Adaptive control of klystron operation parameters for energy saving at storage ring of TPS

Session: MC07, THXC -- Thursday Oral Parallel C, 05/27/2021 1100 – 1200, Oral Session C

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IPAC2021

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- Motivation
- Operation principle
- Various setting for various saturation RF power of klystrons
- Adjust the operation parameters of klystron by PLC controller
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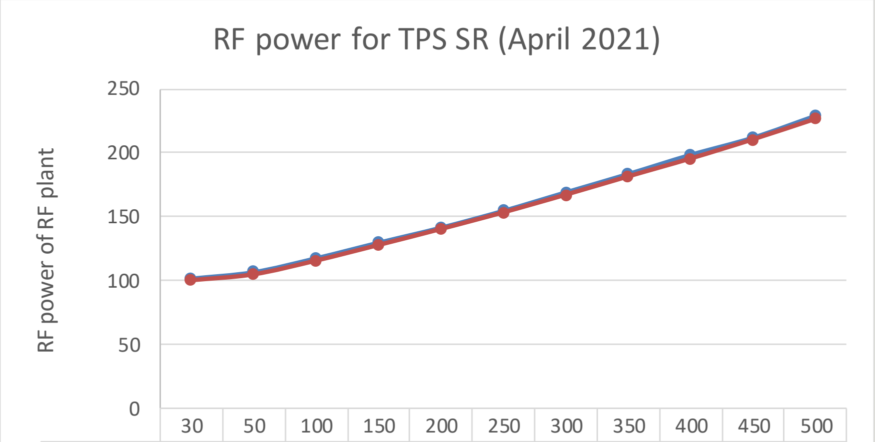
- The power saving effect
- Power saving results of practical operation with SR beam current
- Conclusion & discussion

Introduction

- Two RF plants with 500 MHz 300 kW transmitter, LLRF, RF feed lines and a superconducting module are working in storage ring (SR) of Taiwan Photon Source (TPS)
- The beam energy is 3GeV with maximum beam current of 500 mA
- The required RF power for each RF plant is about **226-228 kW** in April 2021 for total 17 beam lines with **450mA** beam current in daily routine operation
- A third RF plant is being installed from 2019-2022 to support more IDs after phase III beamline construction

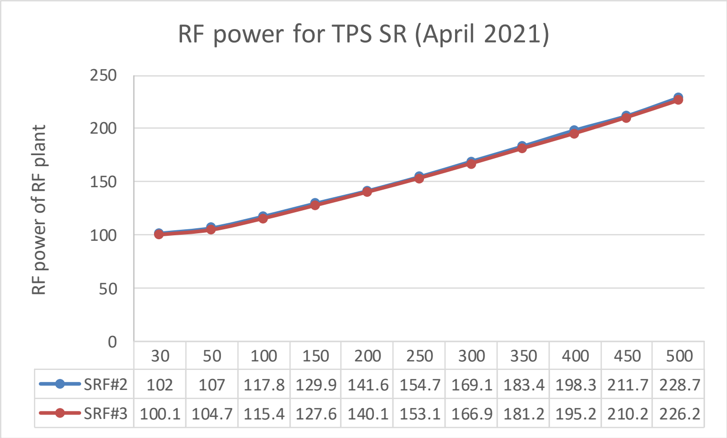


	30	50	100	150	200	250	300	350	400	450	500
SRF#2	102	107	117.8	129.9	141.6	154.7	169.1	183.4	198.3	211.7	228.7
SRF#3	100.1	104.7	115.4	127.6	140.1	153.1	166.9	181.2	195.2	210.2	226.2

Motivation

- The fixed operation parameters of klystron has lower DC-RF efficiency as RF output is not closing its saturation
  - Such condition is not energy efficient
- To afford maximum beam current of TPS SR, the setting of klystron is for maximum RF power (300kW) of each RF plant
- However, SR do not always run at its maximum beam current, the RF power of each plant is about 227kW for 450mA beam current in 2021
- Besides, a third RF plant is going to join the SR operation for more IDs after 2022
- Beam power requirement will be shared by three RF plants and each RF plant will deliver less RF power in the beginning (before completing all phase III BLs)
- Try to make klystron to be more efficient in such situation

