Application of Superconducting Technology for Proton Therapy

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ProNova Solutions, LLC

Introduction

Thanks to the organizers for inviting me to speak today.

I'd like to acknowledge many folks who contributed content to this presentation:

ProNova

Ron Moore, physicist

Jim Volk, physicist

Amy Xia, physicist

Hao Chen, physicist

Aaron Jacques, engineer

Michael Bozeman, product manager

Provision

Niek Schreuder

Ionetix

John Vincent

MIT

Joe Minervini

Alexei Radovinsky

PLUS: A lot of other hard working folks I haven't mentioned.

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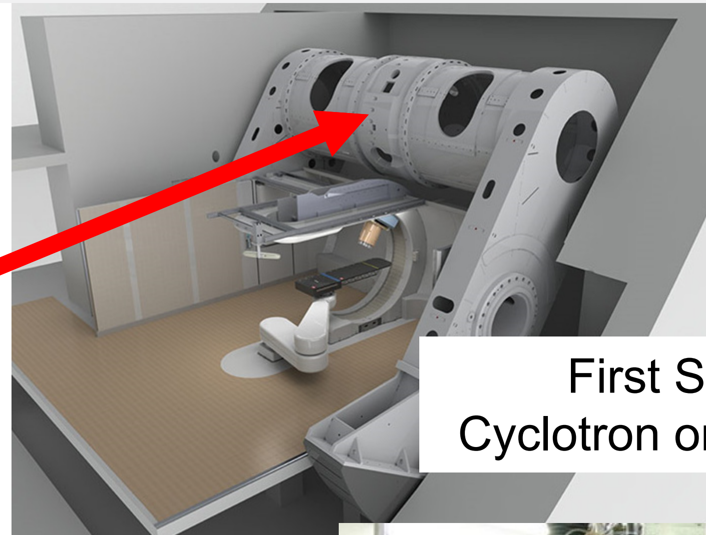
Introduction

Outline:

1. Proton Therapy, why?
2. ProNova SC Gantry and operating results.
3. Other ProNova SC projects:
    1. SC Isochronous Cyclotron (SCIC)
    2. Ironless Cyclotron Project with MIT

Other examples of SC in Proton Therapy



First Superconducting Cyclotron on a Gantry - MEVION

SC Cyclotrons used by IBA and Varian

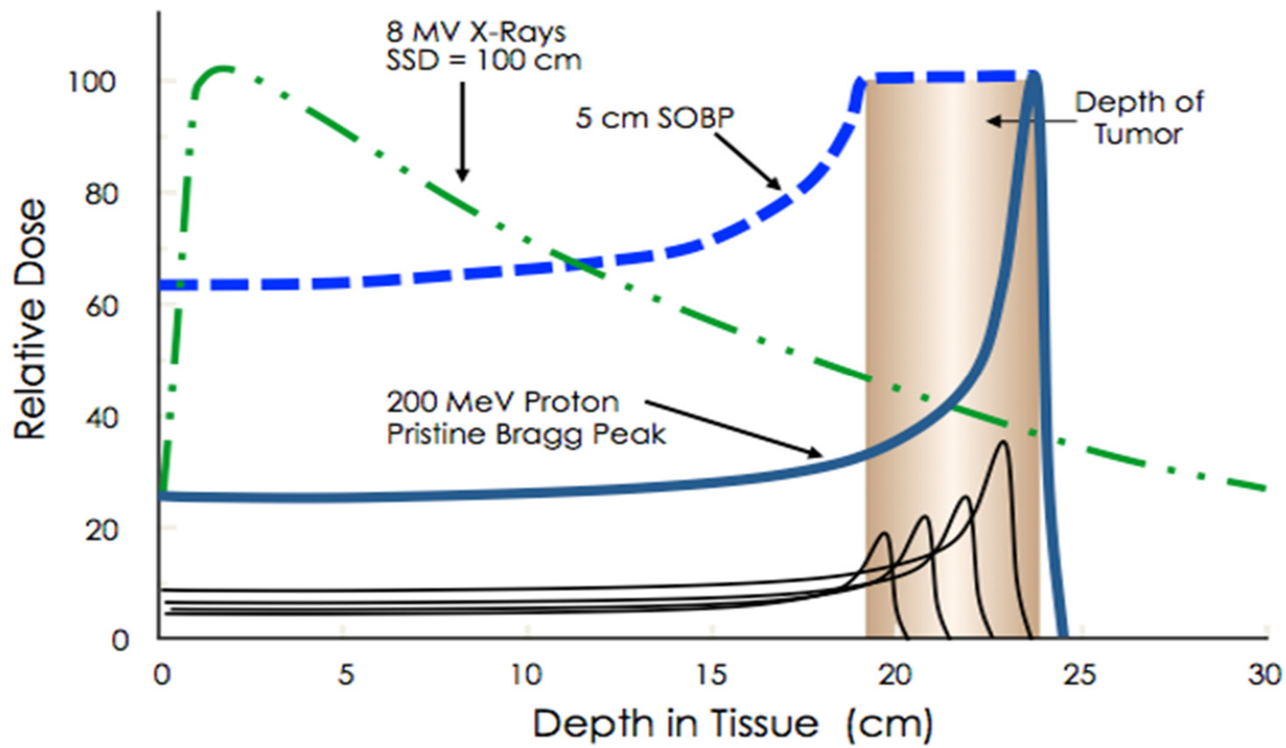
Introduction – ProNova SC Gantry History

CTI -> Provision Center for Proton Therapy -> ProNova Solutions

Indiana University -> ProCure -> SC Achromatic Gantry concept
- ProNova starts SC360 project in late 2012.
- First beam through SC Gantry in late 2015.
- First patient Q2 2017

What is Proton Therapy?

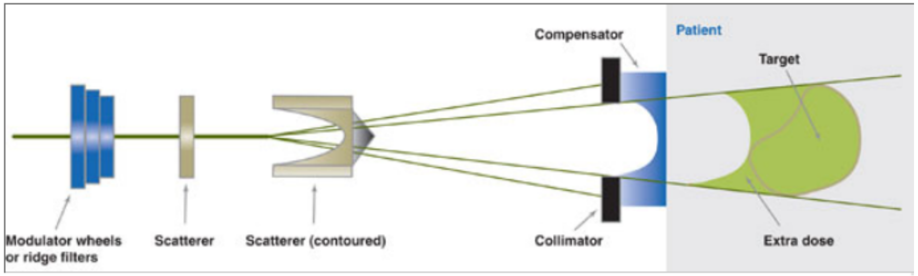
- Protons deposit their maximum energy in the Bragg Peak.
- Photons deposit the maximum energy at a shallow depth.
- Multiple Bragg Peaks at different layers are added to cover the full depth of the tumor.

