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Space Charge Resonances in Linacs

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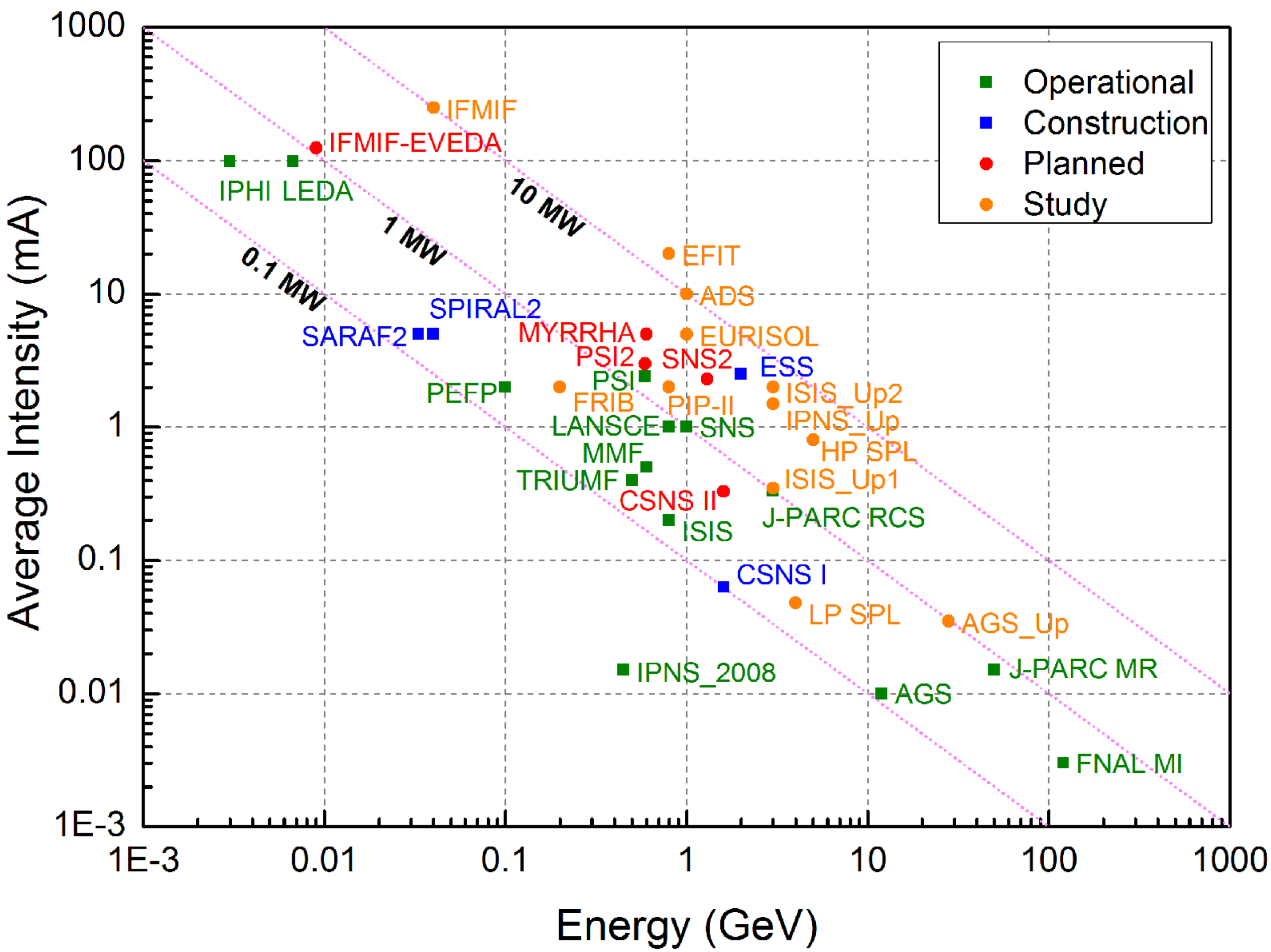
Malmö - 07/07/2016

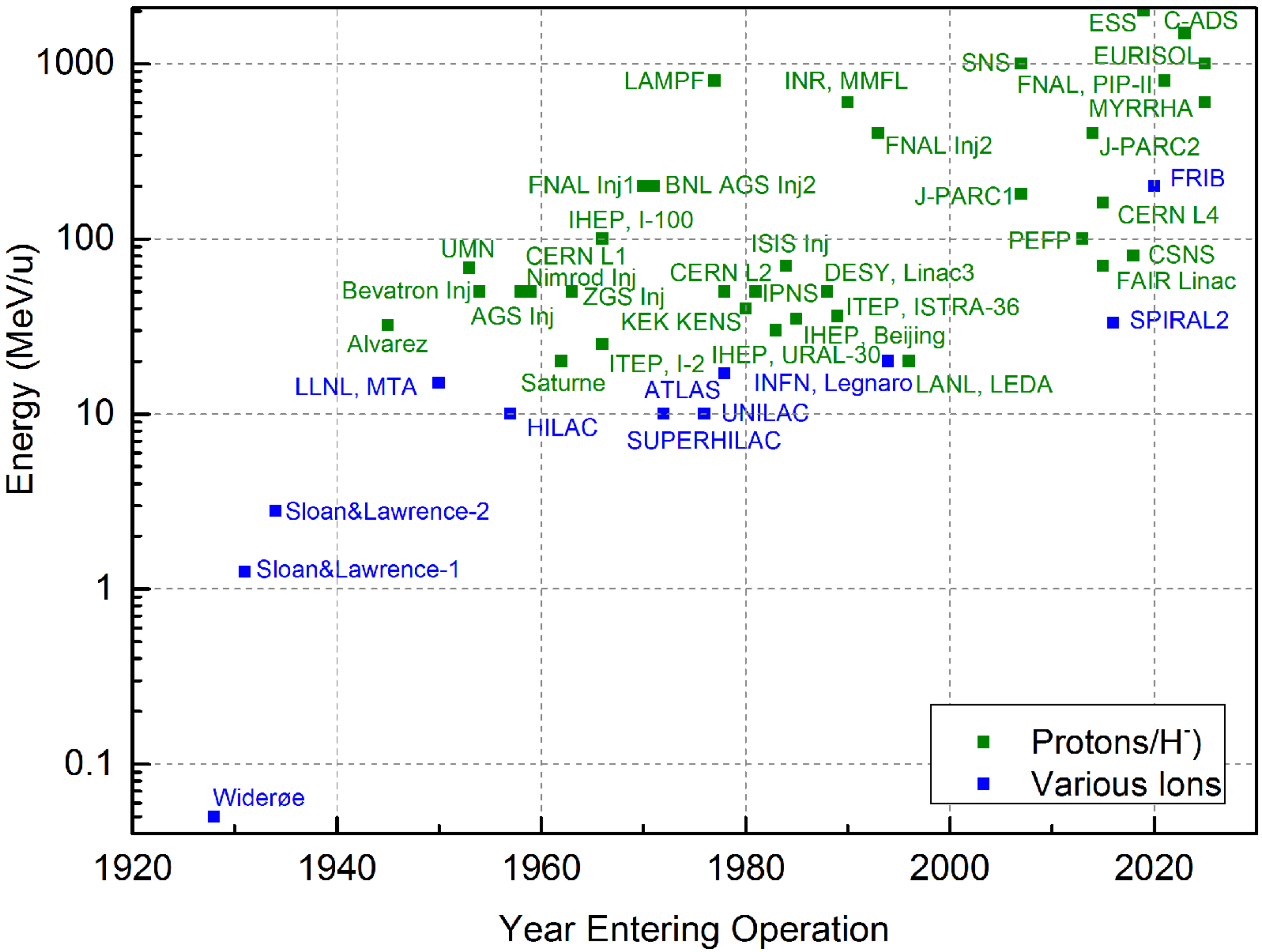
Context

- Beam dynamics design guidelines (meta-criteria) for high intensity proton linacs (HB’10, 12, 14, etc.):
  - Avoid the 90-degree stopband (i.e zero current phase advance less than 90 degrees).
    - Envelope instability
    - Fourth order resonance ($4\sigma=360$)
  - Good matching at the beginning and at transitions between structures.
  - Smooth and continuous phase advance variation, regular lattice, adiabatic changes
  - Tune depression control
  - Tunes chosen to avoid radial-longitudinal coupling resonances
    - Hofmann Resonance Chart
    - Equipartitioning is not necessary to avoid exchange
    - Rate of exchange depends on the crossing speed
    - Individual analysis of coupling resonances, excitation level, etc.

The Beam Power Landscape



Proton/Ion Linac Development



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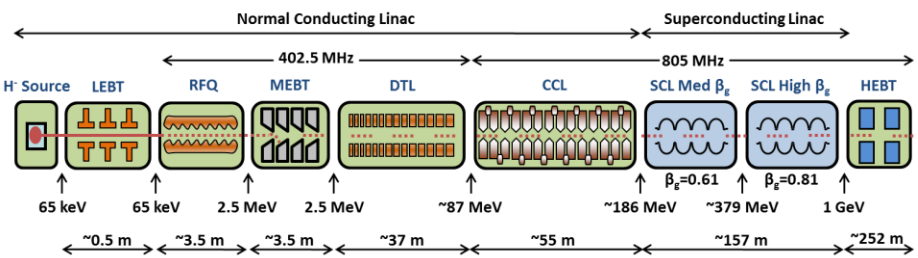
Beam Dynamics Design Approach

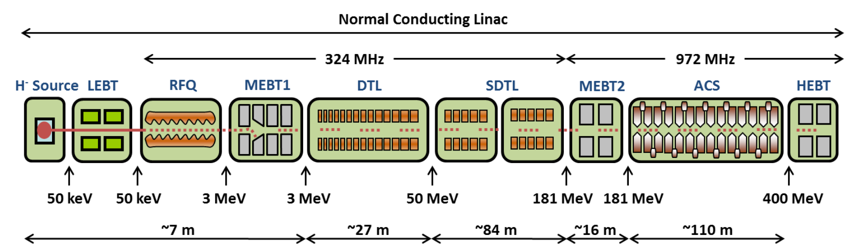
SNS



Ion Species	H^-	
Output Energy	1	GeV
Frequency	402.5/805	MHz
Pulse Length	1.0	ms
Peak Current	38	mA
Protons per Pulse	1.5×10^{14}	
Repetition Rate	60	Hz
Duty Cycle	6	%
Average Beam Power	1.4	MW
Accelerating Structures	RFQ, DTL, CCL, SCL	
Accelerator Length	~257	m

Non-Equipartitioned

J-PARC

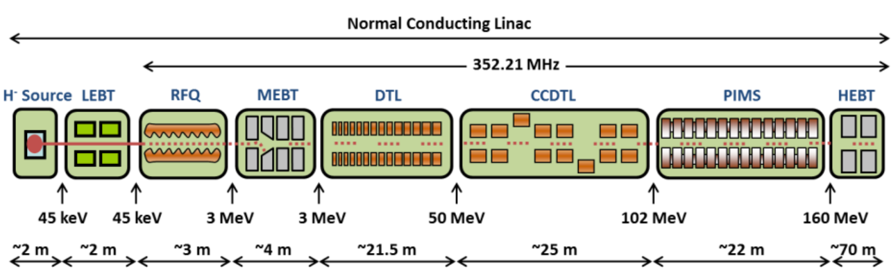


Ion Species	H^-	
Output Energy	400	MeV
Frequency	324/972	MHz
Pulse Length	0.5	ms
Peak Current	30/50	mA
Protons per Pulse	9.4×10^{13}/ 1.5×10^{14}	
Repetition Rate	25	Hz
Duty Cycle	1.25	%
Average Beam Power	80/133	kW
Accelerating Structures	RFQ, DTL, SDTL, ACS	
Accelerator Length	~244	m

