ess

EUROPEAN
SPALLATION
SOURCE

RF Power for ESS

PRESENTED BY MORTEN JENSEN ON BEHALF OF THE RF GROUP

2022-09-23

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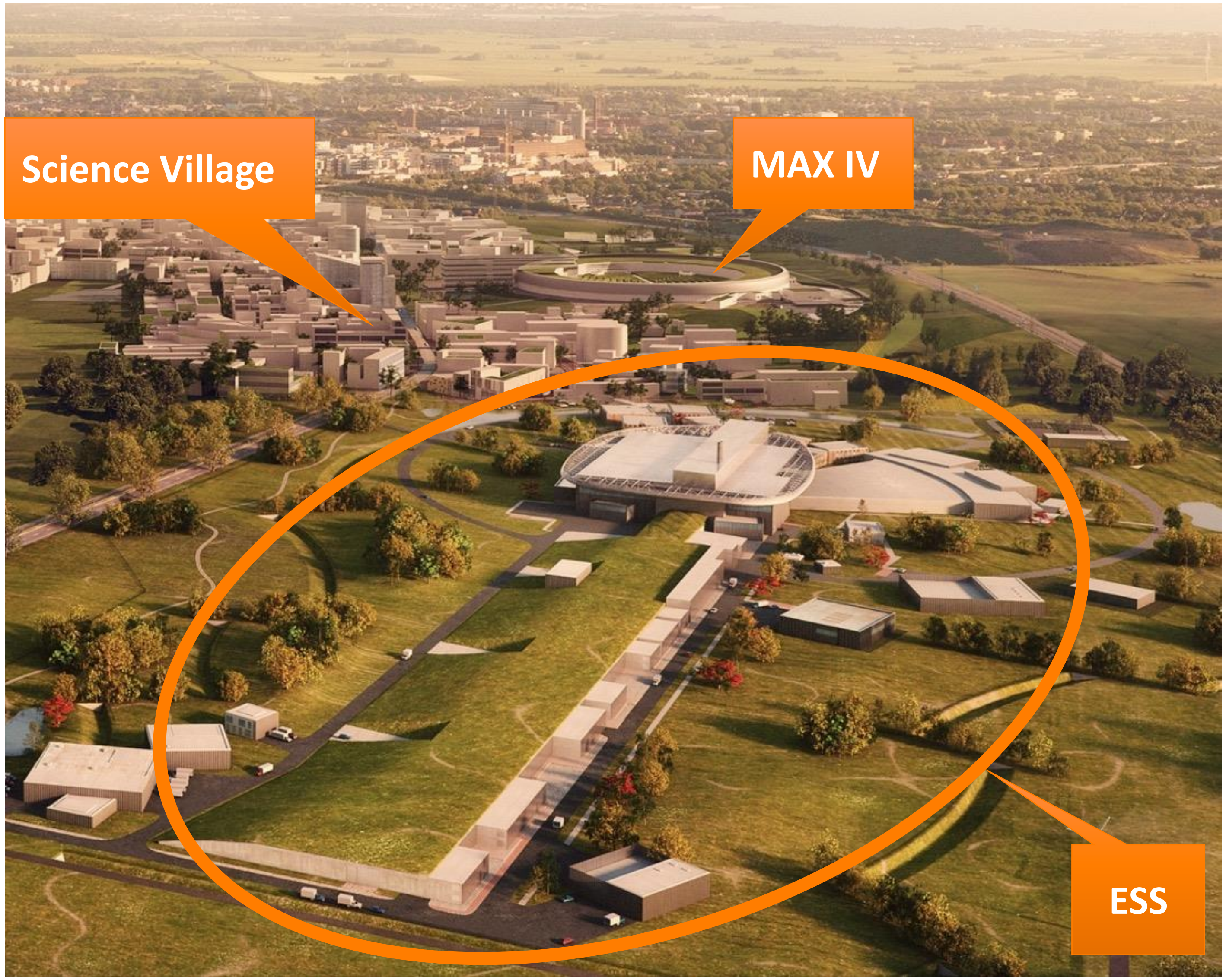
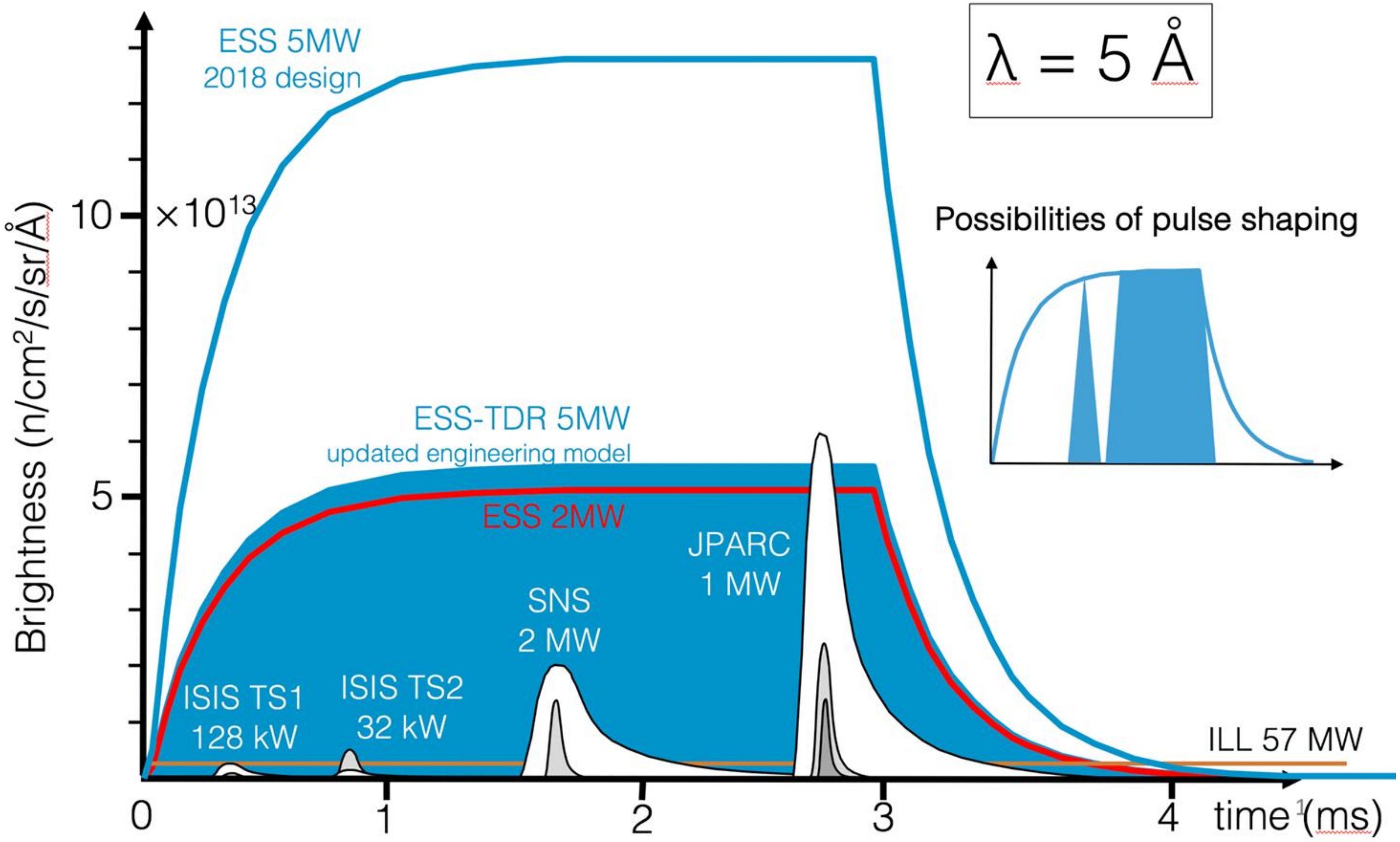
Overview of the Facility

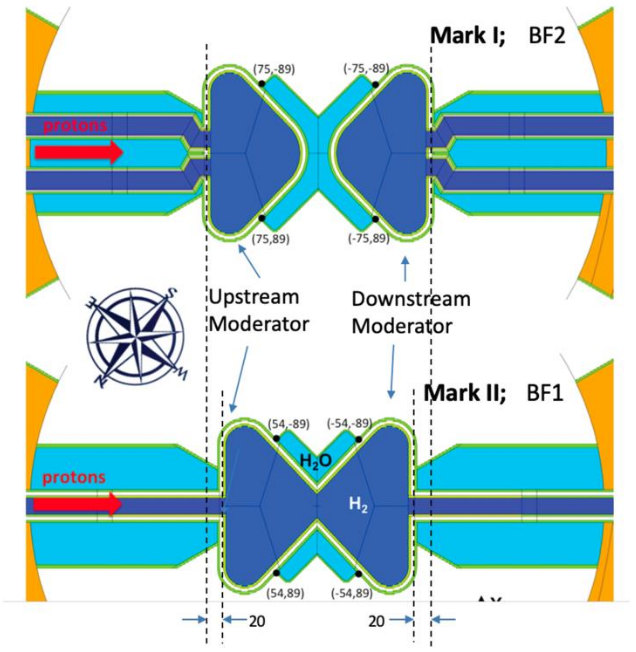
We're building a global science hub in Lund

