

Power Efficiency Estimations for a High Intensity Proton Linac

THPO008

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TRIUMF

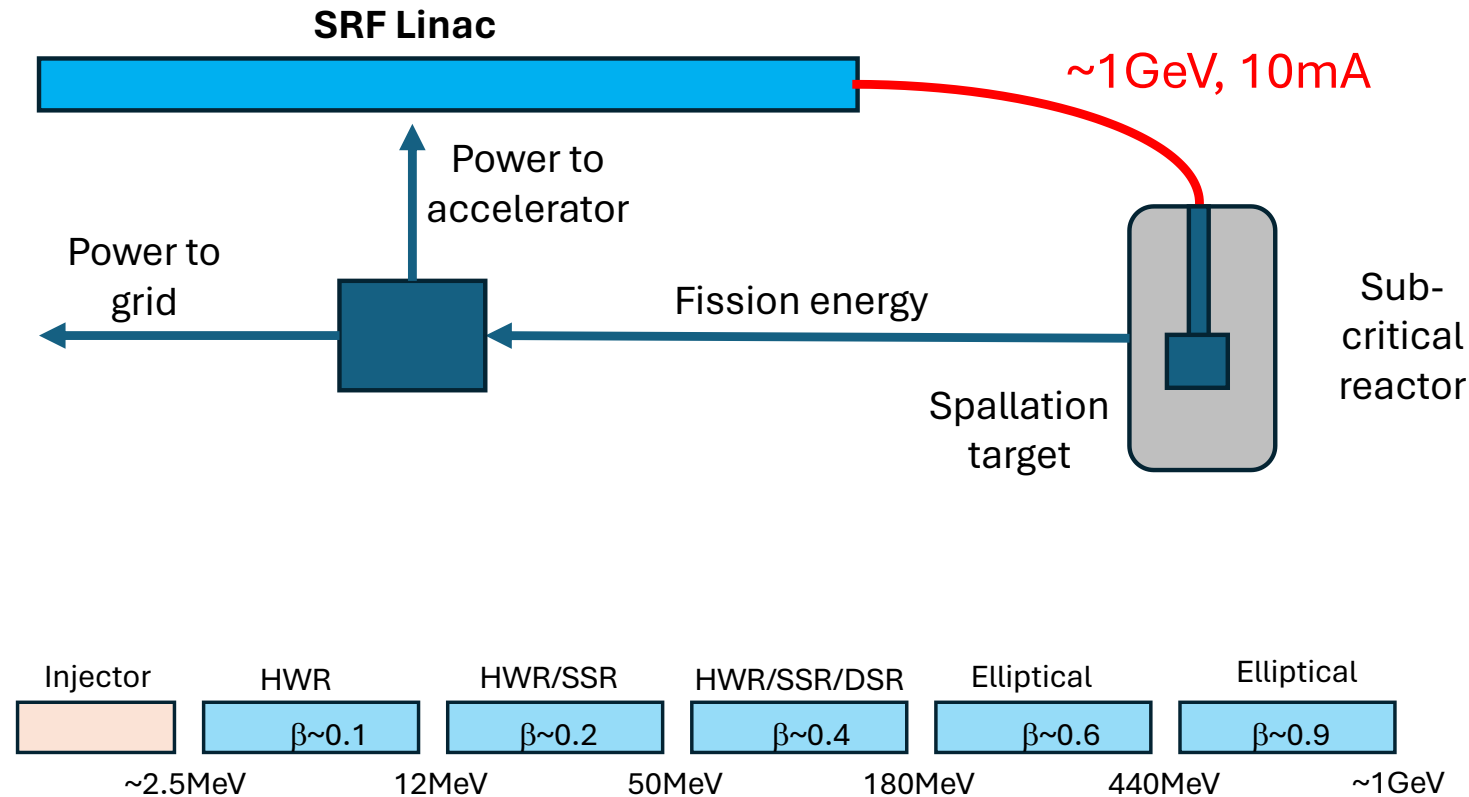


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Motivation

- The Accelerator community needs to evolve to more efficient technologies and support R&D to reduce total energy consumption.
- The Accelerator Driven Systems (ADS) linacs ($E=1\text{GeV}$, $I=10\text{mA}$) serve as a good model to chart where we are now and where we could be