Equipartitioned

Beam Dynamics Design Approach

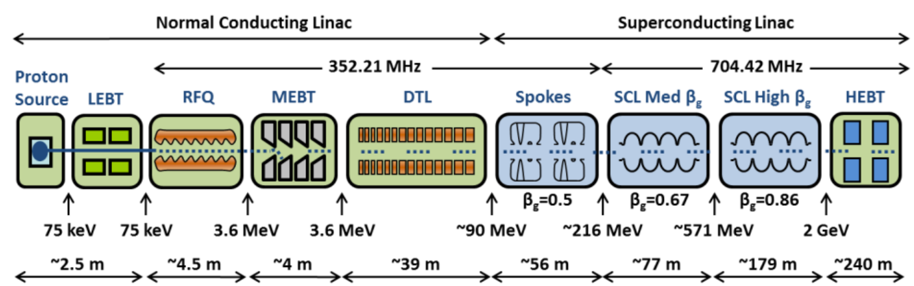
Linac4



Ion Species	H^-	
Output Energy	160	MeV
Frequency	352.21	MHz
Pulse Length	0.4	ms
Peak Current	40	mA
Protons per Pulse	1.0×10^{14}	
Repetition Rate	2	Hz
Duty Cycle	0.08	%
Average Beam Power	5.1	kW
Accelerating Structures	RFQ, DTL, CCDTL, PIMS (*CCL)	
Accelerator Length	~80	m

Equipartitioned

ESS



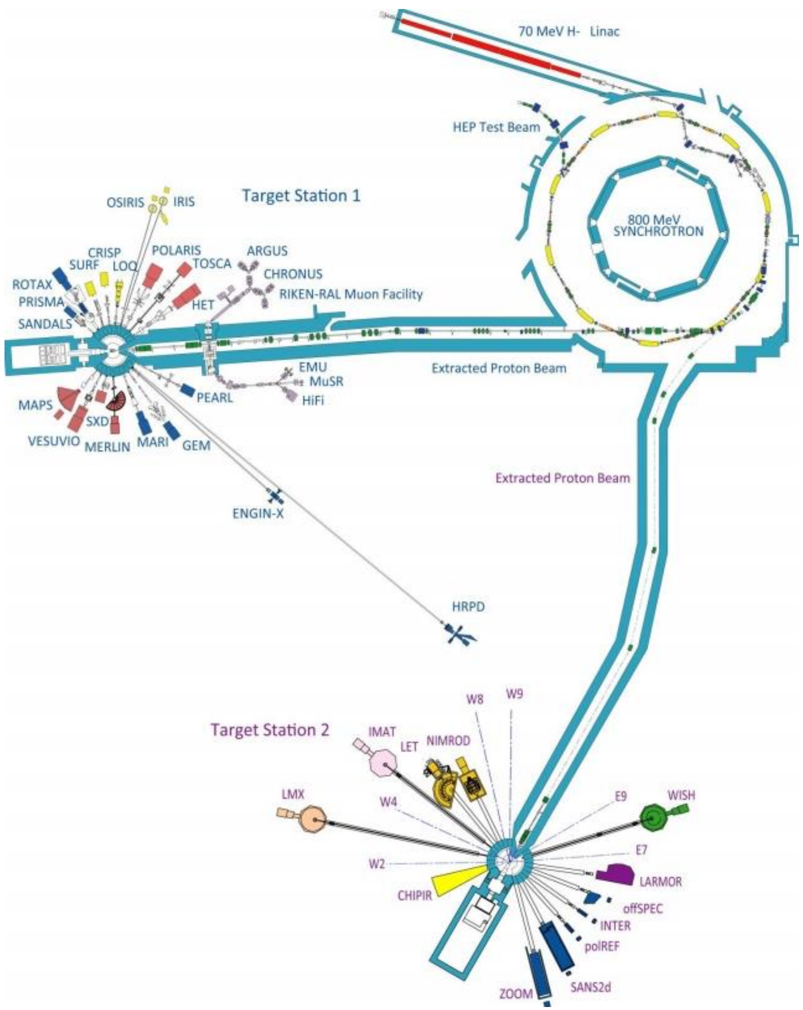
Ion Species	Protons	
Output Energy	2	GeV
Frequency	352.21/704.42	MHz
Pulse Length	2.86	Ms
Peak Current	62.5	mA
Protons per Pulse	1.1×10^{15}	
Repetition Rate	14	Hz
Duty Cycle	4	%
Average Beam Power	5	MW
Accelerating Structures	RFQ, DTL, SC Spokes/Elliptical	
Accelerator Length	~365	m

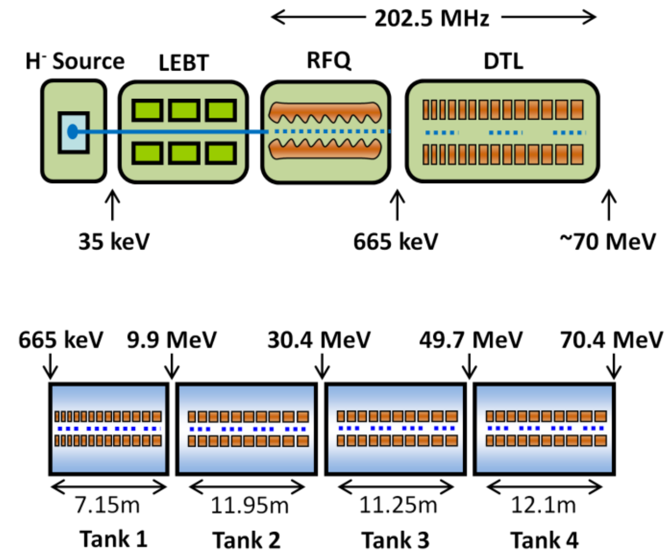
“Equitunes”

But, does all this matter?

- Avoiding space-charge resonances and instabilities can require considerable efforts
  - Strict phase advance laws throughout the linac
  - Working point selection limit
- Design can be suboptimal and more costly
  - Particularly true for superconducting machines
- What is the figure of merit that we are aiming for?
- Can some emittance growth be tolerated?

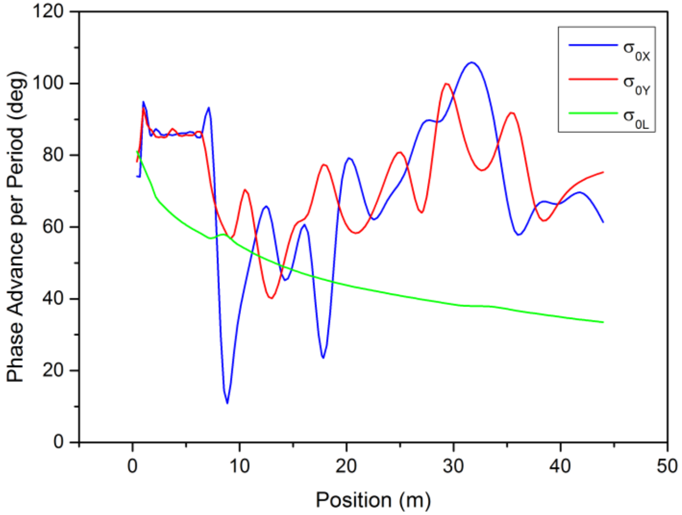
The ISIS Experience

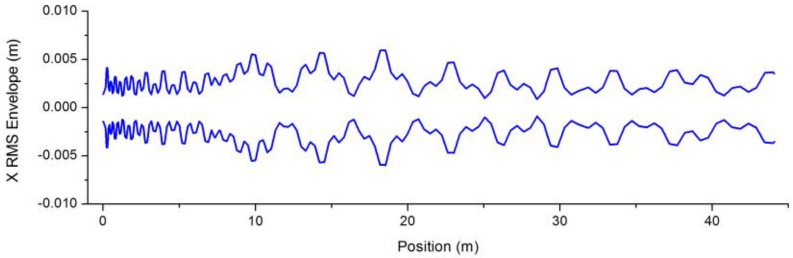


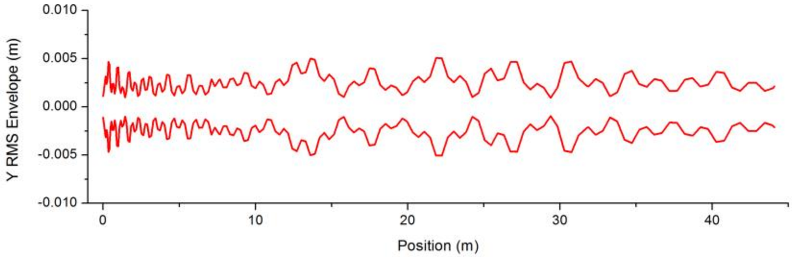


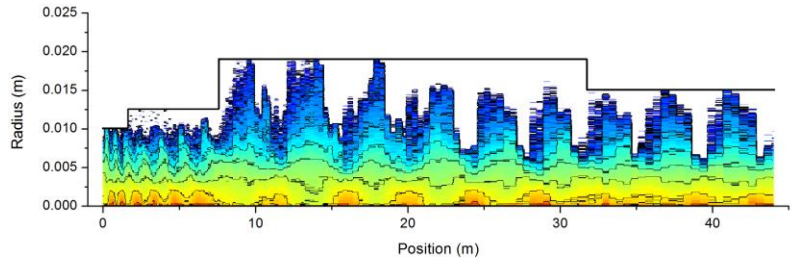
Energy	70.4	MeV
Frequency	202.5	MHz
Pulse Length	200-250	µs
Peak Current	25	mA
Repetition Rate	50	Hz
Total Length	55	m
Duty Cycle	1-1.25	%

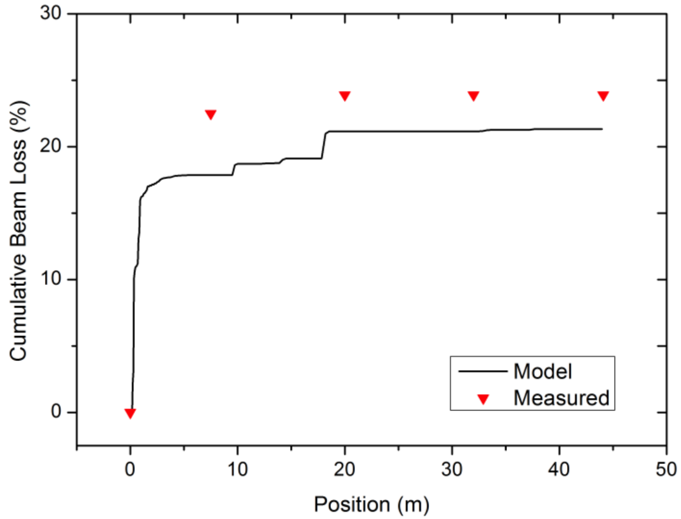
The ISIS Experience: Typical user-run machine setup





