Inertial-melt helix regime to minimize coil mass and debris

2nd ICF magnet workshop, LLE, April 23-24, 2018

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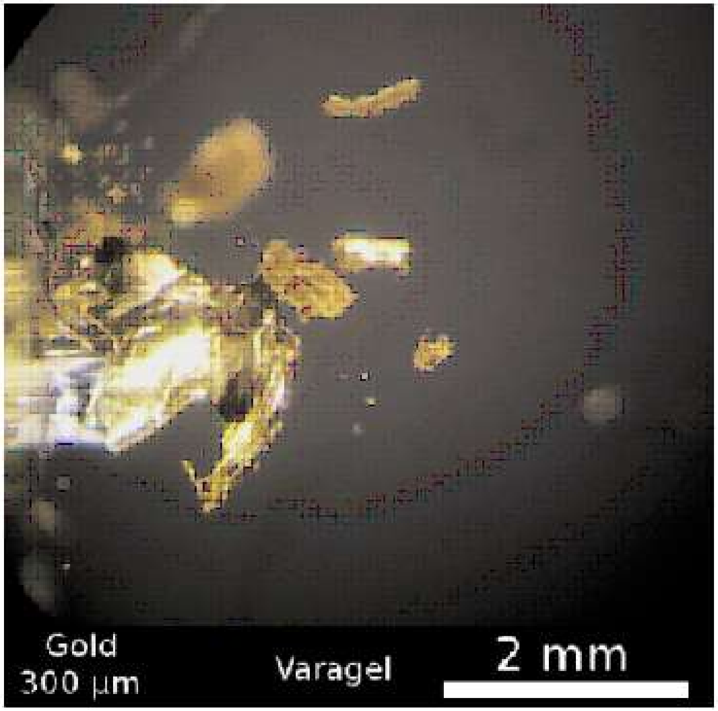
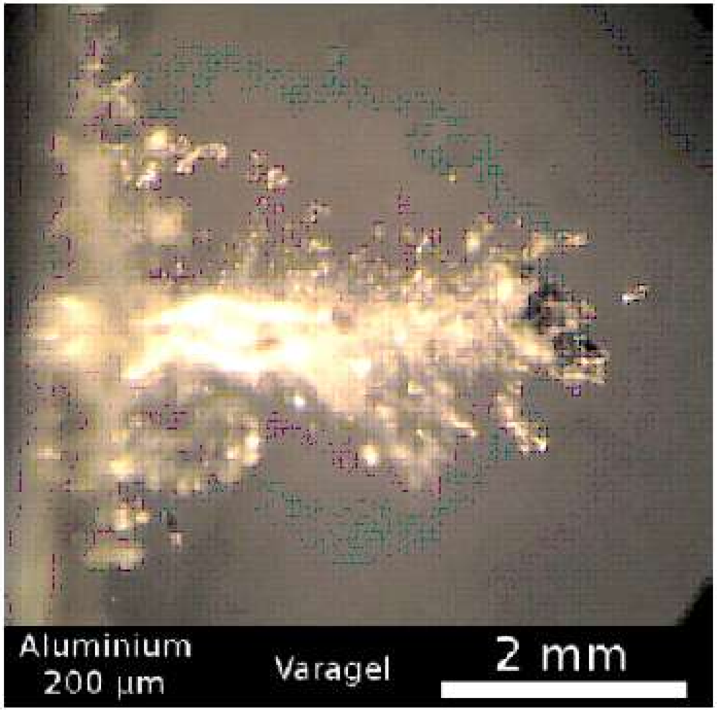
Debris issue: **lasers won't vaporize coils uniformly; likely create high velocity "chunks" via spallation from strong ablation-driven shocks, further propelled by vapor + jxB explosions.**



Typical laser-driven ablation shocks of 30 to 60 Gpa on gold and aluminum targets [From Lescoute, et.al. J. Appl. Phys. 108, 093510 (2010)].



Fragments of 300 to 1000 m/s inferred from depths of fragments captured in Varagel-- can break optics. ***Basic idea: design coils that melt at or near peak field, so that any shocks would smash conductor into benign, fine droplet sprays instead of fragments.This regime works so far for 30T, but can it work for B > 50T?***

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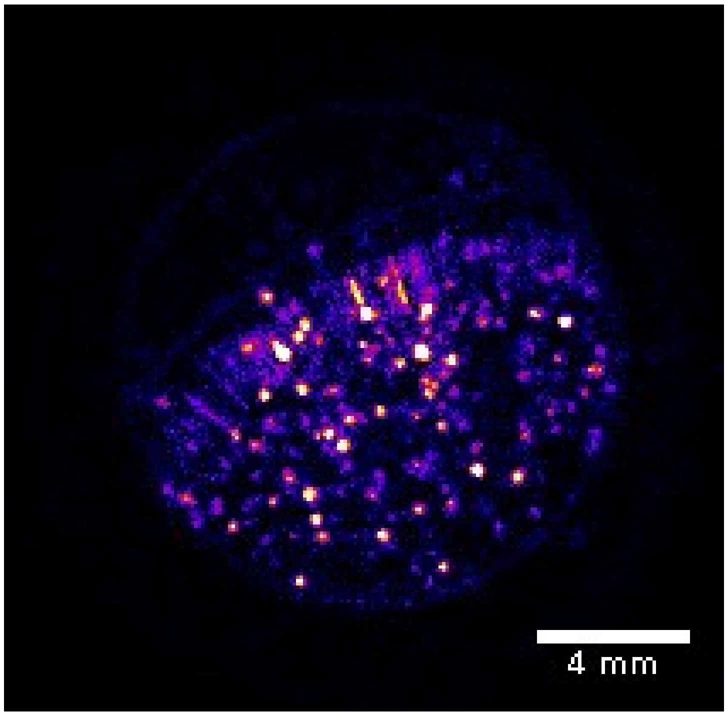
<u>Approach:</u> design coils for minimum mass to ohmically melt by ~ time of peak current, *<u>before</u> laser shock arrives or coil arcs.* Use *inertial confinement with fast dI/dt*. Shock strengths >> liquid metal surface tension→ *melted coils* disassemble into *fine droplet spray*.

