The Energy Efficiency of High Intensity Proton Driver Concepts

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On behalf of the Working Group of the Eucard^2 Workshop on Proton Driver Efficiency :

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Outline

- Motivation
- PSI Cyclotron of the High Intensity Proton Accelerator Facility
- Superconducting Pulsed Linac of the Spallation Neutron Source (SNS).
- Japan Proton Accelerator Research Complex (J-PARC)
- Summary

Motivation

- High power proton driver accelerators are used to generate secondary particles at high intensities, such as pions, muons, neutrons and ultra-cold neutrons or neutrinos.
- The applications of these facilities have a broad spectrum in the fields of particle physics and condensed matter physics. Another industrial application under discussion is Accelerator Driven Subcritical Reactors (ADS).
- The production of megawatt-class proton beams implies the consumption of electrical power on a large scale.

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Operating and planned facilities that utilize a high intensity proton driver accelerator.

	Neutrino	Muons	Neutrons	ADS	RIB's
Cyclotron	Daeδalus[1]	PSI-HIPA TRIUMF	PSI-HIPA	AIMA[2] TAMU-800[3]	TRIUMF RIKEN
RCS		J-PARC	J-PARC ISIS CSNS		
FFAG				KURRI +ongoing studies[4]	
s.c. Linac	PIP II [5]	PIP II [5]	SNS ESS ISNS[6]	ADSS[7] CIADS[8]	FRIB

operating
in construction
concept study

1 Decay-at-Rest Experiment for δcp studies At the Laboratory for Underground Science, MIT/INFN-Cat. et al
2 Accelerators for Industrial & med. Applications, reverse bend cyclotron, AIMA company
3 Cyclotron 800MeV, flux coupled stacked magnets, s.c. cavities, strong focusing channels, Texas A&M Univ.
4 FFAG studies, e.g. STFC
5 SRF linac, Proton Improvement Plan-II (PIP-II), Fermilab, Batavia
6 Indian Spallation Neutron Source, Raja Ramanna Centre of Advanced Technology, Indore, India
7 Accelerator Driven Sub-critical System at Bhaba Atomic Research Centre (BARC), Mumbai,India
8 China Initiative Accelerator Driven System, Huizhou, Guangdong Prov. & IMP, Lanzhou, China

- For each new generation of accelerator facilities we want better flux, rate, brightness, luminosity.

  → typically needs more power!

- Acceptance of these projects by authorities and the public becomes increasingly difficult.

→ Thus, one needs to work on that:

  – Improve efficiency of accelerators
  – Demonstrate efforts to improve efficiency to funding organizations / to public
  – Adapt our facilities to new sustainable energy production

- New projects and operating facilities must focus on improving the energy efficiency with a higher priority.

  This is especially true for linacs suggested for ADS-type applications, which may have to deliver >10 MW beams.

(generic) Powerflow in Accelerators

public GRID

Accelerator
- Radio Frequency
- Magnets
- Vacuum etc.

Auxiliary systems
- cryogenics
- conv. cooling, AC etc.

Instruments
- e.g. particle detectors

beam

conversion to secondary radiation (beam collisions, targets, undulators …)
efficiency?

direct beam application:
- p-therapy
- isotope production

secondary radiation
brightness, effective utilisation?
- **neutrons**
- **muons**
- **neutrinos etc.**
- exotic particles, e.g. Higgs, B-mesons
- synchrotron radiation

finally all converted to waste heat !

figure of merit:
secondary particles, X-rays on sample per KWh

Eucard^2 Workshop on Proton Driver Efficiency

Eucard^2 ?

EUCARD = Integrating Activity Project for coordinated Research and Development on Particle Accelerators, co-funded by European commission.

idea: comprehensive approach to cover the entire power chain from Grid to secondary radiation at the user.

goal: Assess state of the art and development potential for each stage.
(comparison of potential of each link in the chain)
R&D recommendations in each field.

❑ The goal :

- “Efficiency drivers” for different types of the proton drivers
- Wall-plug efficiency limits for the MW-range proton drivers
- The ways of the efficiency improvement
- New technologies should be developed for this.

❑ Proton Drivers:

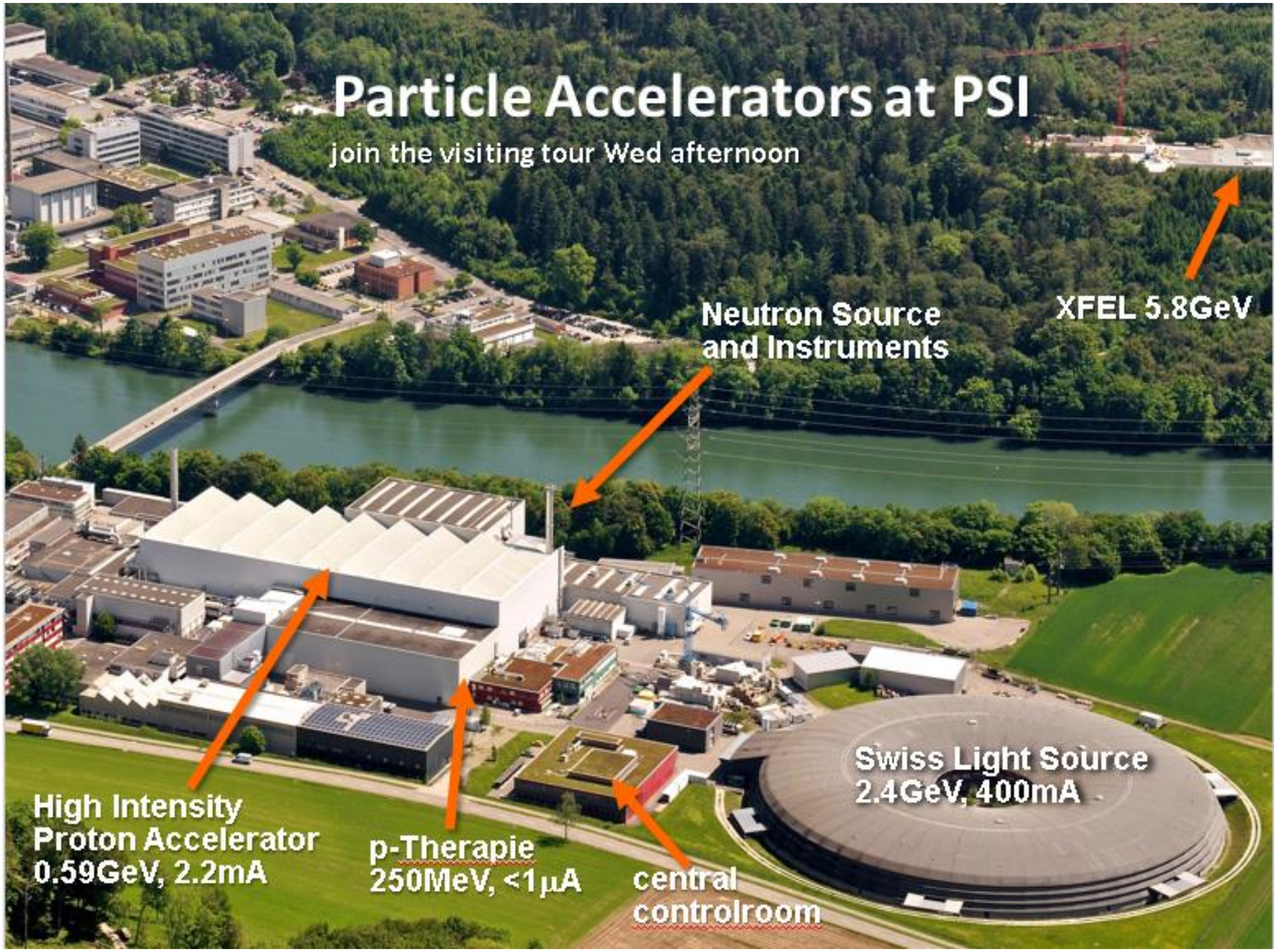
- GeV-energy range
- MW-power range
- Applications: neutrinos, muons, neutrons, ADS.

- Three operating accelerators for GeV- energy scale, MW beam power scale facilities are considered:
  - ***Cyclotron of the High Intensity Proton Accelerator Facility, PSI;***
  - ***Superconducting RF (SRF) Pulsed Linac of the Spallation Neutron Source, ORNL ;***
  - ***RCS and Main Ring of the Japan Proton Accelerator Research Complex, J-PARC .***
- The power consumption breakdown will be shown for three facilities, in order to understand the major energy efficiency drivers.
- "Efficiency": we consider a fraction of grid power converted to beam power, i.e., the ratio of the delivered beam power over the accelerator power consumption, including RF, magnetic system, cooling/cryogenics, but neglecting auxiliary systems and experimental facilities.

$$\eta = \frac{P_{beam}}{P_{magnet} + P_{RF} + P_{cooling} + P_{cryogenics}}$$

depend on beam loading (P_{RF}, $P_{cooling}$)

