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Electromagnetic Pulse Impacts on the Transmission Network

Phase 1-2 Final Briefing

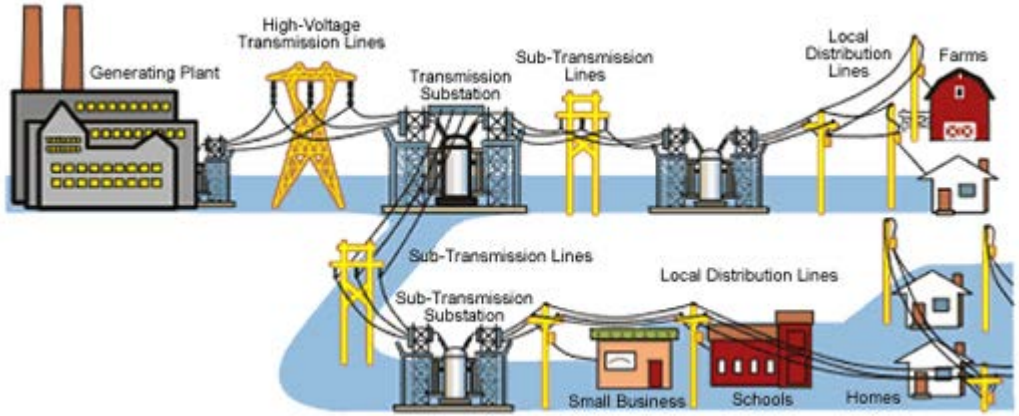
Michael K. Rivera

Oct. 10, 2017

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Study Constraints

- We only consider EMP impacts on the transmission and generation aspects of the bulk electrical system (BES)



- We are only interested in EMP events that cause long term high impact effects
- To the greatest extent possible, work should be unclassified

Phase 1 SOW Deliverables

1. A peer-reviewed methodology for categorizing EMP and GMD events into parameterized classes that cover the full range of nuclear EMP and natural GMD events that are considered plausible by stakeholders identified by DOE/OE and DHS/OCIA
2. A peer-reviewed graphical/tabular classification of the parameterized EMP and GMD events into ranges based on the dominant hazard environment including: nuclear blast/kinetic effects, E1, E3, combined E1 and E3, or GMD.
3. A further classification of the EMP/GMD-dominated ranges into events of “concern” and “no-concern” based on definitions provided by DHS/OCIA and DOE/OE.
4. A preliminary catalog of data, models, and methods anticipated to carry out a study of EMP events. These items will be further characterized by their level of classification within DOE and/or DOD. Models and methods will be further characterized by their domain of applicability.

Phase 2 SOW Deliverables

1. Develop of draft workflow for the study of EMP events and their impact on the BES to be reviewed by OCIA and industry
2. Develop inventory of software and data required to execute draft workflow
3. Screening analysis of Phase 1 “events of concern” using workflow (in what follows we interpret “screening analysis” to mean a “partial execution” of the workflow. The full execution of the workflow is to occur in phase 3).

Phase 1 Deliverables:

3. A further classification of the EMP/GMD-dominated ranges into events of “concern” and “no-concern” based on definitions provided by DHS/OCIA and DOE/OE.
4. A preliminary catalog of data, models, and methods anticipated to carry out a study of EMP events. These items will be further characterized by their level of classification within DOE and/or DOD. Models and methods will be further characterized by their domain of applicability.

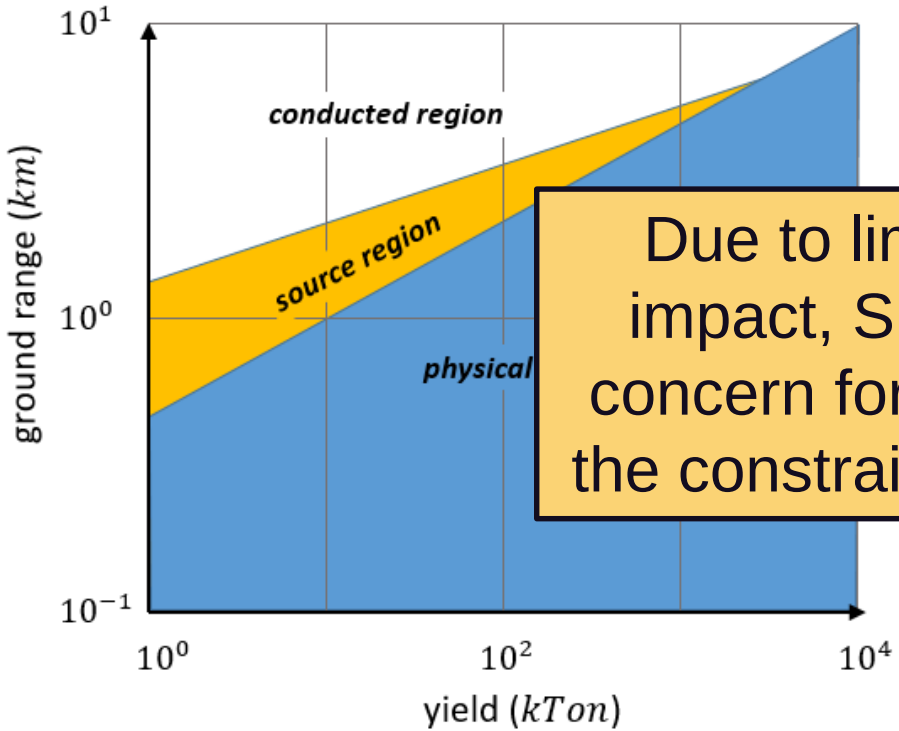
“Merged” Phase 1-2 Deliverables

1. Categorization of EMP and GMD events into parameterized classes. [Phase 1-D1]
2. Classification of the parameterized EMP and GMD events into ranges based on the dominant hazard environment (introduction of benchmark events) [Phase 1-D2]
3. Develop a draft workflow for the study of EMP events and their impact on the BES to be reviewed by OCIA and industry [Phase 2-D1]
4. Develop inventory of software and data required to execute draft workflow [Phase 2-D2,Phase1-D4]
5. Screening analysis of benchmark events using workflow to determine events of “concern” and “no-concern” based on definitions provided by DHS/OCIA and DOE/OE. [Phase 1-D3,Phase 2-D3]

EMP Parameterization
[Phase 1 – D1]

Parameterization of Nuclear Events (SREMP)

Parameterization of endo-atmospheric hazard:



Due to limited range of impact, SREMP is not a concern for the BES under the constraints of this study.

- The blue region indicates extensive physical damage to bulk electric system (BES) components and subsystems.
- The yellow region is the source region MP fields are expected S components and

couple to BES d conductively e lines into the white region potentially damaging other BES components connected to the transmission lines.

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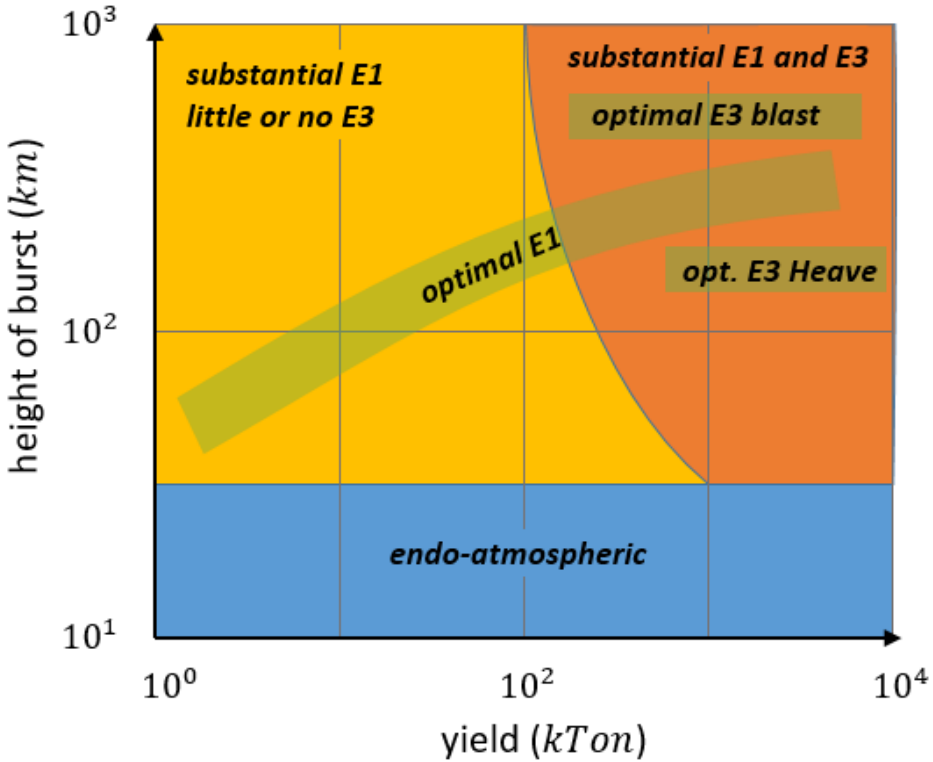
Parameterization of Nuclear Events (HEMP)

Parameterization of exo-atmospheric hazard:



- The blue region denotes endo-atmospheric bursts
- The yellow region corresponds to bursts that create a considerable E1 pulse, but little E3 pulse.
- The orange region denotes bursts that create both E1 and E3 pulses.
- The green bars denote optimal burst altitudes for a given yield device to achieve a particular effect (these bars are meant to be indicative rather than quantitative).

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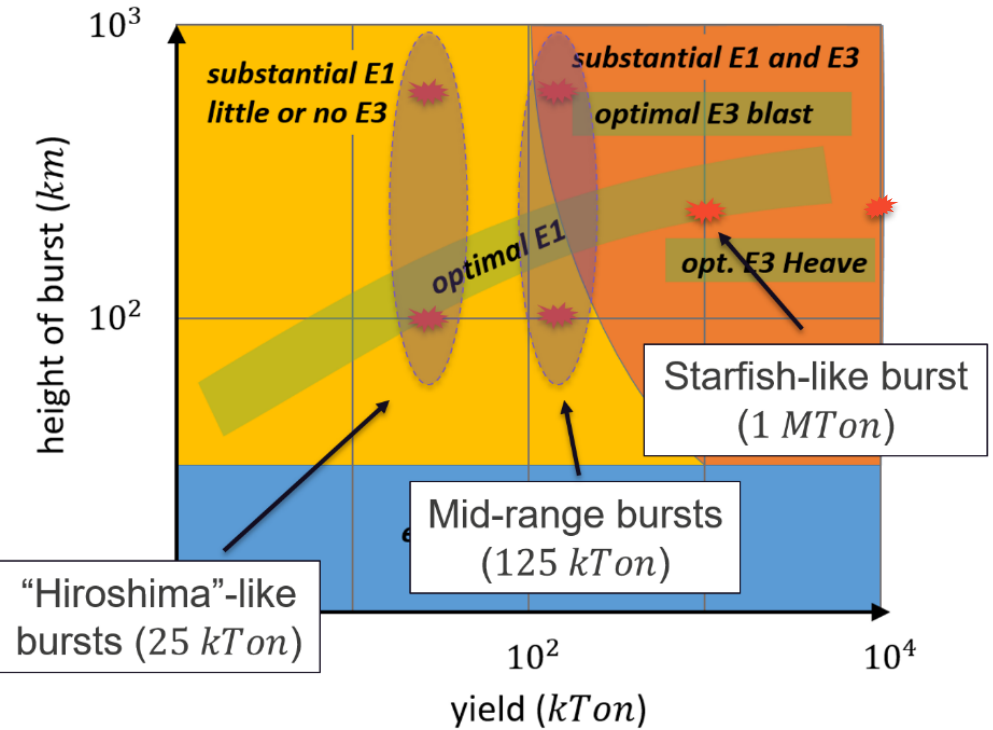
EMP Benchmark Events
[Phase 1-D2]

“Benchmark” Nuclear Events (HEMP)

Benchmark Events



- Do not correspond to any particular nuclear weapon or weapon delivery capability
- Chosen to clearly delineate regions of interest where certain effects are dominant
  - E1
  - E1 + E3 blast
  - E1 + E3 heave
  - E1 + E3 (blast + heave)
  - reviewed by weapons effects experts
  - presented these benchmarks at DOE and MEC meetings.

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Benchmark Events
Qualitative Anticipated Consequences

Yield (kTon)	Height of Burst (km)	E1	E3 Blast @ Edge of E1	E3 Heave Centered on E1	Anticipated Consequence
25	100	Regional -- med	Low	Low	State-protection/comms
25*	400	CONUS -- low	Low	Low	Patchy
125	100	Regional – med/high	Low	Med/High	E1/E3 overlap
125	400	CONUS – low/med	Med/High	Low/Med	Patchy E1/some E3
1000	200	Interconnect – med/high	Med	High	E1/E3 overlap
10000*	200	Interconnect – med/high	Med	High	E1/E3 overlap
10	endo	City	none	none	crater

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Development of Draft EMP Workflow [Phase 2 – D1]

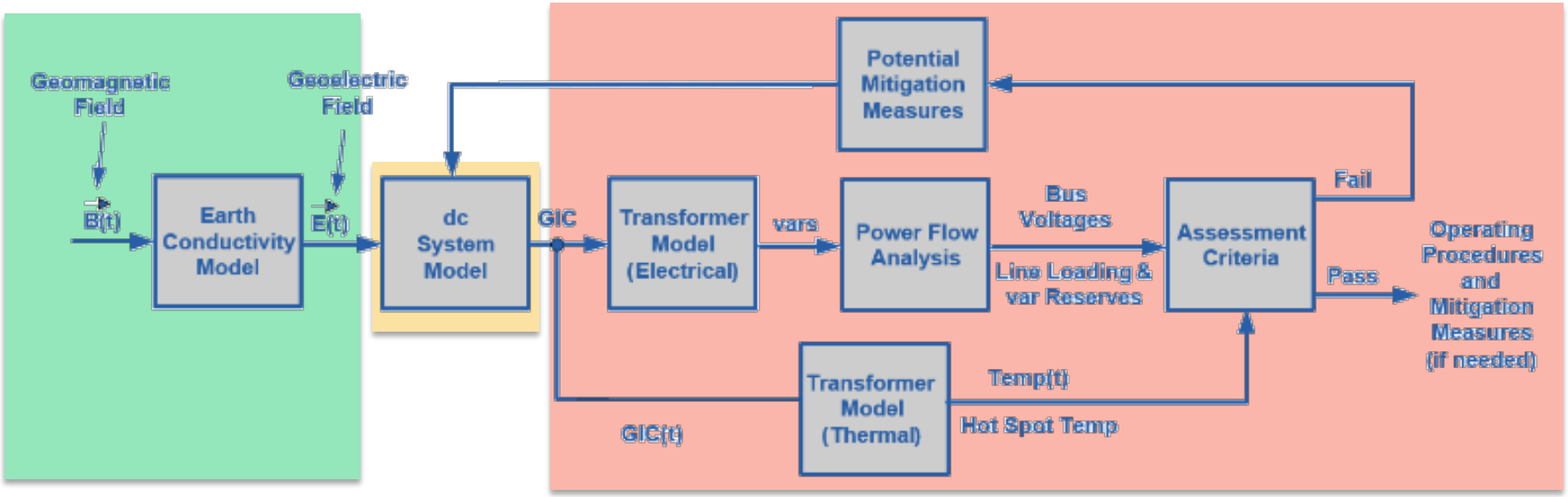
TPL-007-1 Workflow

Transmission System Planned Performance for Geomagnetic Disturbance Events

Purpose: Establish requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events.

TPL-007-1 Workflow

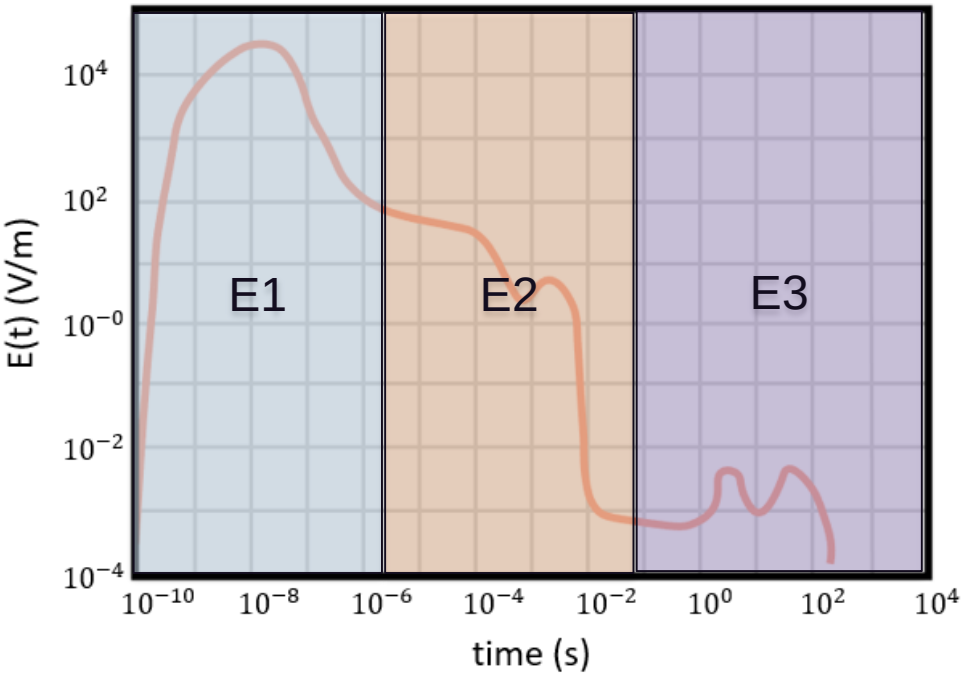
Couple fields to power system

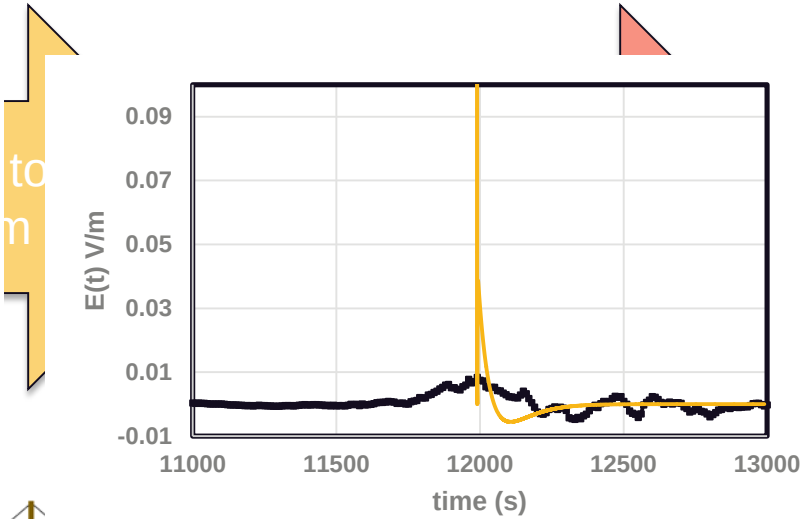


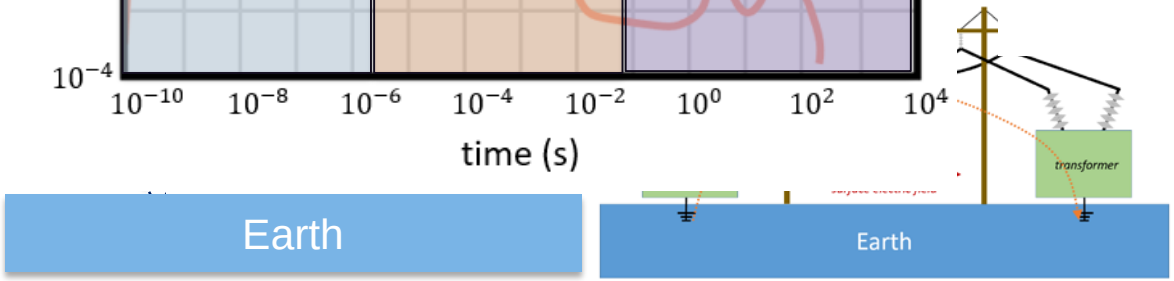
Determine hazard fields

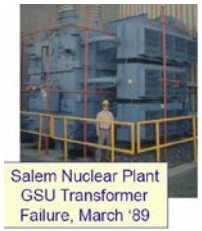
Determine impacts/damage

TPL-007-1 Workflow (Abstraction)

