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BEAM DYNAMICS STUDIES OF THE 8 GEV LINAC AT FNAL

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Content

- Main specifications for the Linac
- Basic concepts for the Linac design
  - RFQ and MEBT
  - Front end up to 420 MeV
  - High energy section, ILC based, 1300 MHz
- Linac structure and base technology
  - Power fan-out to multiple cavities
  - SC accelerating structures above 10 MeV
- Choice of lattice parameters
- High-intensity beam physics
- Detailed design and simulations (from the ion source to injection foil)
  - Machine errors
  - Residual errors with LLRF system
  - H-minus stripping
- Conclusion

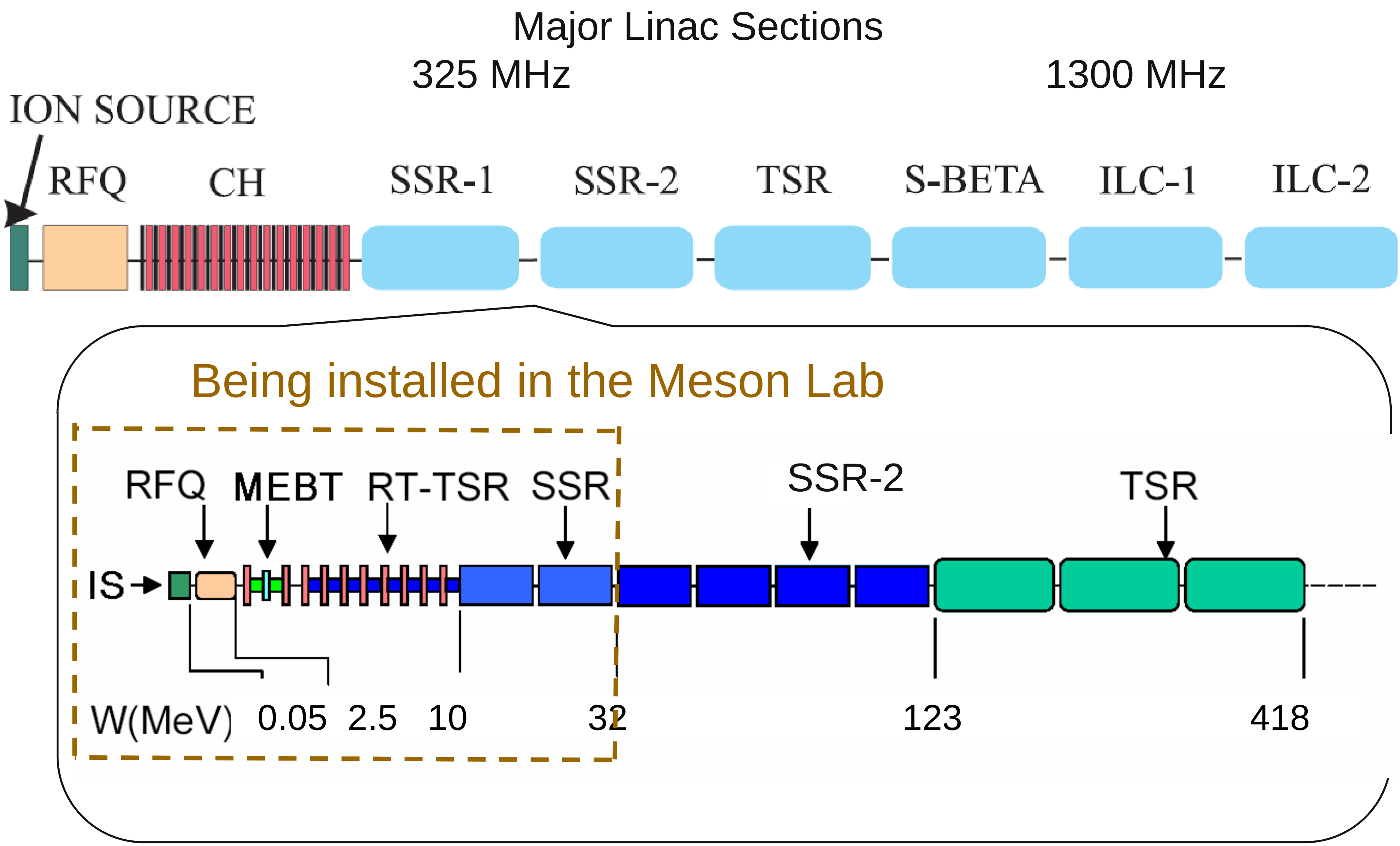
Main Linac Specifications

- ***"A proton driver in the megawatt class or above is required to produce neutrino superbeam and advance our understanding of neutrino mixing, to determine the character of neutrino mass spectrum, and to search for CP violation among neutrinos."***
  - ***2 MW beams at 8 GeV and 120 GeV***
- Provide 8-GeV $1.56 \cdot 10^{14}$ protons per cycle in the MI
- Beam time structure
  - Extraction kicker -0.7 msec
  - Fit into MI 52.8 MHz rf structure without losses
- Repetition rate & pulse length
  - Initial configuration: 2.5 Hz at 3 msec, 0.5 MW at 8 GeV
  - ***Ultimate configuration: 10 Hz, 1 msec, 2 MW at 8 GeV***
- This results in
  - Peak current for beam dynamics design is 40 mA
  - Average current over the pulse is 25 mA
  - Fast chopper in the MEBT (rise/fall time $\leq$ 2 nsec)

8-GeV Linac conceptual design

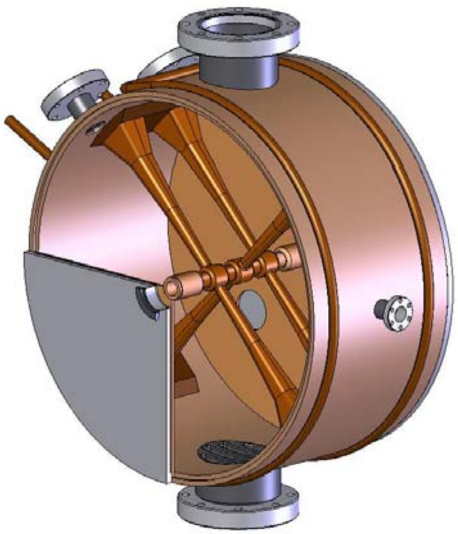
- RF power fan-out from one klystron to multiple cavities
- Two-frequency Linac option to produce multi-GeV hadron beams:
  - 1300 MHz ILC cavities above ~1.2 GeV
  - Develop and use S-ILC cavities (beta=0.81) in the energy range ~400 MeV-1.2 GeV
  - Spoke loaded SC cavities operating at 1300/4=325 MHz
- Front End: ~325 MHz. Klystrons are available from J-PARC
- Below 10 MeV: use the RFQ and 16 RT-CH
- Apply SC solenoid focusing to obtain compact lattice in the front end including MEBT
- RFQ delivers axial-symmetric 2.5 MeV H-minus beam
- Beam matching between the cryostats: adjust parameters of outermost elements (solenoid fields, rf phase)
- In the frequency transition at ~418 MeV, matching is provided by 90° "bunch rotation"
- Avoid beam losses due to halo formation

Linac Structure

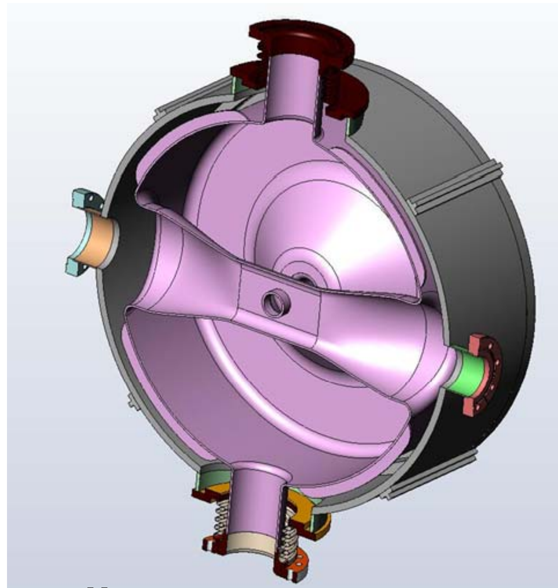


Accelerating cavities (not to scale)

