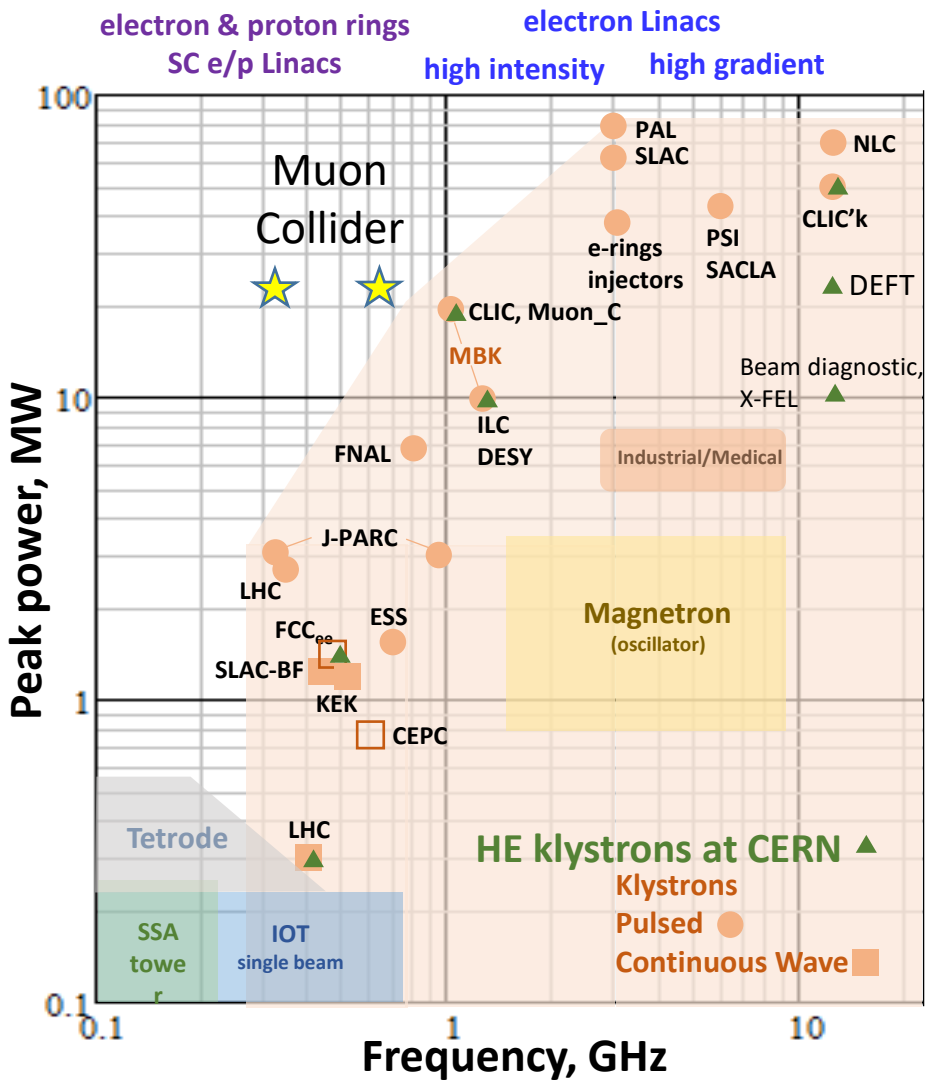
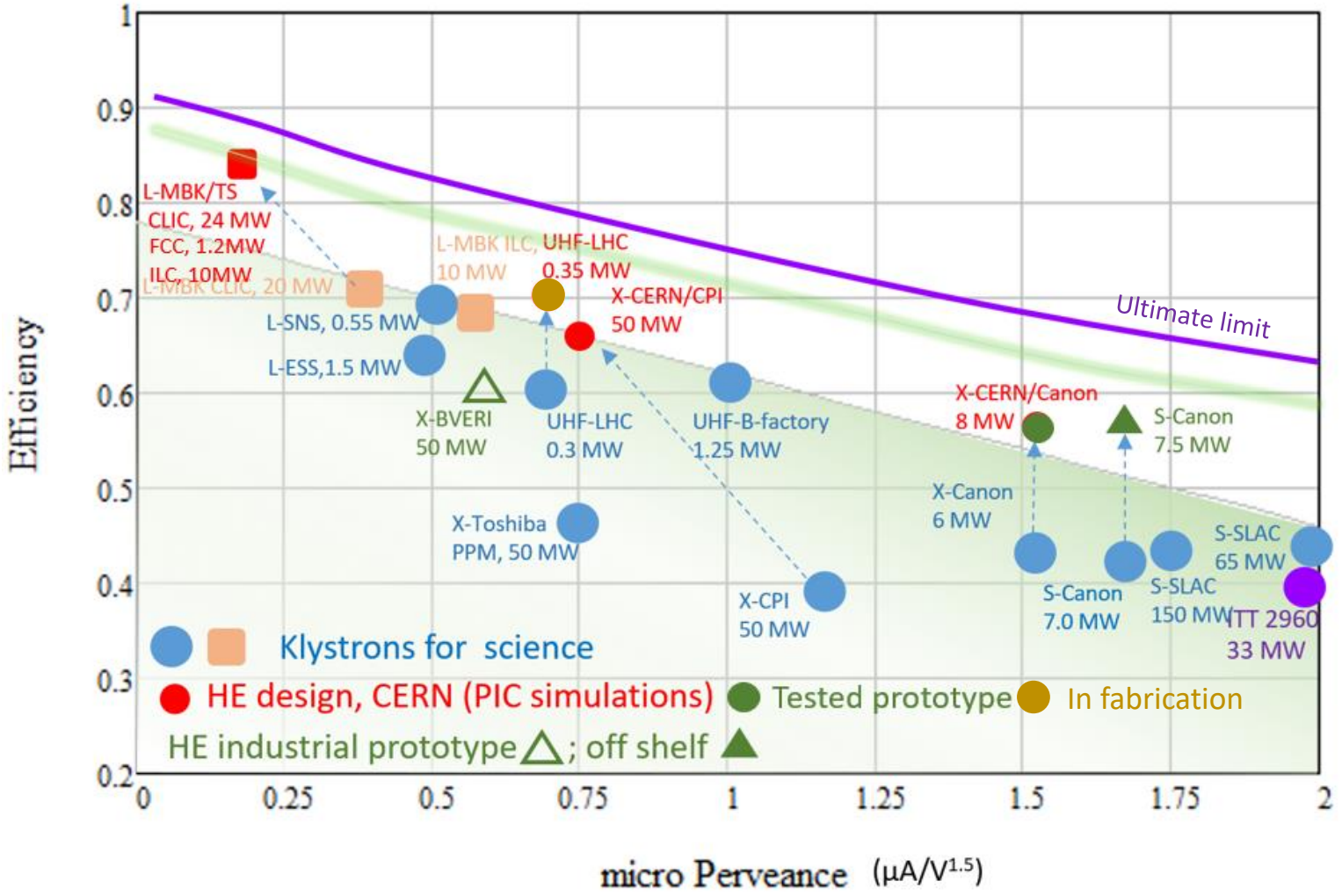
High Efficiency Klystrons for MuCol

G. Burt for HE project team at CERN & Lancaster:
Igor Syratchev
Nuria Catalan
Zain Un Nisa
Anis Baig

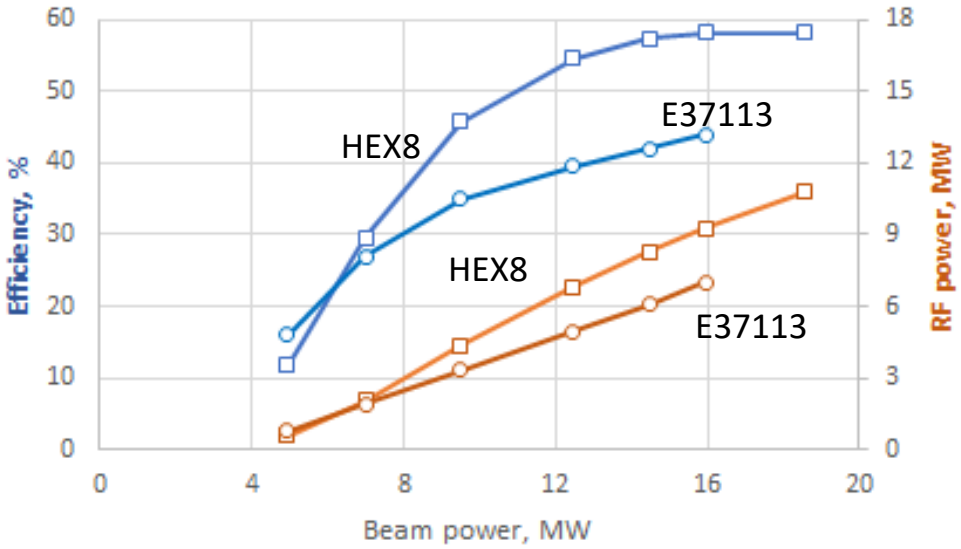
The klystron is a key element of almost all particle accelerators.

