Development and Future Prospects of RF Sources for Linac Applications

Erk Jensen

CERN

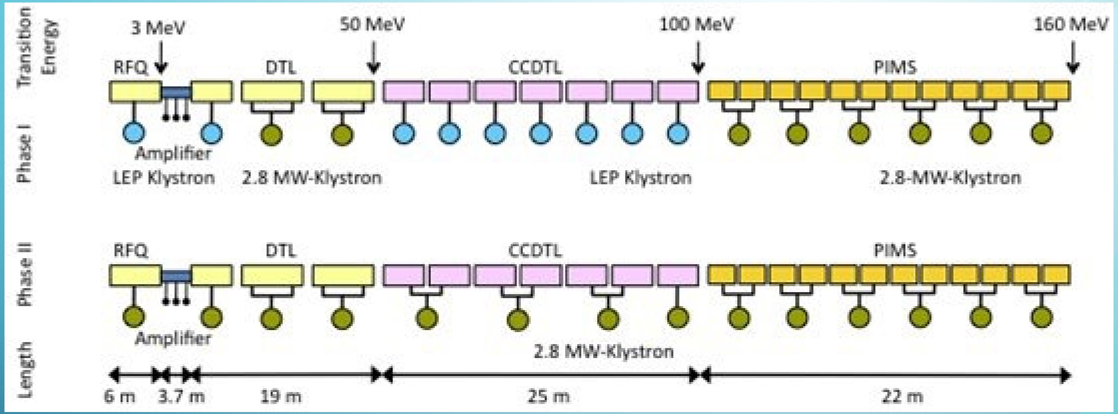
Geneva, Switzerland

Outline

- CERN Linac4 RF sources
- ESS RF sources: klystrons and multi-beam IOTs
- LANSCE 201 MHz Diacrode based system
- CLIC power source, progress with 1 GHz klystrons
- Recent very high efficiency klystron development
- Solid state power amplifiers

CERN Linac4, 352 MHz

CERN Linac4 RF System



RF key parameters:

- 352 MHz
- 600 µs pulses (1.2 ms)
- 0.83 Hz (2 Hz)
- DF $0.5 \cdot 10^{-3}$ $(2.4 \cdot 10^{-3})$

O. Brunner

Recent view of the Linac4 klystron gallery

O. Brunner, F. Gerigk

Klystrons CPI VKP-8352A and Thales TH2179

All Linac4 power sources perform as specified, beam has been accelerated to 107 MeV in July, and everything is ready to accelerate to full 160 MeV.

O. Brunner, F. Gerigk

ESS, 352 MHz and 704 MHz

ESS High Power RF systems

Design Drivers:

Average Beam Power 5 MW

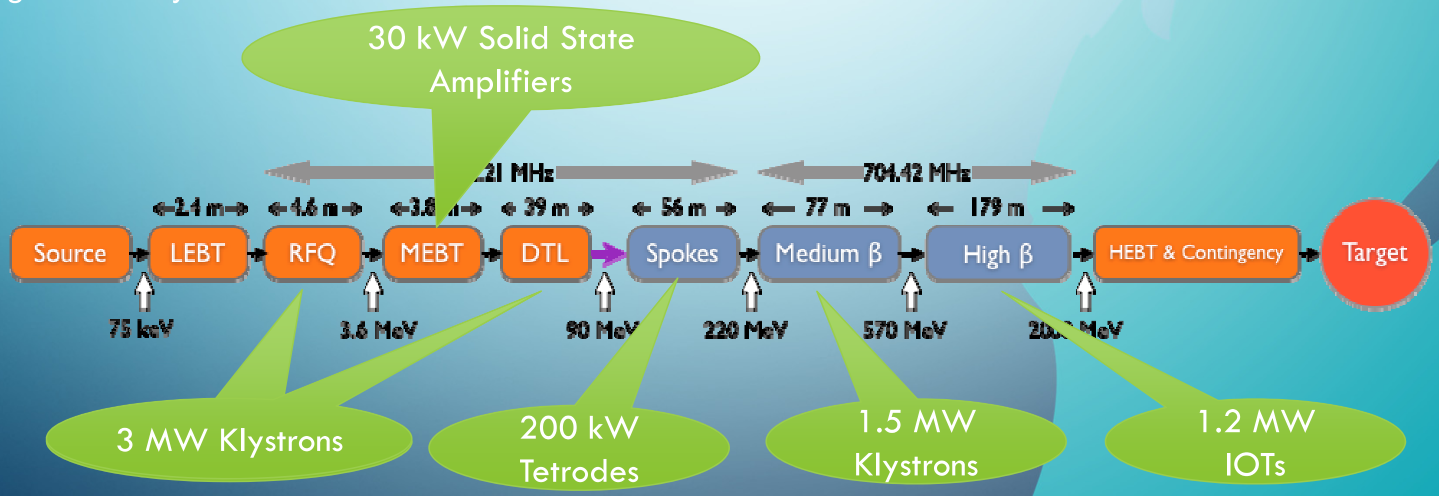
Peak Beam Power 125 MW

High Availability

High Efficiency

RF key parameters:

- 352 MHz, 704 MHz
- 3.5 ms
- 14 Hz
- DF $4.9 \cdot 10^{-2}$



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ESS High Power RF systems

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Section	Power [kW]	Baseline technology	Status	To be ready by
Normalconducting RFQ and DTL	2900	Klystron	In kind (ESS Bilbao)	2019
Normalconducting bunchers	30	Solid State	In kind (ESS Bilbao)	2019
Spoke linac	400	Tetrode	In kind (Elettra)	2019
Medium beta linac	1500	Klystron	Prototyping	2019
High beta linac	1500/1200 Klystron/IOT	MB-IOT (decision end 2017)	Prototyping	2022-23

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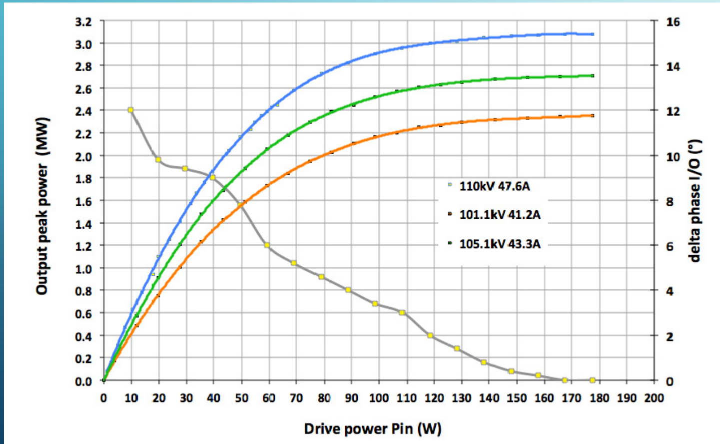
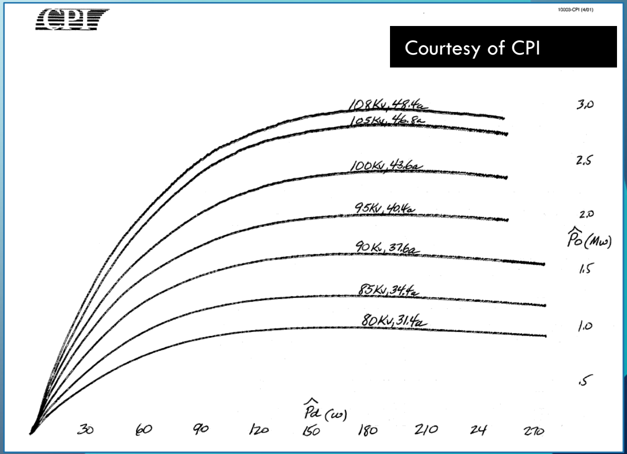
RFQ & DTL klystrons

Thales TH2179

- 2.1 MW saturated power from the RFQ klystron
- 2.9 MW saturated power from the DTL klystrons
- One modulator every two klystrons
- Strong synergy with CERN's Linac4

CPI VKP-8352A





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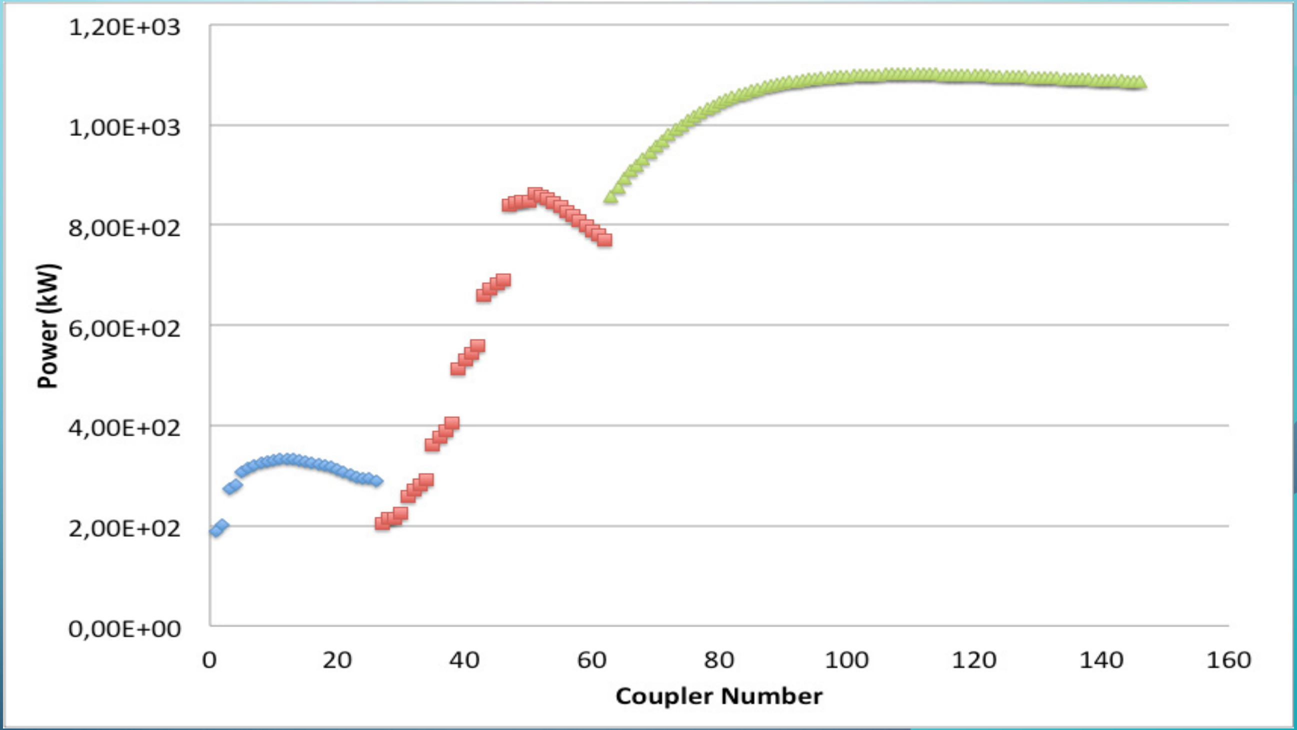
ESS SC accelerator power profile



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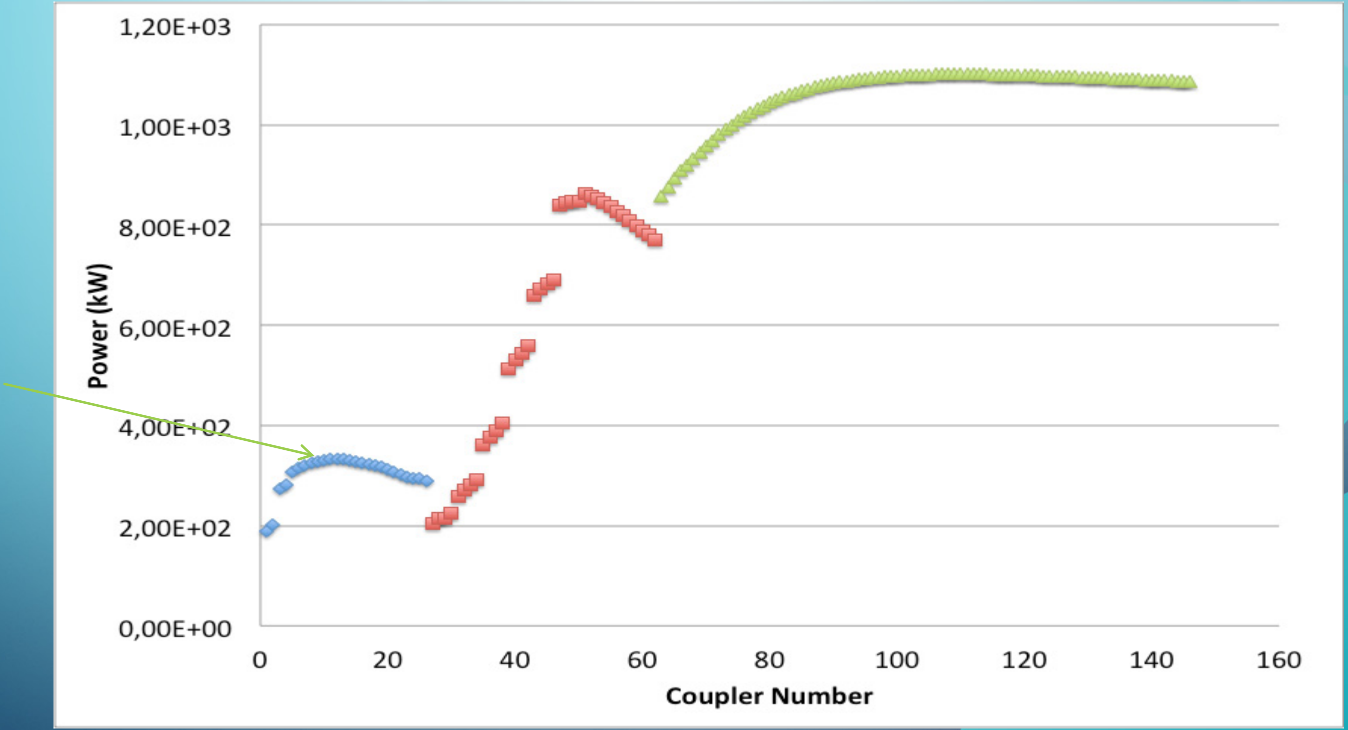

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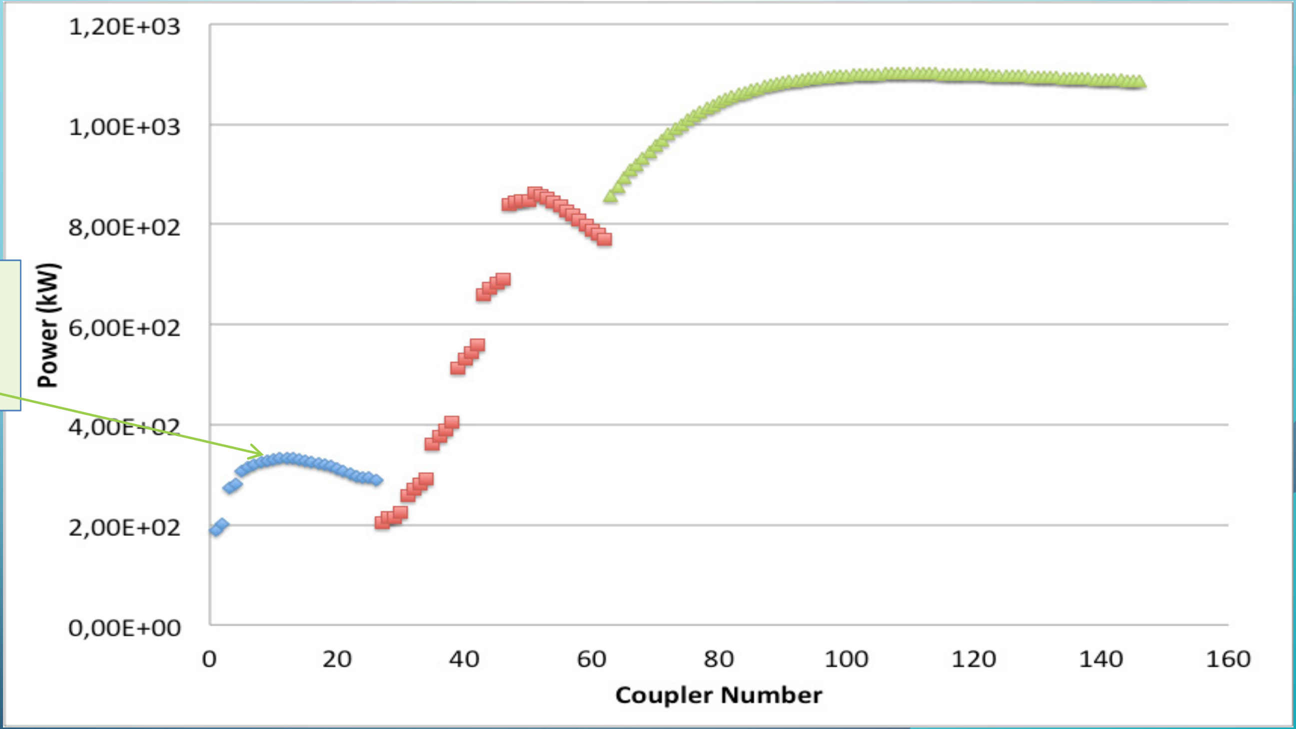