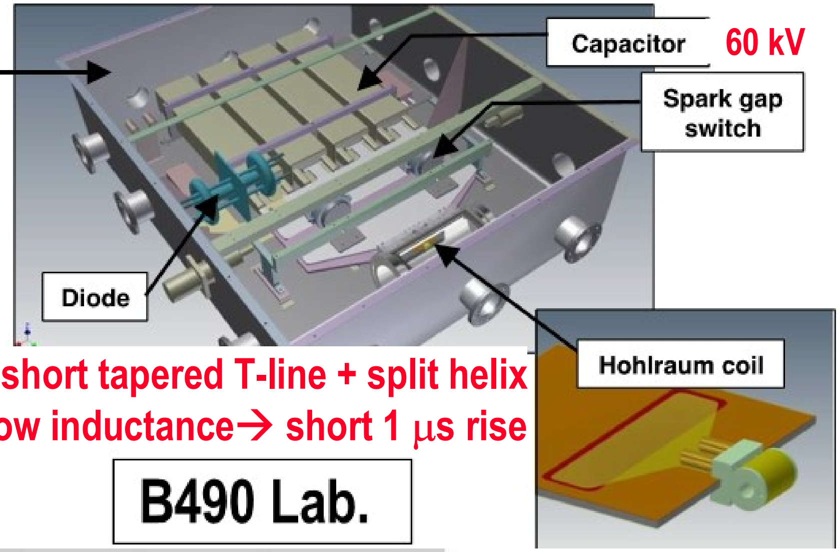


← Relevant data: in 2011-2012, Frank Bieniosek and the NDCX-II team at LBNL volumetrically heated solid thin gold and platinum foils to 4500 degK (beyond melt near boiling) in ~ 2 ns (near-isochoric heating). 500 μs later the *observed debris was a cloud of droplets (left) estimated ave ~ 1 micron size.* This data was not published as Frank died soon after.

More recent 30 T coil tests at NIF confirm fine copper debris/dust when coil reaches melt at peak field, but fragments appear when wire not melted at lower voltage (see talks by Brad Pollock and Evan Carroll).

→ "<u>INERTIAL-MELT</u>" coils: Minimum-mass coils that *melt* with motion limited by *inertia*.

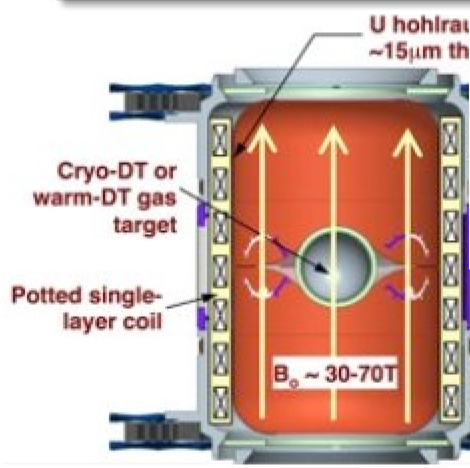
2015 LDRD-tests of split-helix for NIF (Mark Rhodes, LLNL)



60 kV

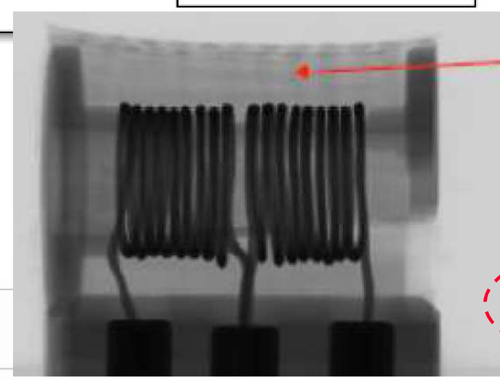
Note short tapered T-line + split helix → low inductance → short 1 μs rise

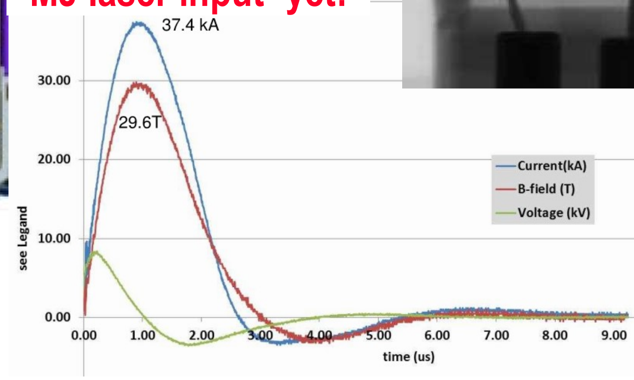
B490 Lab.



Highest 58 T tested July 2015

Radiograph shows wire "containment" @ 840 J magnetic energy. But, no 1.5 MJ laser input -yet!





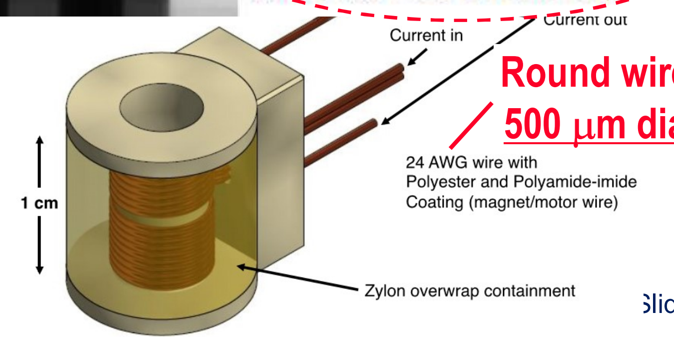
Tensile strength of Zylon composite ~ 5800 MPa.

Tube stress at 50T ~1600MPa.

So shouldn't disassemble

(ALE3D suggests no melt at 50T, 70% of melt at 70T but after peak field is reached)