ESS, MAX IV, Science Village Scandinavia



ESS Performance

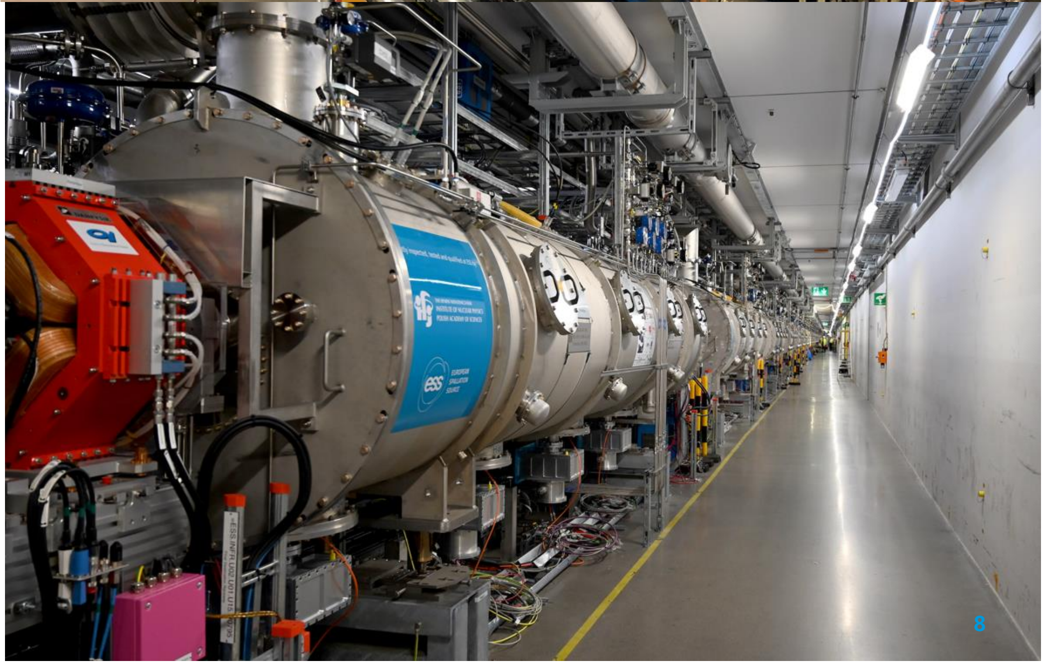




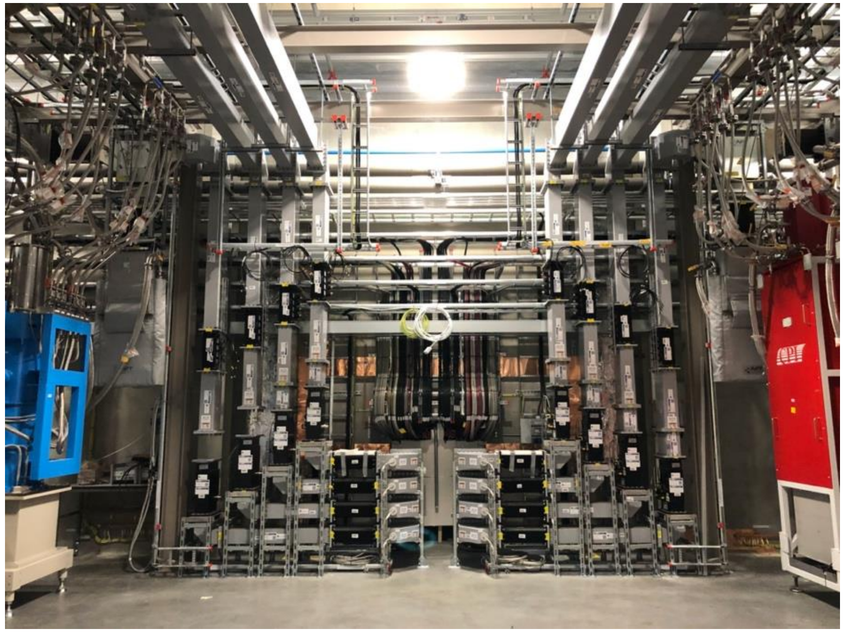
Descoping in accelerator power (and instrument scope) due to budget restrictions compensated by moderator development (Note that deferred scope can be added back later)

From Green Field to ESS

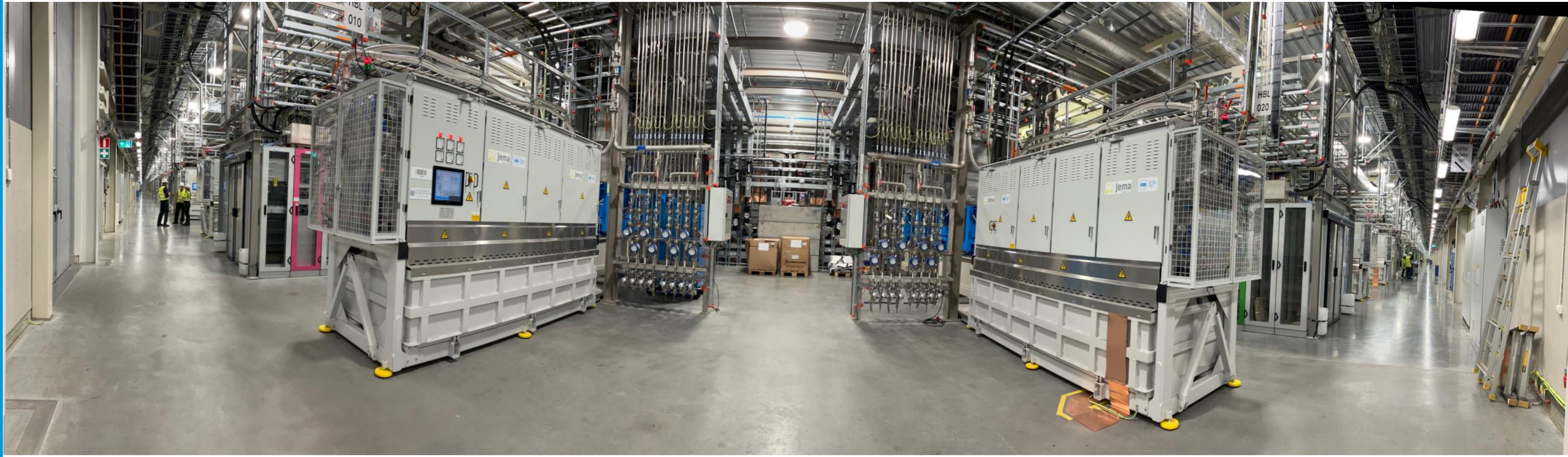
Tunnel view then and now



Klystron Gallery Then and Now



Total of 91 High power RF Systems, MO, and PRL incl all controls, interlock, aux and LLRF.
Approximately 245 racks, > 21000 cables