26 spoke cavities:
352 MHz
Tetrodes

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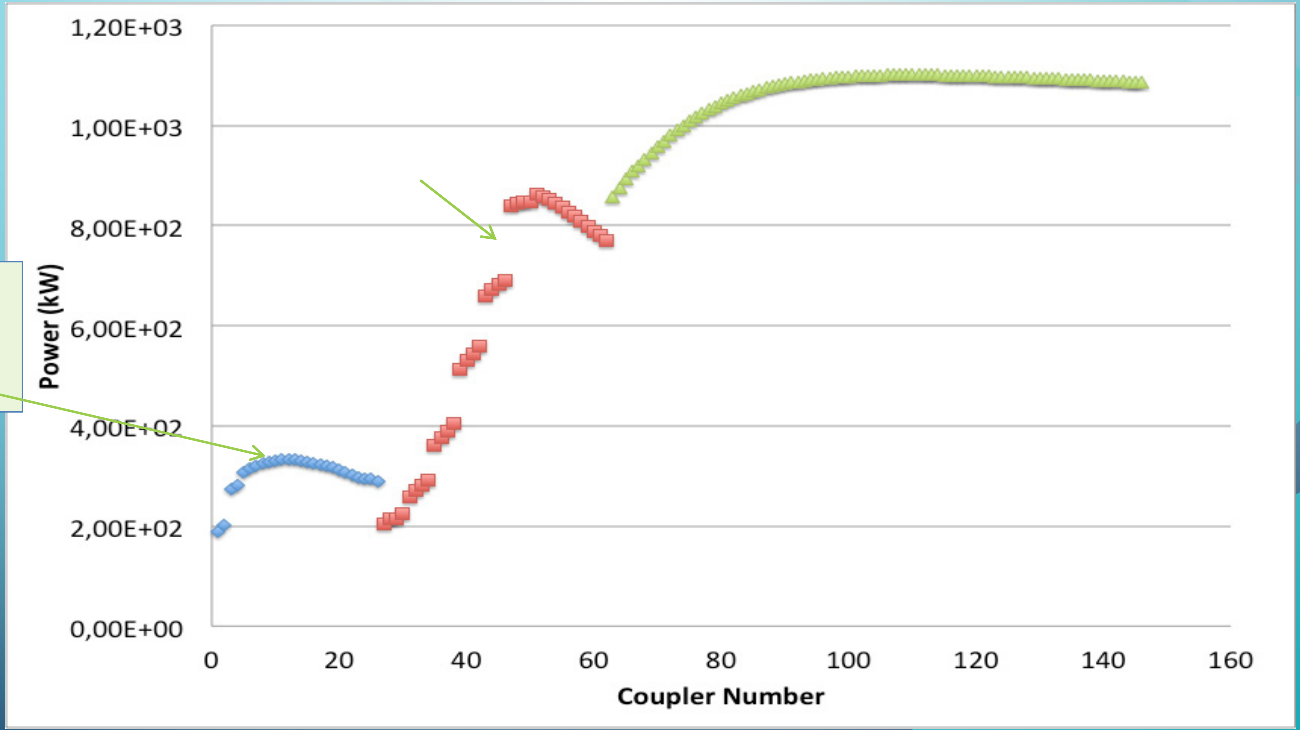
ESS SC accelerator power profile



26 spoke cavities:
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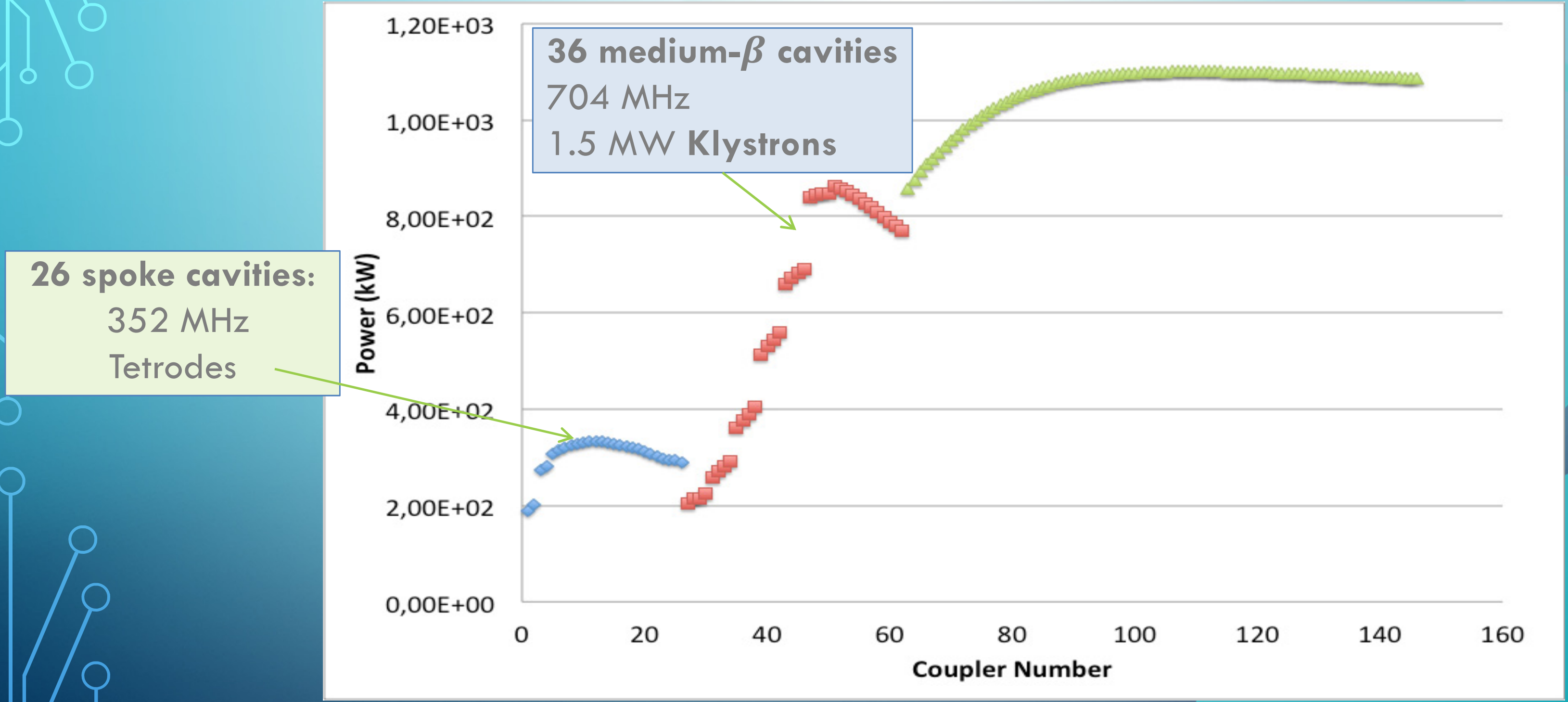

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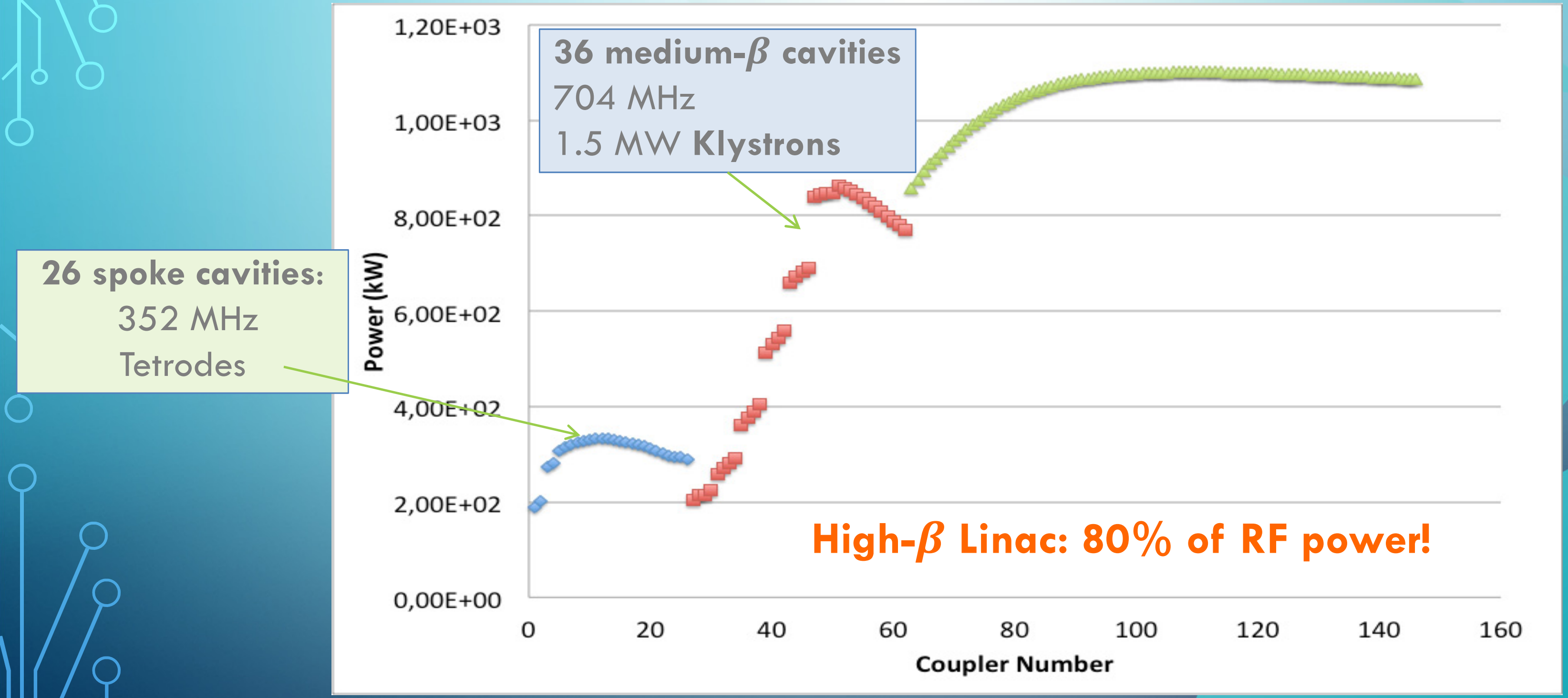
ESS SC accelerator power profile



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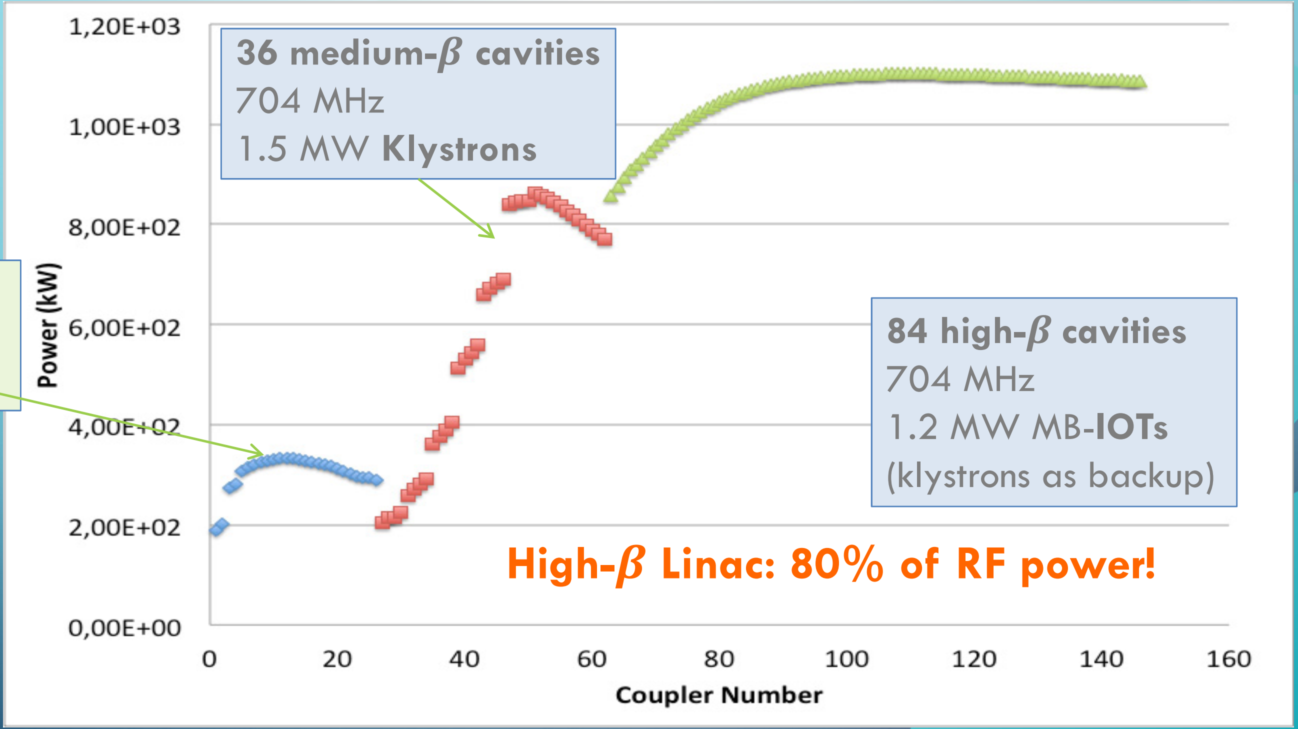

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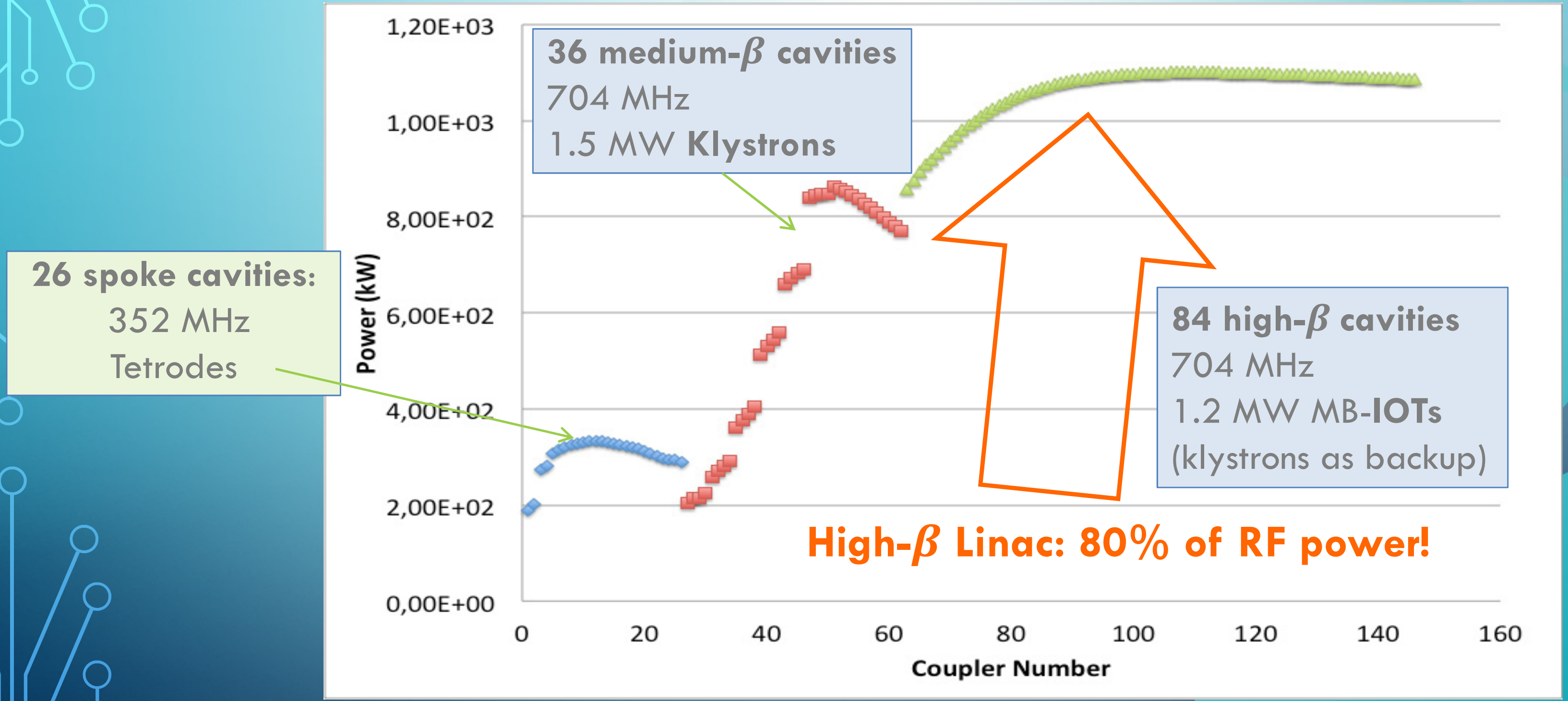