Motivation



	30	50	100	150	200	250	300	350	400	450	500
SRF#2	102	107	117.8	129.9	141.6	154.7	169.1	183.4	198.3	211.7	228.7
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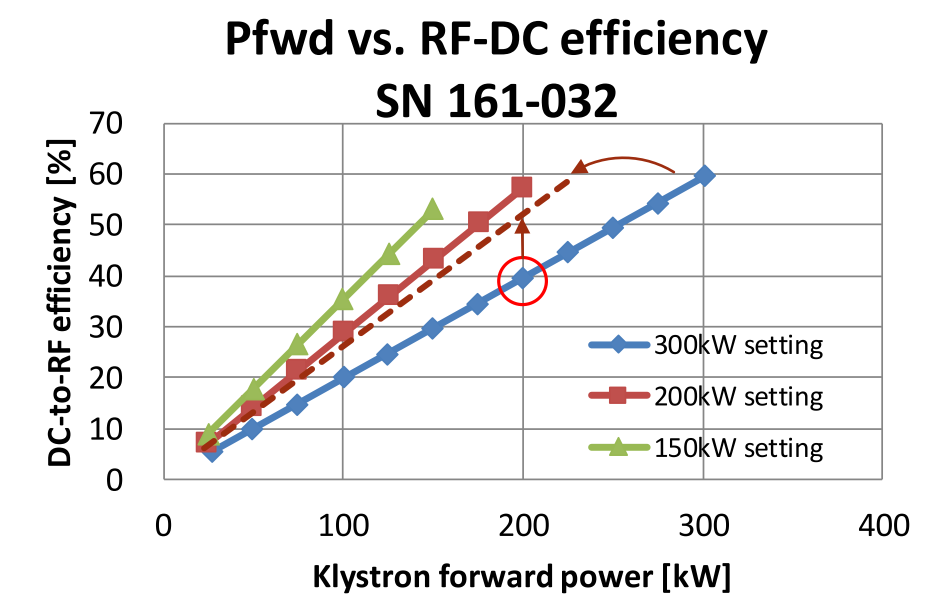
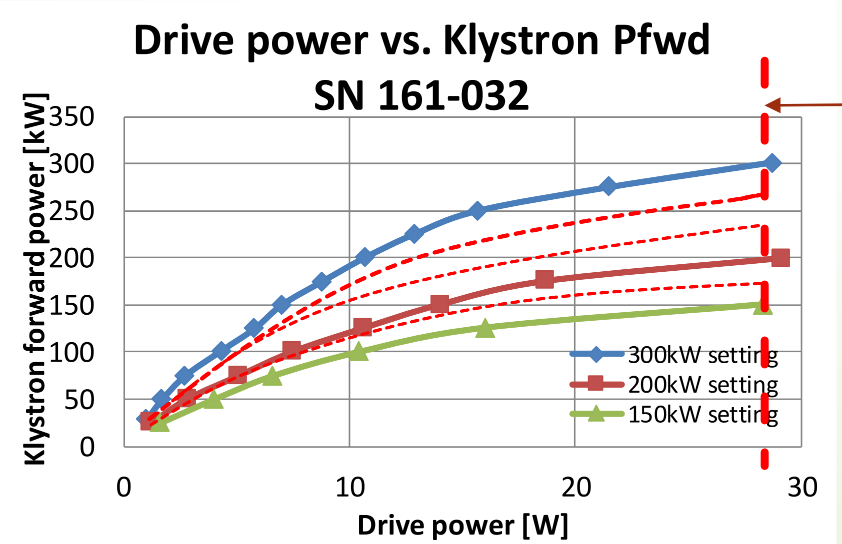
Klystron in TPS

- Upon specification, the factory test data of Thales klystron TH2161B give 3 sets of operation parameters for 150kW, 200kW and 300kW saturation power
- Assume the required RF power is 200kW for 400mA beam current, the 200kW setting of klystron is not enough and 300kW setting would have lower efficiency (40%)at this point
- If we can move the saturation power from 300kW toward 200kW, the klystron can have higher efficiency than 40%
- Higher efficiency means less energy consumption and save electricity