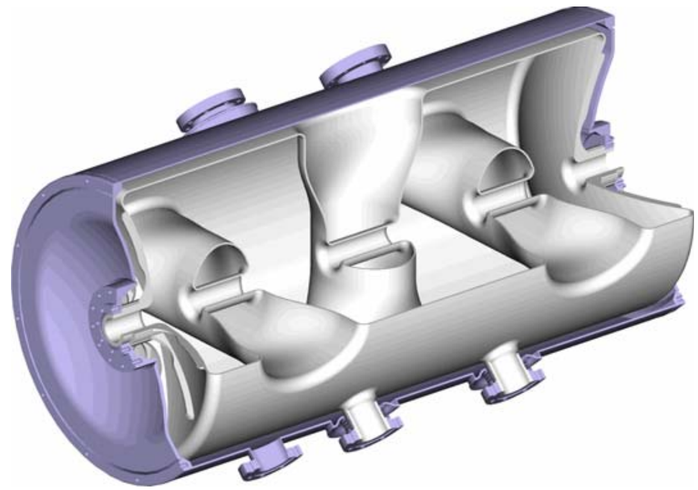
NC spoke



SC single spoke

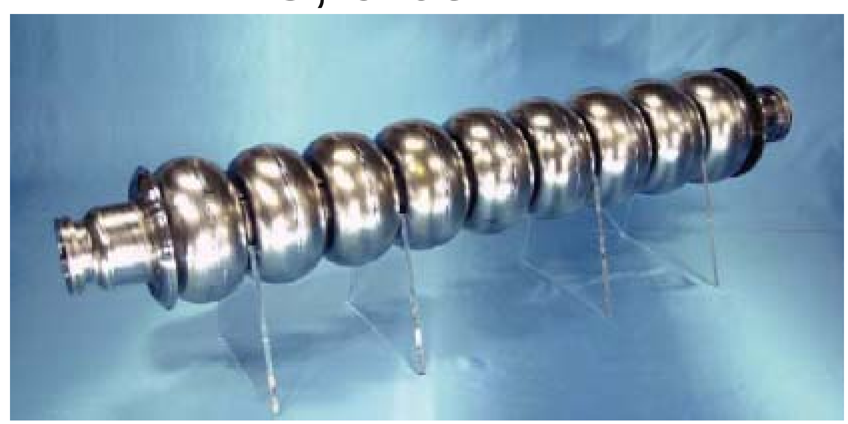


Triple-spoke cavitiy



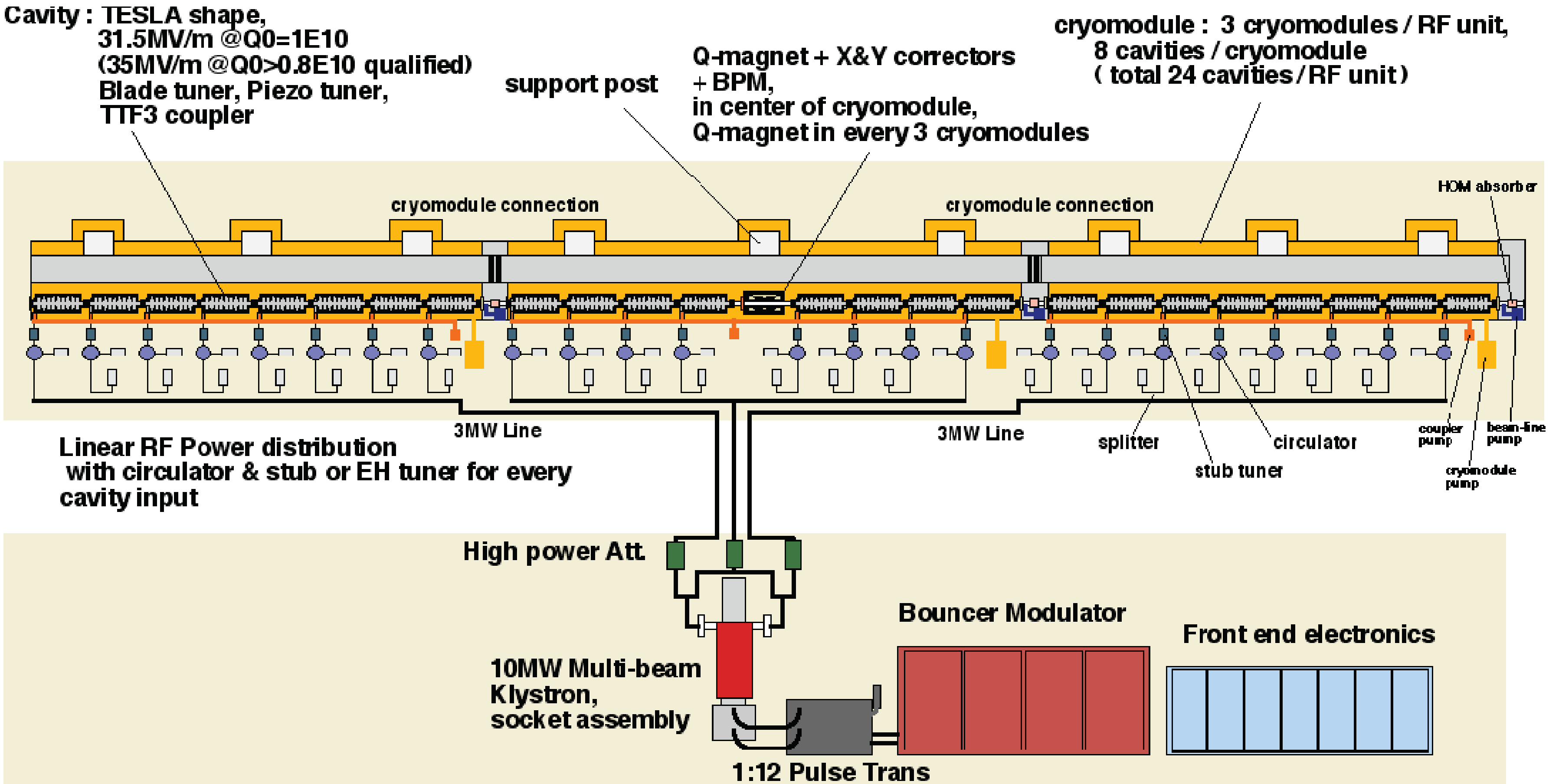
β_G=0.81, 7-cell, 1300 MHz

ILC, 9-cell



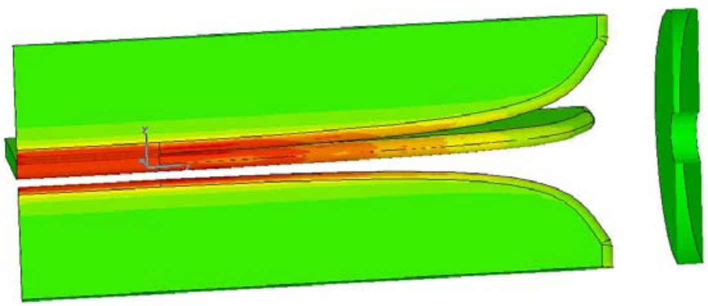
RF power fan-out

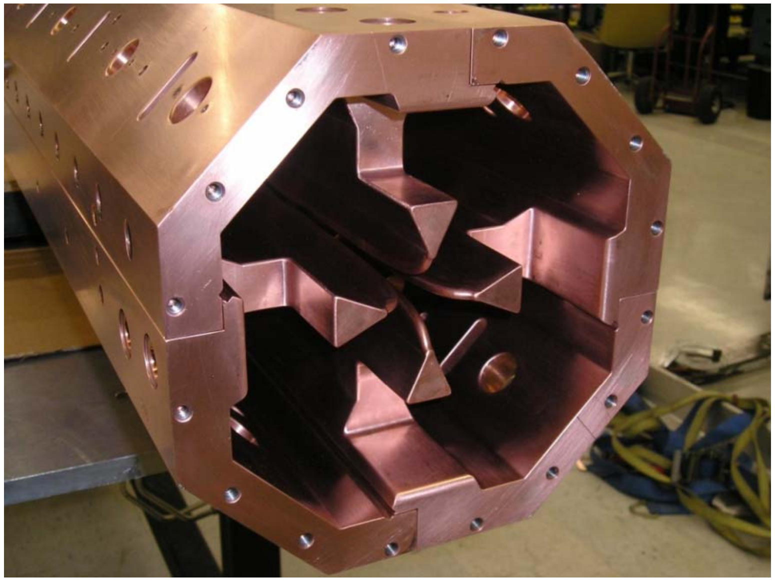
- ILC RF power distribution, similar system in the front end
  - Power couplers in the ILC cavities must be re-designed to handle higher power
  - Front end: fast ferrite phase shifters, high power



