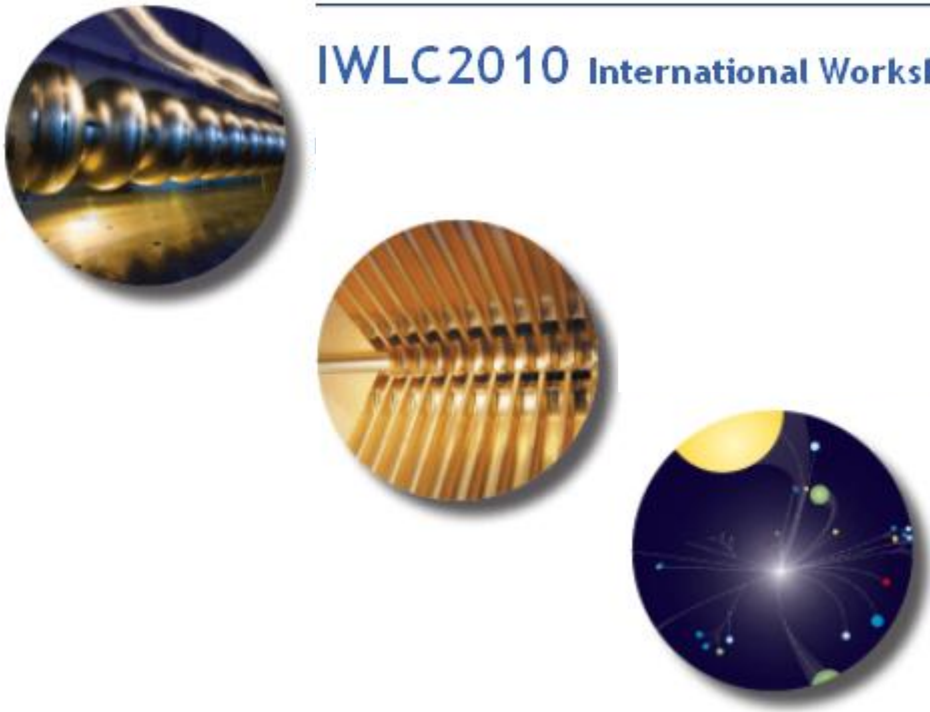
IWLC2010 International Workshop on Linear Colliders 2010



# WHAT IS THE IDEAL POWER SOURCE FOR A LINEAR COLLIDER?

… some thoughts to trigger discussion …

Erk Jensen
CERN, Geneva, Switzerland

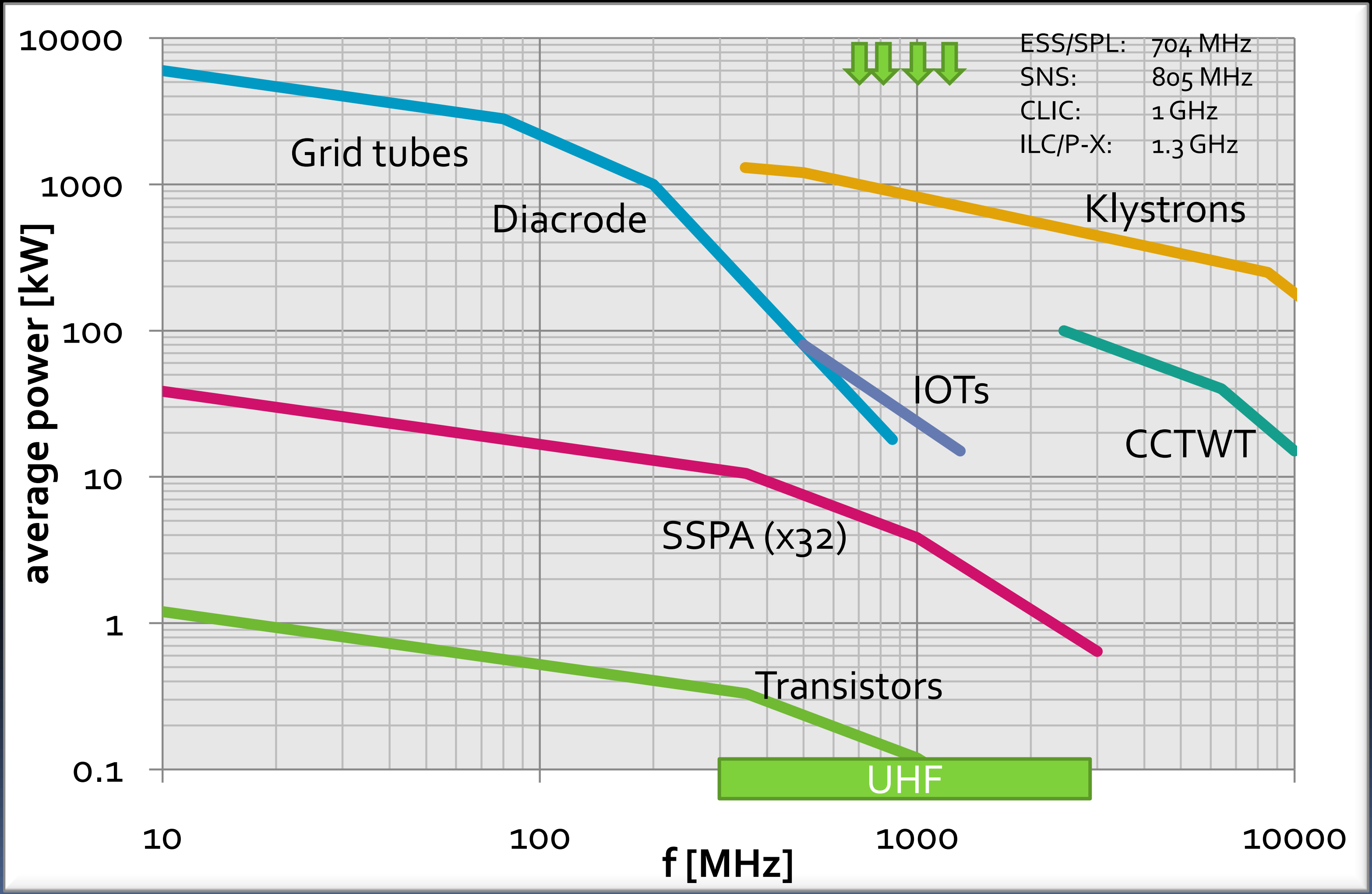
# Outline

- State of the Art (ILC klystrons)
- Future Needs: The Challenges
  - power, efficiency, cost & complexity
- My main message:
  - Joint focused R&D should be intensified!
- High efficiency power source contenders
- Conclusion

# State of the Art

# Typical average power ranges (commercially available)

State of the art



# UHF: State of the art: X-FEL/ILC MBK’s

1. CPI: VKL-8301B (6 beam): 1.3 GHz, 10.2 MW, 10 Hz, 66.3 %, 49.3 dB gain
2. Thales: TH 1801 (7 beam): 1.3 GHz, 10.1 MW, 10 Hz, 63 %, 48 dB gain
3. Toshiba: E3736 (6 beam): 1.3 GHz, 10.4 MW, 10 Hz, 66 %, 49 dB gain