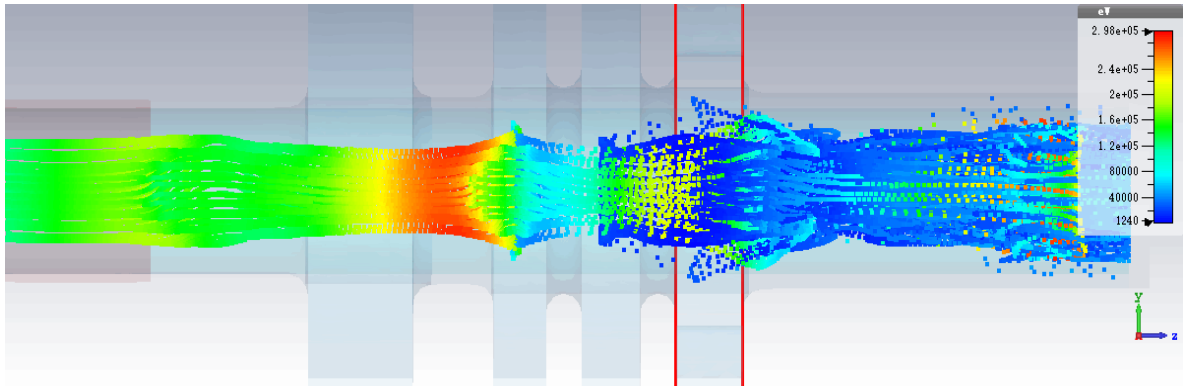


High Efficiency klystrons project at CERN is targeted to improve efficiency and performance of these devices for various applications.



Retro-fit High Efficiency 8 MW, 12 GHz klystron. CERN/Canon collaboration.





- The same modulator
- Re-used solenoid
- Re-used cathode
- New RF window (CERN design)

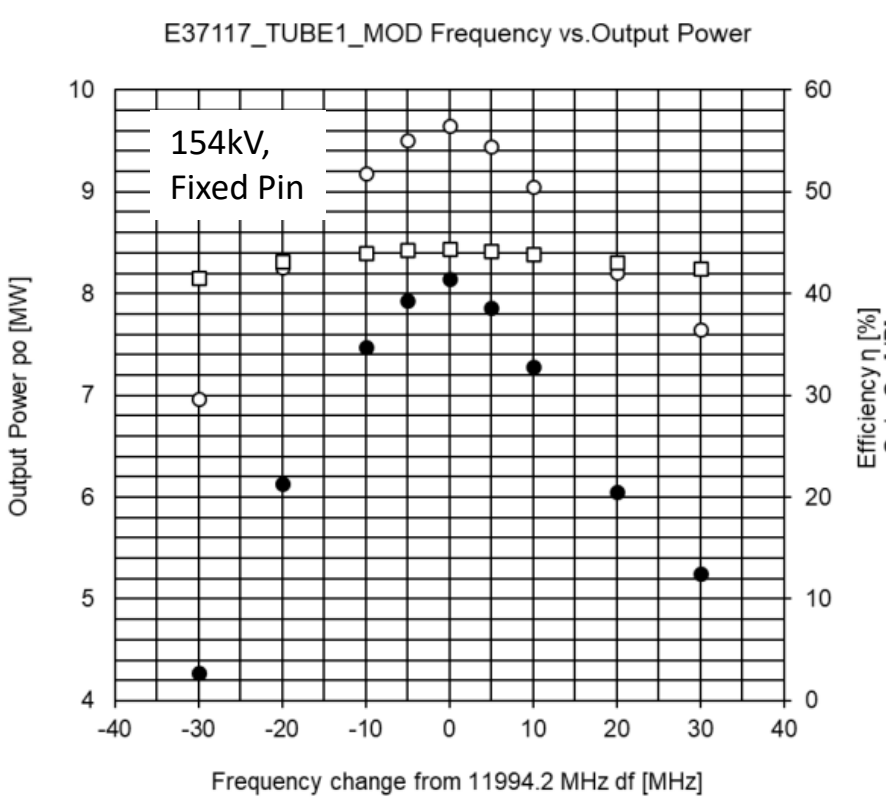
Two tubes arrived at CERN and now they are being installed in the XBOX#3 test area.

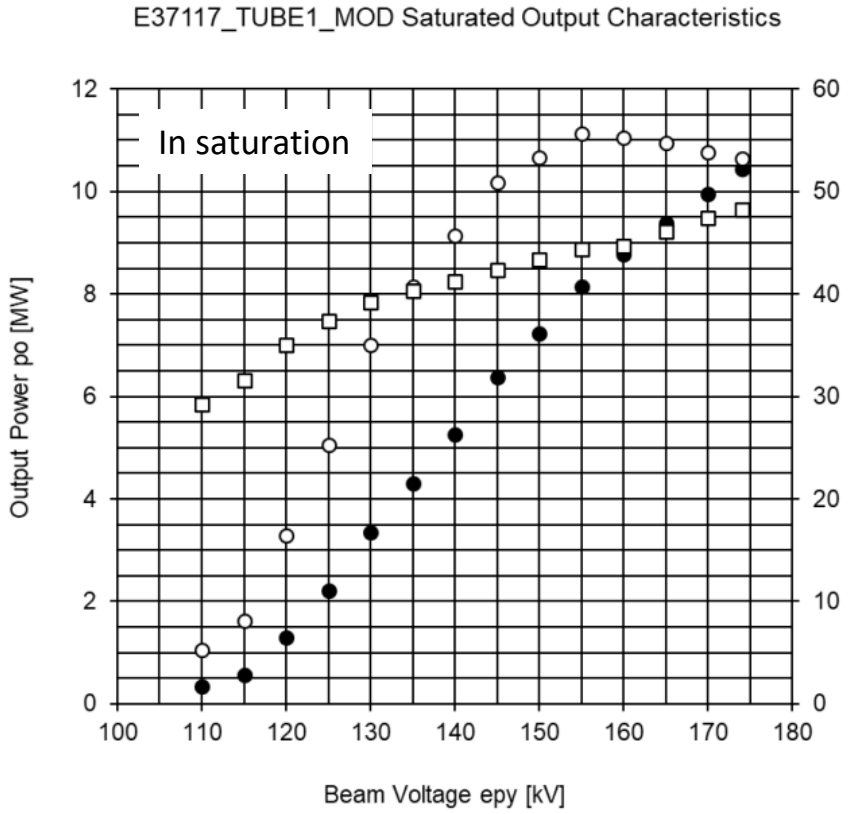
Retrofit design

Canon

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	94	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	48
Efficiency, %	42	56.4
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

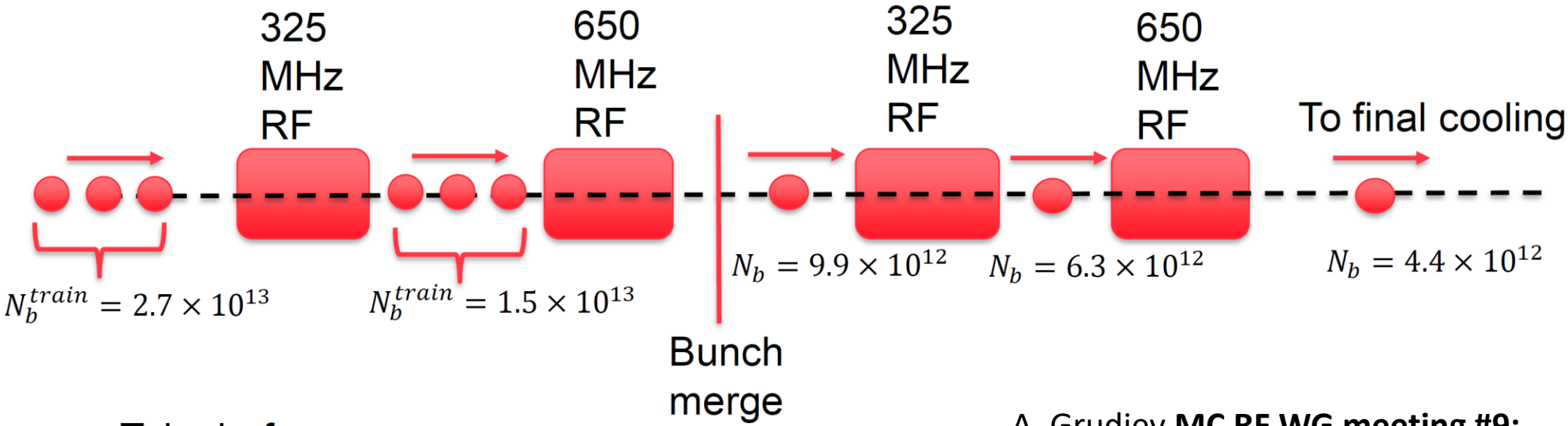
The klystron was successfully tested at Canon in December 2022 up to 10.5MW.





