TRIUMF

DESIGN CONSIDERATIONS FOR A PROTON LINAC FOR A COMPACT ACCELERATOR BASED NEUTRON SOURCE

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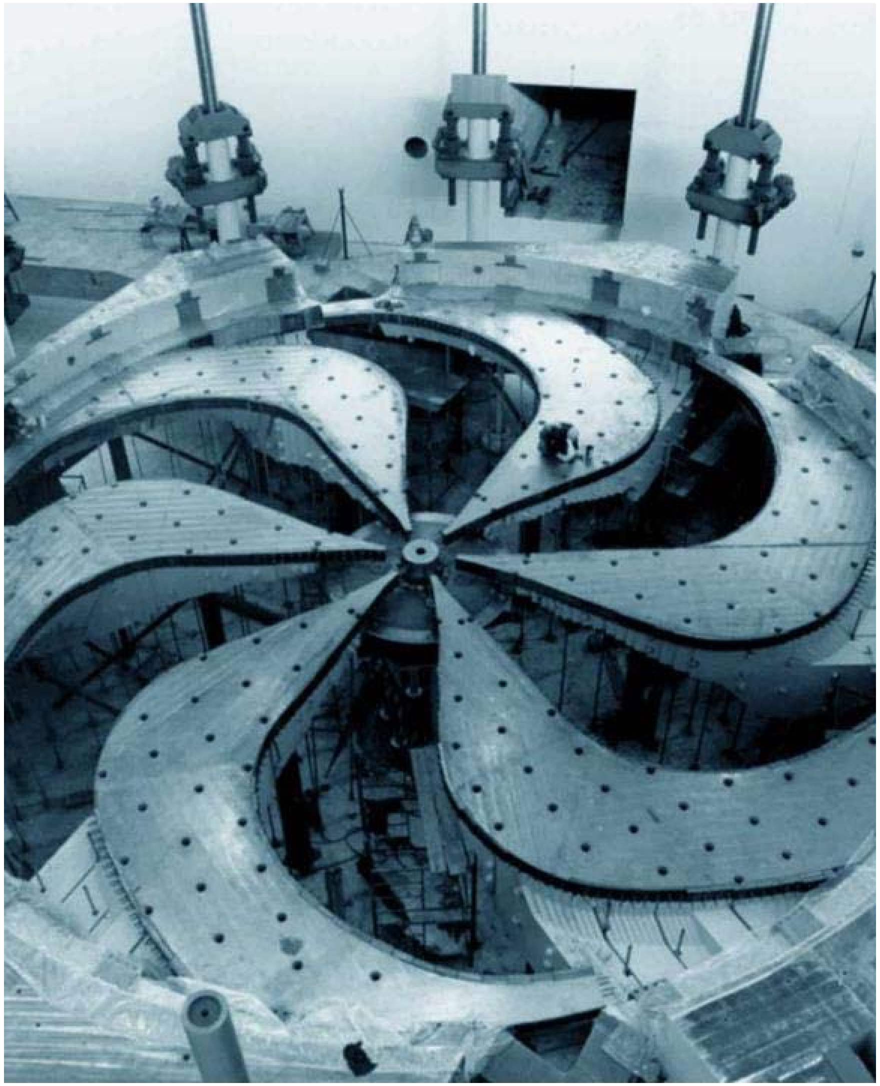
LINAC2022 LIVERPOOL



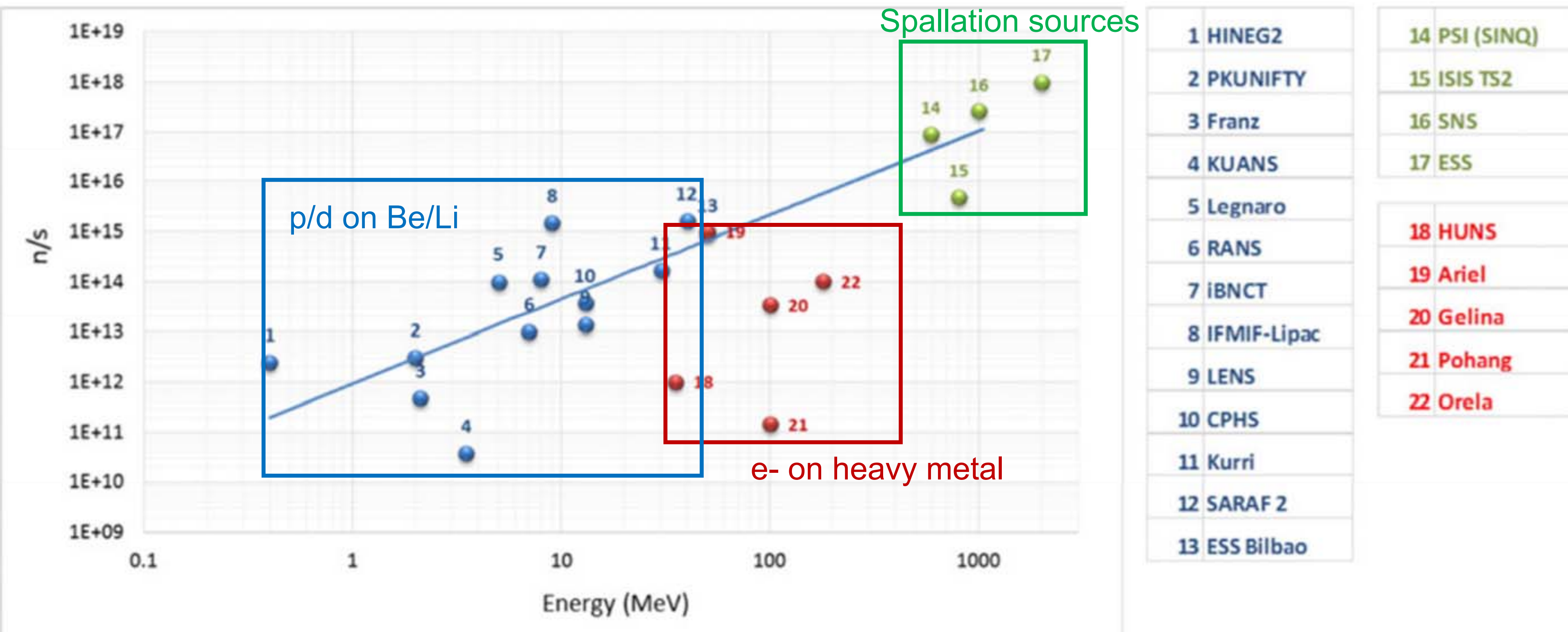
Discovery, accelerated

Current Status of Neutron Beams in Canada

- **Neutron Gap**
  - National Research Universal (NRU) reactor shut down in 2018
  - Canada is facing a neutron gap

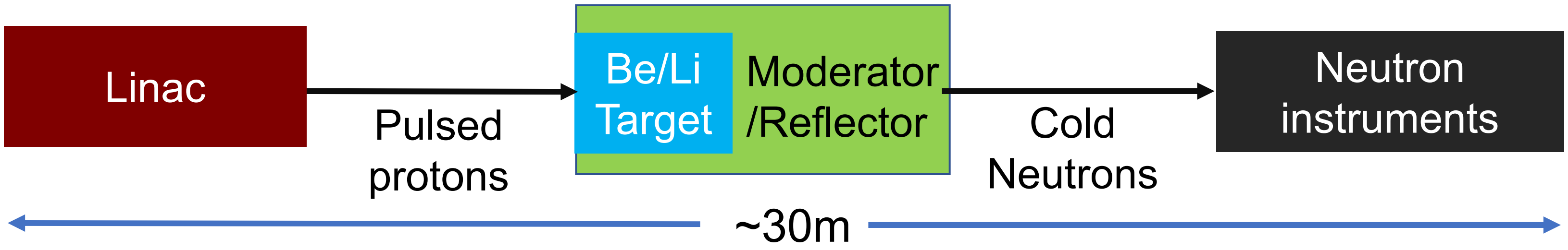
- Similar story globally - major research reactors closed e.g. BER-II, JEEP and Orphée
- Canada and global community need new (affordable) pathways for neutron production

Accelerator Based Neutron Sources



Cost (M$) →

The Compact Accelerator-based Neutron Source (CANS) Concept



Advantages

I. **Compact -** less shielding required – instruments closer to source - Compatible with a university setting

II. **<< $$** compared with reactor and spallation sources

III. **Pulsed neutron beams** – suitable for neutron scattering and imaging augmented with TOF

IV. **Scalable** technology

- Upgrade by increasing proton energy and/or beam intensity - Develop target technology for higher average beam powers

CANS Worldwide

See for example IAEA-TECDOC-1981

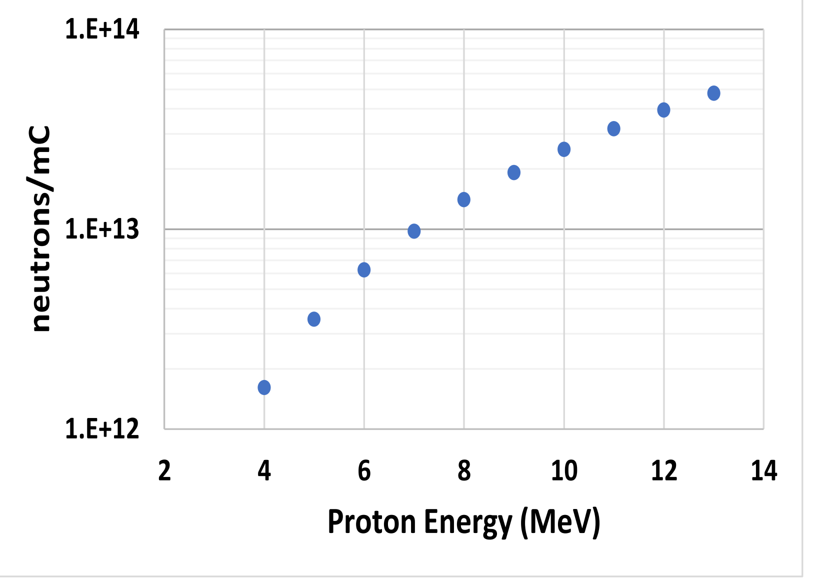
Facility Name	Particle Type	Beam Power (kW)	Final Energy (MeV)	Average Current (mA)	Repetition Rate (Hz)	Peak Current (mA)	Peak Power (kW)	Duty Factor (%)
CPHS	Protons	16	13	1.25	50	50	650	2.5
HUNS	Electrons	1	33	3.3e-2	50	16	500	0.2
IPHI	Protons	0.01	3	1e-5	1	30	300	0.0033
HBS	Protons	300	70	4.3	384/96/26	100	7000	4.3
LENS	protons	4	13	0.3		20	260	1.8
RANS	Protons	0.14-0.7	7	0.02-0.1	20-200	1.5-7.7	10.5-53.9	1.3
NOVA-ERA	Protons	0.4	10	0.04		1	10	4
KUANS	Protons	0.35	3.5	0.1				

- Union for Compact Accelerator-driven Neutron Sources (**UCANS)** formed in 2010 to support the ongoing development of small accelerator-driven neutron sources around the world UCANS
- Conference series: UCANS9, March 28-31, 2022 - hosted by RIKEN, Japan.