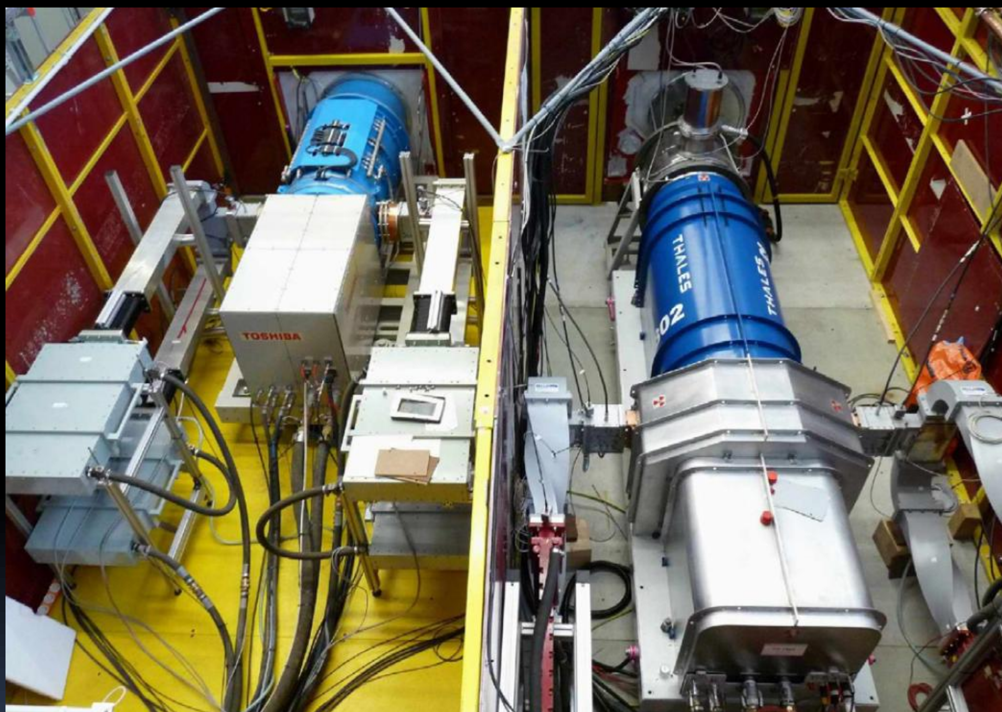
1.

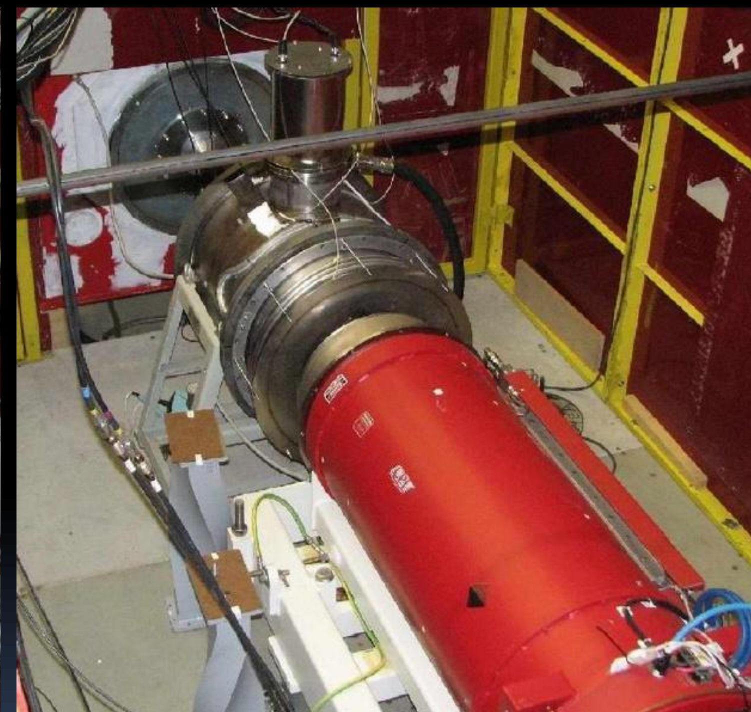
2.

3.

