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COMPACT RF LINAC DESIGN FOR AN ACCELERATOR DRIVEN SYSTEM

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OUTLINE

- Brief introduction – Transmutation of nuclear waste – ADS
- Compact proton RF linac design as an ADS driver
- Recent developments & proton / ion linac design choices
- Linac lattice & Beam dynamics design
- Discussion - Challenges & New technologies

INTRODUCTION – NUCLEAR WASTE

- Nuclear reactors produce energy, but they also produce significant amount of long-lived nuclear waste: minor actinides, long-lived fission products …

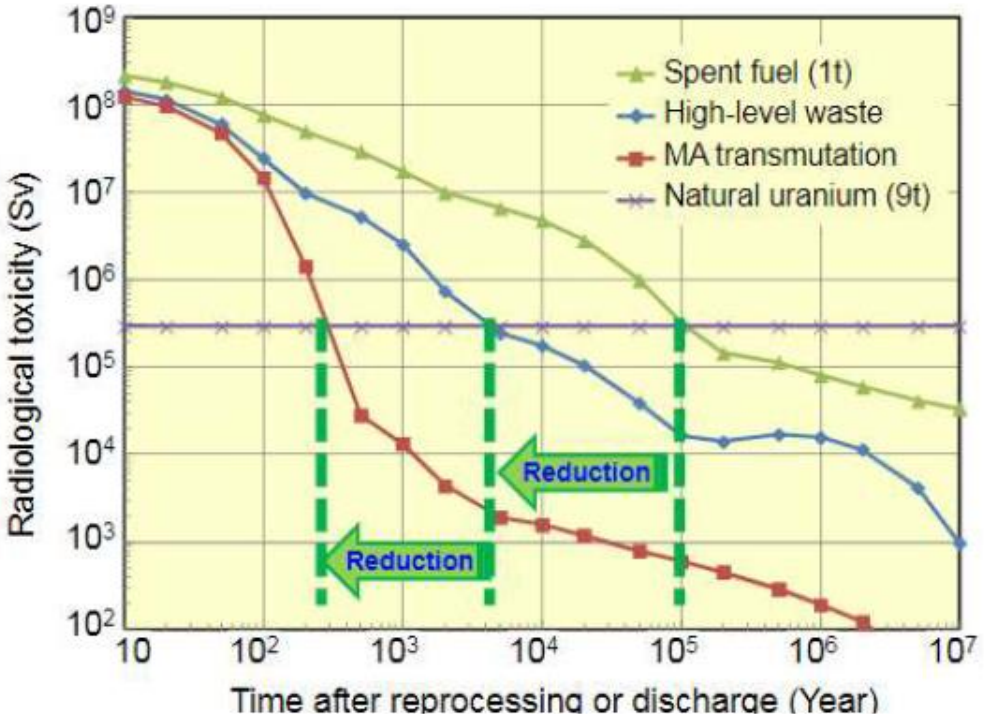


Figure from
B. Yee-Rendon,
See References

TRANSMUTATION OF NUCLEAR WASTE – ACCELERATOR DRIVEN SYSTEM (ADS)

- ❑An ADS system consists of a subcritical reactor driven by an accelerator, with the right fuel mix it can burn long-lived waste while producing energy

- ❑Shown example is from Japan's Atomic Energy Agency

Other ongoing projects include:

- ❑Chinese ADS (CiADS)
- ❑MYRRHA in Europe/Belgium
- ❑…

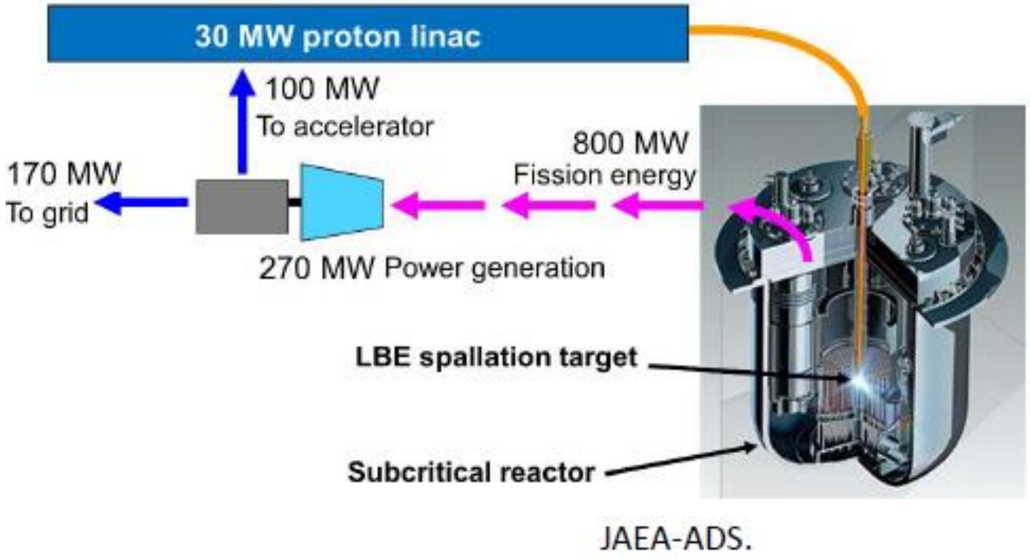
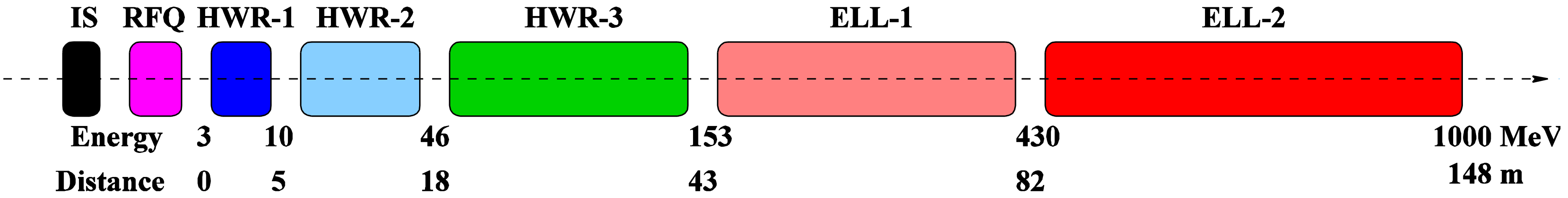


Figure from B. Yee-Rendon, See References

COMPACT PROTON RF LINAC DESIGN

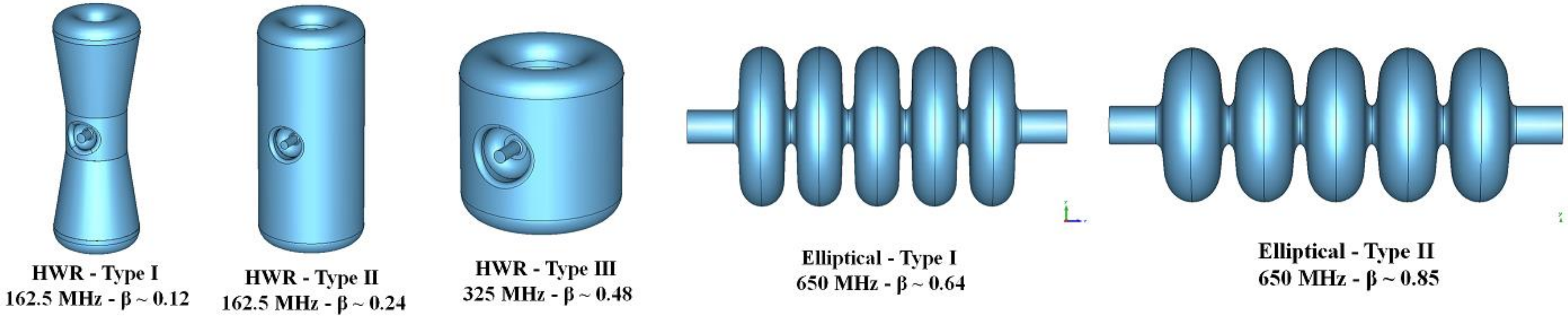


- It consists of
  - An ion source (IS)
  - A radio-frequency quadrupole (RFQ)
  - Three sections of half-wave resonator superconducting cavities (HWR)
  - Two sections of elliptical cell superconducting cavities (ELL)

