Efficient RF power sources for proton driver accelerators

Frank Gerigk, CERN, EuCARD-2 annual meeting
28-30 March 2017, University of Strathclyde, Glasgow

Material from:

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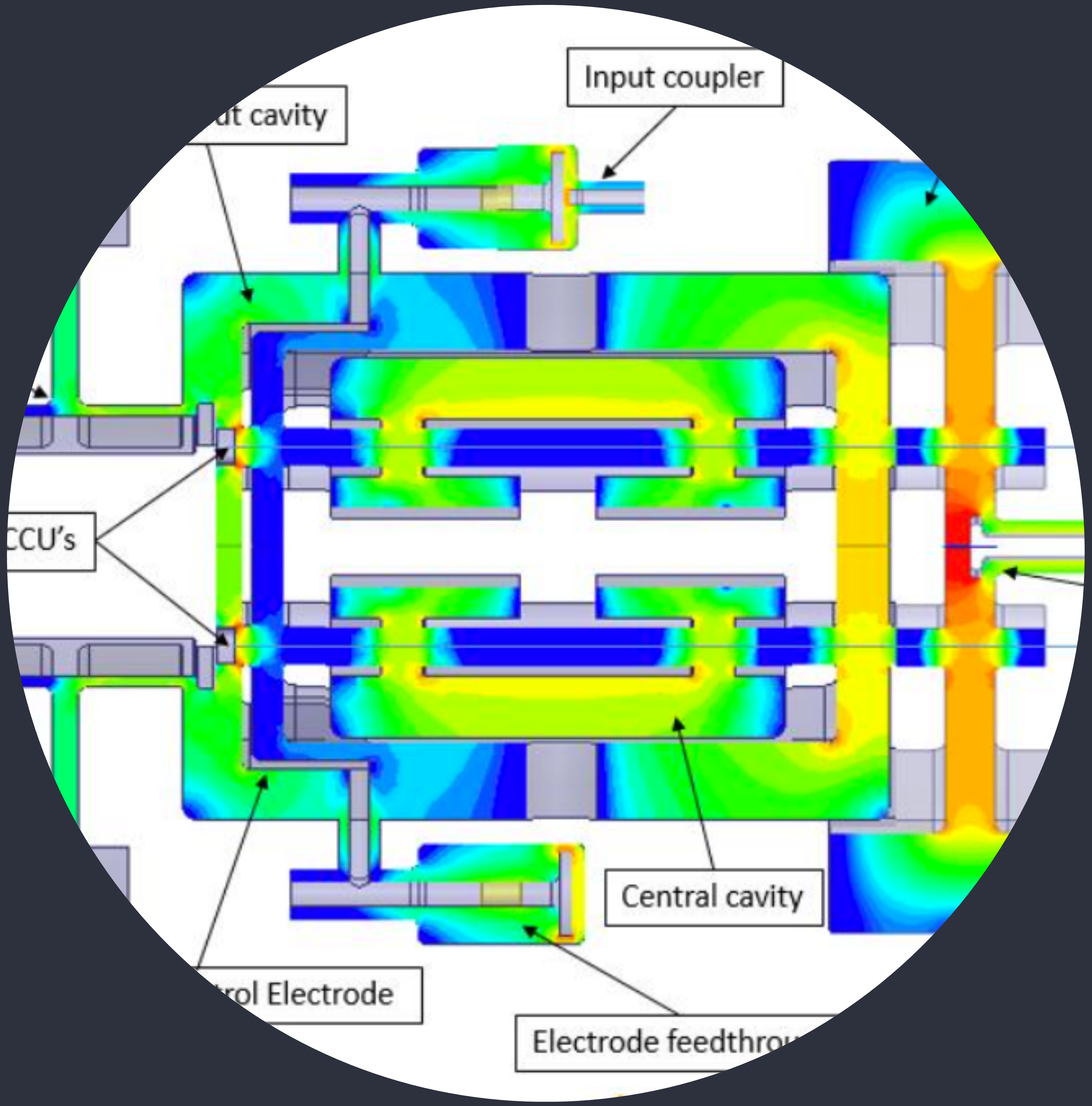
Content



ut cavity
Input coupler
CCU's
Central cavity
rol Electrode
Electrode feedthrou

Proton drivers

and their specific RF requirements

RF power for proton drivers

- We consider sources for linac drivers, as there the RF efficiency is generally more critical than for circular machines:
  - ➡fixed frequency sources (300 - 1300 MHz),
  - ➡high peak power (MW range),
  - ➡pulsed to CW regime.
- Drawing from the “Proton driver efficiency workshop”, a EuCARD-2 event at PSI (29 Feb. to 2 March 2016).

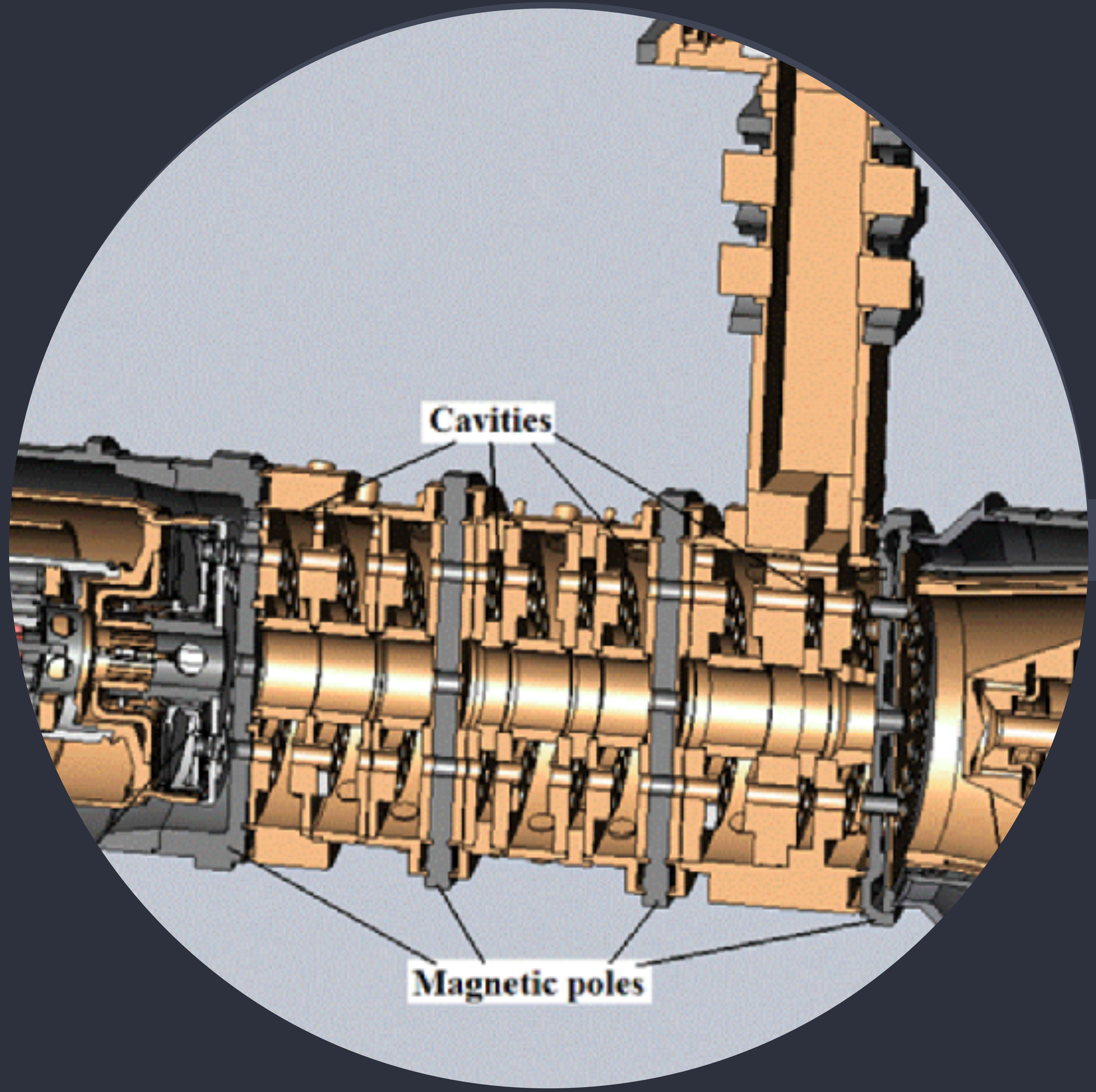
Proton driver efficiency workshop 2016 (PSI)

Modulators

"Modulate" the AC grid voltage to the voltage & time structure needed by the RF power source

Modulator efficiency

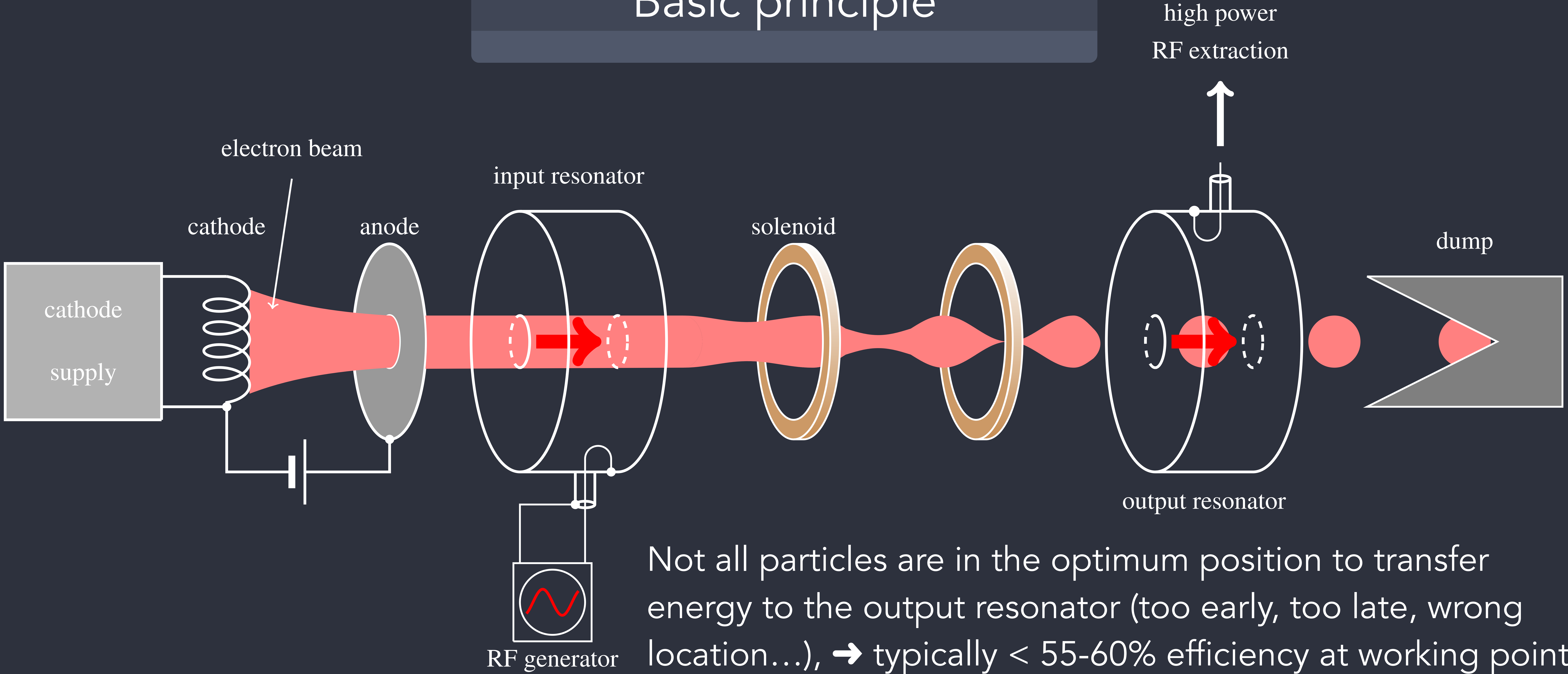
- Main choice for MW class modulators is between
  - i) pulse transformer based and,
  - ii) HF transformer based devices.
- **Pulse transformer** based: ~85 - 90% efficiency, multi-MW level, long rise times: ~300 us (for a reasonably sized transformer)
- **HF transformer** based (Stacked Multi-Level): 90 - 92%, up to 5 MW output power for klystrons, tetrodes or IOTs, short rise time (110 us)
- In general **85% - 92%** efficiency seems to apply to **all types of modulators** (solid state power supplies to klystron modulators), power levels and duty cycles.
- Additional losses occur due to different **rise times** (pulse transformer/HF transformer). Lower voltage favours shorter rise time.