No melt calculated

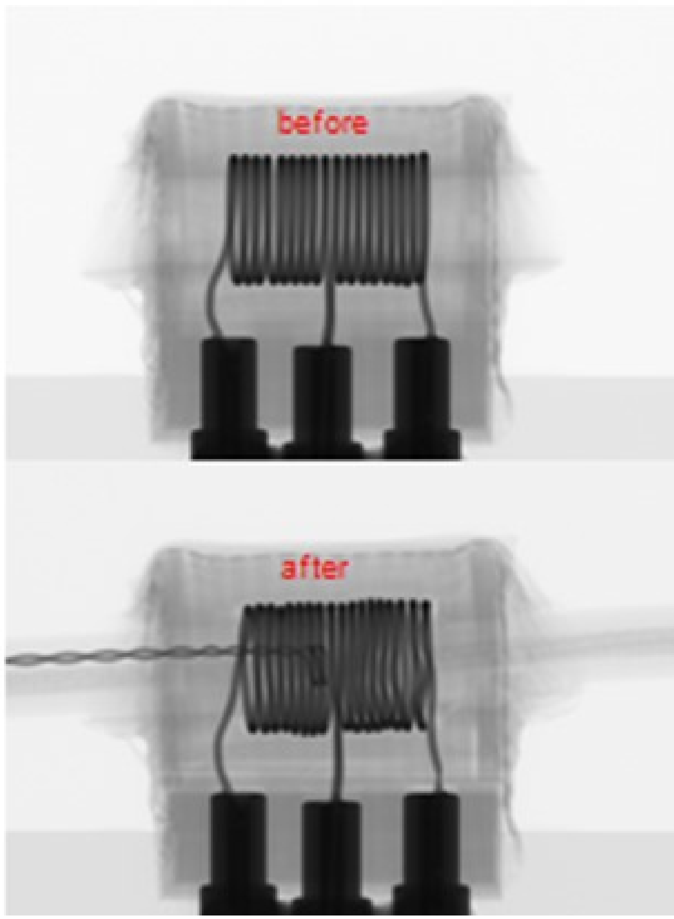


Round wire 500 μm dia

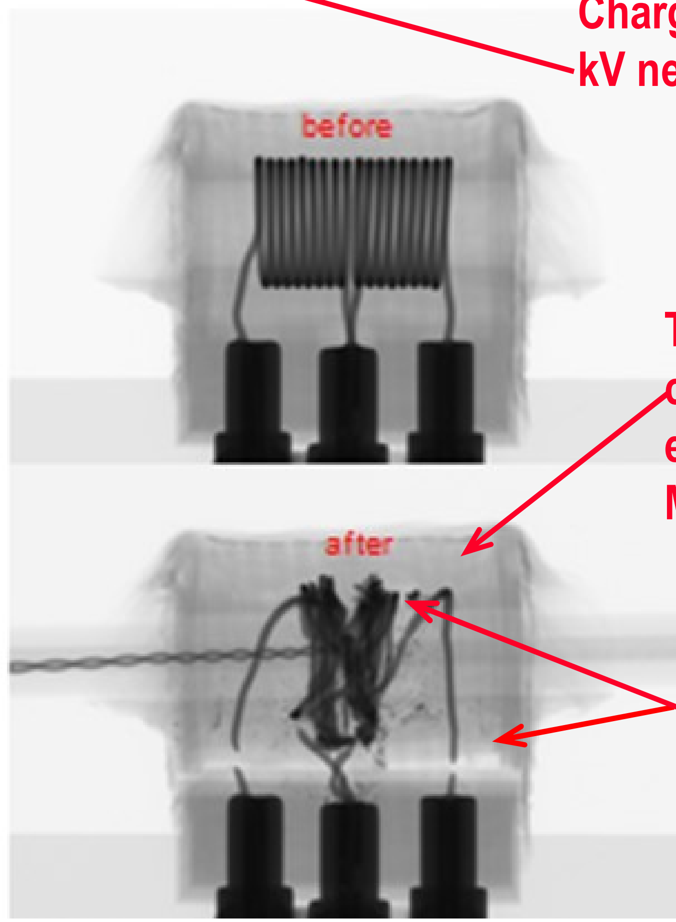
Slide from Mark Rhodes (LLNL) B490 NIF Magnet Test Facility (2015): *epoxy-Zylon composite <u>not</u> strong enough to immobilize wire @ B >50 T*

At 46 tesla, the coils are still not damaged much. Different story at 58 Tesla.

Coil 17: 40 kV shot, 46 Tesla



Coil 19: 50 kV shot, 58 Tesla



Charge voltages > 40 kV needed for B>50T

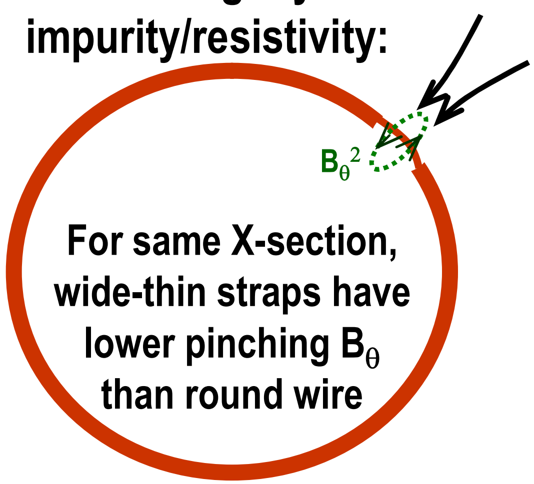
Thick Zylon fiber composite ***will*** explode with MJ-Mbar laser shock inside bore

Note broken wires-- “necking-off”

Without support structure, only inertia limits conductor elongation due to radial jxB forces. Higher voltage, faster rise helps to avoid “necking off” *as long as insulation holds off initial breakdown. More test data needed.*

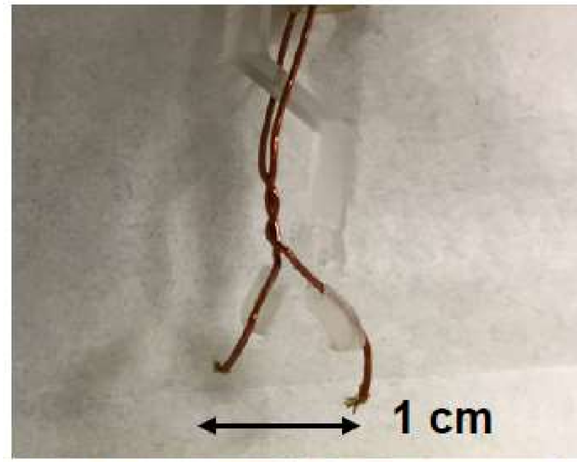
Local “Necking-off” can cause wires to break *before* reaching peak field *if rise is too slow*.

Desjarlais view: An initial local section of a wire can seed a *magnetic pinch instability* from either a slightly smaller x-section or higher impurity/resistivity:



Locally higher I^2R ohmic heating rate in the perturbed wire section leads to loss of strength earlier; tension elongates the local section faster until local magnetic pinch force exceeds remaining neck strength as local T approaches melt. ***Fiber-reinforced epoxy support structures yield enough at high stress that local wire necks can still break before peak field even with epoxy support. Note thermal conduction into epoxy is small for μs time scales.***

Failure modes if current rise is too slow (Gennady Fiksel-Oct 2015 NIF Magnet Mtg.)



MIFEDS

UoT

MODEL: 1-D radial magnetic skin depth diffusion and ohmic heating with time-dependent temperature and electrical conductivity→ find peak fields at melt for given capacitor voltage and external inductance

(1) Rather than employ a two-phase melting EOS, the model simply requires T > 2000 degK using *solid phase* specific heat *for full melt including latent heat of melt*.