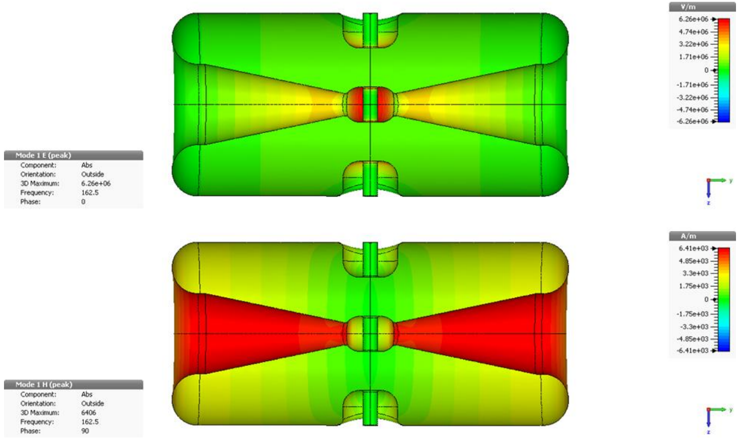
✓ The linac is only 150 m in length, it's about half the length of the SNS linac with the same 1 GeV output energy, but for **25 mA cw** proton beam

✓ It takes advantage of the latest superconducting RF developments, especially, the high accelerating voltages for SC cavities, and compact cryomodule design