Klystrons

Efforts towards higher efficiency

Basic principle

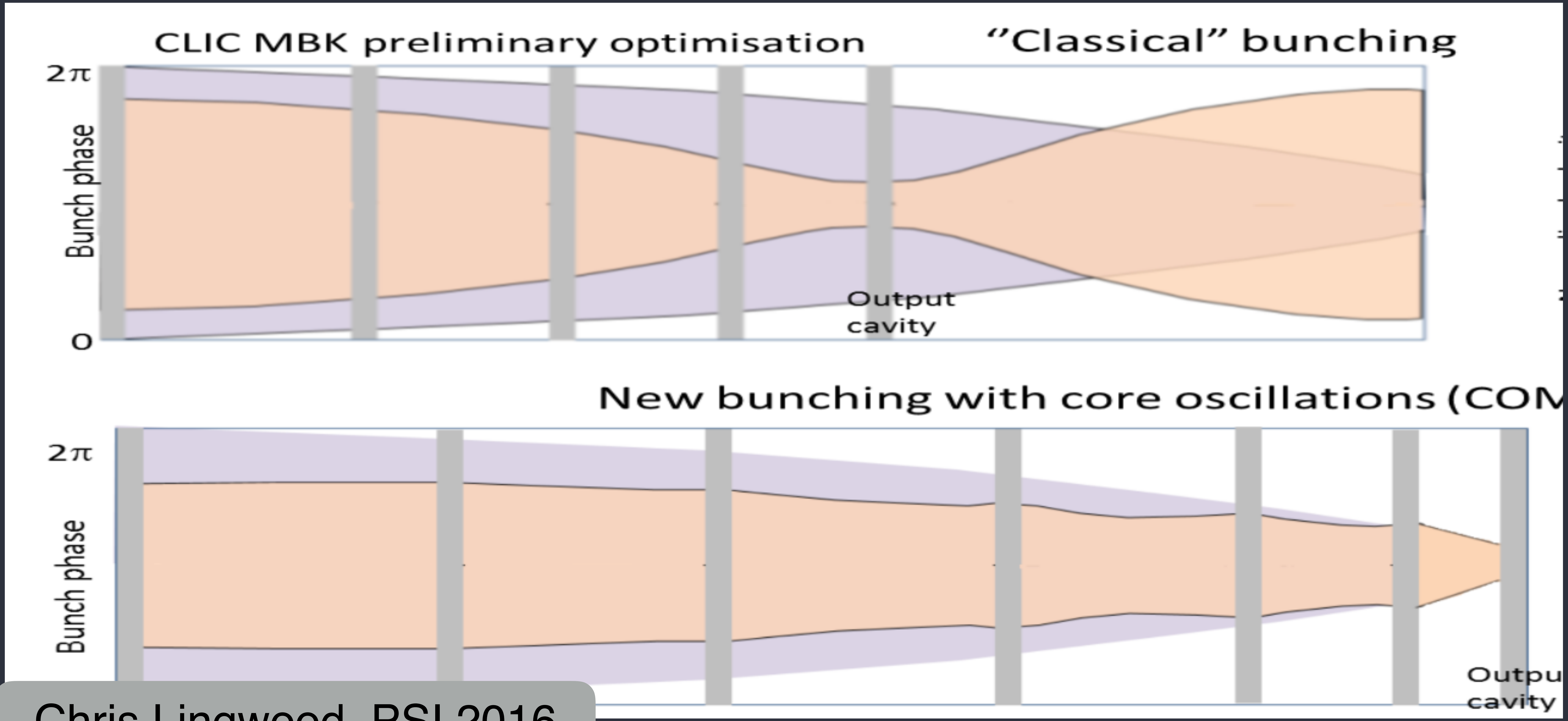


Not all particles are in the optimum position to transfer energy to the output resonator (too early, too late, wrong location…), ➜ typically < 55-60% efficiency at working point.

Modern beam dynamics tools allow optimisation beyond classical klystron limitations:
➜ 3 new principles.

I Core Oscillation Method (COM)

Core oscillates periodically with lattice, while outer particles are focused monotonically towards the centre. COM synchronizes the 2 processes.



Chris Lingwood, PSI 2016

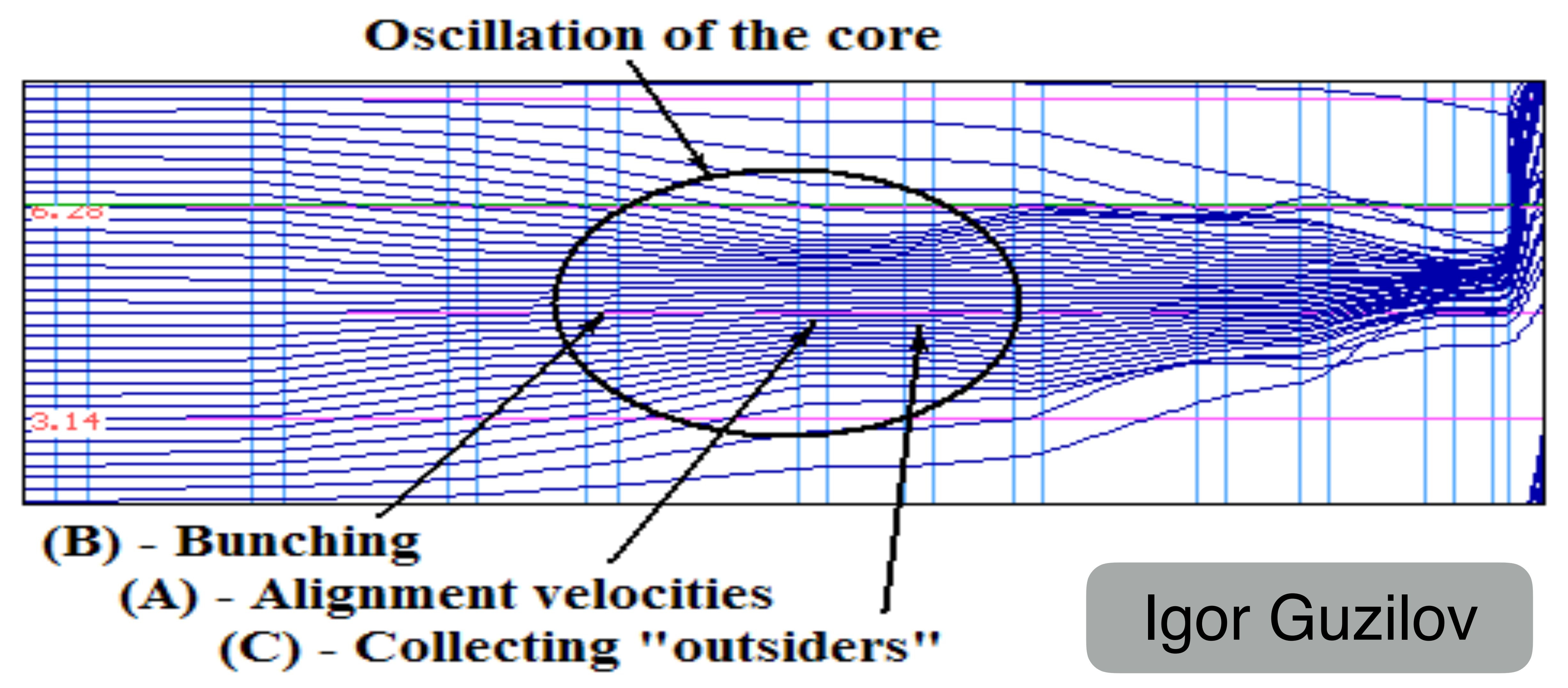
simulations predict efficiencies above 80%

but

very long tubes.

II BAC method by I. Guzilov

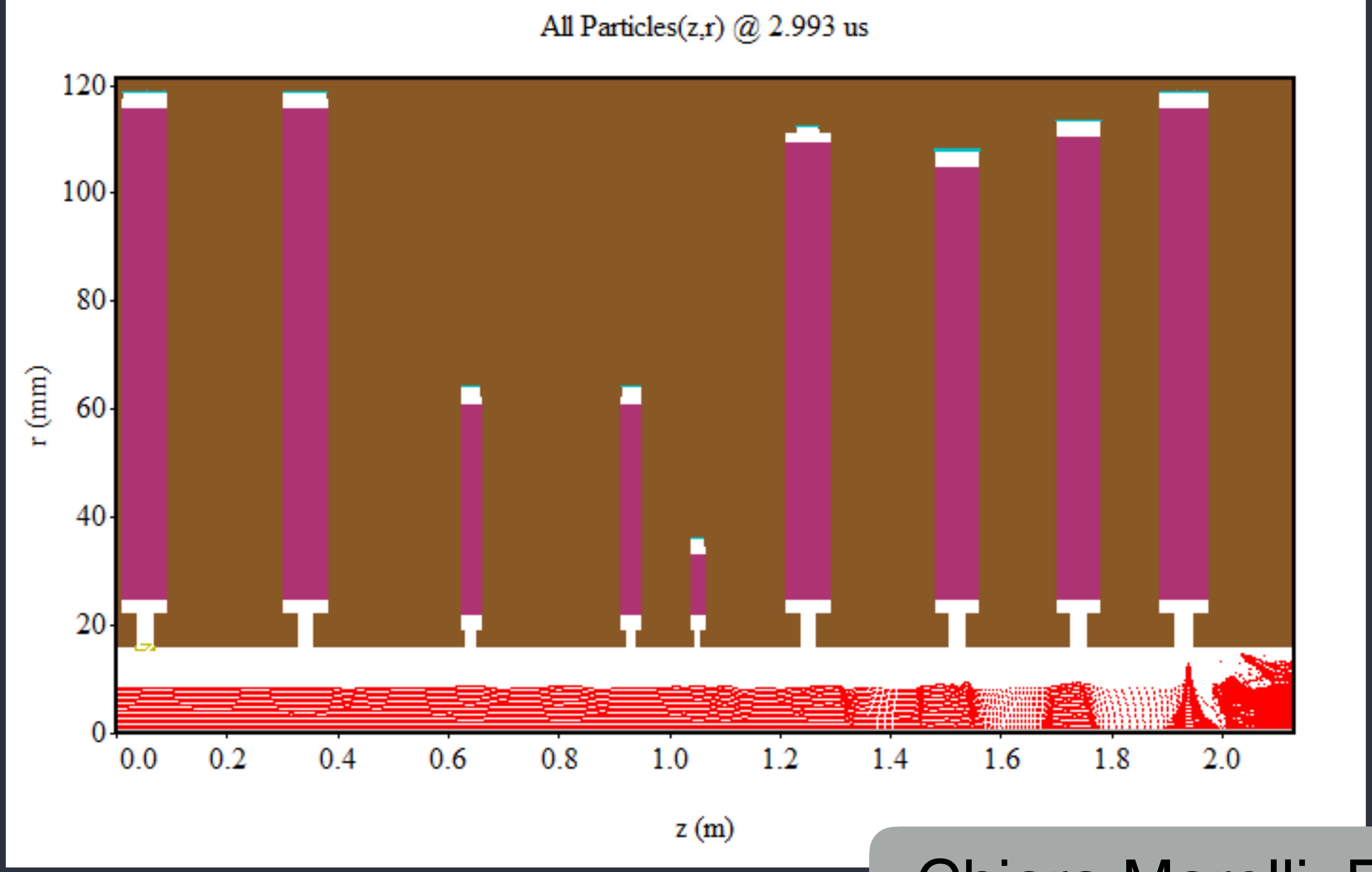
Bunching, Alignment of velocities, Collecting outsiders:
use the tuning of the intermediate cavities to create artificial oscillations



Length reduction by over 50% when compared to COM, plus significant voltage reduction
Disadvantage: high number of cavities

III Core Stabilization Method

CSM uses harmonic cavities (n=2,3) to do what space charge does for COM but in a much shorter distance.



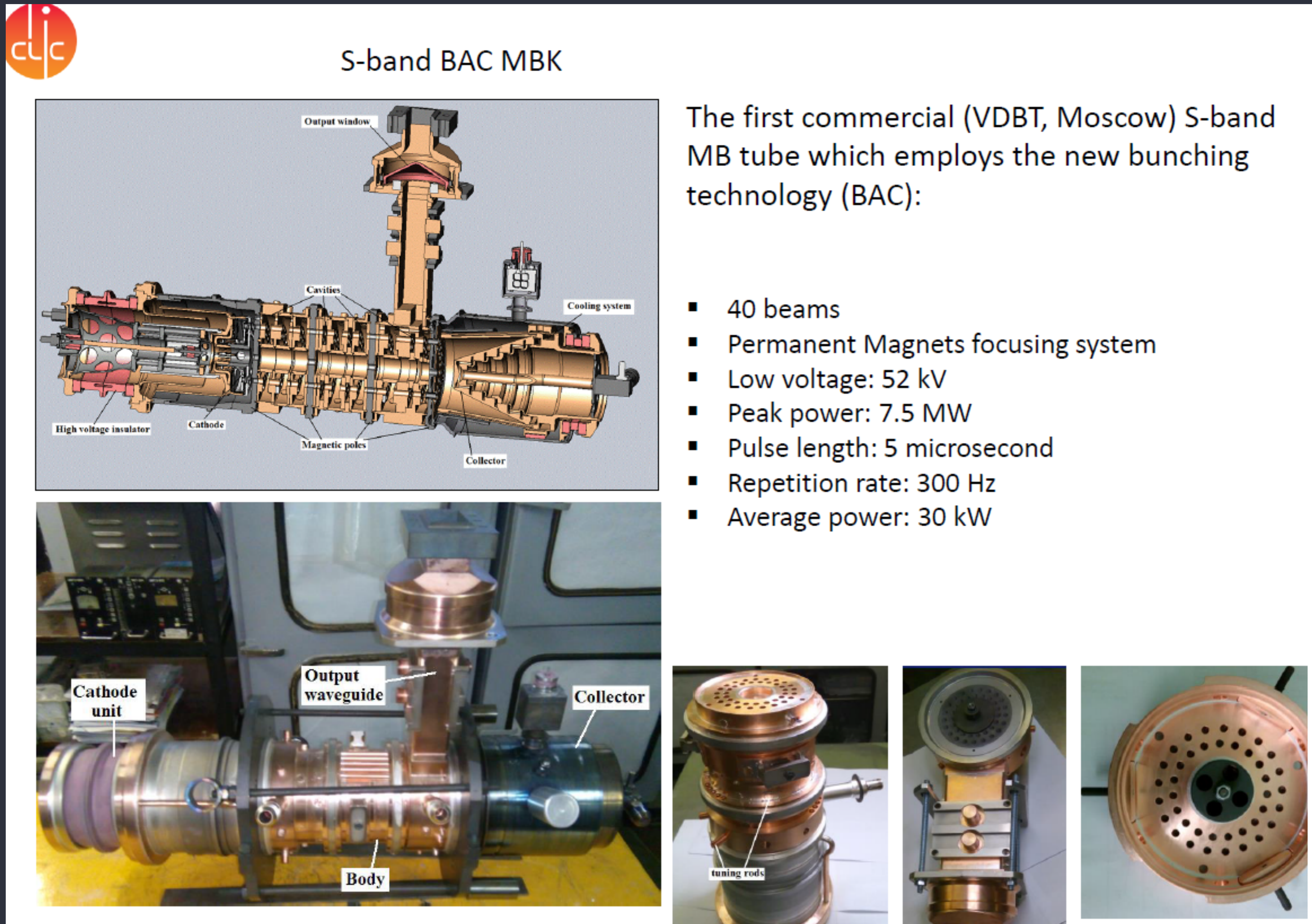
Chiara Marelli, ESS seminar, 2016

Efficiencies >80% for short tubes (e.g. 800 MHz < 2 m)