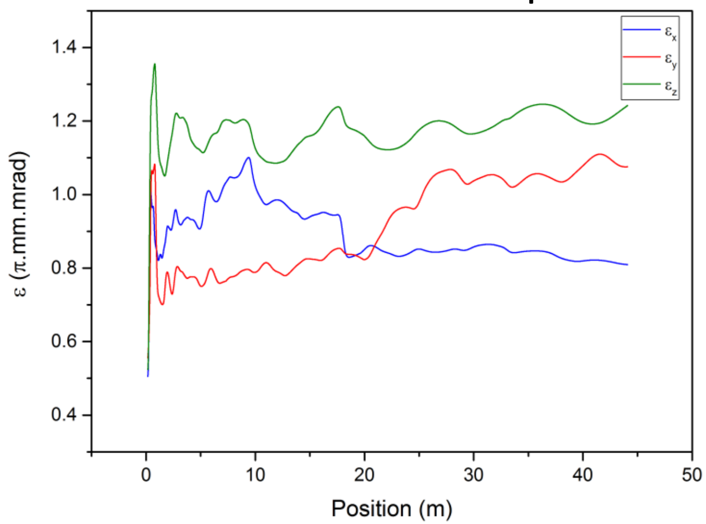




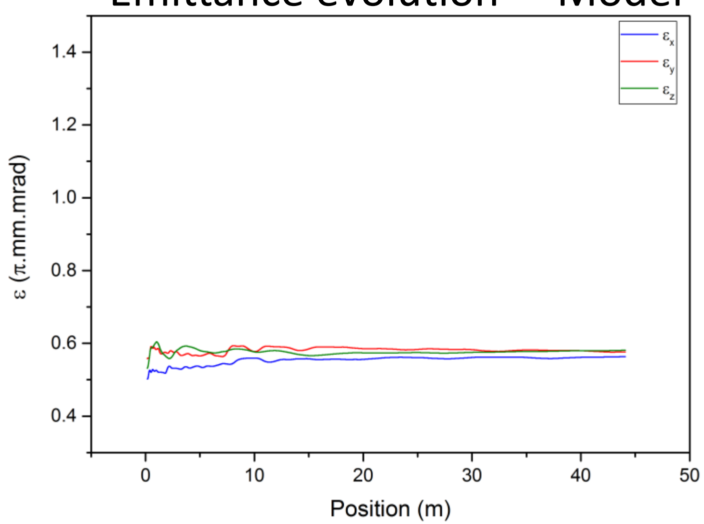


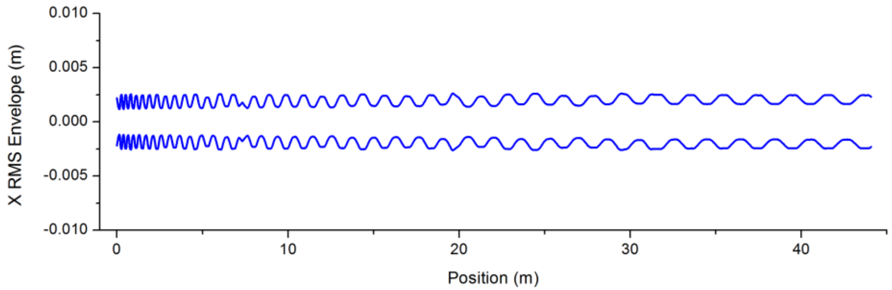
The ISIS Experience:
In an ideal world…

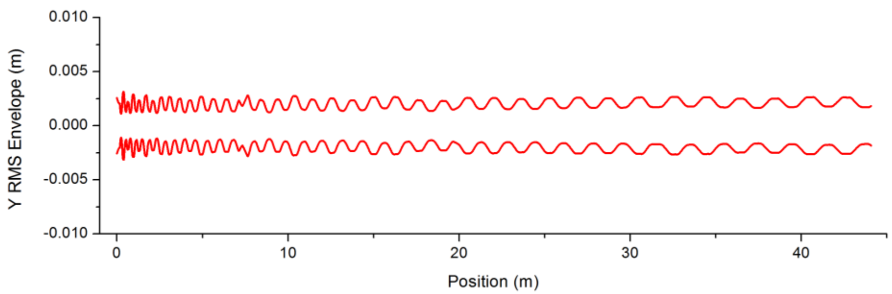
Emittance evolution - “Operational”

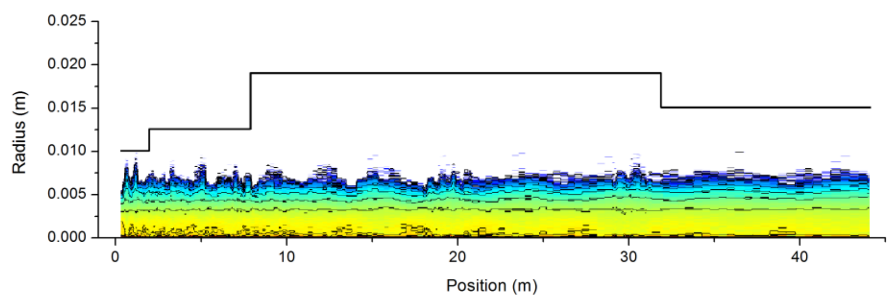


Emittance evolution - “Model”









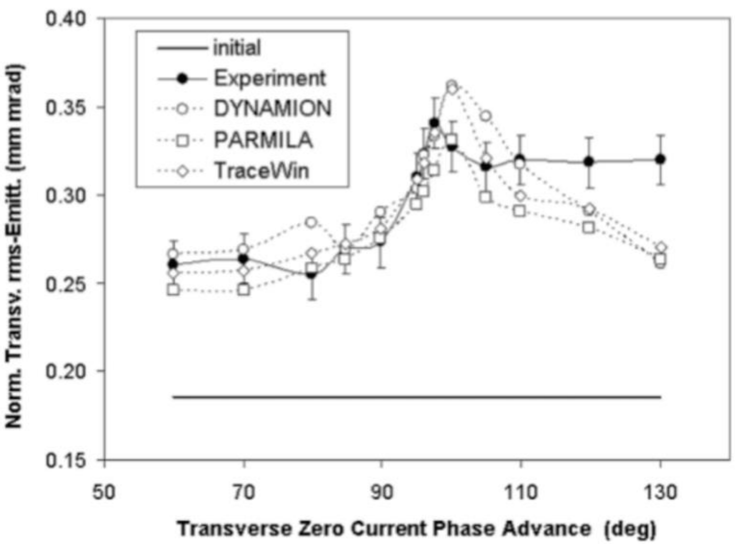
The ISIS Experience

- ISIS simulation model tuning:
  - Avoid mismatches
  - Avoid resonances/instabilities
  - Minimise emittance growth

- ISIS Linac tuning
  - Real-life machine tuning has different aims
  - Reduce losses
  - Control activation to allow hands-on maintenance (crucial for an old machine)
  - In reality the beam core could be mismatched, but the transmission increased

Space-charge Resonances: Experimental evidence: UNILAC

- 2009 Experiment at UNILAC in GSI
- Linac lattice modified to investigate the 90 degree stop-band - kz/kt=1 resonance
- The resulting transverse emittance growth was measured thus giving an indication of a space-charge resonant effect.
- First experimental observation of emittance growth in a linac driven by the kz/kt=1 resonance.



- Several key differences:
  - A heavy ion was used rather than a proton/H- linac.
  - Emittance ration $\varepsilon_t/\varepsilon_t$ closer to 10, which is much larger than those usually found in proton H- linacs where the ratio is closer to 1.
  - Only transverse emittance was measured
- See L. Groening et al. Phys. Rev. Lett., 103, 224801.

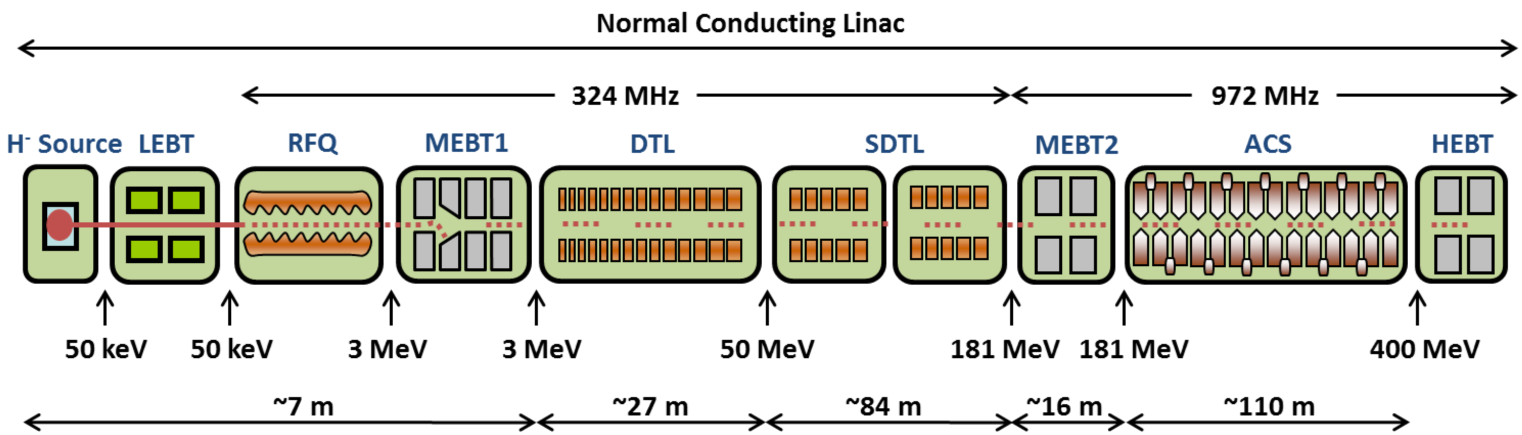
Experimental evidence: SNS

- SNS Experiment
  - 90 degree stop-band
  - CCL lattice modified – phase advance kept constant for the test points
    - 4k=360 deg resonance
    - $2k_t$-$2k_z$=0 coupling resonance
- Wire scanner profile measurements
  - "Beam shoulders" identified, characteristic for this resonance.
- Comparison with simulation
  - Very good agreement
- See D.-O. Jeon Talk/Paper THPM4X01
  - PRAB 19, 010101, 2016

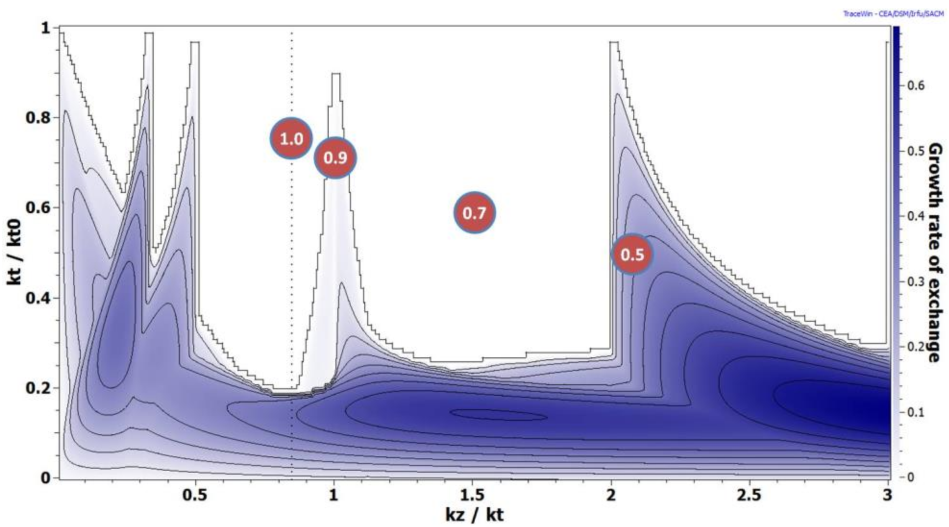
Experimental Evidence: J-PARC

- Beam study campaign started in 2012
  - See THPWO087 – IPAC’13
- A wide variety of operating modes can be deployed
  - J-PARC uses EMQs throughout the machine
- Exploring tunes outside equipartitioning
- Testing alternative lattices to reduce intra-beam stripping losses

Experimental Evidence: J-PARC

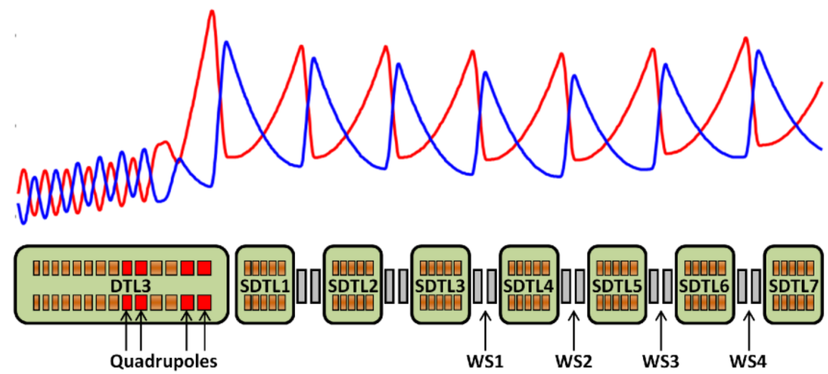


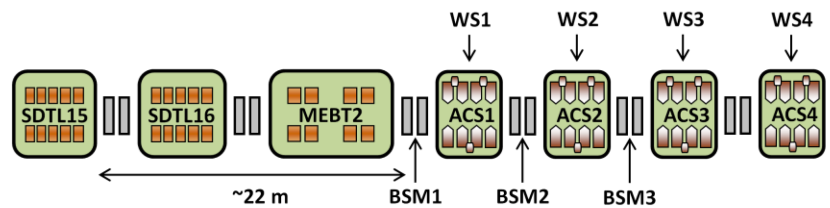
- 2012 campaign: concentrated on SDTL
- 4 working points tested
- Both transverse and longitudinal beam parameters measured



