Stellarray's Projects on Alternative Technologies for Blood, Research and Insect Sterilization

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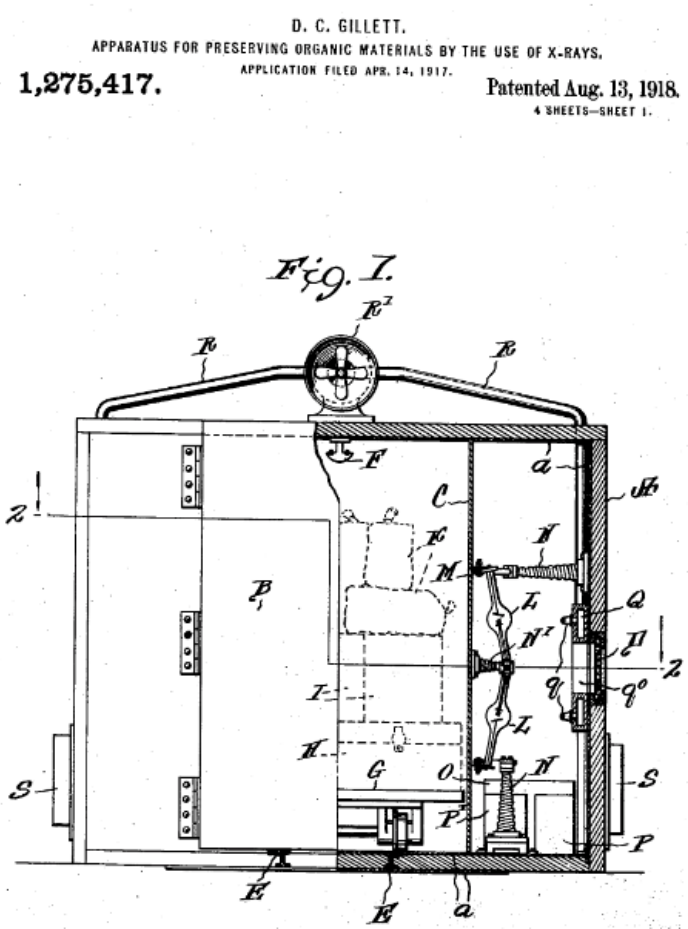
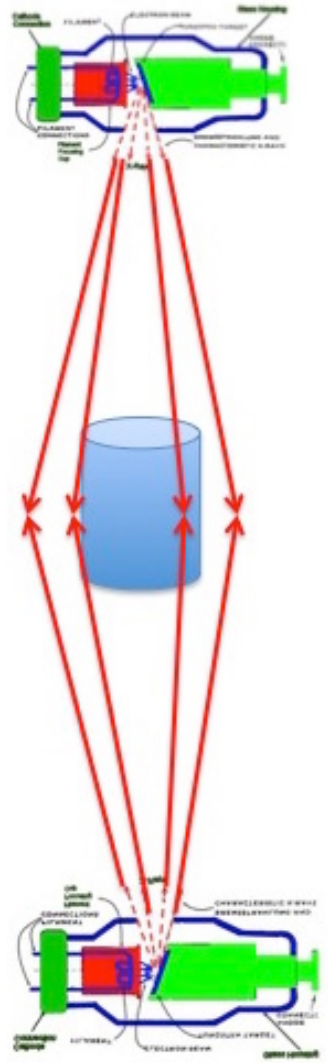
Background, Alternatives

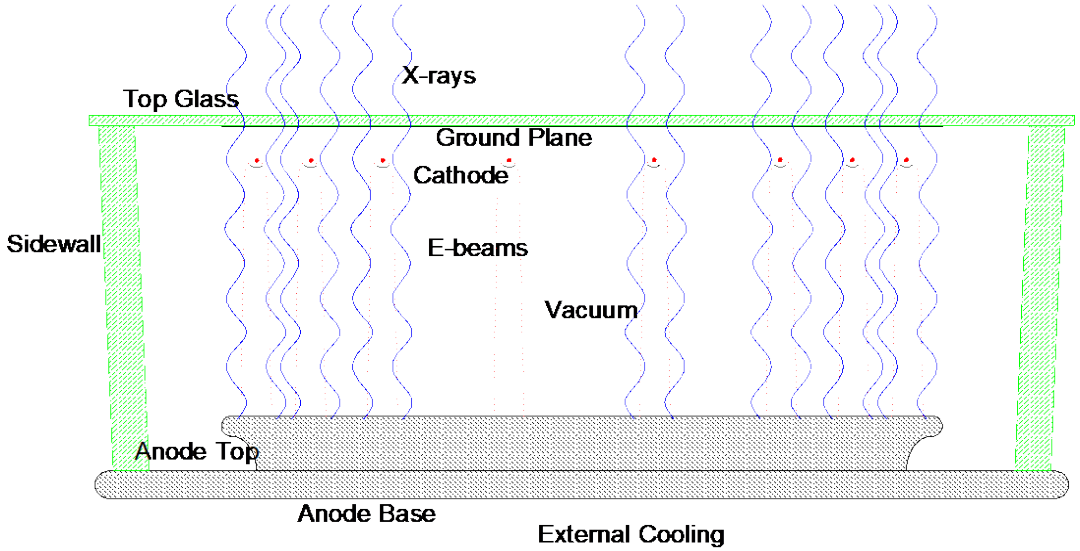
- **Low Voltage (<350 kV) X-ray Sources for Irradiation**
  - 1906 UK Patent, 1918 U.S. Patent
  - Food sterilization, other mass applications never took off
  - Higher energy for medical product sterilization
  - Isotopes dominate blood irradiation, some research and sterile insect
- **X-ray Tube Irradiators**
  - Widely used in research, but not all
  - Available for blood irradiation in U.S. since 2000, limited acceptance
  - Typically two 160 kV tubes, W anodes
  - Issues: throw distance, uniformity, power load on 2 anode spots
  - > kW on few mm^2, sublimates W, shortens tube life
  - Cooling systems fragile
- **Other Alternatives to Cs-137 Cabinet Irradiators**
  - Pathogen inactivation for blood
  - 4 pi irradiator
  - Linacs for e-beam or x-ray, used for medical product sterilization
    - form factor for cabinets
    - don't need high energy for inactivation; penetration, but more shielding
  - Relative biological effectiveness (RBE) – 662 kV a proxy
  - E-beam

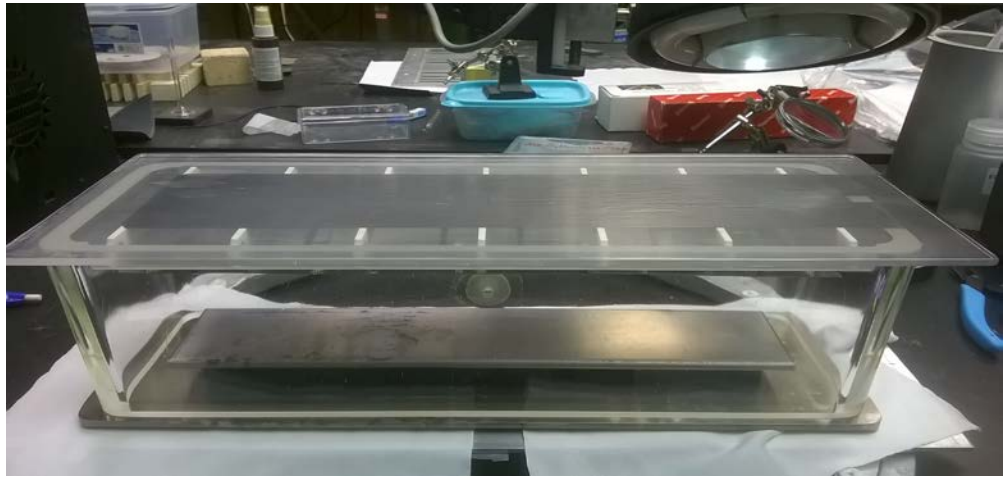

D. C. GILLETT.
APPARATUS FOR PRESERVING ORGANIC MATERIALS BY THE USE OF X-RAYS.
APPLICATION FILED APR. 14, 1917.
1,275,417. Patented Aug. 13, 1918.
4 SHEETS—SHEET 1.
Fig. 1.