Design Considerations

- Beryllium target (despite toxicity) is favoured over Lithium in moderate beam power regime
- For protons on Be choose E<13MeV to avoid tritium production
- Yield (and accelerator costs) increase with energy - 10 MeV is a reasonable balance between cost and performance
- Average beam power limited by target technology P_{beam} ~ < 10-20 kW
- Neutron peak brightness enhanced by pulsing proton beam (proton pulse length 0.1-1ms @ 20-200Hz)

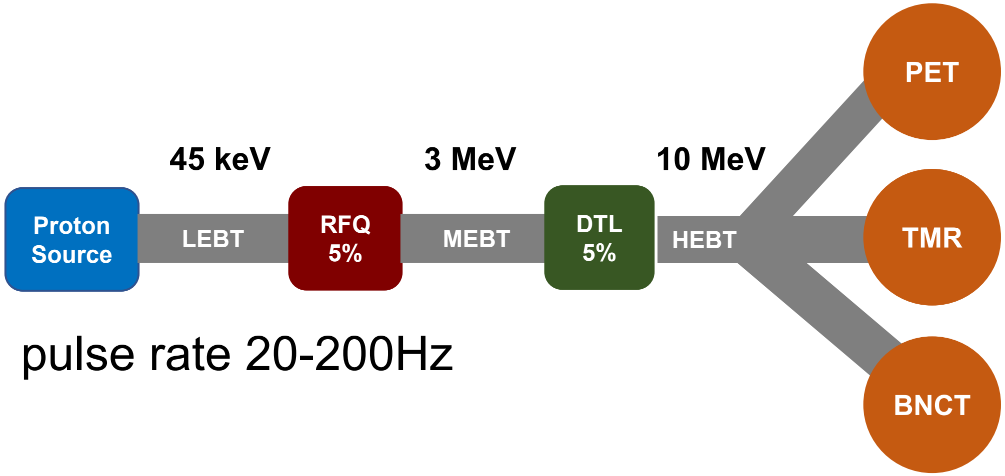
Neutron yield for Protons on Beryllium



PC-CANS (Prototype Canadian CANS)

PC-CANS is a proposal for a high intensity pulsed neutron source at the University of Windsor (Ontario, Canada)

1. Neutrons for Science (cold and thermal)
2. Neutrons for BNCT (epithermal)
3. Protons for 18F for PET



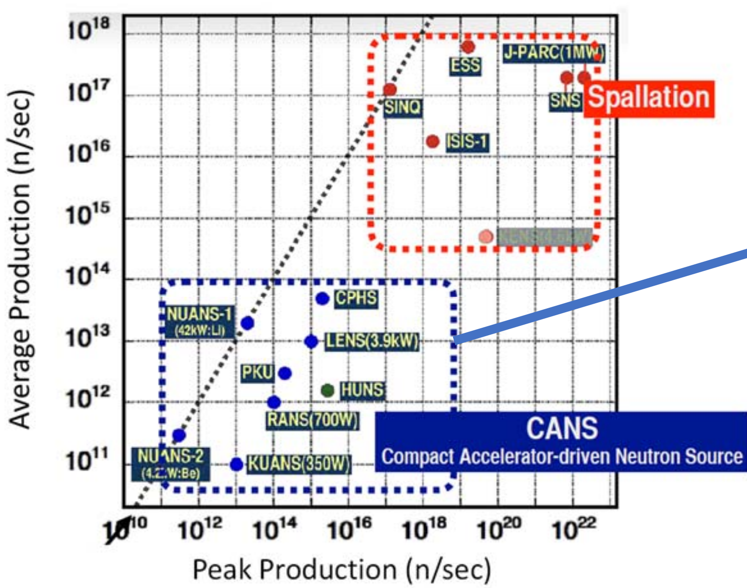
pulse rate 20-200Hz

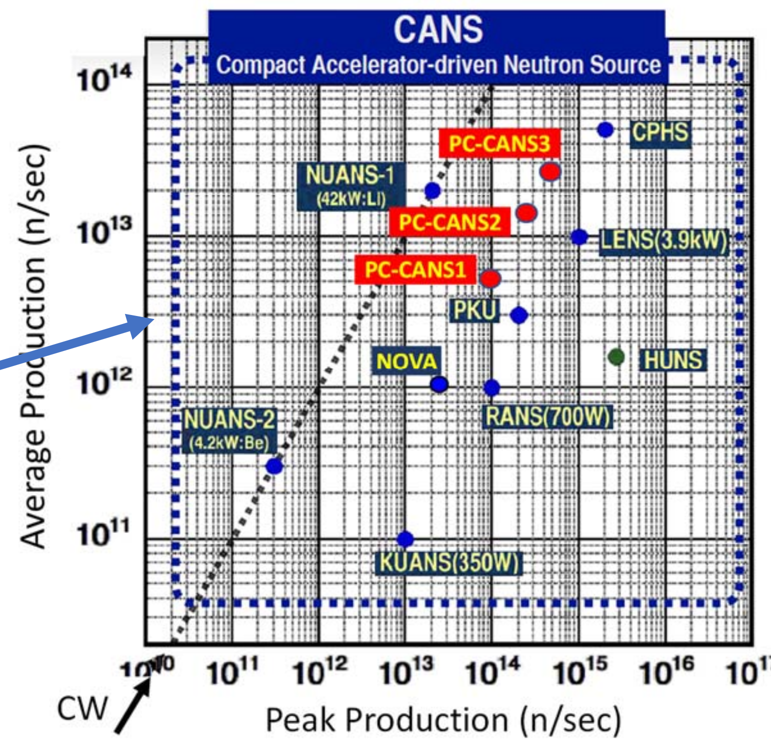
Station	Energy (MeV)	I_{ave} (µA)	DF (%)	P_{ave} (kW)	I_{peak} (mA)	P_{peak} (kW)
Neutron	10	200	5	2	4	40
18F	10	100	5	1	2	20
BNCT	10	200	5	2	4	40
Target totals		500	5	5	10	100
Linac totals	10	1000	5	10	20	200

[1] PC-CANS CDR, TRIUMF internal document, R. Laxdal editor, (2022)
[2] R. Laxdal, Journal of Neutron Research **23**99-117, (2021).

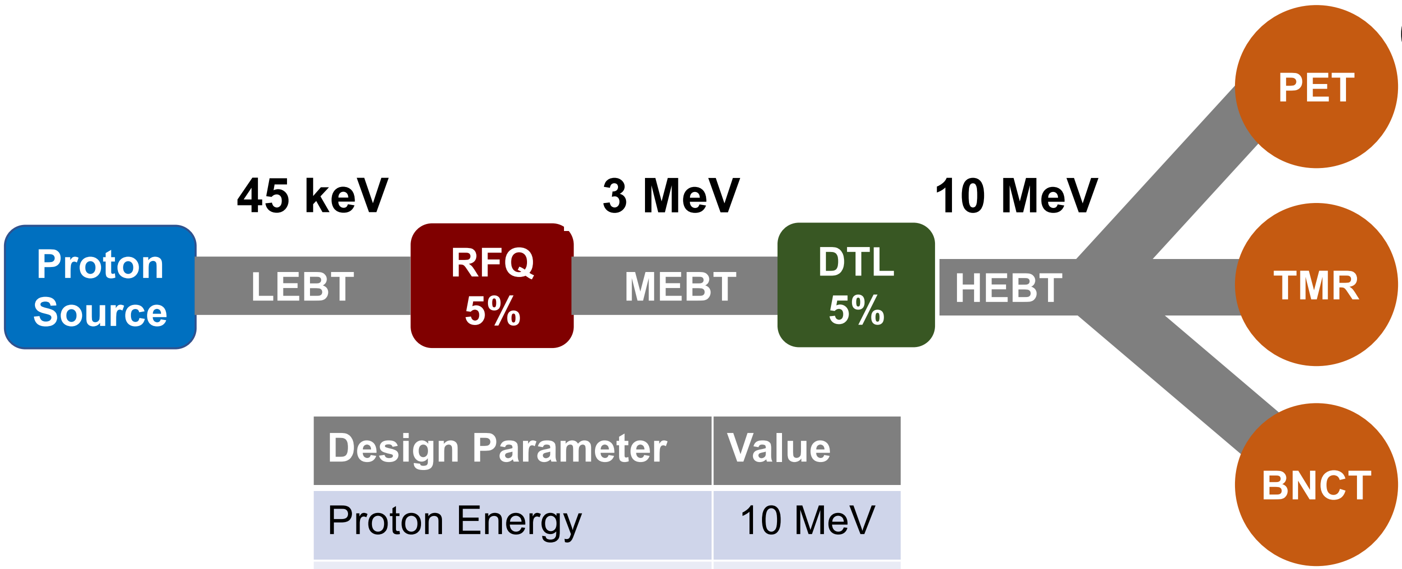
Staged PC-CANS Performance

- Stage 1 – shared (I_{ave} / I_{peak} =200μA/4mA)
- Stage 2 – dedicated (I_{ave} / I_{peak} =500μA/10mA)
- Stage 3 – target upgrade (I_{ave} / I_{peak} =1mA/20mA)





