CW RF Gun Considerations

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- Fernando Sannibale
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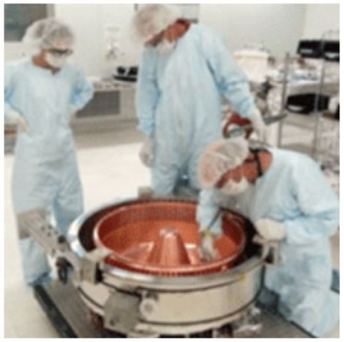
  - Chris Adolphsen
- John Smedley
- SRF Gun R&D Community

Outline

- Design landscape
- Basic RF gun characteristics
- Why go with a CW-capable gun?
  - Operating considerations and tradeoffs
  - Facility implications
- Recent progress
- Conclusions

Design Landscape – One (arguably unhelpful) View

	Pulsed	~CW
Normal Conducting	Typically: • > 1 GHz frequency • Multi-cell structures • 2-6+ MeV • 50-100+ MV/m on cathode • O(1 μs) pulses, O(100 Hz) rep rates Exemplar: SLAC/BNL/UCLA 1.6-cell S-band gun	Typically: • < 700 MHz • Single or multi-cell structures • 1-2 MeV • 5-25 MV/m on cathode • 25% - CW duty factors Examples: APEX, Boeing, LANL 
Super-Conducting	…?	Typically: • 1.3 GHz single- or multi-cell structures, or • < 250 MHz single-cell structures • 1-3 MeV • Gradients of 10-30 MV/m on cathode • 25% - CW duty factors Examples: HZDR, BNL, SLAC/MSU/HZDR

Quarterwave ("quasi-DC") vs. High-Frequency RF gun design

High-Frequency RF guns	Quarterwave RF guns
Typically multi-cell (cathode cell + at least 1 "full" cell)	Typically single-cell
Most are "on" O(1μs), @10-100 Hz; exceptions include: Euro X-FEL gun (600 μs) LANL 700-MHz gun (CW)	Typically intended for CW operation
Typically 1 – 10 GHz	Typically 100 – 200 MHz
Cathode cell length ~ ¼ RF wavelength	Accelerating gap 0.05 – 0.10 RF wavelength
"Classic" Carlsten / Kim / Rosenzweig / Serafini beam dynamics	Beam dynamics more like DC guns, but with higher on-cathode fields and higher beam energy

Going LFCW – why not?

- Lower gradients – more restrictive on charge/time/ε_{th}
- CW operation
  - Implications for shielding
  - Waste heat removal for NCRF systems;
  - Need for a cryo system for SRF
- Facility / operational considerations
  - NCRF – turn on/off needs to be handled carefully; settling times and thermalization
  - SRF – keep the gun cold? Let it warm up? Etc.
  - In both cases, particle-free beamlines preferred
  - Shielding – needs to account for dark current.

Image courtesy LBNL

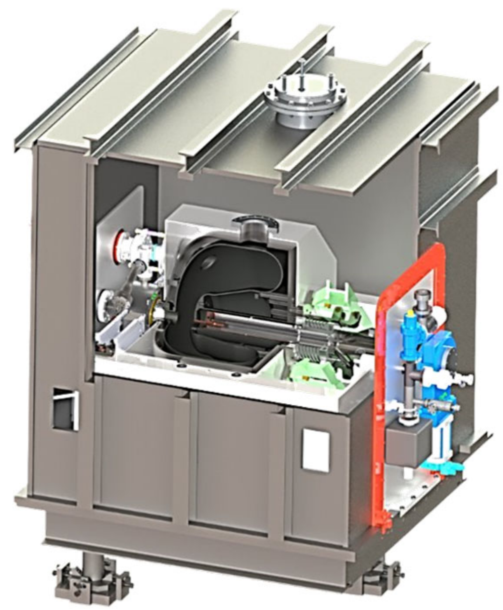


Image courtesy SLAC & MSU

Going LFCW – why?

Two regimes with potential advantage over pulsed:

- Measurements need to extend for > ~ 1 μs (thanks to CW operation);
- Potential for variable pulse spacing < 1 RF period (thanks to DC gun-like dynamics)

Why superconducting?

- Potentially higher fields on the cathode
  - APEX ~ 20 MV/m with standard cathode
  - SLAC/MSU
    - 30 MV/m target
    - 30 MV/m reached in “blank” cavity tests

- Outstanding vacuum

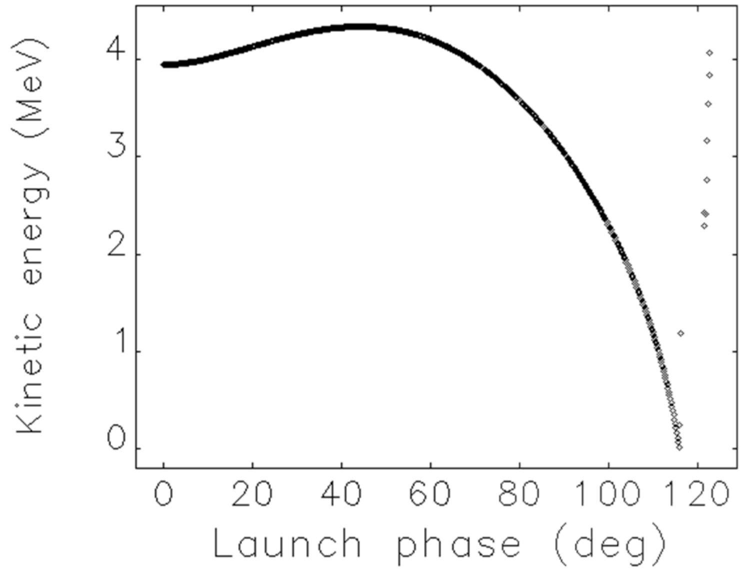
Multiple Beam Pulses

- "Natural" spacing @ the RF frequency
  - Launch the beam at the same phase of the RF field at the cathode
    - Beam parameters same shot-to-shot → downstream optics same
  - Delay between pulses = n / f, where
    - n is an integer, and
    - f is the RF frequency
- A C-band gun (f = 5.712 GHz) can "naturally" make bunches spaced at n*(175 ps), n < 5700*
- A CW VHF gun (f ~ 200 MHz) can "naturally" make bunches spaced at ~5 ns; since the gun is CW, n ~ ∞

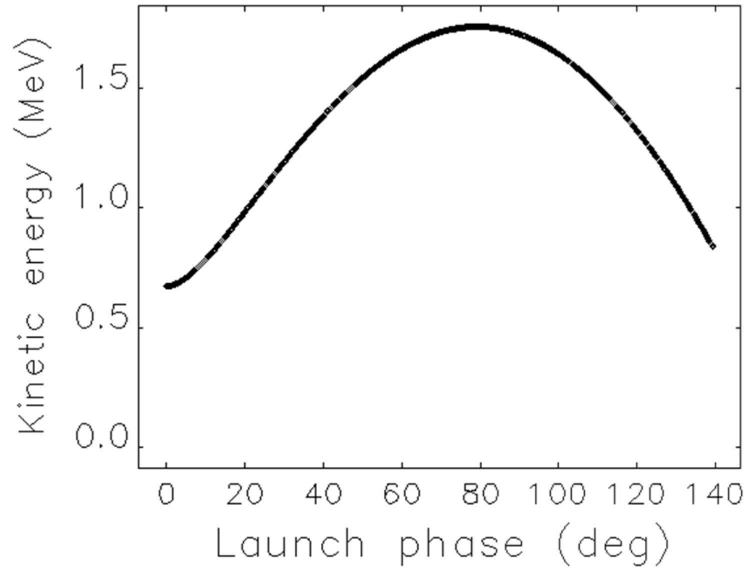
* Assuming a 1-μs RF "flattop"

What if I want a closer (or just different) time spacing?

