Particle Beam Technology and Delivery
- Cyclotrons -

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55th Annual AAPM Meeting

Proton Symposium

This Presentation

Disclosure:

I was with Indiana University from 1987 to May 2013

Now I'm with ProNova Solutions full time since May 2013

Pros and Cons of Cyclotrons in the context of:

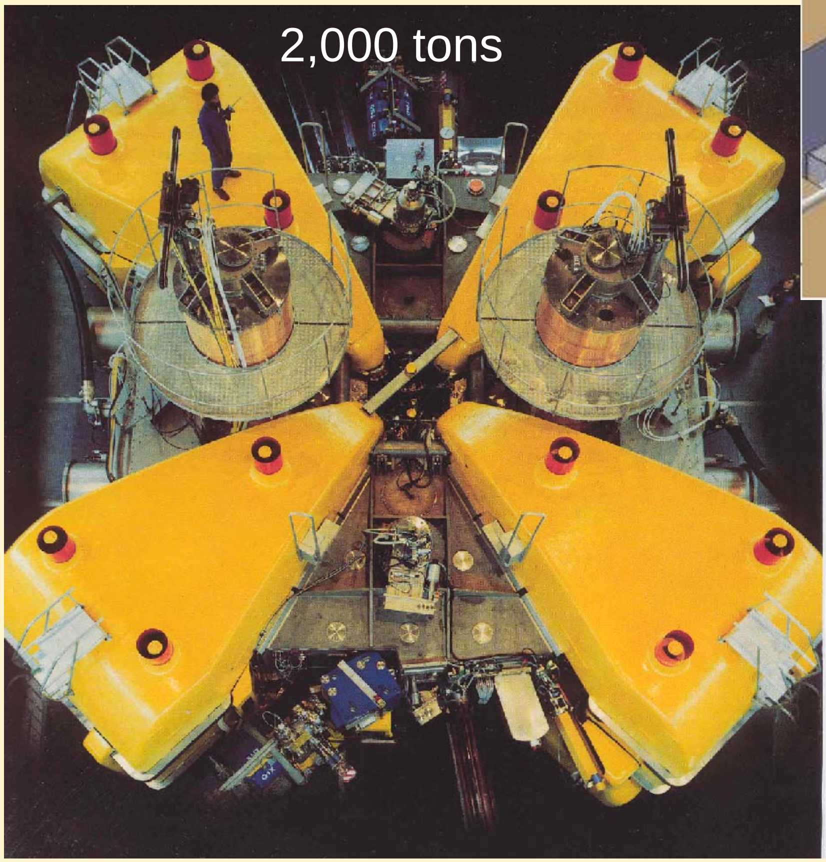
- Technology
- Beam Energy
- Treatment Delivery Options
- Throughput

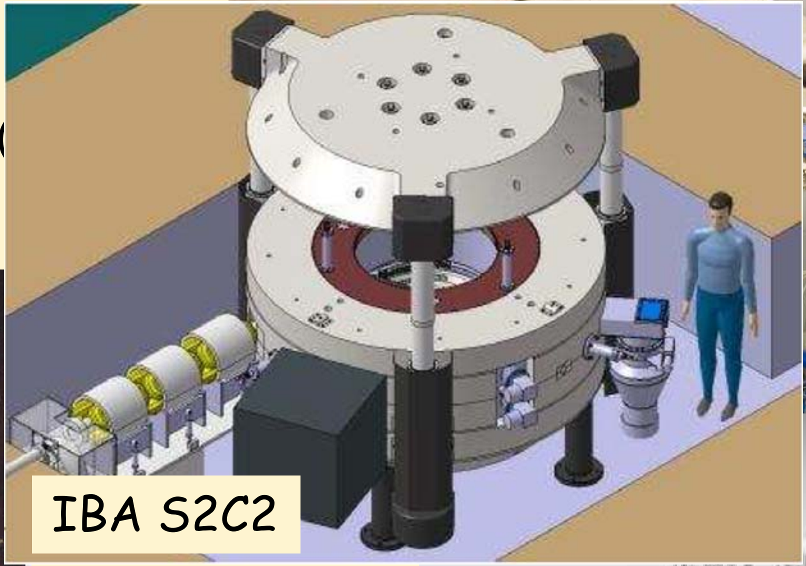
Summary of Pros and Cons

Technology

Cyclotrons in a Proton Therapy Facility

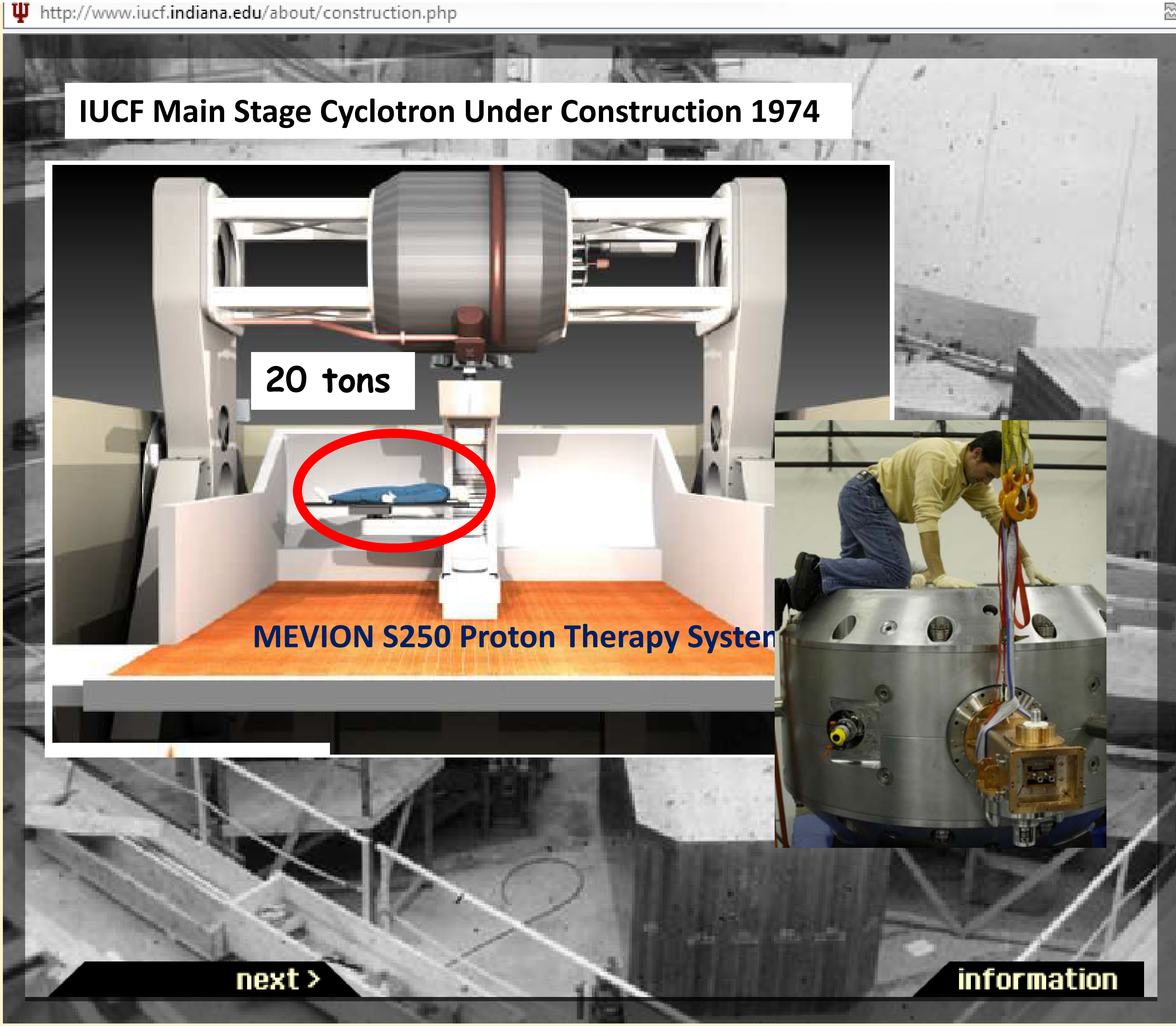
NAC - South Africa and IUCF - Indiana





ACCEL

PSI, Munich, Scripps


http://www.iucf.indiana.edu/about/construction.php
IUCF Main Stage Cyclotron Under Construction 1974
20 tons
MEVION S250 Proton Therapy Systen
next >
information

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Cyclotrons for Hadron Therapy

Machine	Man'f	Type	Energy	Size	Power	Intensity	Peak B field
C230	IBA, Also Sumitomo	NC Iso	230 MeV	220 t 4.3 m	320 kW	Up to 300 nA CW	Up to 2.2 T
SC Proton Cyclotron	Varian	SC Iso	250 MeV	90 t 3.1 m	155 kW	Up to 800 nA CW	< 4 T
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S250	MEVION	SC Syn	250 MeV	20 T 1.8 m	- ?	500 Hz period	~ 9 T
S2C2	IBA	SC Syn	230 MeV	<50 T 2.5 m	- ?	1 kHz period	~ 6.56 T
C400	IBA	SC Iso Light Ion	250 MeV (p) 400 MeV/u	700 T 6.6 m	200 kW for RF	8 nA	2.5 T - 4.5 T

Iso = Isochronous   Syn = Synchrocyclotron

Types of Cyclotrons

Isochronous *eg.* IBA C230, Varian 250 MeV

- Normal or Superconducting coils
- High RF power and voltage
- RF frequency constant ~ 10's of MHz
- Hill & Valley Magnet pole tip profile
- Radially increasing field to compensate for mass increase
- Beam is continuous (CW) with micro-structure of RF

Synchrocyclotron *eg.* MEVION S250, IBA S2C2

- Superconducting coils
- Low power RF and voltage
- Magnet pole tip profile simplified
- RF frequency cycles up and down at ~ 500 Hz to 1,000 Hz
- Beam has macro-pulses corresponding to RF frequency cycles
- Peak beam intensity is ≥ μA's, average is 10's of nA's

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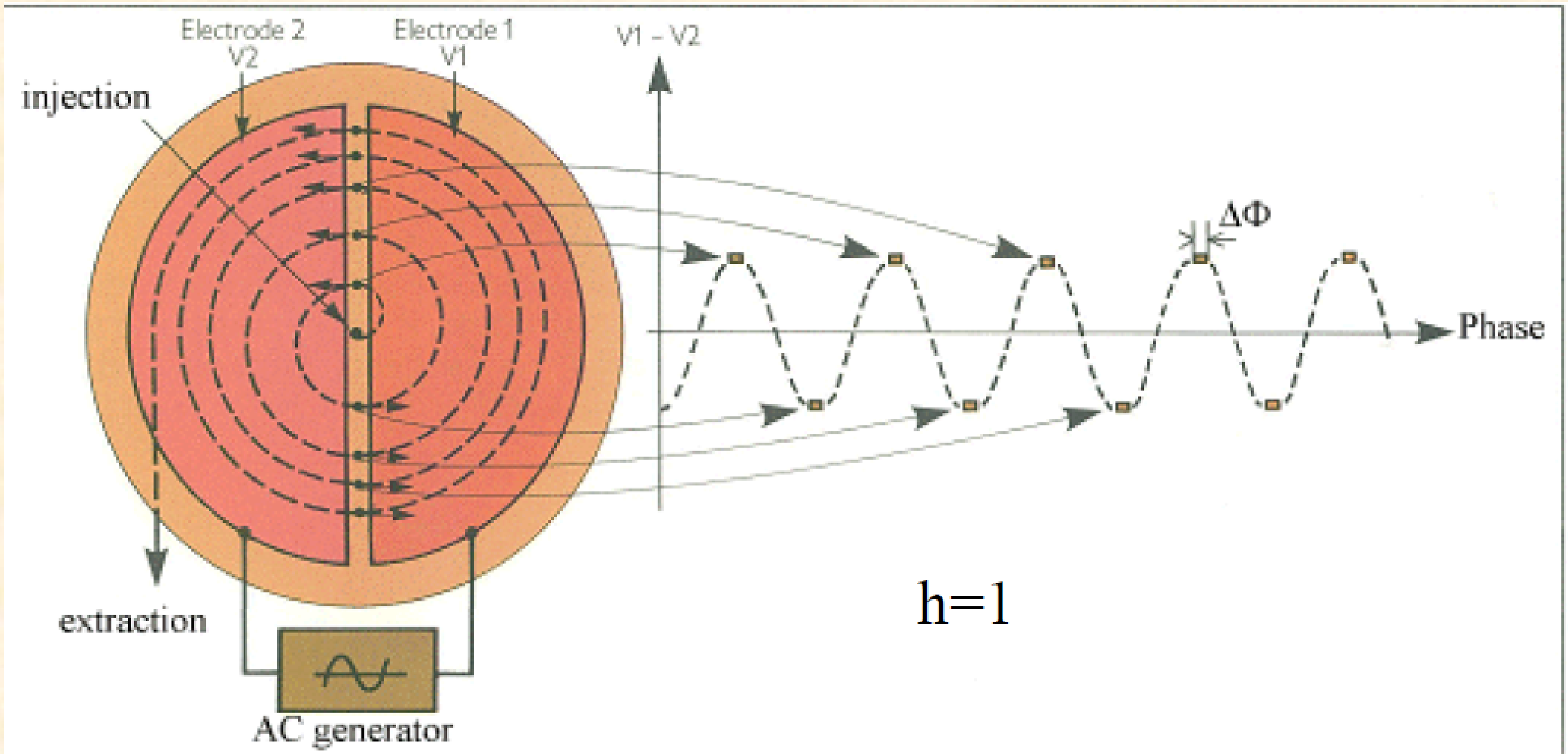
Cyclotron Operation