- At operating frequency klystron showed 57%. That corresponds to 35% RF peak power increase compared to the original Canon tube at the same operating voltage.
- Tube reached 10.5MW. Compatible with existing Xbox#3 ScandiNova modulator (with 175kV max recommended).
- In a range of RF power levels from 6MW to 10.5 MW the klystron is 50%+ efficient and can be used for different application in this range by adjusting modulator type/voltage.
- **The tube is commercially available.**

Cooling channel: beam parameters

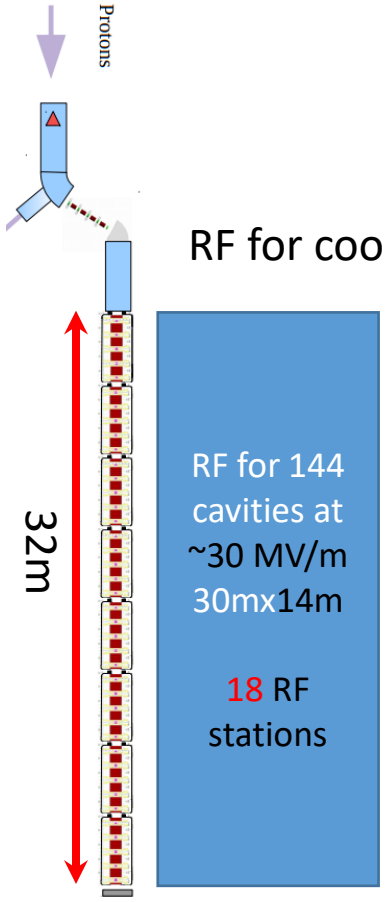


Take before merge
$N_b^{train} = 2 \times 10^{13}$
for simplicity

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



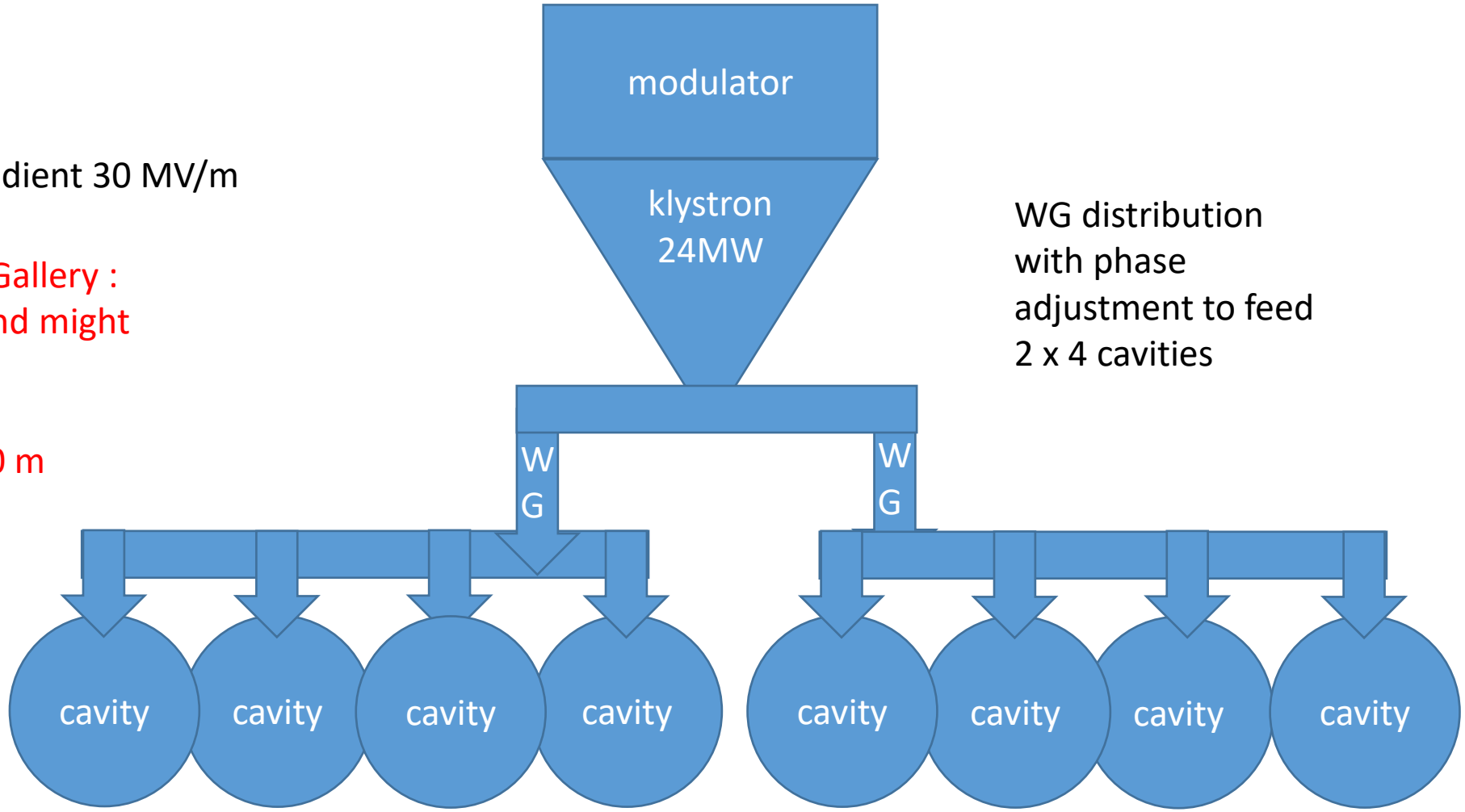
RF for cooling: Max. gradient 30 MV/m

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

18 RF stations

14m

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



WG distribution with phase adjustment to feed 2 x 4 cavities

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


Canon E37503


Thales TH1803

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


Thales TH1801


Toshiba E3736


CPI VKL-8301

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

Scaling the Canon tube to 0.7GHz, 24MW and 30 µsec.

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

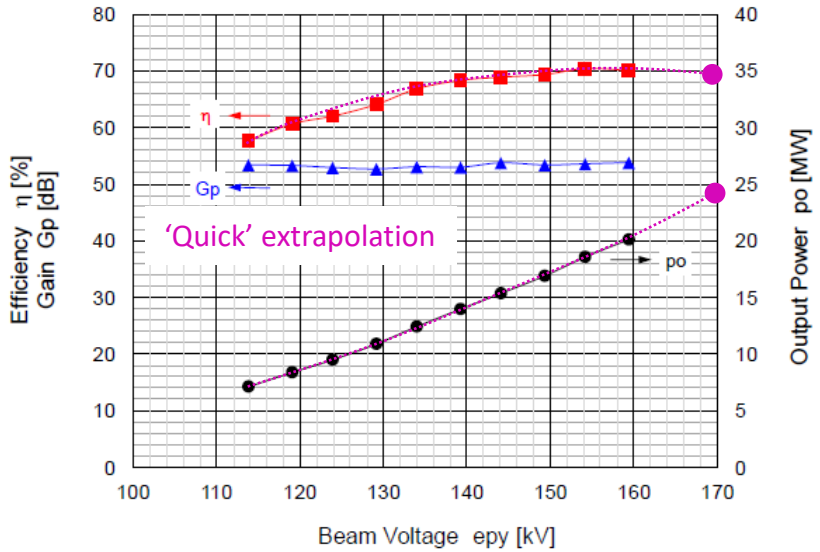
Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons

Jinchi Cai, Igor Syratchev, and Zening Liu

Canon E37503 6 beams MBK		Mu-tube, 0.7 GHz 6 beams MBK	
F=	999,5 MHz	F=	700 MHz
P max=	20.2 MW	P max=	24 MW
T =	150 µsec	T =	30 µsec
V=	159.4 kV	V=	171 kV
I total =	180 A	I total =	200 A
Eff.=	70.5 %	Eff.=	70.0 %
uP=	0.47 µAxV$^{-3/2}$/beam	uP=	0.47 µAxV$^{-3/2}$/beam
Gain =	53.9 dB	Gain =	53.9 dB
P $_{average}$ (50Hz)=	150kW	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.