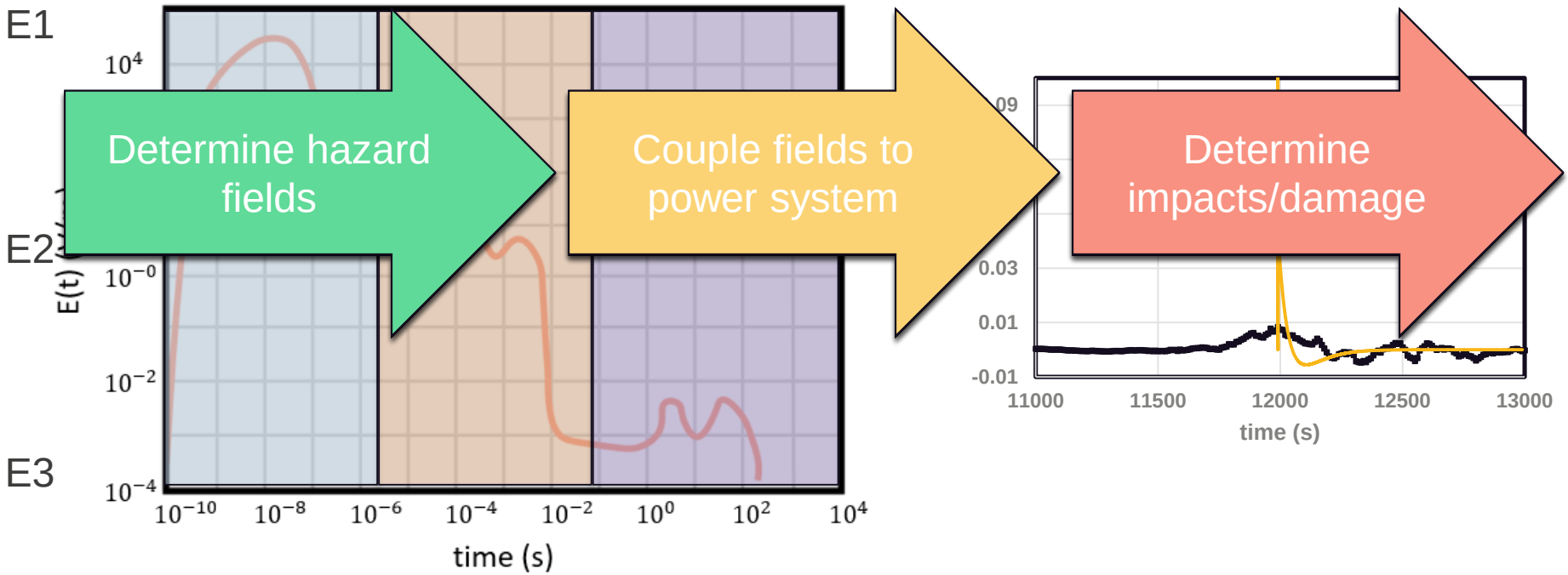




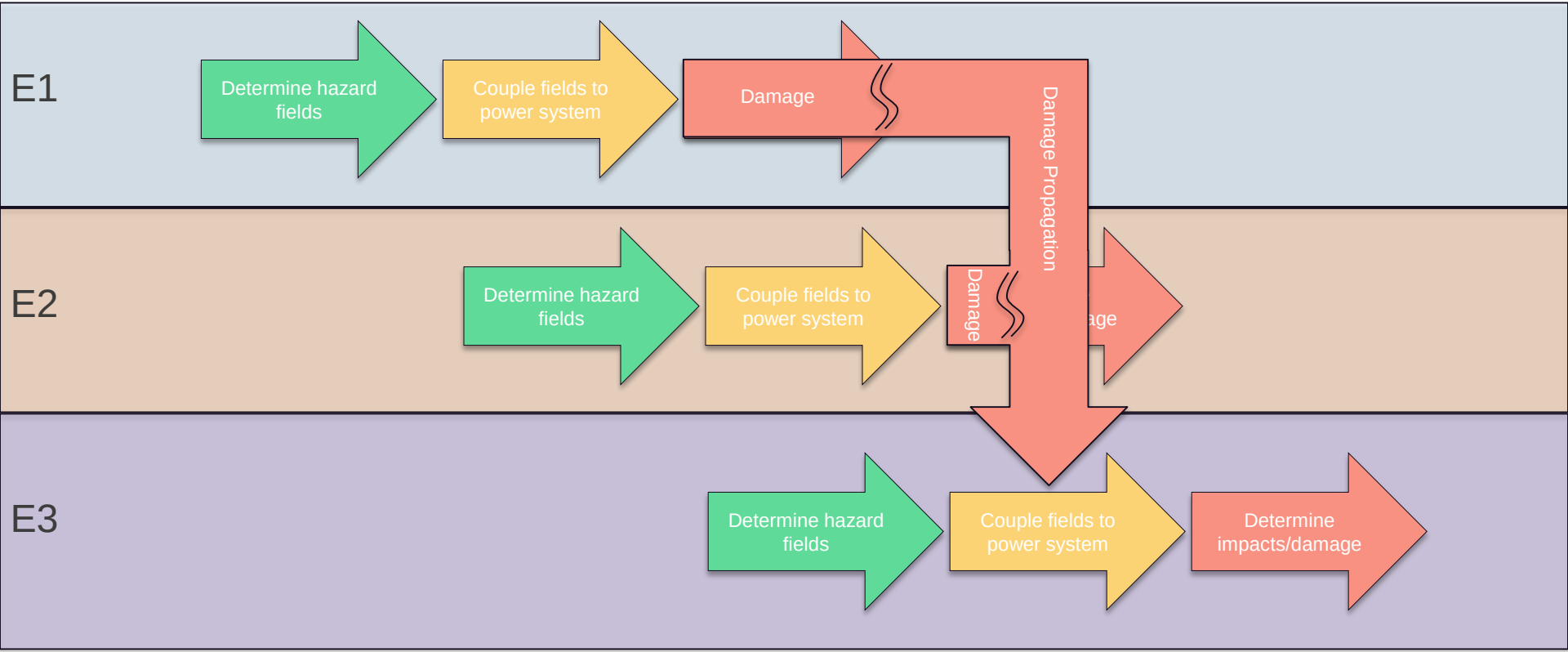




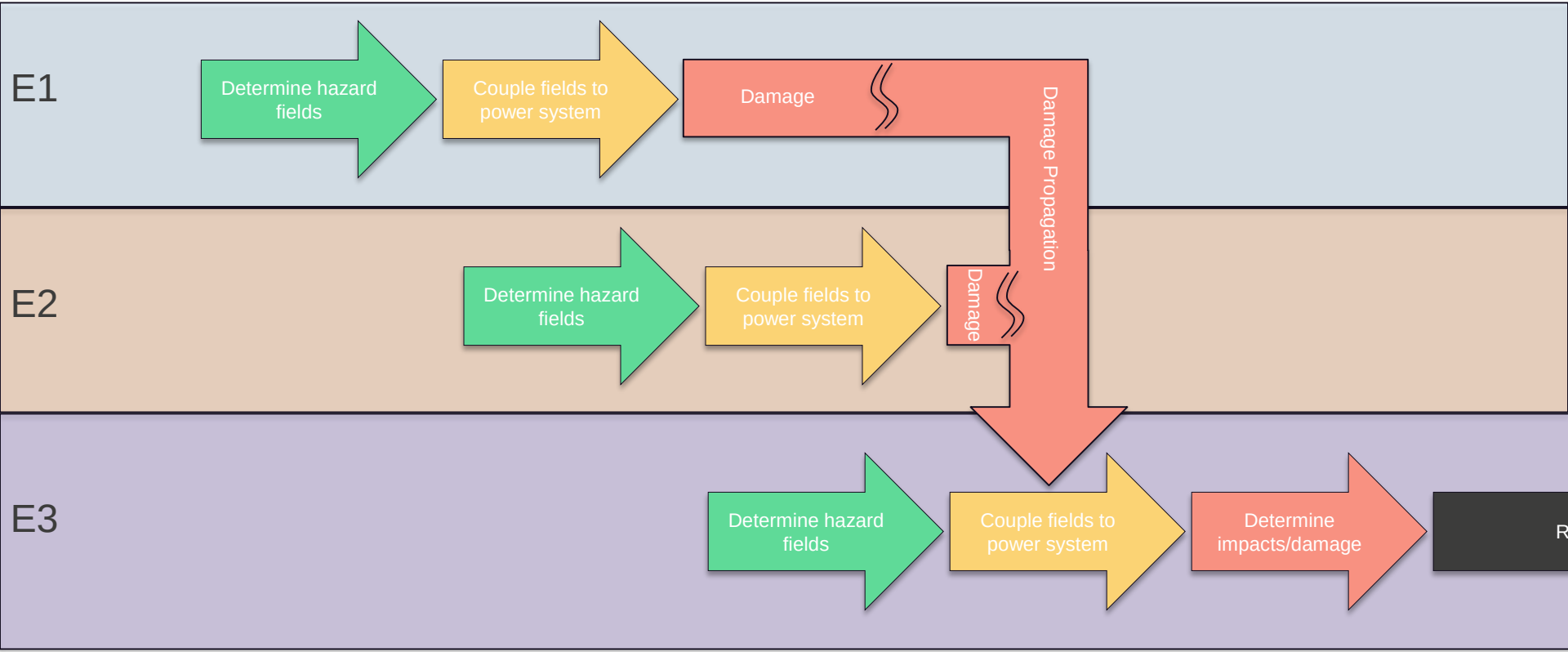
TPL-007-1 Workflow (Abstraction)



EMP Workflow

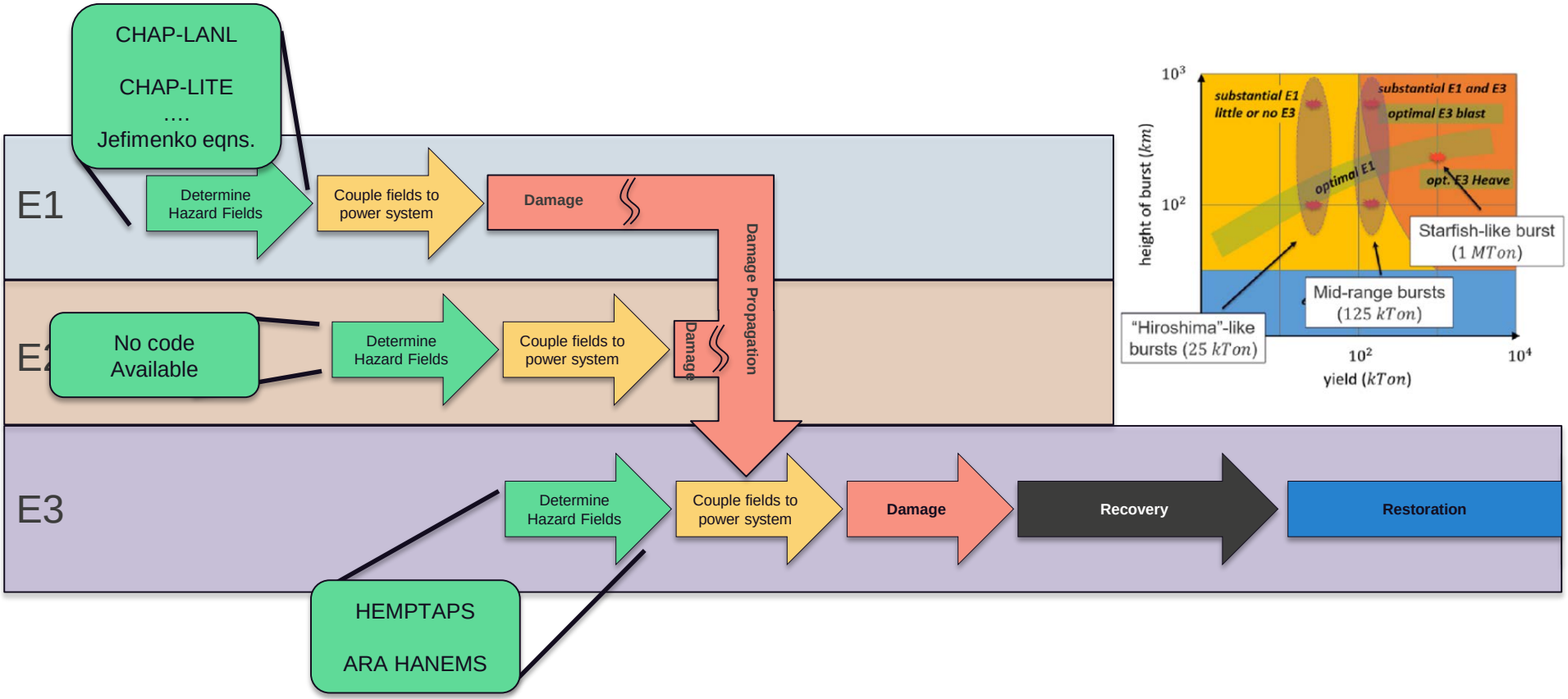


EMP Workflow

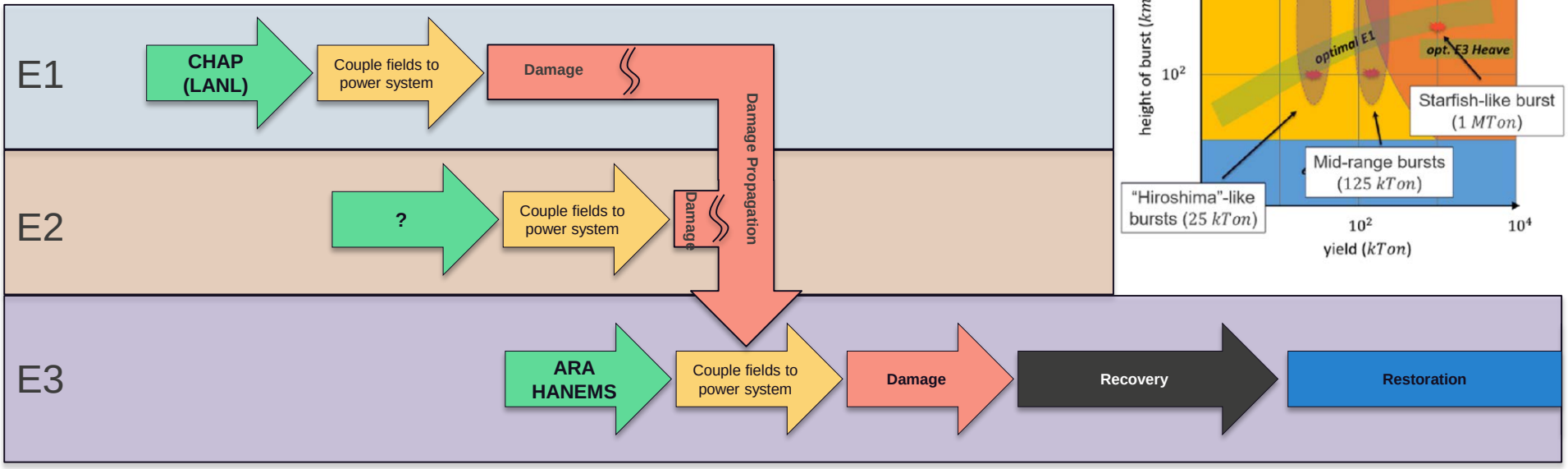


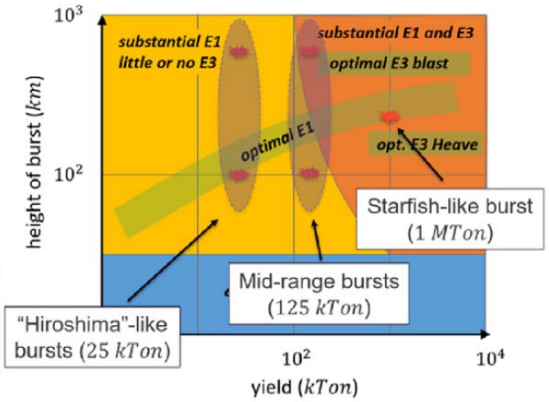
Inventory of Software and Models to be used in EMP Workflow [Phase 1 – D4, Phase 2-D2]

EMP Workflow



EMP Workflow



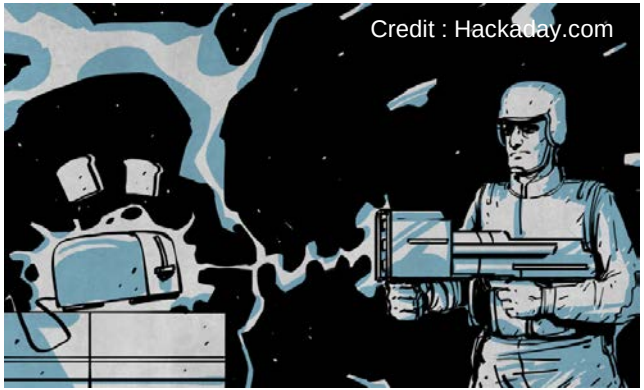


Electromagnetic Field Coupling

Radiated Coupling:

An electromagnetic pulse directly impacts a device causing it to become upset or damaged.

(EMP field level at the device)

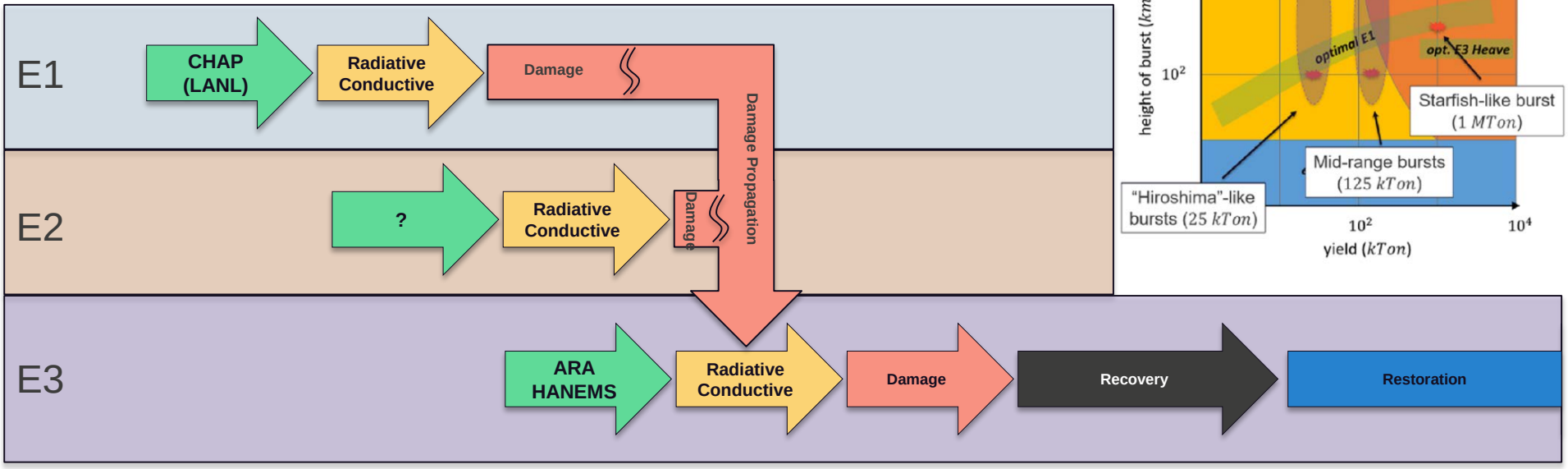


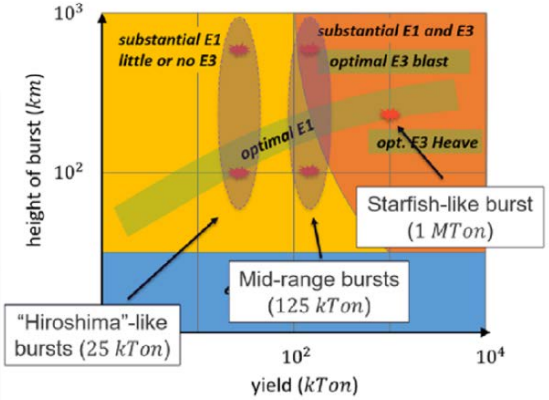
Conducted Coupling:

An electromagnetic pulse couples to transmission / measurement / communication cables that are connected to devices.

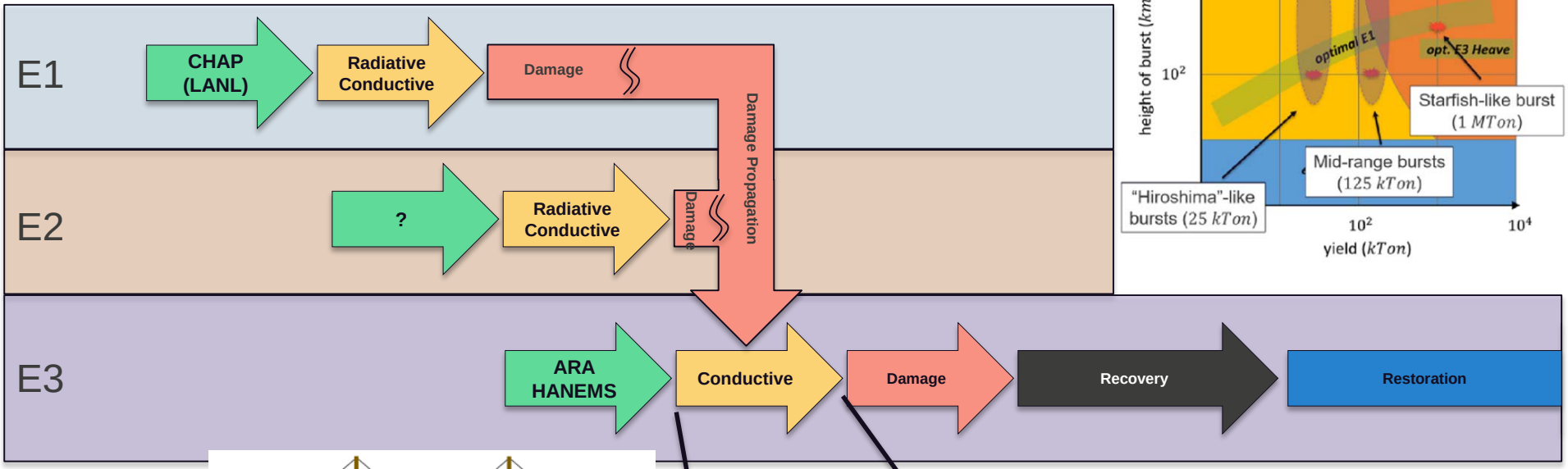
(Size of current or voltage pulse at device terminal)