Radio Frequency Quadrupole

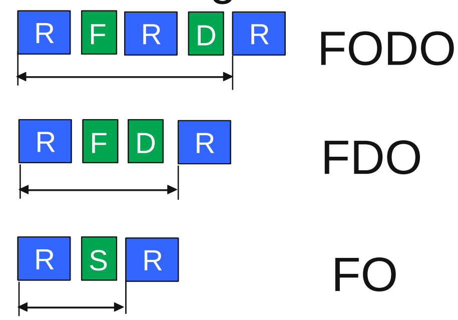
- Basic PD requirements:
  - Cost-effective
  - Produce axially-symmetric beam
  - Small longitudinal emittance
- Design features
  - No emittance growth
  - Strong transverse focusing ($\sigma_0 \cong 43°$)
  - Limiting current 140 mA
  - Acceleration efficiency is 96 % for 45 mA
  - Short, 3 meters
- Output radial matcher





Focusing by SC solenoids

- To provide stability for all particles inside the separatrix, the defocusing factor



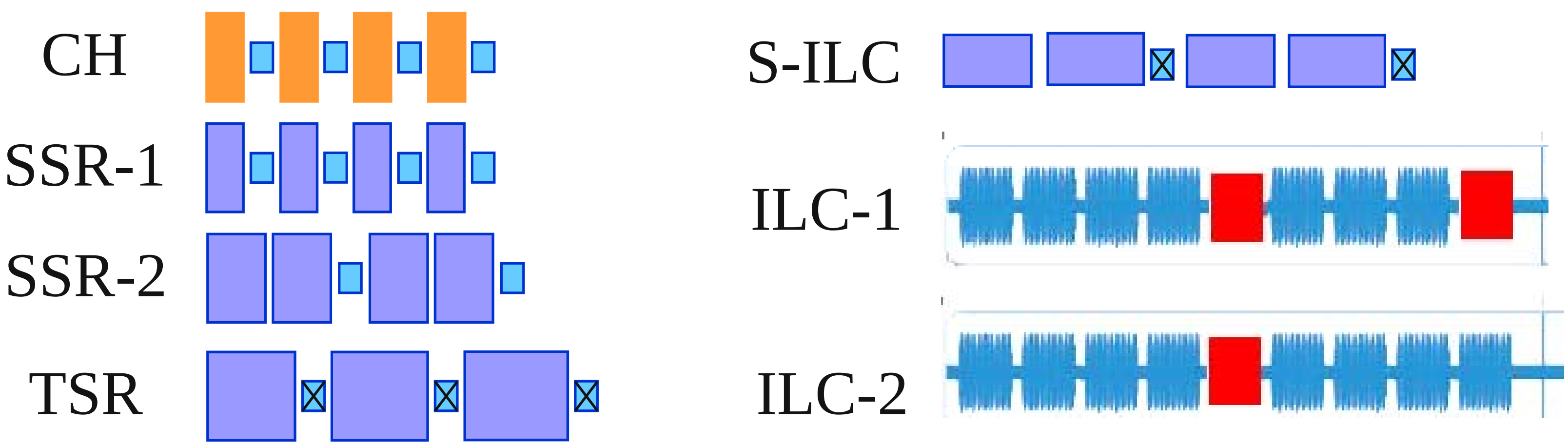
$$\gamma_s = \frac{\pi}{2} \frac{1}{(\beta\gamma)^3} \frac{L_f^2}{\lambda} \frac{eE_m \sin\varphi_s}{m_0 c^2}$$

  should be below ~0.7

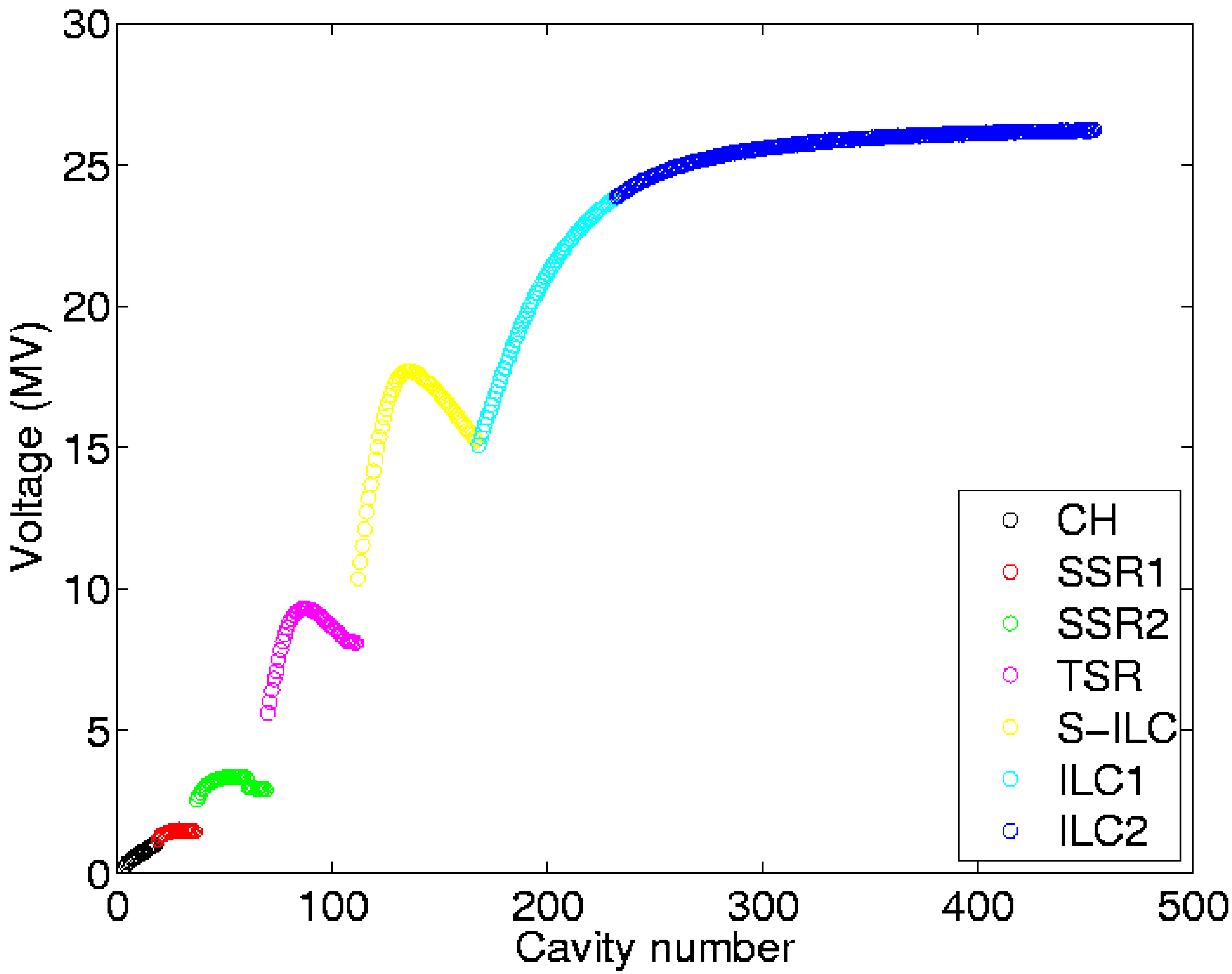
- SC solenoids in the NC section from 2.5 MeV to 10 MeV
  - Solenoids decrease the length of the focusing period (~0.5 m)
  - Small beam size, aperture of the cavities is ϕ18 mm
- Other advantages of solenoids compared to typical FODO
  - Acceptance is large for the same phase advance σ as for quads.
  - Less sensitive to misalignments and errors. The most critical error in quads – rotation about the longitudinal axis – does not exist
  - Beam quality is less sensitive to beam mismatches
- FNAL PD: cryogenics facility is available, major part of the linac is SC
- The 325 MHz Front End up to 420 MeV
  - Long cryostats house up to ~10 SC cavities and solenoids
  - Apply quads above 100 MeV, required for H-minus beam focusing

Cavity parameters and focusing lattice

Section	CH	SSR-1	SSR-2	TSR	S-ILC	ILC-1	ILC-2
β_G	-	0.2	0.4	0.6	0.83	1	
# of res.	16	18	33	42	56	63	224
# of cryost.	-	2	3	7	7	9	28
E_{peak} (MV/m)	-	30	28	30	52	52	
Focusing	SR	SR	SRR	FRDR	FR^2DR^2	FR^4DR^3	FR^8DR^8
L_F , m	0.515-0.75	0.75	1.6	3.81	6.1	12.2	24.4



