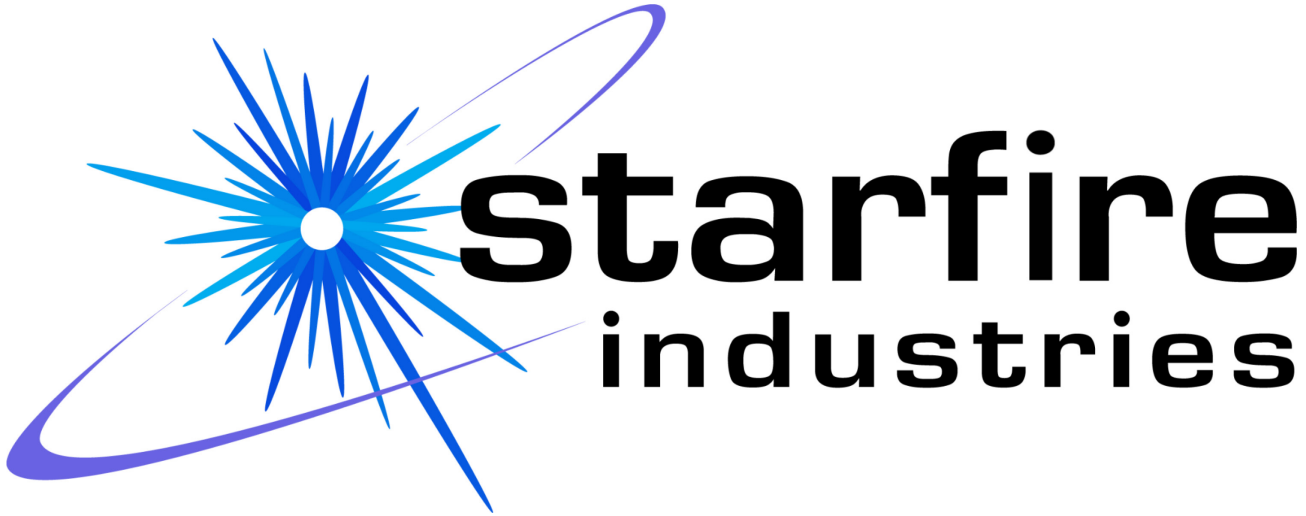
Developing a Deployable 4-MeV Deuteron RFQ Linac for Industrial and Security Applications: Insights from a Small Business Perspective



Presented By:

Brian E. Jurczyk, President
Starfire Industries LLC
Champaign, IL USA
bjurczyk@starfireindustries.com

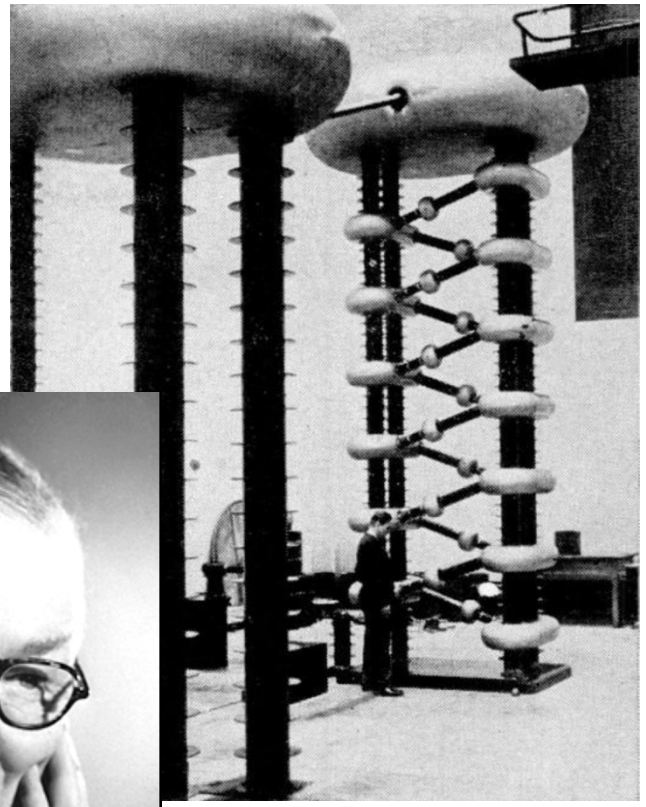
Agenda

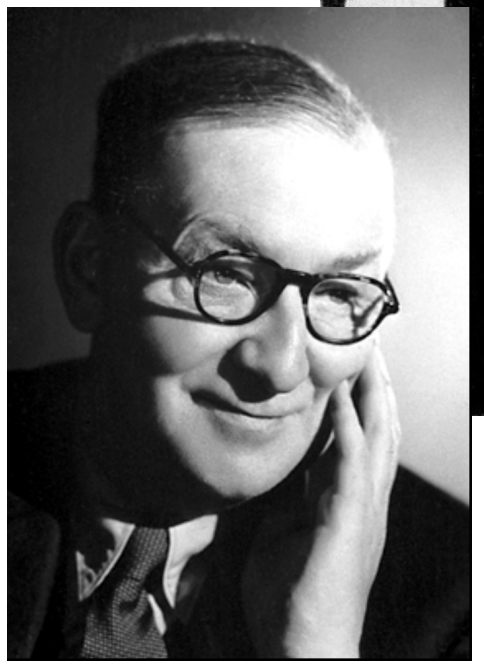
- **Reflections: Opening Plenary Talk**
- About Me/Starfire
- The DARPA ICONS CHALLENGE & 4MeV Centurion™ System
- Reflections: Competitors To Collaborators
- Spin-Off Innovation – IMPULSE® + Positive Kick™
- Broader Relevance To HEP Community & Lessons Learned

Reflections: Opening Plenary Talk

- The story of Cockcroft co-inventing the HV multiplier that led to the 1st particle accelerator
  - $^{7}Li + p \rightarrow 2\ ^{4}He + 17.2MeV$ = Nobel Prize!

- It was **Multidisciplinary Knowledge** from a pre-college apprenticeship… at British Westinghouse (MetVickers)
  - Connecting the dots
  - Doing the math





Reflections: Opening Plenary Talk

- Several themes resonated with me… ***drivers for transformative innovation***
- Setting up the ecosystem to thrive, **evolve** new ideas → innovation
- You need people having ***multi-***disciplinary breadth and depth, “T” shaped
- Surround yourself with decision makers that accept that **spin-off** technologies will materialize…
  - The off-diagonal elements in a matrix that are hard to visualize

#IPAC2019, Suzie Sheehy

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About Me/Starfire

- Not a High-Energy Physicist by Training
  - I did visit ANL and FNAL as a kid!