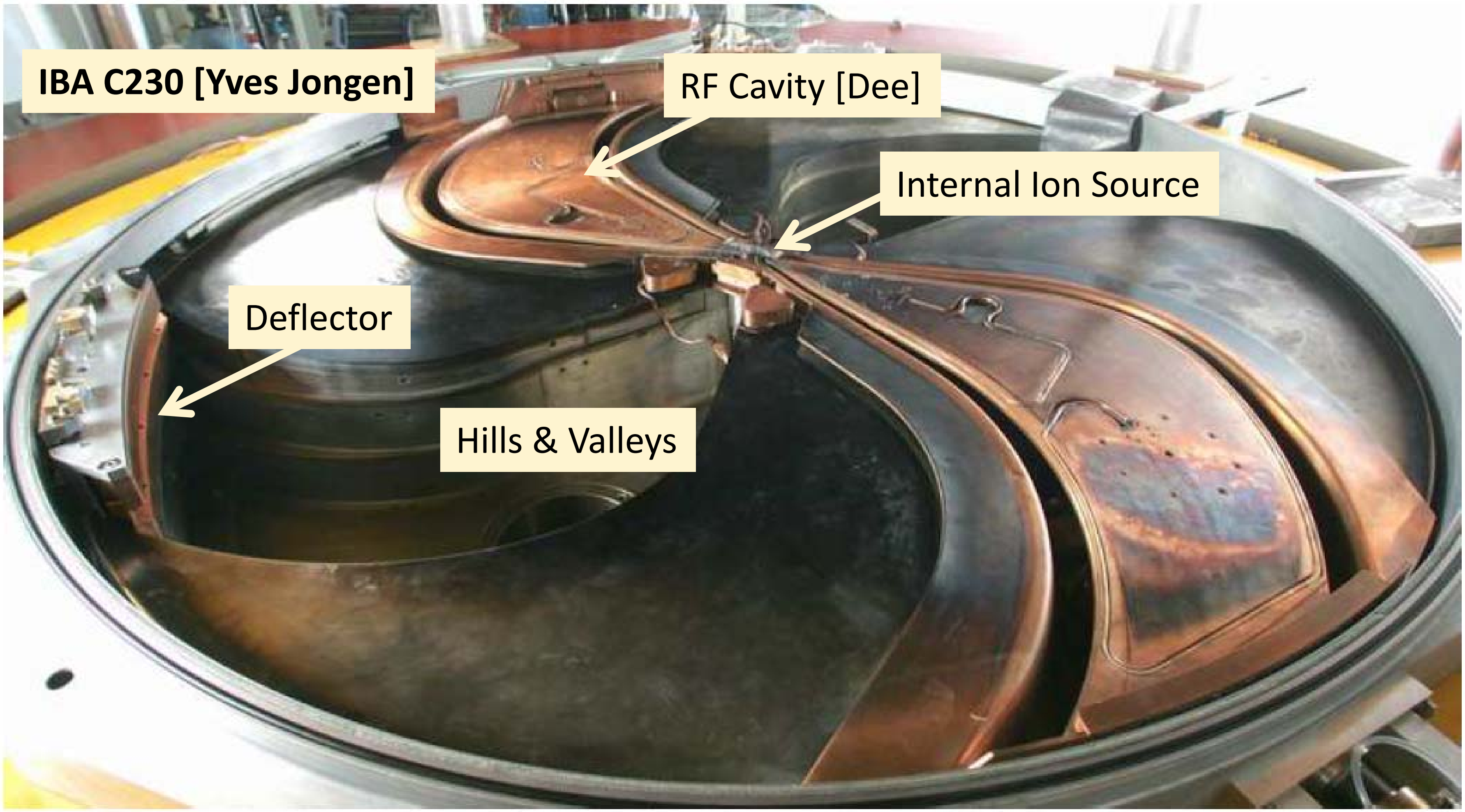
Isochronous – Features

The proton takes the same amount of time to travel one turn.
The rotational frequency is synchronous with the RF frequency.



F. Chautard Cern Accelerator School 2005

Isochronous - Features



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Cyclotron Operation

Isochronous – Internal Ion Source

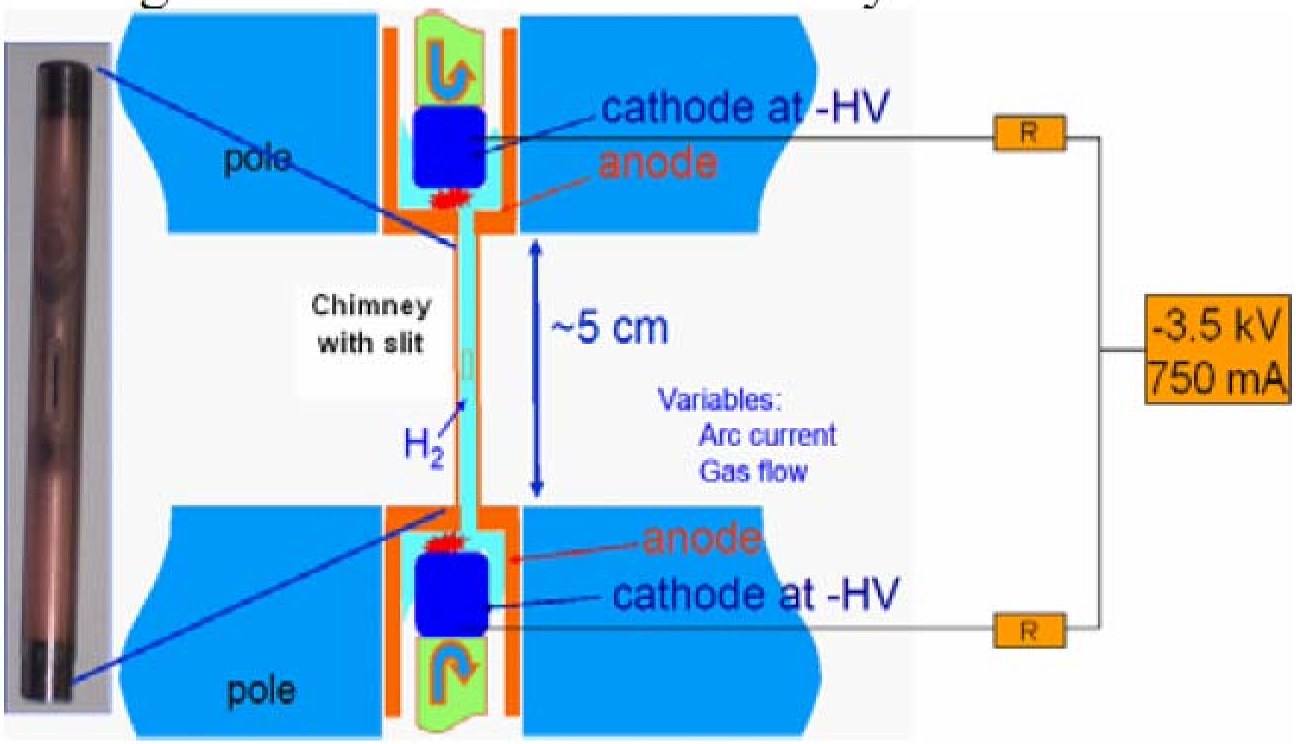

Figure 1. Schematic view of the cold cathode source in the cyclotron center.

Proc. 18th Int Conf. Cycl. Appl. 2007, M. Schippers, et al.

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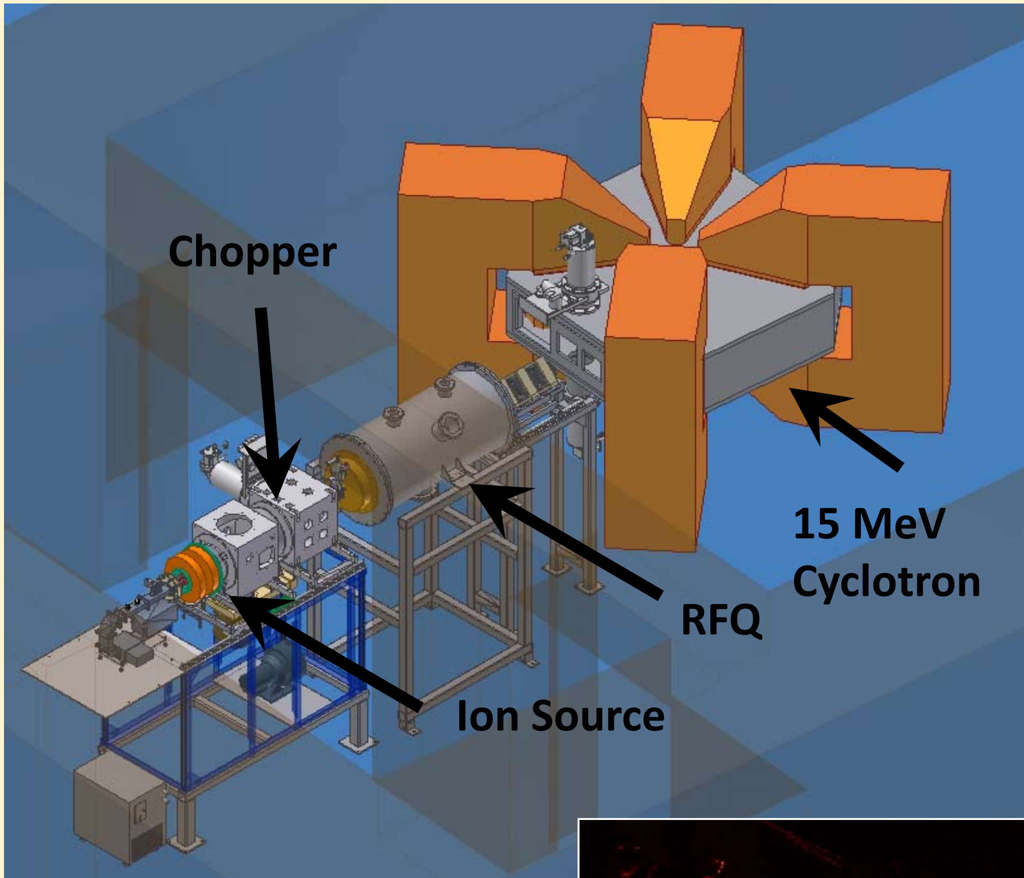
Cyclotron Operation