Overview of Prototype Canadian CANS (PC-CANS)



F-18 for PET
0.1 mA, 1 kW

Neutron Sciences (Cold Neutrons)
1 (20) mA,10 kW
$1x10^6$ ($2x10^7$) n/cm^2/s

Design Parameter	Value
Proton Energy	10 MeV
Duty Cycle	5%
Total Peak Current	20 mA

BNCT (Epithermal Neutrons)
1 mA, 10 kW
$0.5x10^9$ n/cm^2/s

Linac studies

Base Parameters

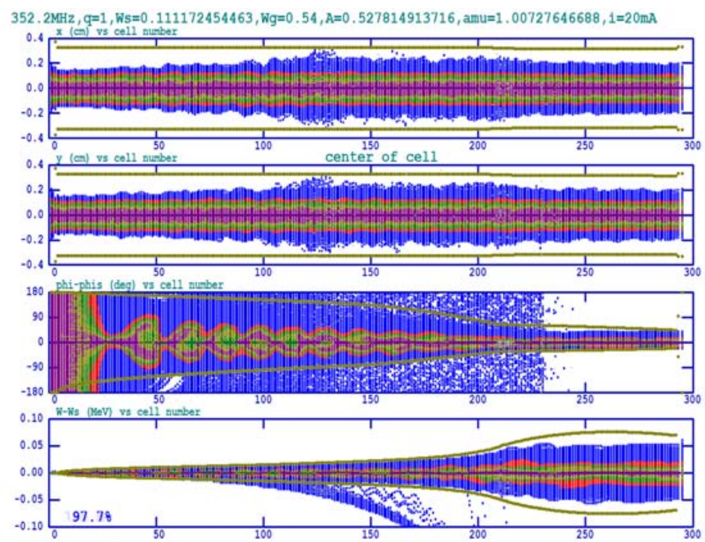
- There are many high intensity proton linacs in the regime from 300-400MHz
- Based on these projects we choose an rf frequency of **352.2MHz** as the baseline for both the RFQ and DTL with an RFQ energy of 3 MeV

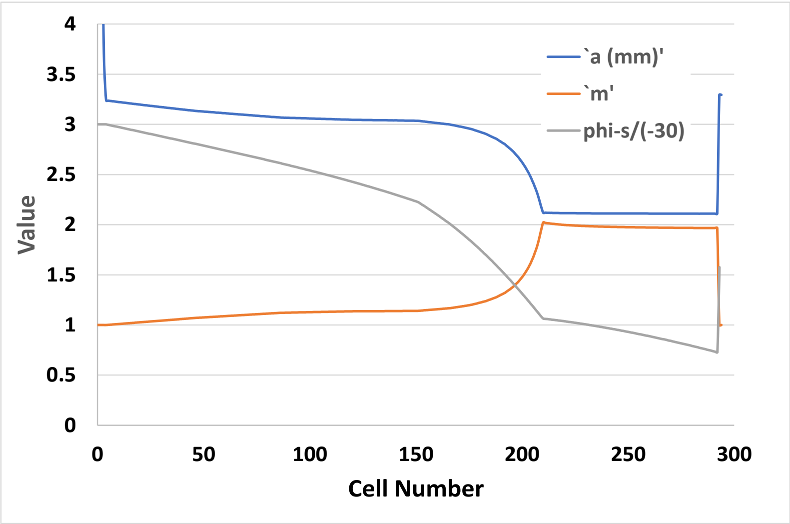
Project	**Freq (MHz)**	**I_peak (mA)**
CERN Linac 4	352	70
ESS	352	70
SNS	402.5	60
J-Parc	324	60
FAIR p-linac	325	70
CPHS (CANS)	325	50
CSNS	324	40

RFQ

- 45keV ->3MeV, 352MHz
- 20mA, 97.7% transmission
- 78 kV, Kilpatrick 1.8
- Peak/Ave rf power loss ~400/28 kW
- Peak beam loading 70kW

Parameter	Value
Injection Energy (MeV)	0.045
Final Energy (MeV)	3
RF Frequency (MHz)	352
Peak beam intensity (mA)	20
Transverse emittance (norm, RMS) cm-mrad	0.025
Longitudinal Emittance (deg-MeV)	0.137
Duty cycle (RF, beam)	7%, 5%
Transmission @ 20mA	97.7%
Length (m)	3.3

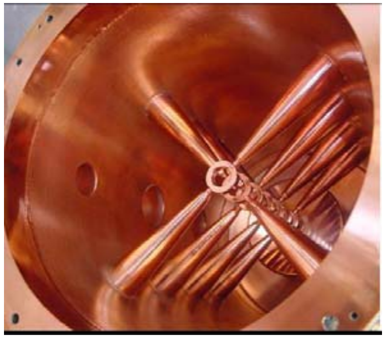


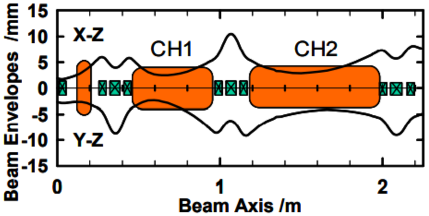


DTL Study

- Several variants are considered using Alvarez or CH structures
- Trace-3D used for rapid prototyping and matching
- LANA and PARMILA used for Multi-particle tracking
- All simulations assume a beam intensity of **20mA**

CH-structure





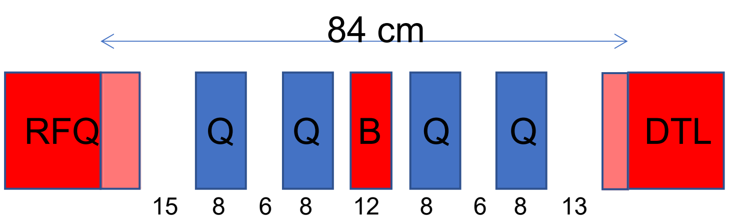
Alvarez structure

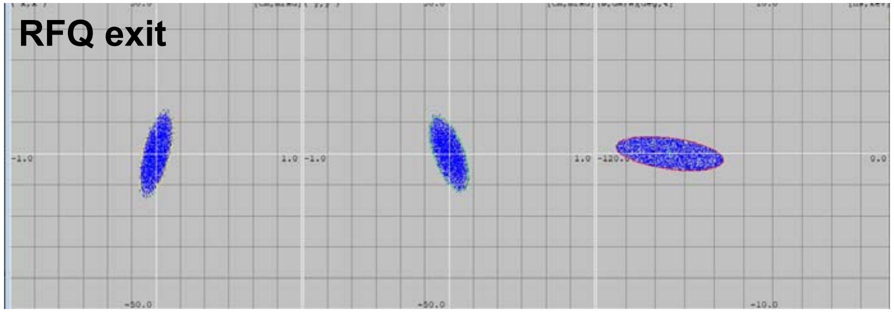
- Nominal beam emittances for DTL study employ 5xRMS PARMTEQ values

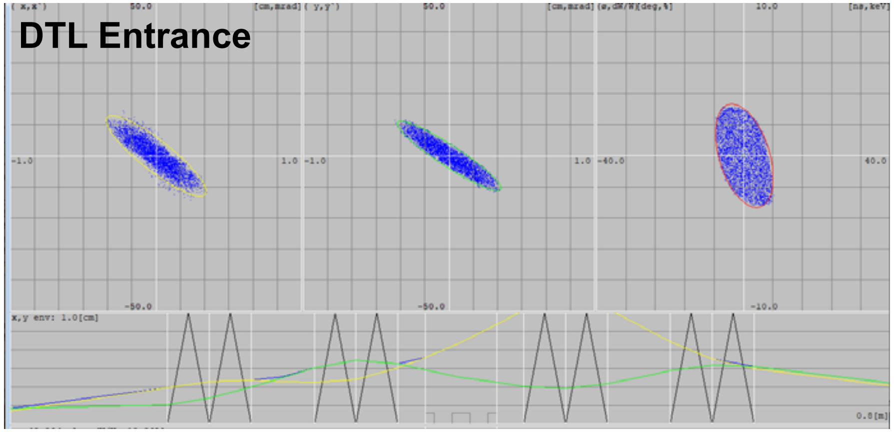
	α	β	units	$\varepsilon_{u\ rms}$	$\varepsilon_{n\ rms}$	units
x	-0.671	10.3	cm/rad	1.56	0.125	cm-mrad
y	0.707	13.8	cm/rad	1.56	0.125	cm-mrad
z	0.423	723	deg/MeV	0.685	0.685	MeV-deg

MEBT

- All variants (except 1) use a common 4 quadrupole (4Q) MEBT with a two-gap buncher at 352MHz
- The buncher is either placed between Q1 and Q2 or between Q2 and Q3 depending on the matching required
- The MEBT is 84 cm long