Operation principle of klystron

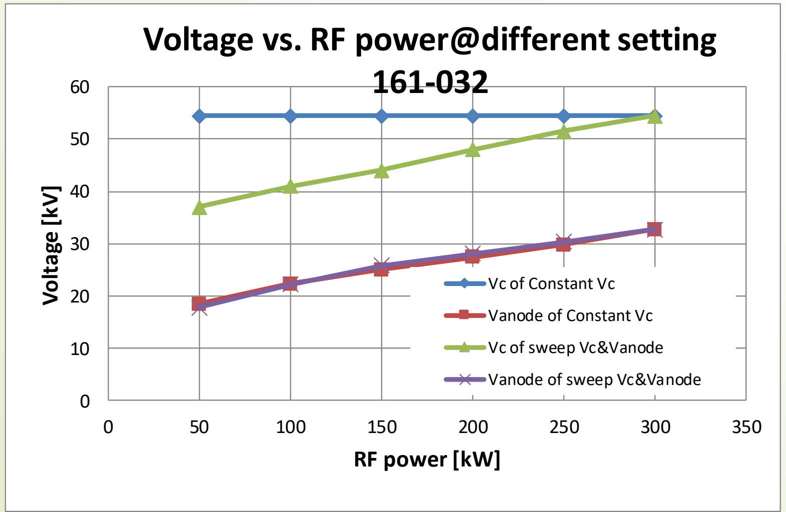
- Here, the detail theory of single beam klystron won't be discussed
- Just observe the drive RF power and its saturation power at different setting
- Obviously, the klystron will reach its saturation output RF power at nearly identical drive RF power
- We can find more saturation RF power values with different settings by fixing drive RF power (dot curves)

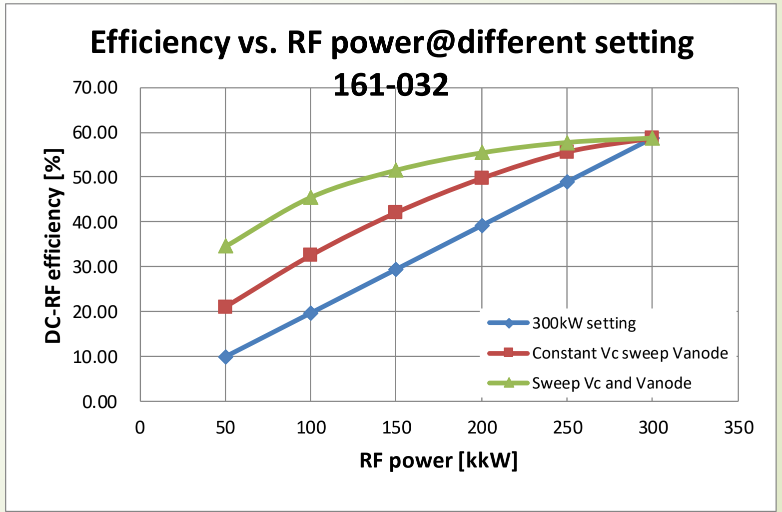


Constant drive power at different saturation output power

Various setting for various saturation RF power of klystrons

- According to above assumption, we can find much more higher efficiency settings in 50kW steps in two category
  - Constant cathode voltage but sweeping anode voltage
  - Sweeping cathode and anode voltages
- We can find the anode voltage (= cathode current) determines the maximum saturation RF power
- But varying cathode voltage can have higher DC-RF efficiency

