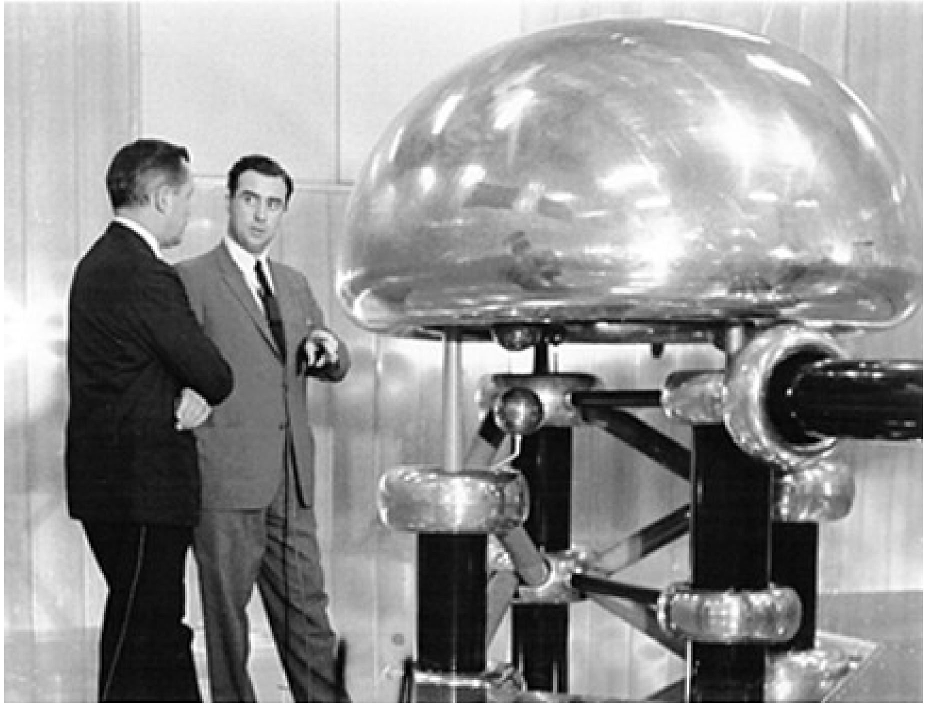
New Accelerator Technologies for Particle Therapy



Niels Bassler
Department of Physics and Astronomy
Aarhus University, Denmark

Sevilla,ES,
14th December 2009

AARHUS PARTICLE THERAPY GROUP

Outline

- Requirements for particle therapy
- Current available accelerator concepts
- New accelerator concepts:
  - FFAG
  - Downscale existing technology
  - Dielectric wall acceleration
  - Wake field acceleration

Particle Therapy: Requirements

Example:

- Protons and carbon ions
- Maximum range: 33 cm
- Field size: 30x30 cm
- Scanning beam
- 2 Gy fraction in less than 1 minute
- Energy change in less than 2 seconds
- proton gantry and a horizontal line for C-12

Translation of Requirements:

The accelerator physicist:

- Two ion sources...
- Max energy 250-270 MeV for protons 400 MeV/u for C-12
- Scanning magnets

  Which scanning system, what FWHM of beam?
- I beam = xxx nA

- Adaption of range:
  - Synchrotron : per acc. cycle
  - Cyclotron : range shifter

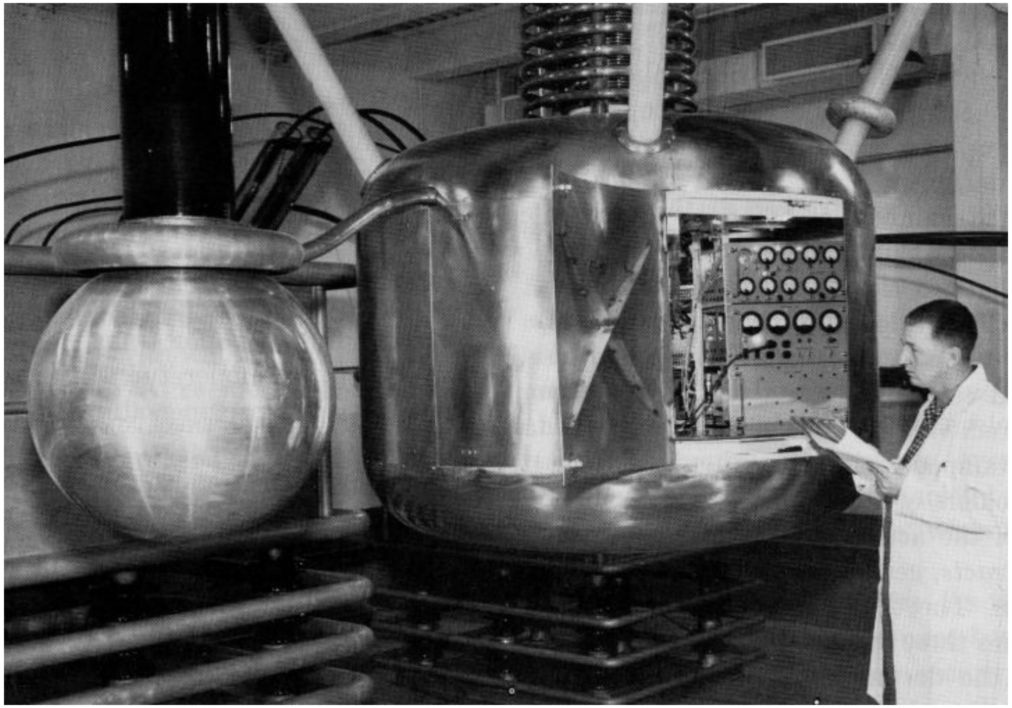
Additional Operation Requirements

- Accurate beam positioning
- Stable beam intensity
- Safety (e.g. spill abortion system)

..and some additional Options:

- Sync patient motion with beam?
- Fast switching between ion species?
- PET monitoring?

