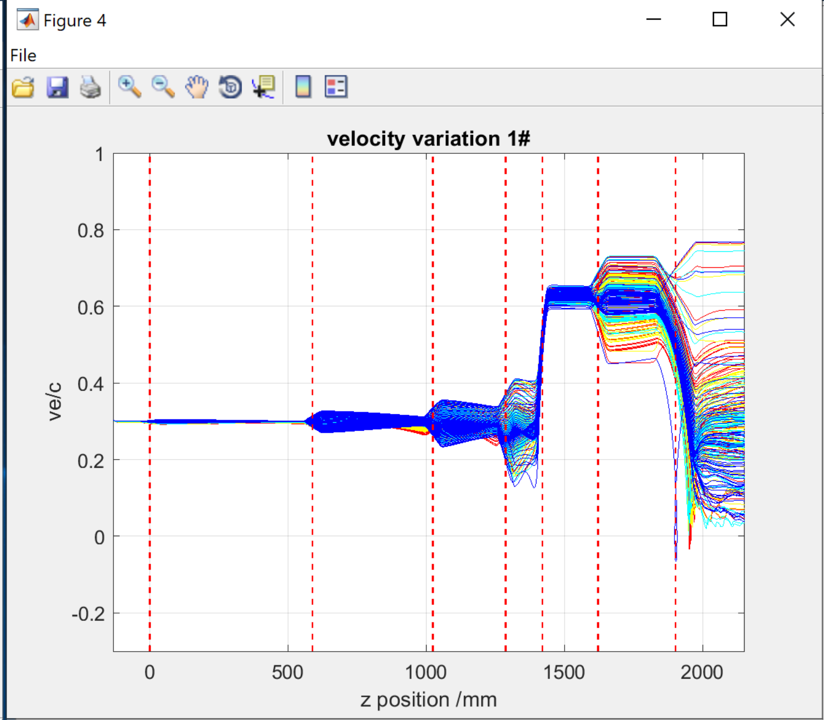


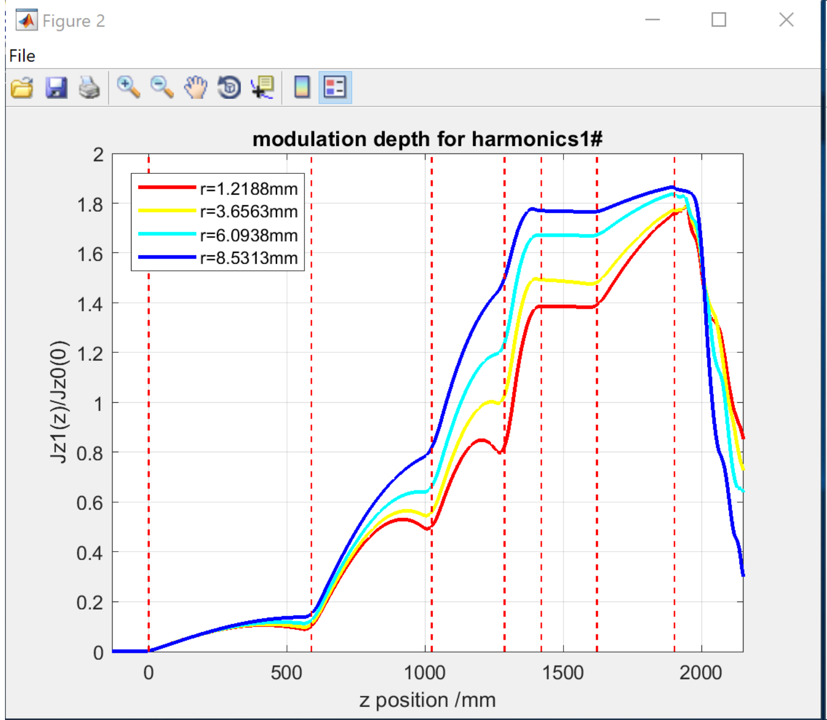
☐ Conv. OL   FigOff ● FigOn   GIF on ▾   ☐ txt out

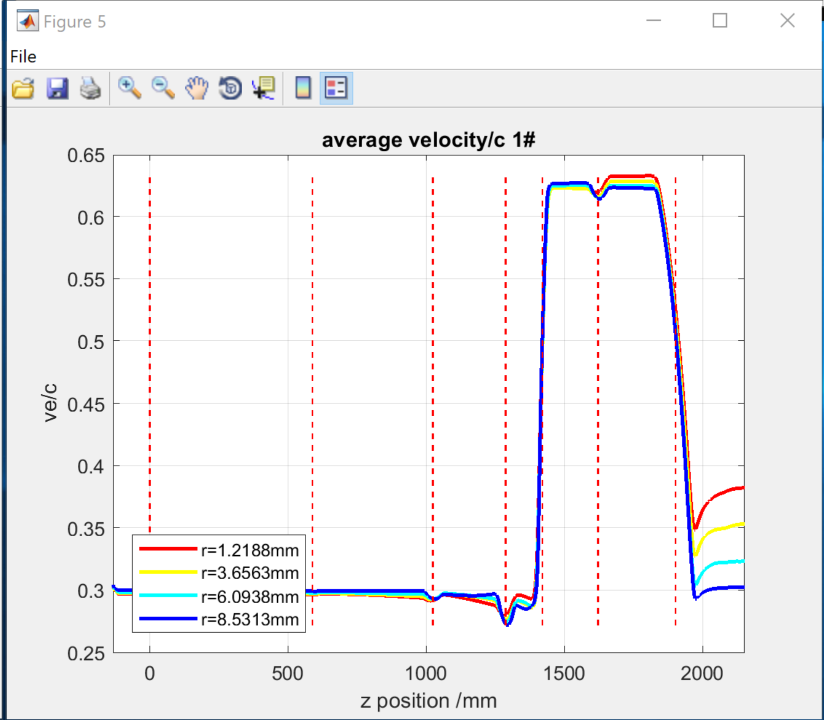
Simulation results summary

| | | | | | |
|---|---|---|---|---|---|
| Pout= | 2.313e+04 | kW | Gain= | 47.62 | dB |
| Eff.RF= | 481.2 | % | Eff.Bl= | 429.4 | % |
| Re.RF= | 9.685e-05 | | Re.El= | 0.003409 | |
| \|J1/J0\|.i= | 1.785 | | \|J1/J0\|.o= | 1.875 | |
| ve/c.min= | -0.09744 | | \|Gama\|= | 0.3767 | |









# Conclusion

- Current 352 and 704 MHz klystrons are limited to 2.9 and 1.5 MW respectively, requiring a lot of klystrons for a muon collider.
- 704 MHz tube may well be within scaling range of the CLIC tubes at 24 MW
- The 352 MHz tube would be very long if scaled from the same tube
- Two-stage technologies significantly shorten low frequency, high power tubes and is suitable for 352 MHz solution
- KlyC simulations show that 12 MW klystron is possible in under 2 m, and further work should push this to 24 MW.
- Reflected electrons is an ongoing issue