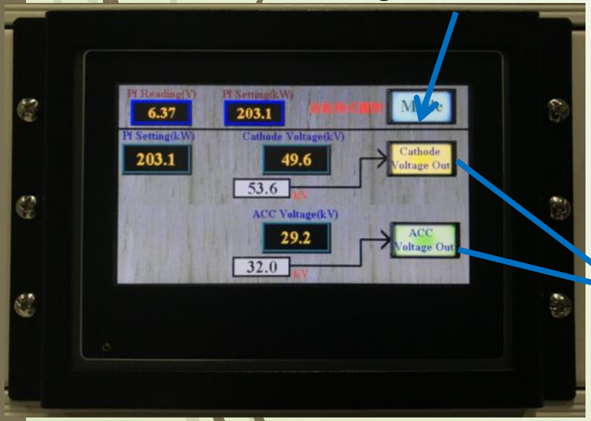


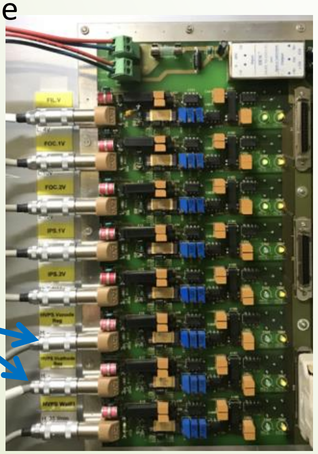


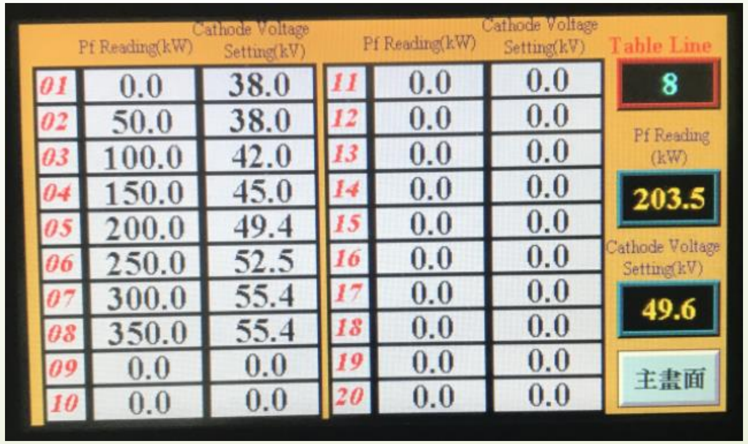
Adjust the operation parameters of klystron by PLC controller

- The high voltage power supply designed by Ampegon (Swiss company) can adjust its cathode/anode by external tuning voltage
- A PLC controller is developed for tracking the present RF power and change the setting of cathode/anode voltage of high voltage power supply accordingly
- The setting value is obtained from the test curve of the klystron without changing focus (solenoidal) current

Power saving mode enable/disable

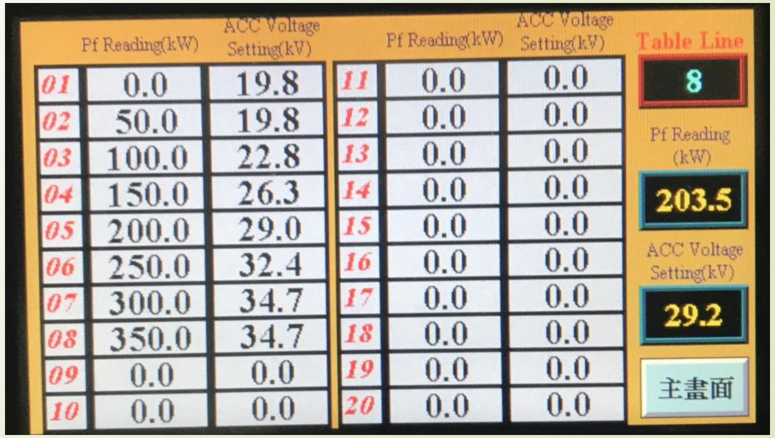






	Pf Reading(kW)	Cathode Voltage Setting(kV)		Pf Reading(kW)	Cathode Voltage Setting(kV)
01	0.0	38.0	11	0.0	0.0
02	50.0	38.0	12	0.0	0.0
03	100.0	42.0	13	0.0	0.0
04	150.0	45.0	14	0.0	0.0
05	200.0	49.4	15	0.0	0.0
06	250.0	52.5	16	0.0	0.0
07	300.0	55.4	17	0.0	0.0
08	350.0	55.4	18	0.0	0.0
09	0.0	0.0	19	0.0	0.0
10	0.0	0.0	20	0.0	0.0

Table Line: 8
Pf Reading (kW): 203.5
Cathode Voltage Setting(kV): 49.6
主畫面



	Pf Reading(kW)	ACC Voltage Setting(kV)		Pf Reading(kW)	ACC Voltage Setting(kV)
01	0.0	19.8	11	0.0	0.0
02	50.0	19.8	12	0.0	0.0
03	100.0	22.8	13	0.0	0.0
04	150.0	26.3	14	0.0	0.0
05	200.0	29.0	15	0.0	0.0
06	250.0	32.4	16	0.0	0.0
07	300.0	34.7	17	0.0	0.0
08	350.0	34.7	18	0.0	0.0
09	0.0	0.0	19	0.0	0.0
10	0.0	0.0	20	0.0	0.0