Cyclotron of the High Intensity Proton Accelerator Facility, PSI



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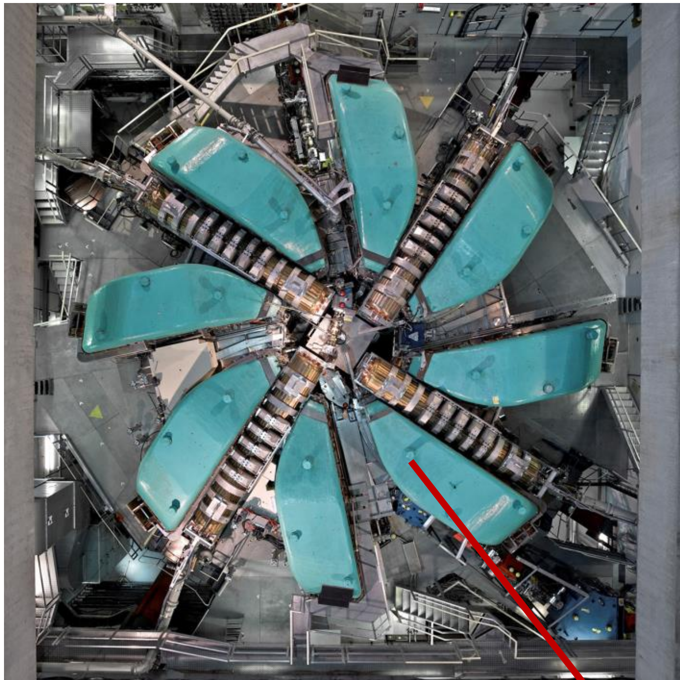
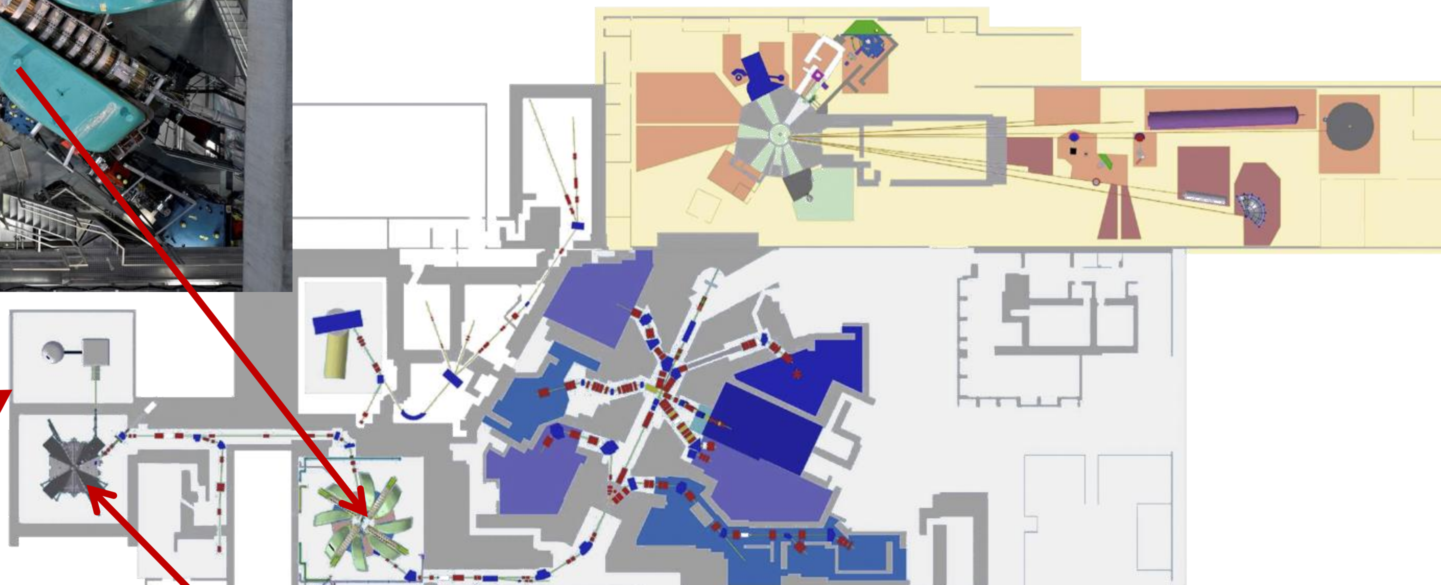
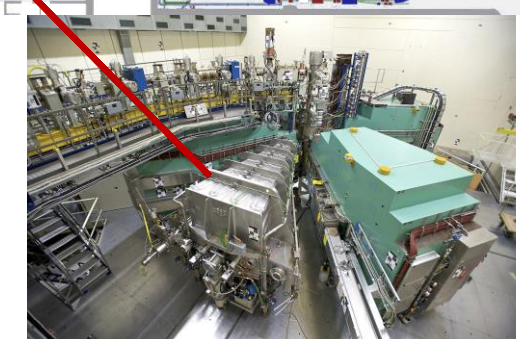


Ring Cyclotron: 590 MeV
2.4 mA
1.4 MW
186 turns
8 sector magnets

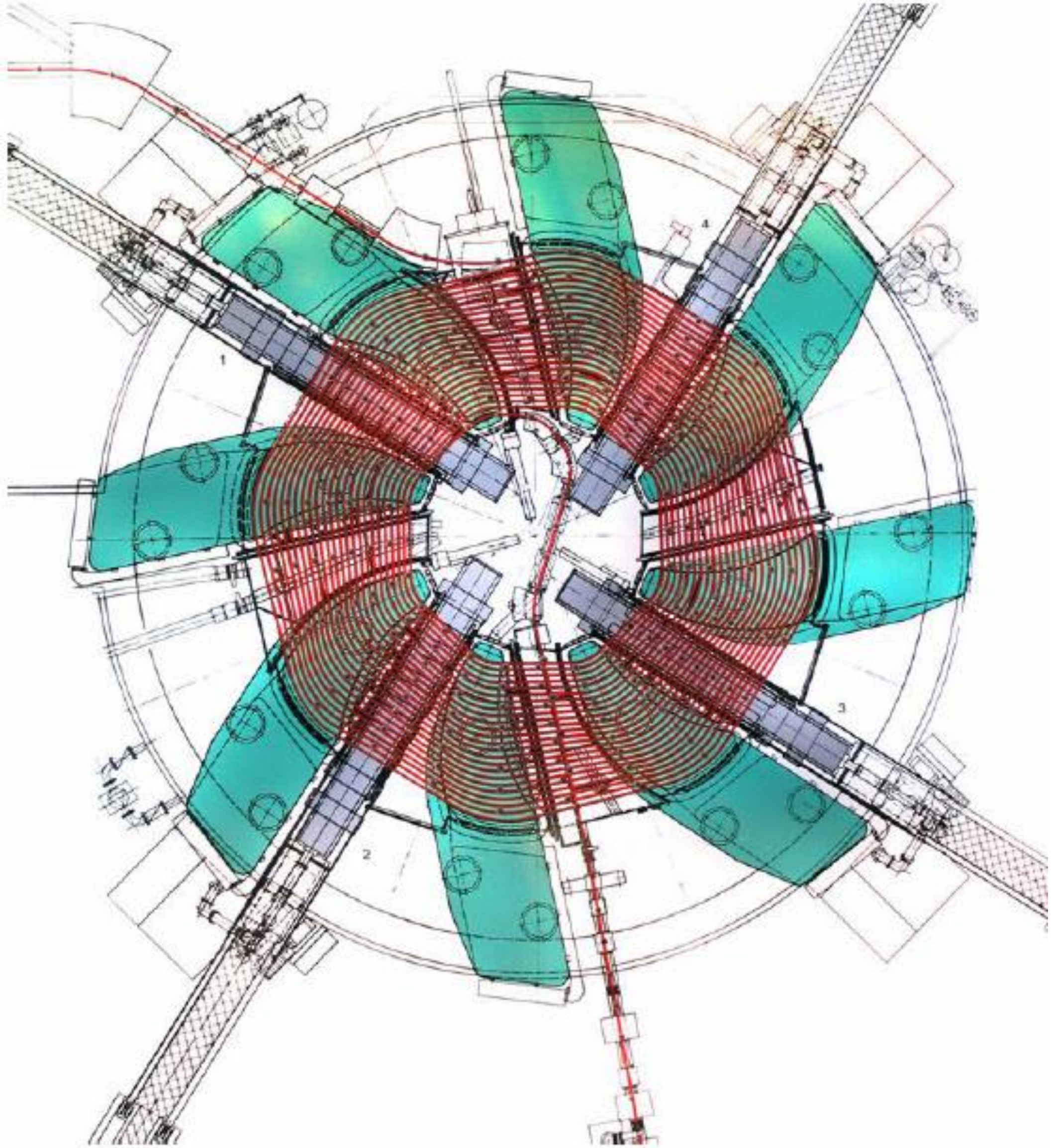




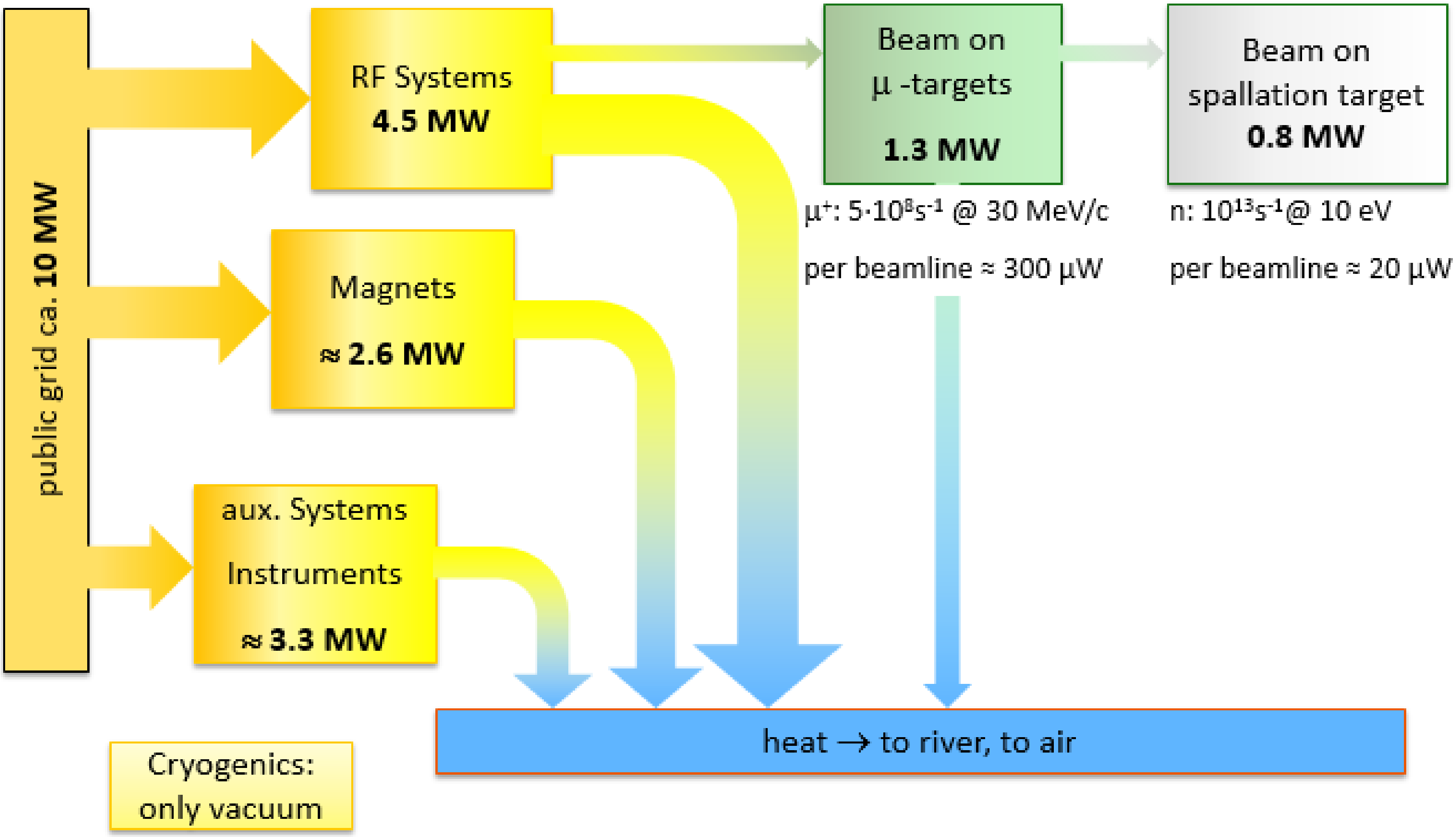
Injector 2: 2.7 mA, 72 MeV

Cockcroft-Walton: 10 mA, 870 keV

The 590MeV isochronous cyclotron at PSI with a diameter of 15m



Grid to Beam Power



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Copper Cavities at PSI

- f = 50.6 MHz
- U_{max} = 1.2 MV (presently 0.85 MV)
- Q = $4.8 \cdot 10^4$
- Transfer of up to **400 kW power to the beam** per cavity

Wall plug to beam efficiency:

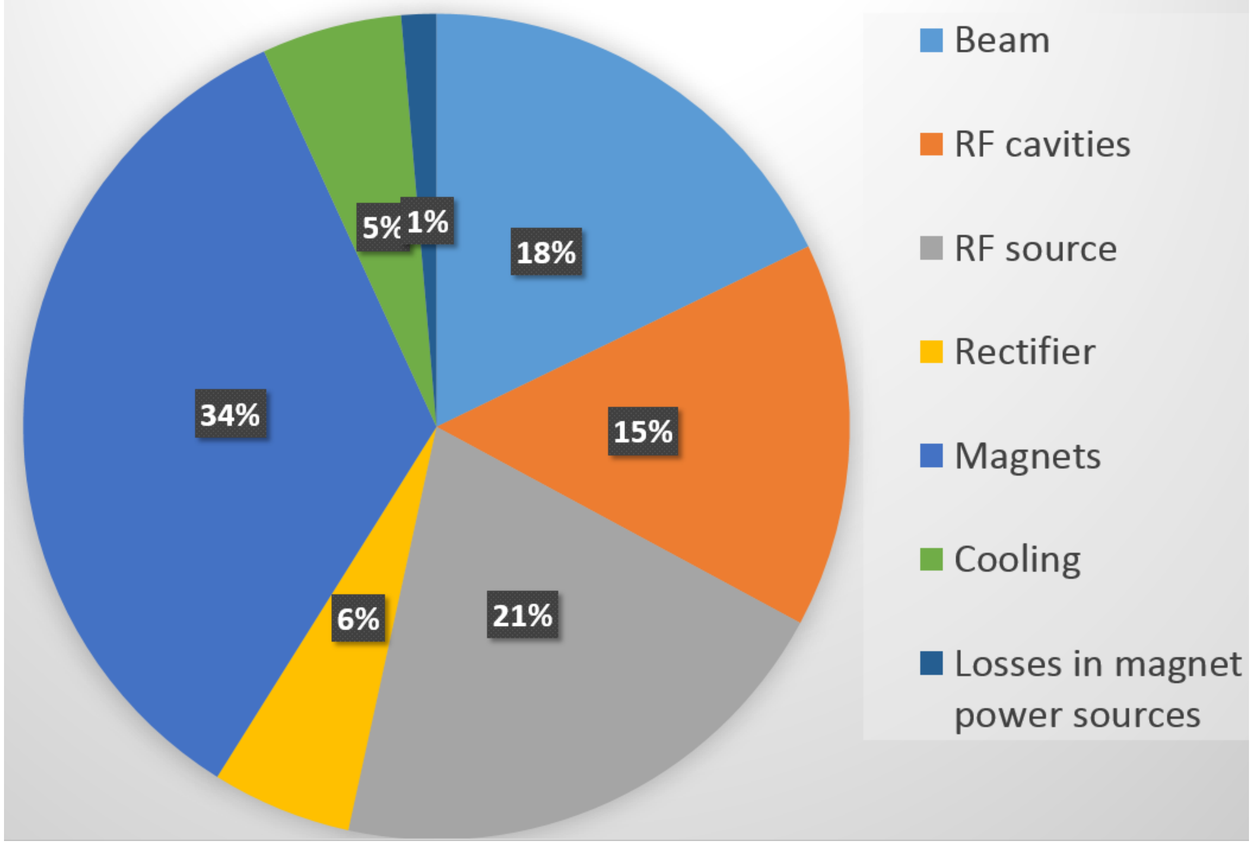
- AC/DC: 90%
- DC/RF: 64%
- RF/beam: 55%
- **All over: 32%**

Inside the resonator

hydraulic tuning devices (5x)

Power consumption breakdown excluding the auxiliary systems.

- ❑ The magnet system consumes 2.6 MW;
- ❑ The entire consumption of the RF system is 4.5 MW;
  - The Ohmic losses in the cavies are about 1.2 MW;
  - Losses in the RF sources are 1.5 MW;
  - Losses in the rectifier are 400 kW.
- ❑ Cooling circuit efficiency is 94%.



The entire efficiency is 18%

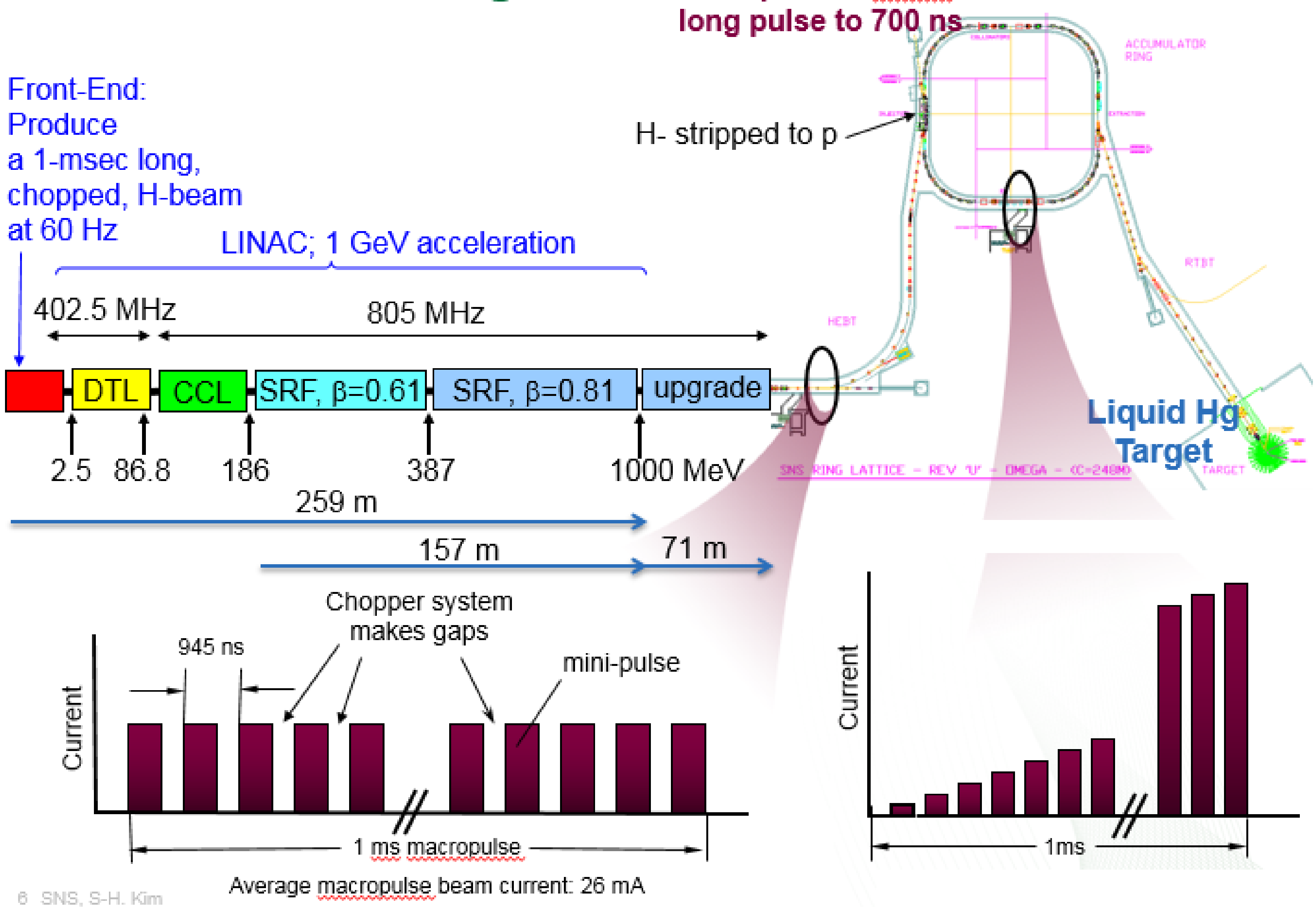
The beam current increase up to 3 mA leads to the beam loading increase and consequently, efficiency increase up to 24%.

"Efficiency drivers":

- Losses in the magnets (34%)
  - Utilization of the superconducting sector magnets. The world's first ring superconducting cyclotron is the 2.6 GeV cyclotron, which provides acceleration of a broad spectrum of ions up to Uranium. It is in operation at RIKEN Nishina.
- Losses in RF sources (21%).
- Losses in the cavities (15%).

Superconducting RF (SRF) Pulsed Linac of the Spallation Neutron Source, ORNL

SNS Machine layout



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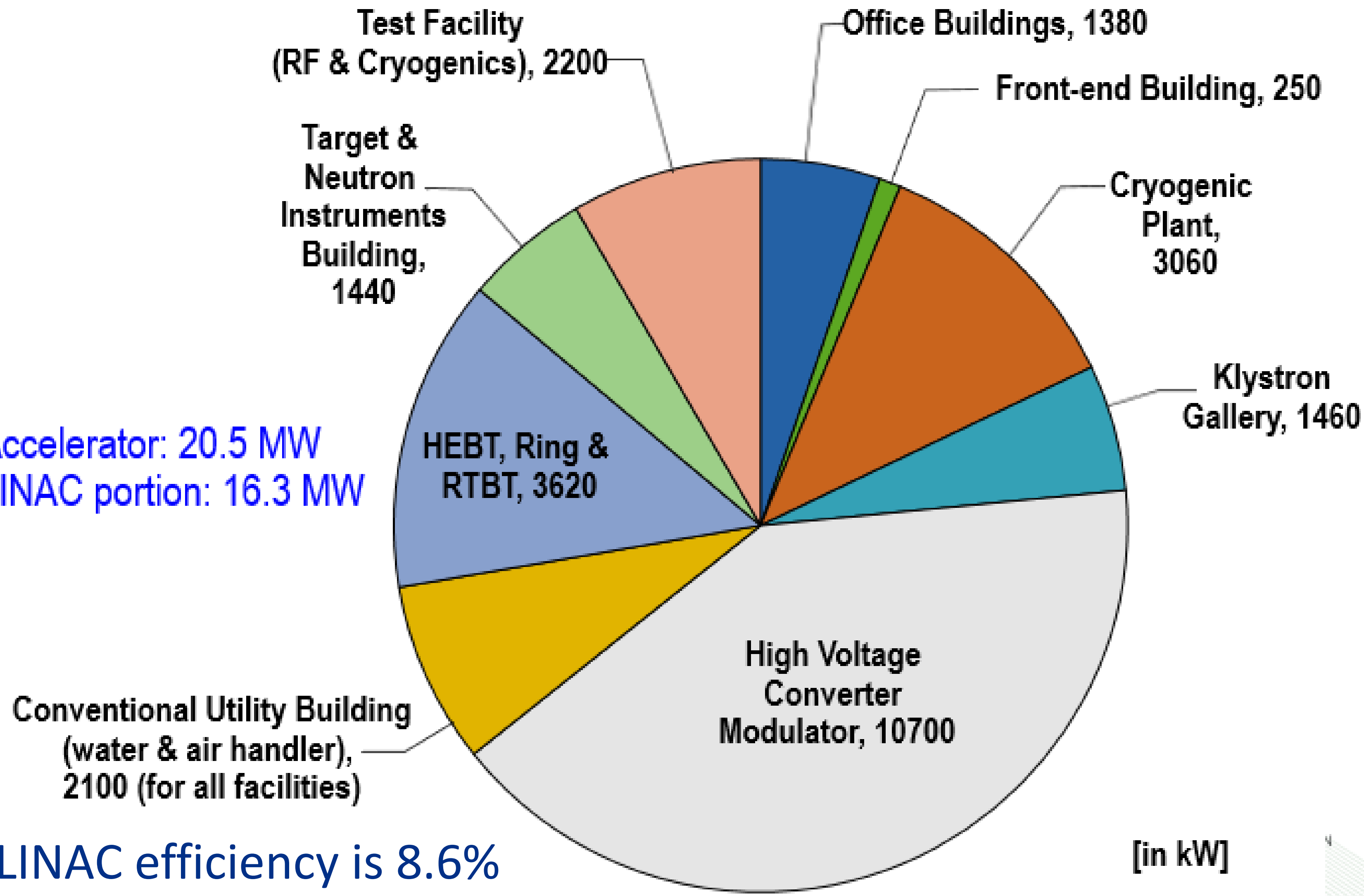
Breakdown of electric power consumption by systems during 1.4 MW operation; 26.3 MW