HEIKA collaboration

- **H**igh **E**fficiency **I**nternational **K**lystron **A**ctivity (HEIKA)
- CERN, SLAC (USA), Lancaster University (UK), Cockroft Institute (UK), Thales Group, L3, ESS (SE), Moscow University of Finance & Law (RU), VDBT (RU), …
- Close collaboration between institutes and industry.
- Use of modern beam dynamics tools to optimise efficiency rather than peak power.
- Goal is to push state of the art efficiency.

BAC klystron test



S-band BAC MBK

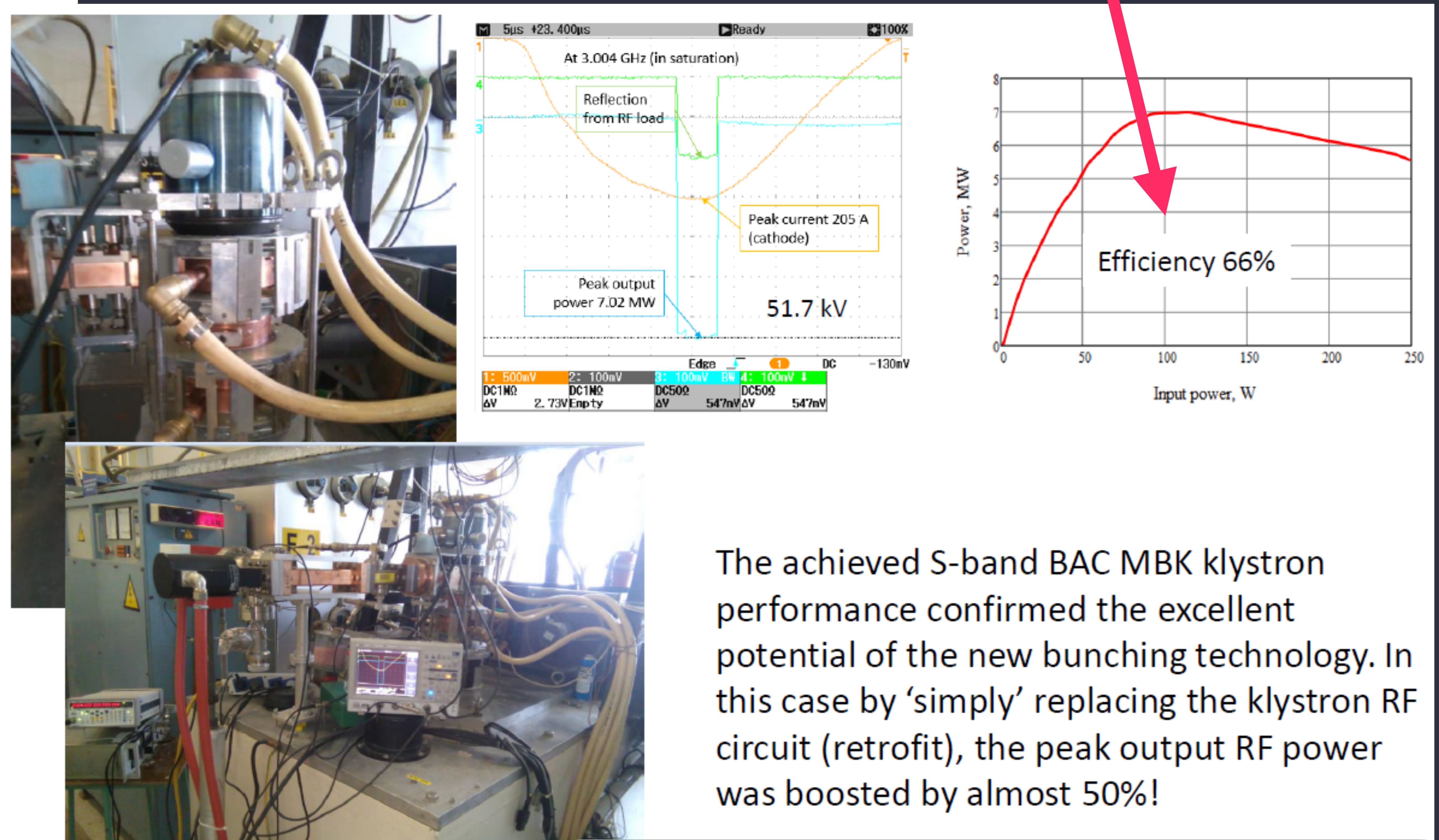
The first commercial (VDBT, Moscow) S-band MB tube which employs the new bunching technology (BAC):

- 40 beams
- Permanent Magnets focusing system
- Low voltage: 52 kV
- Peak power: 7.5 MW
- Pulse length: 5 microsecond
- Repetition rate: 300 Hz
- Average power: 30 kW

Igor Syratchev,

Igor Syratchev, CLIC project meeting 2016

original efficiency 42%



The achieved S-band BAC MBK klystron performance confirmed the excellent potential of the new bunching technology. In this case by 'simply' replacing the klystron RF circuit (retrofit), the peak output RF power was boosted by almost 50%!

Chiara Marelli, ESS seminar 2016

Klystrons summary

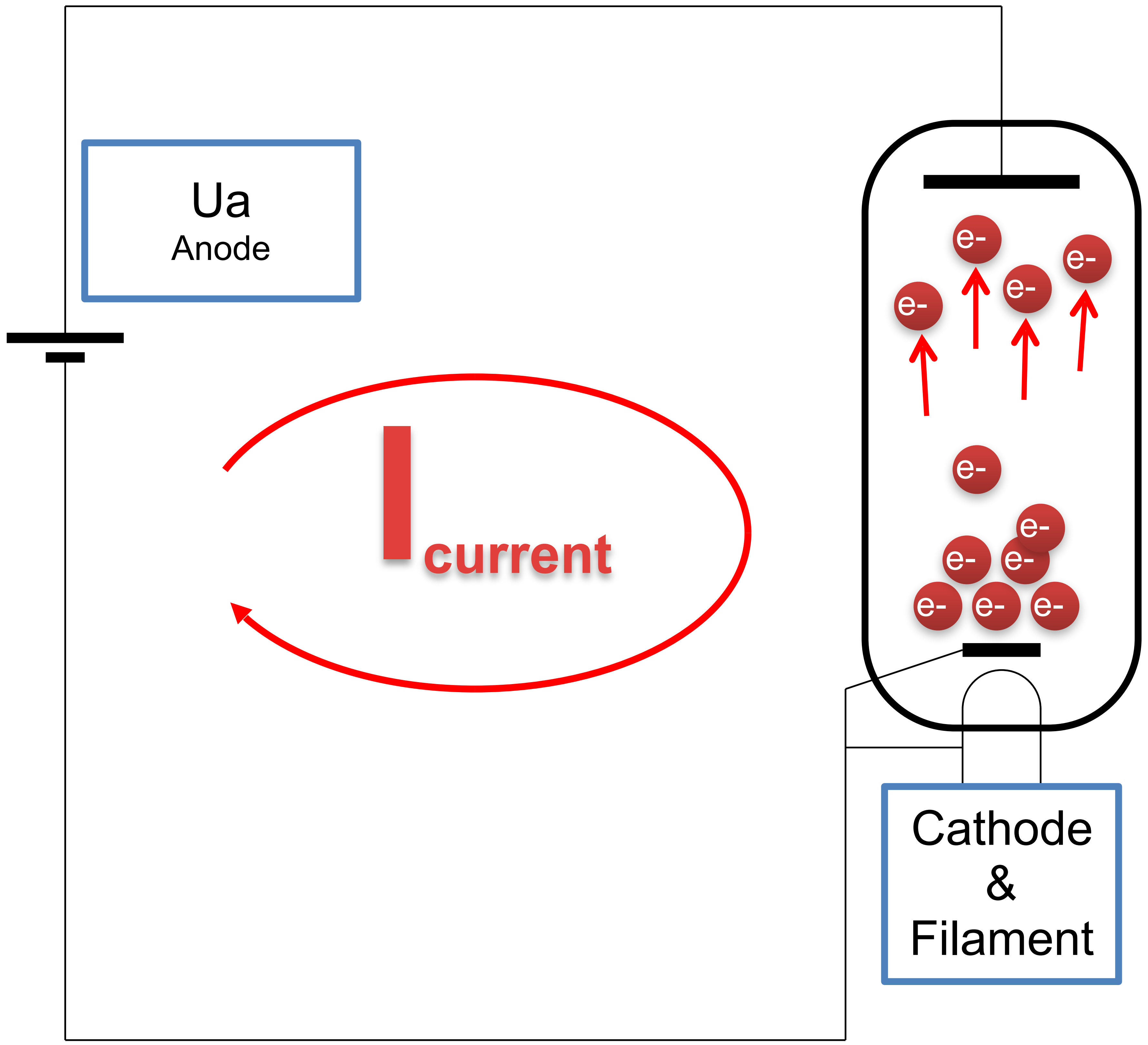
RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]
Single Beam	40-5	1000-3000	300 ns	4 ms		<1200 kW	55 (65 max)	~90-120kV	0.3GHz-1.5GHz
MB	40-5	10,000-15,000 kW (up to 1.5 ms at least	300 ns	4 ms		< 1200 kW (no point)	60 (70 max)	~90-120kV	0.3GHz-1.5GHz
Future Single Beam			-		-		70	40-60 kV	0.3GHz-1.5GHz
Future MB							80	40-60 kV	0.3GHz-1.5GHz

- ms-range klystrons achieve MW-range output power.
- Supplying power values below the max. operational power reduces the efficiency, using a modulating anode helps but may reduce reliability.
- Rise time determined by the modulator: 100 - 300 us.
- Long life time: 40 kh, high-gain (< kW pre-amplifier).
- Efficiency in operation limited by saturation curve. At working point ~55%.
- Vigorous R&D program promises to increase efficiency at working point up to 70% (single beam), or 80% (multi beam) & lower HV requirements (no oil tanks).