Define electrical efficiencies – rf and cryogenics

Wall plug power efficiency

$$\eta_{beam} = \frac{P_{beam}}{Wall\ Power} = \frac{P_{beam}}{PW}$$

RF power efficiency

$$PW_{rf} = P_{gen} \frac{C_{rf}}{\eta_{rf}}$$

RF factor – imperfect matching, margin (assume 1.3)

Efficiency - wall power to rf power – (assume 50%)

Cryogenic power efficiency

$$PW_{cryo} = P_{cryo} \Big|_T \frac{C_{cryo}}{\eta_c(T) \eta_m(T)} = P_{cryo} \Big|_T \frac{300 - T}{T} \frac{C_{cryo}}{\eta_m(T)}$$

Cryogenic margin (assume 1.3)

Carnot

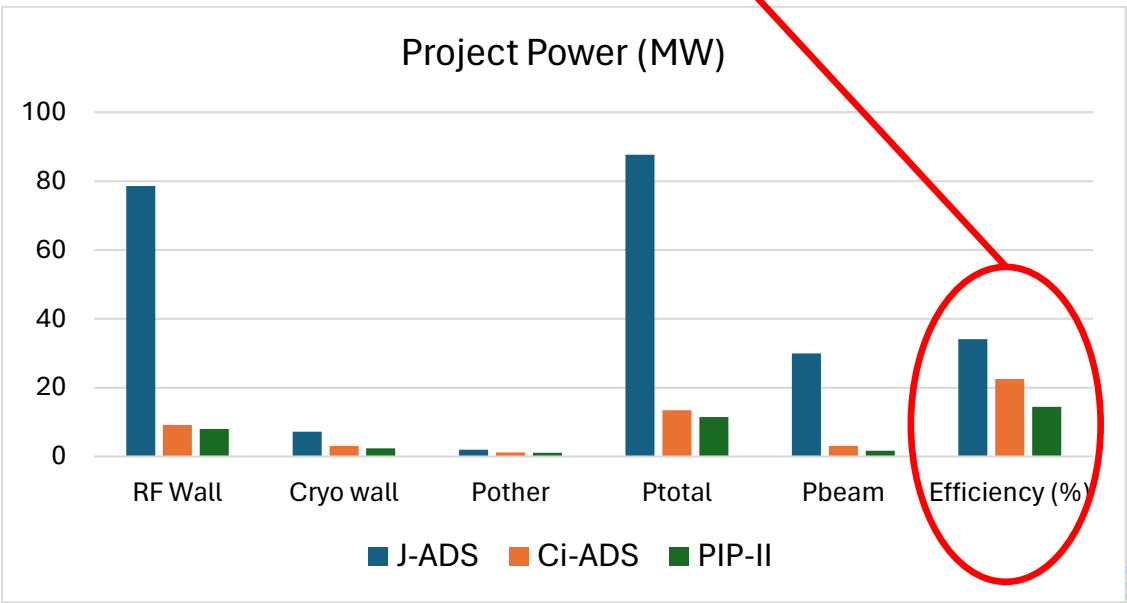
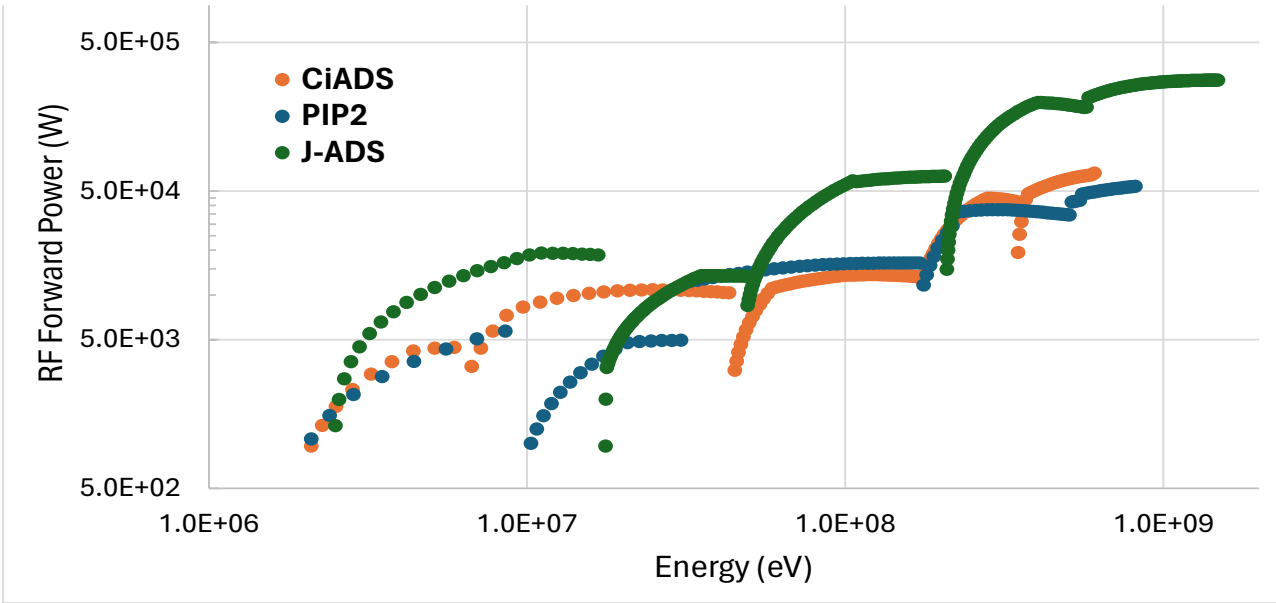
Mechanical