State of the art

# X-FEL MBK's: horizontal test



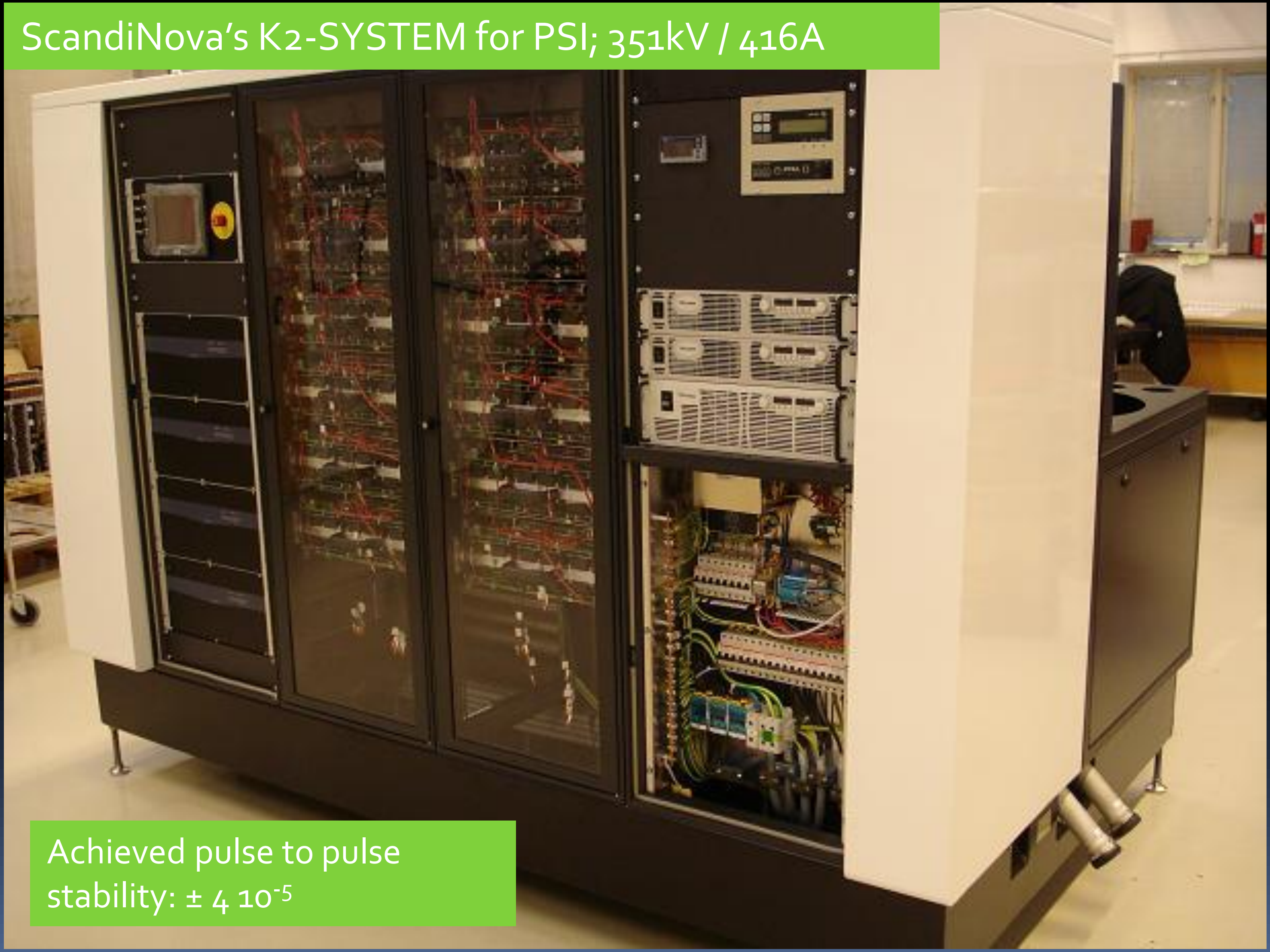



Toshiba E3736 H　　Thales TH 1802　　CPI VKL 8301 B

State of the art

# Modulators

ScandiNova's K2-SYSTEM for PSI; 351kV / 416A



Achieved pulse to pulse stability: ± 4 $10^{-5}$

# Future needs: the challenges

Needed:

- High power
- High efficiency
- Low cost

# Synergies between projects: Generic R&D

| R&D/Projects | | Test Facilities | Protons | | | Ions | | | Electron-Hadrons | | | B Factories | | Linear Colliders | | | | Muons & Neutrinos | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | HL-LHC | HE-LHC | LHiC | NICA | RHIC II | FAIR | LHeC | eRHIC | ELIC | Super KEKB | SuperB | ILC | CLIC | PFWA LWFA | Dielec-tric Acc | Muon Collider | Neutrin Factory | Project X |
| | Coordination | | CERN | CERN | CERN | DUBNA | BNL | GSI | CERN | BNL | JLAB | KEK | LNF | GDE | CLIC coll | SLAC/LBl | SLAC? | MAP | NF Coll | FNAL |
| Electron cloud | Cornell? | CESR-TA | X | X | | X | X | | X | X | | X | X | X | X | | | | | X |
| SC magnets (High Field, Fast Cycling, Super-Ferric, Wigglers) | Magnet R&D network? | CERN, FNAL, GSI | HF | HF/FC | HF | SF | | FC | | | | HF | HF | | W | | | | | |
| Super-Conducting RF | TESLA Tech coll | FLASH, NML, STF, XFEL | | | | | X | | X | X | | X | | X | | | | X | | X |
| High field NC Structures | ? | CTF3, SLAC, KEK | | | | | | | | | | | | | X | | | | X | |
| Low emittance generation | CLIC/ILC WG? | ATF1 | | | | | | | | | | X | X | X | X | X | X | | | |
| Nanometer beam focusing | ATF coll | ATF2 | X | | | | | | | | | X | X | X | X | X | X | | | |
| Alignment and stabilisation | ? | [illegible] | | | | | X | | X | X | X | X | X | | X | X | X | | | |
| RF power source high efficiency | ? | | X | X | X | | | | | | | | | X | X | | | X | | X |
| High beam power generation & handling | ? | SNS, PSI | X | X | | | | | | | | X | X | X | X | X | X | X | X | X |
| Collimation & targets high power beams | ? | HRad,HARP,MERIT | X | X | X | | | | | | | X | X | X | X | | | X | X | X |
| Cooling (Electron, Coherent, Stochastic) | ? | RHIC | | | | S,E | S | | C | C | E | | | | | | | | | |
| Ionisation cooling | ? | MICE,MTA, MuCool | | | | | | | | | | | | | | | | X | X | |
| crab cavities | ? | KEKB | X | | | | | | X | X | X | | | X | X | | | | | |
| Plasmas | LBL, SLAC | BELLA, FACET | | | | | | | | | | | | | | X | | | | |
| Lasers | LBL, Ec. Polyt | BELLA, LULI | | | | | | | | | | | | X | X | X | X | | | |
| Drive beam generation | CTF3 collab | CTF3, FACET | | | | | | | | | | | | | X | X | X | | | |
| Beam dynamics simuations | ? | Test benches | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Beam Instrumentation | ? | | X | | | | | | | | | | | | | | | X | X | X |
| Beam based feedbacks | ? | | | | | | | | | | | | | | | | | | | |
| Energy recovery linacs | CEBAF? | CEBAF, BNL R&D ERL | | | | | | | | | | | | | | | | | | |
| Nanobeam scheme (LPA & Crab waist) | B Fact collab? | DAFNE | X | | | | | | | | | | | | | | | | | |
| Positron generation | ? | | | | | | | | | | | | | | | | | | | |
| Polarisation | ? | | | | | X | X | | X | X | X | | X | X | X | | | | | |
| Dynamic vacuum | ? | | | X | X | X | X | | | X | X | X | X | | X | | | | | |

Taken from:
J.-P. Delahaye, “New Accelerator Projects”, ICHEP10, 22.-28, July 2010, Paris

# Synergies between projects

- HEP:
  - Future $e^+e^-$ colliders (ILC, CLIC, …)
  - Plasma-Wakefield accelerator (drive beam)
  - Proton driver for Muon-collider, Neutrino-factory (Project-X, …)
- Non-HEP:
  - Spallation neutron sources, (SNS, ESS, …)
  - Irradiation Facility (IFMIF, …)
  - ADS

They all need high power, high efficiency, low cost RF power sources!