Key Innovation: Flat Panel X-ray Source

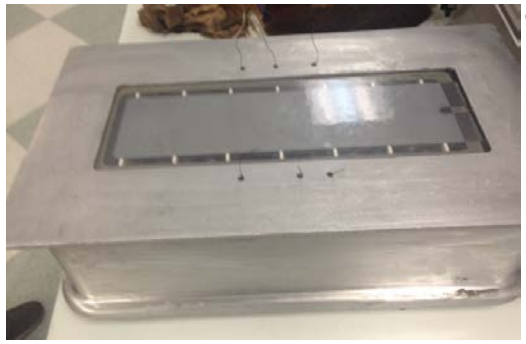
- **Point Source (tube) to Panel Source**
  - Cathode *array* at the flux exit window
  - E-beam showers across to large, broad anode
  - Broad X-ray flux up from anode, out top window
  - Anode area huge (21,000 mm^2 for blood) – no sublimation
  - Directly cool broad metal anode from outside
- **Panel Construction**
  - Filaments or cold cathodes
  - Anode assembly, avoids vacuum triple points
  - Glass walls for hermetic vacuum package
  - Glass exit window, ground plane
  - Materials thermally matched
  - Blood irradiator panels 110 x 350 x 100 mm internal
  - Sized for blood bags laying flat
  - No heel effect like tubes, 3X power efficiency
- **Production**
  - >300 process steps to make panel
  - Frit seals for permanent vacuum
  - Cleanliness is critical

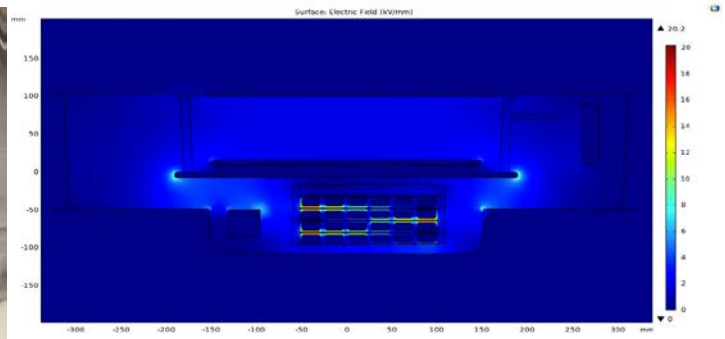


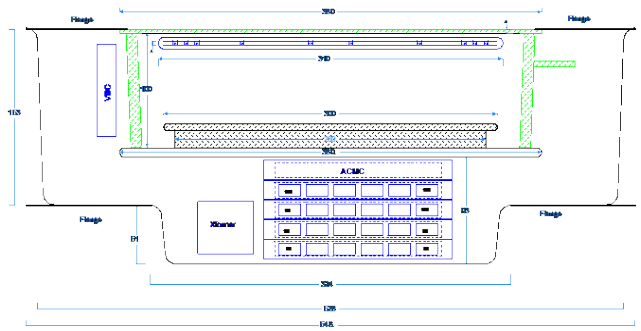


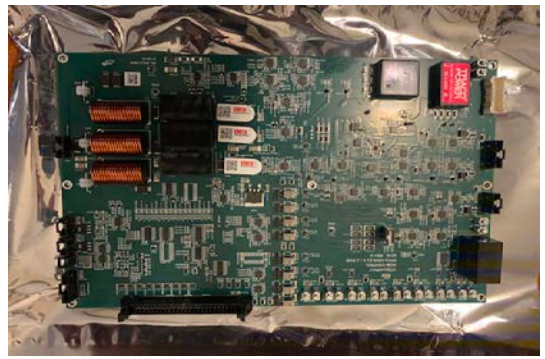
Module Casing & Electrical

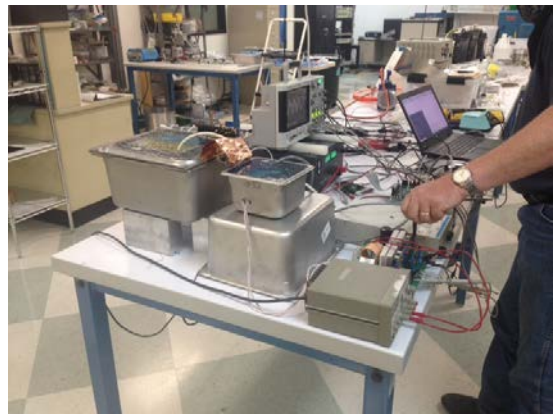
- **Module = panel, high voltage electrical, insulation**
  - Avoids cables, increases safety, decreases volume
- **Casing**
  - Metal pan construction – has to be smooth
  - Model shows high field areas
- **Insulation**
  - Oil traditional, but several drawbacks
  - Tested > 50 “solid state” materials for thermal conductivity
  - Epoxies, silicones, mix with AlN, BN powders
- **Electrical System**
  - Main power
  - Analog control board (includes 8 interlocks)
  - Resonant converter/front end
  - Transformer
  - Cockcroft-Walton stages (AlN packages, under anode)
  - Anode current measurement (feeds back to control)
  - Anode voltage measurement
  - Digital control and interface