Voltage gain per cavity

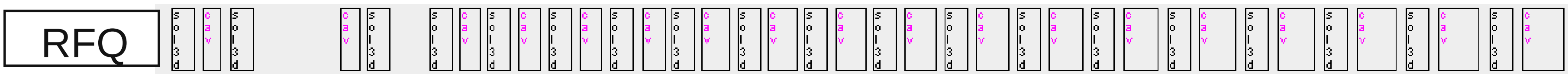


Properties of an ion SC linac, cost-effective design

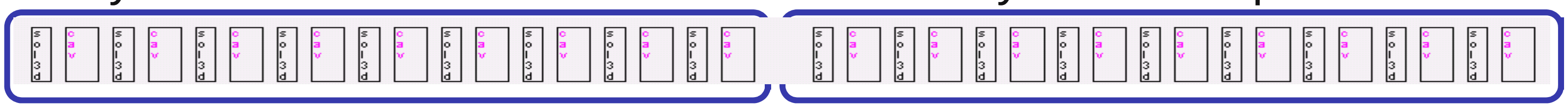
- The acceleration is provided with several types of cavities designed for fixed beam velocity. For the same SC cavity voltage performance there is a significant variation of real-estate accelerating gradient as a function of the beam velocity.
- The length of the focusing period for a given type of cavity is fixed.
- There is a sharp change in the focusing period length in the transitions between the linac sections with different types of cavities
- The cavities and focusing elements are combined into relatively long cryostats with an inevitable drift space between them. There are several focusing periods within a cryostat.
- Apply an iterative procedure for the lattice design
  - Choice of parameters
  - Tune for “zero” beam current
  - Tune for design beam current
  - Multiparticle simulations
  - Iterate to improve beam quality and satisfy engineering requirements

HINS PD lattice, mitigation of the effect of the lattice transitions

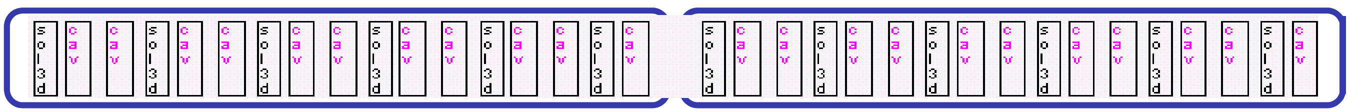
- MEBT and NC section, short focusing periods, adiabatic change from 50 cm to 75 cm



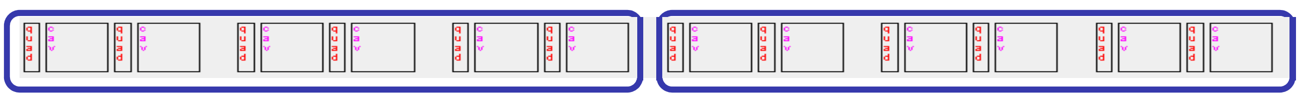
- 2 cryomodules of SSR-1: Minimize the inter-cryostat drift space



- 3 cryomodules of SSR-2: Provide a drift space by missing the cavity



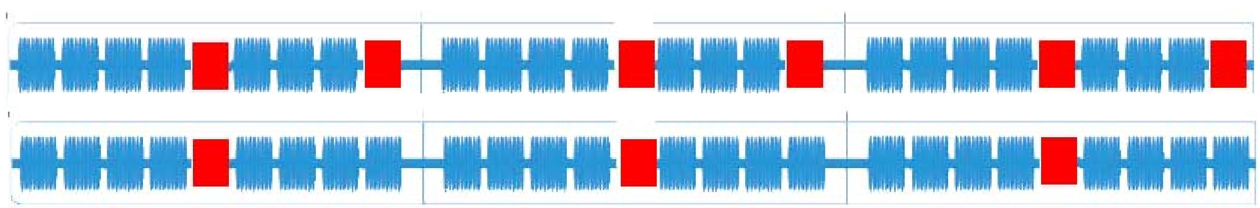
- TSR: Provide an extra drift space inside the cryostat



- High-energy section: additional focusing quad is located between the cryostats

ILC-1

ILC-2



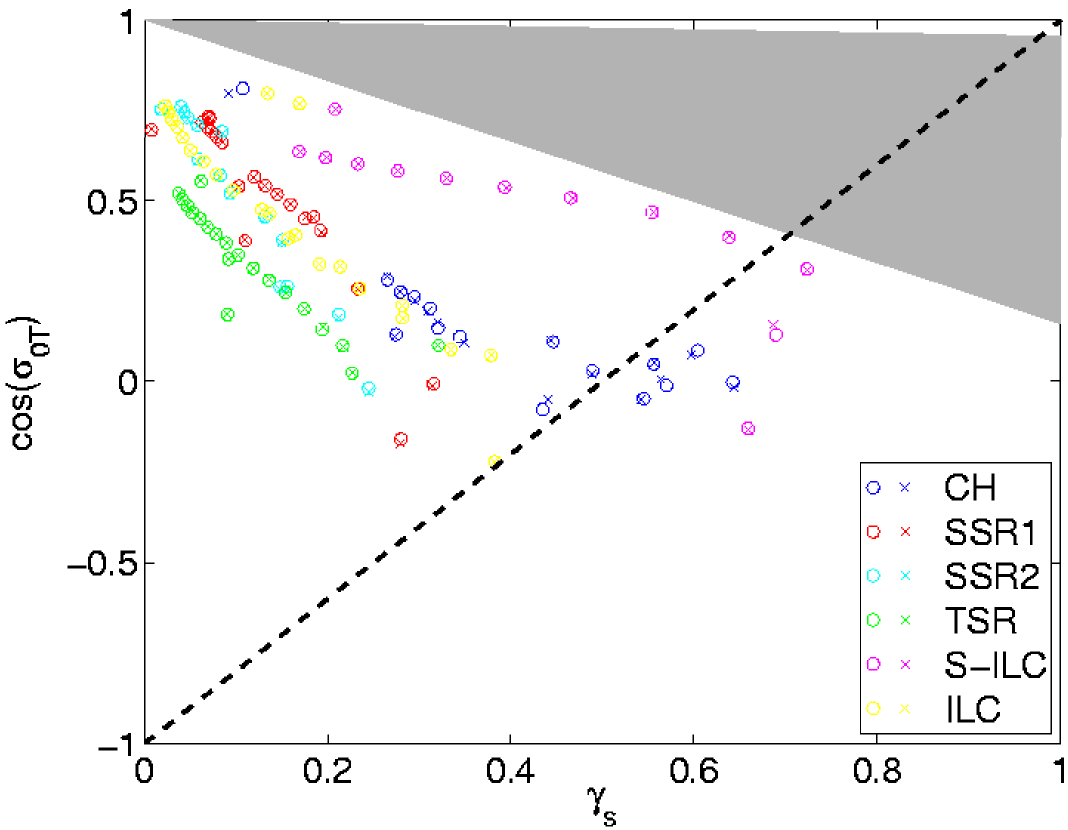
Beam Dynamics Simulations

- The major workhorse is TRACK, recently Parallel-TRACK
- "Zero-current" tune were created using TRACK routines in 3D-fields
- The tuned lattice was simulated with ASTRA for detailed comparison
- Tune depression with space charge:
  - rms beam dimensions are from TRACK or ASTRA

$$\gamma_s = \frac{\pi}{2} \frac{1}{(\beta\gamma)^3} \frac{L_f^2}{\lambda} \frac{eE_m \sin(\varphi_s)}{m_0 c^2}$$