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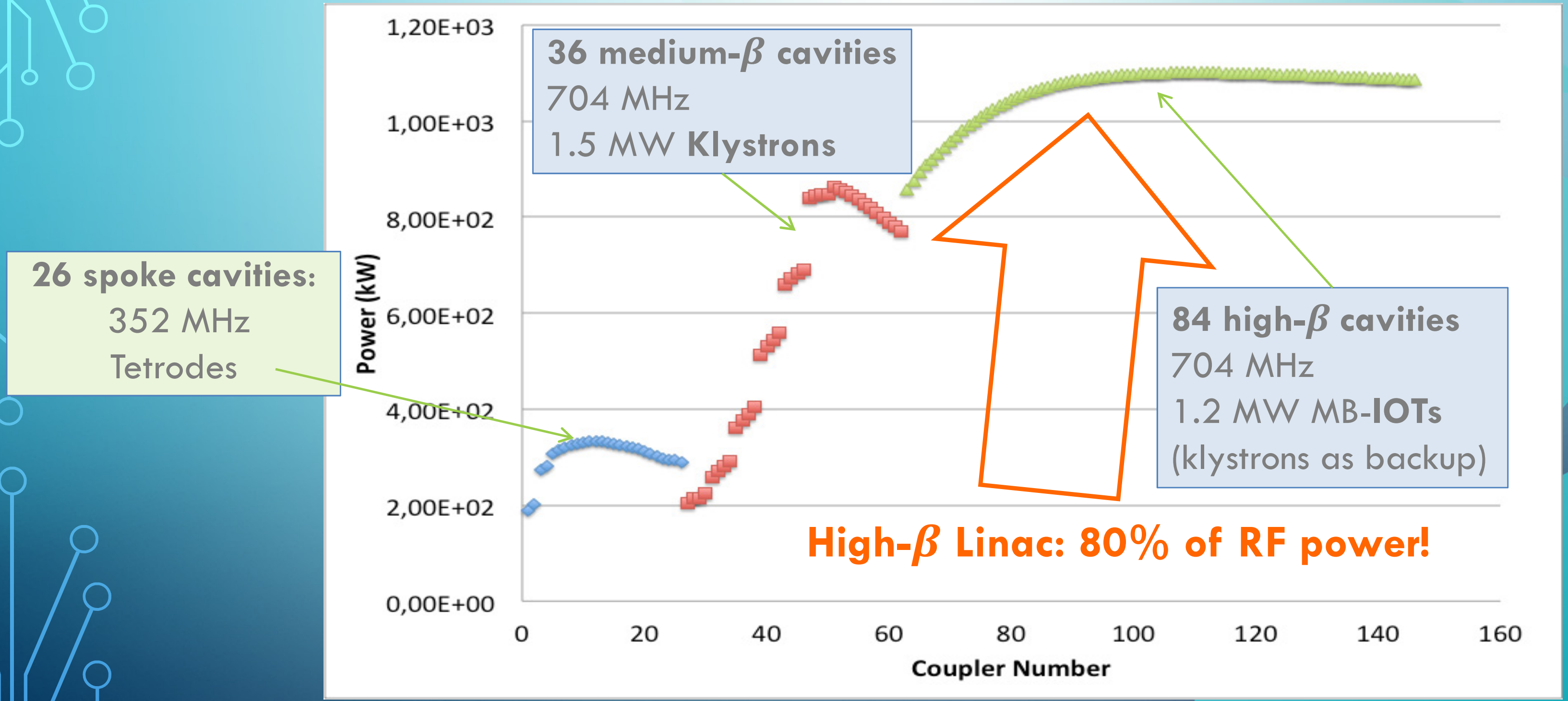
ESS SC accelerator power profile



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704 MHz Klystron Status

- Contracts for three prototypes (Toshiba, Thales and CPI) are proceeding well. One already delivered with the other two to be delivered within the next three months.
- 704 MHz, 1.5 MW klystrons will be used for medium beta linac (36 units) and are a backup for the MB-IOT development for the high beta linac (84 units).

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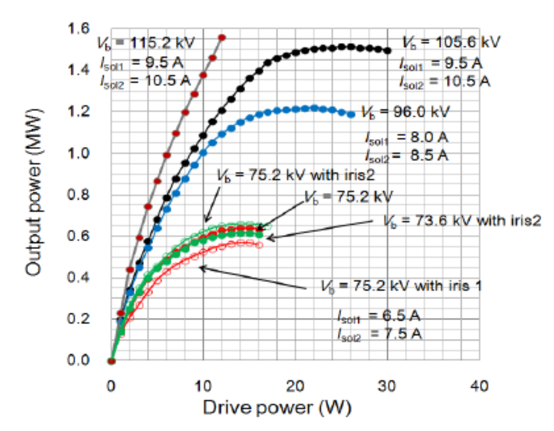
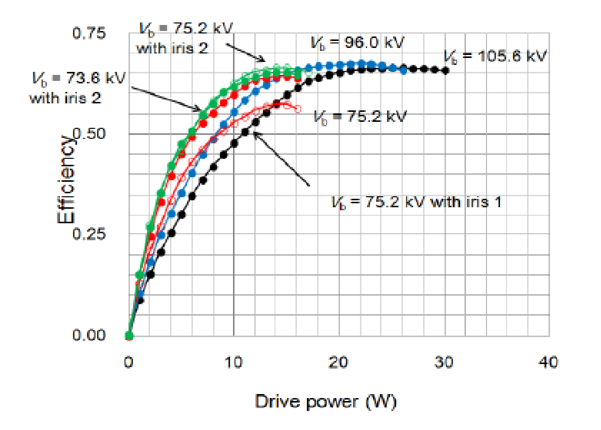
704 MHz prototype Toshiba E37504

Some results from the **Factory Acceptance Test** (February 2016):





Klystron accepted and delivered to Lund!

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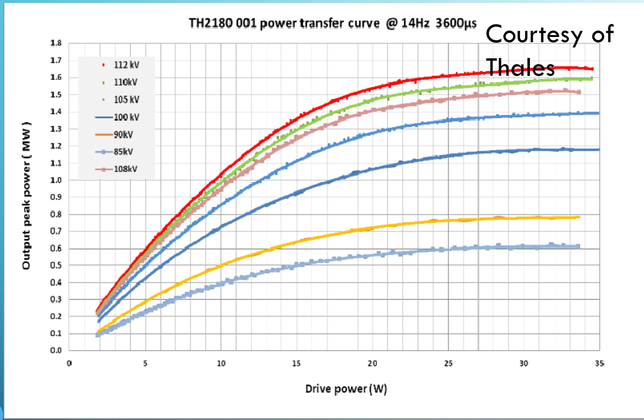
Courtesy of Toshiba

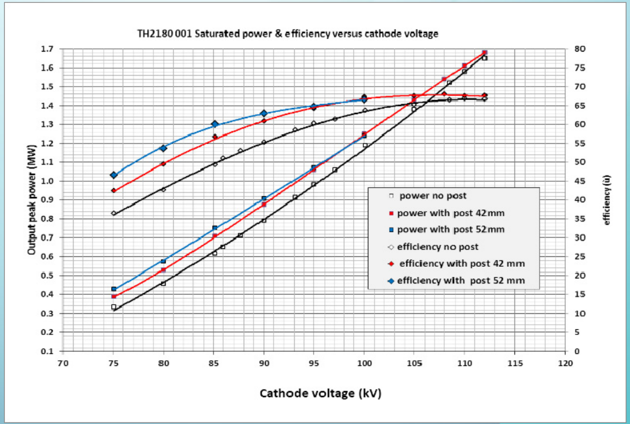
704 MHz prototype Thales TH2180

The tube has been tested at factory at full power for few days in May 2016.

Saturated efficiency 66%.



Courtesy of Thales



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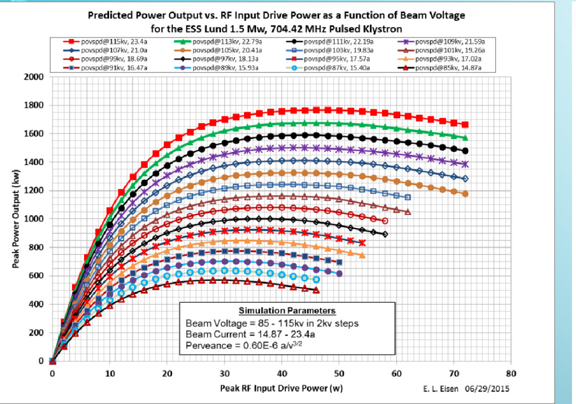
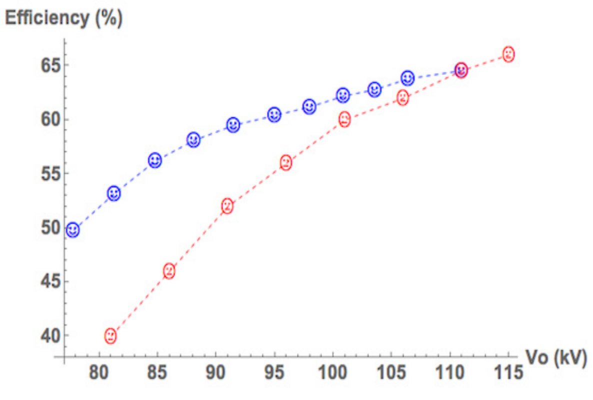
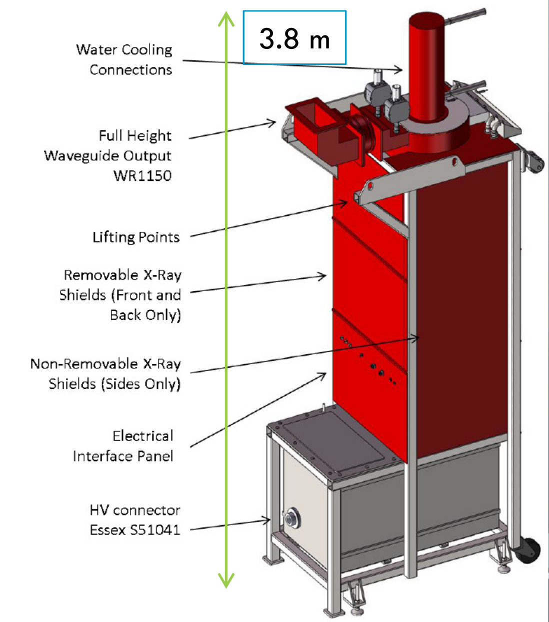
704 MHz prototype CPI VKP-8292A







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1.2 MW, 704 MHz MB-IOTs for ESS

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Target parameters:

Parameter		Comment
Frequency	**704.42 MHz**	**Bandwidth > ± 0.5 MHz**
Maximum Power	**1.2 MW**	**Average power during the pulse**
RF Pulse length	Up to 3.5 ms	Beam pulse 2.86 ms
Duty factor	Up to 5%	Pulse rep. frequency fixed to 14 Hz
Efficiency	> 65%	
High Voltage	Low	Expected < 50 kV
Design Lifetime	> 50,000 hrs	

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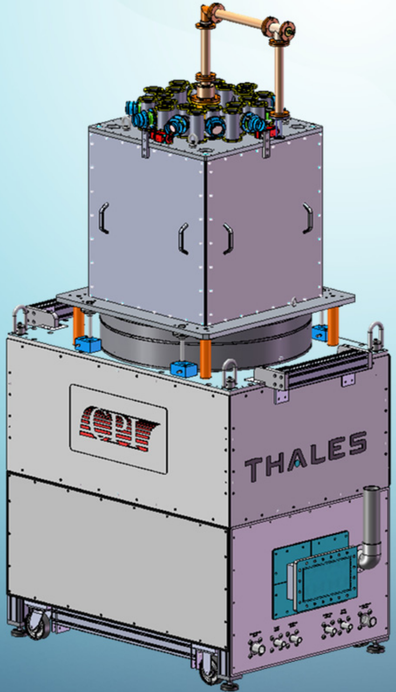
10-beam IOT development projects

Two Contracts placed September 2014 for **Technology Demonstrators**

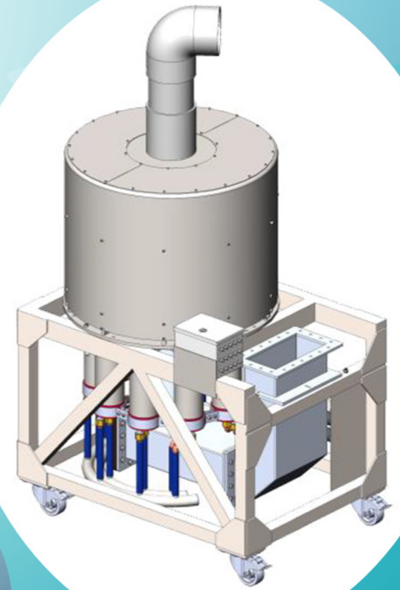
- Thales/CPI Consortium
- L3

Testing will be done at CERN



THALES

CPI
Communications & Power Industries
microwave power products division



L3
communications

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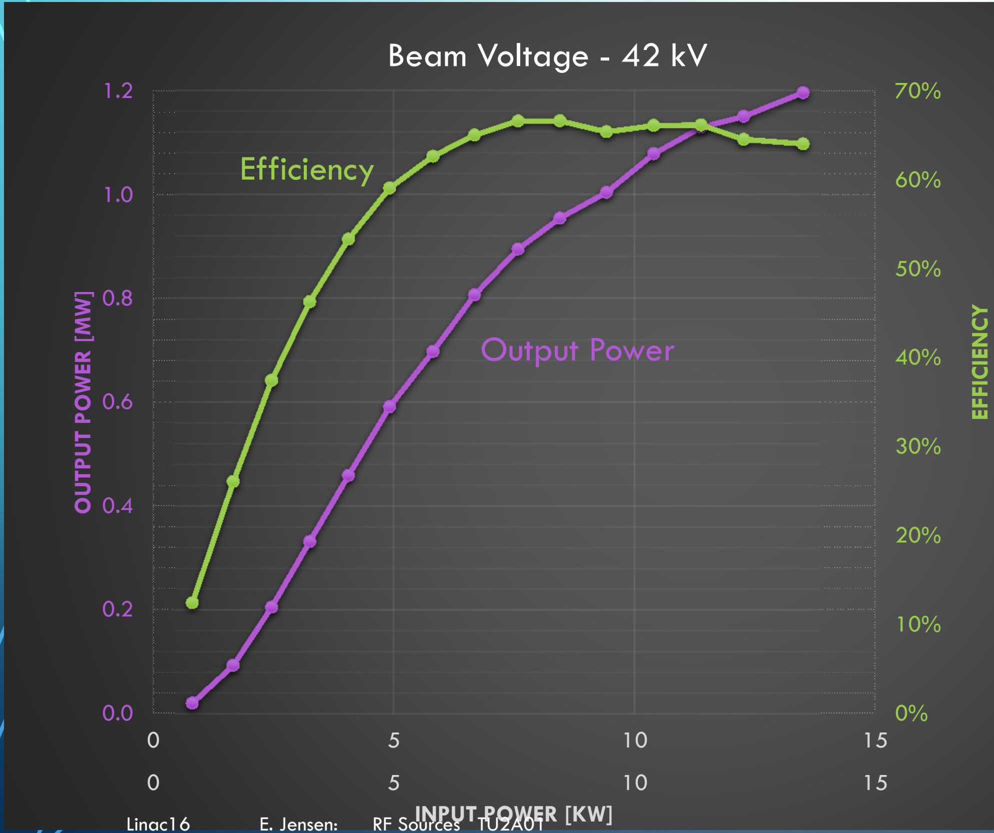
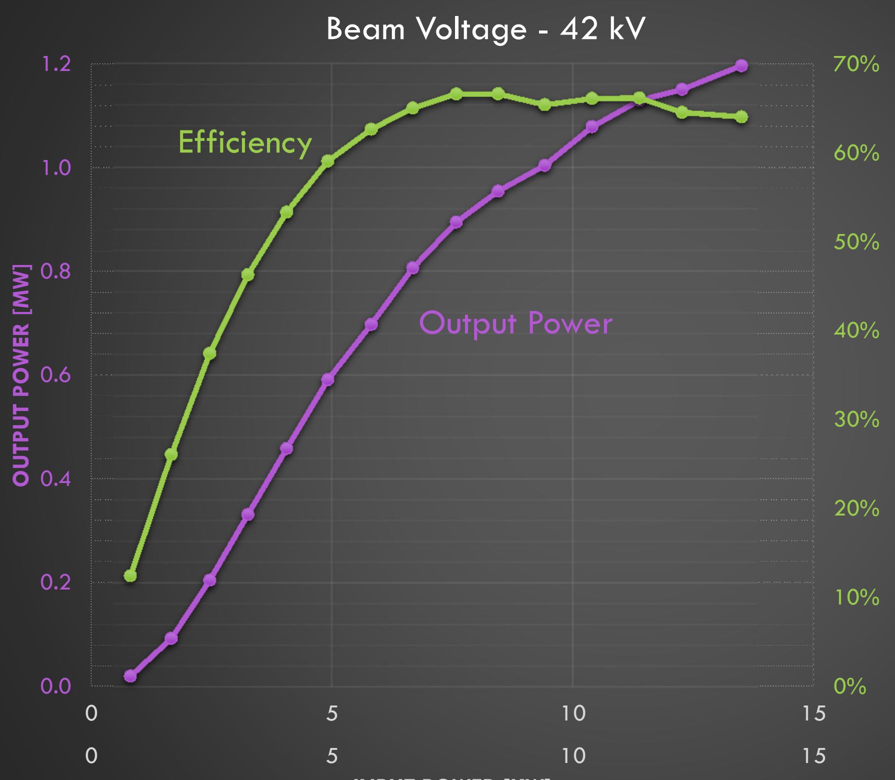
L3 10-beam IOT prototype preliminary results