Gridded tubes

200 MHz tetrode combination in operation at the CERN SPS since 1976 (Eric Montesinos)

Essentials of tetrodes



Vacuum tube

Heater + Cathode

Heated cathode

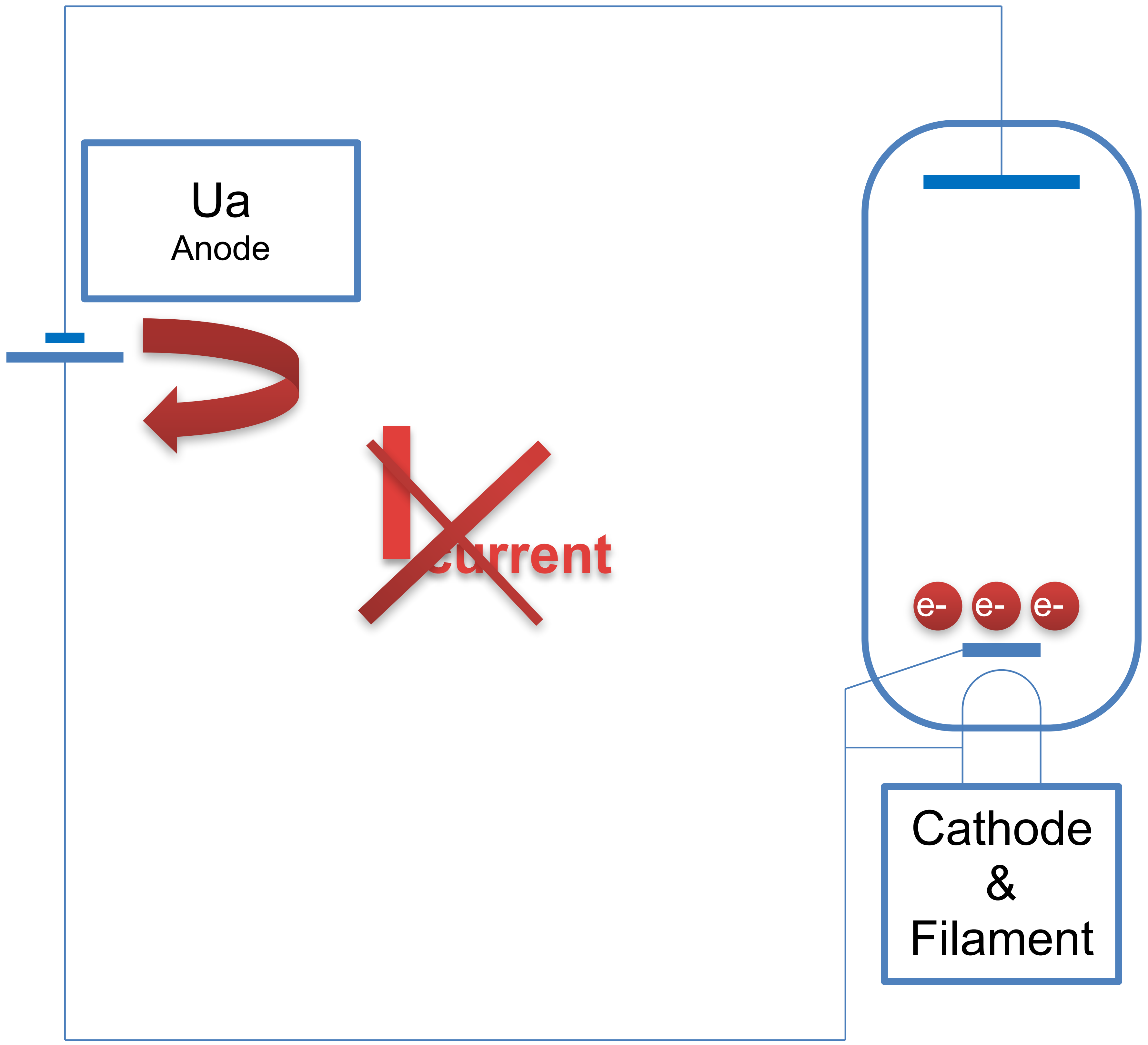
Coated metal, carbides, borides,…

thermionic emission

Electron cloud

Anode

Essentials of tetrodes



Diode

Heater + Cathode

Heated cathode

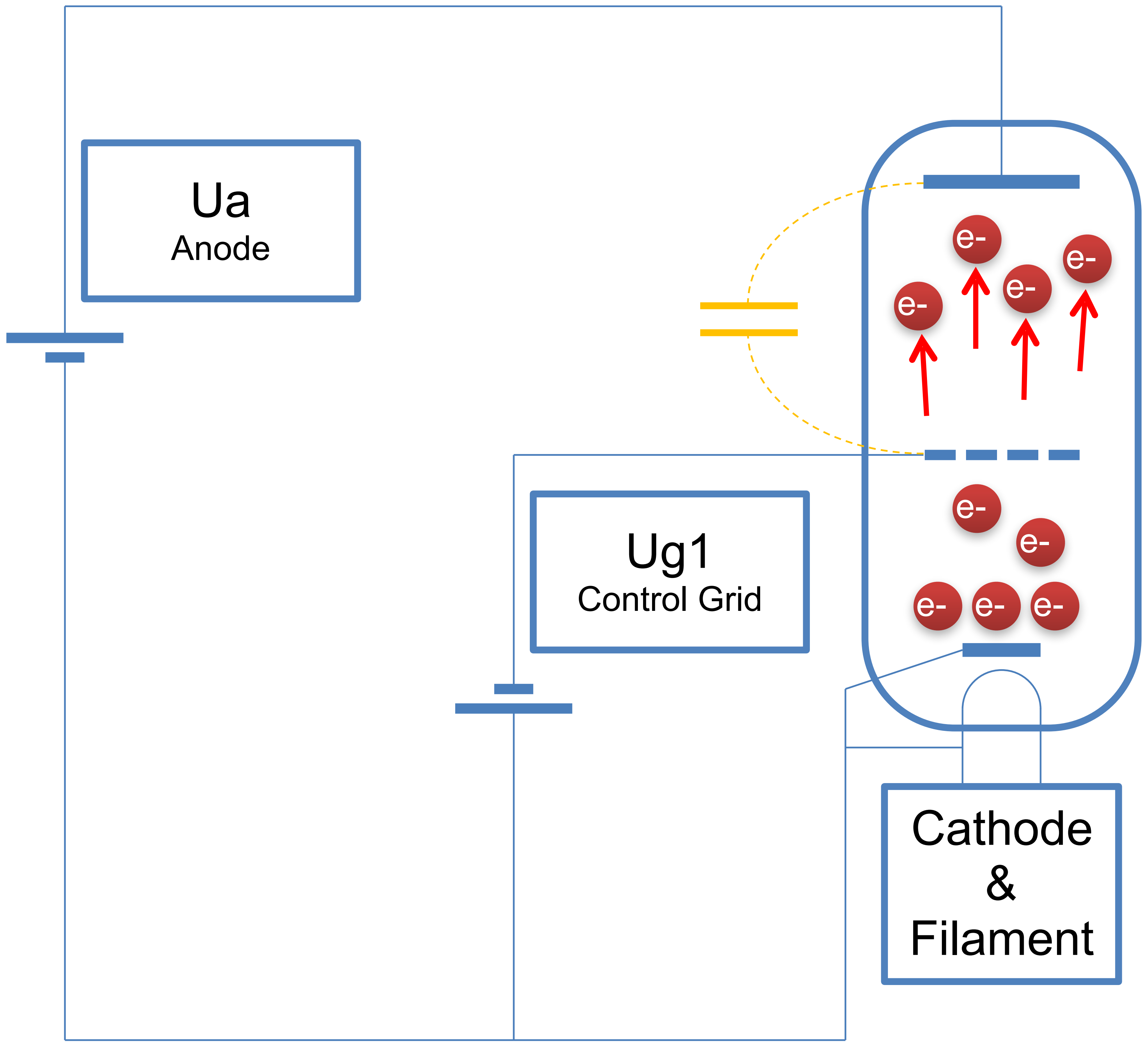
Coated metal, carbides, borides,…

thermionic emission

Electron cloud

Anode

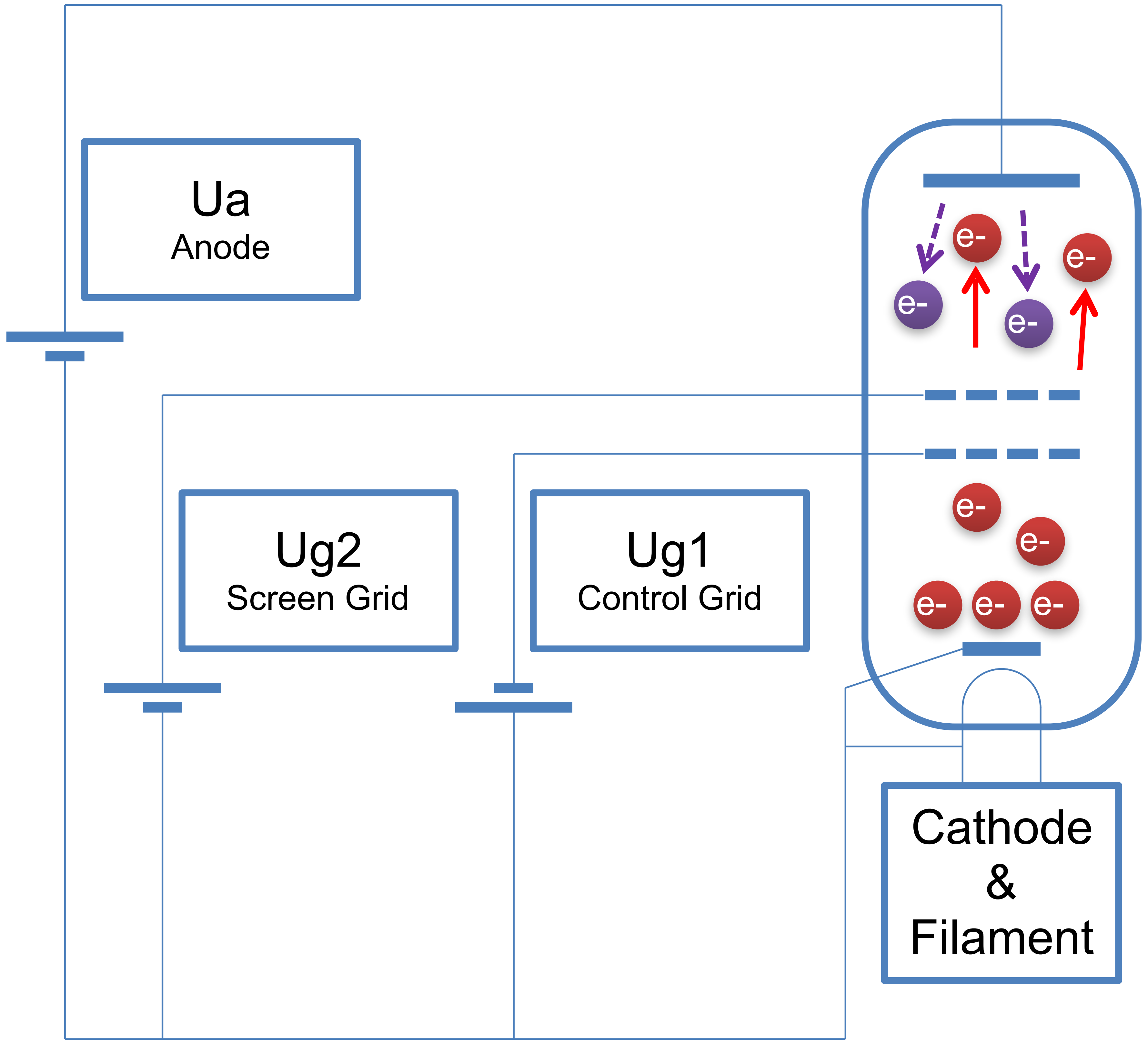
Essentials of tetrodes



Triode

- Modulating the grid voltage proportionally modulates the anode current
- Transconductance
  - Voltage at the grid
  - Current at the anode
- Limitations
  - Parasitic capacitor Anode/g1
  - Tendency to oscillate

Essentials of tetrodes



Tetrode

Screen grid

- Positive (lower anode)
- Decouple anode and g1
- Higher gain

Limitations

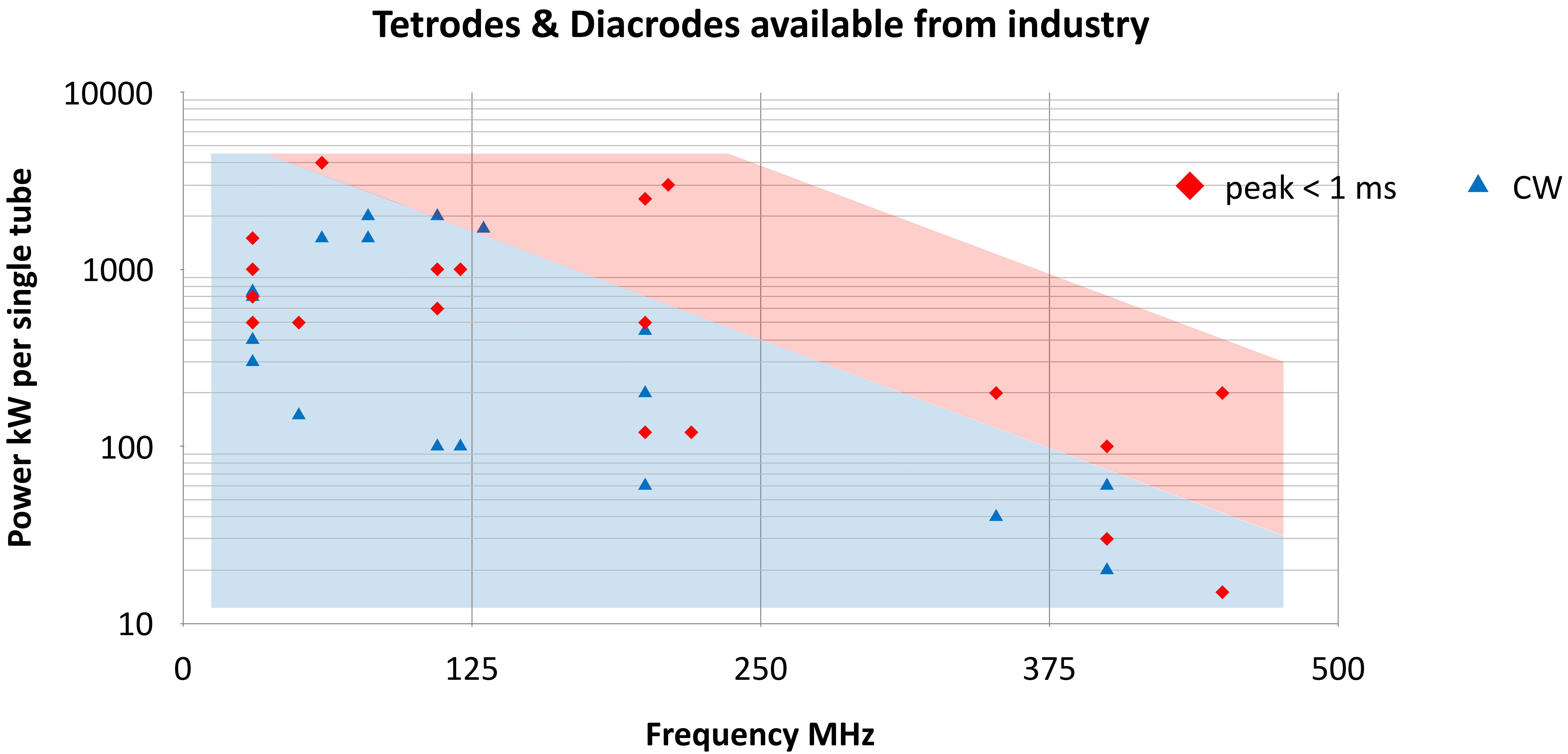
- Secondary electron
- Anode treated to reduce secondary emission

Tetrodes/Diacrodes

- Thales design for an improved Tetrode performance: Diacrode
- Minimizing reactive currents in cathode and grid meshes allows for:
  - i) double the power at a given output frequency
  - ii) double the frequency for a given output power
- Los Alamos successfully operates several Diacrodes since 2015.