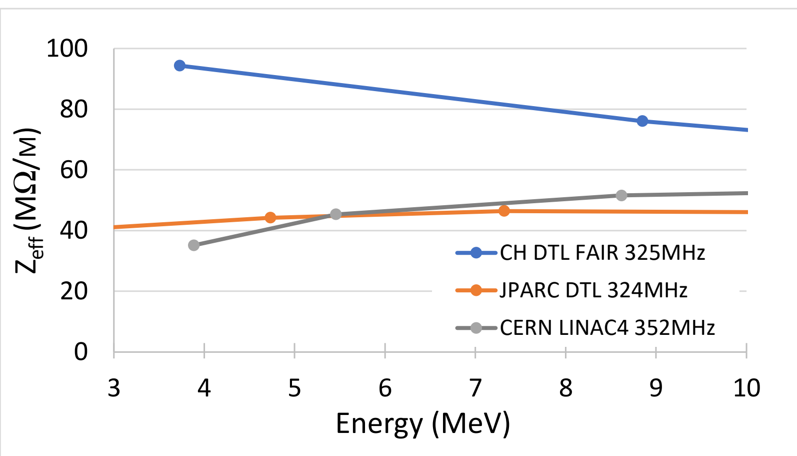


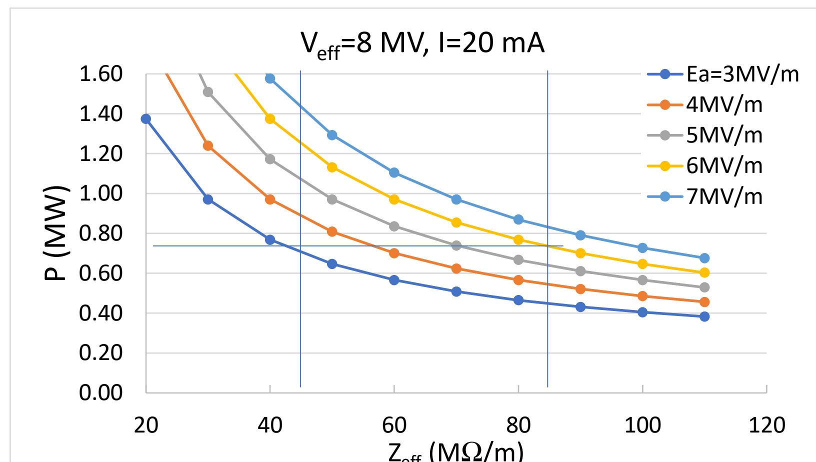


DTL Gradient Considerations

- RF power and linac length are cost drivers
- RF efficiency is characterized by the effective shunt impedance
  - Z_{eff} ~85 MΩ/m for CH and ~45 MΩ/m for Alvarez
- Rf dissipated power is dependent on the gradient chosen
  - Alvarez at 3 MV/m consumes ~same power as CH at 6MV/m for same energy gain

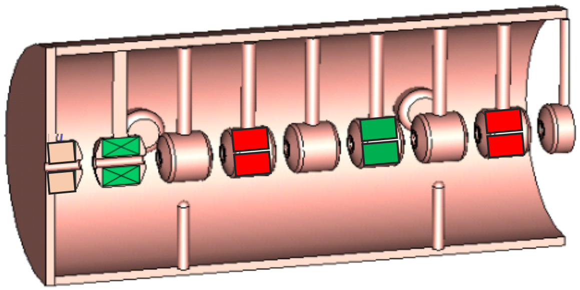
$$P_{rf} = \frac{(E_a L)^2}{Z_{eff} L} + I_b \Delta W$$



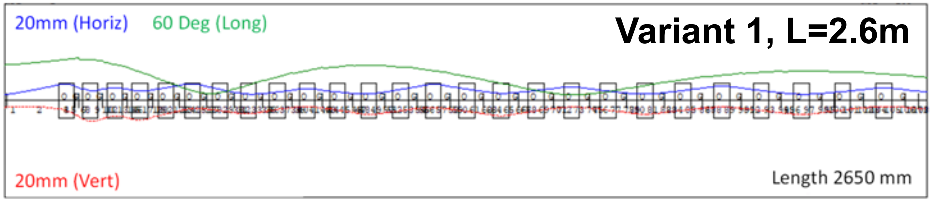


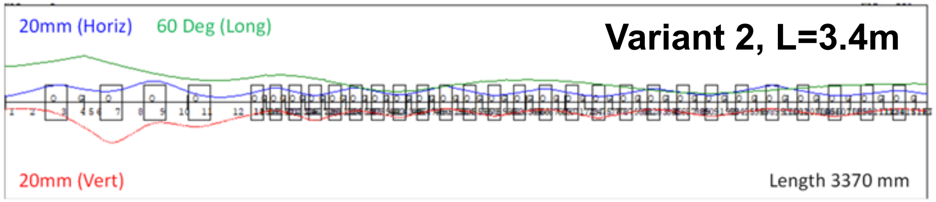
Alvarez

- Adopt PMQs in every second drift tube in FODO lattice
  - Strong transverse focusing
- Longitudinal focusing with -30 deg synchronous phase
- Two variants considered
  - **Variant 1** – no MEBT but with adjustable quadrupoles in first four drift tubes for transverse matching to the FODO
  - **Variant 2** – 4Q MEBT with buncher



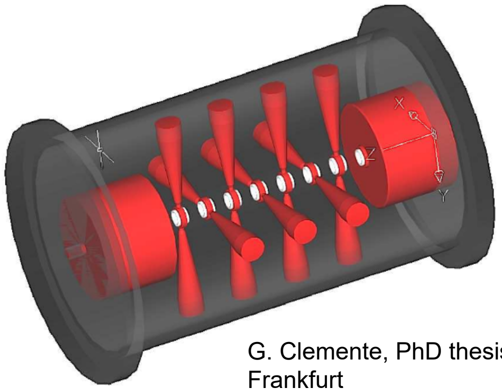
Parameter	**Value**
Drift tubes	26
Eo	3.4 MV/m
Transverse Focusing	F-0-D-0 ±64T/m
Longitudinal focusing	φ_s=-30 degrees
Beam current	20mA



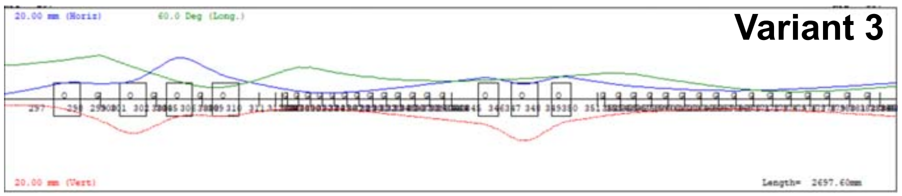


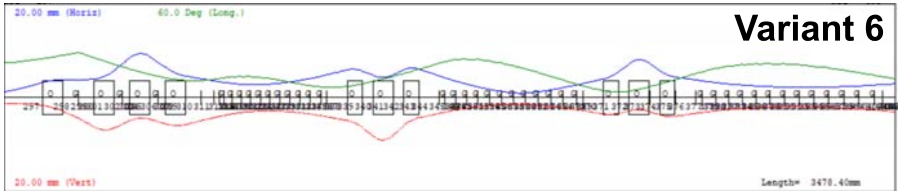
CH Structures

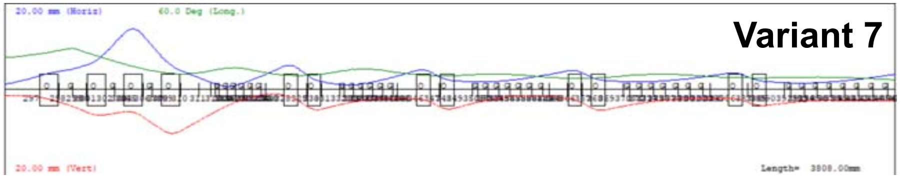
- The accelerating sections are typically short with quadrupole triplets (or doublets) in between accelerating sections for periodic transverse focusing
- Five variants considered:
  - **Variant3**: 0-degree synch phase (KONUS) beam dynamics – triplets
    - E_0=6.6MV/m – two tanks
  - Variant 4, 5, 6 – negative synch phase beam dynamics – triplets
    - **Variant4** – E_0=6MV/m, three tanks
    - **Variant5** – E_0=5MV/m, four tanks
    - **Variant6** – E_0=5MV/m, three tanks
  - **Variant 7** - negative synchronous phase beam dynamics – doublet focusing
    - E_0=6MV/m – five tanks



G. Clemente, PhD thesis, Frankfurt







DTL Study

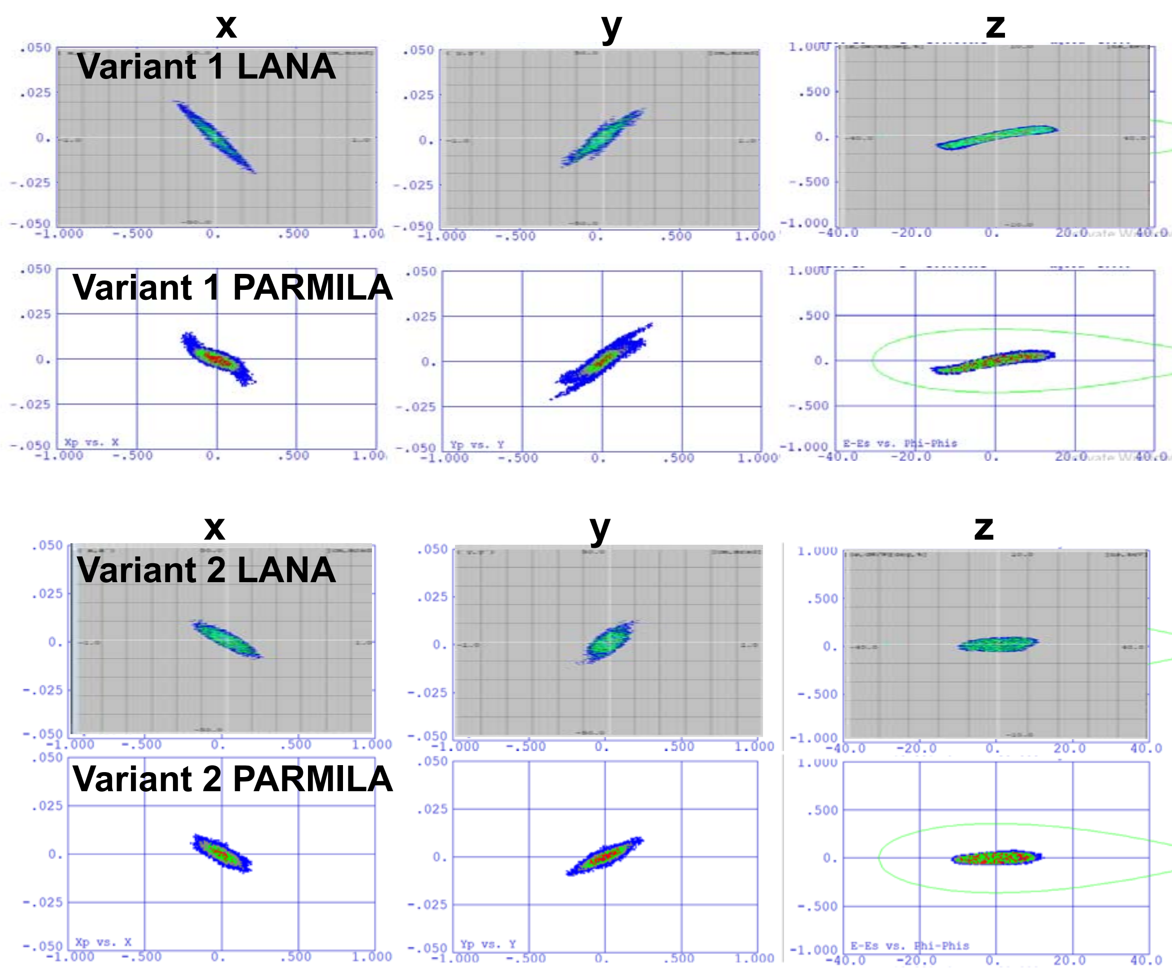
Each variant is Modeled in LANA and PARMILA