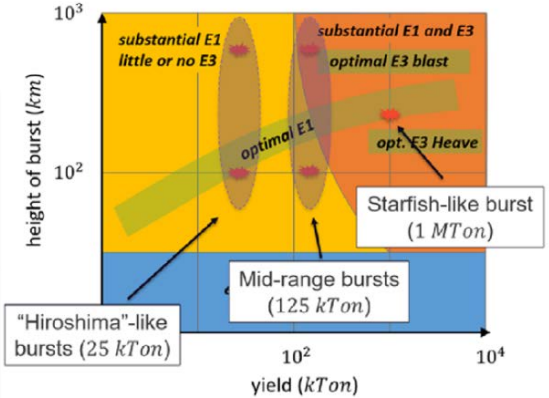
EMP Workflow

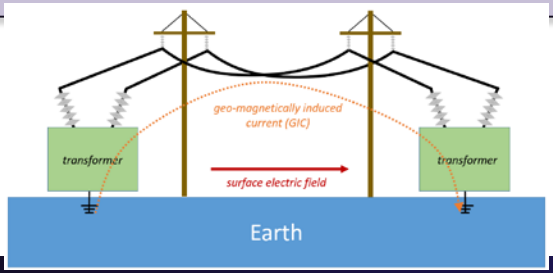




EMP Workflow

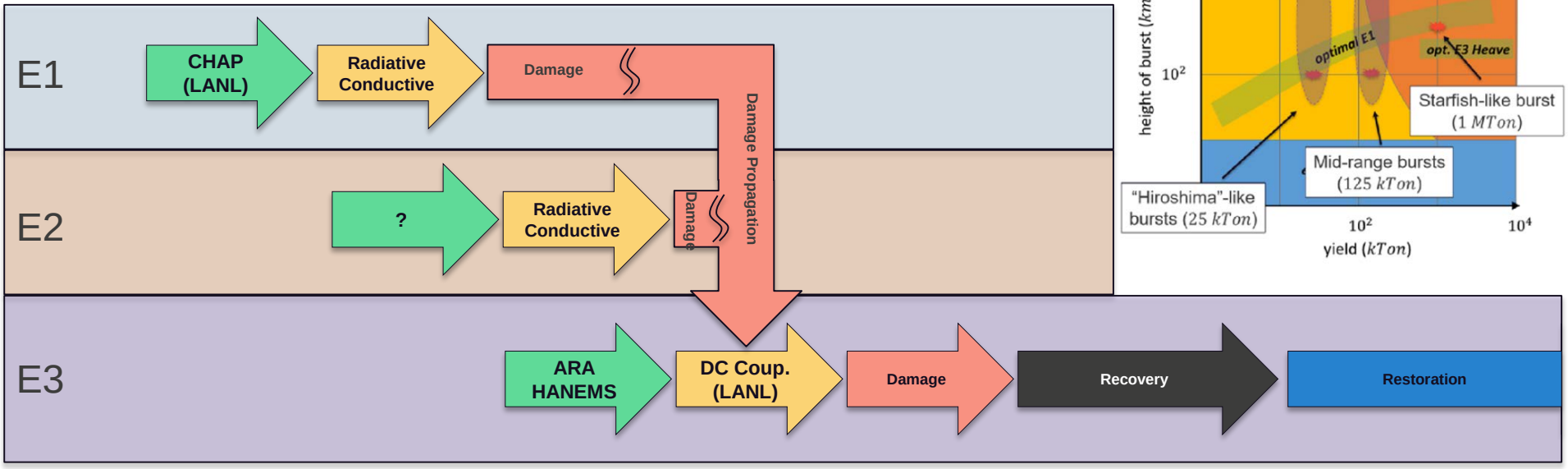


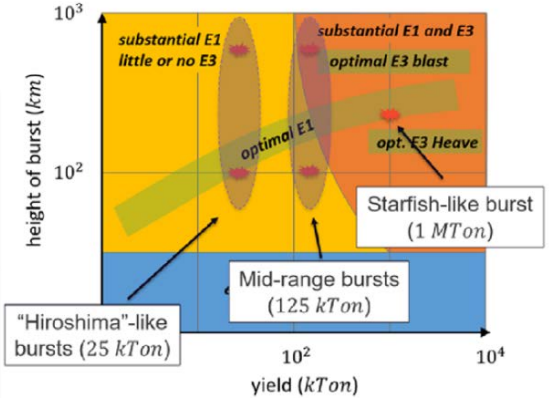




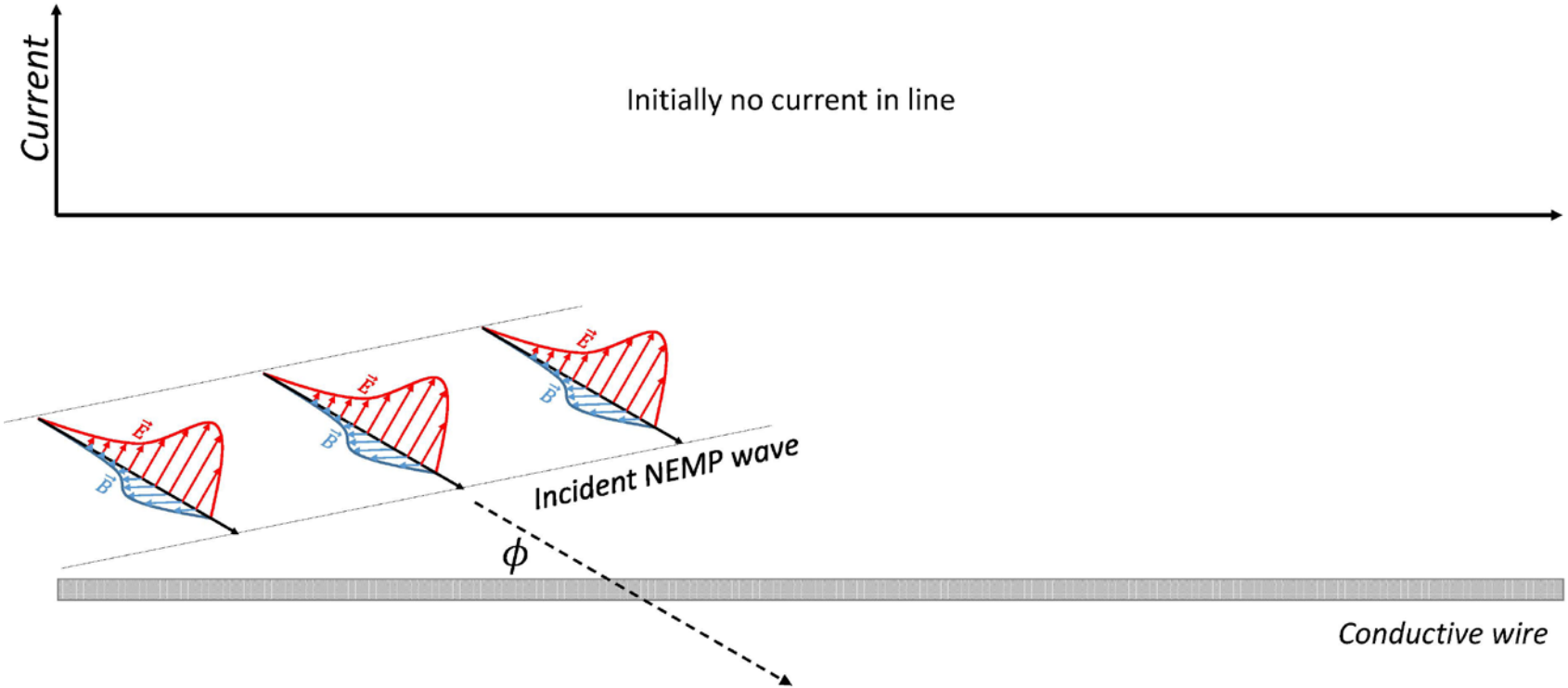
Power World GIC
…
DC GIC Solver
(Pirjola)

EMP Workflow





High Frequency Line Coupling



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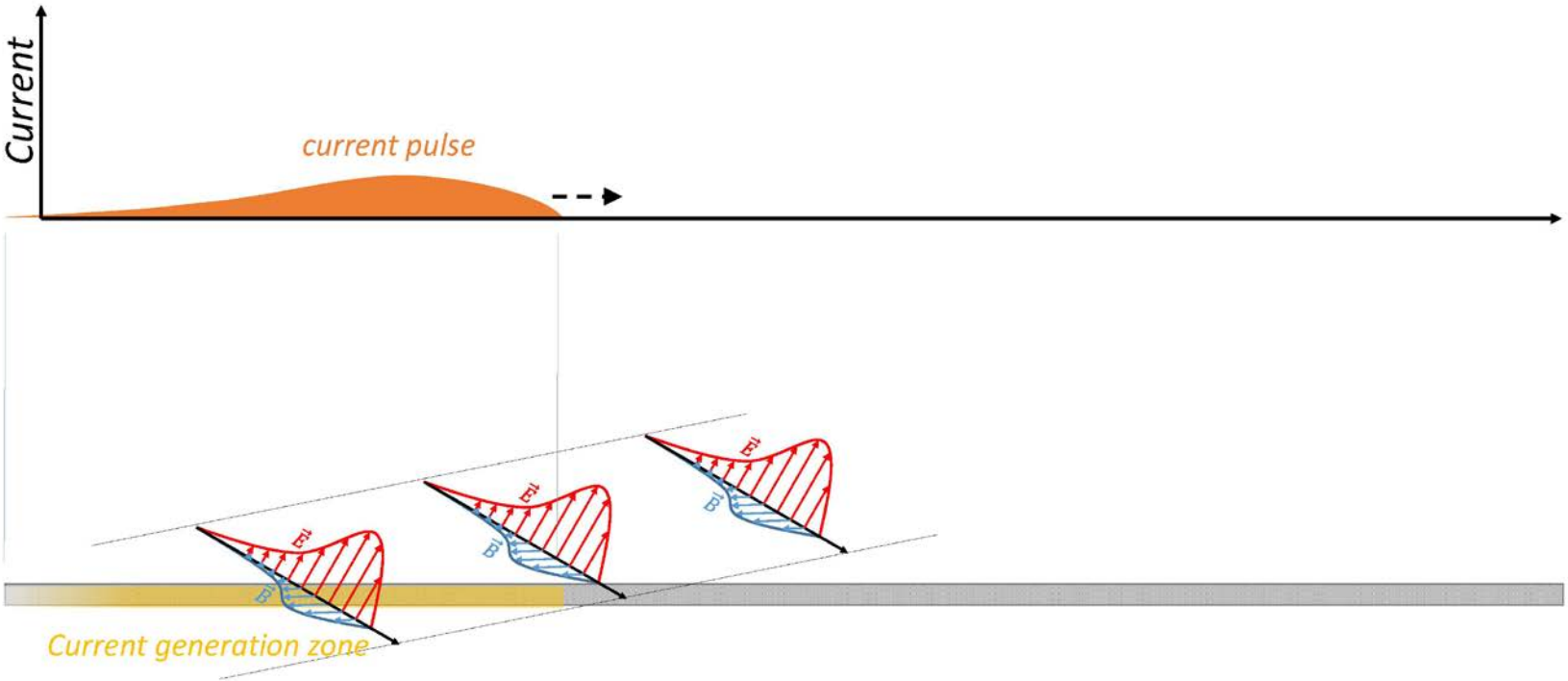

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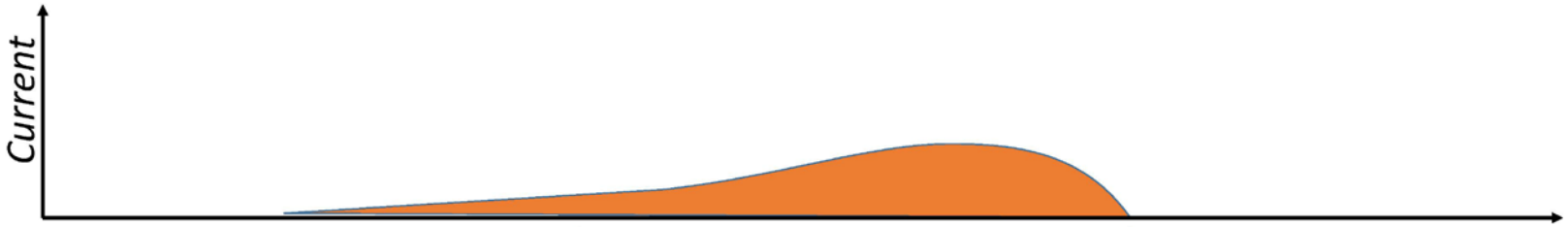
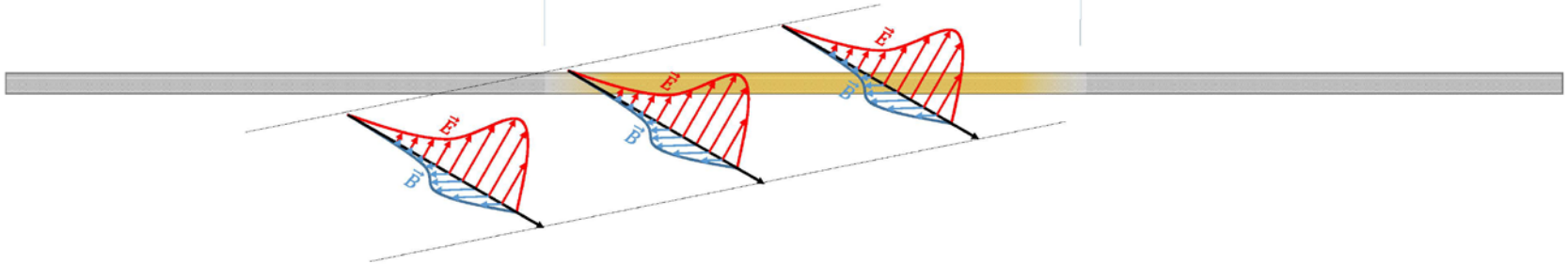
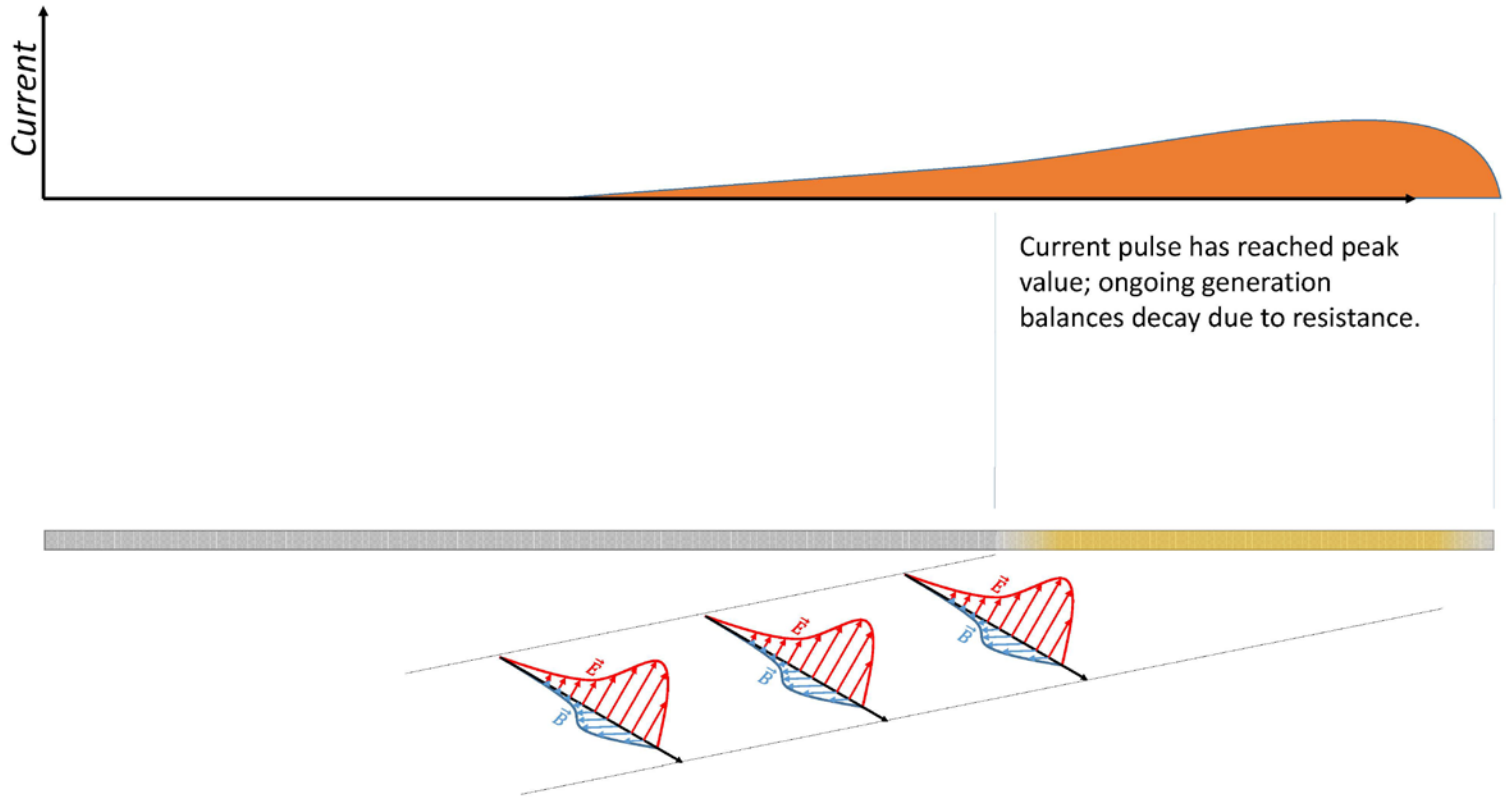


Current here due to previous line coupling. Since there is no generation this will decay due to line resistance.

Current here the sum of previous line coupling (decayed due to resistance) and generation from ongoing line coupling.



High Frequency Line Coupling

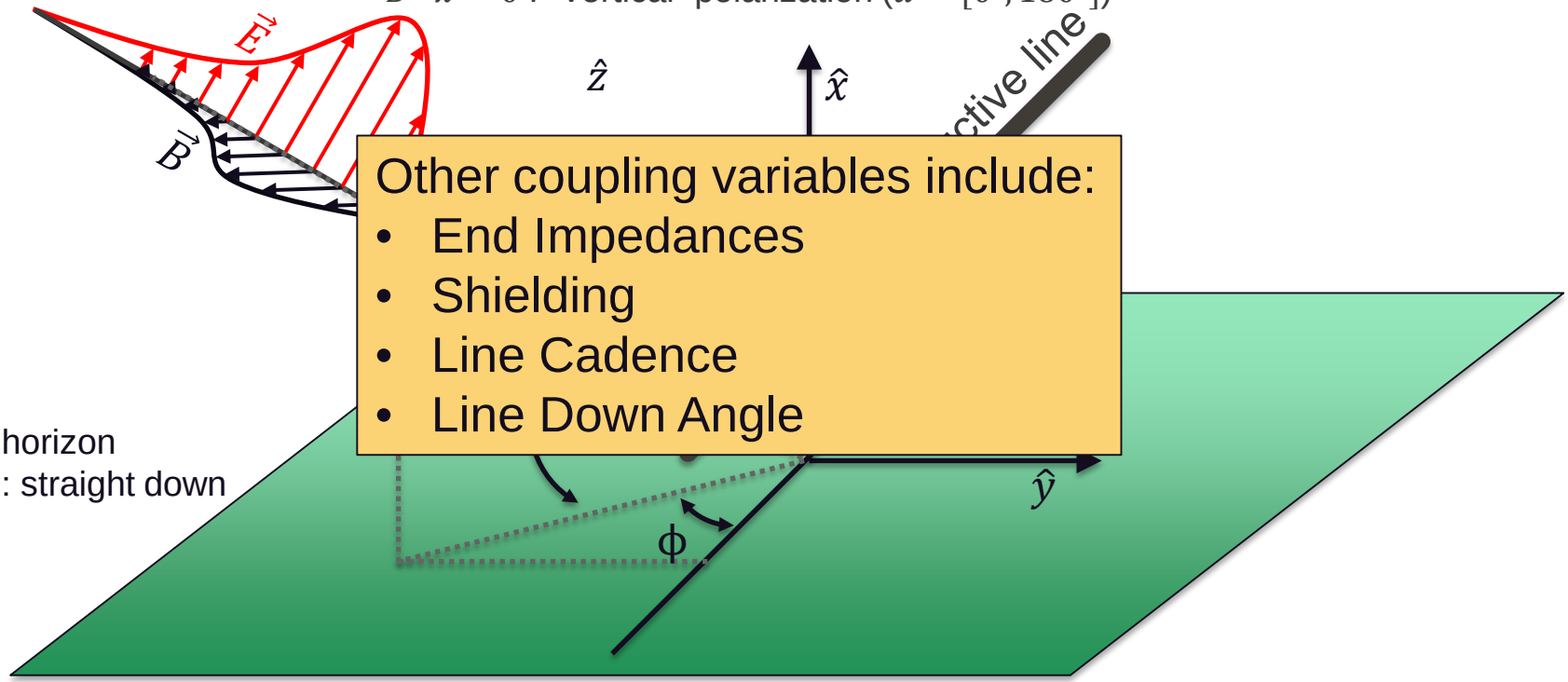


Major field coupling variables

Electric field magnitude and wave form

$\vec{E} \cdot \hat{x} = 0$: "Horizontal" polarization ($\alpha = \pm 90°$)

$\vec{B} \cdot \hat{x} = 0$: "Vertical" polarization ($\alpha = [0°, 180°]$)



Other coupling variables include:

- End Impedances
- Shielding
- Line Cadence
- Line Down Angle

$\psi = 0°$: horizon

$\psi = 90°$: straight down

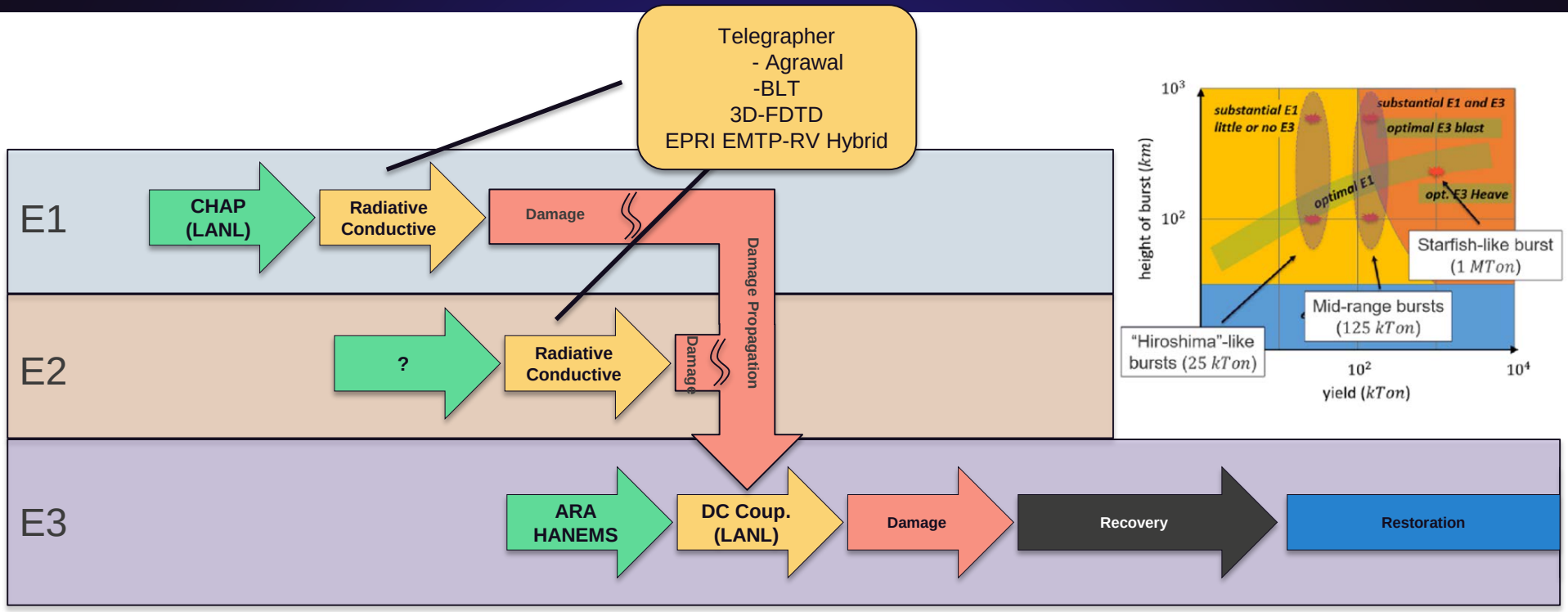
$\phi = 0°$: sweeping mode

$\phi = 90°$: broadside

ground plane

σ : conductivity

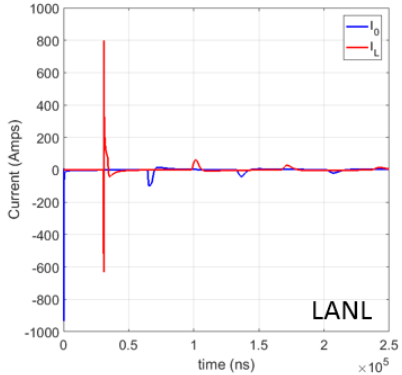
EMP Workflow

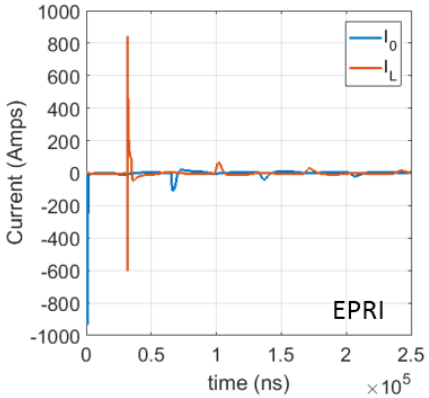


Baum-Liu-Tesche Coupling

Transmission

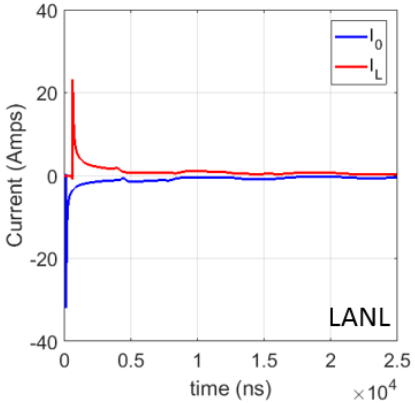
$E_0 = 50kV/m, \alpha = 13°, \psi = 7°, \phi = 22°$
$a = 1.0\ cm, h = 10.0\ m, L = 10\ km$

