EUROPEAN
SPALLATION
SOURCE

RF Power Generation at ESS

Workshop on Efficient RF Sources
4-6 July 2022

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2022-07-04

Outline

November 2021

The ESS Linac

User facilities demand high availability (>95%)

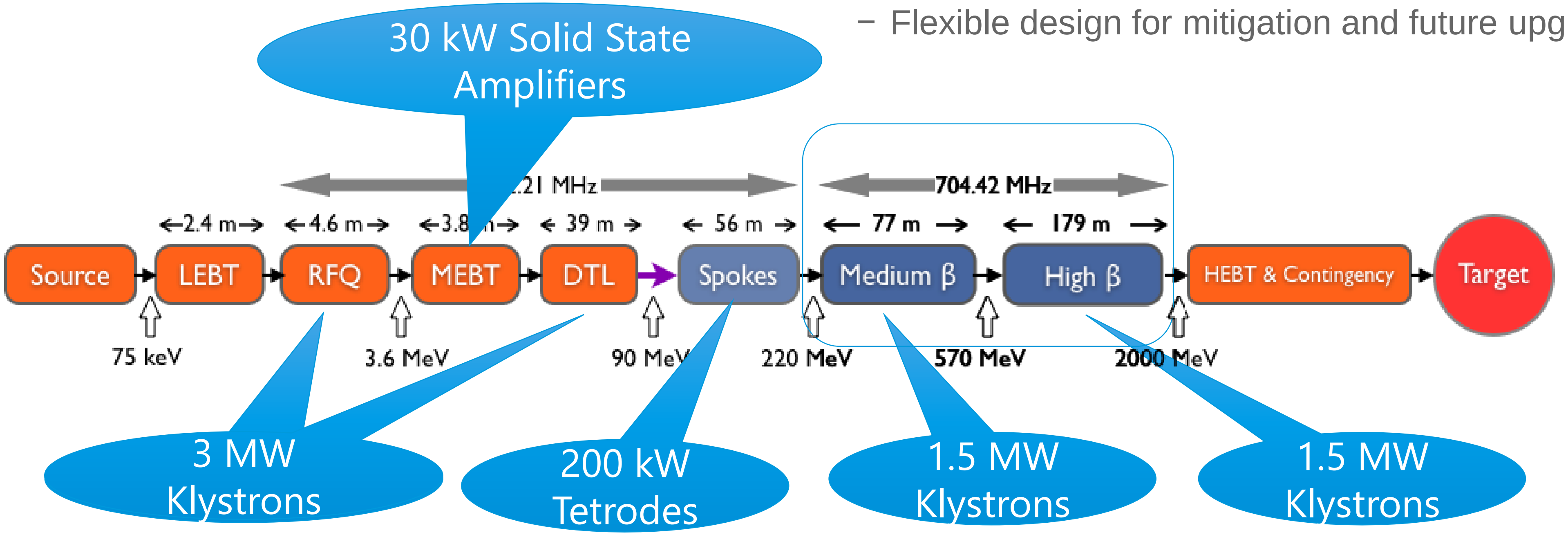
The linac will be mostly (>97%) superconducting

Front end frequency is 352.21 MHz (CERN Standard)

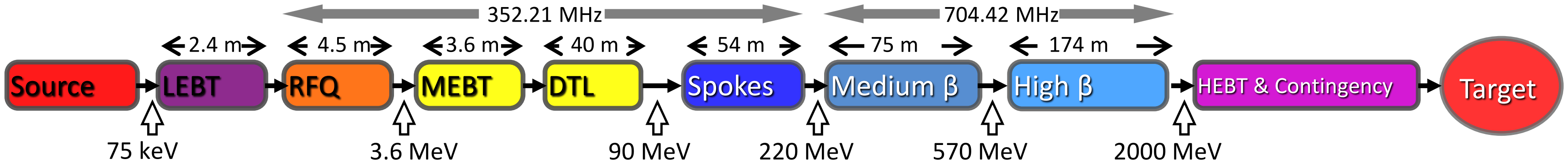
High energy section is at 704.42 MHz

Key parameters (with full high beta in operation):

- 2.86 ms pulses
- 2 GeV
- 62.5 mA peak
- 14 Hz
- 125 MW peak power, 5 MW average
- Minimize energy use
- Flexible design for mitigation and future upgrades



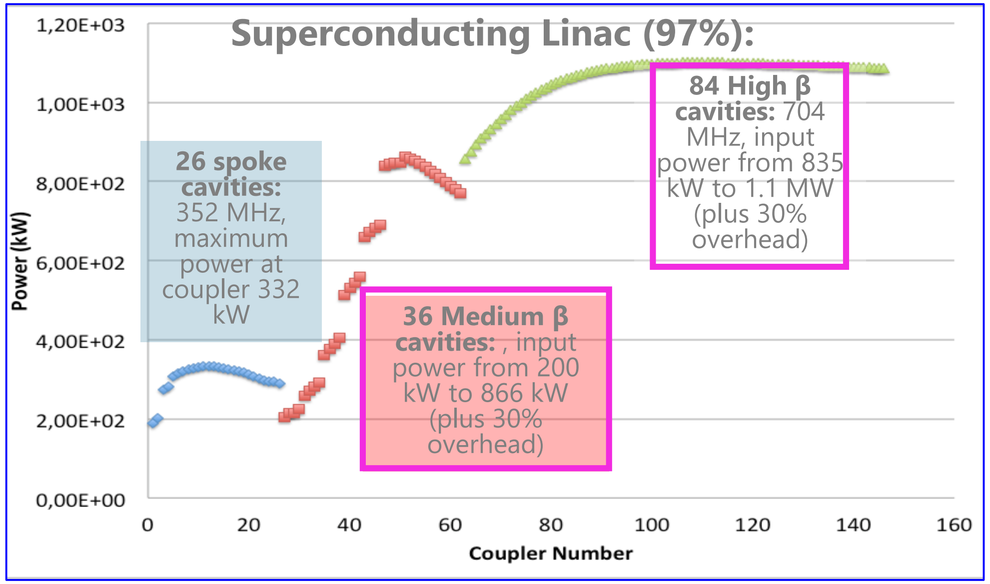
The ESS RF System



Normal-conducting Linac:

- 1 RFQ: 1.6 MW at 352 MHz + 30% (overhead + losses);
- 5 DTL tanks (2 couplers/DTL): 2.2 MW at 352 MHz + 30% (overhead + losses);
- 3 buncher cavities: 22 kW at 352 MHz + 30% (overhead + losses) , 30 kW

Superconducting Linac (97%):



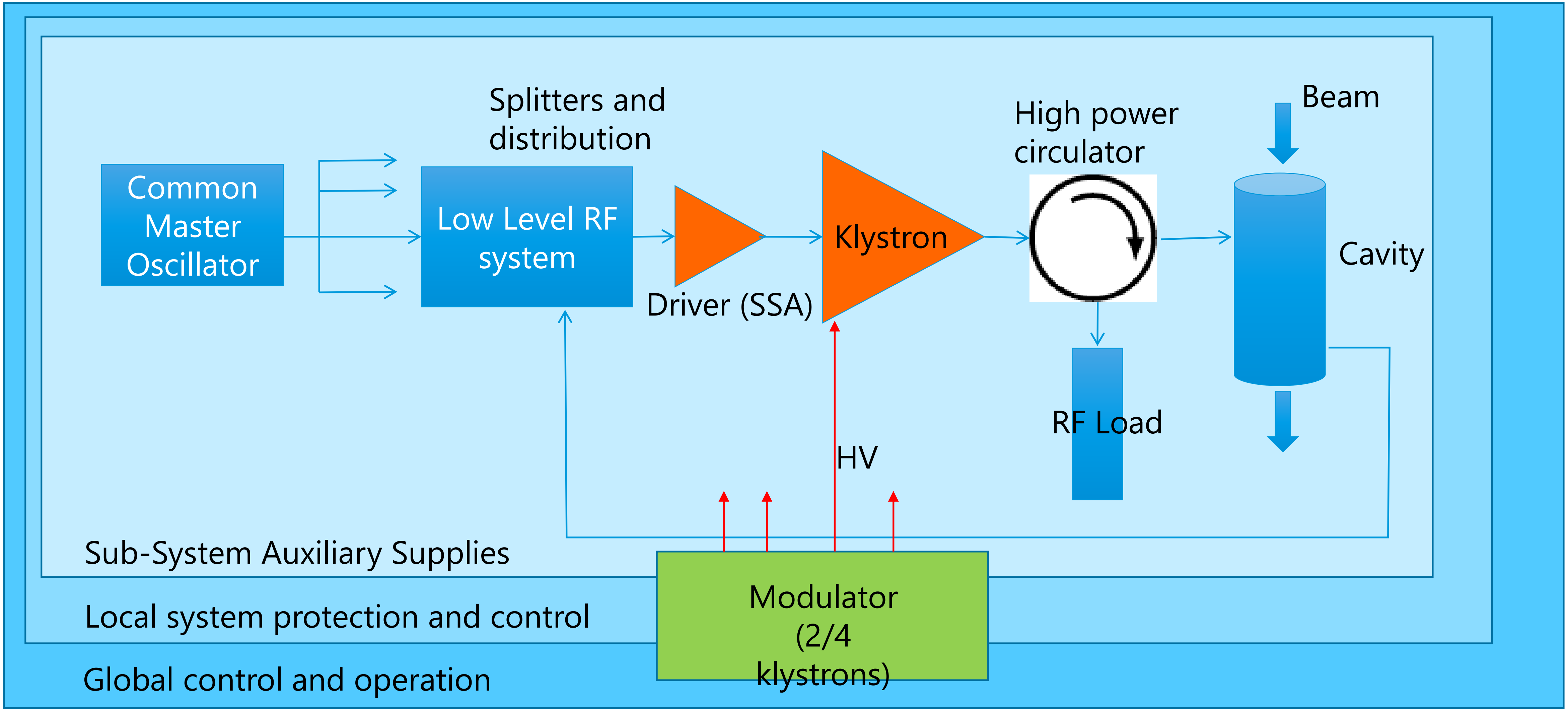
Section	Power (kW)	Baseline technology	Status
Normal conducting RFQ and DTL	2900	Klystron	In-kind (ESS Bilbao)
Normal conducting bunchers	30	Solid State	In-kind (ESS Bilbao)
Spoke linac	400	Tetrode	In-kind (Elettra)
Medium beta linac	1500	Klystron	Direct commercial procurement
High beta linac	1500	Klystron	20 klystrons ordered