General requirements



- 1000 patients/yr (throughput)
- Reliability
- Easy to operate

- Certified for patient treatment

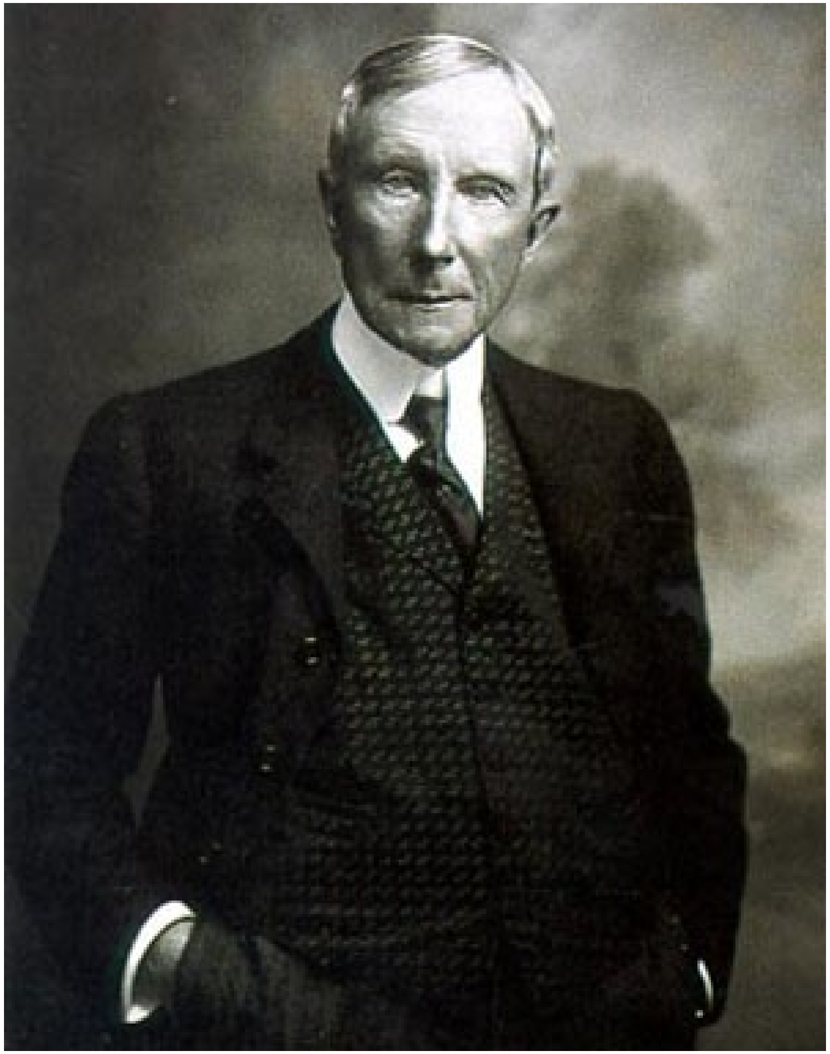
AARHUS PARTICLE THERAPY GROUP

Financial issues

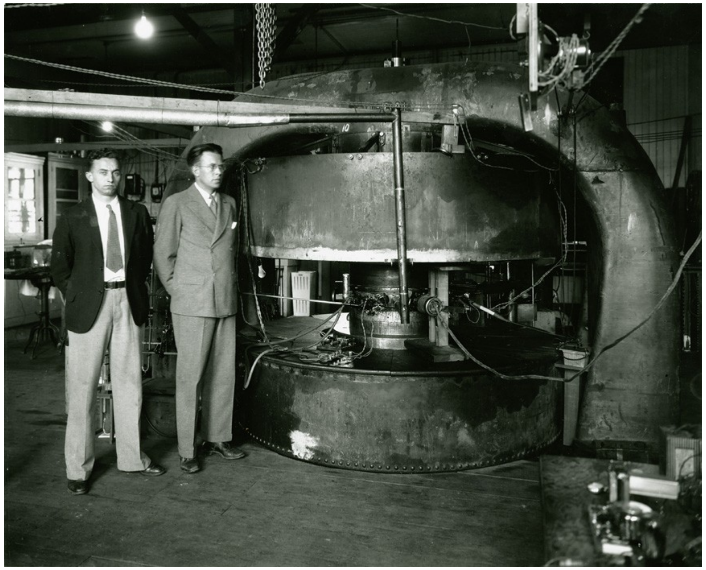
- Price of accelerator facility: say, 100 M€
  - 1/3 concrete
  - 1/3 accelerator
  - 1/3 diagnostics

- Compact layout: *Smaller is cheaper*
- *But it may be limited what actually is being saved...*

  "...less than 20 % if new accelerator concept is developed." (!?)



Current available concepts



CYCLOTRONS
- Isochronous cyclotron (dB/dr != 0)
- Synchrocyclotron (df/dt != 0)

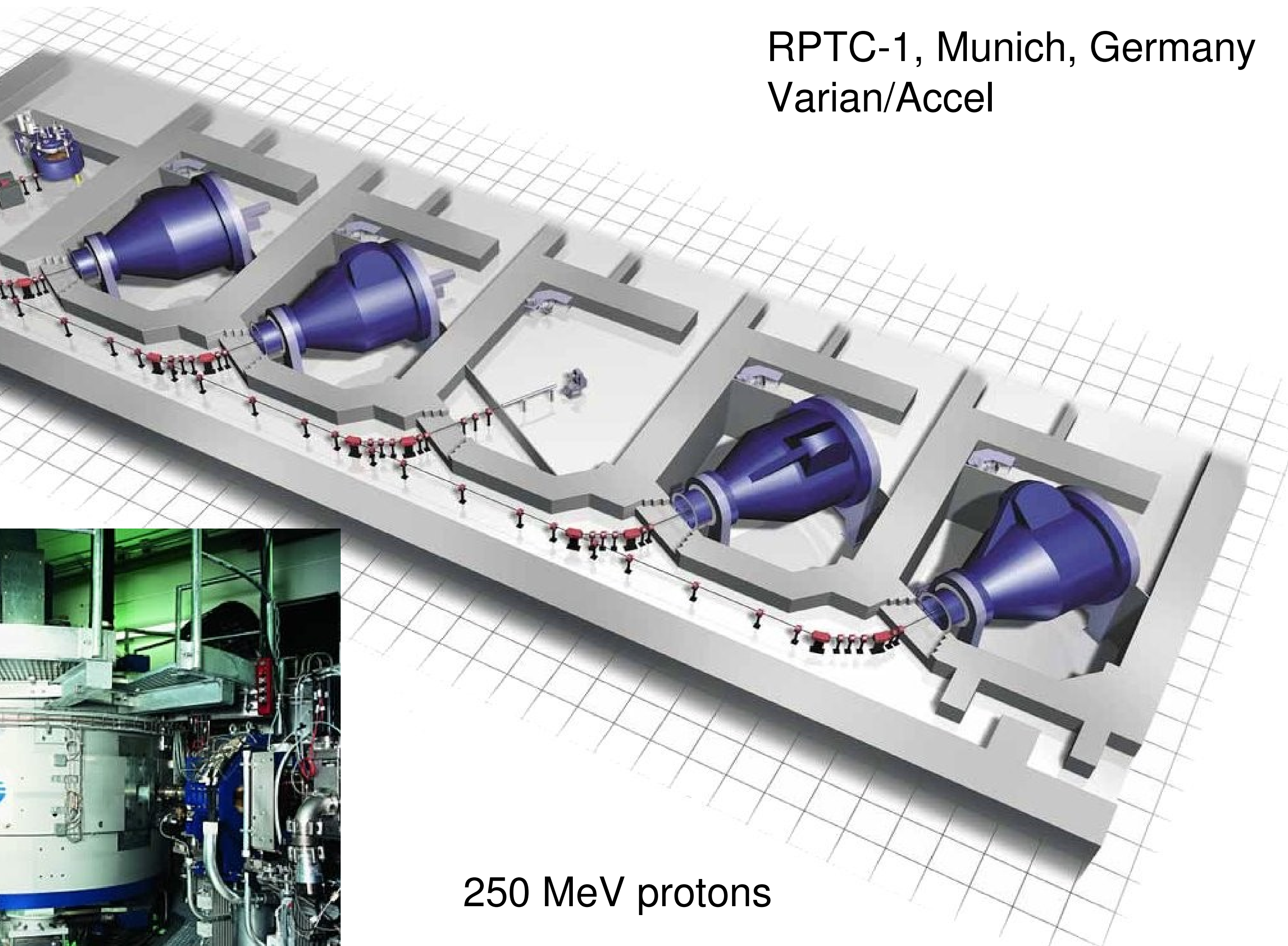
SYNCHROTRONS
- Strong focusing
- Weak focusing
- Rapid cyling