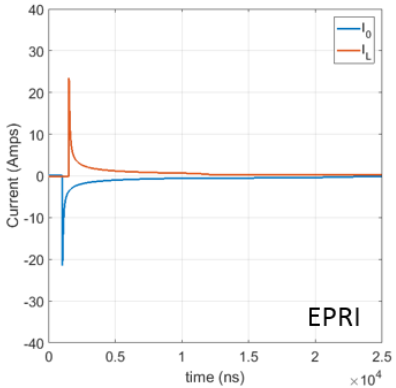




Measurement

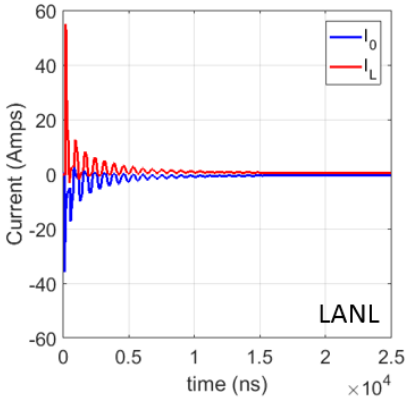
$E_0 = 10kV/m, \alpha = 43°, \psi = 33°, \phi = 80°$
$a = 5.0\ mm, h = 5.1\ mm, L = 1000\ m$

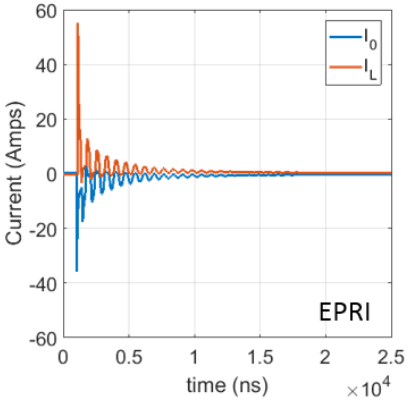




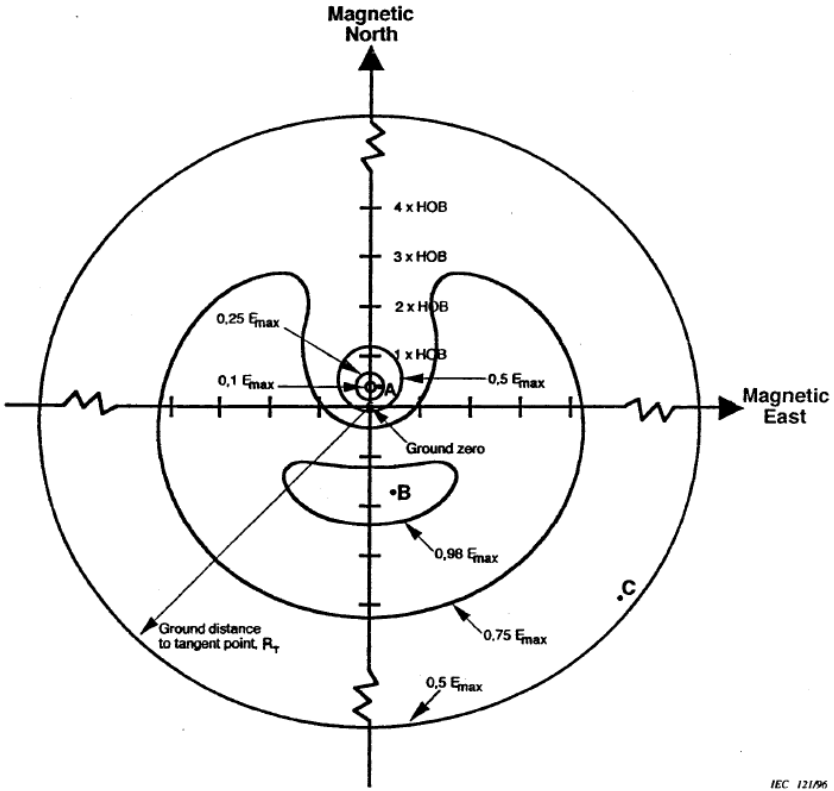
Communication

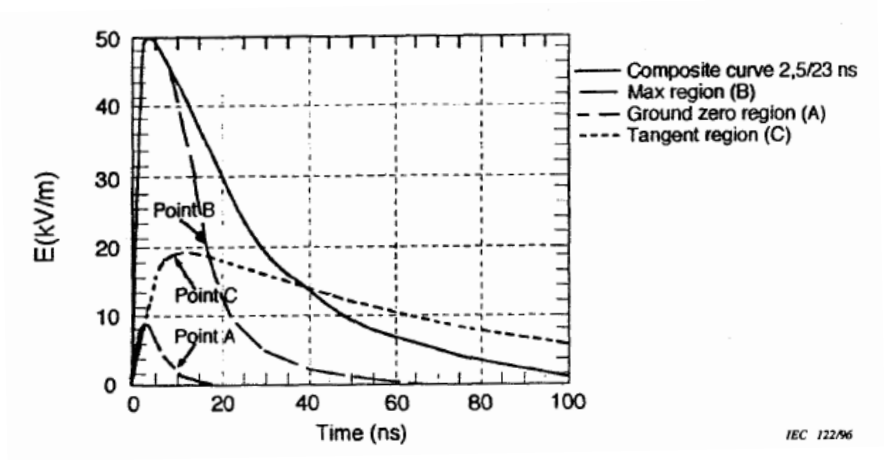
$E_0 = 10kV/m, \alpha = 80°, \psi = 63°, \phi = 54°$
$a = 1.0\ mm, h = 1.0\ m, L = 100\ m$





Waveform simplification

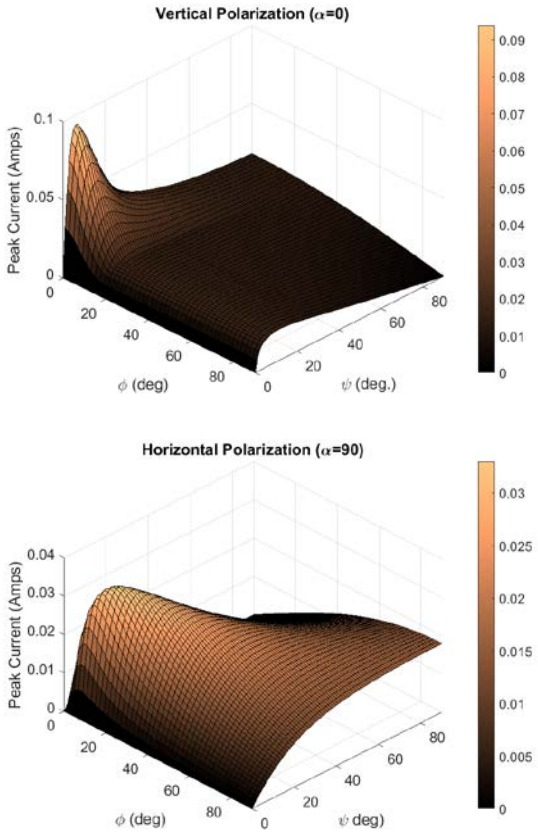




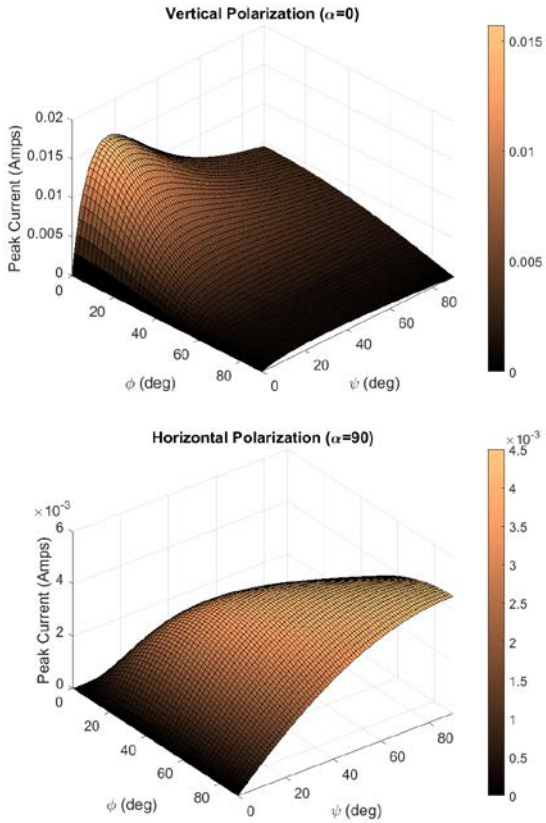
Rather than use the CHAP produced waveform at each location under the burst, we scale the IEC composite waveform by the peak magnitude of field produced by CHAP.

Line Coupling Current Response (1 Ohm termination at 1 V/m)

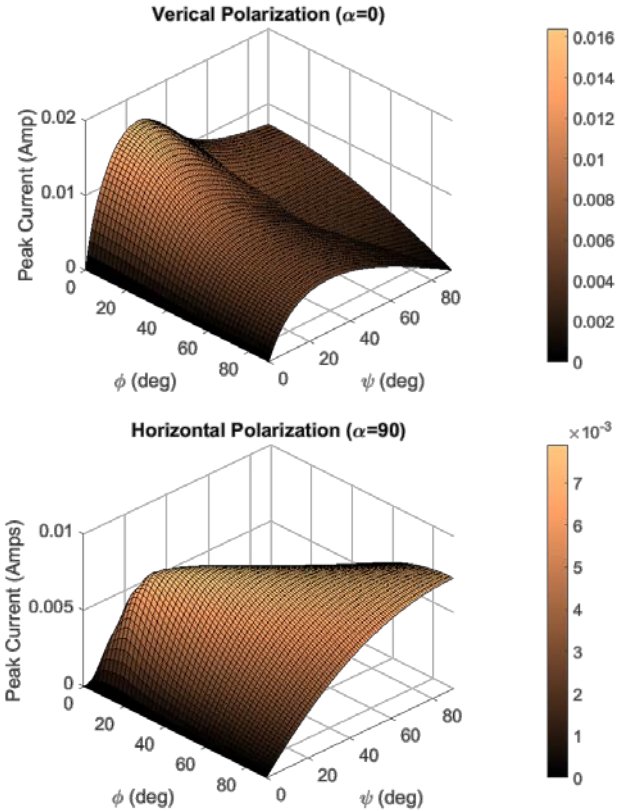
Transmission



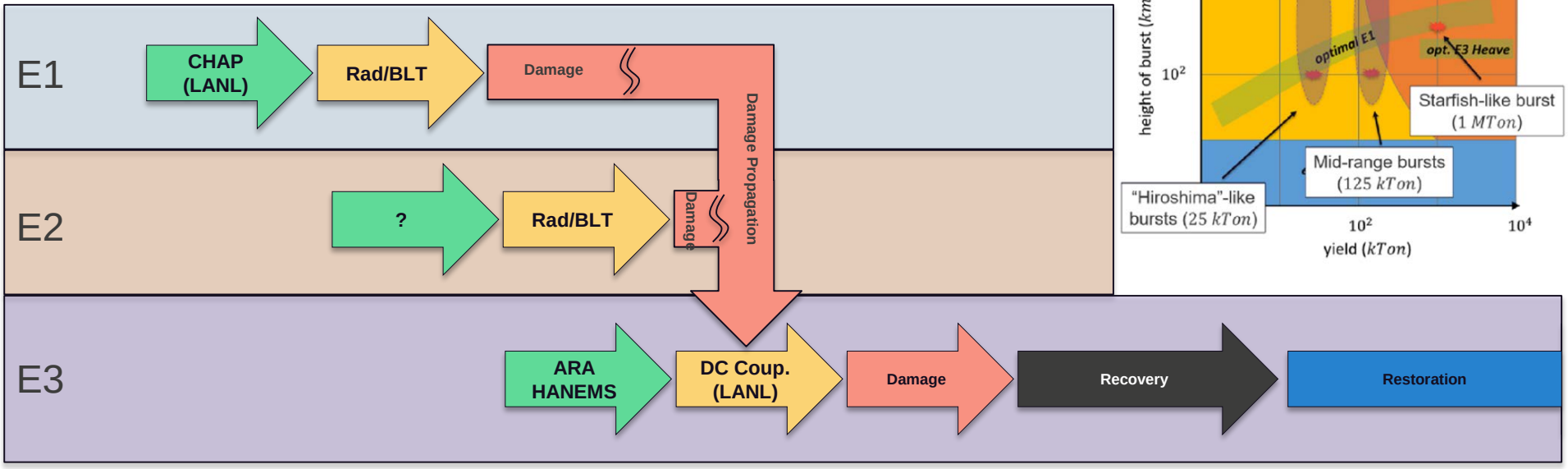
Measurement

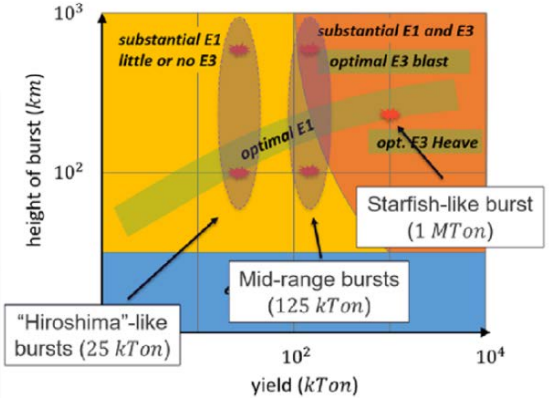


Communication



EMP Workflow





High Frequency Damage

XFMR	Shots #@kV	Peak Voltage (kV)	Time to Peak (ns)	Surge Arrester	Notes	Result
ZS1						Pulser calibration
ZS2	1@400	264	618	No	(1)	T-T failure
ZS3	2@400	288	668	No	(2)	HV-LV failure
ZS4	2@400	280	600	No	(1)	L-L failure
ZS5	1@400	272	550	No	(2)	HV-LV failure
ZS6	2@400	290	643	No	(1)	No damage
ZV1	1@400	296	601	No	(1)	No damage
ZV2	1@400	304	592	No	(2)	HV-LV failure
ZV3	2@400	110	100	Yes	(3)	No damage
ZV4	2@500	110	100	Yes	(3)	No damage
ZV4	2@780	116	110	Yes	(3)	No damage
XV1	1@400	272	500	No	(2)	HV-LV failure
XV2	2@400	115	110	Yes	(3)	No damage
ZW1	2@400	292	552	No	(1)	No damage
ZW2	2@400	16	Oscillatory	No	(4)	No damage
ZW3	2@780	100	110	Yes	(3)	No damage
ZW4	2@1000	112	105	Yes	(3)	No damage
ZD1	2@400	120	550	No	(5)	No damage
ZD2	2@400	20	Oscillatory	No	(4)	No damage
ZE1	2@1000	95	100	Yes	(6)	No damage
ZE2	6@780	95	100	Yes	(6)	No damage

(1) External flashover on HV bushing; T-T failure denotes turn-to-turn failure; L-L failure denotes line-to-line failure
(2) No external flashover; HV-LV failure denotes a high-voltage winding flashover to the low-voltage winding
(3) Surge arrester operation and no external flashover
(4) Surge applied to the low-voltage bushings with no external flashover
(5) Surge applied common mode to both HV bushings with external flashover
(6) Surge applied common mode to both bushings, and both arresters operated

- **Oak Ridge National Laboratories "E1" tests of 7.2 KV distribution transformers**
- **Some transformers experienced permanent damage (seven of the twenty units tested)**
  - turn-to-turn flashover
  - primary-to secondary flashover

High Frequency IEC Protection Concepts and Immunity Levels

Protection concepts	Equipment location	Probability for long lines (percent)	Conducted disturbance a.c. power	Conducted disturbance Telecom	I/O data ports
6 (indoors)	Within a room with excellent RF shielding (80 dB) and POE protection (80 dB)	99	EC4	EC1	---------
5 (indoors)	Within a room or building with good RF shielding (60 dB) and POE protection	9			
4 (indoors)	Within a room or building with nominal to good RF shielding (40 dB) and nominal over-voltage and EMI protection	9			
2B (indoors)	Within a structure with rebar and nominal lightning protection at the a.c. main	5			
1A (indoors)	Within a poorly shielded building or residence **without** lightning protection on the secondary distribution power line	5 9			
1B (outdoors)	Directly connected to the primary voltage distribution power line with nominal lightning protection	9			

NOTE 1 The shielding associated with the protec[illegible] EC4 is the minimum recommended level for power ports due to the normal level of transients observed on power circuits.

NOTE 2 Protection concepts (indoors) are a combination of probable flashover effects and the protection concepts in IEC 61000-2-1.

[a] For buildings with underground lines. For secondary power distribution with lightning protection and telecom lines with gas-tube protection, reduce the level to 8 kV.

Immunity test level	V_{oc} V	I_{sc} A	Waveform	Basic standard	Severity level in the basic standard
EC1	100	2	Damped sinusoids [a]	IEC 61000-4-18	X
			amped sinusoids [a]	IEC 61000-4-18	X
			amped sinusoids [a]	IEC 61000-4-18	1
			amped sinusoids [a]	IEC 61000-4-18	2
			amped sinusoids [a]	IEC 61000-4-18	3
			amped sinusoids [a]	IEC 61000-4-18	4
			5/50 ns	IEC 61000-4-4	4
			5/50 ns	IEC 61000-4-4	X
			5/50 ns	IEC 61000-4-4	X
			25/500 ns	This standard	EC10
			10/100 ns	This standard	EC11
			Fast transient	This standard	ECX

are for common mode values.

25 kV: 1 kV, 4 kV, 8 kV and 16 kV.

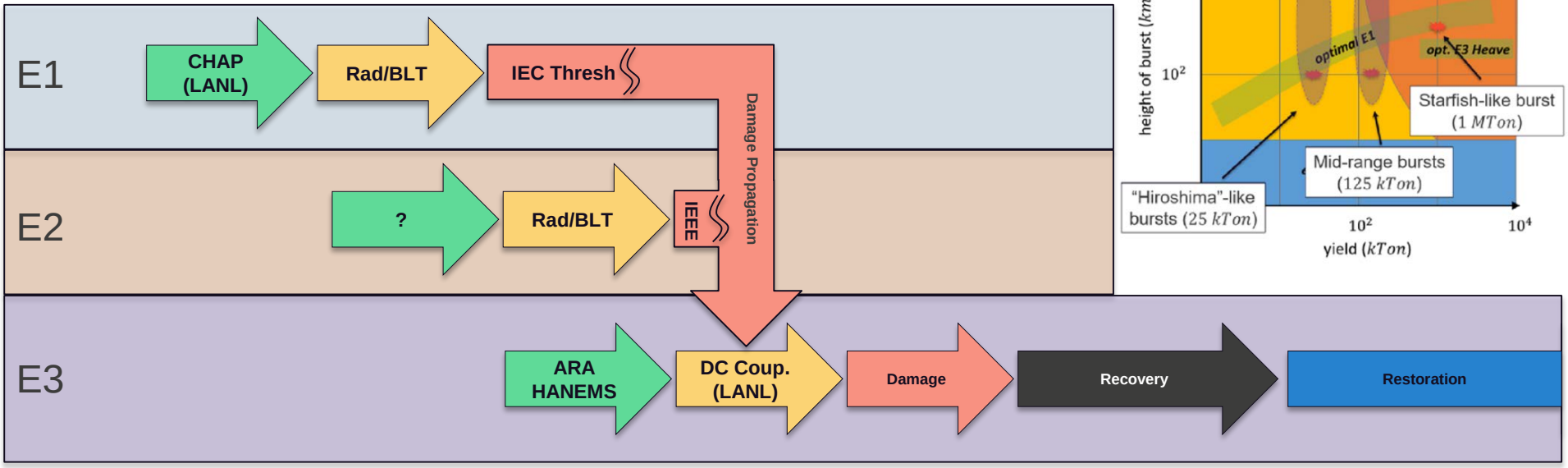
fficient to test with a single pulse.

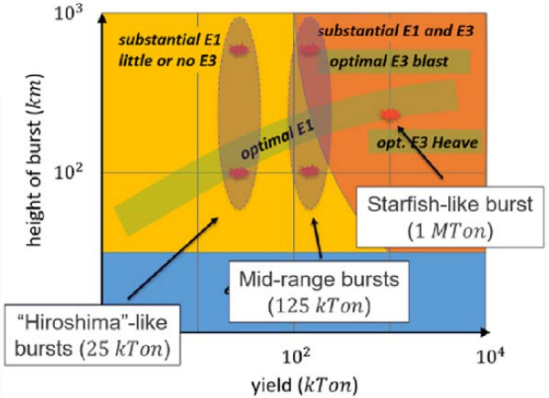
160 kV: 20 kV, 40 kV, 80 kV and 120 kV. This immunity test tly connected to long MV distribution power lines protected ease V_{oc} to 1,6 MV and I_{sc} to 4 000 A (see Annex A).

a Each immunity test level consists of at least three frequencies: 3 MHz, 10 MHz and 30 MHz. The damping parameter Q of the damped oscillatory wave test, as defined by equation (D.1) in IEC 61000-2-10:1998, ranges from 5 to 20.

Given the lack of publicly available test data (to failure), we adopt a binary (i.e damaged/undamaged) model based on exceeding multiples of immunity test levels. This will be substituted with data from EPRI as it becomes available.