T (K)	η_c	η_m^*	$COP(T)$	$COP(T)C_{cryo}$
2	6.71e-3	0.2	745	969
4.4	1.49e-2	0.28	240	312
5	1.69e-2	0.28	211	274
60	2.5e-2	0.17	23.5	30.6

3x difference

Methodology: Estimated efficiencies for PIP-II, C-ADS, J-ADS

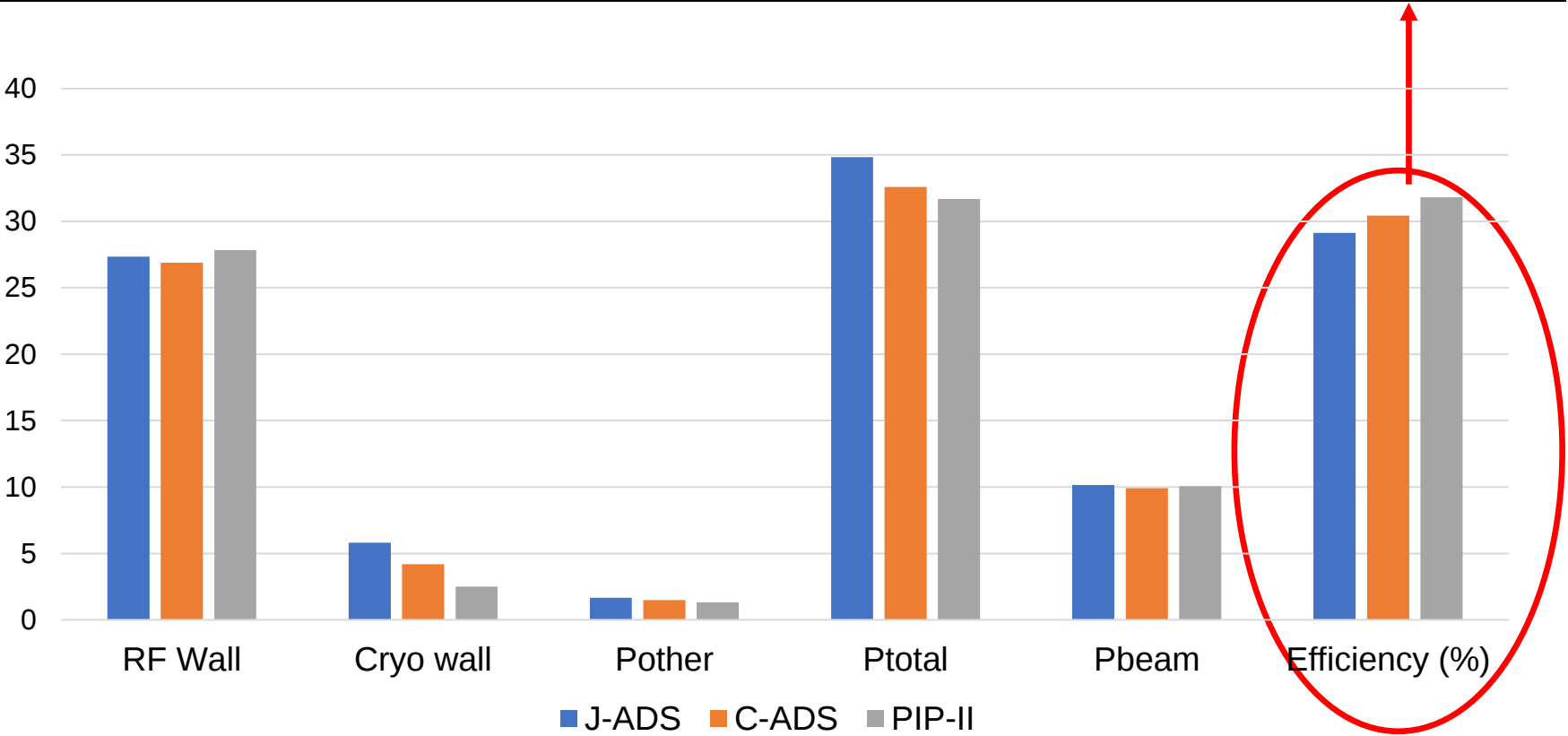