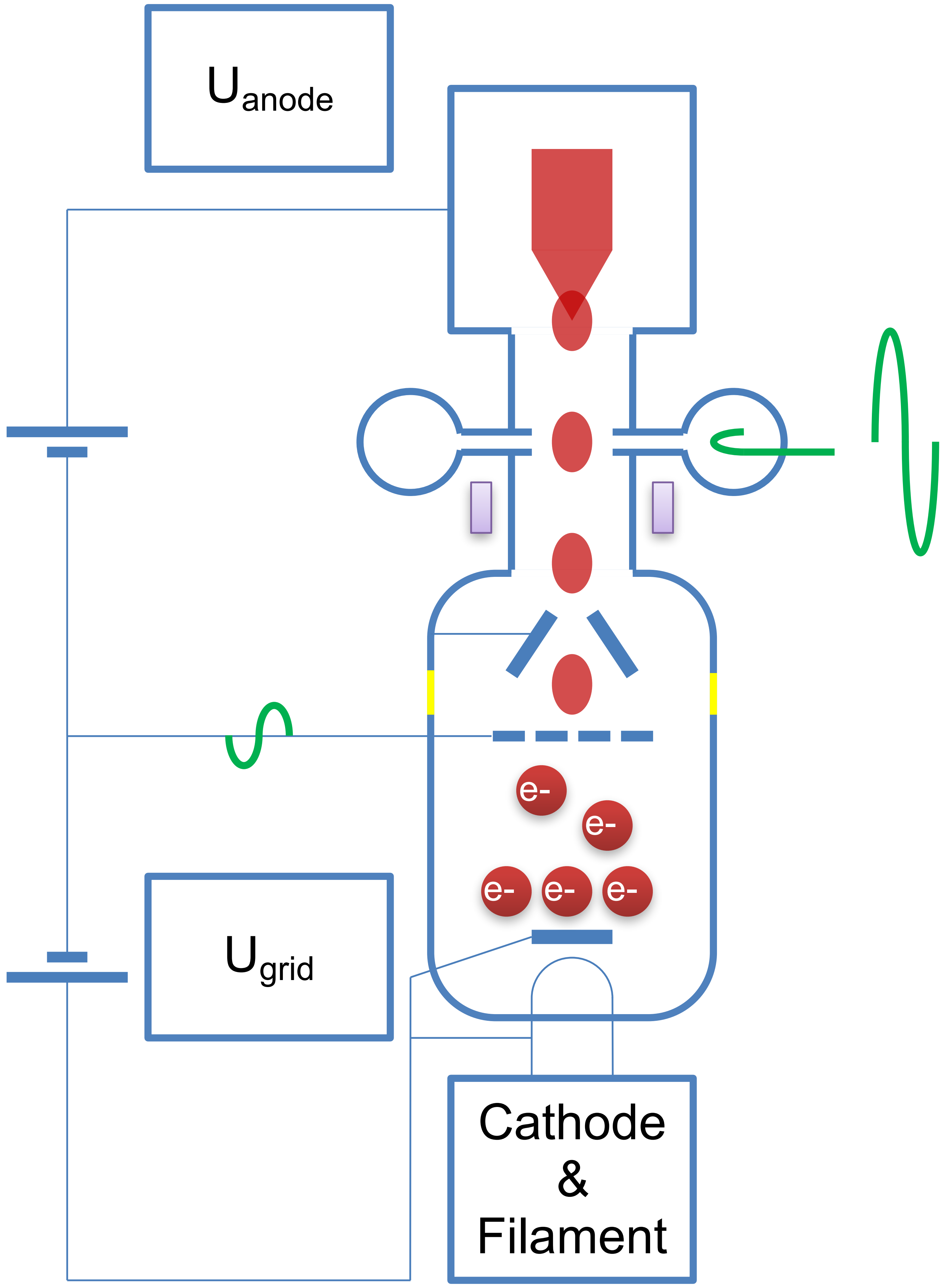
RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
Tetrode: state of the art	14-16	4000	ns	any	any	1500	70	10-25	30-400	
Diacrode: state of the art	14-16	3000	ns	any	any	2000	70	20-30	30-400	

Frequency & Power range of tetrodes



Eric Montesinos

Essentials of IOT



IOT density modulation

converts the kinetic energy into radio frequency power

Vacuum tube

Triode input

Thermionic cathode

Grid modulates e- emission

Klystron output

Anode accelerates e- buckets

Short drift tube & magnets

Inductive catcher cavity (magnetic coupling)

Collector

Eric Montesinos

R&D program, MB-IOT

EUROPEAN
SPALLATION
SOURCE

CERN

In order to provide an alternative to klystrons, ESS launched a R&D program for Multi Beam IOT

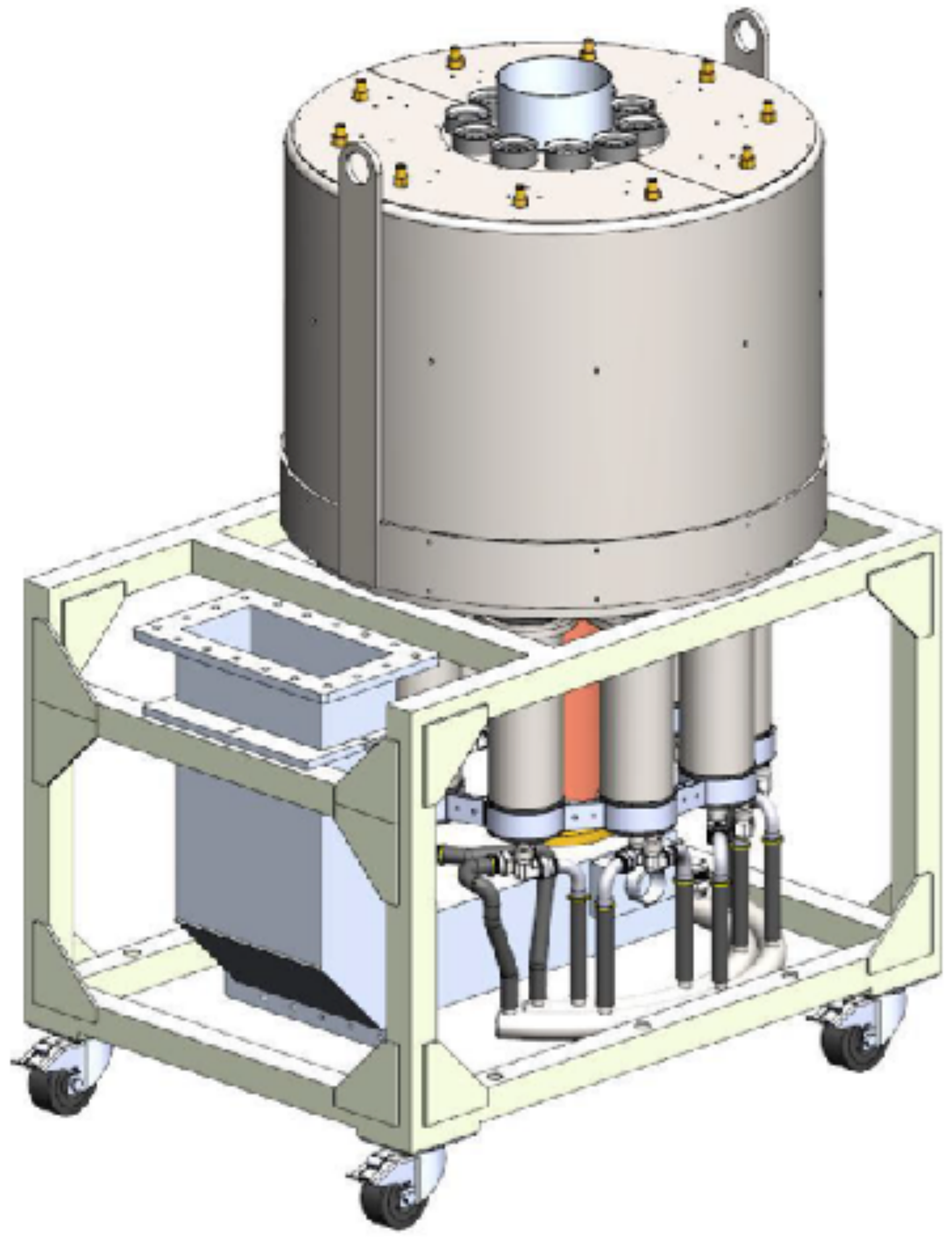
Two prototypes have been produced

The goal is 1.3 MW @ 704 MHz pulsing up to 3.5 ms – 14 Hz

CERN contributes with a test place & reliability test.

RF/DC efficiency ~70%

THALES ELECTRON DEVICES CPI



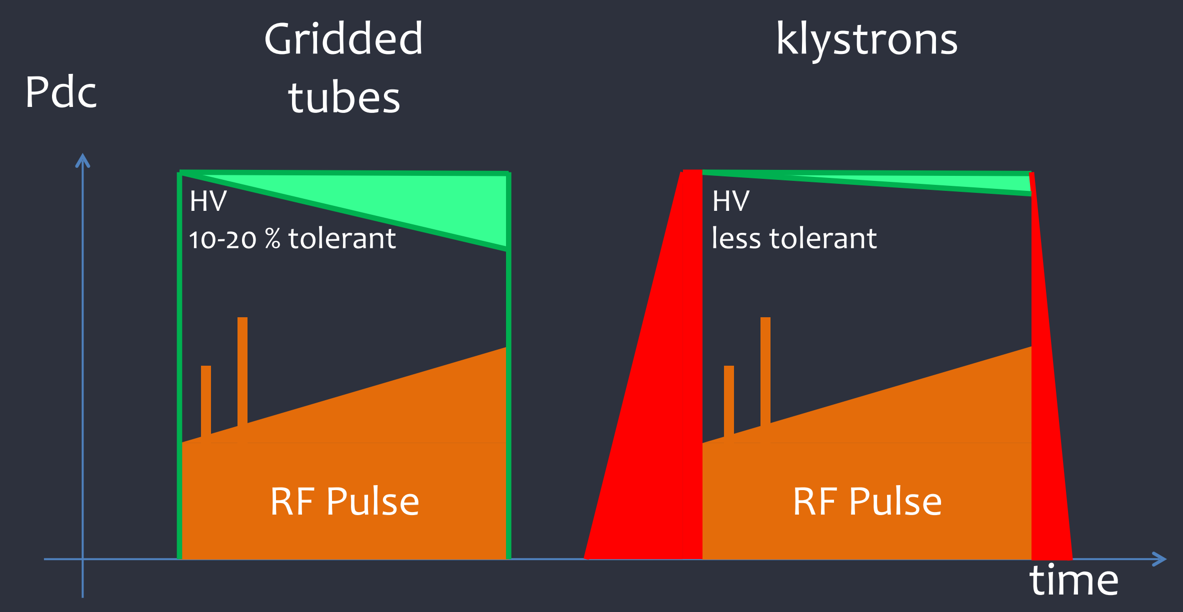
L3 communications

Eric Montesinos

IOTs

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
IOT: state of the art	20-23	130	ns	any	any	85	70	36-38	?-1300	
MB-IOT: performance potential	20-23	1300	ns	any	any	150	70	50	704	first prototype tested

- same points as for tetrodes/diacrodes…
- 2 MBIOT tubes will see a soak test at CERN in 2017/18, so that ESS can decide whether to use these tubes for the high-energy part of the ESS linac.
- new ideas for 3-cavity IOTs, resotrode explored within HEIKA

