TRIUMF

Power Efficiency Estimations for a High Intensity Proton Linac

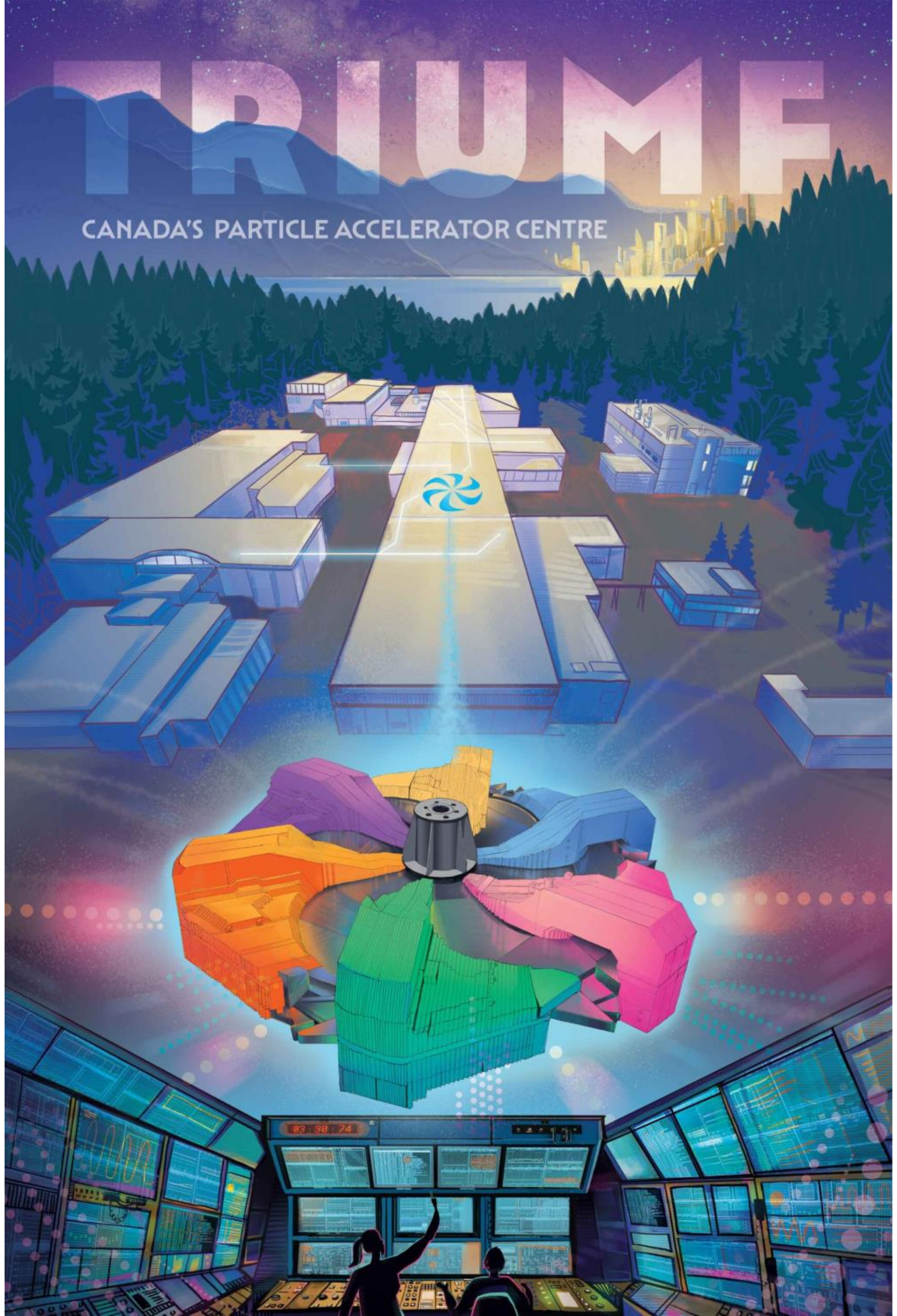
THPO008

Bob Laxdal

TRIUMF

DAEJEON LINAC2026

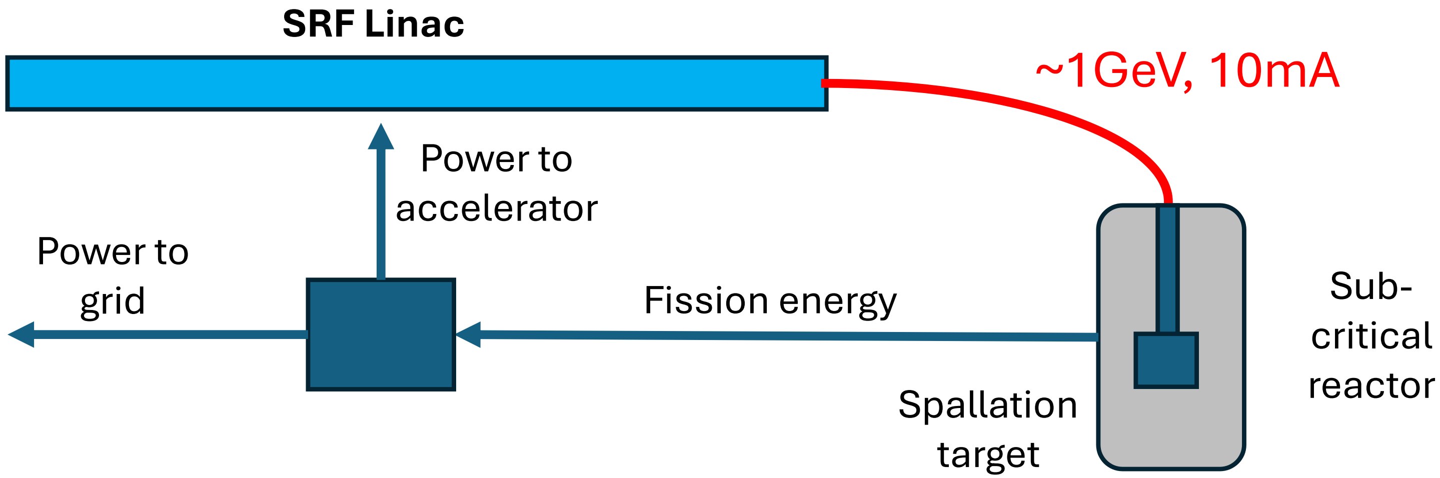
2026-08-20

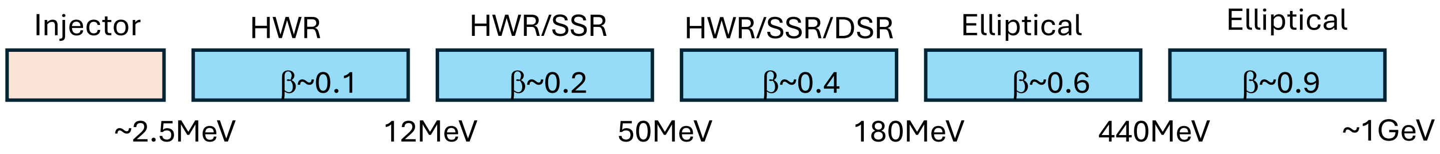


Discovery, accelerated

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=1GeV, I=10mA) serve as a good model to chart where we are now and where we could be





