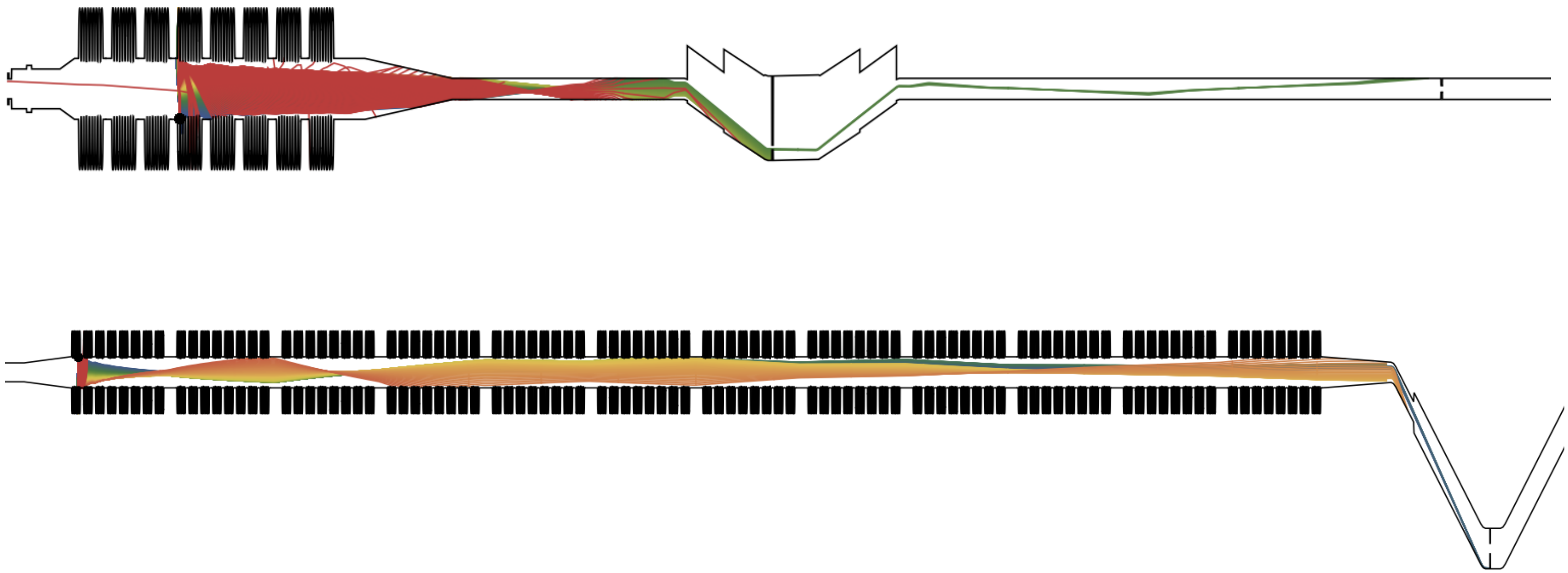
LCLS-II Dark Current



Christopher Mayes – September 16, 2015

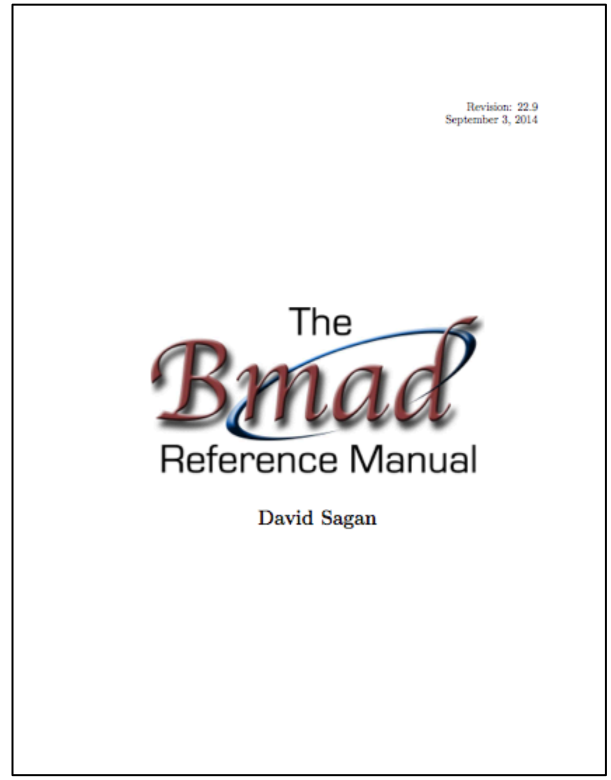
Bmad Overview

- Born at Cornell in mid 90's by David Sagan
- Initially used a subset of the MAD lattice syntax. Hence the name: "Baby MAD" or "Bmad" for short.
- Written in Fortran. Object oriented from the ground up:

```
type (lat_struct) lat
call bmad_parser ('lat.bmad', lat)
```

- Has structure translation code for interfacing with C++
- MAD like lattice syntax
- Well documented:
    - 400 page manual
    - Code
- Under continuous development
- Open source:

http://www.lepp.cornell.edu/~dcs/bmad/



Bmad

Library currently has:

- ~1,000 routines
- ~100,000 lines of code

Routines can do:

- Spin tracking
- Tracking with coherent synchrotron radiation (CSR) with shielding
- Wakefields and HOMs
- Taylor maps
- Intra-beam scattering (IBS)
- Touschek scattering
- Frequency map analysis
- Dark current tracking
- X-ray tracking
- …

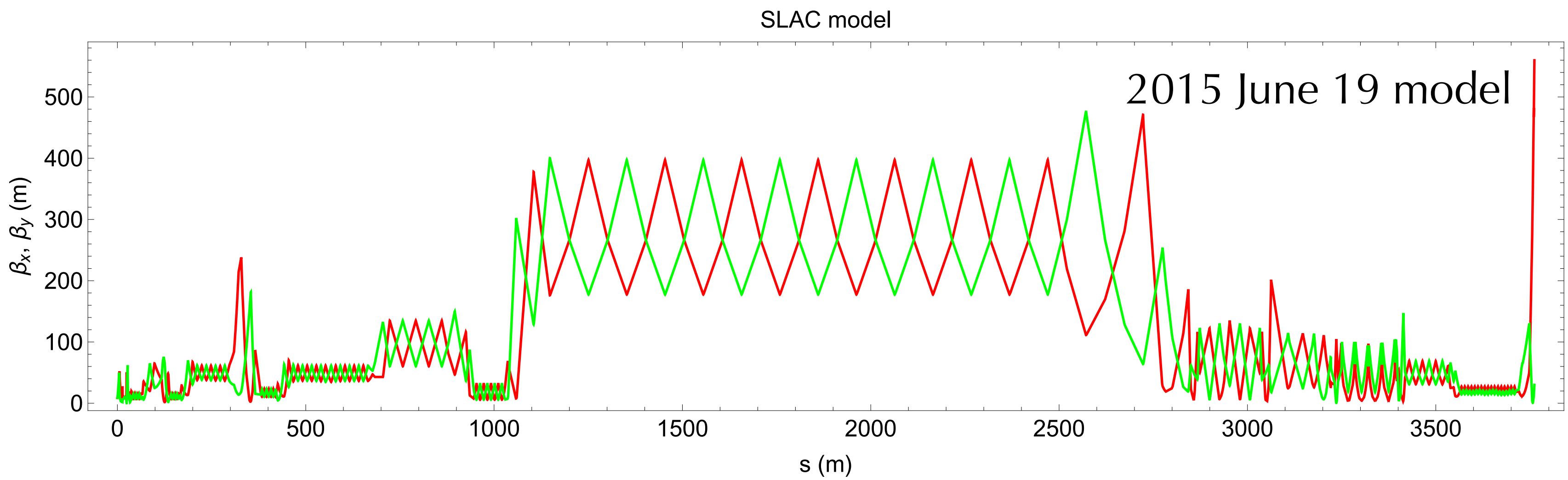
Lattice features

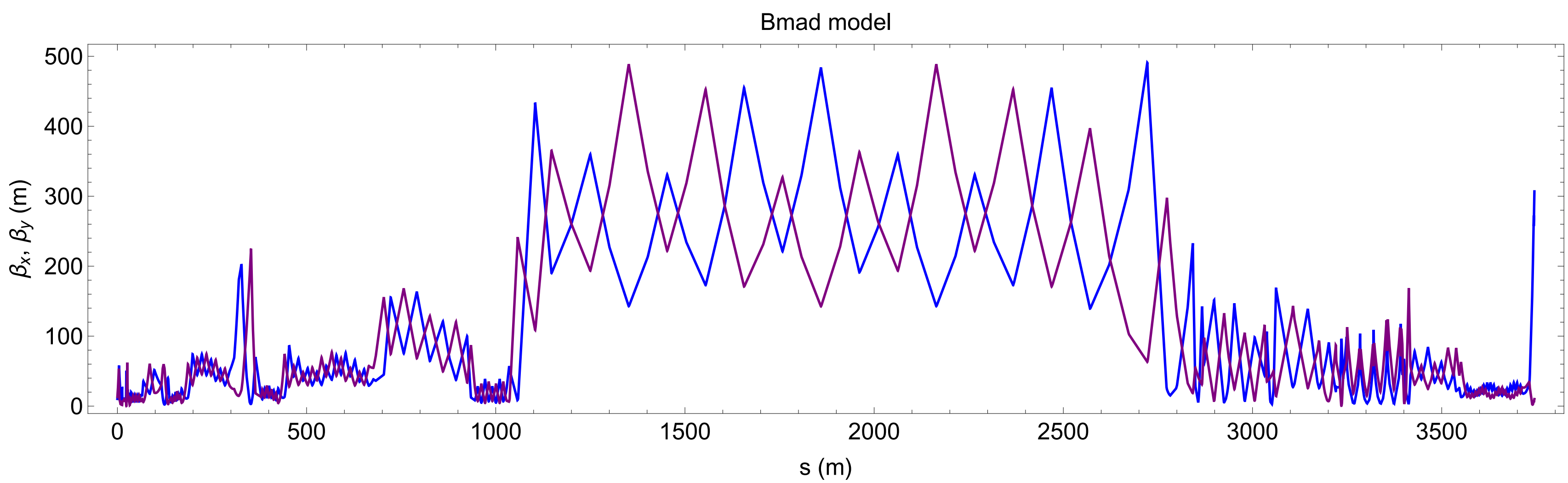
- Superposition – Define overlapping elements
- Controllers – Elements controlling attributes of other elements
- Forking – Joining lines together
- Multipass – Beamlines sharing common elements
- Element-by-element selection of the tracking method
- Custom elements and custom particle tracking
- Chamber walls

Lattice transcription

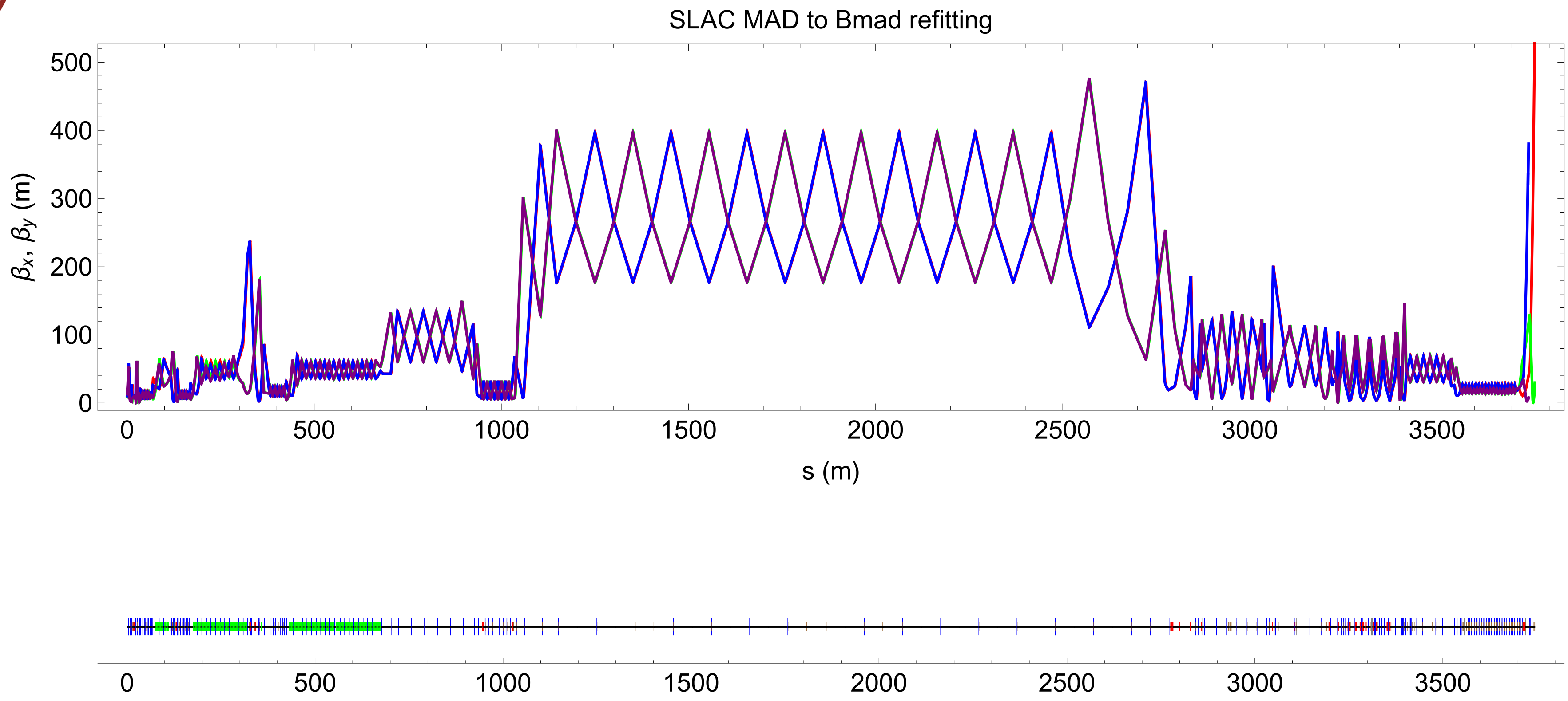
- Lattice translation between Bmad, XSIF, MAD, and SAD
- One way translation to: Astra, OPAL, GPT