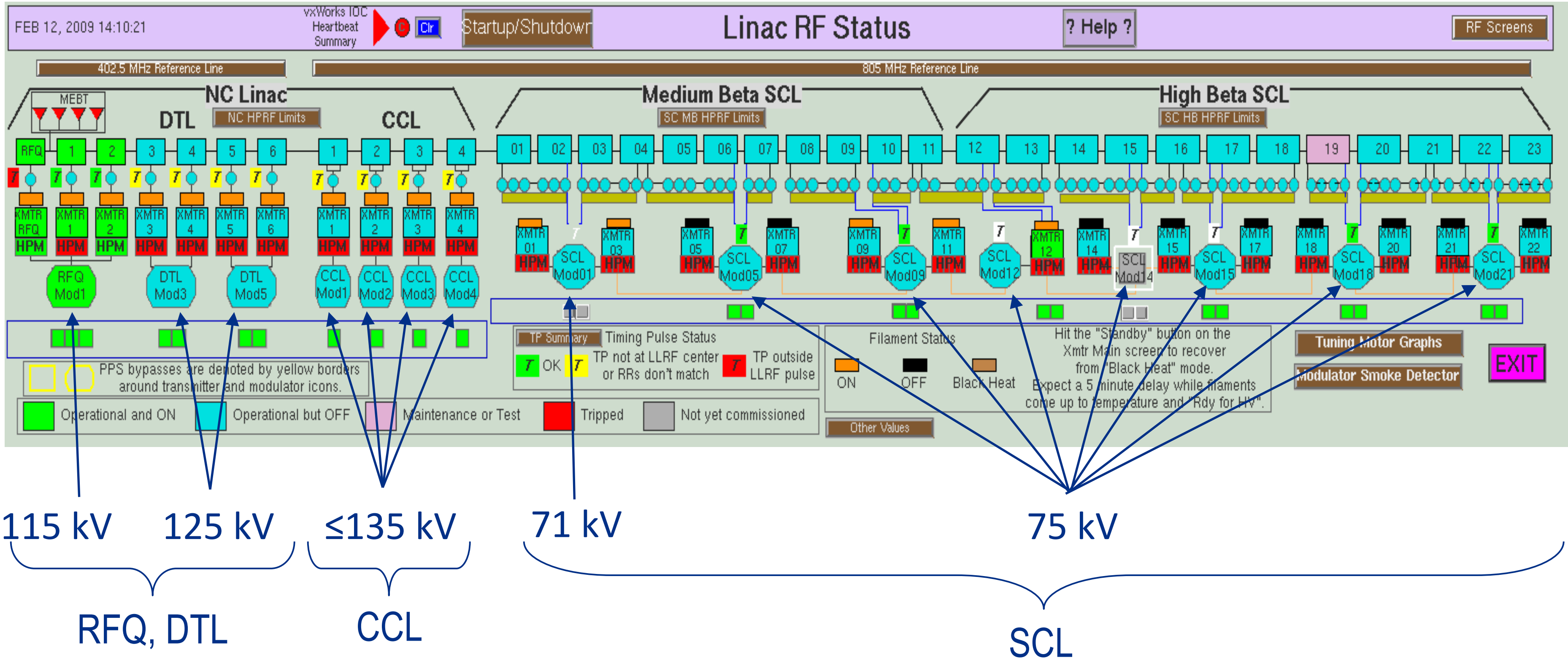
Accelerator: 20.5 MW
LINAC portion: 16.3 MW

LINAC efficiency is 8.6%

Subsystems of the Linac

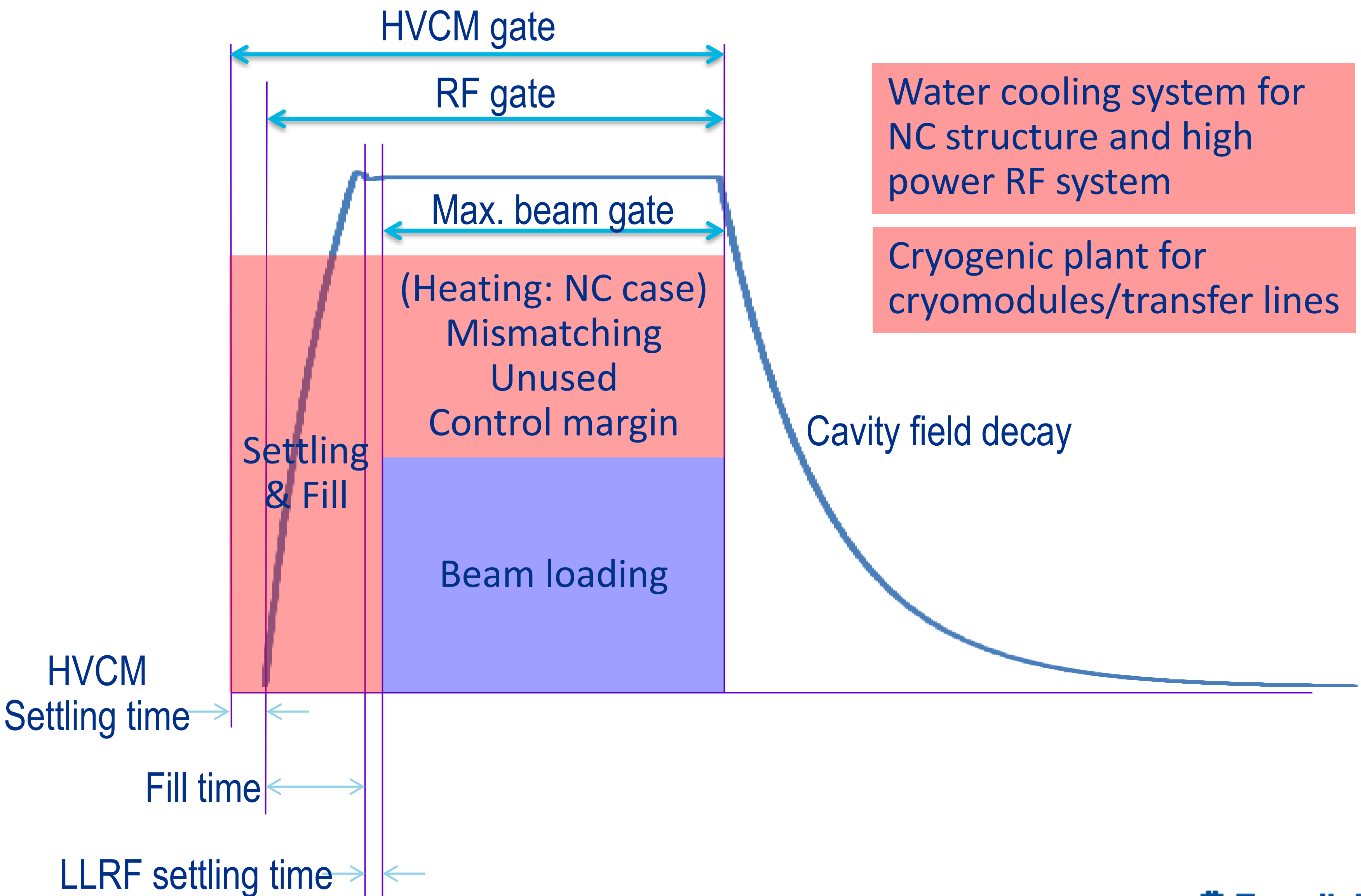
- **Front-end**
  - Ion source, RFQ, Medium energy beam transport
- **Klystron Gallery**
  - Transmitter, vacuum, control, magnet power supply, local pumps, local HVAC, etc.
- **Conventional Utility Building**
  - Compressed air handler, Cooling tower, Chilled water, Hot water
- **Accelerating Structures**
- **High Voltage Converter Modulator (HVCM)**
  - Located in the Klystron Gallery, but has separate electric feeder
  - 15 HVCMs
- **Cryogenic Plant**
  - Warm compressors, 4K cold box, 2K cold box, etc.