Project	E (GeV)	I (mA)	P _{beam} (MW)	# Cav	η (%)
PIP-II CW	0.833	2	1.6	119	15
CiADS-P2	0.6	5	3	151	22
J-ADS	1.5	20	30	293	34



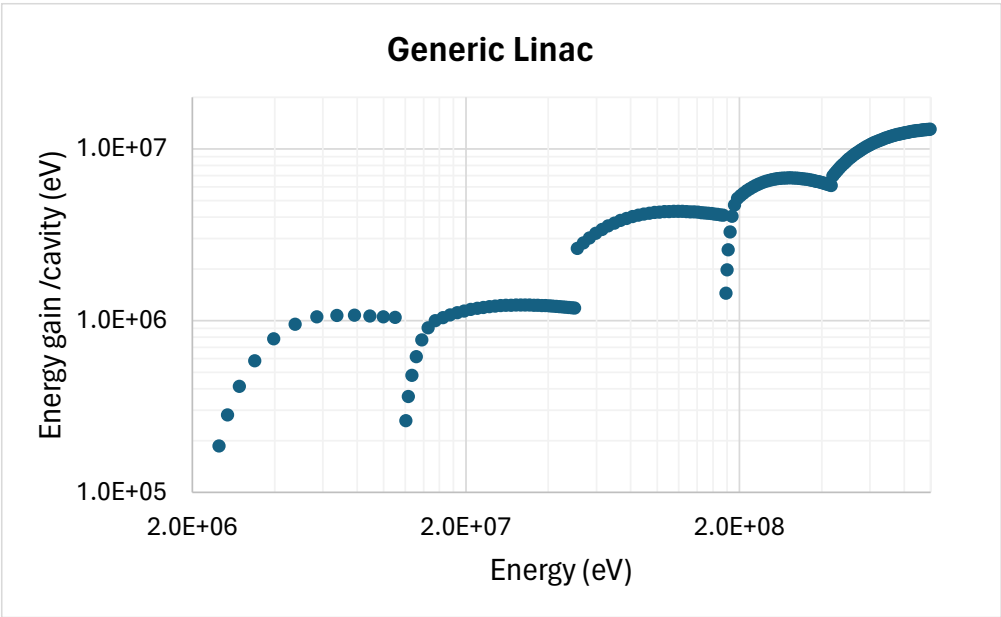
Combined published data -> wall plug power required for cryogenic static loads is **7kW/m**