- B.S. in Aerospace Engineering
- M.S. in Nuclear Engineering
- Ph.D. in Plasma Engineering
- M.B.A. Technology Commercialization

- Co-founded a company to develop nuclear and plasma industrial technologies
  - Beneficial use for fusion today!

*Closet sub-atomic particle physicist

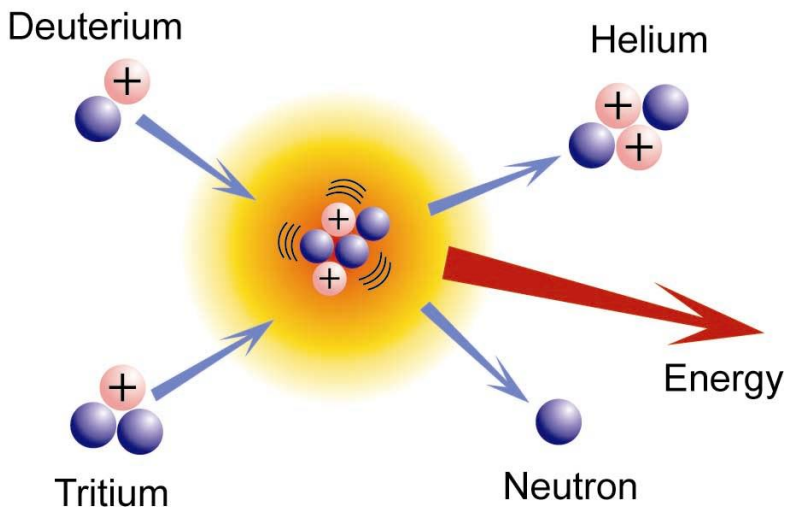
WHY WE EXIST

To deliver industry-changing plasma source and particle accelerator solutions worldwide through innovation in components, systems and service

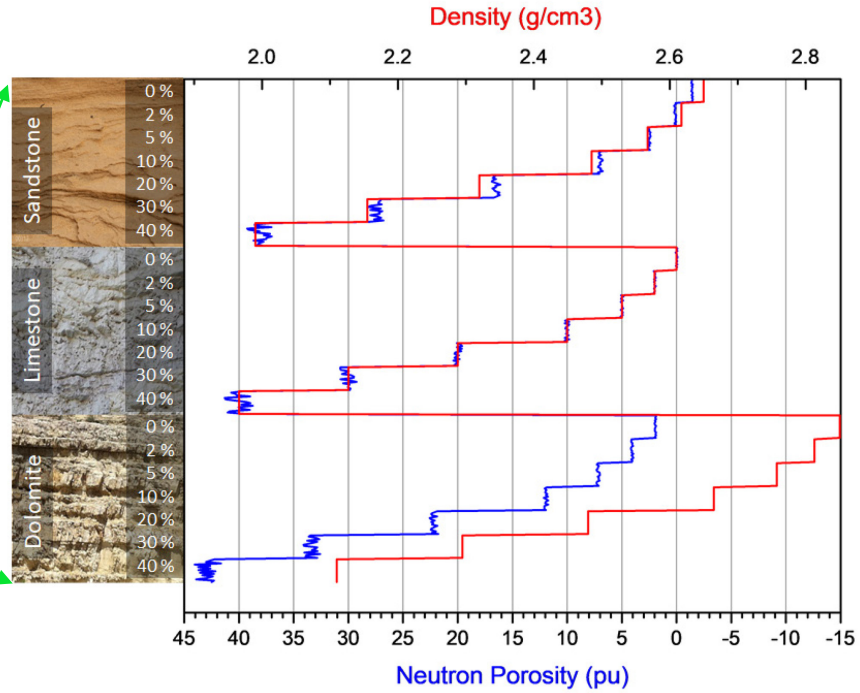
nGen® Sealed Neutron Generators

- Electrostatic Accelerators -- 100 to 250 kV
- Microwave Plasma Ion Sources -- ECR, 10's W
- Ultra-Compact +HV Cockcroft-Walton -- 100W, small!
- Grounded Targets -- High-Flux For Small Power
- Hand Carried -- Portable

- Used for Well Logging
- Gamma Spectroscopy
- Security Applications



nGen®-100



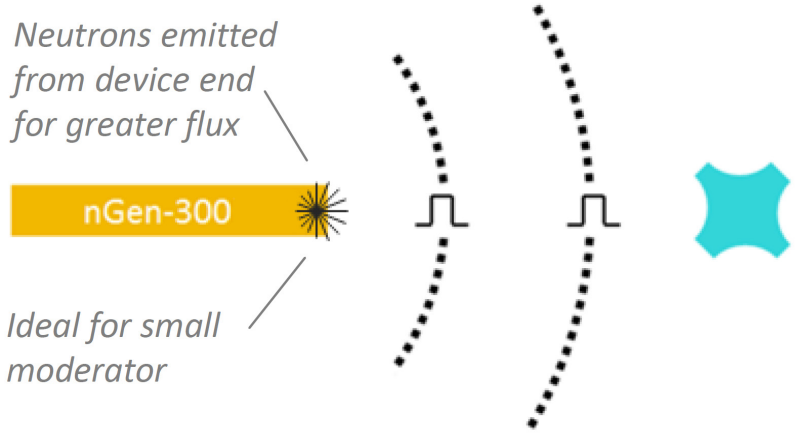
starfire industries

Advanced Logic Technology

MOUNT SOPRIS INSTRUMENTS

DD, DT Neutrons 1-11/16” Slimline CNL—PGNAA Downhole Grounded Target

nGen®-300



Sharp pulsing with 1/e rise and fall times under 5µs and zero dark current

DD, DT Neutrons Sharp Pulsed Battery Powered Grounded Target Snout

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ICONS CHALLENGE

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

ABOUT US / OUR RESEARCH /

Defense Advanced Research Projects Agency › Program Information

Intense and Compact Neutron Sources (ICONS)

Dr. Vincent Tang

The Intense and Compact Neutron Sources (ICONS) program seeks to achieve highly portable, intense neutron sources to enable deployable, high-resolution neutron and x-ray imaging for DoD applications such as non-destructive evaluation, detection of explosives and special nuclear materials, and forensics.

Existing neutron imaging and sensing sources require large, fixed infrastructure to achieve the power needed for high-resolution imaging and do not meet the size, weight, and power (SWaP) requirements for military expeditionary missions. The development of novel, high-intensity neutron sources in a low-SWaP package would have significant national security applications by delivering detailed and accurate internal imaging of objects in relevant environments.