SLAC MAD to Bmad translation





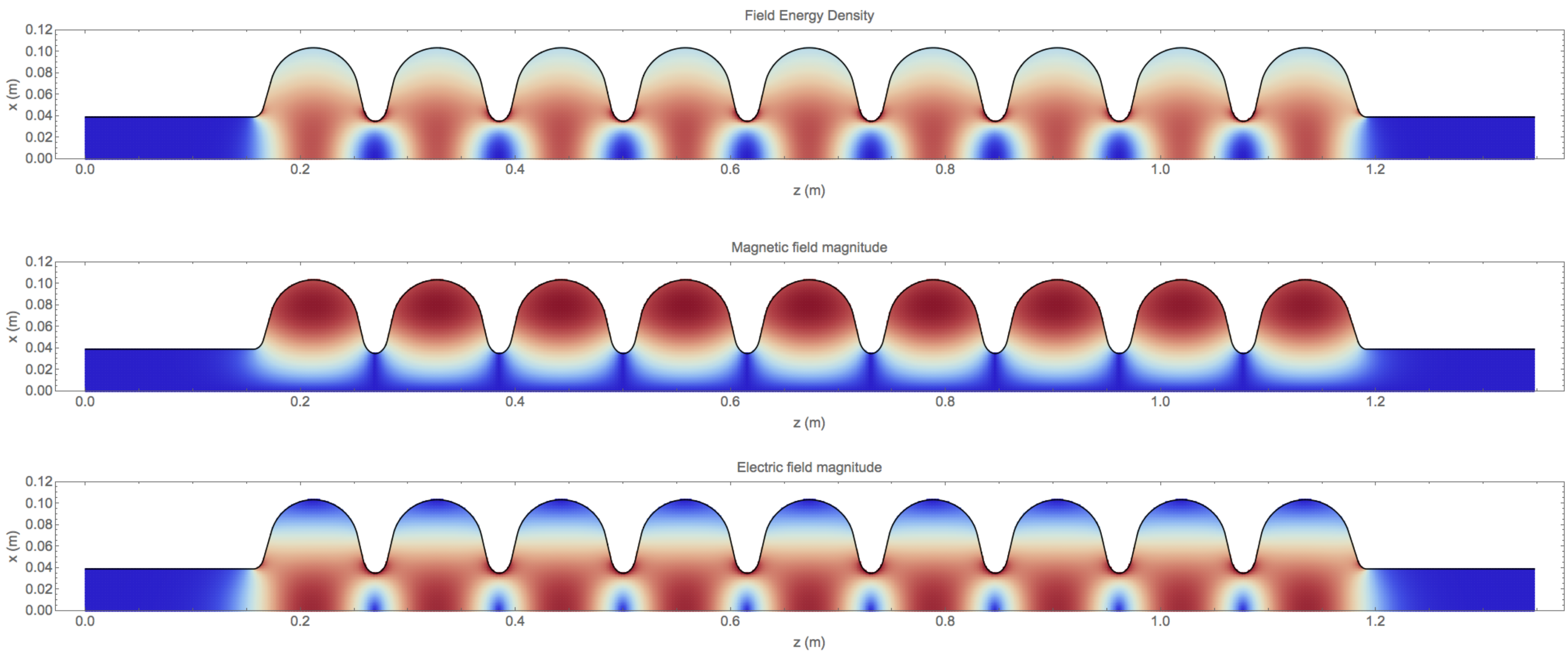
…Refitting



- The discrepancies are due to different cavity focusing models.
- Adjusting 5 quads (< 20% levels) at the ends of L1, L2, and L3 resolves this.
- All other element strengths/values are unchanged
- Dispersion (not shown) agree perfectly

9-cell cavity fields

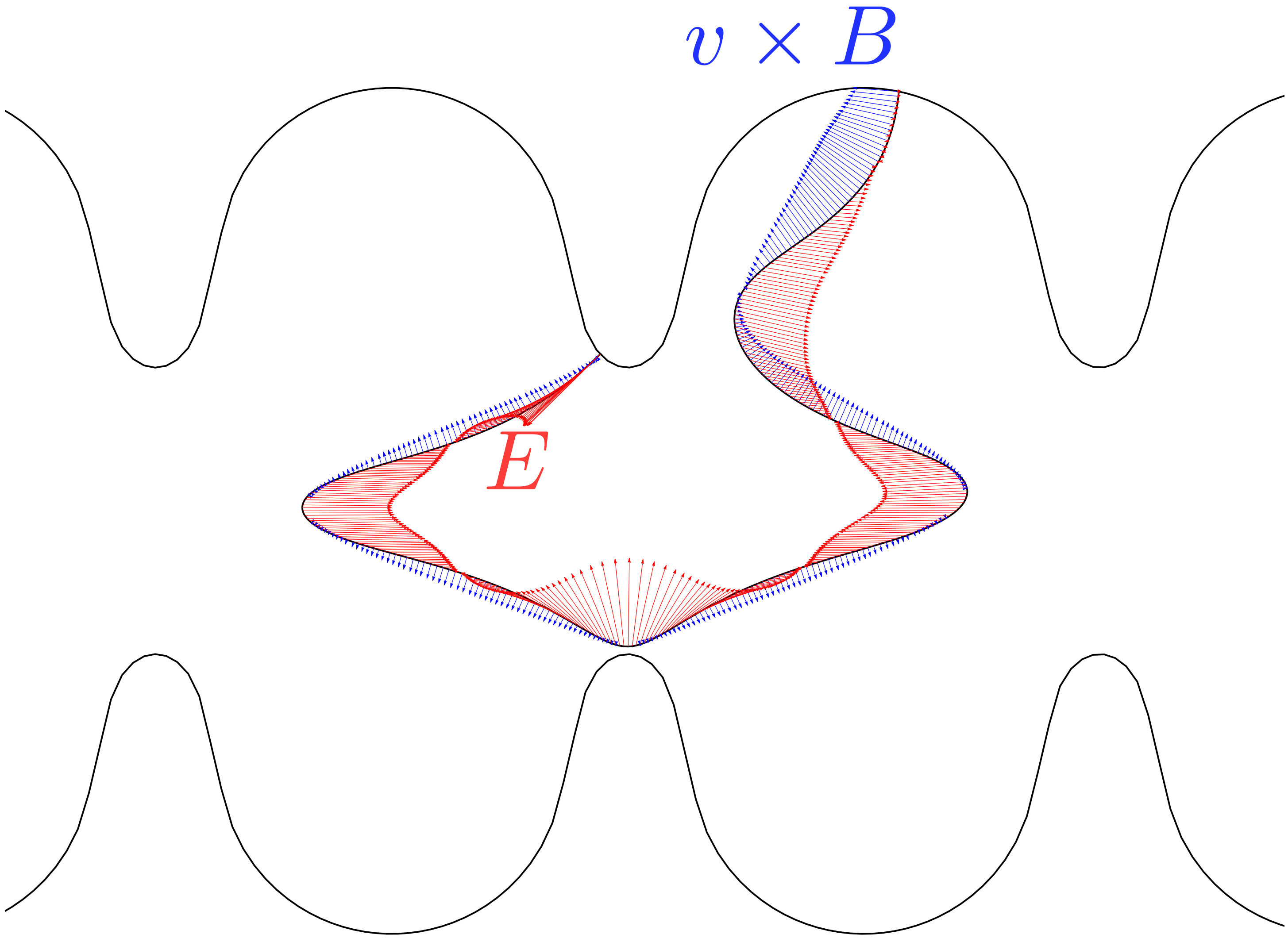
- Cylindrically symmetric data on 1 mm x 1 mm grid
- Wall shape



[data from Valery Shemlin using CLANS]

Bmad time tracking

- `time_runge_kutta` tracking method
- 3D wall shape



Bmad standard vs. field integration matrix

- Bmad standard vs. runge kutta tracking matrix computation are practically identical (<1% difference).
- No refitting was necessary.
- SLAC should consider using this.

Bmad manual

19.13 Lcavity Tracking

The transverse trajectory through an `Lcavity` is modeled using equations developed by Rosenzweig and Serafini[Rosen94] (R&S) with

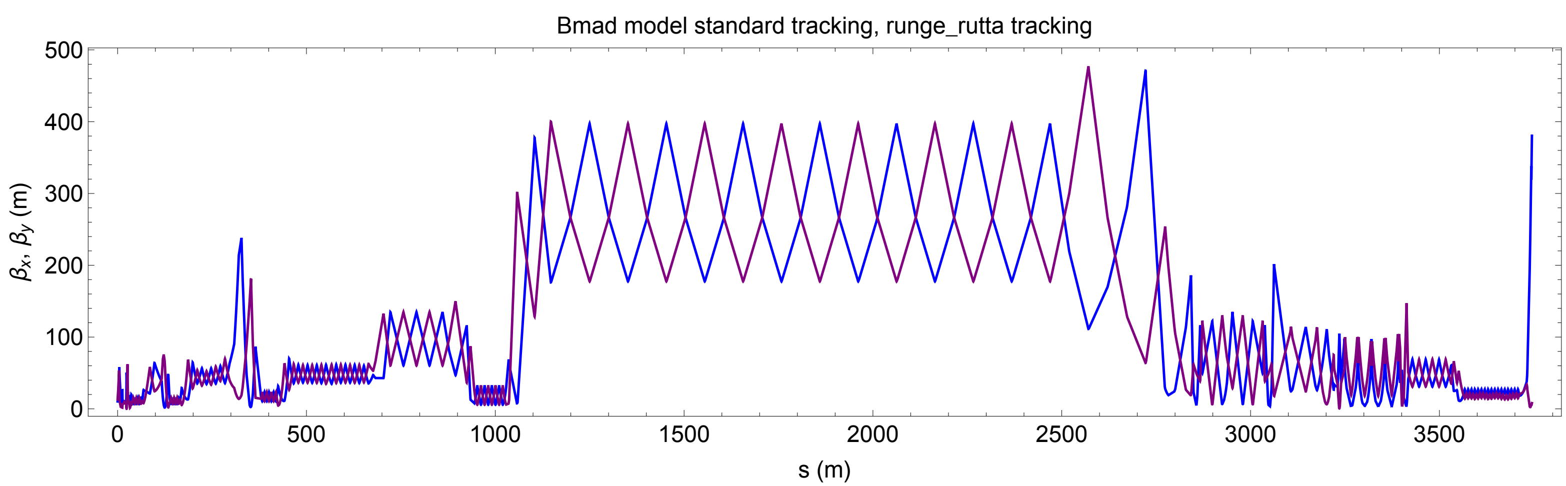
$$b_0 = 1$$
$$b_{-1} = 1 \qquad (19.72)$$

and all other b_n set to zero.