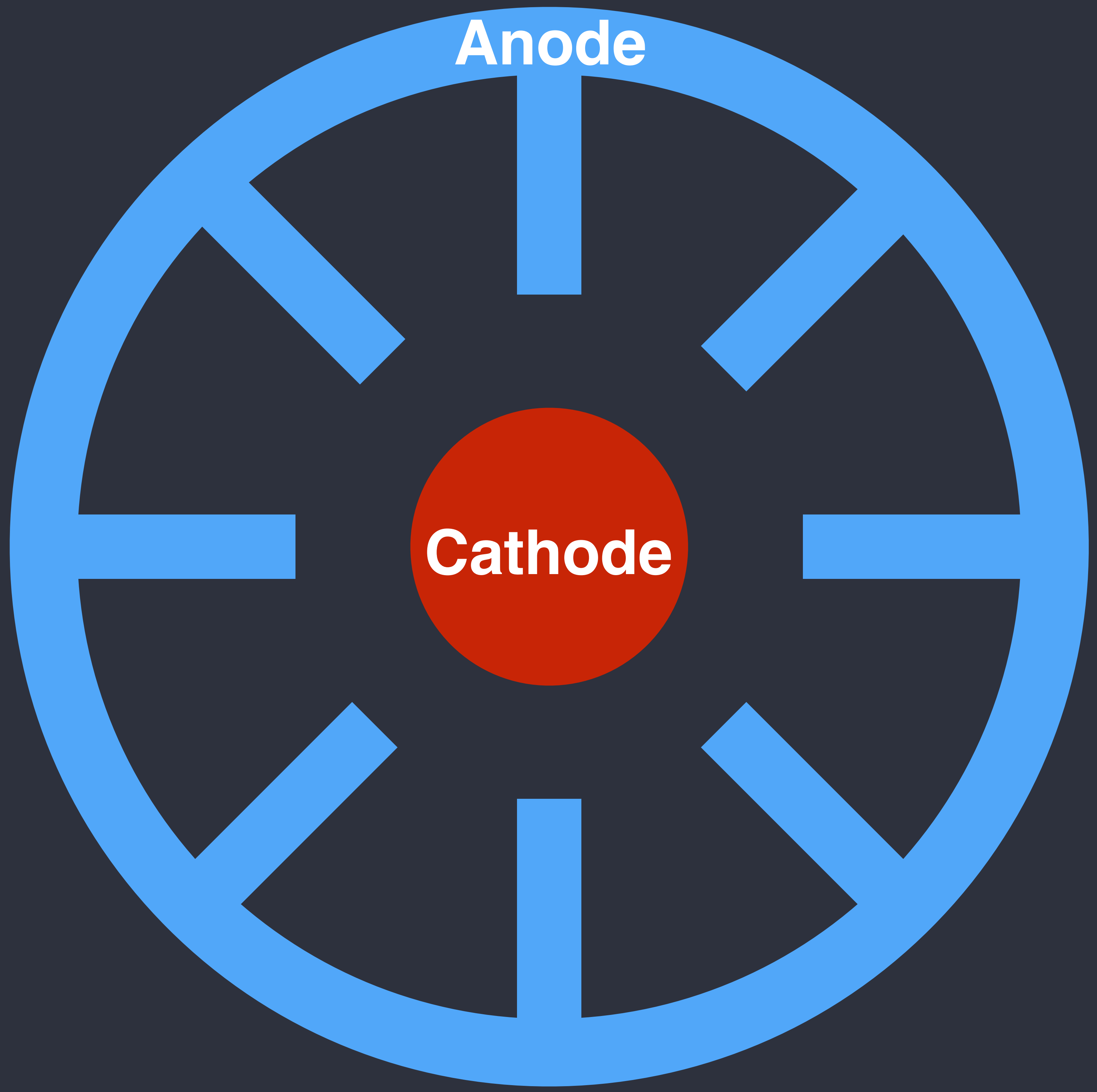


Thales/CPI tube installed in CERN test stand

Magnetrons

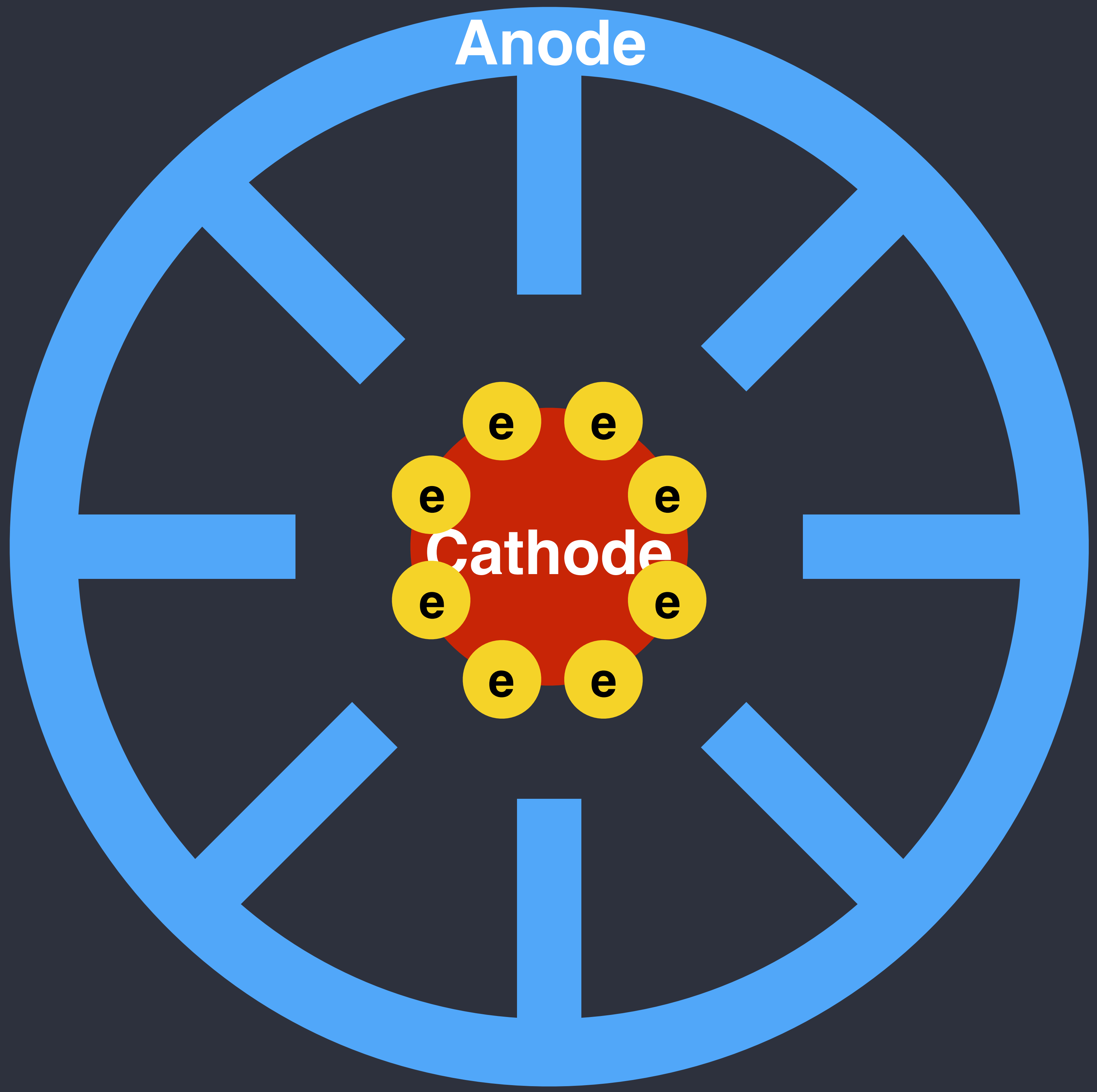
Cross section of a typical microwave cooker magnetron (courtesy: wikipedia)

Magnetrons



Magnetrons

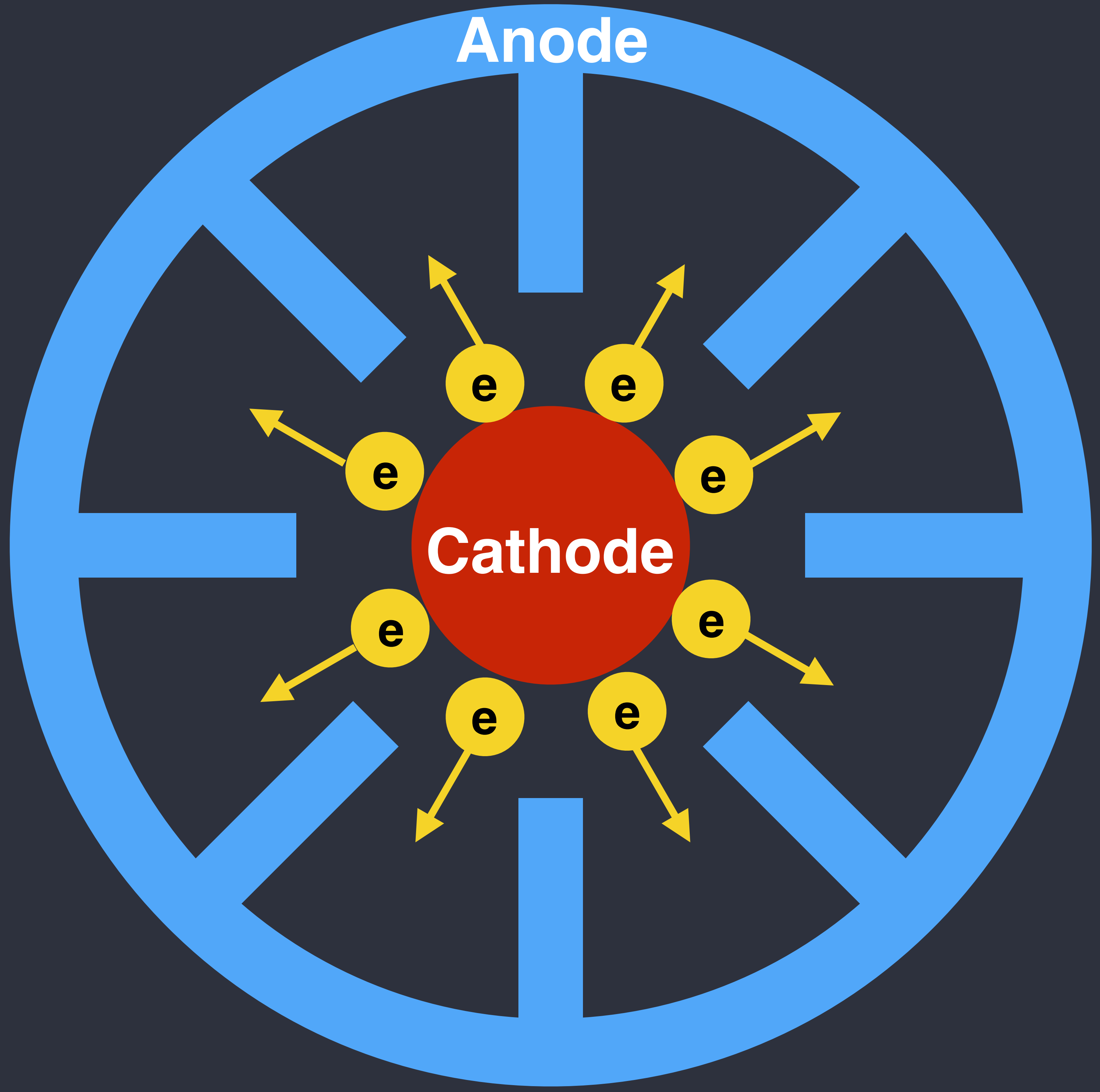
(1) Heat the cathode ➜ release of electrons.



Magnetrons

(1) Heat the cathode ➜ release of electrons.

(2) Electrons are accelerated towards the anode.



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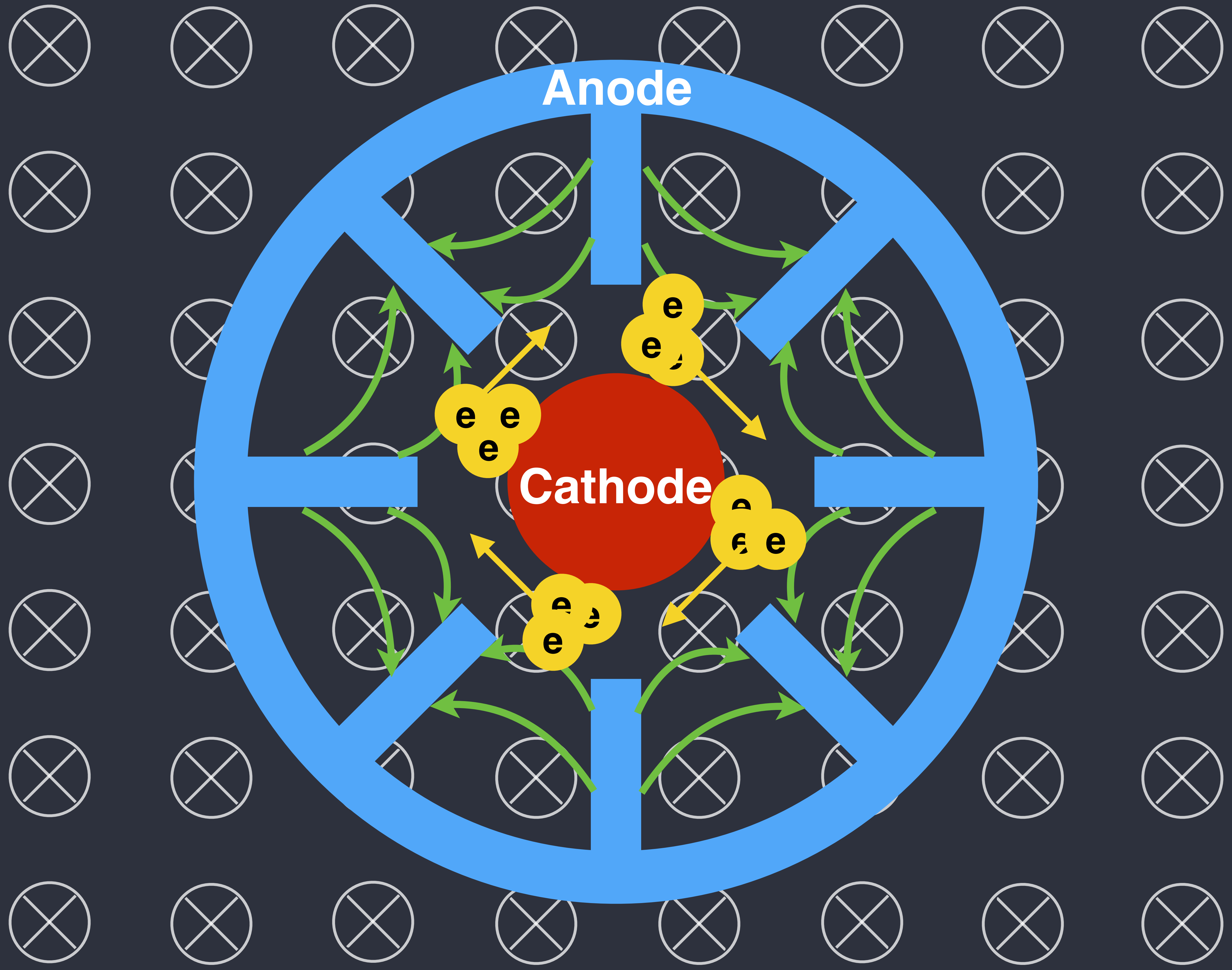
(5) The pi-mode in the cavities modulates the electron current ➜ the modulated current increases the cavity fields