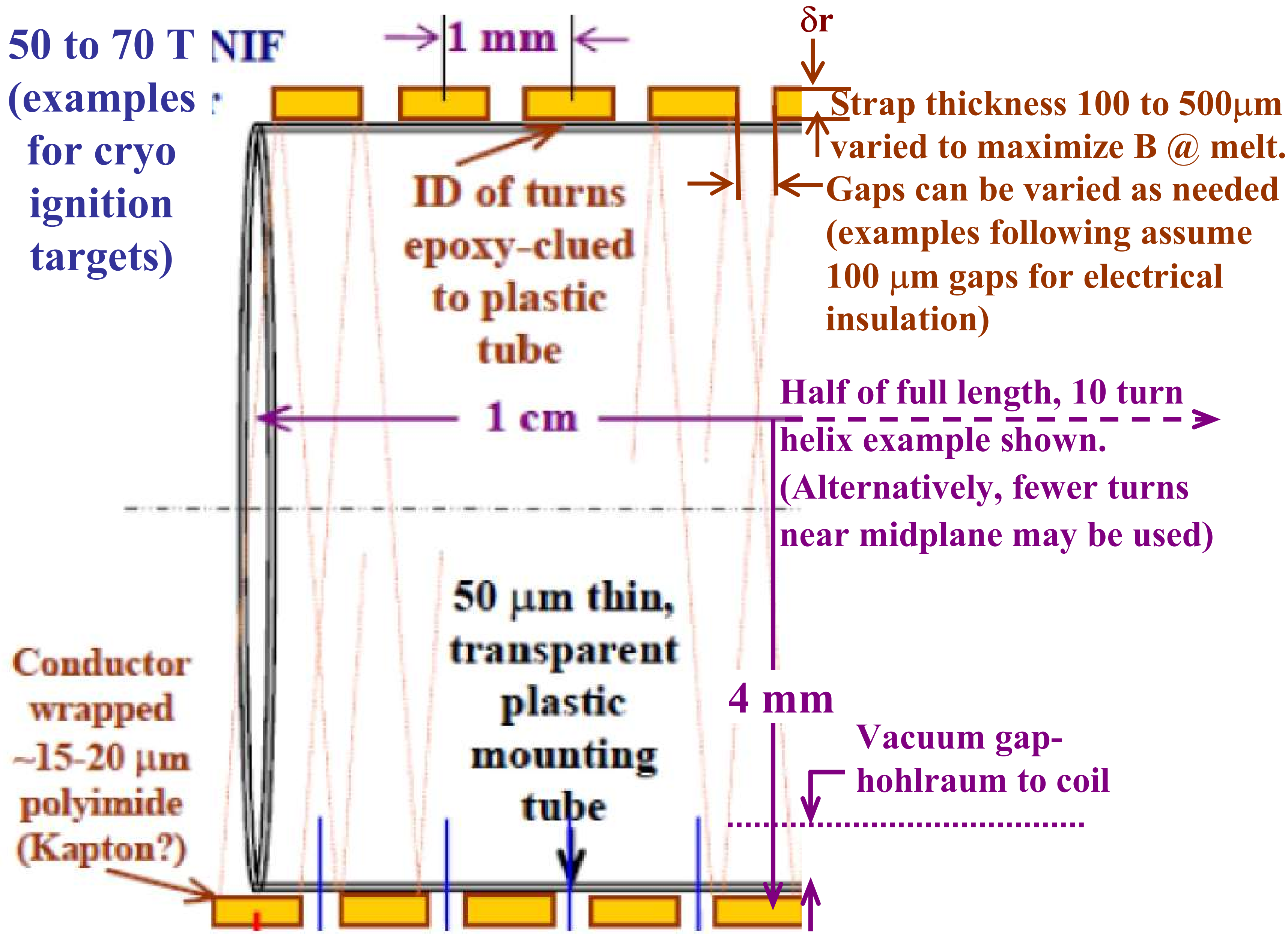
(2) Current-carrying skin depth $\delta s > \delta r$ thickness of conductor by time of peak B, so that inside surface reaches full melt @ > 2000 K, while outside surface reaches incipient melt @ > 1300 deg K. (*minimal strength of any solid phase remnants)*

(3) Minimizing conductor thickness δr to meet above two melt requirements *minimizes conductor mass.*

(4) Square conductor cross-sections (straps) used rather than round wire→gives *minimum resistance for given gap space and radial thickness*.

(5) Radial strap displacements Δr_s estimated *from inertia alone (F=MA from radial jXB forces integrated to peak field).*

Inertial-melt model single layer helix (example sized for NIF hohlraums)



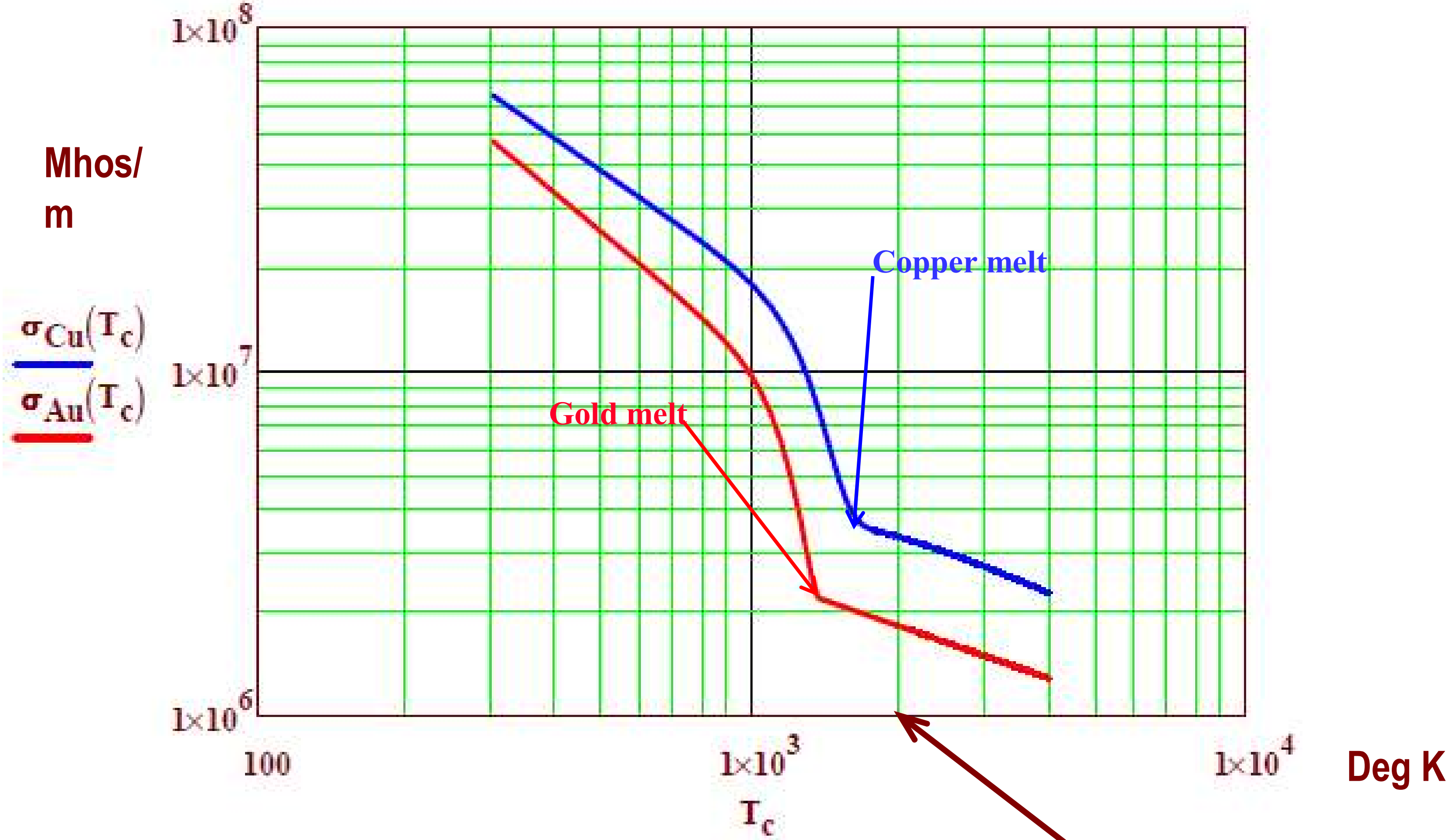
→Three independent variables for this survey (for both copper and gold conductors and for fixed 480 nH external inductance):

(1) Strap Thickness (100 to 500 μm, optimized for max B each case)
(2) Capacitor Voltage (40, 60, or 80 kV)
(3) Number of Turns (10 or 20, in 1 cm-long helix w/100μm gaps)

→The primary up-button to get melt to occur at higher fields is voltage.