180 degree view of Gallery

RF Systems at ESS

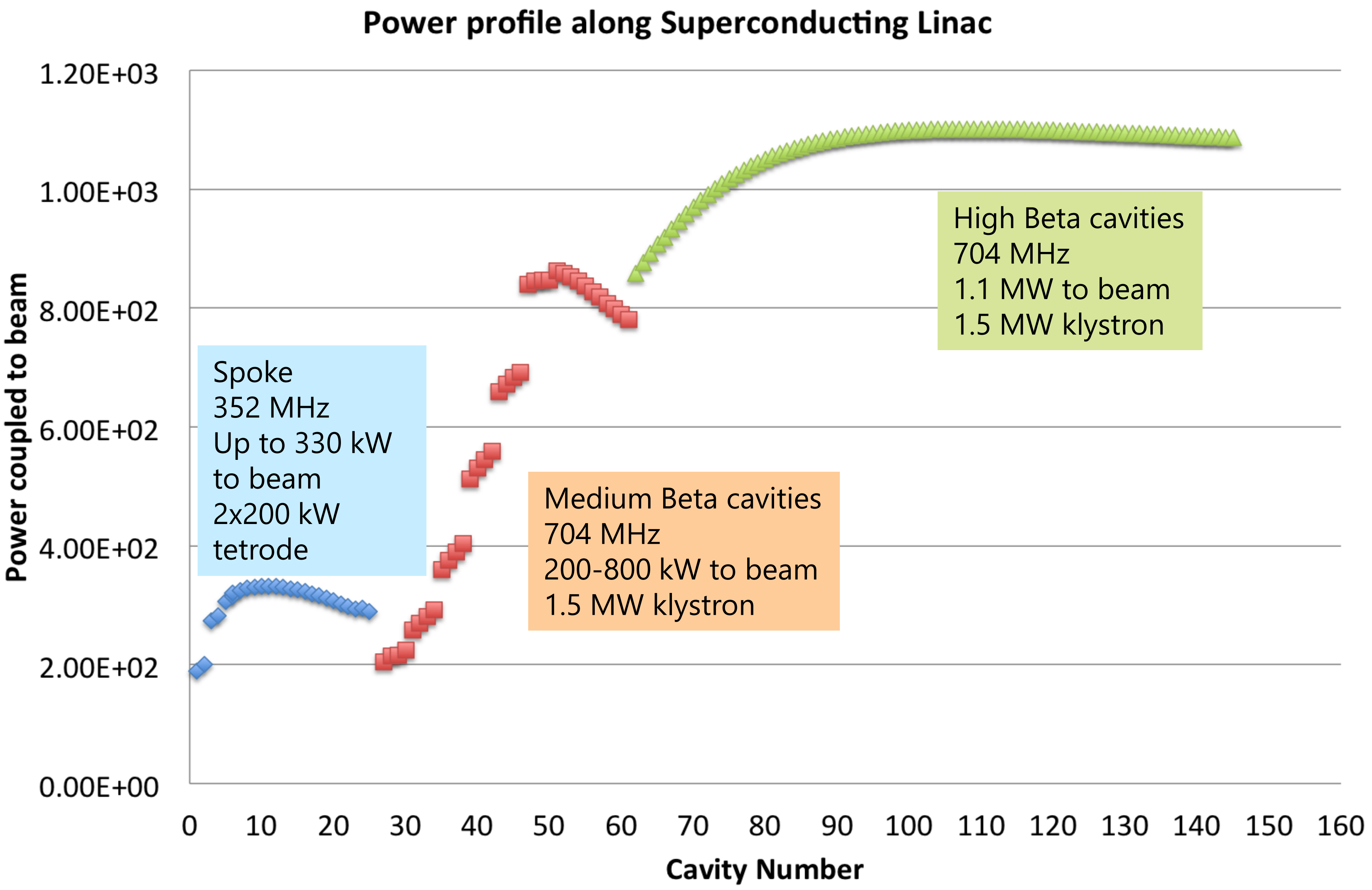
Power profile along superconducting linac

Large spread in power requirements

Use of optimal, available sources

MB/HB will use the same klystron despite different power demand

Warm Linac 352 MHz
RFQ & 5 DTL: 3 MW
3 MEBT: 30 kW



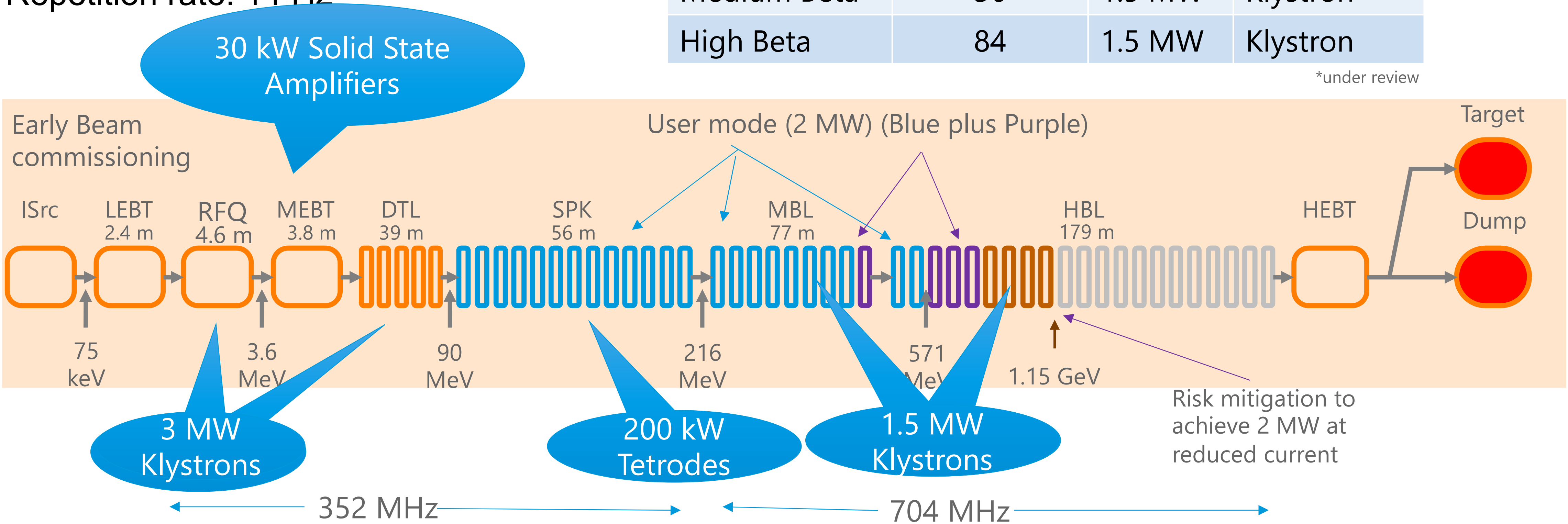
Accelerator Overview (62.5 mA)

Key parameters:

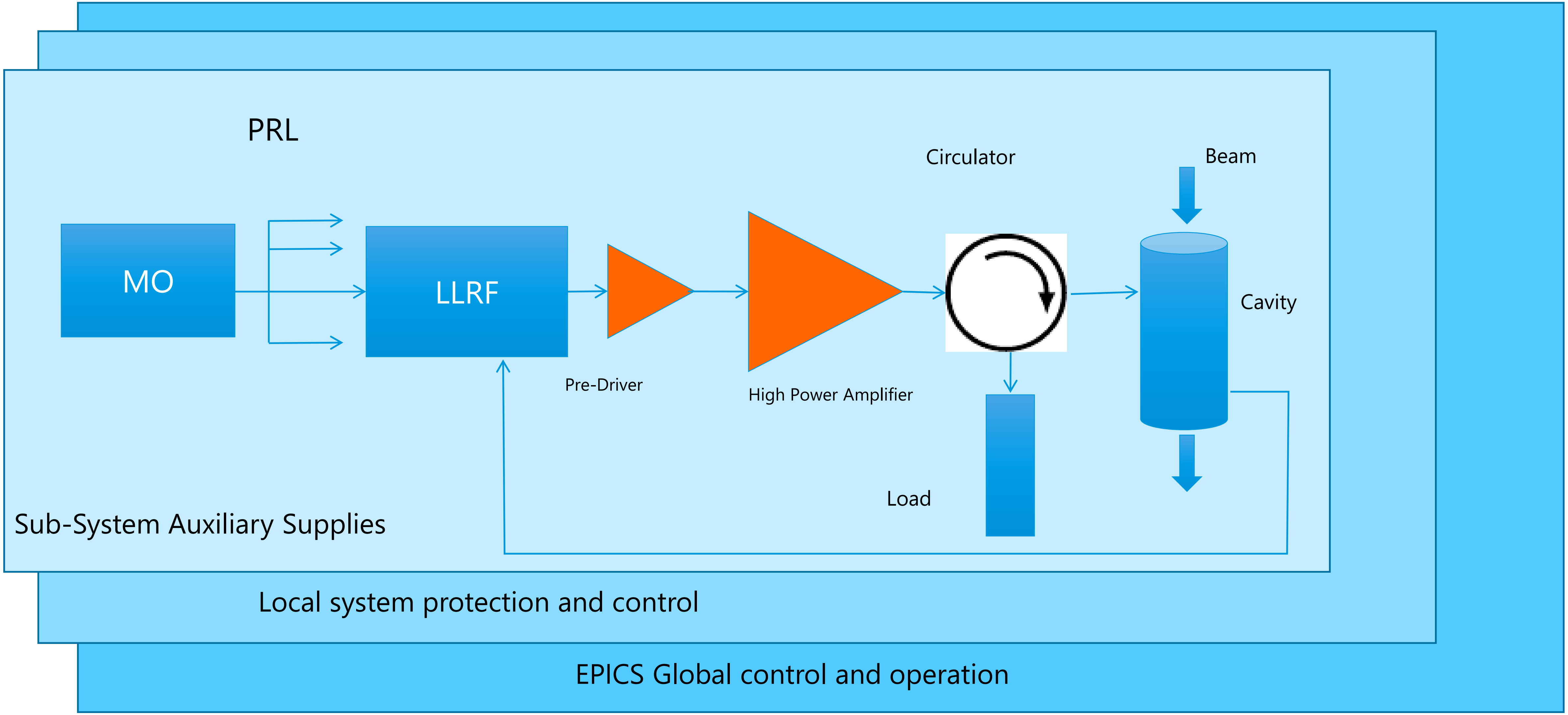
Average Beam Power: 5 MW
Peak Beam Power: 125 MW
Beam pulse width: 2.86 ms
Beam energy: 2 GeV
Final Beam current: 62.5 mA peak
Repetition rate: 14 Hz