Discovery, accelerated

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

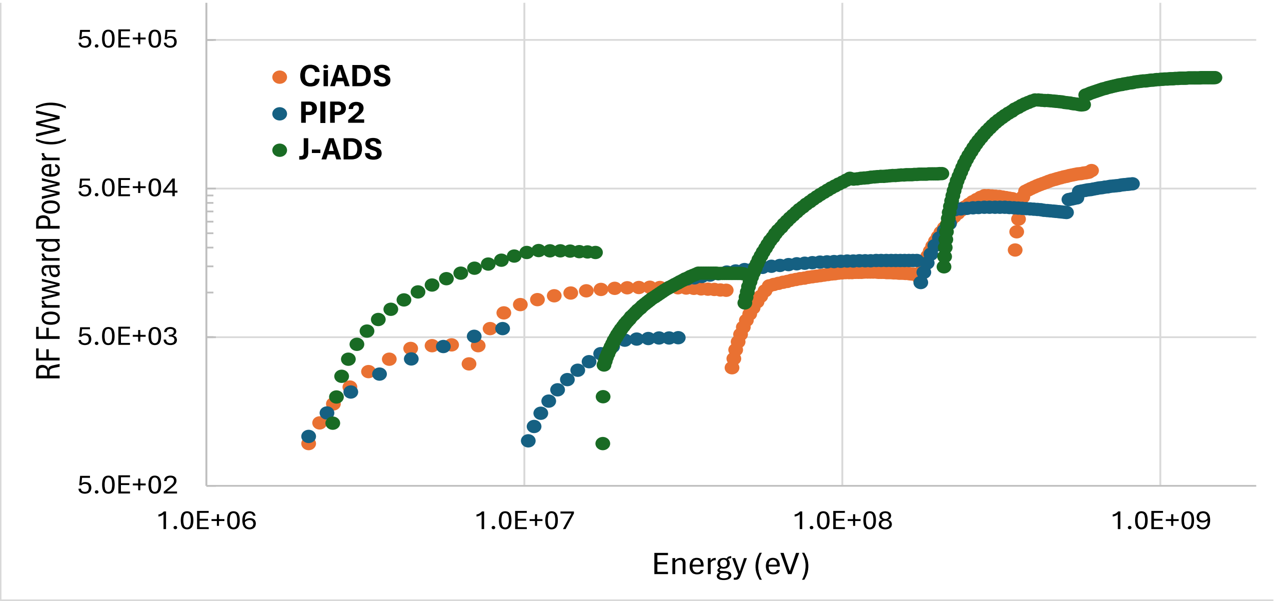
Mechanical

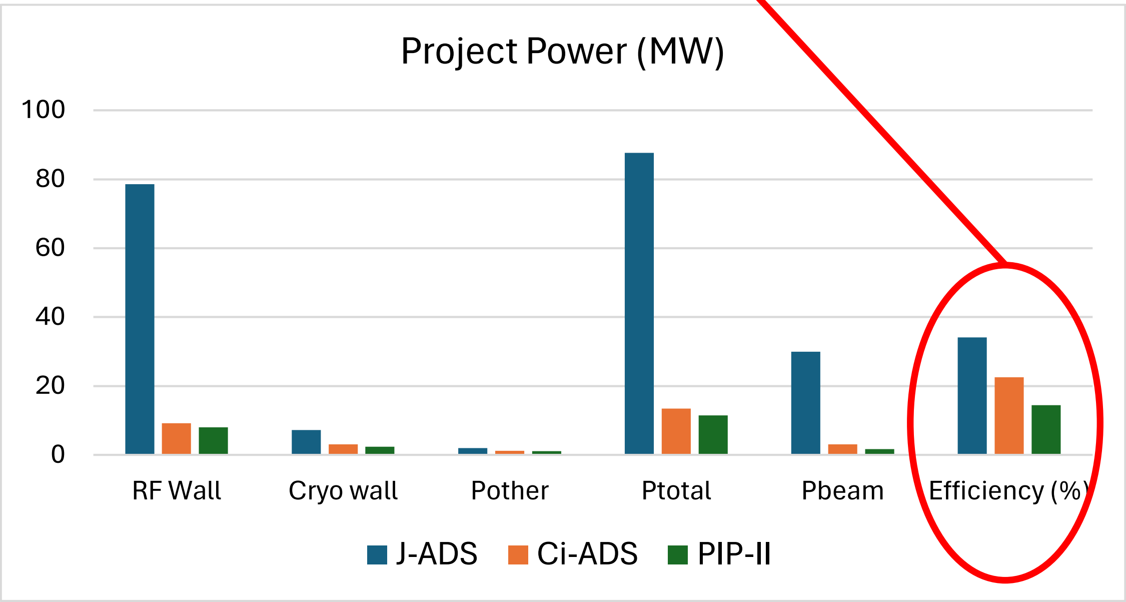
T (K)	η_c	η_m*	$COP(T)$	$COP(T)C_{cryo}$
2	6.71e-3	0.2	745	969
4.4	1.49e-2	0.28	240	312
5	1.69e-2	0.28	211	274
60	2.5e-2	0.17	23.5	30.6