# Power needs for future Linacs

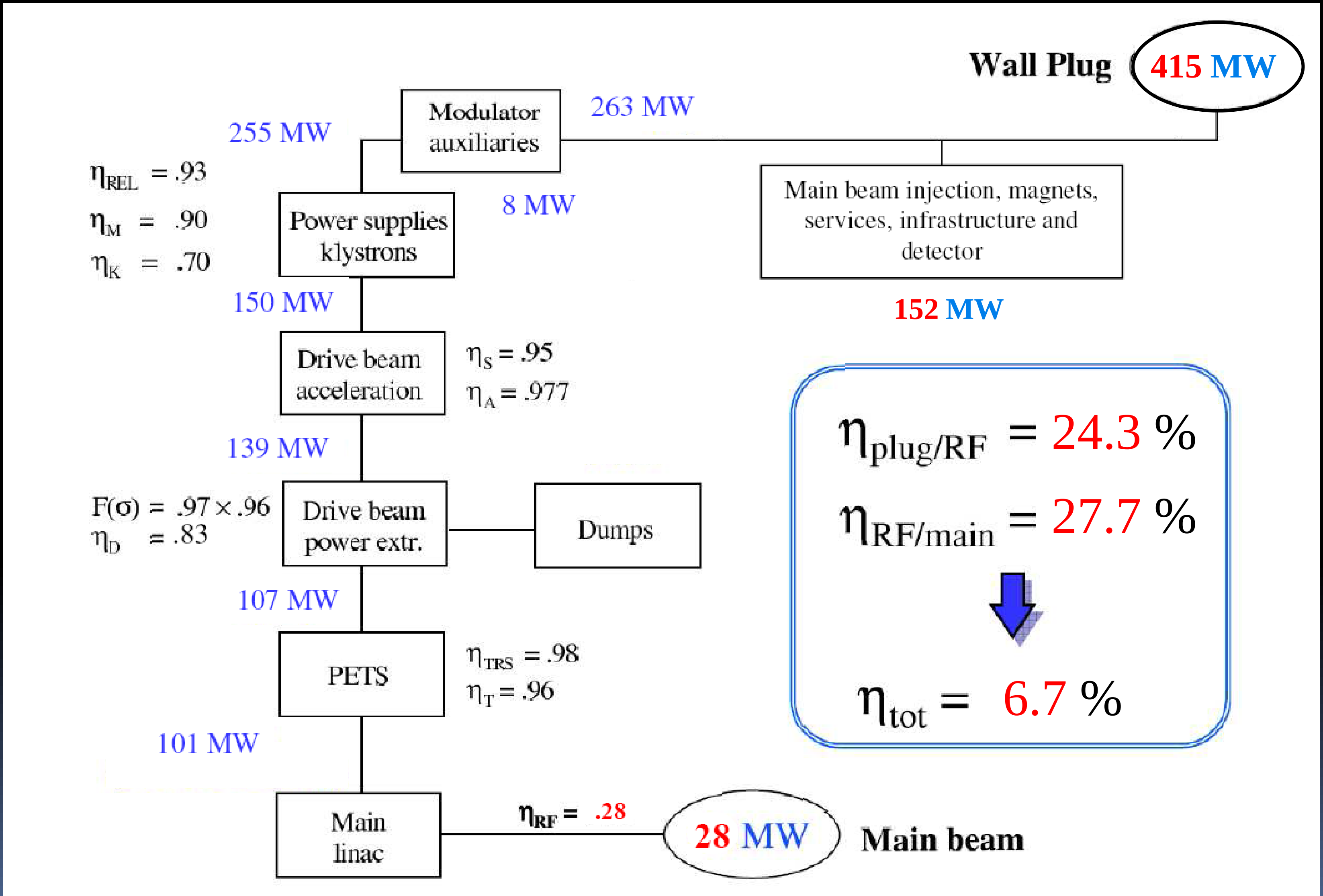
| | ESS | SPL II | ILC .5 TeV | CLIC 3 TeV |
|---|---|---|---|---|
| Frequency | 704 MHz | 704 MHz | 1300 MHz | 1000 MHz |
| Technology | klystrons | klystrons | MBK | MBK |
| Total AC power | 38 MW | 40 MW | 230 MW | 415 MW |
| Modulator output | 17.8 MW | 26.5 MW | 135 MW | 255 MW |
| Power source output | 8.9 MW | 10.7 MW | 88 MW | 180 MW |
| Drive beam power | | | | 140 MW |
| Acc. structure input | 6.5 MW | 7.8 MW | 67 MW | 101 MW |
| Total beam(s) power | 5 MW | 4 MW | 21.6 MW | 28 MW |
| Efficiency | 13.5 % | 10 % | 9.4 % | 6.7 % |

# Challenge: power!

- All these projects require large average power.
- The linear colliders require very large peak power, they follow different approaches:
  - ILC: long bunch trains (1.5 ms, 5.9 GW @ 1.3 GHz)
  - CLIC: beam-based compression from 150 µs down to 244 ns still requires 23 GW @ 1 GHz!
- Is an AC power consumption of ≈ 400 MW acceptable?

# Example: CLIC @ 3 TeV





# With 10 MW tubes, CLIC would need:

(photo shows a 5MW tube)

plus


plus power distribution, loads, …

… x 2400!

… is this the best way to go?

# Challenge: efficiency

- The overall AC to beam efficiency is in the order of 10 %.
- The RF to beam efficiency can be increased with larger beam loading, but at the expense of the gradient.
- The single smallest contributor to this "low" efficiency is the power source → an increase of efficiency would have a large impact!

# Increased efficiency would …

- reduce the environmental impact,
- reduce the size of the installed power,
- reduce the size of the necessary cooling,
- decrease the electricity bill:

Example CLIC @ 3 TeV, 415 MW AC consumption,
5,000 h operation per year, 40 $/MWh:
Annual electricity bill of 91 M$.
Assume that this is for a klystron efficiency of 65 %.
With a klystron efficiency increase by 1 % (66 %),
you would save 1.4 M$ every year in electricity alone.

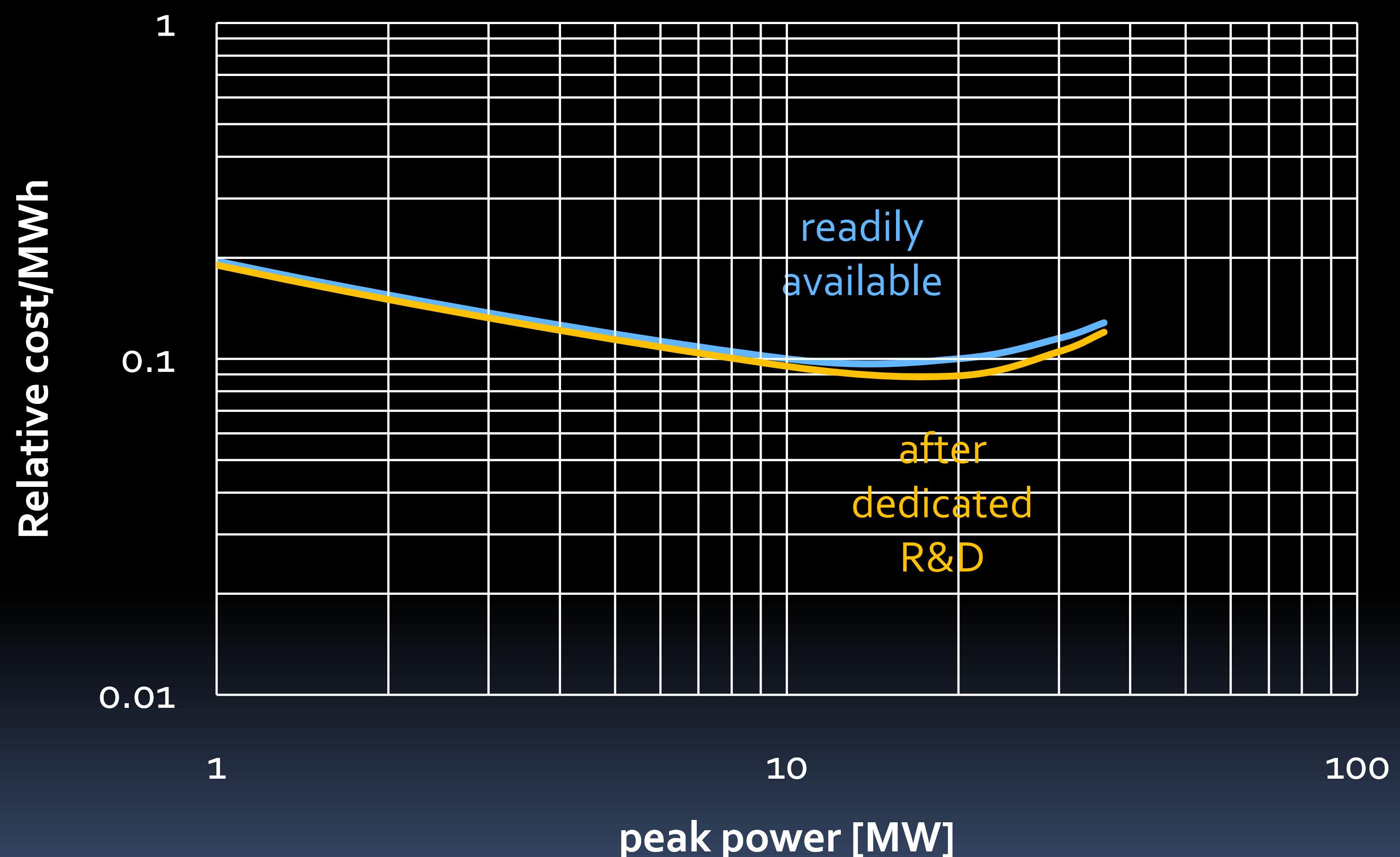
… this alone could already pay for some R&D!

