Linear Induction Accelerator Purpose and Performance Limitations

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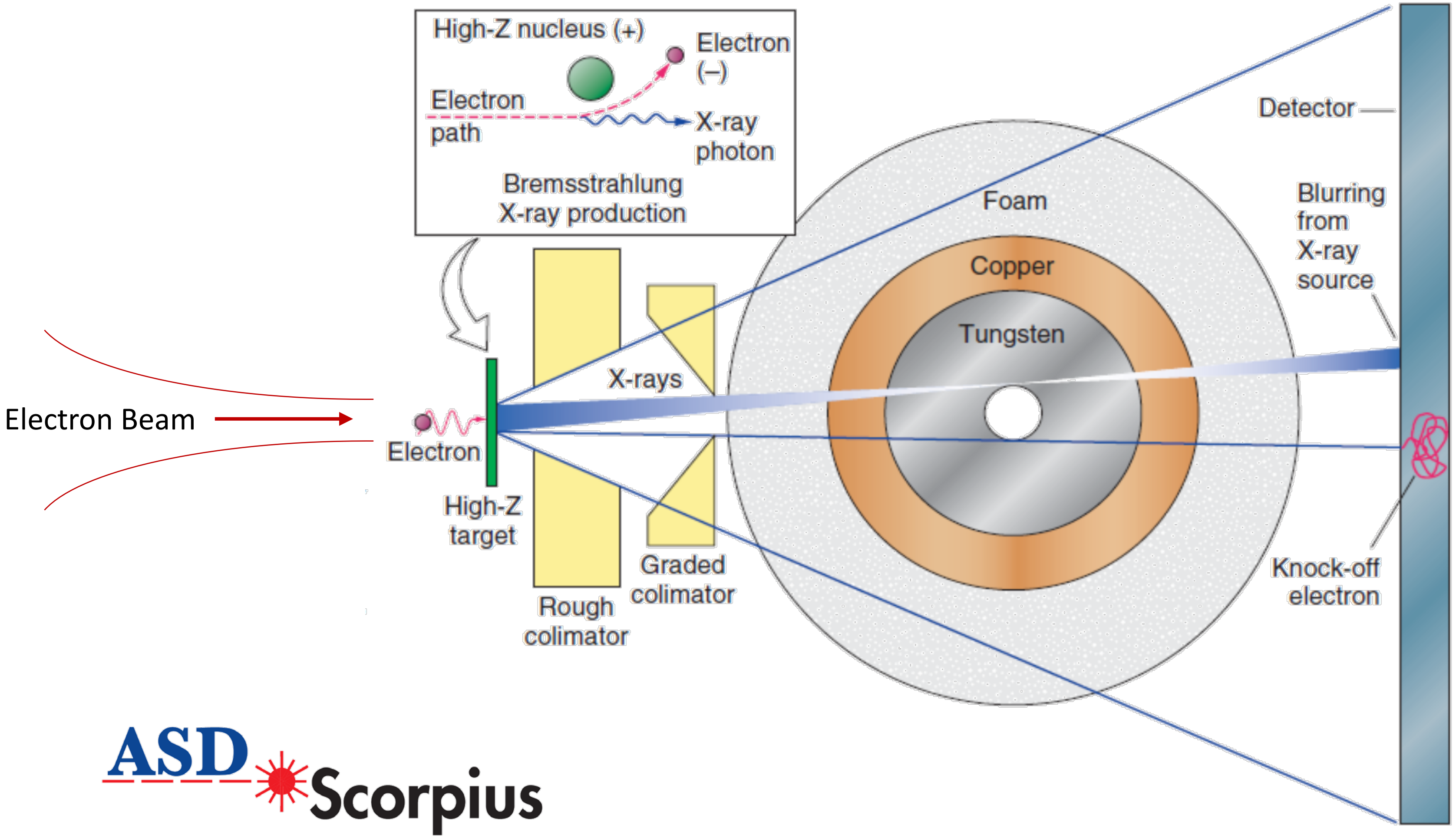
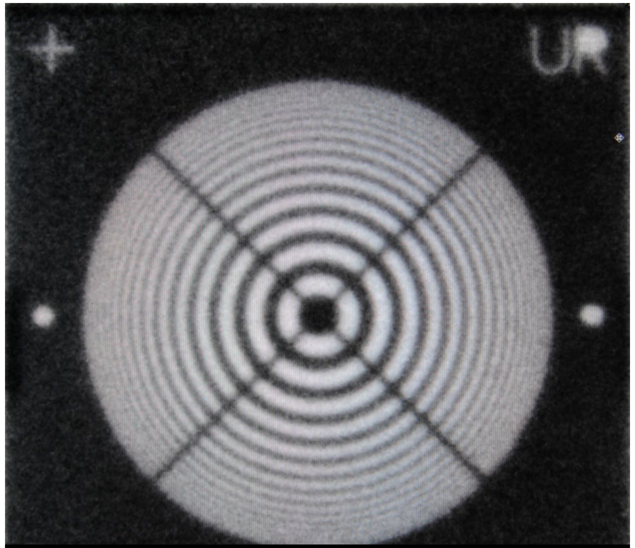
Linear Induction Accelerators are Used in Flash-Radiography