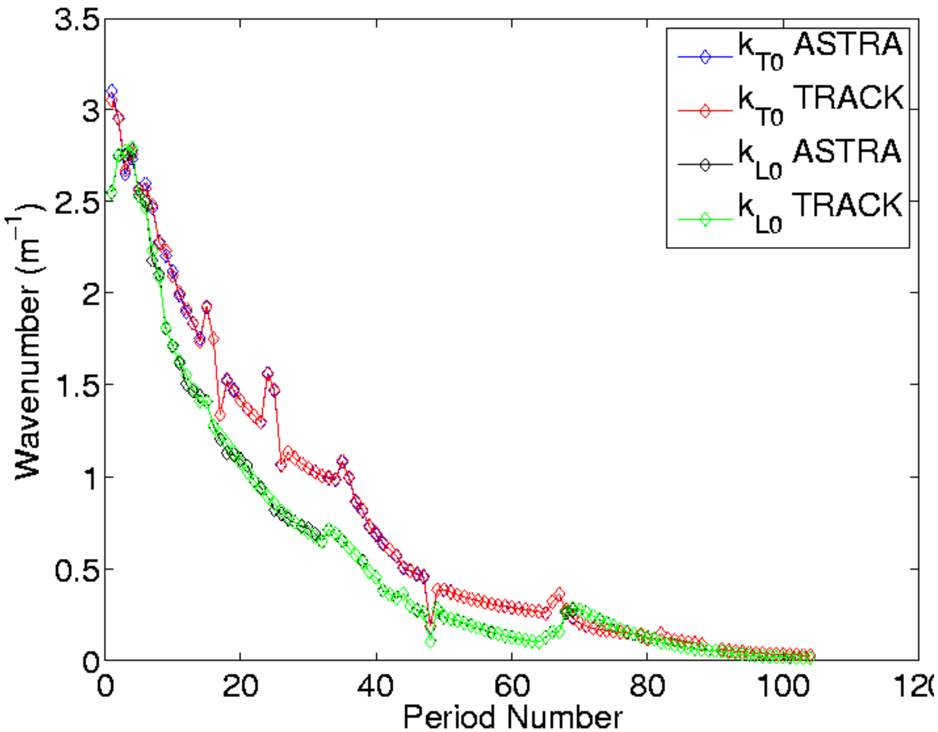
Stability chart for zero current, betatron oscillations

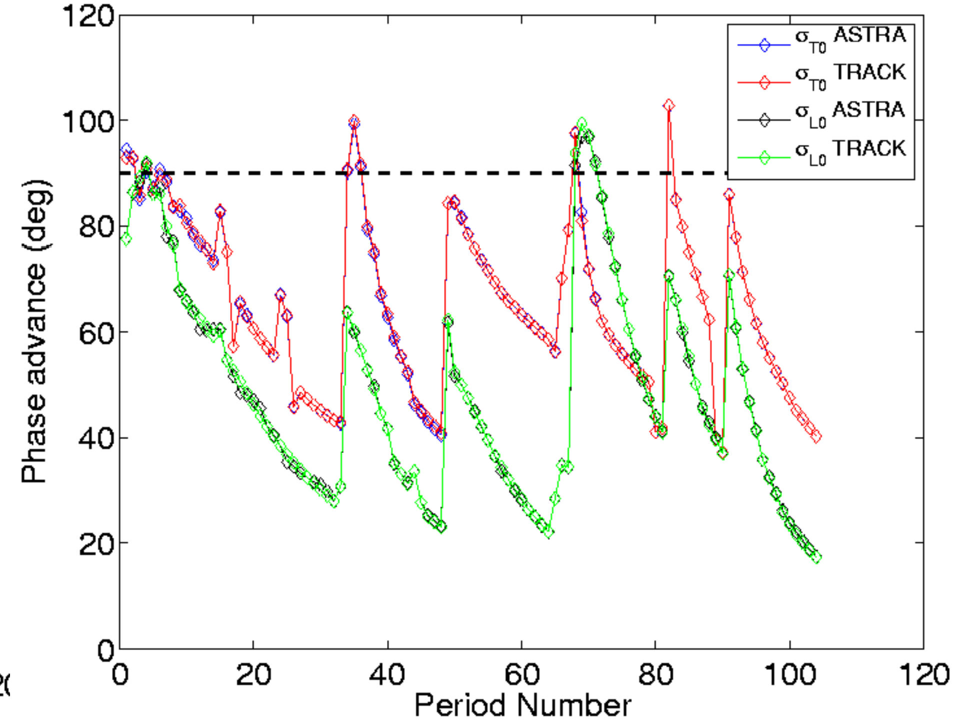
o - TRACK × - ASTRA



Variation of lattice parameters along the linac

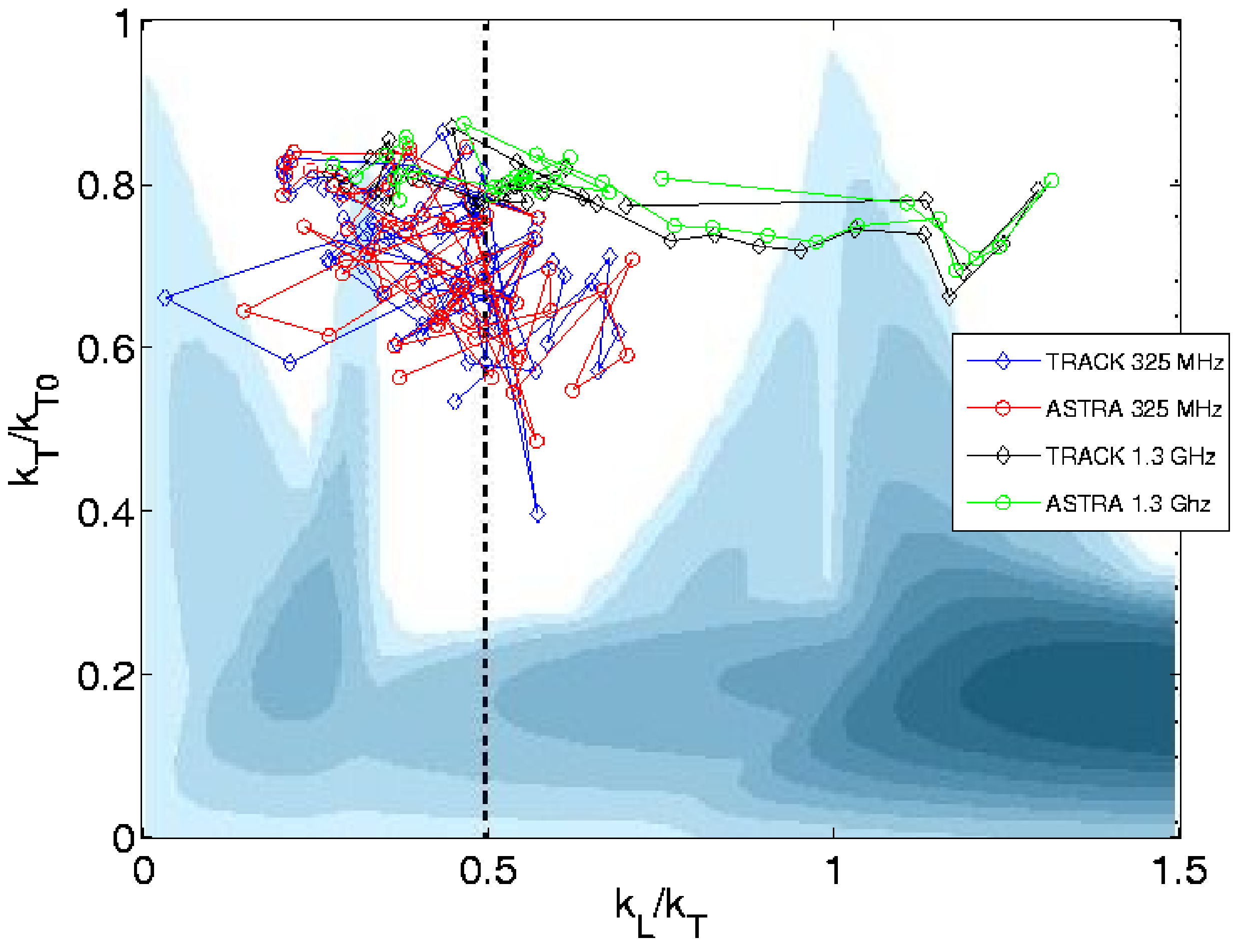
- $\sigma_0 < 90°$
- k_{T0}, k_{L0} adiabatic despite of many lattice transitions with different types of focusing and inter-cryostat spaces, cavity TTF
- Beam matching in the lattice transitions is very important to avoid emittance growth and beam halo formation