Total of 126 klystrons!

- **Will focus on the klystron-based transmitters (most relevant for overall efficiency)**
- **See talk from M. Kumar for the Spoke transmitters**

Klystron-based transmitters

High-level Block diagram



NCL Linac: klystron based power stations

Klystron main specifications

1 RFQ (1.6 MW input power at 352.21 MHz)

5 DTL tanks (2.2 MW input power at 352.21 MHz for each DTL, two couplers per DTL)

Assumption for the specifications was 25% extra power for LLRF regulation + 5% losses in RF distribution

- 2.1 MW saturated power required for the RFQ klystron
- 2.9 MW saturated power required for the DTL klystrons
- One modulator every two klystrons

Currently we have:

- 2 CPI VKP-8352A klystrons (+ 1 spare still at factory)
- 4 Thales TH2179D klystrons (+ 1 spare being manufactured)

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

NCL Linac: klystron based power stations

Status

2 Systems in Operation

✓RFQ: CPI klystron – Bilbao In-kind. Handed over to Ops in May 2021

✓DTL1: CPI klystron – Bilbao In-kind. Handed over to Ops in May 2021

No major issues until now:

- Some trips due to a faulty air pressure sensor which has been replaced for a different design

-Few DC arcs on RFQ klystron

4 Systems fully tested:

DTL2: Thales klystron (ESS) installed and tested

DTL 3/4/5: Thales klystrons (Bilbao In-kind) installed and tested

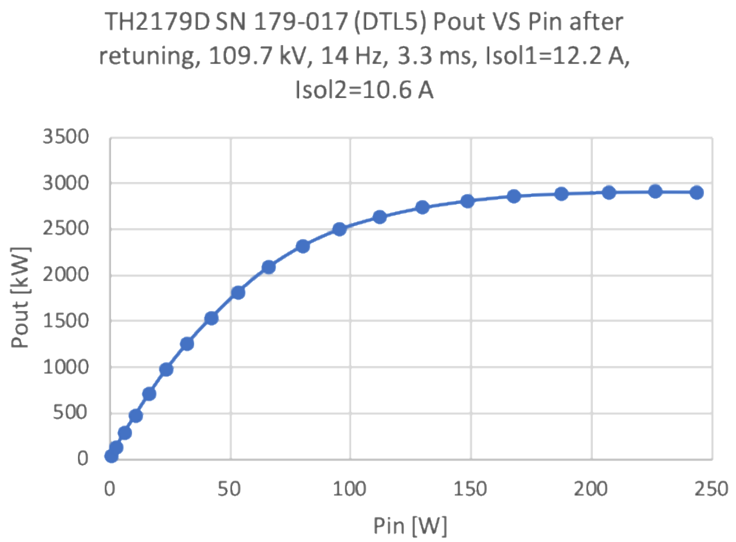
DTL 3 and 5 klystrons had to be retuned due to the presence of sidebands (probably reflected electrons). The sidebands were reflected by the circulator and caused trips on high reflected power

Retuning was successful; new SAT confirmed the performance and now the systems are being further tested

We have experienced issues with arcing in the RFDS in all systems (circulators, E-bends, Magic-T)
Not klystron related and all have been (or are being) addressed…

NCL Linac: klystron based power stations

Status in pictures



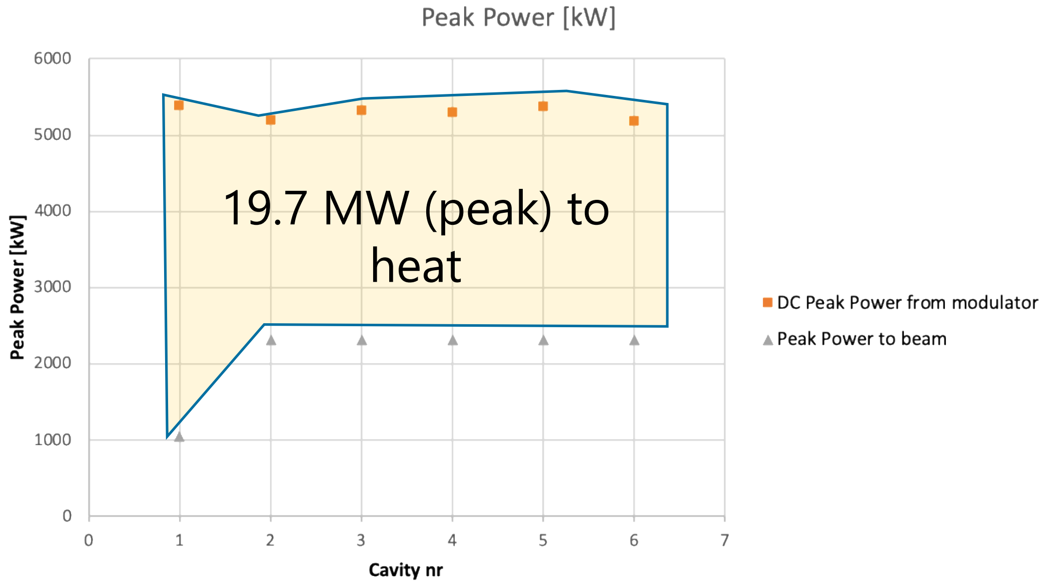
NCL Linac: klystron based power stations

Efficiency

We have to consider:
25% overhead for regulation, 5% losses in the RFDS
Two klystrons are sharing the same modulator -> we have to operate the modulator at the highest HV level (especially relevant for RFQ-DTL1)

CPI Klystrons efficiency at saturation ≈ 53%
- RFQ klystron operational efficiency 31%
- DTL1 klystron operational efficiency 44%

THALES klystrons efficiency at saturation ≈ 52-54%
- DTL2 klystron operational efficiency: 43.4%
- DTL3 klystron operational efficiency: 43.5%
- DTL4 klystron operational efficiency: 43%
- DTL5 klystron operational efficiency: 44.6%



- Not much margin for improvement – except some small reduction in overhead for LLRF
- This calculation DOES NOT include power supplies (filament, solenoids, IPs, HVPS)!

Medium and High Beta Linac

36 Medium beta elliptical cavities: 704.42 MHz, input power from 200 kW to 860 kW (plus 25% for losses compensation and overhead) -> saturated power from klystrons up to 1.1 MW

84 High beta elliptical cavities: 704.42 MHz, input power from 840 kW to 1.1 MW (plus overhead, 1.5 MW required)

One 660 kVA modulator powers 4 klystrons

- 18 Canon E37504 klystrons in Medium Beta
- 18 CPI VKP-8292A klystrons in Medium Beta
- 10 (+8) Canon E37504 klystrons in High Beta
- 10 (+8) Thales TH2180 klystrons in High Beta

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 Linac

Status

Medium Beta

All medium beta klystrons have been installed in the final locations, except one cell (will be used as temporary "test bed" for High Beta klystrons)

Site testing of the first 9 klystrons (6 Canon + 4 CPI) completed with no issues

Next 2 (Canon) klystrons currently under test

We DC condition 4 klystrons at the time. Plan is also to do RF conditioning in parallel in the future