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

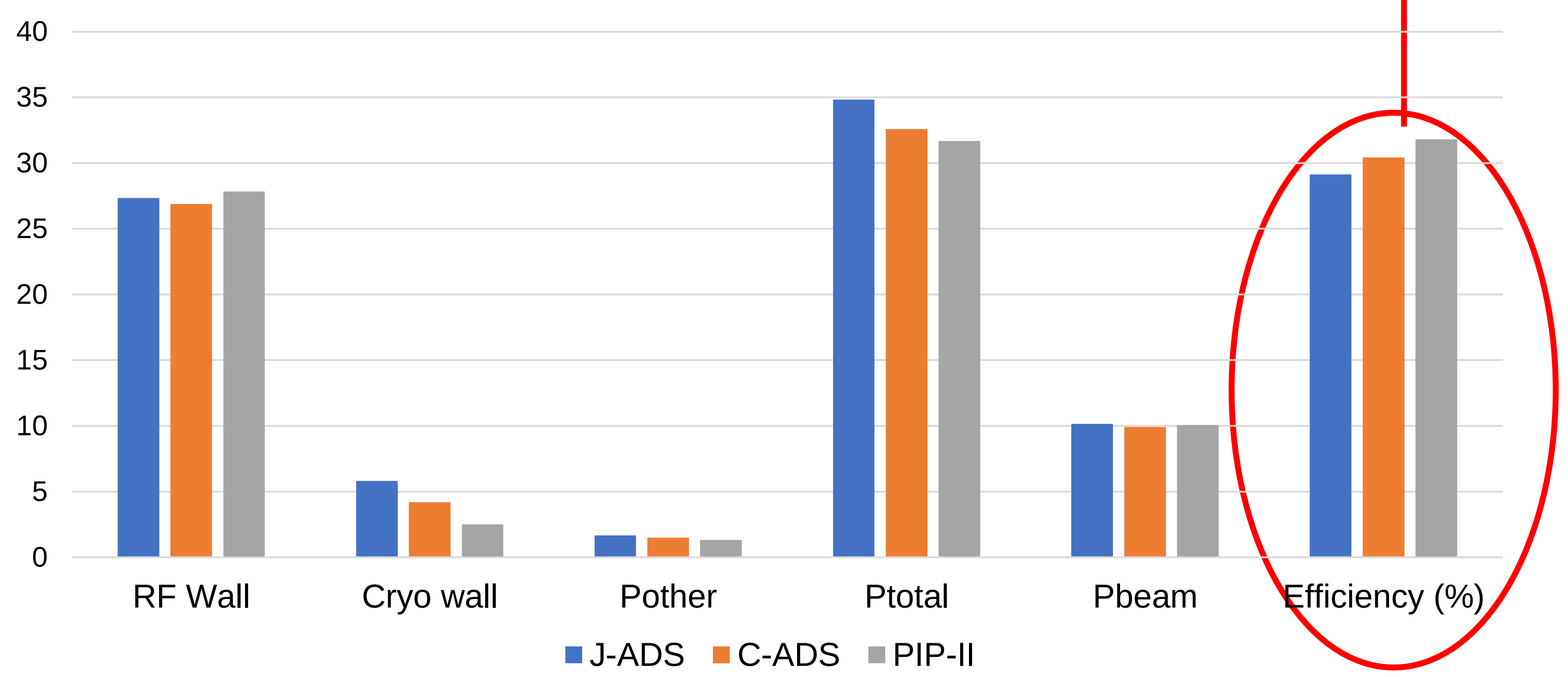




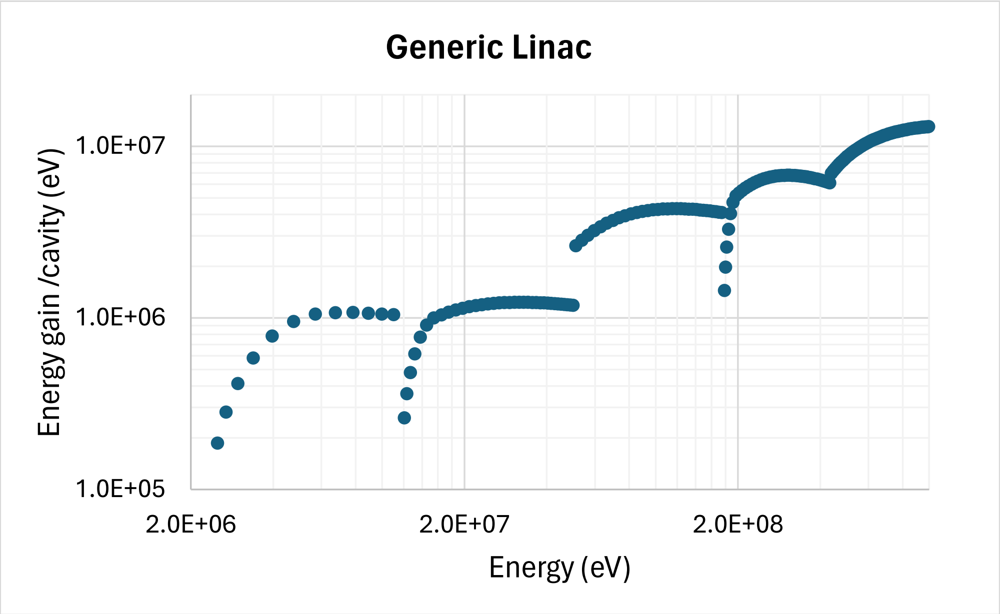
Combined published data -> wall plug power required for cryogenic static loads is **7kW/m**