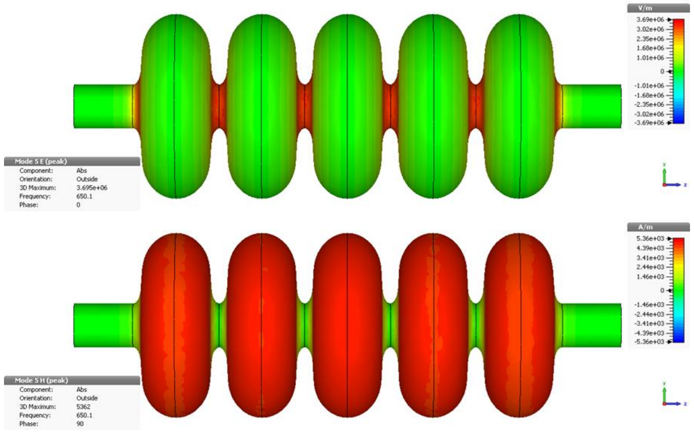
SC CAVITY TYPES – FREQUENCY & VELOCITY



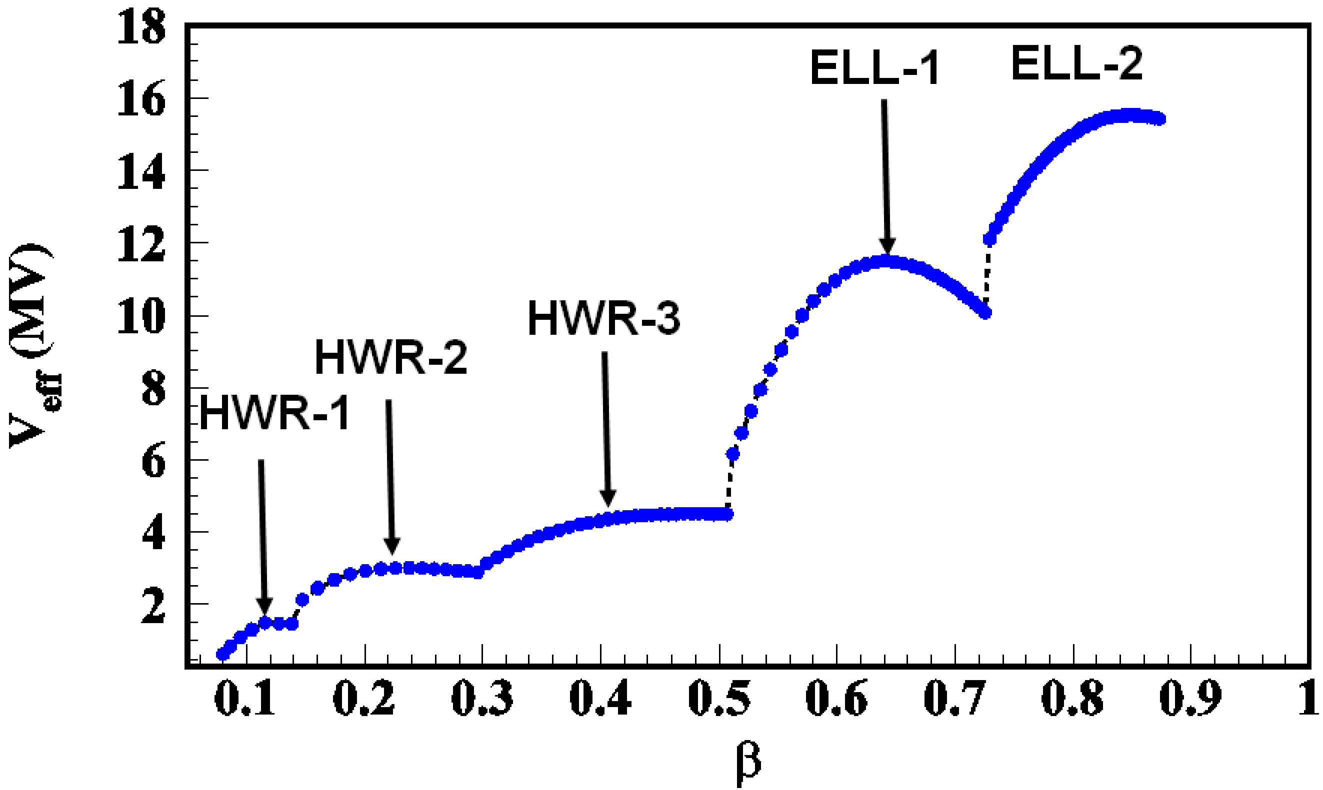
EM Field Distributions for HWR-2



EM Field Distributions for ELL-2



SC CAVITY DESIGN – VOLTAGE PROFILE



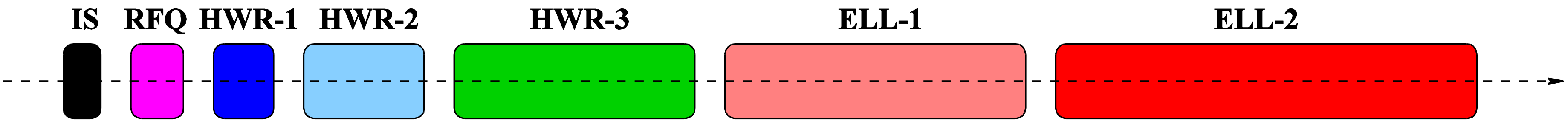
SC CAVITY DESIGN – RF PARAMETERS

Cavity type	HWR-1	HWR-2	HWR-3	ELL-1	ELL-2
Frequency, MHz	162.5	162.5	325	650	650
Optimum β	0.12	0.24	0.5	0.65	0.85
Effective length, cm	22.1	44.6	46.1	74.5	98.1
Epk/Eacc	5.0	4.8	4.1	2.5	2.4
Bpk/Eacc, mT/(MV/m)	5.9	6.2	7.9	4.6	4.4
R/Q ratio, Ω	293	332	292	377	551
G factor, Ω	50	73	117	192	236
Voltage at Epk=40 MV/m, MV	1.8	3.7	4.5	11.9	16.2
Voltage at Bpk=70 mT, MV	2.6	5.0	4.1	11.2	15.5

RECENT DEVELOPMENTS & RF LINAC LATTICE DESIGN CHOICES

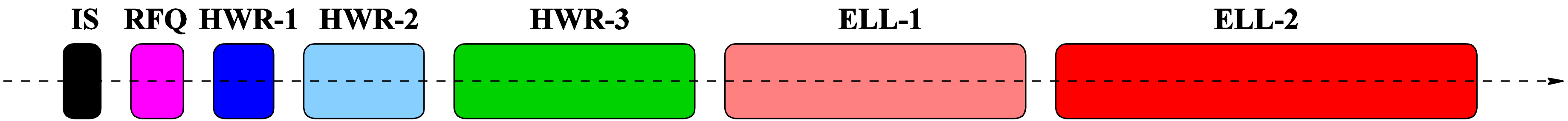
- The key design choices for compact proton & ion RF linacs:
  - **Optimized Superconducting cavity design for high voltage and low cryogenic losses**
  - **Superconducting solenoid focusing inside long cryomodules to minimize warm transitions and the number of required cryomodules.**
  - **Cold BPMs attached to SC cavities inside cryomodule to reduce the number of diagnostics between cryomodules**
  - **Horizontal and vertical steering correctors built into solenoids requiring no additional space for correctors along the beam-line.**
- With these choices, the drift spaces between cryomodules are reduced, benefiting the beam dynamics from a more periodic focusing and acceleration lattice