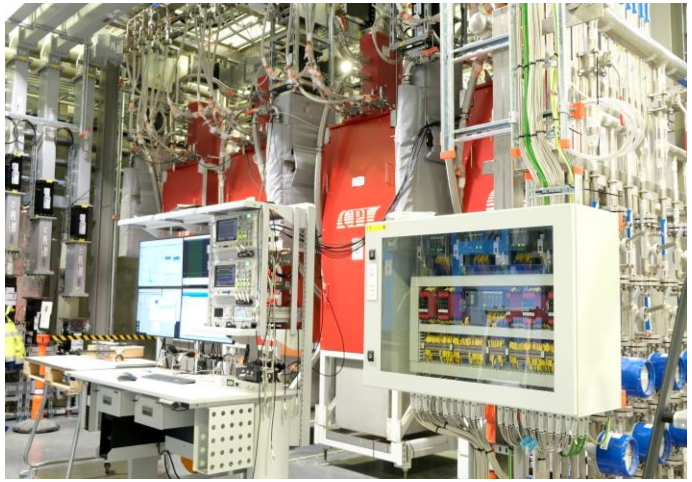
High Beta

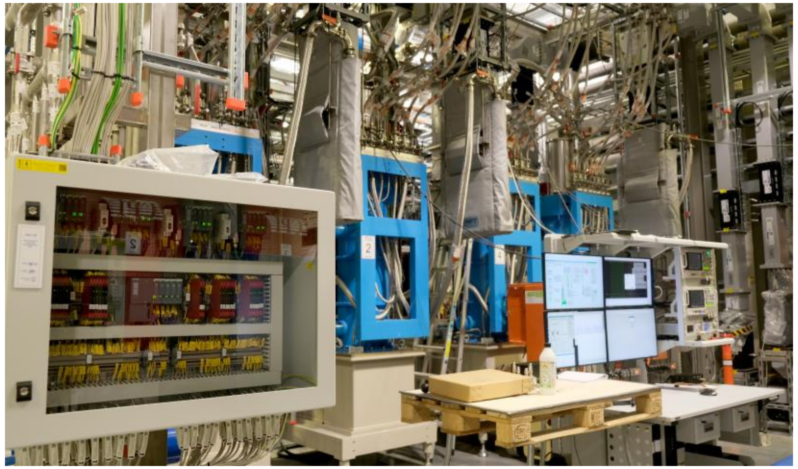
14 high Beta klystrons delivered from Canon; 4 more under manufacture/test at factory

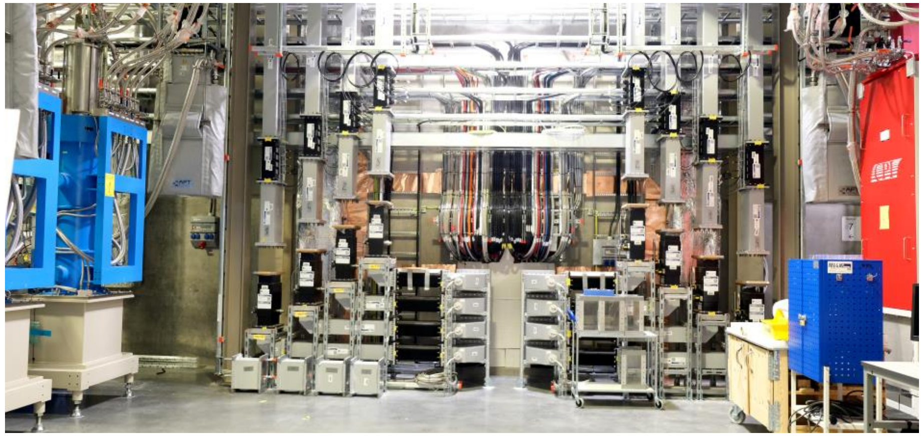
4 High Beta klystrons delivered from Thales; 14 more to come

Medium and High Beta Linac

Status in pictures





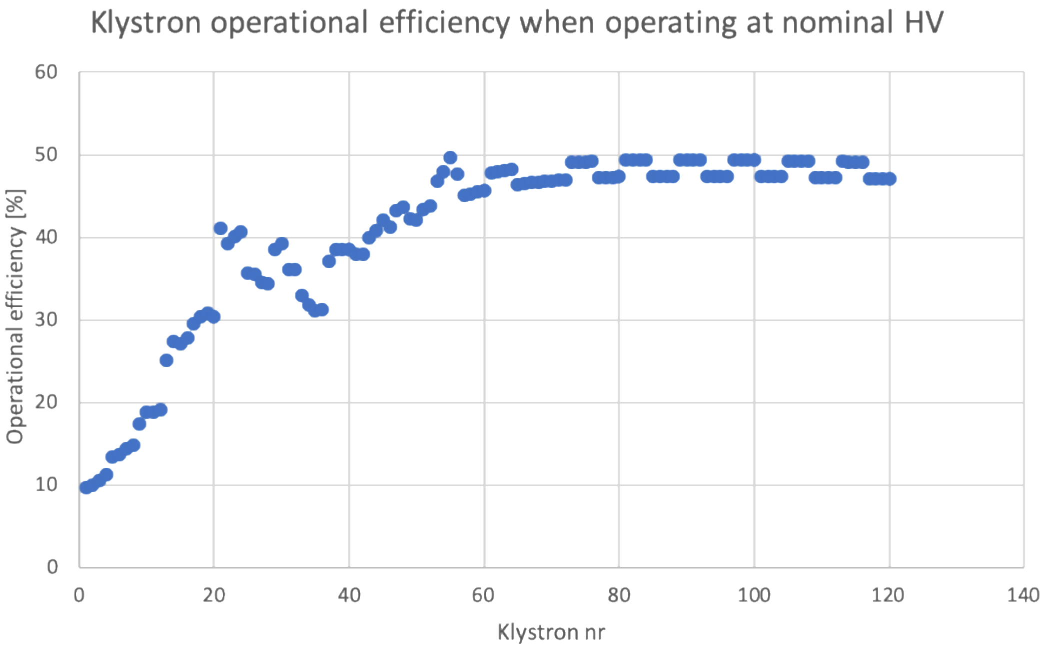


Medium and High Beta Linac

Efficiency at operating point: step 0

CPI Klystrons: efficiency at saturation ≈ 61-65% (from FAT results)
Canon Klystrons: efficiency at saturation ≈ 63/69% (from FAT results)
Thales Klystrons: efficiency at saturation ≈ 63/66% (from FAT results; only 4 delivered)

Efficiency profile **if we operate all klystrons at nominal HV (the HV needed to have 1.5 MW power at saturation)**
(considering only steady state - no transients):



Operating all klystron at full HV is NOT a wise choice:

1. For medium beta we don't need 1.5 MW saturated output power! Efficiency at operation point is low
2. Considerable amount of power to heat that has to be removed
3. Klystron lifetime is reduced

Medium and High Beta Linac

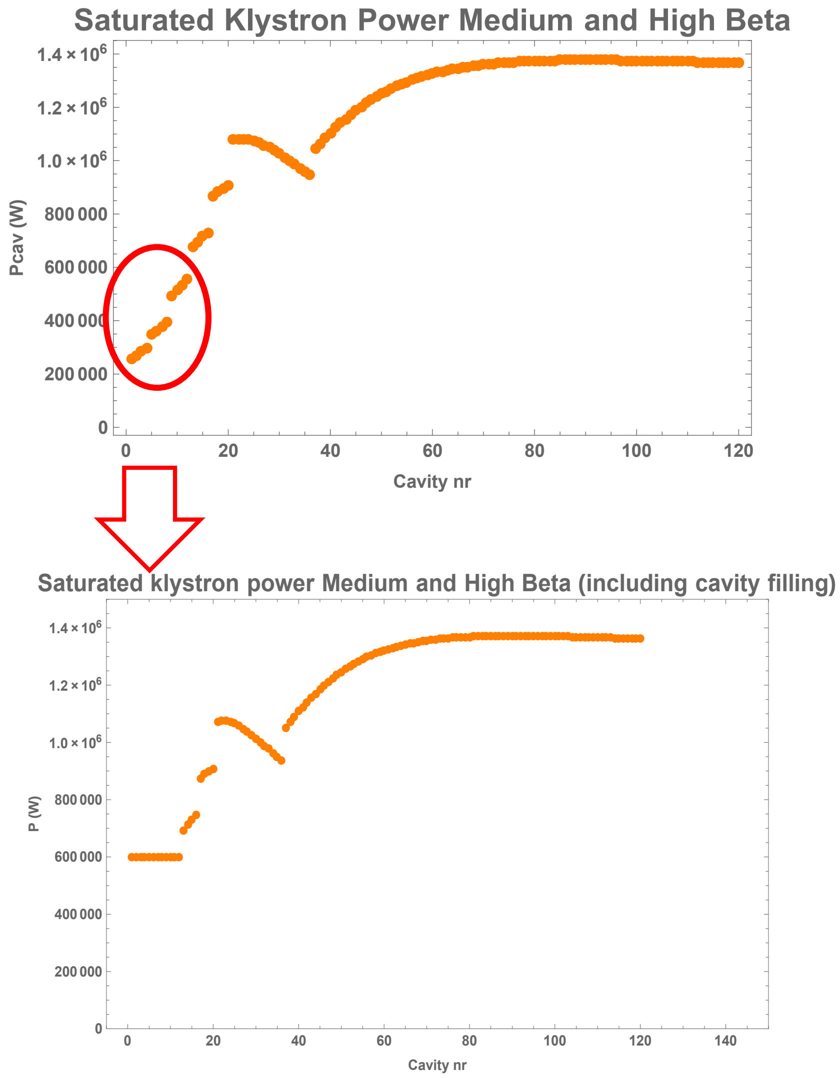
Efficiency at operating point: step 1

We can ***reduce the klystron HV*** for the power stations feeding the first cavities of the 704 MHz linac (where we don't need 1.5 MW klystron saturated power)

HOWEVER, we need to consider a couple of things:

1.