# Challenge: complexity/cost

- Some of these projects cost ≈ 10 G$ or beyond.
- RF sources may be important cost drivers (G$).
- Clearly, when optimizing efficiency, one must not compromise on low cost. Solutions with potential easy mass production are preferred.
- Large complexity will also complicate operation/maintenance.
- For many small units, methods to implement graceful degradation may be implemented.

Future needs: The challenges

# Optimum peak power for an MBK?




The used model may be wrong, but there is an optimum which justifies the R&D.

# My main message:

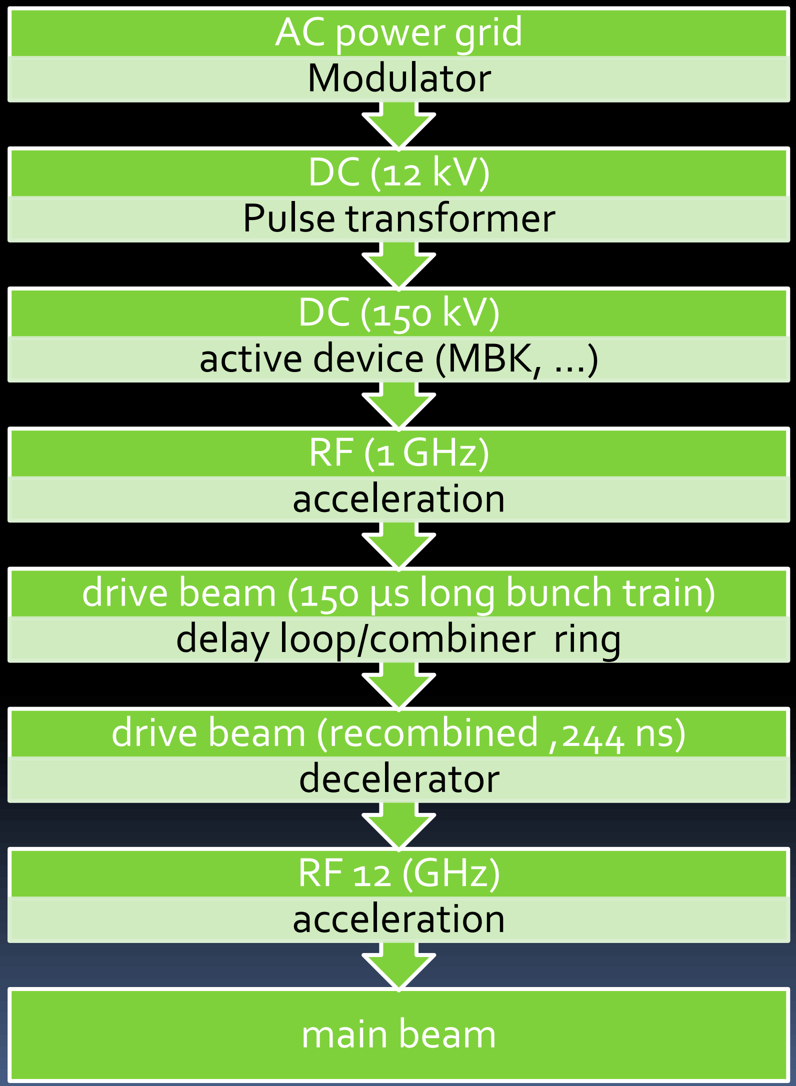
***To address these challenges,***

- the R&D on high efficiency RF power sources should be intensified!
- this R&D effort serves a large number of future Linac applications.
- in order not to be trapped, it should be allowed to step back and look into non-conventional ideas.
- the whole system must be optimized:

# Optimize the whole system!

Example:

- If an increase in efficiency requires larger voltage, you may lose at the modulator/pulse transformer.
- You may gain if you don't need a pulse transformer!
- If you need RF pulse compression, you lose efficiency.
- …



# The contenders

# High $\eta$ power source contenders (1):

- Standard (pencil-beam) klystrons?
  - Lower individual power, much larger number, but those would be extremely well studied and reliable objects.
    - Several companies would participate. Competition plus quantity could keep costs down.
    - Potentially allows system design with graceful degradation.
    - Uncorrelated noise decreases by factor $\sqrt{n}$!

# Klystron efficiency

- 100 % $\eta$ would mean that all electrons will be slowed down to zero by the self-induced field in the output cavity. Can't have that!
- For a maximum $\eta$, one needs:
  - Dirac-delta like bunches through output cavity
    - needs harmonic cavities,
    - space charge forces counteract (small current helps)
  - small ratio energy spread/voltage
    - large voltage helps
  - correct output cavity impedance! (Tolerances!)

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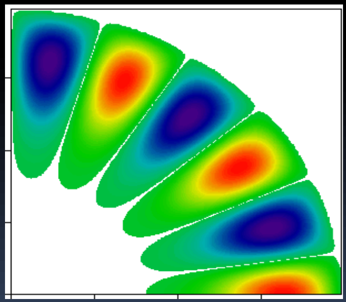
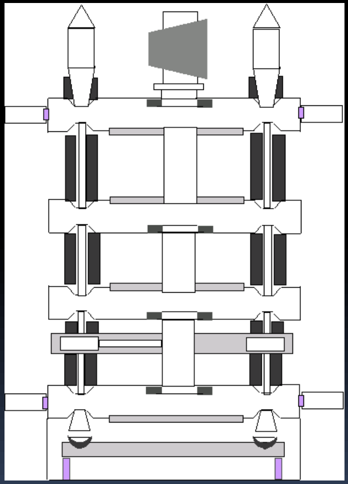
- MBK?
  - Closest to existing, ready-to-use technology! Larger $\eta$ calls for more beamlets and higher voltage. When would it become too complex?

# Multi-beam klystron

- Practical way forward: extrapolate further from the existing 10 MW MBK, but *η of* 65 % will be difficult to surpass!
- Going to the extreme, a very large MBK based on a whispering gallery mode (excellent mode purity!) with many beams is very complex.