Courtesy of L3

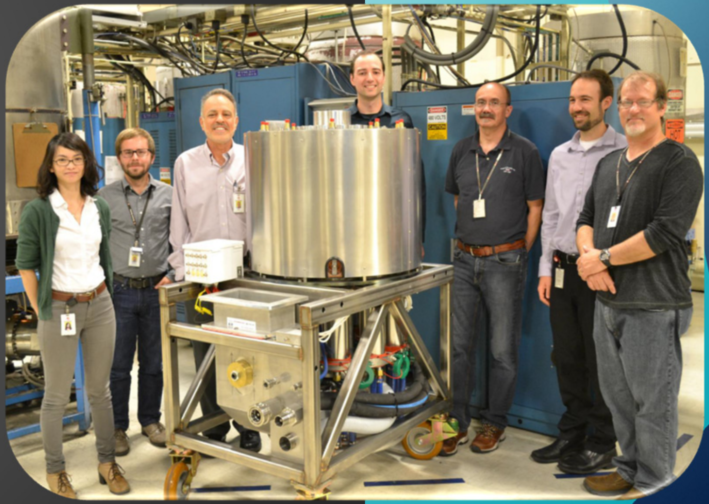
M. Jensen, M. Kirshner

L3 10-beam IOT prototype preliminary results



Efficiency > 60% from 600 kW to 1.2 MW

(HV efficiency only)



Courtesy of L3

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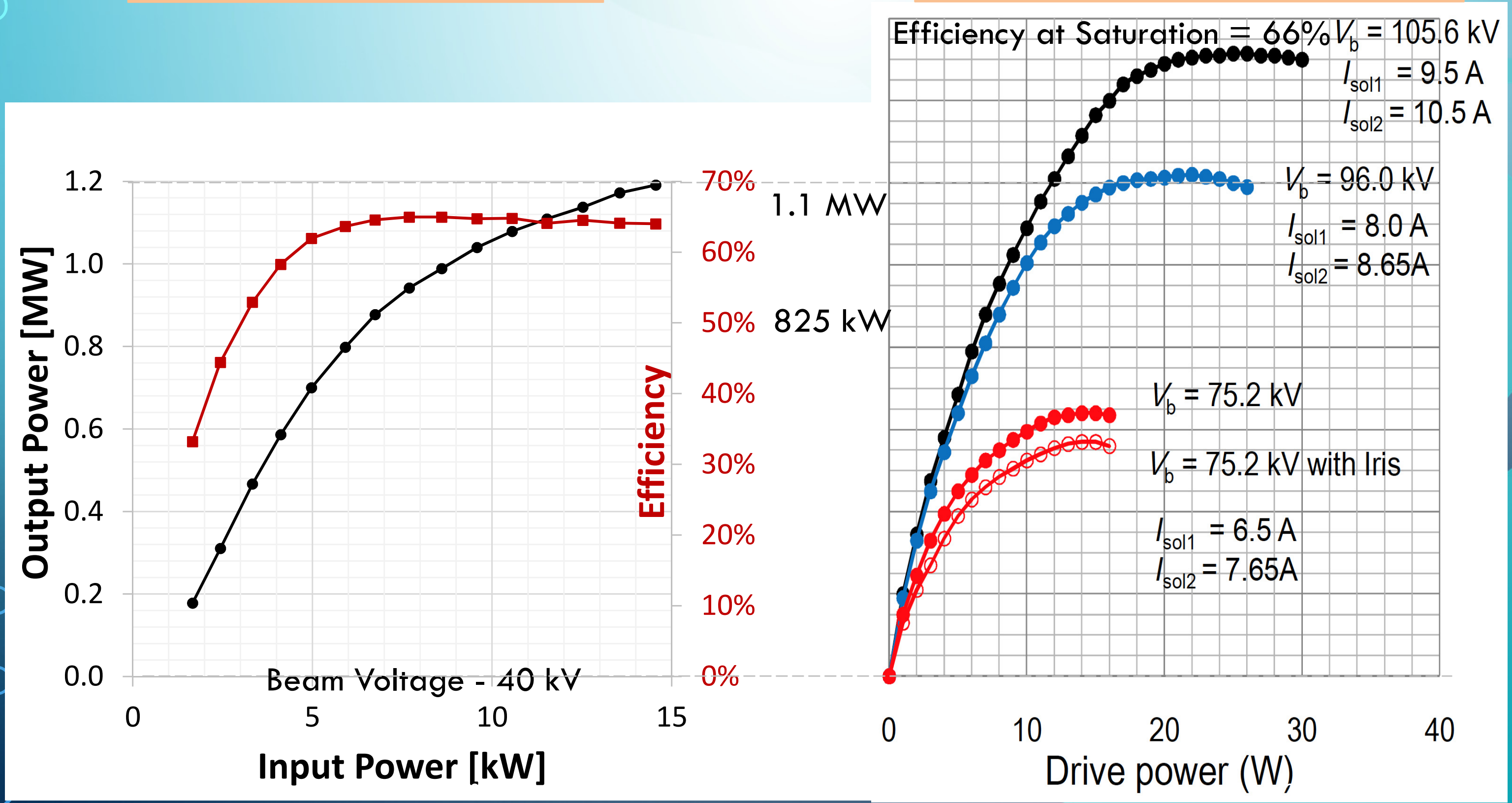
Comparison MB-IOT vs. klystron

MB-IOT prototype L3 L6200

Klystron Toshiba E37504, from FAT



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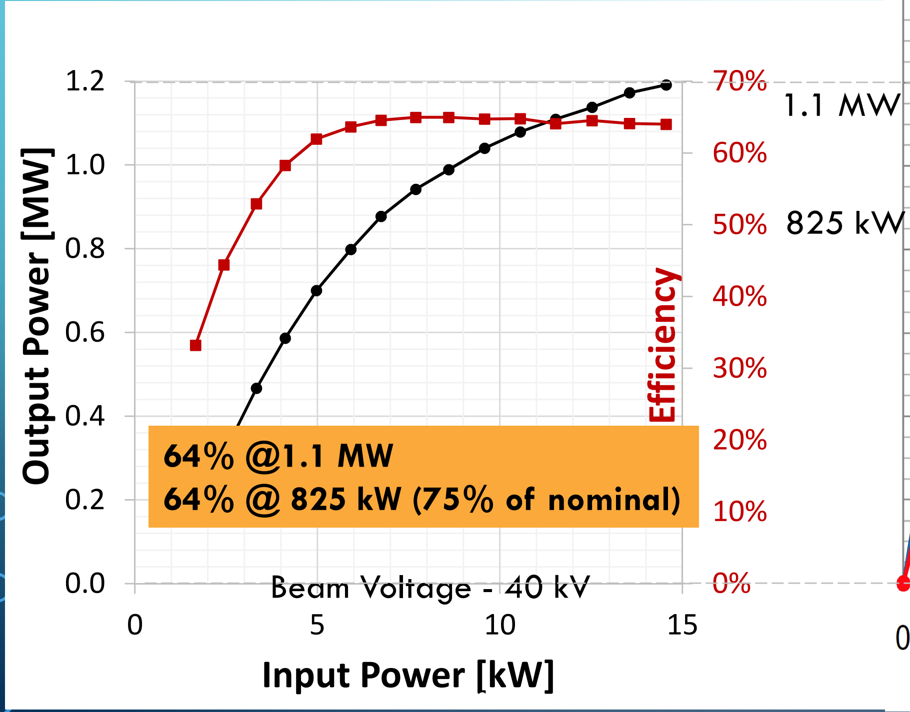
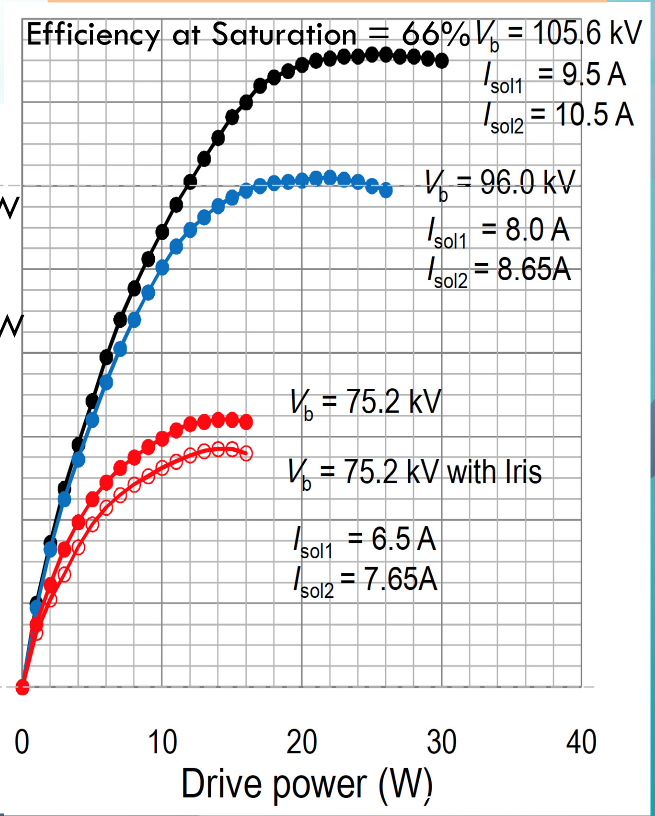


Klystron Toshiba E37504, from FAT



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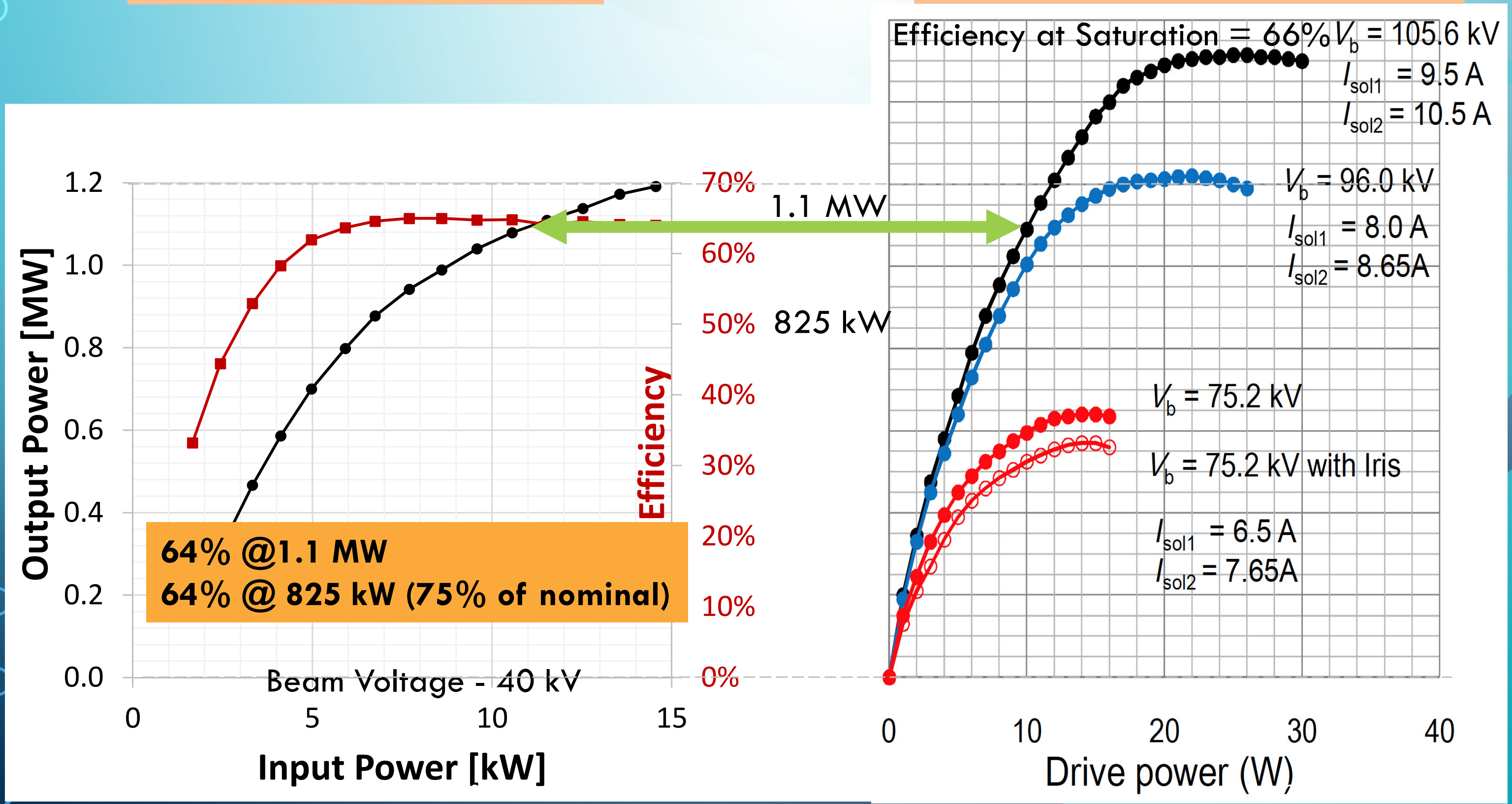

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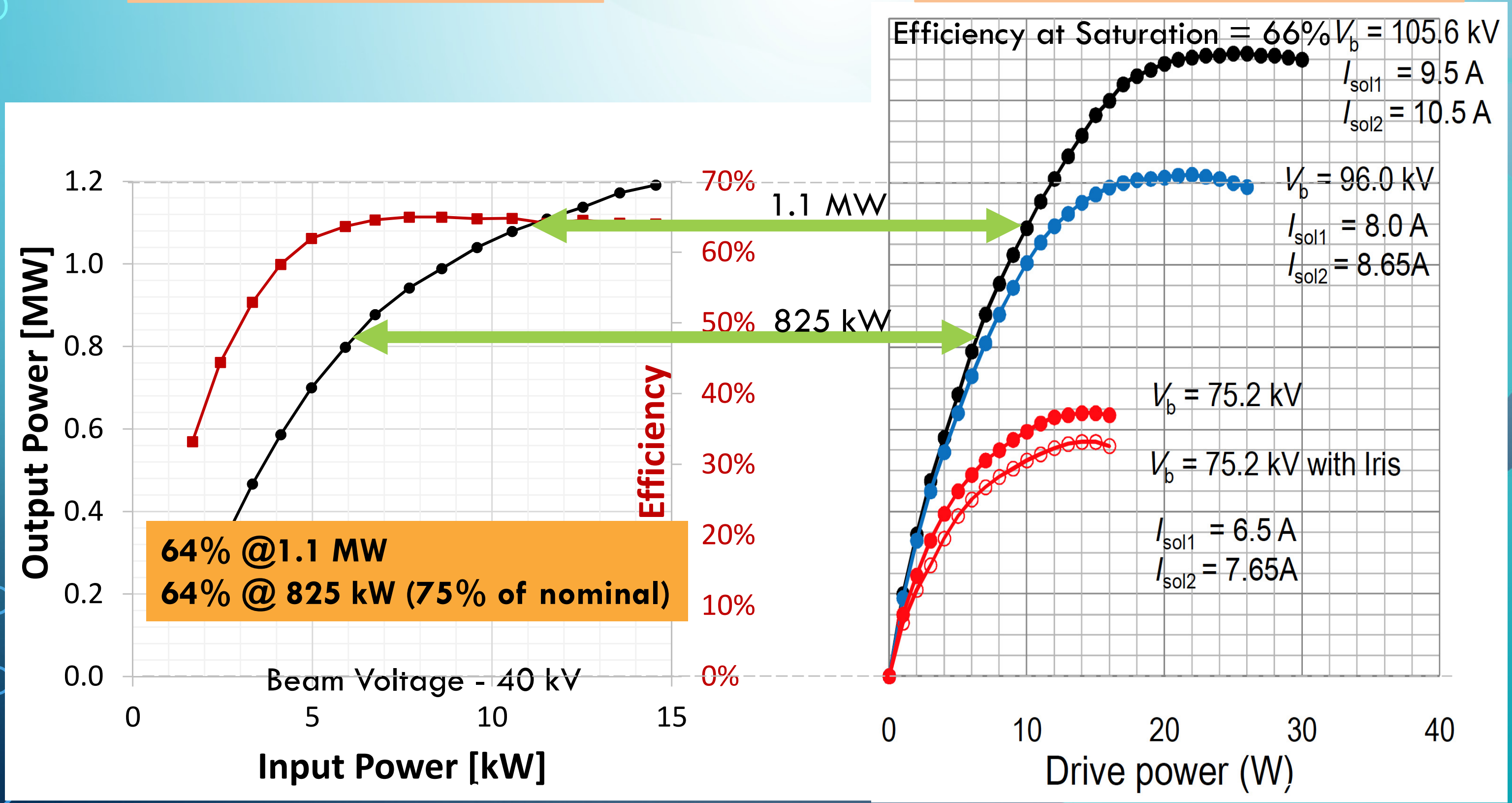