FFAG

NEW TECHNOLOGIES
- Wakefield acceleration
- Dielectric wall

Typical Proton Cyclotron Facility

RPTC-1, Munich, Germany
Varian/Accel

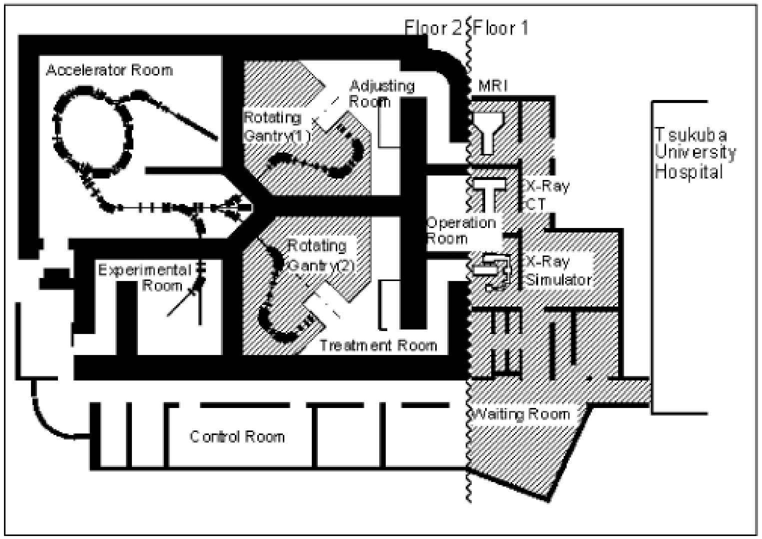


250 MeV protons

Typical Proton Synchrotron Facility

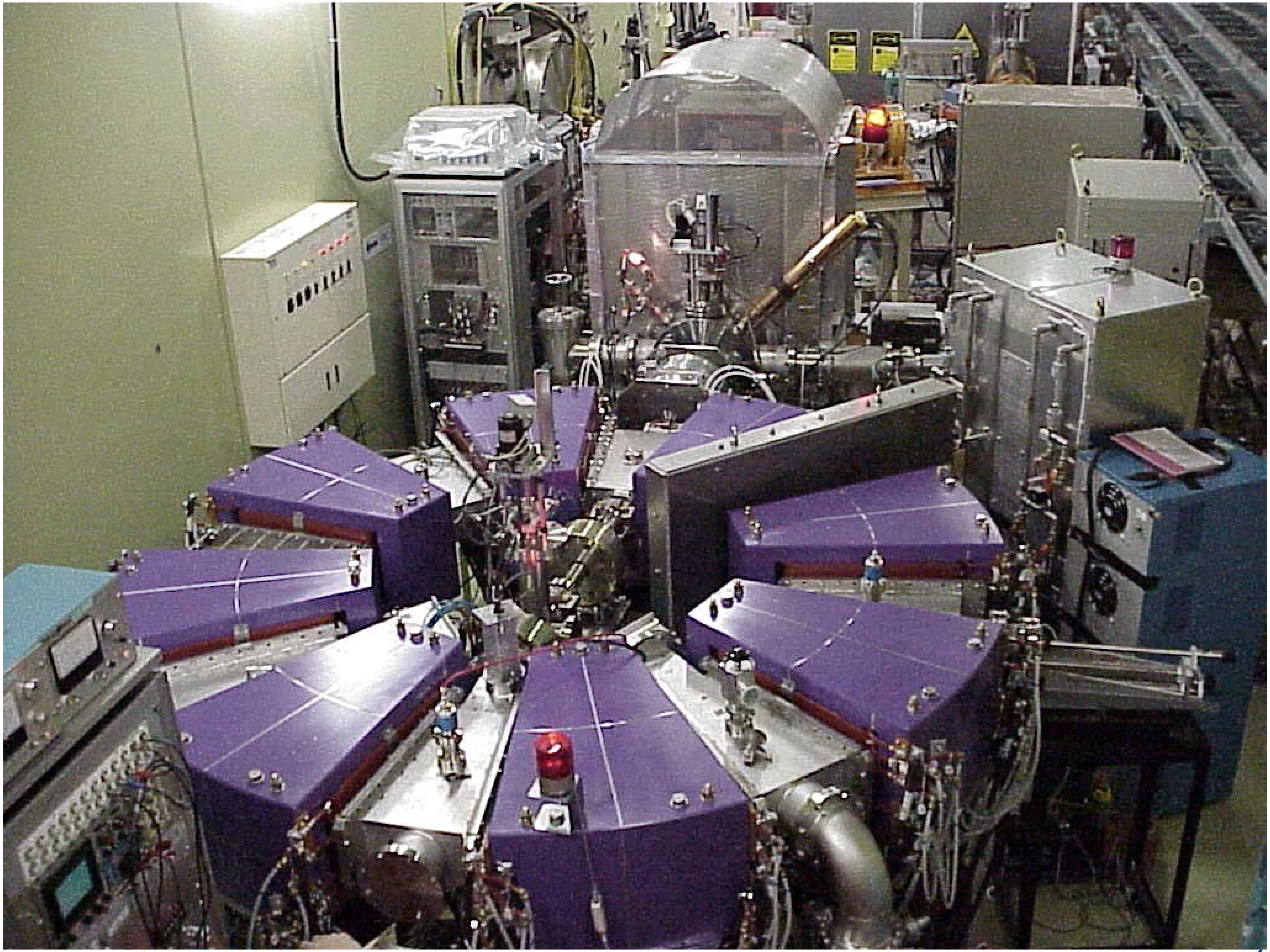
PMRC, Tsukuba, Japan
(Hitachi)

- 250 MeV
- 23.3 m circumference
- 0.5 Hz, 7 nA -> 2 Gy/min



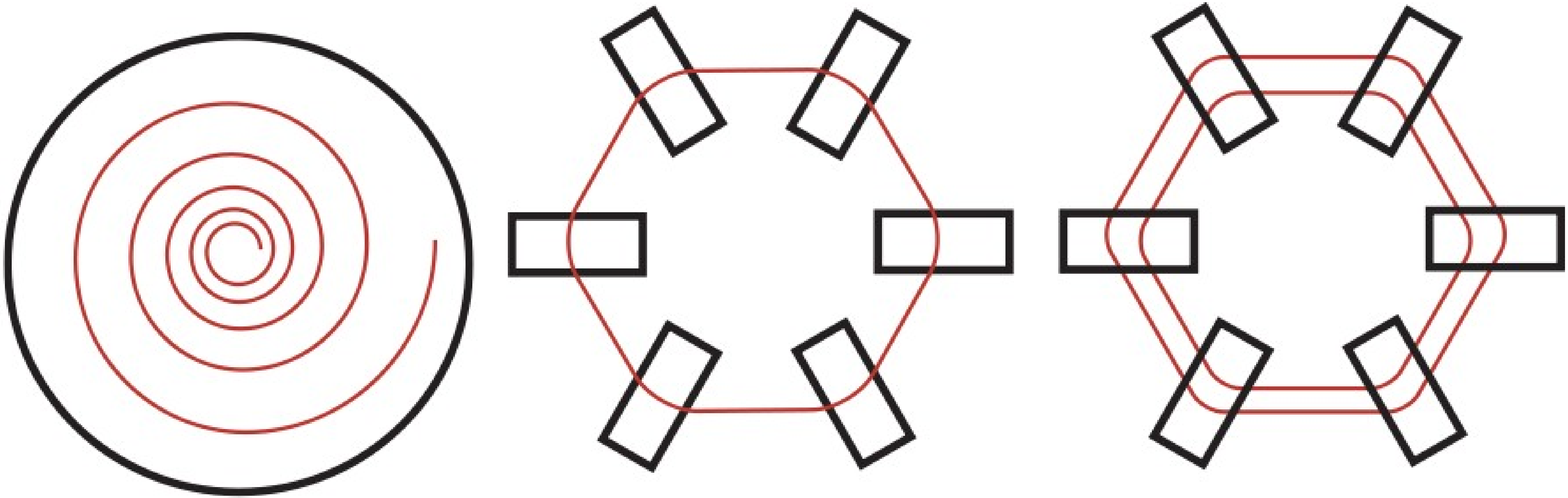
Layout of the proton therapy facility

Fixed-Field Alternating-Gradient (FFAG)



Cyclotron/Synchrotron/FFAG

Yoshiharu Mori, KEK.