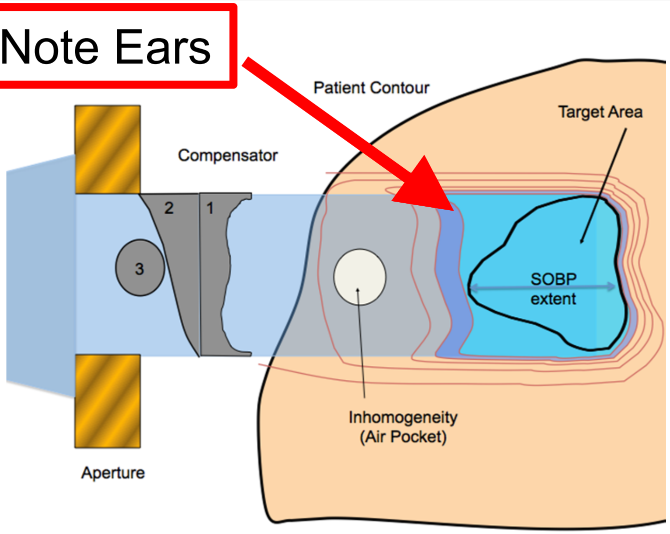


Scattering vs. Pencil Beam Scanning

Scattering System US/DS

More Nozzle components for US / DS



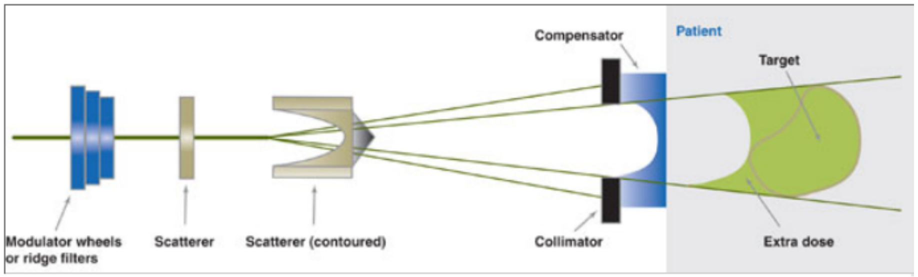


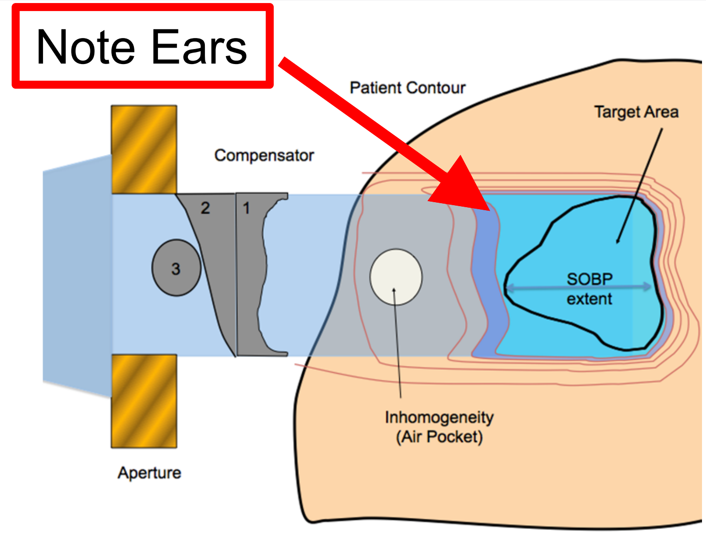
Pencil Beam Scanning

Scattering vs. Pencil Beam Scanning

Scattering System US/DS

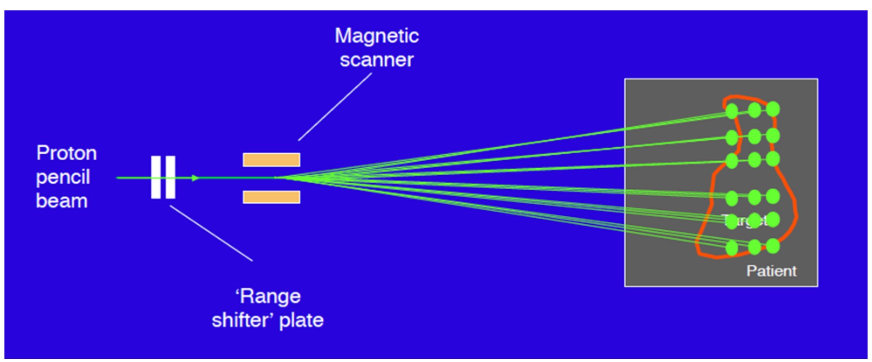
More Nozzle components for US / DS

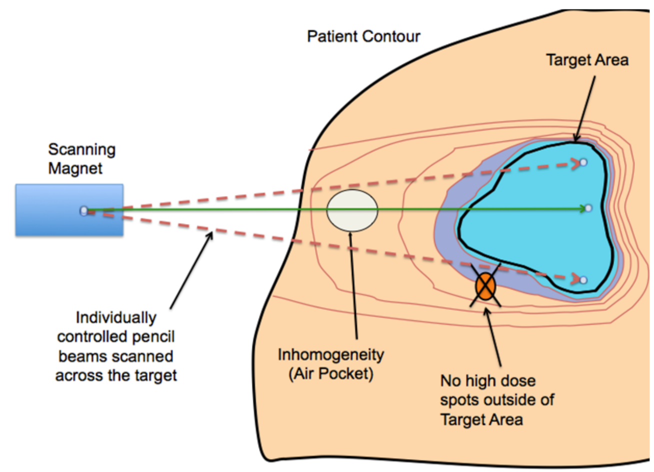




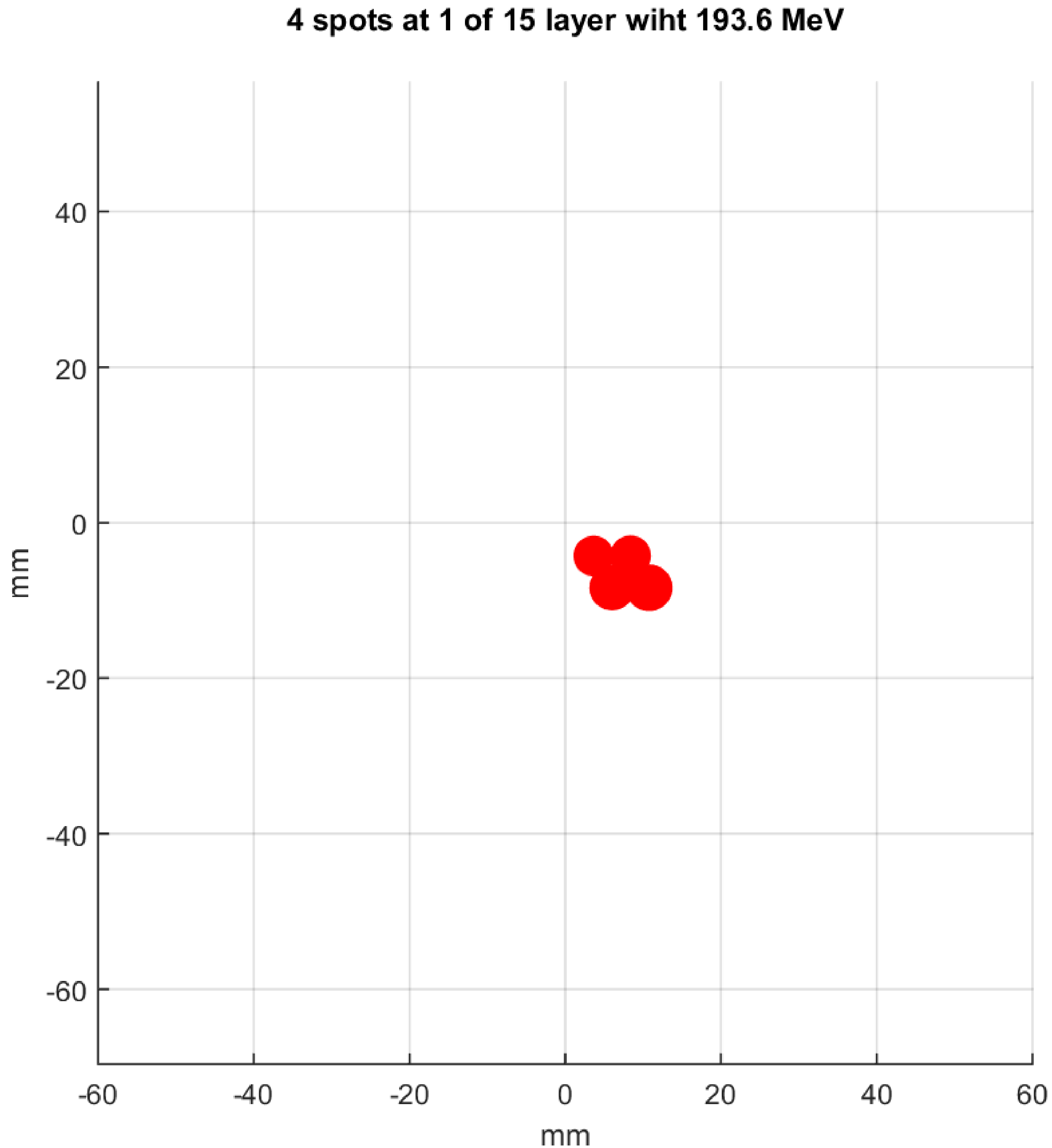
Pencil Beam Scanning

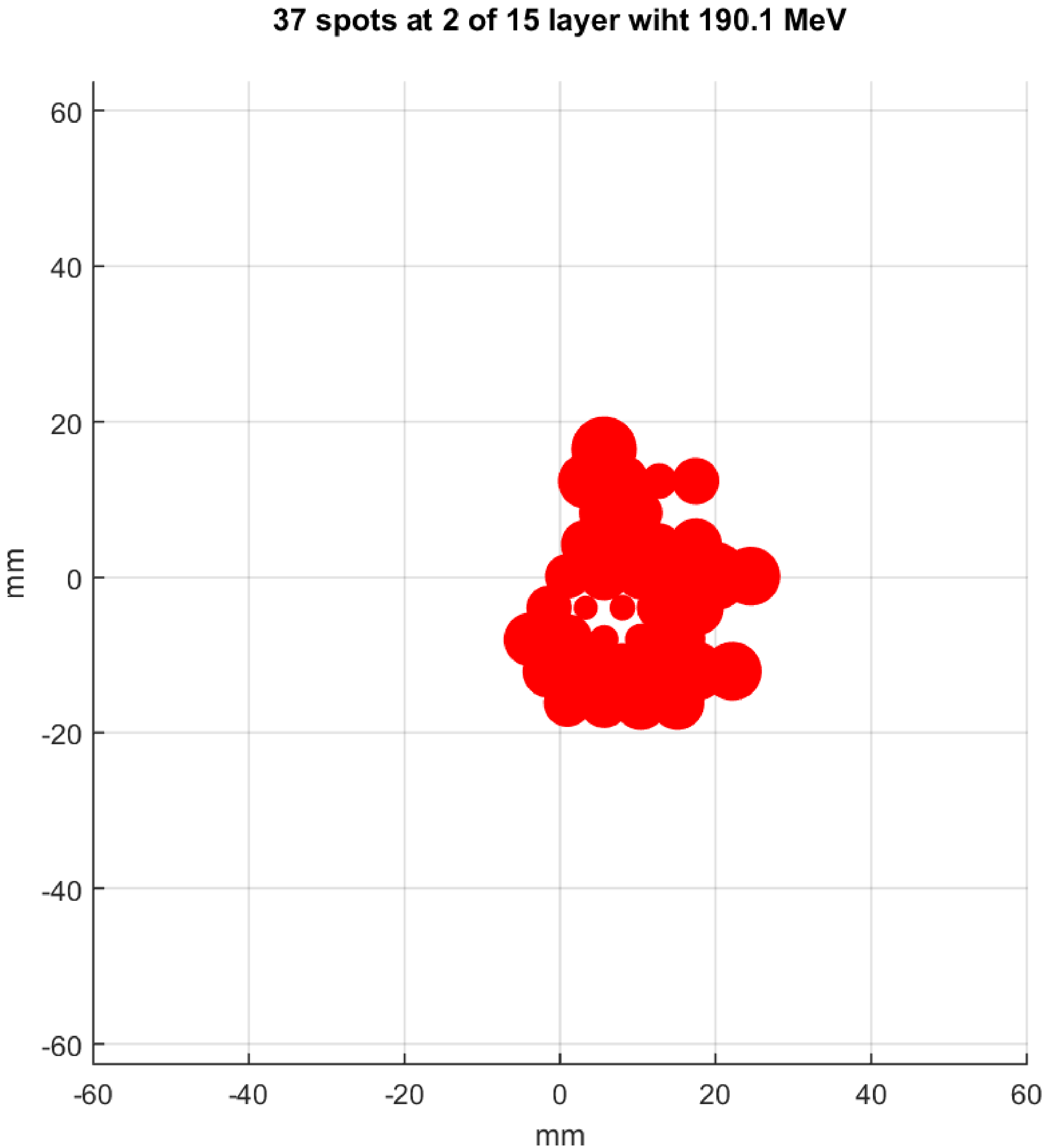
Simplified Nozzle for PBS



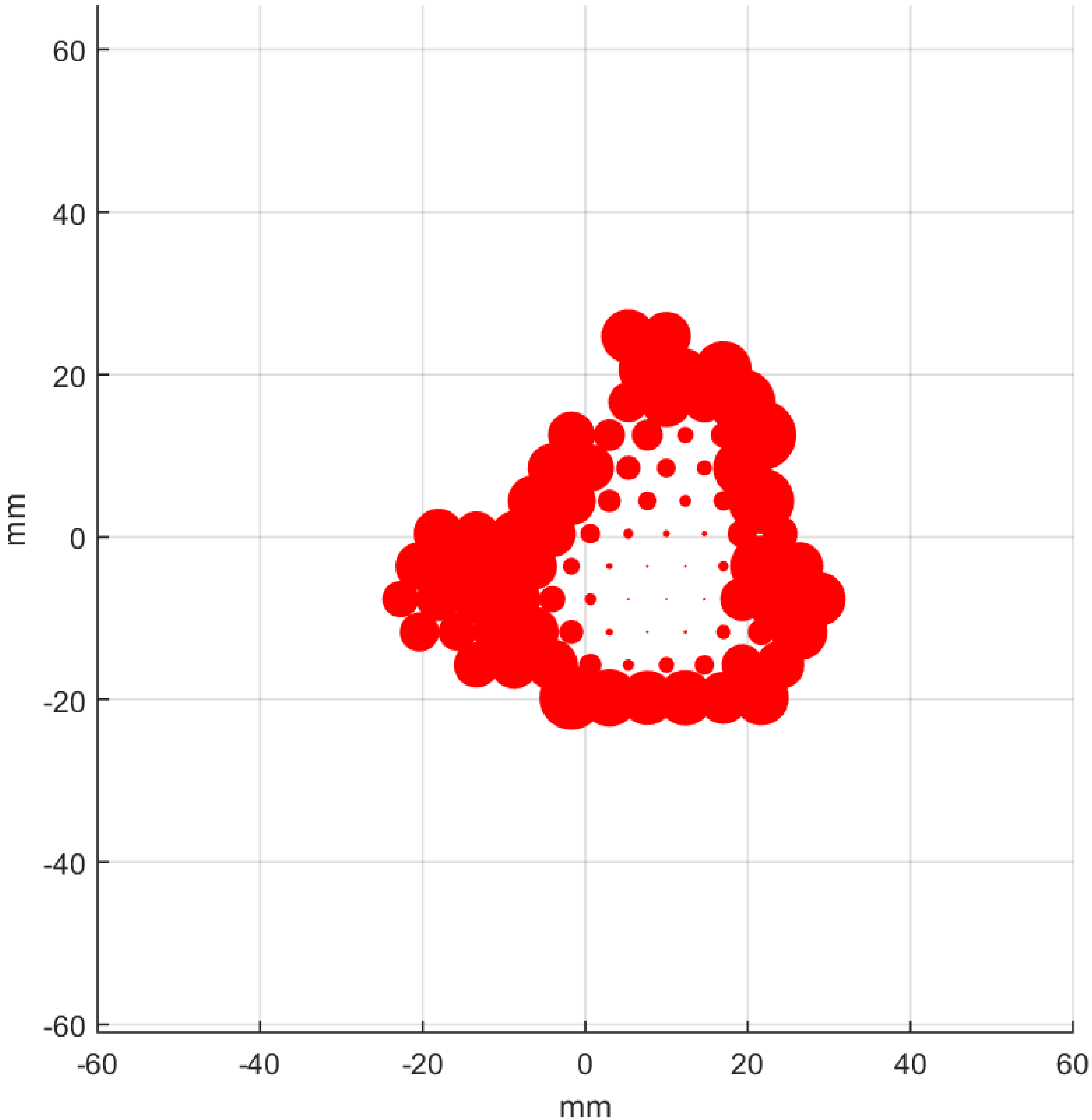


ProNova

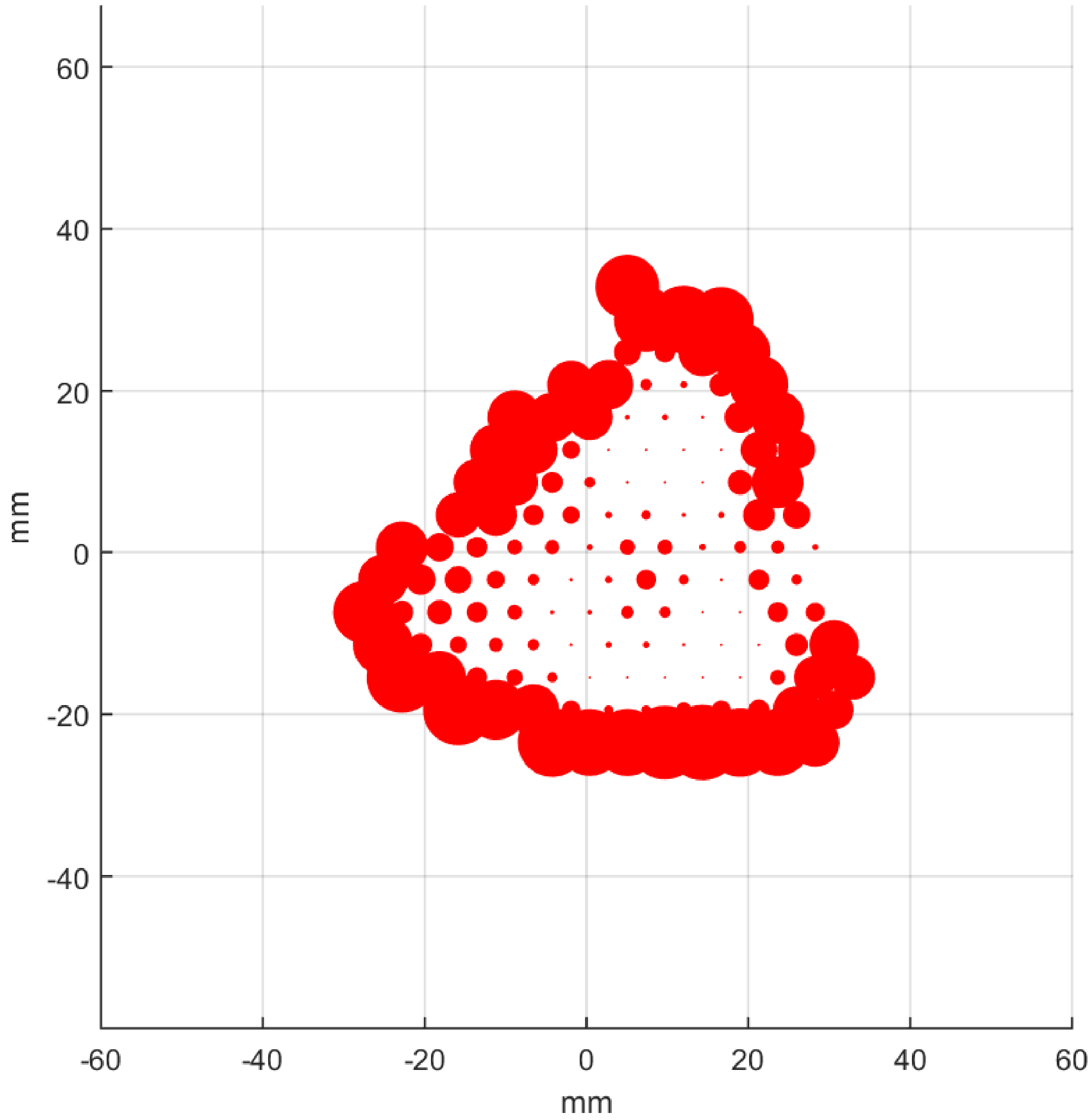

4 spots at 1 of 15 layer wiht 193.6 MeV
40
20
0
-20
-40
-60
mm
-60
-40
-20
0
20
40
60
mm


37 spots at 2 of 15 layer wiht 190.1 MeV
60
40
20
0
-20
-40
-60
mm
-60
-40
-20
0
20
40
60
mm

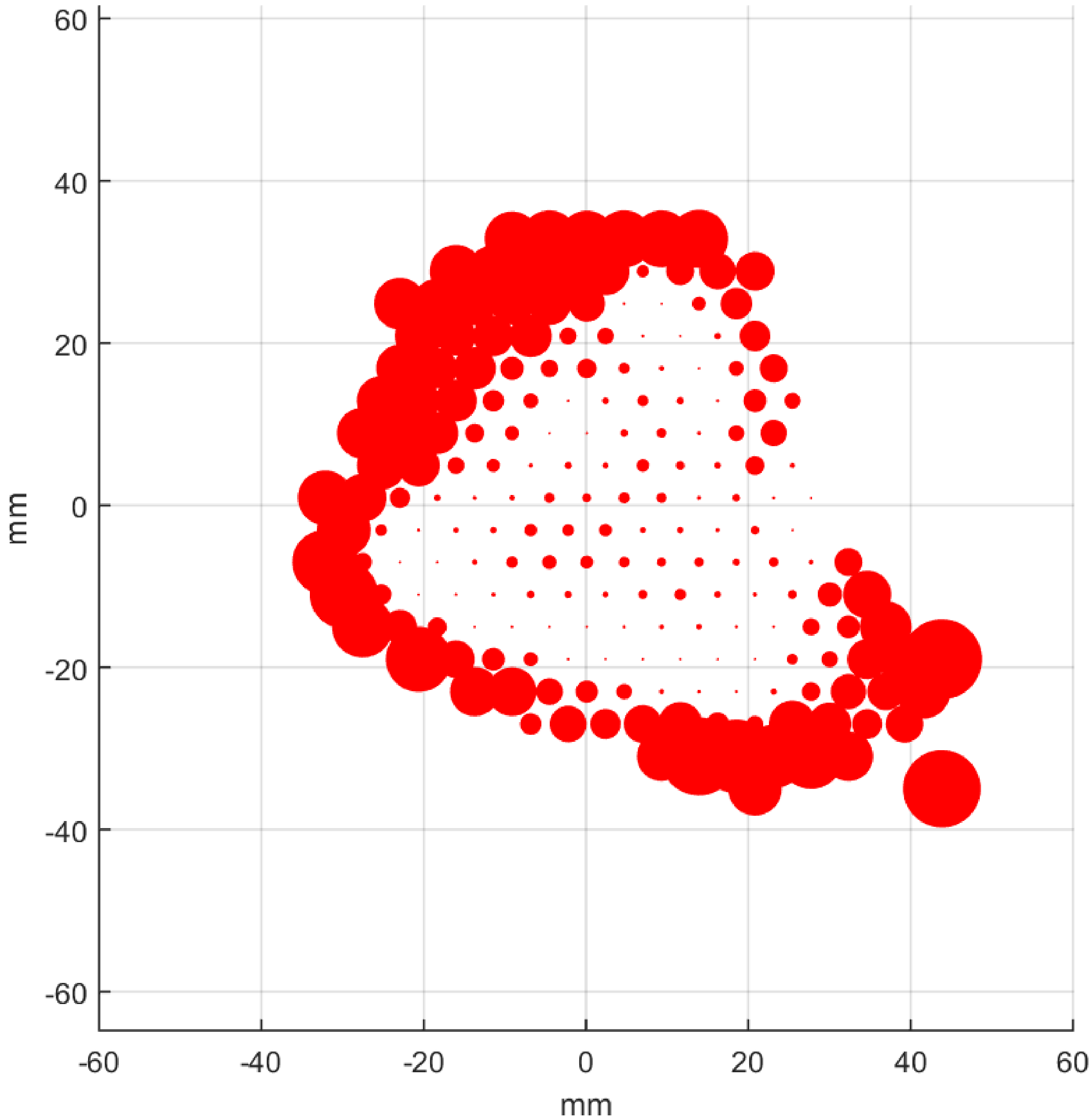
87 spots at 3 of 15 layer wiht 186.5 MeV

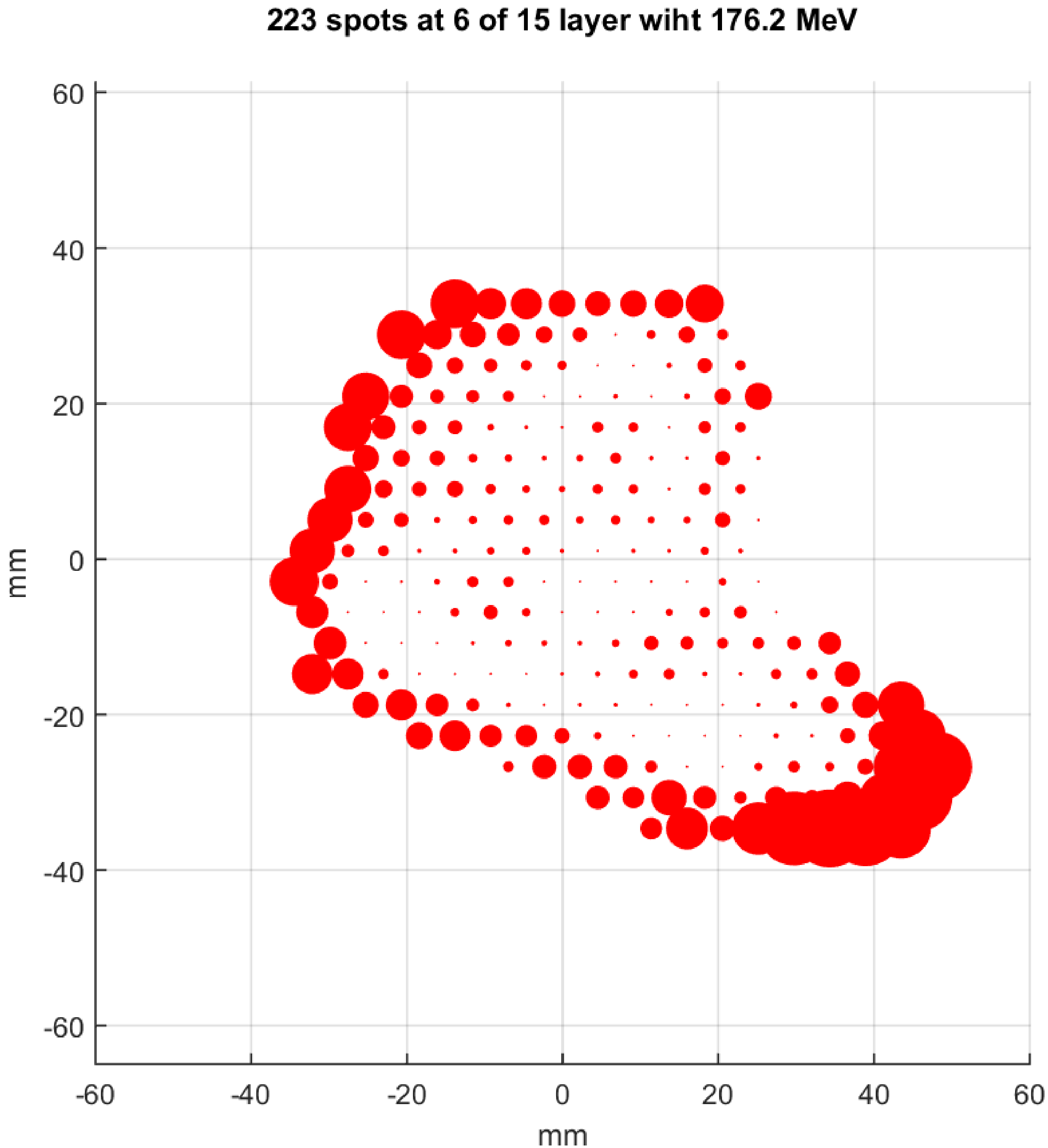


132 spots at 4 of 15 layer wiht 183.0 MeV

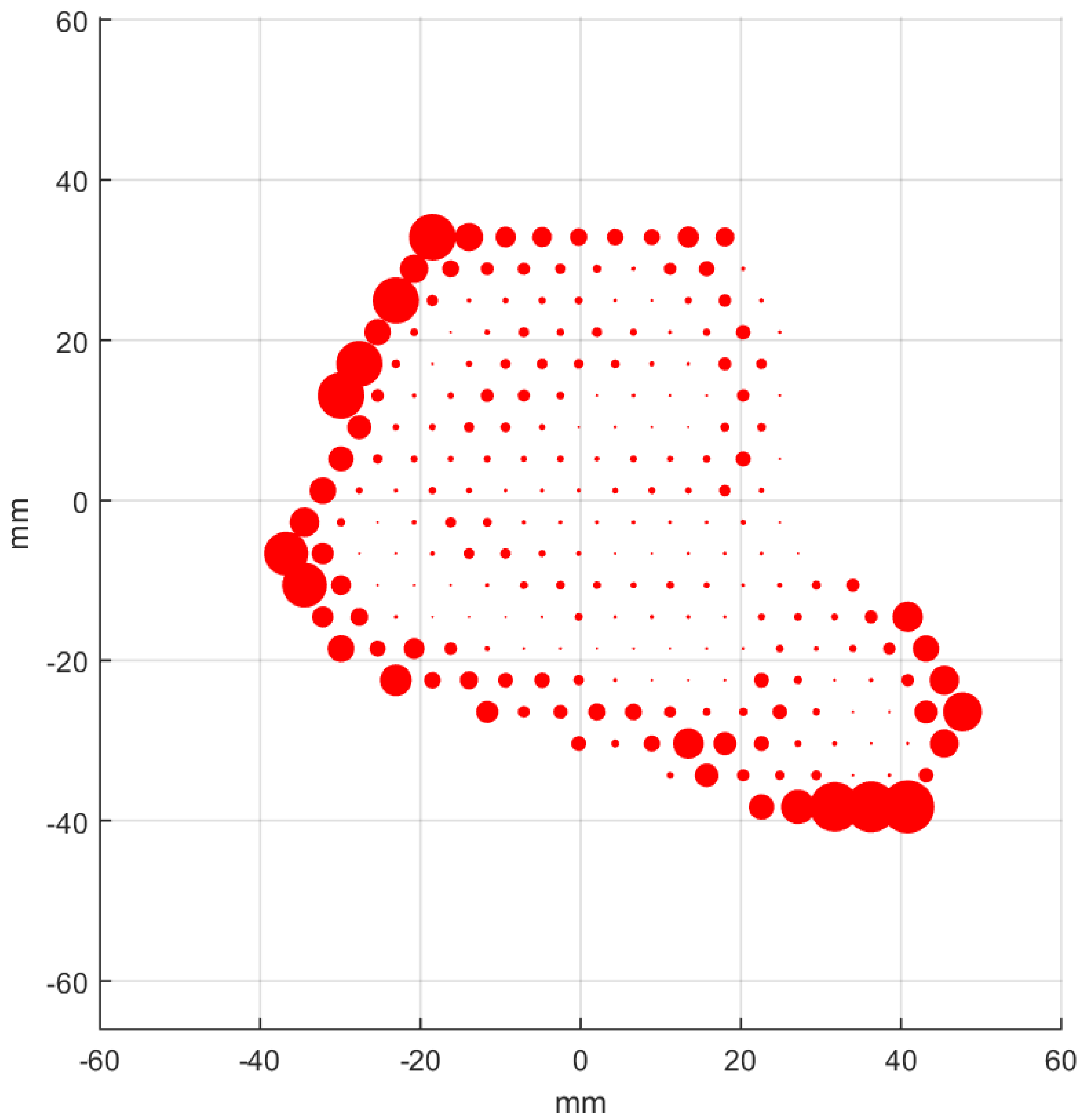


201 spots at 5 of 15 layer wiht 179.6 MeV




223 spots at 6 of 15 layer wiht 176.2 MeV
60
40
20
0
-20
-40
-60
mm
-60
-40
-20
0
20
40
60
mm