- Establish 100% transmission with good quality
- Calculate emittance growth for RMS and 99% contours
- Estimate longitudinal and transverse acceptance

Parameter	**Variant 1**	**Variant2**	**Variant3**	**Variant4**	**Variant5**	**Variant6**	**Variant7**
Type	Alvarez	Alvarez	CH-DTL	CH-DTL	CH-DTL	CH-DTL	CH-DTL
Tanks	1	1	2	3	4	3	5
Drift tubes	25	25	12,15	11,8,11	8,7,9,11	13,10,14	4,4,5,5,6
Eo (MV/m)	3.4	3.4	6.6	6	5	5	6
Synch. Phase φ_s	-30	-30	0, -60, 0	-25, -25, -25	-27, -25, -25, -25	-28, -27, -28	-25

Alvarez variants

- Good agreement between LANA and PARMILA
- Both variants give reasonable performance
- There is better control of longitudinal phase space with external MEBT buncher – less emittance growth



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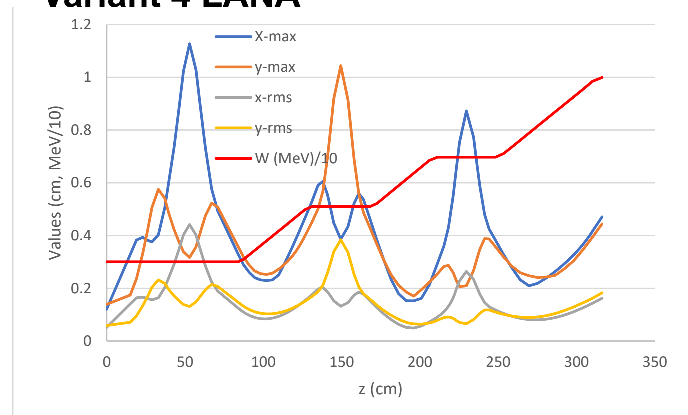
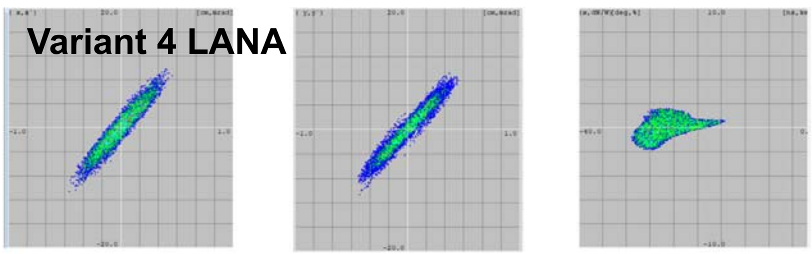
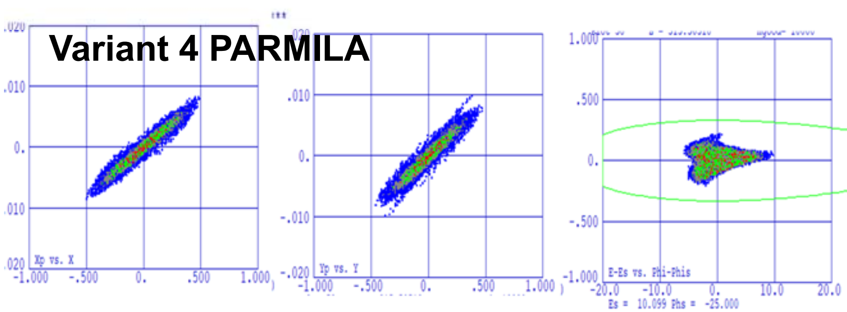
CH – Variants

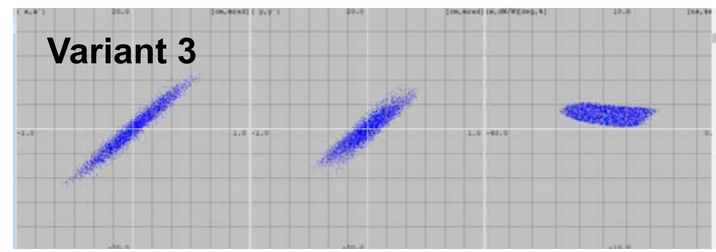
- Good agreement between LANA and PARMILA
- All variants give reasonable performance
- Some variations in emittance growth and acceptance (next slides)