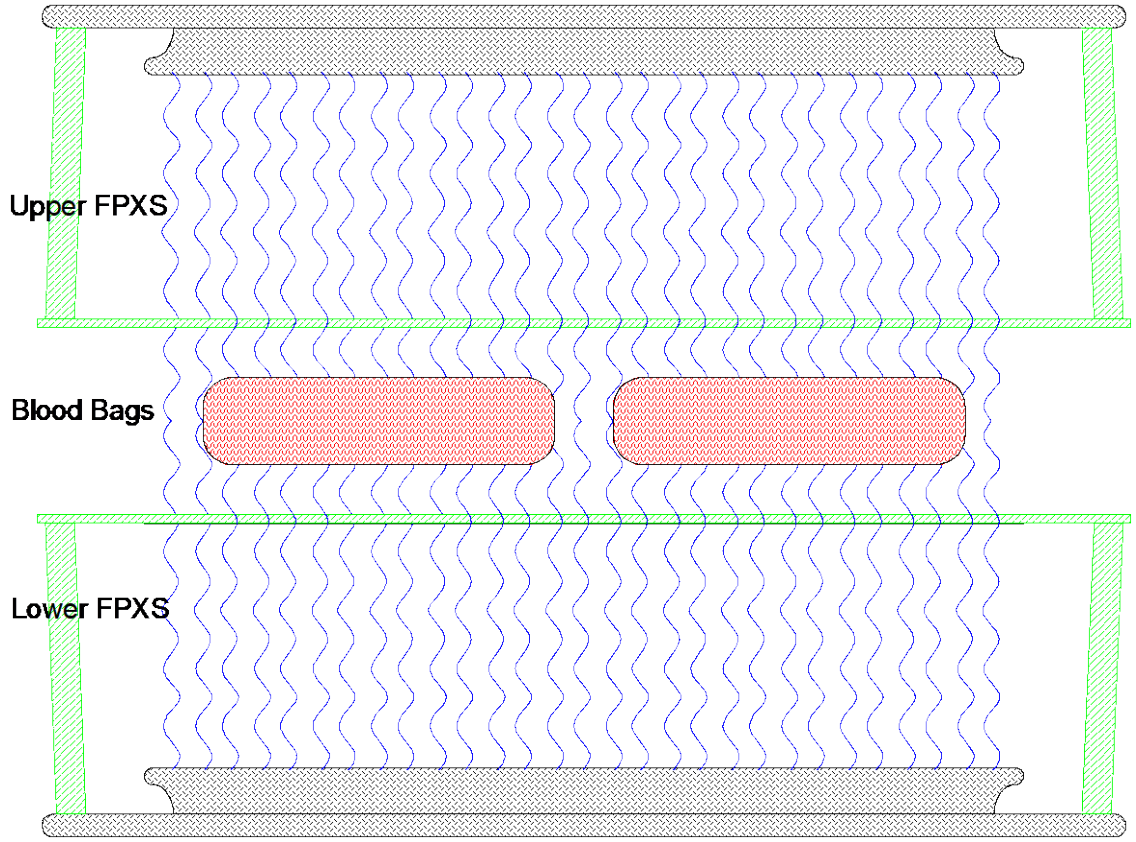


Stellarray Background

- **Founded in 2008**
  - 10 people, experience in field emission devices
  - Air Force SBIR – combined X-ray/UV-C
  - Novel x-ray sources to solve important problems
  - Focus on segments with high impact, high margins
  - Niche market irradiators
- **Source Platforms**
  - **Flat panel x-ray source: irradiation, sterilization**
  - Digitally addressable x-ray source: imaging
  - **Digitally addressable research source - irradiator**
  - Forward flux channel source: collimated beams
  - Grazing beam X-ray/EUV source: irradiation, lithography
  - Cathodoluminescent UV-C sources – pipe, panels
- **Facilities**
  - 15,000 sq. ft. light industrial
  - Class 10,000 clean room
  - Specialized tools for panels made in-house
    - laser deposition thin films
    - frit sealing
  - Radiation test room

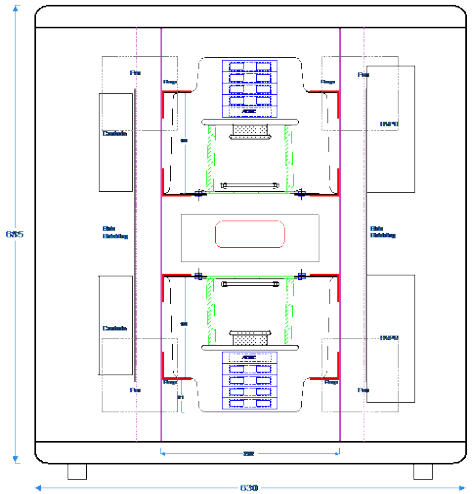
Blood Irradiator Operation & Features

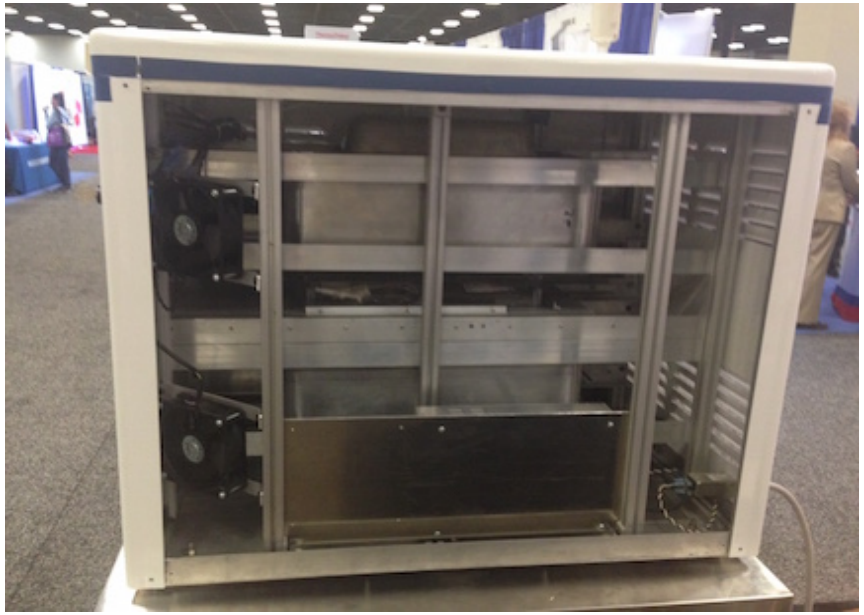
- **Upper and Lower Panel Emit Radiation (Toaster)**
  - Exit window of panels sized for blood bags
  - Blood bags, syringes, etc. into standard tray
  - X-rays emit to target from both sides, close range
- **Panel Electrical**
  - Whole array on at once, both panels
  - Rated for 160 kV, 5 mA (2.7 mA normal for 25 Gy/4 min)
- **Features**
  - Source area and target area ~ the same
  - Efficient use of power & space
  - Gravity flattens blood bags, helps uniformity
  - Lower input power, lighter shielding
  - Self-shielding of panels in pairs
  - Standard wall power (small & medium)
  - No external cooling
  - Compact cabinet ~ microwave
  - Low cost of ownership
  - Faster processing, higher throughput than isotope irradiators



Self-Contained Blood Irradiator

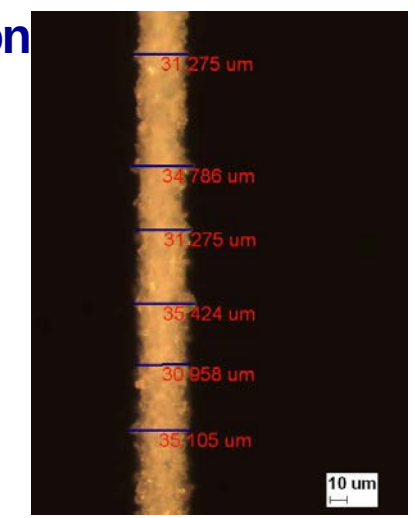
- **Benchtop cabinet**
  - Encloses 1 – 3 pairs of panel modules, 1 – 3 kW
  - 3 models – small, medium, large
  - Small is 685 x 630 x 860 mm (6 sq. ft. footprint)
  - Tray fits into slide, between panels
  - Cooling fans at front side quarters
  - Radiation shielding at 3 levels
- **Dosage**
  - Control electronics keep panels on until current delivered
  - Radiosensitive dose tags on blood bags
- **Reliability**
  - Fans and tray slide the only moving parts in system
  - Source suited for job
  - Panel pair redundancy
- **Development challenges – in sources**
  - Cathode Lifetime
  - Uniform operation
  - High voltage stability