Due to the limited time that we have to fill the superconducting cavities (about 400 us), for the first cavities of the linac we can't set the klystron HV just to give a saturated power of just P_{cav}+25%.
To fill the cavity within 400 (300) us, we need P_{fw}(klystron forward power) to be α*P_c^{ss} (power needed to sustain the cavity gradient in steady state without beam), where α depends on the filling time . This means that P_{fw} needed during filling time for the medium beta cavity is about 450 (625) kW.
.....Luckily, we don't need 25% overhead during filling.



Medium and High Beta Linac

Efficiency at operating point: step 1

2.
Klystron efficiency is usually lower when operating at HV different than nominal

Why does efficiency go down?
In a simplified view:

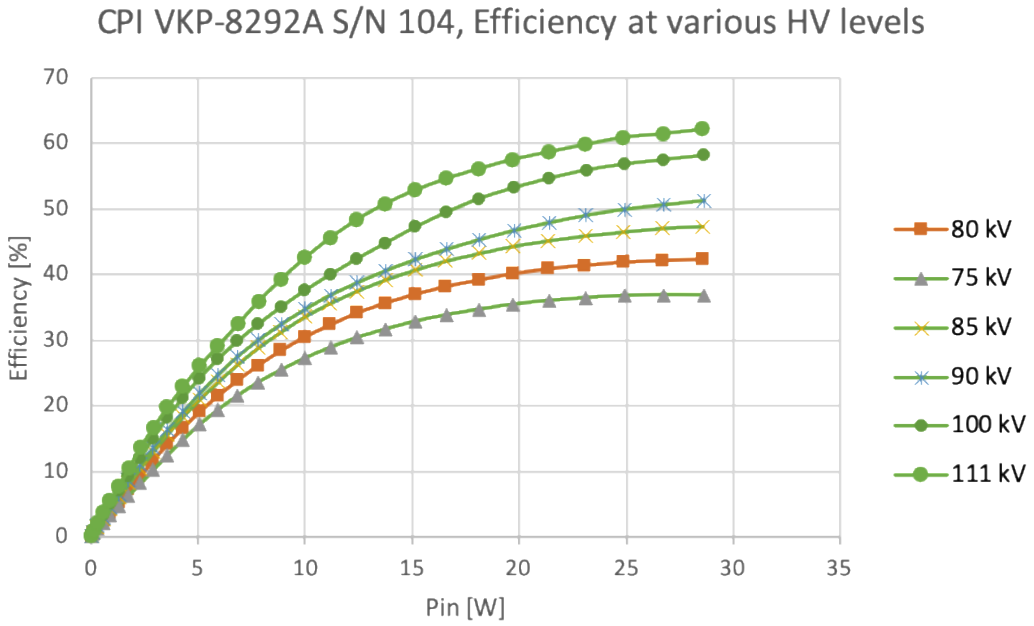
When reducing the beam voltage and current the space charge forces between the electrons vary (reduced plasma wavelength changes)

In other words, the cavity position is not optimal anymore

Furthermore, the impedance of the beam increases -> the external Q of the output gap is also not optimal anymore

Possible solutions:

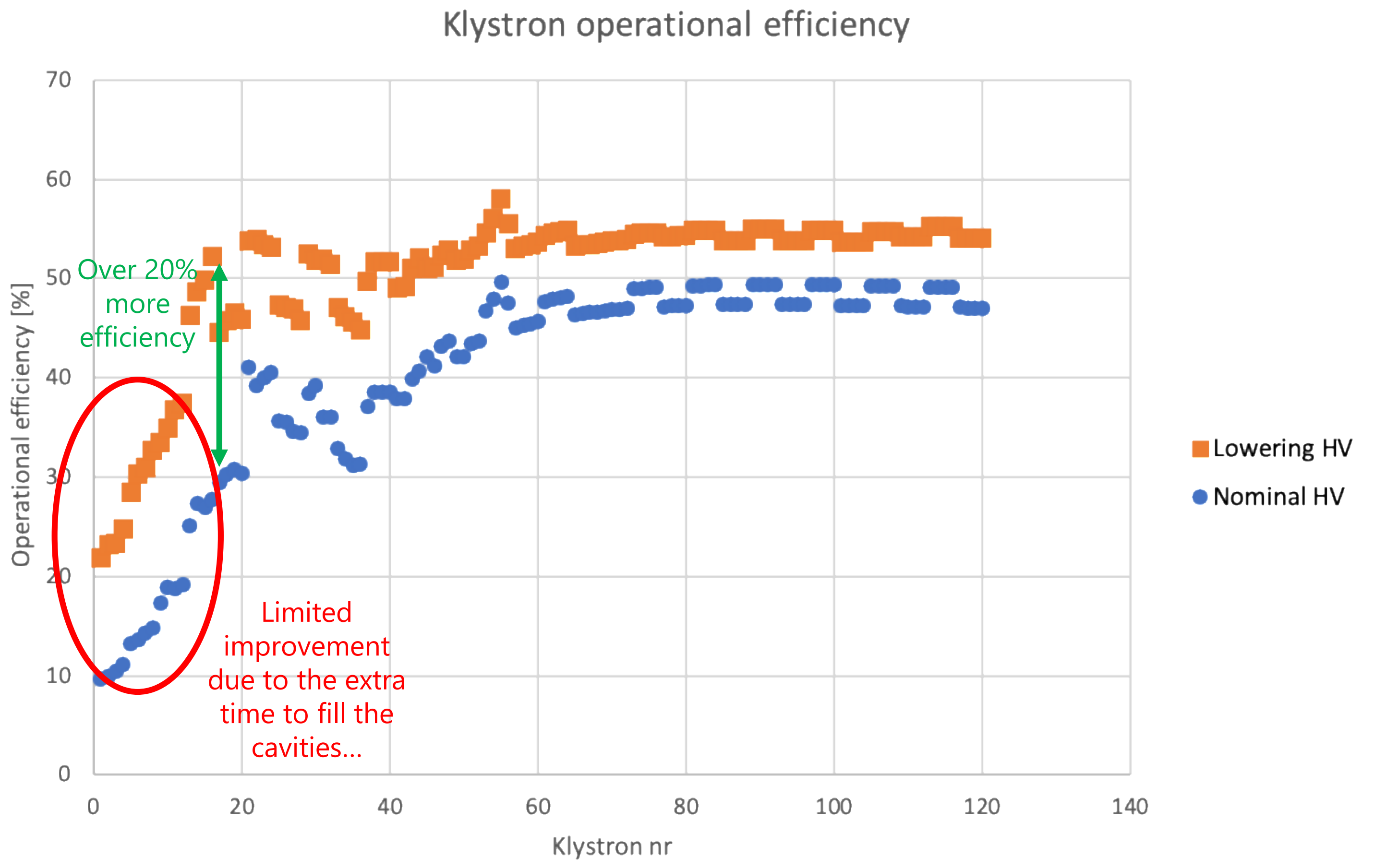
- The plasma wavelength can be slightly changed by acting on beam radius -> changing magnetic focusing field
- The external Q of the output cavity can be adjusted by varying the matching of the output cavity (output VSWR)



Medium and High Beta Linac

Efficiency at operating point: step 1

By just lowering klystron HV we get:

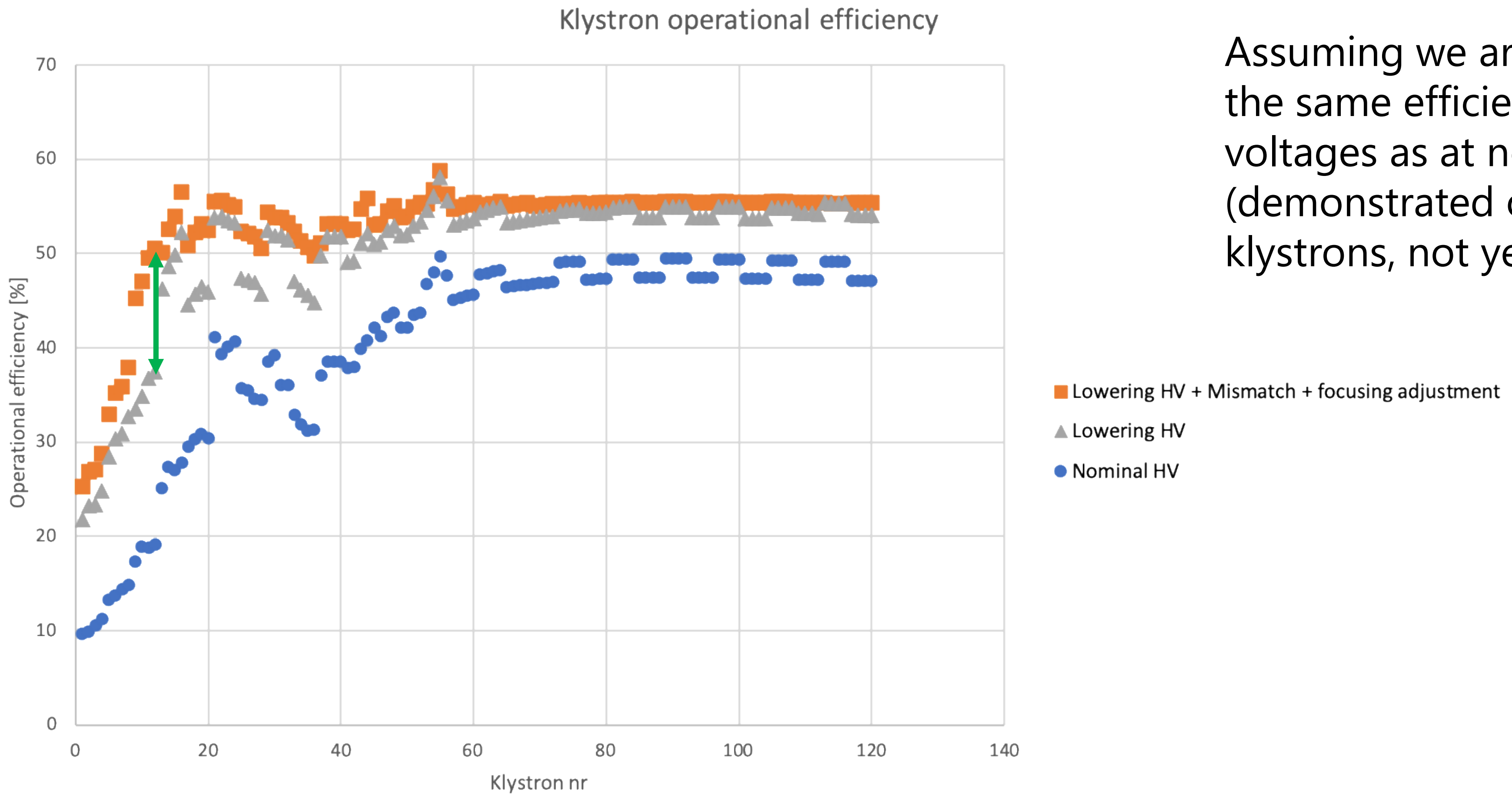


Assumptions:
- Data from SAT for tested klystrons
- Data from FAT for klystrons not yet tested on site.
- Canon/Thales klystrons assumed for all High Beta Linac

Medium and High Beta Linac

Efficiency at operating point: step 2

Use of **output mismatch AND solenoid adjustment** to improve efficiency at lower beam voltages



Assuming we are able to keep the same efficiency at low voltages as at nominal (demonstrated on all Canon klystrons, not yet on the others)

Medium and High Beta Linac

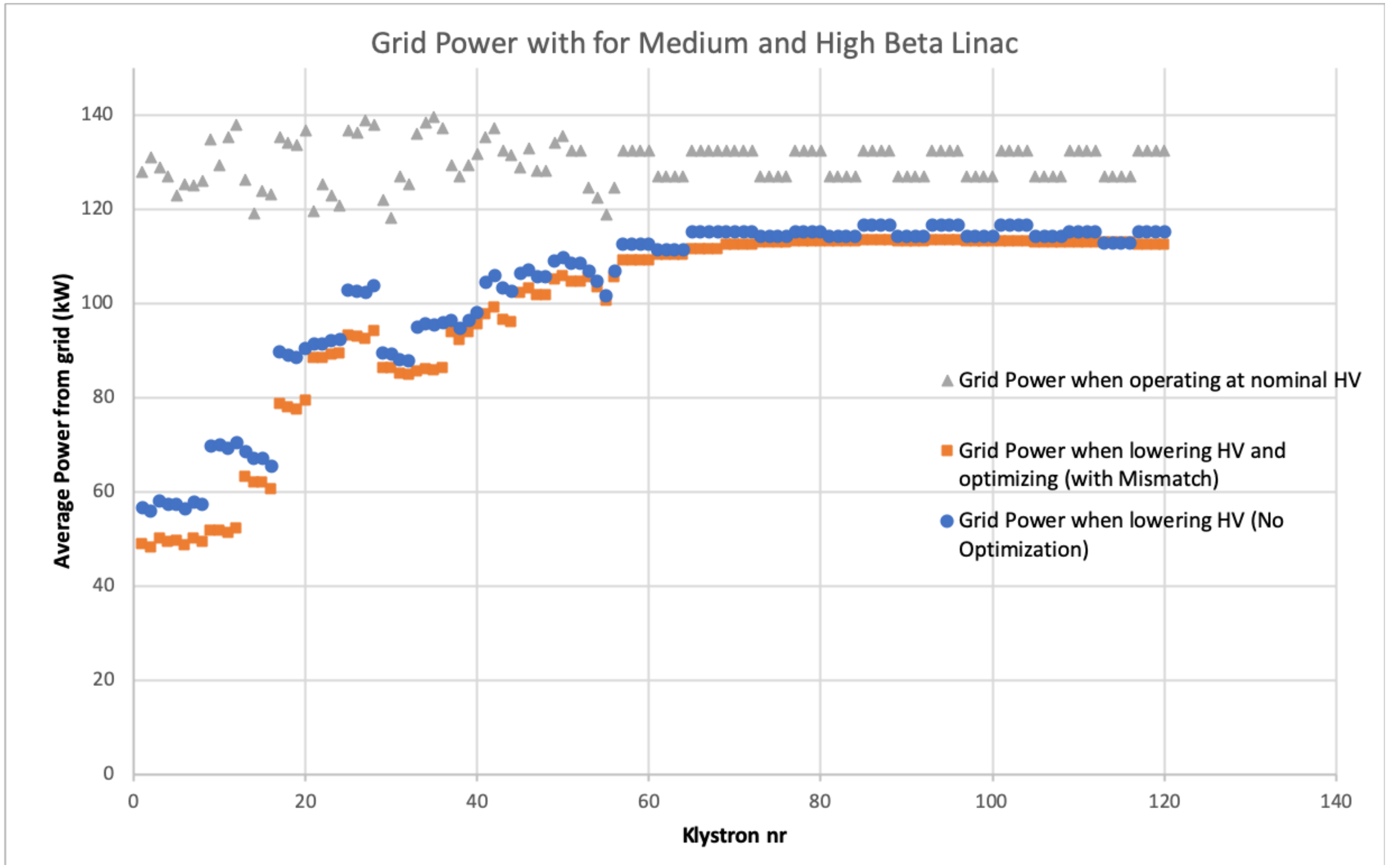
Electricity Savings when optimizing klystron operation

Savings using mismatch in **all** cells
Assumptions:
- Modulator efficiency: 90%
- Price of electricity: 0.09 €/kWh
- Klystrons operating 5500 h/year

- Savings/year lowering HV: 1627 k€/year
- Savings/year lowering HV + Optimization with mismatch≈ 1881 k€/year
- Savings/year just due to Optimization with mismatch: 253 k€/year

…probably more if the price of electricity goes up

And that's not it….