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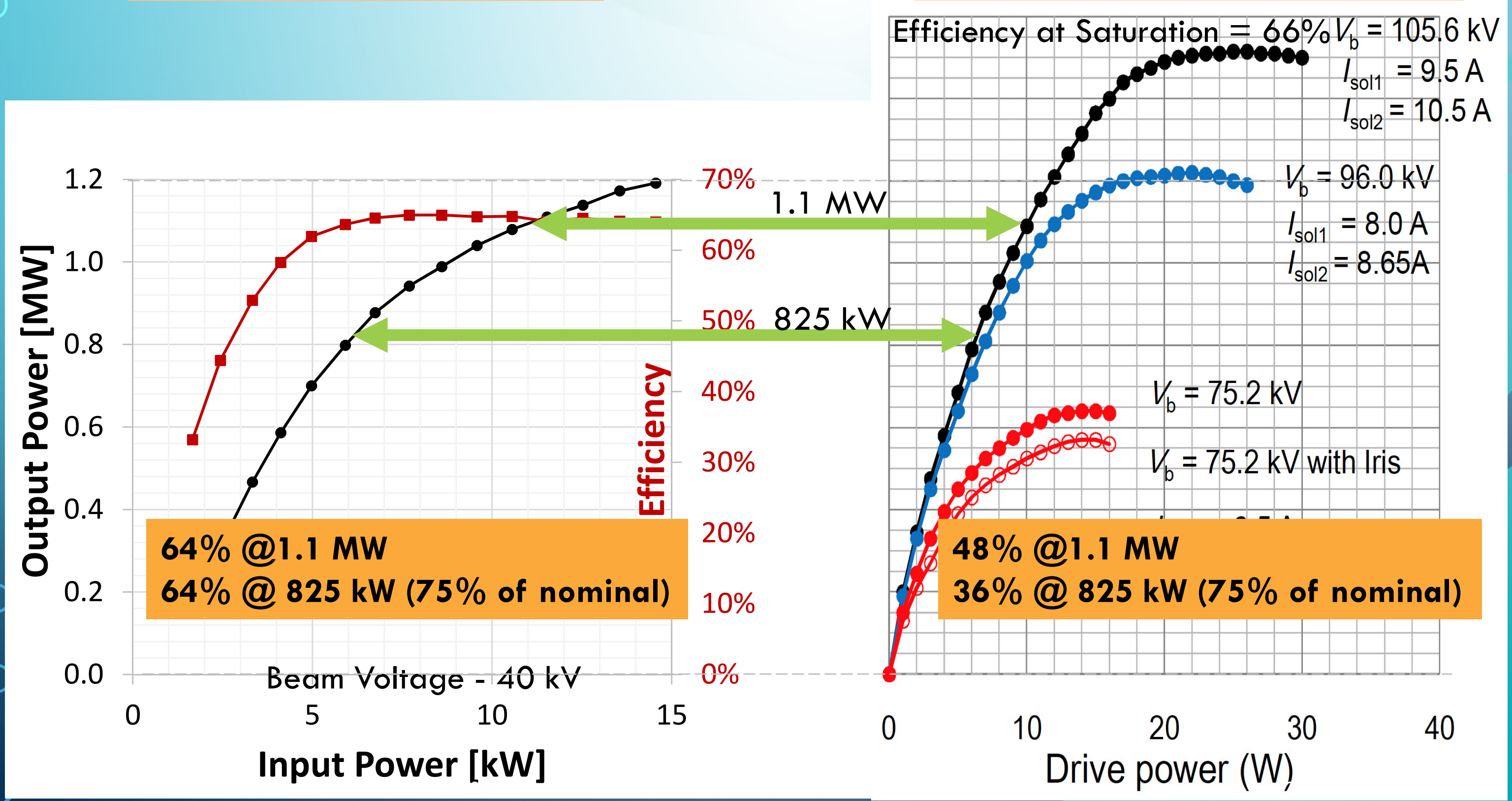

64% @1.1 MW
64% @ 825 kW (75% of nominal)

48% @1.1 MW
36% @ 825 kW (75% of nominal)

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ESS: Current status and next steps

- Both MB-IOT contracts are proceeding well with both tubes expected to be delivered within 6 months
- CERN MB-IOT test stand @ CERN progressing
- ESS currently planning to in-house test stand for end of 2017
- Pre-series / Prototype units under discussion as part of the plan to mature the technology for series production

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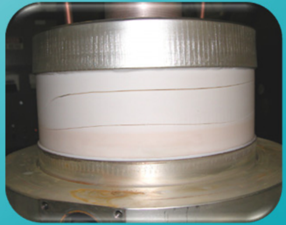
LANSCE, 201 MHz

LANSCE 201 MHz system history

- Originally installed in 1972 (!) – based on **Burle 7835** triodes
- When RCA still existed, 7835 power triodes were manufactured closely to their original design. Over the past 15 years, material substitutions, process changes, and loss of original know-how eroded tube lifetime & performance.
- 201MHz high power RF system at DTL RF stations 2 - 4 became incapable of reliably producing needed average power, leading to loss of 120 Hz operation from 2006.
- Excessive outgassing in most tubes at high DF, poisoning cathode emission.
- Manufacturer unable to test using RF power to prove this.
- Ceramic/metal seals stressed leading to occasional ceramic cracks.



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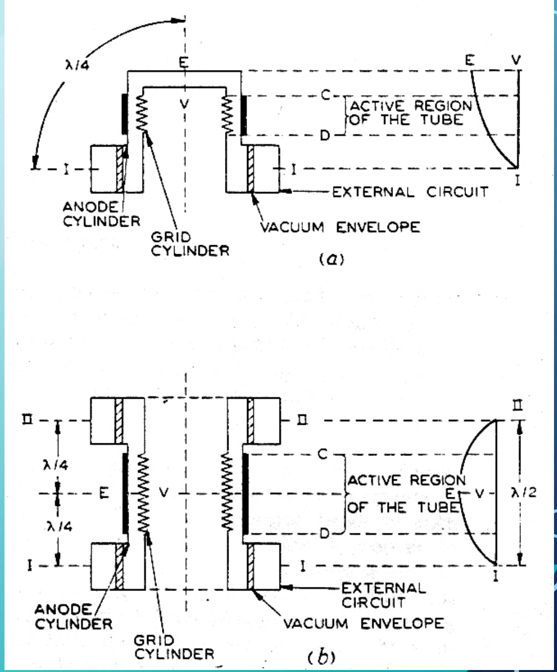
Burle 7835 triode → Thales TH628L diacrode



Diacrode is actually a double-ended Tetrode, also the Burle triode is double-ended.

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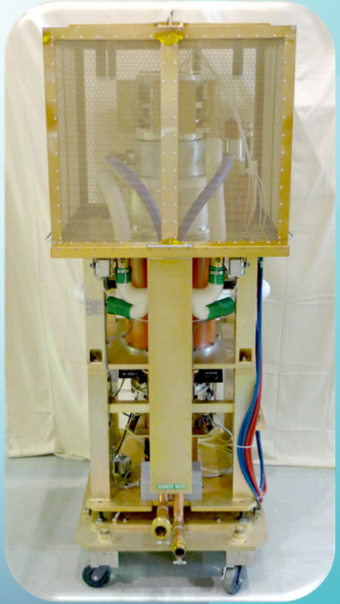
LANL in-house Power Amplifier development



- Designed 2009 – 2011, Tested > 9000 hours with 6 tubes
- Tested to $(2 \; ... 2.5)$ MW at 12% DF, operated at $(1.3 \; ... 1.8)$ MW
- Commercialized by Continental Electronics Corp., 7 built

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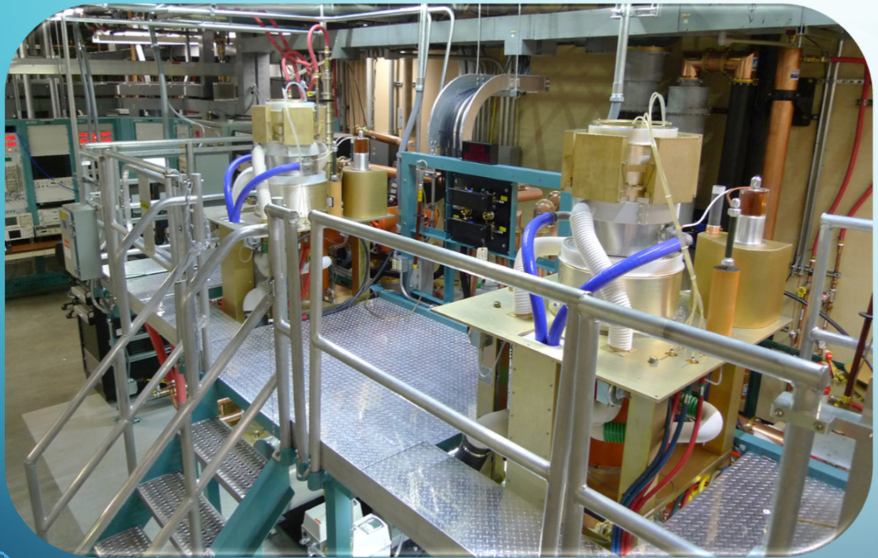
Dual amplifier platform



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Behind the platform – "coaxial plumbing"

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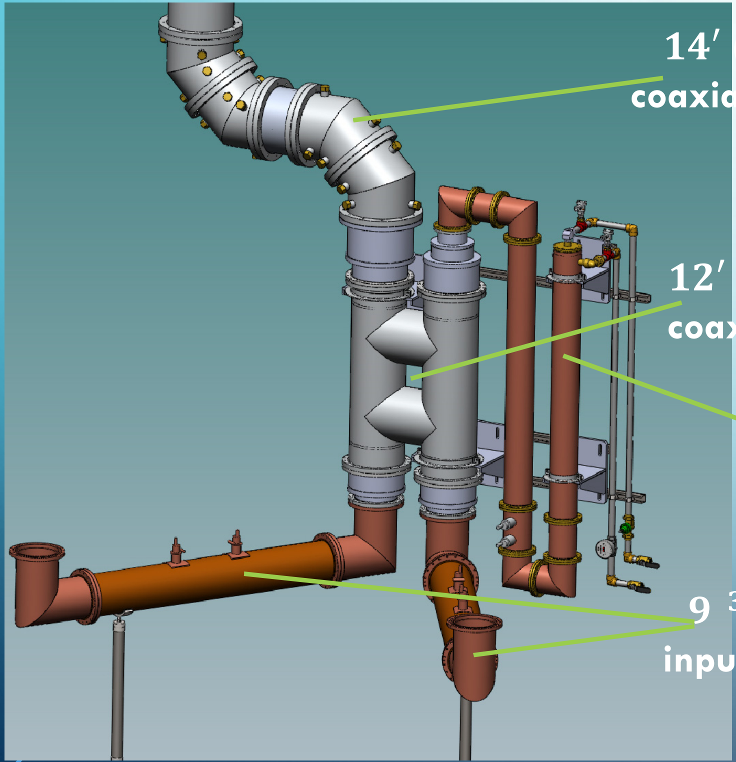
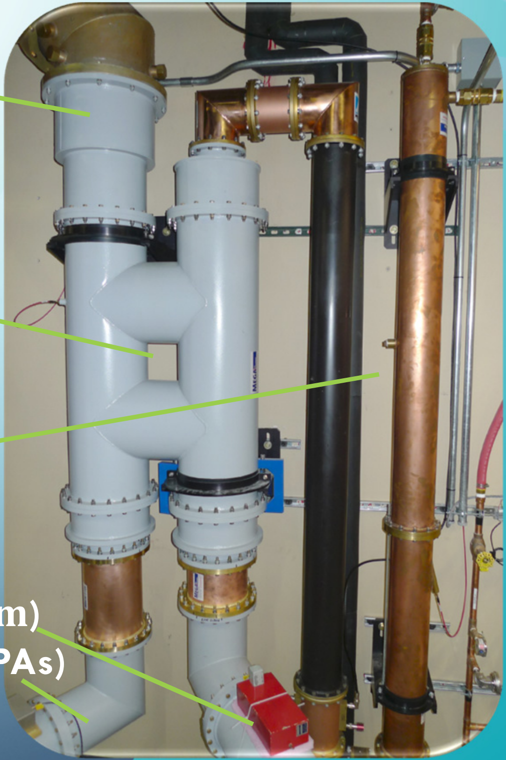
LANL Power combiner 3.2 MW





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LANL 201 MHz system: experience

- Compared with old triode-based system:
  - No more need for complex high level anode modulation ("250K modulator"), which wasted a lot of power.
  - Reduced number of tubes from 6 to 3 (1 TH781, 2 TH628)
  - 50% reduced heat load, smaller CV installation, smaller HV.
  - Faster tube exchange (1 day → 2 hours!)
- Operational experience:
  - Three TH781 driver tetrodes now have 7,000 … 21,000 filament hours without degradation
  - First two TH628 installed in 2014, now having ~ 12,000 filament hours, no degradation
  - Second pair of TH628 installed in 2015, have > 8,200 hours
  - Third pair installed and commissioned in June, 2016.
  - No tube failures so far, present inventory of 9 tubes.

Please see TUPLR046 by John Lyles!

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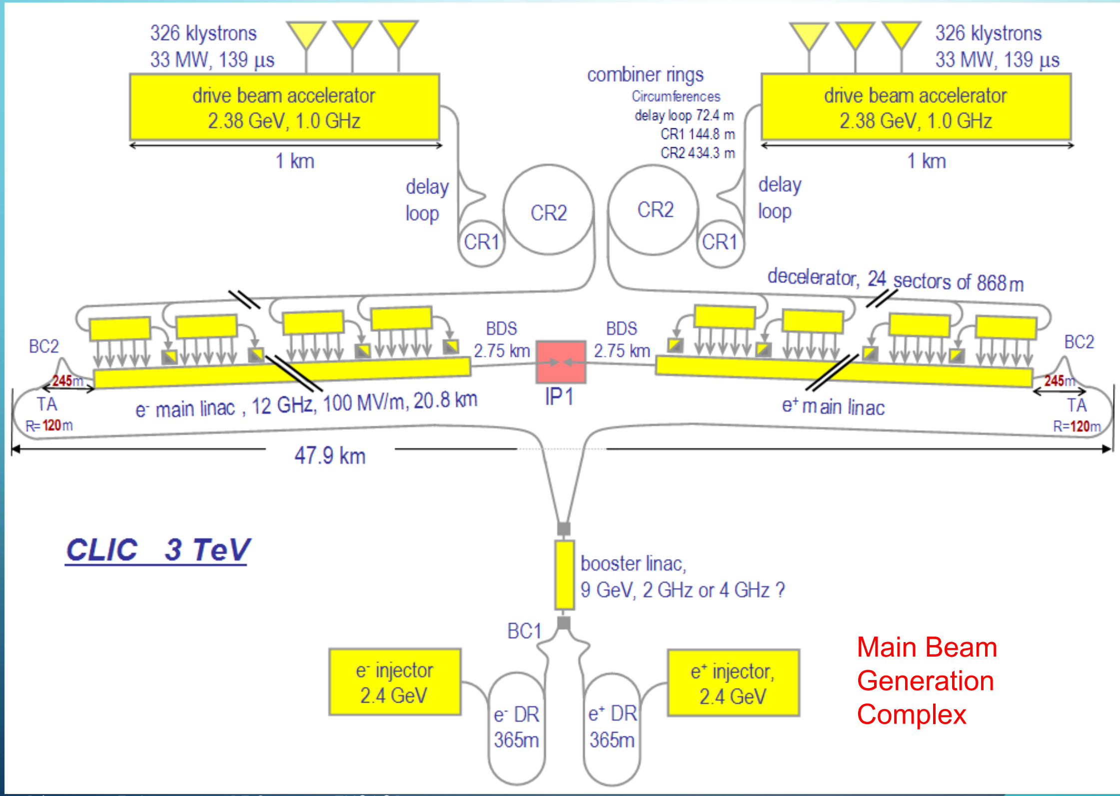
CLIC, 1 GHz