Experimental Evidence: J-PARC

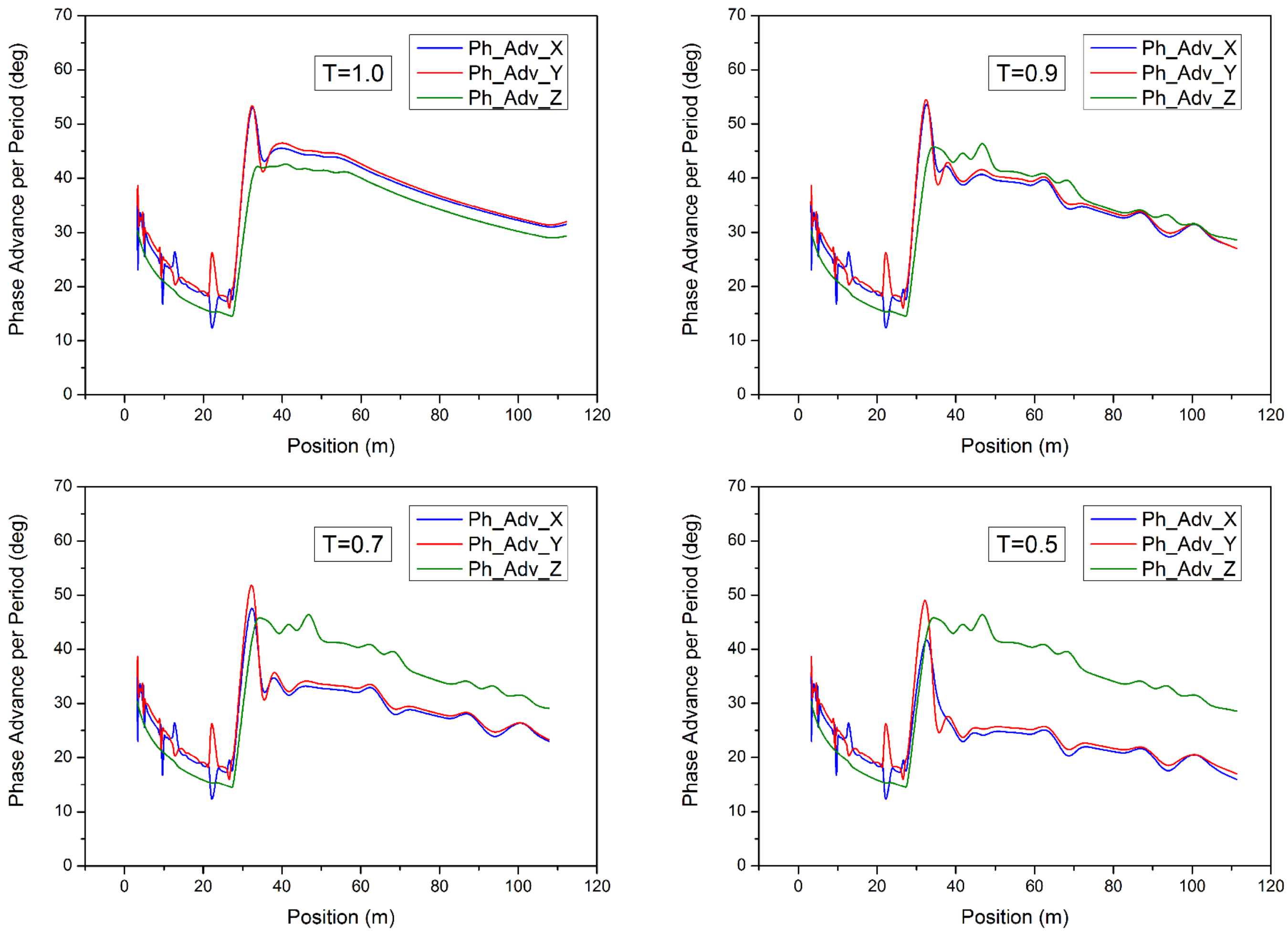
- Procedure
  - Full machine tuning for a 15 mA operating current. Front-end and DTL settings kept constant for all measurements
  - New SDTL working point lattice deployed
  - New DTL-SDTL transverse matching
  - SDTL output measurement of transverse (wire scanners) and longitudinal (bunch shape monitors) parameters





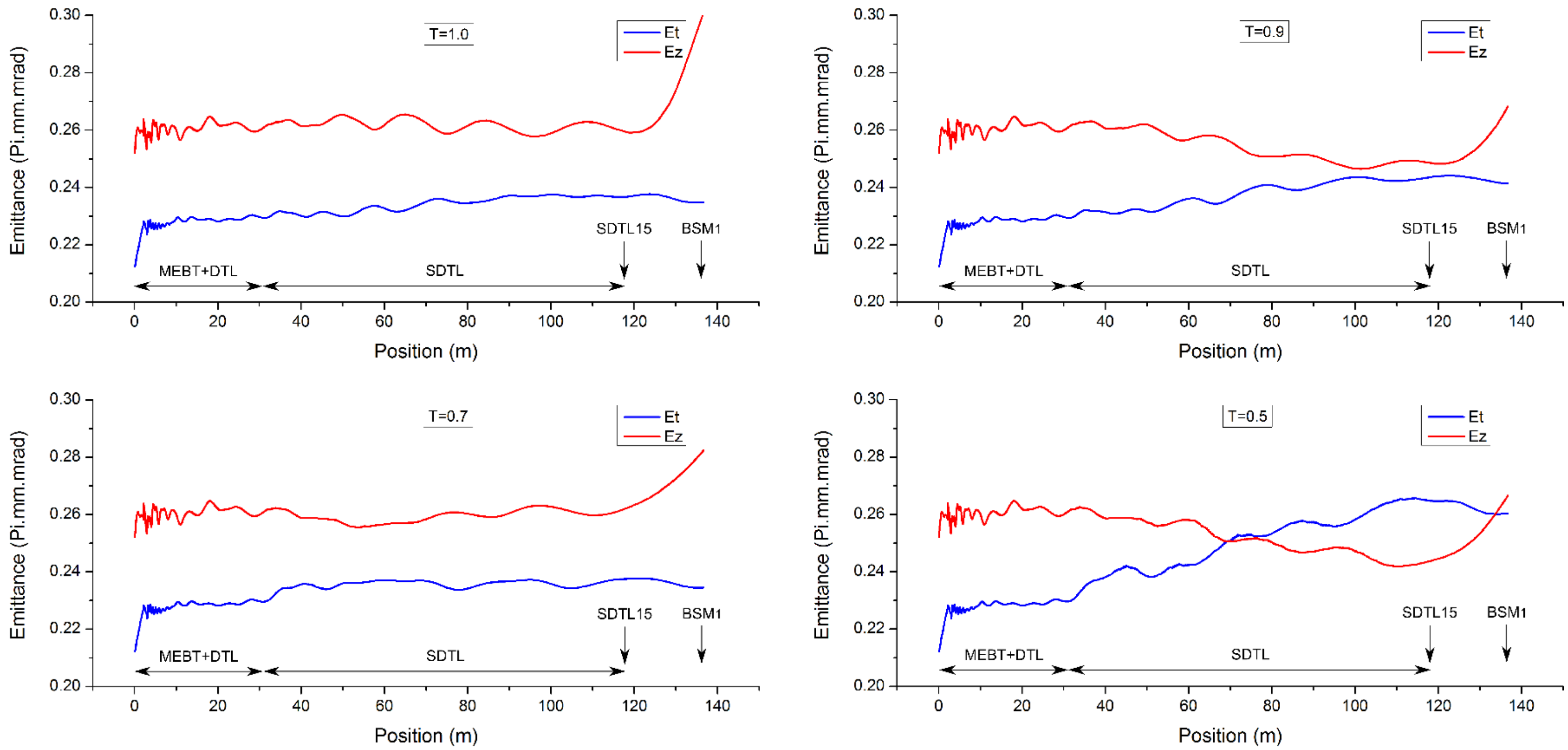
Experimental Evidence: J-PARC

- Phase advances for the four working points.



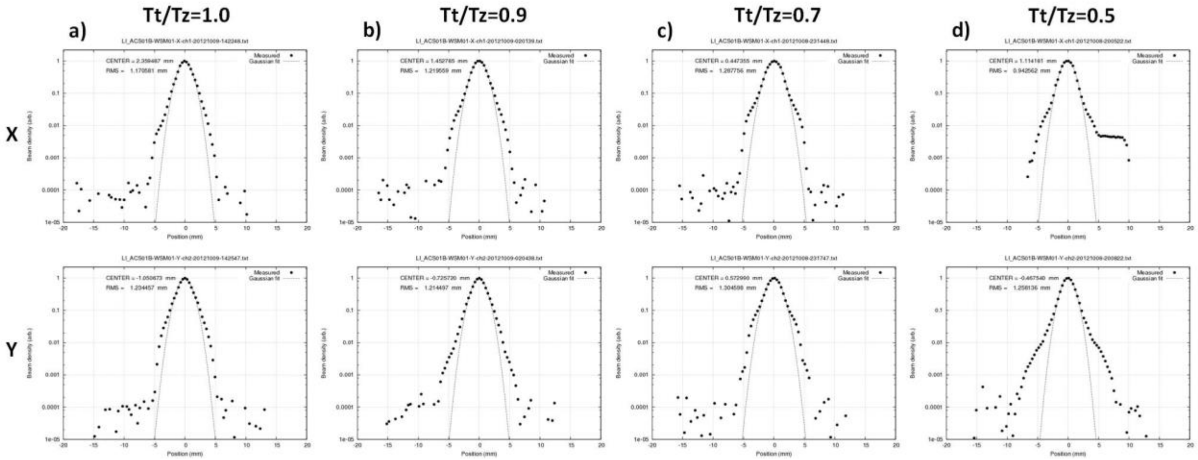
Experimental Evidence: J-PARC

- Simulation

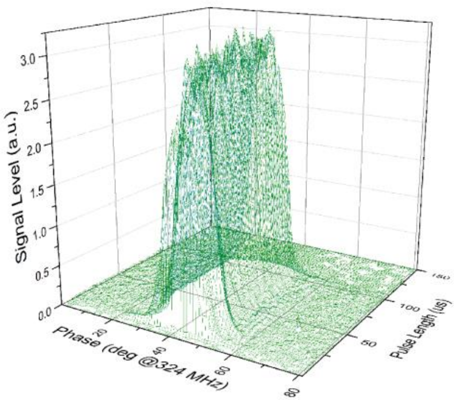


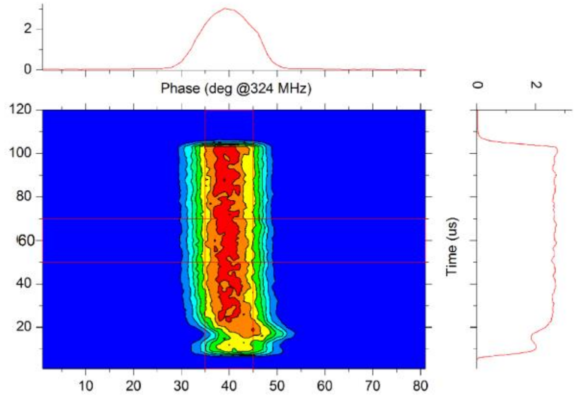
Experimental Evidence: J-PARC

- Measurement results



Tt/Tz	ε_t (Pi.mm.mrad)	ε_z (Pi.mm.mrad)
1.0	0.216	0.269
0.9	0.229	0.233
0.7	0.253	0.223
0.5	0.293	0.161