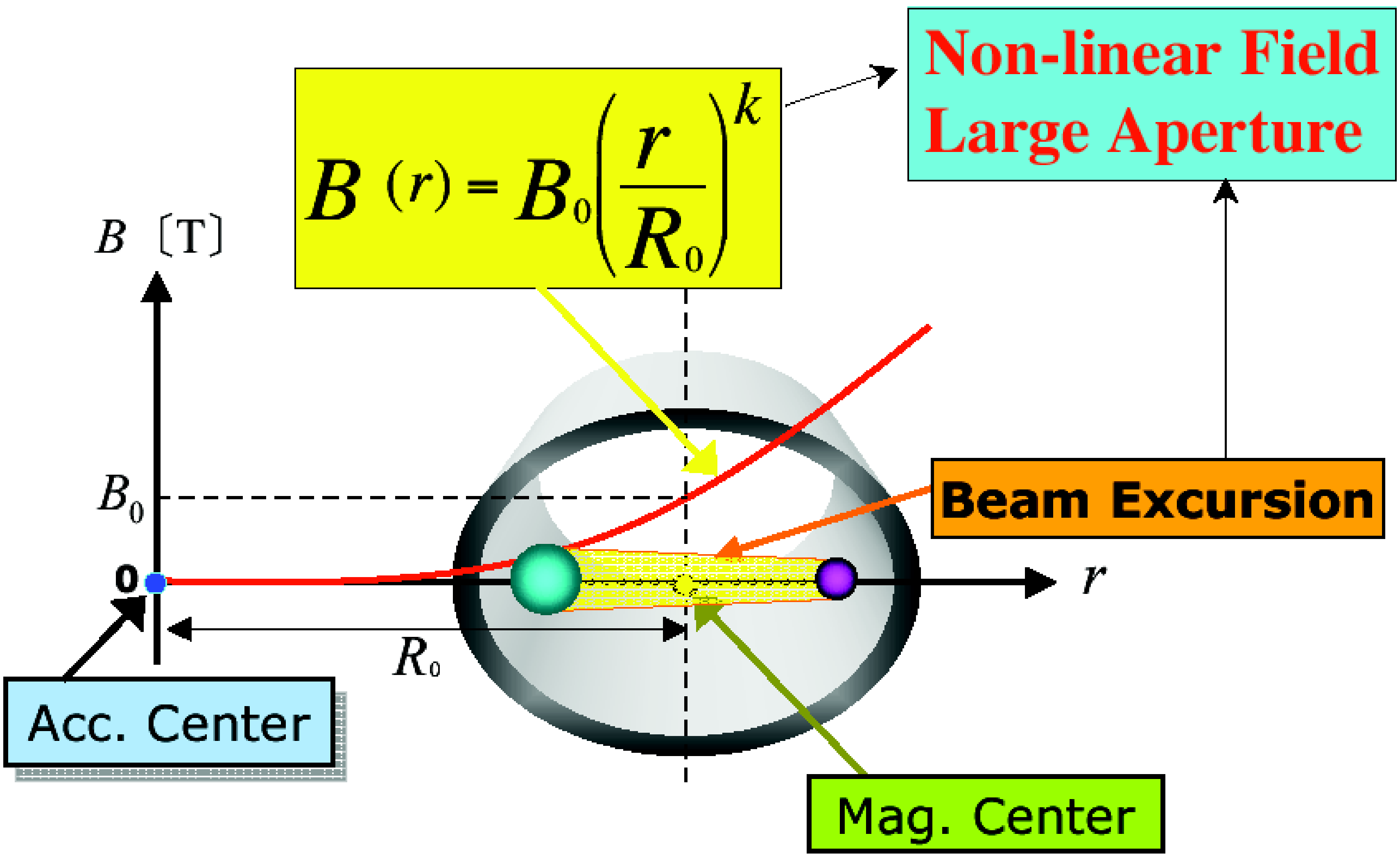
CYCLOTRON
- Isochronous cyclotron

  dr/dt > 0
  df/dt = 0 *(not sync.cycl)*
  dB/dt = 0
  dB/dr > 0

SYNCHROTRON
- Fixed closed orbit
  dr/dt = 0
  df/dt > 0
  dB/dt > 0

FFAG
- Var. closed orbit
  dr/dt > 0
  df/dt > 0
  dB/dt = 0
  dB/dr > 0

Scaling FFAG Bending Magnet

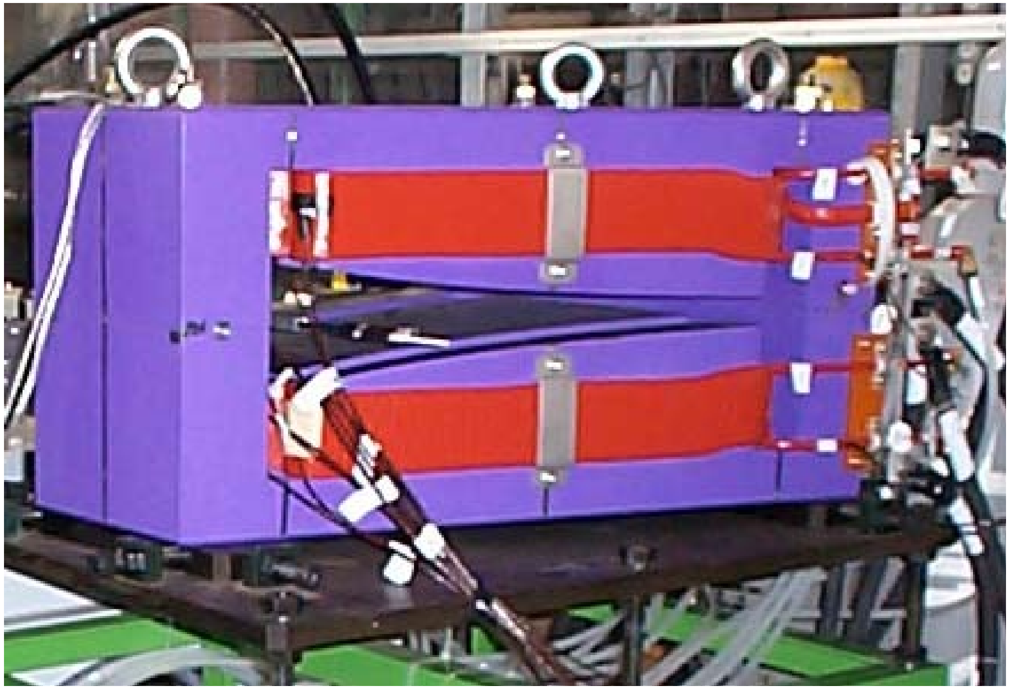


Disadvantage for high proton/carbon energies. Fix: “Non-scaling FFAG”.

Yoshiharu Mori, KEK.

FFAG Bending Magnet

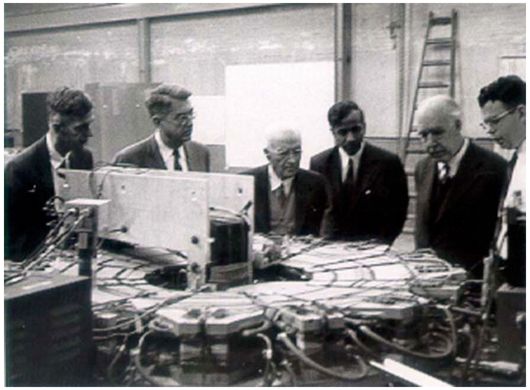
- Synchrotron: fixed orbit, varying B-field
- Cyclotron: dB/dt = 0 (dB/dr is 0 for the synchrocyclotron), varying orbit
- FFAG: fixed B-field, like cyclotron, orbit increases with Energy, but is closed.

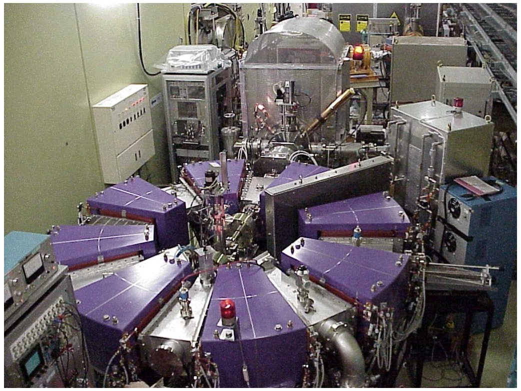


Yoshiharu Mori, KEK.

History and Current Status of FFAGs

- First electron FFAG 1953 (MURA)
  - 400 keV electrons
- Long break, due to lack of technology:
  - New RF cavity: (no ferrite)
    250 Hz with 1.5-4.6 MHz sweeps
  - Magnet design:
    3D design F/D magnets,
    zero chromacity
- First proton FFAG 2000 (KEK)
  - 500 keV protons
- Non-scaling FFAG
  - Breaks $B(r)=B(r/R_o)^k$
- Proton/carbon ion therapy FFAG is under construction: PAMELA http://www.conform.ac.uk



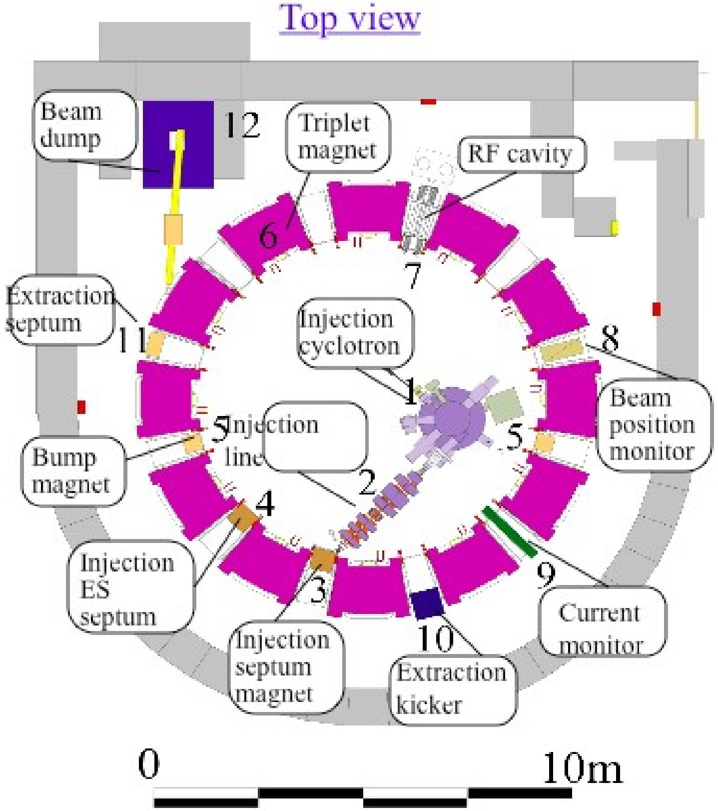


C. Ohkawa and Y. Mori

150 MeV Proton Scaling-FFAG

150MeV Proton FFAG

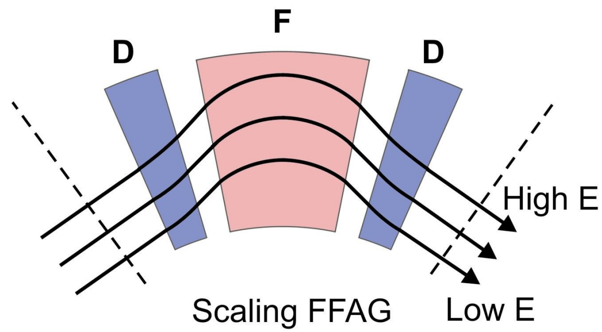
Top view



Design parameter

Magnet	radial sector type (DFD triplet)
Num. of cell	12
k-value	7.6
Ek	12 => 150MeV (10 => 125MeV)
Av. radius	4.47 => 5.20m
betatron tune	hor. : 3.69 ~ 3.80 ver. : 1.14 ~ 1.30
Peak Field (@beam orbit)	F-mag. : 1.63T D-mag. : 0.78T
revolution	1.55 ~ 4.56MHz
repetition	250Hz

27th Mar, 2005 / 日本物理学会 @ 東京理科大学 5



Focusing using alternating gradients.