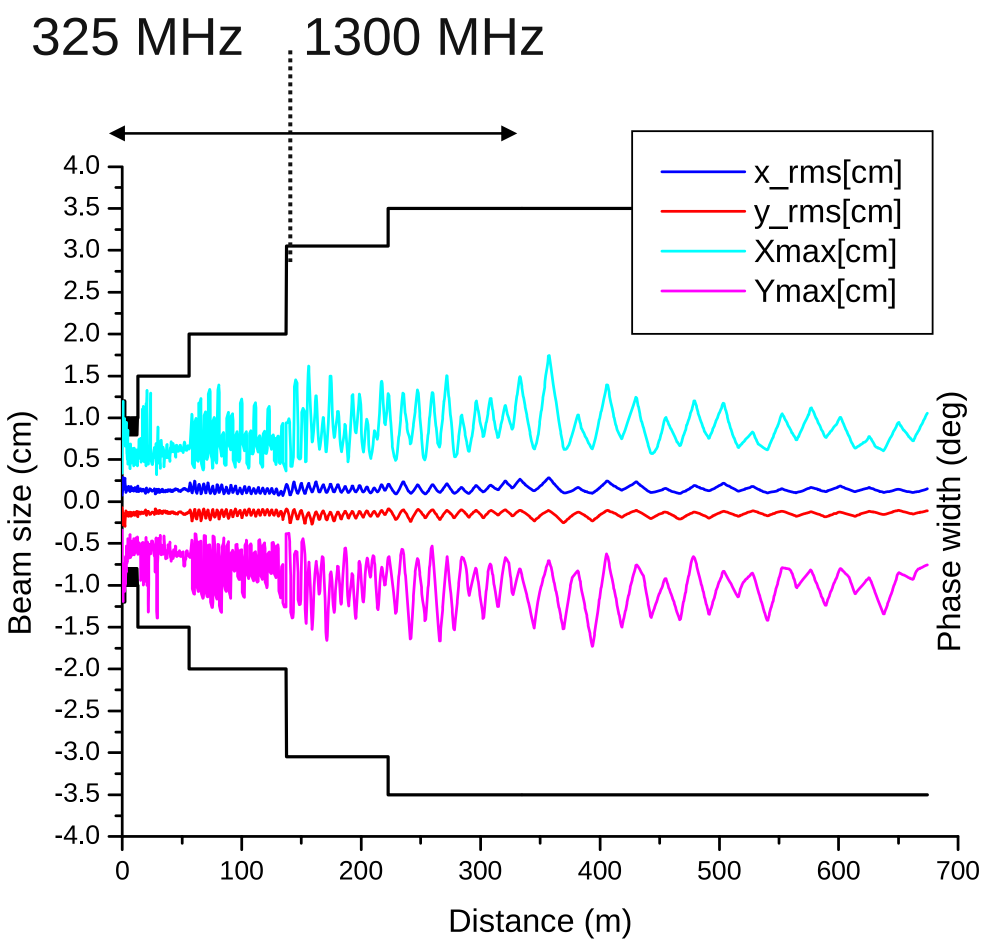


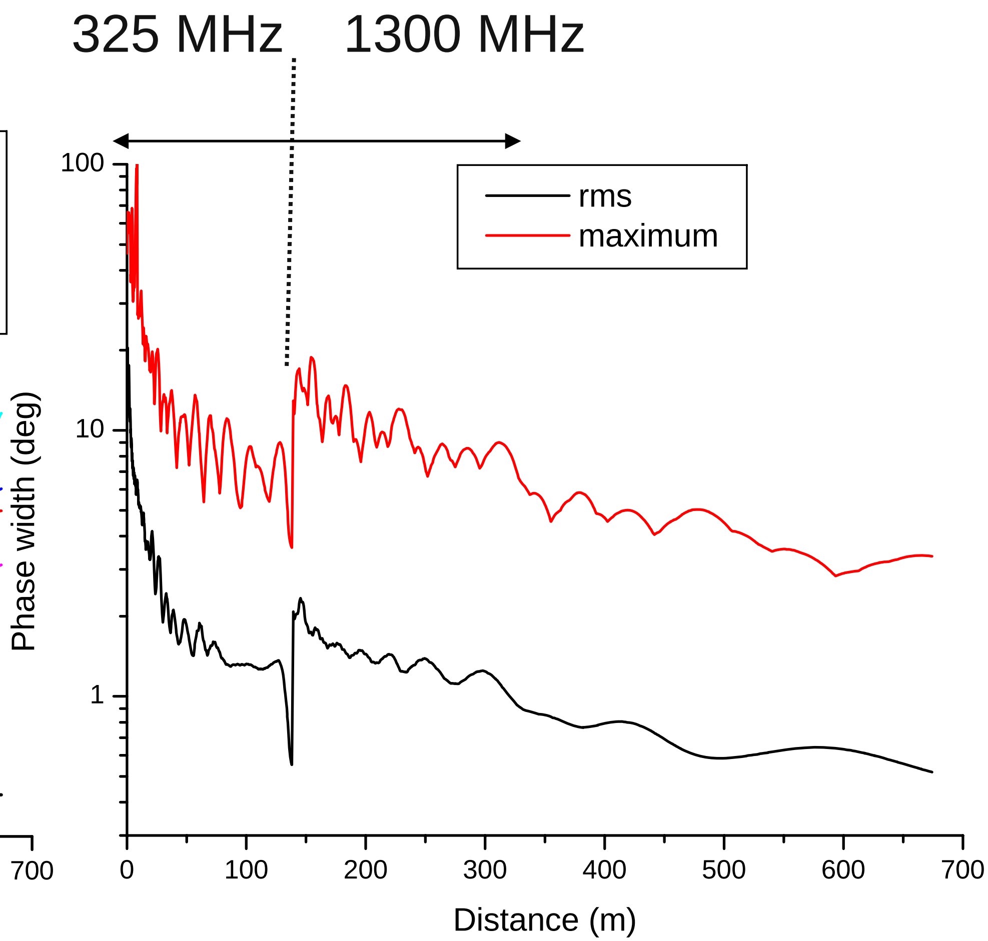
Hofmann's chart for the PD Front End

- Avoid strong space charge resonances (white area)
- Provide equipartitioning of betatron and synchrotron oscillation temperatures along the linac, primarily in the front end



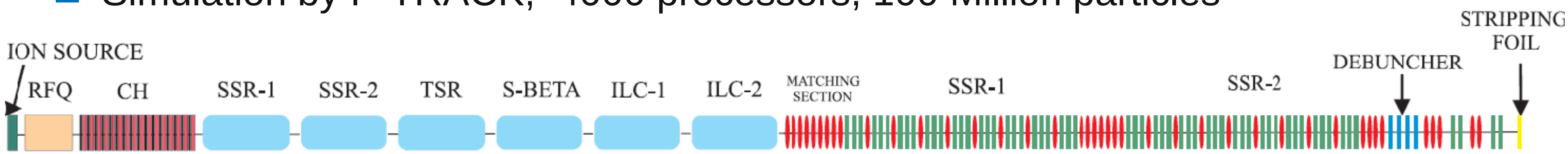
Beam envelopes, 45 mA RFQ entrance, 43.25 mA in the linac