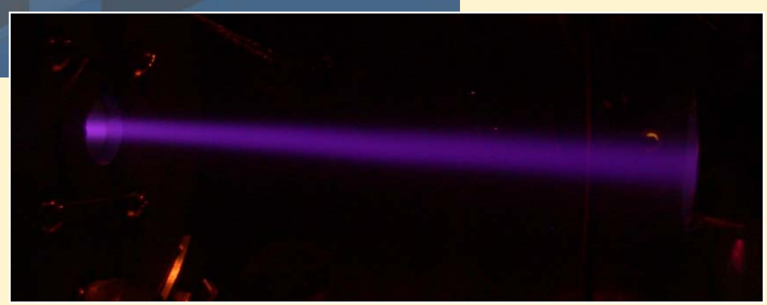
Isochronous - External Ion Source

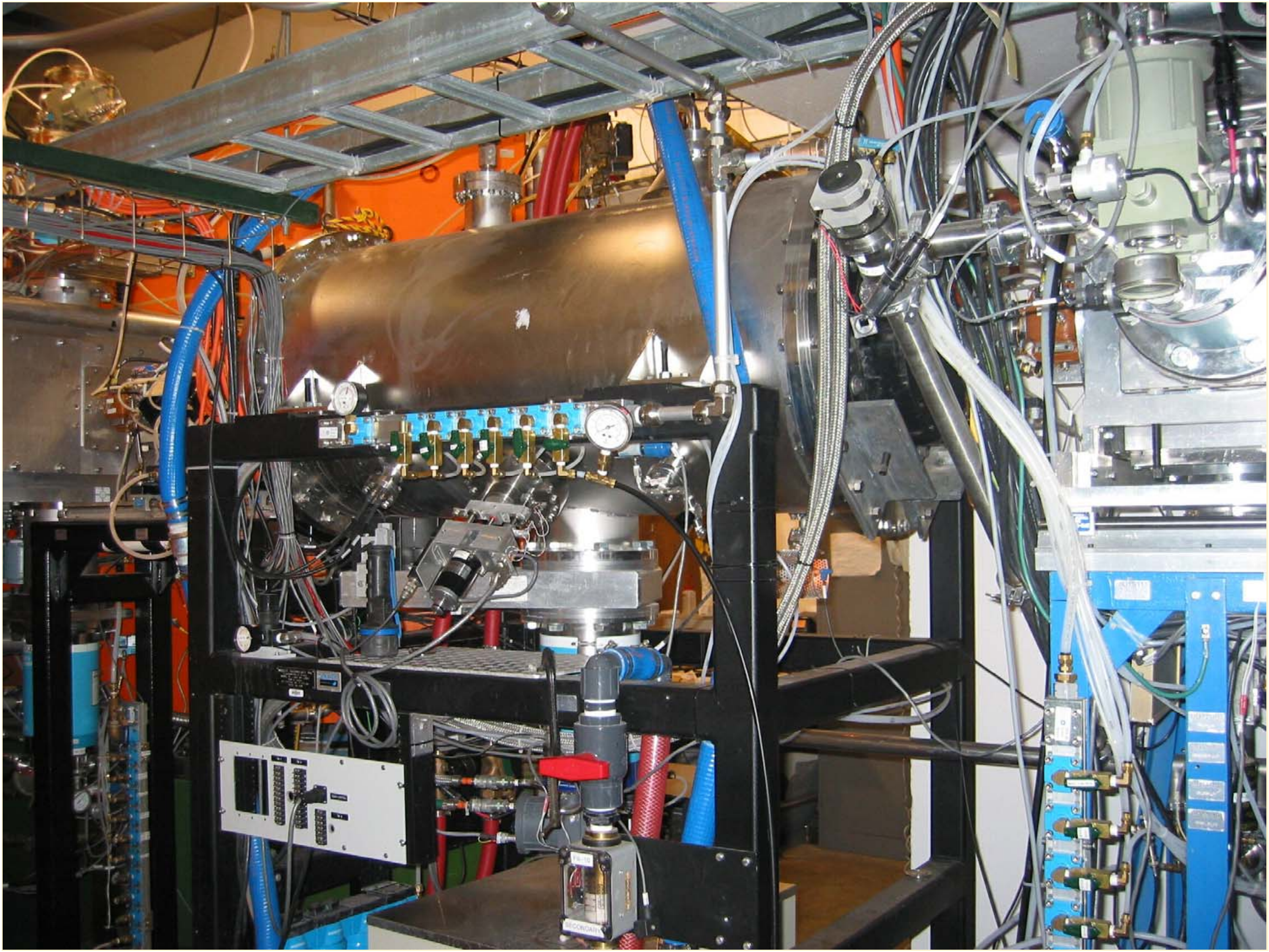


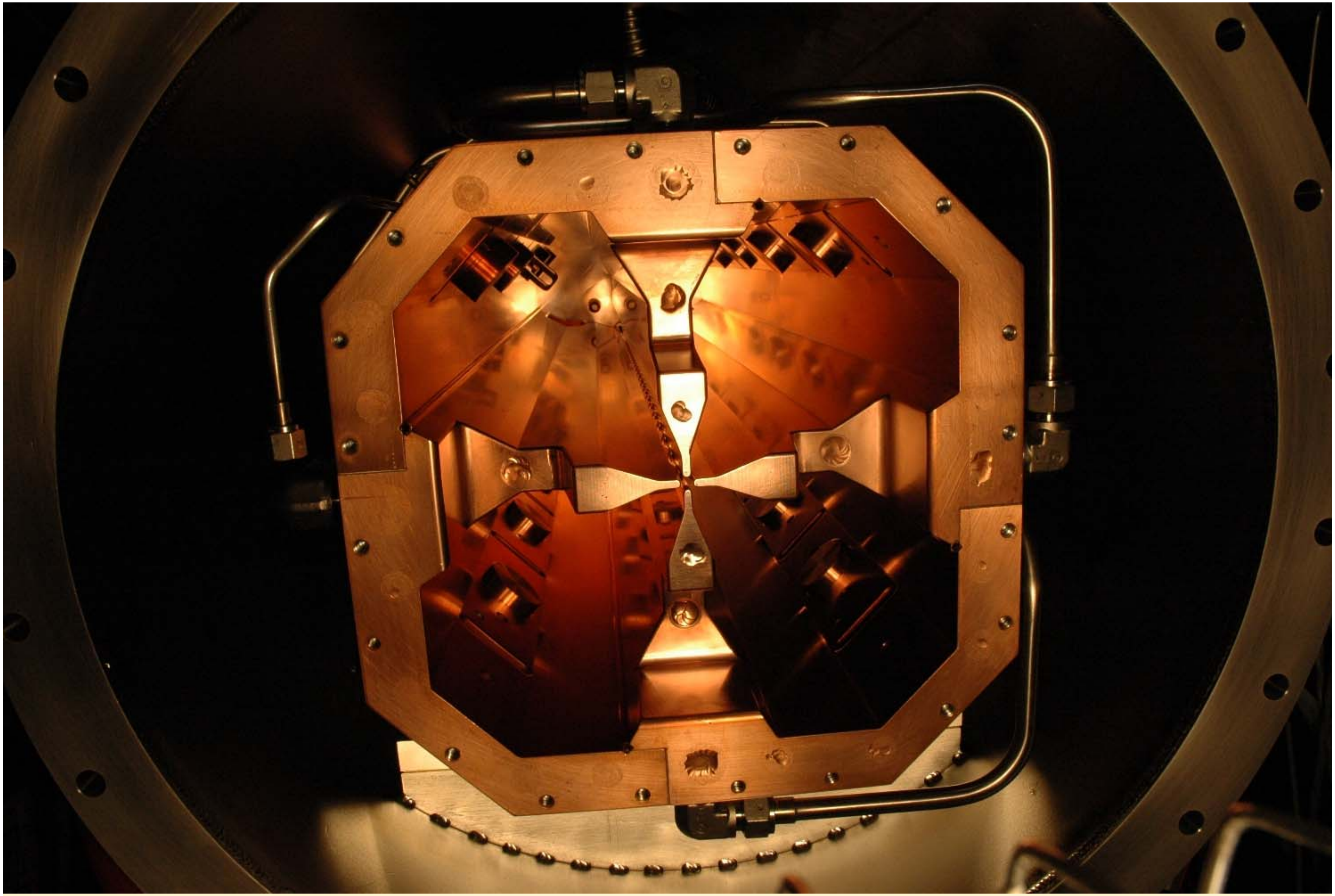
Beam Intensity Modulation System and Chopper used at Ion Source to control beam intensity during treatments.

Frequency of RFQ = 213.48 MHz
Frequency of Cyclotron = 35.58 MHz

Need to chop out unwanted pulses
AND
modulate beam intensity.
(automatic or manually)







Cyclotron Operation

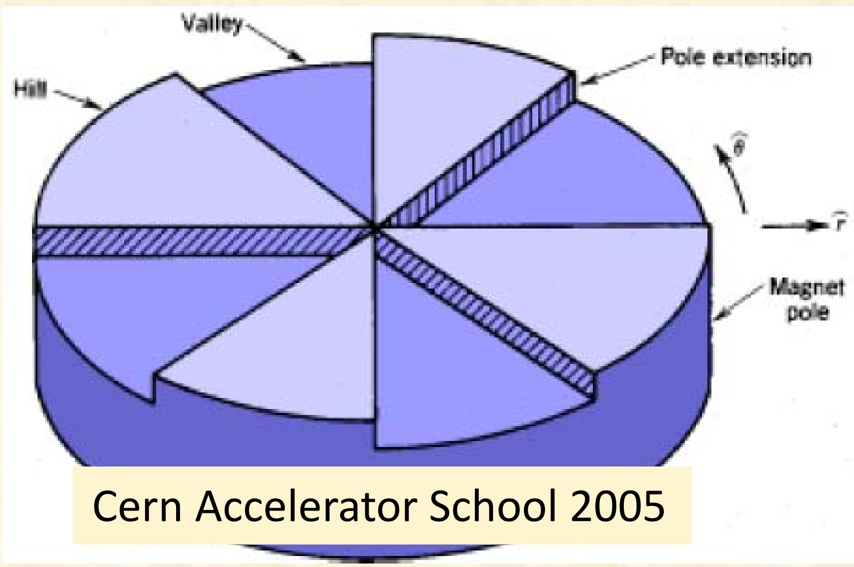
Isochronous – Complex Magnetic Field

Relativistic mass increase: $B(r) = \gamma(r)B_o$

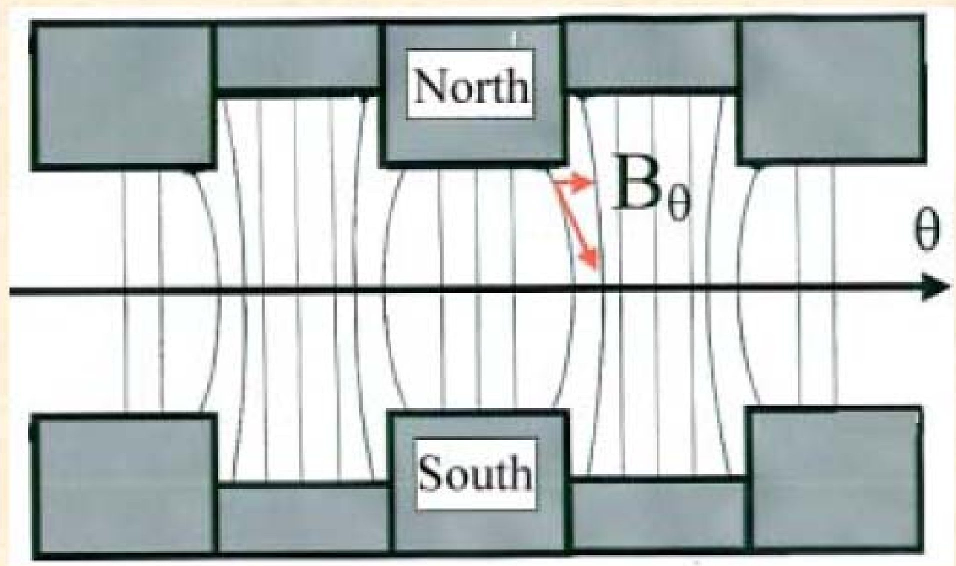
Increasing radial field to maintain isochronism

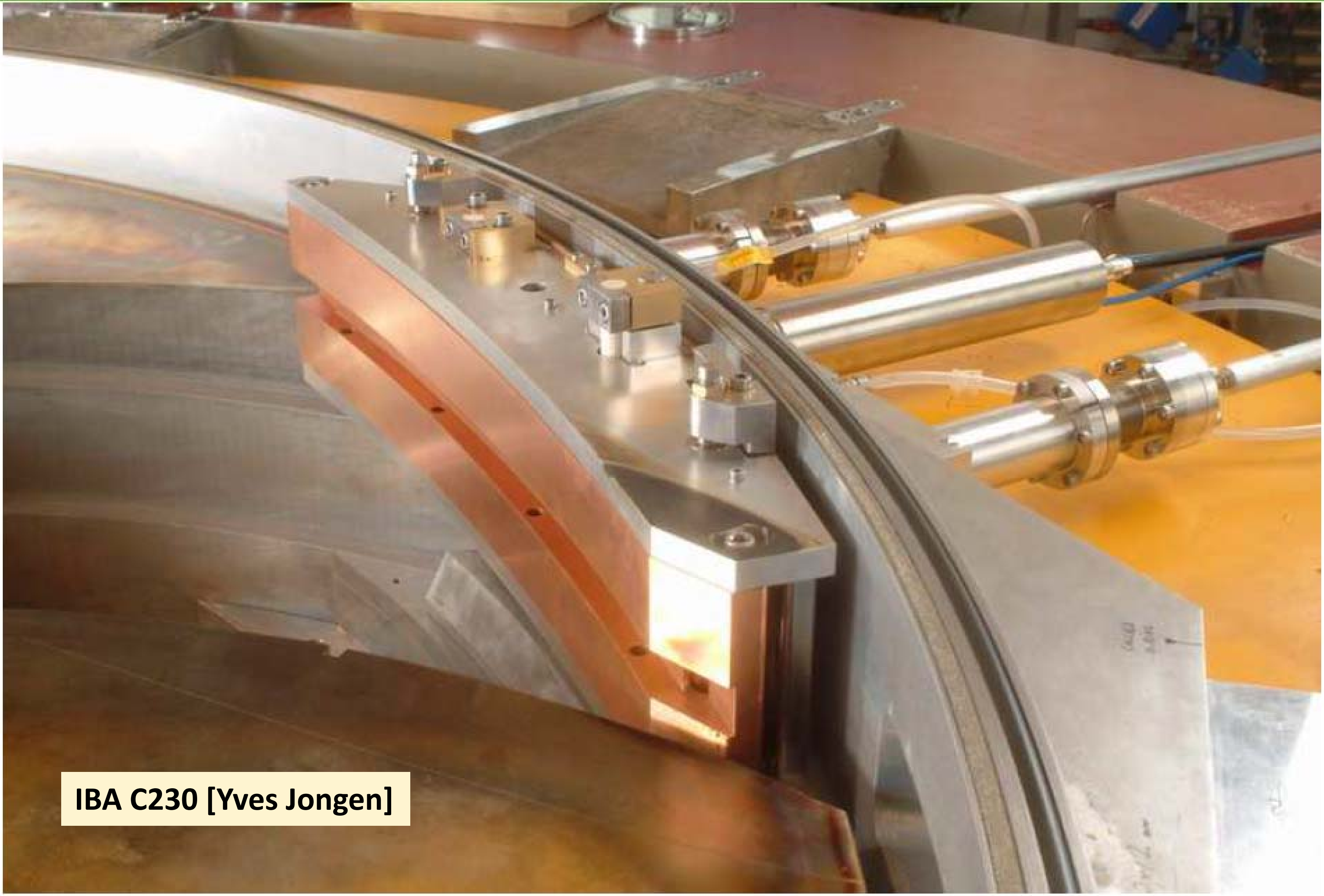
Vertical focusing:

Non-normal entry and exit
Alternating field gradients



Cern Accelerator School 2005

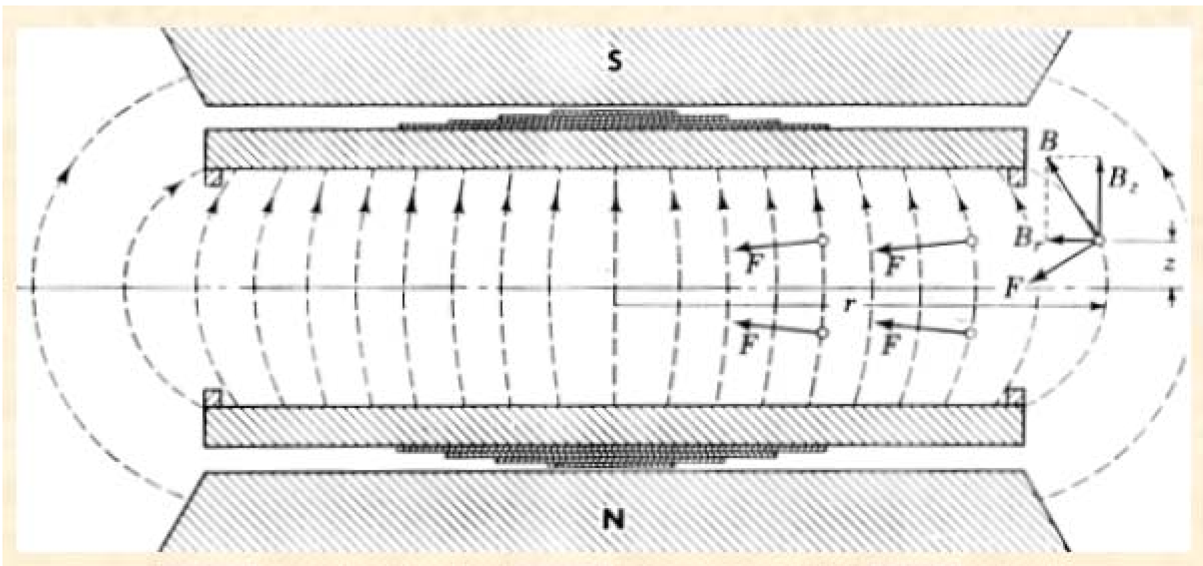



IBA C230 [Yves Jongen]

Cyclotron Operation

Synchrocyclotron – Features

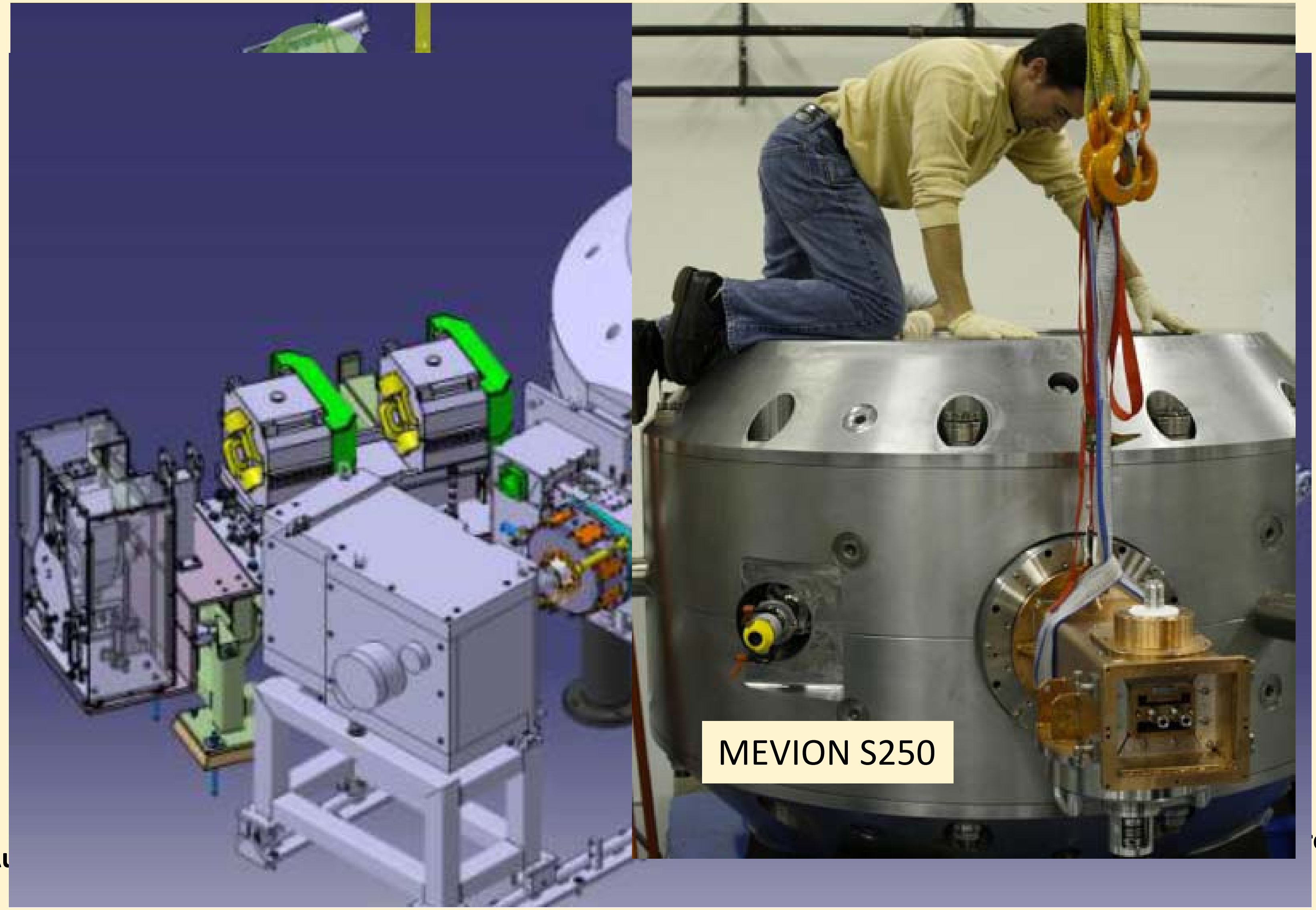
Simultaneous radial and axial focusing: **Weak focusing**



Cern Accelerator School 2005

Cyclotron Operation

Synchrocyclotron – Features



Cyclotrons – Maintenance, Operability

History

Cyclotrons have a poor reputation due to;

a) Failures of the RF system and resonators [Dees]
b) Difficulty reproducing or stabilizing B field
c) Ion Source maintenance requirements
d) High power consumption
e) Longer recovery from power quality events (PQE's).

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Cyclotrons – Maintenance, Operability

Today

Cyclotron issues are largely resolved;

a) Varian proton cyclotron ~ 99% availability
b) Indiana Cyclotron > 98% availability
c) C230 improving with updates
d) SC cyclotrons power efficient
e) Lower power -> UPS for PQE's.
f) BUT: Internal Arc Source STILL an issue!!

Cyclotrons – Maintenance, Operability

Today

Cyclotron Maintenance and Operation;

a) Experience and design -> reduced maintenance
b) New cyclotrons are becoming automated

Ion Source Maintenance:

a) For Isochronous machines	every few days!!
b) For Synchrocyclotron	every few weeks
c) External Ion Source (IU)	every 6 months ☺

Cyclotrons – Beam Quality

Isochronous Cyclotron

Parameter	Value
Fixed Energy, typ.	230 to 250 MeV
Energy Variability	IU = ± 0.1 MeV, others up to ± 0.4 MeV
Energy Spread	ΔE ~ ± 0.05 to 0.5 MeV
Intensity range	pA to ~ 800 nA
Intensity modulation	CW

Cyclotrons – Beam Quality

Synchrocyclotron

Parameter	Value
Fixed Energy, typ.	230 to 250 MeV
Energy Variability	Not published
Energy Spread	Not published
Intensity range	pA to ~ 800 nA
Intensity modulation	Modulated @ 500 to 1,000 Hz, ~ 0.1 % to 0.2 % Duty Factor
Peak Intensity	~ 1,000 x Average ~ 100's nA up to μA's

Cyclotrons for Hadron Therapy

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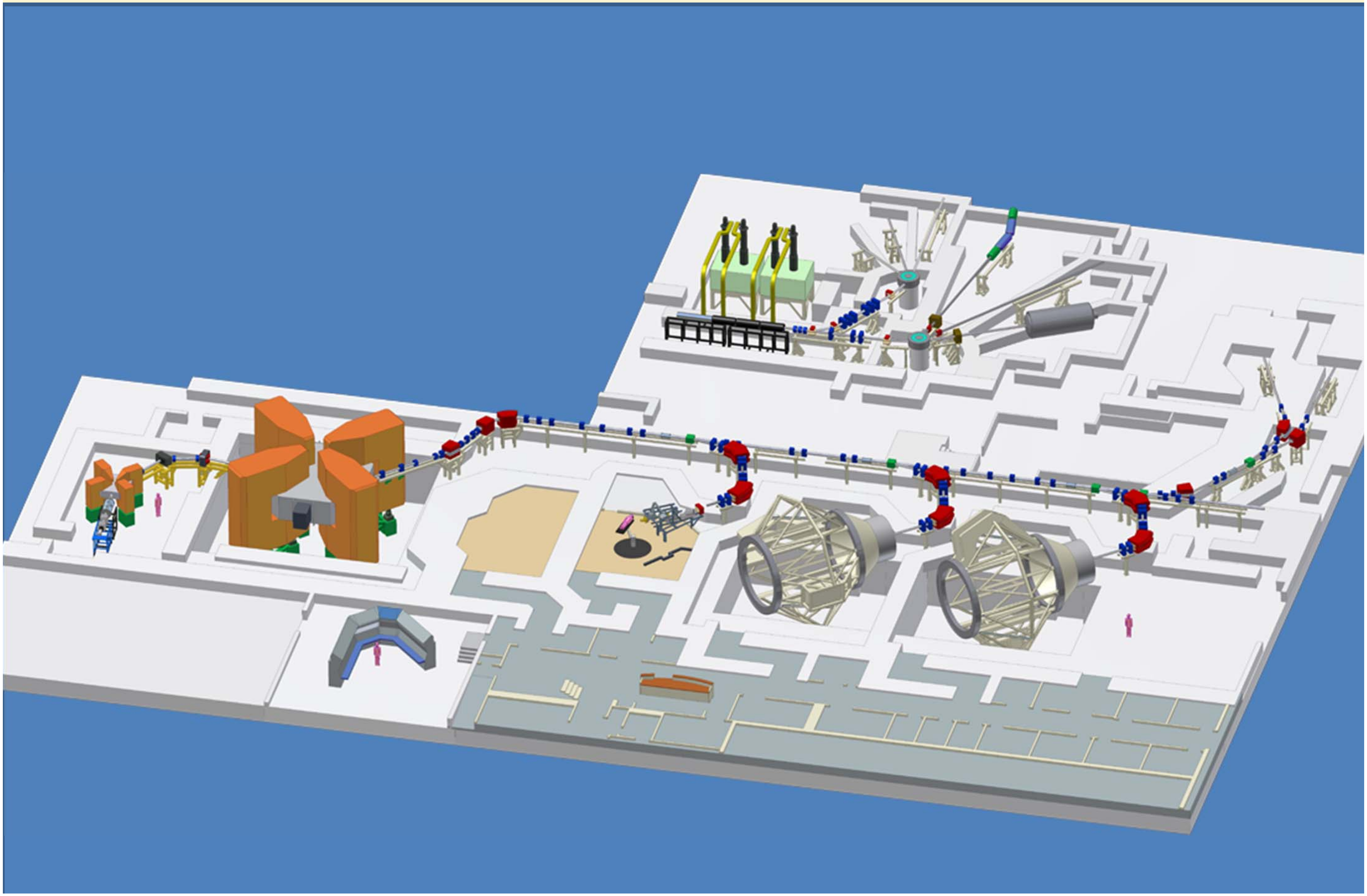
Iso = Isochronous   Syn = Synchrocyclotron