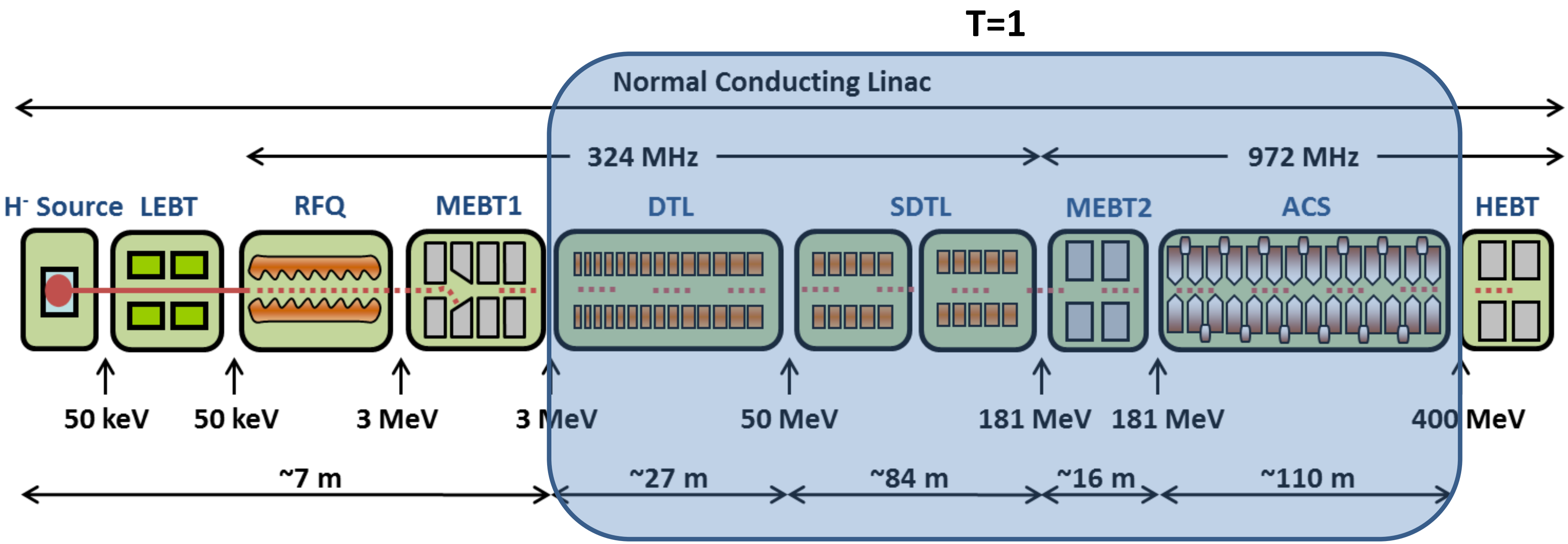
Experimental Evidence: J-PARC

- 2012 campaign conclusions
  - Experimental observation of emittance exchange in a linac driven by the kz/kt=2 resonance.
  - First emittance exchange measurement in a linac with emittance ratios close to 1
  - Cases 1.0 and 0.9 consistent with simulation
    - Weak exchange for 0.9
  - Unexpected exchange for 0.7
    - Transverse mismatch at DTL-SDTL transition?
  - Unexpected transverse halo

Experimental Evidence: J-PARC

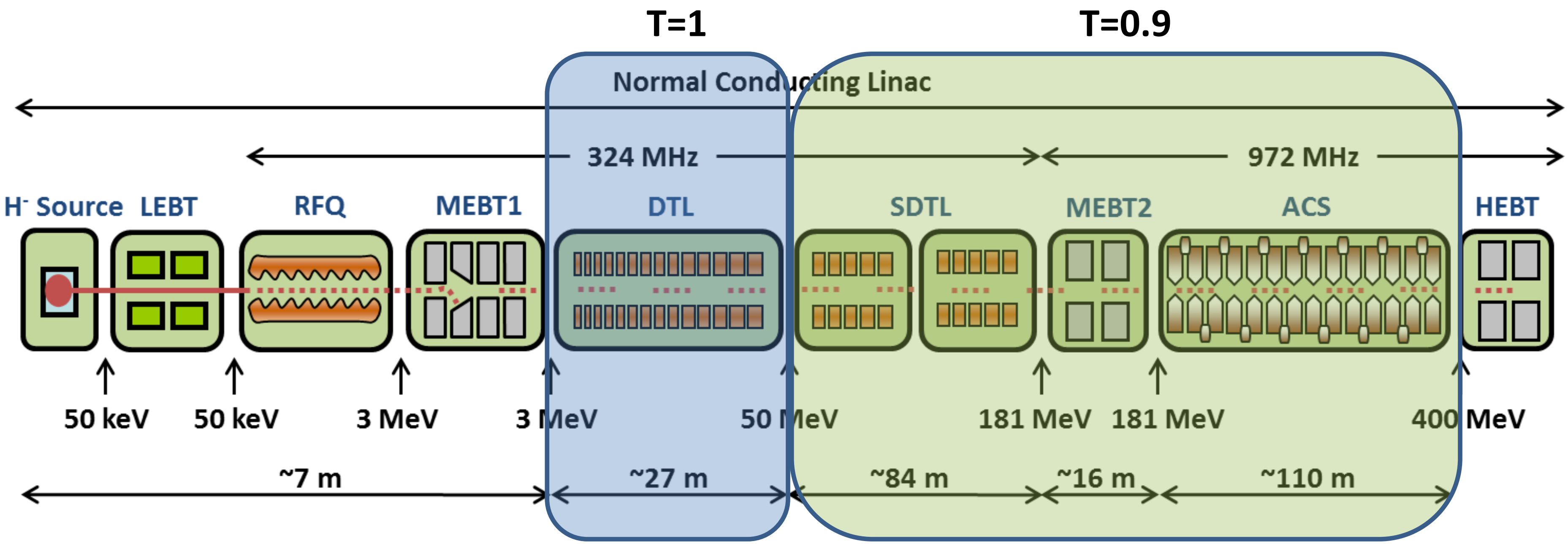
- 2015 - 2016 campaign
  - Several measurements performed with different configurations
  - Time consuming
  - A lot of data to analyse
  - Encouraging results
  - For more details see Y. Liu's talk/paper – TUAM6Y01

Case 1 – 40 mA



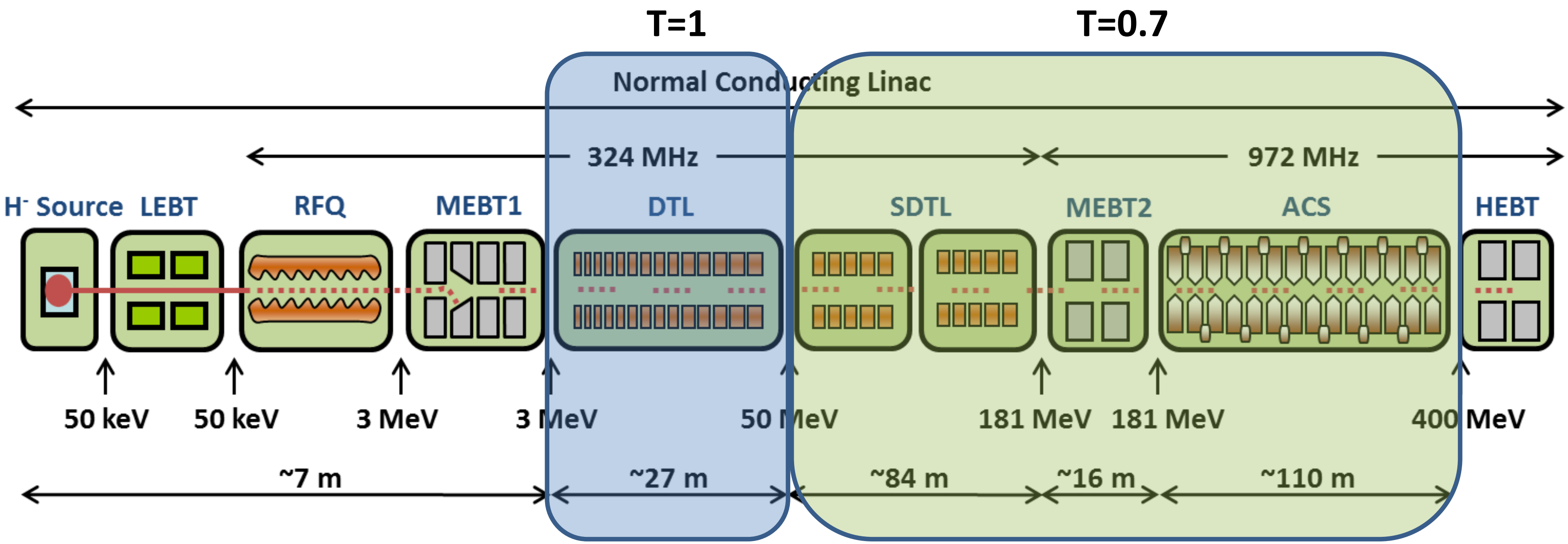
T=1
Normal Conducting Linac
324 MHz
972 MHz
H- Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

Case 2 – 40 mA



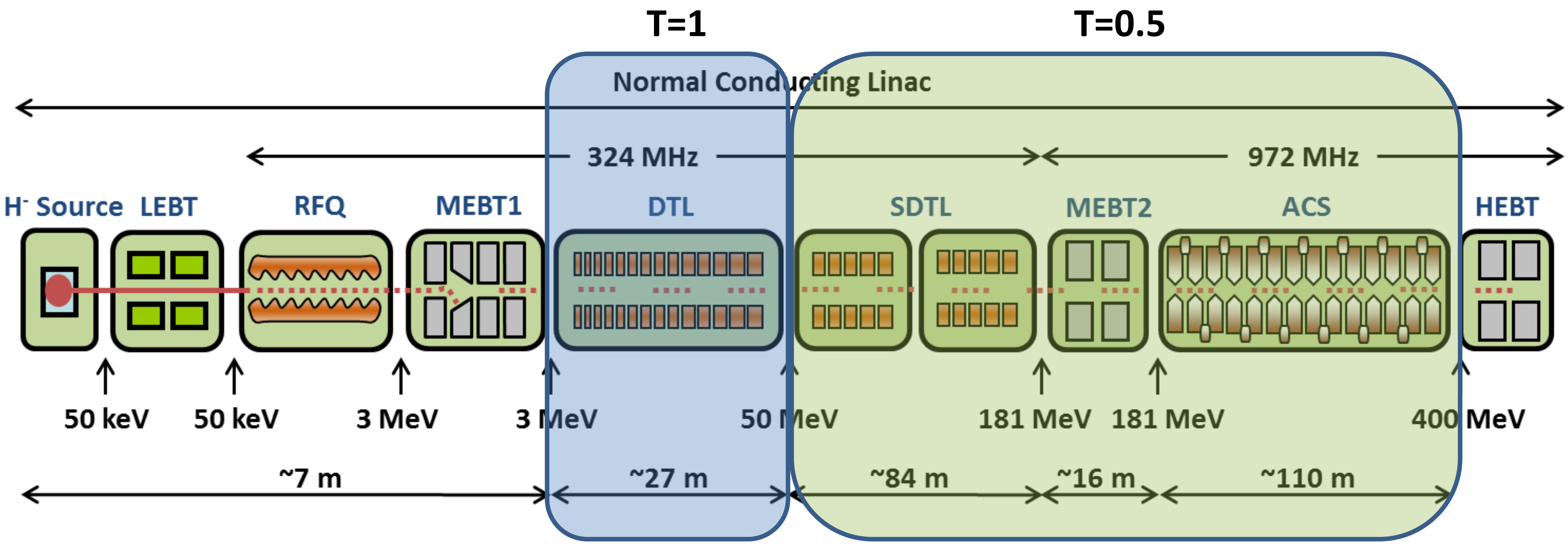
T=1
T=0.9
Normal Conducting Linac
324 MHz
972 MHz
H- Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