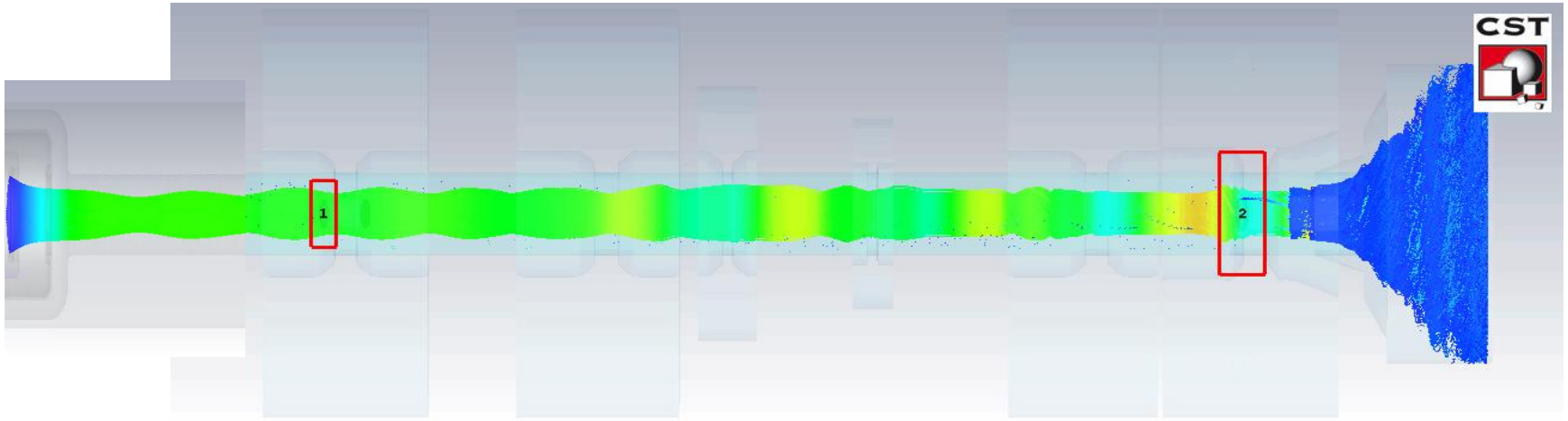


Cost and schedule:

- 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.).

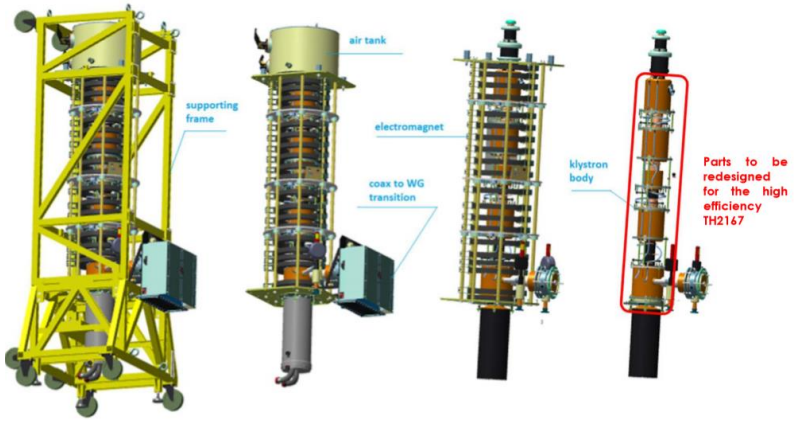
Retro-fit High Efficiency (70%) 350kW, CW, 0.4 GHz CSM LHC klystron upgrade.

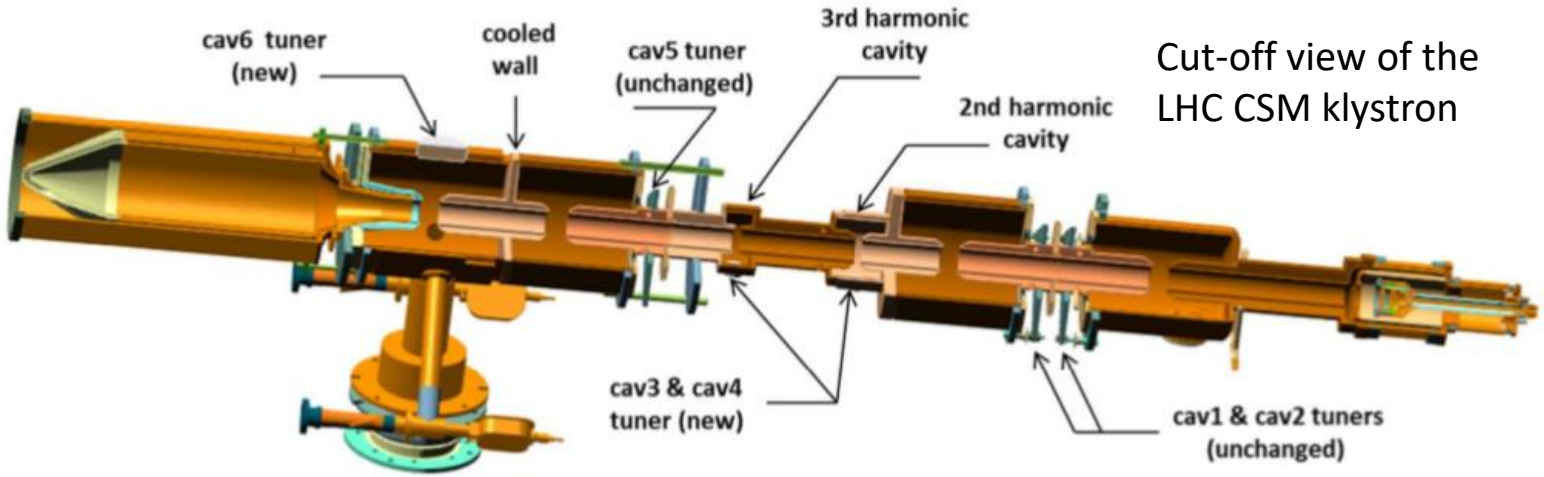
(in collaboration with Thales)



	LHC/CSM	LHC/Thales
Frequency, GHZ	0.4	0.4
Beam power, MW	0.5	0.5
Perveance,	0.72	0.72
RF power, MW	**0.35**	**0.30**
Efficiency, %	70	60

Re-used housing, electron gun and solenoid





Cut-off view of the LHC CSM klystron

In fabrication. Will be tested in March 2024.