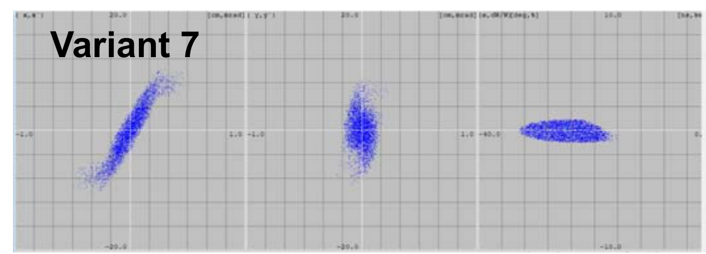
Variant 4 LANA



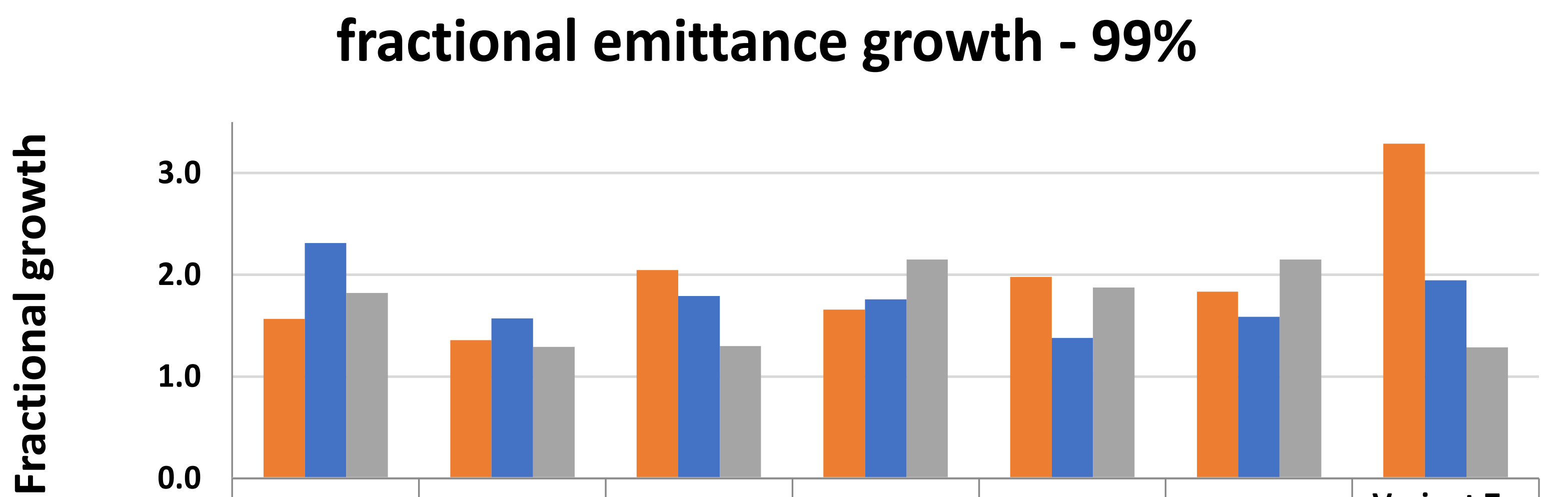






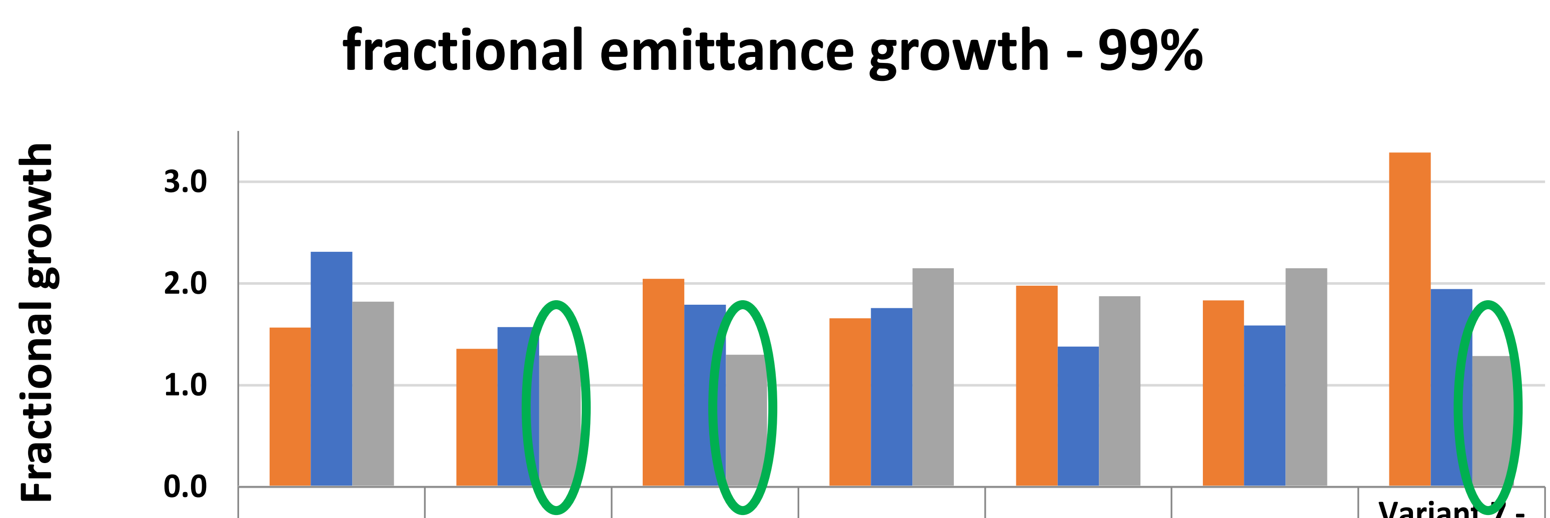


Summary plot – emittance growth 99%



	Variant 1 - Alv No MEBT	Variant 2 - Alv-4Q MEBT	Variant 3 - CH Konus	Variant 4 - CH-6MV-3Tank	Variant 5 - CH-5MV-4tank	Variant 6 - CH 5MV-3tank	Variant 7 - CH 5 tank doublet - 6MV/m
eps_x (99%)	1.57	1.36	2.05	1.66	1.98	1.83	3.29
eps_y (99%)	2.31	1.57	1.79	1.76	1.38	1.59	1.94
eps z(99%)	1.82	1.29	1.30	2.15	1.87	2.15	1.29

Summary plot – longitudinal growth 99%



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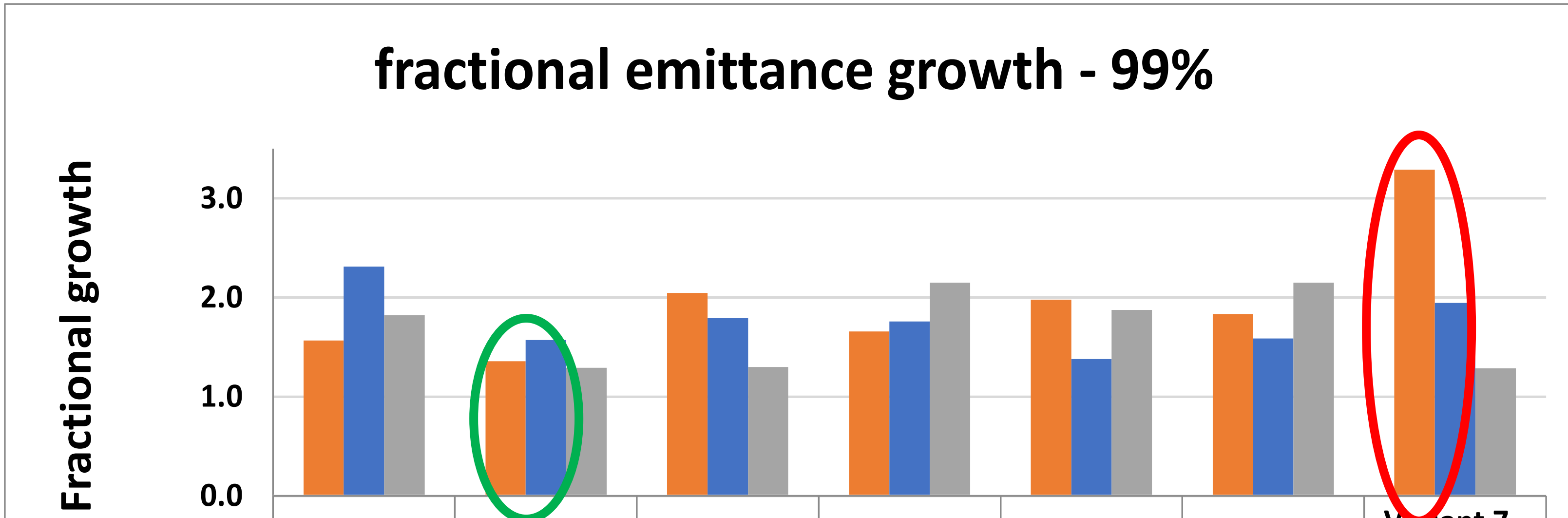
eps z(99%)	1.82	1.29	1.30	2.15	1.87	2.15	1.29

Summary plot – transverse growth 99%



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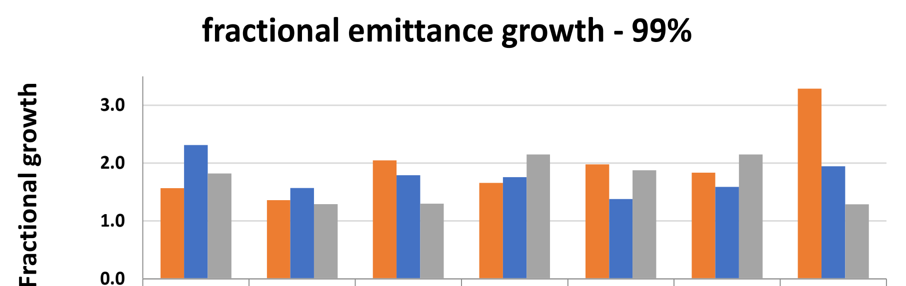
eps z(99%)	1.82	1.29	1.30	2.15	1.87	2.15	1.29

Summary plot

- All variants give reasonable results wth 100% transmission in all cases
- Alvarez with MEBT (Variant2), KONUS (Variant3) and 5 tank CH with doublets (Variant7) have the smallest longitudinal emittance growth.
- The smallest transverse emittance growth is with the Alvarez with MEBT (Variant2)
- The largest transverse growth is from doublet solution (Variant7)



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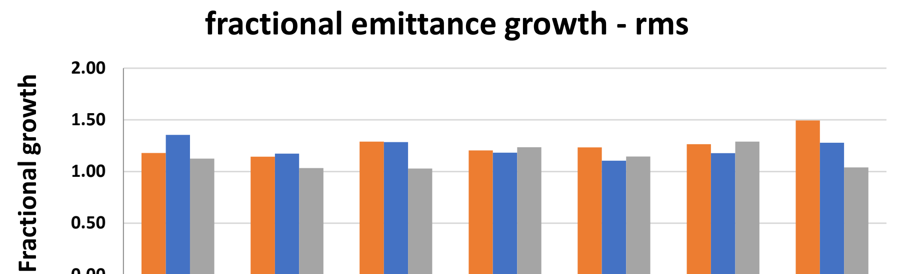

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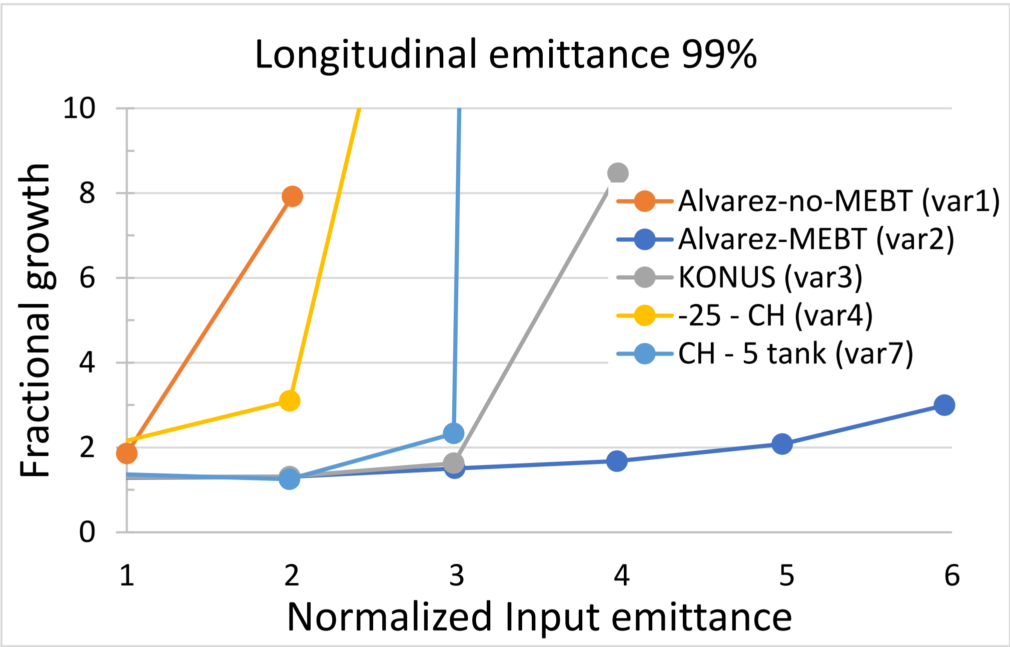
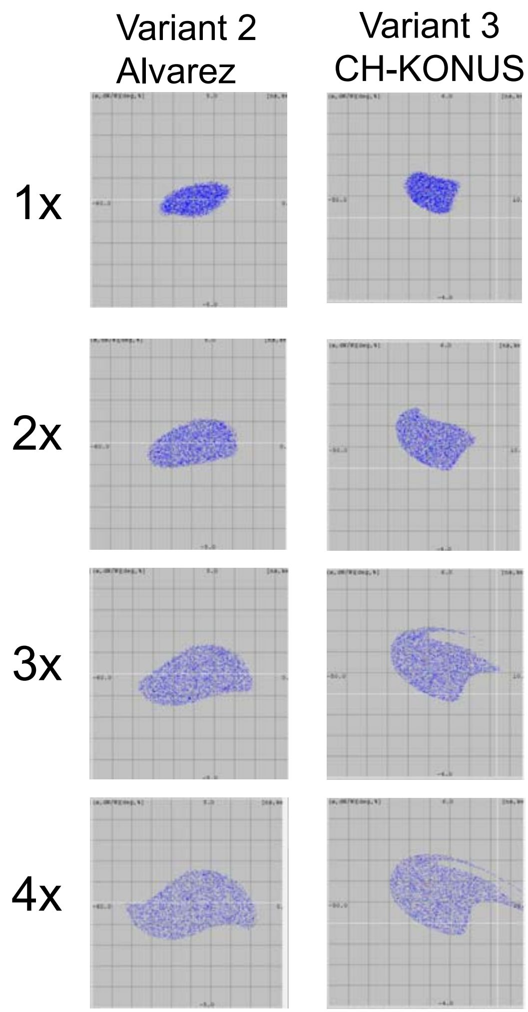
eps-x rms	1.18	1.14	1.29	1.20	1.23	1.26	1.49
eps-y rms	1.35	1.17	1.28	1.18	1.10	1.18	1.28
eps-z rms	1.12	1.03	1.03	1.24	1.15	1.29	1.04