The transport equations in R&S were developed in the ulta-relativistic limit with $\beta = 1$. To extend these equations, the transport through the cavity body (R&S Eq. (9)) has been modified to give the correct phase-space area at non ultra-relativistic energies:

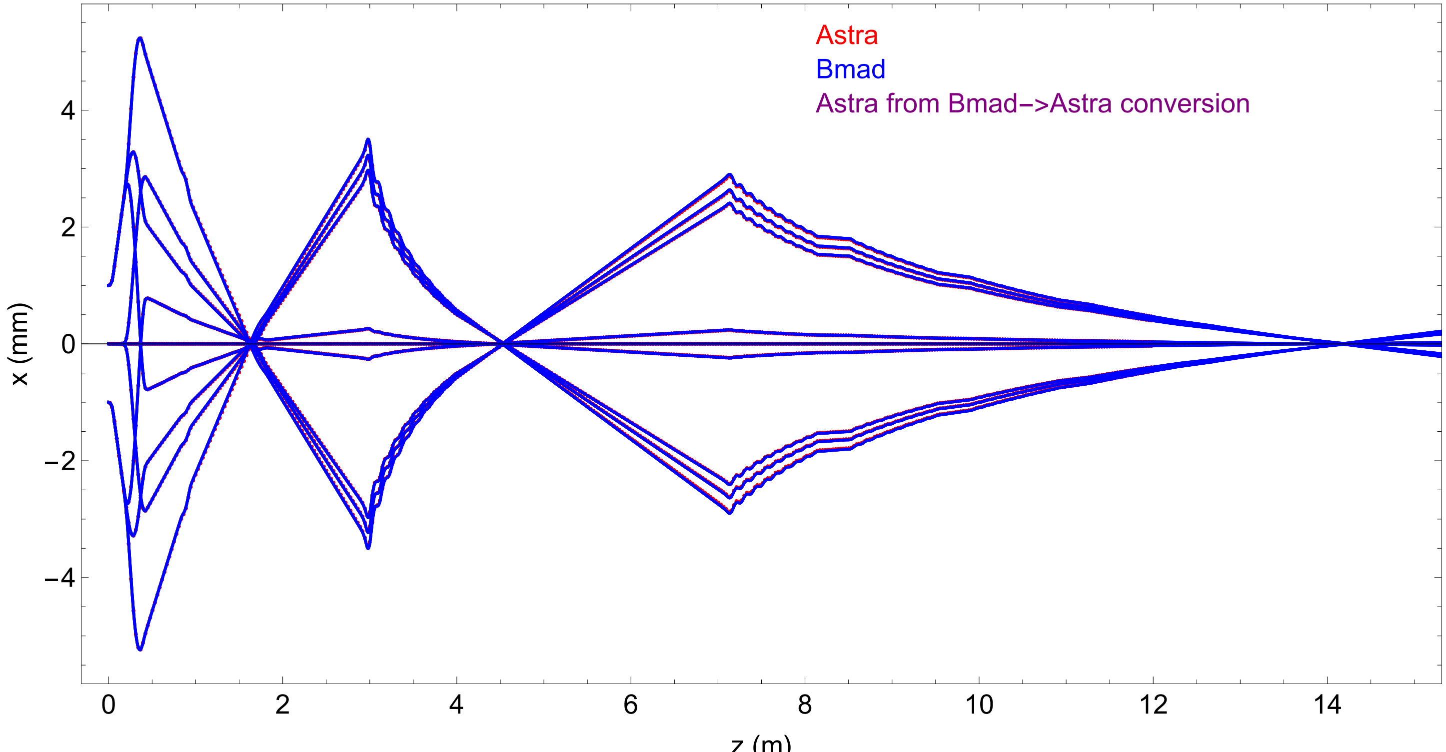
$$\begin{pmatrix} x \\ x' \end{pmatrix}_2 = \begin{pmatrix} \cos(\alpha) & \sqrt{\frac{8}{\eta(\Delta\phi)}} \frac{\beta_1 \gamma_1}{\gamma'} \cos(\Delta\phi) \sin(\alpha) \\ -\sqrt{\frac{\eta(\Delta\phi)}{8}} \frac{\gamma'}{\beta_2 \gamma_2 \cos(\Delta\phi)} \sin(\alpha) & \frac{\beta_1 \gamma_1}{\beta_2 \gamma_2} \cos(\alpha) \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_1 \qquad (19.73)$$

The added factors of β give the matrix the correct determinate of $\beta_1 \gamma_1 / \beta_2 \gamma_2$. *While the added factors of β do correct the phase space area, the above equation can only be considered as a rough approximation for simulating particles when β is significantly different from 1. Indeed, the only accurate way to simulate such particles is by integrating through the actual field [Cf. Runge Kutta tracking (§5.1)]*

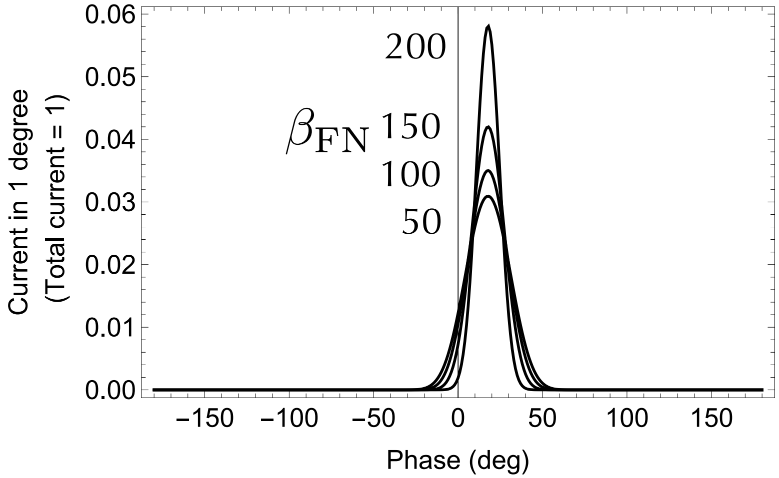


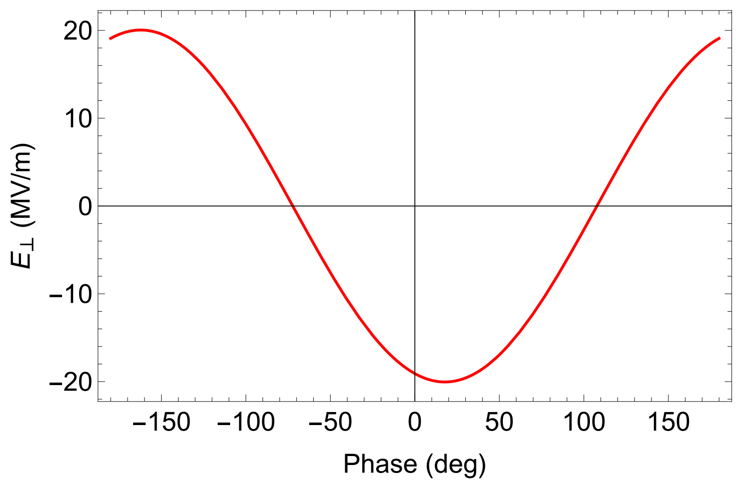
Injector (INJ) model

- The reference model is the optimized ASTRA 300 pC injector, ‘newbaseline300.in’, courtesy of Feng Zhou
- All field maps were converted to Bmad’s format. An equivalent Bmad model was written.
- Bmad has a Bmad->Astra conversion program. This is used to verify that the two models are the same.
- Quads before HTR are tweaked to accept the space charge dominated beam out of the injector, so that the start-to-end LCLS2 model is realistic



Field emitter current





The instantaneous current is given by the Fowler-Nordheim equation:

$$I_{\mathrm{FN}}\left(E_\perp\right) = a_0\, A_{\mathrm{FN}}\left(\beta_{\mathrm{FN}} E_\perp\right)^2 \exp\left(-\frac{a_1}{\beta_{\mathrm{FN}} E_\perp}\right)$$

For Niobium,

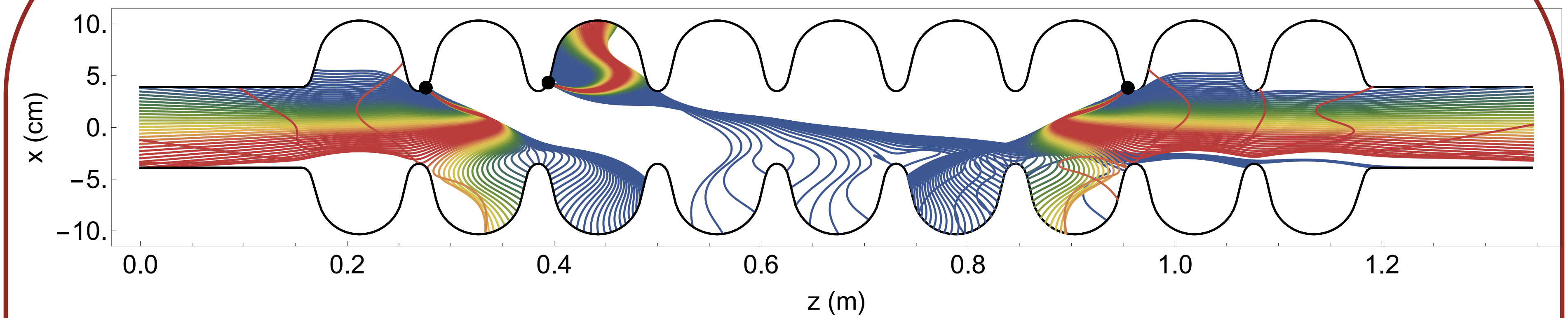
$$a_1 = 5.464 \times 10^{10}\ \mathrm{V/m}$$

[H. Padamsee, RF Superconductivity, p. 94]

The field enhancement factor β_{FN} is determined empirically. We use a value of 100 in these simulations.

a_0 sets the total average current

Field emitter tracking



- Locate a position on the cavity wall
- Sample the field normal $E_\perp$ at even intervals over 1 rf period
- Create particles at this position at these times, with weights determined by the Fowler-Norheim equation.
- Only accept particles where $qE_\perp > 0$
- For simplicity, normalize weights to sum to 1
- Track each particle until lost at the wall

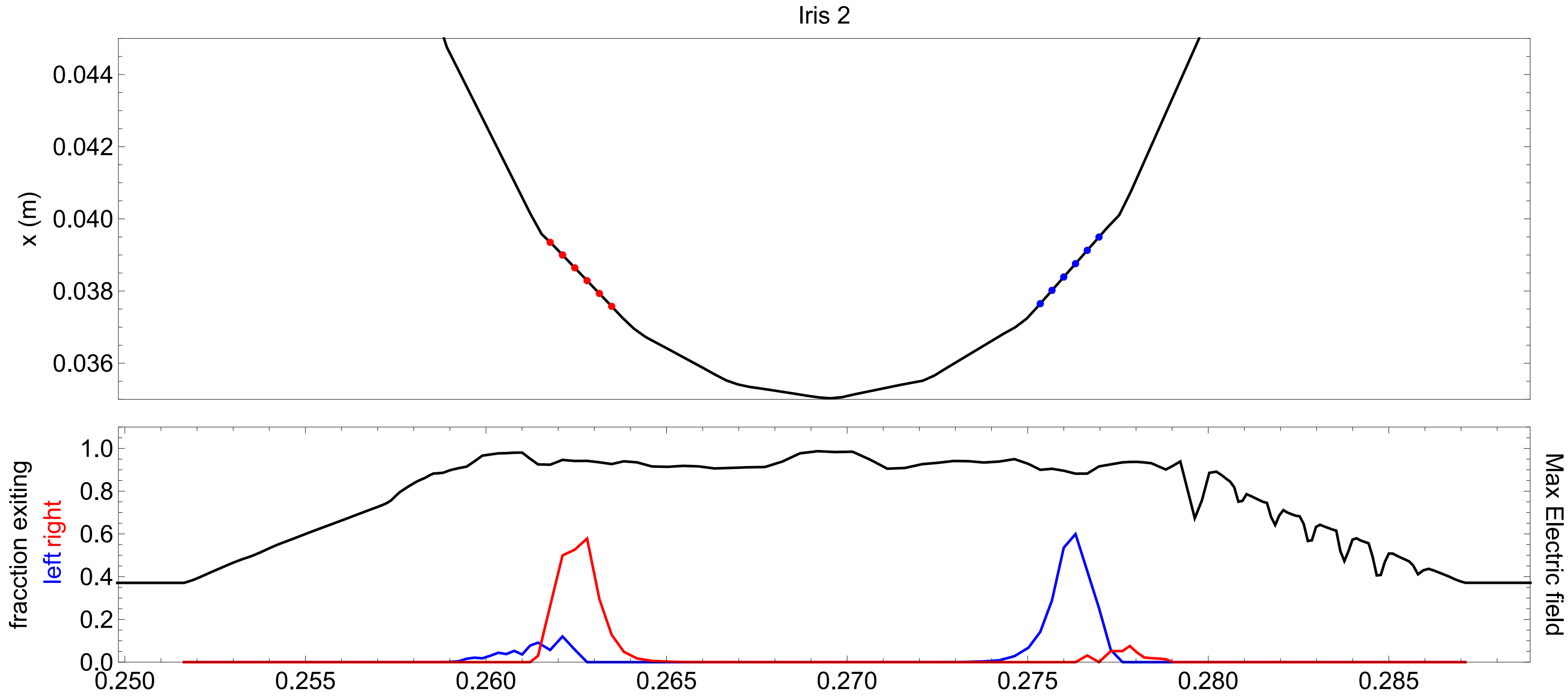
Field emitter iris scan

Total cavity voltage: 15 MV.
Fowler-Nordheim field enhancement factor (beta): 100.
Each track represents charge from 1 degree of the rf period.
Red is more charge.