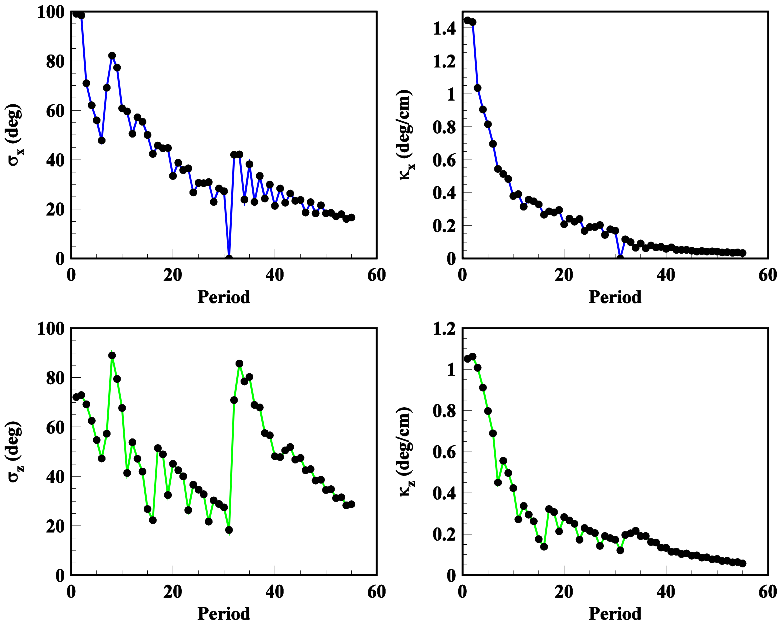
LINAC DESIGN - LATTICE & CRYOMODULES

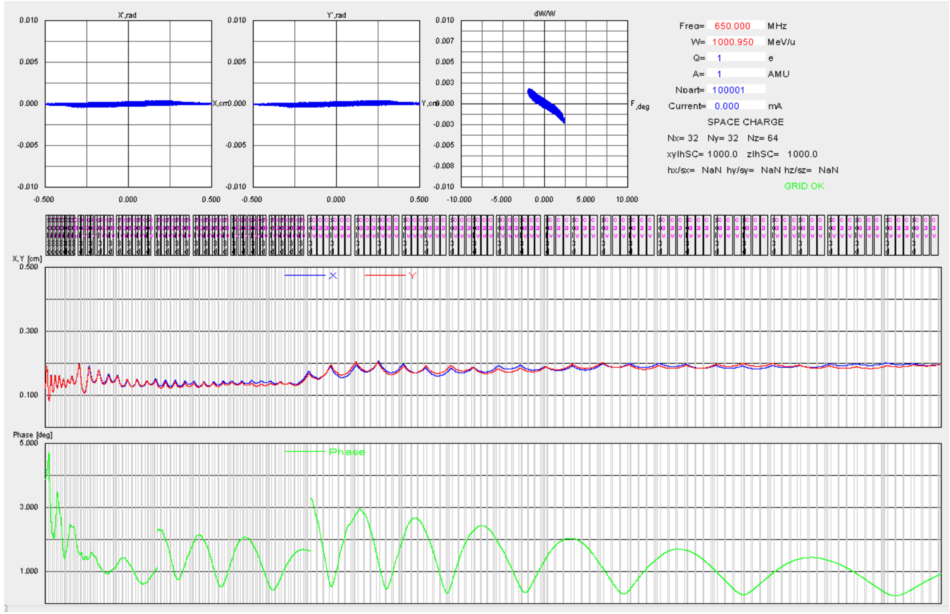


Section	HWR-1	HWR-2	HWR-3	ELL-1	ELL-2	Total
Frequency, MHz	162.5	162.5	325	650	650	
Input energy, MeV	3	10	46	153	430	
Output energy, MeV	10	46	153	430	1001	
Voltage per cavity, MV	1.5	3.0	4.5	11.5	15.7	
Synchronous phase, deg	-30	-25	-25	-25	-25	
Cavities per cryostat	7	7	7	6	6	
Cryostat arrangement	7(sc)	3(s2c)sc	3(s2c)sc	2(s3c)	2(s3c)	
Number of cryostats	1	2	4	5	7	19
Number of cavities	7	14	28	30	42	121
Number of solenoids	7	8	16	10	14	55