Yoshiharu Mori, KEK.

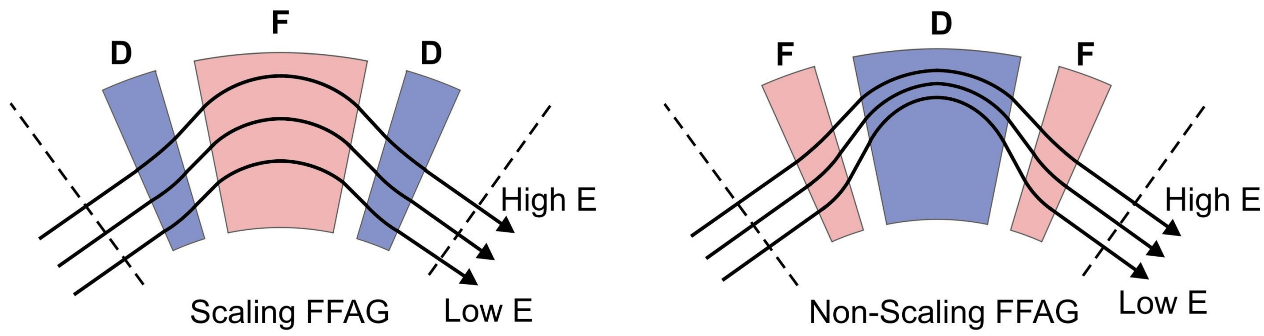
Proton FFAG Accelerator

2006 @ KEK, Tsukuba, Japan.

- Cyclotron for injection
- 150 MeV
- 100 Hz
- 90 % Extraction efficiency

Yoshiharu Mori, KEK.

Non-scaling FFAG for Particle Therapy

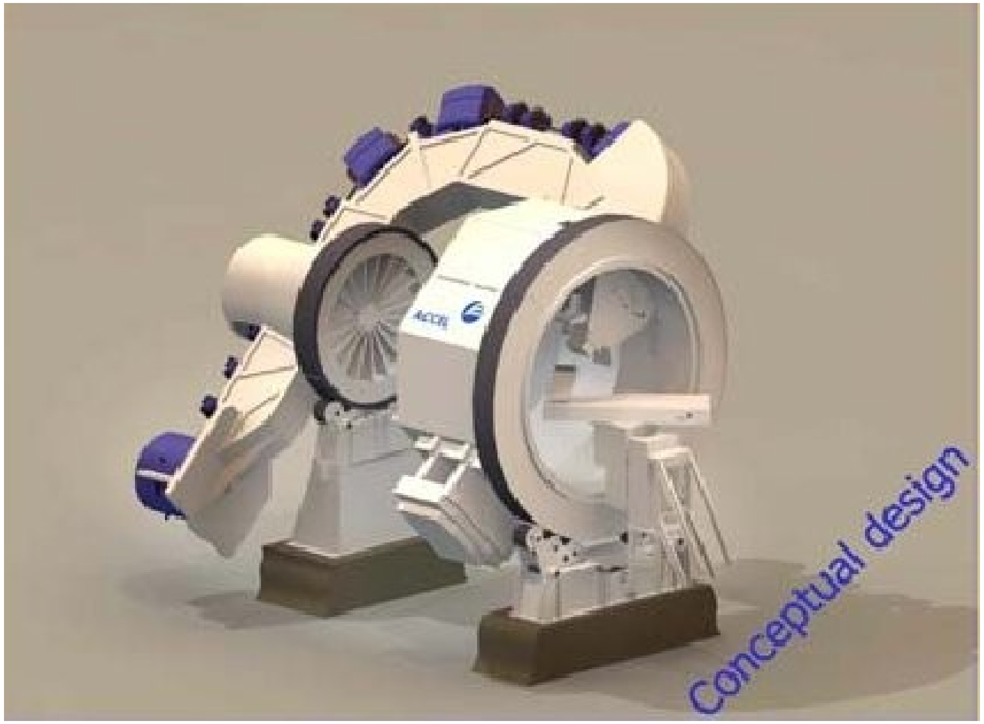


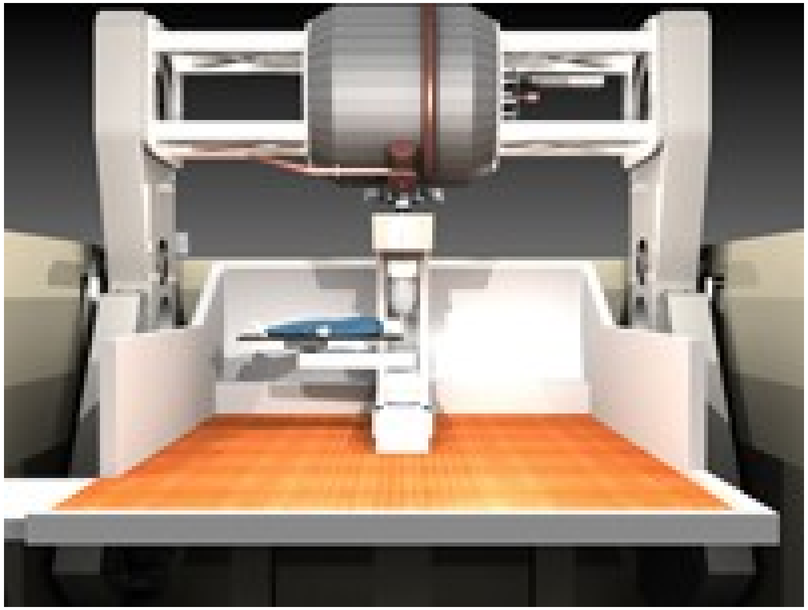
- Non-scaling FFAG
  - Breaks $B(r)=B(r/R_o)^k$
- Fast cycling: perhaps up to 1 kHz ---> high currents
- Fixed magnetic field: eases operation, similar to cyclotron.
- FFAGs can also accelerate heavier ions
- Variable beam energy extraction (cyclotron are monoenergetic)
- Compact ring, easy accessible -> easy maintenance.
- Multiple extraction points possible
- High efficiency -> low activation of structure
- ***Not cheaper/smaller but faster and stronger***