https://www.youtube.com/watch?v=xjRR7xE6MXc

Danger Zones

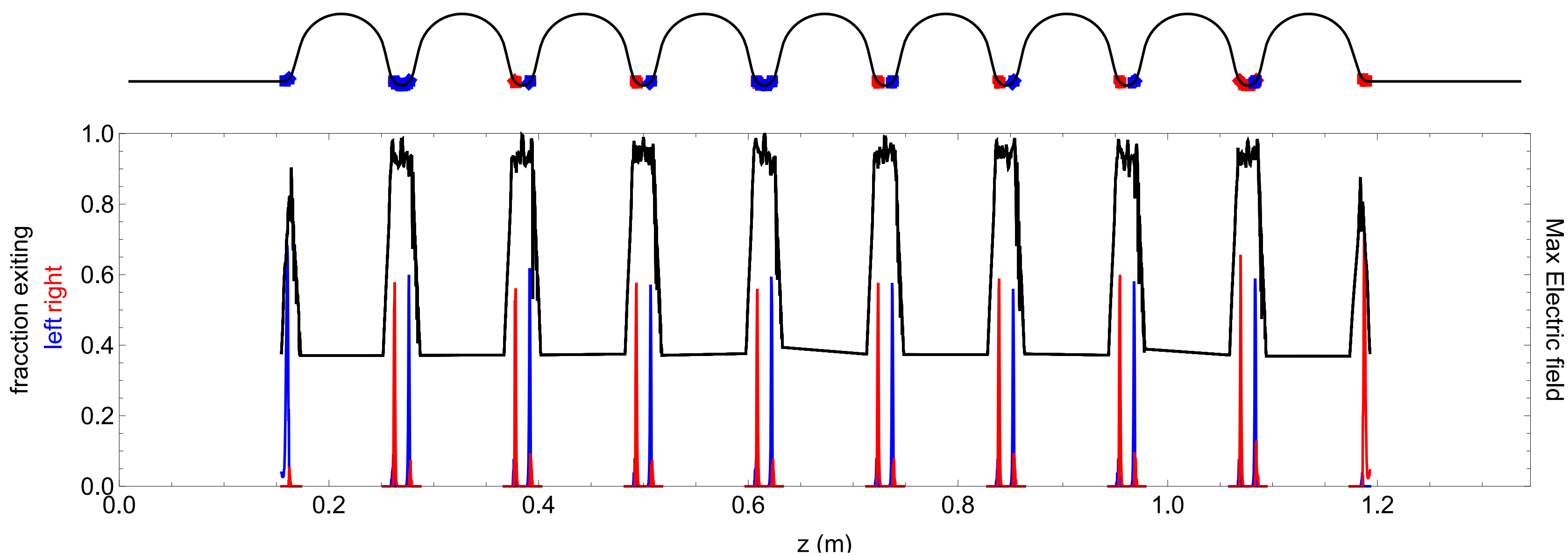
Only very small regions on the cavity wall can harbor field emitters that produce particles that can escape the cavity.



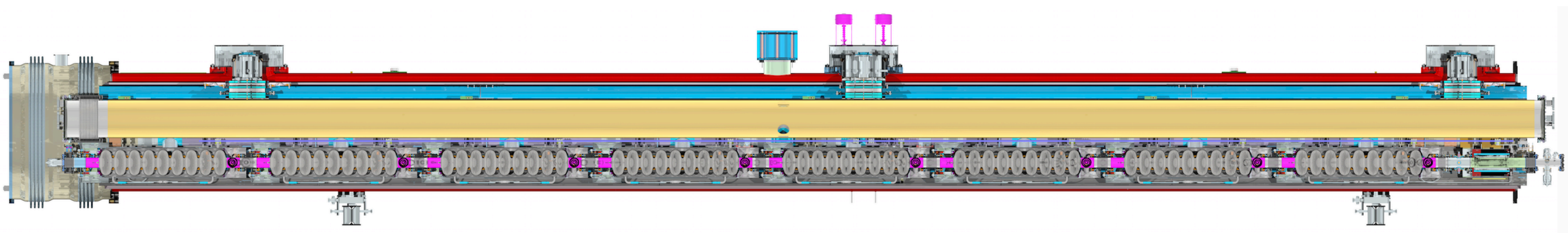
Danger Zones

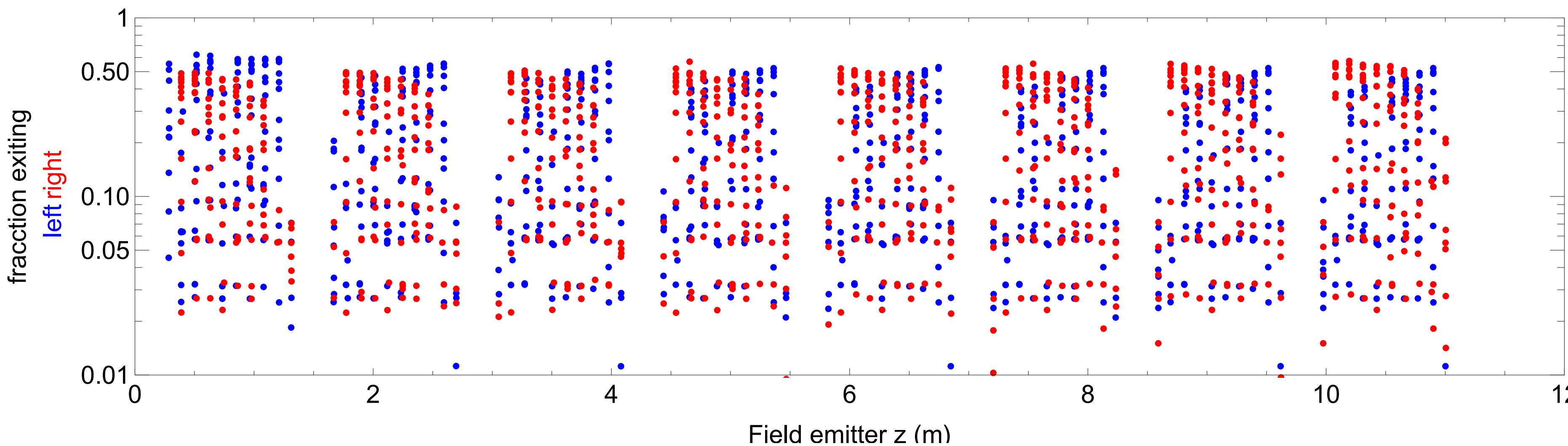
Only very small regions on the cavity wall can harbor field emitters that produce particles that can escape the cavity.

All irises exhibit roughly this same pattern.
We save time, we only track from danger zone field emitters.

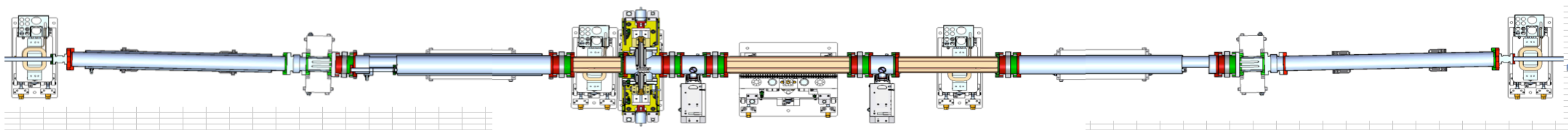


LCLS2 Cryomodule

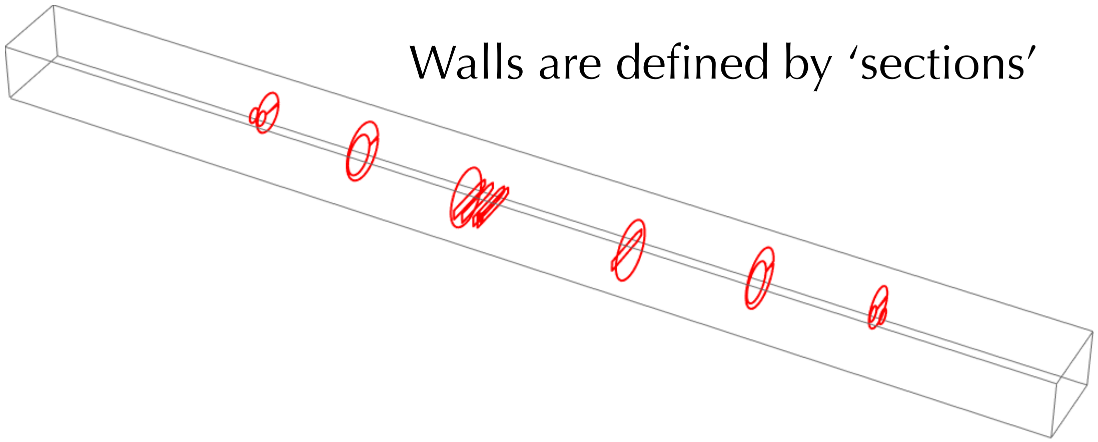




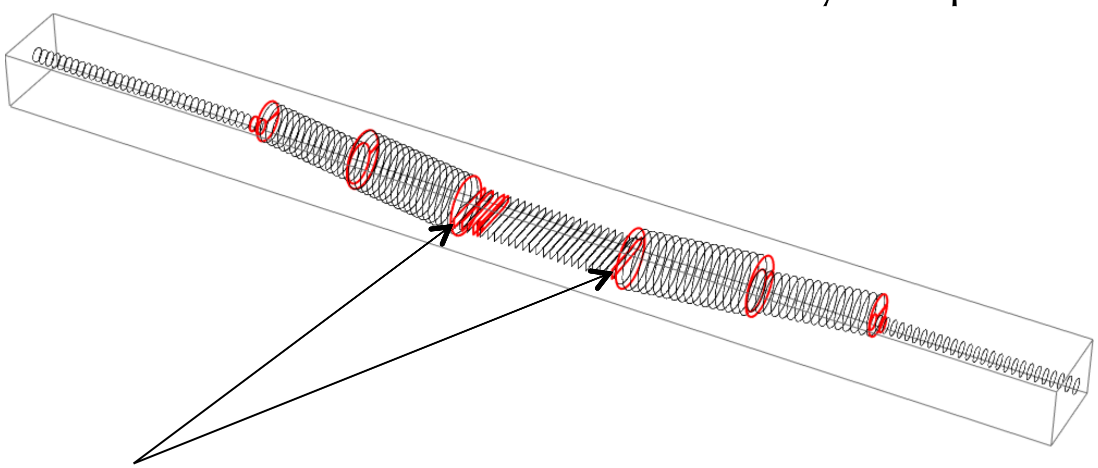
Bmad wall example: HTR chicane



Walls are defined by ‘sections’