SNS High Power RF configuration

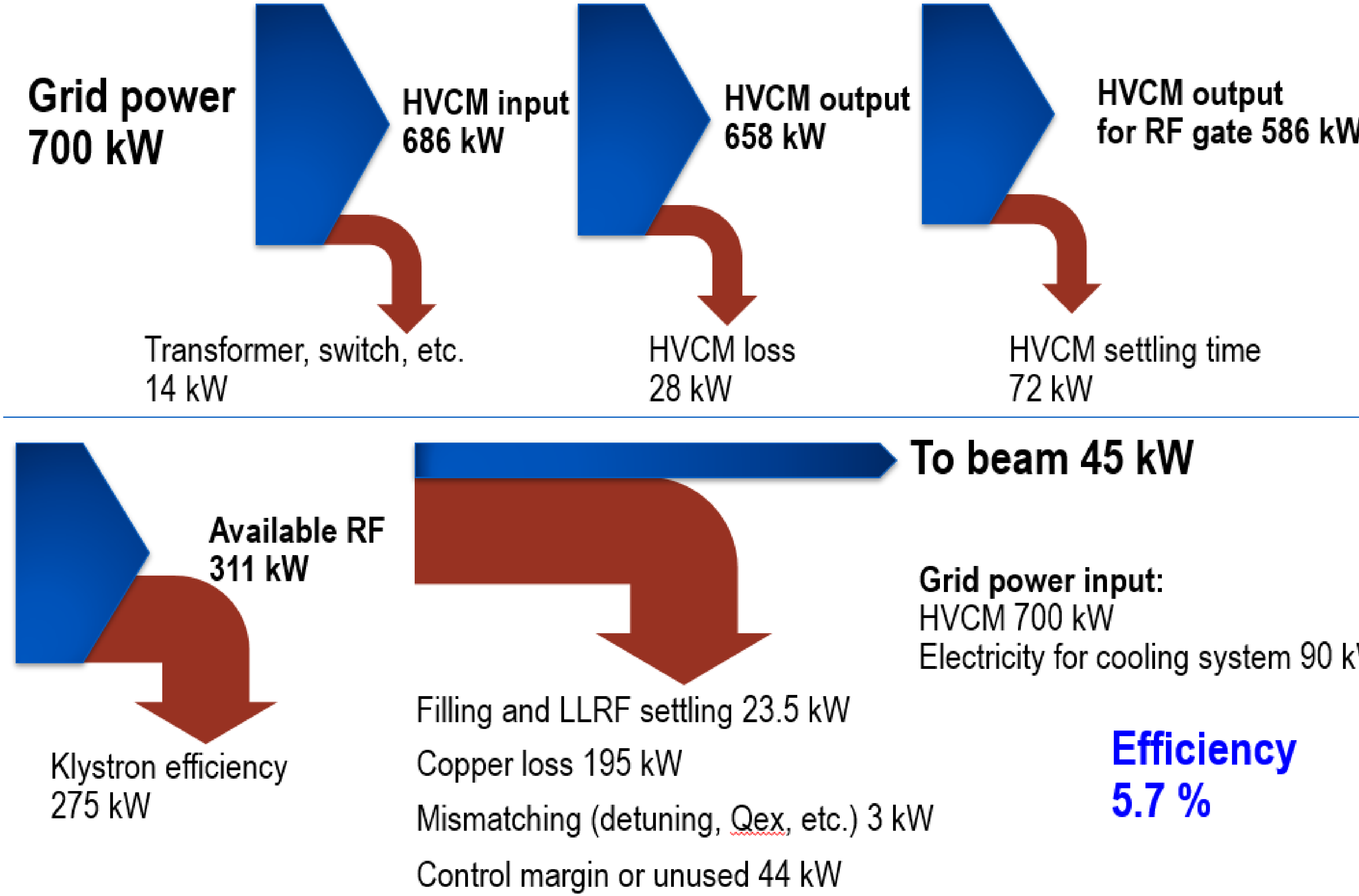


- 15 HVCMs
  - 3 HVCMs for 1 RFQ and 6 DTL (2.5 MW 402,5 MHz klystron x 7)
  - 4 HVCMs for 4 CCL (5 MW 805 MHz klystron x 4)
  - 8 HVCMs for 81 SRF cavities (0.55 MW 805 MHz klystron x 81)

Pulse Structure at SNS



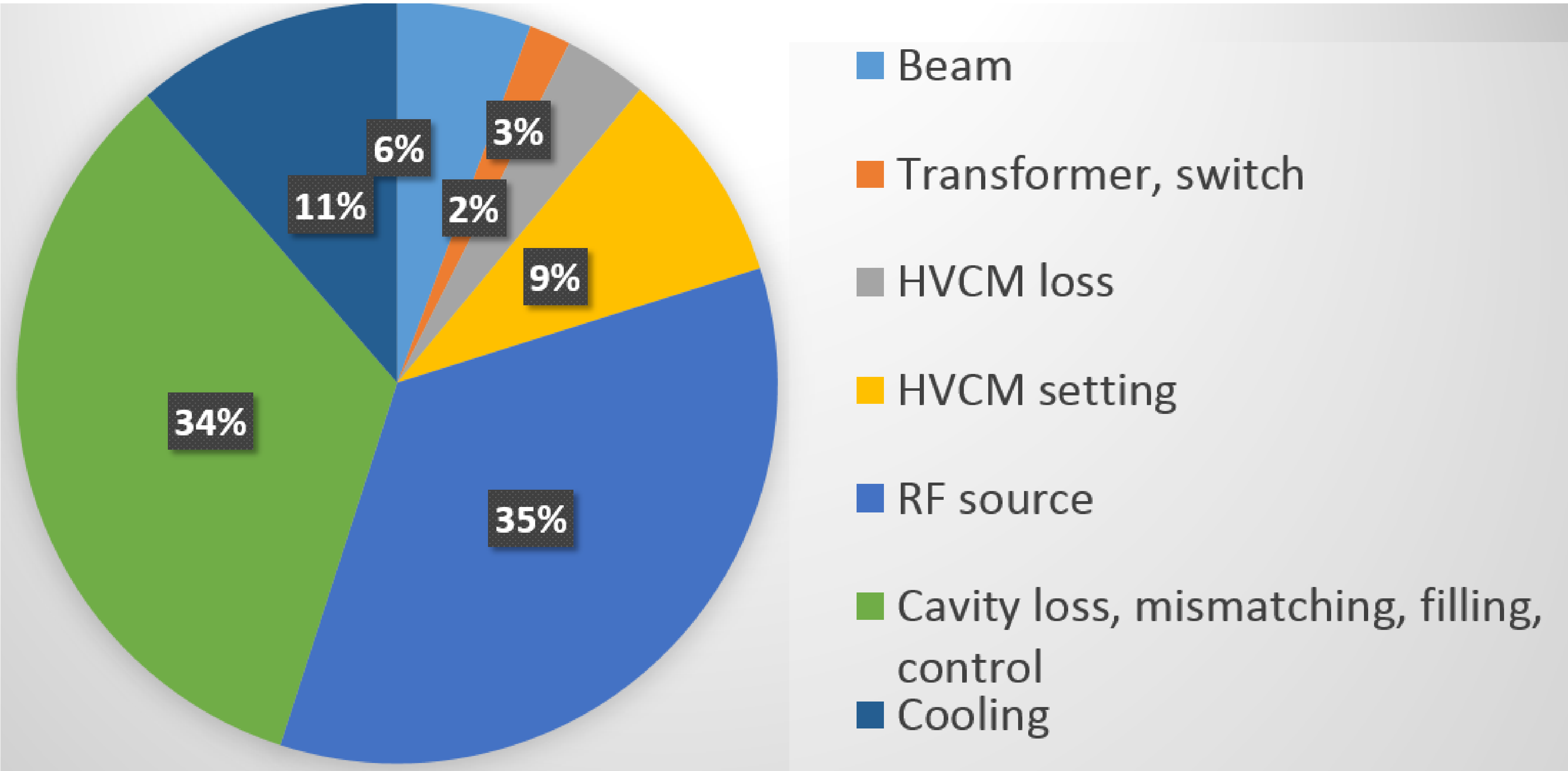
Power flow from grid to beam during 1.4 MW operation (CCL module 4)



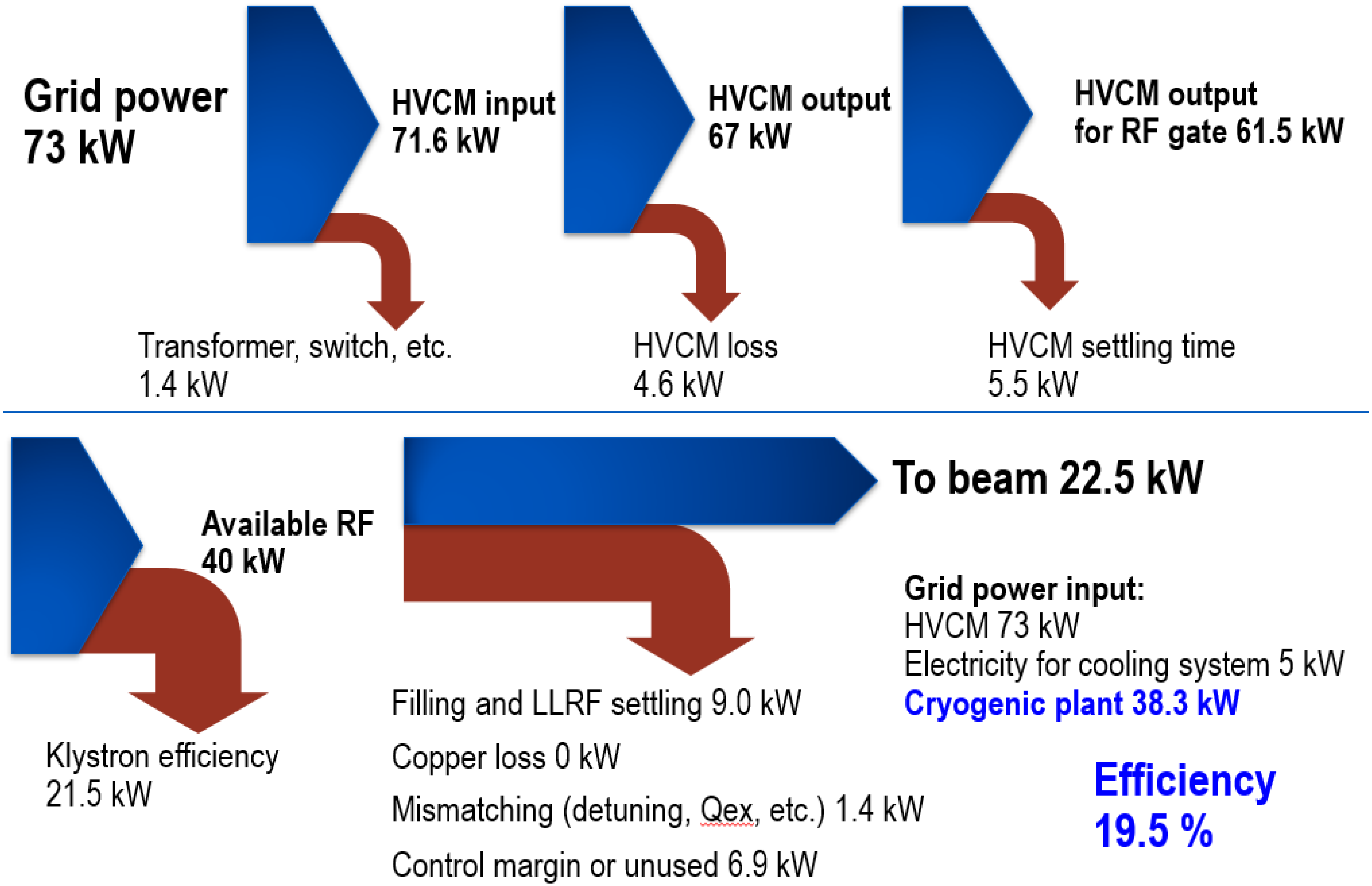
Grid power input:
HVCM 700 kW
Electricity for cooling system 90 kW