The CLIC 2-beam scheme – layout for $\sqrt{s} = 3$ TeV



R. Corsini et al.

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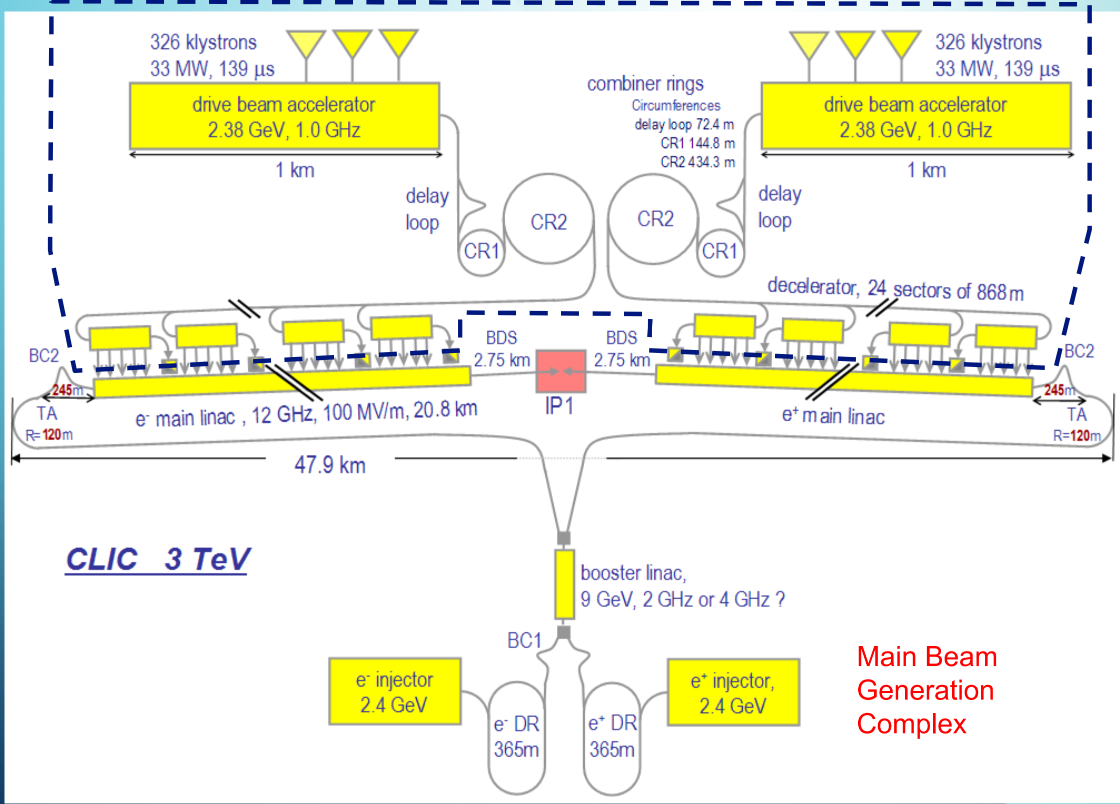

CLIC RF power source

Main Beam Generation Complex

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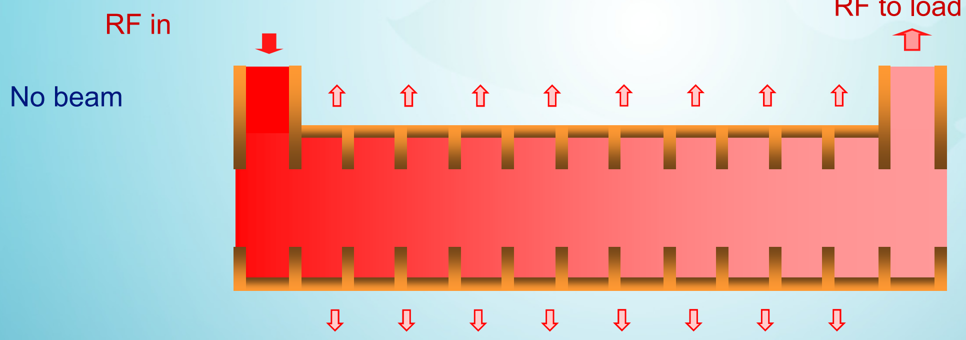
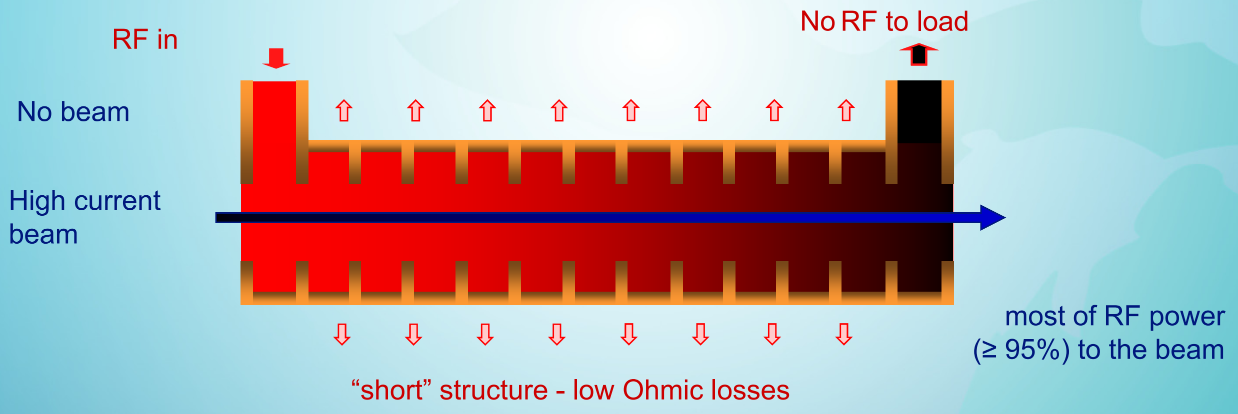
Fully beam-loaded acceleration



"short" structure - low Ohmic losses

R. Corsini et al.

Fully beam-loaded acceleration



R. Corsini et al.

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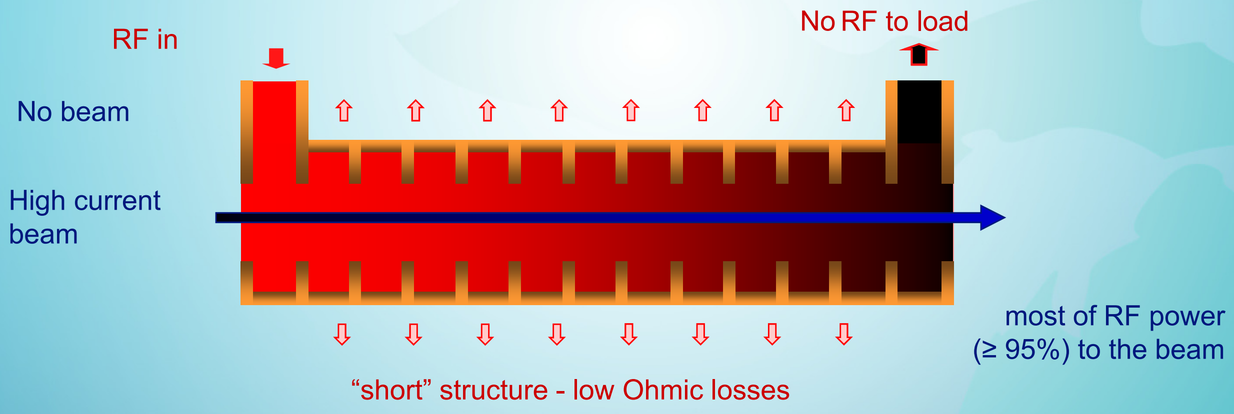
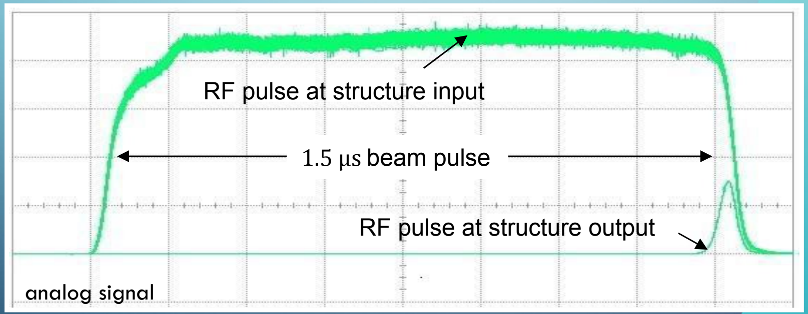


Validation measurement in CTF3 in 2006



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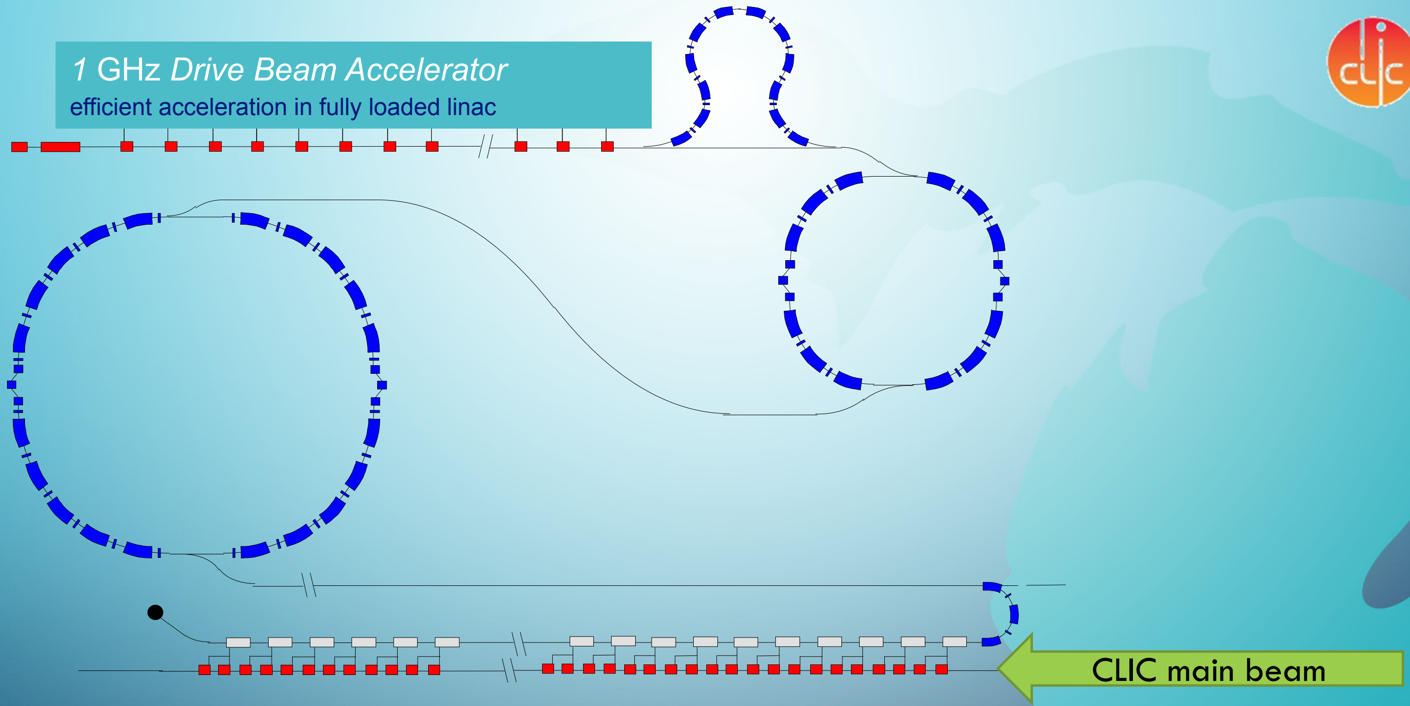
Drive beam compression (by factor 24 × 24 = 576)



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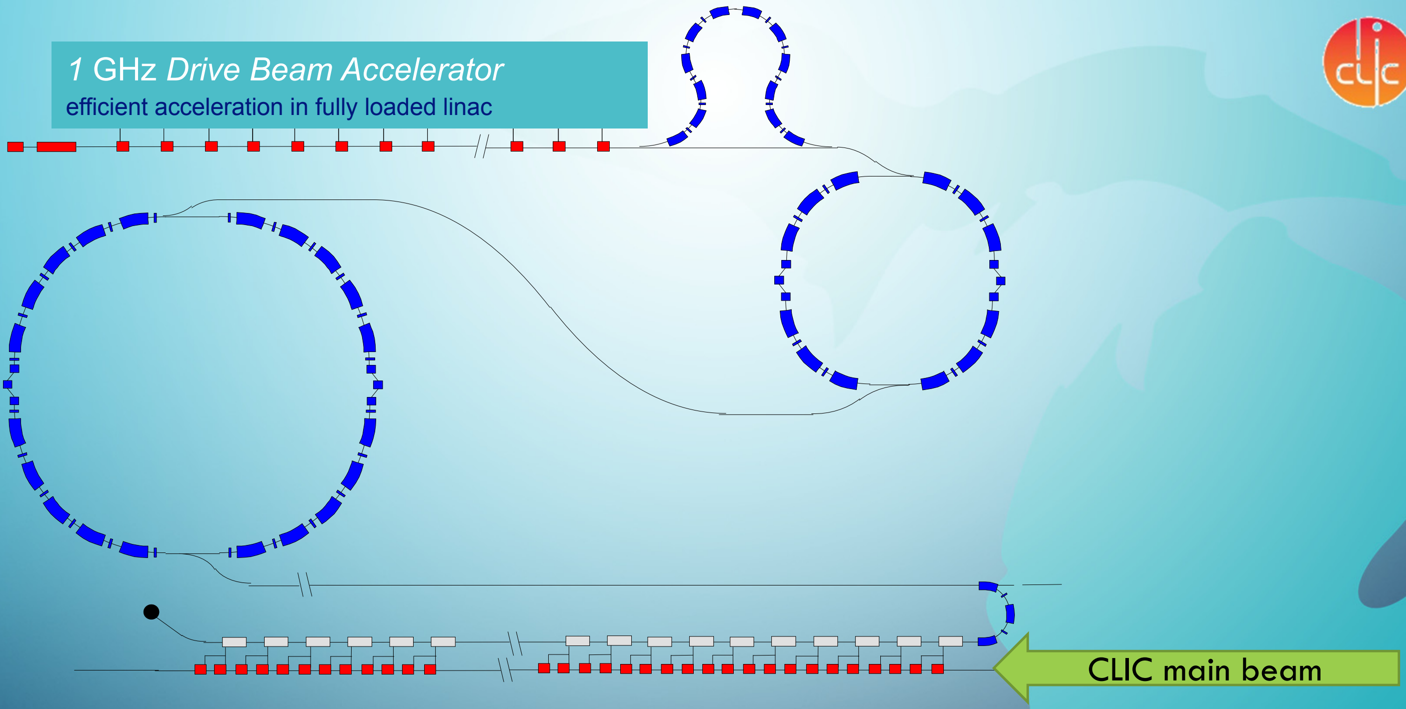
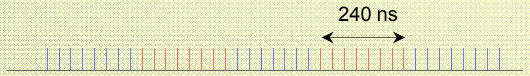


Drive beam time structure - initial



140 μs total length - 24 × 24 sub-pulses - 4.2 A
2.4 GeV - 60 cm between bunches (500 MHz)

R. Corsini et al.

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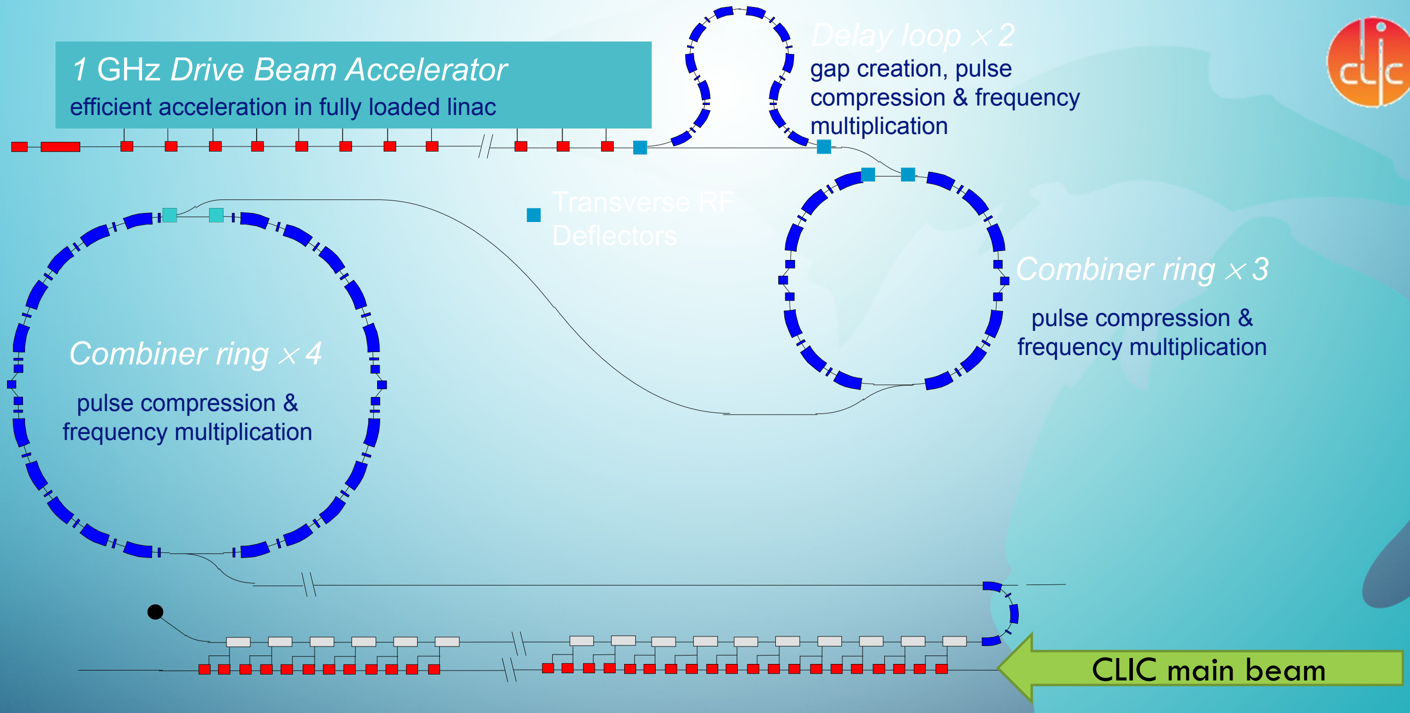