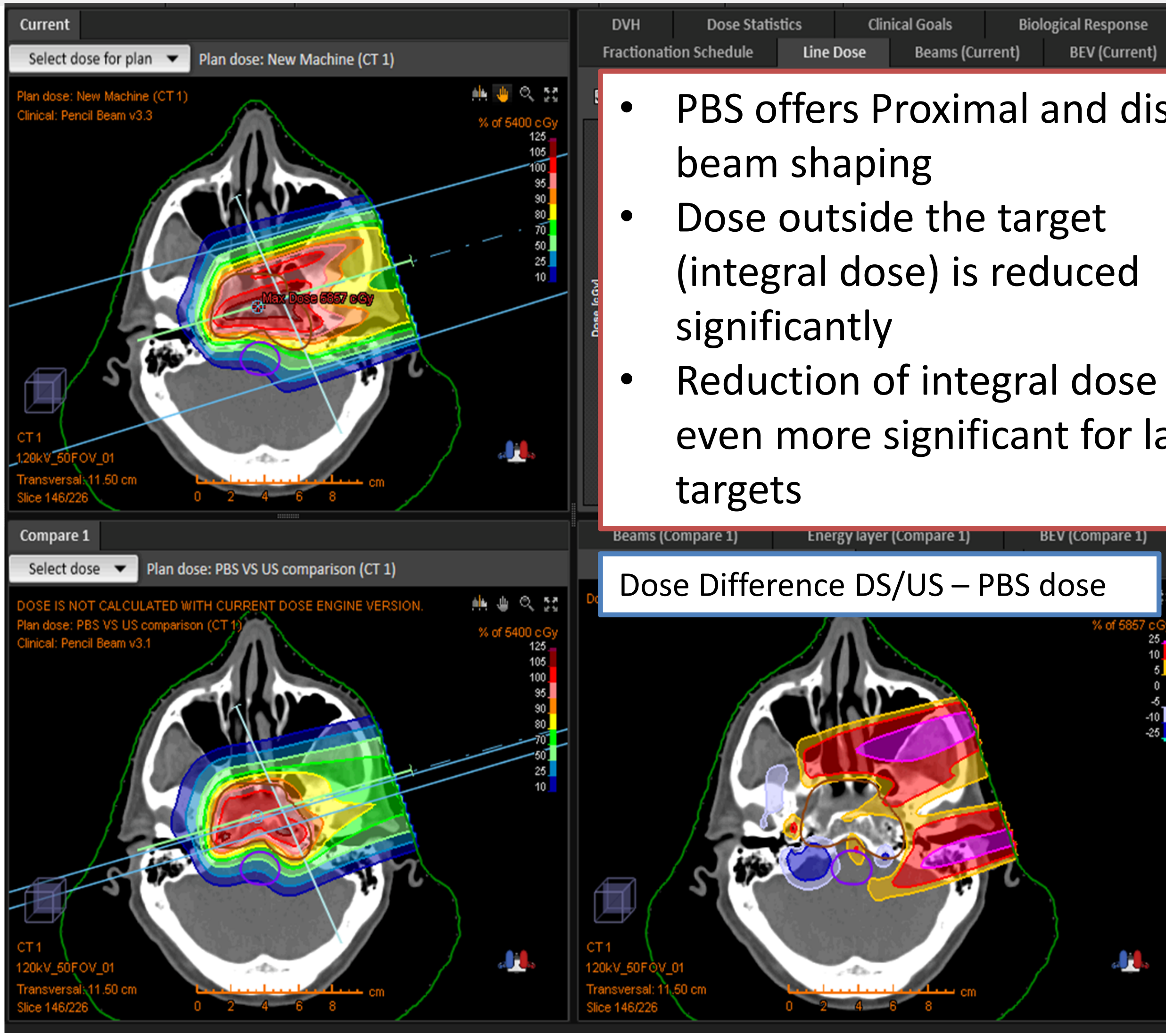
238 spots at 7 of 15 layer wiht 172.7 MeV



Further reduction of Integral Dose with Pencil Beam scanning

Double scattering / Uniform Scanning

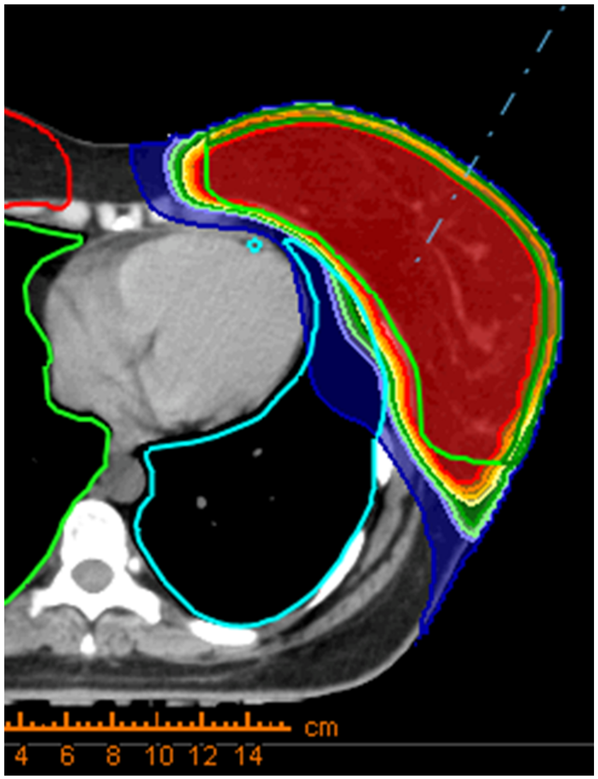
Pencil Beam scanning

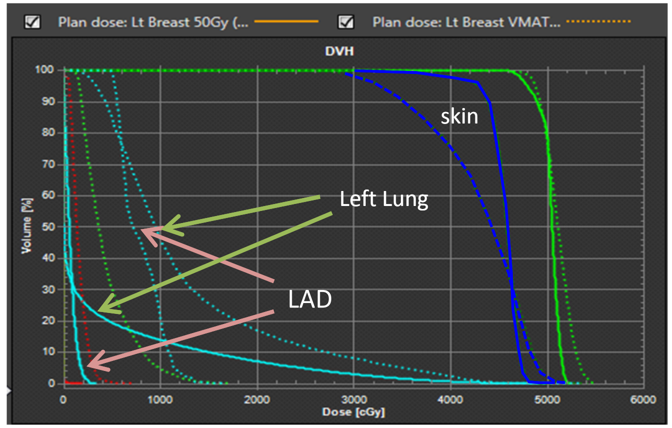


- PBS offers Proximal and distal beam shaping
- Dose outside the target (integral dose) is reduced significantly
- Reduction of integral dose even more significant for large targets

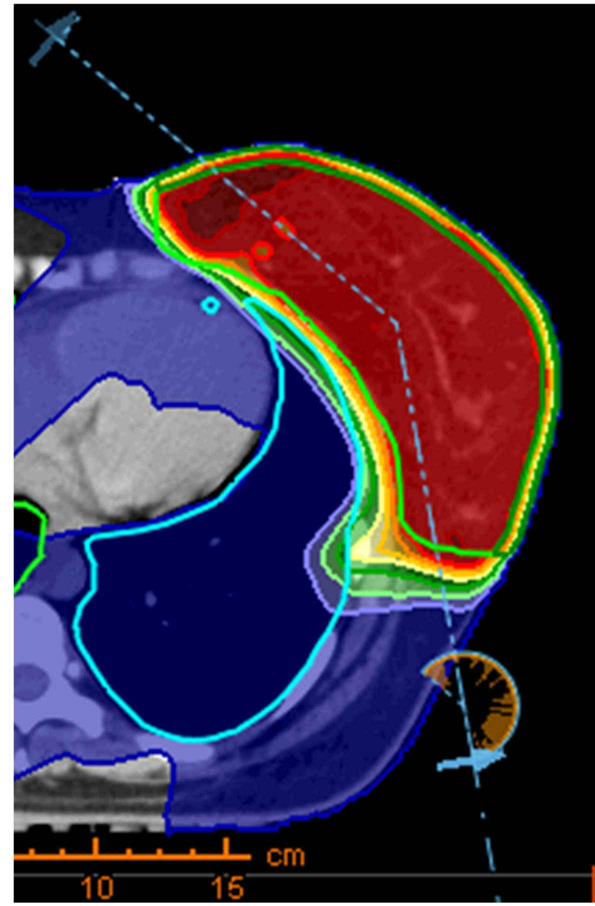
Large Intact Breast with DIBH

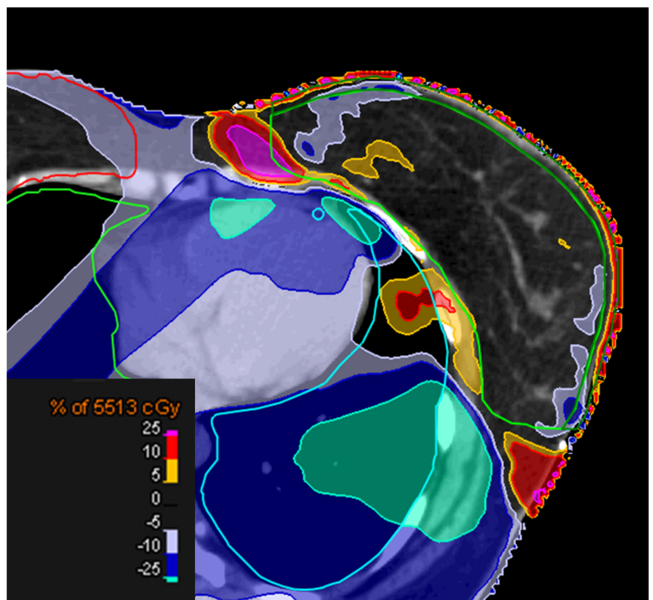
Protons





V-MAT 6 MV Photons





Protons minus V-MAT 6 MV Photons

ProNova

Pencil Beam Scanning in Proton Therapy. IMPT

Pencil Beam Scanning/IMPT has opened the door to treating large, non-contiguous targets with the focus on:

- Improved Local Control
- Prevention of Complications
- Prevention of Secondary Tumors

More than 80 % of all external beam radiation treatments are now projected to have a dosimetric advantage with PBS

(Compared to 20% before PBS)

SC Technology on the ProNova SC360

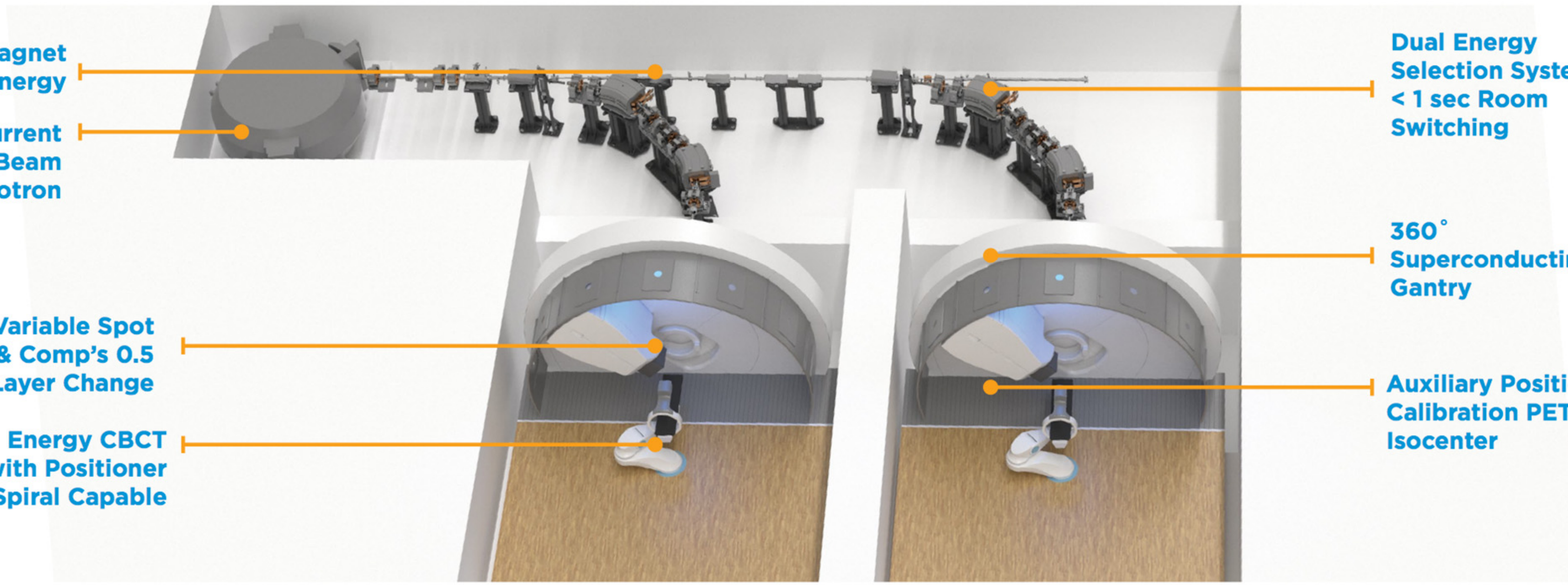
Design

SC Technology on the ProNova SC360

ProNova Solutions Technology Focuses On:

- Intensity Modulated Proton Therapy (IMPT)
- Sparing of sensitive organs and normal tissue.
- Reduce size and cost of the facility.
- Rapid delivery times.
- Design equipment to be clinical user oriented.
- State-of-the-art Imaging.
- Improve accessibility of the best treatment options.

SC Technology on the SC360 - Design



Superconducting Gantry

Rectangular Treatment Room

Dual ESS with Rapid Switching

3D Imaging with PET

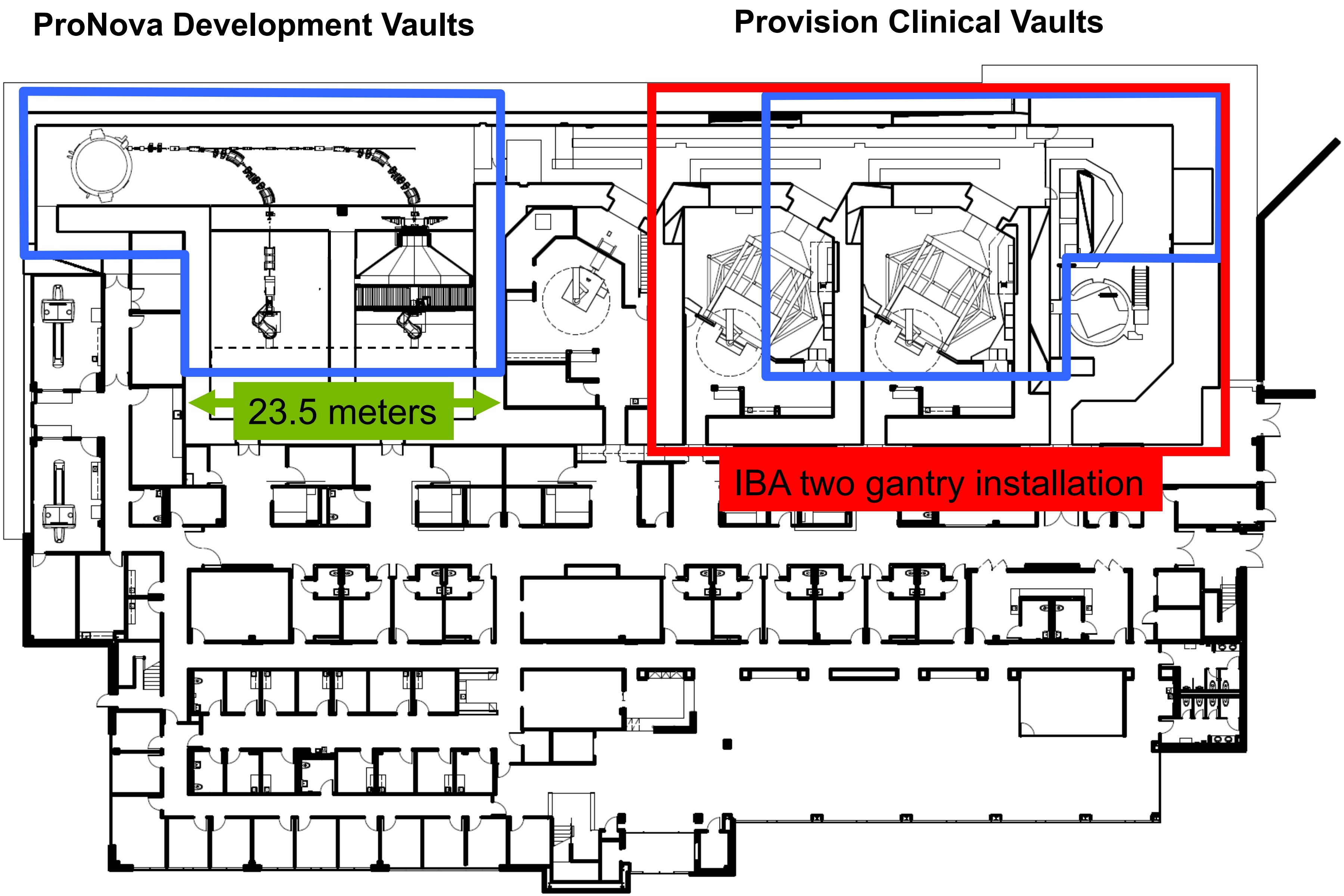
ProNova's gantry vault is 41% smaller, yet the treatment room area is 23% larger due to the Superconducting Gantry beamline