- Assume some boundary conditions:
  - Beams should be at the same energy
  - Beams should have the same transverse parameters



“generic” 1.6-cell S-band gun
100 MV/m on cathode



SLAC/MSU SRF gun
30 MV/m on cathode

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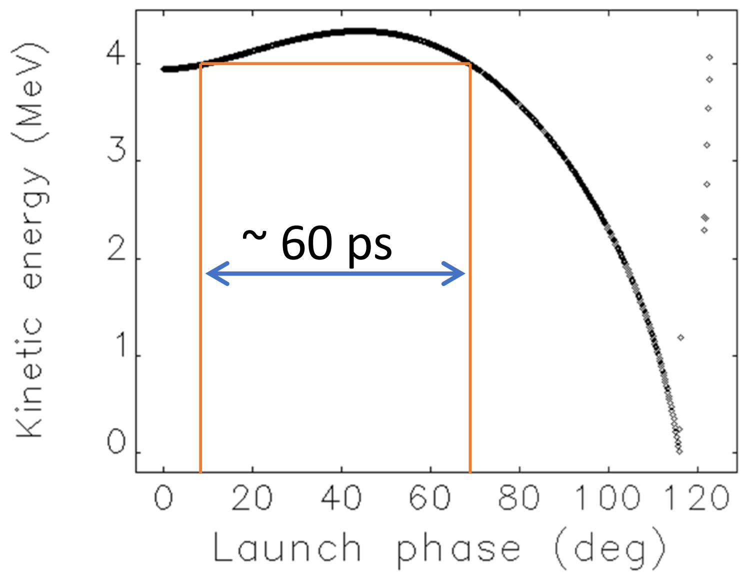

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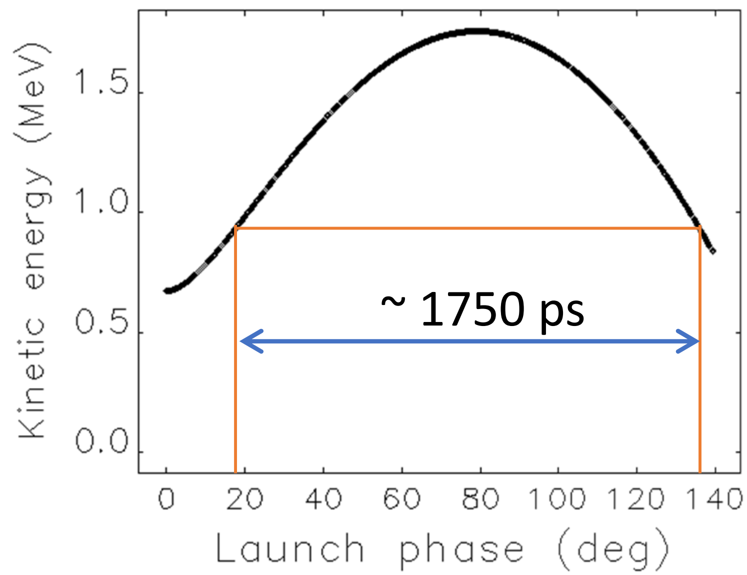

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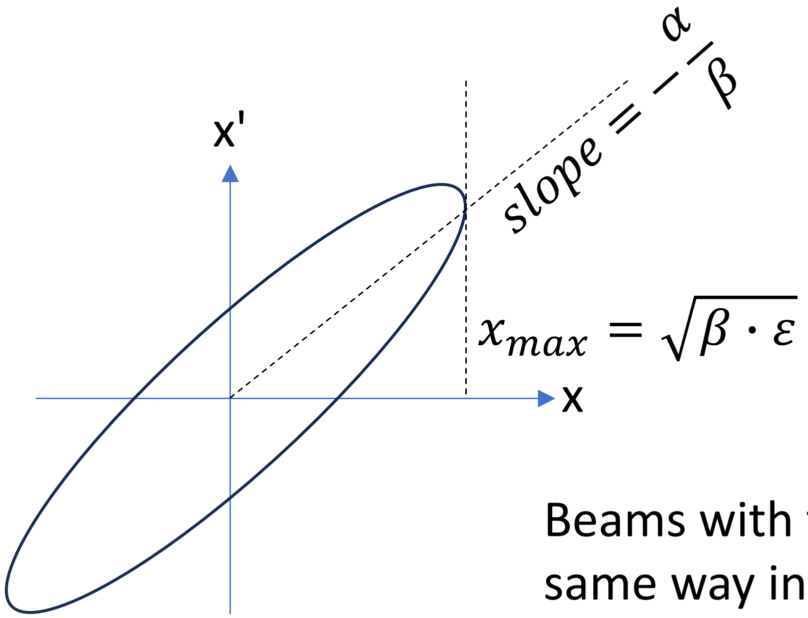
Transverse Beam Parameters



Area of ellipse = ε

Twiss (or Courant-Snyder) parameters for a beam:

β ~ normalized beam size
α ~ normalized divergence angle
$\gamma = (1+\alpha^2)/\beta$

Beams with the same Twiss parameters behave in the same way in a focusing system, just scaled by the emittance (e.g. bigger / smaller)

Beams with the same emittance, but different Twiss parameters, behave differently in a focusing system (e.g. waists in different locations)

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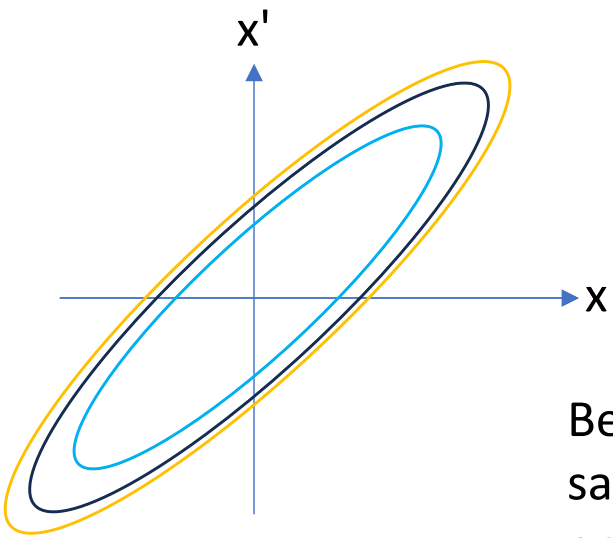