The wall between sections is found by interpolation

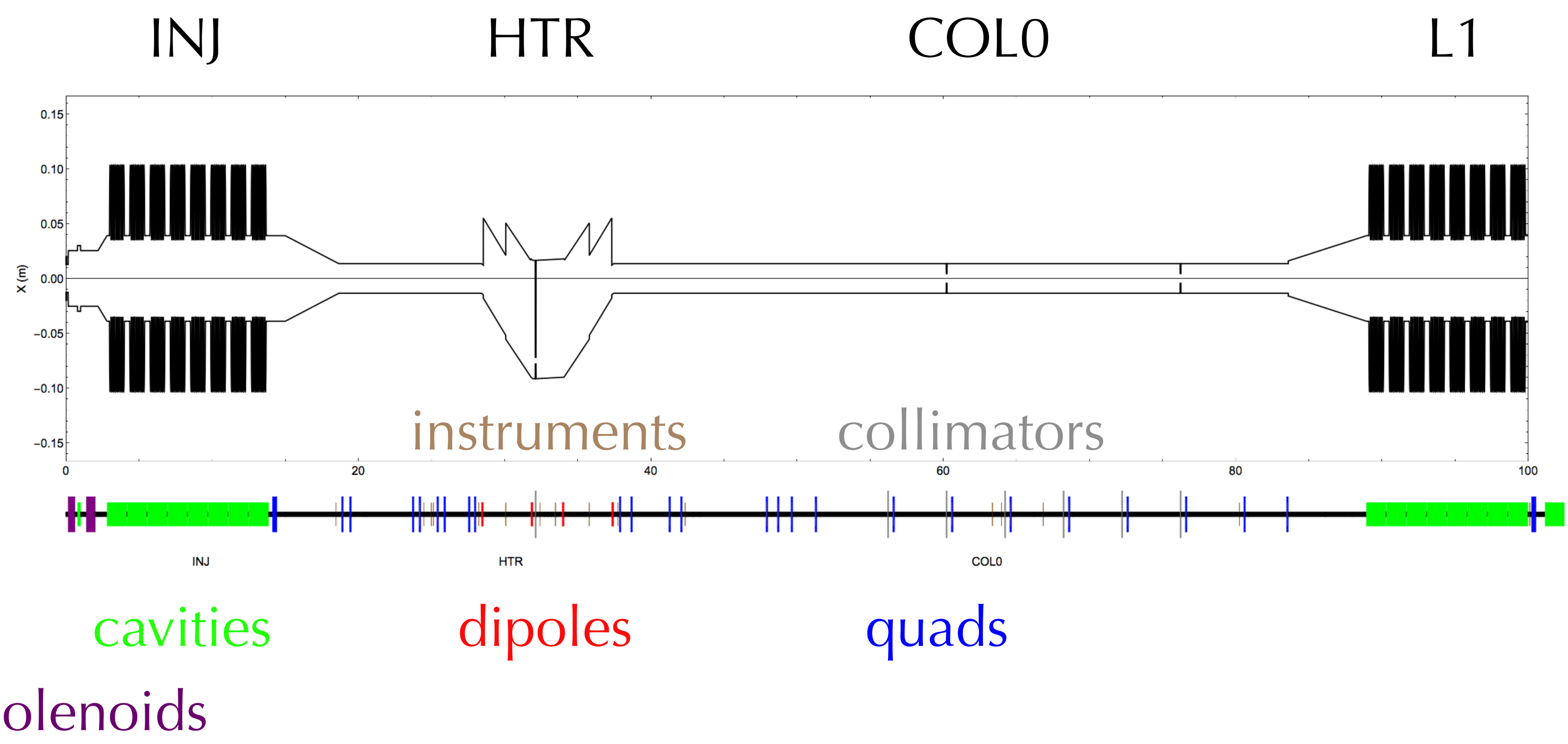


‘mask’ elements are placed to simulate this special case of two pipes

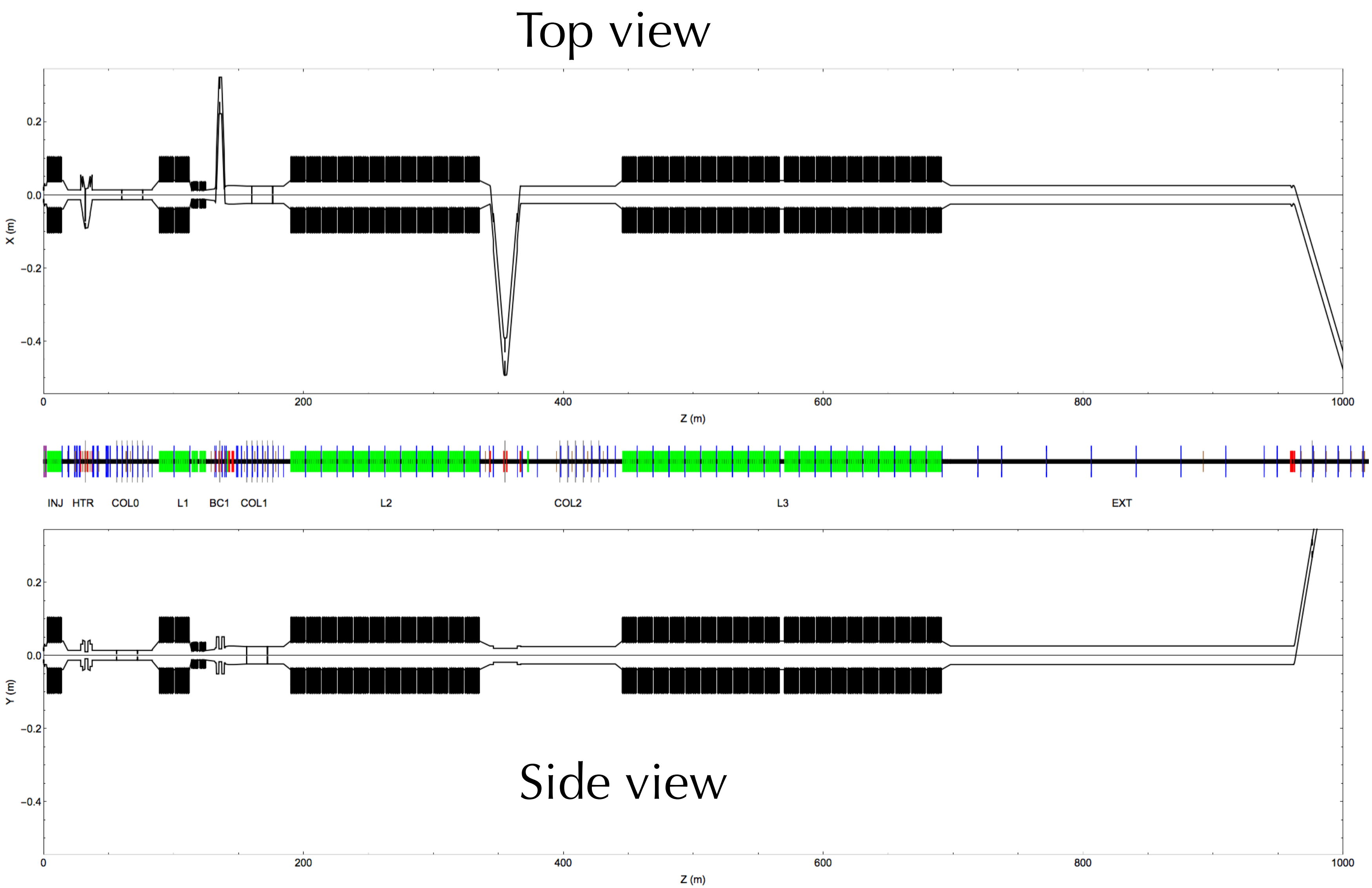
wall definition file

```
! First pipe
DH01A[wall]= {
  section = {s = 0, v(1) = {HTR_ROUND_PIPE_OFFSET, 0, HTR_ROUND_PIPE_R}},
  section = {s = DH01A[L], v(1) = {HTR_ROUND_PIPE_OFFSET, 0, HTR_ROUND_PIPE_R}}}


! Second pipe
HTR_SECOND_PIPE_R =  (106e-3)/2
HTR_SECOND_PIPE_OFFSET_1 = HTR_ROUND_PIPE_OFFSET +13e-3
HTR_SECOND_PIPE_OFFSET_2 = HTR_ROUND_PIPE_OFFSET +16.5e-3
DH01B[wall]= {section = {s = 0, v(1) = {HTR_SECOND_PIPE_OFFSET_1, 0, HTR_SECOND_PIPE_R}}}


! Transition to dual-rectangular pipe (here one big pipe)
DH01C[wall]= {
section = {s = DH01C[L] -0.05, v(1) = {HTR_SECOND_PIPE_OFFSET_2, 0, HTR_SECOND_PIPE_R}},
section = {s = DH01C[L],
 v(1) = {HTR_x1-HTR_offset, HTR_y1},
 v(2) = {-HTR_x1, HTR_y1},
 v(3) = {-HTR_x1, -HTR_y1},
 v(4) = {HTR_x1-HTR_offset, -HTR_y1}}}

! Dual pipe mask
HTR_dual_pipe_mask: mask
HTR_mask_x1 = (29.83e-3)/2
HTR_mask_y1 = (19.05e-3)/2
HTR_dual_pipe_mask[wall] = {
! Laser heater section
section = {type = clear,
 v(1) = {HTR_mask_x1, HTR_mask_y1},
 v(2) = {-HTR_mask_x1, HTR_mask_y1},
 v(3) = {-HTR_mask_x1, -HTR_mask_y1},
 v(4) = {HTR_mask_x1, -HTR_mask_y1}},
! Straight-through section
section = {type = clear,
 x0 = -HTR_offset,
 v(1) = {HTR_mask_x1, HTR_mask_y1},
 v(2) = {-HTR_mask_x1, HTR_mask_y1},
 v(3) = {-HTR_mask_x1, -HTR_mask_y1},
 v(4) = {HTR_mask_x1, -HTR_mask_y1}}}

BCXH2A_mask: HTR_dual_pipe_mask, superimpose, ref = BCXH2A, ref_beg
BCXH3B_mask: HTR_dual_pipe_mask, superimpose, ref = BCXH3B, ref_end

! Bend 2
BCXH2B[wall] = {
section = {s = BCXH2B[L],
 v(1) = {HTR_x1-HTR_offset, HTR_y1},
 v(2) = {-HTR_x1, HTR_y1},
 v(3) = {-HTR_x1, -HTR_y1},
 v(4) = {HTR_x1-HTR_offset, -HTR_y1}}}



!--------------
CEHTR[wall] = {
section = {s = 0,
 v(1) = {HTR_x1-HTR_offset, HTR_y1},
 v(2) = {-HTR_x1, HTR_y1},
 v(3) = {-HTR_x1, -HTR_y1},
 v(4) = {HTR_x1-HTR_offset, -HTR_y1}},
section = {s = 0.006,
 v(1) = {0.003,  HTR_y1},
 v(2) = {-0.003,  HTR_y1},
 v(3) = {-0.003, -HTR_y1},
 v(4) = {0.003, -HTR_y1}},
section = {s = 0.054,
 v(1) = {0.003,  HTR_y1},
 v(2) = {-0.003,  HTR_y1},
 v(3) = {-0.003, -HTR_y1},
 v(4) = {0.003,  -HTR_y1}},
section = {s = 0.06,
 v(1) = {HTR_x1-HTR_offset, HTR_y1},
 v(2) = {-HTR_x1, HTR_y1},
 v(3) = {-HTR_x1, -HTR_y1},
 v(4) = {HTR_x1-HTR_offset, -HTR_y1}}}


! Bend 3
BCXH3B[wall] = {
section = {s = BCXH3B[L],
 v(1) = {HTR_x1-HTR_offset, HTR_y1},
 v(2) = {-HTR_x1, HTR_y1},
 v(3) = {-HTR_x1, -HTR_y1},
 v(4) = {HTR_x1-HTR_offset, -HTR_y1}}}
```