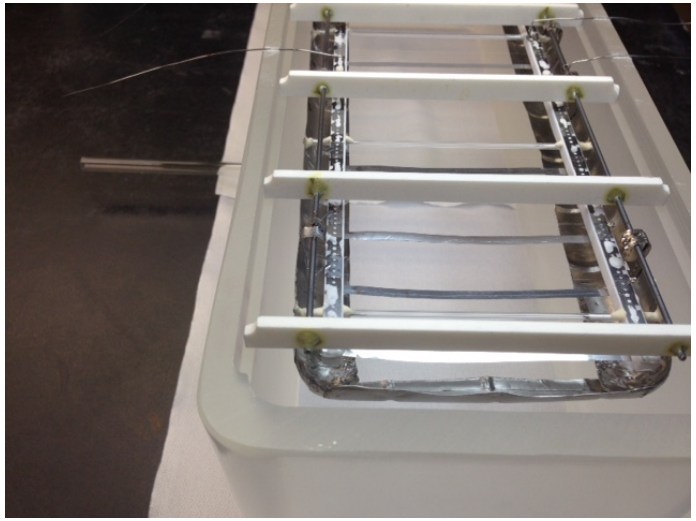


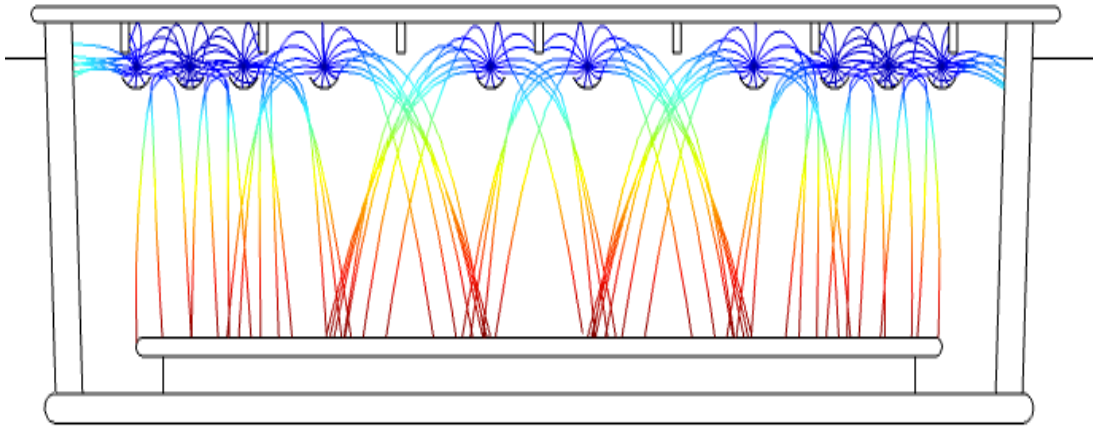


Source – Cathode Lifetime

- **Initial panel lifetime goal is 2,000 hours, > 5 years operation**
- **Lifetime limiting factors – filaments & arcing**
- **Triple oxide filaments**
  - Used in vacuum fluorescent displays, 40,000 hrs
  - Carbonate coating (Sr, Ba, Ca) → oxide, low work function
  - 650° vs > 2,000° for W
  - Temp vs lifetime logarithmic
- **Filament lifetime accelerated tests**
  - Low at first
  - 0.5 second soft start got them to rated values
- **Activation protocols very sensitive**
  - Converts carbonate coating to oxide
- **Ion bombardment**
  - Worse than first thought
  - Strip the oxide in < hour
  - Tried thoriated W
  - Added thin shielding strips under filaments - worked
  - New longitudinal design has even better shielding



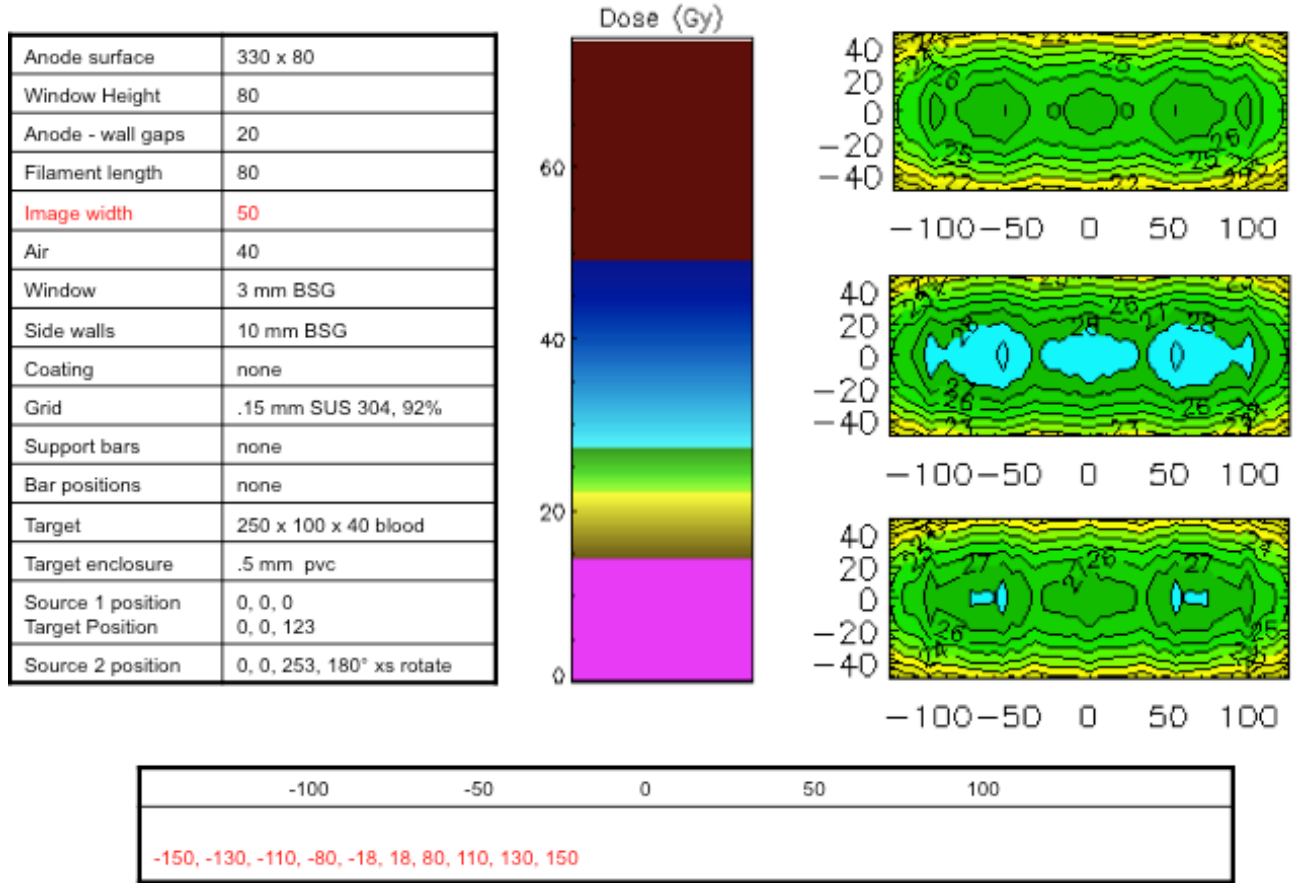




Source – Uniform Operation

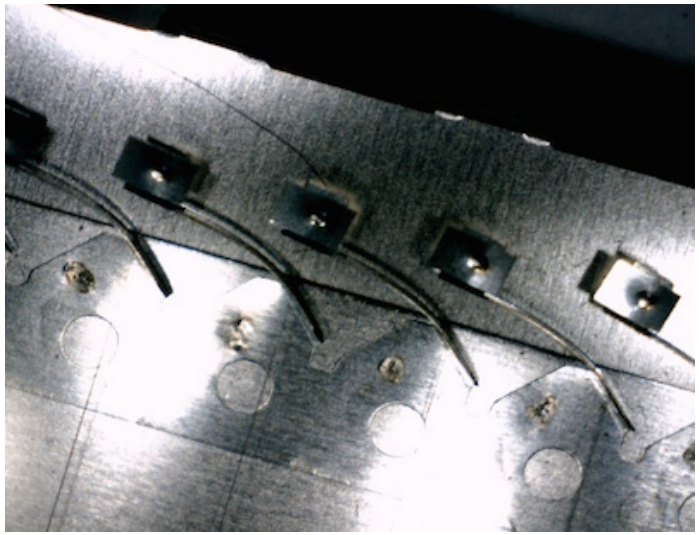
- **Uniformity requirements**
  - Blood: 25 Gy mid-plane (> 15 Gy, < 50 Gy)
  - Stellarray systems, < 10% variation
  - x-y uniformity by placement of filaments
  - z axis uniformity by V_a & system design
- **Uniformity modeling**
  - XSST tool – based on PENELOPE
  - Input panel & system design
    - e.g filament placement, source dimensions
  - Computes x-ray generation, distribution, absorption
  - Generates dose map at high, middle and low planes
  - Get very high uniformity
  - >500 model variations run
  - Unexpected findings:
    - anode top to bag distance very important
    - thickness of bags not very important
  - Model confirmed against blood bag phantom