Medium and High Beta Linac

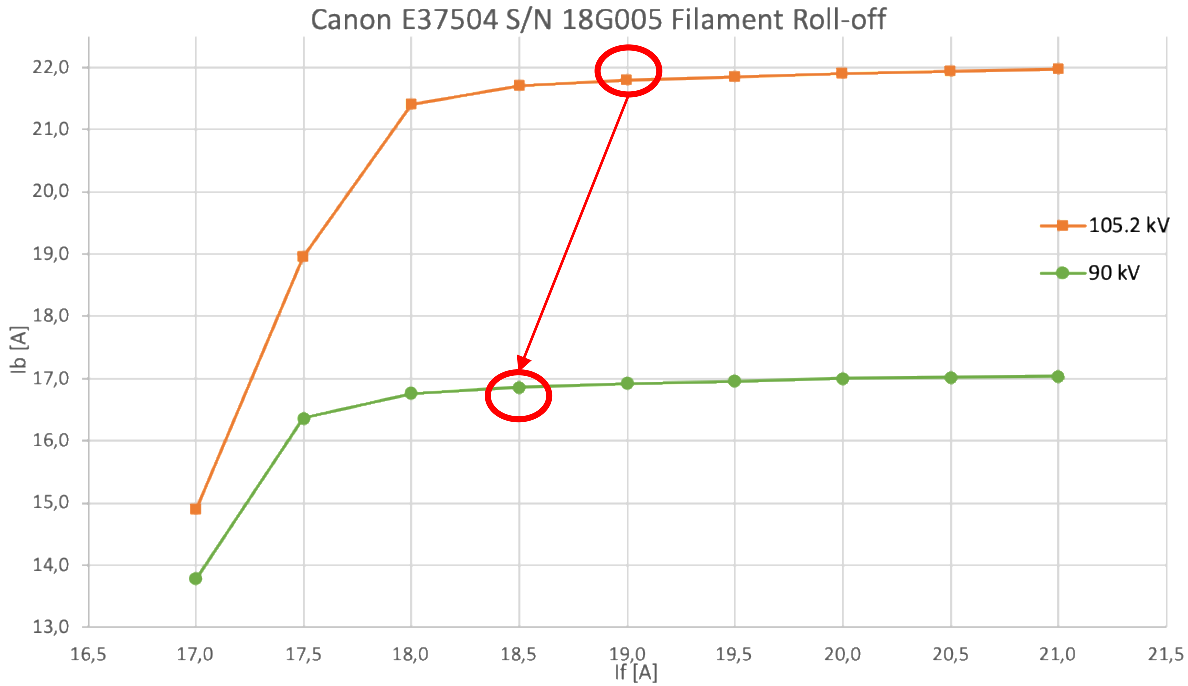
More savings….

Filament power could be reduced at lower HV, potentially increasing klystron lifetime

20% increase in klystron lifetime will mean 7 k€/year/klystron (if we assume 400 k€ for klystron cost and klystron lifetime 10 years) -> 350 k€/year for 50 klystrons

Reducing HV means less stress on the equipment (klystron cathode, collector, modulator components…)

The heat load is reduced -> less power required for cooling



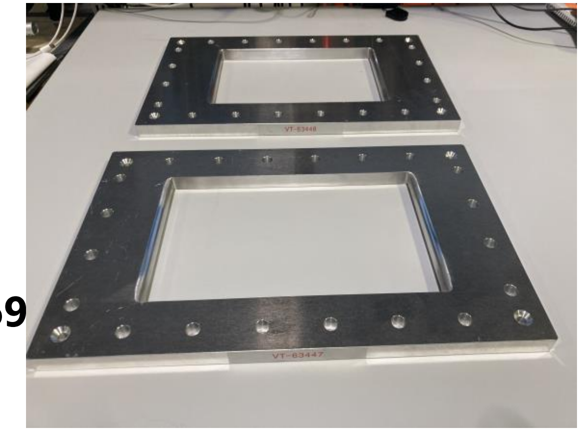
Medium and High Beta klystrons

Test of Canon E37504 at lower HV

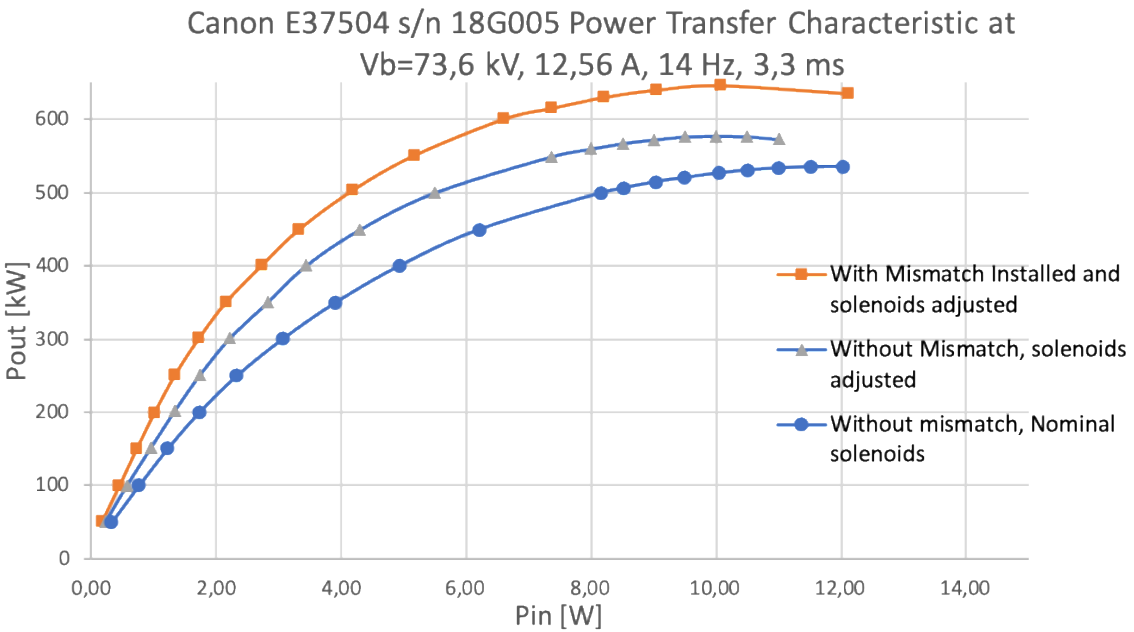
Results from Canon E37504 S/N 18G005 testing at ESS site

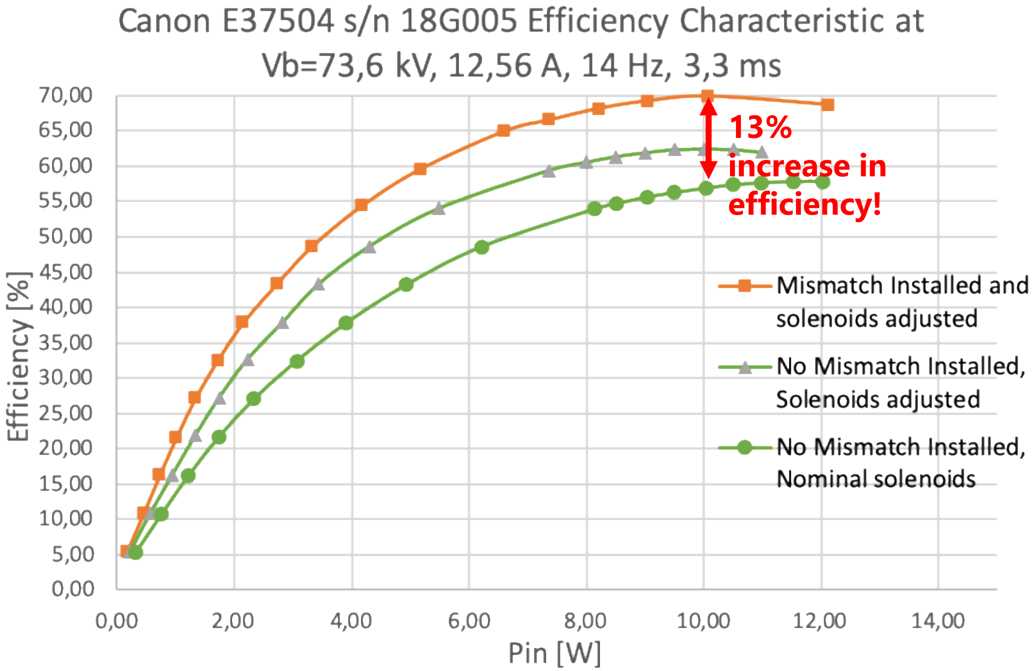
Nominal HV: 106.8 kV (21.74 A)
Saturated Output Power at nominal HV: 1.55 MW

- **Saturated Efficiency at nominal HV: 66.7%**
- **Saturated efficiency at 73.6 kV (with iris installed and solenoids adjusted: 69**



No instabilities, spurious or abnormal phase behavior





Medium and High Beta klystrons

Replacement of klystrons with newly designed tubes

What happens if we use HE klystrons? We have seen that, in short:

Efficiency of current medium beta klystrons is 62-69%.

Operational efficiency is not more than 55% (with mismatch optimization and for high beta klystrons)

Studies on new bunching techniques have shown the possibility of efficiency up to 80% for the ESS parameters.

This will require possibly a different modulator design (HV over 115 kV).

However, a **new design**, **compatible with current modulators**, could increase the saturated efficiency above 70%.