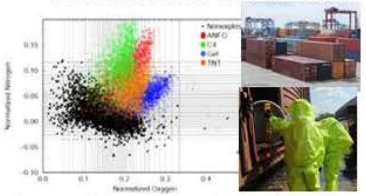
nd highly portable neutron sources would have
D applications

Enable in-the field neutron imaging for

Non-destructive evaluation
(e.g. corrosion, welds, water ingress)

Neutron image of H2O penetration in F18 honeycomb

SNM, explosives, and contraband detection



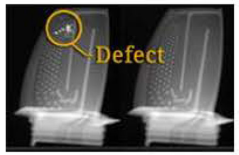
Elemental ratio IDs explosives/chem agents
SNM ID from fission signatures

Forensics and attribution

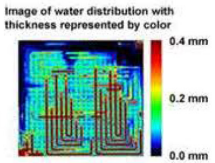
Imaging of adversary M&S

Enable factory and laboratory neutron imaging for

Manufacturing QA and Engineering R&D

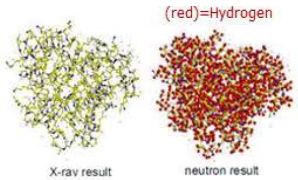


Turbine blades QA



Fuel cell development

Basic science R&D



Atomic structure, especially low-Z elements, and stress measurements for materials development

DARPA ULTIMATE GOAL #2

- 4 MeV deuteron accelerator
- 3 mm spot size for high brightness
- 2E10 n/s/str for 6.5 MeV neutrons
- Forward directed beam
- 250L, 80 lbs, 2kW, sealed

DARPA ICONS CHALLENGE

Start
13 Different Sets
Of Ideas From
Diverse Teams

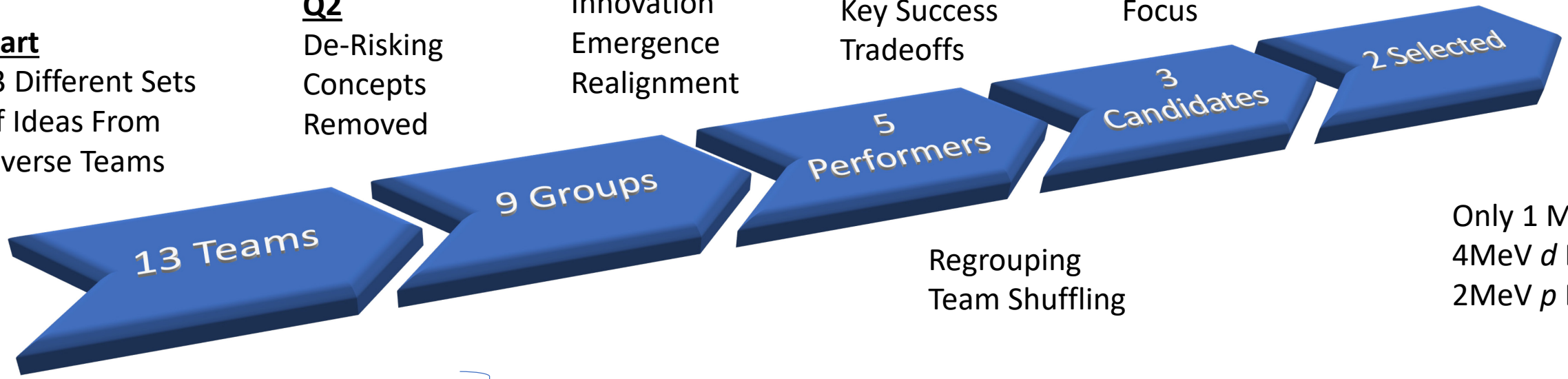
Q2
De-Risking
Concepts
Removed

Q4
Innovation
Emergence
Realignment

Q6
Demonstration
Key Success
Tradeoffs

Q8
Leadership
Clarity
Focus

Q12
Only Small Businesses
Made It To The End



Regrouping
Team Shuffling

Only 1 Made
4MeV *d* Beams
2MeV *p* Beams

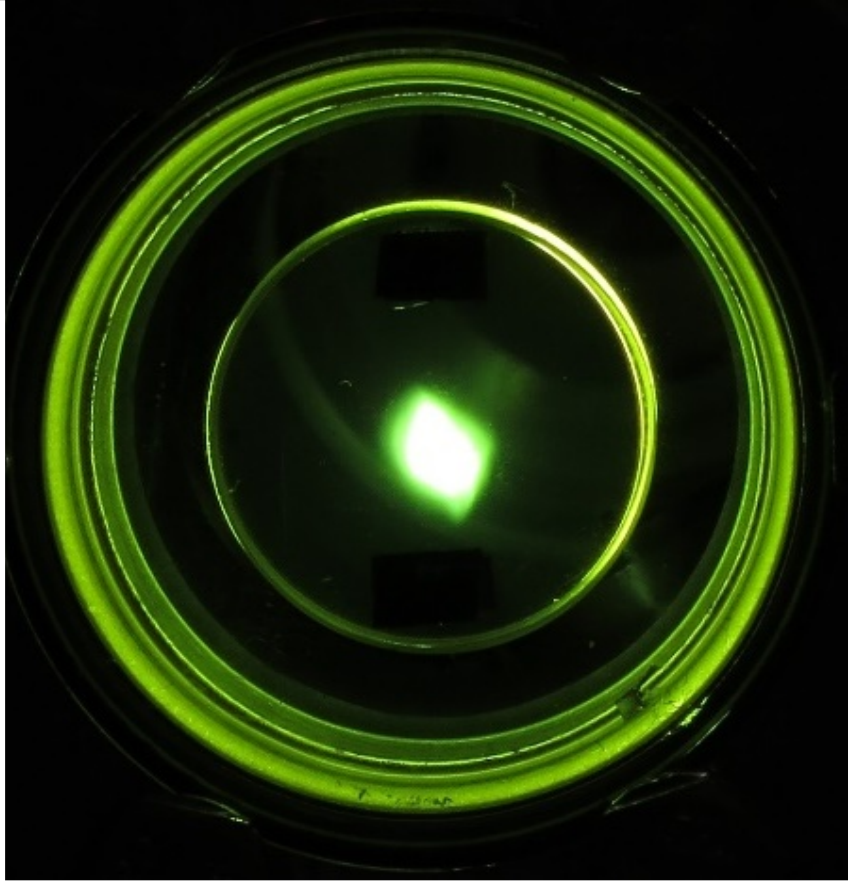
- National Labs
- Research Institutes
- Large Companies
- Small Businesses
- Universities
- Consortia