Longitudinal acceptance

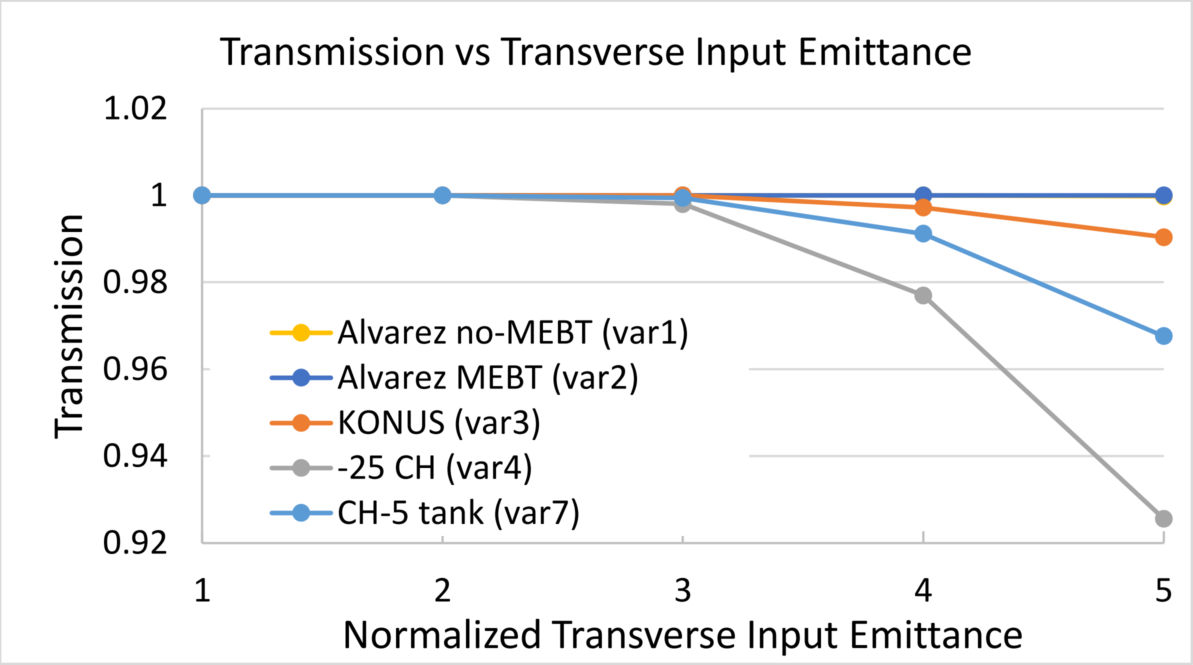
Longitudinal acceptance is estimated by looking at the fractional emittance growth for sequentially increasing input emittances





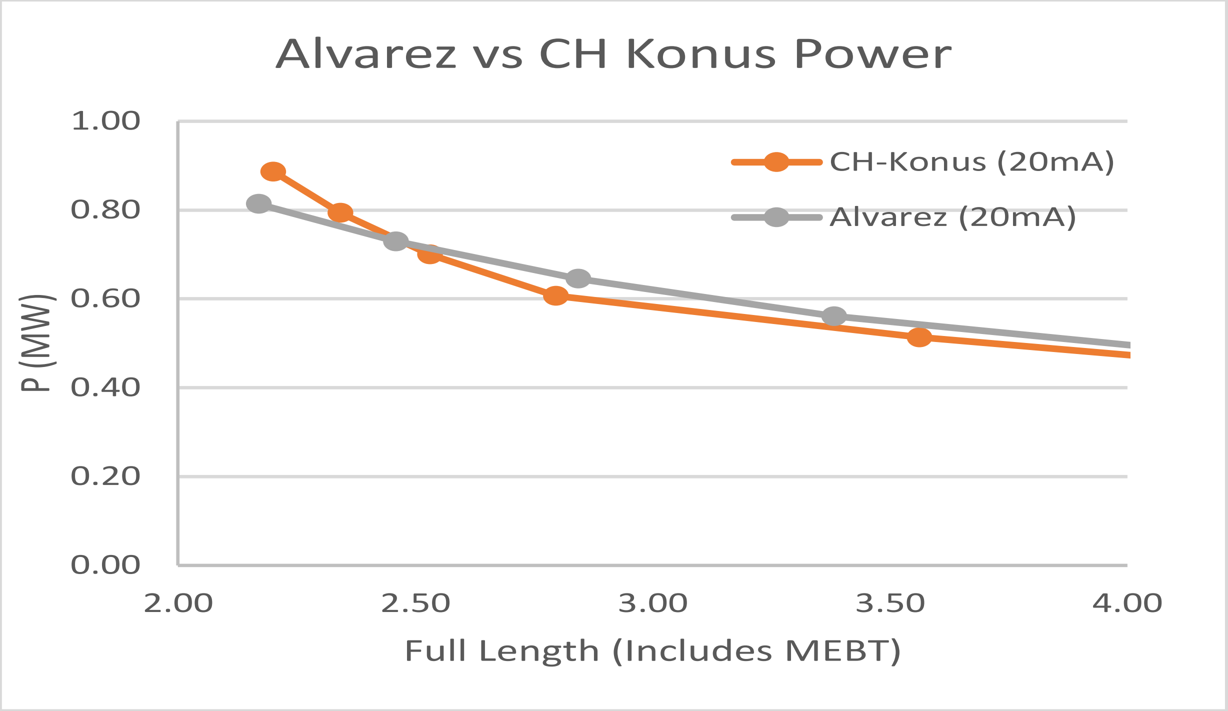
Transverse acceptance

Transverse acceptance is estimated by looking at the transmission for sequentially increasing input emittances



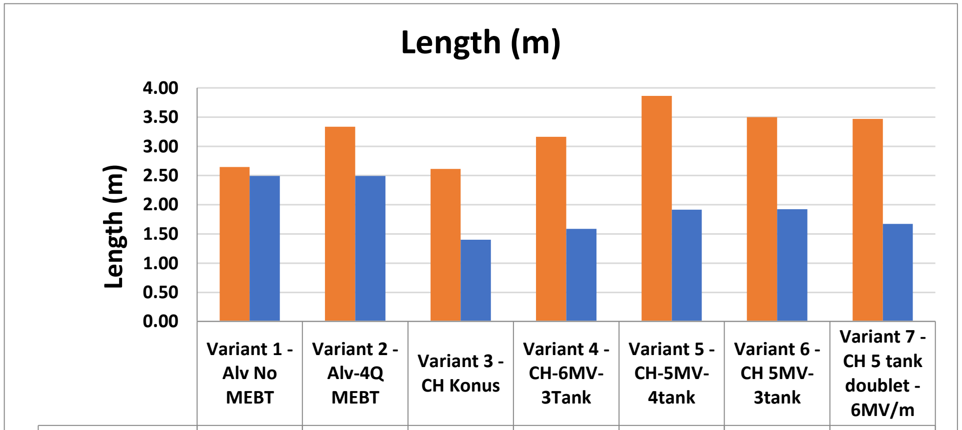
Total Peak RF Power vs length (Alvarez vs CH (Konus))

The Alvarez no-MEBT variant consumes about the same rf power per unit length as the CH (KONUS) given the need for external optics with the CH structures

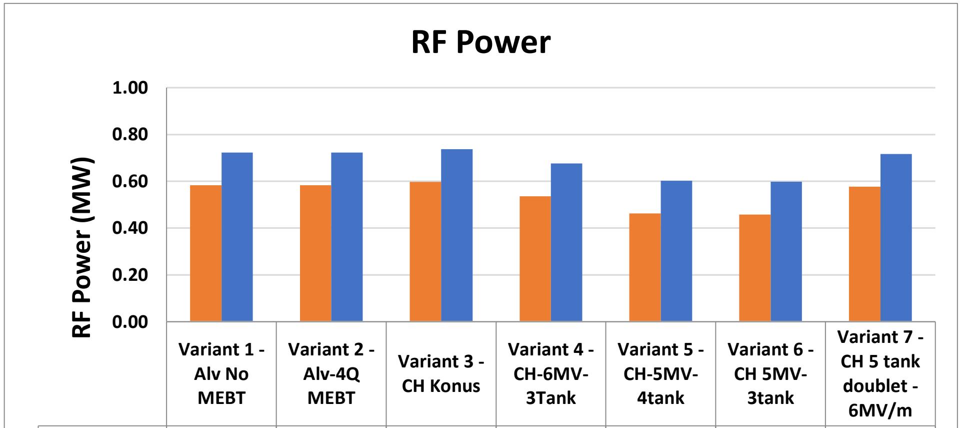


DTL – length – rf power

- The tank (rf) length is directly related to the chosen gradient while the linac length is impacted by the number of external focusing sections required.
- Total power is reduced for lower gradients but may require additional triplets in the CH variants.
- Choice of the gradient will come from a cost optimization of structure and rf power.