Medium and High Beta klystrons

High Efficiency alternative

Specifications and “constraints”:

- Single beam
- Compatible with existing ESS modulator (max HV 115 kV, max μPerveance 0.6)
- Output power: 1.5 MW
- Compact design
- Gain > 41 dB
- Efficiency > 70% (at saturation): 73-75% preferred
- High reliability and lifetime expected

Main design features:

- Beam voltage: 115 kV, beam current 18 A microperveance 0.46
- Expected efficiency: 74% -> Output power 1.5 MW (saturation)
- CSM design with 2-3-2 harmonic setup
- Two gain cavities after the input to increase gain
- Total of 8 cavities

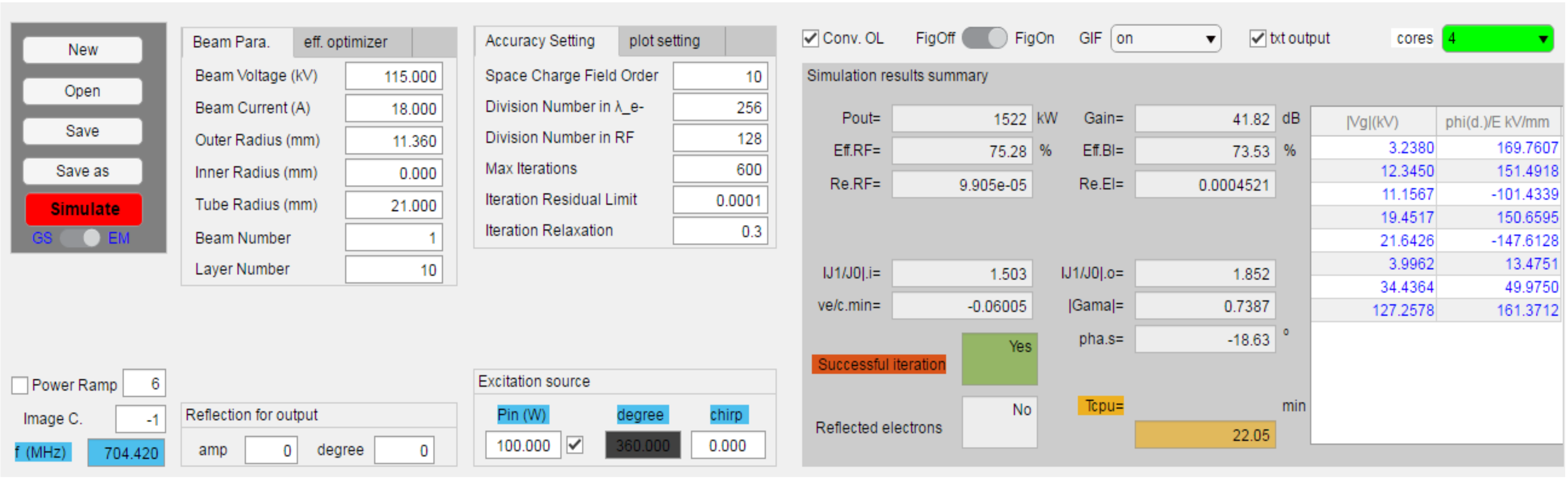
↓

ESS – 8

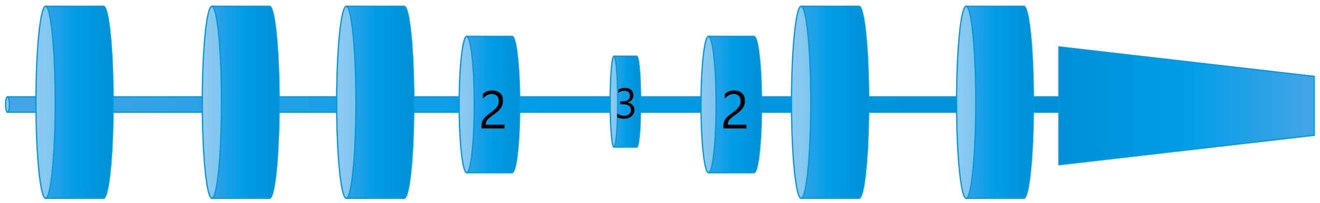
Medium and High Beta klystrons

High Efficiency alternative: ESS-8

First design and optimization with KlyC V4 (1.5 D, CERN code)



- 8 Cavities, length < 1.5 m
- Predicted balanced efficiency 73.5% (takes into account ohmic losses, DC and RF space charge, voltage “depression” at emission)
- Output power at 115 kV: 1.52 MW
- Gain: 41.3 dB



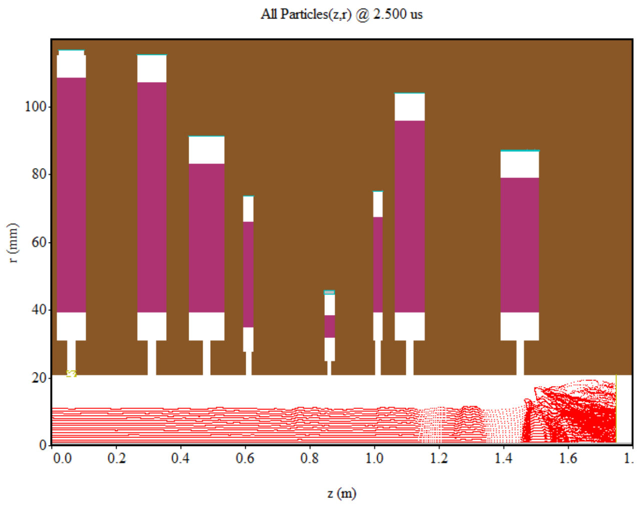
Medium and High Beta klystrons

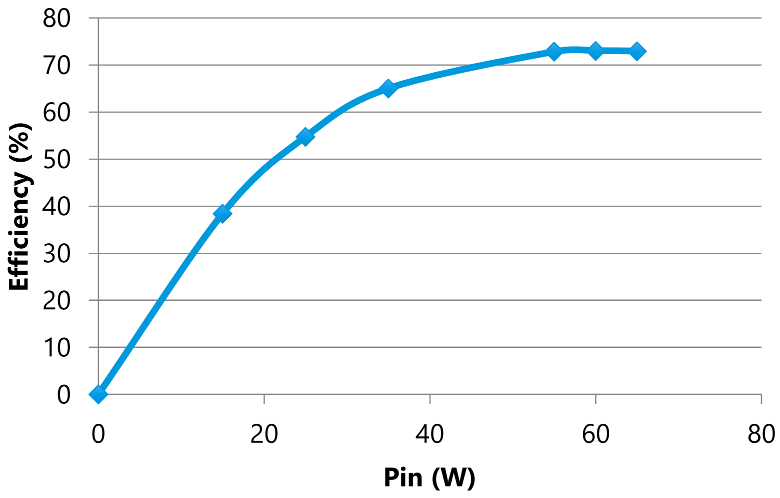
ESS-8: Magic 2D simulations

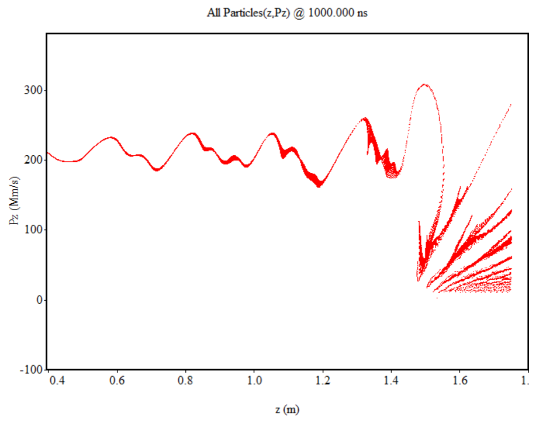
2D simulations with MAGIC to validate KlyC results and check for possible instabilities due to 2D effects

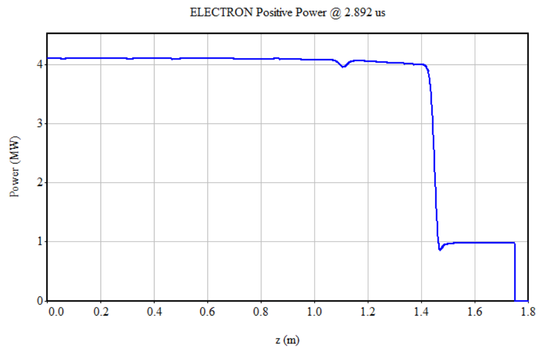
115 kV, 18 A, Bz=0.062 T

Balanced efficiency: 73 % (includes ohmic losses, beam interception, spent beam power, space charge power, voltage depression at emission).









Further optimization possible!