Treatment Delivery Options

Cyclotrons in a Proton Therapy Facility



Cyclotrons in a Proton Therapy Facility

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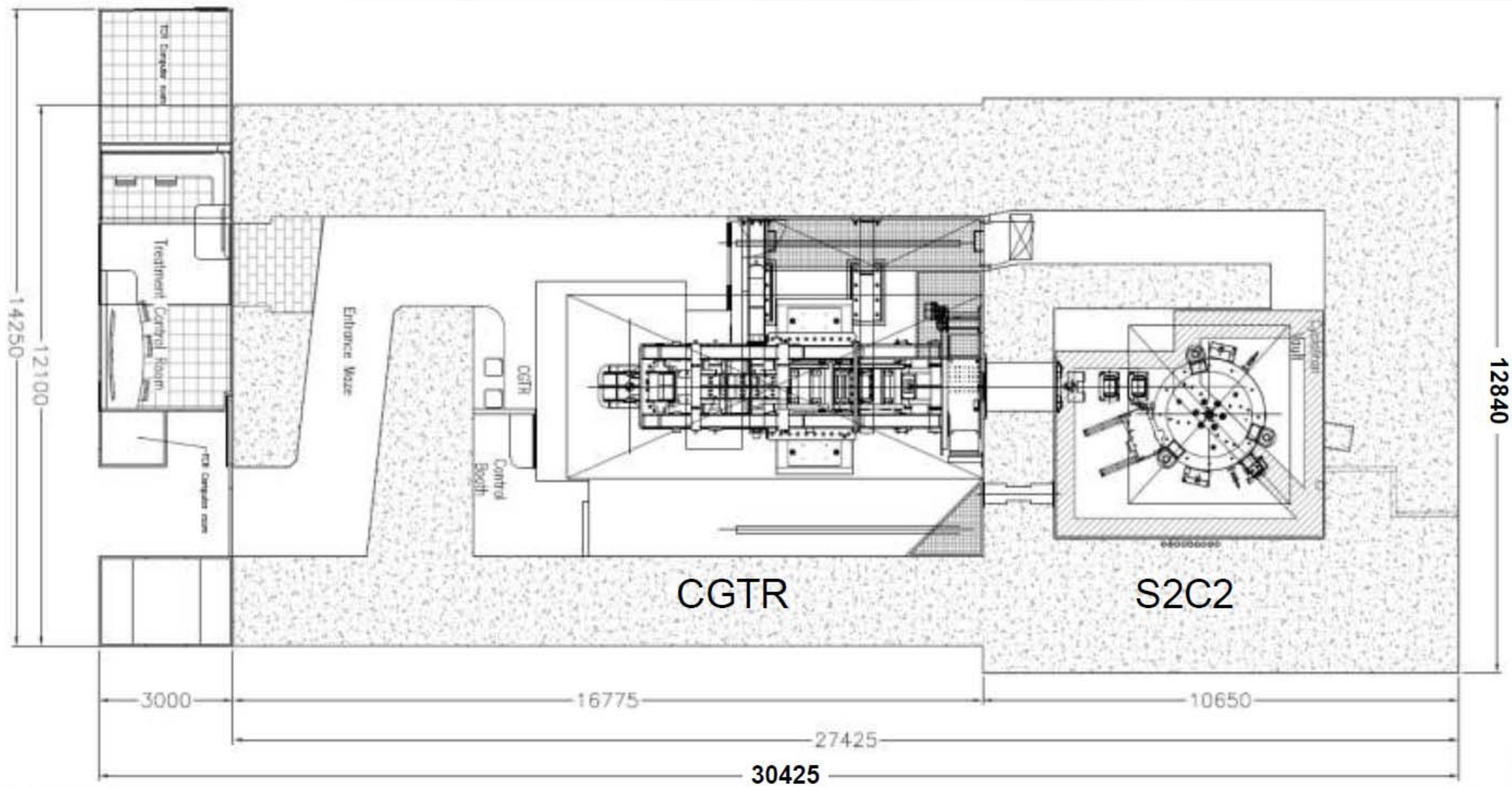
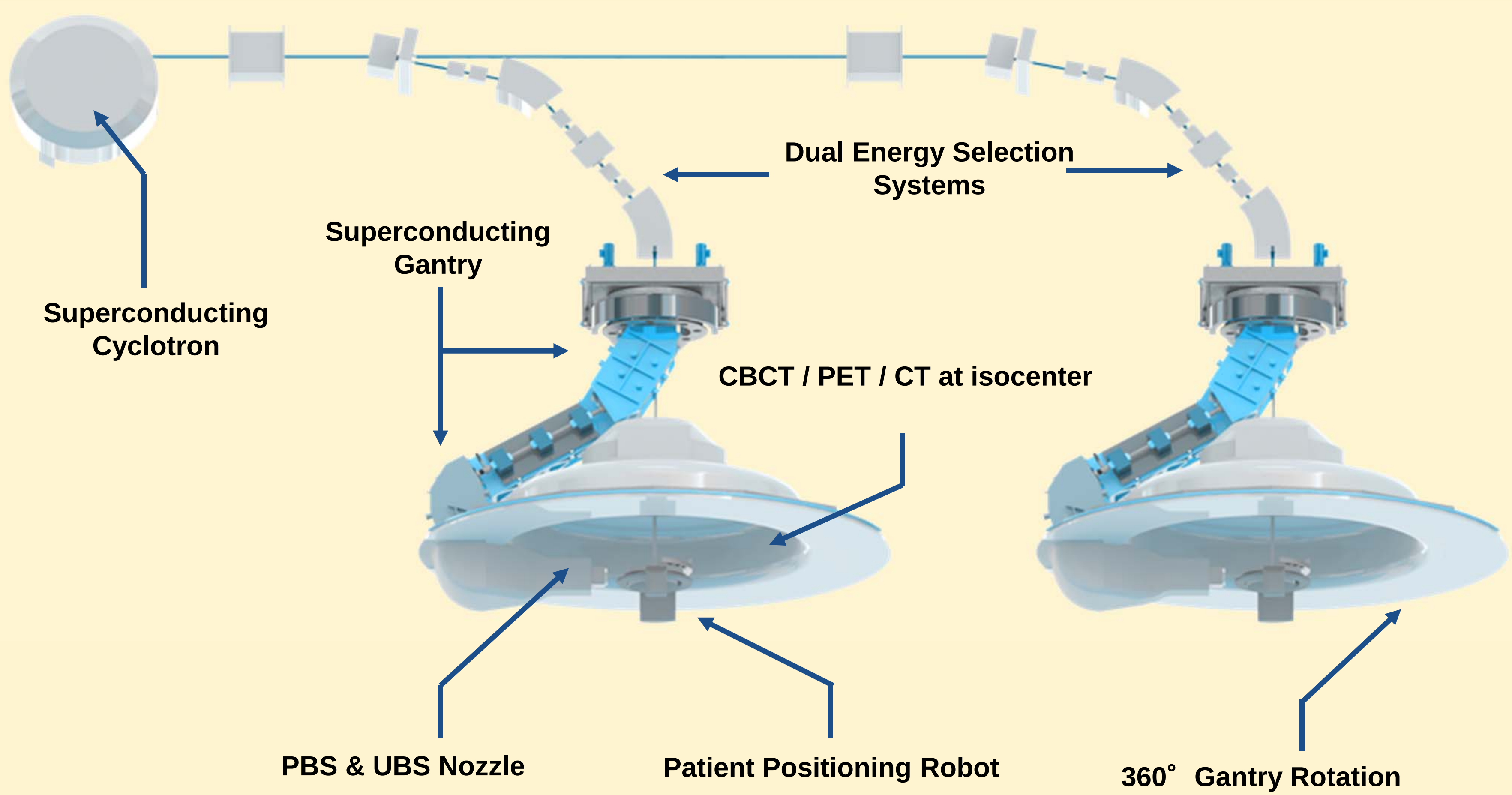
Proteus One® layout

30.4m x 12.8m

Energy Selection part of Gantry



SC360 Efficient 2-Room Solution



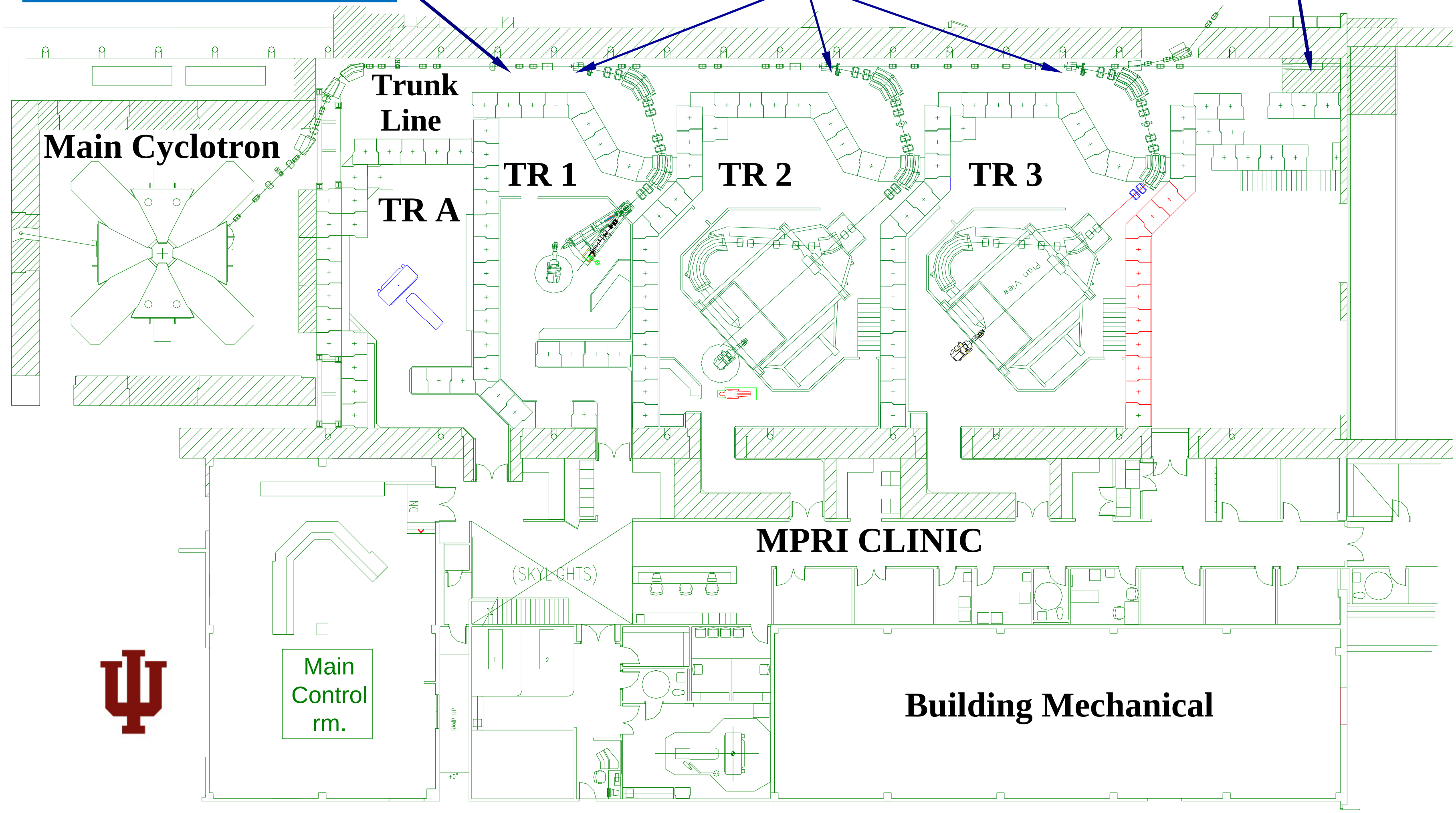
Disclaimer: The ProNova SC360 has not been cleared by the U.S. Food and Drug Administration (FDA) for commercial distribution in the U.S. and is not available for commercial distribution at this time