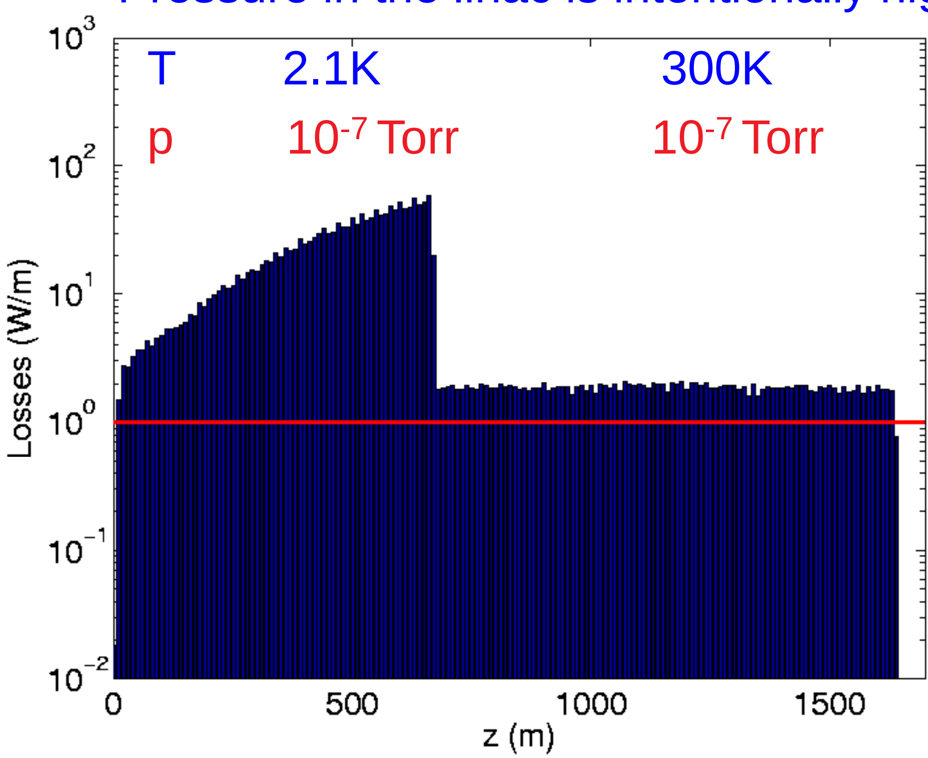


Beam losses due to H^- stripping

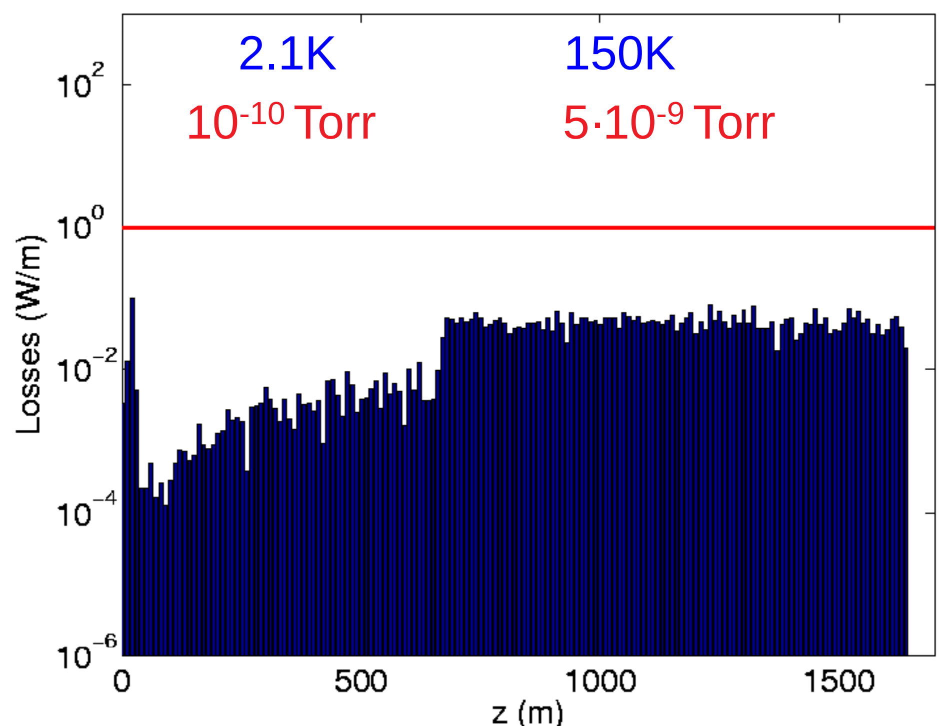
- H^- stripping now in the beam dynamics simulation code TRACK (residual gas, black-body radiation, magnetic field)
- Simulation by P-TRACK, 4000 processors, 100 Million particles



Pressure in the linac is intentionally high



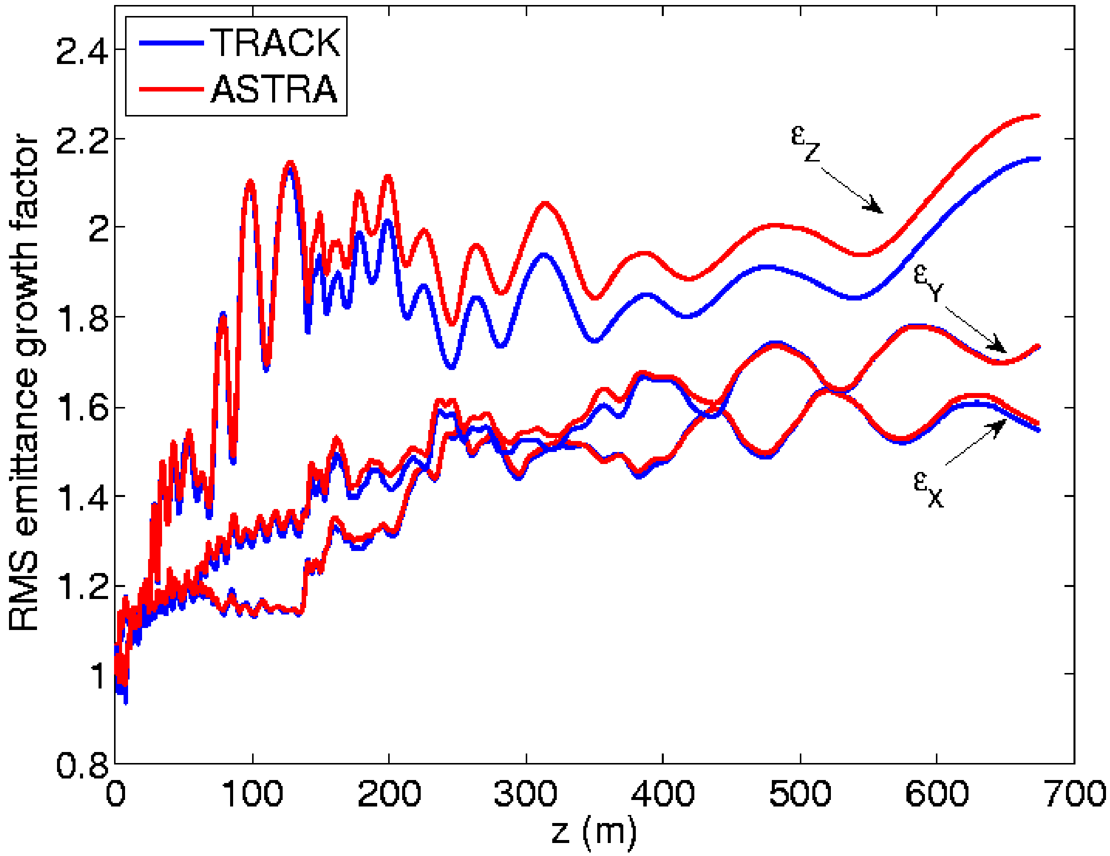
Realistic pressure, cold HEBT



RMS emittance growth

- Main contribution from
  - MEBT, irregular lattice
  - Inter-cryostat drift space
    - *Beam diagnostics*
  - Lattice transition
    - *Increase of focusing length*
  - Long focusing periods in the S-ILC section
  - Beam matching is good but not perfect

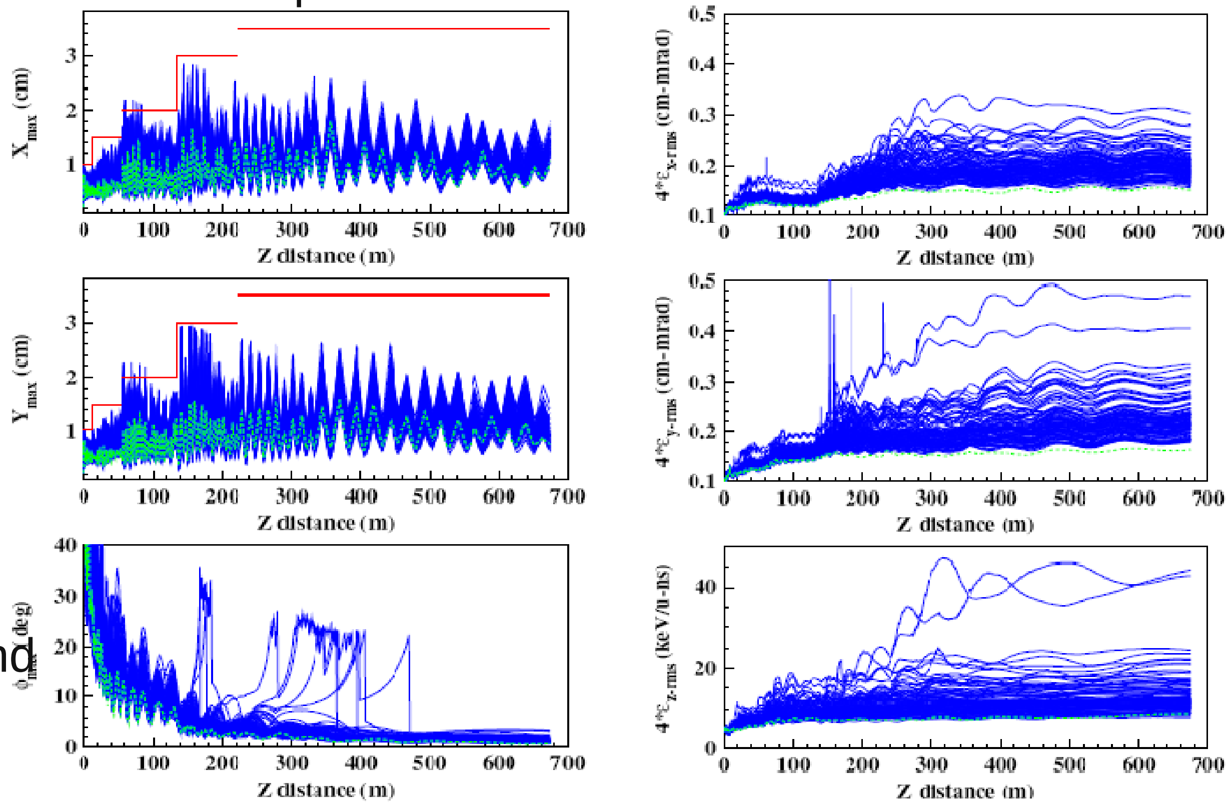
- **Emittance growth is low and acceptable for the HINS PD**