SC Technology on the SC360 - Design

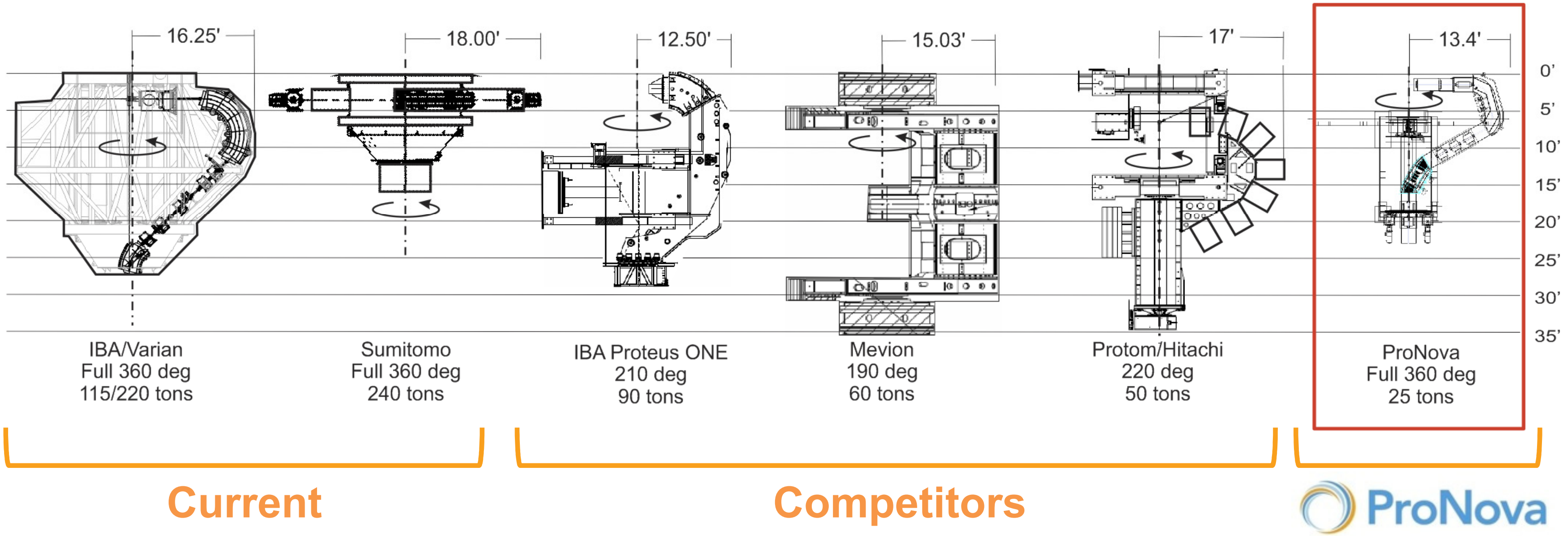
SC360 Main Design Features

Accelerator	Isochronous Cyclotron	230 MeV
Proton current range	< 1 nA up to 300 nA	CW
Main Trunkline	Permanent magnet unitary transformation from room to room.	5 PM Quads
Energy adjustment	Beryllium Degrader, one per room	4 cm to 33 cm
Energy selection beamline	90 Degree achromat	2 Dipoles 6 Quads
Gantry	Two SC Achromats, Normal conducting Quadrupoles and steerers	5 NC Quads 60˚ Achromat 150˚ Achromat
Nozzle	X,Y combined function scanner Vacuum through to Ion Chamber	PBS/IMPT only

ProNova Unit 1 Install & Provision Center for Proton Therapy

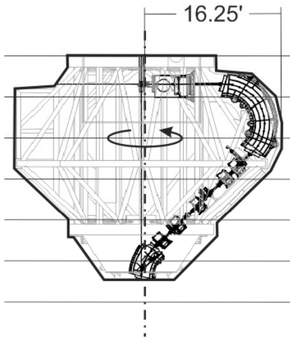


Leveraging Superconducting Technology

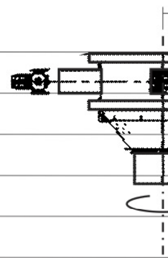


- **Superconducting magnet benefits**
  - Dramatically smaller size, weight, and power
  - 2X higher magnetic field, 0.5X bend radius
- **ProNova leverages superconducting magnet technology**
  - Maintains 360° rotation similar to radiation therapy
  - Ample room for full ring imaging at isocenter
  - Simplified shipping and installation reducing cost and time to market

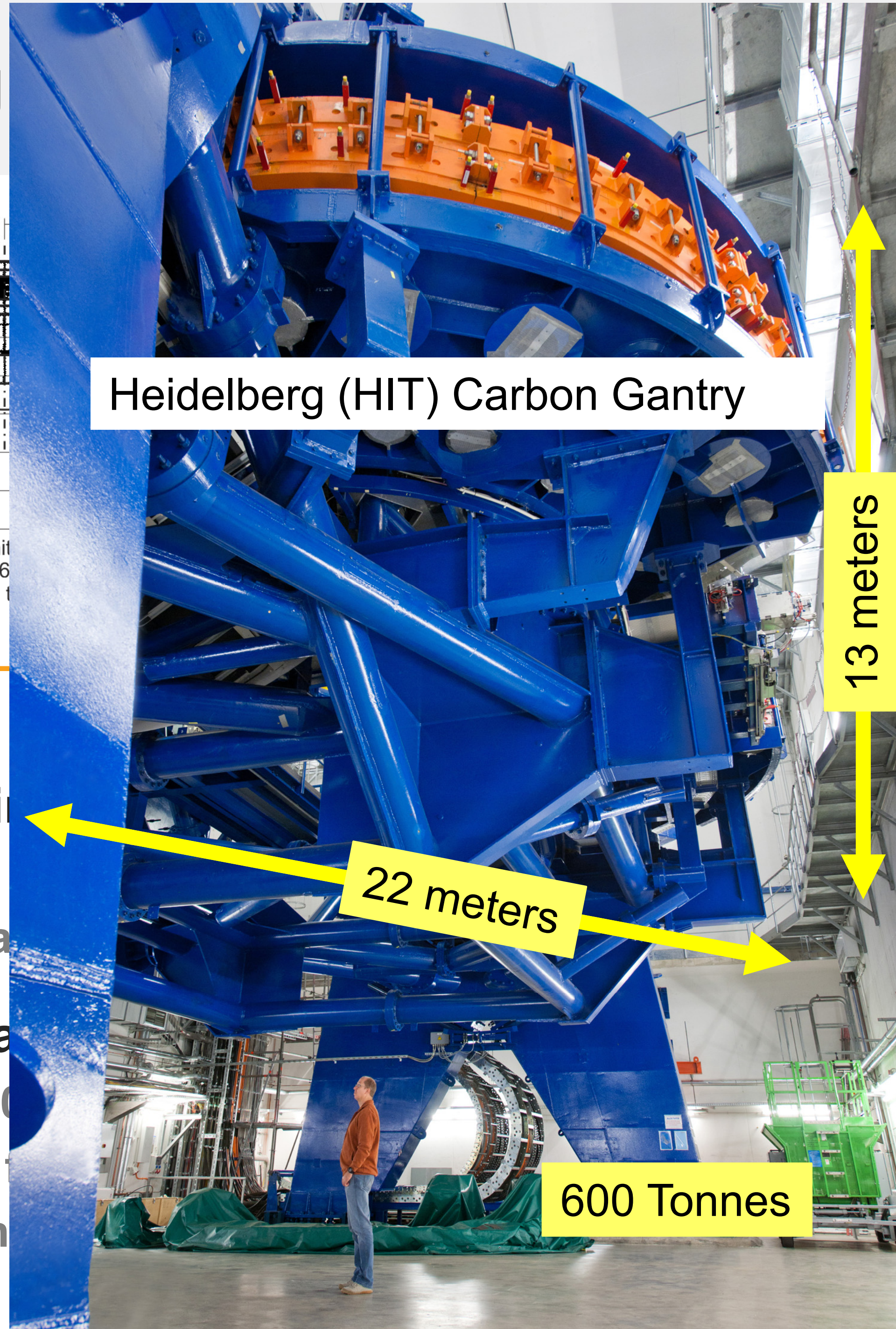
Leveraging ology

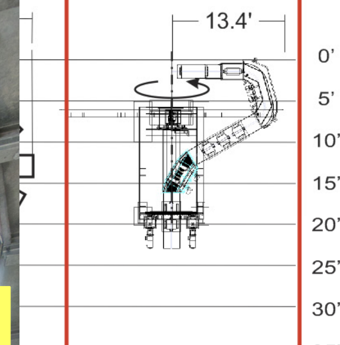


IBA/Varian
Full 360 deg
115/220 tons



Sumit
Full 36
240 t





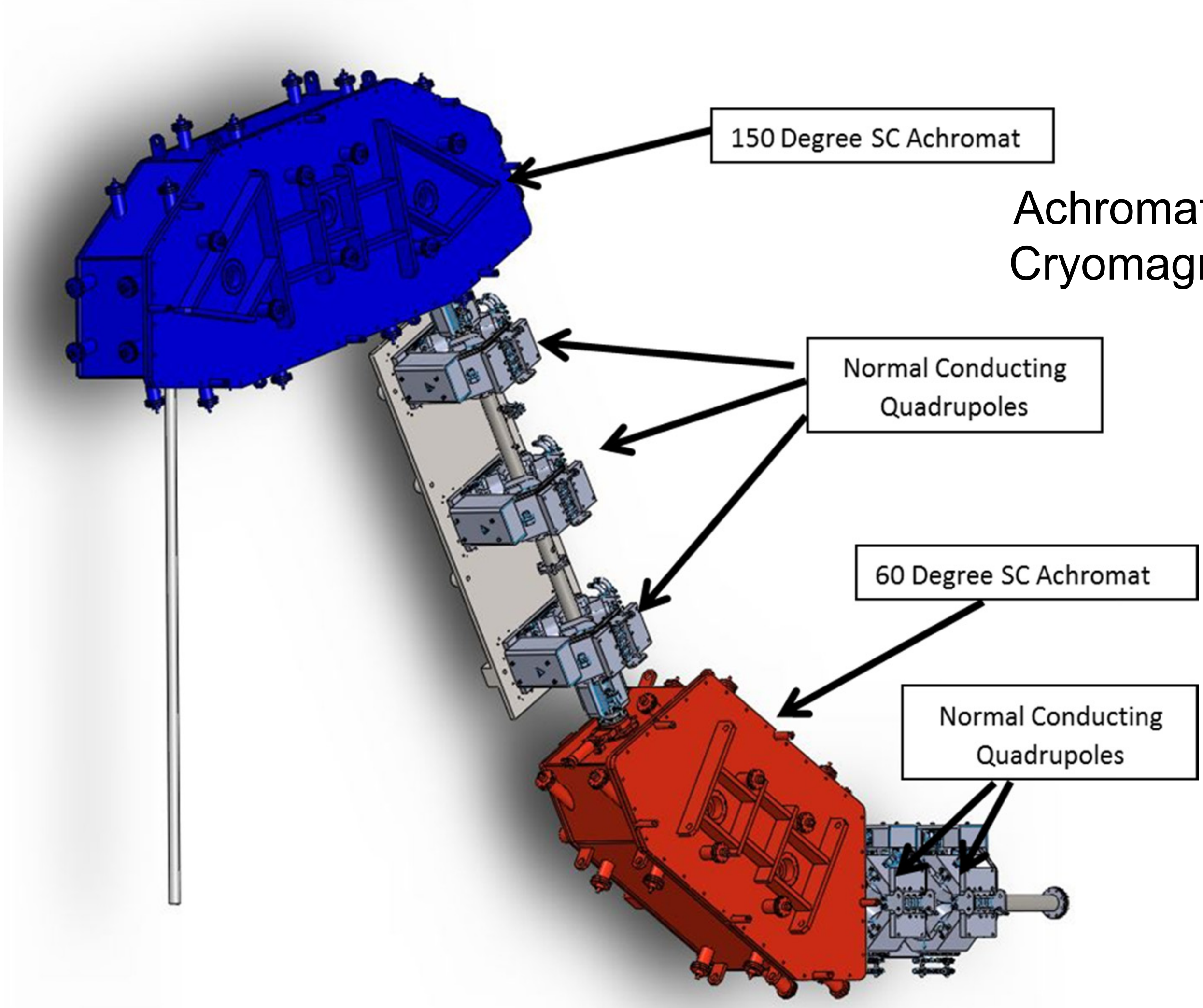
ProNova
Full 360 deg
25 tons

Current

ProNova

- **Superconducti**
  - Dramatically
  - 2X higher ma
- **ProNova levera ogy**
  - Maintains 36
  - Ample room
  - Simplified sh time to market

SC Technology on the SC360 - Design



Achromats Built in collaboration with Cryomagnetics, Inc. Oak Ridge, TN.

Patented - Vladimir Anferov et al, US 2011/0101236 A1, Compact Isocentric Gantry

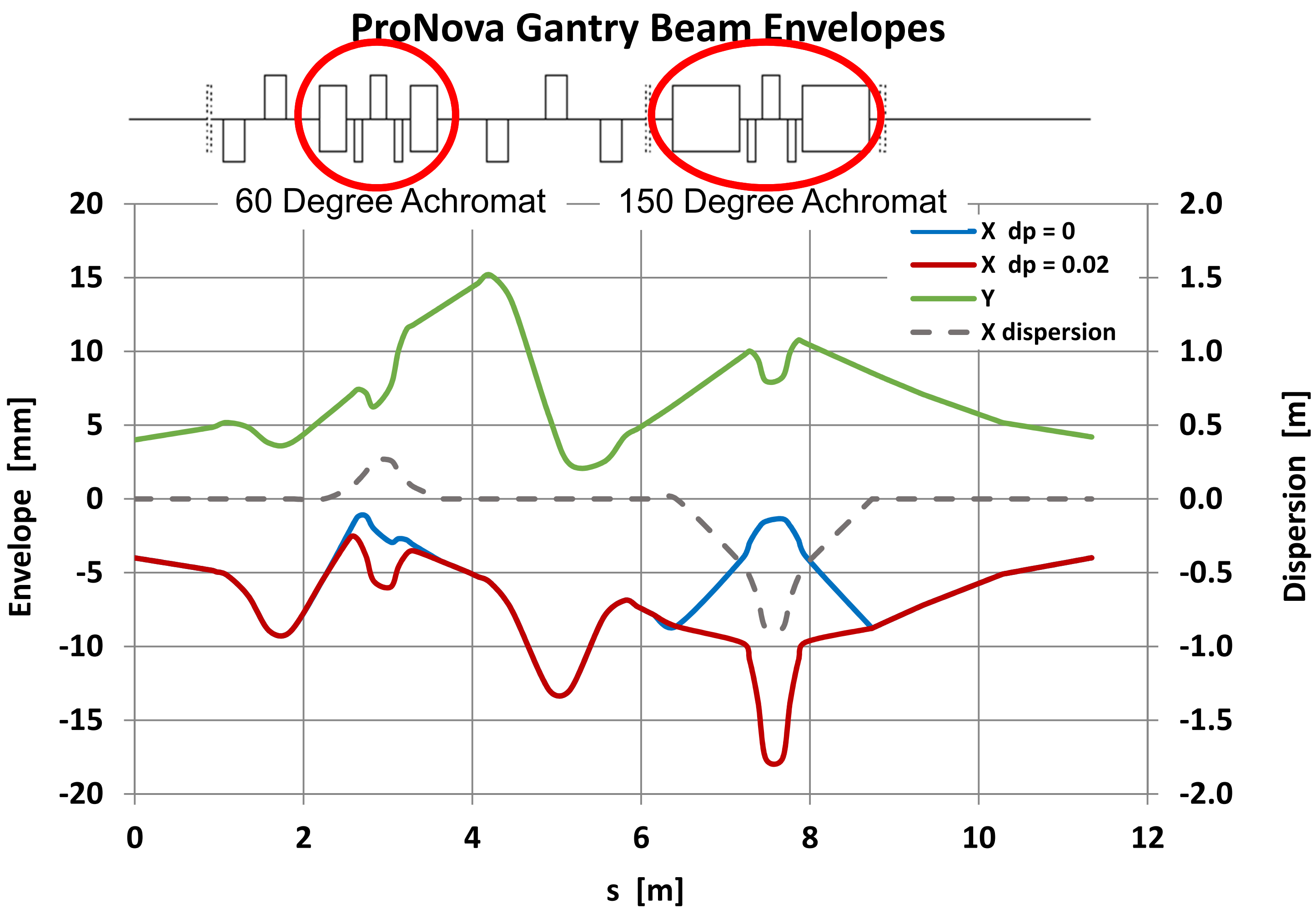
Advantages of an achromatic beamline

- **When switching between the energy layers the dipoles do not need to ramp fast:**
  - Small SOBP can be delivered without ramping the SC dipoles.
  - Momentum spread $\Delta p/p \approx 3\%$ corresponds to > 3.4 cm range acceptance at 200MeV

- **Better beam transmission from degrader into the nozzle**
  - Momentum spread after degrading 230 MeV to 70 MeV is ~ 2%
  - Thus, improved beam transmission compared to a non-achromatic beamline

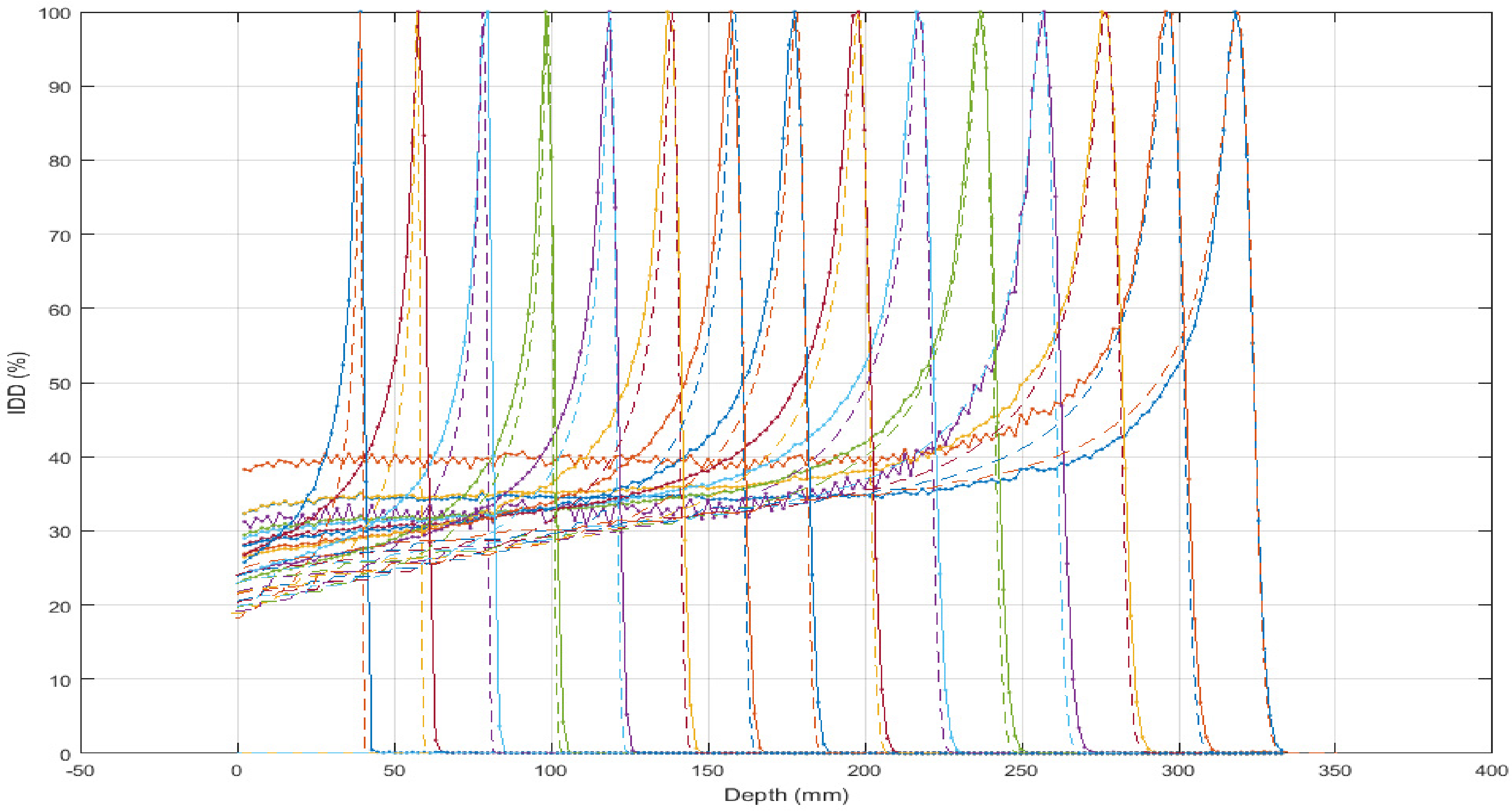
- **Bragg peak shape (width) is preserved (see data)**
  - Simpler commissioning
  - Simpler nozzle design