Efficiency
5.7 %

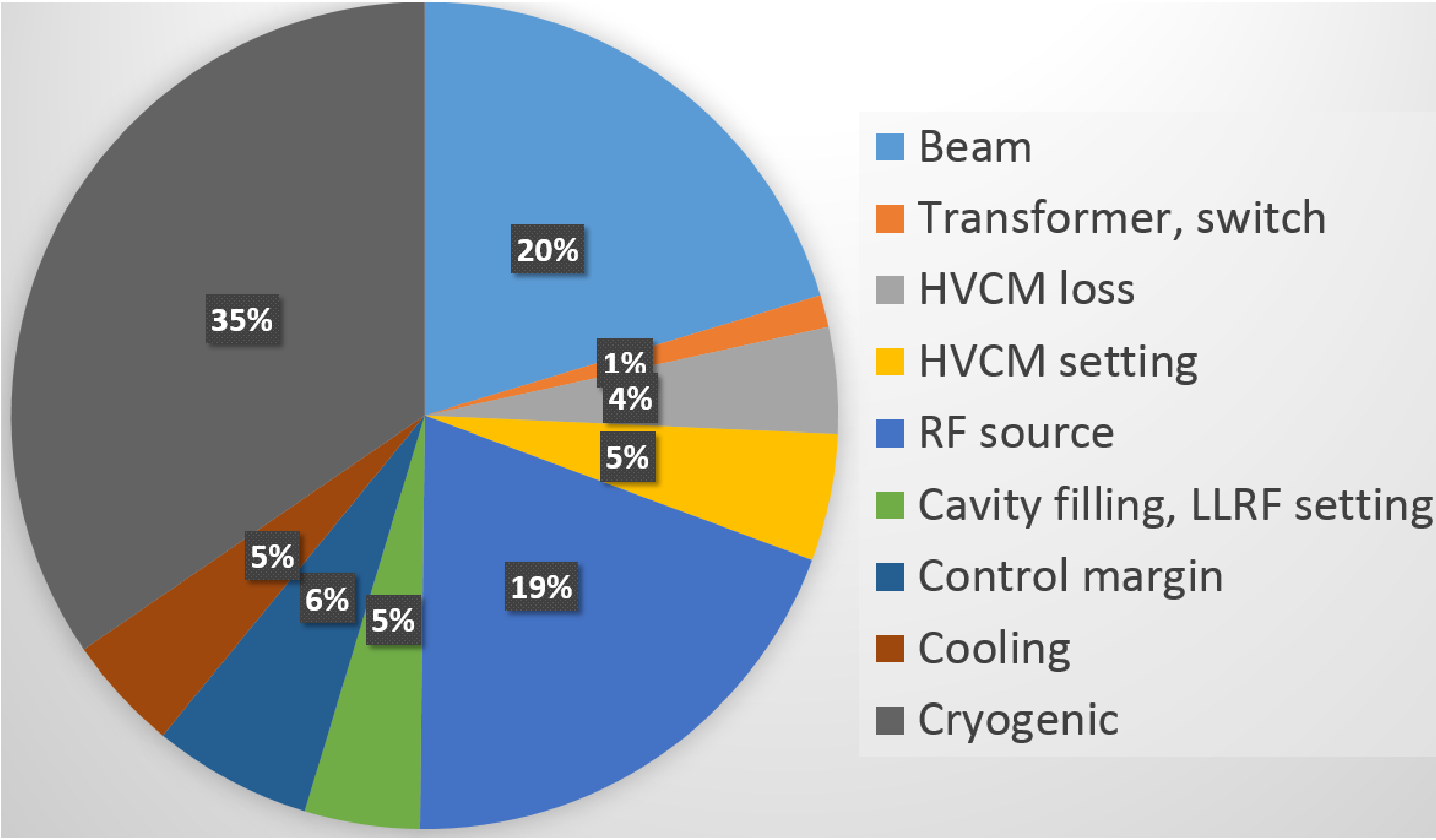
Power consumption breakdown (CCL module 4)



Power flow from grid to beam during 1.4 MW operation (Ex. SRF cavity; 20d)



Power consumption breakdown (SRF cavity; 20d)



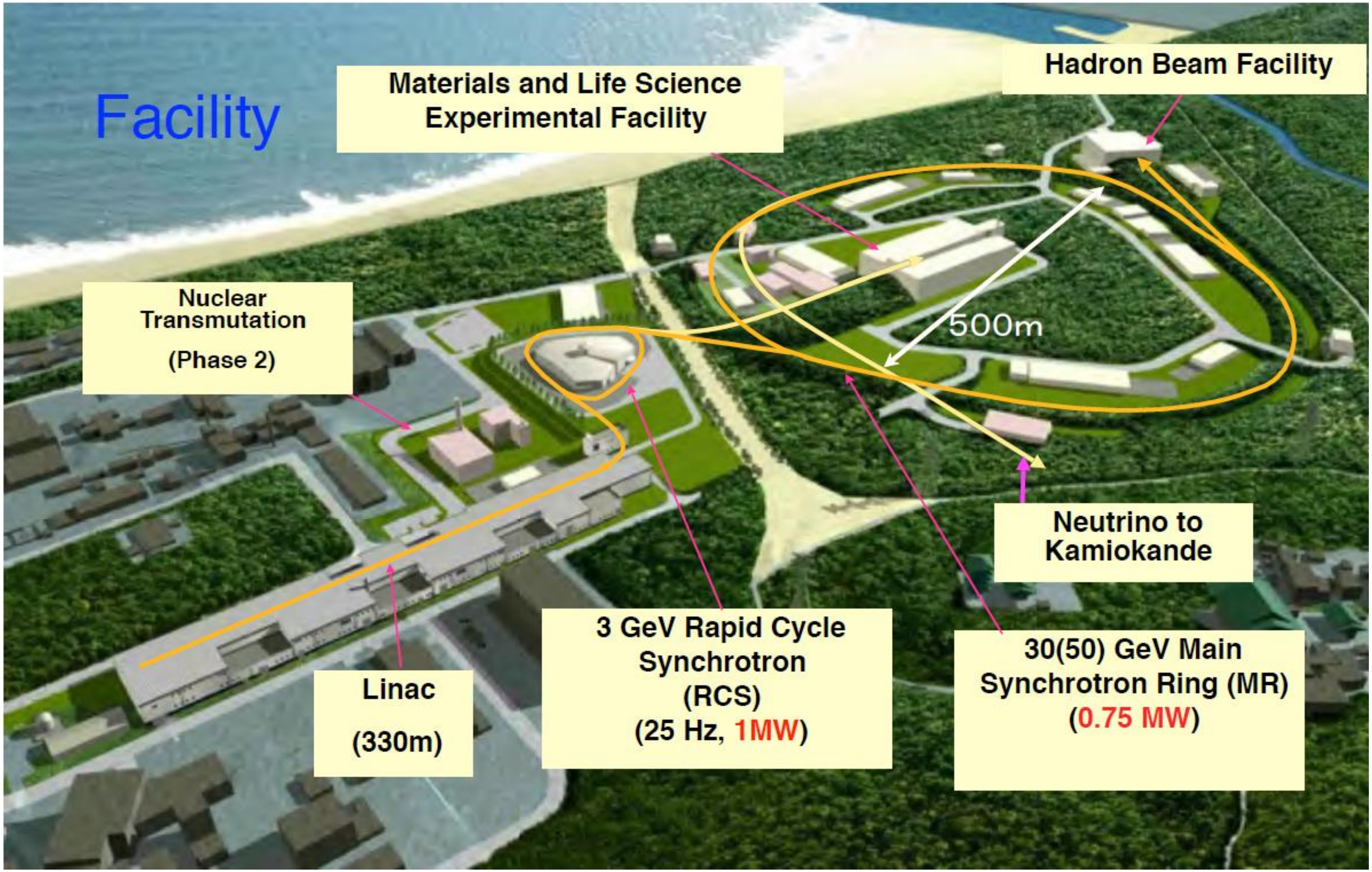
Areas for further improvement

Currently SNS is working on those

- RF and SRF
  - Cavity performance (general)
  - Settling time (high power machine)
  - Control margin (general)
  - Fill time (high Qex machine)
  - Mismatching (low beam loading)
- Cryogenic and SRF
  - Turn down capability (general)
  - Cryogenic efficiency (general)
  - Static loss (low duty)
  - Dynamic loss (high duty)

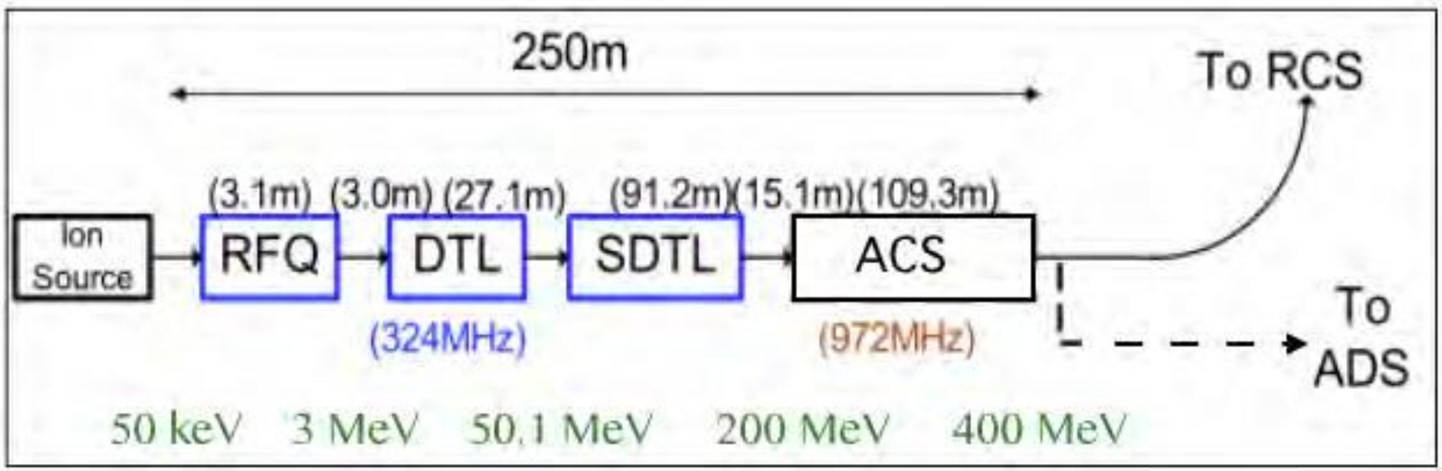
Japan Proton Accelerator Research Complex (J-PARC)

Joint Project between KEK and JAEA



Proton Linac:

• Major Parameters
– Accelerated particles: H- (negative hydrogen)
– Energy: 400 MeV, SDTLs and ACS
– Peak current: 40 mA (~ 50 mA for 1MW at 3GeV)
– Repetition: 25 Hz (additional 25 Hz for ADS application)
– Pulse width: 0.5 ms (beam pulse), 0.65 ms (for RF pulse)



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Synchrotron Rings (RCS and MR)

Features

- Magnetic alloy loaded cavity:
- High field gradient > 20kV/m
- Multi-harmonic forward beam-loading compensation
- MR: Slow and fast extractions for nuclear and particle physics experiments