Renormalized projects to 1GeV and 10mA

Project	E (GeV)	I (mA)	P _{beam} (MW)	# Cav	η (%)
PIP-II CW	1	10	10	131	31.8
CiADS-P2	1	10	10	183	30.4
J-ADS	1	10	10	258	29.1

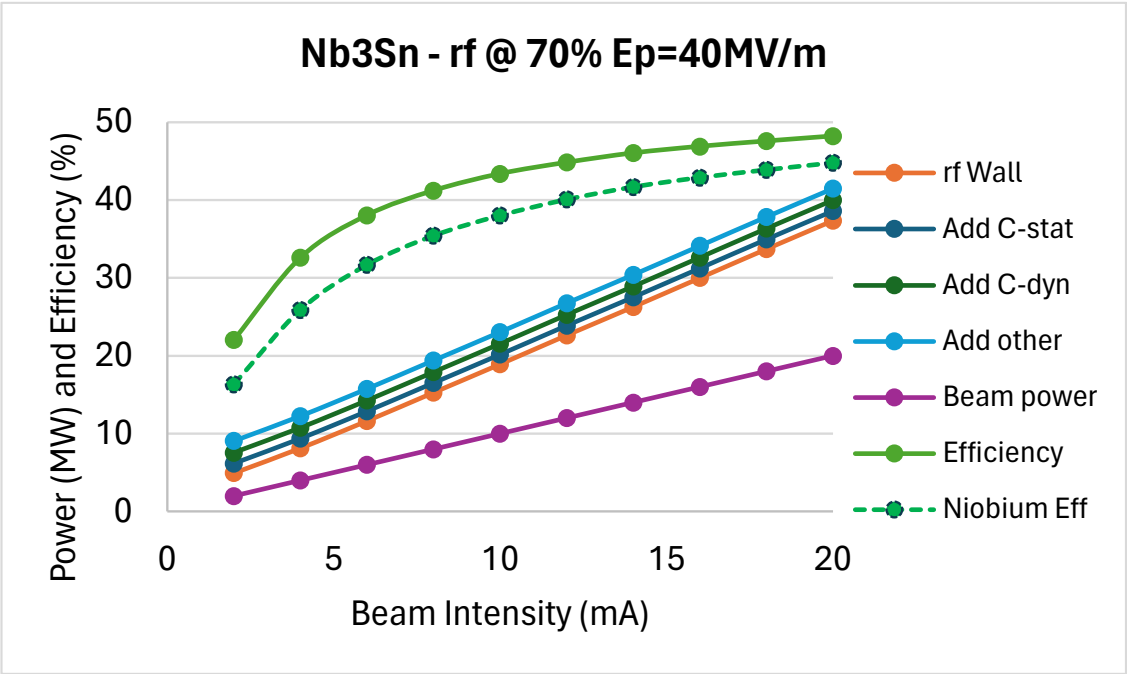


Strawman linac for parameter scanning



Type	beta-g	Ngap	frequency	Ncav	Ncm
HWR	0.115	2	1.63E+08	12	2.00
SSR	0.235	2	3.25E+08	36	6.00
DSR	0.44	3	3.25E+08	32	8.00
elliptical	0.64	5	6.50E+08	44	11.00
elliptical	0.89	5	6.50E+08	52	13.00

- Constructed a strawman high intensity linac with five cavity types
- Allowed modifications of E_a , R_s , detuning, RF efficiency
- Nb3Sn modelled with same parameters as Niobium but operating at 4.2K



Conclusions

- SRF technology allows very high linac electrical efficiencies despite the cryogenic power requirements
- For high beam intensity $I > 5\text{mA}$, the wall plug power is dominated by rf power
 - Improving the efficiency of wall power conversion to rf power will have the most significant gain
 - Reducing dynamic load by more efficient heat treatments or materials (Nb₃Sn) will have more impact as rf efficiency improves