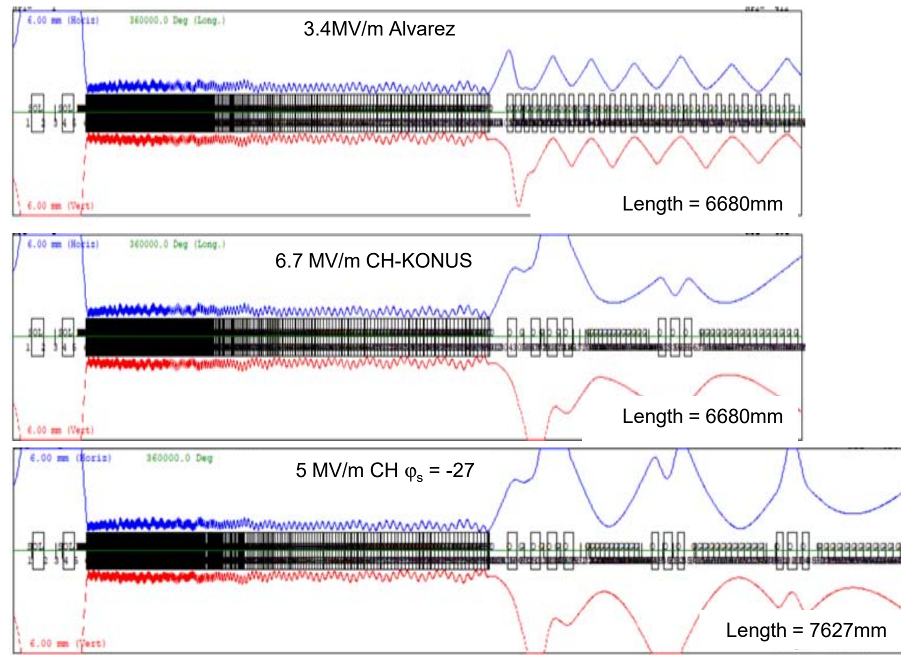
	Variant 1 - Alv No MEBT	Variant 2 - Alv-4Q MEBT	Variant 3 - CH Konus	Variant 4 - CH-6MV-3Tank	Variant 5 - CH-5MV-4tank	Variant 6 - CH 5MV-3tank	Variant 7 - CH 5 tank doublet - 6MV/m
Length (m)	2.65	3.33	2.61	3.16	3.86	3.50	3.47
Tank length (m)	2.49	2.49	1.40	1.58	1.91	1.92	1.67



	Variant 1 - Alv No MEBT	Variant 2 - Alv-4Q MEBT	Variant 3 - CH Konus	Variant 4 - CH-6MV-3Tank	Variant 5 - CH-5MV-4tank	Variant 6 - CH 5MV-3tank	Variant 7 - CH 5 tank doublet - 6MV/m
Power Loss	0.58	0.58	0.60	0.54	0.46	0.46	0.58
Total Power	0.72	0.72	0.74	0.68	0.60	0.60	0.72

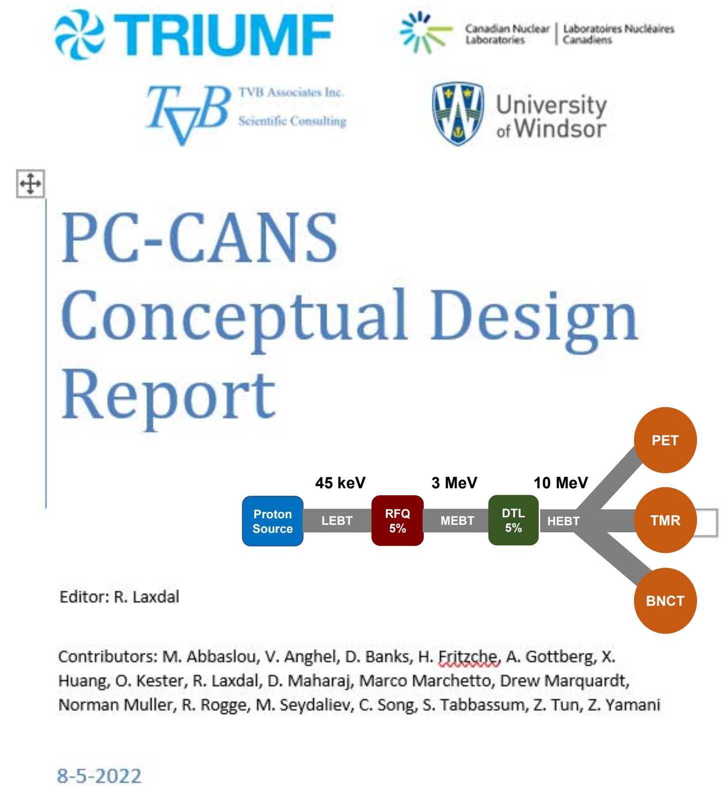
Summary

- Several DTL variants are compared: Alvarez DTL, CH-DTLs operating in negative synchronous phase or in zero-degree synchronous phase (KONUS).
- All variants yield reasonable beam quality in a small footprint with the Alvarez with MEBT offering the best overall acceptance and beam quality
- Final choice will come down to cost and performance as well as ease of operation and robustness of design



Summary of Linac activities and funding prospects

- Proposal submitted in July 2022 – announcement expected in June 2023
- Conceptual design released in support of proposal
- Linac studies including further analysis, RF design, detailed costing are continuing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PC-CANS Conceptual Design Report

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Thank you
Merci

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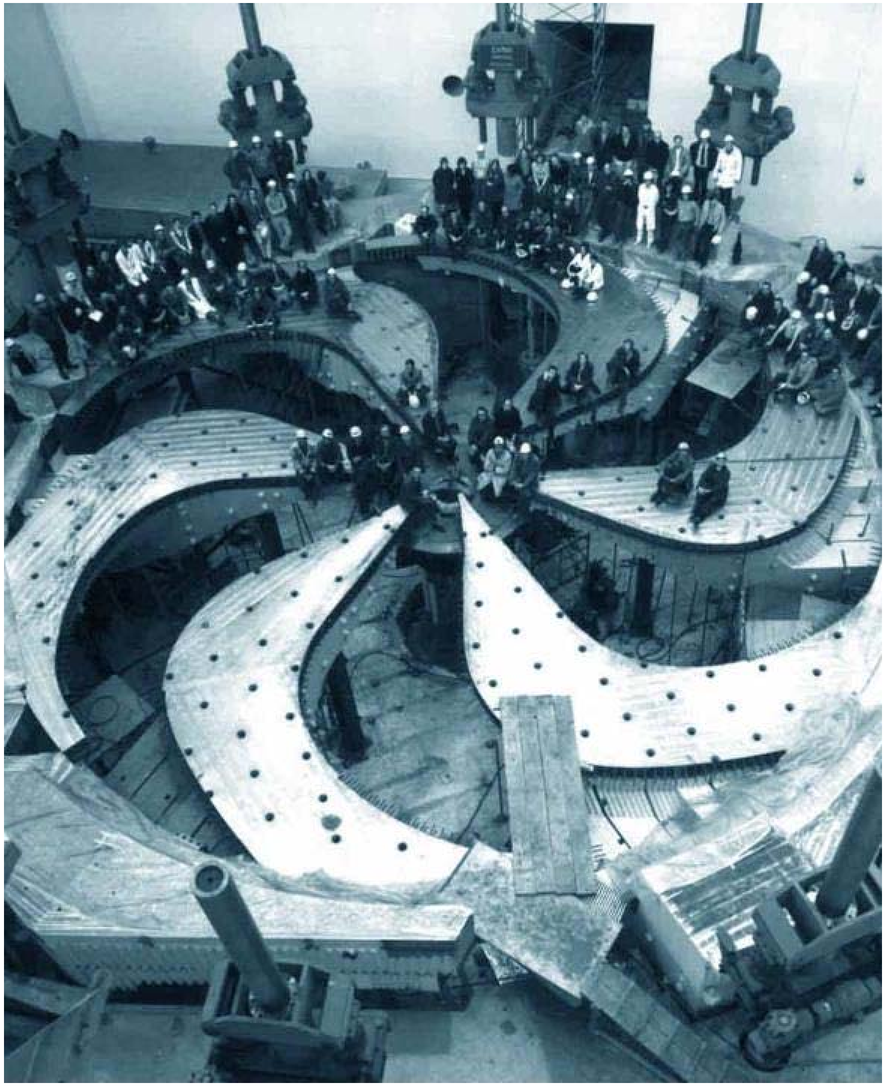

Discovery, accelerated

Expected Performance

Applications		I_{ave}/I_{peak} (mA)			
		PC-CANS1 0.1/2	PC-CANS1 0.2/4	PC-CANS2 0.5/10	PC-CANS3 1/20
Neutron Science	Cold [a] ($n/cm^2/s$)	-	$2.3x10^5/4.5x10^6$	$5.7x10^5/1.1x10^7$	$1.1x10^6/2.3x10^7$
	Thermal [a] ($n/cm^2/s$)	-	$5.8x105/1.2x10^7$	$1.5x10^6/2.9x10^7$	$2.9x10^6$/5.8x107
	SANS[d] ($n/cm^2/s$)		$1.4x10^4$	$3.4 x 10^4$	$6.8 x 10^4$
BNCT	Epithermal [b] ($n/cm^2/s$)	-	$1x10^8$	$2.5x10^8$	$5.0x10^8$
PET	18F (GBq) [c]	240	-	-	-

a Yield at 2 m from the target
b Yield from MgF2 (ref [14])
c Saturated yield
d Assuming $\Delta\lambda$=2-7.4 A, Qmin=0.0042 A^{-1}