The electron beams are:

- Temporally short (tens of nanoseconds),
- Relativistic (16 to 22 MeV),
- High current (1.5 to 2 kA),
- Focused onto high-Z targets to generate intense bremsstrahlung (X-rays).

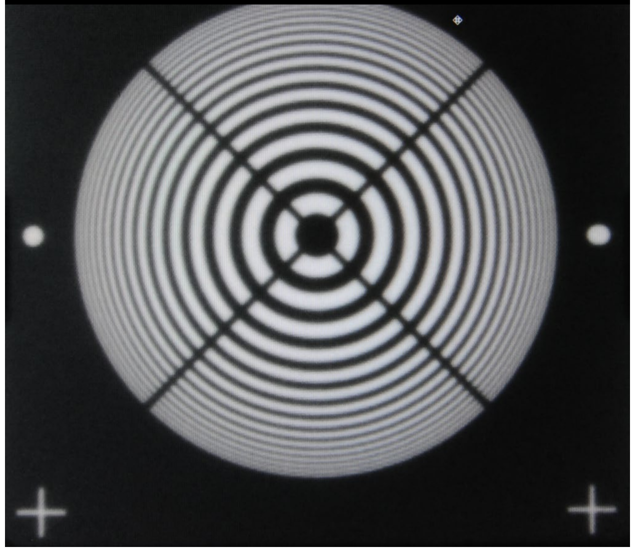


X-Ray Images of a Circular Resolution Target



Good Spatial Resolution

Better Spatial Resolution



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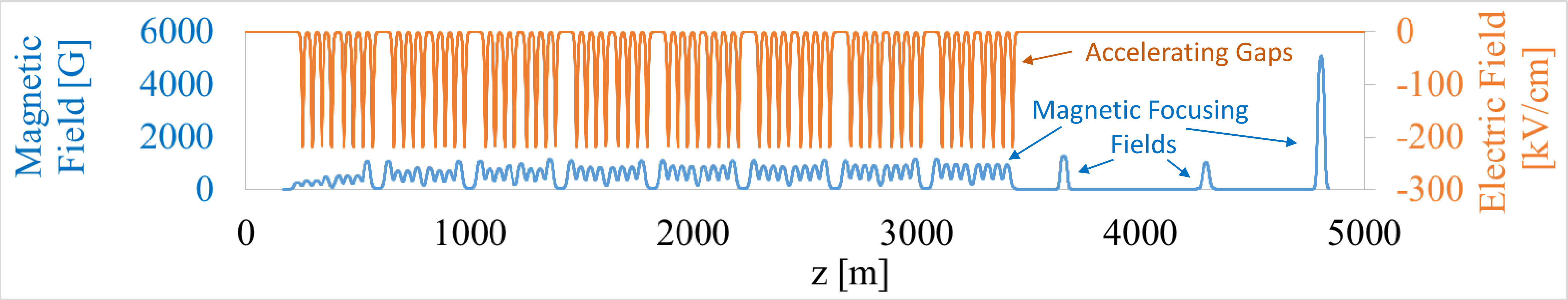
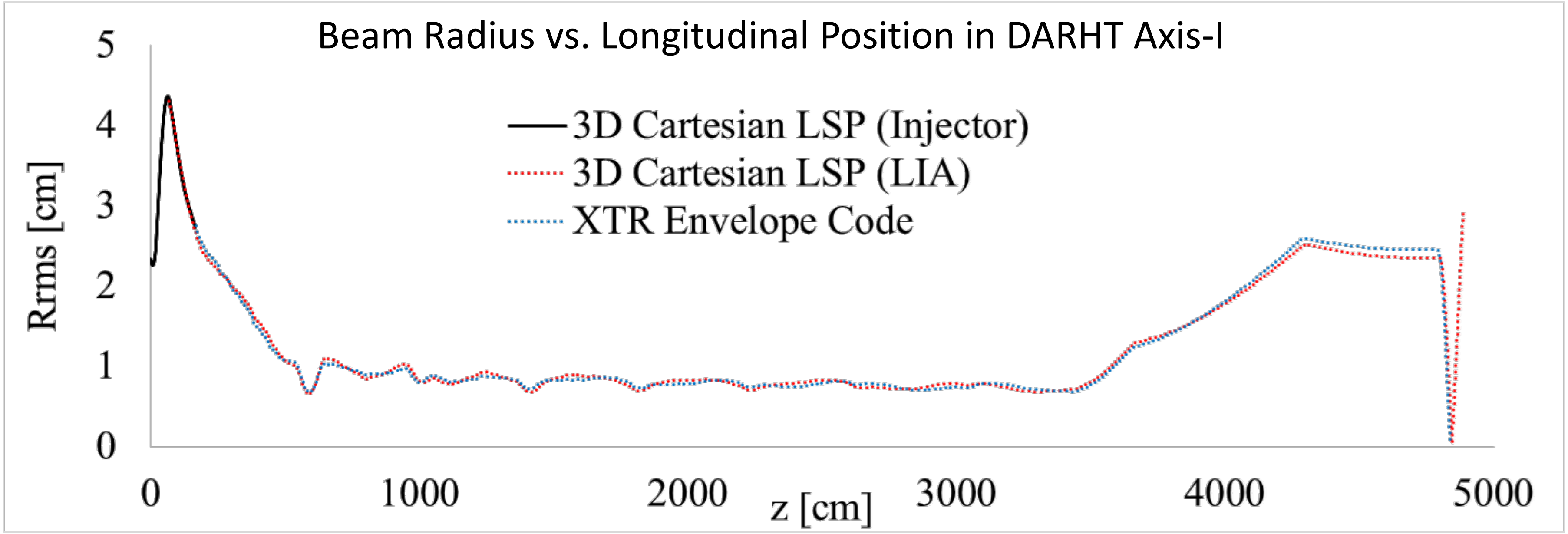
Electron Beams are Accelerated by Electric Fields and Confined by Magnetic Fields