Cathode to L1 wall

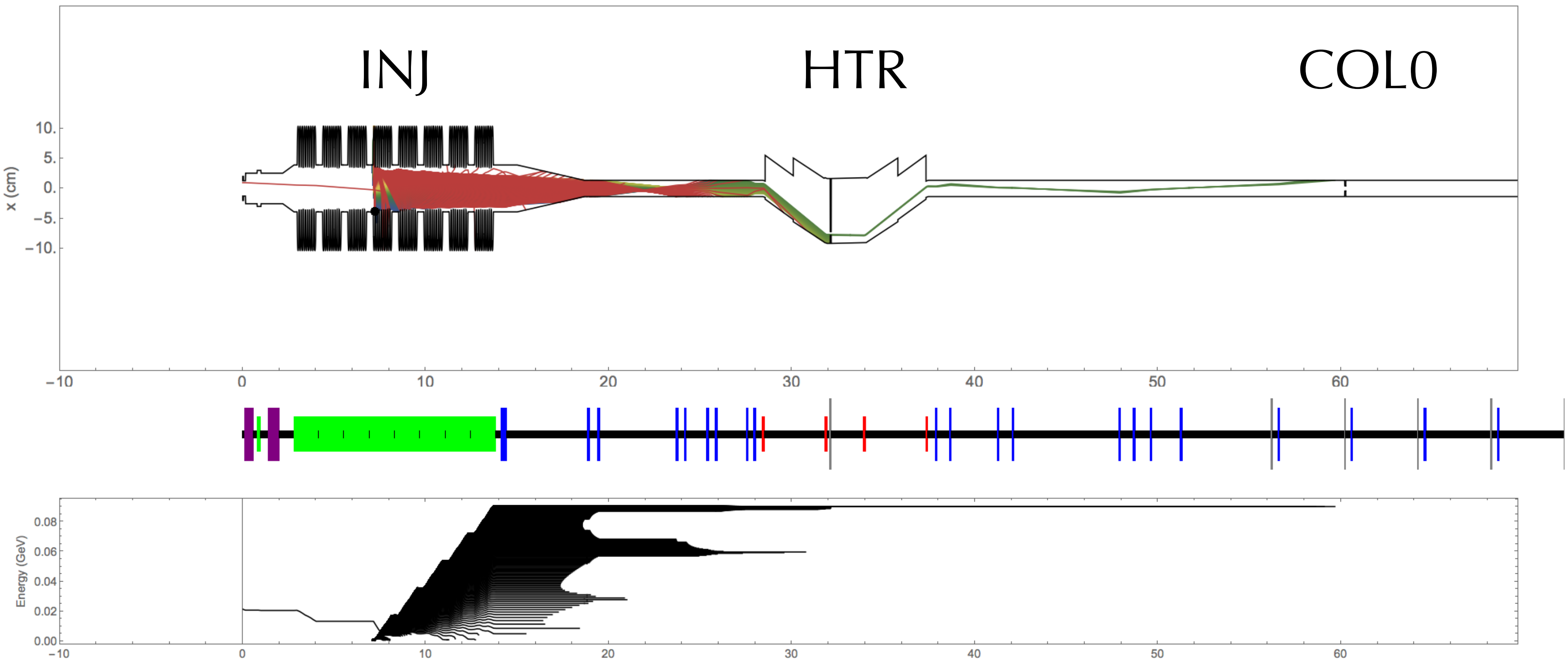


LCLS2scH 2015 June 19



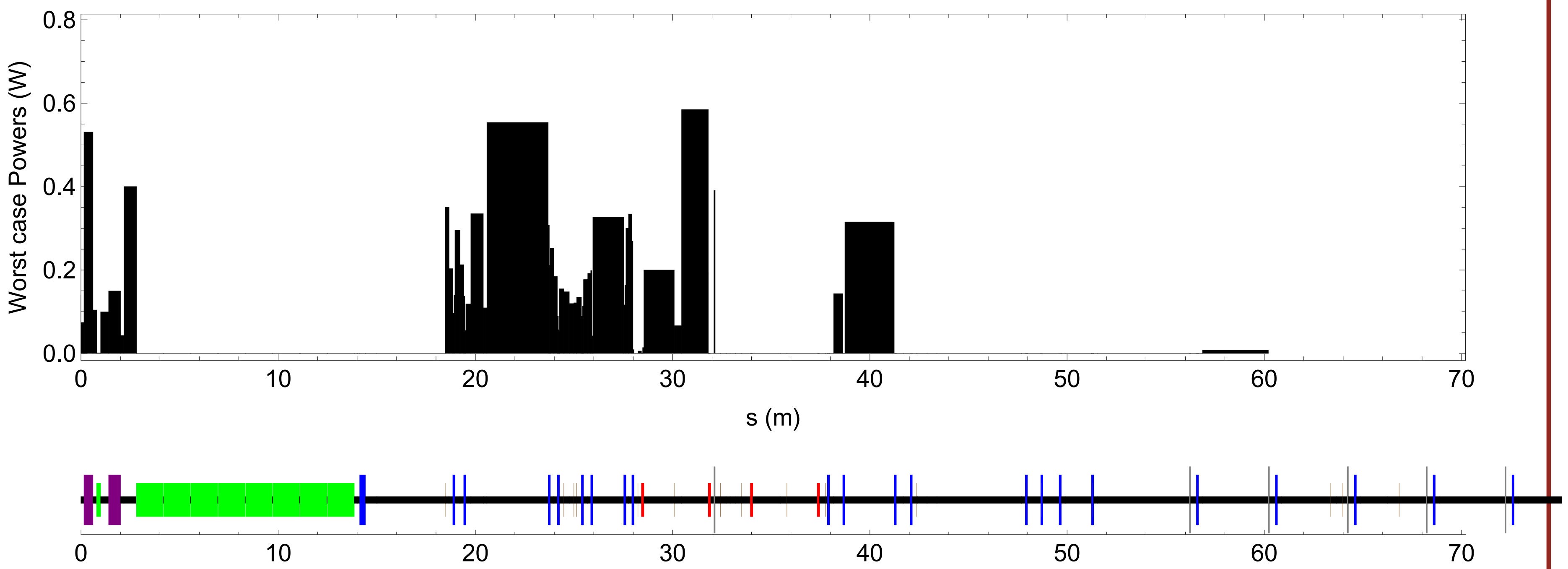
Cryomodule field emission tracking

- Field emitters are placed in danger zones, at random angles (~5000 emitters)
- For each emitter, particles are created and tracked (~1000 per emitter)
- Weights for particles escaping the crypmodule are renormalized to sum to 10 nA
- Power and current deposition are tallied per element



CM01 powers

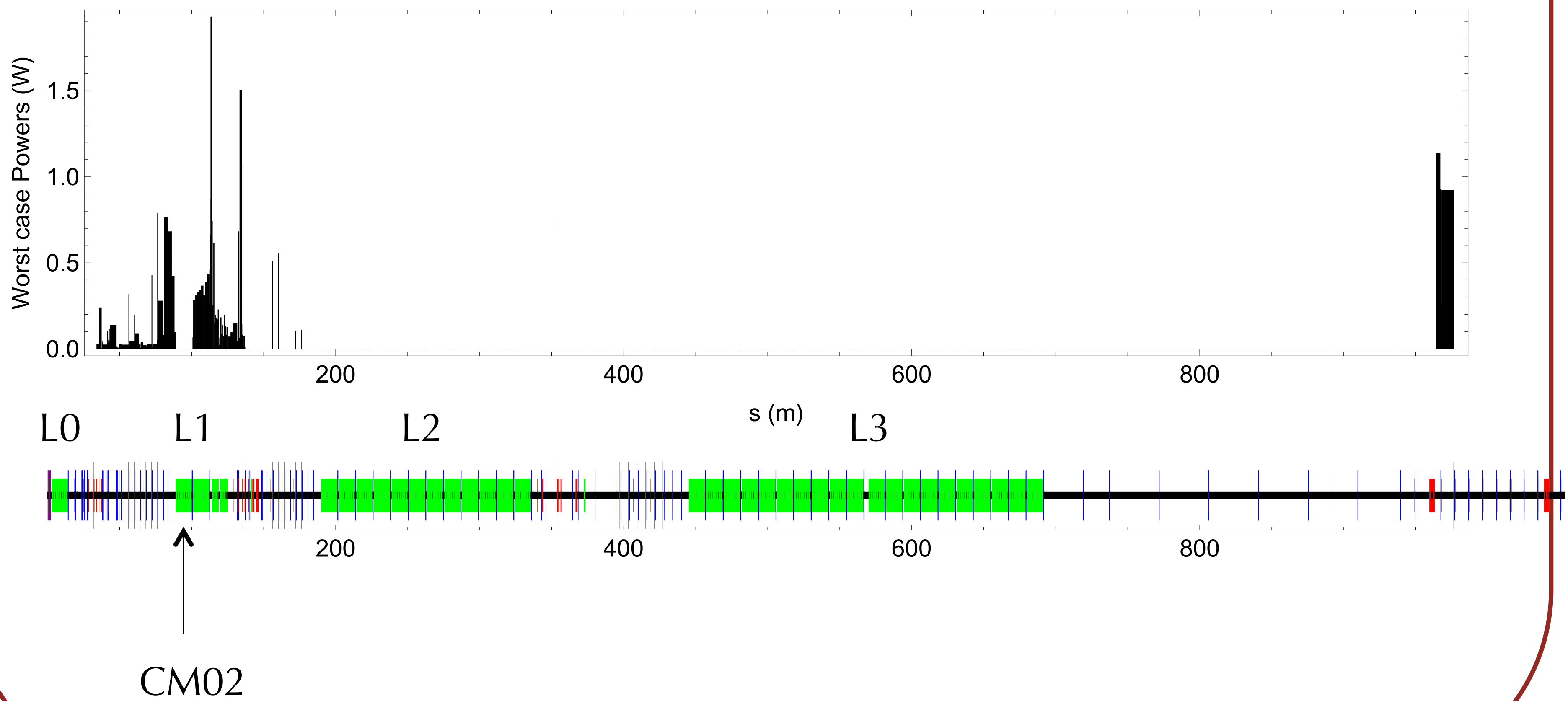
- Worst case power deposition due to a field emitter in CM01, per element.
- Losses inside CM01 are not plotted.
- The plot represents the full range of particles tracked. Here, no particle made it past 70 m.



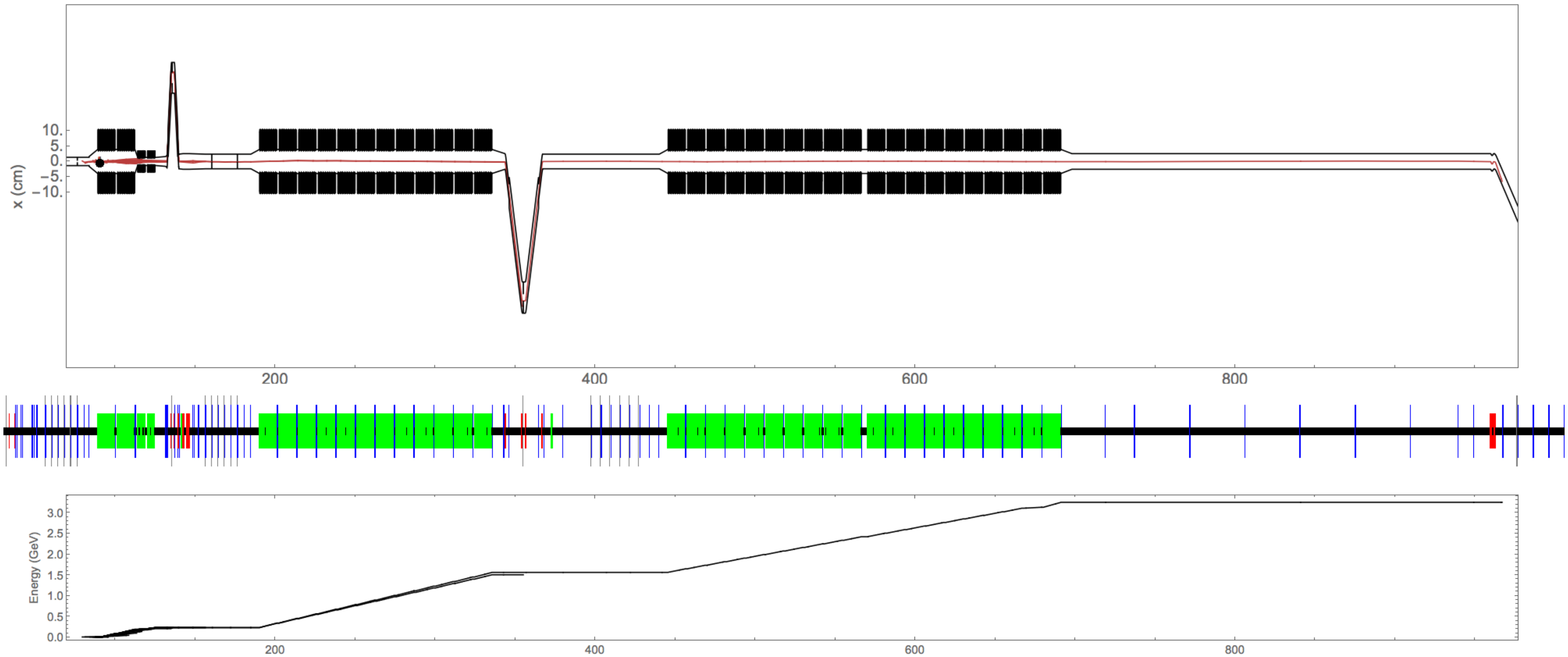
INJ HTR COL0

CM02 powers

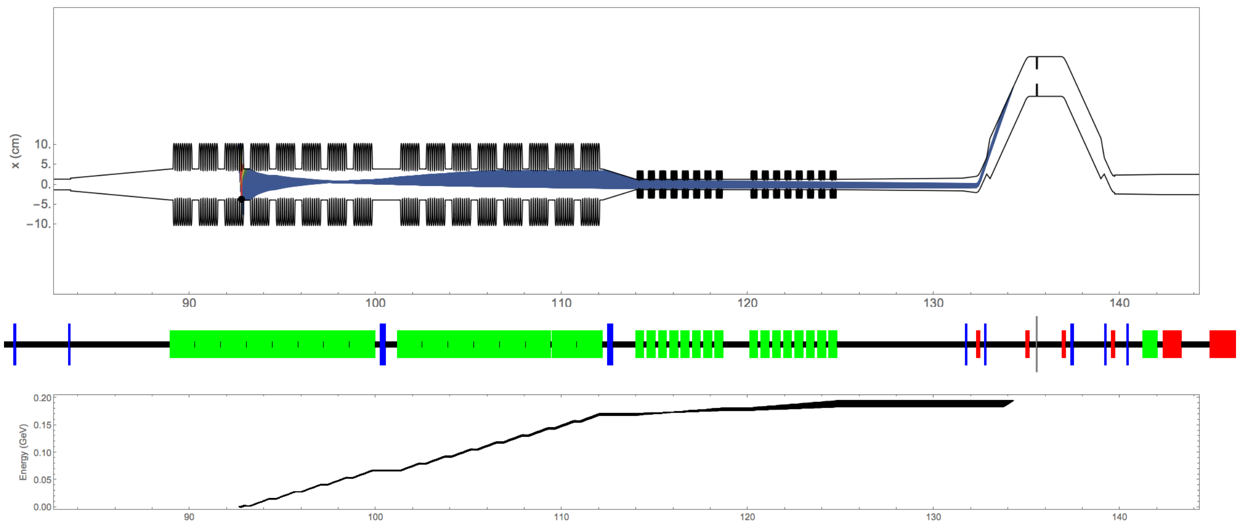
- A few lucky field emitters in CM02 can make it all the way to the dogleg.
- Backwards particles can't make it past the laser heater (HTR)
- Almost no possibility to cause loss in L2, L3