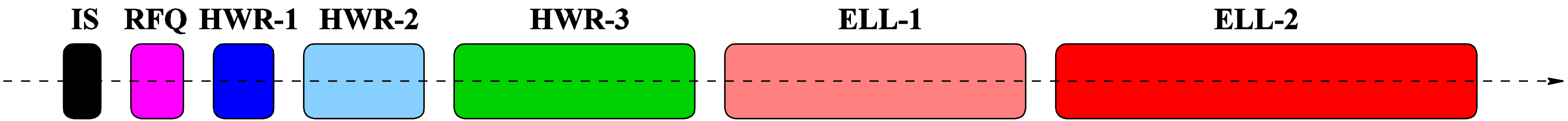
LINAC DESIGN – BEAM DYNAMICS - 0 MA



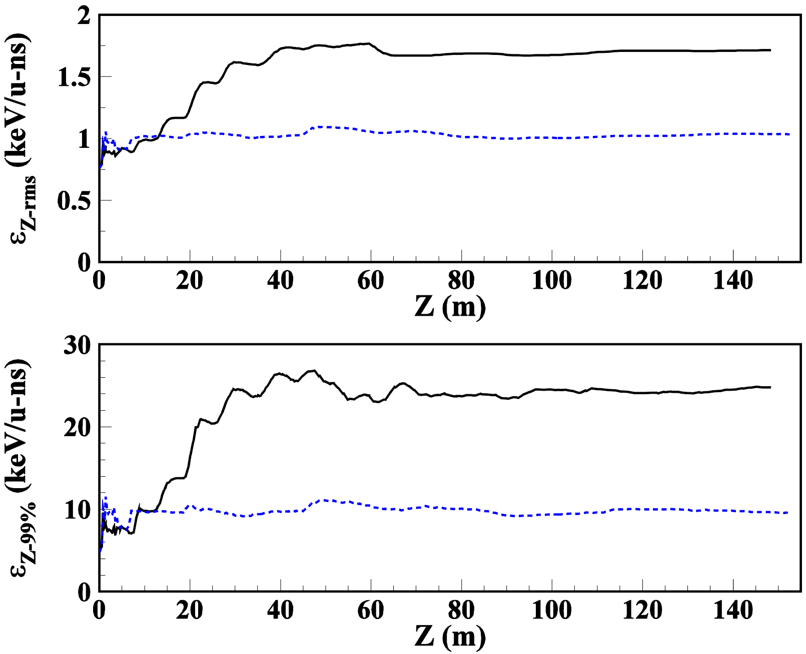




LINAC DESIGN – BEAM DYNAMICS - 25 MA



✓ **Longitudinal matching optimized with space charge for a 25 mA beam and the overall rms emittance growth was reduced to ~ 33%.**



Original tune from 0 mA

Optimized tune for 25 mA

DISCUSSION - CHALLENGES & NEW TECHNOLOGIES

- CW operations of a high-intensity proton/ion linac is very challenging due to the high beam power involved and potential damage

- An ADS system requires a driver linac with high reliability to maintain a steady state in the target and reactor system, and minimize thermal stress

- Building redundancy in the driver linac and not operating cavities at the voltage limit can address some of the reliability issues

- New superconducting RF technology such as Nb_3Sn has the potential of significantly reducing the operating cost by not requiring a large cryogenic installations…

RELEVANT REFERENCES

- “Overview of ADS projects in the world”, B. Yee-Rendon, Proceedings of Linac-2022 Conference, 28th Aug. - 2nd Sep. 2022, Liverpool, UK
- “ADS design concept for disposing of the U.S. spent nuclear fuel inventory”, Y. Gohar et al, Annals of Nuclear Energy 160 (2021) 108385
- “Design options for a superconducting ion linac”, B. Mustapha et al, NIM A 992 (2021) 165014
- “Advanced low-beta cavity development for proton and ion accelerators”, Z. Conway et al, NIM B 350 (2015) 94-98

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THANK YOU

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