SC Technology on the SC360 - Design



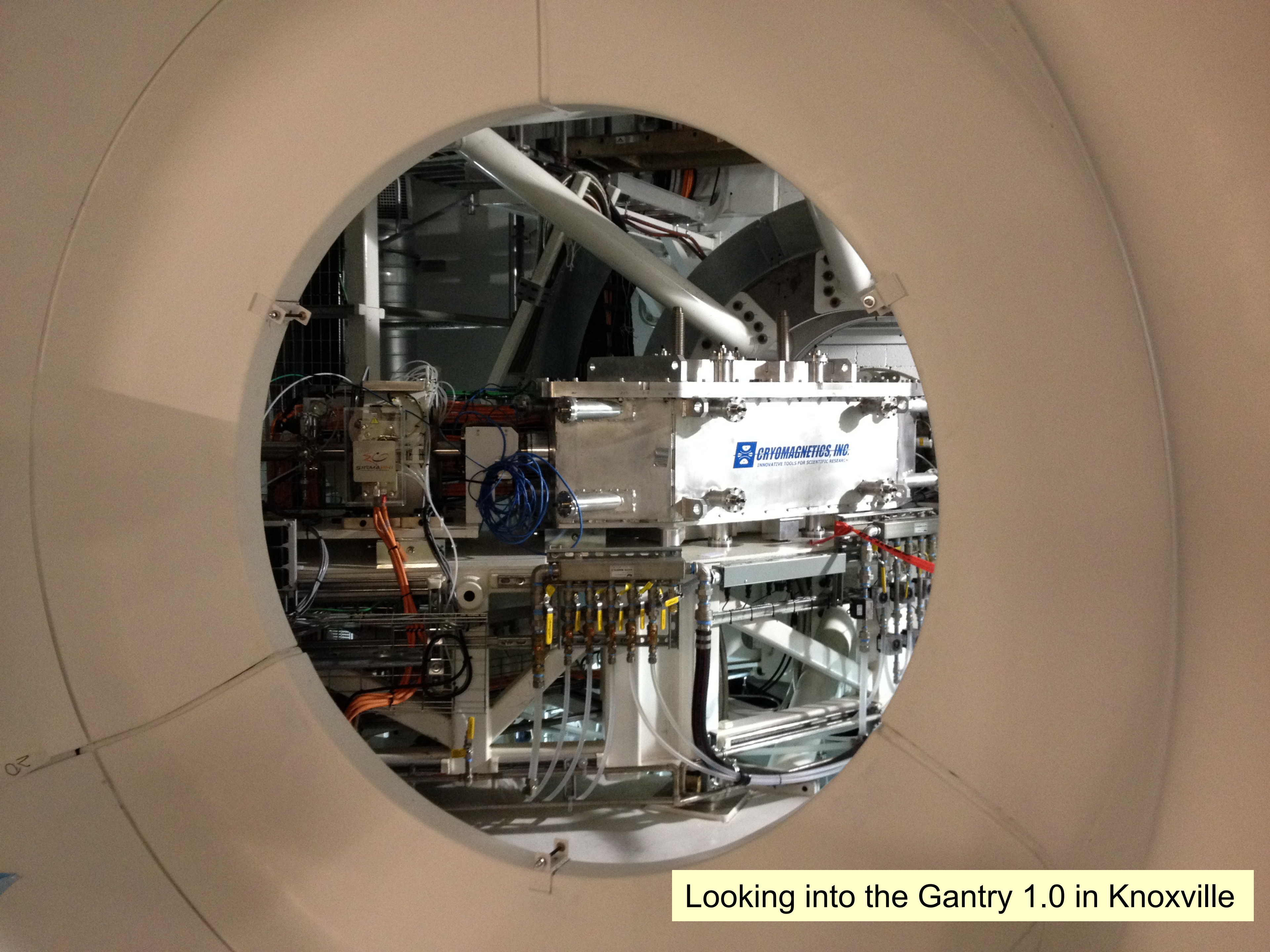
Advantages of an achromatic beamline

Bragg Peak widths vary slowly with range
Fewer layers needed to complete a Treatment Volume Delivery



SC Technology on the SC360 - Design

Gantry with Partial Covers



Looking into the Gantry 1.0 in Knoxville

SC Technology on the SC360 - Design

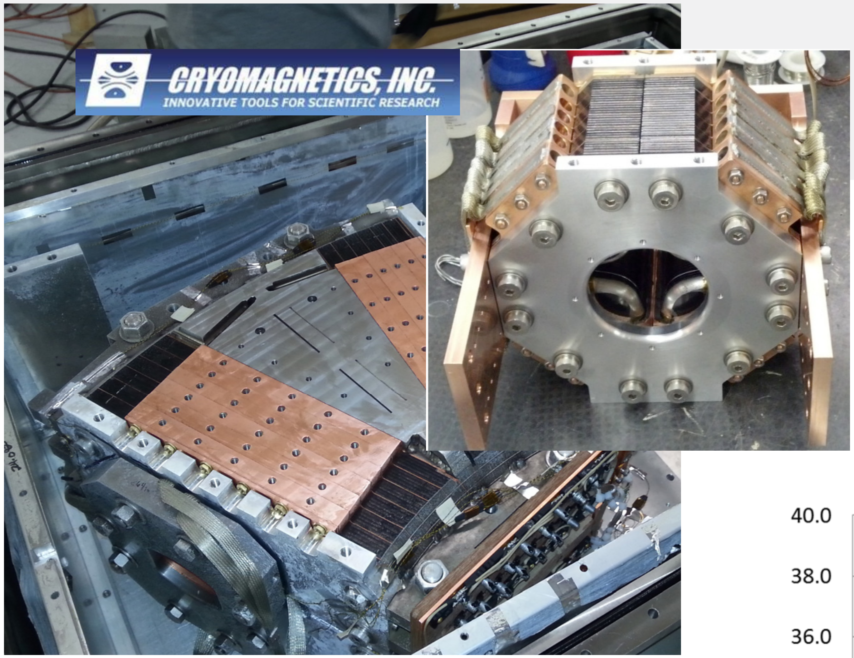
Gantry Beamline Operational Design Features

Normal Conducting Magnets	Quadrupoles X/Y Steerers	5 2
Diagnostics	4 quadrant collimators	3
SC Achromats type	150 Degree 60 Degree	DQQQD DQQQD
SC Magnets cooling	2 x 1.5 W GM He refrigerators	Each
Vacuum	Beamline pumped by cold mass	No pumps
Peak power consumption, all magnets	Magnets Refrigeration	~39 kW ~28 kW

SC Technology on the SC360 - Design

SC Achromat Design Features

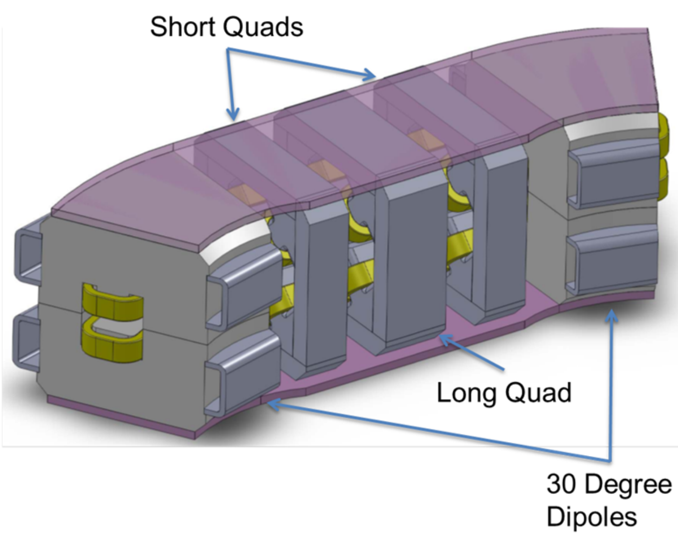
SC Magnet Design	Cold steel core with epoxy impregnated coils
Conductor	NbTi
Peak operating current	110 Amperes Dipoles 80 Amperes Quadrupoles
Peak field in conductor	4.85 Tesla
Dipole operating range	2 T to 4.1 T (70 MeV to 250 MeV) 40 A to 110 A Ramps at ~ 0.25 s/MeV or ~ 2 A/s max
Dipole good field region	5 cm transverse
Quadrupole Pole Tip Field	Maximum 1.6 Tesla
Quadrupole good field region	3 cm diameter

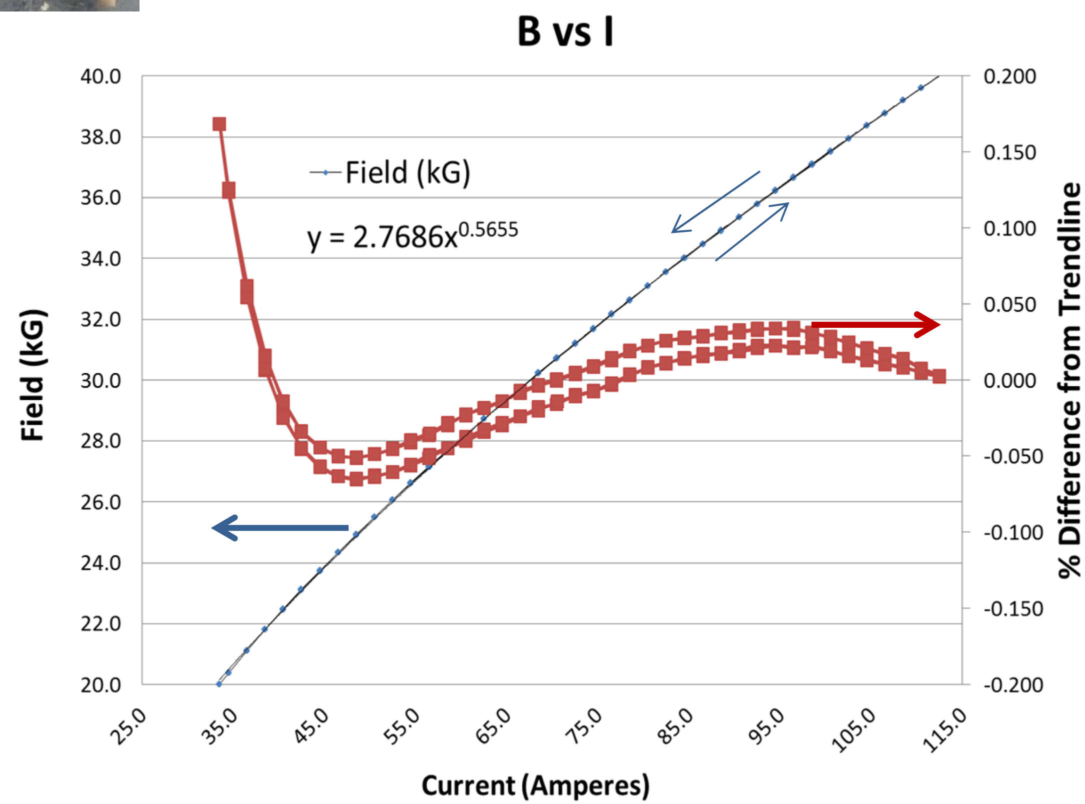


Gantry Beamline – Achromats

Dipole steel is fully saturated:
Hysteresis < 200ppm

Quads are laminated.





SC Technology on the SC360 - Design

Gantry Mechanical Design Features

SC Magnets Weight	150 Degree Achromat 60 Degree Achromat	6000 lbs 3500 lbs
Size	Diameter Axial depth face to face Including nozzle (To Isocenter)	27’ 1” 16’ 8” 21’ 3”
Support	Rear support Front support	Single bearing 72 Cams/fixed race
Rotation	Angle Speed (360 degrees start to stop)	+/- 185 degrees 1 minute
Rotational Accuracy	Motion about Isocenter Angular accuracy	+/- 0.5 mm Max +/- 0.25 degrees

SC Technology on the SC360 - Operation

Operational experience with SC Gantry to date.

- More than 1000 hours of SC magnet operation, ~ 500 hours with beam.
- No quenches experienced during normal use including:
  - Gantry rotation and E-Stops
  - Ramping layer to layer
  - Warming up to 1.0 K above operating temperature
- The final 510(k) submission including responses to the FDA was completed with extensive beam data shown in subsequent slides.
- First patient expected to be treated on gantry Q2 2017.

SC Technology on the SC360 - Operation

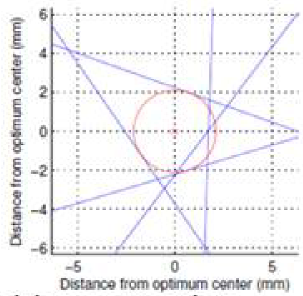
Operational experience with SC Gantry to date.

DoseLab Starshot Results

DoseLab version: 6.60
Date: July 12, 2016
Machine: SC360, #:001
File: "StarShot_01.tif"
Starshot type: Not specified
Performed by: Hao Chen
Tolerance set: None

Diameter: 4.22 mm

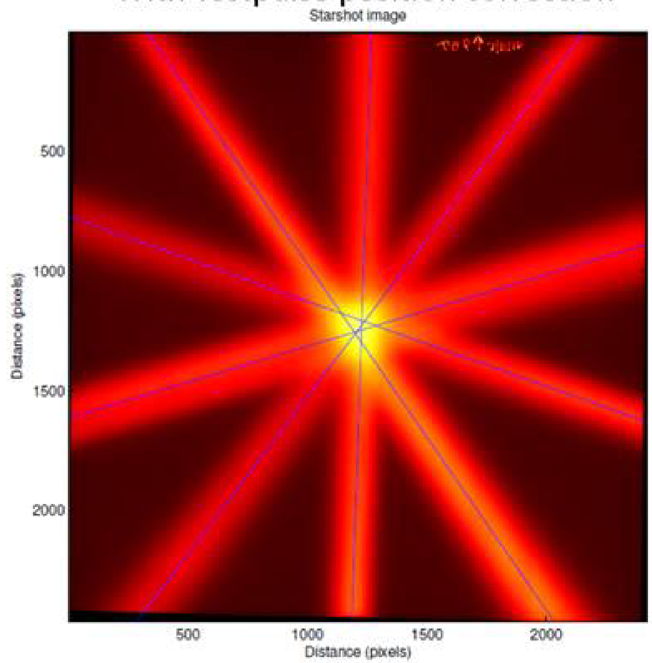
Note:
TR4 Starshot with testpulse function on



Starshot measures the coincidence of the beam with the mechanical center of rotation of the gantry.

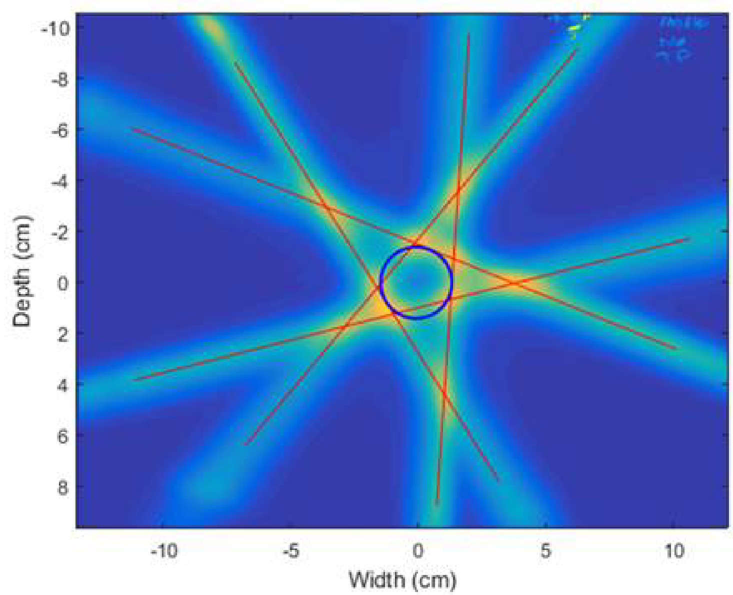
With no position correction +/-10.0 mm radius
With non-optimized correction +/- 2.1 mm
With optimized correction < +/- 1.0 mm (not shown)