EMP Workflow

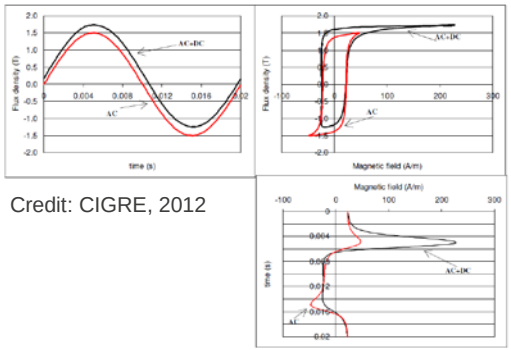




DC Damage

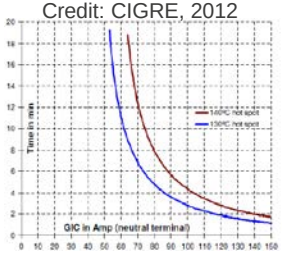
DC currents flowing through transformer neutrals have deleterious effects on transformers

Transformer Saturation

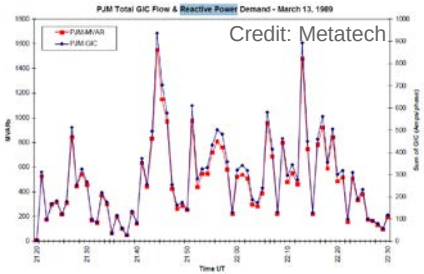


Credit: CIGRE, 2012

Credit: CIGRE, 2012

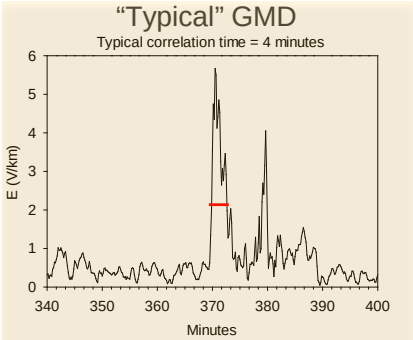


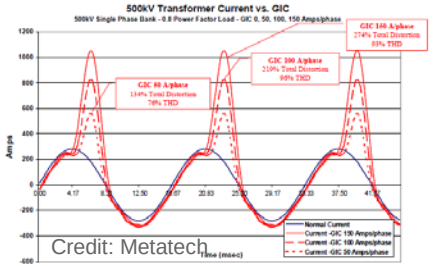
Transformer heating—degradation and potential failure–several minutes



Credit: Metatech

Increased transformer VAR consumption—potential voltage collapse—seconds→minutes



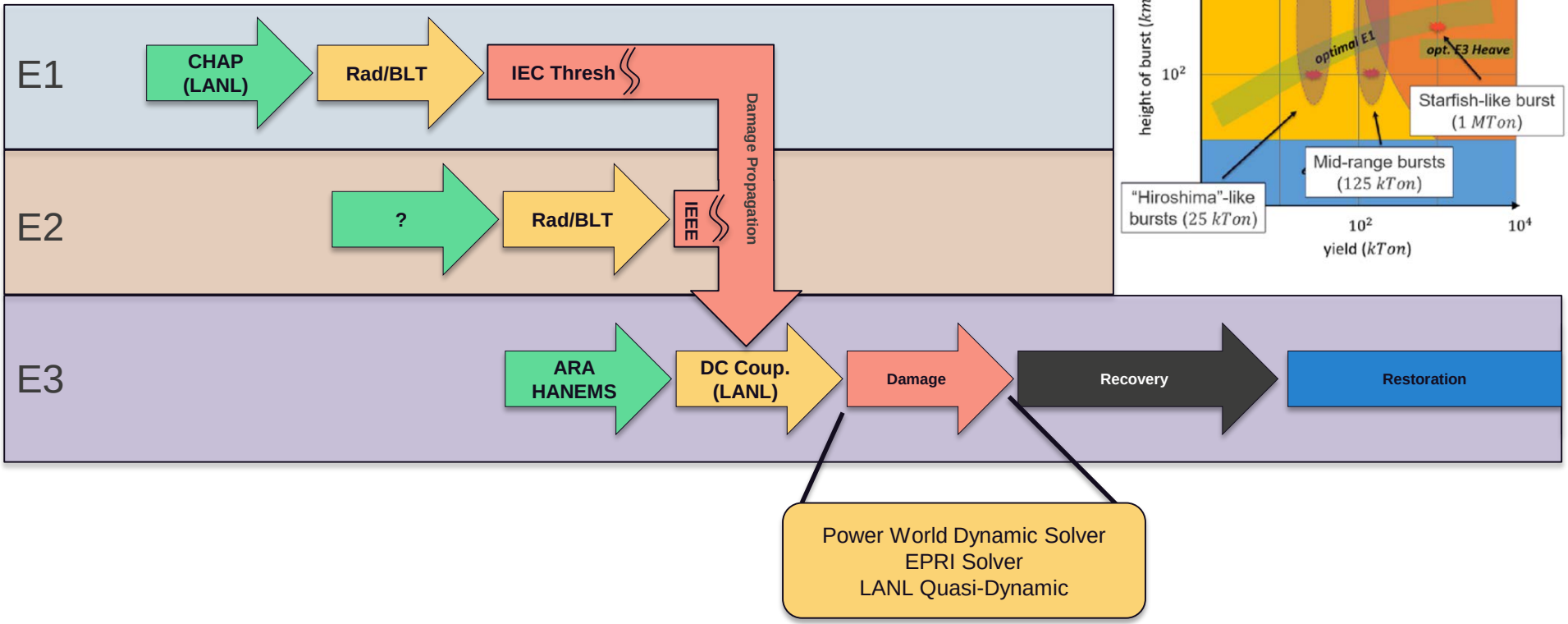


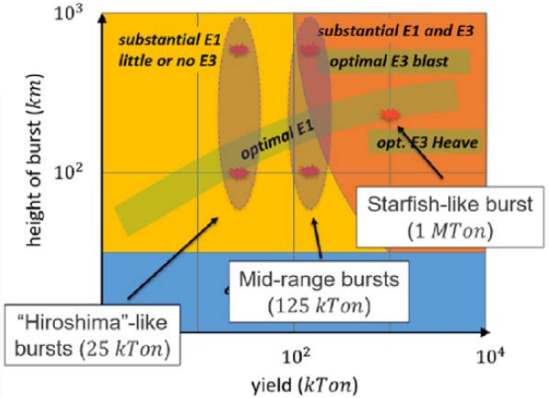
Credit: Metatech

Harmonic generation—potential relay misoperation—seconds

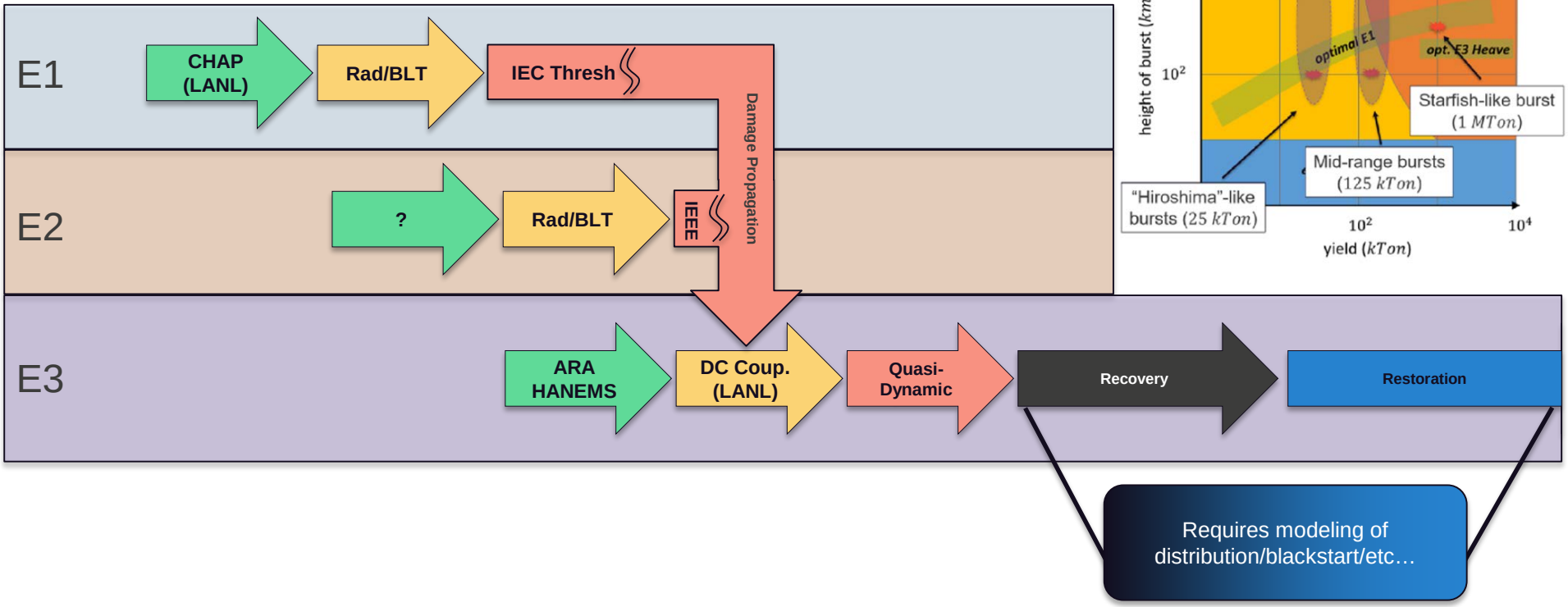
"Behaviour of transformers under DC/GIC excitation: Phenomenon, Impact on design/design evaluation process and Modelling aspects in support of Design" T. NGNEGUEU et al, CIGRE, 2012

EMP Workflow





EMP Workflow



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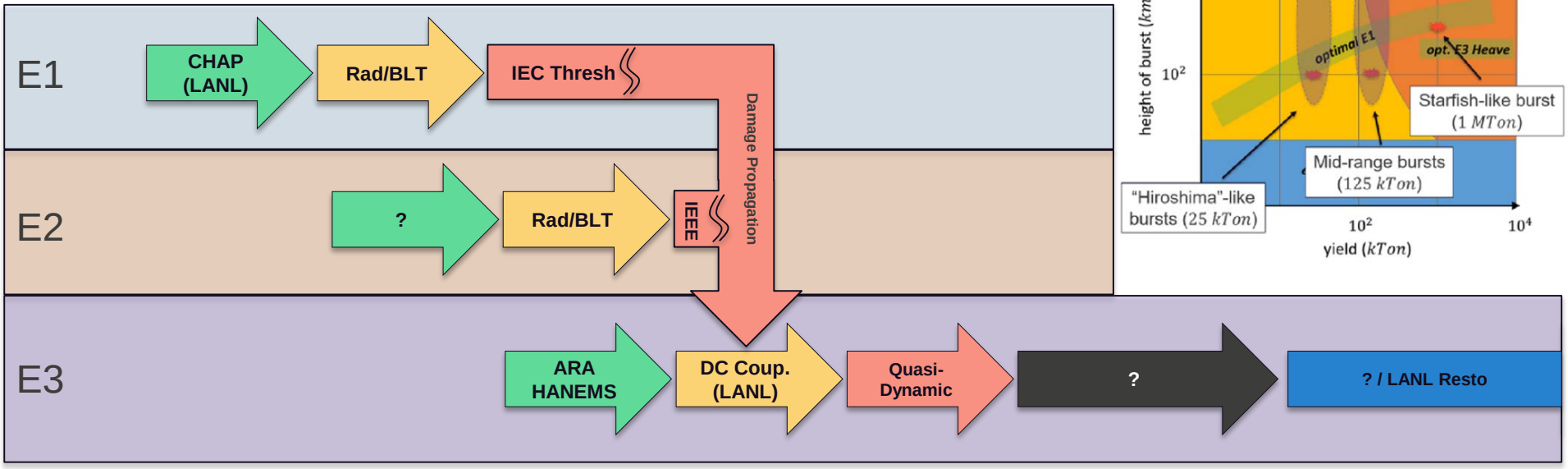
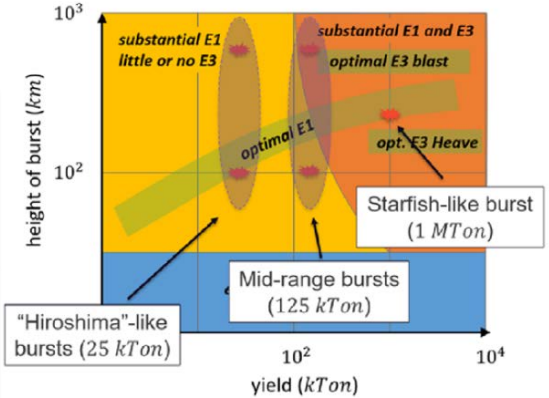




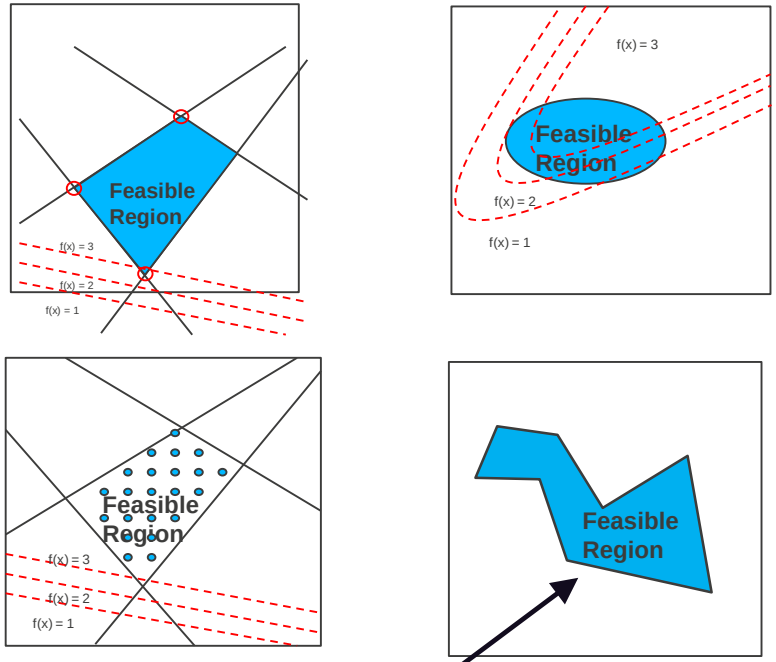
Damage Propogation Overview

- **Solving the AC power flow physics for severe (large) contingency case is difficult**
  - Commercial solvers used in typical power system analysis often diverge under these conditions—provide no solution
  - Typically leads to a time consuming, manually-driven analysis process
  - Not suitable for automated analysis

- **The Severe Contingency solver is an automated solver for calculating electric power outages (load shed) for contingency events**

Technical Challenges: Convexity

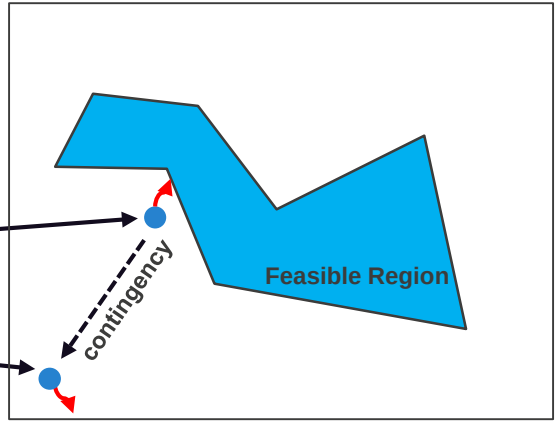
- **Problems that exhibit <u>convex</u> structure are typically easy to solve (e.g., the "DC approximation" to AC power flow)**
  - Linear
  - Cones
  - Ellipses
- **Problems that exhibit <u>non-convex</u> structure are typically hard to solve**
  - Discrete
  - Sines, Cosines
  - Bilinear (some)
- **<u>AC power flow equations are non-convex</u>…**



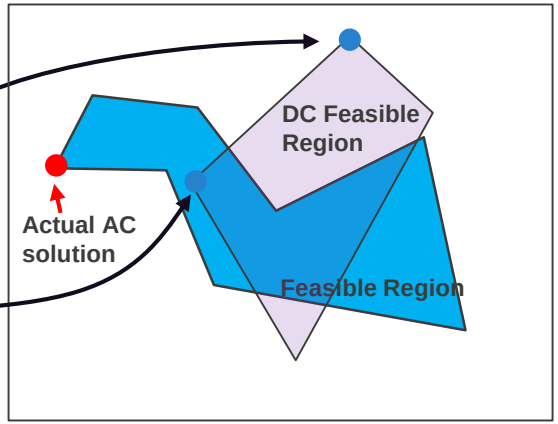
Each point in the feasible region represents a combination of voltage, real and reactive generation and load, tap ratios, etc. that does not violate physical constraints or power flow physics

Technical Challenges: Convexity

- **Current practice with commercial "Full AC solvers"**
  - Works fine when the solver has good initial conditions
    - Use solution from 15 minutes ago as initial conditions for current system state
  - Contingencies move system far away, making it hard to recover a solution

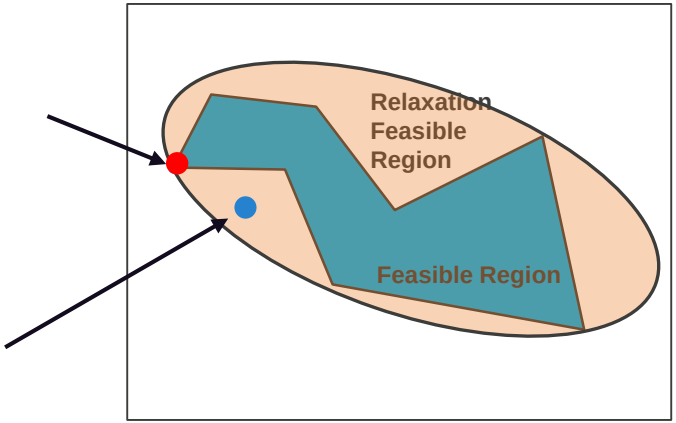


- **Typical approach—use linear DC power flow approximation**
  - Computationally tractable, but….
  - Misses key modeling details (voltages)
    - Relationship to full AC power physics not guaranteed
    - Solution could be worse or better than AC solution

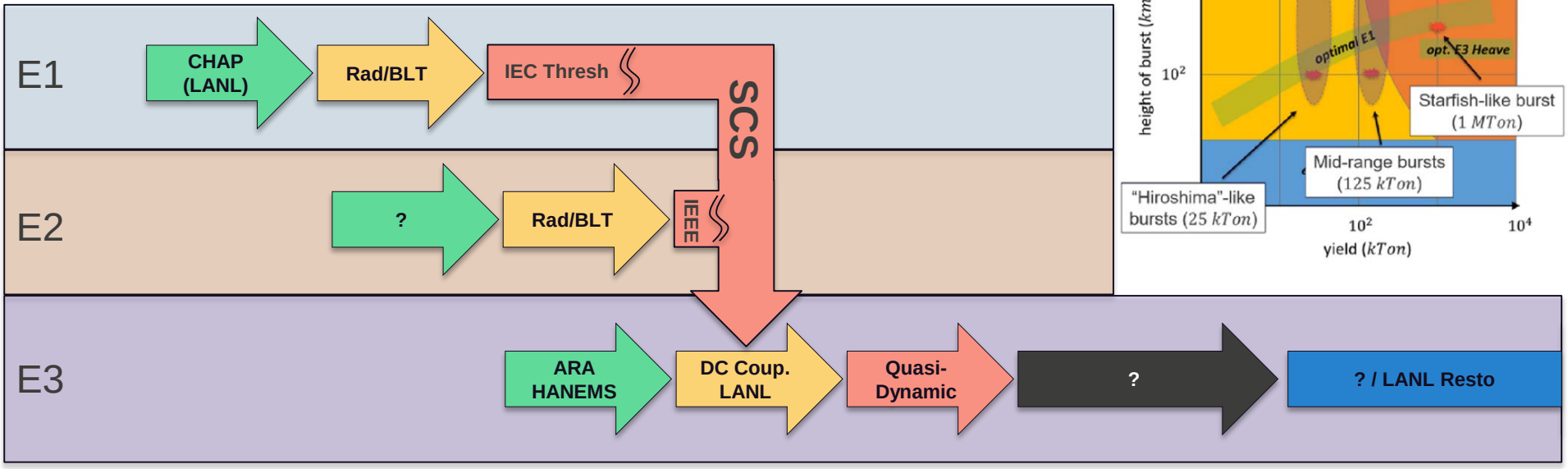


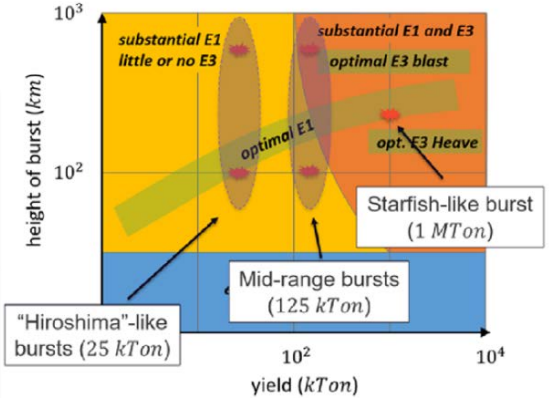
Technical Challenges: Convexity

- **Our Approach—Convex Relaxations**
  - Computationally Tractable
  - Relationship to AC physics has <u>theoretical guarantees</u>
    - Best case—If relaxed solution is AC feasible, then the “Full AC” solution is feasible as well
    - Worst case—“Full AC” load shedding will be at least as large as the load shedding computed for the relaxation
      - Provides a good starting point to automatically “hot start” a commercial solver
  - Solutions on academic validation cases show that the relaxation is very tight--we expect <u>Best Case</u> a large fraction of the time

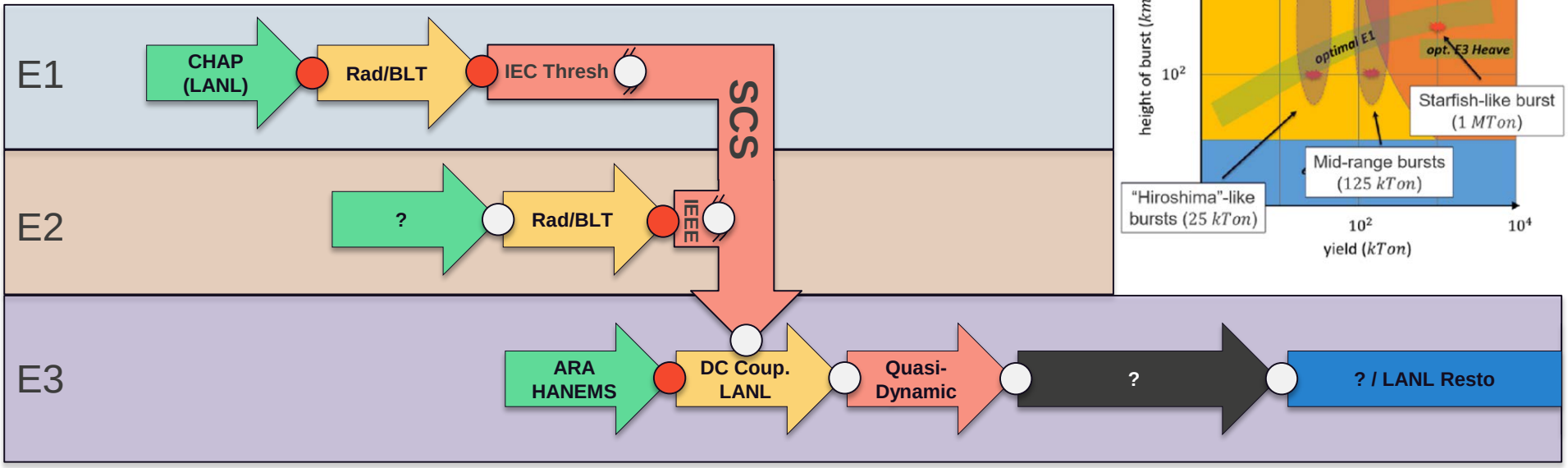


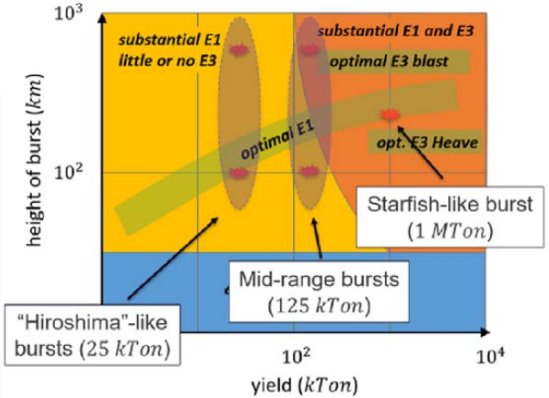
EMP Workflow





EMP Workflow (Current Status)