Linac Section	Number of systems	Output Power	Amplifier technology
RFQ and DTL	6	3 MW	Klystron
MEBT	3	30 kW	SSPA
Spoke	26	400 kW	Tetrode*
Medium Beta	36	1.5 MW	Klystron
High Beta	84	1.5 MW	Klystron

*under review



Typical RF System



RF Systems in Normal Conducting Linac (NCL)

Normal Conducting Linac at 352 MHz includes:

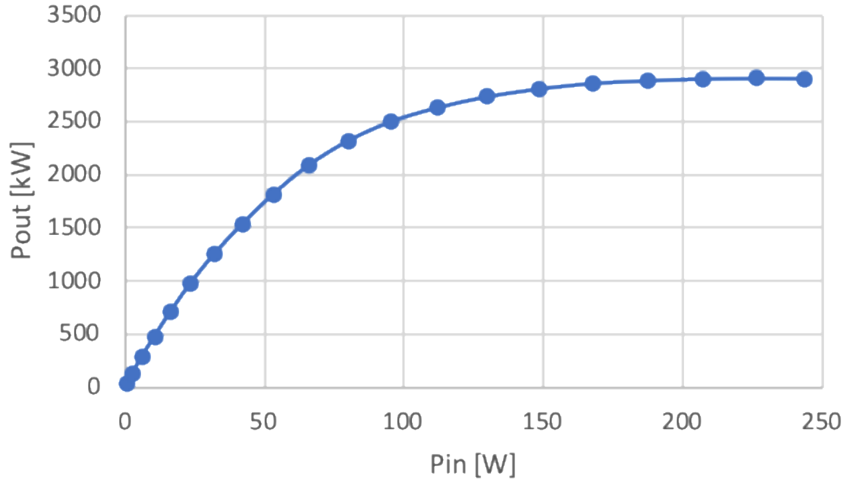
1 RFQ 2.9 MW klystron

5 DTL tanks 2.9 MW klystron

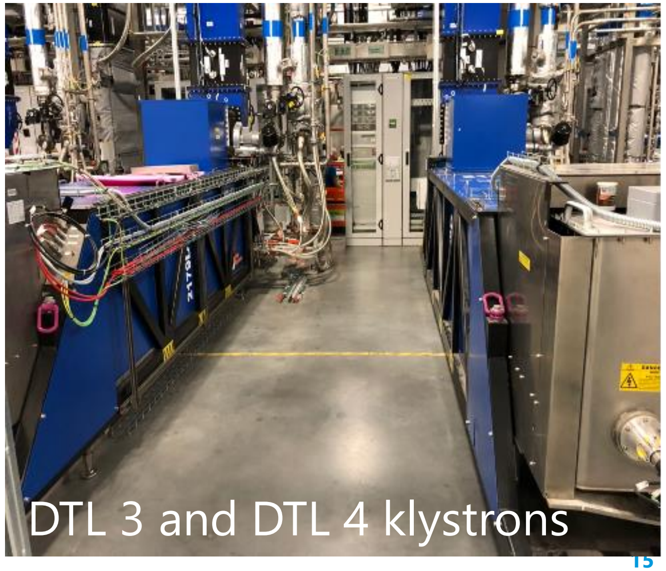
RF systems installed, tested and commissioned with beam

Nominal output power	2.9 MW
Frequency	**352.21 MHz**
BW	≥ +/- 1 MHz
Pulse width	3.5 ms
Repetition rate	14 Hz
Perveance	$1.3*10^{-6}$
Efficiency	>52%
VSWR	Up to 1.2
Power Gain	≥ 40 dB
Group Delay	≤ 250 ns
Harmonic Spectral content	≤ -30 dBc
Spurious Spectral content	≤ -60 dBc

TH2179D (DTL 5)




RFQ and DTL 1 klystrons

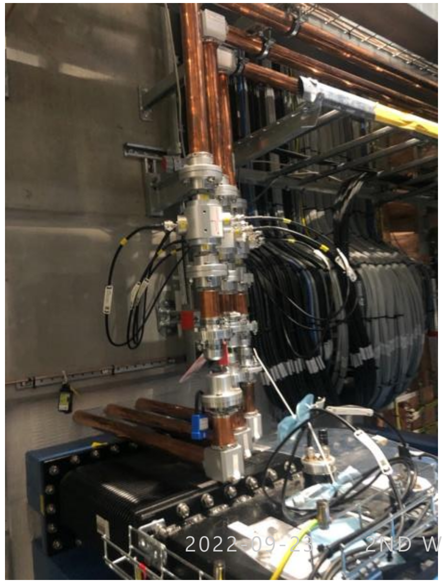

DTL 3 and DTL 4 klystrons

Three MEBT (Buncher Cavity) RF Systems

30 kW output
Frequency: 352 MHz Solid State Power Amplifiers

Consists of five hot-swappable RF modules combined
High Power Circulator and Load
Internal interlock system and state machine

Output line:
35 m, 1 5/8″ coaxial line incl couplers and tuning

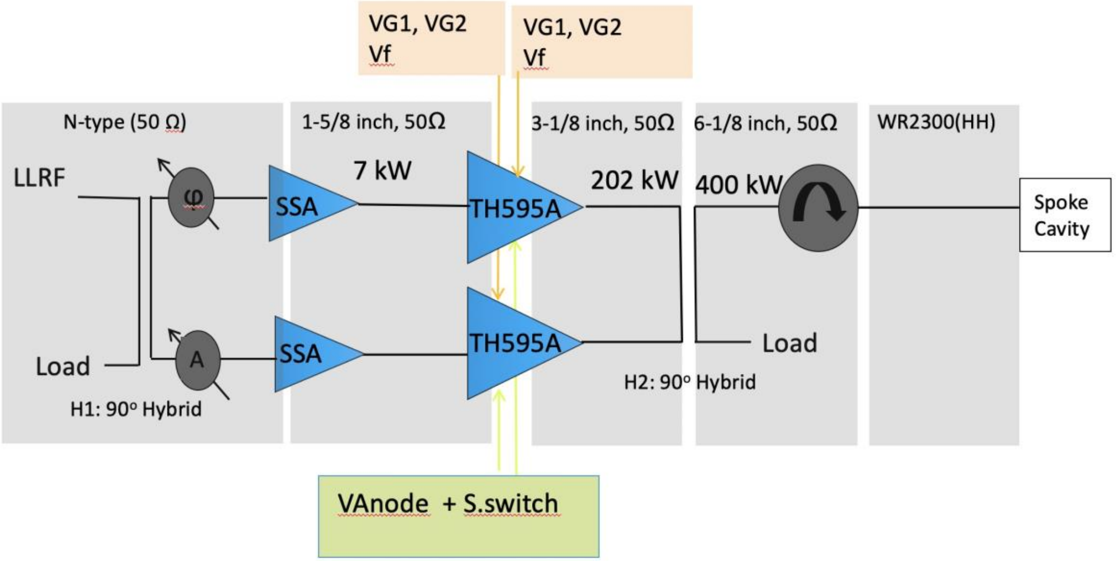


For more details please refer to:
The ESS MEBT 30 kW solid state amplifiers, B. Lagoguez,, CWRF 2022

26 Spoke Systems

Amplification to 400 kW
Frequency: 352 MHz

26 Tetrode based amplifiers by combining two 200 kW
LLRF, Interlocks, waveguides, loads and circulators etc.



For more details please refer to:
Radio Frequency Power Stations at ESS, R. Yogi, CWRF 2022

Medium and High Beta Linac

Responsible for the bulk of acceleration

Power to Beam plus Overhead for regulation:

Tight requirements for cavity field stability

LLRF has to compensate for perturbations:

- Beam current variation
- Microphonics
- RF variation (ripple, phase and amplitude)

Overhead need: 25%

36 Medium beta elliptical cavities:

84 High beta elliptical cavities (5 MW):

- **Phase 1: 2 MW capable (20 RF systems)**
    - Currently funded and in construction
- **Phase 2: upgrade to 3 MW (44 RF systems)**
- **Phase 3: Upgrade to 5 MW (84 RF systems)**

Nominal output power	**1.5 MW**
Frequency	**704.42 MHz**
BW	≥ +/- 1 MHz
Pulse width	**3.5 ms**
Repetition rate	**14 Hz**
Efficiency	**>63%**
VSWR	Up to 1.2
Power Gain	≥ 40 dB
Group Delay	≤ 250 ns
Harmonic Spectral content	≤ -30 dBc
Spurious Spectral content	≤ -60 dBc