With Testpulse position correction



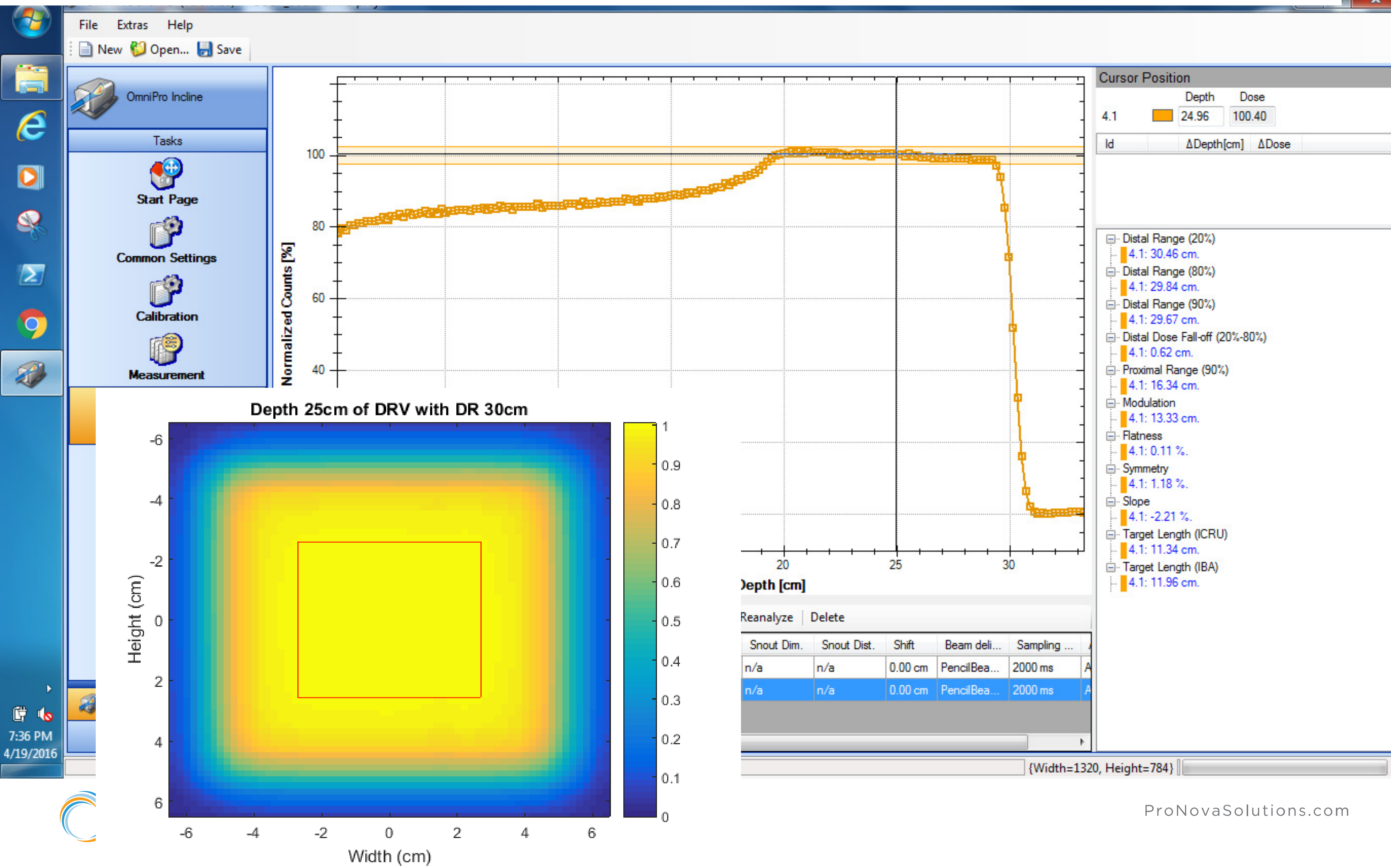
DoseLab

No Testpulse position correction



SC Technology on the SC360 - Operation

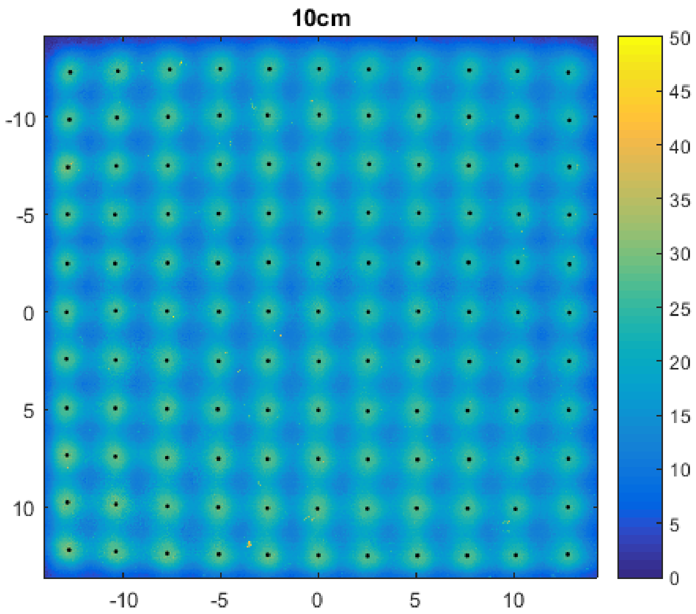
Transverse and distal dose profiles measured for a sample Dose Reference Volume



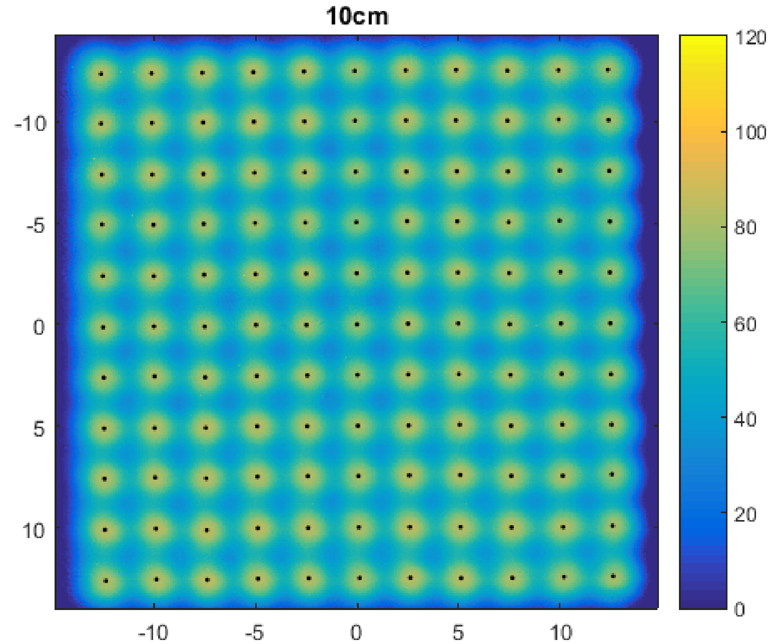
SC Technology on the SC360 - Operation

Operational experience with SC Gantry to date.

11 x 11 spot pattern with 25 cm x 25 cm field size at 10 cm WET



10 cm maximum deviation: 4 mm

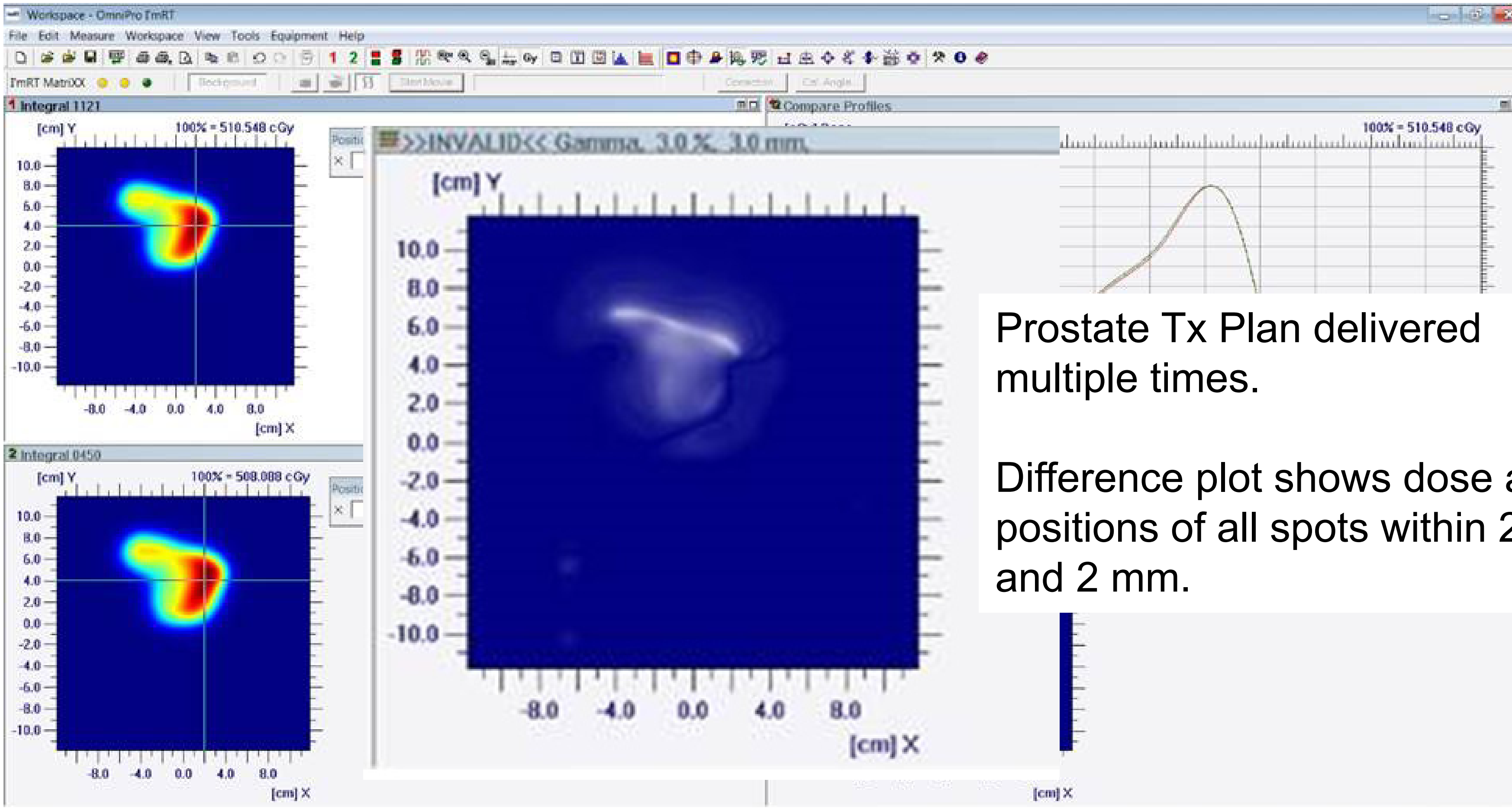


10 cm maximum deviation: 2 mm

Scanning Magnet Pillow Effect: Uncorrected versus corrected

SC Technology on the SC360 - Operation

Operational experience with SC Gantry to date.



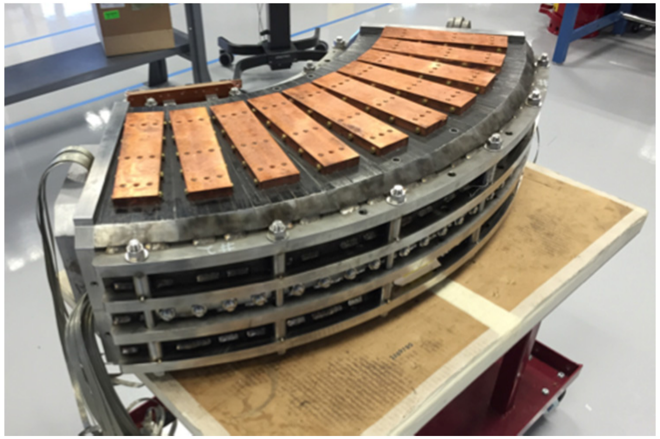
Prostate Tx Plan delivered multiple times.

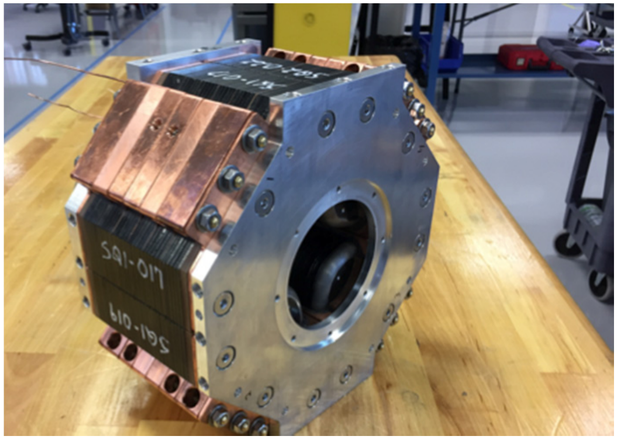
Difference plot shows dose and positions of all spots within 2% and 2 mm.

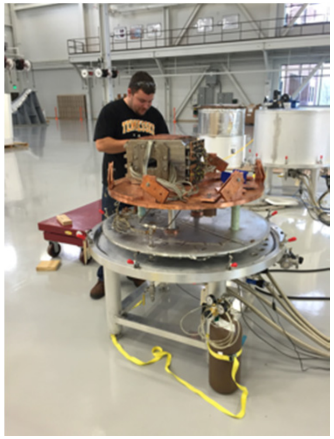
Manufacturing

SC Technology on the SC360 – Manufacturing

Gantry and SC Achromat Manufacturing at the ProNova Factory



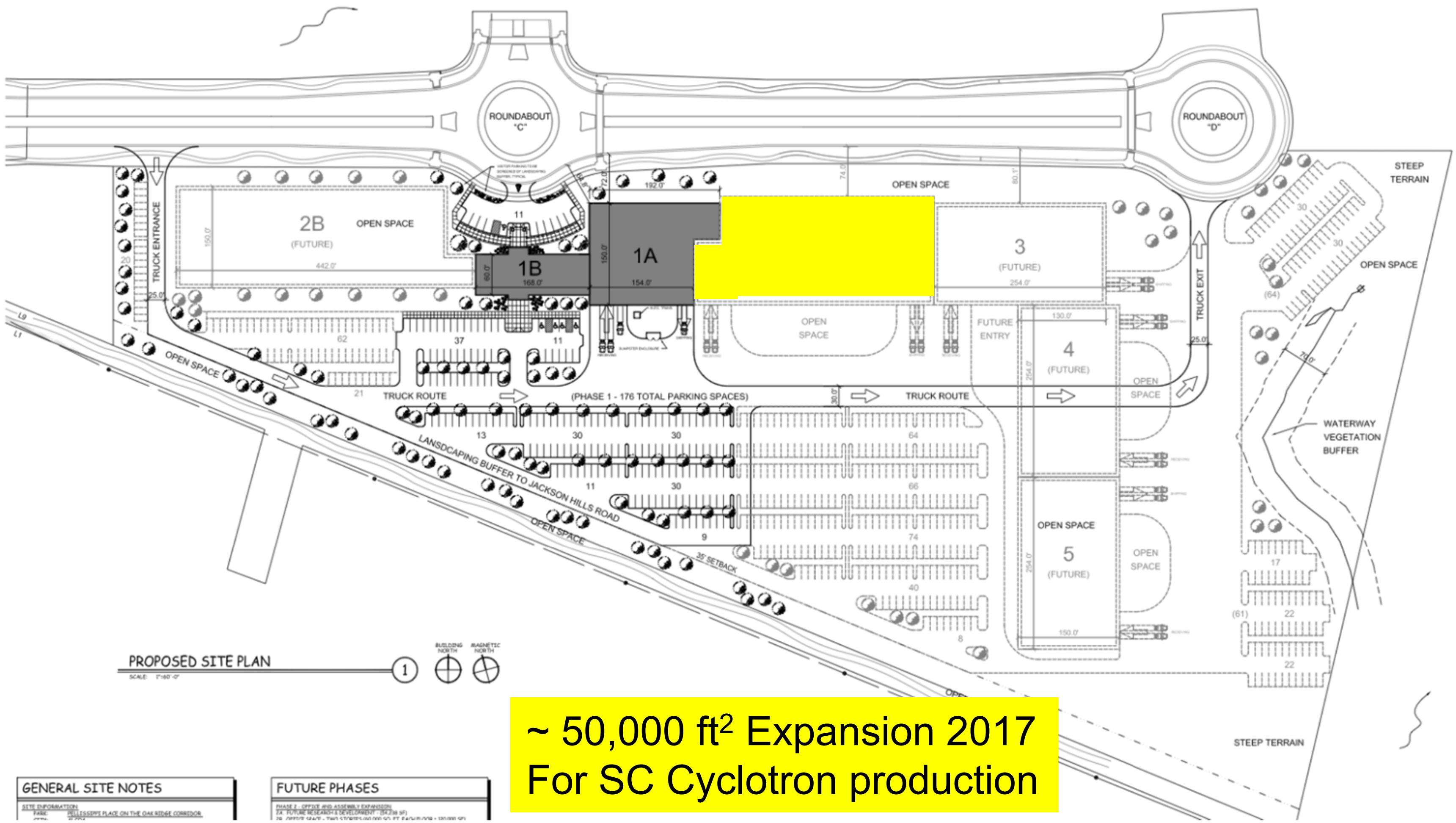




SC Technology on the SC360 - Manufacturing

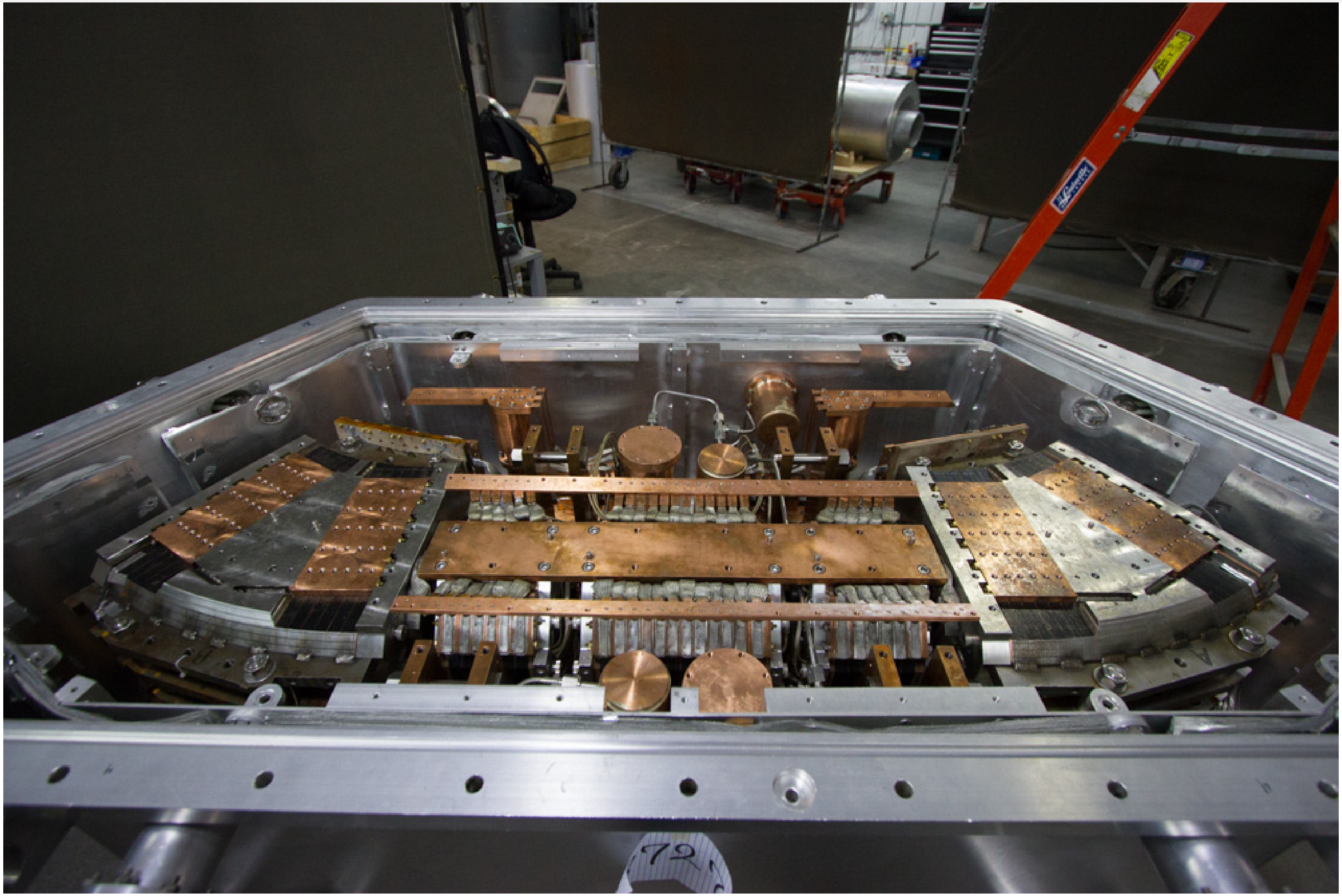
ProNova Site Layout

~ 55,000 ft^2 Existing (2014)