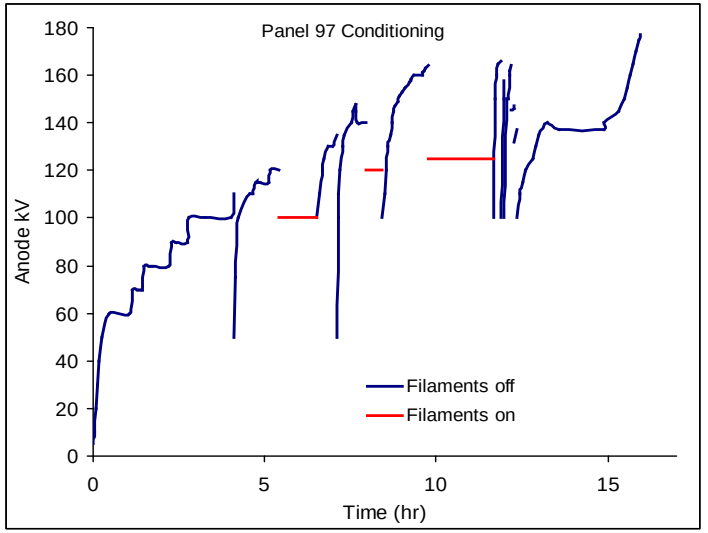
Anode surface	330 x 80
Window Height	80
Anode - wall gaps	20
Filament length	80
Image width	50
Air	40
Window	3 mm BSG
Side walls	10 mm BSG
Coating	none
Grid	.15 mm SUS 304, 92%
Support bars	none
Bar positions	none
Target	250 x 100 x 40 blood
Target enclosure	.5 mm pvc
Source 1 position Target Position	0, 0, 0 0, 0, 123
Source 2 position	0, 0, 253, 180° xs rotate

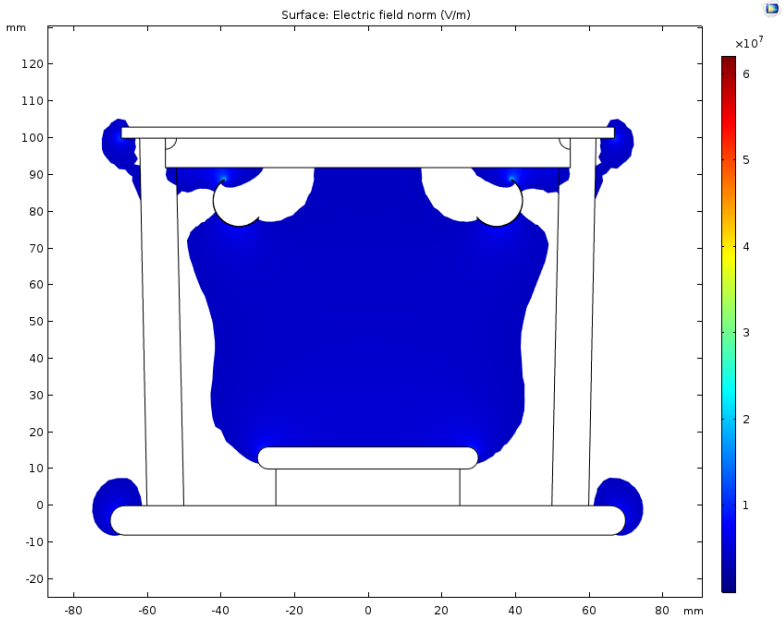


Source – High Voltage Stability

- **Major challenge**
  - 160 kV across < 100 mm space
- **Major factors inducing arcs**
  - Vacuum level
  - Source design
  - Triple points: conductor – insulator - vacuum
  - Sharp features
- **Methods**
  - Standard good vacuum practices, QC
  - Fabrication processes for sealing – frit machines
  - Spot knocking/break-in
  - Extensive modeling of field/charge balance in enclosure
    - panel, emitter array & anode design changes
  - Testing in panels
- **Results**
  - Excellent vacuum: 1 – 2 x 10^{-8} Torr
  - Steady increases in stable voltage
  - Reached 177 kV; reached 20 mA
  - Close to 160 kV, but not yet consistent
  - Target beta installations in June 21