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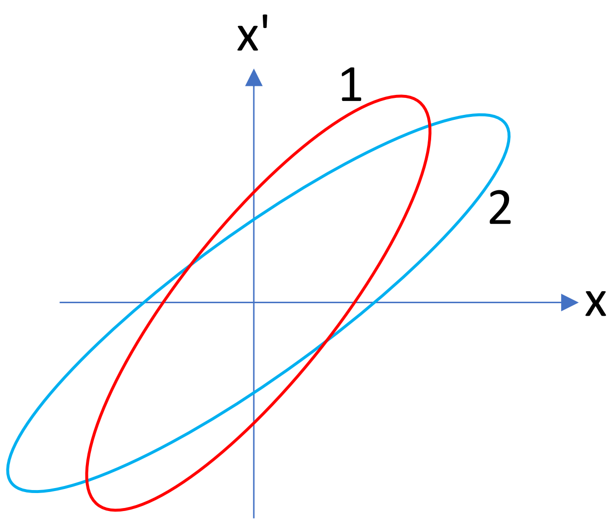
The Mismatch Parameter



$$\zeta \equiv \frac{1}{2}(\beta_1\gamma_2 - 2\alpha_1\alpha_2 + \beta_2\gamma_1)$$

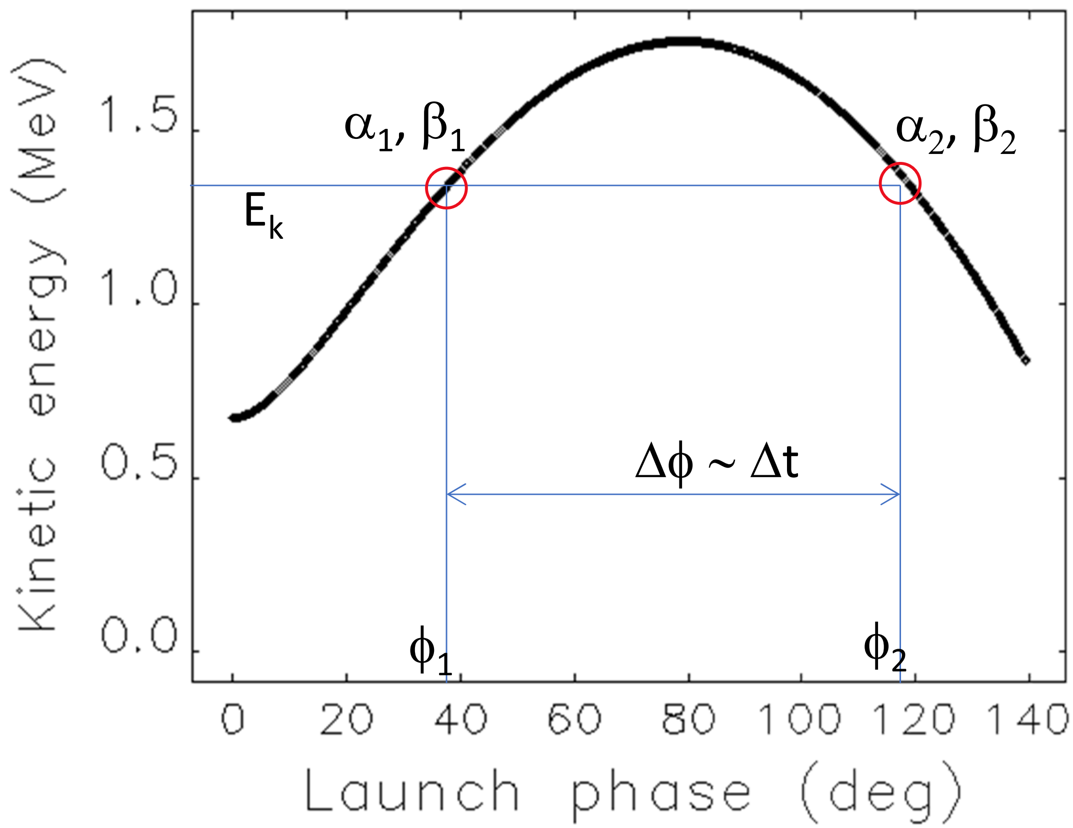
$$\zeta \equiv \frac{1}{2}\left(\beta_1\frac{1+\alpha_2^2}{\beta_2} - 2\alpha_1\alpha_2 + \beta_2\frac{1+\alpha_1^2}{\beta_1}\right)$$