Abstract

The Accelerator community needs to evolve to more efficient technologies and support R&D to reduce total energy consumption. This requires a change in culture - we need to focus on energy efficiency with the same priority as achieving higher performance. Some linac installations like those for Accelerator Driven Systems (ADS) are advertised as being powered by the nuclear energy they produce with the surplus power going to the grid. In this case power efficiency is a key parameter in the design. Power usage can be impacted by various factors including temperature of operation and rf surface resistance. This paper presents modeling exercise to motivate future R&D towards improving power efficiency and in particular, focused on linacs used to drive ADS.



Linacs for Accelerator Driven Systems



Project	Q (kV)	Intensity (mA)	Beam power (MW)	No. Grids
PIP-4	0.033	2	1.6	101
JAEA-ADS (PIP)	0.4	30	100	100
PIP-15	1.5	30	100	200

Wall plug power efficiency $\eta_{beam} = \frac{P_{beam}}{P_{rf-wall} + P_{cryo-wall} + P_{other-wall}}$ RF, cryogenics, other loads

RF power efficiency $P_{rf-wall} = P_{gen} \frac{C_{rf}}{\eta_{rf}}$ RF factor - imperfect matching, margin (assume 1.5)
Efficiency - wall power to rf power - (assume 50%)

Required generator power $P_{gen} = \frac{P_{beam}}{4Q^2} \left((1 + \beta + b)^2 + 4Q^2 \left(\frac{\delta\omega_d}{\omega_0} \right)^2 \right)$ $b = \frac{P_{beam}}{P_{max}} = \frac{1.6 \Delta V_{max}}{P_{max}}$

Optimized coupling $\beta_0 = \sqrt{(1 + b)^2 + 4Q^2 \left(\frac{\delta\omega_d}{\omega_0} \right)^2}$

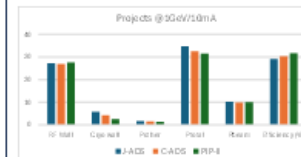
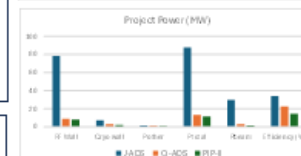
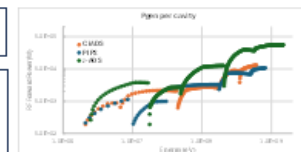
For high beam loading $P_{gen|min} \approx P_{beam} (1 + a^2)$ $a = \frac{Q_0 \delta\omega_d}{b \omega_0}$ $b \gg Q_0 \frac{\delta\omega_d}{\omega_0}$

Cryogenic power efficiency $P_{cryo-wall}|_{T=300} = \sum_{k=1}^N P_{cryo}|_{T=300} COP(T_{load}) C_{cryo}$ Cryo factor - margin (assume 1.3)
Efficiency - wall power for cold loss

T (K)	η_c	η_m^*	$COP(T)$	$COP(T)C_{cryo}$
2	6.71e-3	0.2	745	969
4.4	1.49e-2	0.28	240	312
5	1.69e-2	0.28	211	274
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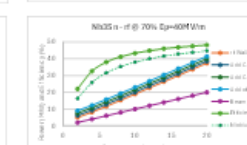
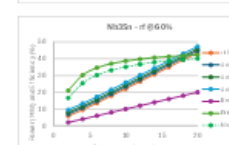
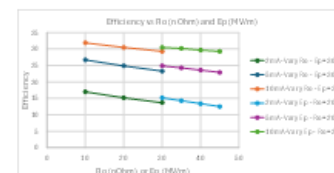
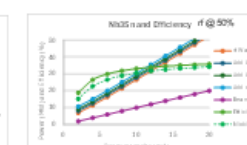
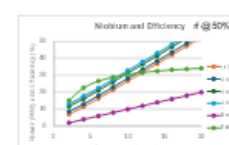
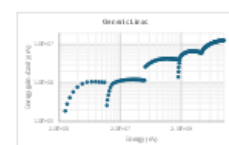
Dynamic losses from $P_{loss} = \frac{V^2}{Q} R_x$ with $R_x = R_{acc}(T) + R_0$
Estimate static losses at 2K, 5K, 70K of cryomodules and distribution lines - values from J-ADS, C-ADS, PIP-2 publications