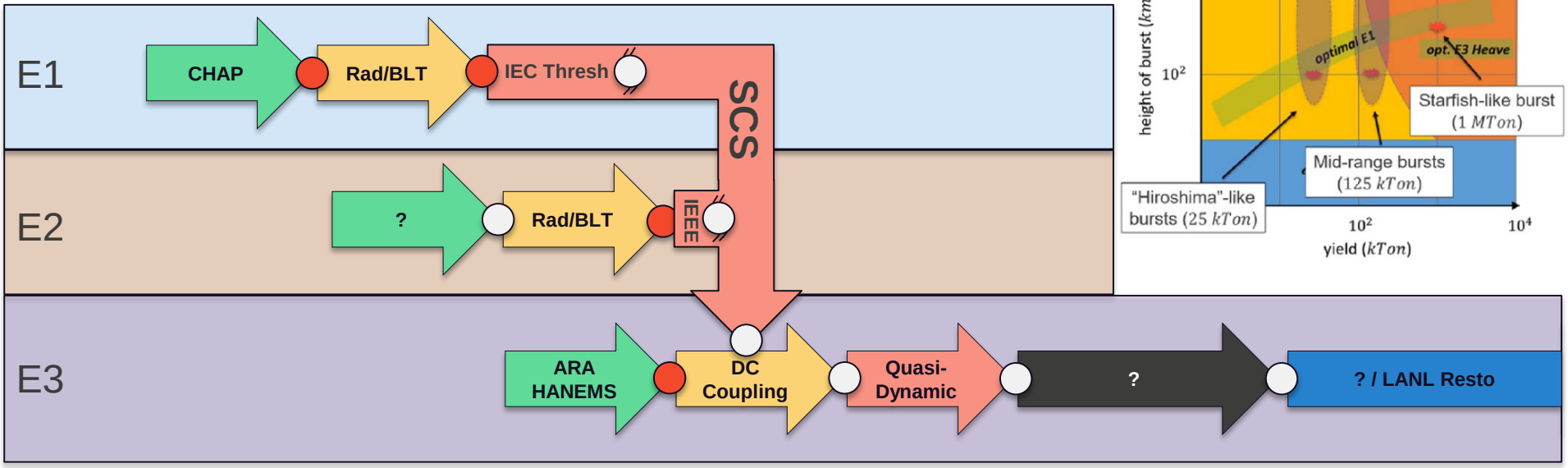


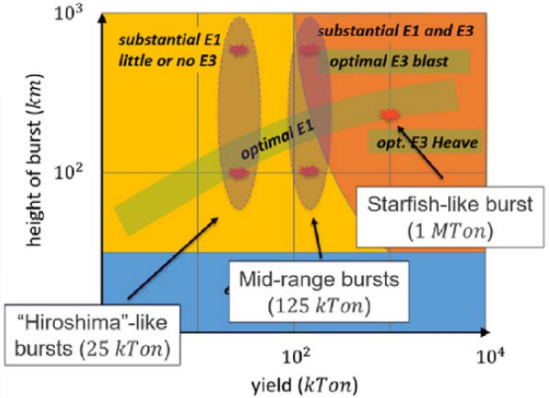
● Code successfully coupled

○ Code not coupled

Screening Analysis of Benchmark Events [Phase 1-D3, Phase 2-D3]

EMP Workflow (Field Generation)





Code successfully coupled

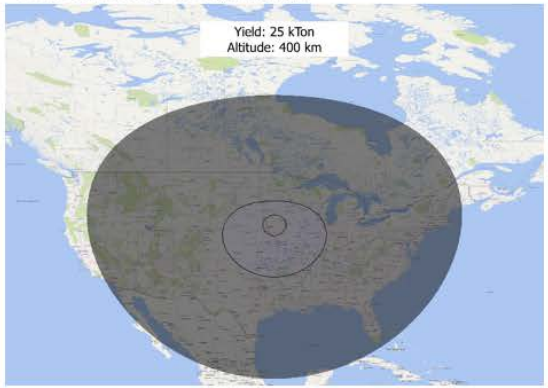
Code not coupled

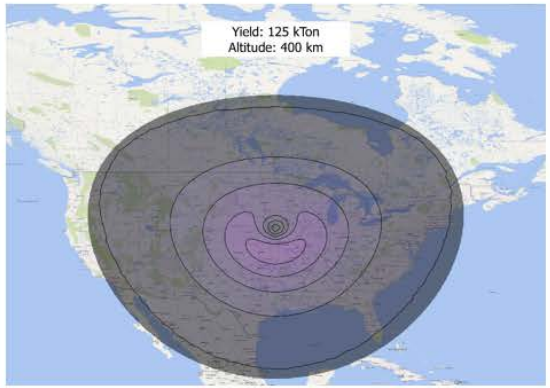
E1 Fields for Benchmark Scenarios (Notional Radiated Hazard)

LA-UR-17-24992

Gamma Source: 0.3% Yield, 0.2/sh rise, 2/sh fall
IGRF12 Magnetic Field
Radiated Hazard (CHAP): Peak Electric Field

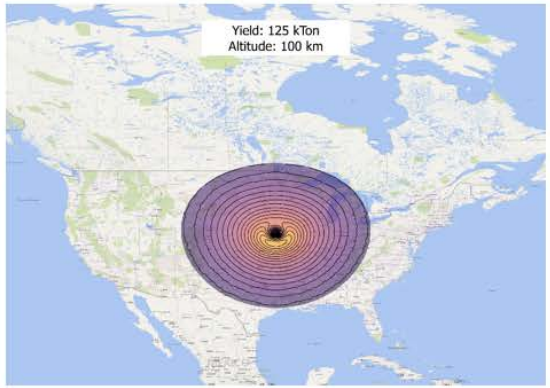
Contour Levels every 1 kV/m

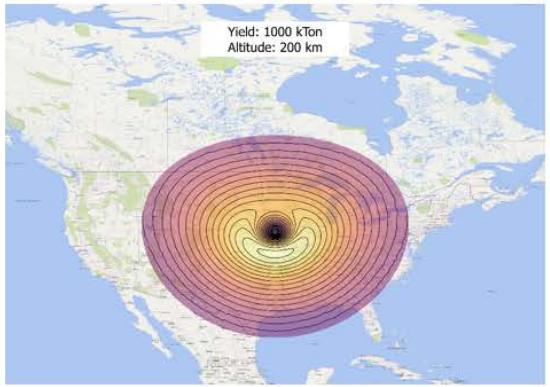




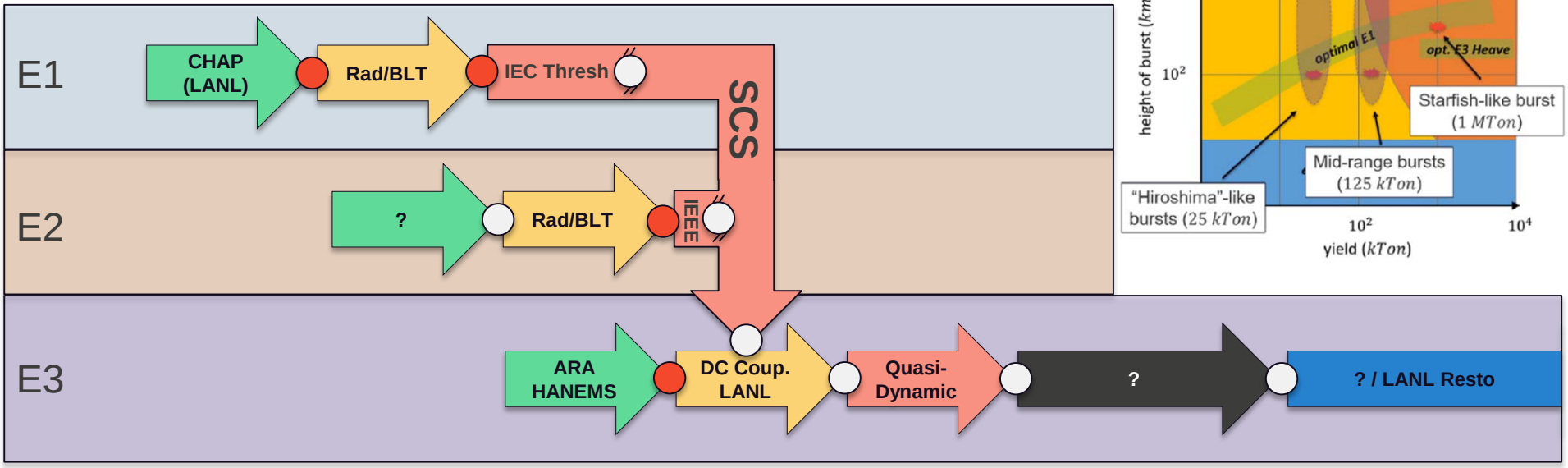
Maximum Field Values

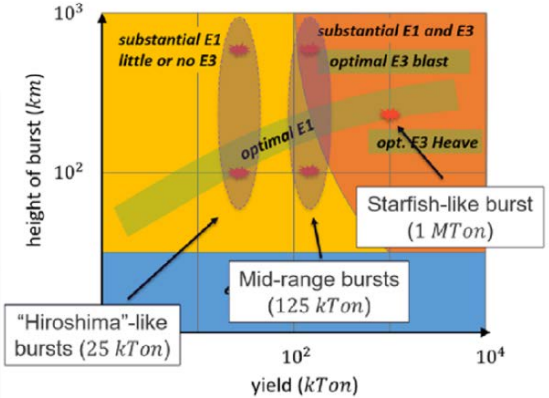
Yield (kTon)	H.O.B. (km)	Maximum Peak Electric Field (kV/m)
25	100	11.8
25	400	1.7
125	100	20.7
125	400	5.6
1000	200	25.3





EMP Workflow (Current Status)





Code successfully coupled

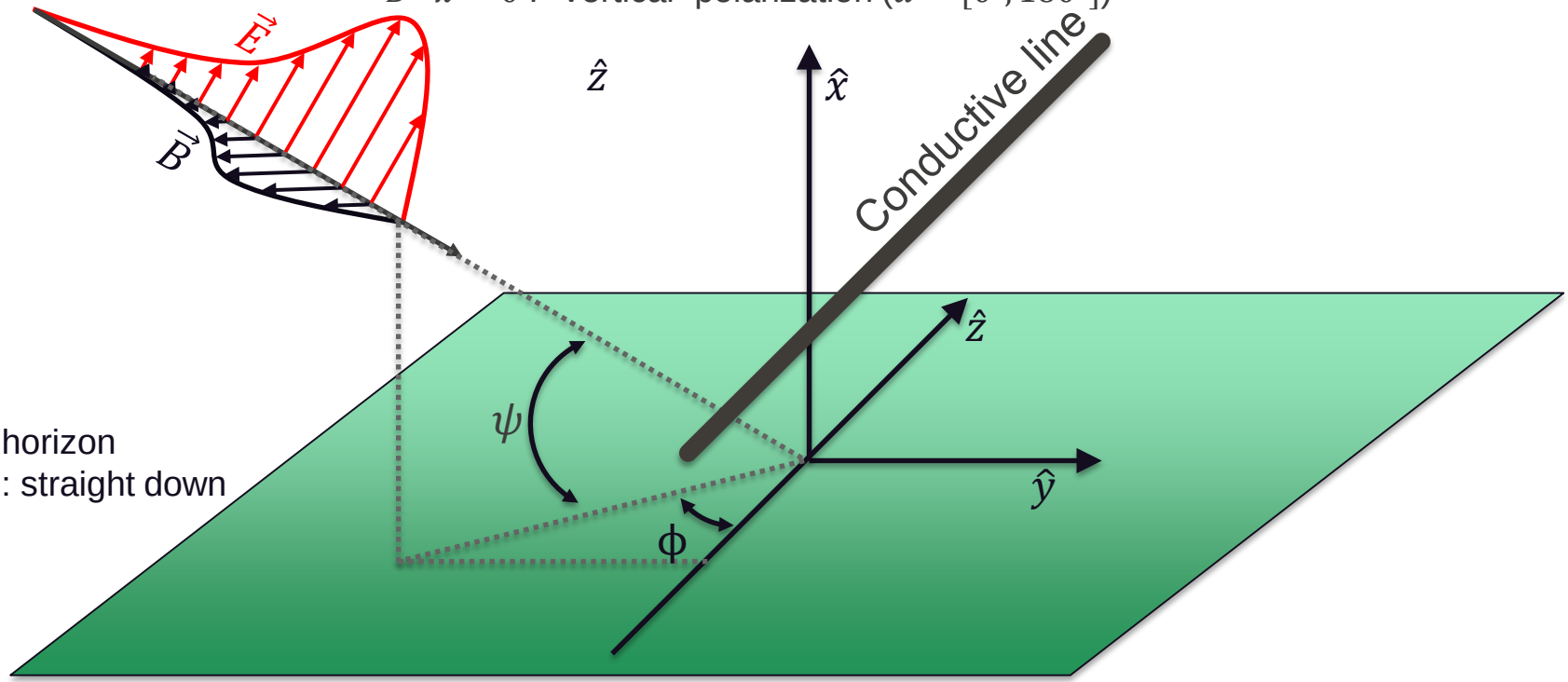
Code not coupled

Major field coupling variables

Electric field magnitude and wave form

$\vec{E} \cdot \hat{x} = 0$: "Horizontal" polarization ($\alpha = \pm 90°$)

$\vec{B} \cdot \hat{x} = 0$: "Vertical" polarization ($\alpha = [0°, 180°]$)



$\psi = 0°$: horizon

$\psi = 90°$: straight down

$\phi = 0°$: sweeping mode

$\phi = 90°$: broadside

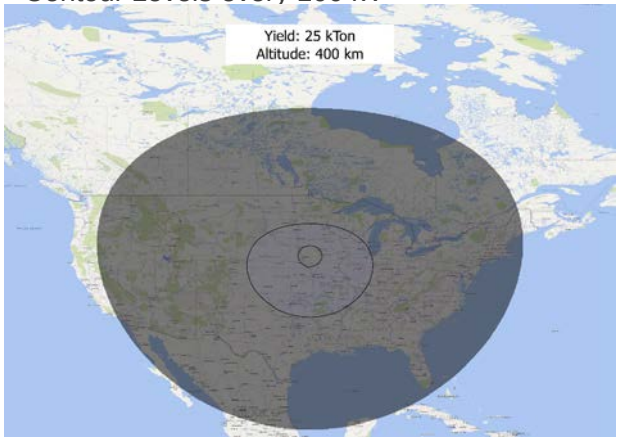
ground plane

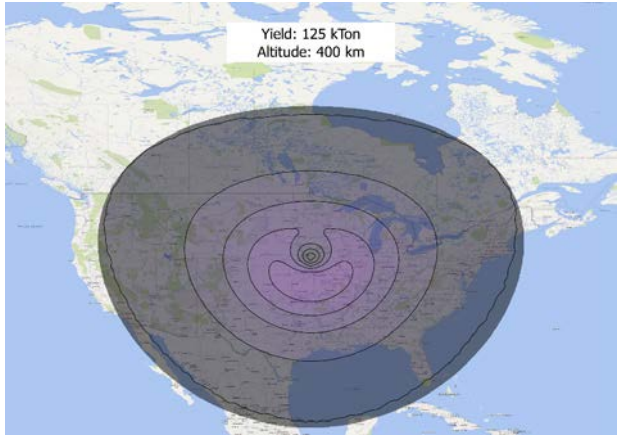
σ : conductivity

50 meter High Aerial Line (10 km long)
End Impedance: 1 GΩ

Worst Case Peak Voltage (Not Realizable)

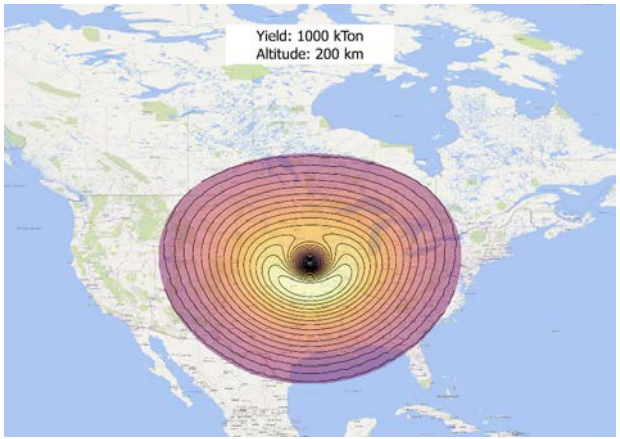
Contour Levels every 100 kV





Maximum Field Values

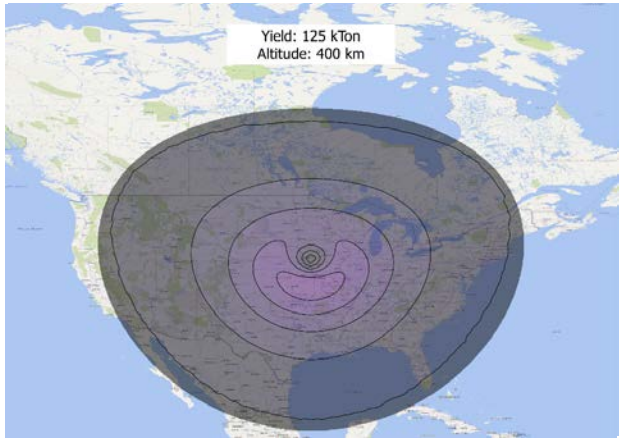
Yield (kTon)	H.O.B. (km)	Worst Case Peak Voltage (kV)
25	100	1264
25	400	181
125	100	2199
125	400	591
1000	200	2694



50 meter High Aerial Line (10 km long)
End Impedance: 1 GΩ

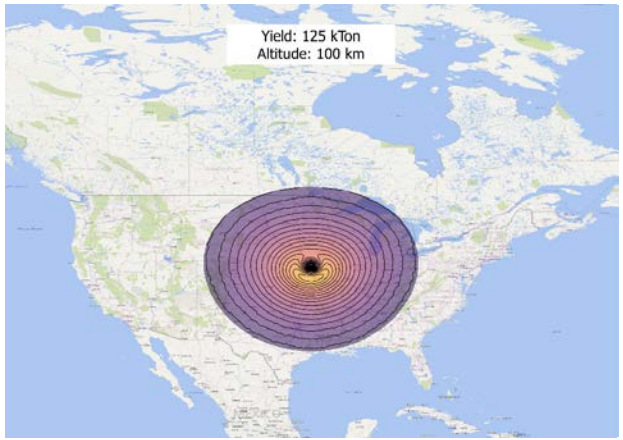
Maximum Peak Voltage

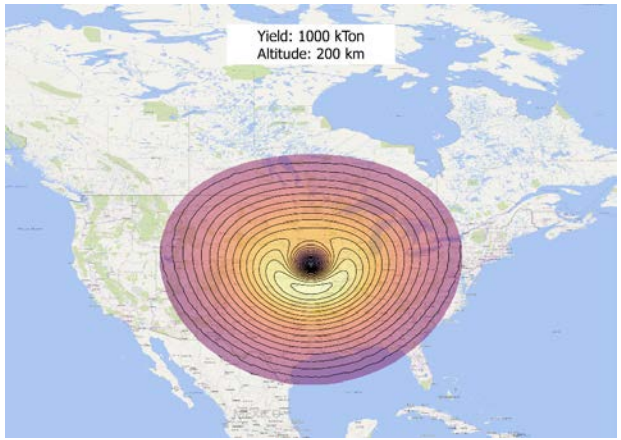
Contour Levels every 40 kV



Maximum Field Values

Yield (kTon)	H.O.B. (km)	Maximum Peak Voltage (kV)
25	100	223
25	400	21.6
125	100	606
125	400	98.3
1000	200	954

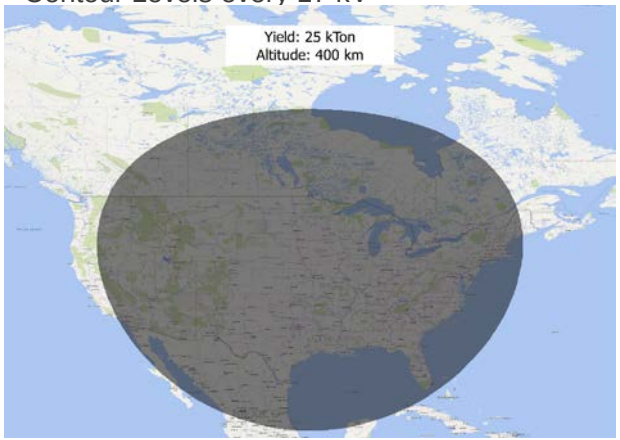


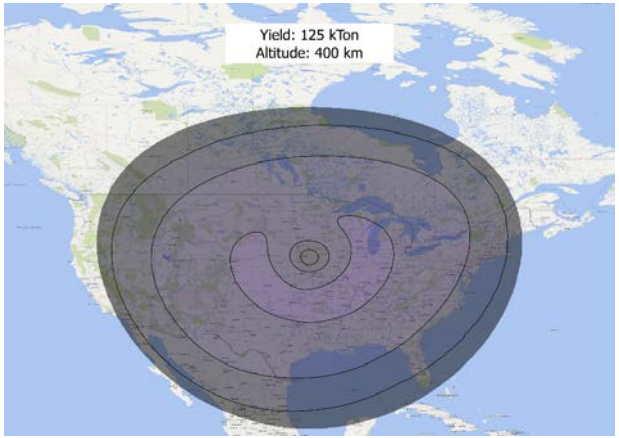


50 meter High Aerial Line (10 km long)
End Impedance: 1 GΩ

Expected Peak Voltage

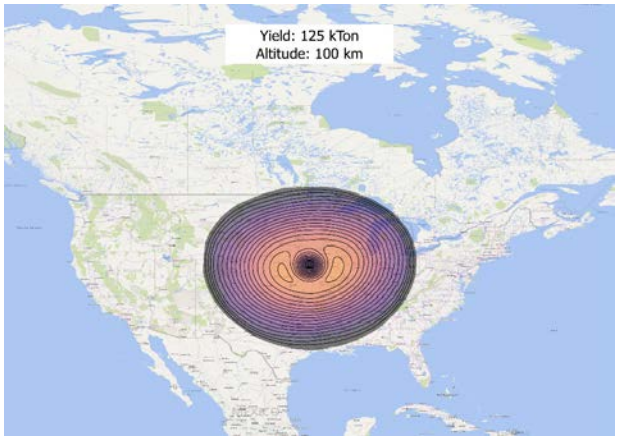
Contour Levels every 17 kV

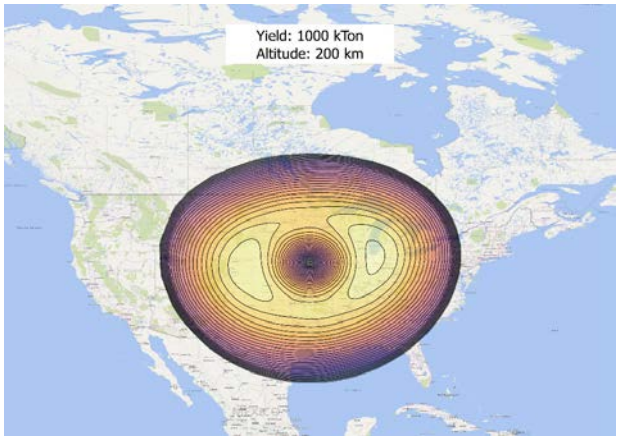




Maximum Field Values

Yield (kTon)	H.O.B. (km)	Expected Peak Voltage (kV)
25	100	134
25	400	15.1
125	100	295
125	400	55.3
1000	200	413

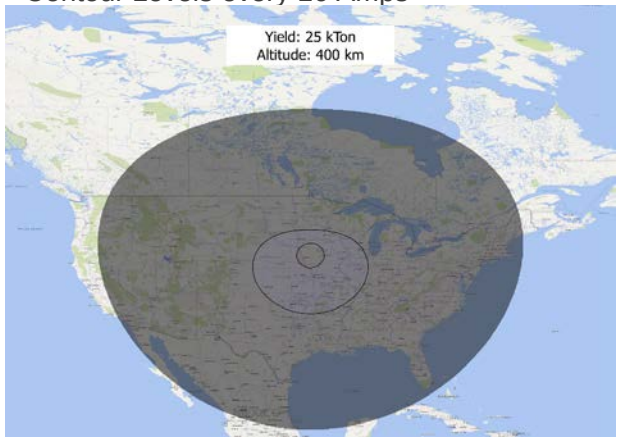


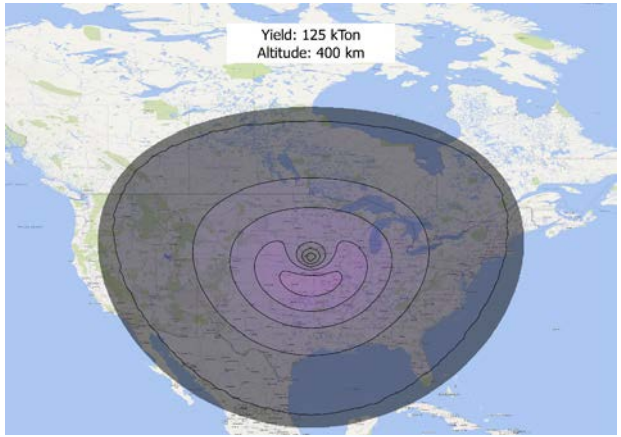


Measurement Line (on the ground) (100 m long)
End Impedance: 1 Ω

Worst Case Peak Current (Not Realizable)