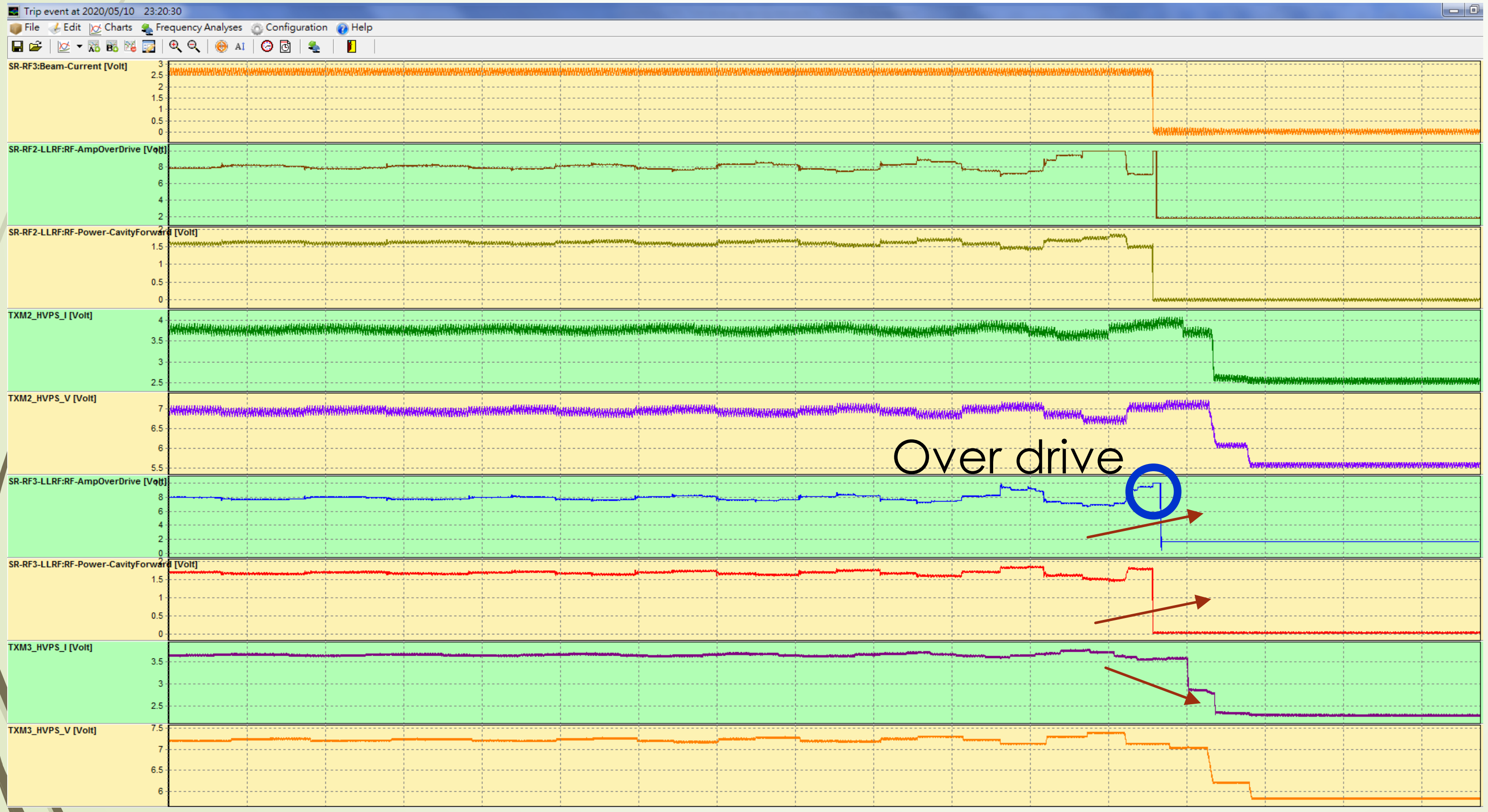
Table Line: 8
Pf Reading (kW): 203.5
ACC Voltage Setting(kV): 29.2
主畫面

Encountered problems

- The saturation of LLRF
  - LLRF will saturate as the klystron is closing its saturation RF power
  - At such condition, LLRF cannot control the klystron power anymore and easily trip as it touches its high set point
- The RF station phase will change as cathode voltage is tuning
  - Obviously, the electron speed (energy) of klystron is determined by the cathode voltage and the RF output power phase will also vary with the cathode voltage
  - As klystron phase is changing, cavity phase lock loop of LLRF will start to change its phase shifter and also change the station phase of each RF plant
  - The RF power balance among two sets of RF plant will start to change
  - The PLC will also start to track the changing RF power and adjust its setting for klystron
  - However, the reaction speed of PLC is far slower than LLRF
  - An oscillation like condition will happen

RF power oscillation between 2 sets RF plant

- At sweeping cathode and anode voltage power saving setting, one of the two RF systems will trip finally as drive power reaches its high set point