Existing tubes

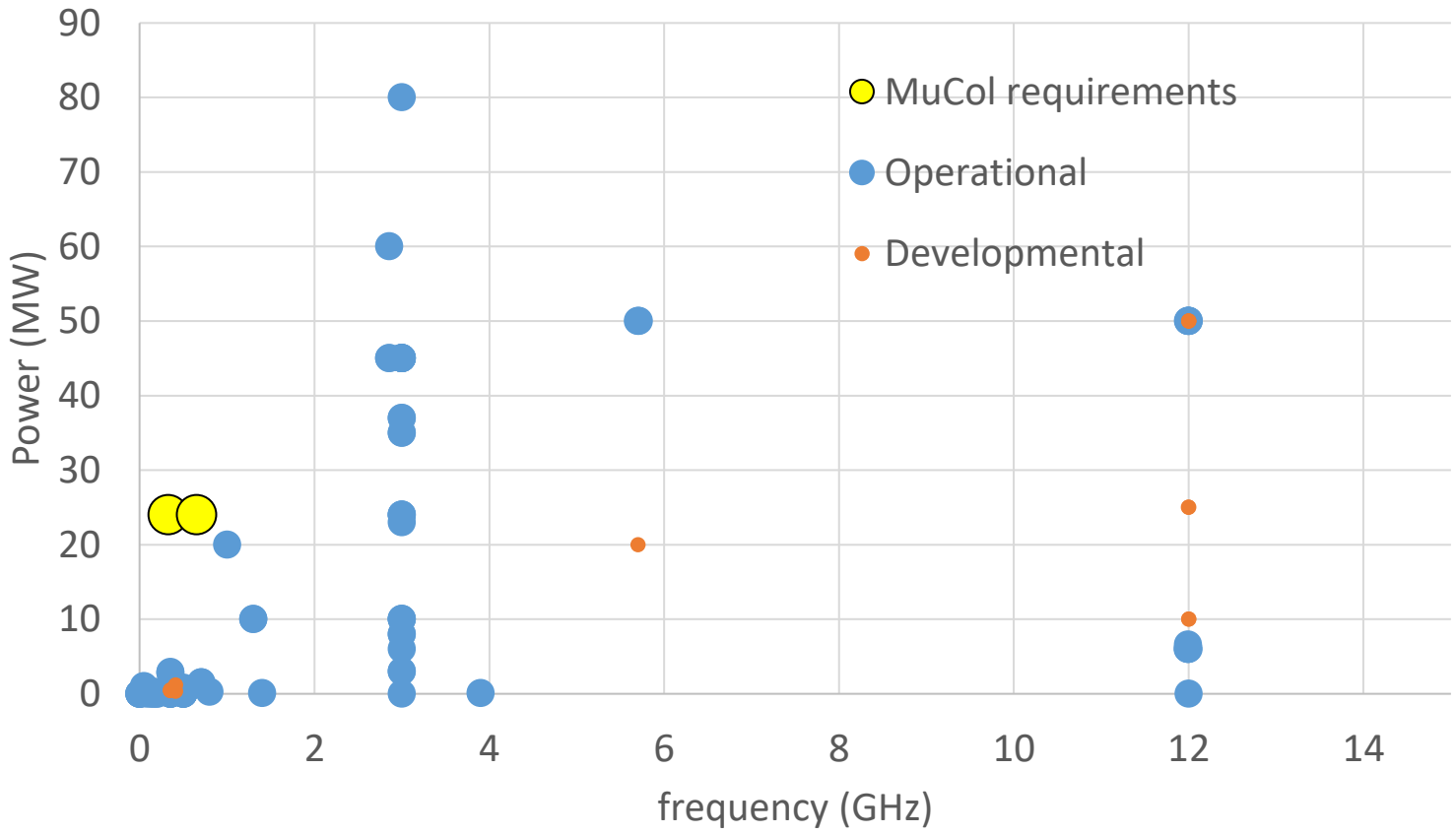
While tubes >24 MW exist they are all above 3 GHz

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



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:

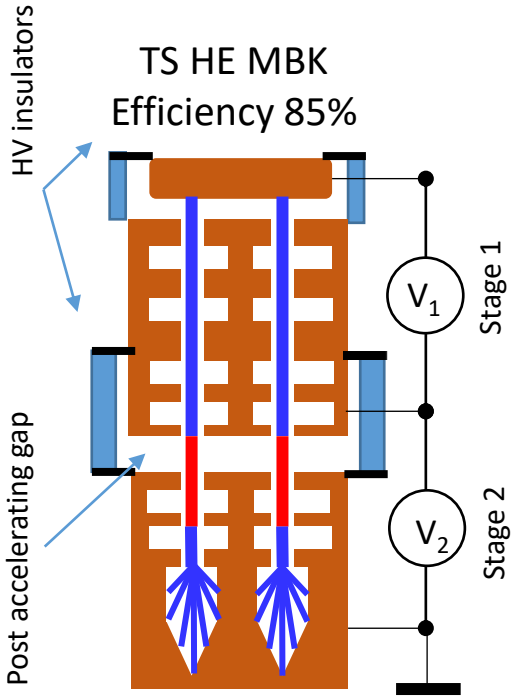
FCC hh ee he

ILC

International MUON Collider Collaboration

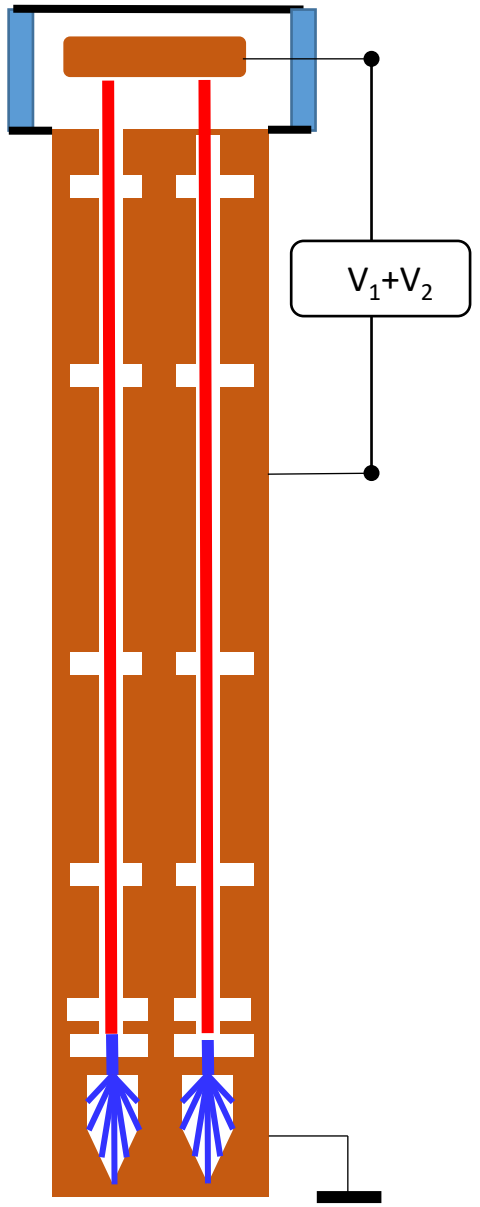
CLIC

CEPC

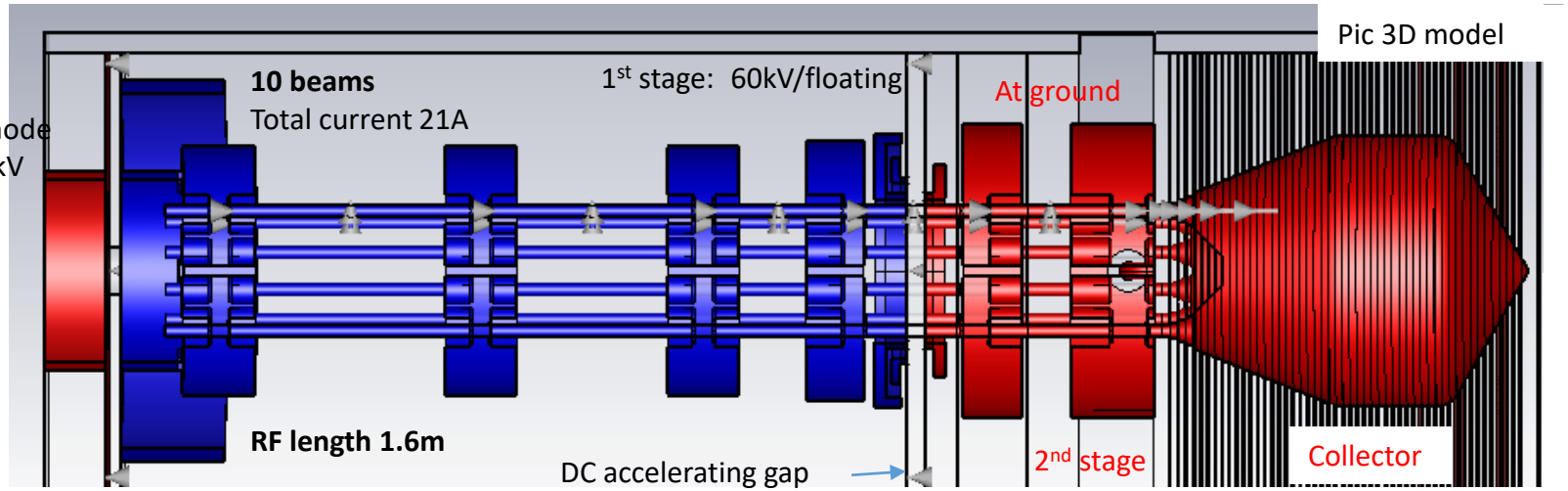


TS HE MBK
Efficiency 85%

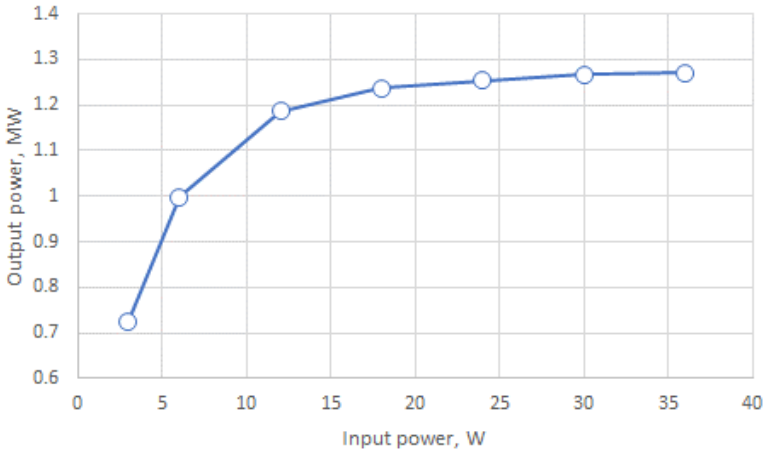
Commercial HE MBK
Efficiency 70%

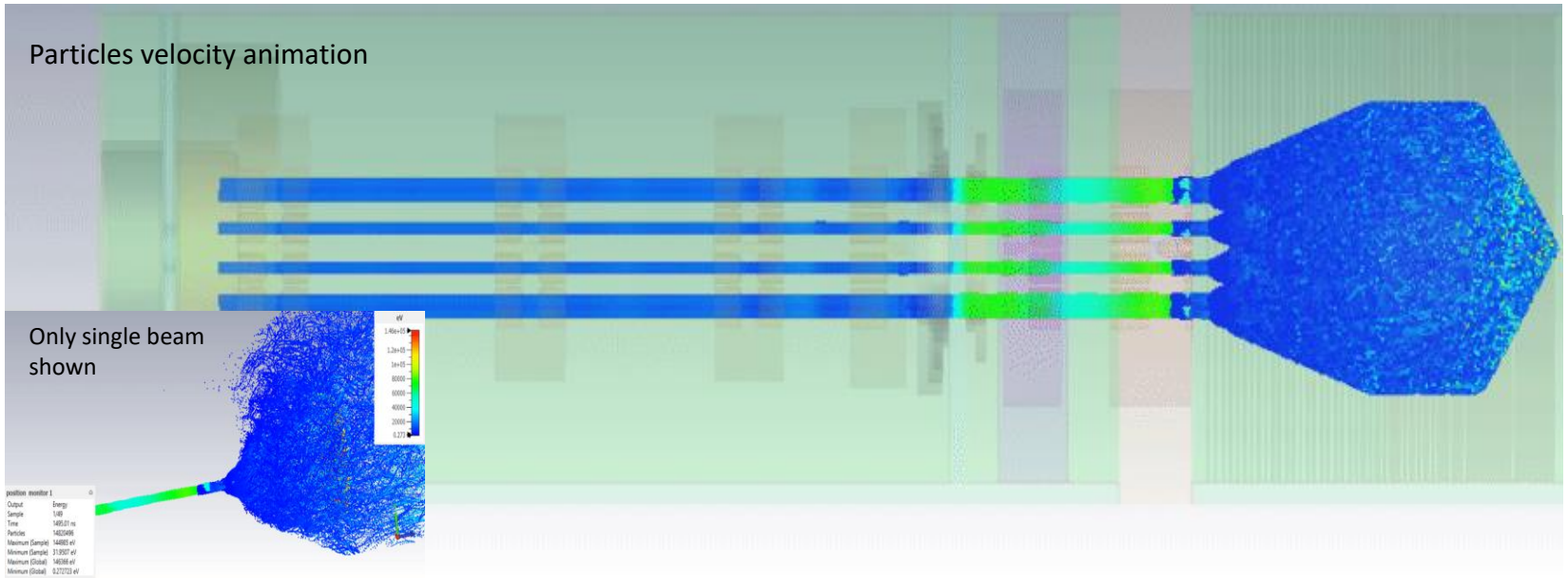


FCC Two-stage MBK klystron: **CW, 400MHz, 1.28MW.**



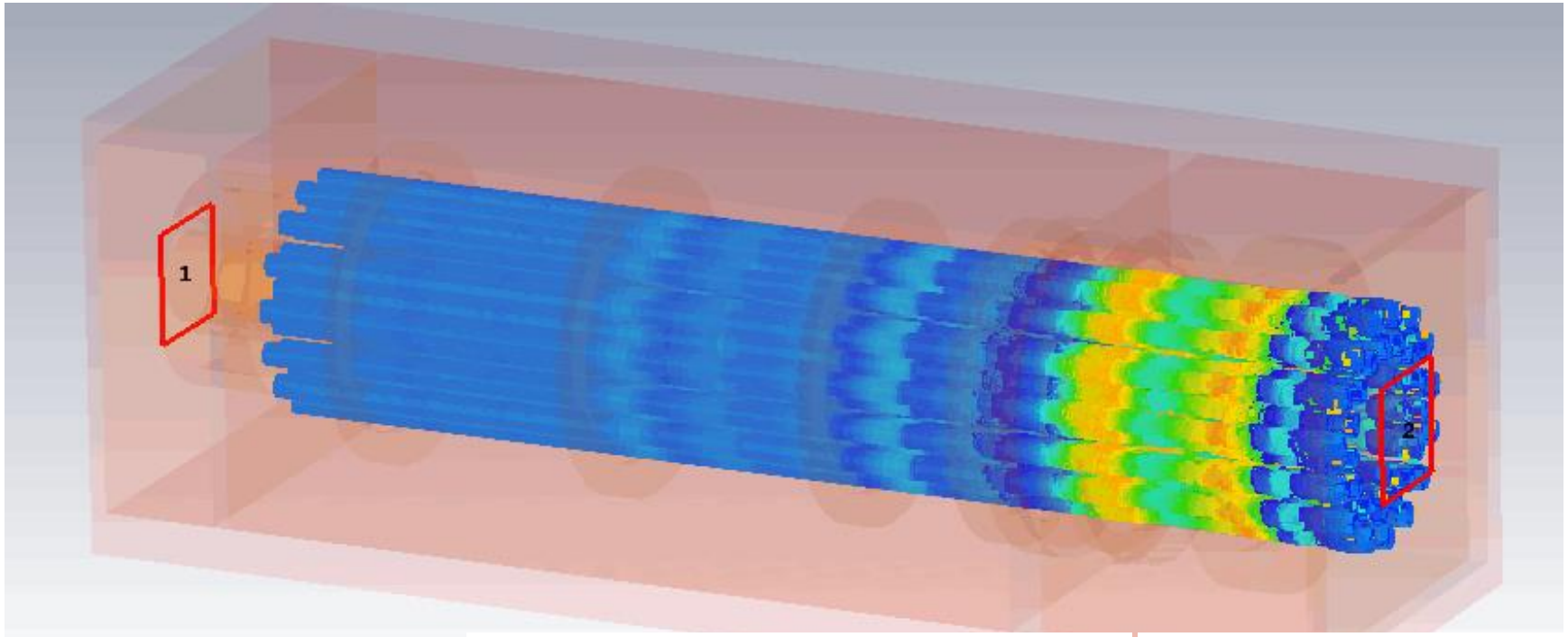
Power gain curve at nominal voltage (PIC results)