High statistics simulations for 8-GeV, 100 seeds with all errors

Envelopes

RMS emittances



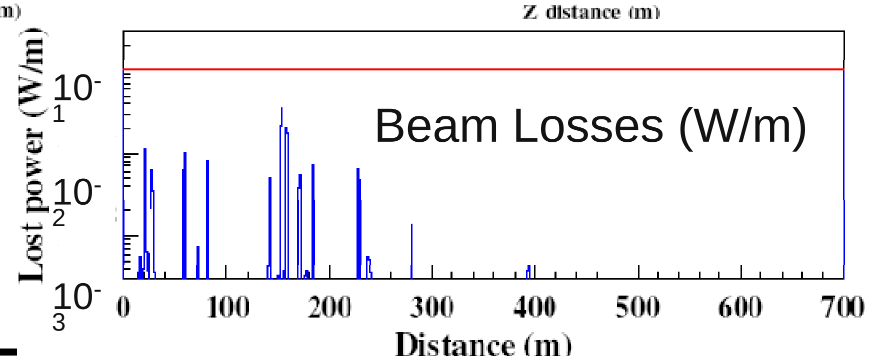
- Error simulations
  - Random, multiple seeds
  - For the static errors correction is applied in each seed
  - Dynamic errors are not corrected
- Type of errors
  - Misalignments
  - Dynamic errors of RF and focusing field

Misalignments: sol. - ±0.2mm, quads - 0.15mm

Quads rotation: ±5 mrad

Cavities: ±(0.5 -1.0) mm

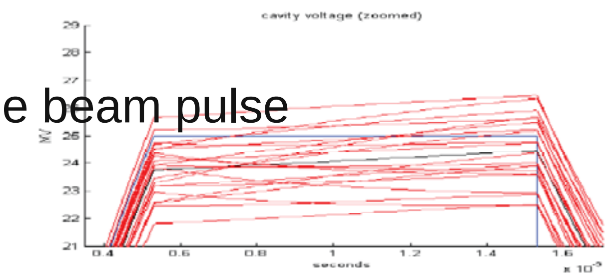
RF errors:1 deg and 1%, rms



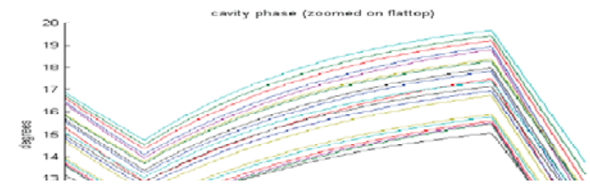
Next important step in the beam dynamics simulations

- Incorporate realistic model of LLRF together with feedforward and feedback systems for the "one klystron" – "multiple cavities"
  - With static phase shifters, ILC and high energy section
  - With dynamic phase shifters, Front End
- Advantage of this model: realistic RF errors along the beam pulse
- The LLRF simulator includes
  - Control of vector sum signal
  - Non-relativistic particles
  - Non-crest acceleration
  - Beam loading
  - Possible spread of maximum achievable voltages in the cavities
  - Cavity electrical and mechanical properties
    - *Lorentz detuning*
    - *Microphonics*

E

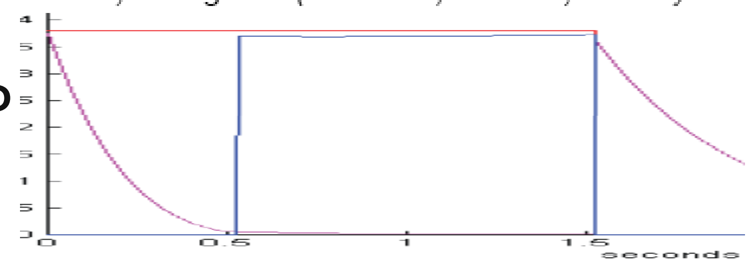


φ



THP115 - Cavity Gradient Optimization in Pulsed Linacs Using the Cavity Transient Response
G.I. Cancelo, A. Vignoni (Fermilab, Batavia, Illinois)

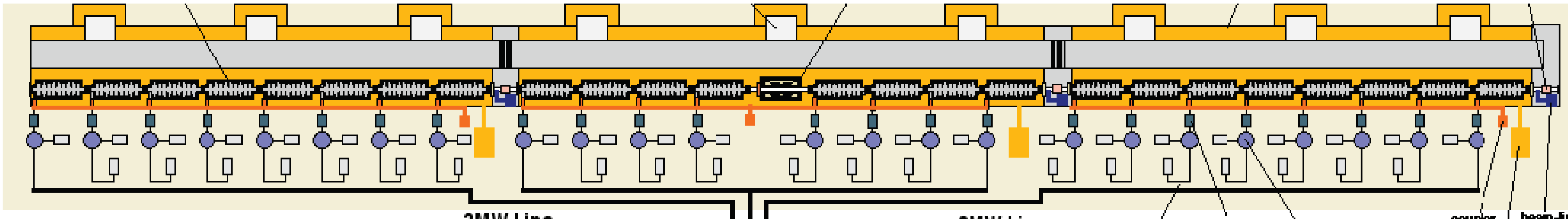
P



- Preliminary studies of the LLRF
  - Optimize static parameters cavity-RF coupling, phase setting for each cavity, t_{opt} of RF
  - In high-energy section over the length of the beam pulse $\Delta E/E < 1\%$, $\Delta\varphi < 1°$

There is a room for further optimization of the high-energy section

- Use five ILC RF units in the energy range 2.4-8 GeV

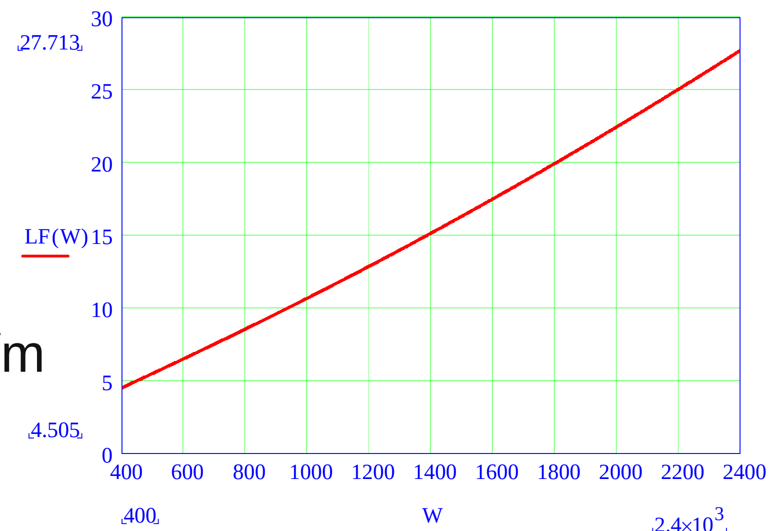


- Try to adopt ILC cryostats with minimal change down to 420 MeV
- Optimize number of cells in the β_G=0.81 cavity
- Select FODO or FDO but the length of the focusing period must be less than in this plot
- From

$$\gamma_s = \frac{\pi}{2}\frac{1}{(\beta\gamma)^3}\frac{L_f^2}{\lambda}\frac{eE_m \sin(\varphi_s)}{m_0 c^2}$$

for $\gamma_S \cong 0.7$, $E_{\text{real estate}}$ =10 MV/m
φ_S=30°

Maximum length of the focusing period as a function of beam energy (MeV)



Conclusion

- New concept of pulsed H-minus/proton linac design has been developed
  - Fully SC above 10 MeV
  - Cost-effective design of the SC linac can provide acceptable beam quality for peak current ~45 mA
- RFQ provides axial-symmetric beam
- Focusing of high-intensity beams with SC solenoids provides several advantages compared to quadrupole focusing
- Beam dynamics design of the linac is based on high-intensity beam physics approach
- High-statistics BD simulations with all machine errors and H-minus stripping show very low beam losses (<0.1 W/m) for typical set of machine errors
- Work in progress
  - Optimization of the lattice in high energy section
  - Include realistic LLRF model into parallel TRACK