SR beam current

RF#2 LLRF control voltage

RF#2 cavity forward power

RF#2 TXM cathode current

RF#2 TXM cathode voltage

RF#3 LLRF control voltage

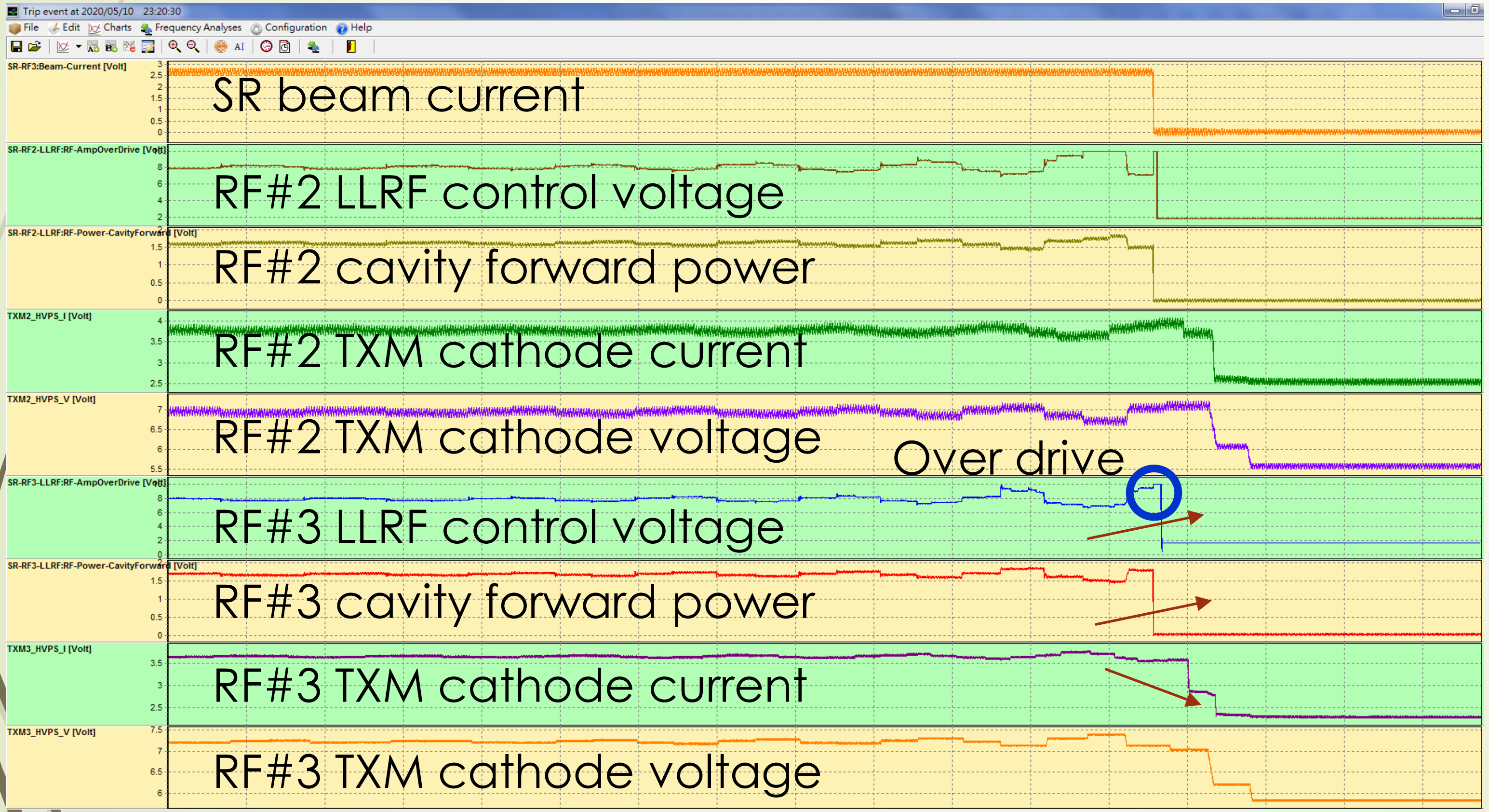
RF#3 cavity forward power

RF#3 TXM cathode current

RF#3 TXM cathode voltage

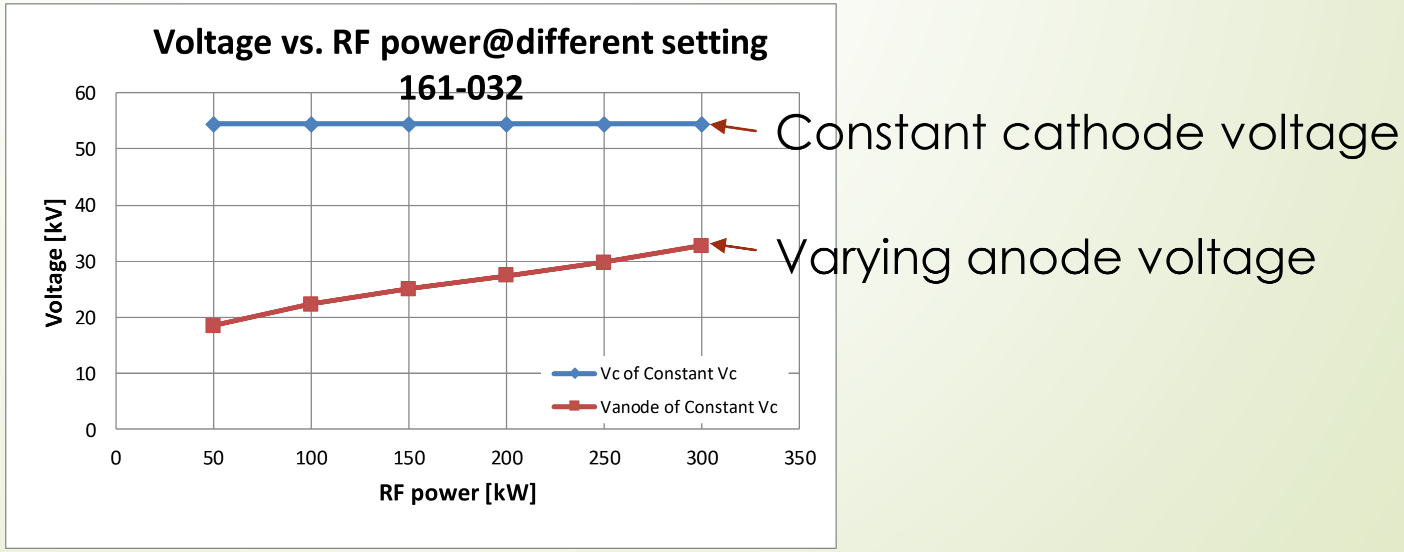
RF power oscillation between 2 sets RF plant

- At sweeping cathode and anode voltage power saving setting, one of the two RF systems will trip finally as drive power reaches its high set point



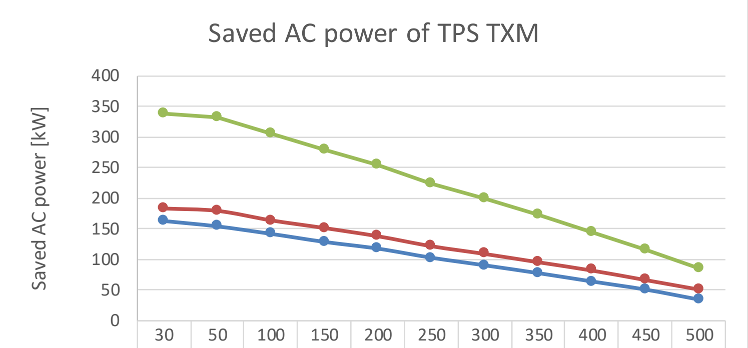
How to avoid control problems?

- The setting of klystron shall not just at its saturation power