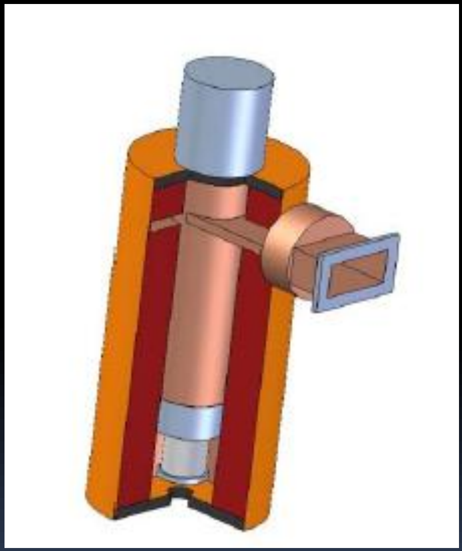




# Lower DC Voltage MBKs?

- … the other extreme?
  Proposed by FAR-TECH @ PAC07:
  - 36 kV DC
  - 830 kW,
  - 20 beams MBK

> FAR-TECH, Inc. has been developing a klystron that operates at reduced power (830 kW, 1/12 of a standard ILC klystron). Initially this klystron will be used in the ILC testing program at FNAL. This tube design also offers several advantages as an ILC power source. The low-voltage design (36 kV) can simplify the modulator and klystron gun socket design. The RF distribution system can be simplified and its losses reduced. During operation, the linac would more easily tolerate the loss of a single klystron, and the RF feedback system would be simplified.



Ref: N. Barov et al., "A Low-Voltage Klystron for the ILC and ILC Testing Program", PAC07

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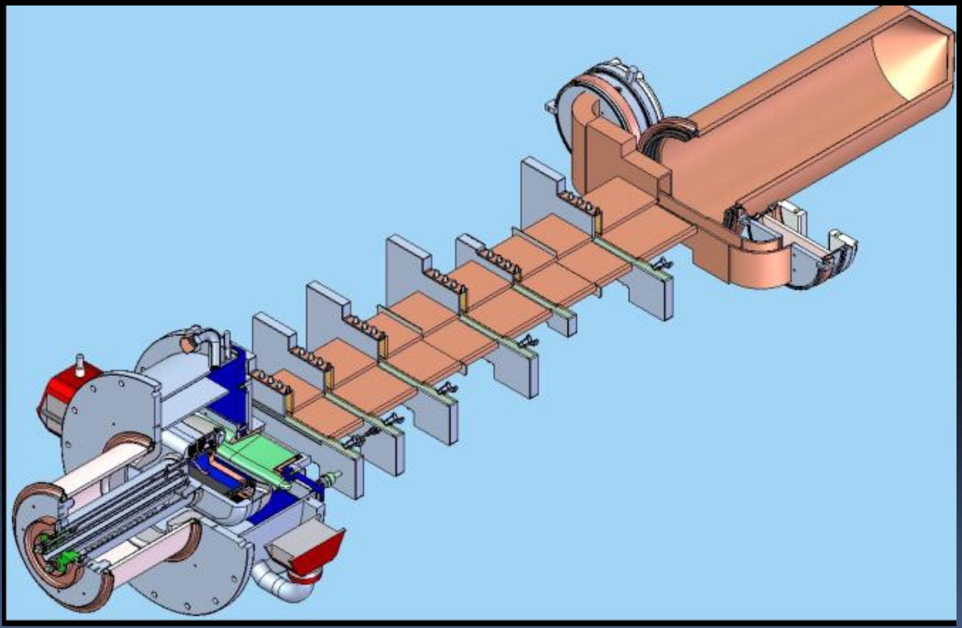
- Sheet-beam klystrons?
  - They promise to be much cheaper for larger quantities, but there is no demonstration today that would support this claim.

# Sheet beam klystron

- Instead of many beams, also flat beams would reduce the effect of space charge forces and thus potentially increase $\eta$.
- Potential advantage:
  Fabrication techniques may be better suited for cost-effective mass production.

SLAC design of a 1.3 GHz, 10 MW SBK



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- Sheet-beam klystrons?
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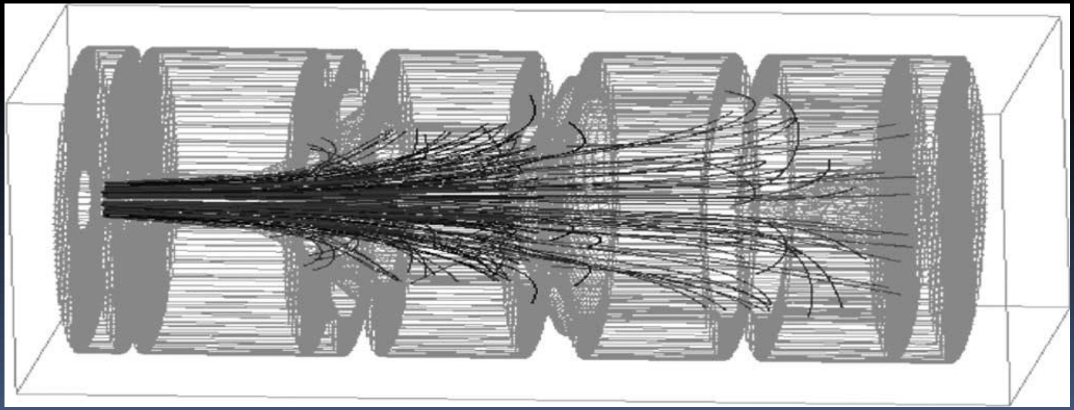
- Klystrons with multi-stage depressed collectors?
  - Allows to recover beam energy and thus increase $\eta$, even for zero RF drive.
  - Allows to operate klystron below saturation with high $\eta$.
  - Complexity?

# Multi-stage depressed collector?

## Idea:

- The collector consists of a number of electrodes with different potential.
- the spent electron beam drifts against a potential and is intercepted at lower energy.
- more energetic electrons drift further and their energy is recuperated.