~2-6 collaborators
for each team

wide scope of
technologies

Highly Competitive

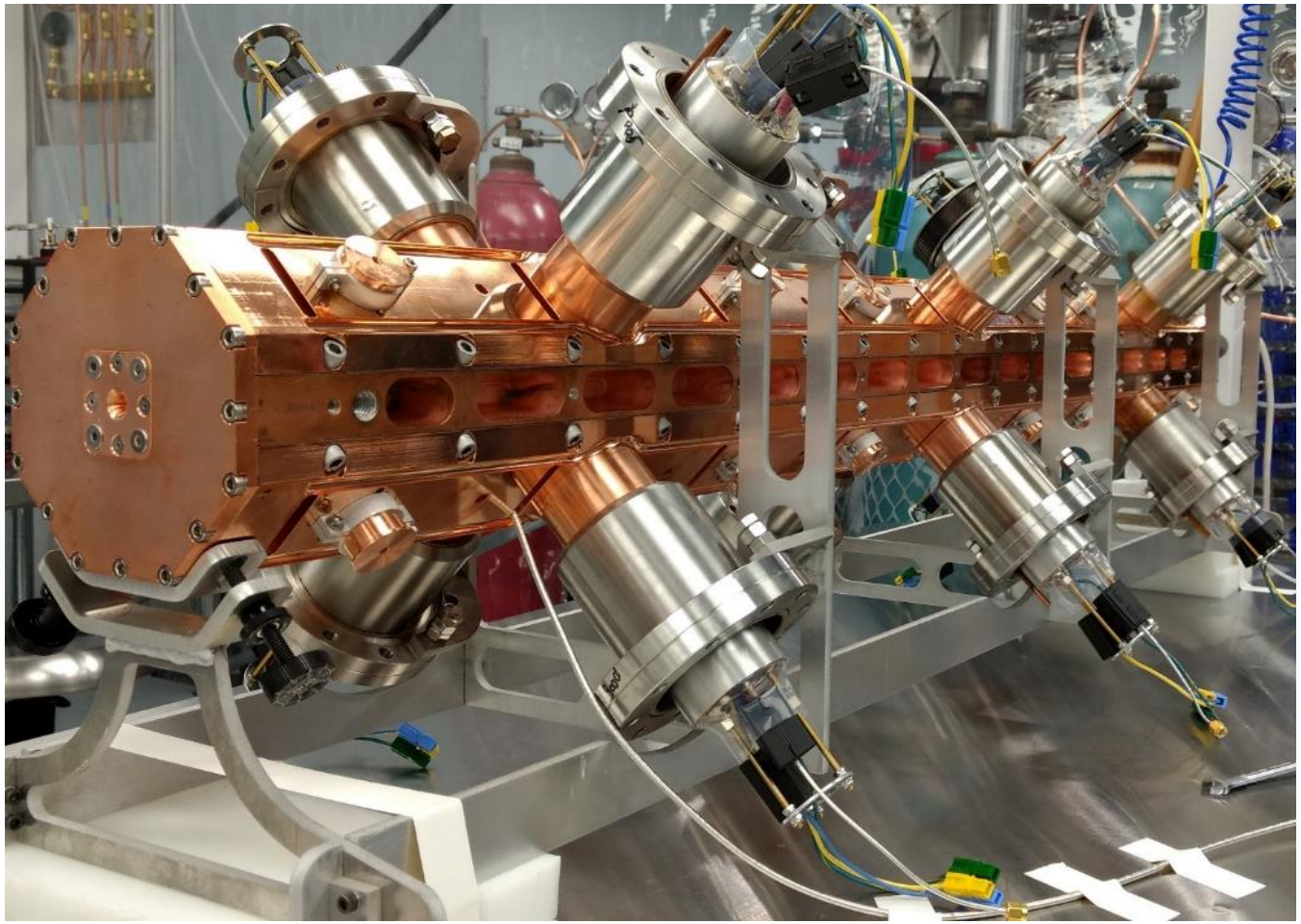




Centurion™
Ultra-Compact, Portable
High-Brightness, 1—5 MeV RFQ LINAC

Loading Up The Mk. 1 Centurion™
For ICONS Demo Day In Maryland

THIS IS EVERYTHING!



The Centurion™ TECHNOLOGY

- **Distributed RF Power Injection Using RFQ Cavity As Power Combiner (patent pending)**
  - Hermetic Copper-Ceramic Sealing Technology
  - Air-Side CPT Coupling For Easy Installation
- **Pulsed ECR Plasma Ion Injector**
  - Very Low Beam Emittance
  - Based On nGen™-300 Pulsed System
- **High-Gradient Ion Acceleration (>4MV/m)**
  - Advanced Power Control & Arc Suppression
  - Proprietary Fabrication Methods
- **Small Beam Diameter @ 1-5 MeV**
  - Closely Couples With Moderator/Collimator
  - High-Flux Thermal Management
- **High Power Efficiency For Small Size**

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Reflections: Competitors To Collaborators

- Unless you have an existing off-the-shelf solution → it is hard to enter the HEP community because you compete with the very same people who would be your customer

- Industrial innovators are often competing for the very same resources

- This is why there are so few industrial companies in this space that are “cross-disciplinary” and most new ventures are spinoffs directly from the Consortia or Research Facility

Setup For Transformative Innovation

- Suzie Sheehy touched briefly on this topic in her Plenary; *this interdisciplinary competition is a barrier to* ***multidisciplinary entry*** *into the HEP community*

- To enable the best conditions for transformative innovation…

- It takes a community using ***emotional intelligence*** to build relationships, establish trust and create a foundation for a **non-zero-sum**, **evolutionary**, **collaborative**, **cooperative**, **simultaneous**, **pooling** "R&D game" based on ***imperfect information*** – to get the best win-win!

Example Collaborative R&D Centers

- Common goal to develop solutions or techniques to solve basic challenges facing several companies at the same time
  - ***Ex. Our NSF Center for Lasers & Plasmas For Advanced Manufacturing***
- R&D managers from 20-40 different companies meet twice a year with several University teams in a "closed door" setting where the companies openly describe their problems, the challenges they face, steps that failed…
- Access to this "*dirty laundry*" information that companies cannot publicly talk about… is the Key Information that enables **multidisciplinary** innovation
- Starfire developed tech for High-Power Impulse Magnetron Sputtering because of someone else's dirty laundry!