ProNova

Fixed Energy 208.4 MeV P
Series of Double Achromats
Fast Kicker to Each BDS Line

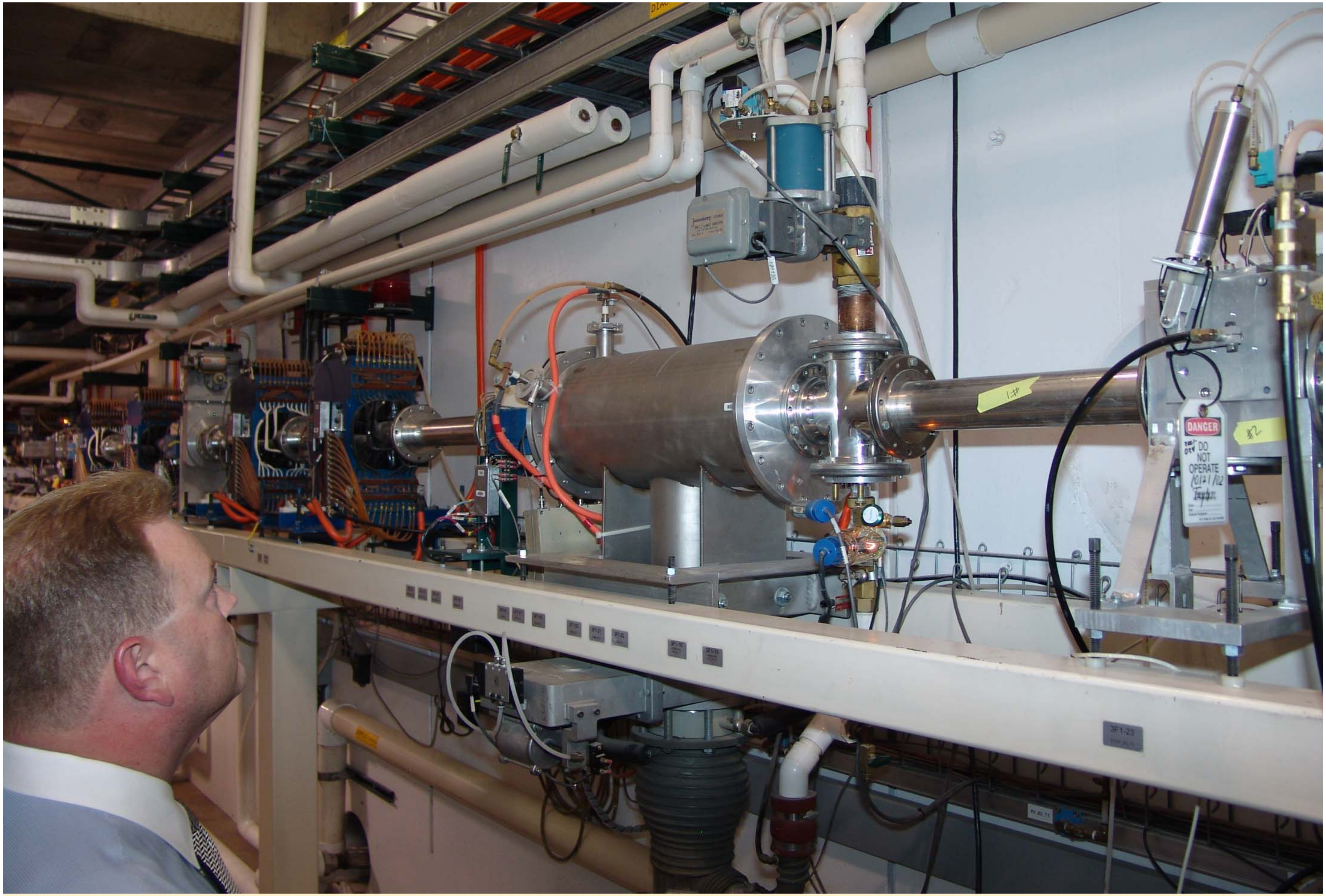
Fast (2 msec) Ferrite Kickers &
Independent Be Degraders

Beam Dump with MLFC
to monitor Energy and
Intensity



Fast Switching Between Tx Rooms

- Fast ferrite kicker magnet & Lambertson allows for rapid switching between rooms.
  < 1 second
- Each room can set up for an energy independently of all other rooms.
- Each room has an Energy Degrader and Energy Selection beam line.


DANGER
DO
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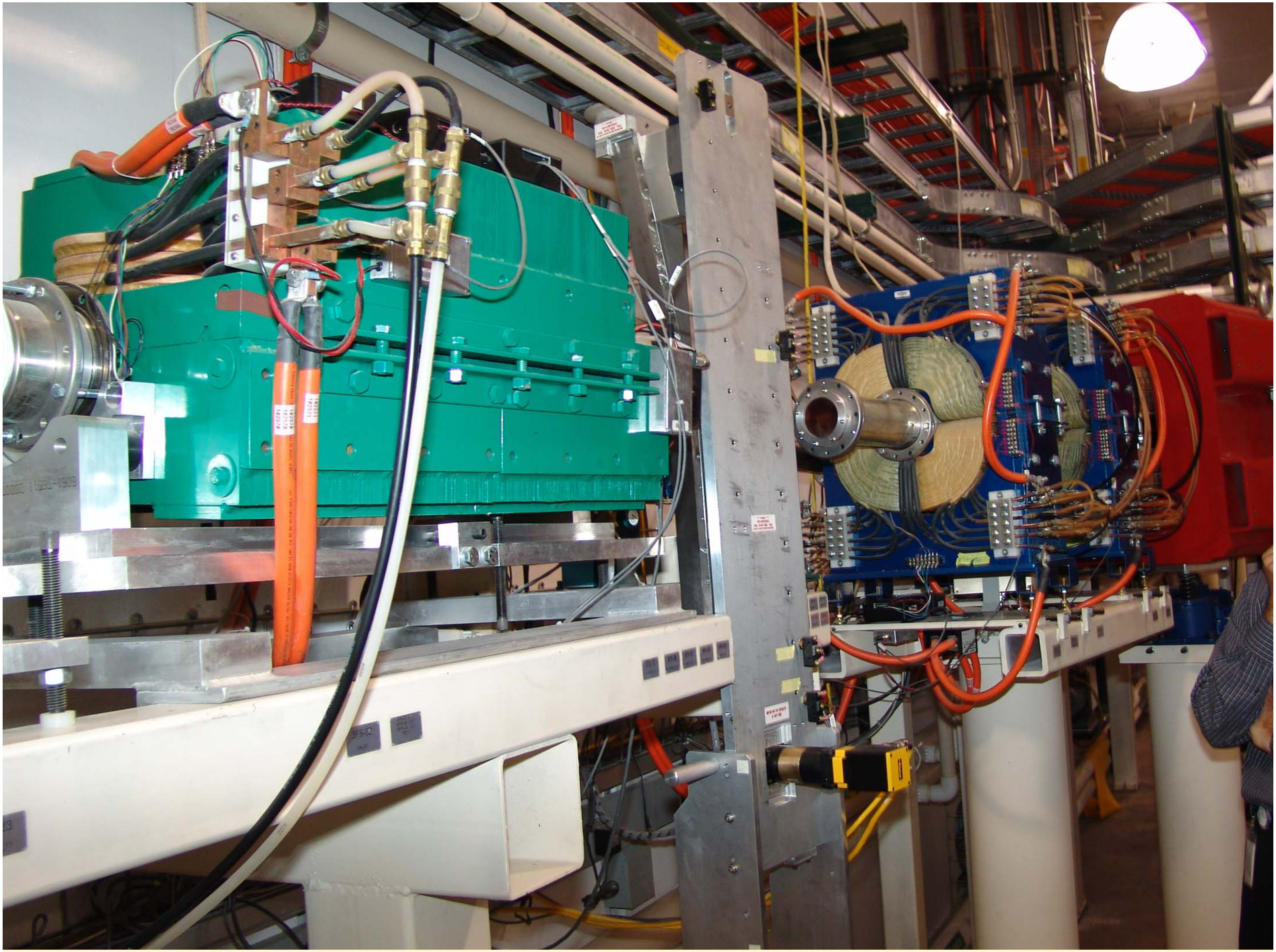
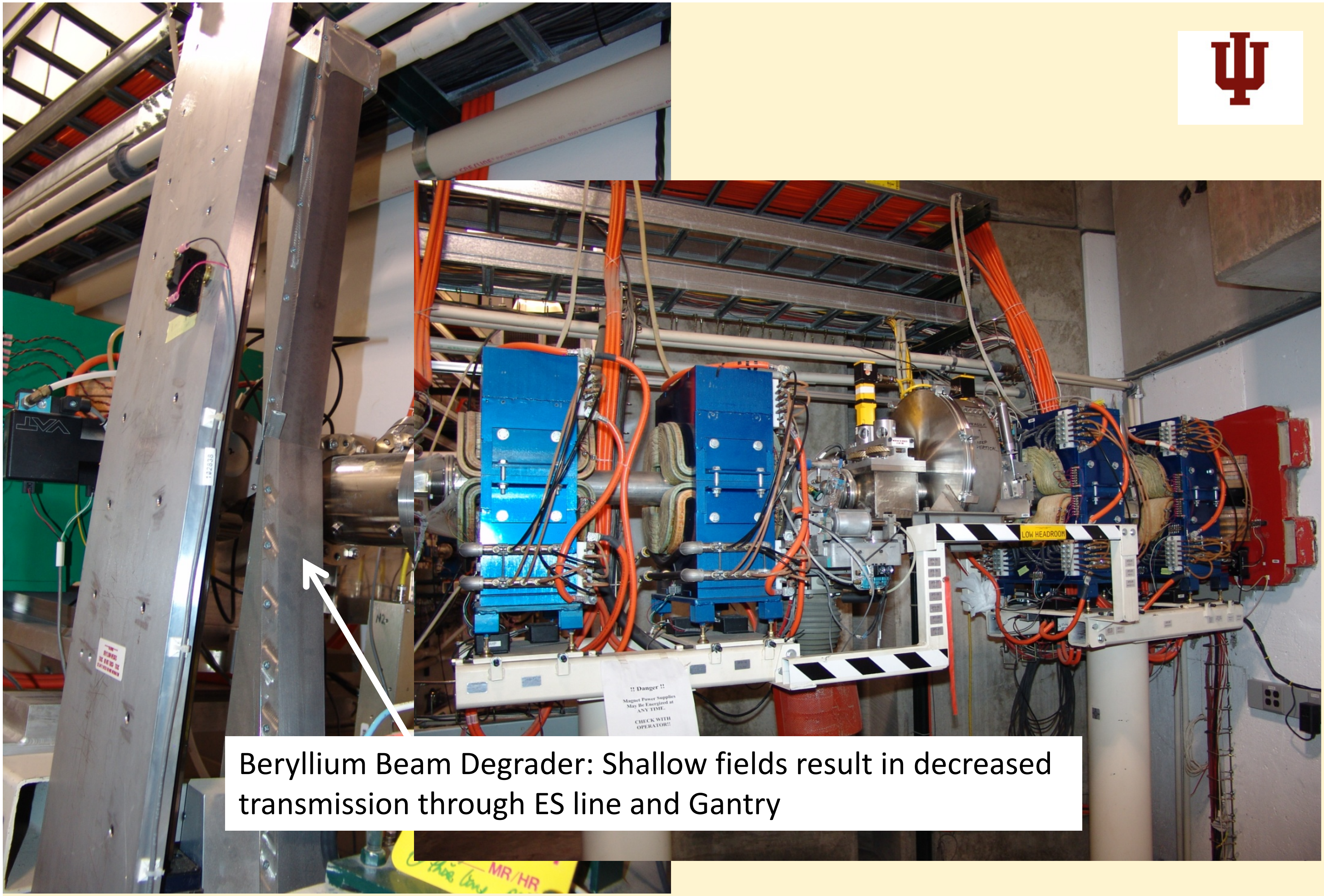
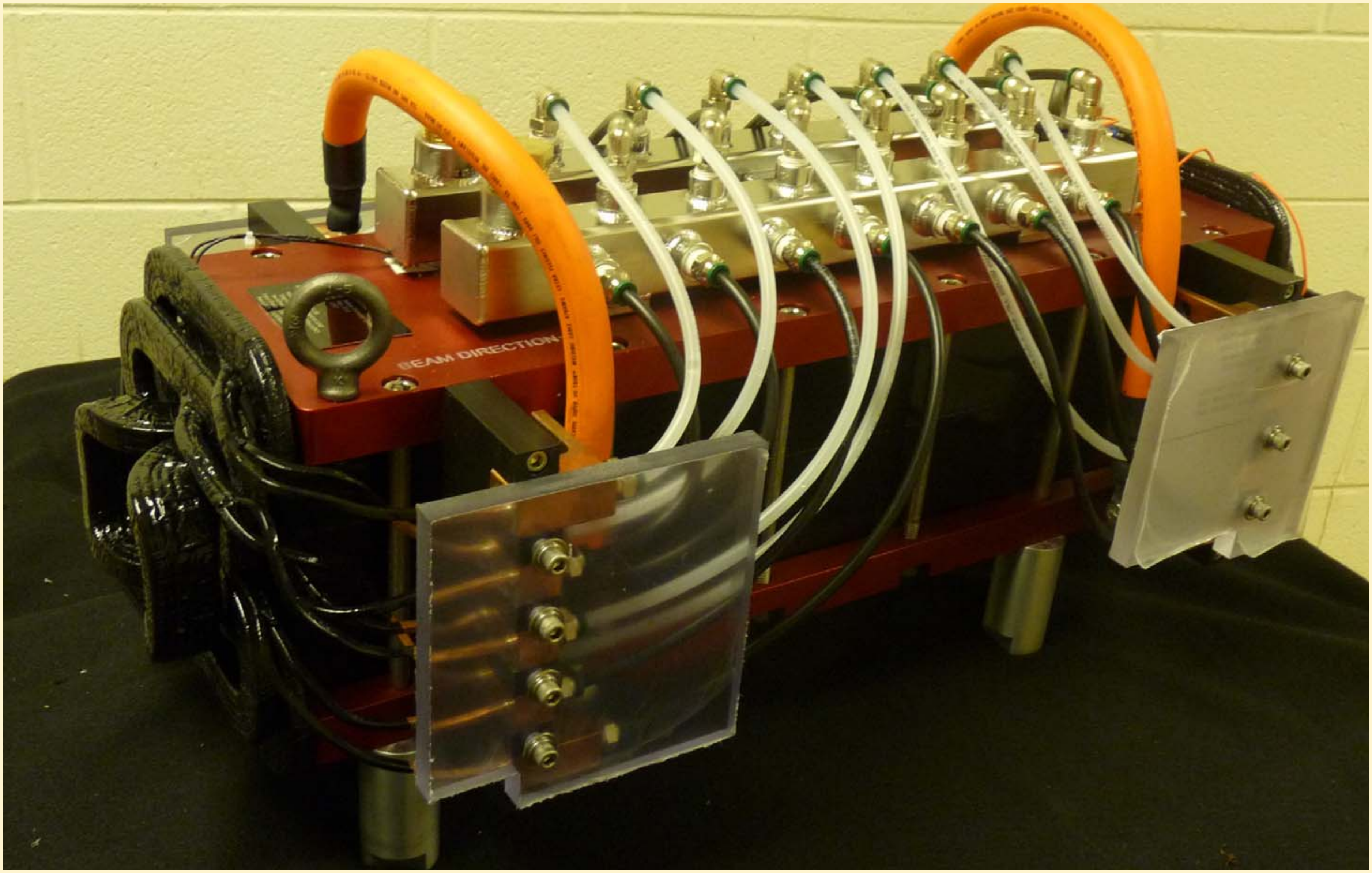