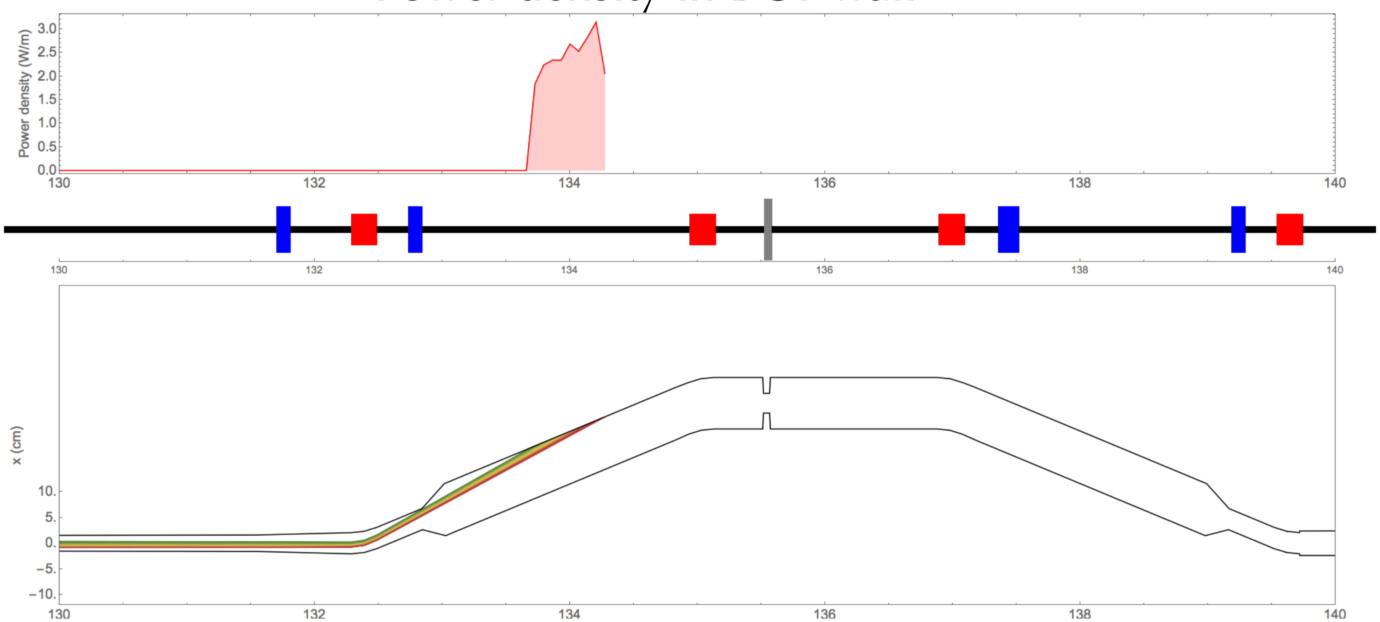
CM02 example field emitter 796



CM02 example field emitter 2087

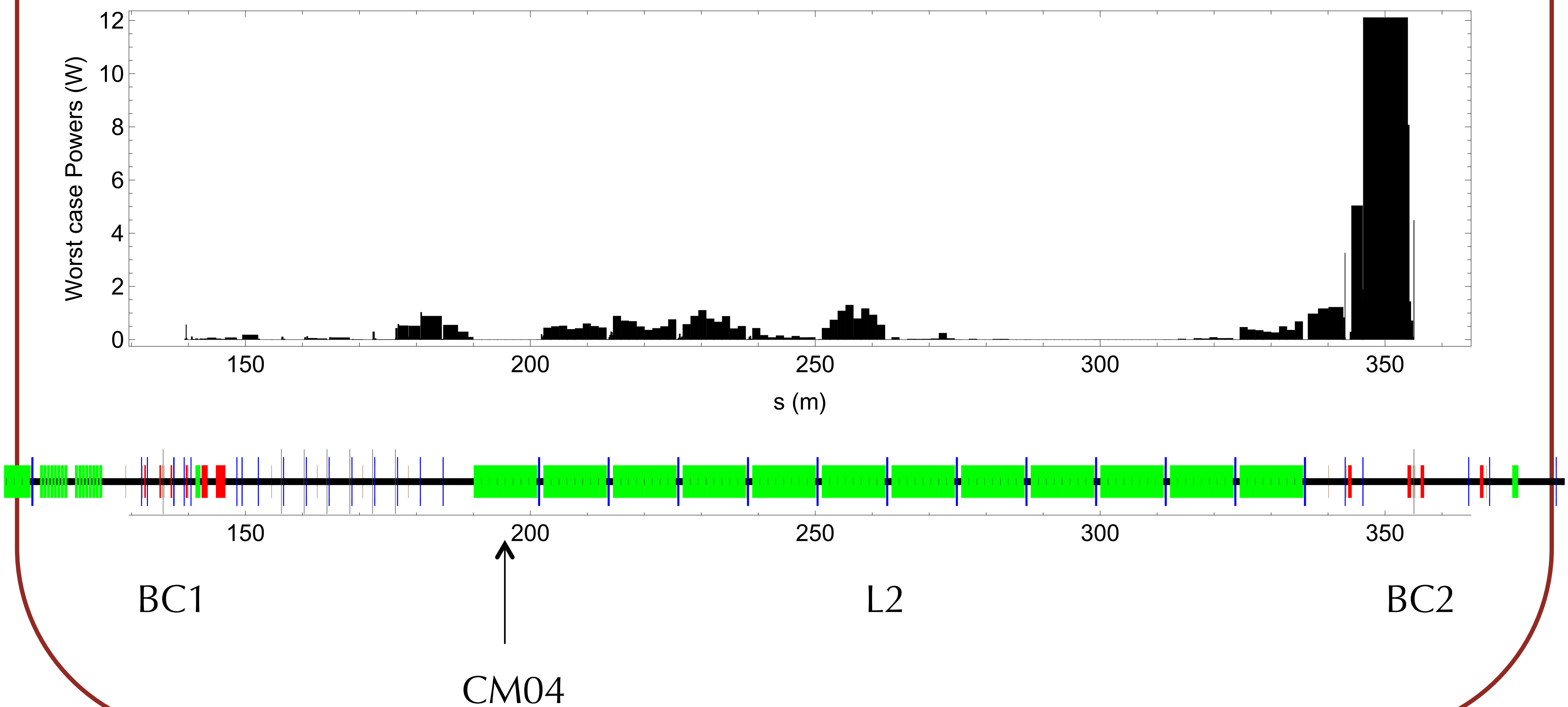


Power density in BC1 wall

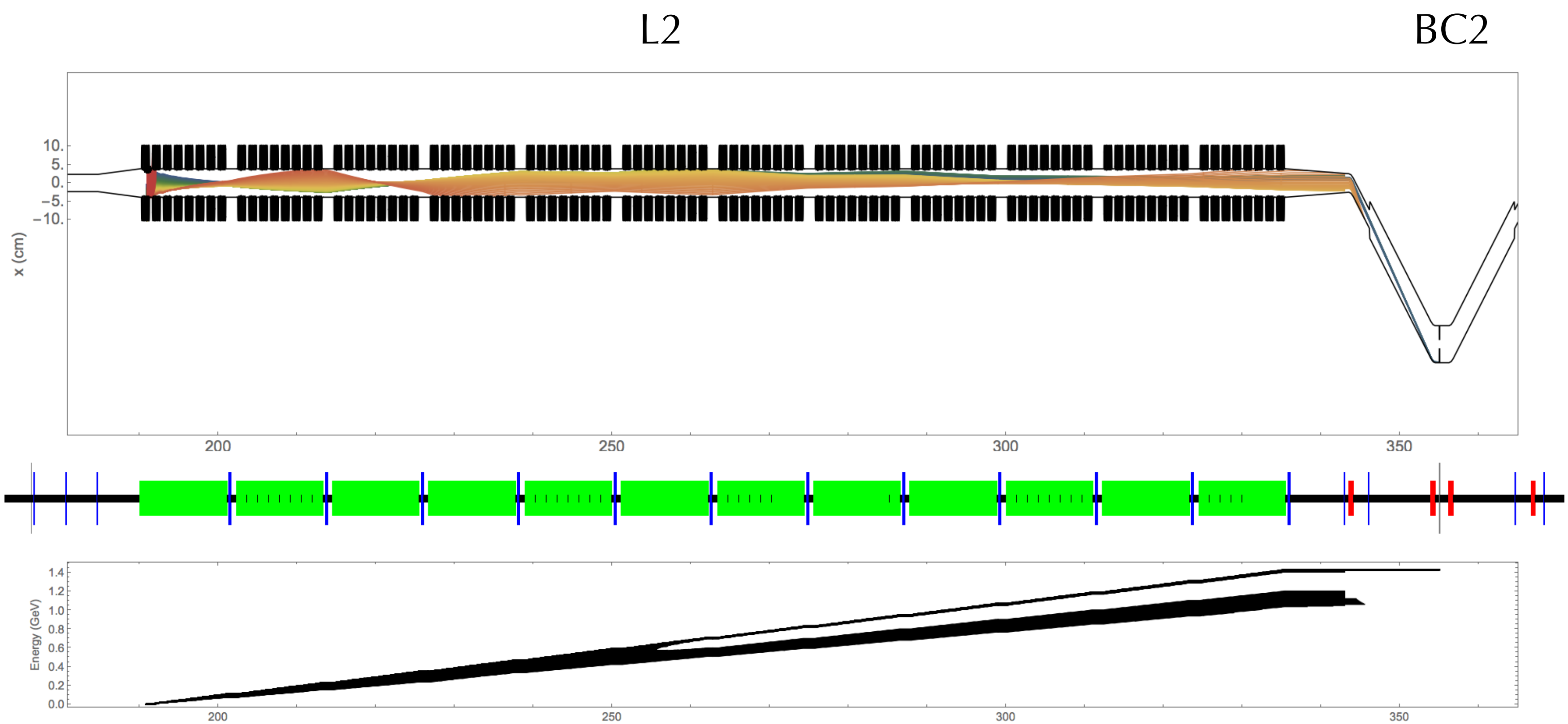


CM04 powers

- CM04 losses are always between BC1 and BC2
- The plot represents the full range of particles tracked. Here, no particle made it past 70 m.