Medium and High Beta RF Sources

Medium Beta Installation

- 20 Canon Klystrons
- 12 CPI klystrons
- 4 Thales klystrons

High Beta Installation

- 19 Canon Klystrons
- 1 Thales klystrons

Test Stand 2 – CM testing

- 1 Canon Klystron
- 1 CPI klystron
- 1 Thales klystron

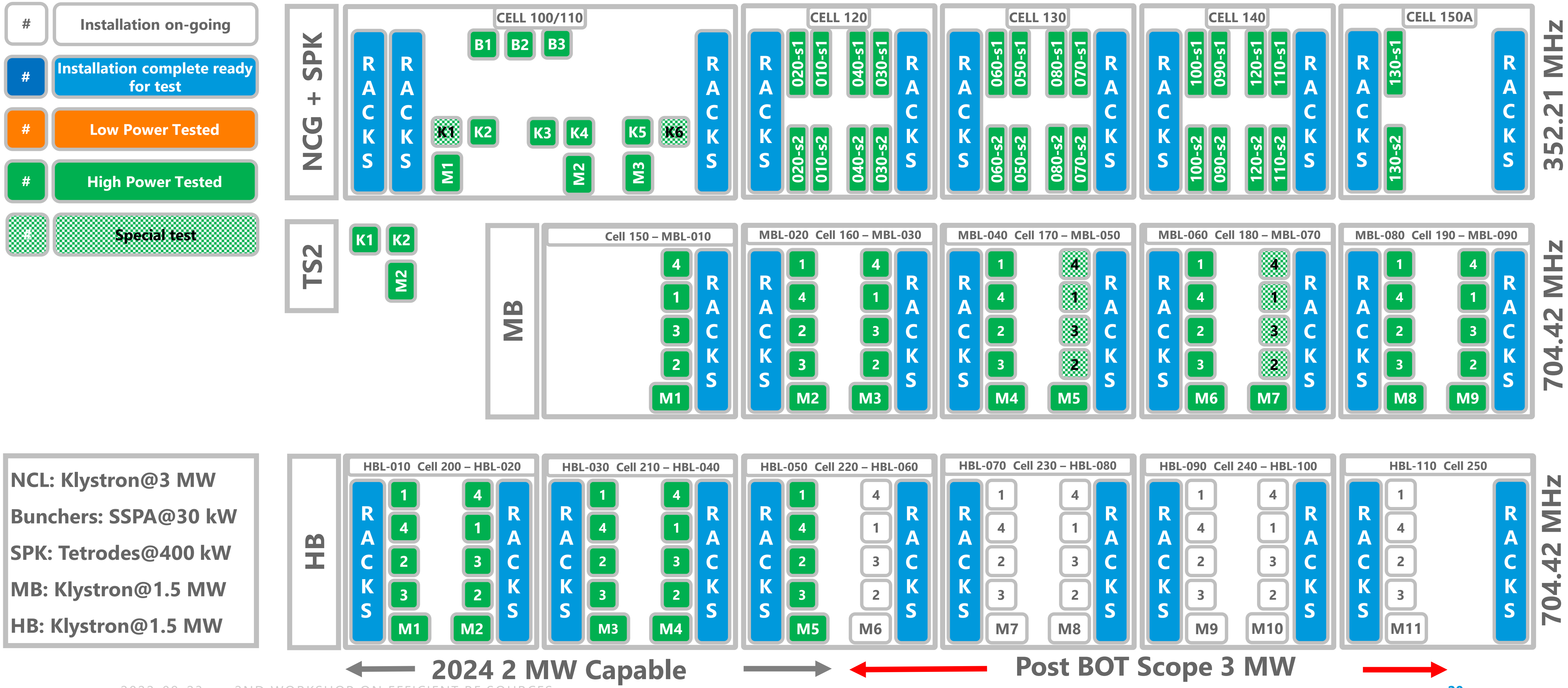
Spare klystrons

Klystrons not yet installed
(Delivered or to be delivered)