The High Current, Relativistic Electron Beams are Subject to Instabilities and Unwanted Motion

	Description of the Effect	Description of Mitigation
Beam Break-Up (BBU) Instability	Beam excites transverse RF magnetic field modes inside accelerating gaps and cavities. The growth rate Γ is exponential, $\max(\xi/\xi_0) \sim (\Upsilon/\Upsilon_0)^{1/2} e^{\Gamma}$	Suppression is achieved by applying a strong magnetic field B. $\Gamma = \left\langle \frac{1}{B} \right\rangle \frac{I_{beam} N_{gap} Z_{\perp}}{c}$ These values are fixed by design: I_{beam} = beam current, N_{gap} = number of gaps, Z_t = gap transverse impedance $[\Omega/m]$
Corkscrew Motion	Fluctuation in beam energy and misalignment of solenoid magnetics leads to gyration of the beam centroid (maps out a corkscrew shape).	Ensure stringent alignment tolerances and pulsed power steady state requirements are met. Optimize beam steering.
Aberrations in the Final Focus	Aberrations in the solenoid field leads to spherical and chromatic aberrations which limit the smallest achievable spot size.	Optimize the radius to the final focus solenoid, taking into account all contributors to spot size growth.
Envelope (Lattice) Instability	Mismatched magnetic tunes oscillate the electron beam radius and pump electrons from the inner radii to the outer radii.	Ensure accelerator tunes are optimized.
Emittance Growth	Can be thought of as a temperature of the electrons. Measured using Lapostolle emittance	Ensure proper tuning and steering to reduce the envelope instability, spherical aberrations in solenoids, instabilities, and corkscrew motion. Ensure pulsed power operates at steady state (steady E and I).
Ion Hose Instability	The electron beam ionizes background gas (poor vacuum). Both ion channel and beam are attracted to each other and drive beam and ion channel oscillations.	Ensure vacuum requirements are met and tunes mitigate beam spill. Increase magnetic guide fields.
Resistive Wall Instability	The electron beam is attracted to the beam pipe by its image charges and repelled by its image current. If the beam pipe is not 'perfectly' conducting, the magnetic field, due to image current, decays on a magnetic-diffusion time scale, leading to a dynamic Lorentz force.	Suppression is achieved by using conducting beam pipes and applying a strong magnetic field B. For more detail, see C. Ekdahl, "The Resistive-Wall Instability in Multi-Pulse Linear Induction Accelerators," *IEEE Transaction on Plasma Science*, Vol. 45, No. 5 (2017).
Image Displacement Instability	The electron beam is attracted to the beam pipe by its image charges and repelled by its image current. The forces become unbalanced at acceleration gaps and cavities, and the beam is steered.	Suppression is achieved by applying a strong magnetic field B. $B[kG] > \frac{1}{b}\sqrt{\frac{1.36\gamma\beta w\, I[kA]}{L}}$ w = gap width, b = beam pipe radius, L = distance between gaps
Diocotron Instability	Concave beam profiles are subject to a sufficiently strong shear in the $\boldsymbol{E}\mathrm{X}\boldsymbol{B}$ rotation velocity of the plasma column and become unstable.	Ensure injector design generates high energy non-hallow beams.