Pathway To The Centurion™ 4-MeV RFQ Linac

- We spoke with luminaries who commercialized RFQ linacs 30+ years ago
  - Many are retired, exited the business or now provide HEP consulting services
- Some shared “linac dirty laundry” on what worked, what did not work, what was tried, what failed, where it went sour, etc.
  - KEY Information
- Starfire’s engineering team could apply our cross-disciplinary knowledge, experience in other fields, our manufacturing capability, and re-visit concepts to develop novel solutions
  - We approached the problem with a clean slate, fresh perspective and unbiased
- Starfire got into the RFQ LINAC business… now with a spin-off technology: **IMPULSE® + Positive Kick™** coatings for accelerators

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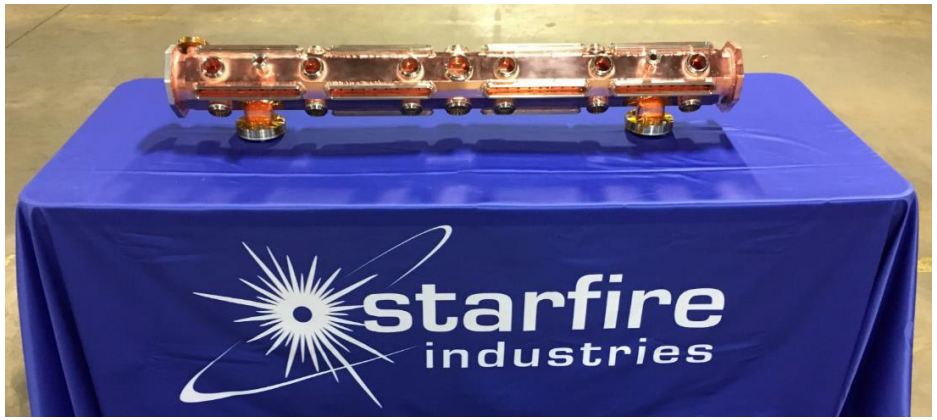
Spin-Off Innovation: IMPULSE® + Positive Kick™

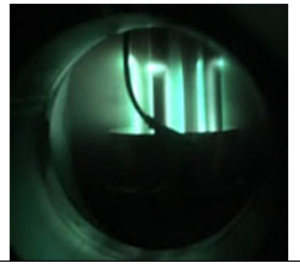
Thin-Film Coatings

- Deposit high-conductivity copper directly in-situ
- Improve RT cavity Q at joints & interfaces
- Densify copper film for less migration
- Smoothen surface for higher gradients
- Enable reactive nitride/oxide deposition
- Lower manufacturing cost

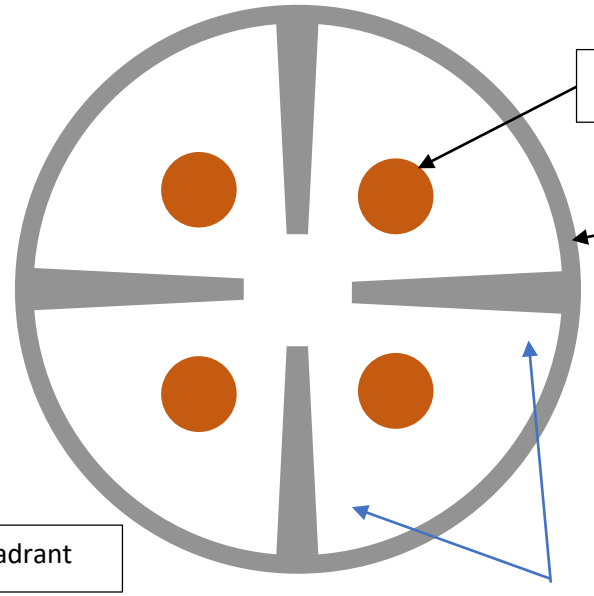


2-2 IMPULSE® & 20-20 IMPULSE® Products

- High-Power Impulse Magnetron Sputtering
- Positive Kick™ is key enabler!
- Nanoscale ion polishing



4 Sputter Cathodes, 1 In Each Vane Quadrant

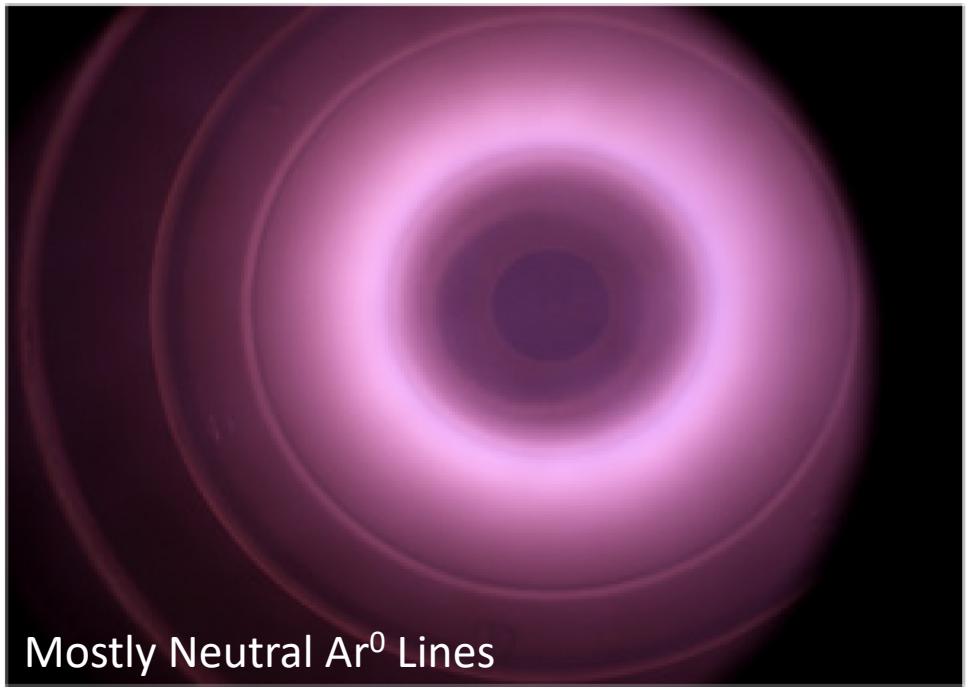


IMPULSE™ Pulsed Power Modules For PVD

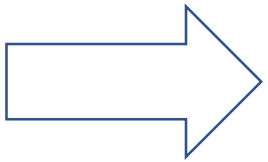
HiPIMS Sputtering Positive Kick™ Superconducting Films R&D/Production