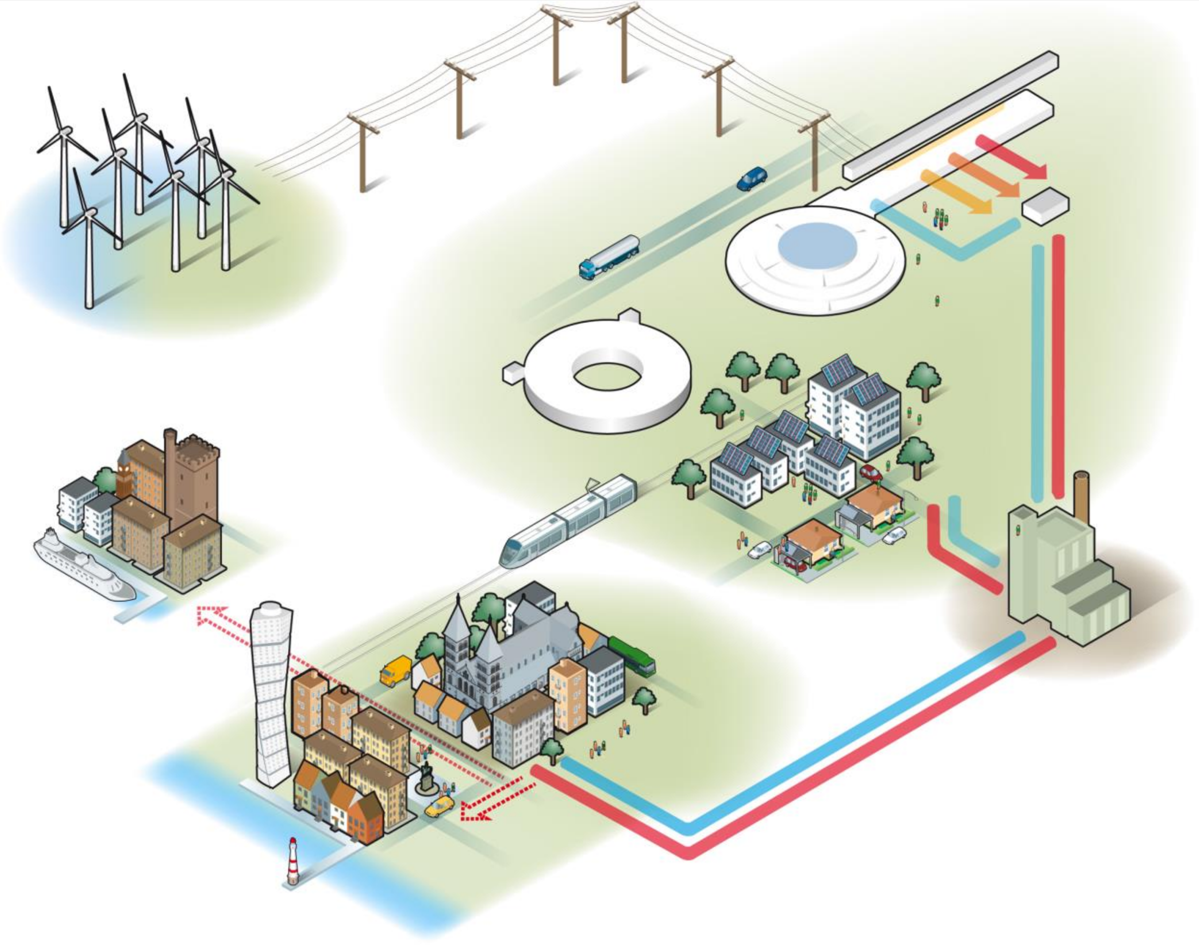
- 6 CPI
- 1 Canon
- 13 Thales

G02 – Status of RF Systems Aug 2024

Ready for Beam on Target (RBOT) Baseline



Efficiency Considerations



Medium and High Beta Linac

Energy efficiency optimisation

Klystron Efficiency at Saturation: 61-69 %

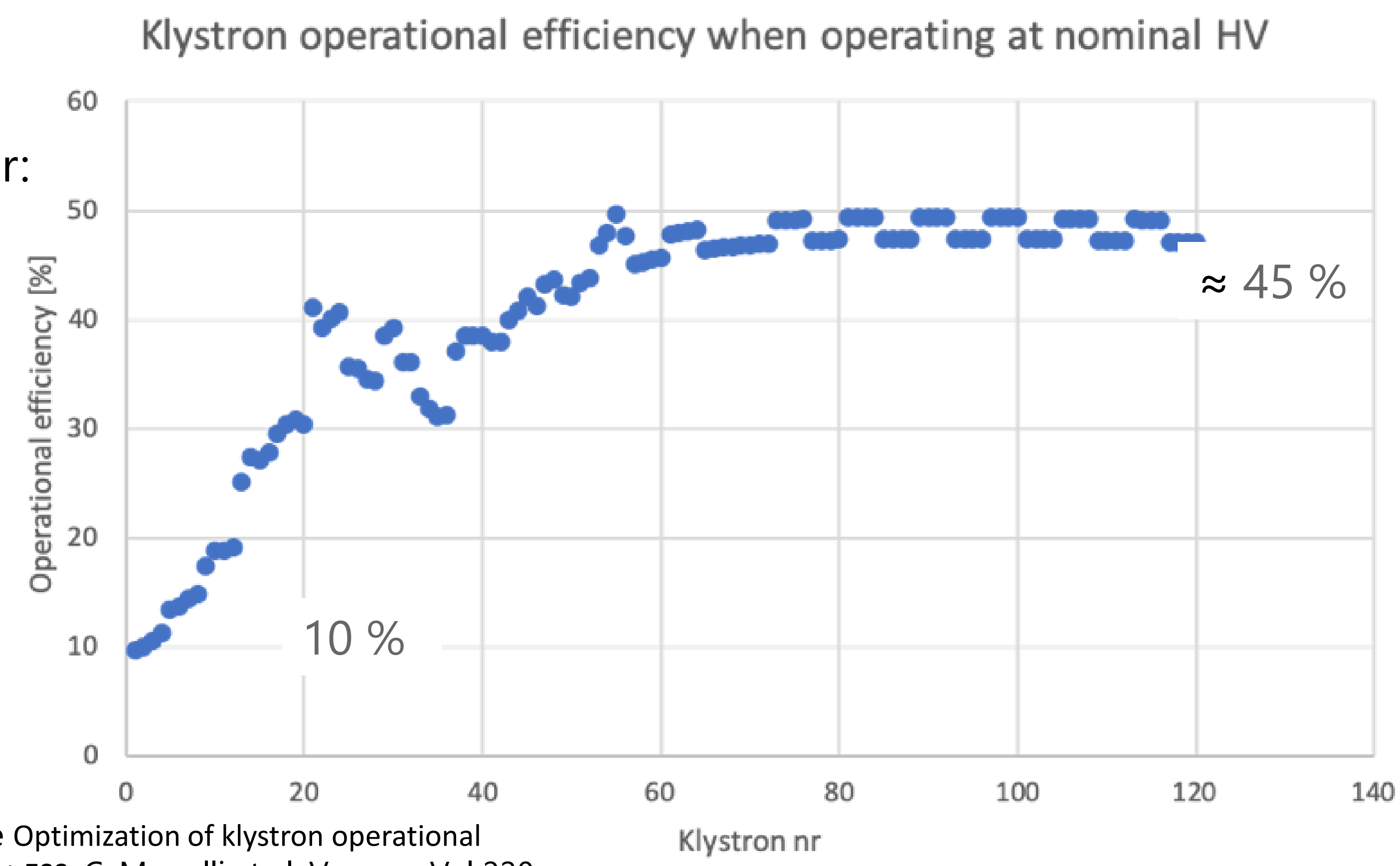
CPI Klystrons: ≈ 61-65%
Canon Klystrons: ≈ 63/69%
Thales Klystrons: ≈ 63/66%

But klystrons saturate at maximum power
In actual operation, output power is much lower:

- 20-25% overhead needed for regulation
- Power to beam and filling time

Result:
Efficiency at point of operation is low

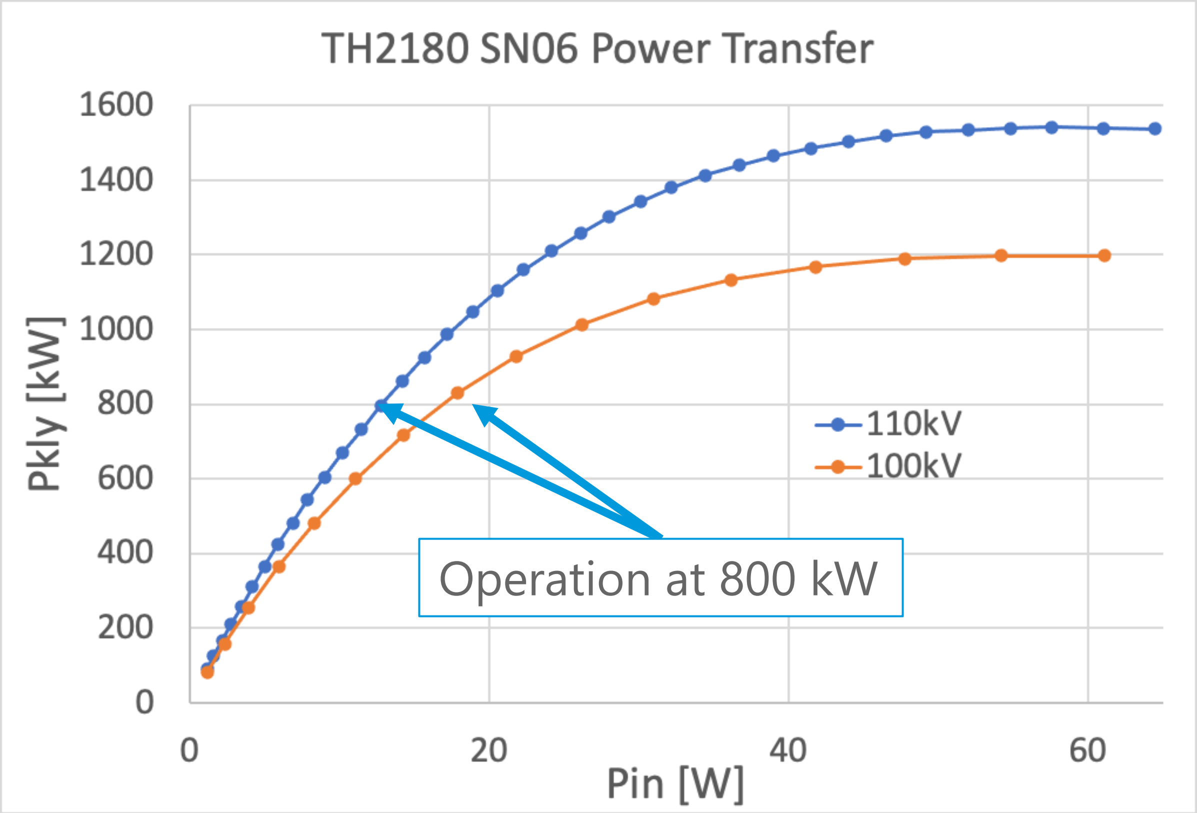
Efficiency can be improved by:
Reduction in HV
Installation of output mismatch
Optimisation of solenoid

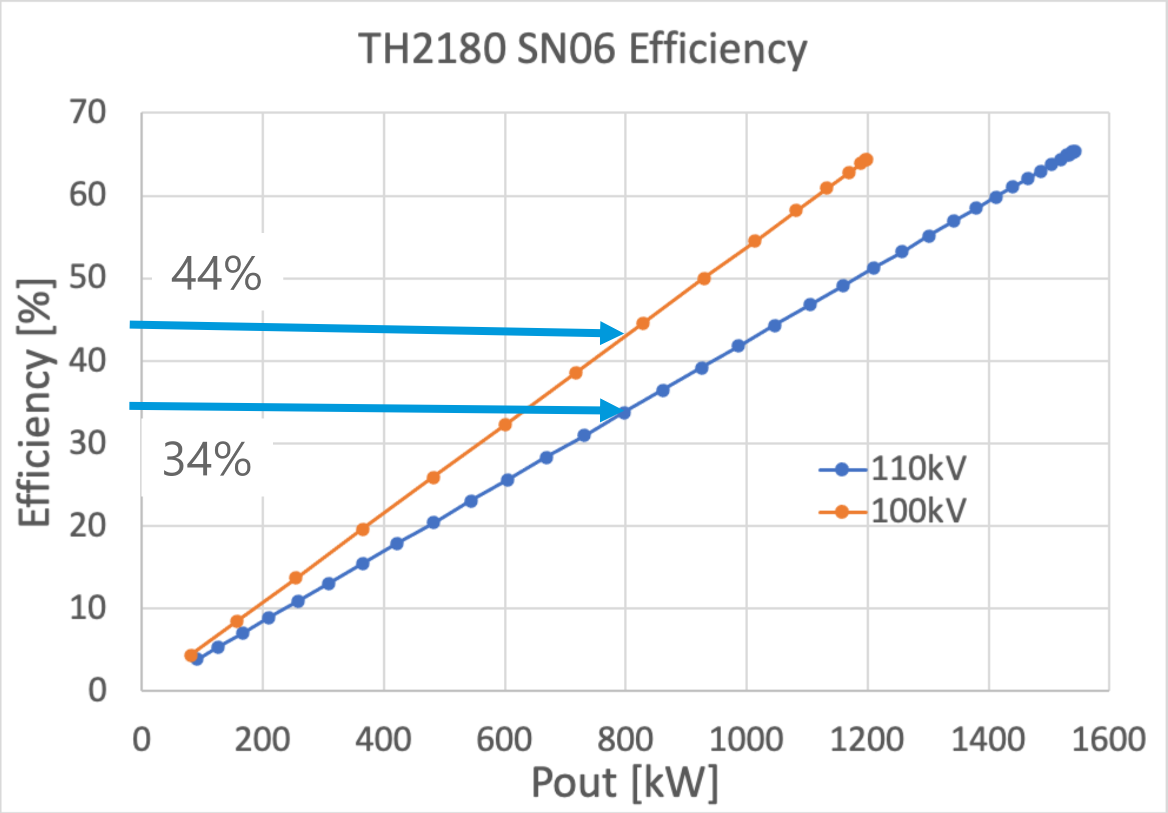


Please see Optimization of klystron operational efficiency at ESS, C. Marrelli et al, Vacuum Vol 220, Feb 2024