The Envelope Equation Helps us Understand Beam Transport through the Accelerator

External Forces

Internal Forces (Defocusing)

$$\frac{d^2 R_{env}}{dz^2} + \frac{1}{\beta^2 \gamma}\frac{d\gamma}{dz}\frac{dR_{env}}{dz} + \left[\frac{1}{2\beta^2\gamma}\frac{d^2\gamma}{dz^2} + k_\beta^2\right] R_{env} = \frac{K}{R_{env}} + \frac{\varepsilon_n^2 + \left(P_\theta / m_e c\right)^2}{(\beta\gamma)^2 R_{env}^3}$$

Adiabatic damping by axial electric field

Focusing by radial electric field

Focusing by solenoidal magnetic field

Centripetal force

Emittance (“temperature”)

Space-charge force

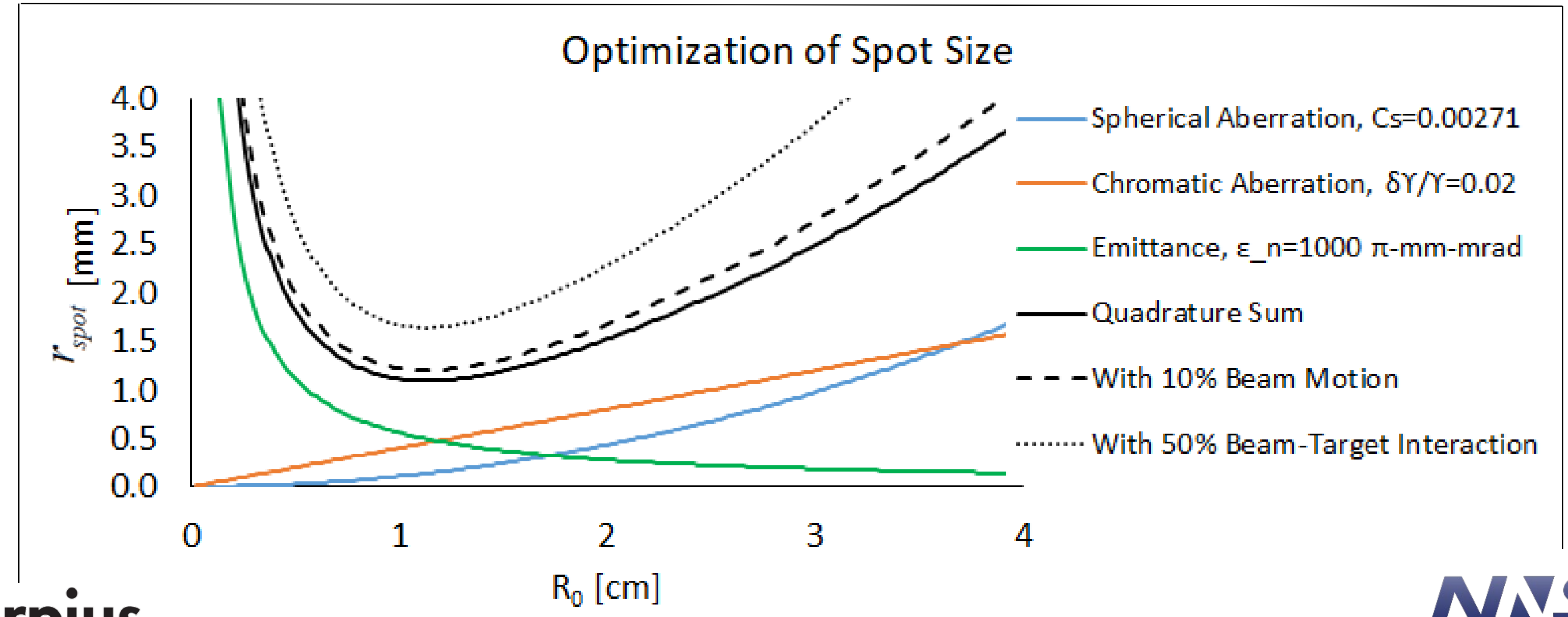
Defocuses in vacuum.
Focuses in gas (plasma).