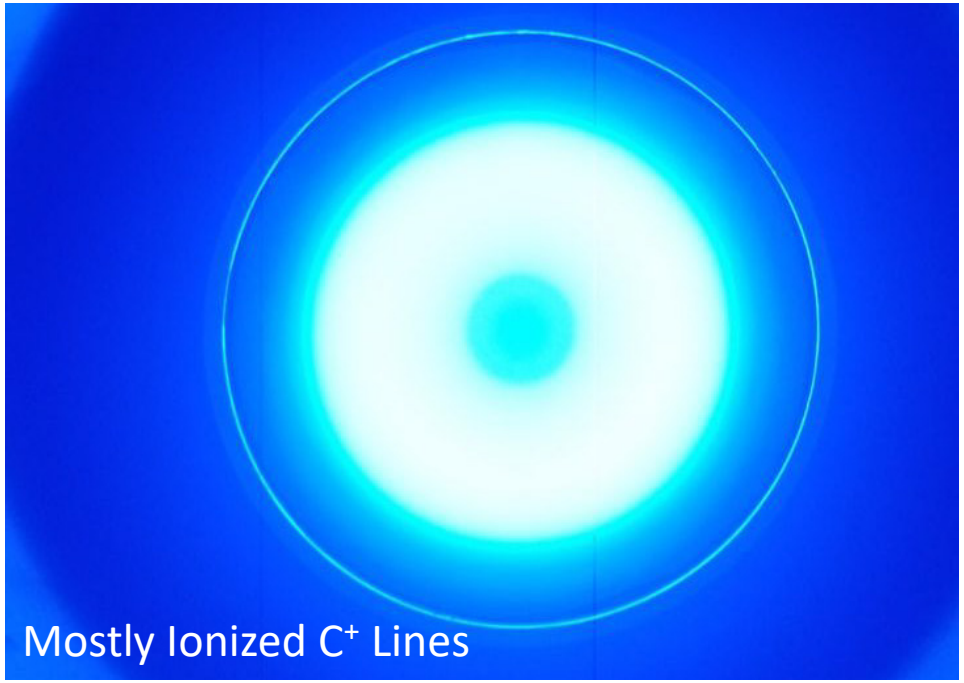
starfire industries

What Is HiPIMS?



Pulsed Discharge Striking HiPIMS Color Change

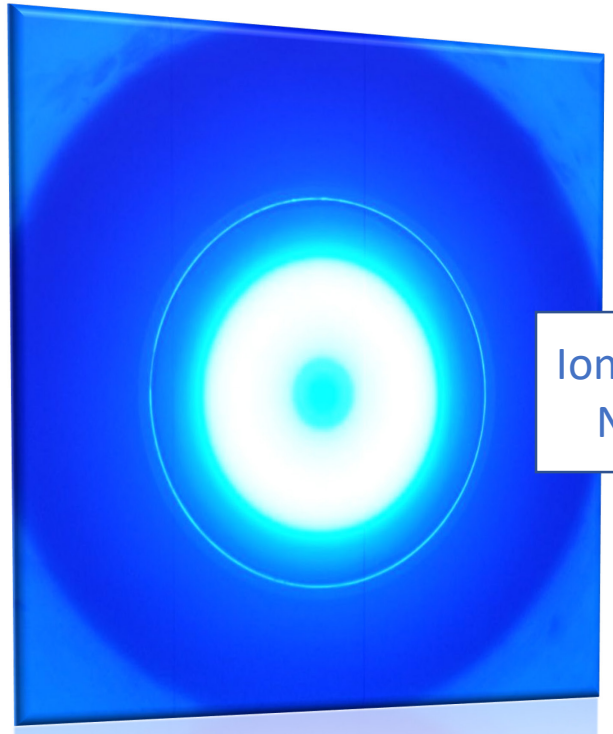




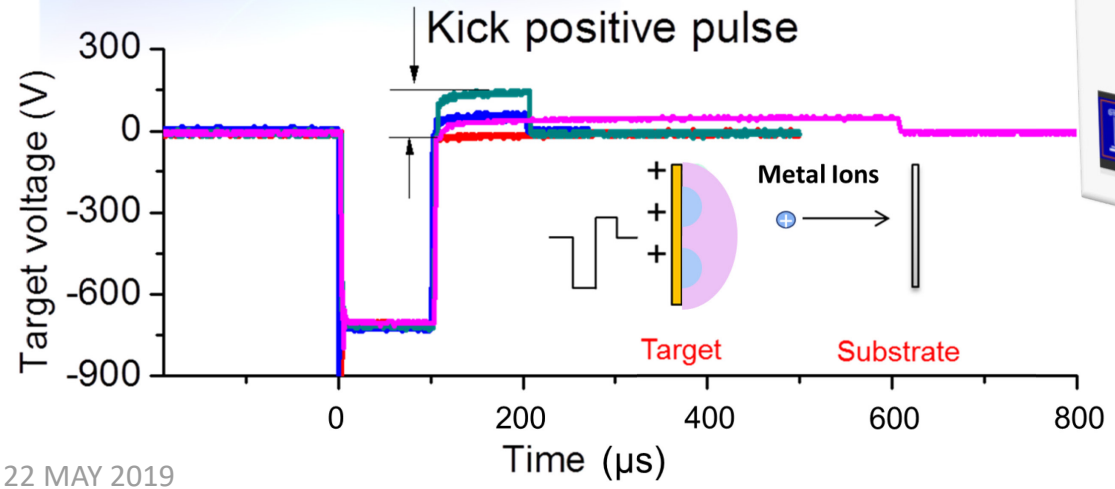
DC Sputtering (dominantly pink argon plasma)
<0.01A/cm^2 current density
0.1-1A current
~1-3% ionized sputtered metal

HiPIMS Sputtering (dominantly color metal plasma)
>1A/cm^2 peak current density
10-100's A currents
~10-90% ionized sputtered metal

Same Sputter Gun, Same Time-Average Power, Same Material, Same Pressure → Completely Different Films



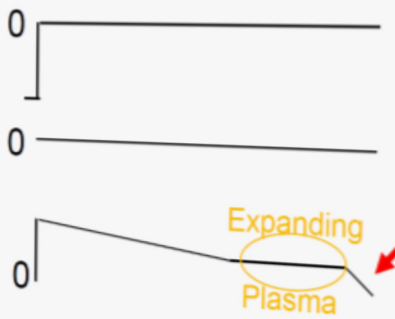
Ions Kicked Away
Not Recycled



Results of the Positive "Kick"