Comparing static load estimates from the three proposals yields a static cryogenic wall power requirement of 7kW/m



Method

- Constructed a strawman high intensity linac with five cavity types
- Allowed modifications of E_{acc} , R_{acc} , detuning, RF and cryo efficiency
- Nb3Sn modelled with same parameters as Niobium but operating at 4.2K



Cumulative wall power required for given beam power as various loads are added - comparing Niobium vs Nb3Sn vs RF Efficiency (50%, 60%, 70%) - Assumes 1GeV, E=30MeV/m, R=20nOhm, Ep=30MeV/m unless where indicated.

Conclusions

- SRF technology allows very high linac efficiencies despite the cryogenic power requirements
- For high beam intensity $I > 5mA$, the wall plug power is dominated by rf power
- Improving the efficiency of wall power conversion to rf power will have the most significant gain
- Reducing dynamic load by more efficient heat treatments or materials (Nb3Sn) will have more impact as rf efficiency improves
- Electricity efficiency relatively independent of linac architecture in beam loaded regime

Thank you,
Merci

Come to poster THPO008
for discussion

RF and dynamic cryo power

Required generator power

$$P_{gen} = \frac{P_{cav}}{4\beta} \left((1 + \beta + b)^2 + 4Q_0^2 \left(\frac{\delta\omega_d}{\omega_0} \right)^2 \right)$$

$$b = \frac{P_{beam}}{P_{cav}} = \frac{I \Delta W_{cav}}{P_{cav}}$$

Optimized coupling

$$\beta_0 = \sqrt{(1 + b)^2 + 4Q_0^2 \left(\frac{\delta\omega_d}{\omega_0} \right)^2}$$

For high beam loading

$$P_{gen}|_{min} \approx P_{beam} (1 + \alpha^2)$$

$$\alpha = \frac{Q_0}{b} \frac{\delta\omega_d}{\omega_0} \quad b \gg Q_0 \frac{\delta\omega_d}{\omega_0}$$

Required cryogenic power

$$P_{cryo} = P_{dyn} + P_{static}$$

$$P_{dyn} = \frac{V^2}{R}$$

$$V = E_a L \quad R = \frac{R}{Q} \frac{G}{R_s}$$

Wall plug power efficiency

$$\eta_{beam} = \frac{P_{beam}}{PW_{rf} + PW_{cr-dyn} + PW_{cr-st} + PW_{other}}$$

PW is wall plug power feeding rf, cryogenics, magnets, services

$$\eta_{beam} = \frac{P_{beam}/PW_{rf}}{1 + PW_{cr-dyn}/PW_{rf} + \dots} \cong \frac{\eta_{rf}/C_{rf}}{1 + PW_{cr-dyn}/PW_{rf} + \dots}$$

$$P_{gen}|_{min} \approx P_{beam} (1 + \alpha^2)$$

$$PW_{rf} = P_{gen} \frac{C_{rf}}{\eta_{rf}}$$

$$\left. \frac{PW_{cr-dyn}}{PW_{rf}} \right|_{cavity} \cong \frac{\eta_{rf}}{\eta_c(T)\eta_m(T)} \frac{P_c}{P_b} = \frac{\eta_{rf}}{\eta_c(T)\eta_m(T)} \frac{V}{IRT_n \cos \phi}$$

$$P_c = \frac{V^2}{R} \quad P_b = IVT_n \cos \phi$$

$$\left. \frac{PW_{cr-dyn}}{PW_{rf}} \right|_{cavity@2K} \approx \frac{1}{I(mA)}$$

For $E_p=30\text{MV/m}$ and $R_o=20\text{nOhm}$

Conclusion: for $I > 5\text{mA}$ the rf efficiency dominates the wall plug power efficiency