Downscale existing technology

Reducing size of **CYCLOTRON** based facilities

Reducing Size of Cyclotron Based Facilities





Varian

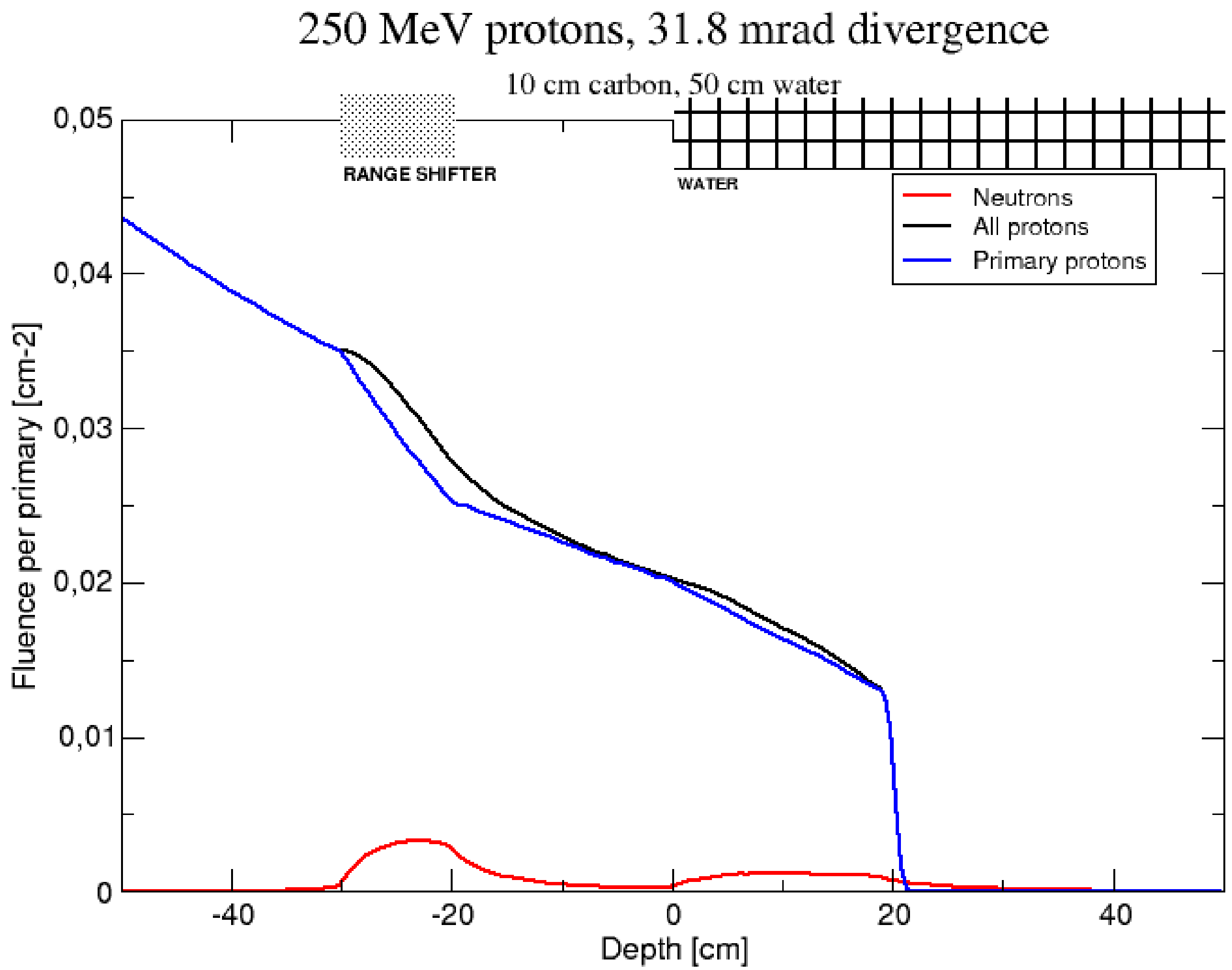
StillRiver

- Superconducting cyclotron itself cannot be made much smaller than 1-2 meters Ø
- Entire facility is tried to be scaled down via innovative gantry designs.

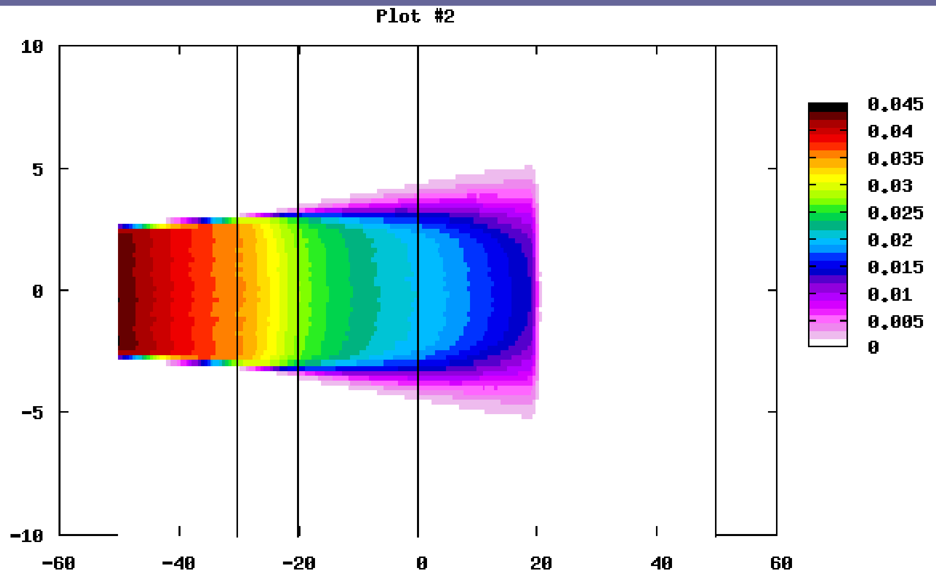
StillRiver

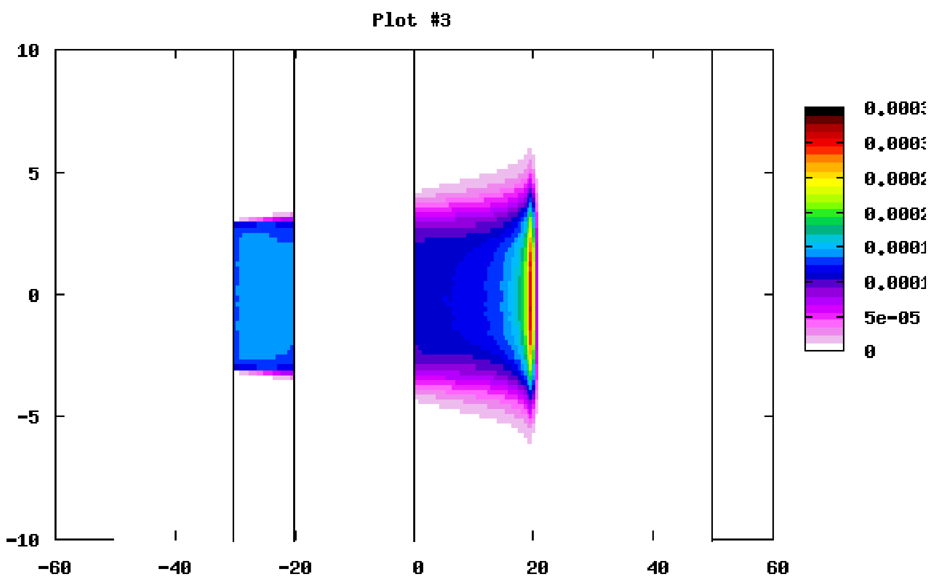

MONARCH250
COMPACT PROTON THERAPY
Has not received FDA 510k clearance
Still River
SYSTEMS

Secondary neutrons?



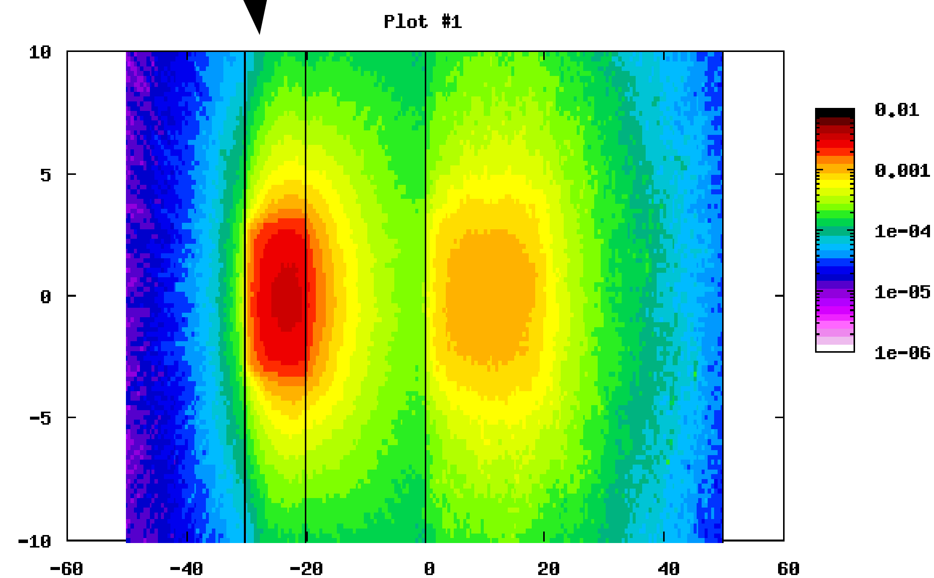
Secondary neutrons?





Carbon range shifter

Neutron fluence map



Water target

Reducing size of **SYNCHROTRON** based facilities

Decrease size, Russian way

Reducing size of synchrotrons?

- Russian technology
- Bought by “ProTom”
- Small, simple, inexpensive

- But is it really small?

Loma Linda, Ca.