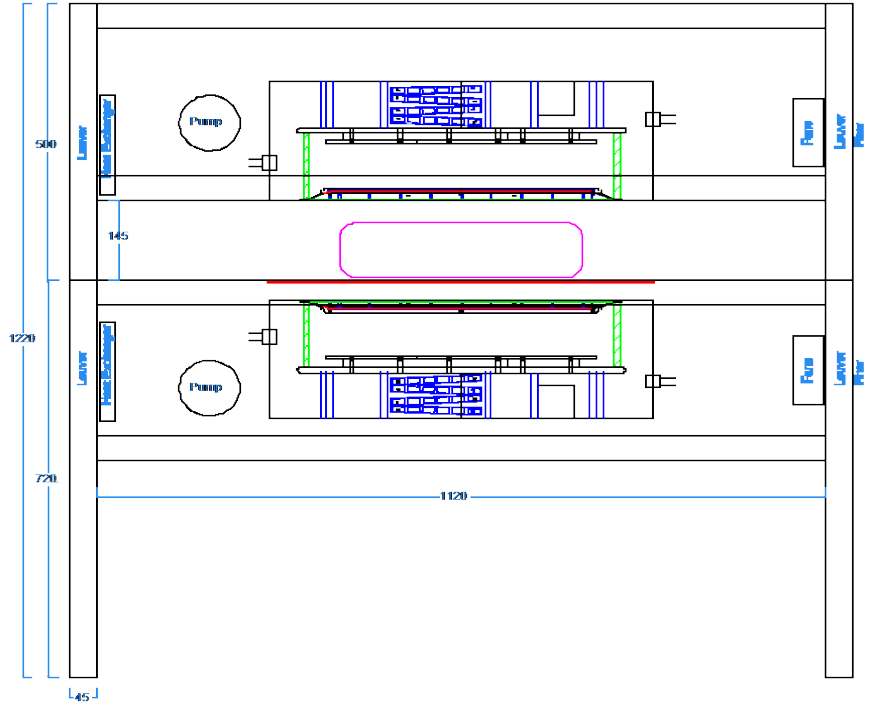


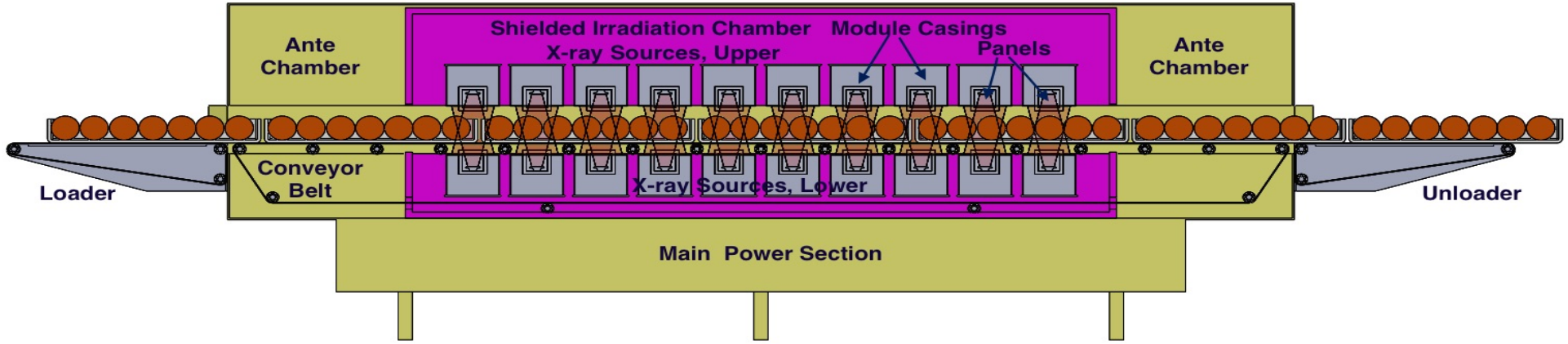




Sterile Insect X-ray Irradiator

- **Sterile Insect Technique**
  - Irradiate insect pest larvae – adults healthy but infertile
  - 66 worldwide, 11 in U.S. – most isotope
- **High-Volume, Modular Conveyor System**
  - Panel pairs, 3.6 kW per pair (MFF)
  - Size of airport baggage scanner (40 sq. ft. footprint)
  - Frame, transport system, closed loop cooling, fans, shielded louvers
  - HV amplifier built-in; change front end for new grid
- **Development**
  - New panel design
  - Add panel pairs to scale
  - Modularity for range of conditions & doses
  - Automation





Sterile Insect User Needs

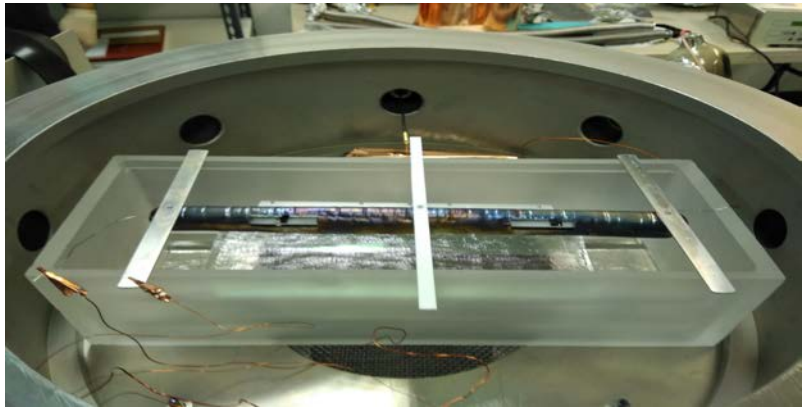
- **New Technology has to be Better**
  - Fit process flow, save time
  - Easy to operate, economical
  - Adaptable, serviceable for remote location, power grids
- **Doses & Uniformity**
  - Each species has an optimal dose, 4 Gy to 400 Gy
  - Most common: 75 Gy for fruit flies, 60 Gy for mosquitos
  - Coverage areas different
  - Dose uniformity ratio (DUR) critical – 1.3 (IAEA)
- **Edinburg, TX Mexican Fruit Fly Facility (USDA)**
  - MFFs attack citrus crops
  - Current facility produces 150 Mn ppw, expanding to 400 Mn ppw
  - Nurture citrus medium – irradiate pupae – disperse both sides of border
  - Process in trays (31 x 16 x 1”), then “sausages” (4 x 16”, 50K pupae each)
  - Two Cs-137 units, sausages inserted in Al sleeve (3 mm walls)
  - **One by one, 320 in 8 hrs**
- **Early estimates for SIXI**
  - Save operators time; fit process in-line
  - DUR better than 1.1

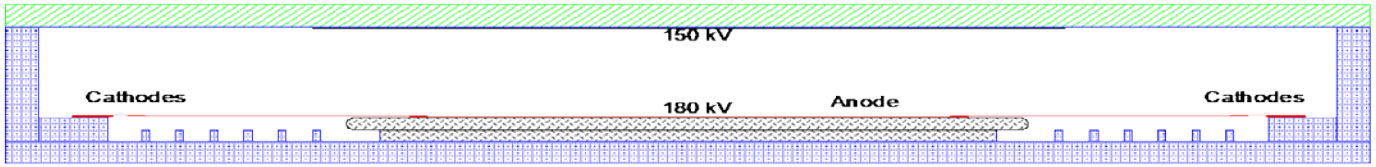


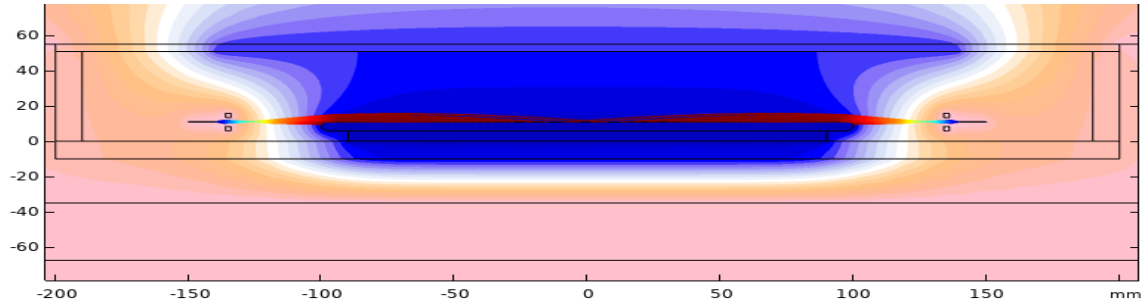


SIXI Panels & Modules

- **SIXI panels**
  - Same FPXS architecture & advantages
  - SIXI panels 540x120x110 mm
  - Designed to suit trays or sausages
  - Longitudinal cathode arrays, shape for x-axis uniformity
- **SIXI modules**
  - Higher power: 180 kV, up to 20 mA
  - Closed loop oil cooling
  - Multiple panels in casing
- **Electrical system**
  - Same eight components
  - HV components in casing
  - Full-wave eight-stage CWA; two transformers
  - Change main power & power inverter/front end
- **Grazing beam source**
  - Change architecture for higher conversion efficiency
  - E-beams in at shallow angle; upper & lower anodes
  - Iterative model: pyPENELOPE, COMSOL, IDL
  - FPXS PE @ 160 kV 1.9%, 3X tube
  - GBXS 47% over FPXS; 2.8% PE