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

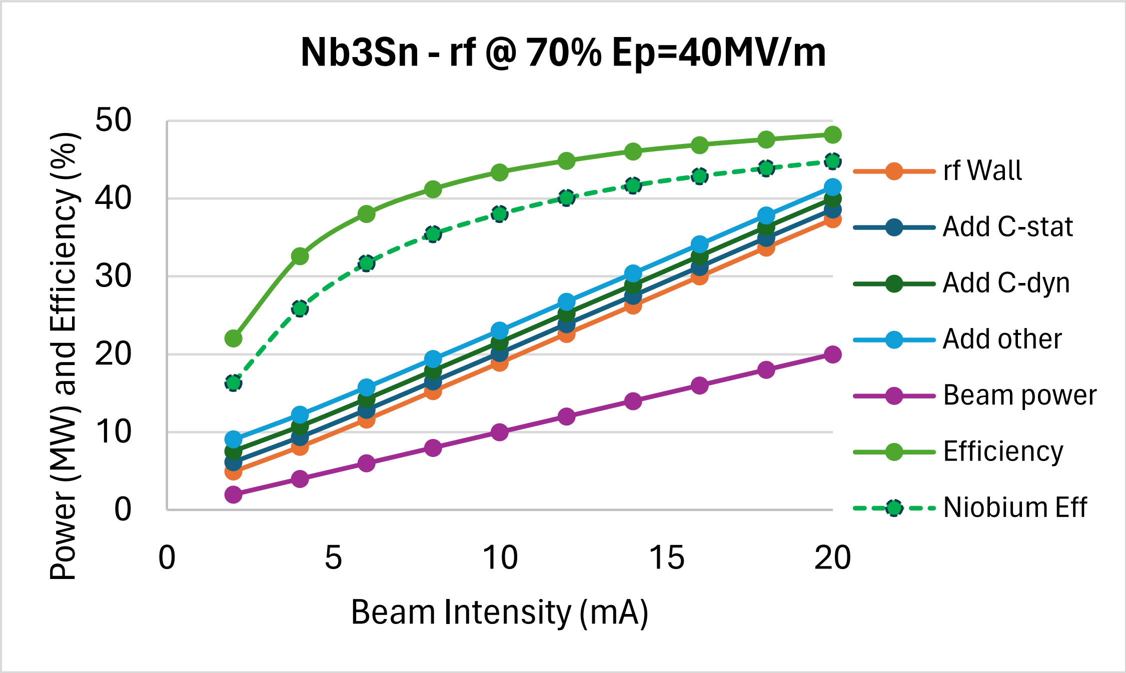


Strawman linac for parameter scanning



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

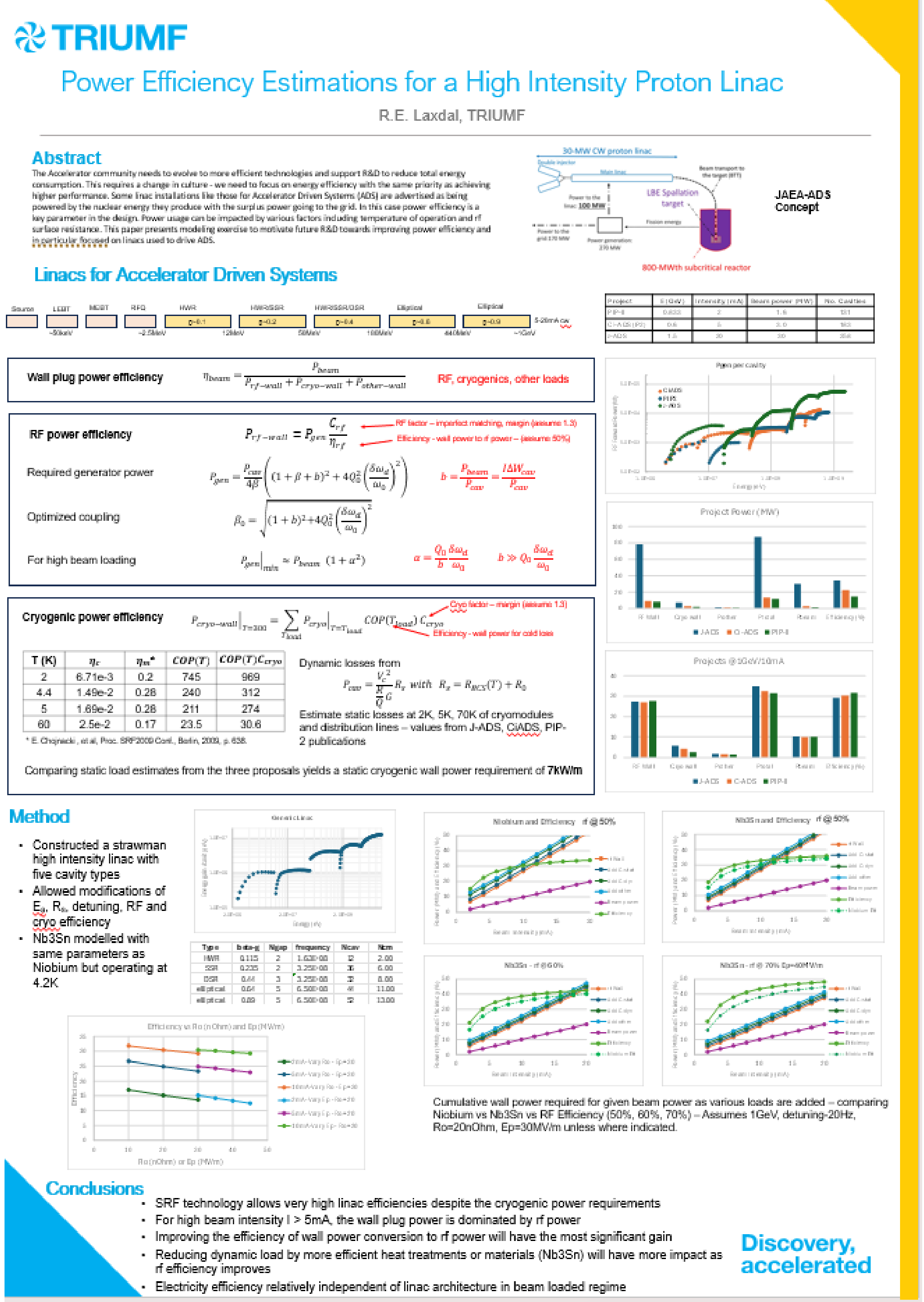


Conclusions

- SRF technology allows very high linac electrical efficiencies despite the cryogenic power requirements
- For high beam intensity I > 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

Thank you,
Merci

Come to poster THPO008
for discussion



Discovery, accelerated

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

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

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

Required cryogenic power

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

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

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

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

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

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

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

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

$$P_c = \frac{V^2}{R} \qquad P_b = IVT_n cos\varphi$$

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

For Ep=30MV/m and Ro=20nOhm

Conclusion: for I > 5mA the rf efficiency dominates the wall plug power efficiency