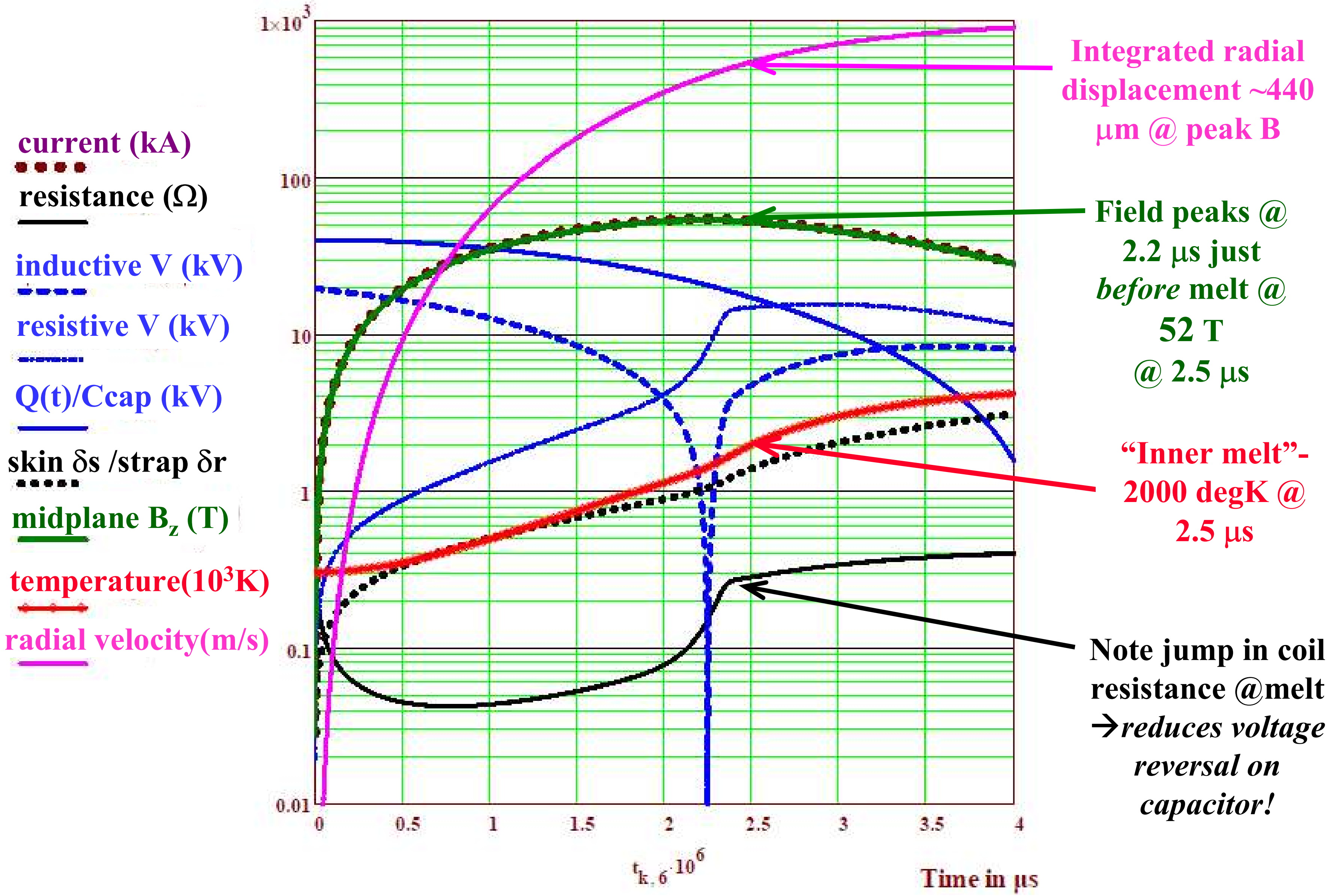
→The primary limit on strap thickness to engender fine debris is to have all of the conductor X-section at or above melt temperature >1300 K by time of peak field (insure near-complete loss of conductor strength).

Modeled electrical conductivities σ_{Cu} and σ_{Au} (units of mhos/m) decrease with temperature, with pronounced drops at melt T_c. →*Temperature rise rate $dT_c/dt \sim I_c(t)^2\ \sigma^{-1}$ fastest near peak I_c.*