Decrease size, Russian way

Table-top synchrotron, BINP, Novosibirsk

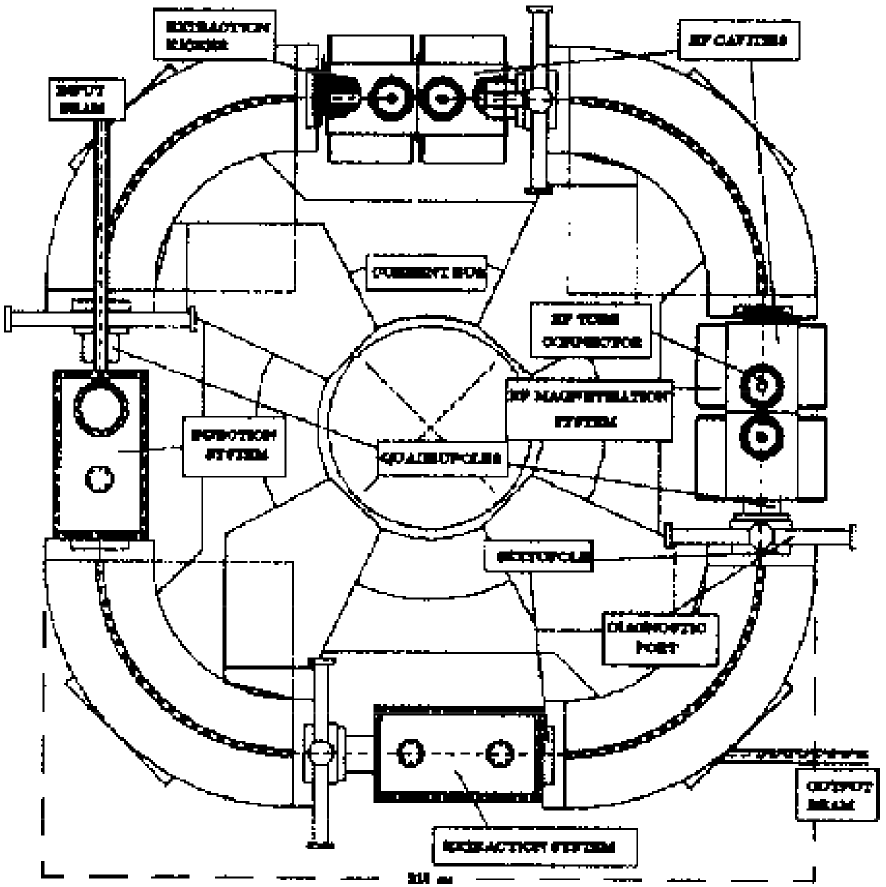


Fig. 1 - Schematic design of the proton synchrotron

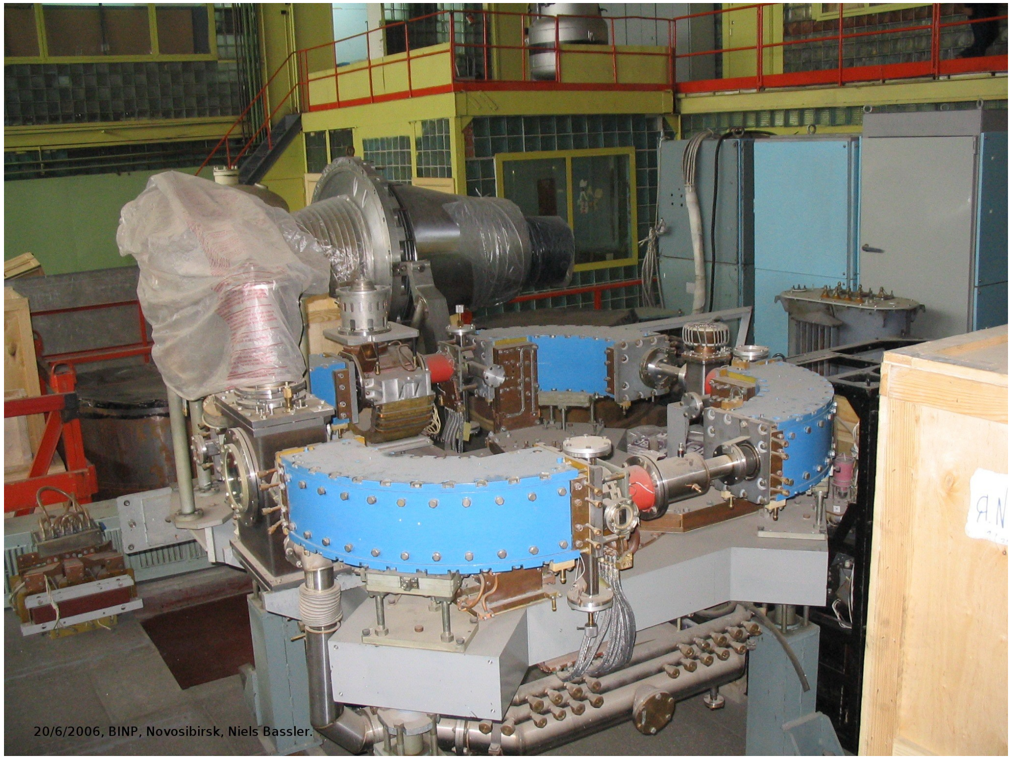
- Down-scale all known components to technical limits
- 1.6 m x 1.6 m

Table-top synchrotron, BINP, Novosibirsk

- Circumference = 6.4 meter
- E_max = 200 MeV
- Injection at 12 MeV
- RF 7.42 - 26.5 Mhz
- Sweep 3.5 msec
- B = 4 T, iron free magnets

Status

- Many-turn injection was shown
- Beam stored 2 orders magnitude lower than projected
- No RF
- No extraction
- 1 MW cooling at 10 Hz?
- ***Project abandoned***



(Thanks to Vladimir A. Vostrikov, BINP)

Decrease size, Russian way

Table-top synchrotron, BINP, Novosibirsk

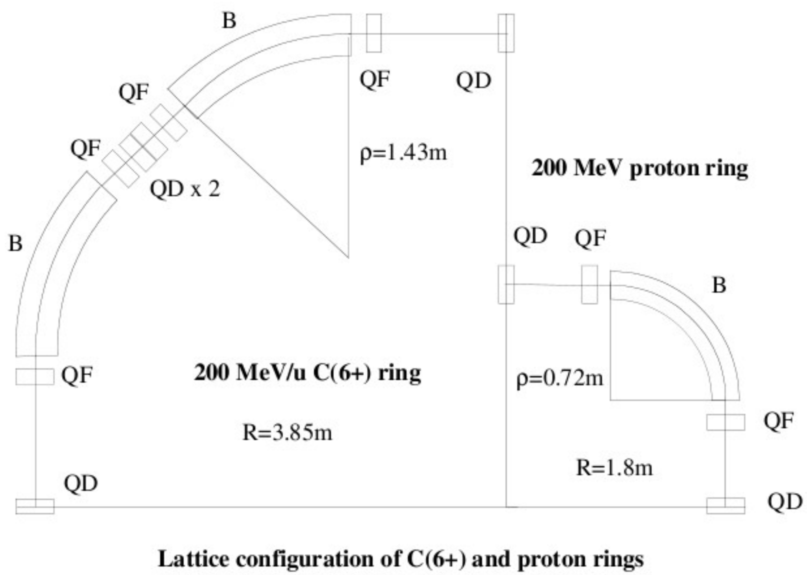


Figure 1: Magnet configuration for a superperiod of the proton (right half) and carbon ion ring (left half).