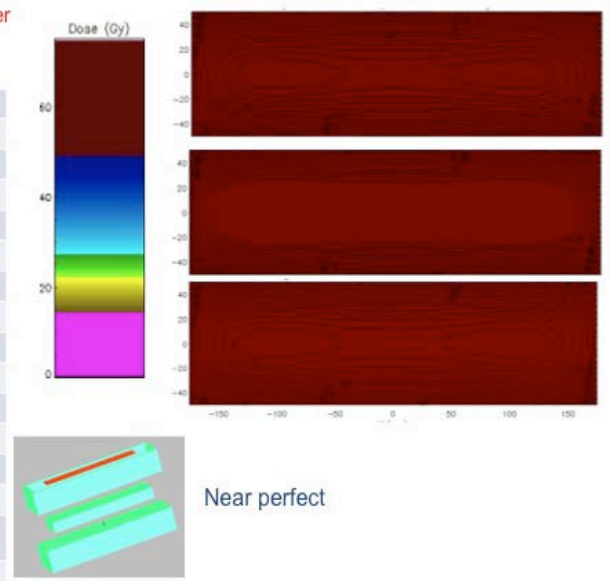


SIXI Estimates

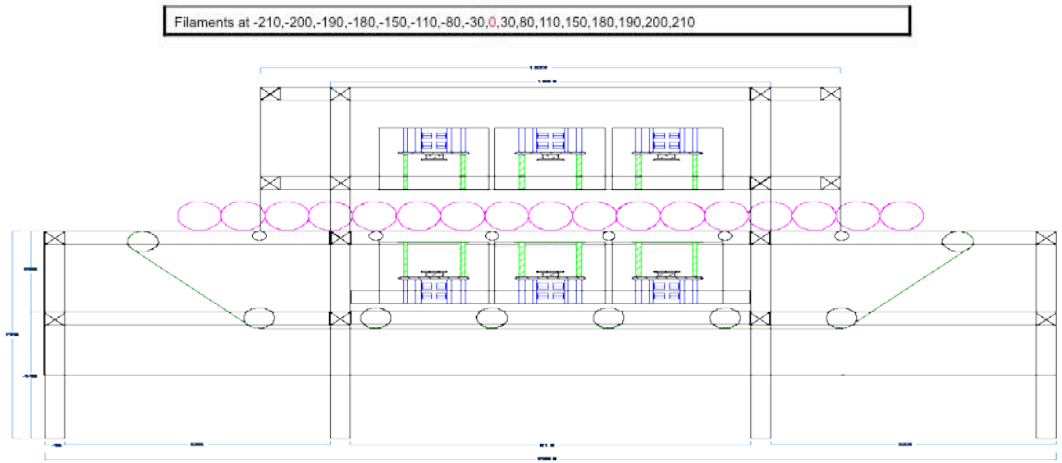
- **Dose Uniformity**
  - Modeled cases in XssT
  - Configurations for 1.1 DUR
  - z-axis – panel parameters; y-axis – conveyor; x-axis – panel design
- **Three-pair system for Edinburg – beta in 1 year**
  - Panels 180 kV, 10 mA: 12 kW system
  - Irradiate 5-6 sausages to 75 Gy in four minutes
  - 750,000 pupae; 90 Mn in eight hours
  - Half of current *weekly* output; easily handle expansion
  - Five pair system (20 kW) yield 162 Mn pupae in 8 hrs
- **Testing**
  - Sausage phantoms
  - Radiation shielding; USC 1020.40 + paper
  - Measure heat output; fan efficiency
- **Reference design**
  - System description & model for users
  - World different power supplies

Two Panels, 180 kV, 10 mA, 440x60 Anode
240 sec, Tray Target, more filaments at ends, add in glass, longer anode, shorter tray

Anode surface	440x60
Window Height	80
Anode - wall gaps	30, 30
Filament length	70
Image width	50
Air	0
Window	3 mm BSG
Filter	none
Side walls	10 mm BSG
Coating	none
Grid	None/air
Support bars	None/air
Bar positions	
Target	400 x 100 x 40, larvae
Target enclosure	.1mm PVC
Source 1 position Target Position	0, 0, 0 0, 0, 150
Source 2 position	0,0,300, 180 x-axis rotate

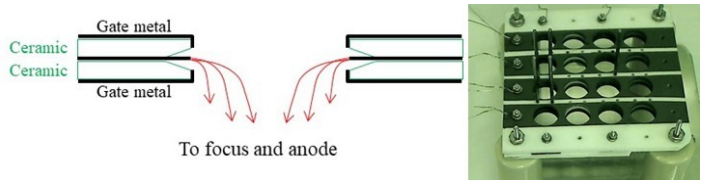


Near perfect

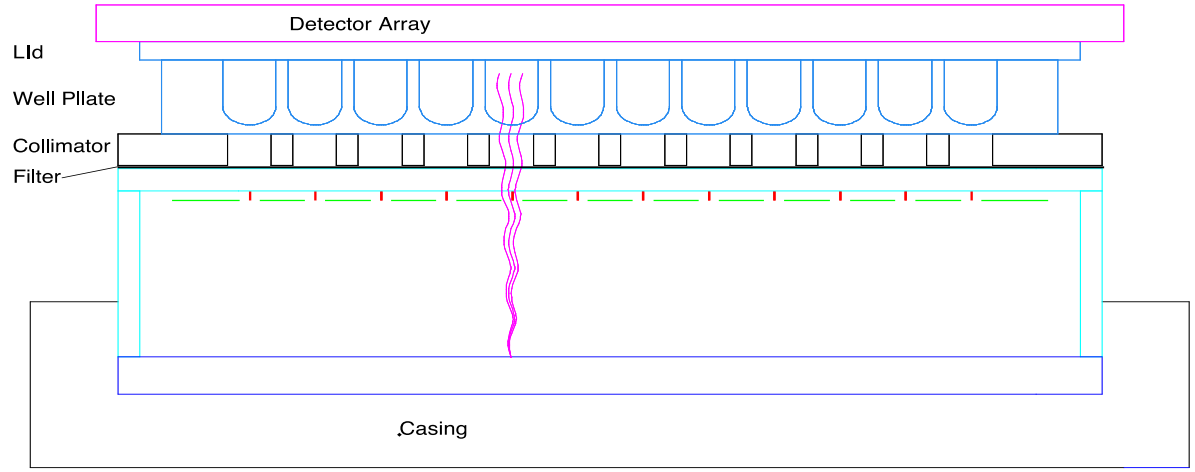


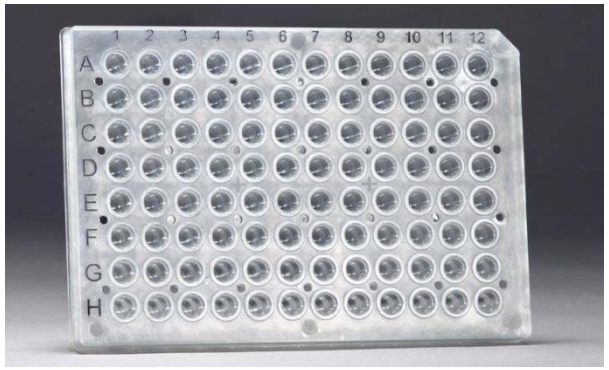
Digitally Addressable Research Irradiator

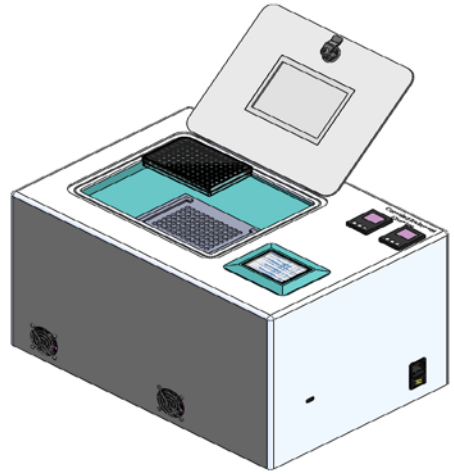
- **Irradiate individual wells in 96-well plate**
  - For cell & small sample studies
  - Vary dose, time, energy for >> sample numbers
  - Help develop RBE curves, personalized therapy
  - Programmable control & automation
- **Custom-Made Digital X-ray Source**
  - Matrix cold cathode array opposite broad anode