Beryllium Beam Degrader: Shallow fields result in decreased transmission through ES line and Gantry

Beam Spreading



Beam Spreading

Accelerator impact on nozzle design;

Passive Scattering:

- Used for treatment of eyes.
- Only option offered by MEVION today.
- Option is being phased out.

Uniform Beam Scanning:

- Ideal for CW beams using fast scanning magnets.
- Multiple repaints can mitigate for tumor movement.
- Synchrocyclotron pulsed beams may be possible:
  - Use a large spot
  - Scan slowly

Beam Spreading

Accelerator impact on nozzle design;

Pencil Beam Scanning, at least two flavors:

- Spot scanning (spot by spot)
- IMPT or continuous raster scanning or pencil beam scanning

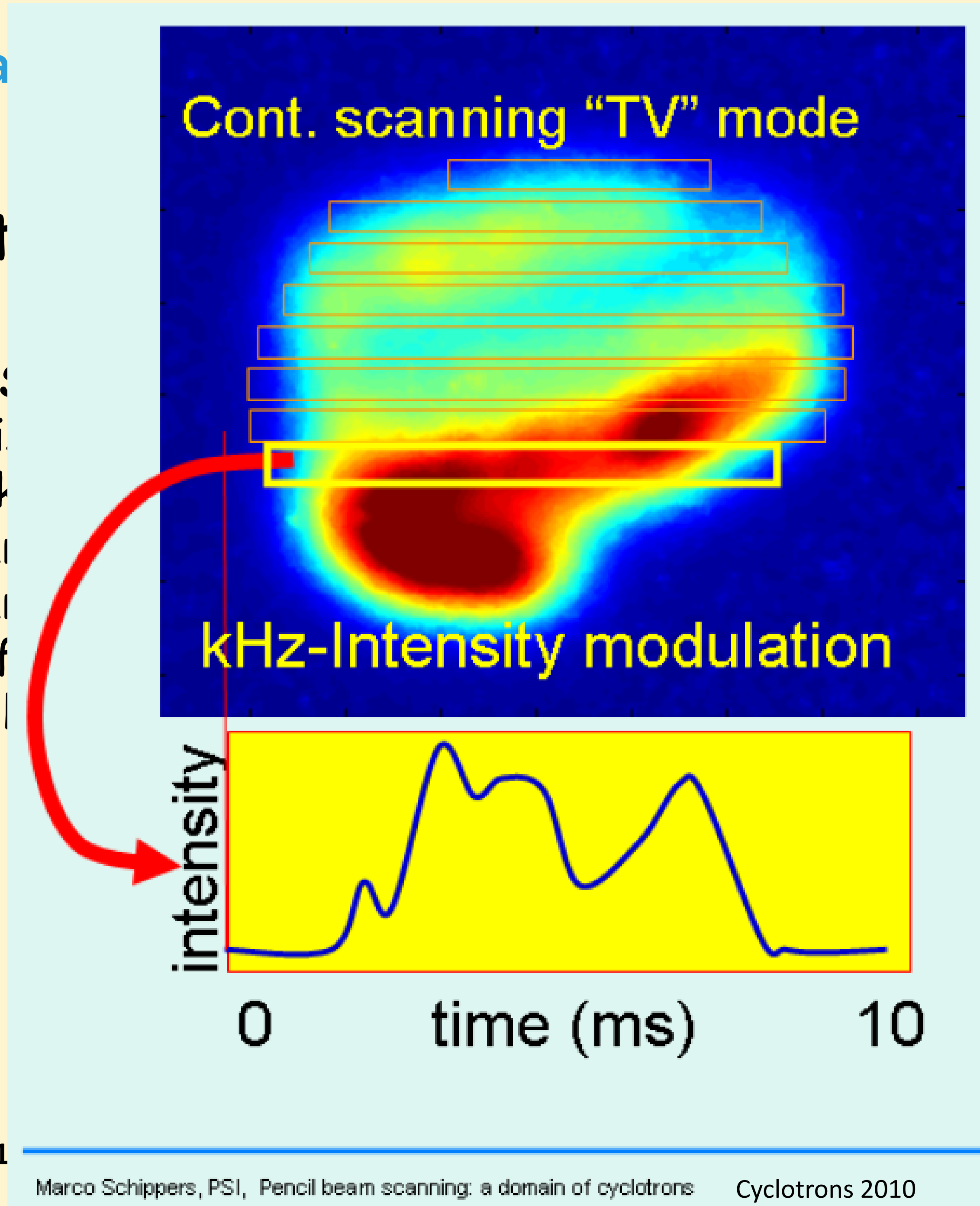
Spot scanning:

- Need precise dose control of beam intensity over a wide dynamic range.
- Each voxel irradiated.
- Ideal for CW machines with precise intensity control.
- Pulsed beams can be used with diligence.
- Tx times improved with rapid energy stepping, $<$ 0.5 sec/5mm

Accelerat

Pencil Beam S

- Beam i
- Need k
  - Va
  - Va
- Ideal f control.
- Multipl g, < 0.1 sec/5mm



Dose Measurement

Acc

Dose

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Typic

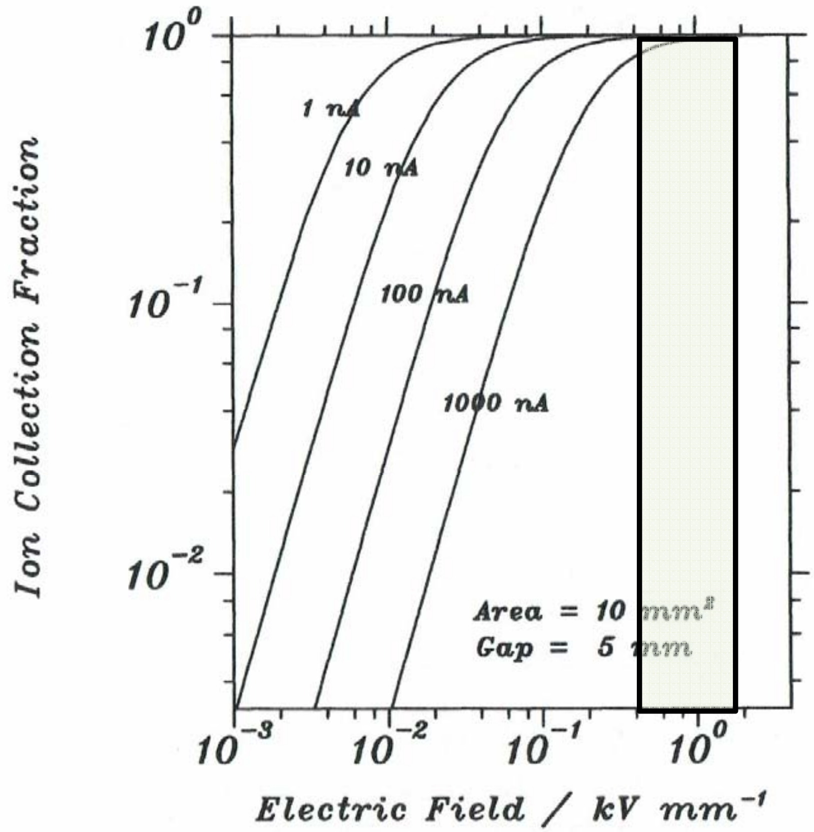


Fig. 6.4. Fraction of ions collected in air *versus* collection electric field for several proton currents calculated from Boag's theory (Boag, 1966).

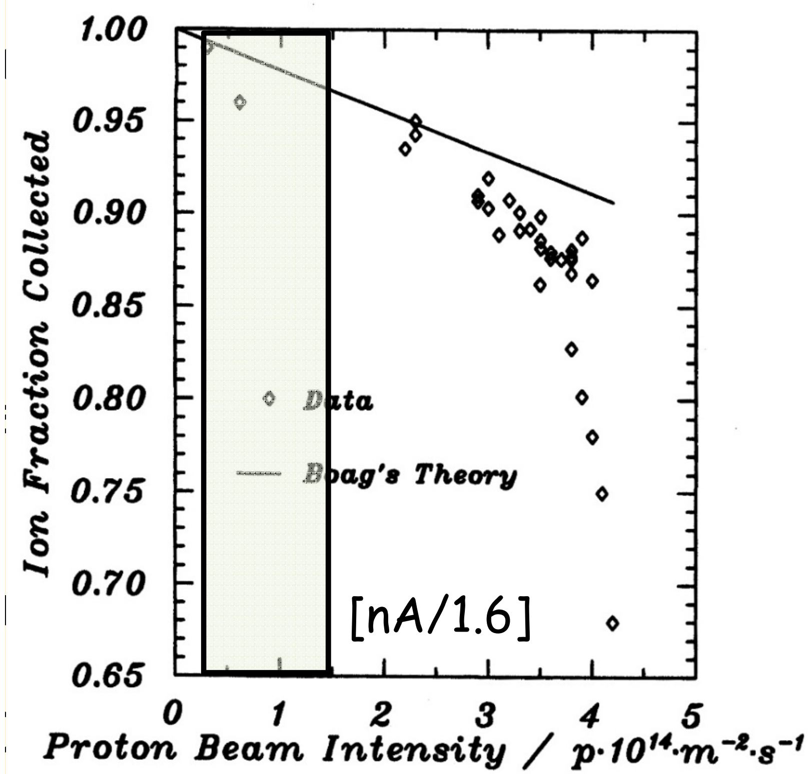


Fig. 6.5. Fraction of ions collected in air *versus* proton fluence rate in a pulsed proton beam (Cole *et al.*, 1987) and Boag's theory (Boag, 1966) for a proton beam of constant intensity. The measured values are for beam intensities averaged over a one second time interval.