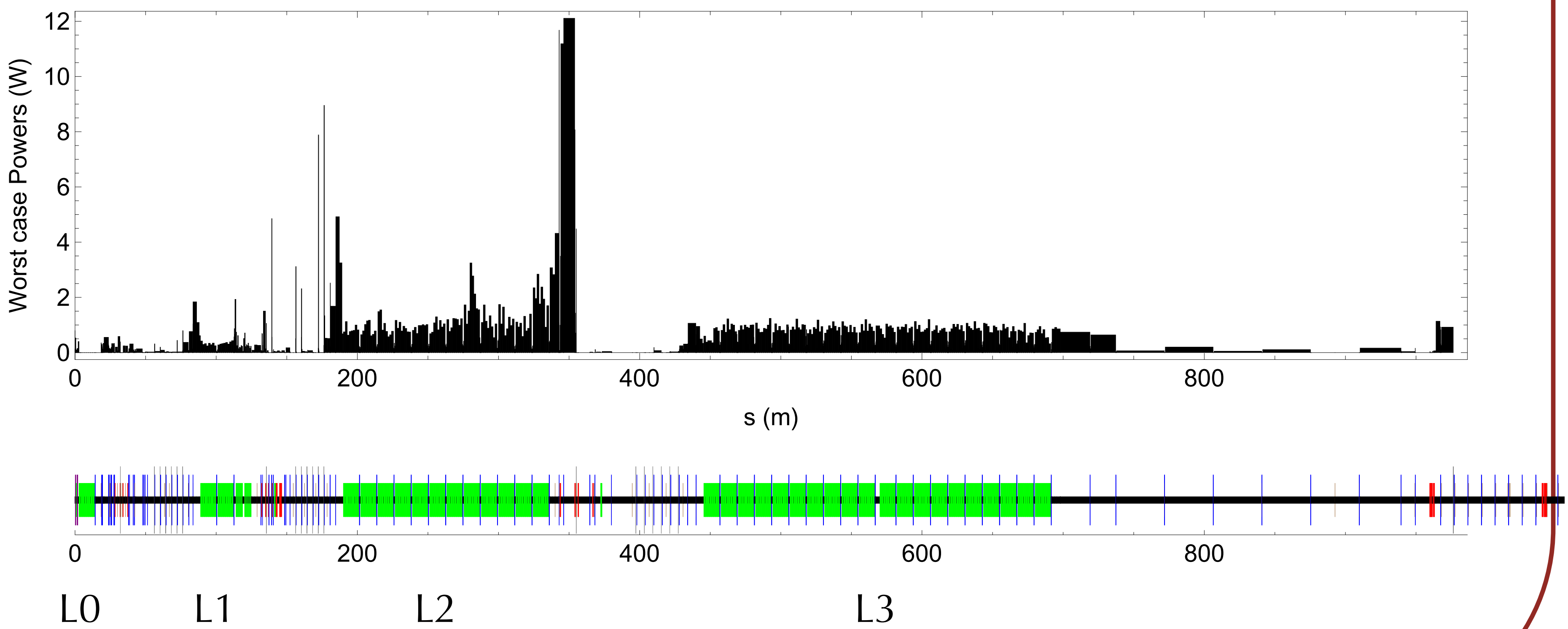


CM04 example field emitter 628



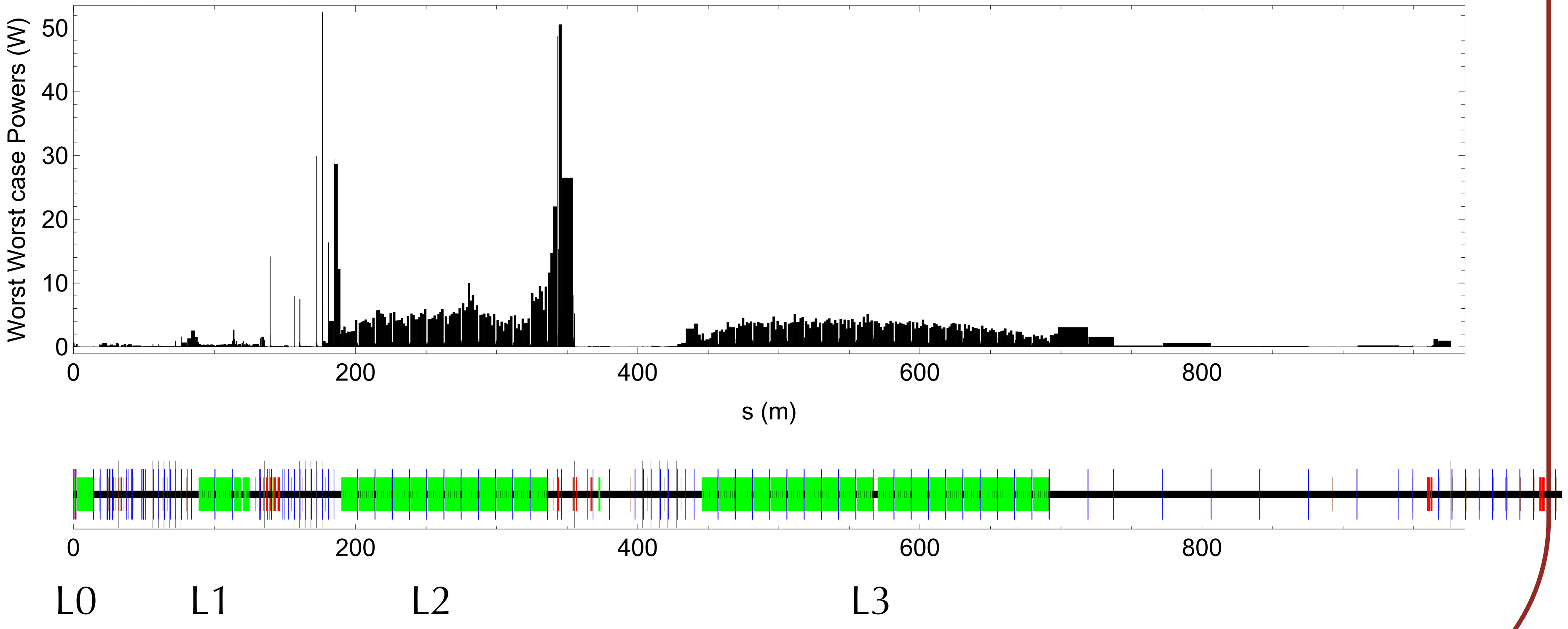
Worst case summary

- Worst case power experienced per element from a field emitter in one cryomodule, with emission exiting the cryomodule totaling 10 nA.
- No particle due to field emission can make it past the dogleg.



Worst Worst case summary

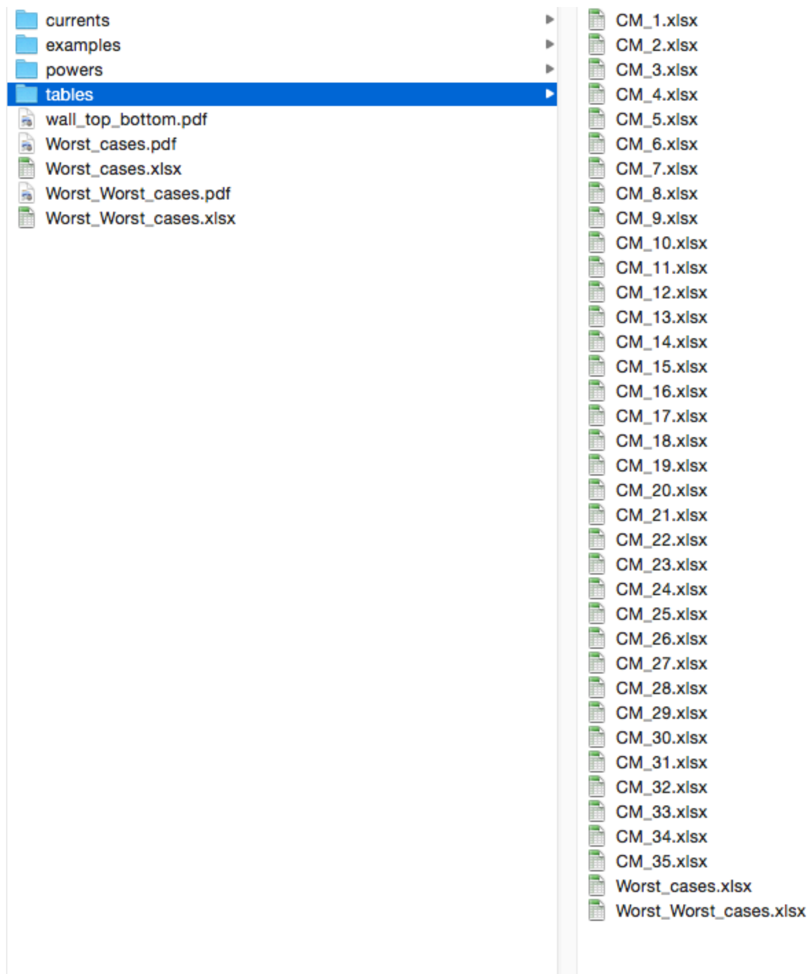
- Worst Worst case power experienced per element, assuming that all cryomodules have a field emitter with 10 nA exiting.

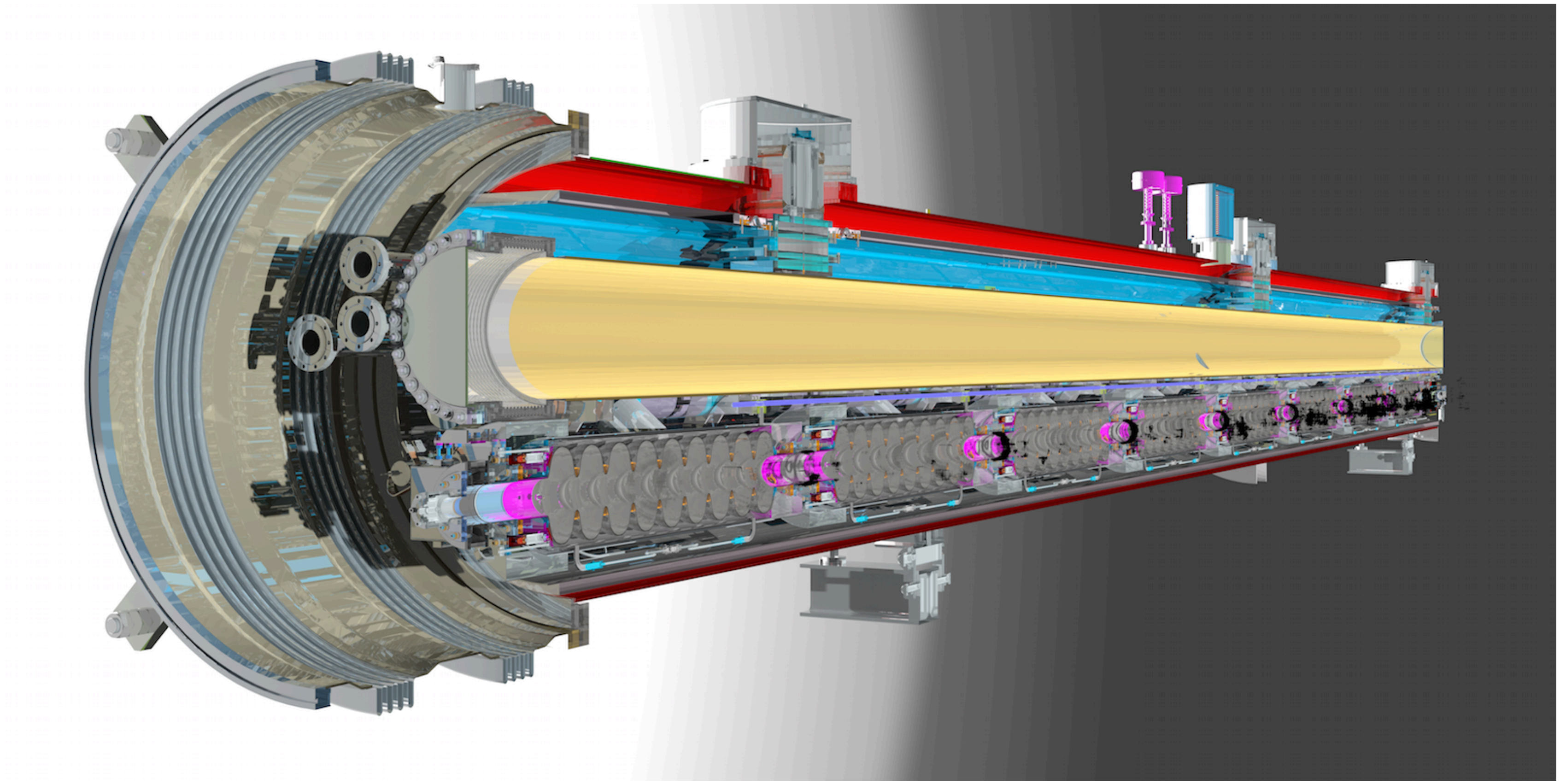


Summary Data

Summary particle loss plots and data can be found at:

http://www.lepp.cornell.edu/~cem52/LCLS2/data/





End