~ 50,000 ft^2 Expansion 2017
For SC Cyclotron production

SC Technology on the SC360 – Manufacturing

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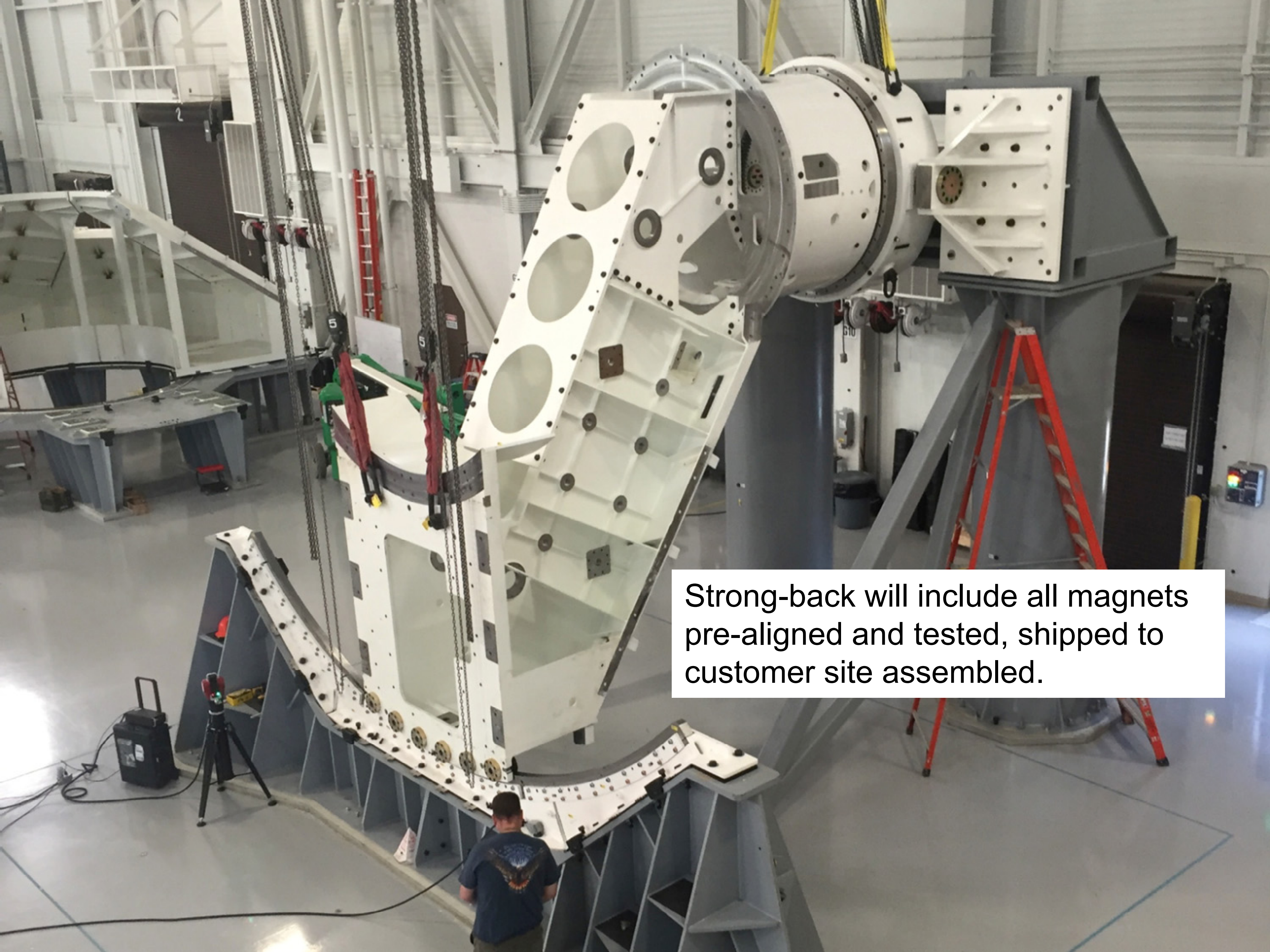
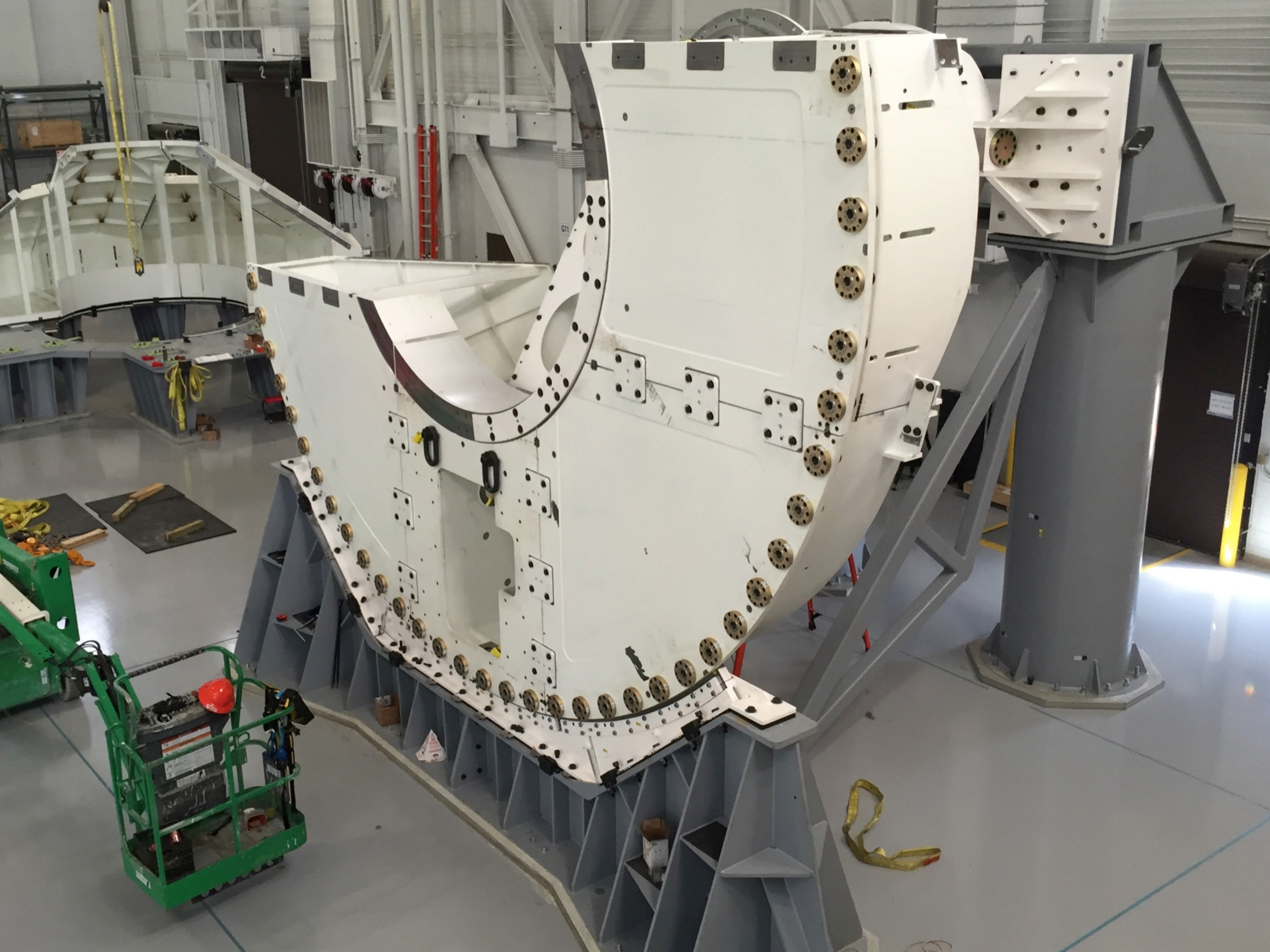
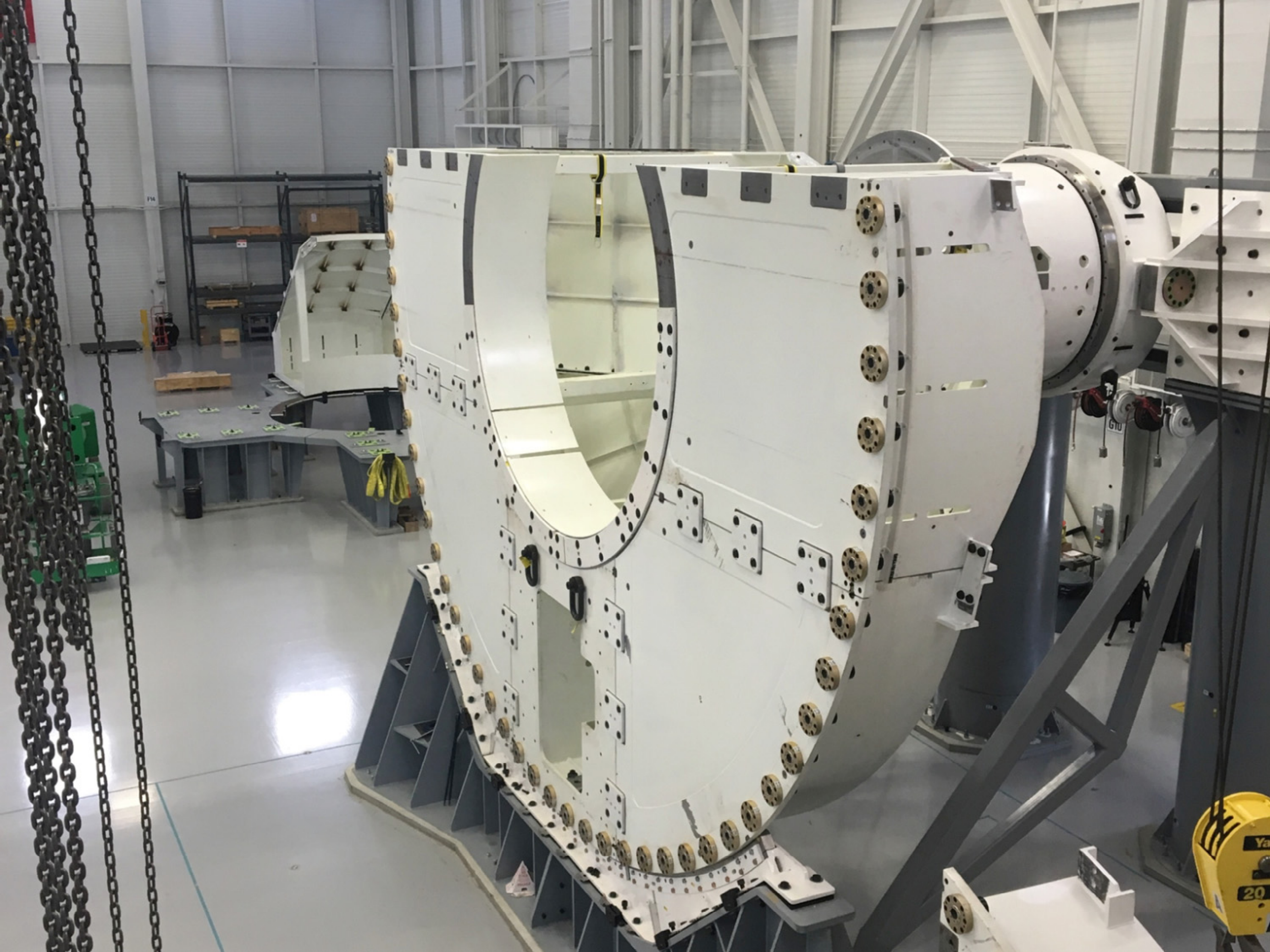


Strong-back will include all magnets pre-aligned and tested, shipped to customer site assembled.

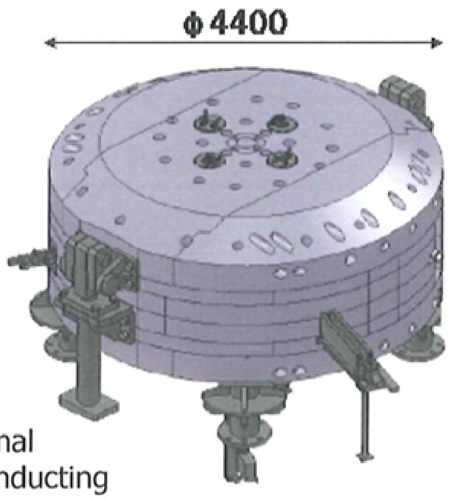



G10
20


SC Technology on the SC360 – Manufacturing

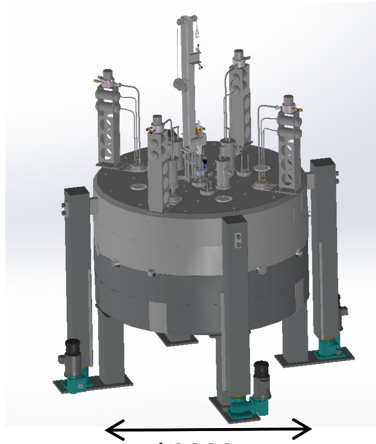
SC Cyclotrons for ProNova

ProNova Accelerator Evolution



Conventional normal conducting cyclotron

Sumitomo - ProNova Collaboration



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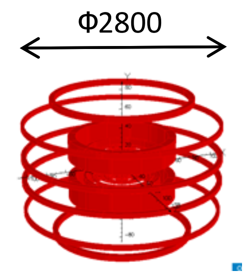
ProNova Development



Ironless variable energy SC synchrocyclotron (no degrader necessary)

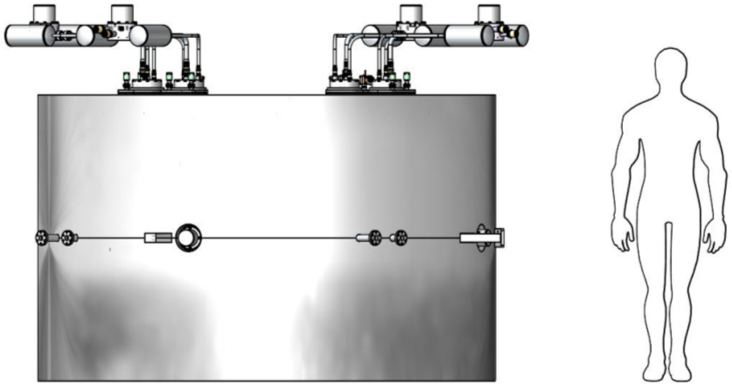
MIT – ProNova Collaboration

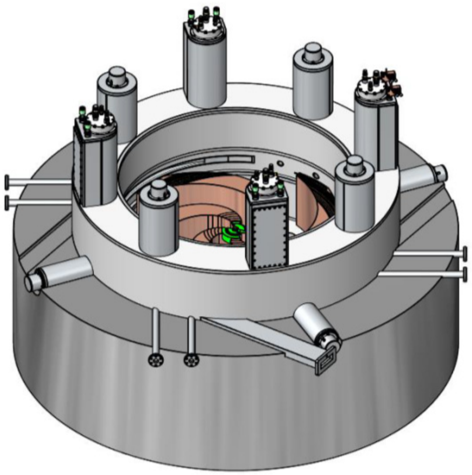
	Resistive Cyclotron	SC Cyclotron	Ironless SC Synchroyclotron
Size	Φ4.4m	Φ2.8m	Φ2.8m
Weight	220 ton	50 ton	5 ton
Power	340 kW	< 240 kW	75 kW
Energy	230 MeV	230 MeV	70-230 MeV
Max beam current	300 nA	600 nA	100 nA avg

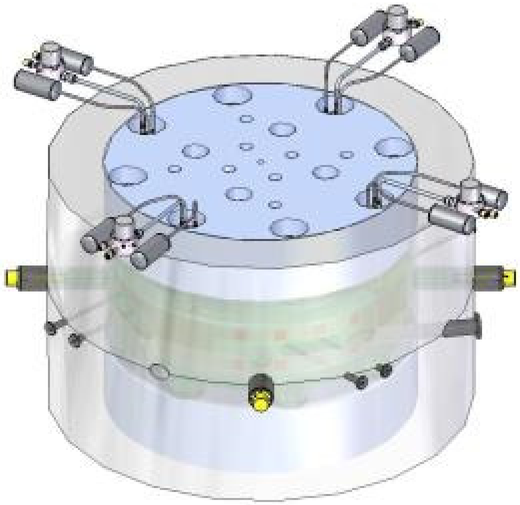
SC Isochronous Cyclotron

Superconducting Isochronous Cyclotron

- **60 tons, 230 MeV**
- **Design Phase 2015-2017**
- **Design Transfer Q4/2016**
- **Prototype Phase 2017-2018**
- **Ready to ship Q4/2018**



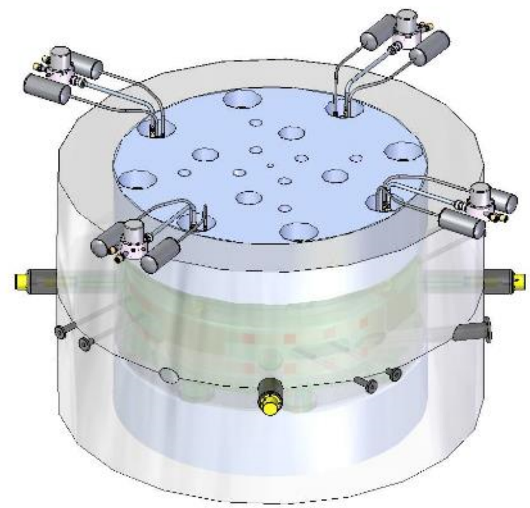




Superconducting Isochronous Cyclotron

tesla IONETIX PRONOVA

- **Specifications**
  - Size - 9 feet or 2.8 meters
  - Weight - 60 tons
  - Power - 240 kW