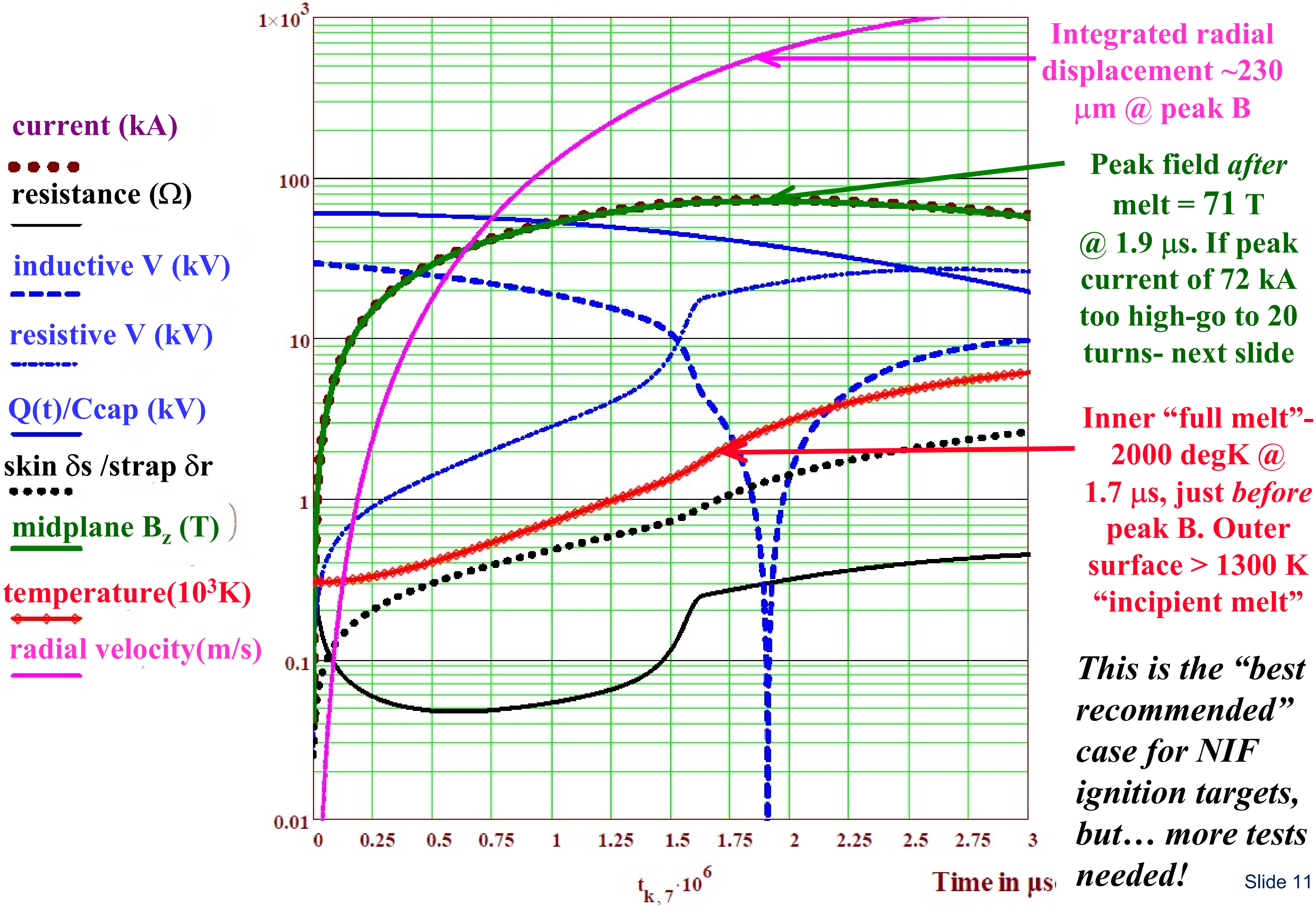


Complete (all liquid phase) melt is assured if calculated current peaks when T_c > ~2000 K

Results for 350 µm-thick copper strap, 10 turns, 1 mm spacing, 100µm gaps, 40 kV capacitor voltage, 480nH external inductance, 460nH helix:



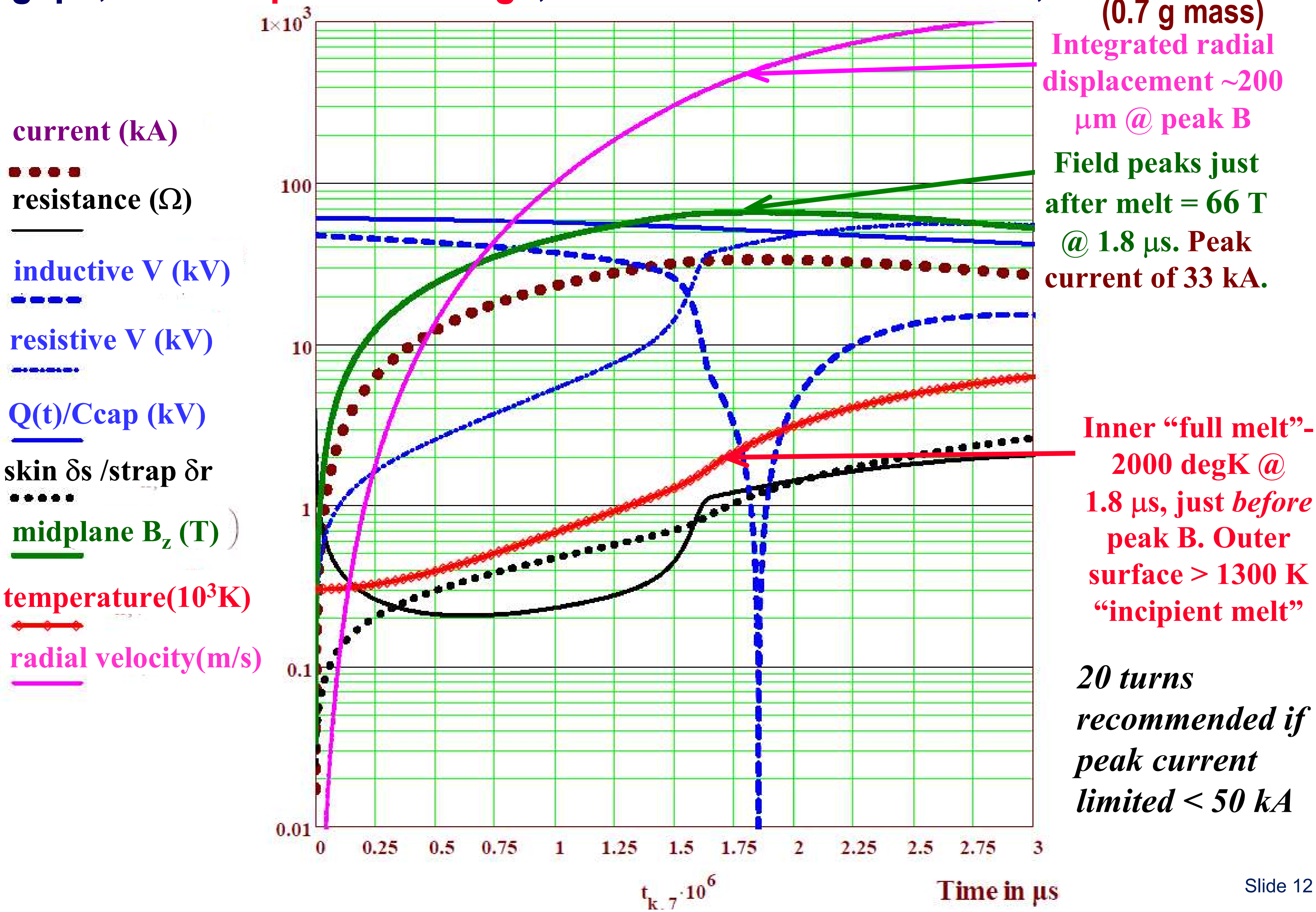
Results for 400 μm-thick copper strap, 10 turns, 1 mm spacing, 100μm gaps, 60 kV capacitor voltage, 480nH external inductance, 460nH helix:



This is the "best recommended" case for NIF ignition targets, but… more tests needed!