ICRU Report 59 — Typical region of operation

Throughput - Efficiency

Patient Throughput

Improve patient Tx Times;

- Faster dose delivery to treatment volume
- Reduce setup time

Accelerator can impact this by:

- High average beam current (as much as needed).
- Reduced overhead to switch energies.
  - (Rapid < 0.5 s stepping of energies.)
- Reduced overhead to switch rooms.
  - (Individual ES lines and degraders.)

High Beam Intensity: Patient Safety System Example

Proceedings of ICALEPCS2003, Gyeongju, Korea

THE CONCEPT OF THE PROSCAN PATIENT SAFETY SYSTEM

I.Jirousek, A.Coray, G.Dave, T.Korhonen, A.Mezger, E.Pedroni, M.Schippers, PSI, Switzerland

Table 1: The beam intercepting devices, their reaction times and the corresponding dose errors.

Device	Response time	Dose (at 5Gy/s) (0.2 nA)	Dose (500 nA)
Kicker	50 μsec	0.025 cGy	63 cGy
Beam blocker at area entry	60 msec	30 cGy	750 Gy
Ion source	20 μsec	0.01 cGy	25 cGy
HF	20 μsec	0.01 cGy	25 cGy
Beam blocker after kicker	≤ 1 sec	≤ 500 cGy (= 5% Tot.dose)	≤ 13 kGy
Beam blocker at beamline entrance	≤ 1 sec	≤ 500 cGy (= 5% Tot.dose)	≤ 13 kGy

Need FAST beam shut off ~ 10's μs

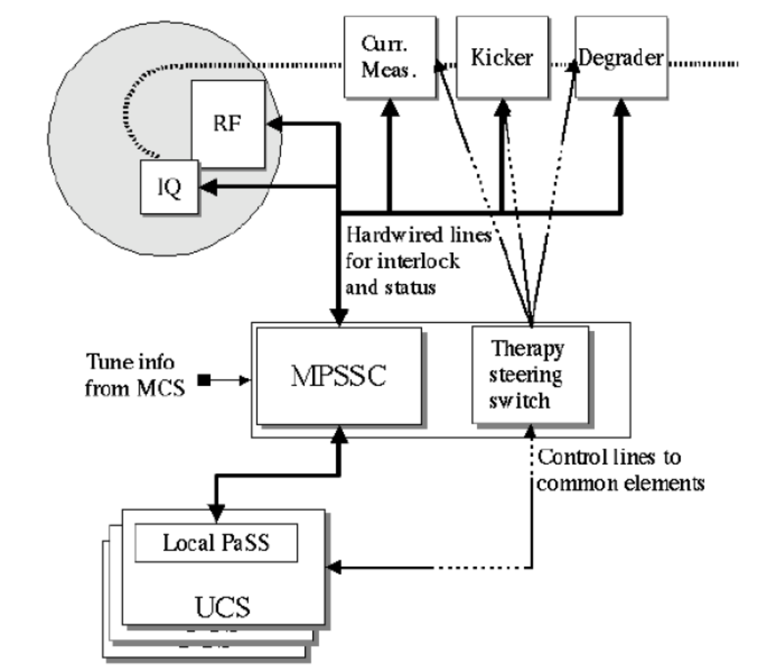


Figure 1: Schematic diagram of Patient Safety System.

Patient Throughput

Why High Beam Current?

Basic Goal: Tx Time with beam < 2 minutes

→ 2 Gy/min over a 1 liter target volume

BUT What about . . .

- Hypofractionation
- Beam Gating
- Large Tumors with Shallow Fields

Patient Throughput

Why High Beam Current?

Very shallow large area Tx's are challenging

Example: 25 x 20 x 4 cm Hodgkins, range 4 cm, 2 Gy/fract.

- 2.0 Liters at a depth of 4 cm. (Note: IU transmission ~ 0.5 % at 4 cm range.)

Tx Time	Tumor Volume	Gating DF	Cyclotron Intensity
2 Minutes	2.0 Liters	0.4	250 nA
1 Minute	2.0 Liters	0.4	500 nA

Indiana University ProNova

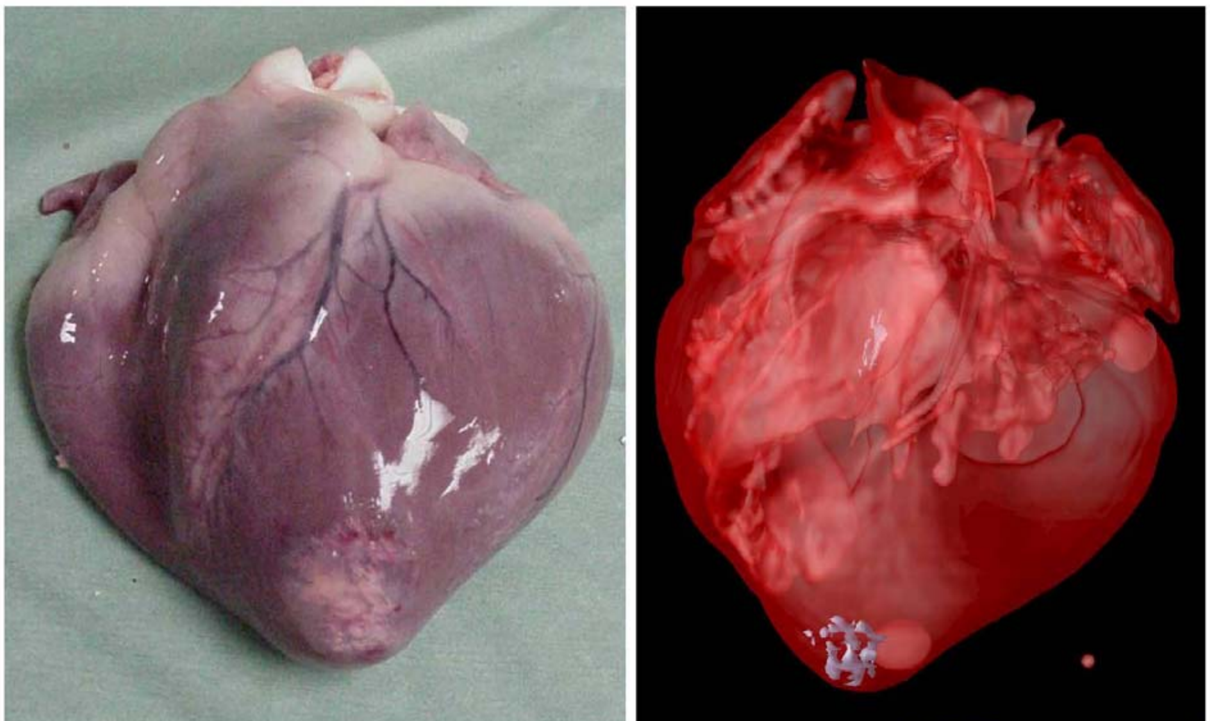
Proton Pig

(S. Klein)

Pulsed Beam Delivery

Synchronized to Breathing & Heartbeat

Dose Delivery Success



Heart

CT Reconstruction

Conclusions

Why use a Cyclotron?

1. Small, compact.
2. Can provide high beam intensities, eg for Hypofractionation.
3. CW beam is an advantage for beam delivery;
    1. Pencil beam scanning,
    2. Fast gating.

BUT . . .

1. Greater maintenance demands.
2. Need an ES line and degrader.

FRM1CIO04 Proceedings of CYCLOTRONS 2010, Lanzhou, China

FAST SCANNING TECHNIQUES FOR CANCER THERAPY WITH HADRONS – A DOMAIN OF CYCLOTRONS

J.M. Schippers, D. Meer, E. Pedroni,
Paul Scherrer Institut, 5234 Villigen, Switzerland

Most of the currently developed new accelerator concepts are based on pulsed accelerators (synchrocyclotron, FFAG, linac based systems, DWA, laser driven systems). In the application proposals these are often considered to be appropriate for spot scanning. However, pulse repetition rate and accuracy of the dose per pulse are important issues to be considered with such machines. Considering that one needs to apply typically 8000 spots in a volume of 1 litre within a reasonable time of the dose delivery, a minimum pulse rate of a few hundred Hz is necessary for a single coverage of the tumour and at least a few kHz are necessary when rescanning is desired. Further, in the proposed systems the dose rate during the dose application in a spot is usually very high. Therefore the event driven approach in which the beam is intercepted when the required dose has been reached, cannot be used. In this case the dose per spot is determined by an intensity pulse from the ion source. The phase (width) of the pulse should match the phase acceptance window of the accelerator. Much attention should be given to the achievable accuracy in the dose per pulse (1%) and whether this dose can be varied at least a factor 20 from pulse to pulse.

Thank You

(Vladimir Anferov)

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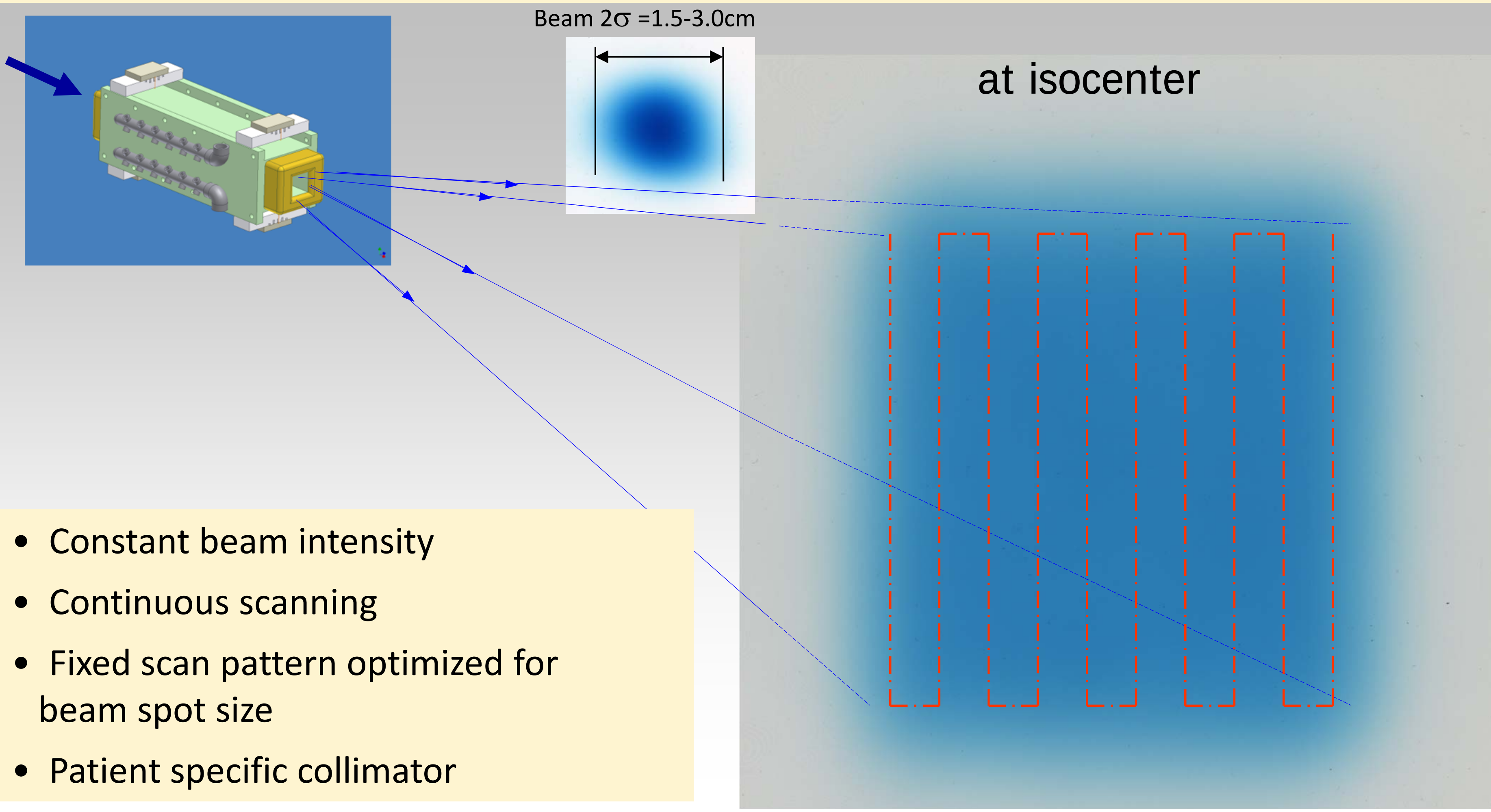
Active beam spreading using wobbling

Wobbling = multiple painting of a treatment area to achieve uniform dose distribution.



- Constant beam intensity
- Continuous scanning
- Fixed scan pattern optimized for beam spot size
- Patient specific collimator