A Practical Example

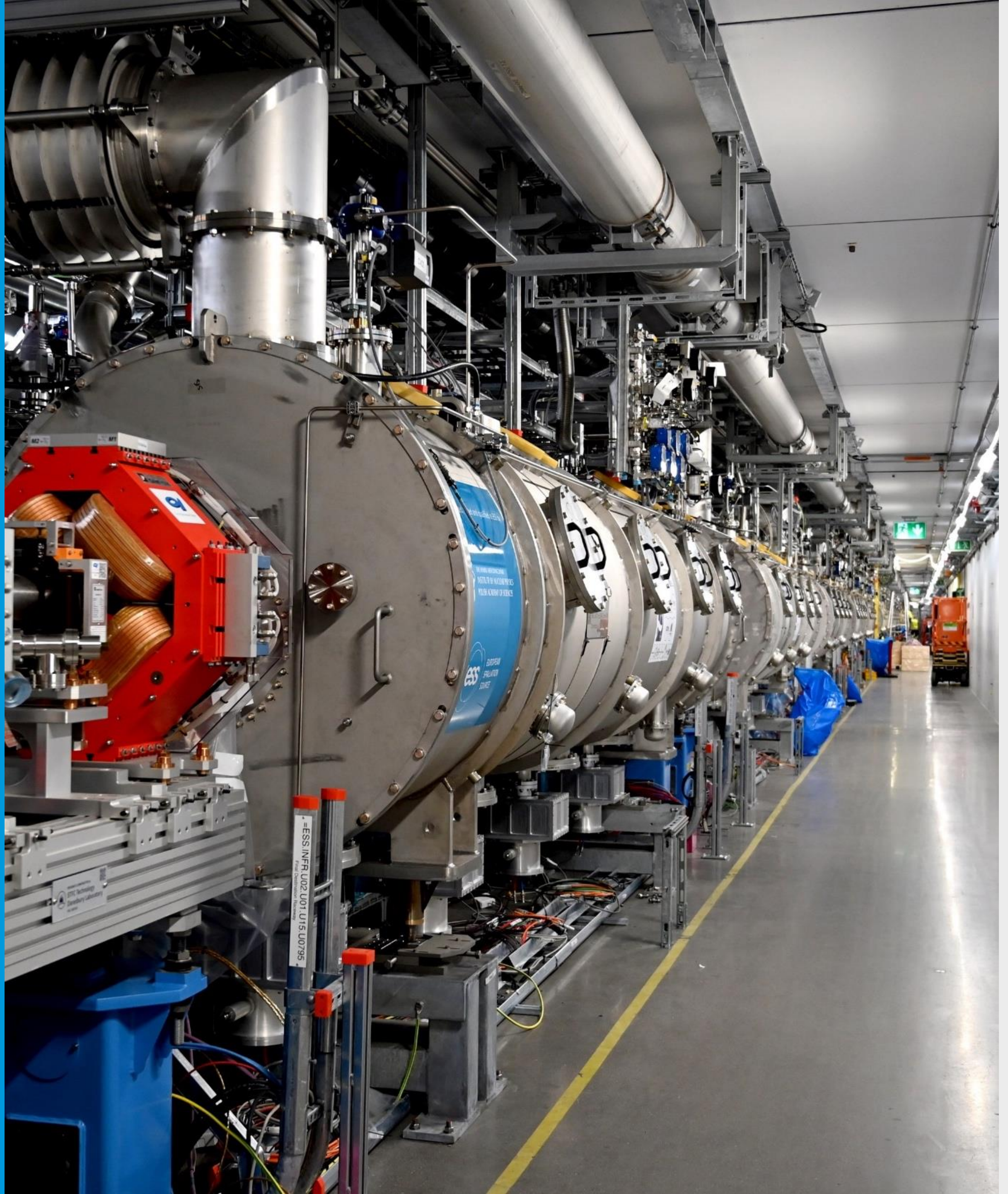
Efficiency for operation below saturation





It is hard to achieve more than 45% (klystron RF efficiency) at point of operation
Not including further reduction due to Modulator efficiency, filament and solenoid consumption

Looking Ahead



What will the future hold?

ESS construction project:

- 2 MW capable average power on target
- 6 NCL klystrons, 26 Spoke tetrode based systems, 56 MB/HB klystron systems ✓

2 MW to 3 MW upgrade

- Not formally funded, ie not part of initial scope for operation in 2028
- Would require another 24 additional 1.5 MW klystron systems
- Cryomodules, utilities and much of the RF system is already available
  - **Needs klystrons and klystron auxiliaries**
- Upgrade cost relatively low!
- If approved shortly, the same technology is most likely and possibly the only practical solution

3 MW – 5 MW upgrade

- Will require significant investment
- Likely to be low priority while expanding the science capability

Opportunity to push for technological improvement

- New development – next generation?
- Time to consider gridded tubes?
- Time to consider higher risk, significant step up in performance
- Focus on operational power closer to saturation.

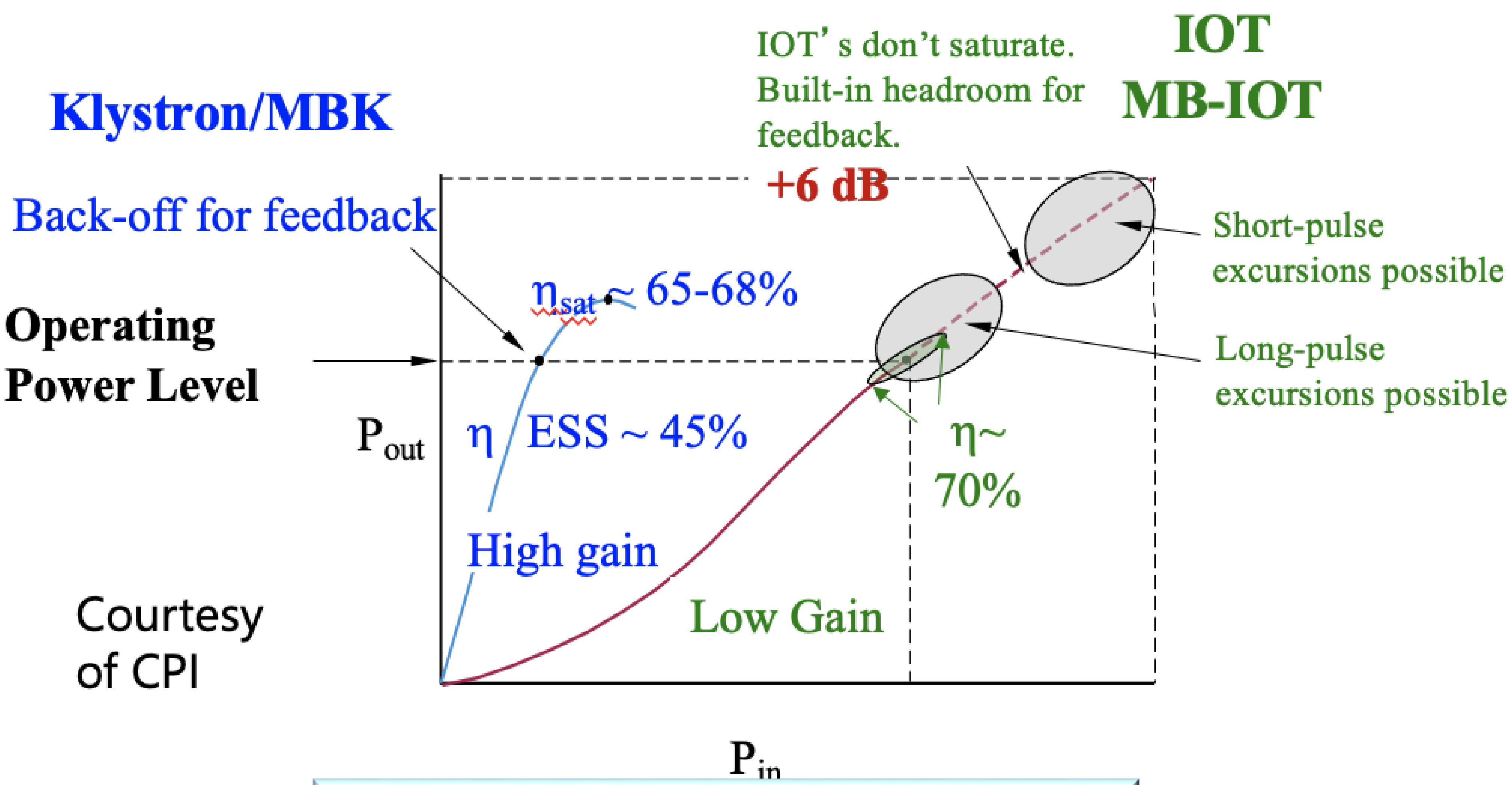
Some solutions could be 'backwards' compatible, eg HE klystron approach ie would support existing installation

- Reuse of magnets, possible klystron retrofit.
- Klystron retrofit of end-of-life klystrons when it happens.