Results for 400 μm-thick copper strap, 20 turns, 0.5 mm spacing, 100μm gaps, 60 kV capacitor voltage, 480nH external inductance, 1840nH helix:

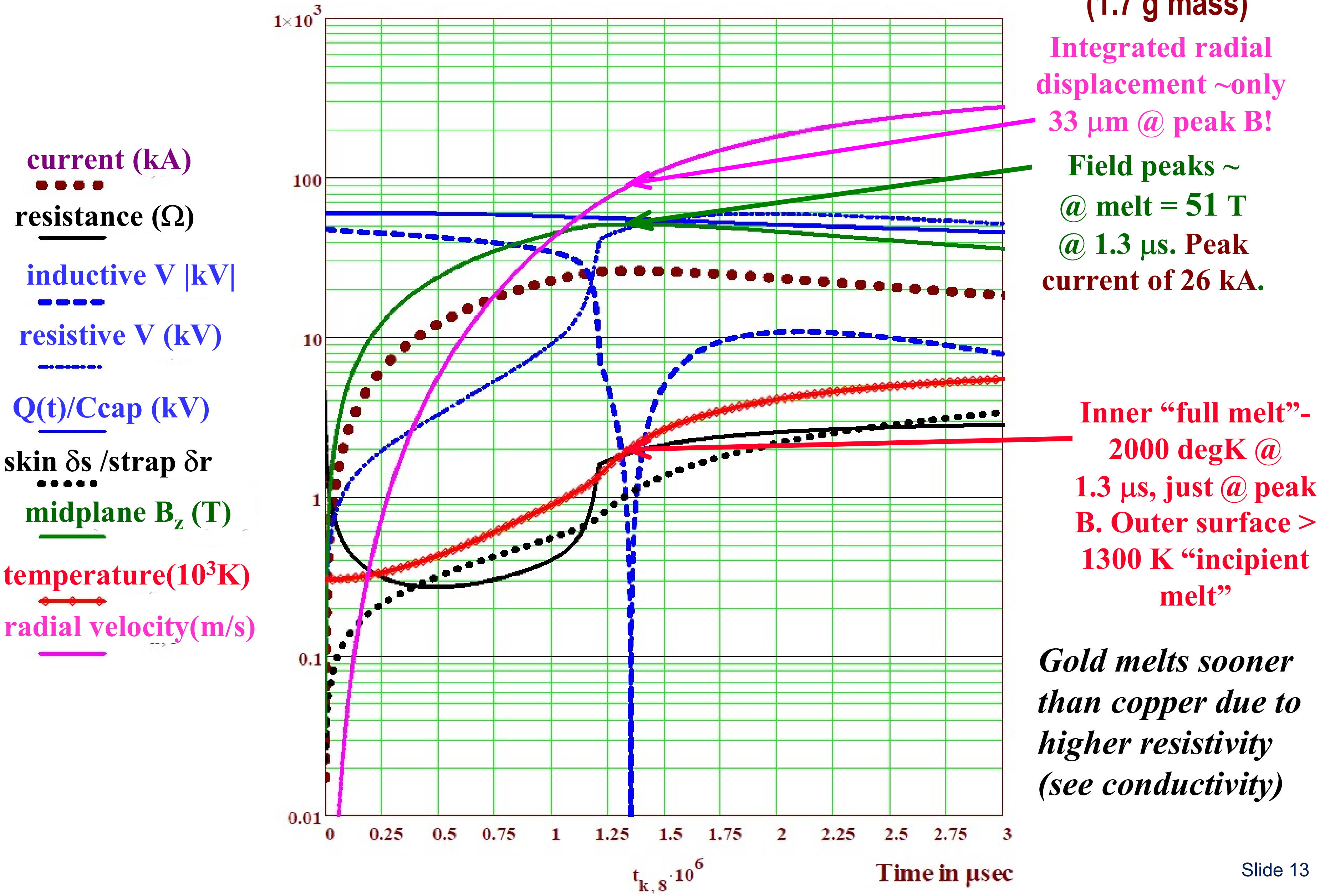
(0.7 g mass)



20 turns recommended if peak current limited < 50 kA

Results for 450 µm-thick gold strap, 20 turns, 0.5 mm spacing, 100µm gaps, 60 kV capacitor voltage, 480nH external inductance, 1840nH helix:

(1.7 g mass)



Gold melts sooner than copper due to higher resistivity (see conductivity)

Findings and recommendations based on inertial-melt model results:

(1) Subject to tests of premature neck-breaking, incomplete melting, and electrical breakdown, inertial-melt helix regimes should be able to satisfy NIF low mass coil requirements) < 0.7 g for copper straps at fields of *50 to 70 Tesla desired for ignition*.

(2) *If further tests show premature strap breaking (neck pinching)* prevents reaching 50 T with copper, then use gold conductor, even though 15-30% lower B with higher resistance.

(3) Capacitor charge voltage of 40 kV marginally enables 50 T with copper, so capacitors *rated higher at 60 or 80 kV are recommended for supply capability with margin*.

(4) Some capacitors and spark gap switches may limit peak currents < 50 kA, in which case 20-turn helixes rather than 10 turn helixes are recommended. *20-turn coils enable peak fields ~ 92% as high as 10-turn coils @ melt, with half the current.*

(5) With shorter rise times reaching melt, 80 kV drive gives only ~7% higher peak fields compared to 60 kV, and so *given increased risk of voltage breakdowns, 60 kV capacitor charge voltage is recommended rather than 80 kV.*

(6) Melted coil resistance becomes high enough at peak field to critically damp ring-back to protect capacitors after peak B. *Surprisingly, integrated resistive losses remain small compared to magnetic energy.*

Testing recommendation: more testing to insure > 50 T

- **Voltage holding:** inertial-melt helix coils need to be re-tested @ capacitor voltages higher than 30 kV (present test stand), to at least 60 kV, and maybe to 80 kV. (May require new capacitors, but those are inexpensive for only a few kJ). Test 50-100 μm thin dielectic coatings (e.g., polymide or CVD diamond coatings around conductors and lead connections- small additional mass to improve voltage holding).

- **External inductance:** for T-line lengths compatible with the new cryo TARPOS: test parallel cables vs parallel plate strips. Depending on external T-line inductance, split-helix coils may give worse coupling than single helix; more turns may be needed.

- **Minimum δs/δr, T outer surface for tolerable 2-phase debris:** test various strap thicknesses at melt for voltages at 40 and 60 kV, and for 6 vs 10 turns, for copper and for gold, for calculated δs/δr's ranging from 2 down to 1. Lower values preferred for higher B, *if no large fragments appear in aerogel debris catchers.*

- **Short-sample tests for neck breaking:** use fast optical streak images of machined local neck perturbations driven to melt at peak currents 30 - 60 kA. Analyze with ALE3D. Compare pinching of equal cross sections, rectangular and round, copper and gold.