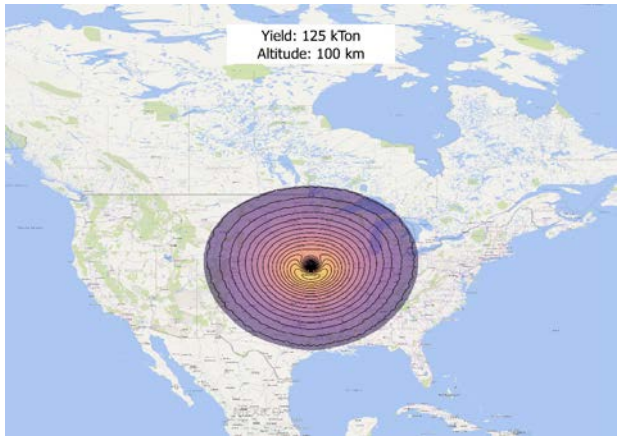
Contour Levels every 16 Amps

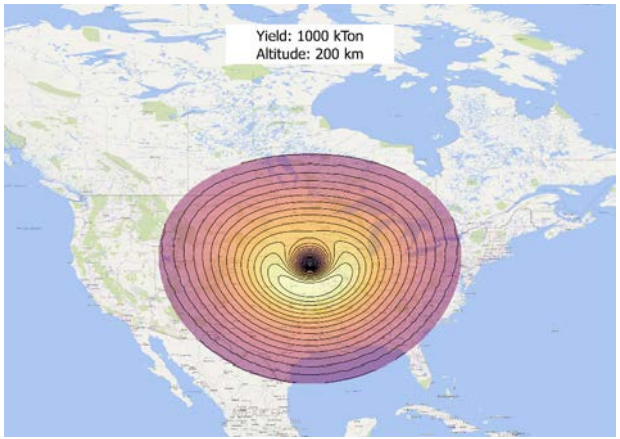




Maximum Field Values

Yield (kTon)	H.O.B. (km)	Worst Case Peak Current (Amps)
25	100	187
25	400	26.7
125	100	325
125	400	87.3
1000	200	398

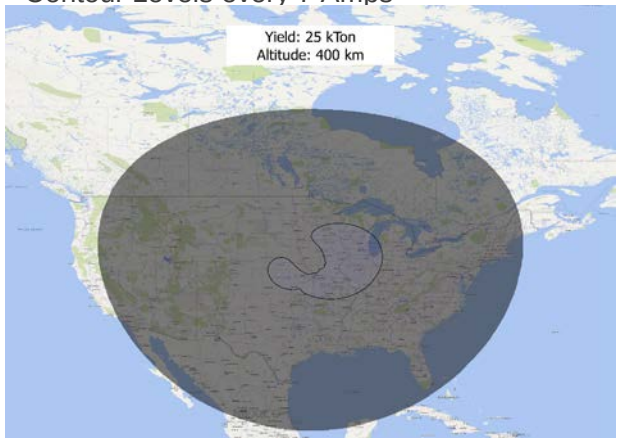


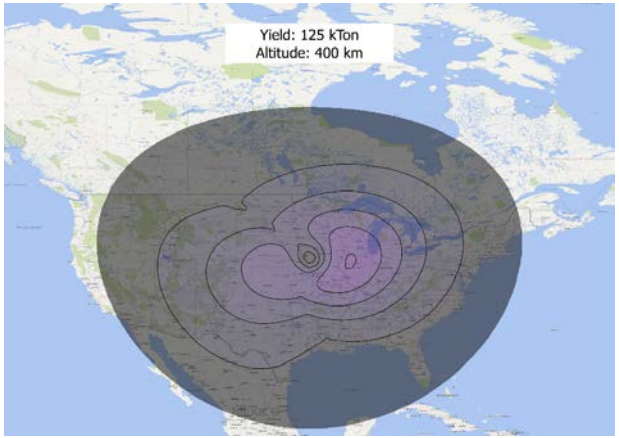


Measurement Line (on the ground) (100 m long)
End Impedance: 1 Ω

Maximum Peak Current

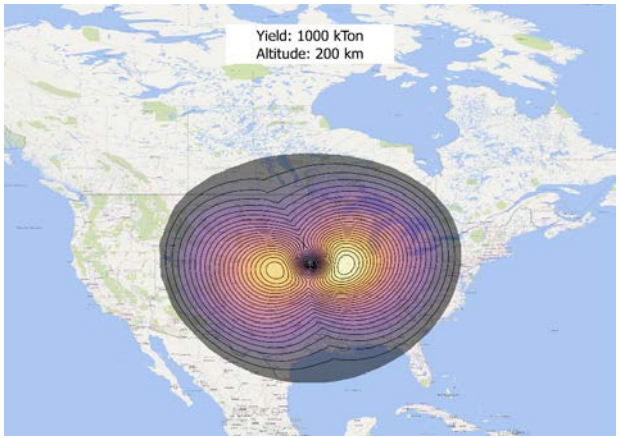
Contour Levels every 7 Amps





Maximum Field Values

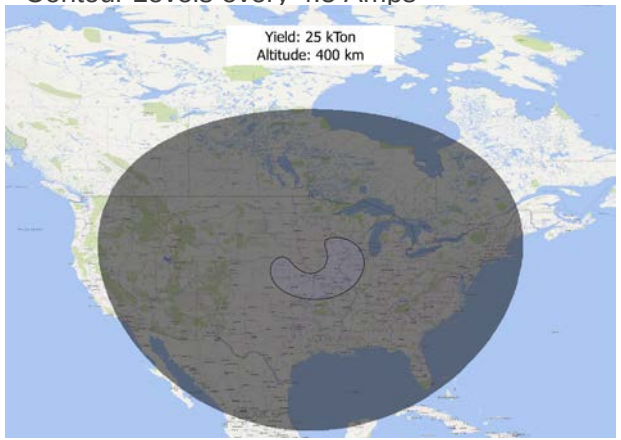
Yield (kTon)	H.O.B. (km)	Maximum Peak Current (Amps)
25	100	75.3
25	400	10.5
125	100	139
125	400	35.4
1000	200	175

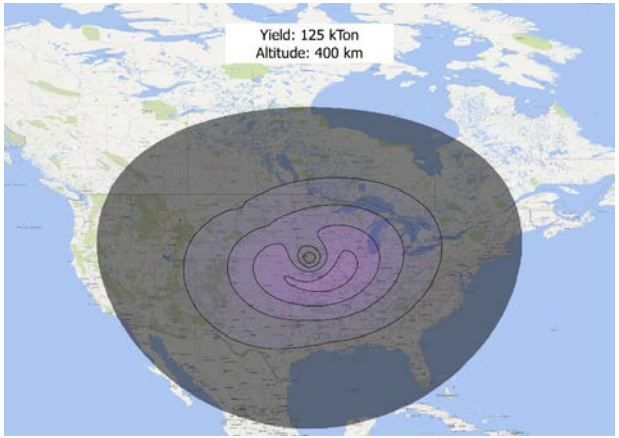


Measurement Line (on the ground) (100 m long)
End Impedance: 1 Ω

Expected Peak Current

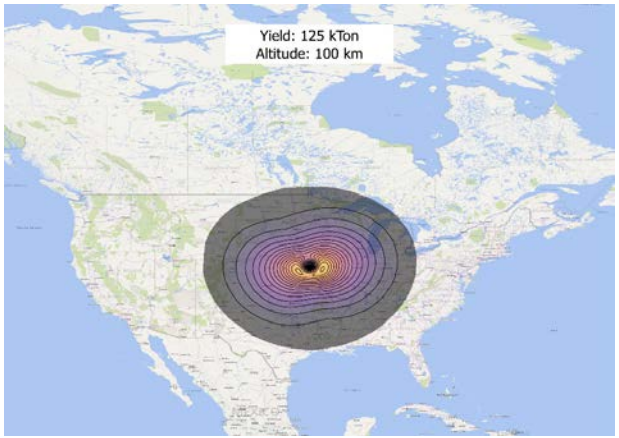
Contour Levels every 4.5 Amps

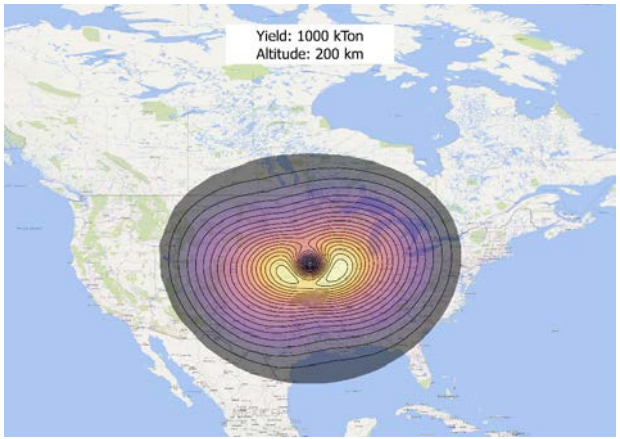




Maximum Field Values

Yield (kTon)	H.O.B. (km)	Expected Peak Current (Amps)
25	100	41.4
25	400	5.9
125	100	72.7
125	400	19.5
1000	200	89.5

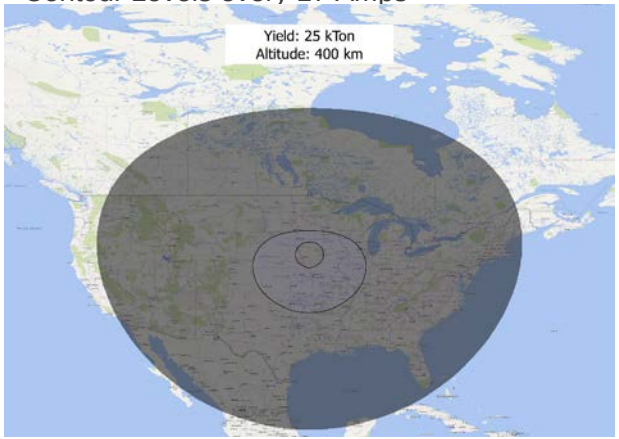


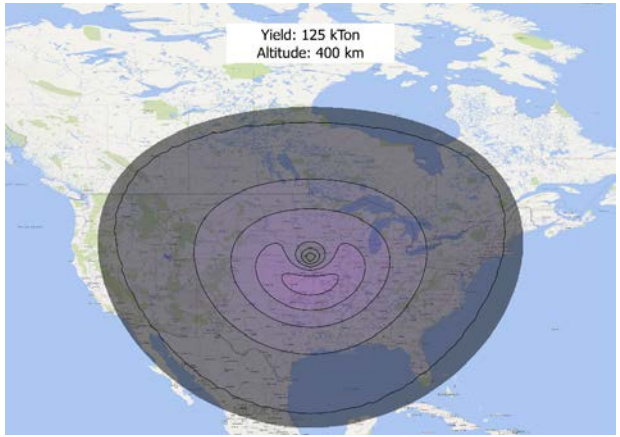


2 meter High Communication Line (25 m long)
End Impedance: 1 Ω

Worst Case Peak Current (Not Realizable)

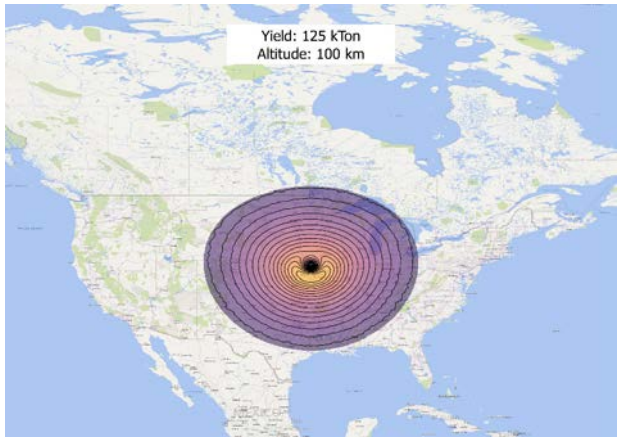
Contour Levels every 17 Amps

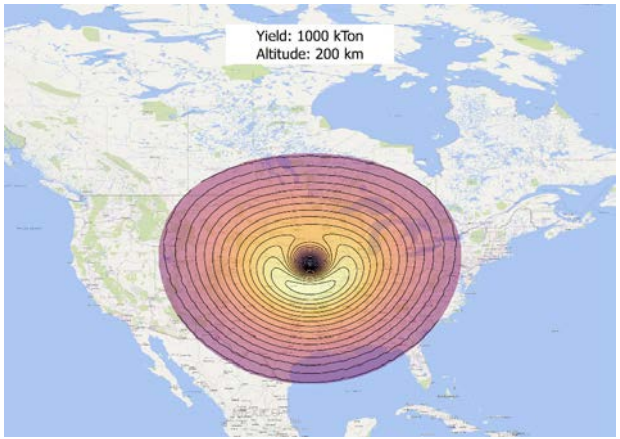




Maximum Field Values

Yield (kTon)	H.O.B. (km)	Worst Case Peak Current (Amps)
25	100	195
25	400	28.0
125	100	340
125	400	91.3
1000	200	416

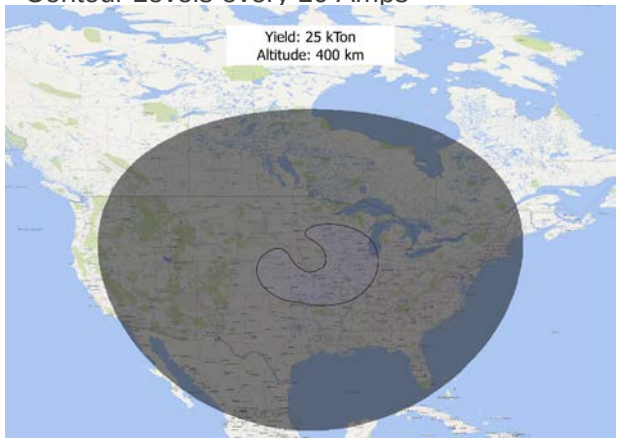


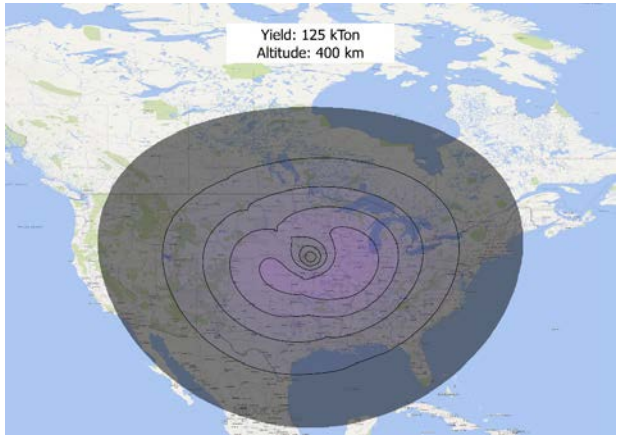


2 meter High Communication Line (25 m long)
End Impedance: 1 Ω

Maximum Peak Current

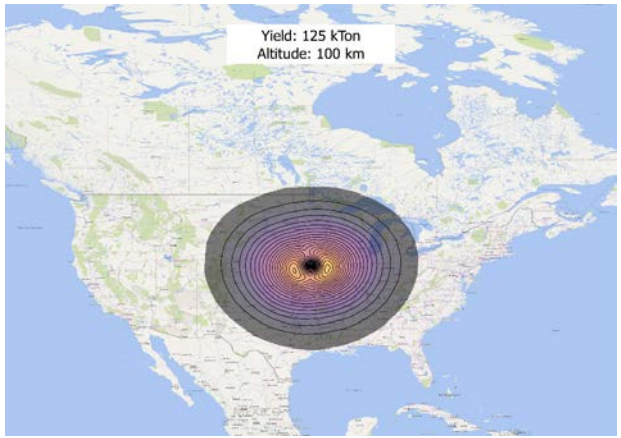
Contour Levels every 10 Amps

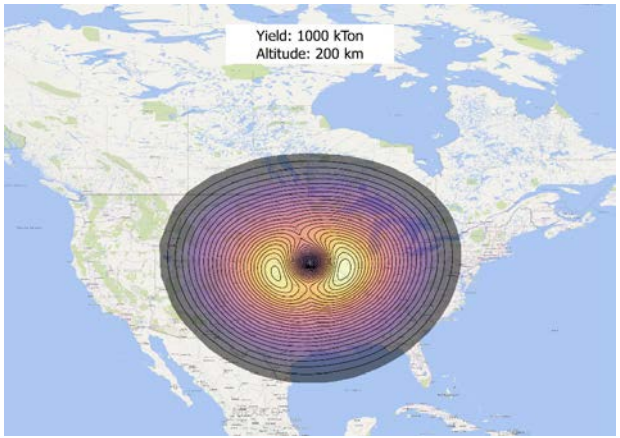




Maximum Field Values

Yield (kTon)	H.O.B. (km)	Maximum Peak Current (Amps)
25	100	108
25	400	14.0
125	100	204
125	400	48.9
1000	200	256

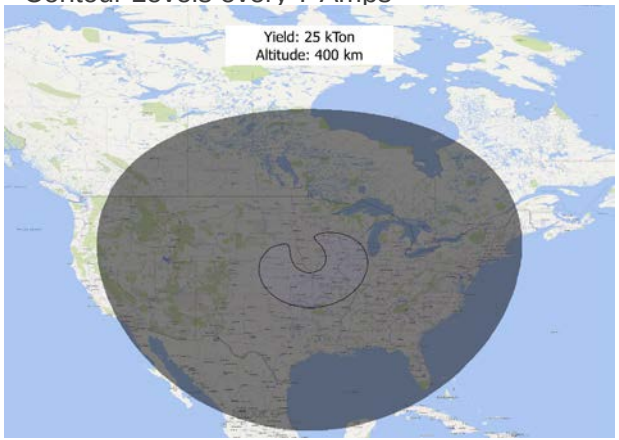


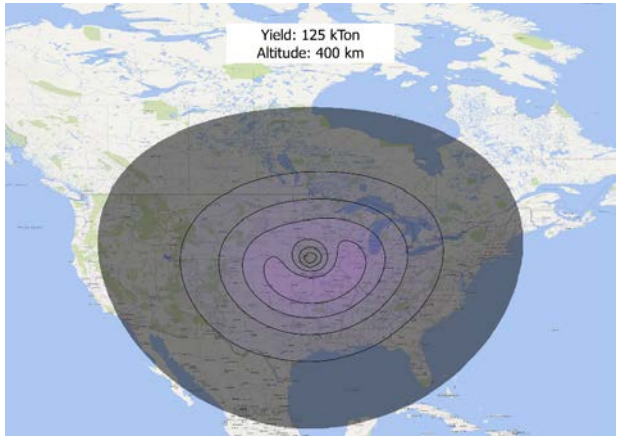


2 meter High Communication Line (25 m long)
End Impedance: 1 Ω

Expected Peak Current

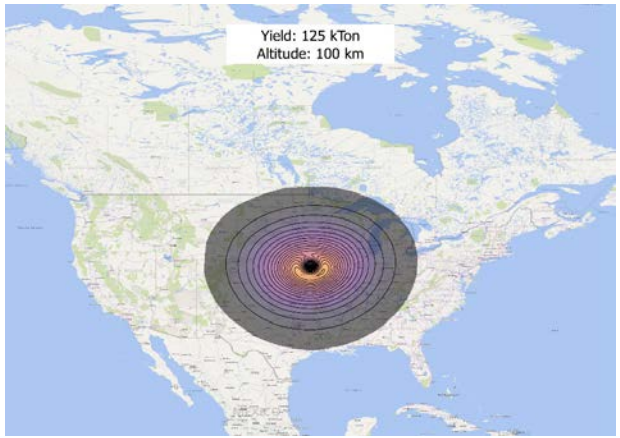
Contour Levels every 7 Amps

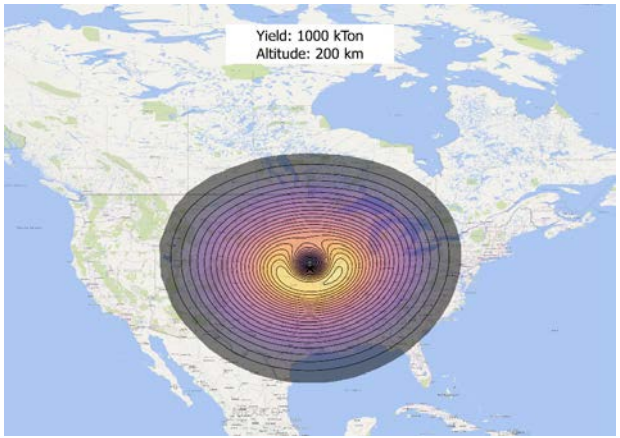




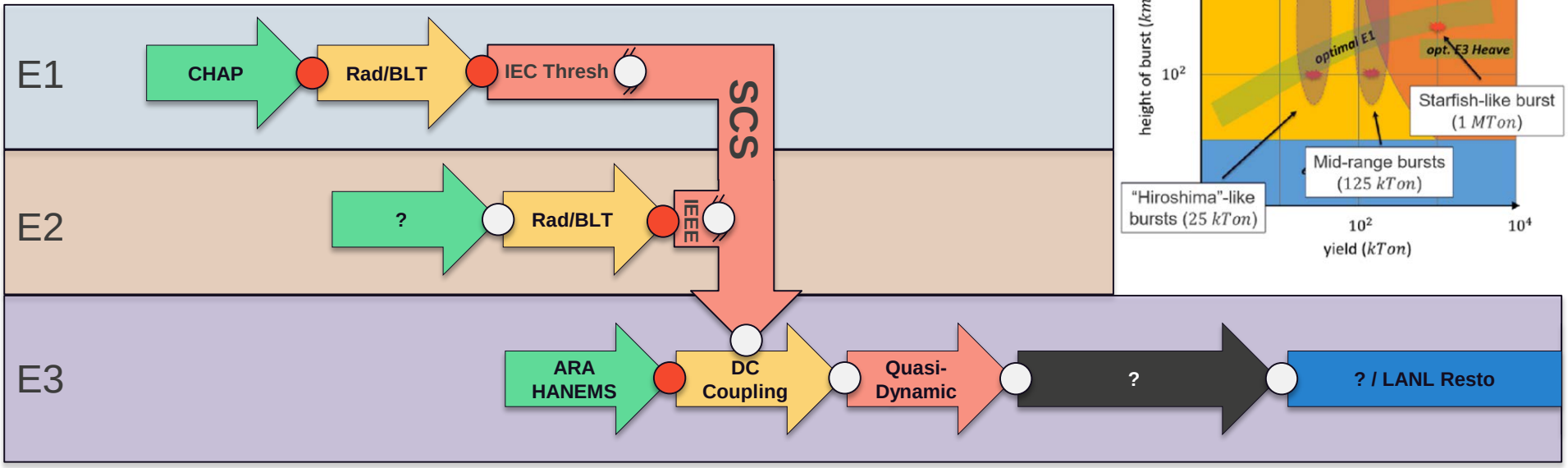
Maximum Field Values

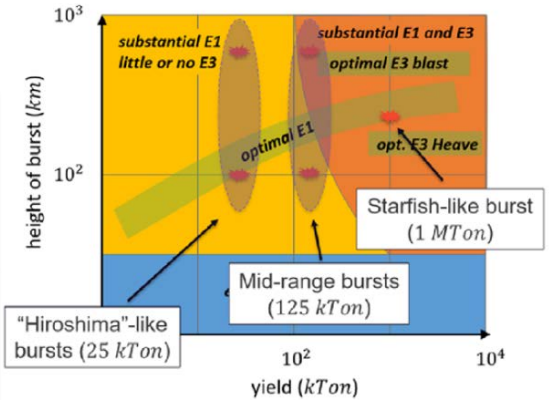
Yield (kTon)	H.O.B. (km)	Expected Peak Current (Amps)
25	100	71.1
25	400	9.7
125	100	127
125	400	32.6
1000	200	156