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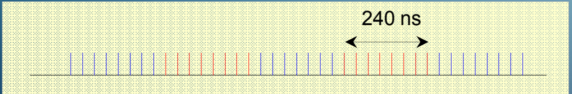

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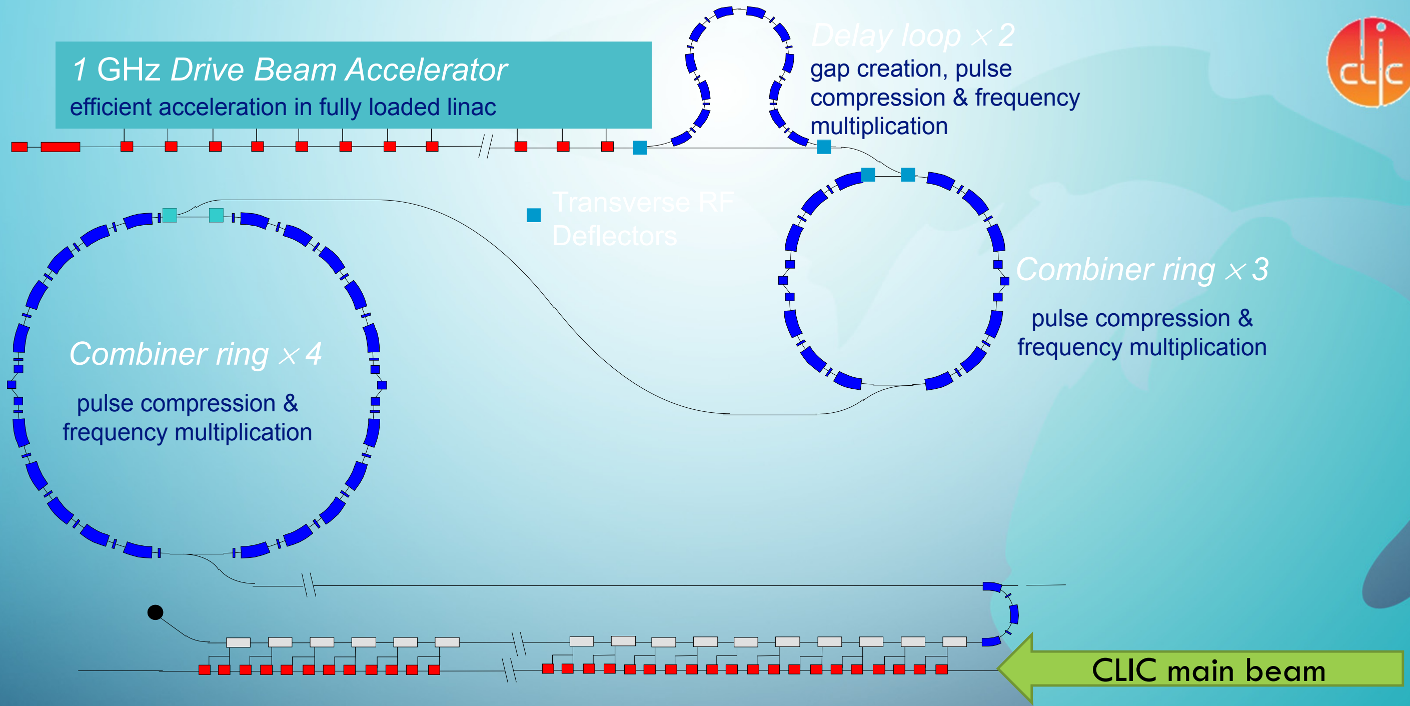
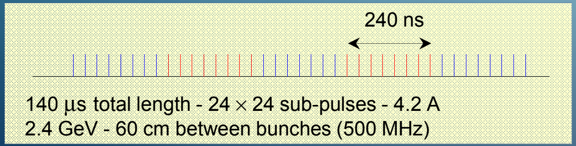
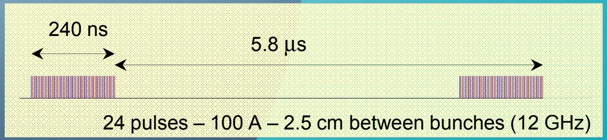


Drive beam time structure - initial



Drive beam time structure - final



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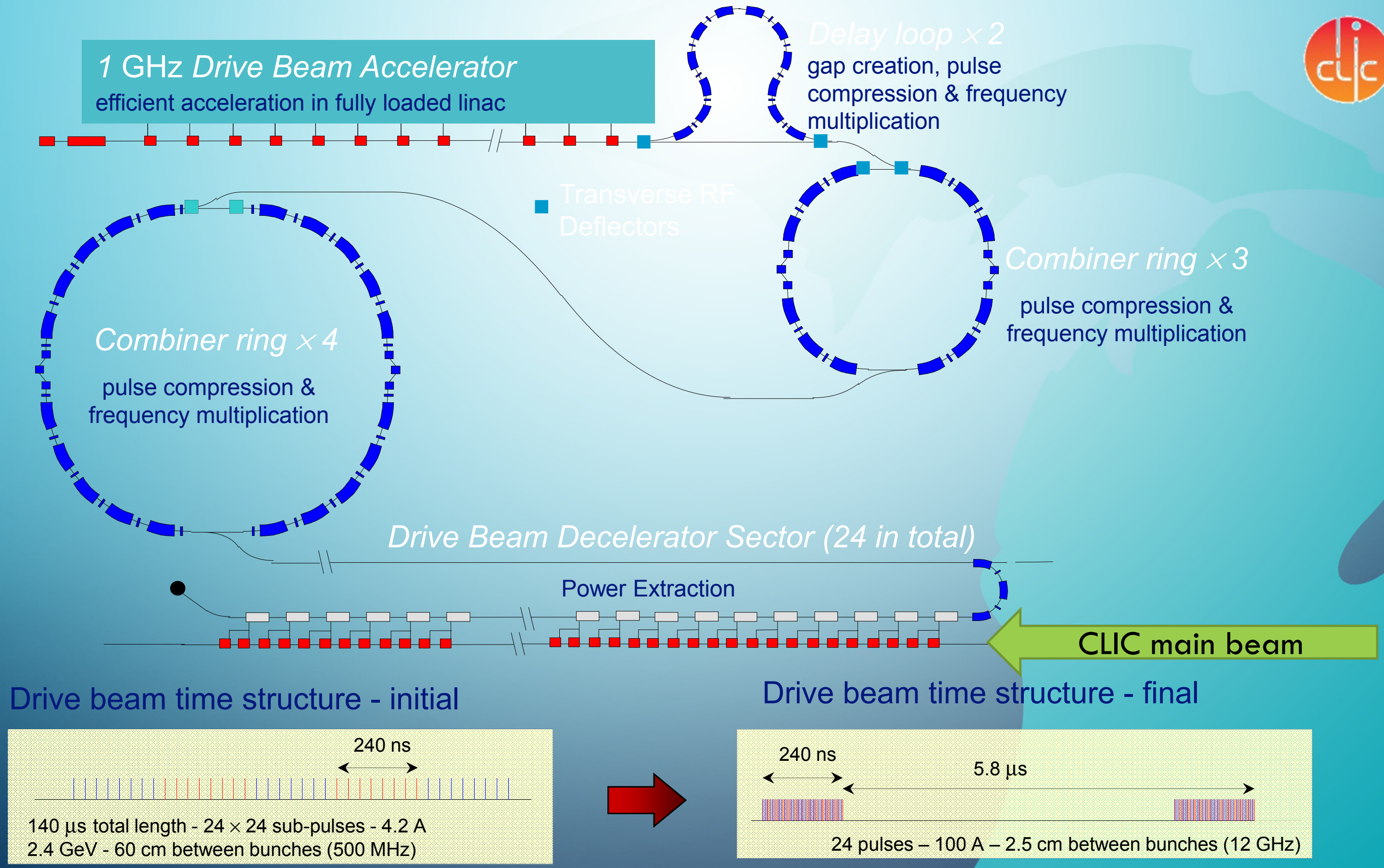
Drive beam compression (by factor 24 × 24 = 576)

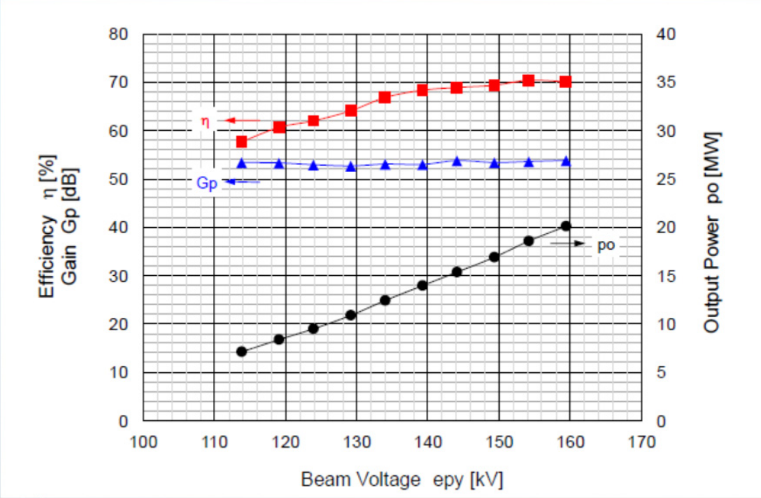


R. Corsini et al.

CLIC 1 GHz klystron progress

Spec: $1\ \text{GHz}, 20\ \text{MW}, 150\ \mu\text{s}, 50\ \text{Hz}, \eta > 70\%$,
Contracts placed with Toshiba and Thales.
Thales: 10-beam tube, calculated $\eta = 77\%$.

Toshiba: 6-beam tube, calculated $\eta = 75\%$,
prototype built and tested (FAT)
Measured:
$0.9995\ \text{GHz}, 21\ \text{MW}, 150\ \mu\text{s}, 25\ \text{Hz}, \eta > 71.5\%$,



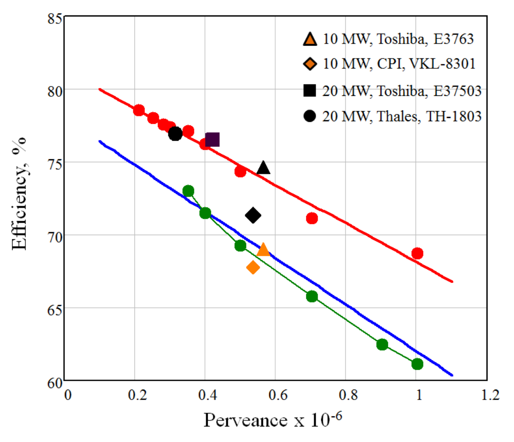
S. Doebert

Development towards very high efficiency klystrons

Work towards higher efficiency klystrons

- Traditional klystrons reach large η only for low perveance $p = \frac{I_{beam}}{V^{1.5}}$, which means high voltage, low current.
- E.g.: $100\ \text{kV},\ 10\ \text{A} \rightarrow p = 0.316 \cdot 10^{-6} \frac{\text{A}}{\text{V}^{1.5}} = 0.316\ \mu\text{perv}$
- Low current per beamlet helps; this led to multi-beam devices.
- Traditional approach limited to $\eta \approx 80\%$ at $0.2\ \mu\text{perv}$.
- A recent invention seems to surpass this limit (see next slides)!

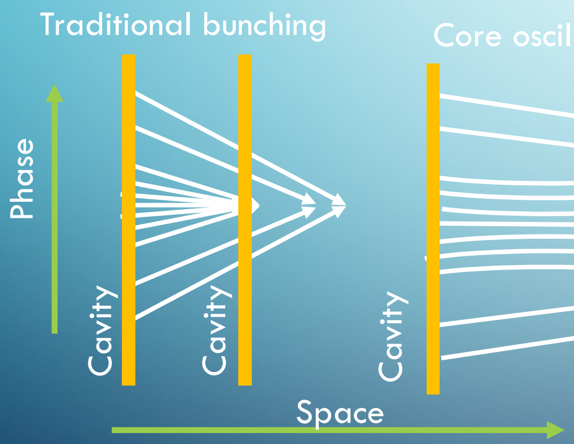
→A. Baikov, C. Marrelli and I. Syratchev, *"Toward High-Power Klystrons With RF Power Conversion Efficiency on the Order of 90%"*, IEEE Transactions on Electron Devices, Vol. **62** No. 10, 2015

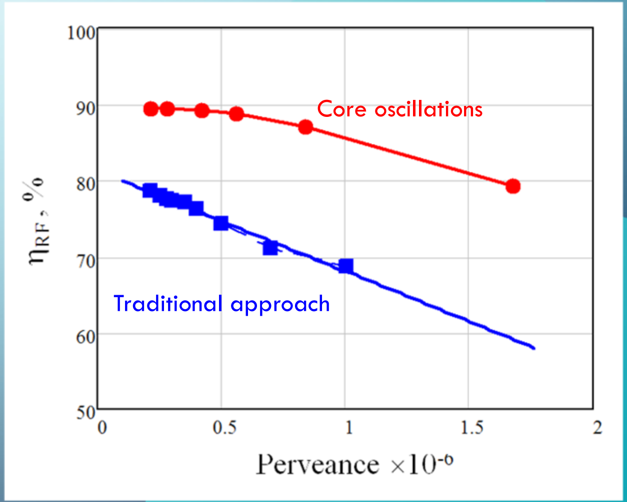


An international collaboration, including Labs, Universities and Industry was initiated;
Members of "HEIKA": I. Syratchev/CERN, A. Baikov/MFUA, I. Guzilov/VDBT, C. Lingwood, D. Constable, V. Hill/U Lancaster, R. Marchesin, Q. Vuillemin/TED, C. Marrelli/ESS, R. Kowalczyk/L-3, T. Habermann/CPI, A. Jensen/SLAC

Method to get high efficiency: Core Oscillation

- Basic idea: Allow space charge debunching, bunch repeatedly:
  - Bunch core oscillations, allows outliers to slowly join the bunch.
  - This leads to very efficient, but very long tubes

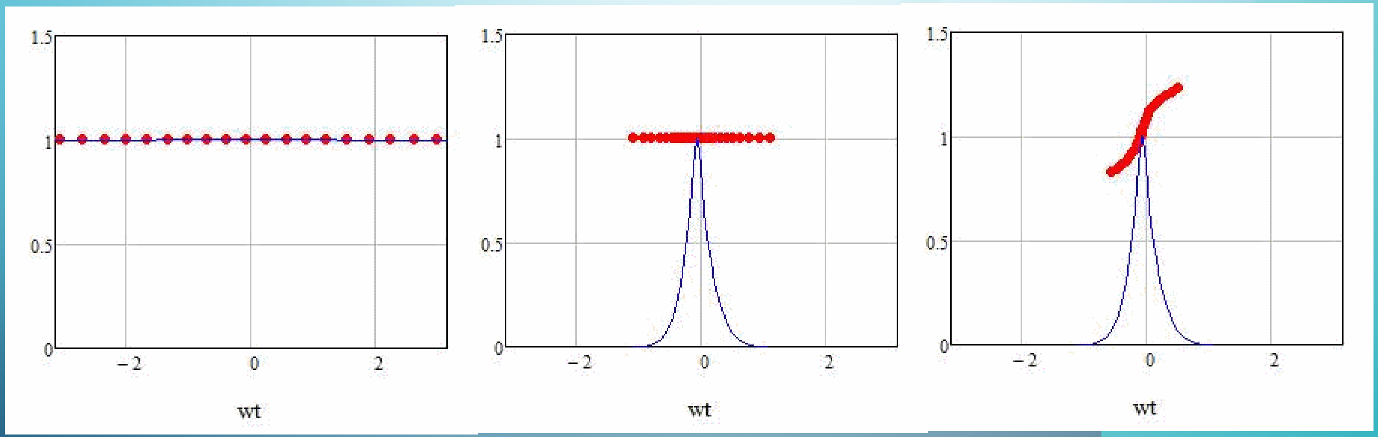




A. Baikov, C. Lingwood, I. Syratchev

Bunch congregation

- To take out max power we also need to take care of the velocity spread.



The fully saturated (FS) bunch

Final compression and bunch rotation prepare congregating FS bunch.

After deceleration all the electrons have identical velocities.