The Major Contributors to Spot Size Limitations Can be Quantified

- Beam parameters like emittance (temperature) and magnet aberrations add in quadrature sum.
- Motion and target affects scale as a percent increase.

$$r_{spot}^2 = \left(\frac{\varepsilon_n z}{\beta\gamma R_0}\right)^2 + \left(2R_0\frac{\Delta\gamma}{\gamma}\right)^2 + \left(C_s R_0^3\right)^2 + \text{motion} + \text{beam target}$$

Spot Size; Emittance Contribution; Energy Spread/Variation Contribution; Spherical Aberration Contribution



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The Key Performance Parameters (KPPs) are Requirements Scorpius Must Achieve

Initial **O**perating **C**apability (**IOC**):	**F**inal **O**perating **C**apability (**FOC**):
1. Four radiographic pulses	1. Four radiographic pulses
2. Ability to vary the time between pulses (as measured center to center) in a ≥1500 ns window, at a pulse spacing ≤500 ns for 2 pulses	2. Ability to vary the time between pulses (as measured center to center) in a ≥3000 ns window, with the expectation of achieving a minimum pulse spacing ≤200 ns for any 2 pulses
3. Radiographic pulse lengths: between 20 and 80 ns with the ability to control the length (effective dose) of each pulse to within 5 ns	3. Radiographic pulse lengths: between 20 and 80 ns with the ability to control the length (effective dose) of each pulse to within 5 ns
4. Radiographic figure of merit: ≥1.2 line pairs per mm visible for 2 pulses with an overburden representing a nominal Object A density	4. Radiographic figure of merit: ≥1.5 line pairs per mm visible for 4 pulses with an overburden representing a nominal Object A density
5. Radiographic figure of merit: ≥0.8 line pairs per mm visible for 2 pulses with an overburden representing a nominal Object C density	5. Radiographic figure of merit: ≥1.2 line pairs per mm visible for 4 pulses with an overburden representing a nominal Object C density

IOC is an ASD Project Responsibility

FOC is an NNSS Responsibility

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Everything here supports the Hydrodynamic and Subcritical Experiment Execution Support (HSEES) Program.

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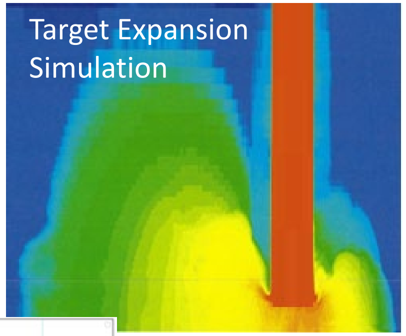
The KPPs Become More Stringent for FOC (NNSS Responsibility)

The operating window is twice as long as Scorpius IOC and DARHT Axis-II.

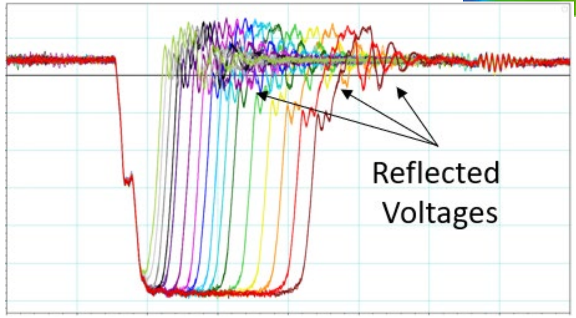
- IOC is ≥1500 ns
- Axis-II is 1600 ns
- FOC is ≥3000 ns



More time for target expansion and movement of desorbed contaminants.

Minimum spacing between pulses increases.

- ≤500 ns for any 2 pulses
- ≤200 ns for any 2 pulses



Closer pulse spacing leads to increased interference with reflected voltages in the pulsed power circuits.

The two image requirement increases to four images with increased spatial resolution.

- IOC is two images with ≥1.2 line pairs per mm visible (overburden representing a nominal Object A density) and ≥0.8 line pairs per mm (overburden representing a nominal Object C density)
- FOC is four images with ≥1.5 line pairs per mm visible (overburden representing a nominal Object A density) and ≥01.2 line pairs per mm (overburden representing a nominal Object C density)

Image resolution requirements increase while beam-target interactions have more time to grow and there's an increase in reflected voltage interference.

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Thank you for your attention.

Takeaway Messages:

- ASD is responsible for achieving initial operating capability (IOC).
  - Once achieved, the ASD Project will close (November 2027).
- The NNSS is responsible for achieving final operating capability (FOC).
  - This supports the Hydrodynamic and Subcritical Experiment Execution Support (HSEES) Program.
- Beam-target interactions negatively influence multi-pulse LIAs.
  - Mitigating the effects can improve performance of DARHT Axis-II, FXR (double-pulse mode), Scorpius, and the proposed LLNL n-pulse LIA.