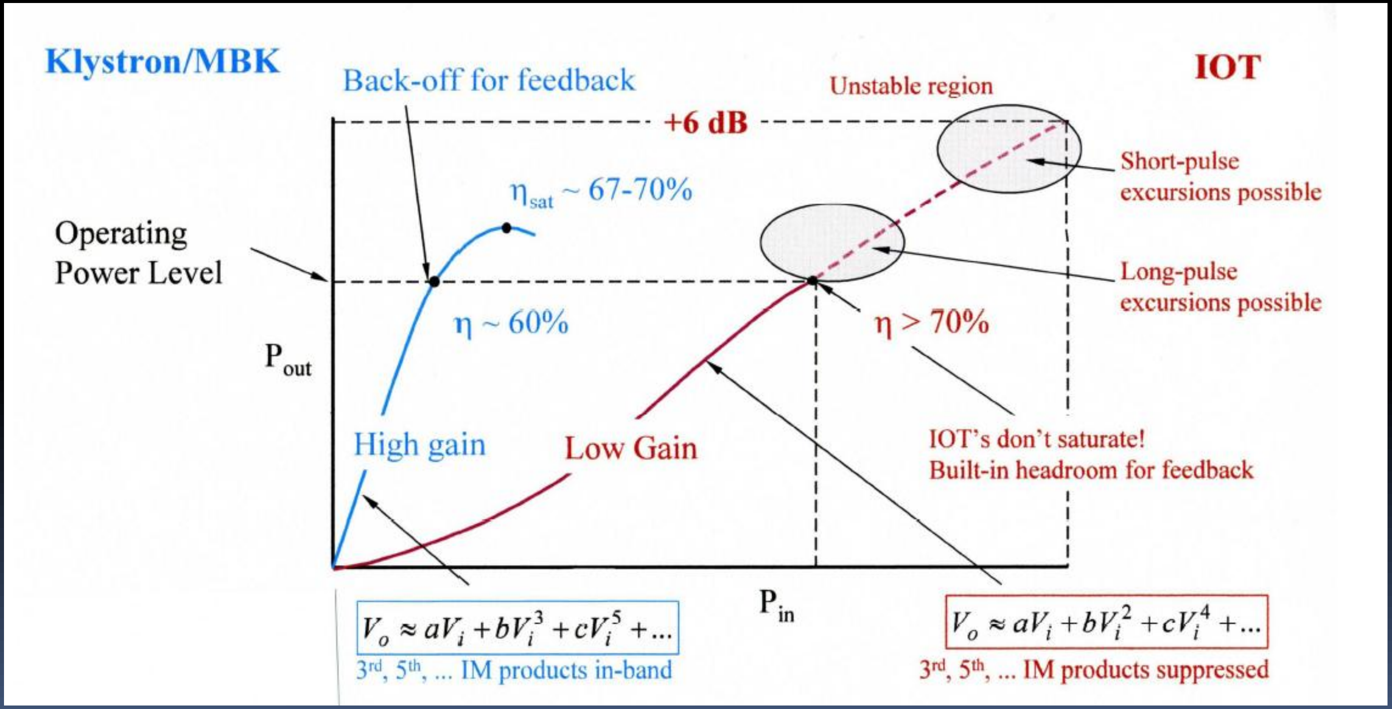


# High $\eta$ power source contenders (2):

- IOT's?
  - Present day IOT's: ≈ 80 kW. Reliability? Less gain! Large $\eta$ possible!

# IOT working point

Advantage: IOT's operate at high efficiency with differential gain!



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  - HOM-IOT?

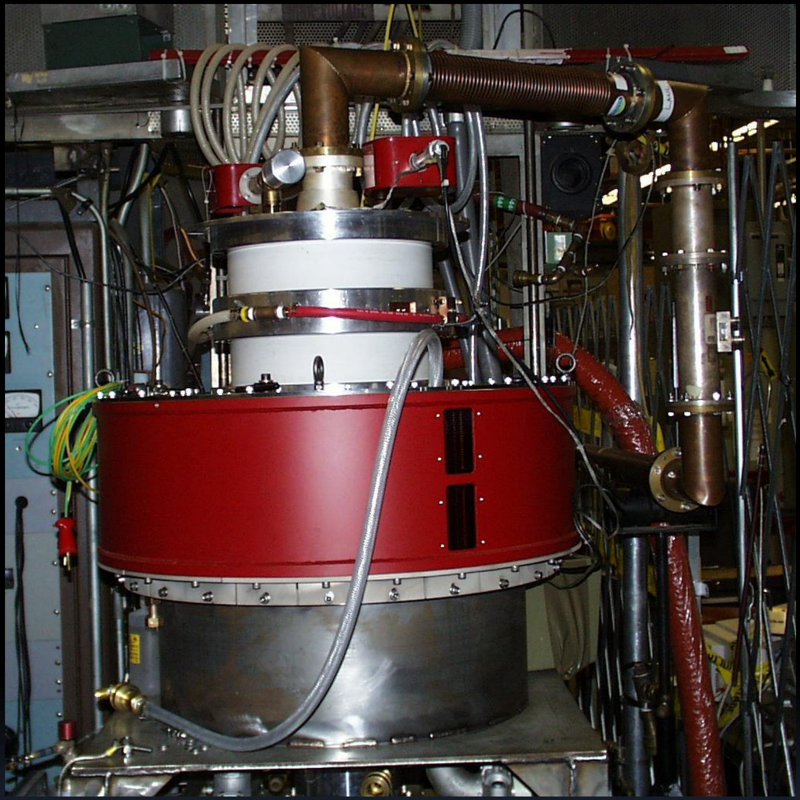
# HOM IOT's

## According to CPI:

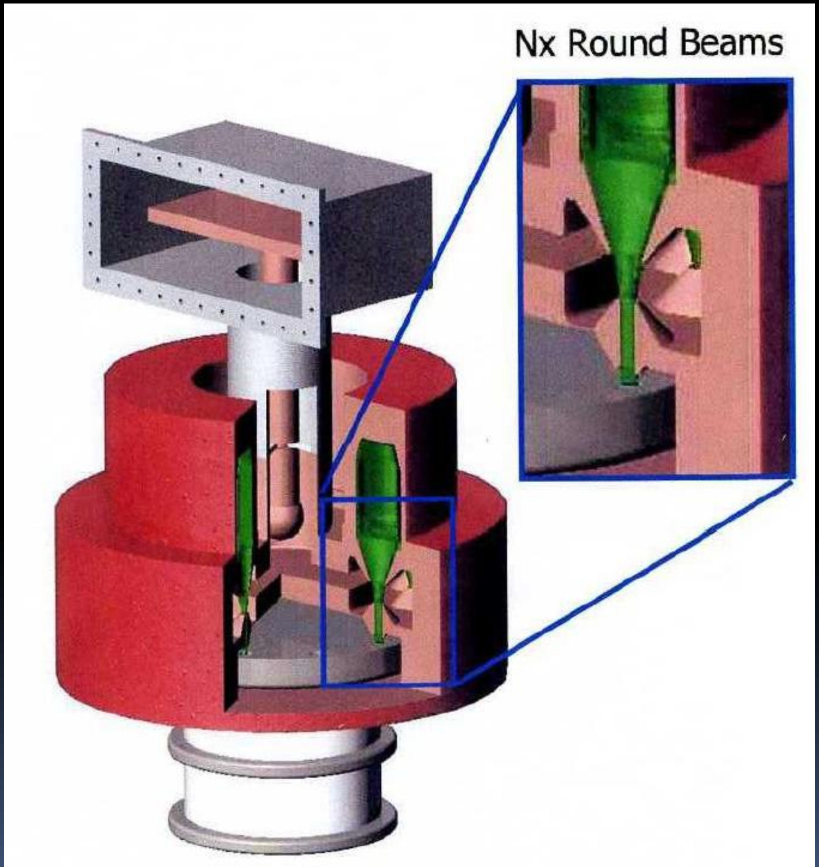
- IOT VHP-8330 reached 930 kW @ 700 MHz.
- up to 1.5 MW at 1 GHz should be possible,
- > 80 % efficiency at this power level are possible,
- IOT's would be cheaper/MW (!)
- typical DC voltage range: 35 kV,
- **no modulator** necessary → pulses via RF drive!

$\eta_{\text{Klystron}}\,\eta_{\text{Modulator}} \approx 60\ \%$ would become $\eta_{\text{IOT}}\,\eta_{\text{power distribution}} \approx 70\ \%$;
this would reduce wall plug power quite significantly!