  - Give more DC power to klystron (lower efficiency) and left control margin to LLRF
- Avoid sweeping cathode voltage
  - Keep cathode voltage at constant: no change station phase
  - Save less power but stable operation

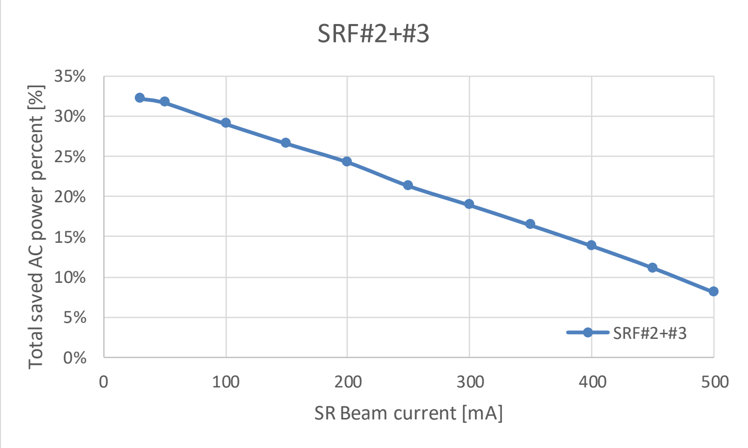


The power saving effect

- Saved AC power: compared to original constant setting
  SRF#2: 526.4 kW AC power
  SRF#3: 521.4 kW AC power
- The horizontal scale is SR beam current
  - As beam current is lower, the energy saving effect will be higher
  - The energy saving effectiveness is obvious for lower RF power requirement of each TXM