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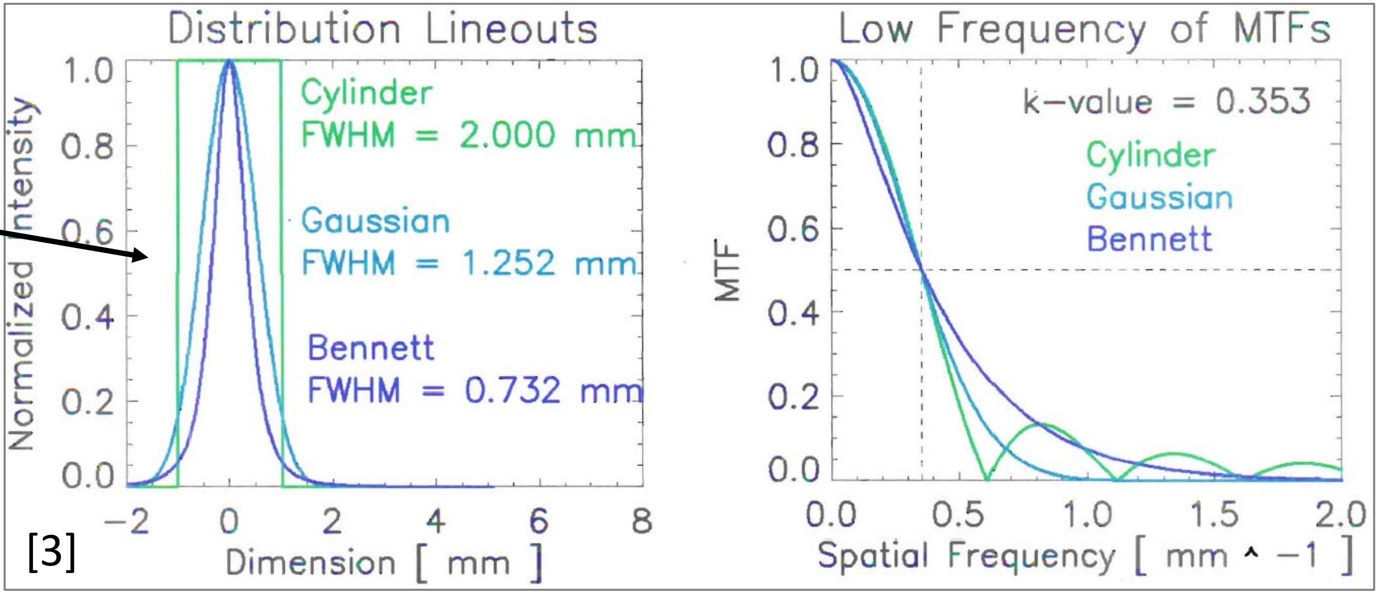
Backup Slides

Commissioning Will Use LANL Methods for Radiographic Evaluation of IOC and FOC

Spot Size will be evaluated using the LANL definition (d_{LANL}) [1,2]:
i.e. the diameter of a uniformly illuminated disk that has the same spatial frequency at a Modulated Transfer Function (MTF) of 0.5 as the actual source spot.

Different source distributions:



[3]

Limiting Resolution (line pairs per millimeter) will be the spatial frequency at which the contrast of the image of an opaque grating is 5% [2].

[1] Karl Mueller, *Measurement and Characterization of X-ray Spot-Size (LA-UR-89-1886)*
[2] Carl Ekdahl, *Characterizing flash-radiography source spots,* Journal of the Optical Society of America A, Vol. 28, Issue 12, 2011
[3] Trent McCuistian, Evan Rose, Dave Moir, Howard Bender, Carl Carlson, Craig Hollabaugh, Rusty Trainham, *Spot Size Measurements of the DARHT First Axis Radiographic* Source (LA-UR-08-3854)

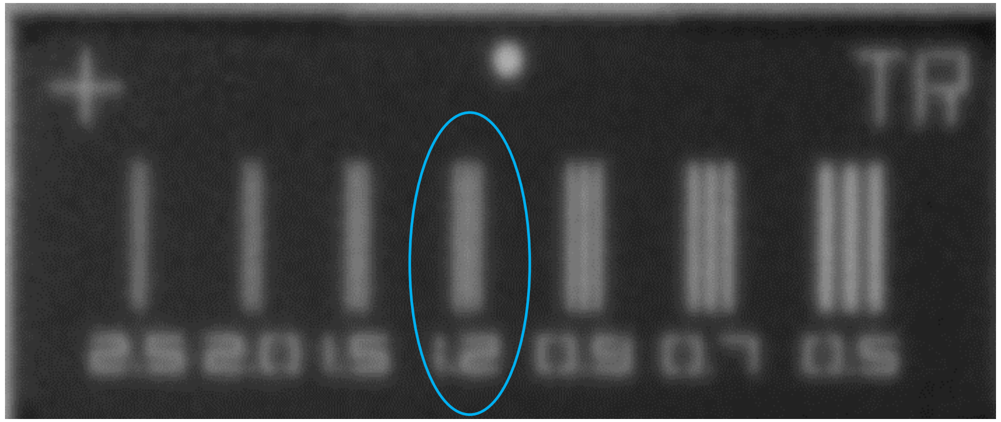
Where Did our Radiographic Requirements Come from?