Extra slides

Inertial-melt helix model results related to risk factors

Conductor, # of turns, charge voltage	Opt. strap δr (μm) for max B	Peak field Bz (T)	Conductor Mass (g)	Radial strap Movement (μm)	Voltage gradient in gaps (kV/cm
Cu, 10 turns, 40kV	350	51.7	0.71	437	197
Cu, 10 turns, 60kV	400	71.4	0.81	232	295
Cu, 20 turns, 60kV	400	65.6	0.72	202	238
Cu, 20 turns, 80 kV	350	70.5	0.63	124	318
Au, 10 turns, 40kV	500	48.3	2.15	77	197
Au, 10 turns, 60kV	450	59.7	1.93	36	295
Au, 20 turns, 60kV	450	51.1	1.72	33	238
Au, 20 turns, 80 kV	400	54.3	1.53	21	318

Inertial-melt helix model results related to risk factors (cont.)

Conductor, # of turns, charge voltage	t=0 voltage across helix (kV)	Current @ peak field (kA)	Skin-depth @ peak field / strap δr	Resistive coil losses (J)	Magnetic energy (J)
Cu, 10 turns, 40kV	19.7	52.6	1.04	17	642
Cu, 10 turns, 60kV	29.5	72.6	1.28	78	1223
Cu, 20 turns, 60kV	47.7	33.4	1.17	63	1037
Cu, 20 turns, 80 kV	63.6	35.9	1.48	107	1198
Au, 10 turns, 40kV	19.7	49.2	1.23	31	561
Au, 10 turns, 60kV	29.5	60.8	1.56	298	857
Au, 20 turns, 60kV	47.7	26	1.05	206	628
Au, 20 turns, 80 kV	63.6	27.7	1.4	539	711

Computational model (Mcad) evolves time-dependent quantities for 6000 time steps and for 9 different thicknesses of conductor (100-500μm)

Current-carrying cross section for 1strap-turn $A_{cs}(N_t, t, \sigma_c, \delta r) := \delta z_c(N_t)\cdot\delta_s(t,\sigma_c)\cdot\left(1-\exp\left(-\delta r\cdot\delta_s(t,\sigma_c)^{-1}\right)\right)$ (m^2), which smoothly transitions to both limits. **Eq. 28**

The resistance of the coil itself $R_{cs}(N_t, t, \sigma_c, \delta r) := (2\cdot\pi\cdot a_c\cdot N_t)\cdot\left(\sigma_c\cdot A_{cs}\left(N_t, t+10^{-9}, \sigma_c, \delta r\right)\right)^{-1}$ **Ω.**

The rate of rise of current: $dIc_{dt}(N_t, t, \sigma_c, \delta r, Q, I_c) := (L_c(N_t)+L_e)^{-1}\cdot\left(Q\cdot C_c^{-1} - I_c\cdot R_{cs}(N_t, t, \sigma_c, \delta r) - I_c\cdot R_e(L_e)\right)$ (A/s).

Rate of rise of T_c for Copper $dT_{dtCu}(N_t, t, T, \delta r, I_c) := \left(\frac{I_c}{A_{cs}\left(N_t, t+10^{-9}, \sigma_{Cu}(T), \delta r\right)}\right)^2\cdot\left(\sigma_{Cu}(T)\cdot C_{pCu}(T)\cdot\rho_{Cu}\right)^{-1}$ (deg K/s)

Integration of dI/dt, charge Q(t) of the capacitor, and diffusion growth of the skin depth (t), for

$k_m := 6000$ time steps $k := 1..k_m$ $\delta t := 2\cdot t_o\cdot k_m^{-1}$ $t_o = 2\times10^{-6}$

$N_t = 10$ $a_c = 4\times10^{-3}$ $\delta t = 6.667\times10^{-10}$ $k_m\cdot\delta t = 4\times10^{-6}$

evaluated for $j := 1..9$ strap thicknesses $\delta r_j := [100+50\cdot(j-1)]\cdot10^{-6}$ (m)

Copper, 20 turns, 60 kV

Cu: $A_{jxB20Cu}(I_c, \delta r) := \left[B_{z20}(I_c, 0)^2\cdot(2\cdot\mu_o)^{-1}\right]\cdot 2\cdot\pi\cdot a_c\cdot\delta_z(20)\cdot\left(2\cdot\pi\cdot a_c\cdot\delta z_c(20)\cdot\delta r\cdot\rho_{Cu}\right)^{-1}$ m/s²

$\delta_z(20)\cdot10^3 = 0.5$ mm

Au: $A_{jxB20Au}(I_c, \delta r) := \left[B_{z20}(I_c, 0)^2\cdot(2\cdot\mu_o)^{-1}\right]\cdot 2\cdot\pi\cdot a_c\cdot\delta_z(20)\cdot\left(2\cdot\pi\cdot a_c\cdot\delta z_c(20)\cdot\delta r\cdot\rho_{Au}\right)^{-1}$ m/s²

$\delta z_c(N_t) := \delta_z(N_t) - 10^{-4}$ $\delta z_c(20)\cdot10^6 = 400$ $V_{co} = 6\times10^4$ V, $Q_o = 0.24$ N_t=20 turns, $L_e = 4.8\times10^{-7}$ $R_e(L_e) = 0.23$

$$\begin{pmatrix} t_{1,j} \\ Ic_{1,j} \\ Q_{1,j} \\ \delta s_{Cu_{1,j}} \\ T_{Cu_{1,j}} \\ v_{rs_{1,j}} \end{pmatrix} := \begin{pmatrix} 0 \\ 0 \\ Q_o \\ 10^{-5} \\ 300 \\ 0 \end{pmatrix} \quad \begin{pmatrix} t_{k+1,j} \\ Ic_{k+1,j} \\ Q_{k+1,j} \\ \delta s_{Cu_{k+1,j}} \\ T_{Cu_{k+1,j}} \\ v_{rs_{k+1,j}} \end{pmatrix} := \begin{bmatrix} t_{k,j}+\delta t \\ Ic_{k,j} + dIc_{dt}\left(20, t_{k,j}, \sigma_{Cu}\left(T_{Cu_{k,j}}\right), \delta r_j, Q_{k,j}, Ic_{k,j}\right)\cdot\delta t \\ Q_{k,j} - Ic_{k,j}\cdot\delta t \\ \delta s_{Cu_{k,j}} + \left(\mu_o\cdot\sigma_{Cu}\left(T_{Cu_{k,j}}\right)\right)^{-1}\cdot\left(\delta s_{Cu_{k,j}}\right)^{-1}\cdot\delta t \\ T_{Cu_{k,j}} + dT_{dtCu}\left(20, t_{k,j}, T_{Cu_{k,j}}, \delta r_j, Ic_{k,j}\right)\cdot\delta t \\ v_{rs_{k,j}} + A_{jxB20Cu}\left(Ic_{k,j}, \delta r_j\right)\cdot\delta t \end{bmatrix}$$

<--time (s)
<--current (A)
<--charge (C)
<--skin depth (m)
<--temperature (degK)
<--radial velocity (m/s)

Eq. 47