	30	50	100	150	200	250	300	350	400	450	500
SRF#2	162.9	154	141.7	128.4	117.3	102.3	89.7	76.8	63.1	49.7	33.2
SRF#3	182.4	178.6	163.3	150.8	137.5	121.4	108.8	95.4	82	66.6	51.2
Total	338.1	332.6	305	279.2	254.8	223.7	198.5	172.2	145.1	116.3	84.4

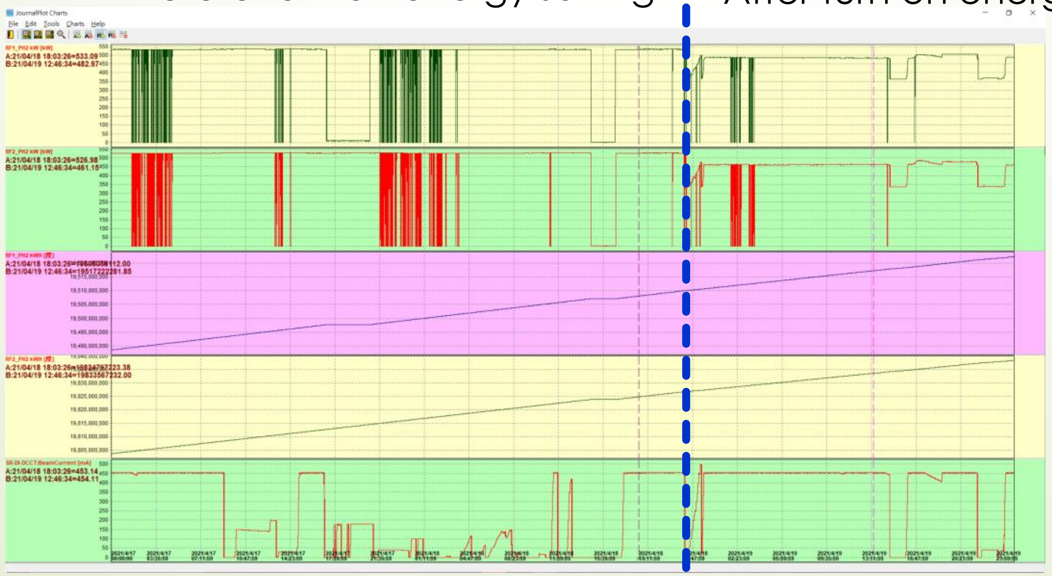


Power saving results of practical operation with SR beam current

- As turning on energy saving module :
  - The AC power consumption is lower and will change with the variation of SR beam current
- For 450mA SR beam current (daily operation value in 2021)
  - SRF#2: 533kW → 482kW, ΔP=51kW
  - SRF#3: 526kW → 461kW, ΔP=65kW
- Total: 116kW (**11.4%** power saving)

Before turn on energy saving

After turn on energy saving



SRF#2 TXM AC power

SRF#3 TXM AC power

SRF#2 TXM AC energy

SRF#3 TXM AC energy

TPS SR Beam current

Power saving effect statistic

- The power saving effect will be determined by the beam current distribution among machine operation shifts
- A statistic of beam current usage is listed below,
  - So far, the maximum saved energy is around **86000 kWh** in a routine user beam time per month

Item	Duration (hr)	Percent [%]	Saved AC power [kW]	Saved AC energy /month[kWh]
CPL aging	4	0.56	250 kW	1000 kWh
Low beam (30mA) current machine study	24	3.37	338 kW	8112 kWh
High beam (500mA) current machine study	72hr (3days)	10.11	84 kW	6048 kWh
User beam time (450mA)	612hr (25days+3shifts)	85.96	116 kW	70992 kWh
Total	29day+16hr (8hr OFF)	100		86152 kWh (11.4% power saving)

Conclusion & discussion

- An **adaptive control of operation parameters of klystron** by PLC can have higher DC-RF efficiency and save energy
- Tuning **the cathode and anode voltage both** can save much more energy but will **change RF plant station phase** significantly and cause system trip eventually due to **RF power racing** between two RF plants
- Add **klystron phase lock loop** may fix the station phase of RF plant as cathode voltage is tuning → save more energy
- Tune **anode voltage only** according to the required RF power will save less AC power but have **constant station phase**
- The principle of energy saving operation
  - Maintain proper control margin: LLRF cannot work too close to its saturation point → loose the setting and spend more energy
  - The setting of lower RF power can save more energy
- Besides energy saving, the stability of system still remains the major concern

Thanks for your attention