- Higher Deposition Rate
- Higher Ion Fraction
- Better (denser) Films
- Less Stress on Films
- Target neutralized so reactive sputtering has fewer arcs

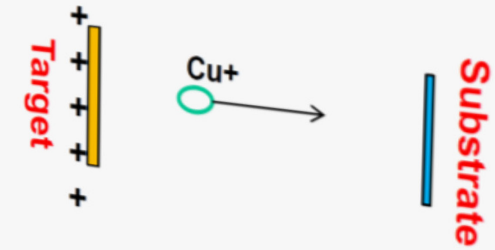
Plasma Potential Distribution



❑ During pulse :
generate metal ions

❑ After pulse :
repel the metal ions which had not yet recirculated

At the substrate



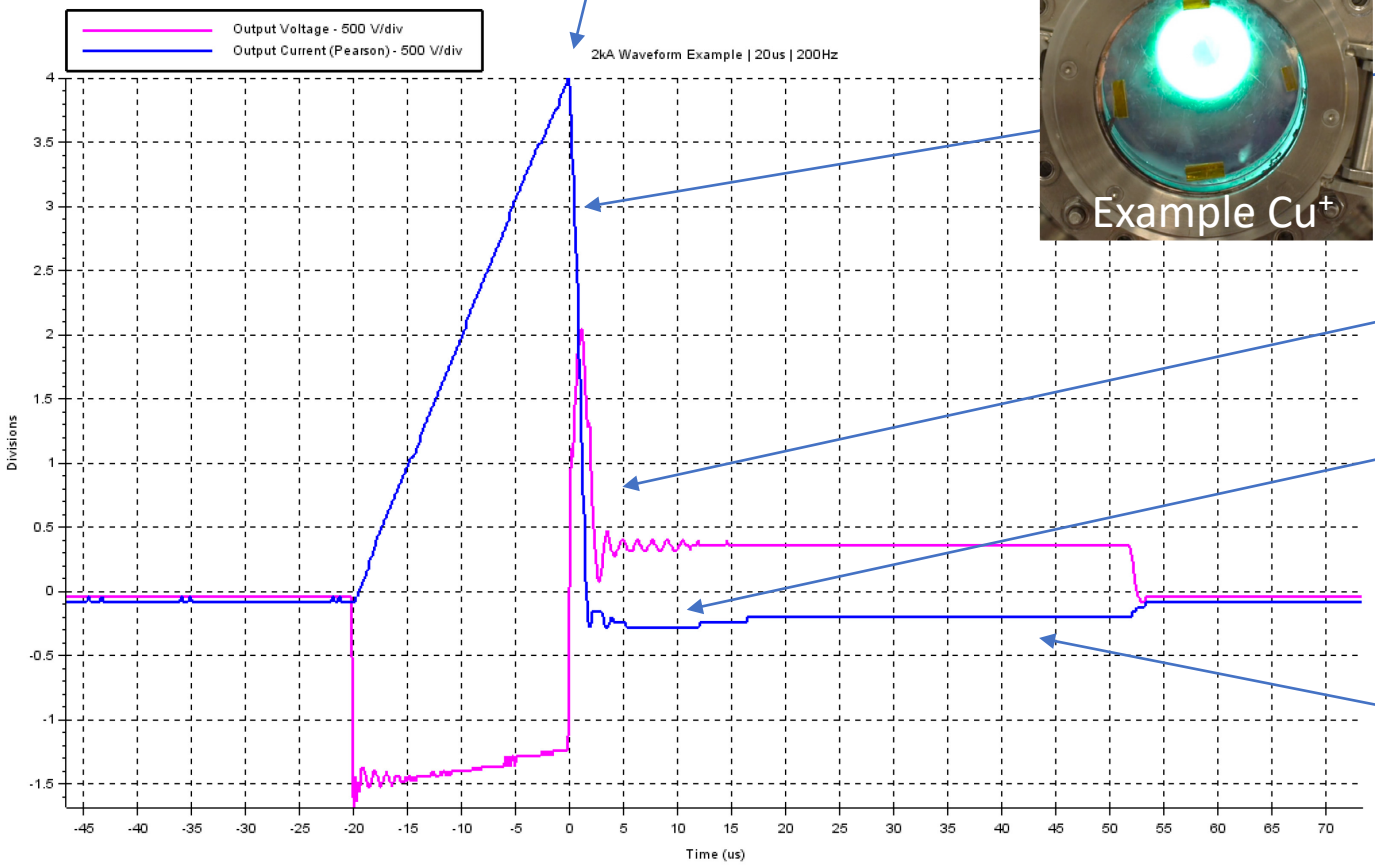
- ❑ The metal ion flux
- ❑ The deposition rate
- ❑ The ionization fraction

CPMI Center for Plasma-Material Interactions http://cpmi.uiuc.edu

HIPIMS 2017
Braunschweig, Germany
June 13-14, 2017

An ultra-fast 2kA peak current pulse from the 20-20 IMPULSE™ with a copper target and Positive Kick™ pulse

Note Triangular Waveform; Current rises monotonically driving a metal vapor plasma at the target surface



20usec wide main pulse; high Cu^+ plasma generated

-750V drive is reversed to +200V within 2usec

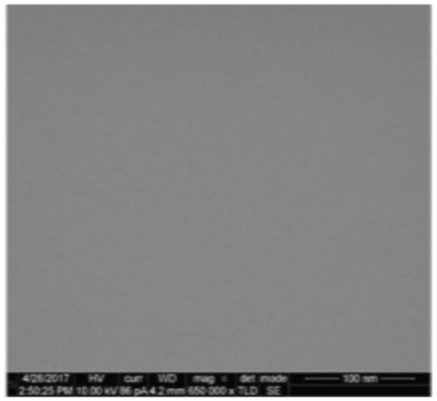
Cu^+ ions that would recycle back to target are pushed away towards substrate (short-term Kick effect)

Plasma potential is raised at the substrate leading to broader plasma bombardment and conformality (long-term Kick effect)

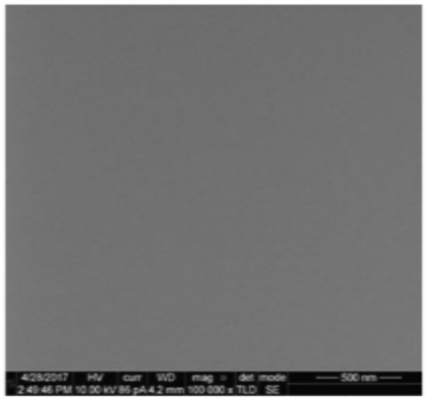
SEM images of Carbon coating with HIPIMS (IMPULSE power supply)