Case 3 – 40 mA



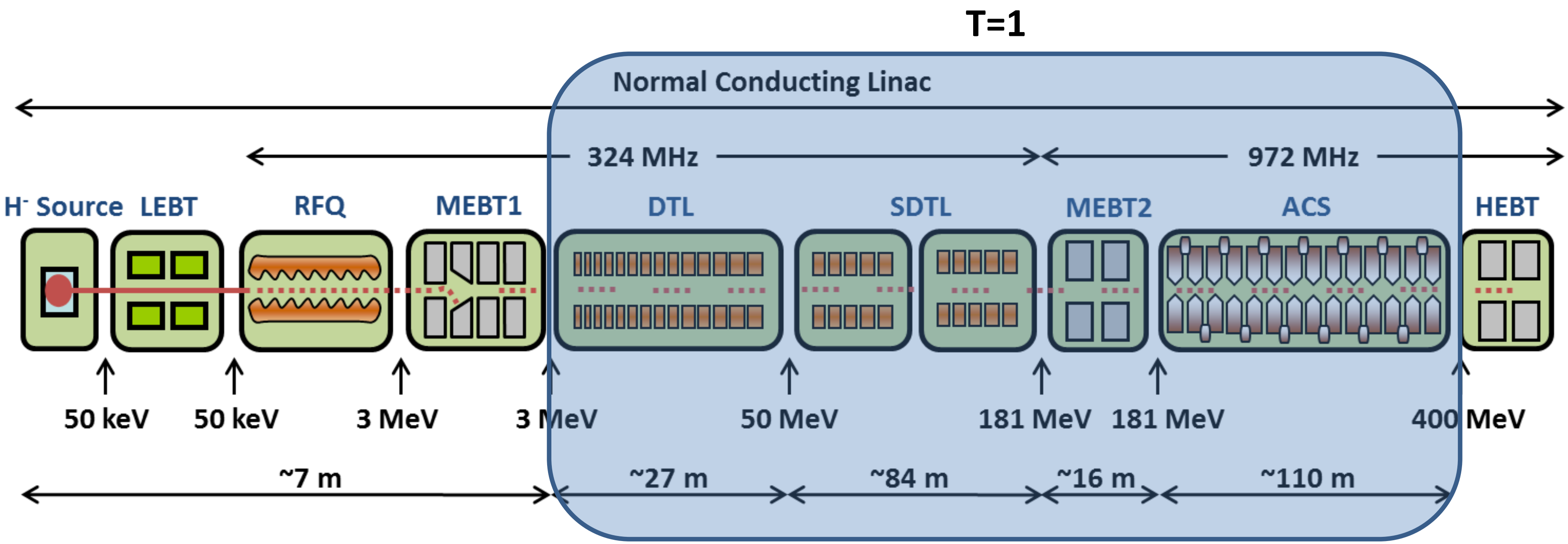
T=1
T=0.7
Normal Conducting Linac
324 MHz
972 MHz
H- Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

Case 4 – 40 mA



T=1
T=0.5
Normal Conducting Linac
324 MHz
972 MHz
H- Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

Case 5 – 40 mA


T=1
Normal Conducting Linac
324 MHz
972 MHz
H⁻ Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

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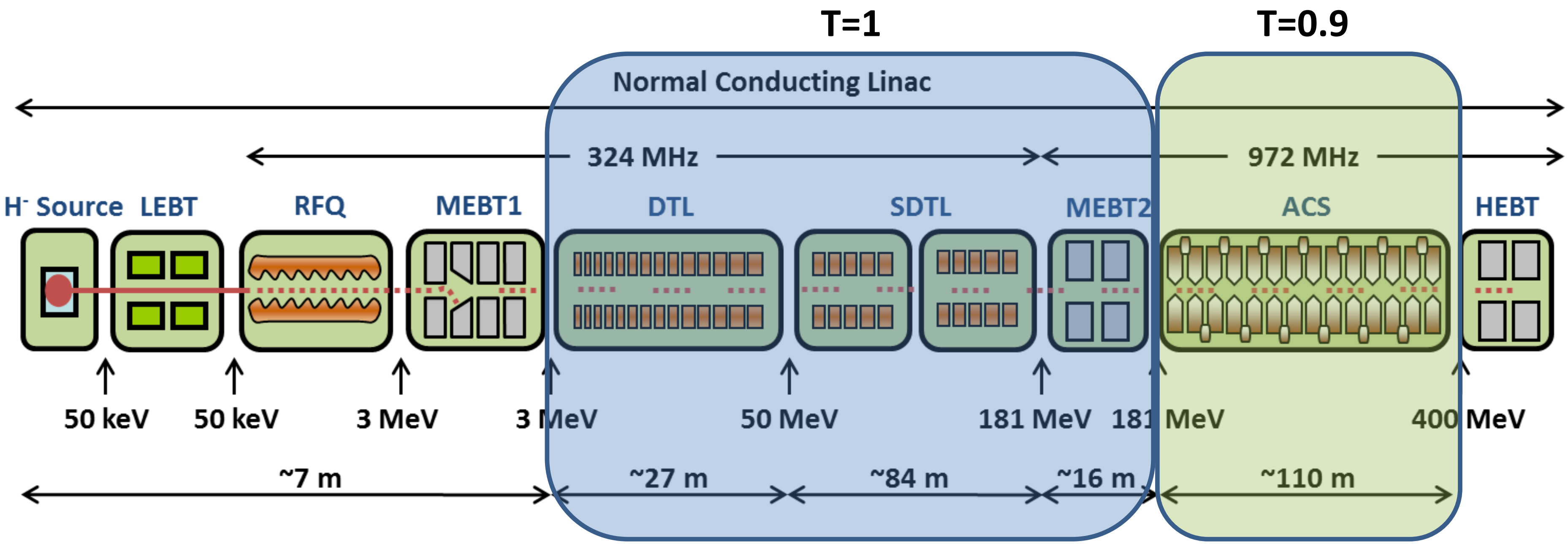
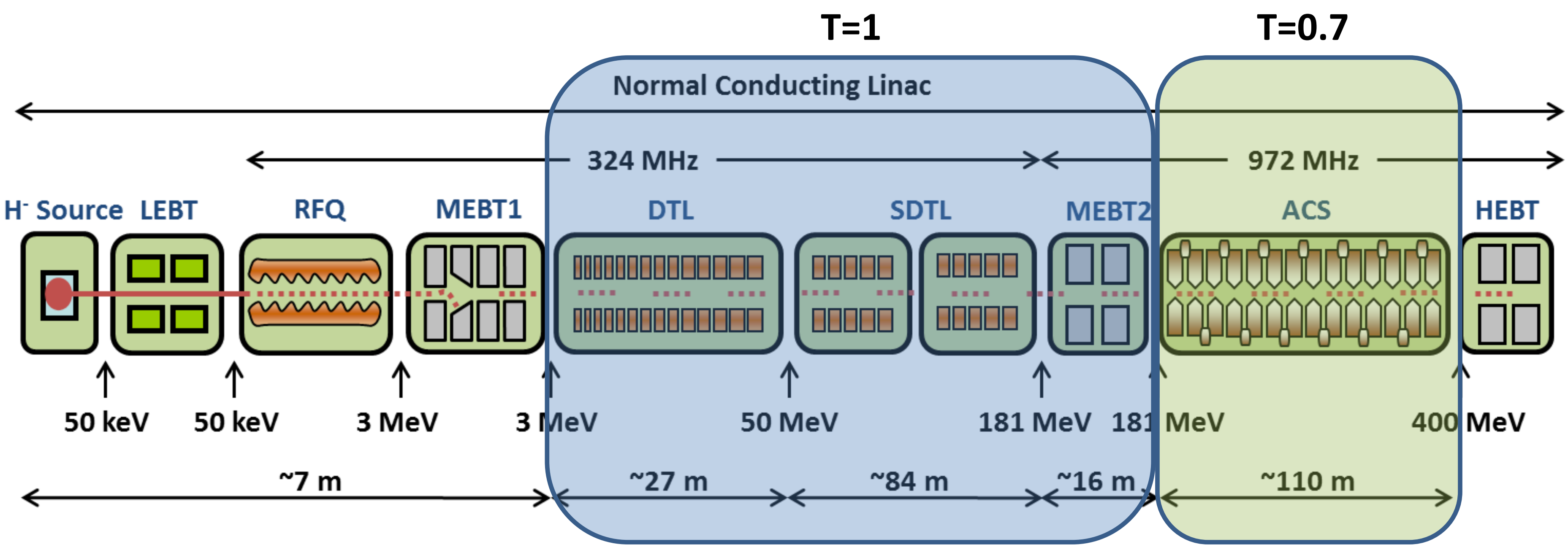
Case 6 – 50 mA

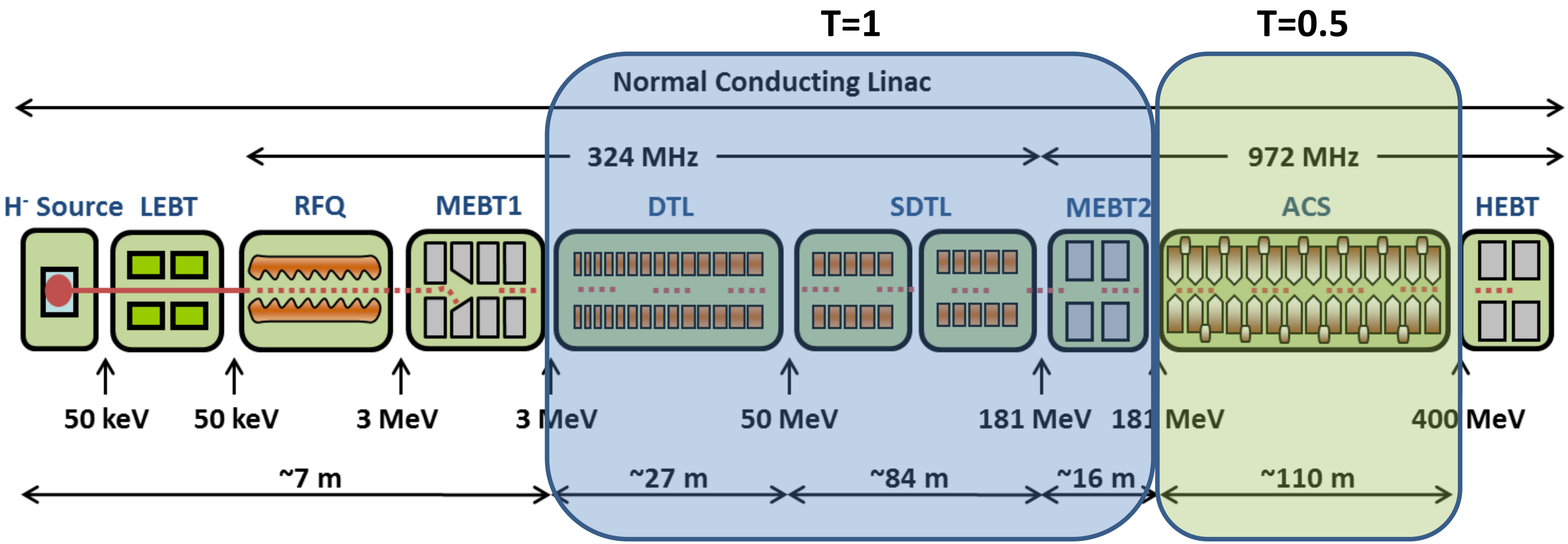


Case 7 – 50 mA



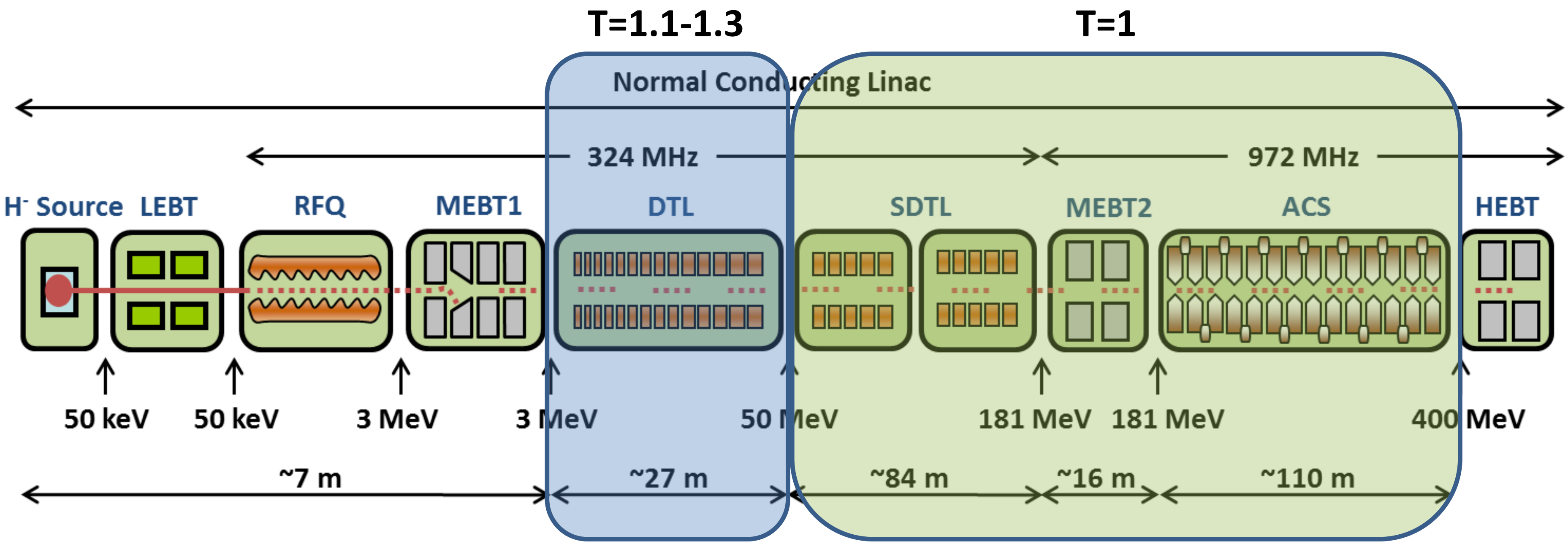
T=1
T=0.7
Normal Conducting Linac
324 MHz
972 MHz
H- Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