Medium and High Beta klystrons

Energy savings

Comparison with present klystrons

Assumptions:

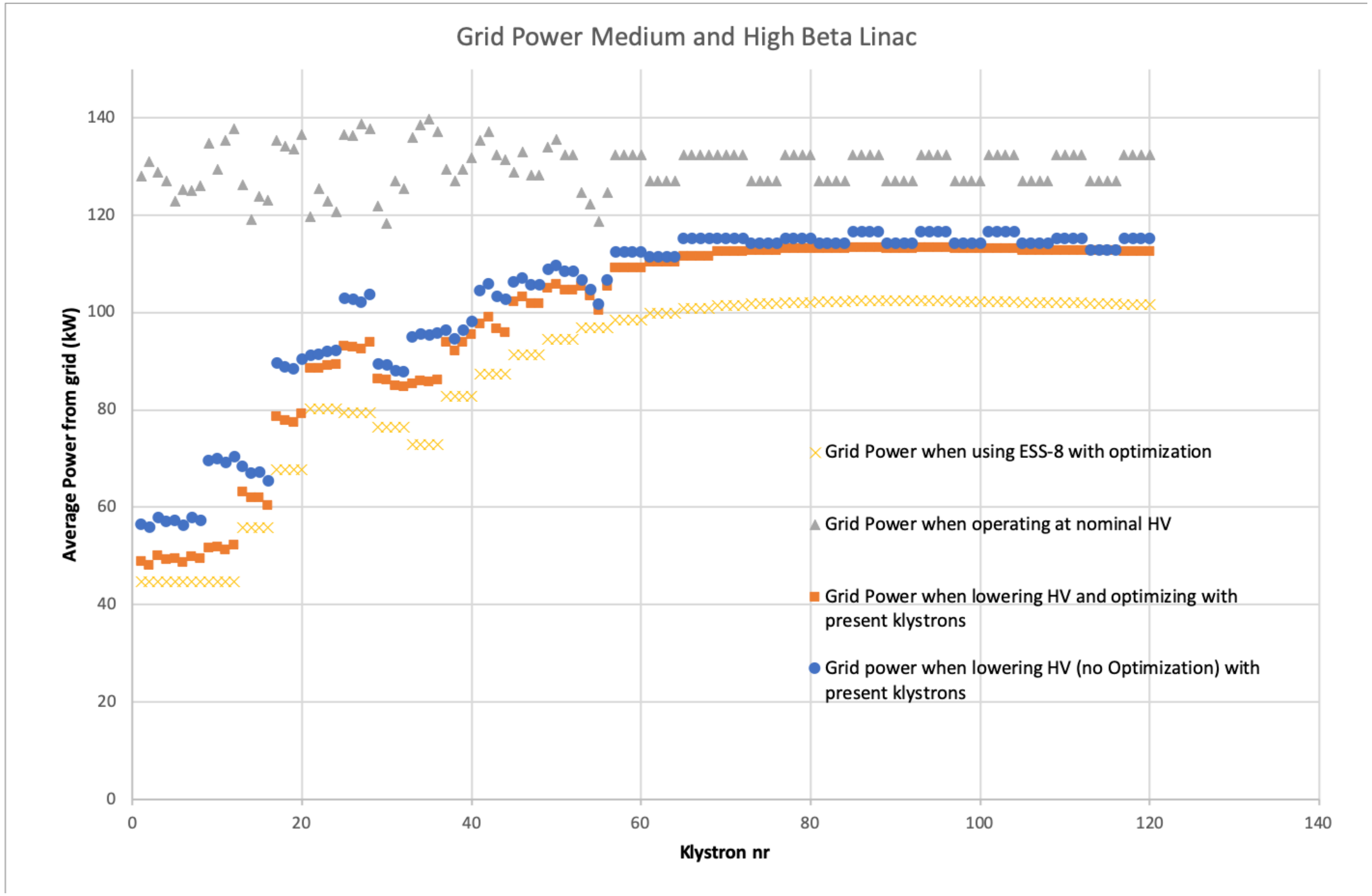
1. Use of mismatch and optimization of focusing field to increase the efficiency at lower HV
2. Same efficiency at lower HV than at nominal HV *(…this might be a bit optimistic…)*
3. 4 klystrons are sharing the same modulator (same HV).
4. Required output power from each klystron includes 25% overhead for LLRF regulation and losses in RFDS
5. Each klystron will operate for about 5500 h/year (with a duty cycle of 5%), and a cost of electricity of about 0.09 €/kWh
6. Modulator efficiency is 90%.

Medium and High Beta klystrons

Savings going to HEK

Savings/year going to ESS-8 HEK: 594 k€/year (compared to current klystron optimized for low power) …probably more if the price of electricity goes up….

Savings/year compared to operation with current klystrons at nominal HV: 2475 k€/year



Summary

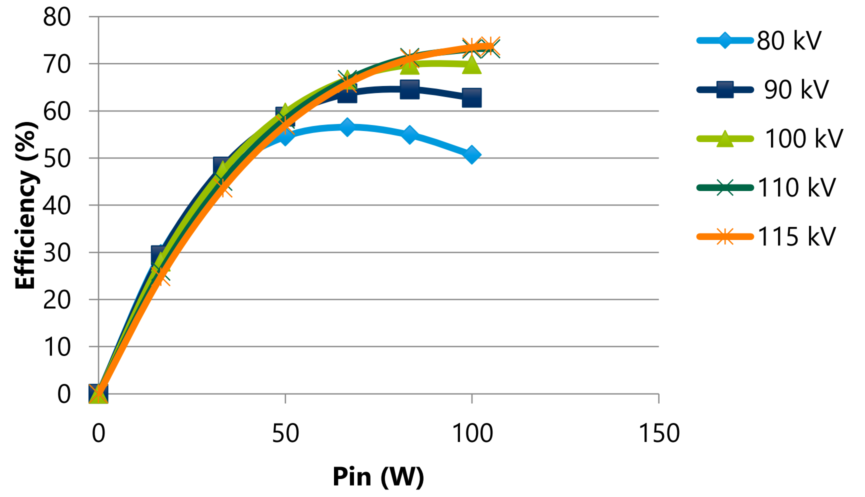
- NCL klystrons have been installed and tested and some are in operation. Not much margin for efficiency improvement.
- Medium Beta klystron testing is underway; site acceptance tests and early operation seem to confirm the factory performances
- Efficiency in the Medium (and High) Beta Linac can be improved with relatively small effort just by lowering high voltage and using the output mismatch; this would allow ESS to save 21 GWhr/year.
- Only electricity savings have been considered. But operating at lower HV would also possibly extend equipment lifetime, reduce heat load to the cooling systems, etc…
- Klystron performances with mismatch will have to be further validated but the first results are promising.
- High efficiency option is promising, but it will require a lot of work and some initial investment for R&D. Klystron manufacturers will have to be involved.
- 28 GWhr/year saved by going to HEK

Thank you!

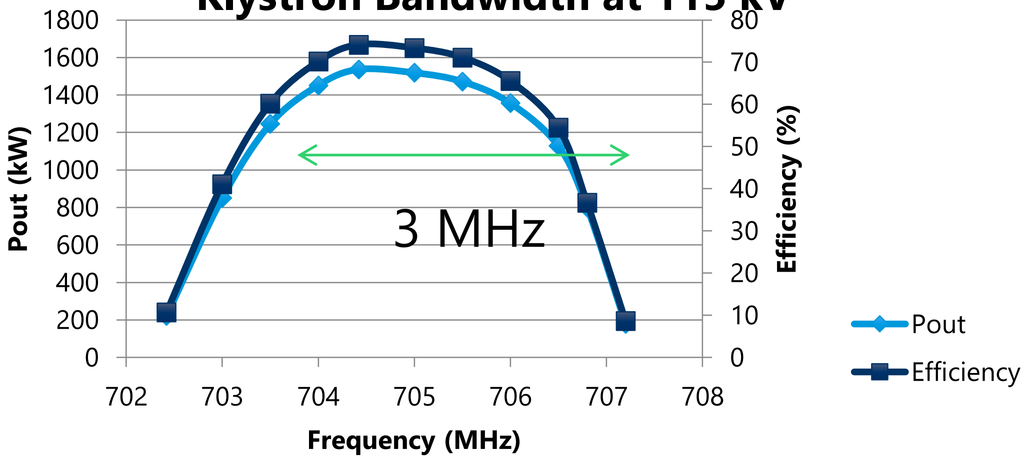
Medium and High Beta klystrons

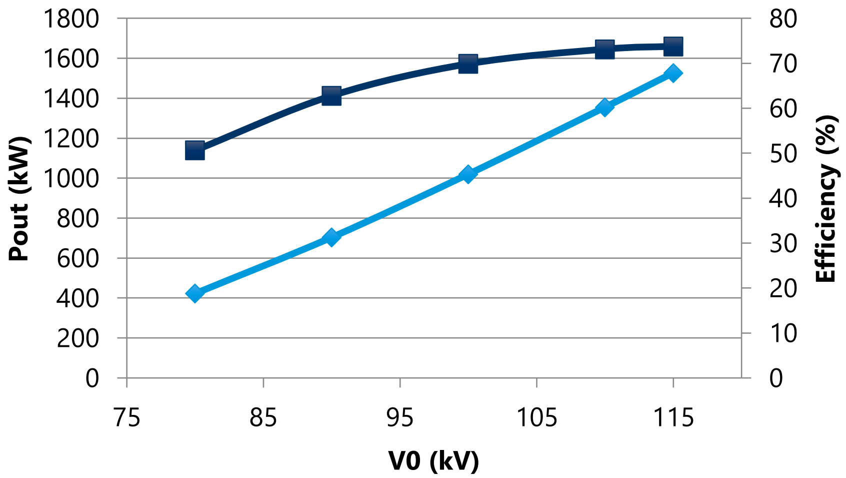
High Efficiency alternative: ESS-8

Operation at various beam voltages (no optimization)



Klystron Bandwidth at 115 kV





Operation on mismatched load (VSWR 1.2, variable phase)