1µm

2µm

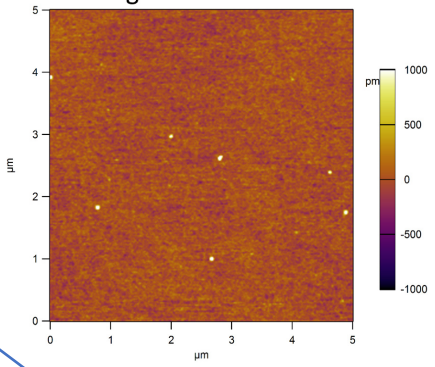


100nm

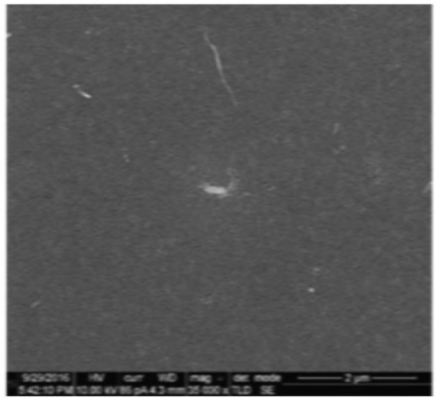


500nm

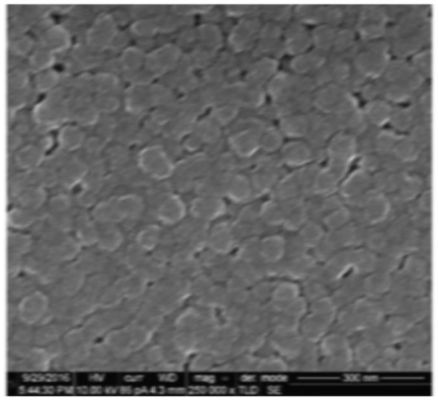
HiPIMS + Kick 500W
Roughness = 0.10nm



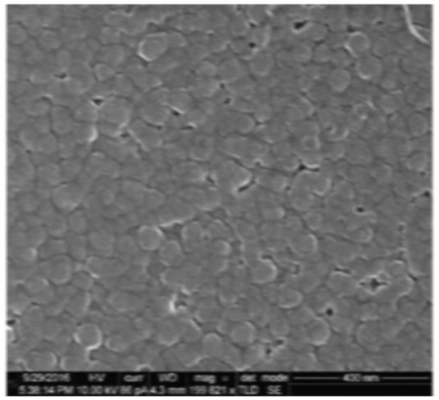
SEM Images of Carbon coating with DC magnetron sputtering



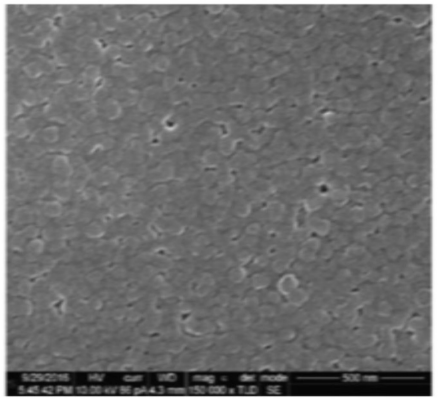
2µm



300nm



400nm



500nm

Fully-Dense
Ultra-Hard
Smooth
R_a = 0.1-nm
"at-C"
>75% sp^3

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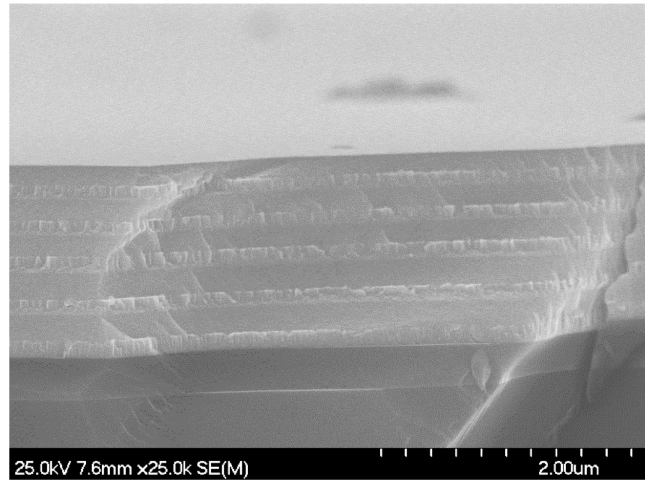
Relevance To HEP Community

- Enable coatings inside SRF cavities without having to “bias” the whole chamber (ship in a bottle)
- Coating cavities for higher accel gradient (atomic smoothness, reduced surface atom mobility)
- Allow nanocomposite surfaces for tailored “defect” length scale for higher voltage breakdown
- Coating cavities for higher Q at RT and SC
- Enable 3D-like coatings
- Co-deposition to control stoichiometry and morphology
- Allow reduced secondary and field emission properties
- Layered DAA cavities for laser-based accelerators
- Good for SC Magnet tape & wires



Example Multilayer Metal/Nitride Stack 115nm/235nm

Nanolayers can be done With stress control >10 microns high

Relevance To HEP Community

- Last summer, Fabio Avino @ CERN presented a paper showing results using Starfire's IMPULSE® + Positive Kick™ to deposit high-quality Nb thin-films 'quasi-conformally' on 3D net-shape Cu structures for WOW Crab Cavities [HiPIMS 2018]

- He also published data showing the controllability of the Positive Kick™ to adjust ion energy to the substrate to adjust morphology, stress and minimize Ar implantation vs. Nb [PSST 2019]

- Li Xiao at Peking University presented results for superconducting NbN using the same technique [HiPIMS 2018]

- JLab, FNAL, SLAC, others…

Lessons Learned

- Our foot is in the door into the HEP community now that we have an “off-the-shelf” technology that people can see and use
- The IMPULSE® + Positive Kick™ has a bright future, especially after the talks yesterday on 4.2K directly-coupled cryocoolers w/o liquid He

- Can industry collaborate without being competitive with its customers?
  - Yes, if you are lucky and find the right group of people to work with

- The Centurion™ 4 MeV LINAC already has traction for field-deployable PIGE for ^{19}F groundwater and soil environmental characterization
- LMIC relocatable/mobile PET isotope production for C, N, O
- Specialized neutron inspection and radiography applications

Thank You For Your Attention