Case 8 – 50 mA

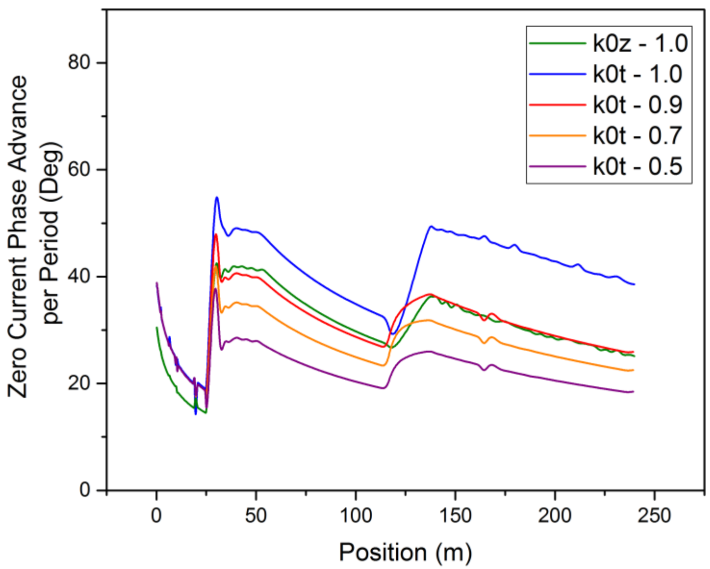


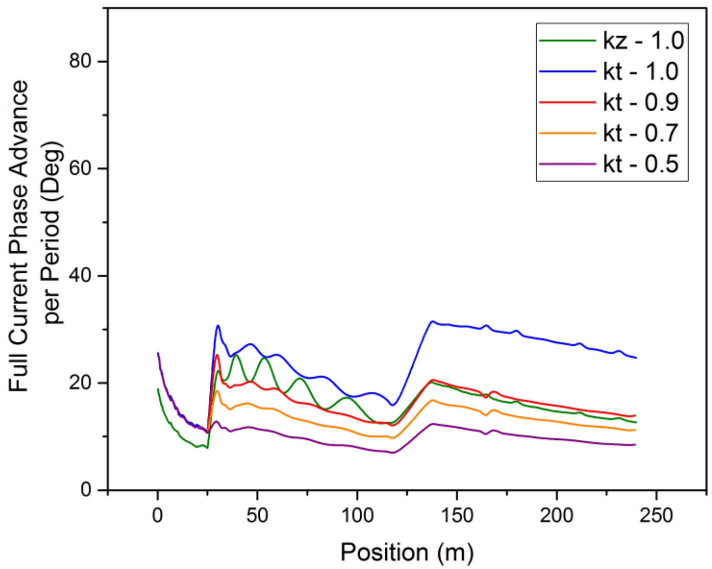
T=1
T=0.5
Normal Conducting Linac
324 MHz
972 MHz
H- Source
LEBT
RFQ
MEBT1
DTL
SDTL
MEBT2
ACS
HEBT
50 keV
50 keV
3 MeV
3 MeV
50 MeV
181 MeV
181 MeV
400 MeV
~7 m
~27 m
~84 m
~16 m
~110 m

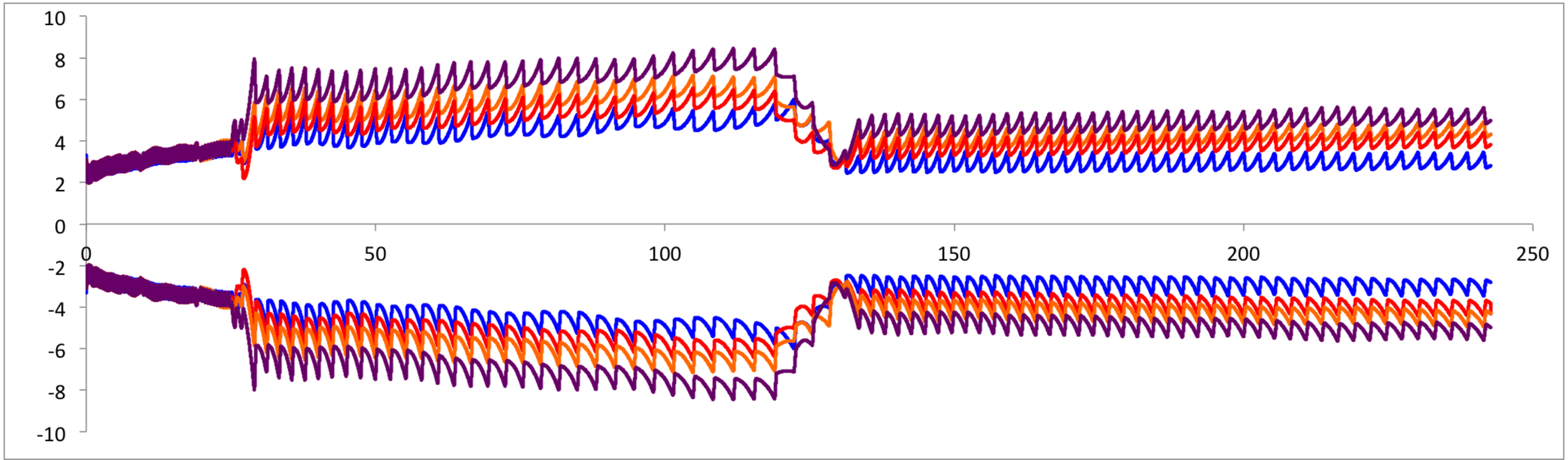
Case 9, etc. – 40 mA



Preliminary Results (40 mA)

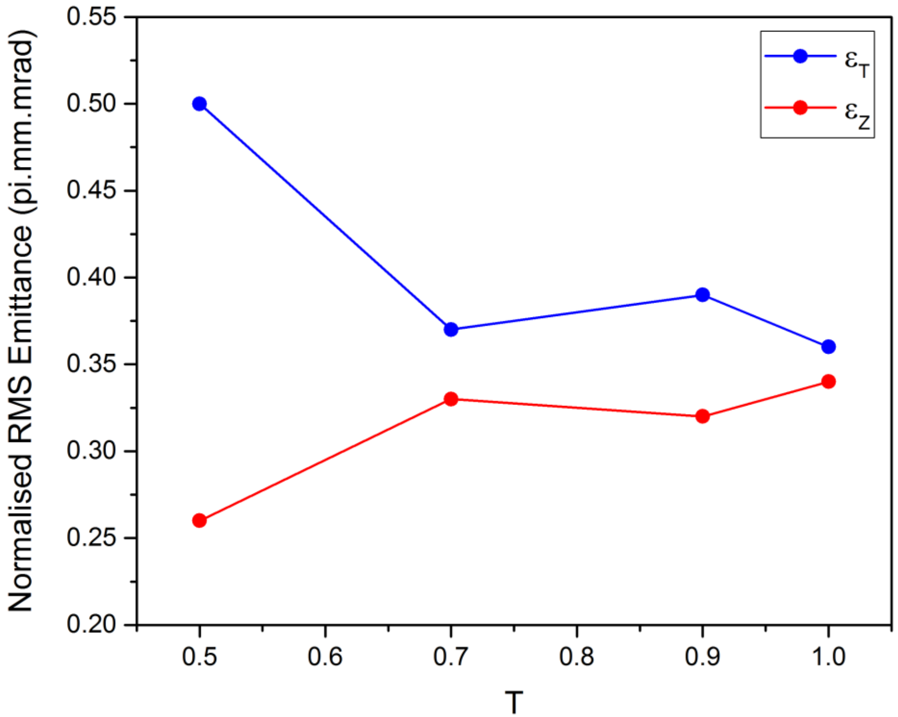






Preliminary Results (40 mA)

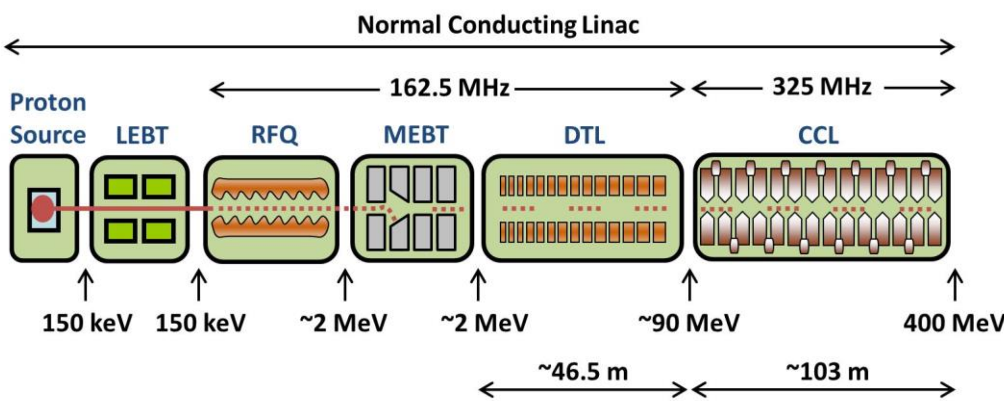
Tt/Tz	ε_t (Pi.mm.mrad)	ε_z (Pi.mm.mrad)	Obs
1.0	0.36	0.34	
0.9	0.39	0.32	$2k_z-2k_t=0$
0.7	0.37	0.33	
0.5	0.5	0.26	$k_z-2k_t=0$