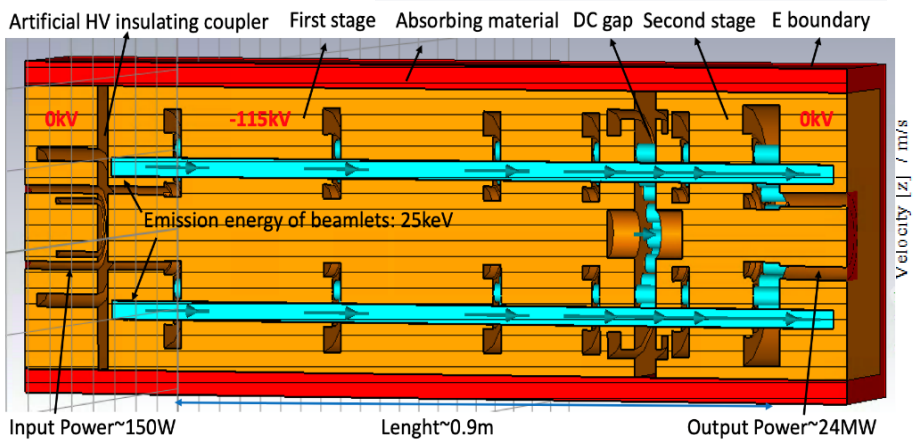


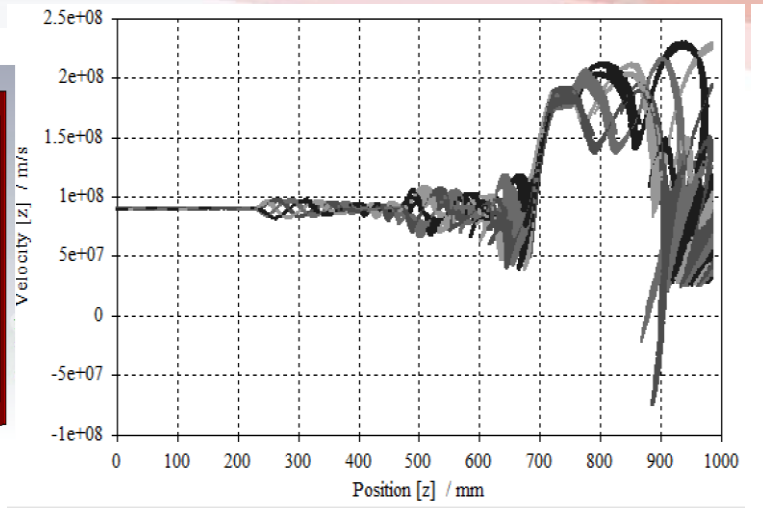


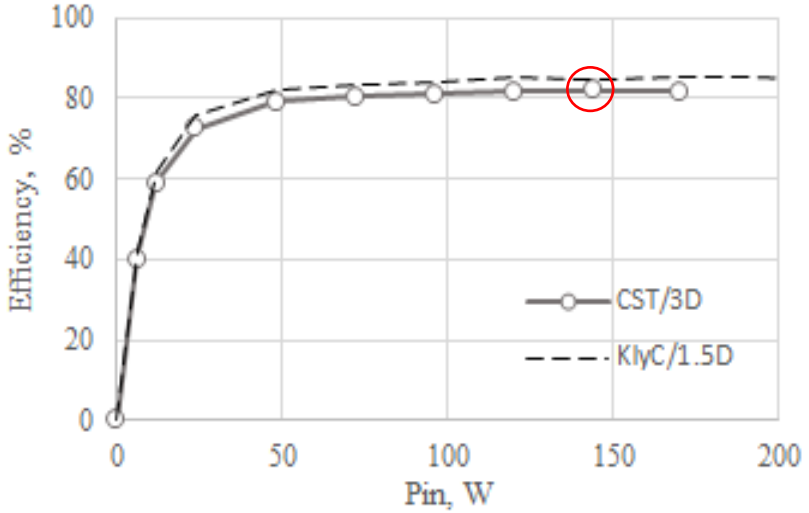
- **Very Efficient: 84%**
- **Compact: ~2.5m length in total**
- **Low voltage: 60kV+12kV**
- **High saturated power gain: 46dB**

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









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

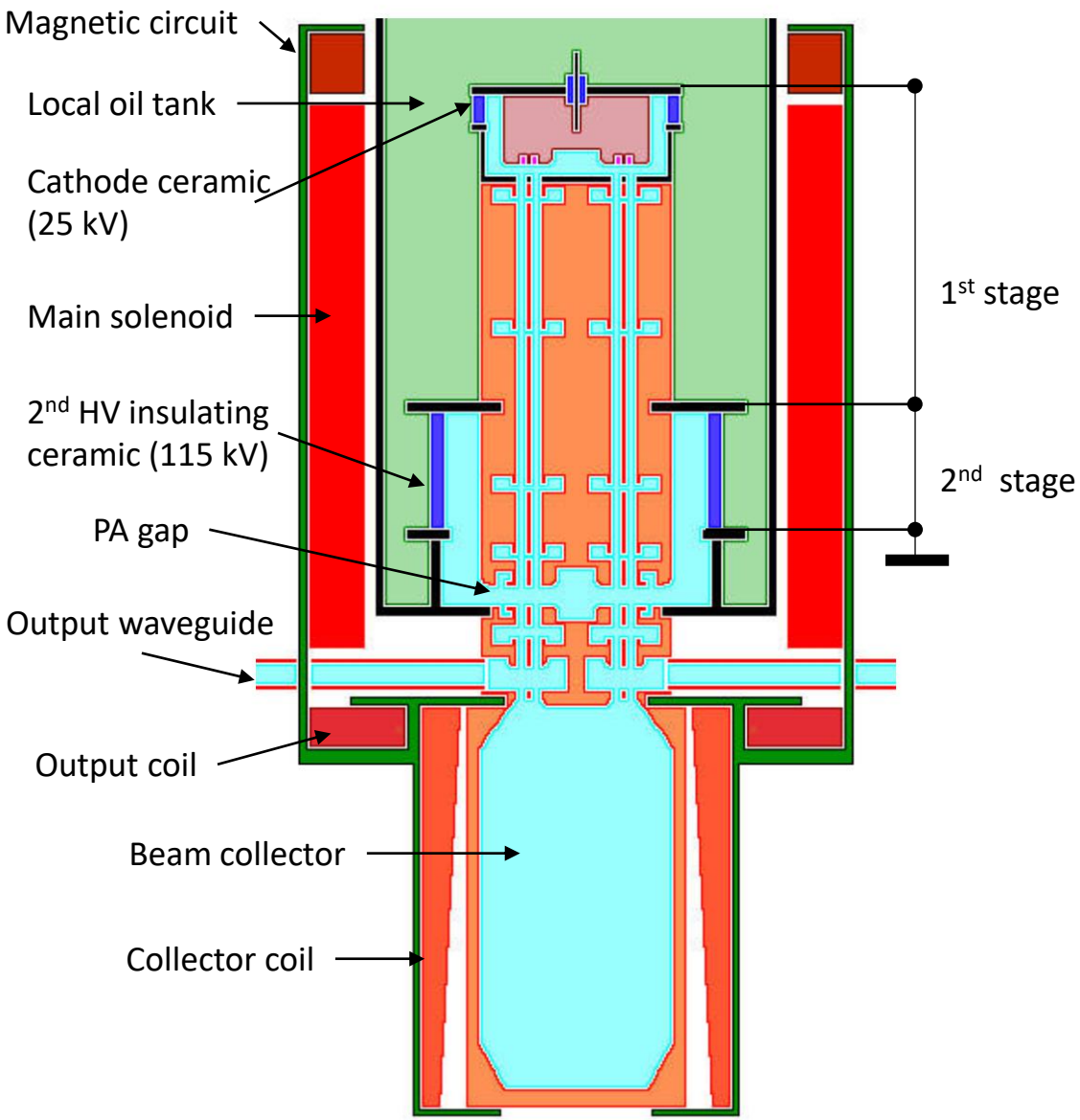
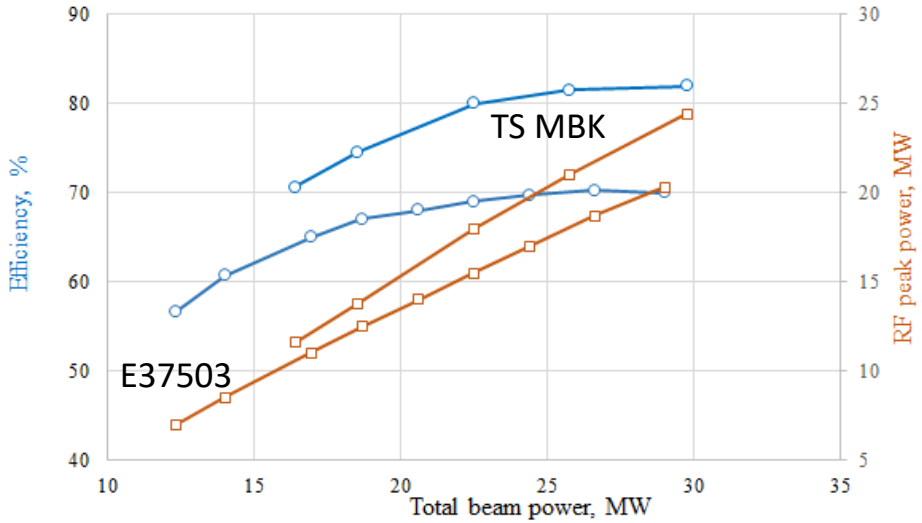
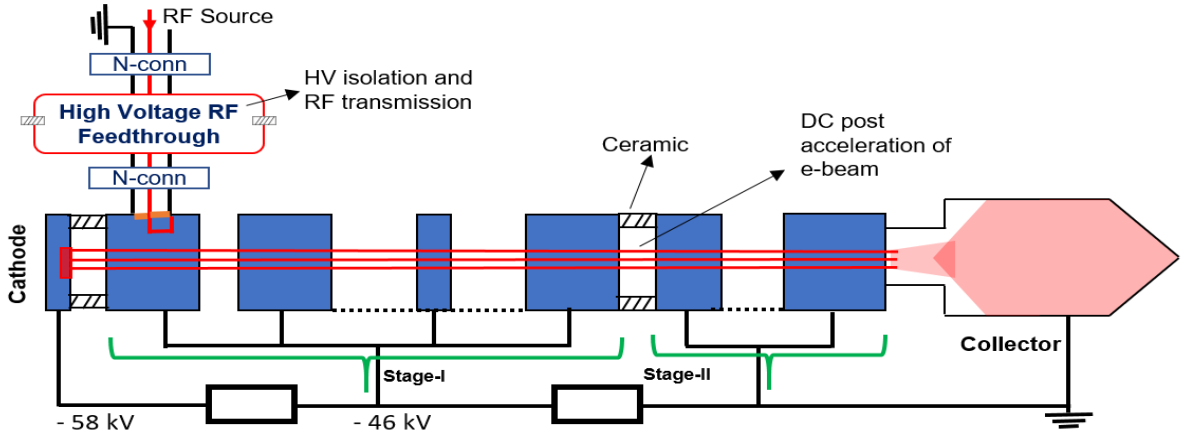