But the efficiency of 'standard' klystrons will be limited when operated below saturation

The advantage of gridded tubes

Back to the Future?



Courtesy of CPI

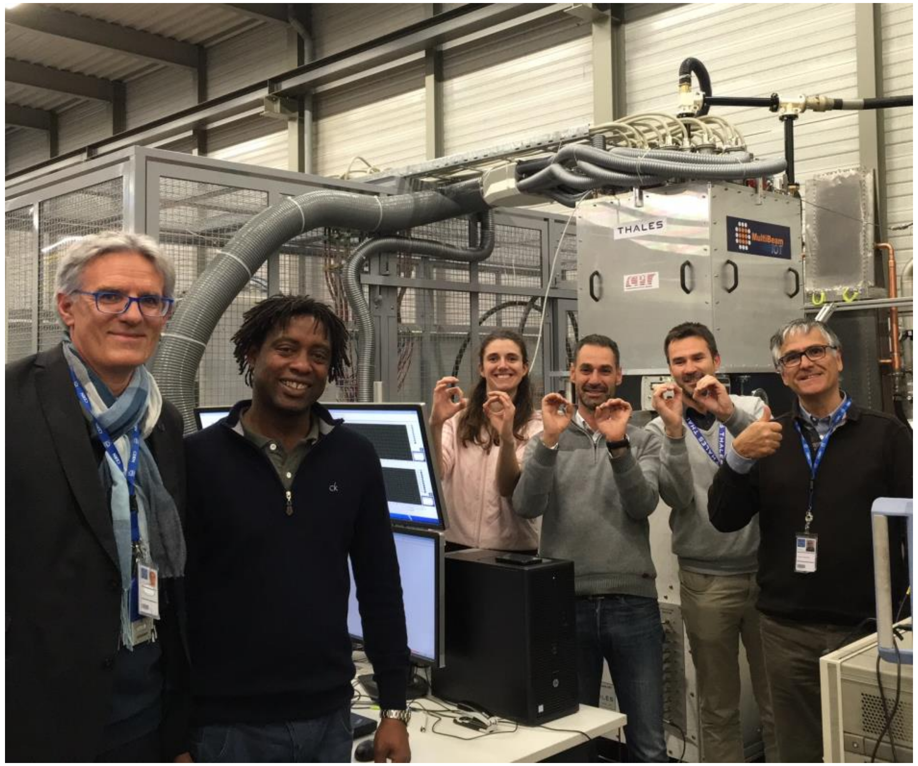
Klystrons: Back-off for feedback cost 30%
IOTs: Operate close to max efficiency

See WEXGBF1
IPAC 2018
M. Jensen

The Original ESS MB-IOT

World Record

MBIOTs were delivered and high power tested at CERN.
Both IOTs delivered 1.2 MW

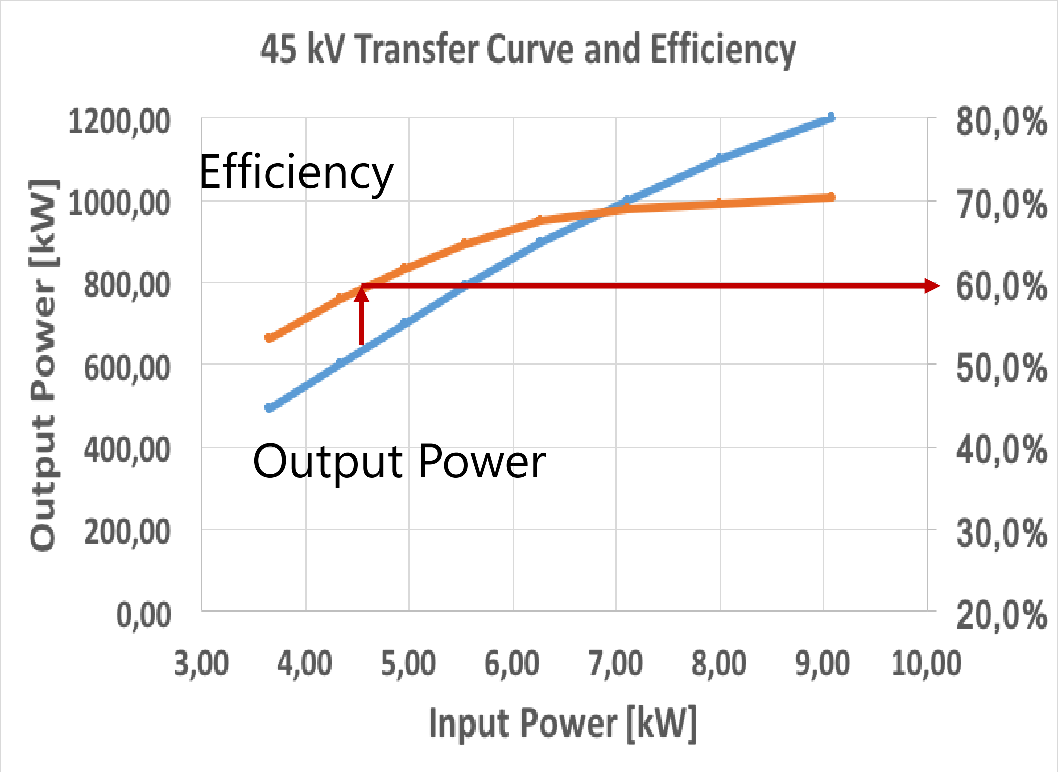


Thales/CPI MBIOT

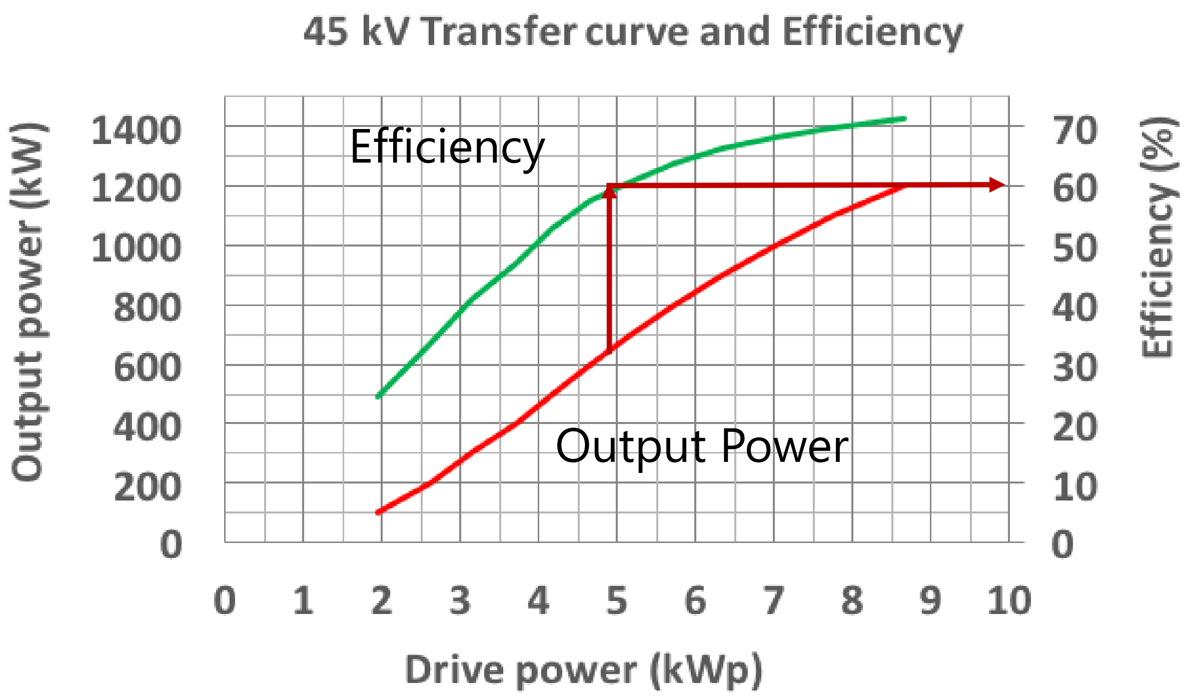
L3 MBIOT

Results of the 10-beam IOT

L3 MBIOT



Thales/CPI MBIOT



70 % efficient at 1.2 MV

Efficiency remains > 60% from 650 kW

High efficiency at point of operation even when overhead is required

That was 7 years ago!

ESS was under schedule pressure and it would require to be industrialised and optimised.

Ready for a new challenge? Can we do better?

Thank you for your attention.
Any Questions?