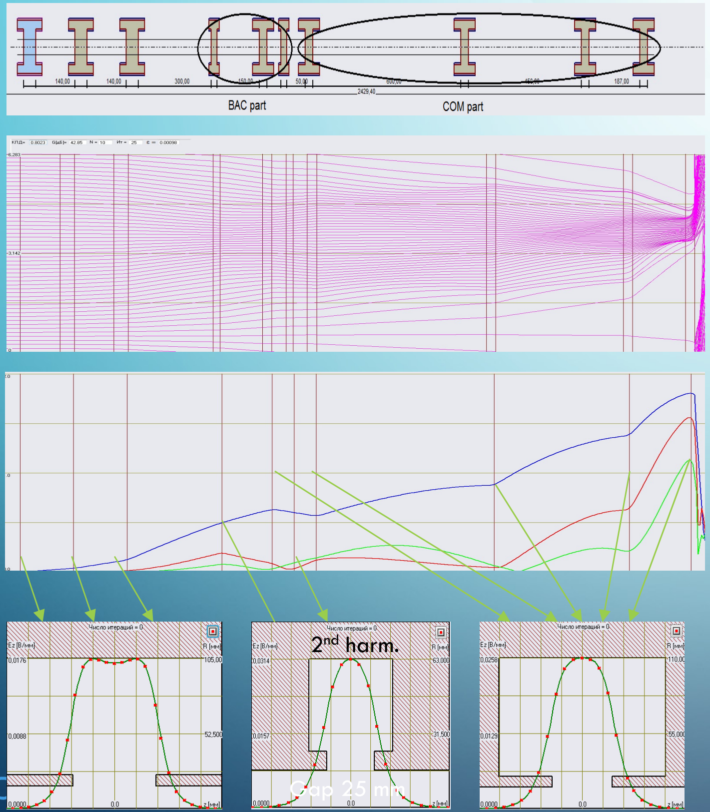
V. Kochetova, C. Lingwood, I. Syratchev

The 3rd ingredient
BAC: Bunch – Align – Compress

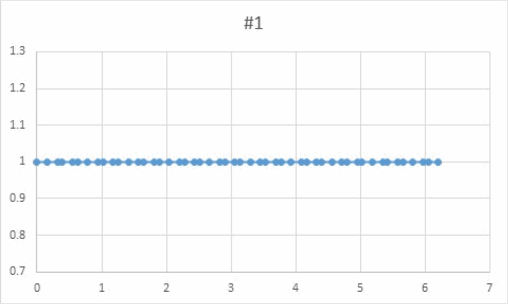
- Help the core oscillation process with additional cavities for the tube to become shorter

I. Guzilov, C. Lingwood, I. Syratchev

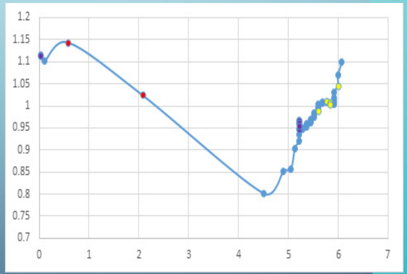
BAC klystron, design still in progress ($\eta \approx 83\%$)

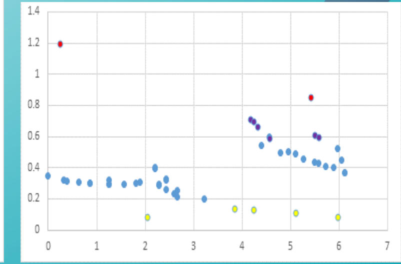


Velocities at entrance of every consequent cavity (animation)



Velocities before and after output cavity.
Bunch has nice congregation and well saturated

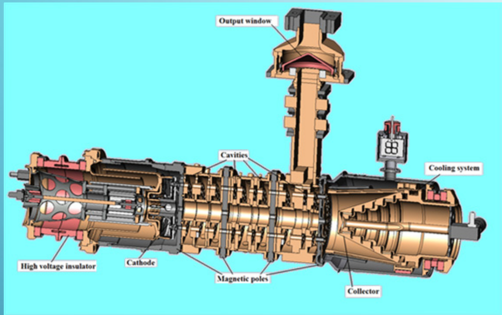


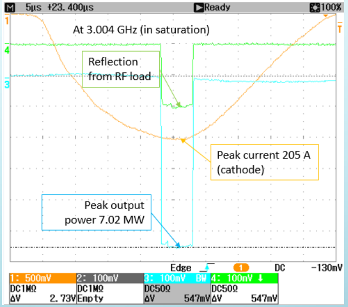


I. Guzilov, C. Lingwood, I. Syratchev

First experimental results

- A prototype S-band 40-beam klystron was built by VDBT in Russia



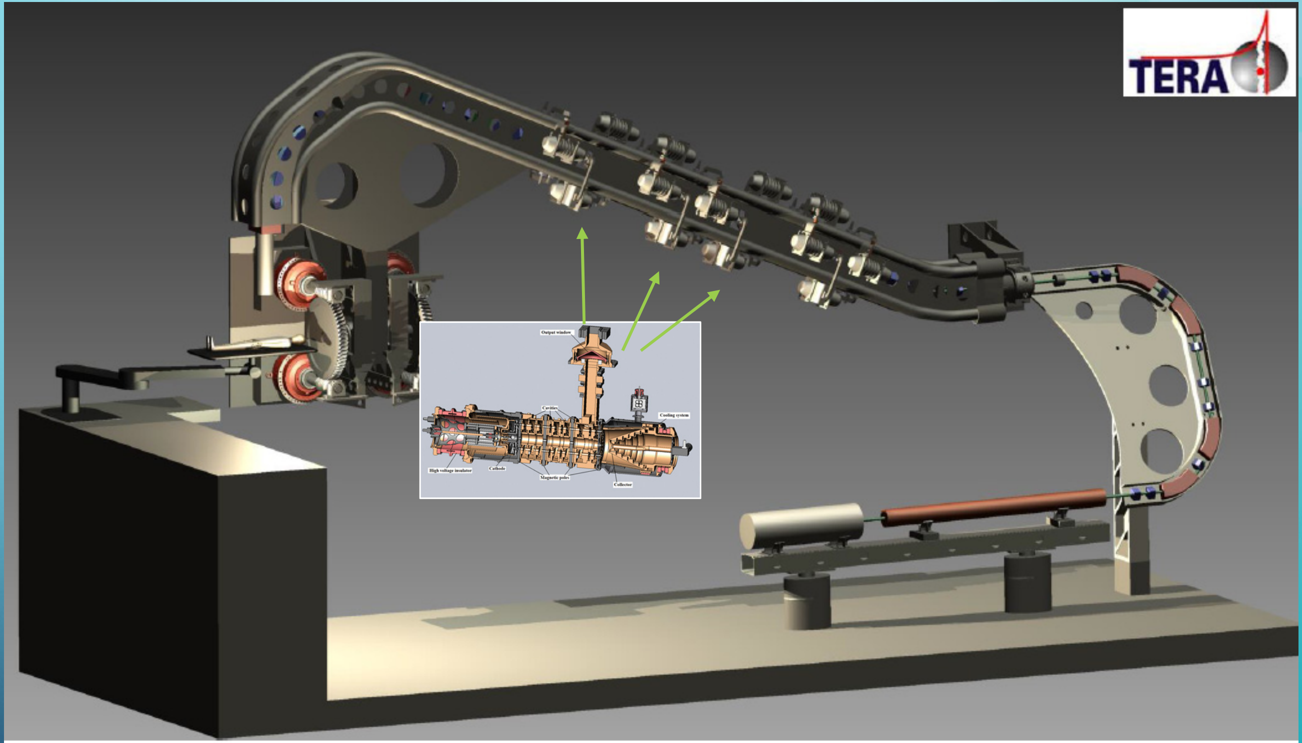


Parameter	specification	1st prototype measurement (preliminary)
RF frequency	2.99855 GHz	3.004 GHz
Peak power	> 6 MW	7.02 MW
RF gain	> 45 dB	48 dB
Efficiency	> 60% (aiming at > 70%)	66%
Voltage	≤ 60 kV (aiming at 52 kV)	51.7 kV
pulse length × rep rate	$\geq 7.5\ \mu s \times 300\ Hz = 2.25 \cdot 10^{-3}$	7.5 μs × 300 Hz

Klystron in the test set-up

I. Guzilov, I. Syratchev

Possible use for such a klystron …



Courtesy of M. Vaziri, TERA Foundation 3

I. Guzilov, I. Syratchev

Solid-State Power Amplifiers

Solid-State Power Amplifiers (SSPAs)

- The general trend from vacuum electronic devices towards solid state does not spare particle accelerators.
- Circular machines have been using SSPA's for about 10 years (Soleil, ESRF)
- CERN has placed a contract for two 2 MW, 200 MHz RF systems with industry (Thales Communication & Security)

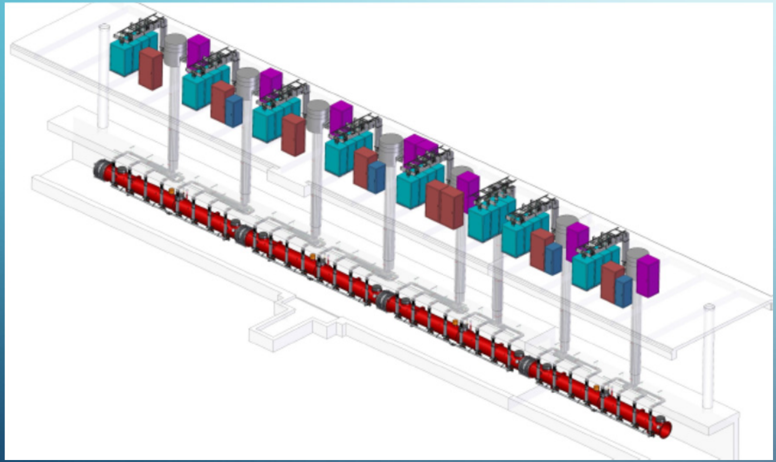
N.B.: The tender specifications were on performance, not on technology!

- The very high powers of pulsed Linacs do not (yet) seem in reach; SSPAs better suited for CW or large DFs.

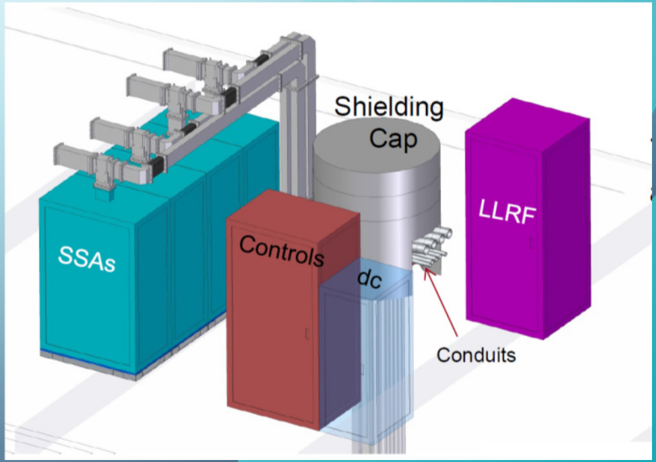
LCLS-II: Solid state power amplifiers

- LCLS-II: 1.3 GHz, CW, SC linac, 100 μA beam current, 4 GeV.
- Requires 284, 3.8 kW CW power stations – suited to go solid-state!

8 of the 284 RF stations with their penetrations



A typical RF station



D. Yeremian, C. Nantista

LCLS-II: The first 7 SSPAs built by R&K, Japan

- Specifications were hard on performance, quality, reliability*) & maintainability.
- Now shipped to FNAL and JLAB for tests (… also for testing cryomodules)

*) C. Adolphsen: uptime for LCLS-IISSA system: $99.99999974\% = 1 - 2.6 \cdot 10^{-9}$

D. Yeremian, C. Nantista

Higher power with SSPAs?

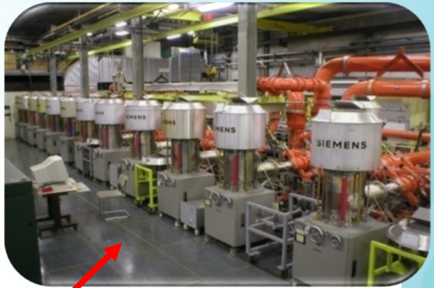
- It is unlikely that single transistors will become much larger.
- RF power transistors are not developed for accelerators but for wireless networks (phone, internet, …)
- RF for accelerators: 0.1% of the market.
- Single transistor rated at 1kW is probably as good as it gets.
- Power combiners are key!

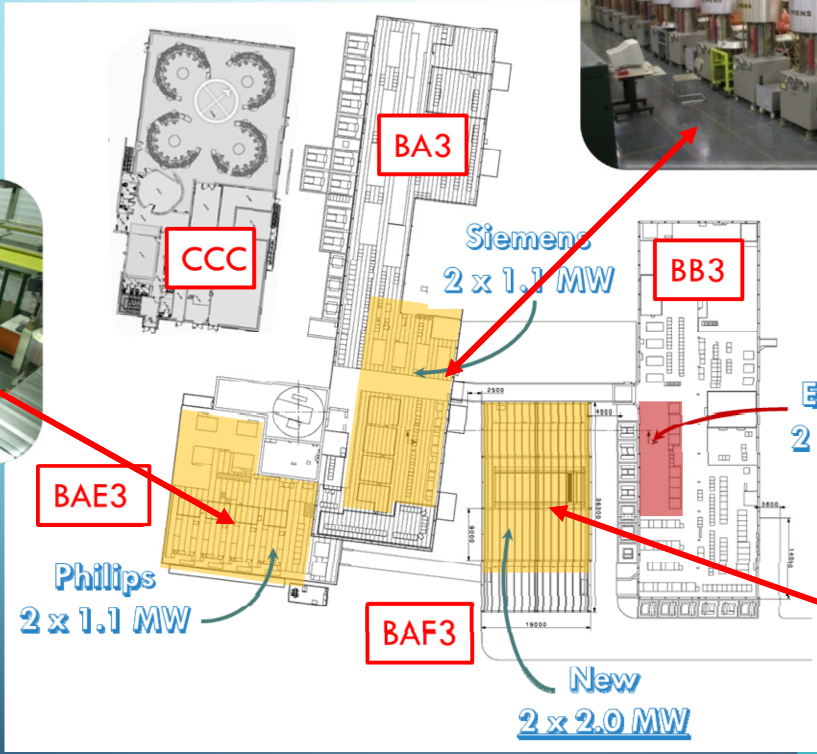
Voltage limits		
	2002	2006
900 MHz	41 V/m	3 V/m
1800 MHz	58 V/m	
2100 MHz	61 V/m	

Device	Distance	Power
Phone	20 km	2 W
Microcell	2 km	10 W
Macrocell	20 km	50W

E. Montesinos

New CERN 2 MW SSPAs





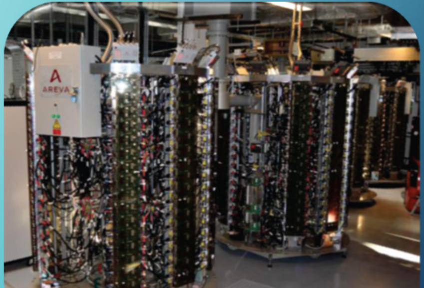
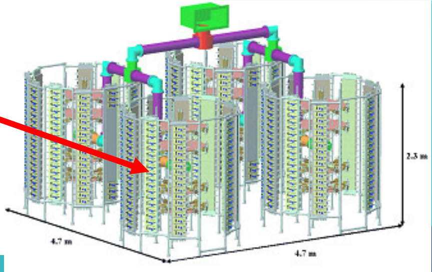


Photo: ESRF 150 kW towers



E. Montesinos

Cavity combiners for High Power SSPAs

- 144:1 combiner prototype built at CERN

E. Montesinos

Progress with CERN 200 MHz SSPAs

THALES
GERAC
ELECTROMAGNETISME

Status:

- ✓ Specific Power supplies validated
- ✓ First RF blocs tested up to 2 kW
- ✓ First Input cavity splitter and first output cavity combiner constructed

Summary

- RF Sources for Linacs have made remarkable progress over the last years.
  - CERN's Linac4 is ready for beam to 160 MeV,
  - ESS is progressing with exciting R&D on multi-beam IOTs,
  - LANSCE has modernized their RF systems to be ready for the next decade,
  - CLIC test facility CTF3 has successfully demonstrated the CLIC RF Source principle.
- Exciting and promising R&D indicate future trends for RF Sources
  - Very high efficiency seems possible with a novel klystron bunching mechanism!
  - Solid-state Power Amplifiers are reaching linac-specific parameters.

Thank you for your interest!

Special Thanks

I have used material from many sources and authors, not all of which I can explicitly acknowledge here.

I would however like to express my special thanks to O. Brunner, R. Corsini, S. Doebert, F. Gerigk, E. Montesinos, S. Ramberger and I. Syratchev from CERN,

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M. Kirshner from L3,

J. Lyles from LANL,

C. Adolphsen, C. Nantista and D. Yeremian from SLAC,

the HEIKA collaboration ("High Efficiency International Klystron Activity")