Characterizes the relative orientation of the beam ellipses in phase space

ζ = 1 → perfectly matched

At a waist (α=0), 10% size difference → ζ = 1.08

Calculating Mismatch for a Given Pulse Spacing



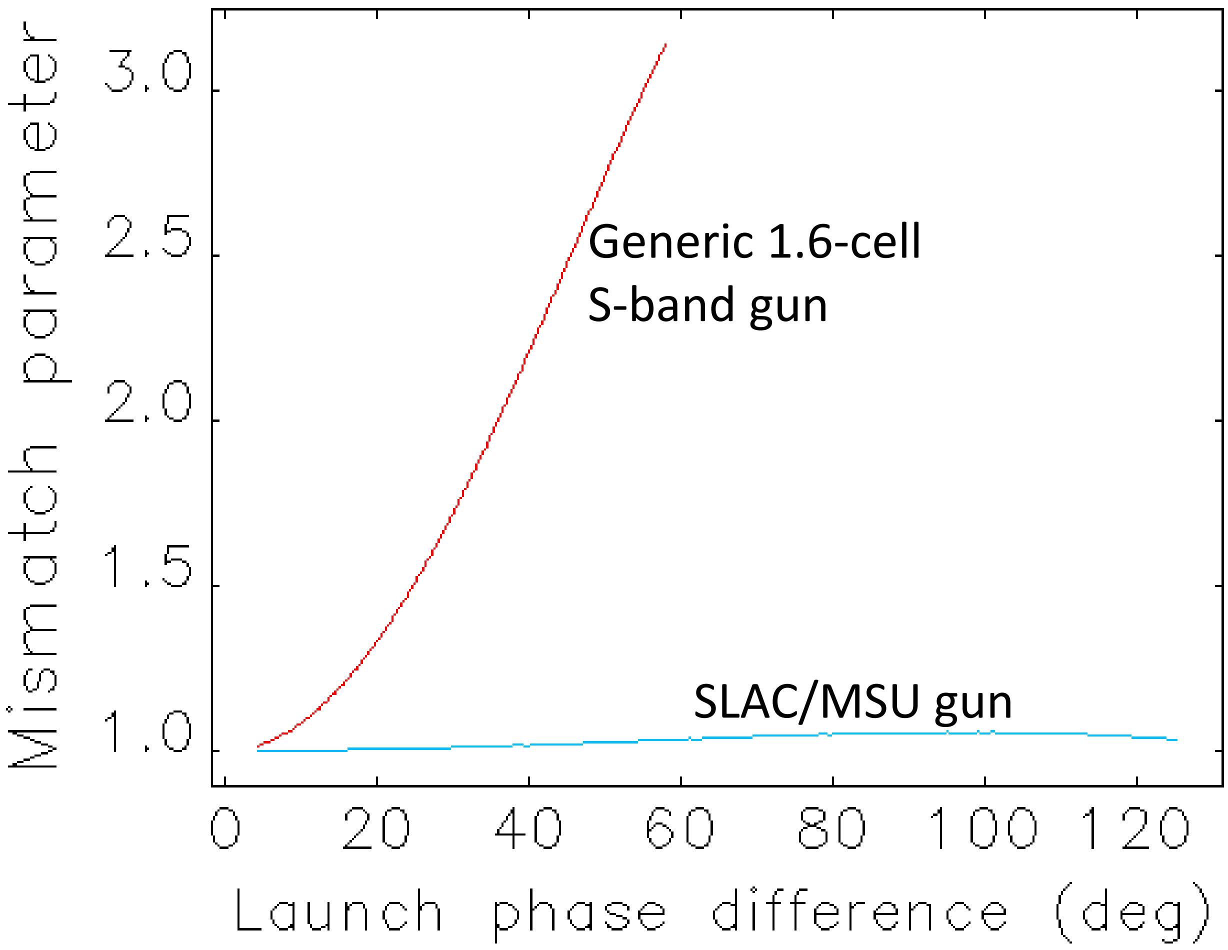
For a given beam kinetic energy E_k:

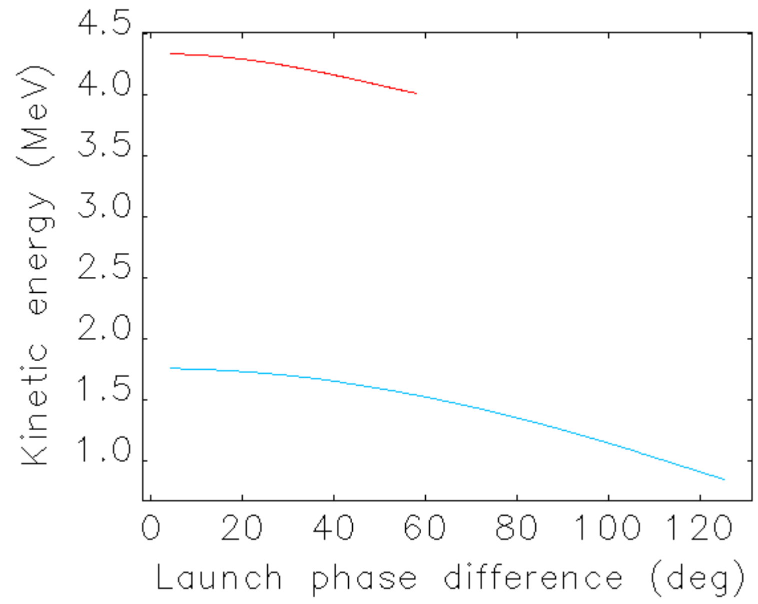
- Find launch phases $\phi_{1,2}$
- Calculate time delay Δt at gun exit
- Find Twiss parameters at gun exit
- Calculate mismatch parameter

For these simulations:

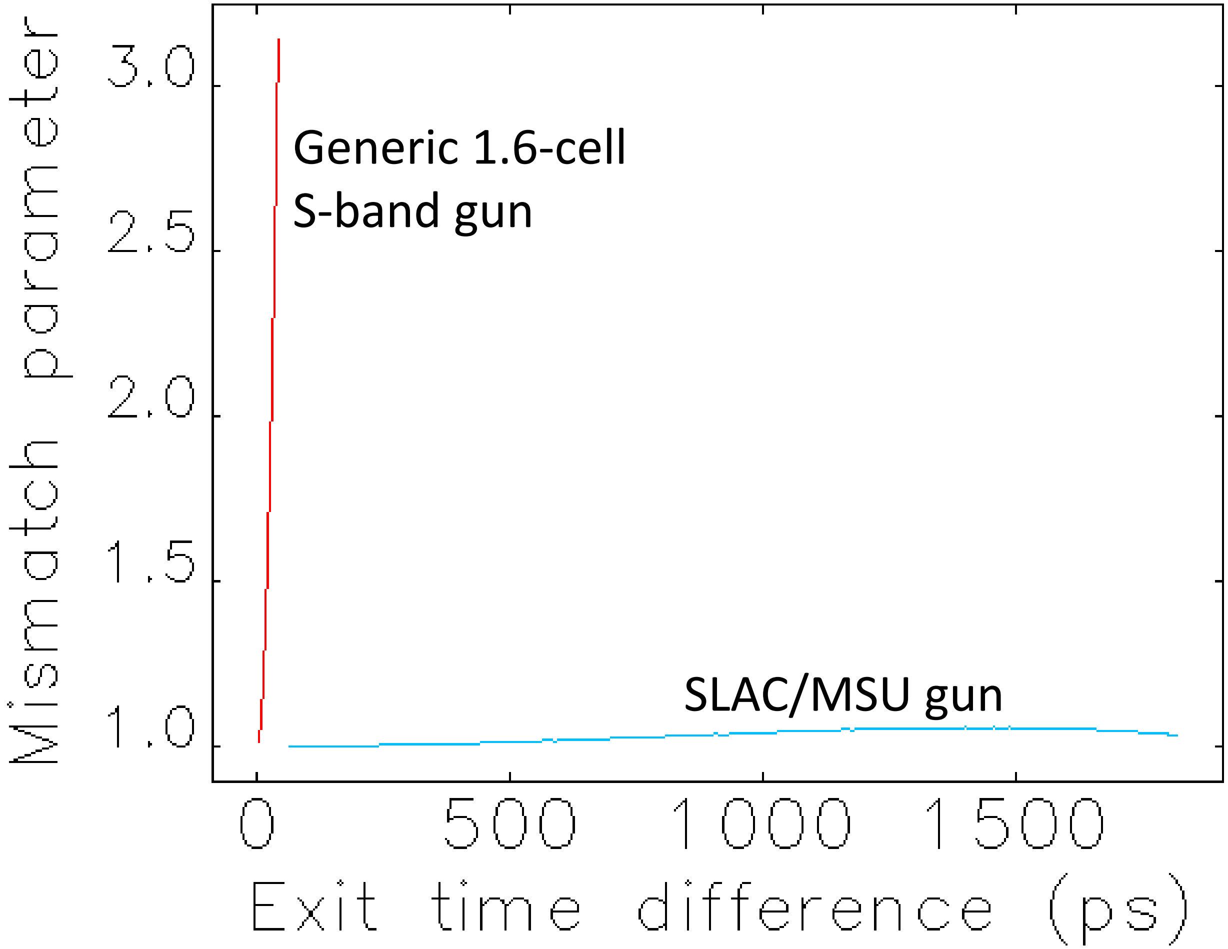
- Only RF; no solenoid, d/s transport;
- No space charge;
- “Short” bunches (~ 1 ps duration)