EMP Workflow (Damage)

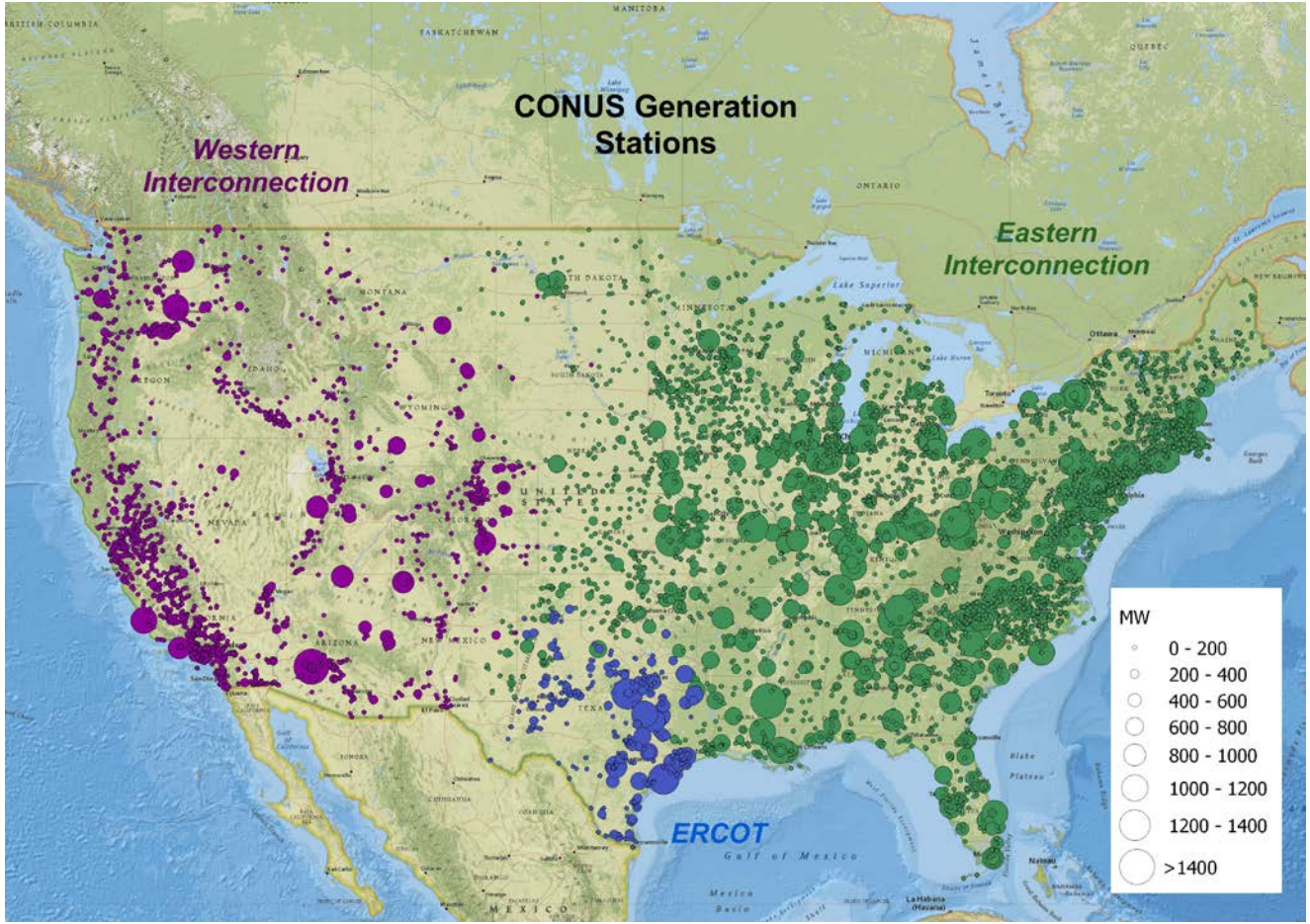




● Code successfully coupled

○ Code not coupled

EMP Impact on U.S. Generation



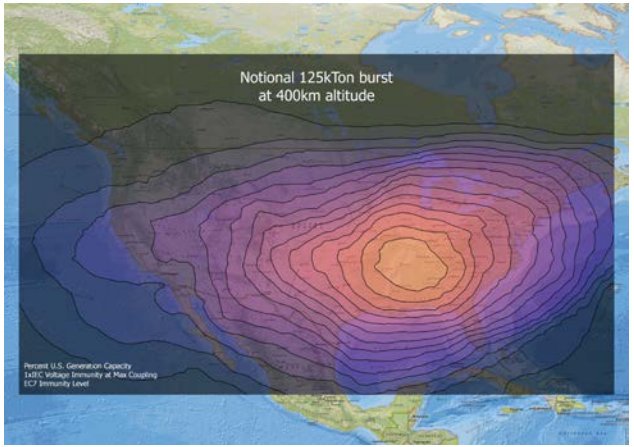
Methodology:

1. Evaluate a CHAP field for the 5 notional scenarios for a grid of ground zeros that cover CONUS

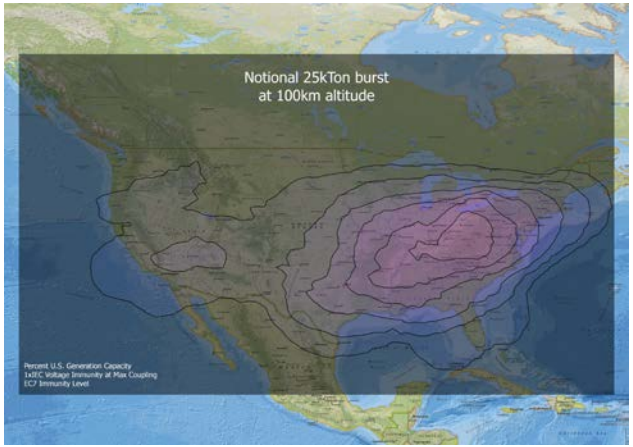
2. For each ground zero location, determine the number of generation substations that have equipment which exceed IEC threshold

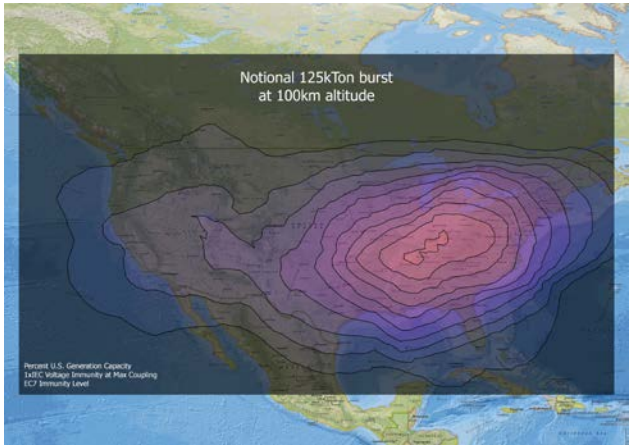
EMP E1 Impact on U.S. Generation (1×EC7)

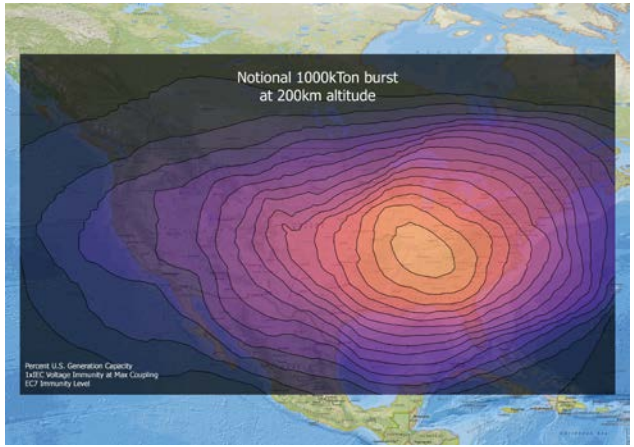
Contour Levels every 5%



Yield (kTon)	H.O.B. (km)	Max Percent
25	100	34
25	400	1.1
125	100	51
125	400	73
1000	200	78



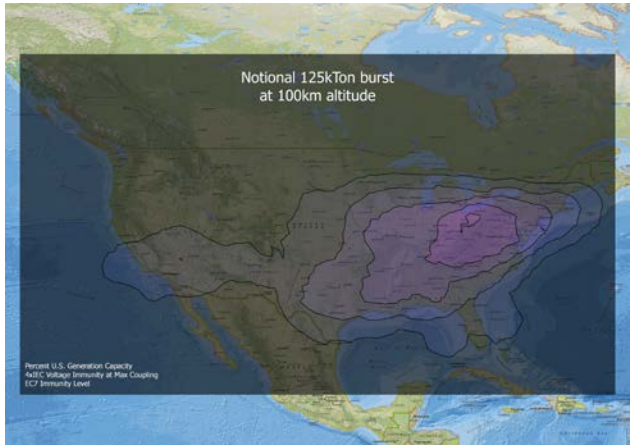


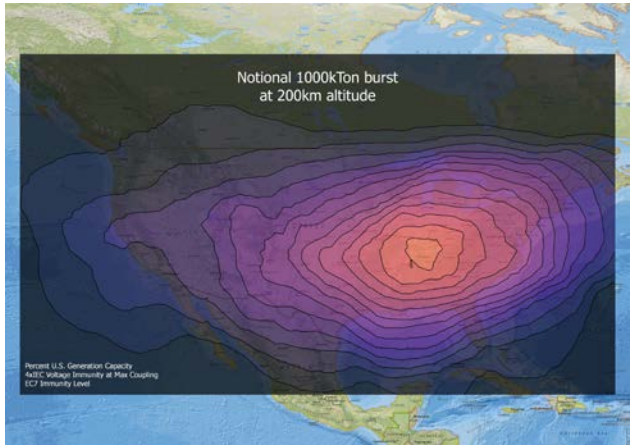


EMP E1 Impact on U.S. Generation (4×EC7)

Contour Levels every 5%

Yield (kTon)	H.O.B. (km)	Max Percent
25	100	9
25	400	0
125	100	26
125	400	0
1000	200	66



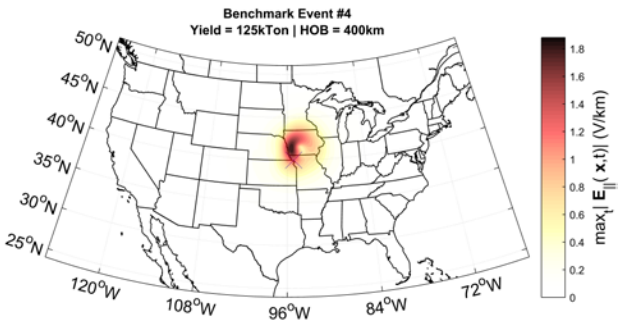


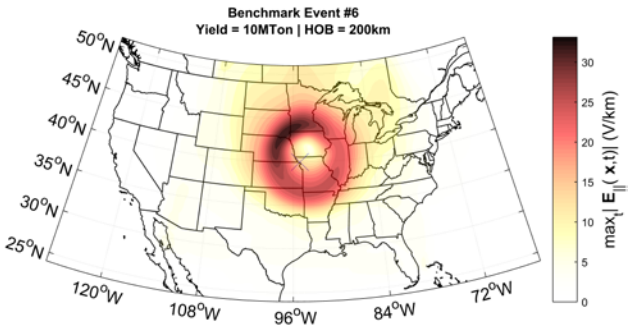
Benchmark Events (Reminder)

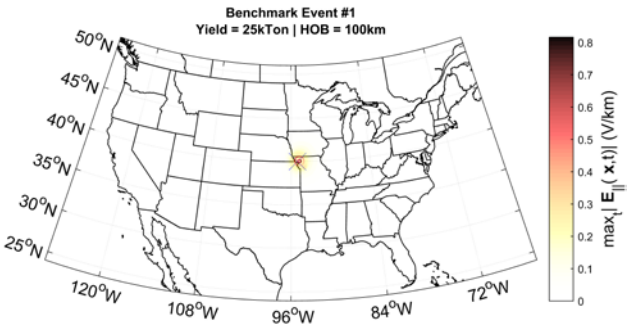
Yield (kTon)	Height of Burst (km)	E1	E3 Blast @ Edge of E1	E3 Heave Centered on E1	Anticipated Consequence
25	100	Regional -- med	Low	Low	State-protection/comms
25*	400	CONUS -- low	Low	Low	Patchy
125	100	Regional – med/high	Low	Med/High	E1/E3 overlap
125	400	CONUS – low/med	Med/High	Low/Med	Patchy E1/some E3
1000	200	Interconnect – med/high	Med	High	E1/E3 overlap
10000*	200	Interconnect – med/high	Med	High	E1/E3 overlap
10	endo	City	none	none	crater

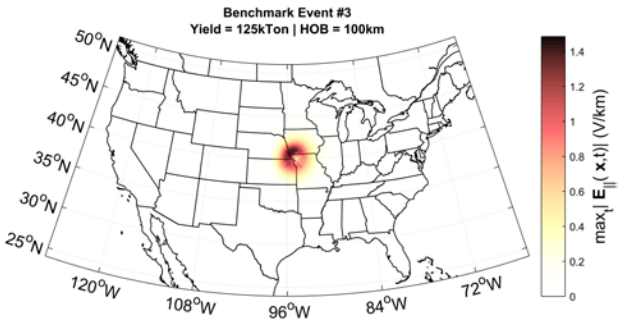
E3 Fields for Benchmark Scenarios

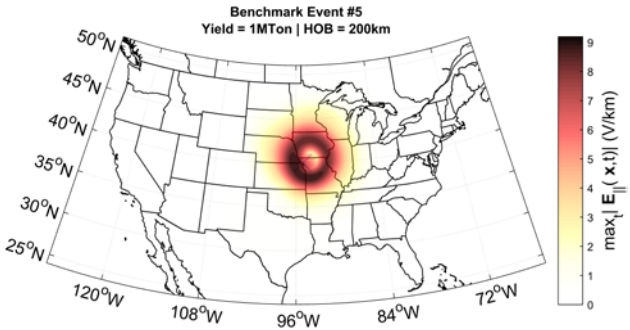
Yield (kTon)	H.O.B. (km)	Maximum Field (V/km)
25	100	0.85
125	100	1.5
125	400	1.9
1000	200	9.2
10000	200	35





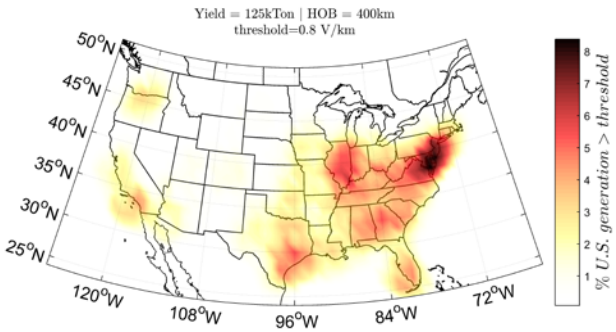


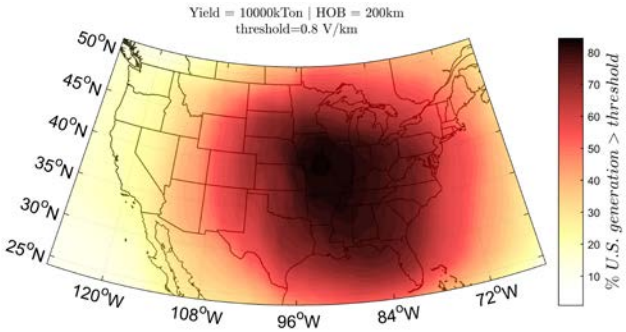


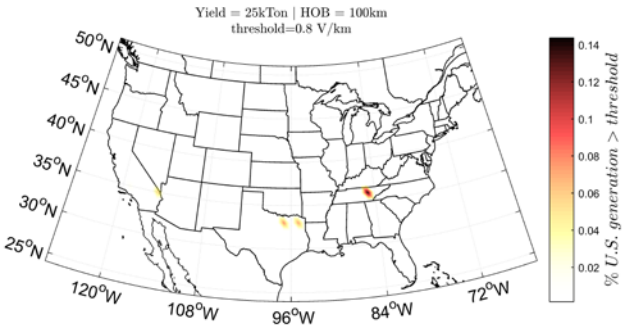


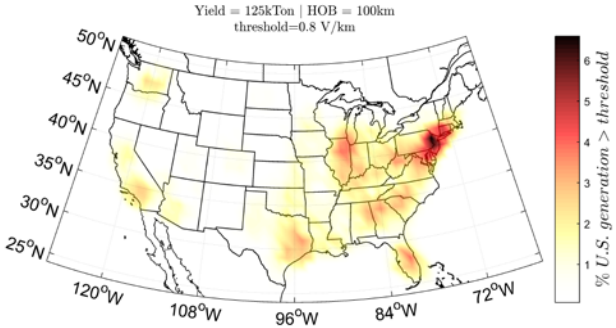
E3 EMP Fields across U.S. Generation (0.1xTPL-007-1)

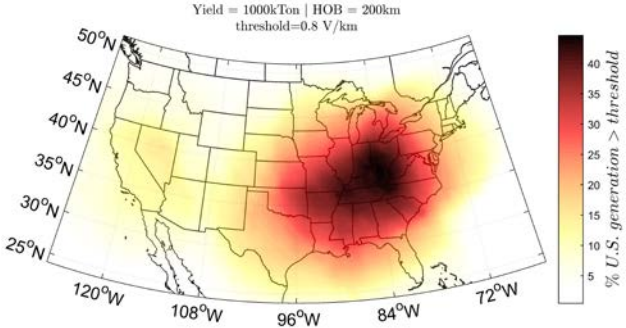
Yield (kTon)	H.O.B. (km)	Max Percent
25	100	0.14
125	100	7
125	400	8.5
1000	200	45
10000	200	88





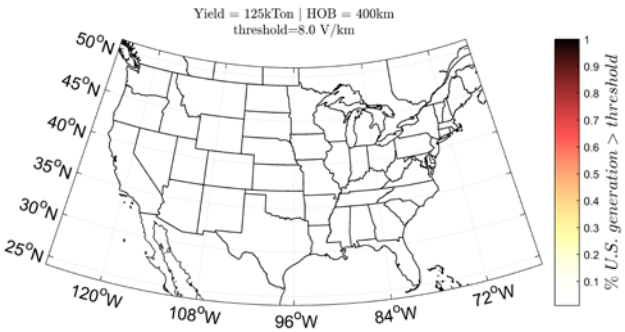


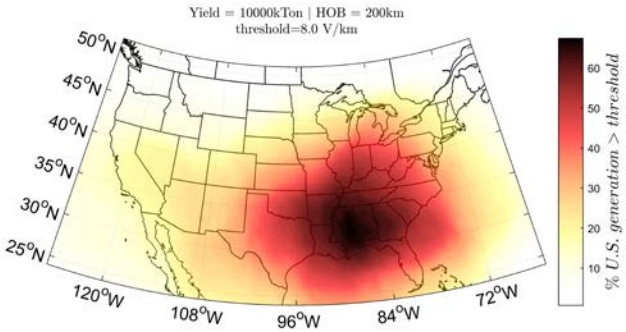


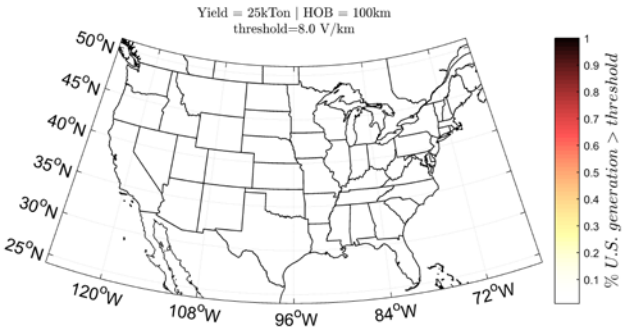


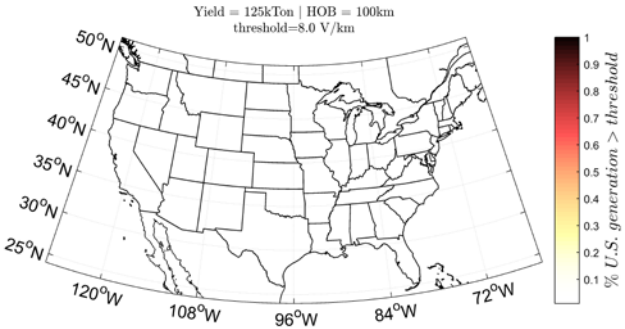
E3 EMP Fields across U.S. Generation (1xTPL-007-1)

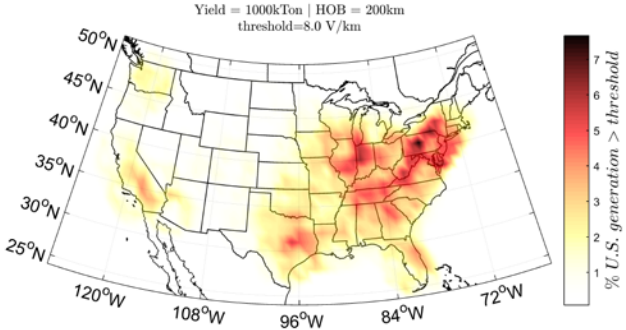
Yield (kTon)	H.O.B. (km)	Max Percent
25	100	0
125	100	0
125	400	0
1000	200	8
10000	200	68











Benchmark Events (Reminder)

Yield (kTon)	Height of Burst (km)	E1	E3 Blast @ Edge of E1	E3 Heave Centered on E1	Anticipated Consequence
25	100	Regional -- med	Low	Low	State-protection/comms
25*	400	CONUS -- low	Low	Low	Patchy
125	100	Regional – med/high	Low	Low/Med	E1/E3 overlap
125	400	CONUS – low/med	Med/High	Low/Med	Patchy E1/some E3
1000	200	Interconnect – med/high	Med	High	E1/E3 overlap
10000*	200	Interconnect – med/high	Med	High	E1/E3 overlap
10	endo	City	none	none	crater