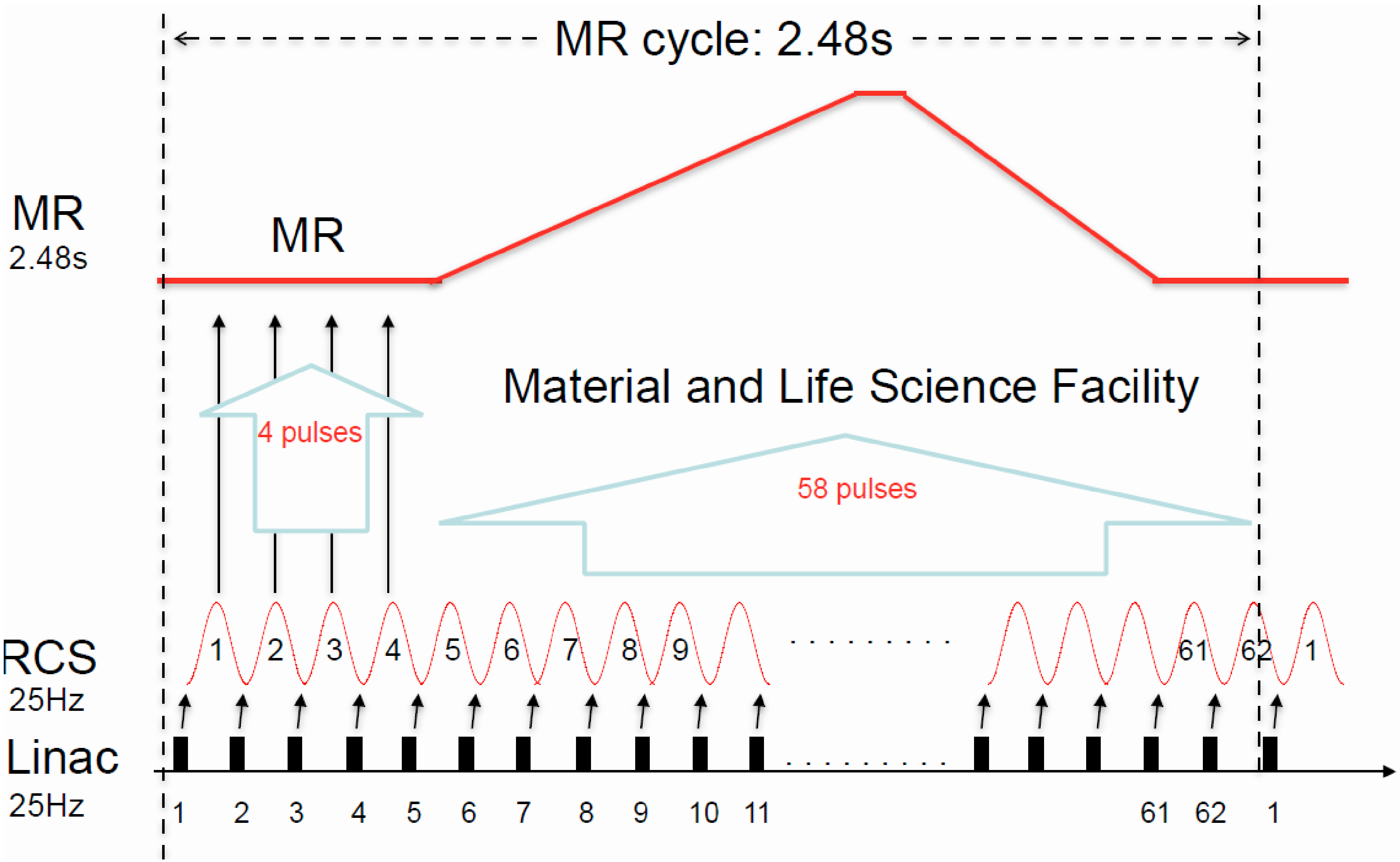
3GeV Rapid cycling synchrotron (RCS)

Circumference	348.3 m
Injection energy	400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Output beam power	1 MW
Harmonic number	2
Accel. peak voltage	420 kV

Main ring synchrotron (MR)

Circumference	1567.5 m
Injection energy	3 GeV
Extraction energy	30 [50] GeV
Repetition rate	$^{1}/2.48s$ [$^{1}/3.64s$]
Output beam power	0.75 MW
Harmonic number	9
Accel. peak voltage	280 kV

Operation cycle:



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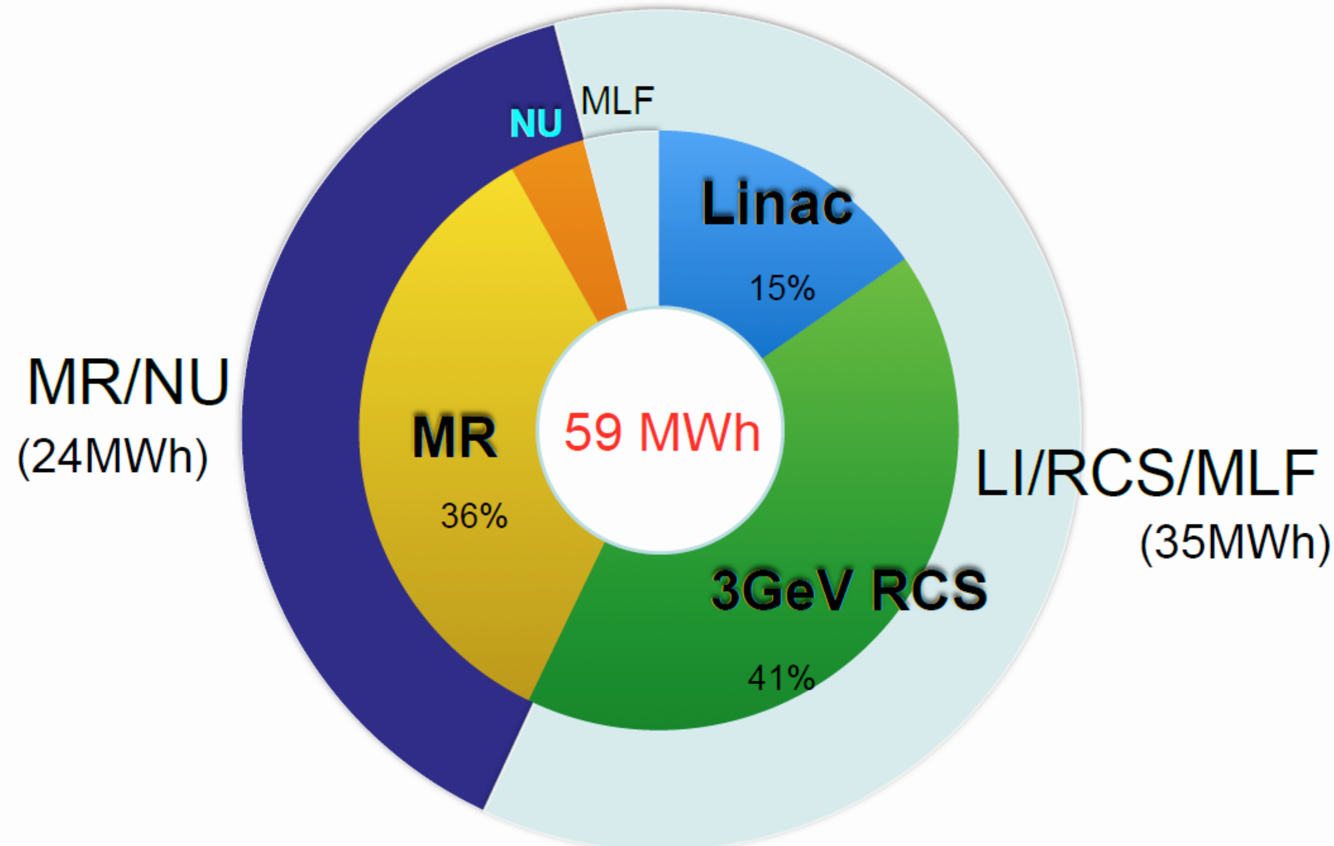
The RF power consumption breakdown for the J-PARC facility.



- MR Magnets: **10.3 MWh** per hour
- MR RF: **5.6 MWh** per hour
- RCS Magnets: **9.6 MWh** per hour
- RCS RF: **7 MWh** per hour

Linac and RCS: Power consumption: 32.6 MW; beam power: 1 MW

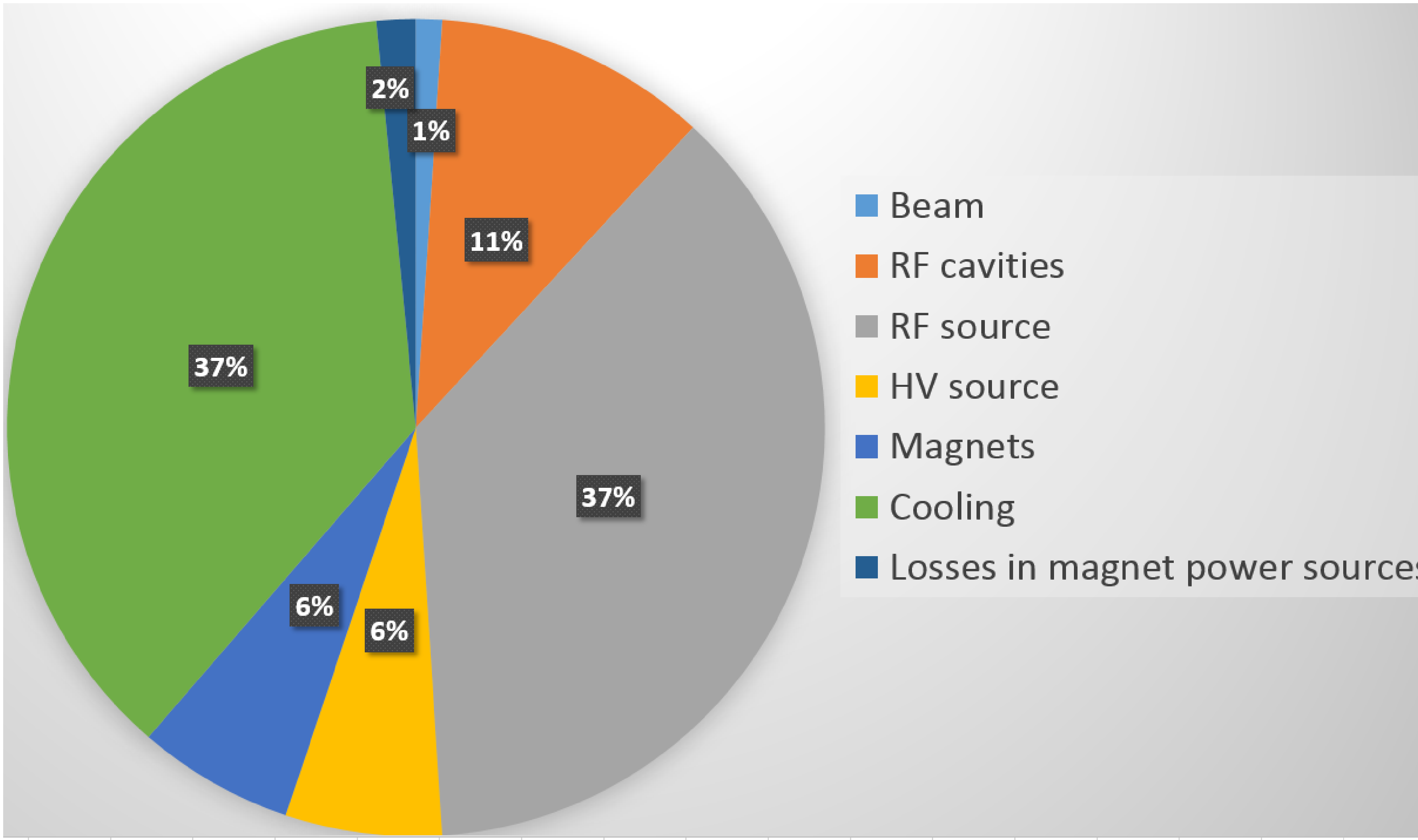
Efficiency ~3%

A number of improvements are in process of implementation:

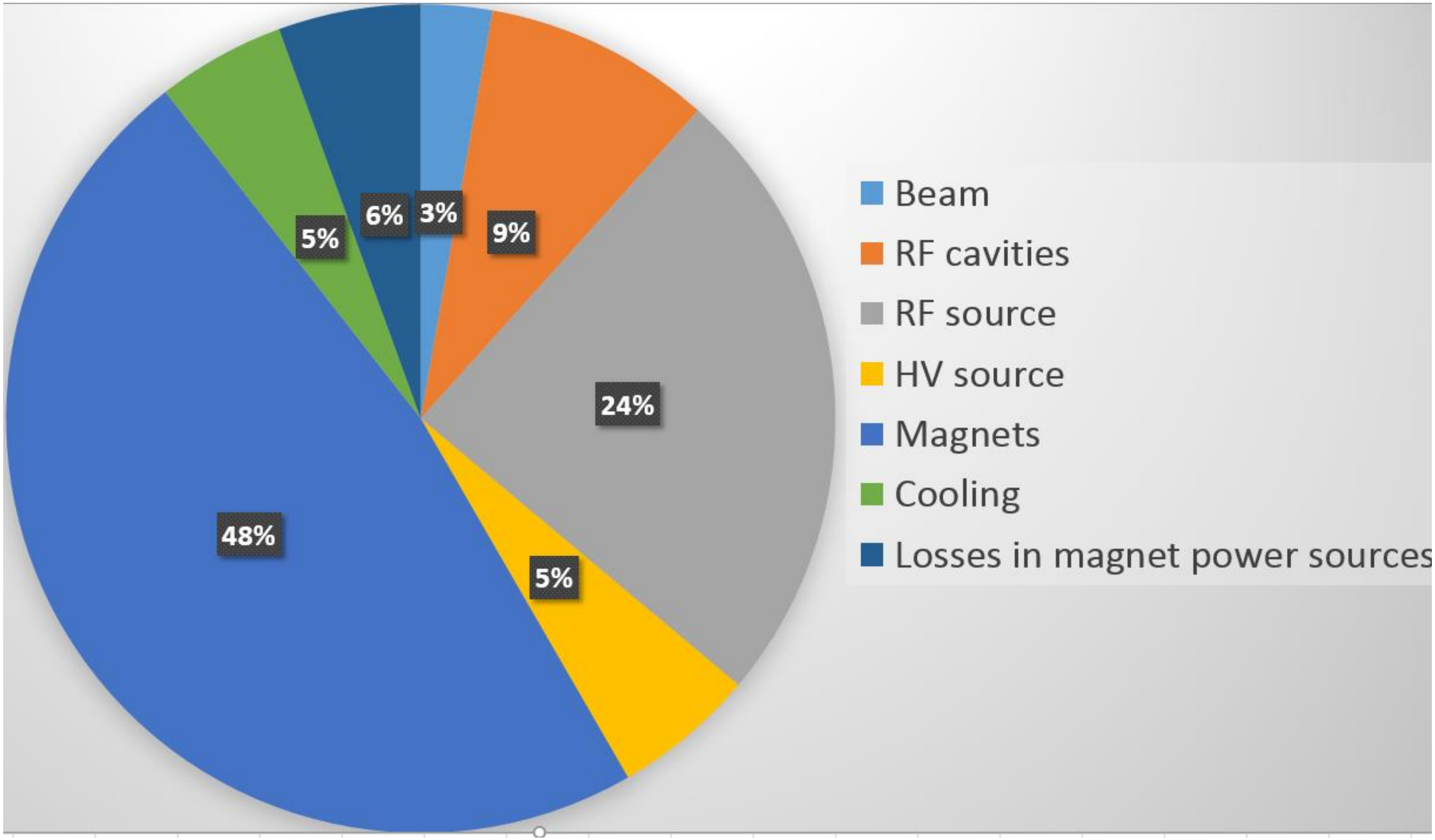
- New power supplies with capacitive energy storage for the main magnets are under development. The power variation at the electrical system keeps its present value even after the upgrade.

- High gradient RF cavities loaded with high performance magnetic alloy (FT-3L) cores started to be installed. The total loss with these cavities is half of that with existing cavities.

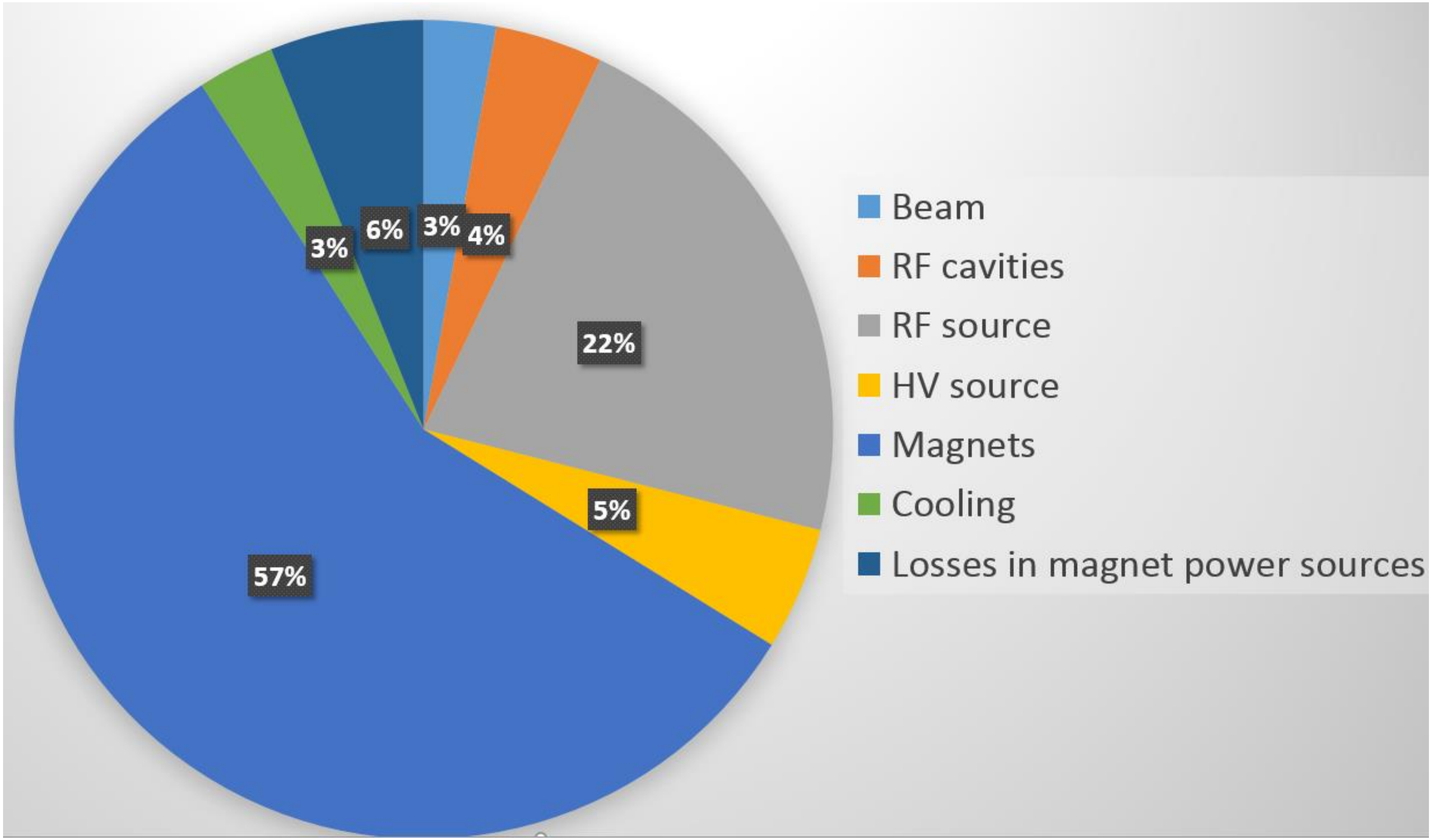
Power consumption breakdown in the J-PARC linac



Power consumption breakdown in the J-PARC RCS



Power consumption breakdown in the J-PARC MR



	PSI cyclotron	SNS linac	J-PARC linac and RCS
Beam energy	0.59 GeV	1 GeV	3 GeV
Beam Power	1.4 MW	1.4 MW	1 MW
Power consumption	4.5 (RF) in total 10 MW	16.3 MW	32.6 MW
Fraction of grid power converted to beam power	~18-19%	~9%	~3%

	PSI Cyclotron	SNS RT part	SNS SC part	JPARC linac	JPARC RCS	JPARC MR
Beam energy	72-590 MeV	186 MeV	186-1000 MeV	400 MeV	0.4-3 GeV	3-30 GeV
Beam power	1.24 MW	0.26 MW	1.4 MW	67 kW [0.133MW]	0.5 MW [1MW]	0.47 MW [0.75MW]
Total RF consumption from the plug	4.5 MW	4.8 MW	5.9 MW	3.6MW	7 MW	5.6 MW
Losses in the RF cavities	1.4 MW	1.2 MW	~ 0 MW	0.70MW (inc. WG loss+Pr)	1.6 MW	0.7 MW
Losses in the RF sources	1.56 MW	1.8 MW	1.7 MW	2.4MW	4.4 MW	3.6 MW
Losses in the HV sources	0.3 MW	0.2 MW	0.3 MW	0.4MW	7*15% =1 MW	5.6*15% =0.8 MW
Total Power consumption for magnets	2.6 MW	0.05 MW	0.15 MW	0.4MW (inc. cable loss)	9.6 MW	10.4 MW
Losses in the power sources	0.1	~ 0 MW	~ 0 MW	0.1MW	9.6*10% ~1MW	=10.4*10% =1 MW
Cooling (water and air)	0.4 MW	0.9 MW	0.4 MW	2.6MW	0.9MW	0.5 MW
Refrigeration	~0 MW	N/A	3.1 MW	N/A	N/A	N/A

Summary

- Further development of existing types of accelerators and related technology in order to reach higher efficiency:
  - Cyclotrons;
  - SRF linacs;
  - RSCs

  Related technology:
  - SC (including HTS) and permanent magnets;
  - SRF and RT cavities with low losses (especially high Q_0 and resonance control for SRF);
  - Capacity energy storage for synchrotron magnets.

- New or alternative ideas and approaches should be developed for both new and explored basic accelerator parameters
  - FFAG;
  - Other new ideas.

- RF is an important "efficiency driver" for all the considered accelerators. New high efficiency RF sources and operation techniques should be developed:
  - high-efficiency klystrons,
  - magnetrons.

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