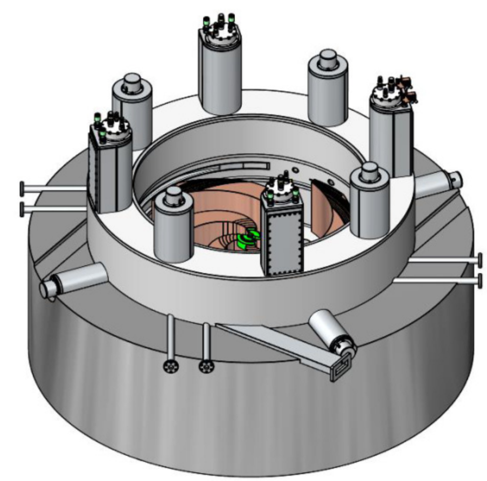
- **Design Requirements**
  - Beam emittance < 5π mm•mr / 3π mm•mr H/V
  - 600 nA max current @ 230 MeV
  - Fast intensity modulation
  - 75% extraction efficiency

- **Development Schedule**

  2016
  - Subsystem assembly & Cont. system engineering

  2017
  - Magnet and extraction system assembly and testing

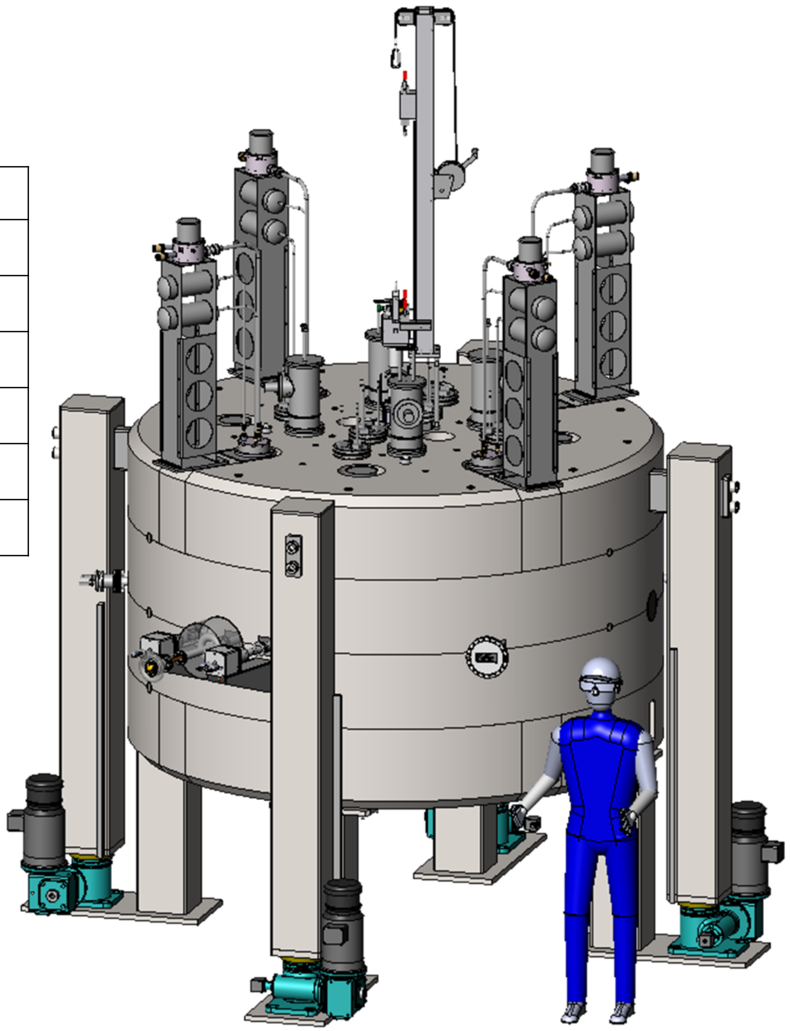
  2018
  - March-Commissioning
  - June-Cyclotron ready



Superconducting Isochronous Cyclotron

Cyclotron Dimensions

	Height (mm)	Height (feet)
Floor to Bottom Cap	940.4	3' 1"
Floor to Beam Line	1725.4	5' 8"
Floor to Top Cap	2510.4	8' 3"
Floor to Top of Cryo Pumps	3730.4	12' 3"
Floor to Top of Ion Source Tower	4610.4	15' 2"
Bottom Cap to Top Cap	1570	5' 2"



- The cap is designed to be raised an additional 1174 mm or about 4 feet.
- The ion source tower can be removed before raising the cap.
- This makes the height of the machine 15’ 2”

SC Ironless Variable Energy Synchrocyclotron

ProNova Future Projects – Ironless Cyclotron

- Design based on MIT Patent
- Development Schedule 2022

Massachusetts Institute of Technology

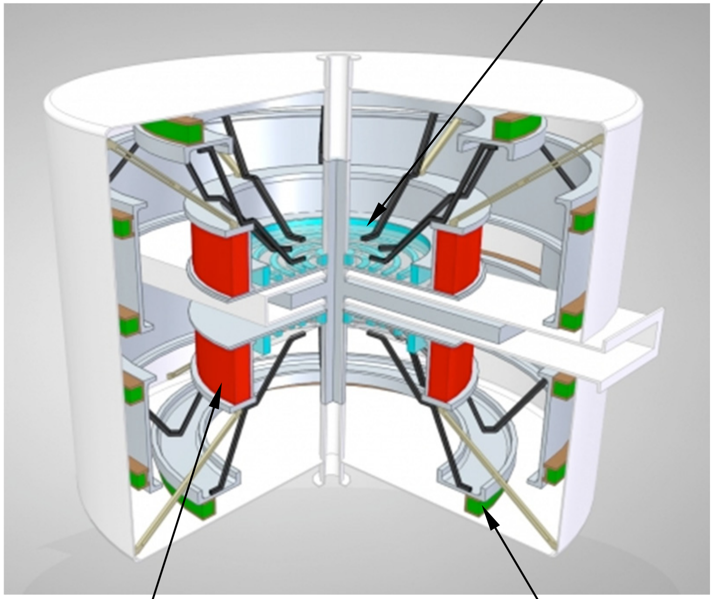
Accelerator Stewardship Grant HEP Award DE-SC0013721

Joe Minervini MIT PI, Vladimir Derenchuk ProNova PI

MIT Plasma Science and Fusion Center

Alexey Radovinsky, Joe Minervini, Phil Michael, Leslie Bromberg

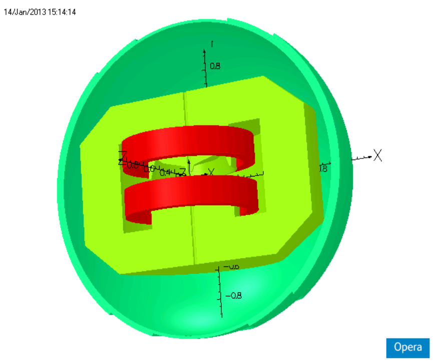
Field Shaping Coils

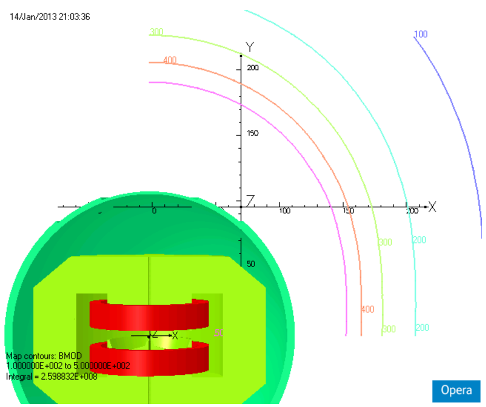


Magnetic Field coil

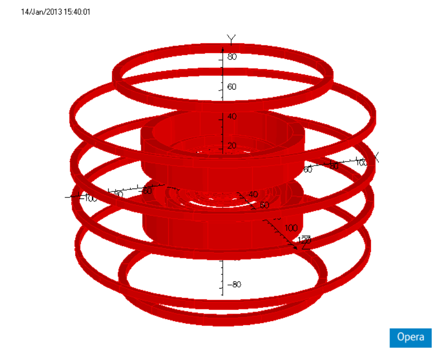
Field Shielding Coils

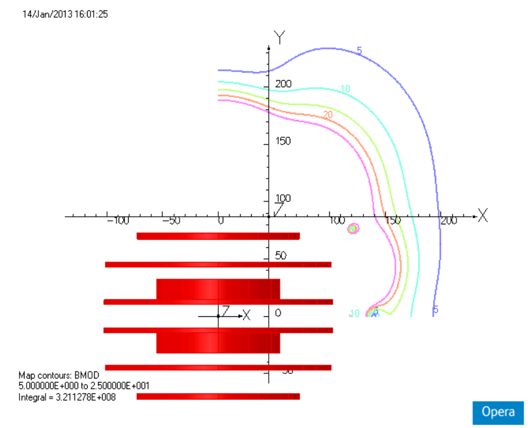
ProNova Future Projects – Ironless Cyclotron





With Iron0		Ironless
	Beam	
1,1	Ion [Z,q]	1,1
252.6	T [MeV]	252.7
8.23	Bex [T]	8.11
0.297	Rex [m]	0.302
	Magnet	
180.4	j [A/mm2]	235.9
10.7	Bmax [T]	12.4
9.7	Energy [MJ]	31.3
209	B(R=2m) [G]	4
416	B(Z=2m) [G]	13
25	Weight [tons]	4





- About the same size
- Ironless synchrocyclotron is *6 times* lighter
- Fringe fields are *orders of magnitude lower*
- Magnetic *field scales linearly* with operating current
- Much *more space* for RF system

From Minervini et al, Accel Appl 2015.

ProNova Future Projects – Ironless Cyclotron

Ironless cyclotron allows the possibility of Variable Energy

Assume Energy/Range Modulation:

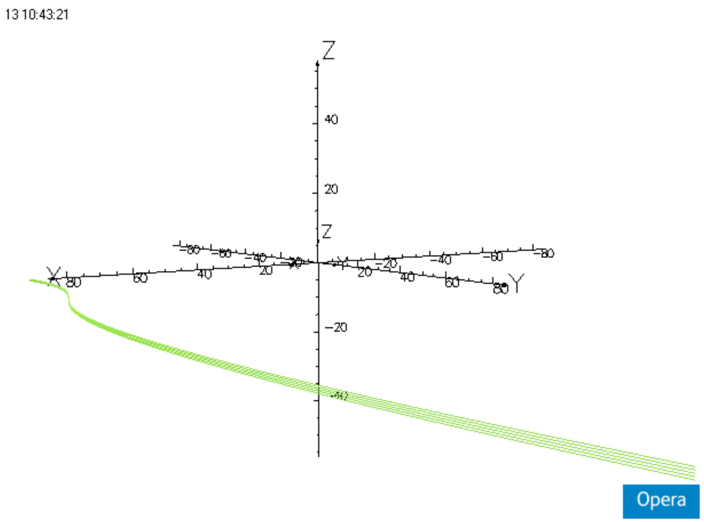
- 2 MeV steps for protons (~0.5 cm step in range)
- 2 MeV/ nucleon steps for carbon (~0.1 cm step in range)
- ~500 millisec step rate (minimum)
- 15 cm Maximum Treatment Volume extent in depth

For a 230 MeV cyclotron this means that that the beam energy, T, shall be linearly reduced from T=230 MeV to 160 MeV in 7 seconds at a rate of 10 MeV/s.

ProNova Future Projects – Ironless Cyclotron

- To maintain the same particle trajectories for variable beam extraction energy the coil current, the RF frequency and the per turn energy gain (i.e. RF cavity voltage) have to be modulated in a certain way.

The shape of the particle trajectory is independent of the extraction beam energy.



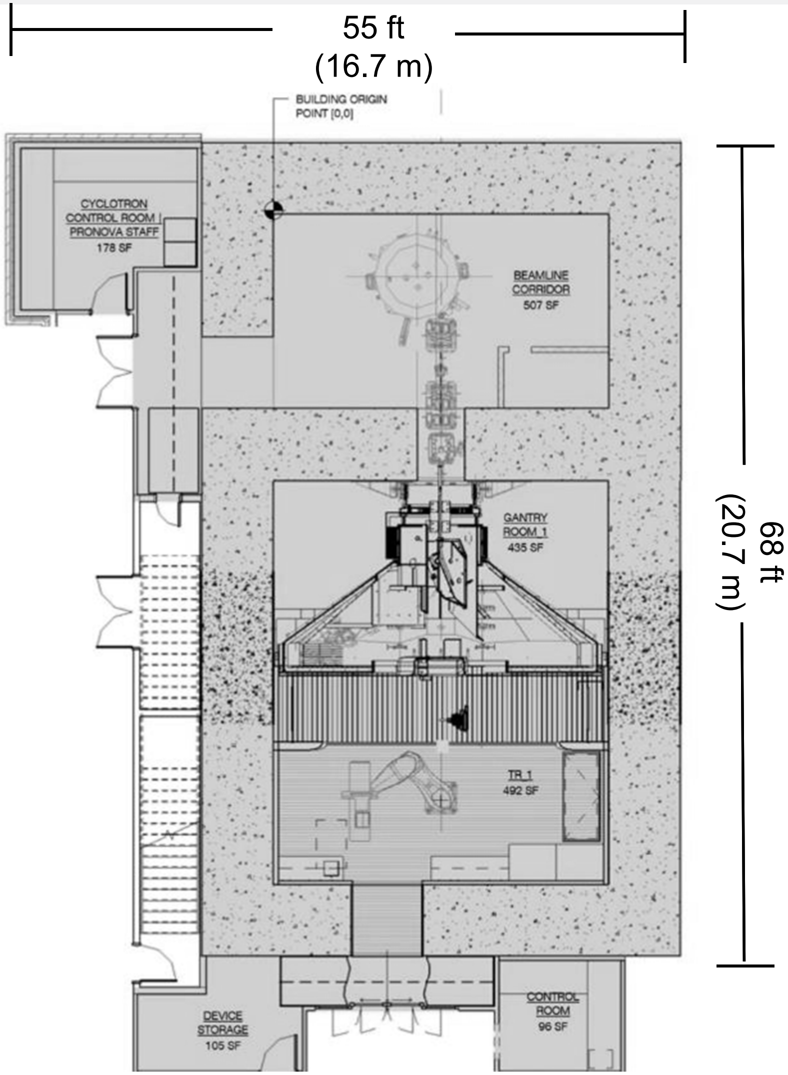
VF Model:

- The proton was launched from the spots with the same X- and Y- coordinates at Rex with the respective energy, T=(1.0, 0.8, 0.6, 0.4 and 0.2)*To and corresponding B=K_B(T)B_0. To distinguish between the trajectories the initial spots were spaced axially in Z-direction by 1 mm.

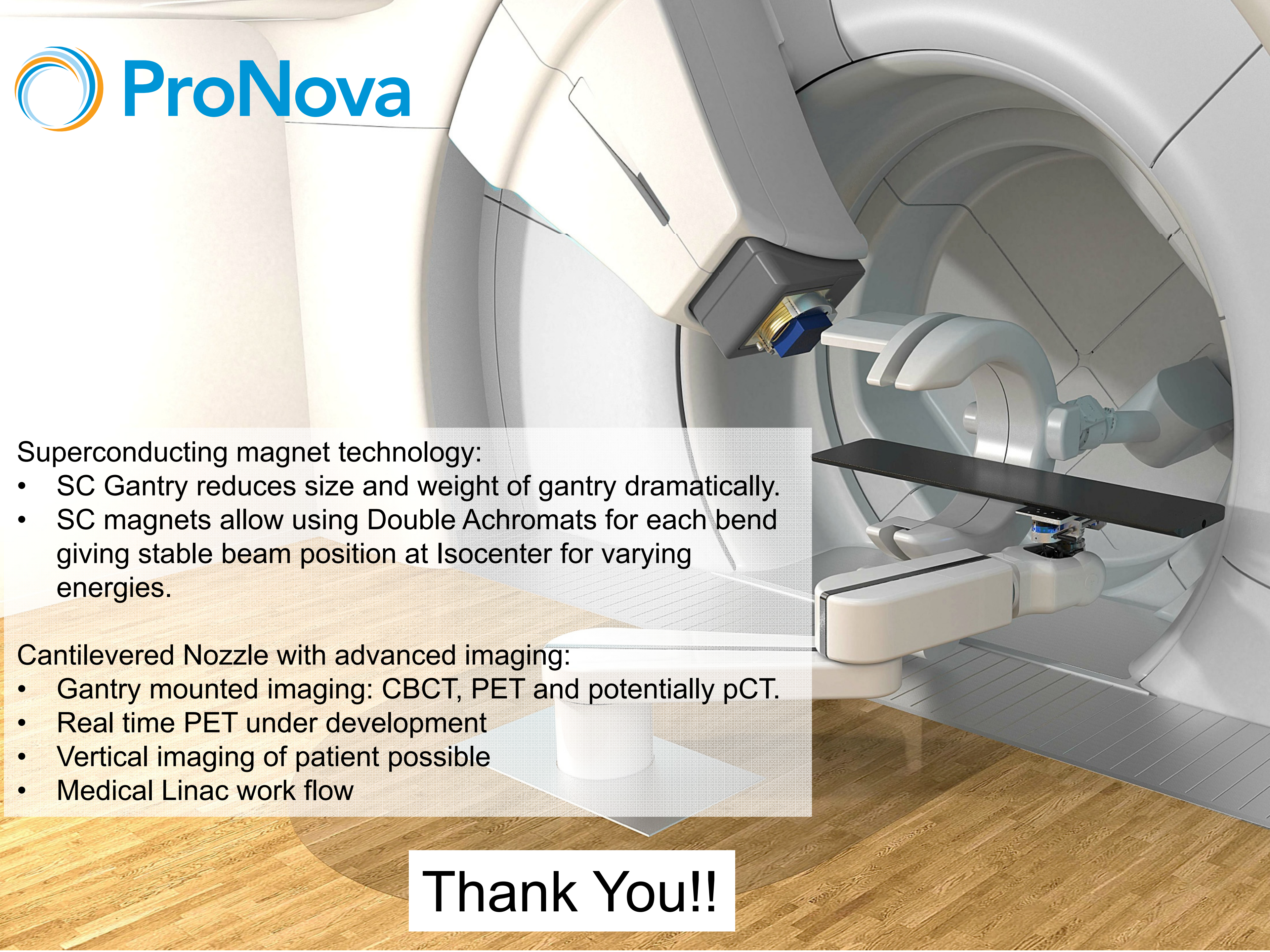
- *This confirms the above conclusion that for a properly scaled coil current matching the scaled beam energy the trajectories of the particle are the same.*

One-Room In-Line Ultra Compact

- **Total Vault Area***
  - 2,720 ft^2
  - 252 m^2
- **Vault - 926 SF**
  - Gantry room 434 ft^2 (40 m^2)
  - Treatment Room 492 ft^2 (46 m
- **Cyclotron Room**
  - 507 ft^2
  - 47 m^2



*Concrete thinness and or material will depend on local regulations and site conditions



ProNova

Superconducting magnet technology:

- SC Gantry reduces size and weight of gantry dramatically.
- SC magnets allow using Double Achromats for each bend giving stable beam position at Isocenter for varying energies.

Cantilevered Nozzle with advanced imaging:

- Gantry mounted imaging: CBCT, PET and potentially pCT.
- Real time PET under development
- Vertical imaging of patient possible
- Medical Linac work flow

Thank You!!