Mismatch vs. Launch Phase Difference





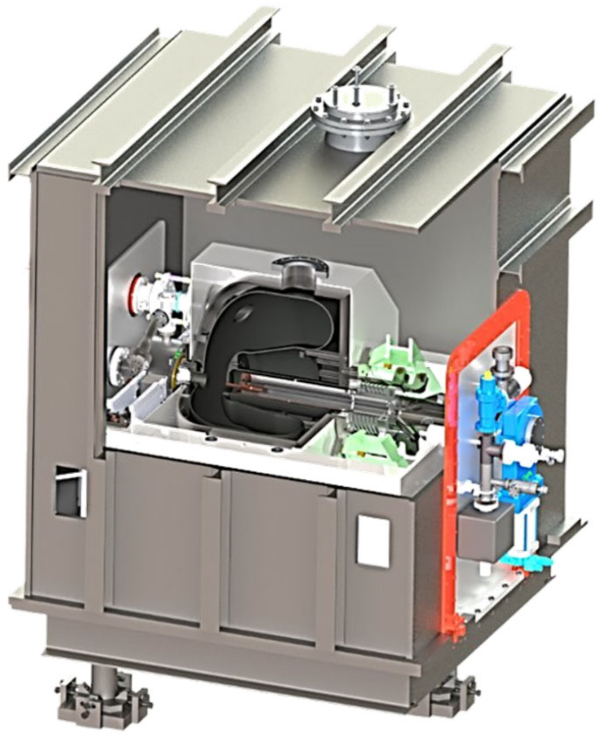
Mismatch vs. Beam Exit Time



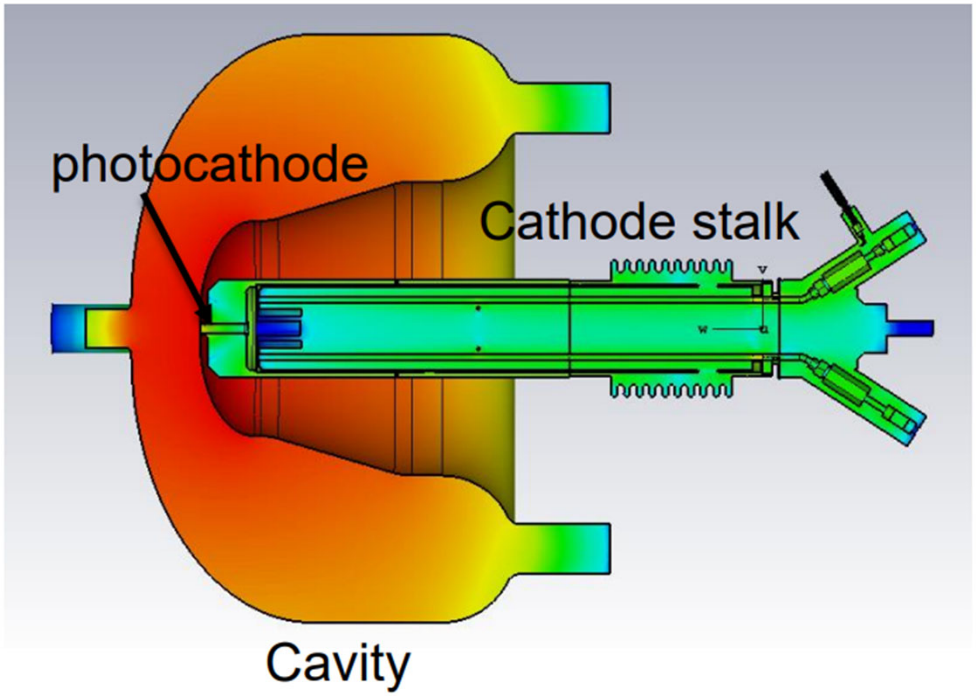
SRF Gun R&D: LCLS-II-HE & FRIB

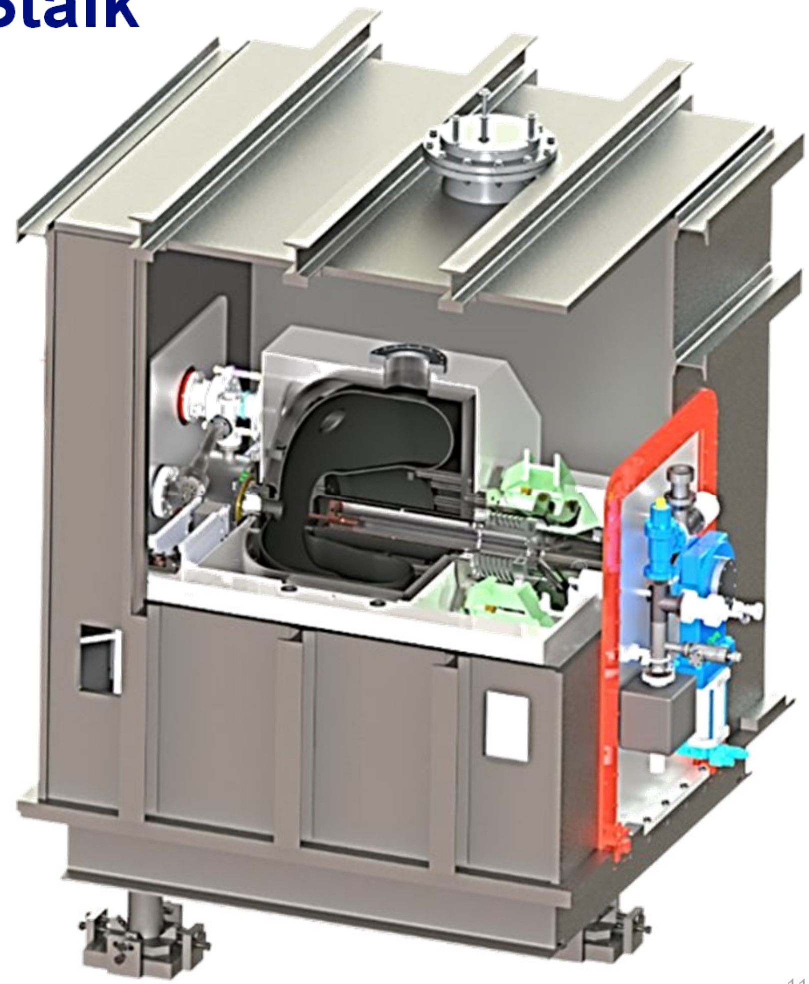
- Ultimate Goals
  - Beam source for a new injector for LCLS-II-HE
  - Whole injector not currently in scope, but should be "upgrade capable"
  - Intended to allow effective operation of LCLS-II-HE to 20+ keV X-rays