# Multi-beam HOM IOT's



left: existing VHP-8330




right: planned VKP-8330B

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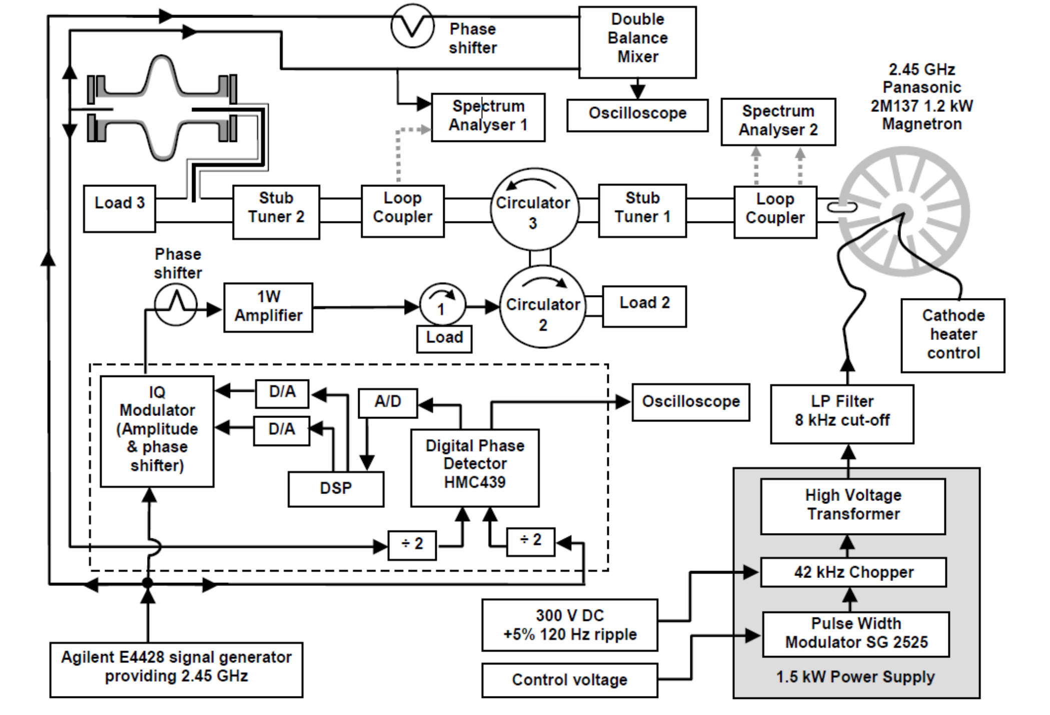
  - HOM-IOT?
- Magnetrons?
  - Not an amplifier, but injection-locked oscillator,
  - Potentially better $\eta$, but phase noise ?
  - How long for the magnetron pulse to stabilise? Unused part of pulse reduces effective $\eta$!

# Magnetrons

- Magnetrons have potentially very high $\eta$,
- 1 kW magnetrons are used by the millions in almost every kitchen – they are cheap.
- Also larger magnetrons have a good ratio MW/$.
- But they are oscillators, not amplifiers!
- They make a lot of phase noise!
- If you run an accelerator with more than one magnetron, you need to phase-lock them.

# Injection locked magnetrons

- Recently, JLAB and CI collaborators could successfully demonstrate injection locking of a simple magnetron.
- They obtained encouraging 0.8° rms phase noise with very moderate locking power!
- Is the high $\eta$ compatible with the locking and with short pulses?



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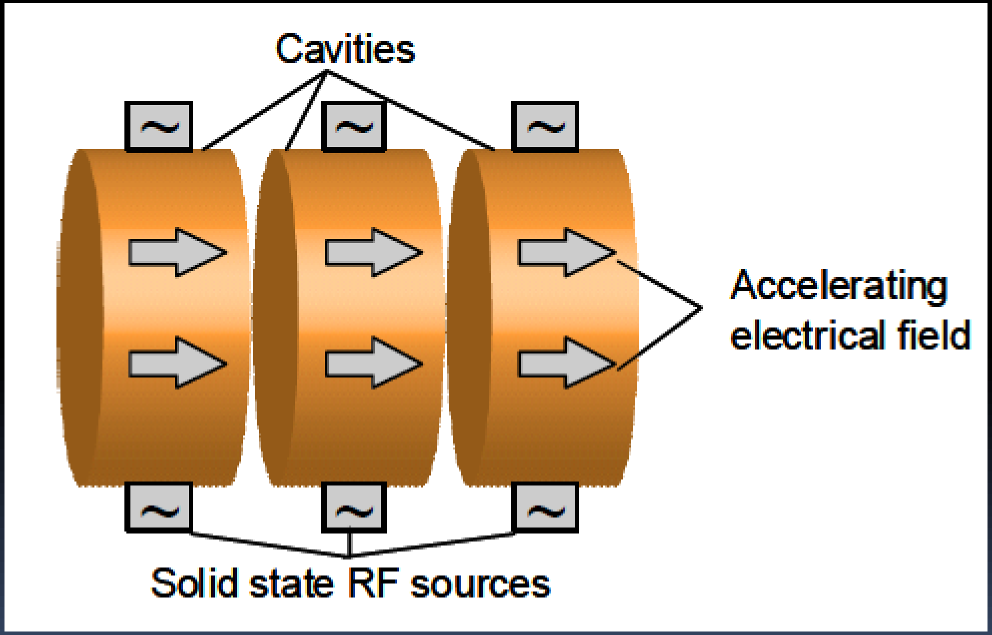
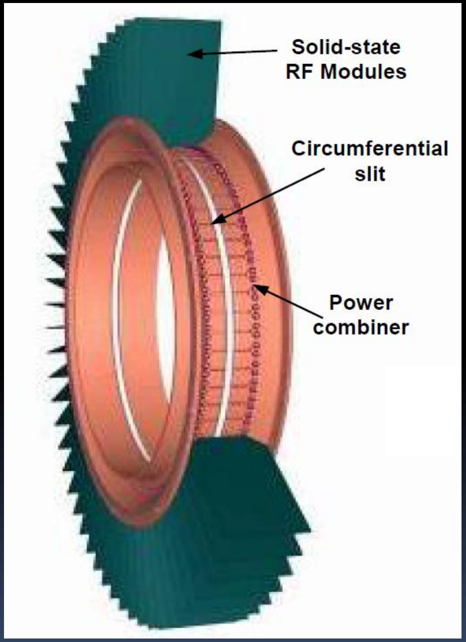
- Direct Solid-state drive?
  - Many solid state modules close to the cavity,
  - Use the cavity as power combiner
  - Compatible with radiation? Transistors fast enough? Decoupling?

# Solid state direct drive?

Recent proposal by Siemens/Erlangen group:

- Use the cavity as power combiner!
- Use SiC vJFETs




There are certainly issues to be resolved, but the idea is new and deserves study. Not sure about the frequency reach.

# Conclusions

- Across the different communities, future Linac applications need
  - very large power,
  - maximum efficiency,
  - minimum cost

  RF power sources.
- Intensified R&D focused on these needs should be encouraged!
- The optimization must include all subsystems.