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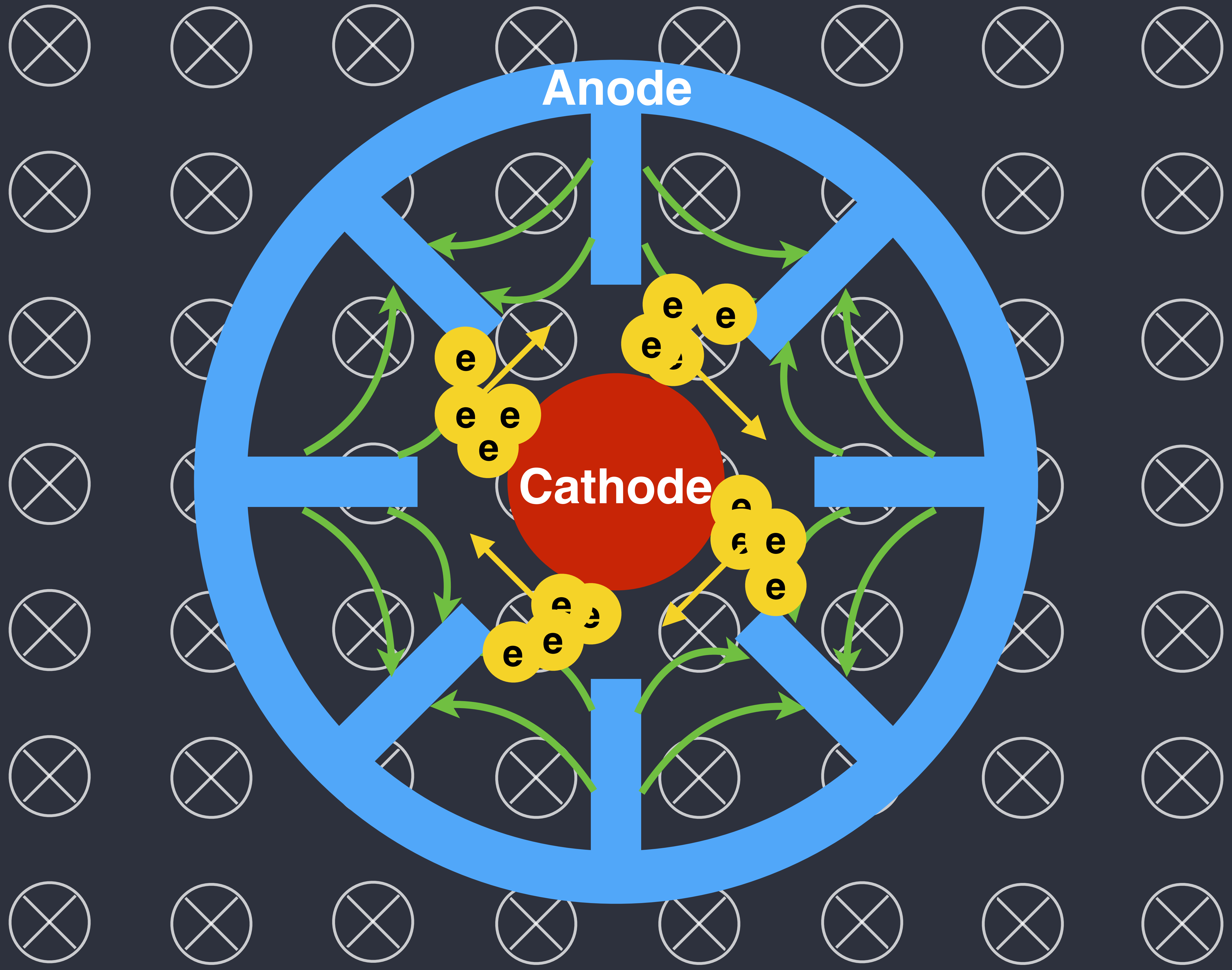
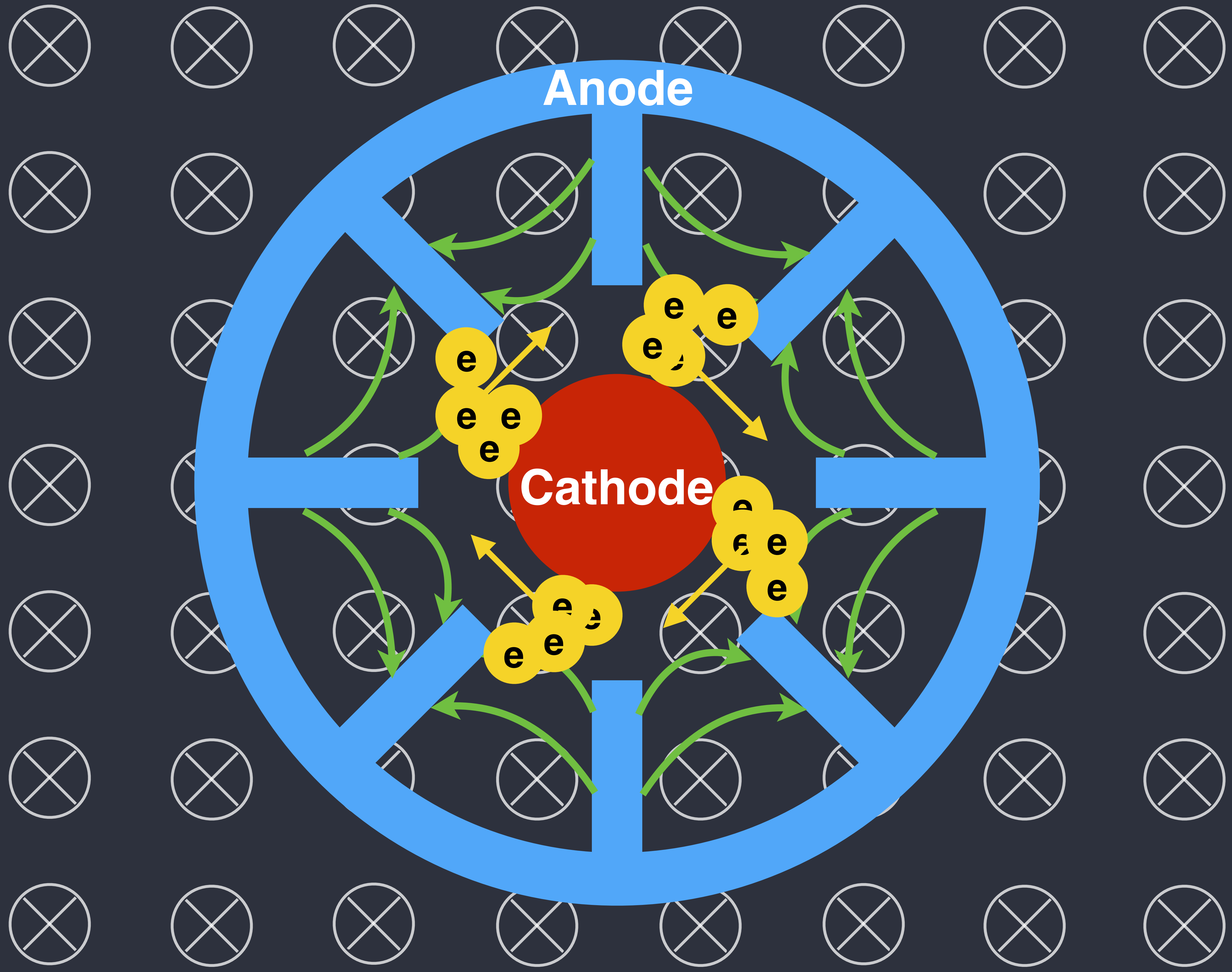
(5) The pi-mode in the cavities modulates the electron current ➜ the modulated current increases the cavity fields

(6) Power is coupled out from one of the cavities & electrons hit the anode: current flow



Magnetrons

- Free running oscillator: frequency is not stable enough to drive multiple phase-locked cavities.
- but very high efficiency, up to 90% for the tube alone.
- The use of stabilising control loops for the frequency + phase locking via injected RF has shown promising results in recent years.

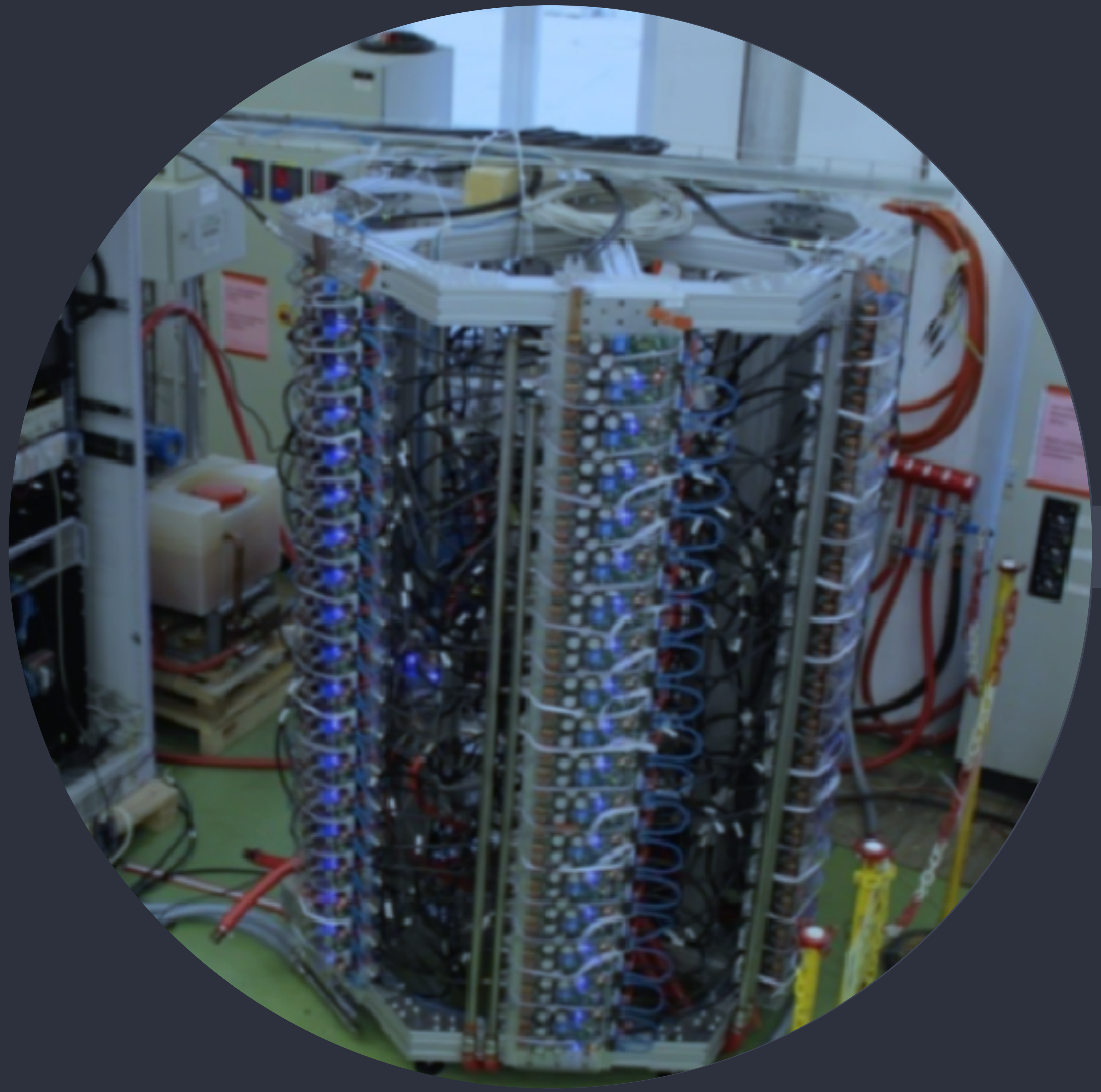


Magnetrons

RF source type	Gain [db]	Op. output power pulsed [kW]	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW [kW]	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
State of the art: CPI ECONCO	**25**	**?**	**?**	**-**	**-**	**100**	**80**	**20**	**826 - 929**	**tube only**
CCR/CPI	**25**	**100**	**?**	**10 ms**	**10**	**10**	**80**	**22**	**1300**	**tube only**
Performance potential?	**25**	**100**				**100**	**60**		**400**	**AC-RF**

- Proof of principle studies at Lancaster University & FNAL
- Phase control of 1 magnetron, using 2 magnetrons with phase control gives amplitude control.
- Constant output power devices; fast phase modulation can move power into sidebands, which will be reflected back from the cavities —> amplitude control with a single device.
- High potential for high efficiency (85%) at moderate price.
- R&D effort should be increased.