- Goals of the R&D program
  - Build a prototype gun cryomodule (cavity, solenoid, etc.) and cathode insertion system
  - Gradient test to 30+ MV/m on the cathode surface
  - Hopefully will be extended to include beam generation w/ semiconductor photocathode

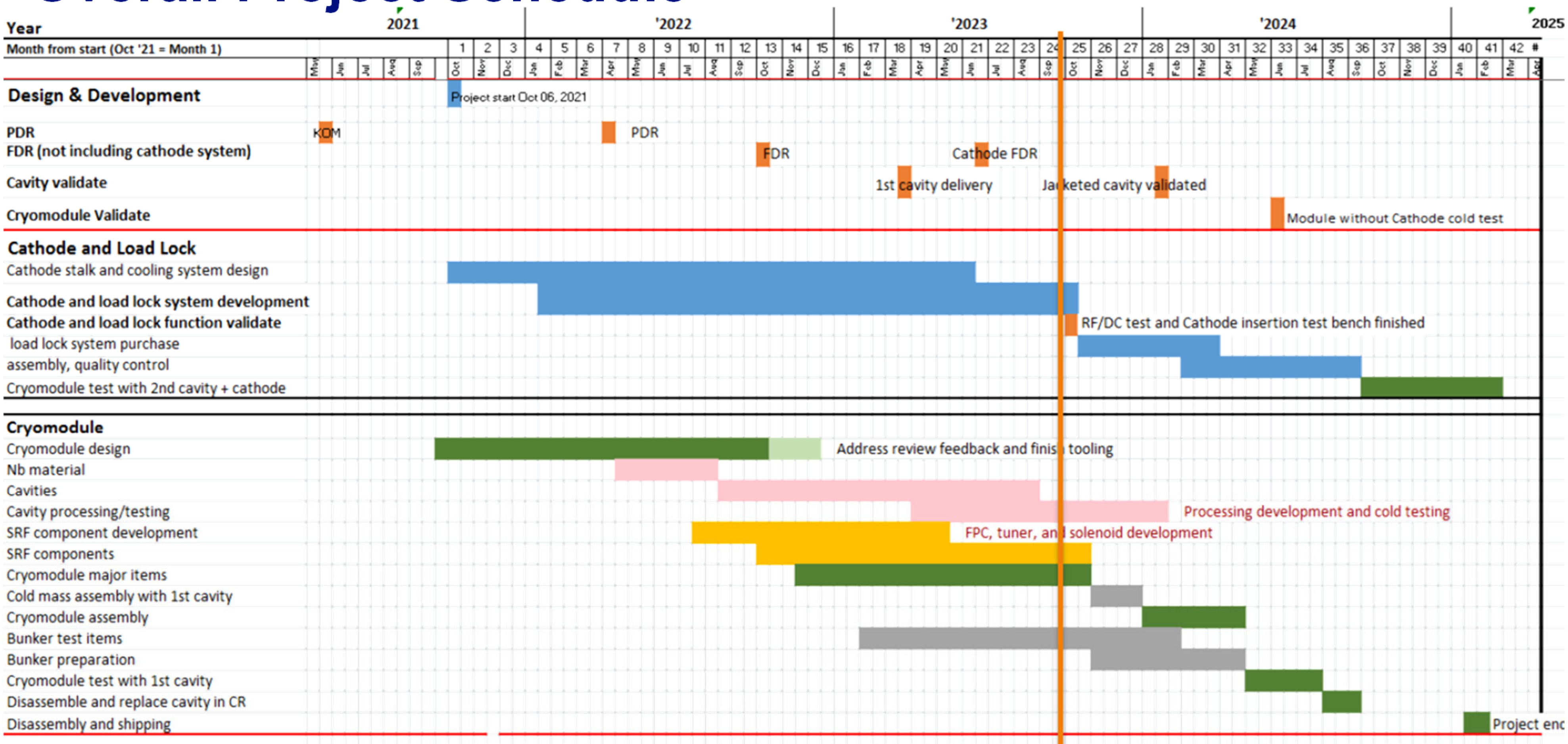


SRF Gun Cavity and Cathode Stalk

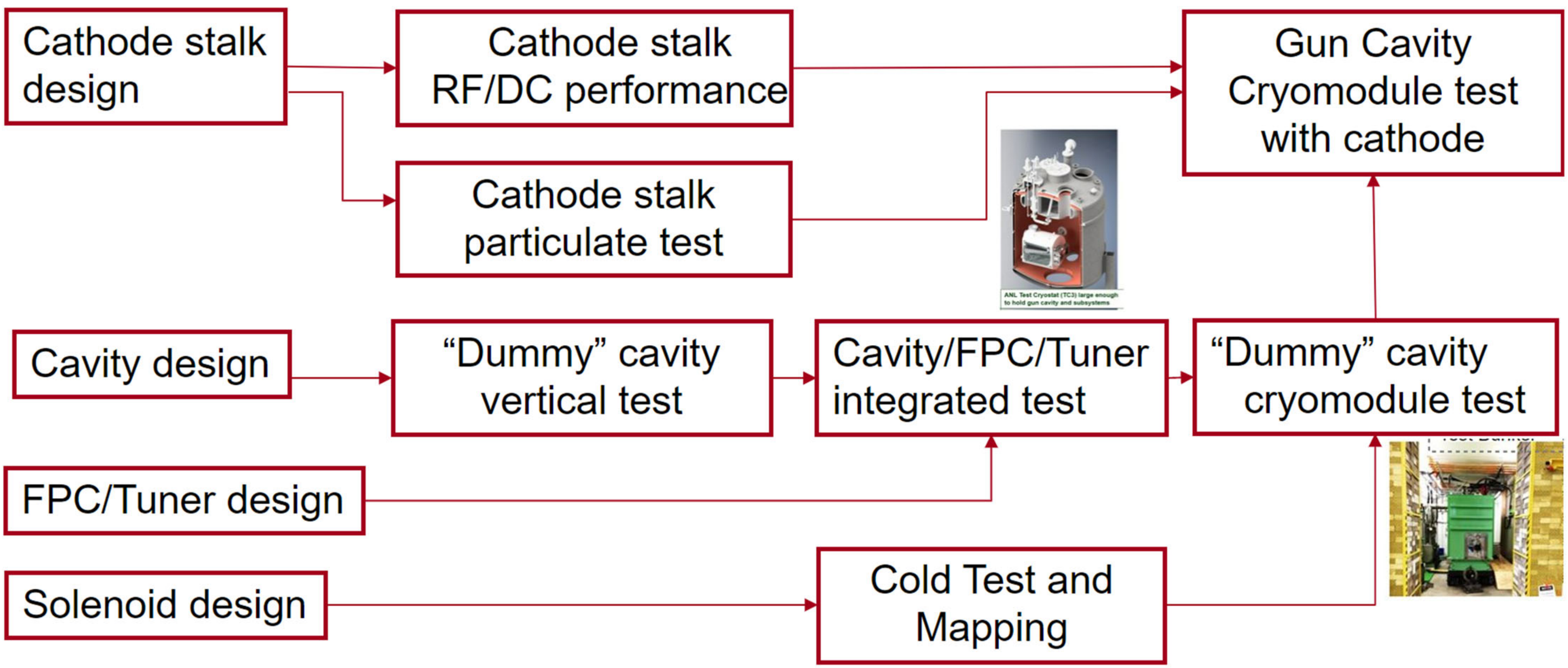




Overall Project Schedule



SRF Gun R&D: Development Process, Risk Mitigation



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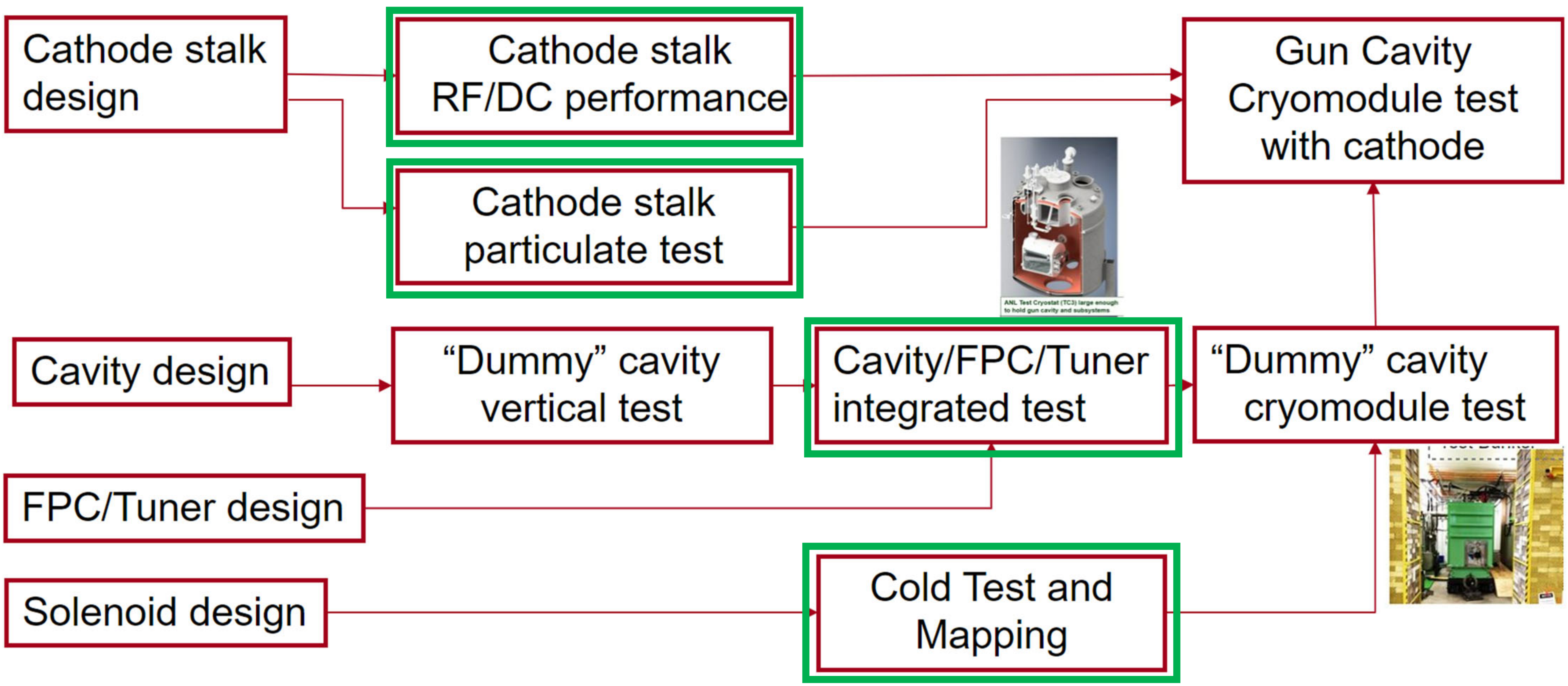