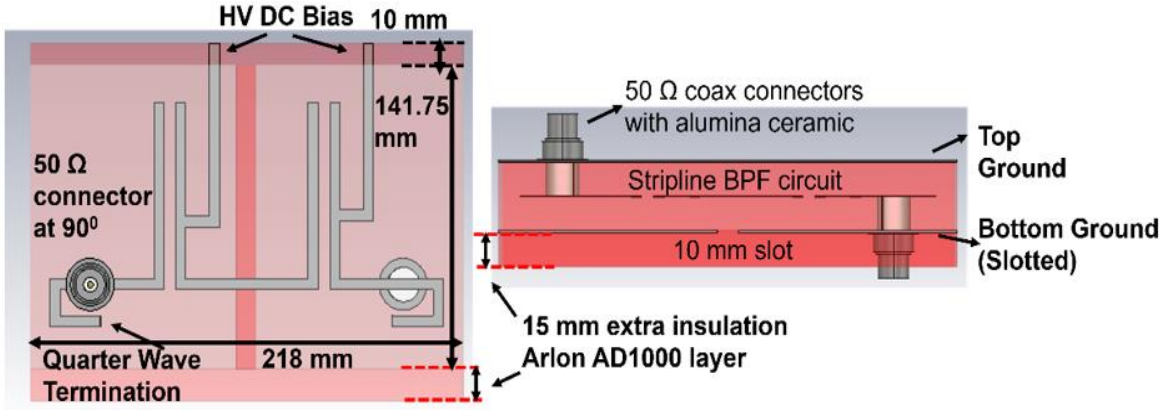
TABLE I. DESIGN AND SIMULATED PARAMETERS (CST/3D) OF THE CLIC TS MBK AND CANON MBK E3750 CATALOGUE DATA

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

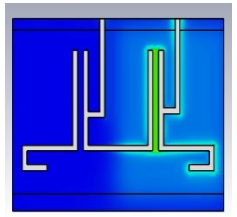


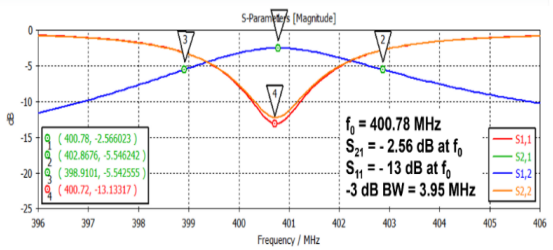
FCC Two-stage MBK klystron: **HV isolated RF feed-through with strip-line topology.**





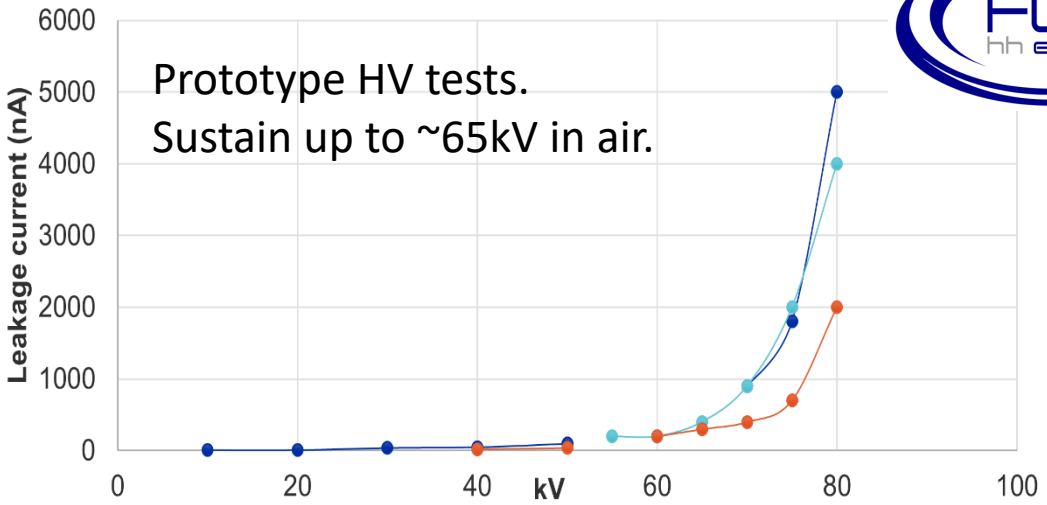
(HV)

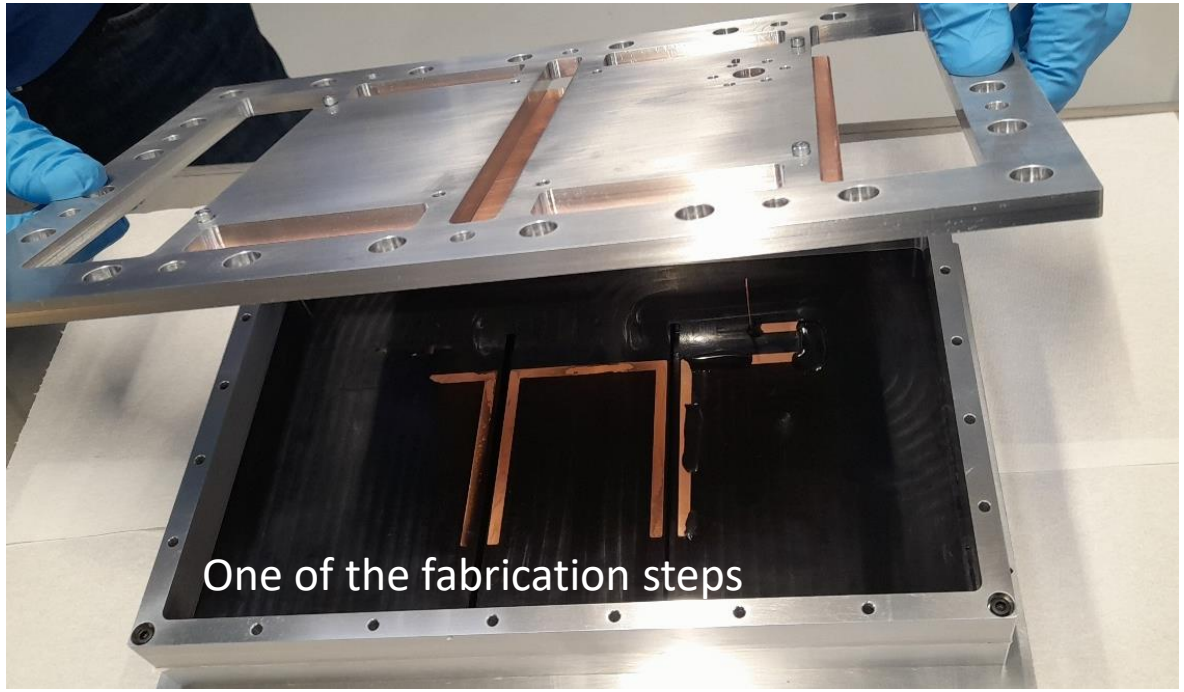




(RF)

Project will be completed in October 2023





Conclusion

- 650 MHz tube may well be within scaling range of the CLIC tubes
- The 325 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 325 MHz solution
- Significant synergy with CLIC and FCC developments