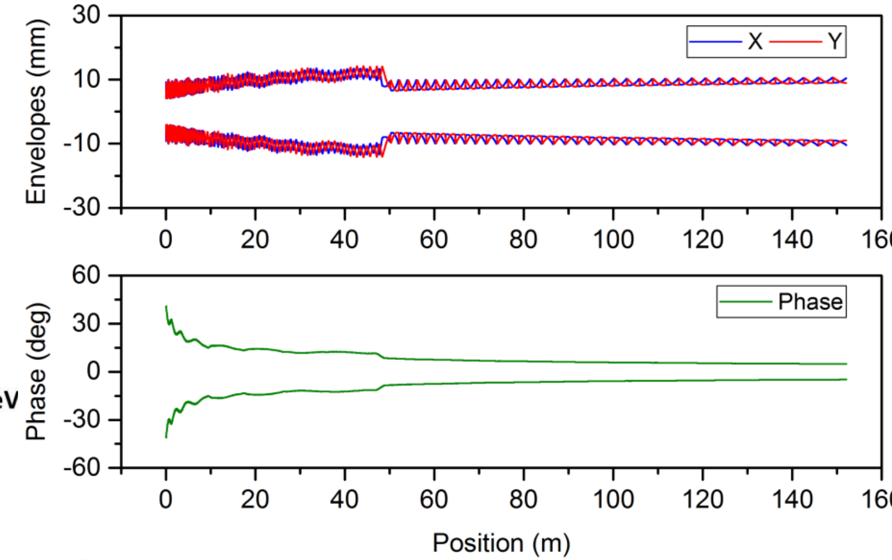


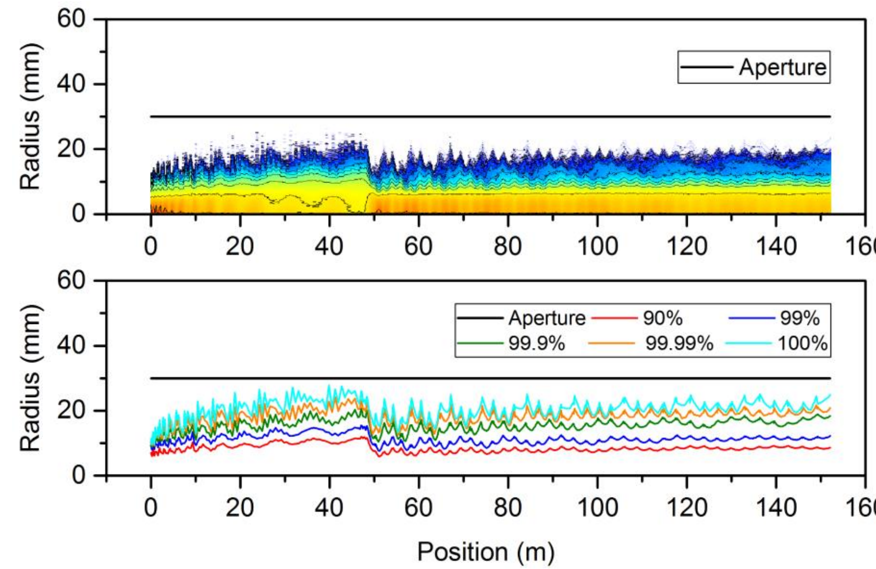
Pushing the intensity frontier

- Generic beam dynamics studies of ultimate intensity limits in proton linacs
- Industry-Oxford-STFC collaboration
- Parameters Space:
  - **Energy**: Up to 1 GeV
  - **Intensity**: Up to 1 A
  - **Power**: Hundreds of MW
- Several options developed
  - What are the limits/bottlenecks?
  - What is the parameter space?
  - Can technology be pushed?
- Details in MOPOY047 (IPAC16)

Pushing the intensity frontier

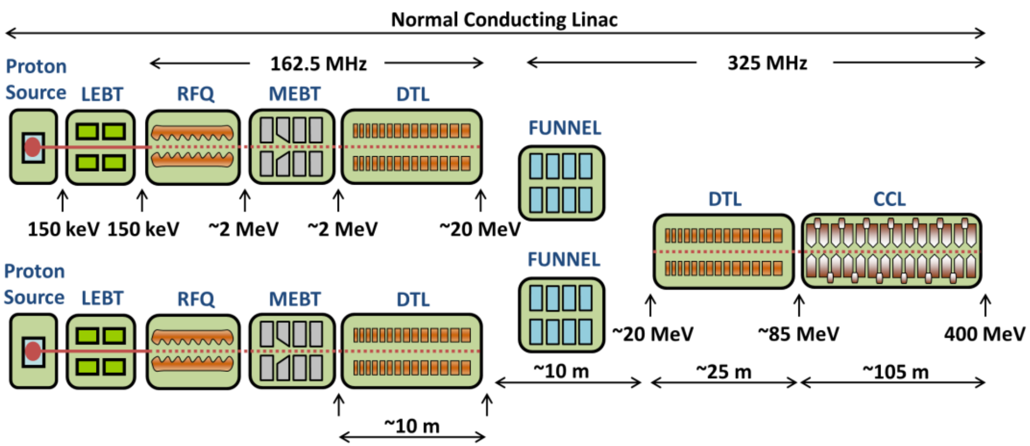


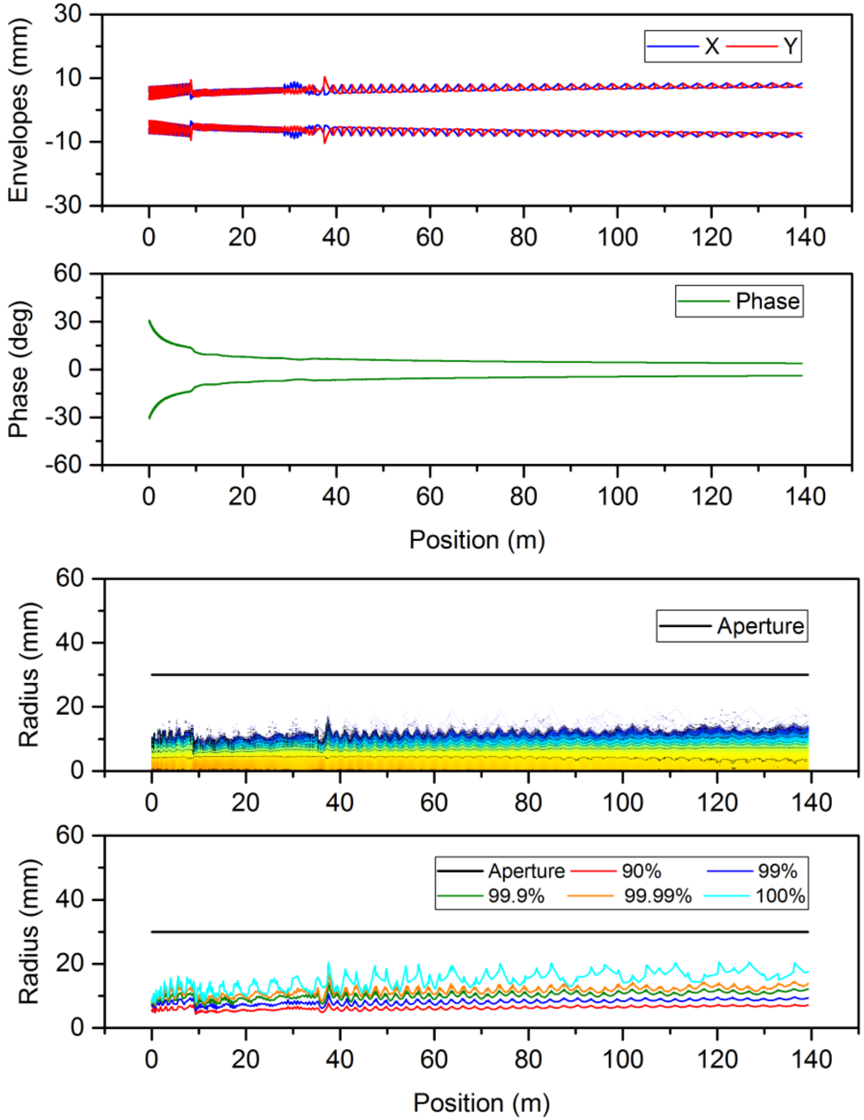




- 1 A, NC structures
- Design avoids $2k_z-k_t=0$, $2k_z-2k_t=0$, $k_z-2k_t=0$
- Emittance growth: 30% (transv.), 10% (long)
- “No losses”, but small aperture to beam size ratio.

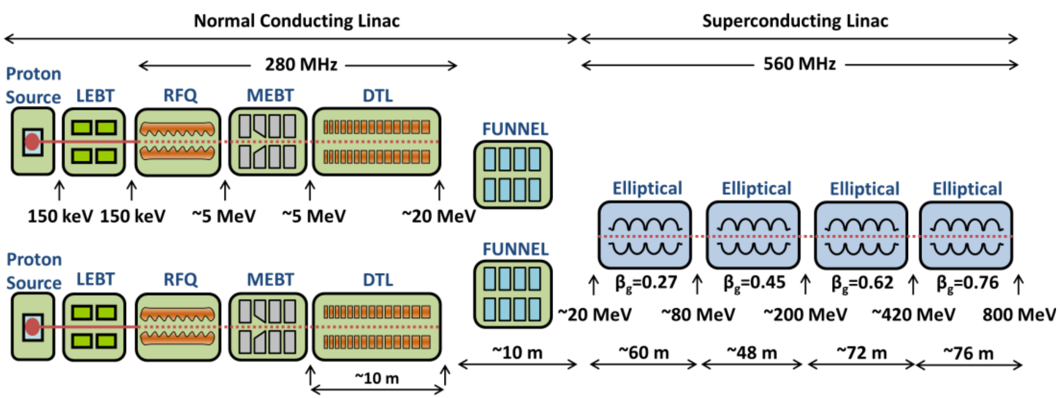
Pushing the intensity frontier

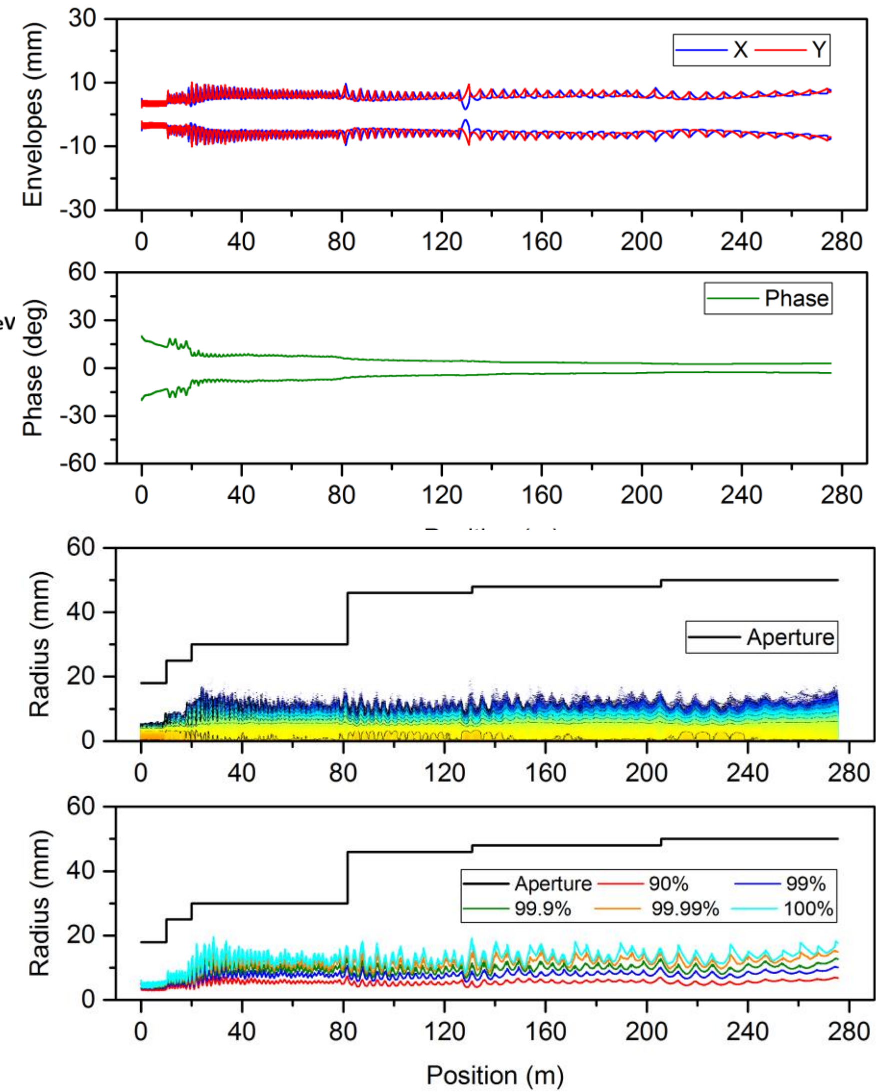




- 0.5 A, NC structures
- Design avoids $2k_z-k_t=0$, $2k_z-2k_t=0$, $k_z-2k_t=0$
- Emittance growth: 20% (transv.), 5% (long)
- Better aperture to beam size ratio.

Pushing the intensity frontier





- 0.25 A, SC structures
- Design crosses $2k_z-k_t=0$ and $2k_z-2k_t=0$
- Higher emittance growth: 40% (transv.), 100% (long)
- Best aperture clearance

Conclusions and Discussion

- Existing facilities show discrepancy between simulation models and machine operation
  - Halo matching vs. core matching
  - How can this be improved?
  - What is the figure of merit that we are aiming for?
  - Can some emittance growth be tolerated?
- A better understanding of space-charge resonances is emerging, but experimental evidence and impact remain limited.
  - A more robust experimental program needed
  - SNS, J-PARC?
    - Beam physics perhaps not a priority for running facilities
  - Machines under construction
  - Linac4 is an opportunity
  - Smaller experiments like IBEX (See WEAM6X01 – C. Prior) could bring interesting results