In-Process

“Blank” cavity He jacket stackup

Horizontal test @ ANL

Image courtesy M. Kelly, ANL

Cathode stalk DC/RF test stand

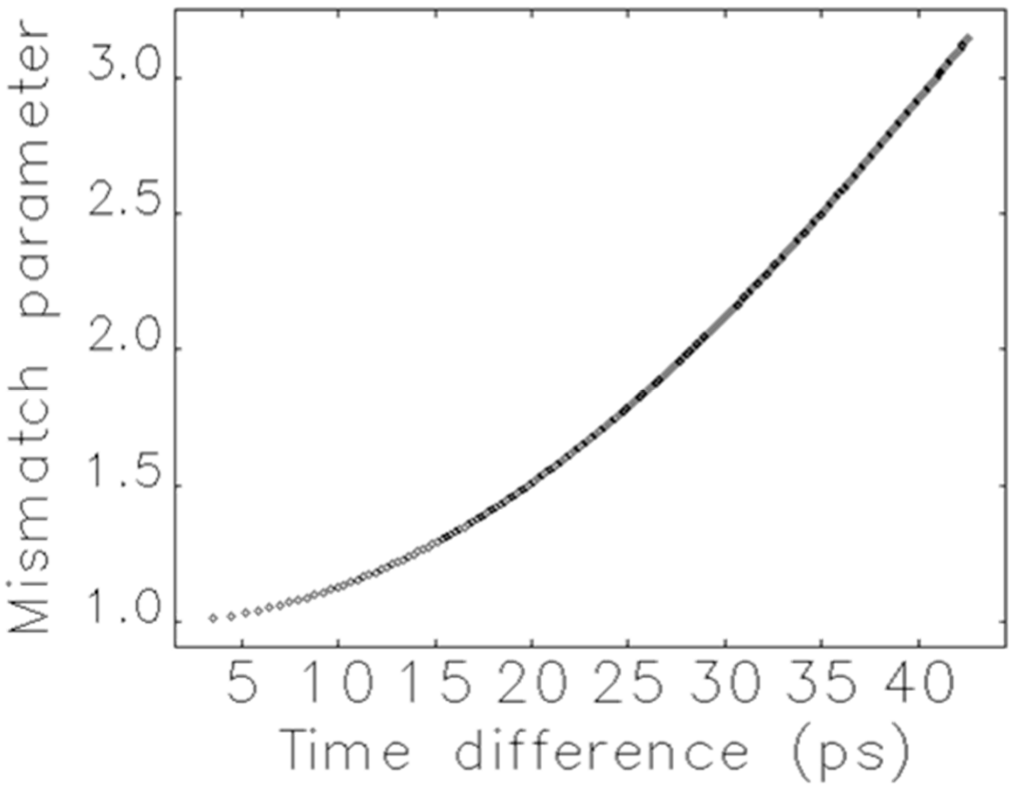
Conclusions

- High-gradient, n.5-cell guns are quite mature; specific designs being generated for UED/UEM now
- VHF-type guns are still relatively new and few, NCRF and SRF; but progress very encouraging!
  - VHF-type guns pretty much designed as FEL injectors, so, further tailoring performance is a real possibility.
- CW guns arguably require more infrastructure than pulsed, but in return may offer expanded performance envelopes along several axes.
  - Variable pulse timing seems interesting, but needs further study, e.g. dealing with time-varying downstream elements (energy gain, buncher, etc.)

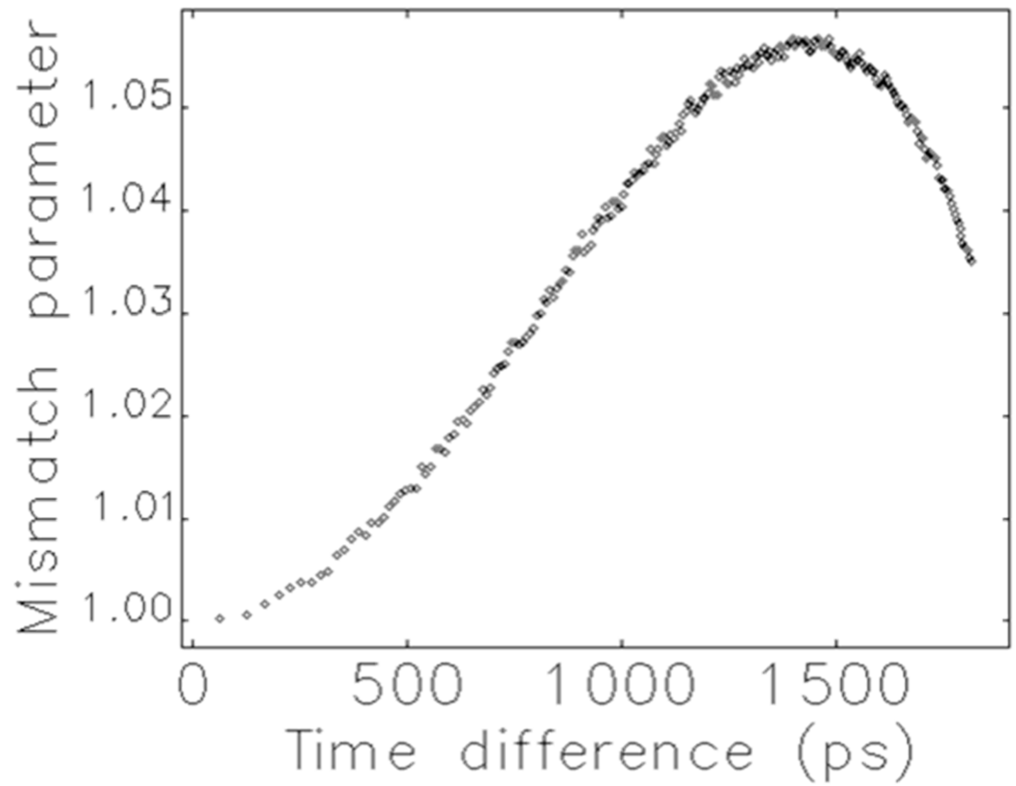
Backup Slides

Mismatch vs. Exit Time Difference

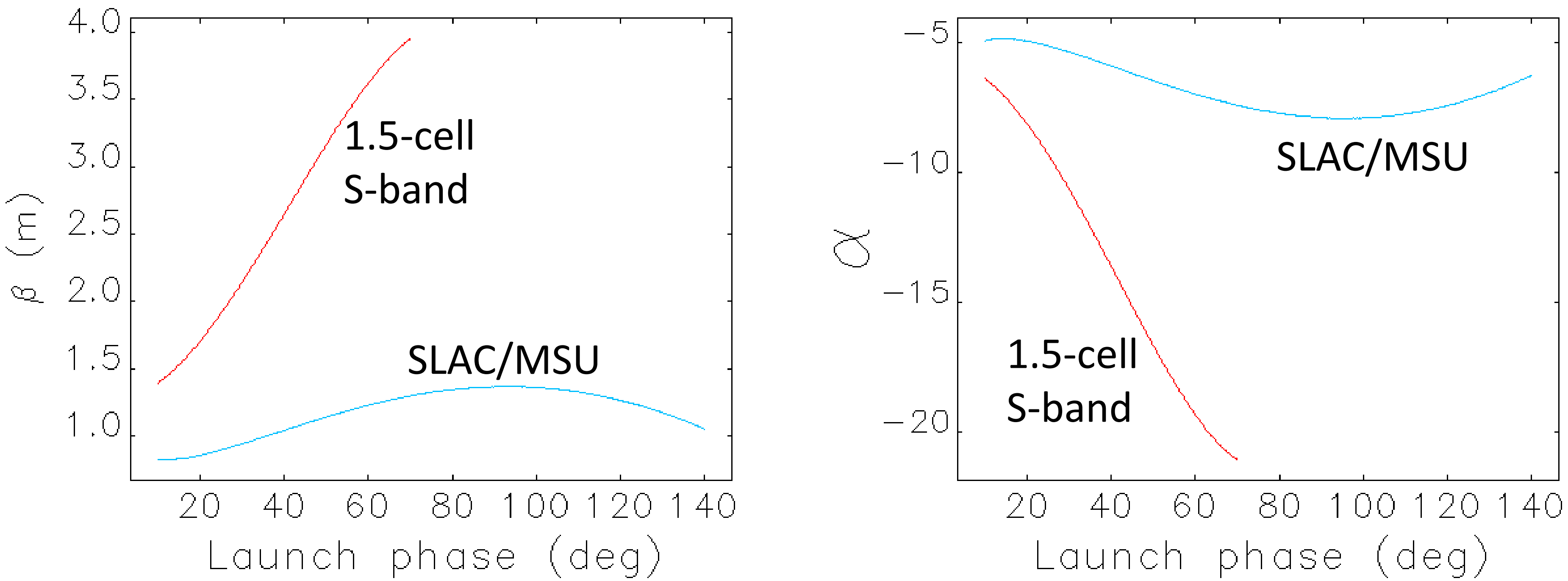
1.6-cell S-band, 100 MV/m



SLAC/MSU, 30 MV/m



Twiss parameters vs launch phase



Twiss parameters vs. beam energy