Spot Size of D_{LANL} = 2.76 mm

- Discussed in the Conceptual Design Report, Appendix A.
- This is the value used for Axis-I radiographic analysis.
- This is not necessarily the spot size that is measured with a pinhole aperture.

Limiting Resolution of 1.2 line pairs per millimeter

- Listed in the FOC requirements.
- This is the measured (post analysis) value from Axis-I resolution targets.



PowerPoint of an image of a radiograph, i.e. more blurry than the original.

From Carl's Paper, [2] in previous slide:

- Limiting Resolution = 3.18636/D_{LANL} ,
- i.e. 2.76 mm results in 1.2 lp/mm.

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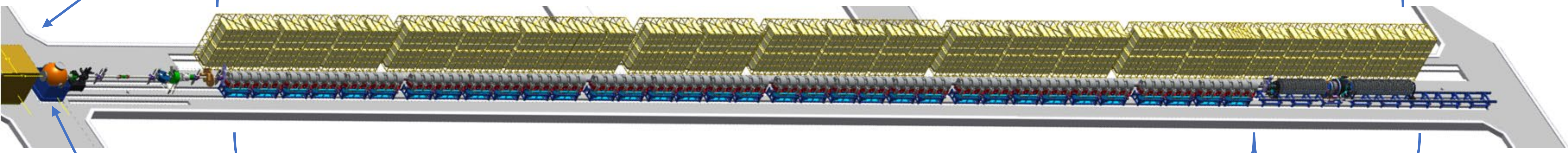
Computer Model of the Scorpius Accelerator in the U1a Complex

Detector System
(Radiographic Camera)

Solid State Pulsed Power: Provides the power for the injector and accelerator to generate the electric fields that accelerate the electron beam. Scorpius' pulse power is a major technological advancement over DARHT and FXR but will be more challenging to operate and maintain.

Electron Beam Direction



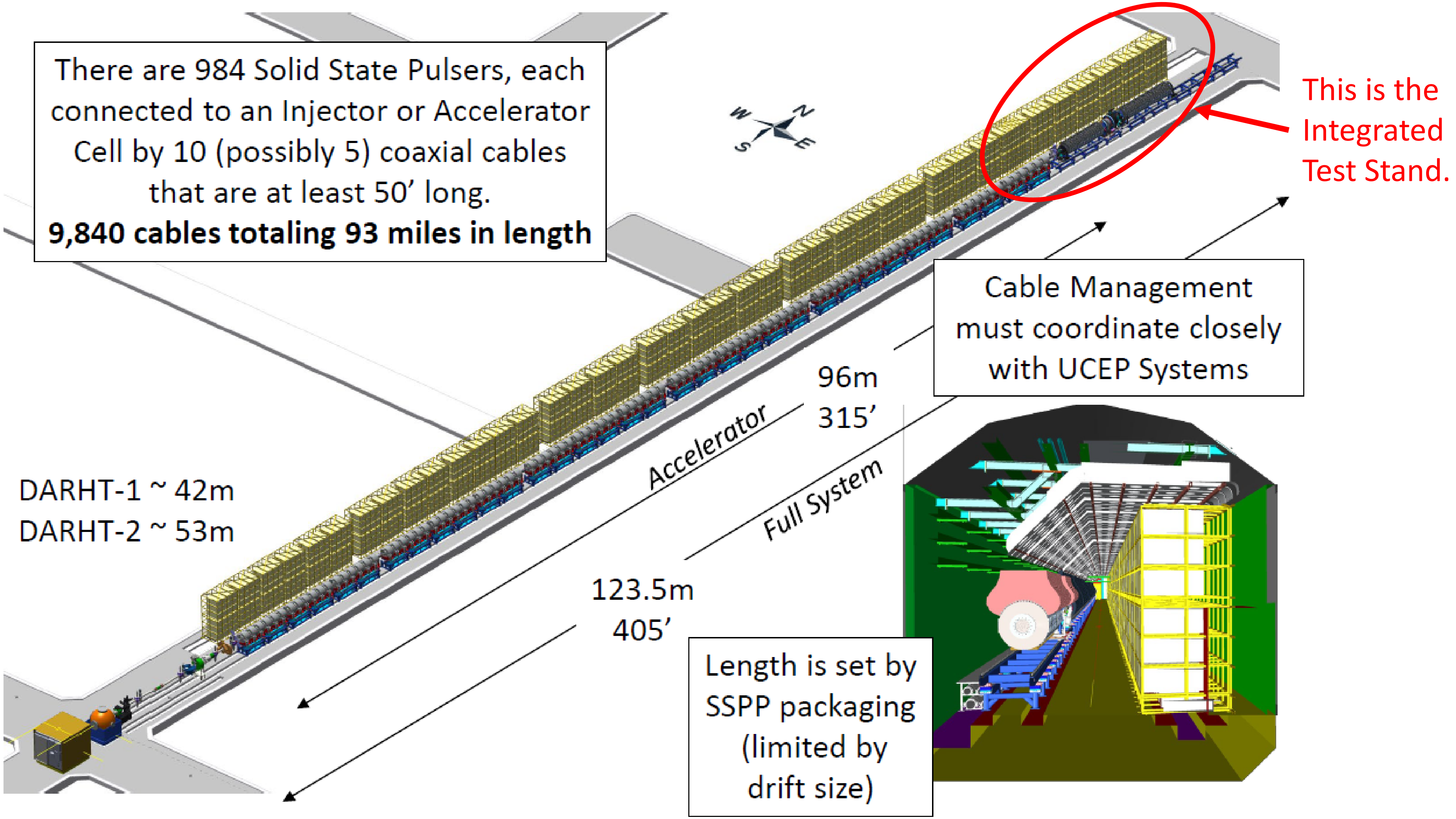
Object to be radiographed is confined in a "vessel."