  - X-rays from small anode spots (xels)
  - Collimation in panel, on top, in plate
  - Wells have small volumes (mL)
  - Small power yields high dose (DNA repair studies)
  - 10 - 100 kV, 0.01 - 2 mA/xel (next model higher)
- **Compact Cabinet**
  - Top loading, gas tight chamber (tri-gas flow)
  - Other sections for source & controls
  - 500 x 300 x 350 mm, < 50 kG
  - Uses standard wall power

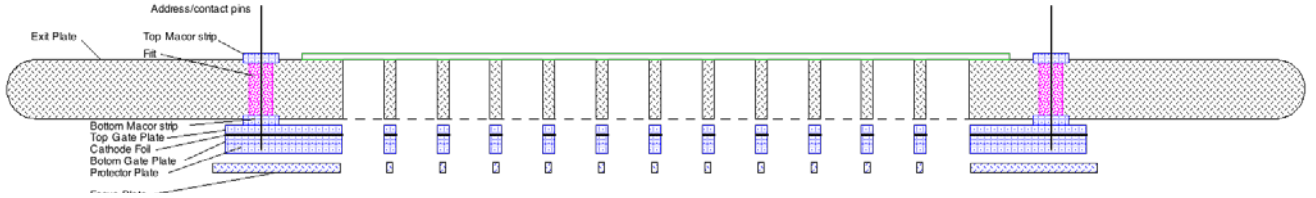


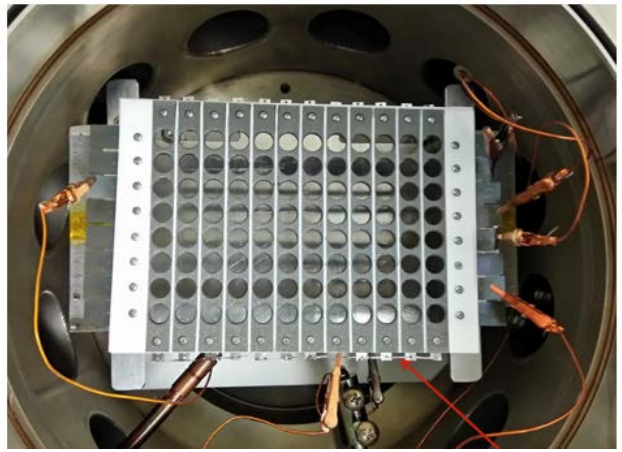


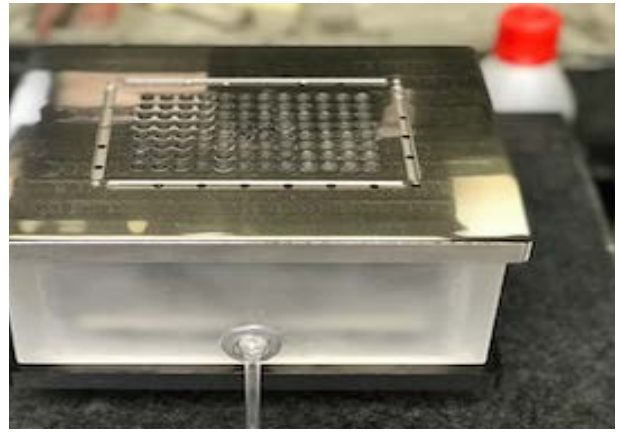


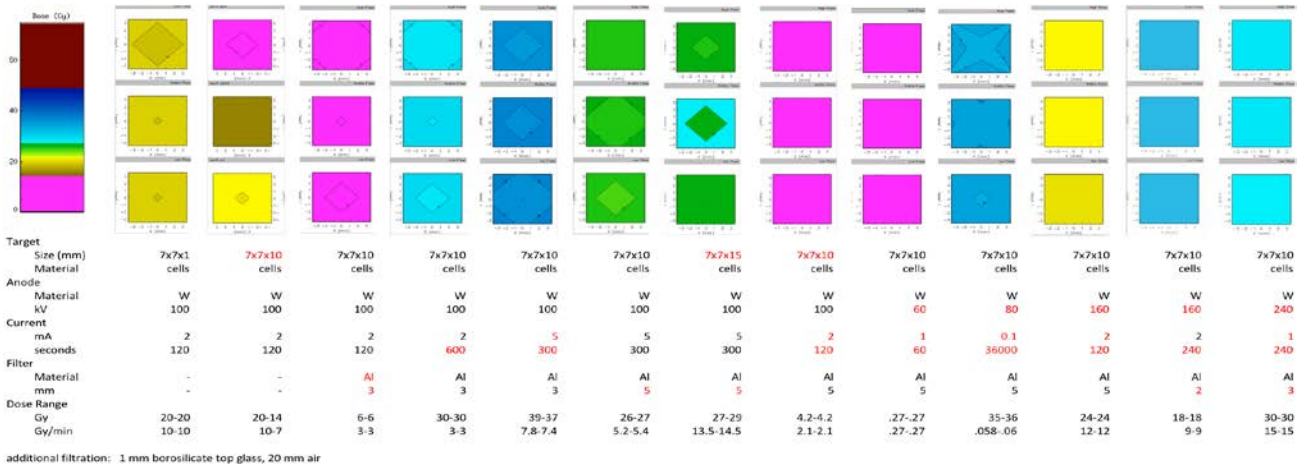
DARI Progress

- **Four generations of sources**
  - Emitter assembly, stacks of plates
  - Separate cathode layer from gate plates
  - Gate lines on ceramic gate plates
- **Cathode arrays**
  - Thin-film, annular (7 mm) edge emitters
  - Emit into opening, focus, beam to anode
  - Alternating emitter layers on 25µm Mo ribbons
  - Nano-layered carbon or Mo/diamond
  - Exceeded 2 mA target
- **Panels**
  - Top plate with 96 holes, thin glass on top
  - Similar anode as FPXS
  - Have operated to 118 kV
- **Cabinet & electrical**
  - Stainless steel cabinet
  - Have anode supply; making digital controls
- **Uniformity**
  - Modeled with XssT; filtration
  - Highly uniform in wells; high dose rates









Target													
	Size (mm)	7x7x1	7x7x10	7x7x10	7x7x10	7x7x10	7x7x10	7x7x15	7x7x10	7x7x10	7x7x10	7x7x10	7x7x10
	Material	cells	cells	cells	cells	cells	cells	cells	cells	cells	cells	cells	cells
Anode													
	Material	W	W	W	W	W	W	W	W	W	W	W	W
	kV	100	100	100	100	100	100	100	100	60	80	160	160	240
Current													
	mA	2	2	2	2	5	5	5	2	1	0.1	2	2	1
	seconds	120	120	120	600	300	300	300	120	60	36000	120	240	240
Filter													
	Material	-	-	Al	Al	Al	Al	Al	Al	Al	Al	Al	Al	Al
	mm	-	-	3	3	3	5	5	5	5	5	5	2	3
Dose Range													
	Gy	20-20	20-14	6-6	30-30	39-37	26-27	27-29	4.2-4.2	.27-.27	35-36	24-24	18-18	30-30
	Gy/min	10-10	10-7	3-3	3-3	7.8-7.4	5.2-5.4	13.5-14.5	2.1-2.1	.27-.27	.058-.06	12-12	9-9	15-15

additional filtration: 1 mm borosilicate top glass, 20 mm air

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