Solid state



65 kW, 500 MHz solid state amplifier at PSI (Marcos Gaspar, PSI)

Solid state

RF source type	Gain [db]	Op. output power pulsed	Rise /Fall time [us]	Pulse length range [us]	Rep rate range [Hz]	Op. output power CW	Efficiency at working point [%]	High voltage needs [kV]	Frequency range [MHz]	Comment
ELBE		16 kW	0.02/0.06	0.001 - 100	0-CW	16 kW	47%	-	1300	
R&K		16 kW	0.01/0.01	any	0-CW	16 kW	36%	-	1300	forced air/water
Tomcod		-		-	CW	10 kW	45%	-	700	up to 80 kW
R&K		-		-	CW	20 kW	?	-	509	forced air/water
PSI		~70 kW	0.045	any	0-CW	~70 kW	~50%	-	500	grid to RF
Cryoelectra		-		-	CW	45 kW	51%	-	500	
LNLS		-		-	CW	25 kW	57%	-	472	
ESRF		70 kW		any	1 - CW	70 kW	55%	-	352	DC-RF
Soleil		30 kW		any	0-CW	30 kW	50%	-	352	DC-RF, 180 kW
Tomco		-		-	CW	10 kW	55%	-	350	up to 110 kW
Cryoelectra		-		-	CW	16 kW	46%	-	118	
Siemens		-		-	CW	18 kW	75%	-	72.5	
Cryoelectra		-		-	CW	115 kW	57%	-	72.8	
R&K		60 kW		any	0-CW	60 kW	56%	-	1.8	
State of the art		**10 - 100 kW**	**10-60 ns**	**any**	**any**	**10-100 kW**	**45-55%**	**-**	**0-1300**	
potential?										
R&D: Siemens/ESS		48 kW		3000	14 Hz	-	60%	-	352	up to 400 kW
Thales		135 kW		-	CW	135 kW			200	test at CERN

Solid state

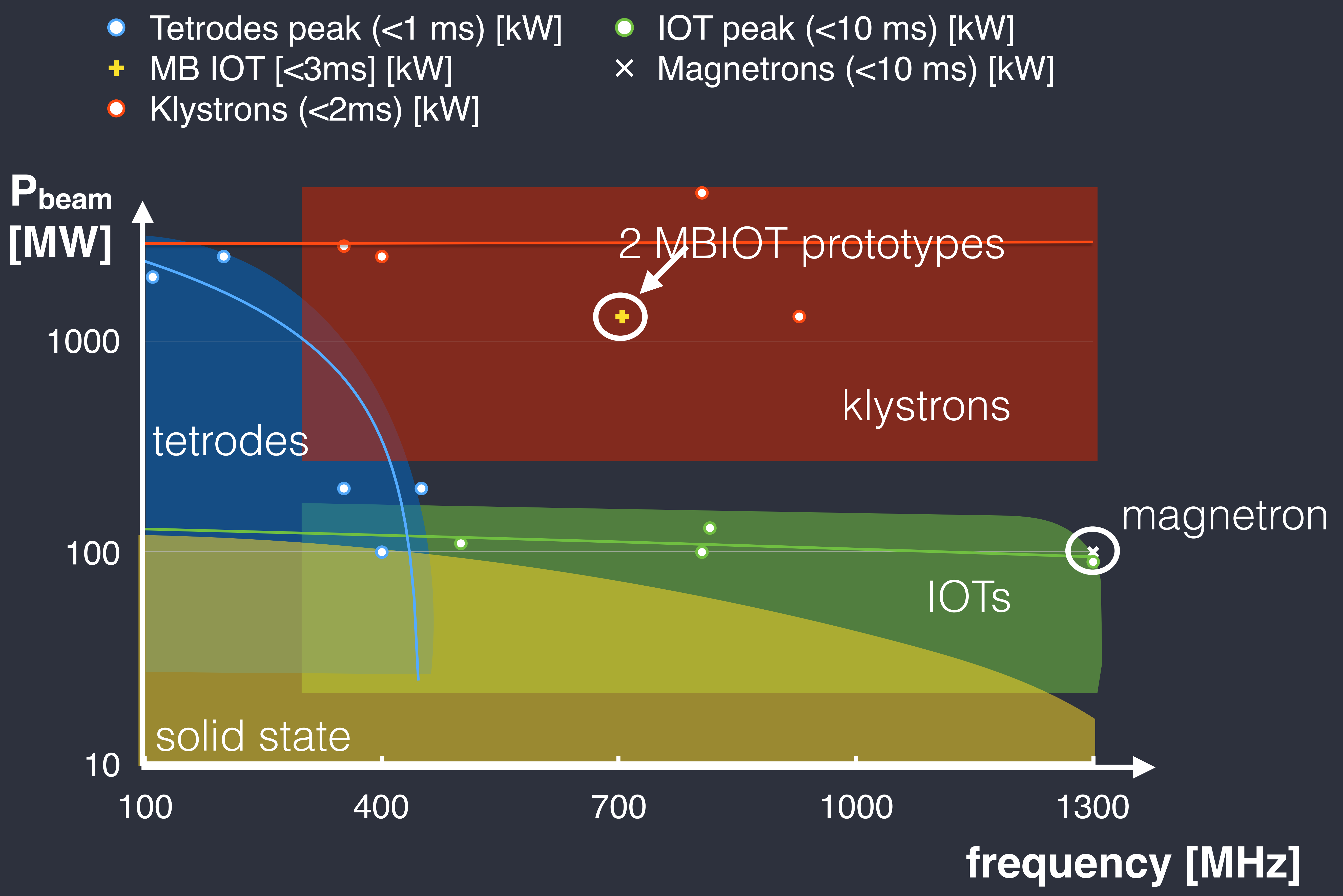
- Frequency range 0 - 2.5 GHz but with lower efficiency and power output/transistor for frequencies > 700 MHz,
- Can be operated at lower output power without loosing too much efficiency.
- At present maximum power < 200 kW.
- Overall DC to RF efficiency ~55%.
- Modular systems, hot swapping of faulty modules possible.
- Newer systems make use of combining cavities instead of 2x2x2… combiners (200 MHz 135 kW Thales tower under soak test at CERN, intention is to have a 2 MW system for the SPS)
- Unlikely that higher-power transistors will be developed (no one else needs them..)

Summing up

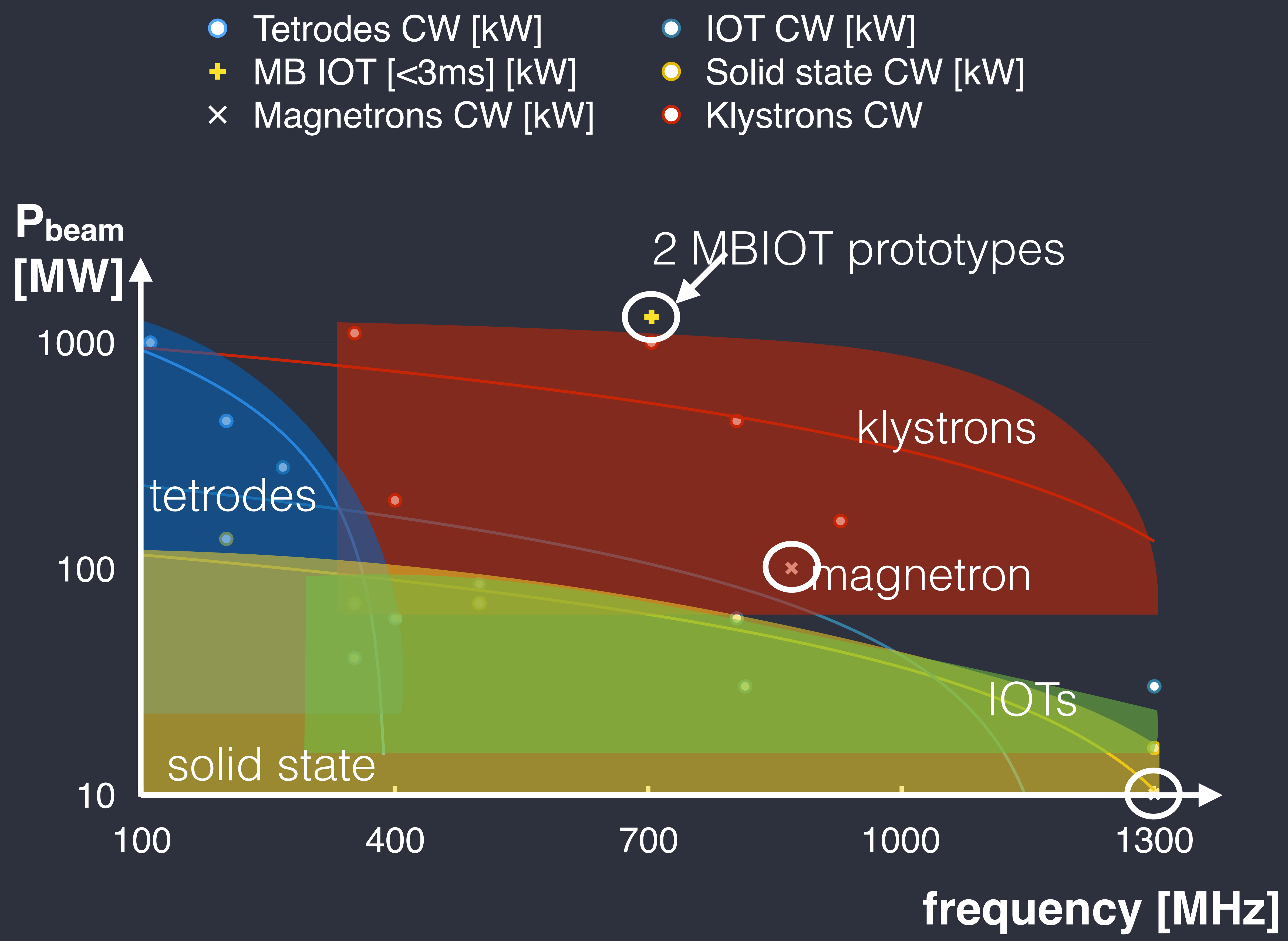
RF sources for proton drivers

Power/frequency chart

Pulsed Operation



CW Operation



Parameter overview

from Proton Driver Efficiency Workshop, Feb 2016, PSI

parameter	Tetrodes	IOTs	klystrons	solid state	magnetrons
gain [db]	15	20	40-45	stacked	25
output power pulsed [kW]	4000	130/1300	1000 - 15000	0 - 150	100
output power CW [kW]	1500	100/150	1200	0 - 150	100
HV needs [kV]	10-25	< 50	90-120 (60*)	-	20
pulse length [us]	any	any	~4 ms	any	?
rise/fall time [us]	ns	ns	0.3	0.01 - 0.06	?
DC to RF efficiency[1] [%]	70	70	55 (>70*)	45 - 55	70*
frequency [MHz]	30 - 400	? - 1300	300 - 1500	0 - 1300	400 - 1300
active development	no (Diacrode)	2 MB-IOT	yes	yes	too little

*under development, 1 - at working point

Summary: today

from Proton Driver Efficiency Workshop, Feb 2016, PSI

- AC - DC: Power supplies 85 - 92% for all systems (solid state to klystrons).
- Modulator rise times have an impact on efficiency (e.g. HV klystron modulators).
- DC - RF: Magnetrons claim up to 85% efficiency (to be proven in a complete system); gridded tubes: 70%, klystrons: 55%, solid state: 55%.
- Adding cooling systems, reduces total efficiency by up to ~0.73 compared to DC-RF.

Summary: developments

adapted from Proton Driver Efficiency Workshop, Feb 2016, PSI

- R&D on **klystron efficiency** improvement is very active. Higher efficiency not only means electrical savings, but also simpler lower-voltage modulators and no need for oil tanks.
- **MB-IOTs** reach the MW class and may become an alternative to klystrons. (First tests are promising). To be continued.
- **Solid state** is developing and has the same efficiency at lower power (100 kW range) as klystrons at high power (MW range). Unlikely that higher power transistors will be developed soon (not needed for broadcasting, telephone networks, …). Future lies with **combining cavities** instead of combining networks.
- Work on **magnetrons** just started; R&D needed, presently only 2 labs: FNAL and Lancaster University. **High potential** for lower prices and higher efficiency (85%). More labs should join!

THANKS

FOR

Listening