Accelerator System: Further accelerates the electron beam and transports it downstream, towards the target. (More acceleration = more beam energy = more x-rays = more dose).

Injector System: Generates the electron beam, provides an initial acceleration and transports the beam to the accelerator.

Global Controls: Ensure the machine is ready to fire and manage the timing of the pulse power and diagnostics throughout the machine.

After Testing the Integrated Test Stand, Scorpius Installation will be Completed at U1a



ASD will Integrate a Large Subset of Scorpius Systems to Test Integrated Systems

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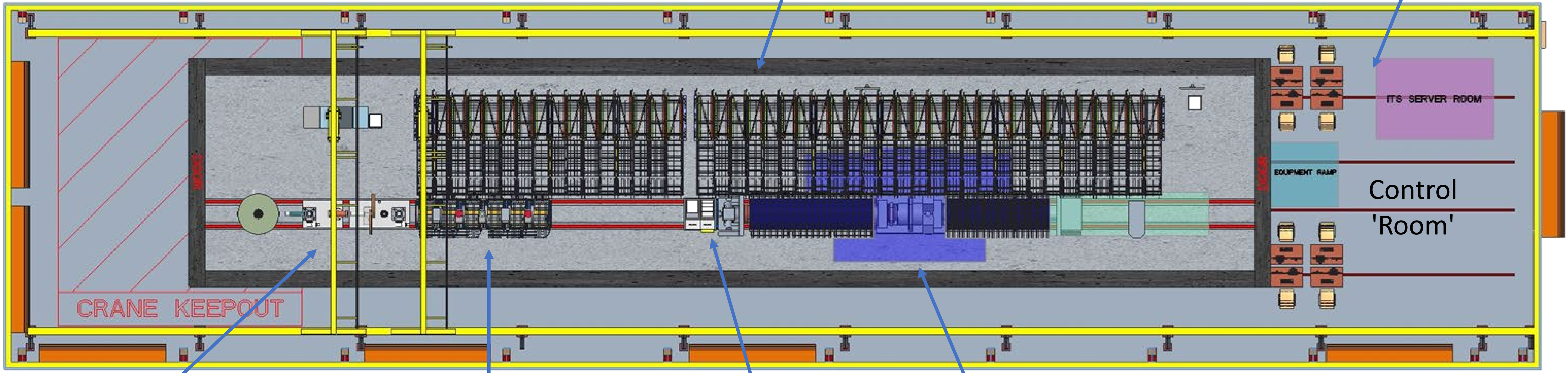
The Integrated Systems Make the Integrated Test Stand (start-up ~2025)

First opportunity to generate beam and test requirements.

Solid State Pulse Power

Global Controls



Control 'Room'

Diagnostics

Reconfigured Safety Interlock System

DST Validation Tests of:
- spinning wheel
- beam stop
- vacuum
- solenoids
- etc.

Accelerator Validation Tests
- modulation with beam

Injector Validation Tests
- first electron beam
- modulation with beam
- voltage stand-off
- performance
- etc.

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