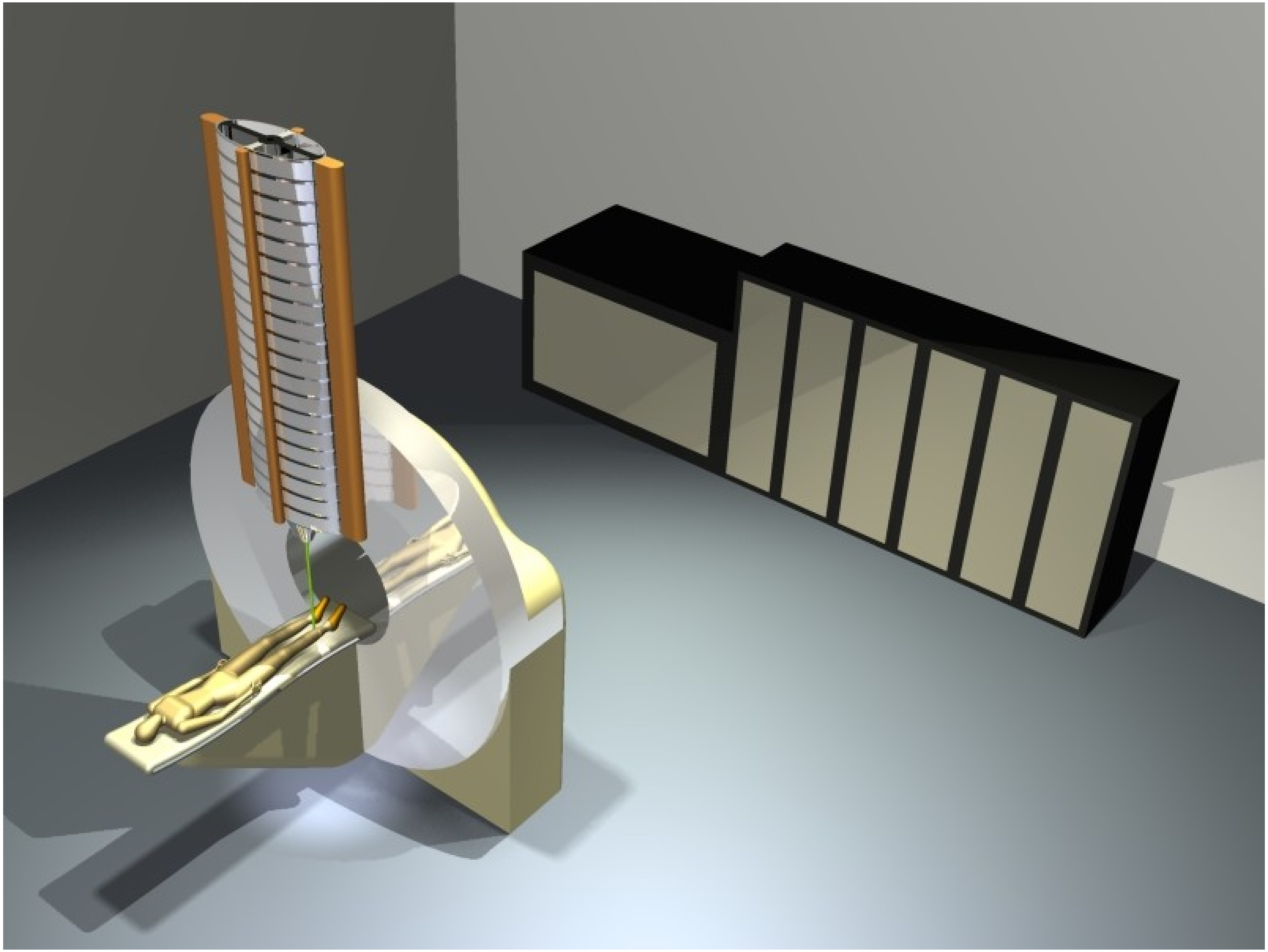
- Project restarted with more "realistic" parameters, with Japanese group KEK/NIRS
  - Emax = 200 MeV
  - Einj = 2 MeV
  - <10 Hz repetition
  - RF 1.7 – 15.0 Mhz
  - 11.3 m circumference
- Carbon version
  - Emax 200 MeV/u
  - < 10 Hz repetition
  - 24.2 m curcumference
- ***Abandoned for unknown reasons after ~ 1 year.***

AARHUS PARTICLE THERAPY GROUP

Dielectric Wall Accelerator

Dielectric Wall Accelerator (DWA)

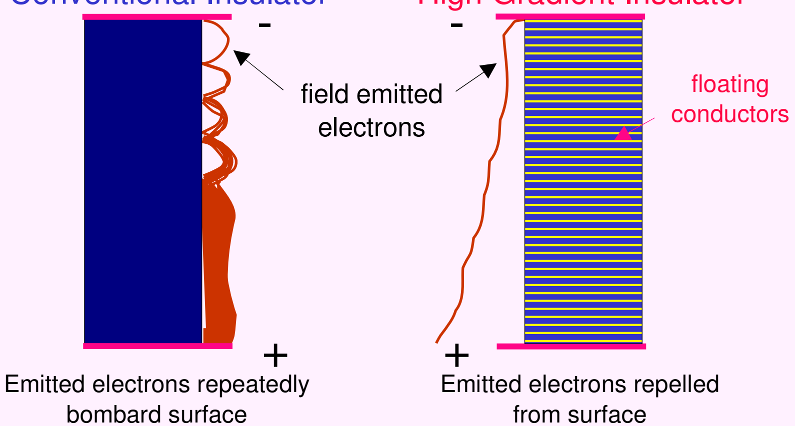
“*Proton acceleration at the fifth at the cost, and the size of a X-ray machine*”



Proton ThomoTherapy.

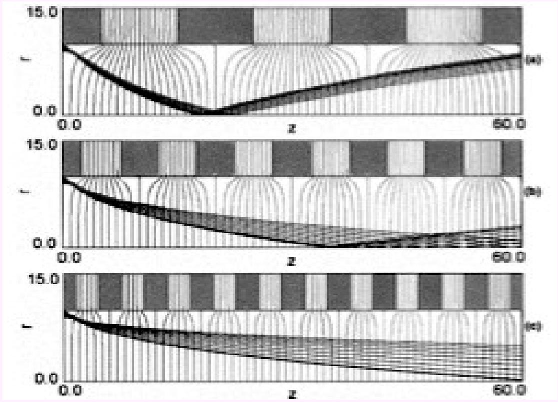
High Gradient Insulator (HGI)

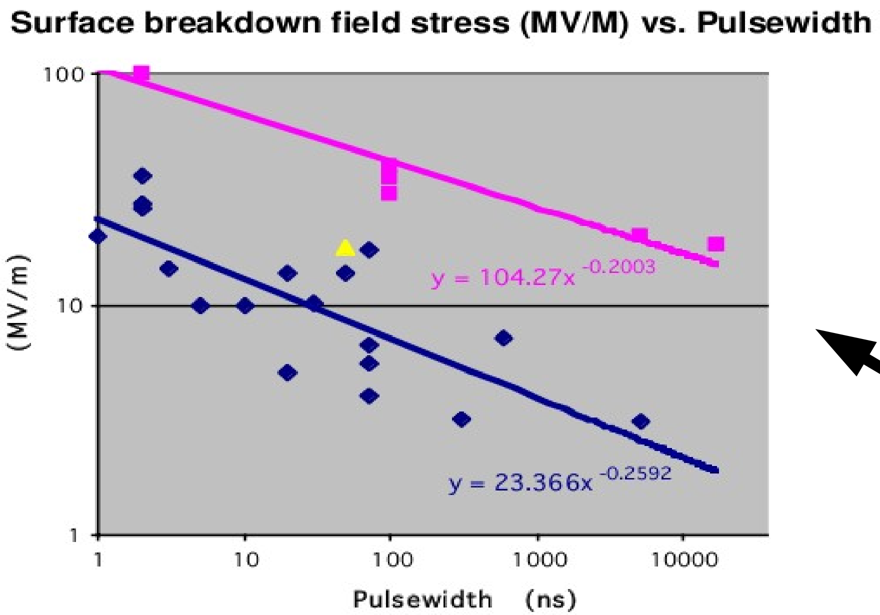
Closely spaced conductors inhibit the breakdown process



HGI structure forms a periodic electrostatic focusing system for low energy electrons

Leopold, et. al., IEEE Trans. Diel. and Elec. Ins. 12, (3) pg. 530 (2005)



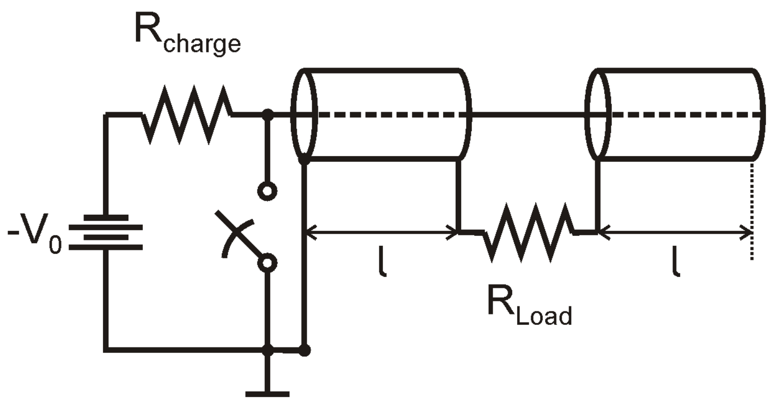


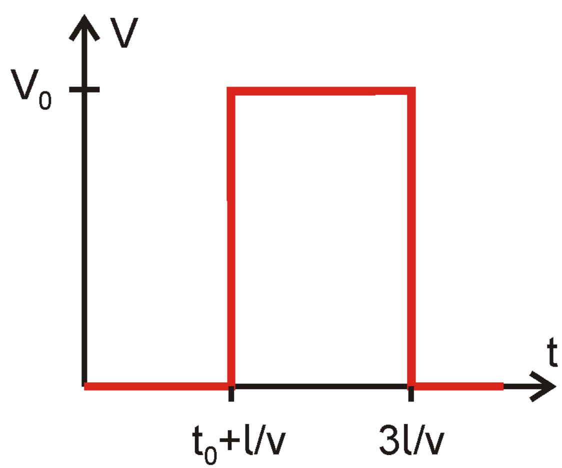
(Yu-Jiuan Chen , LLNL)

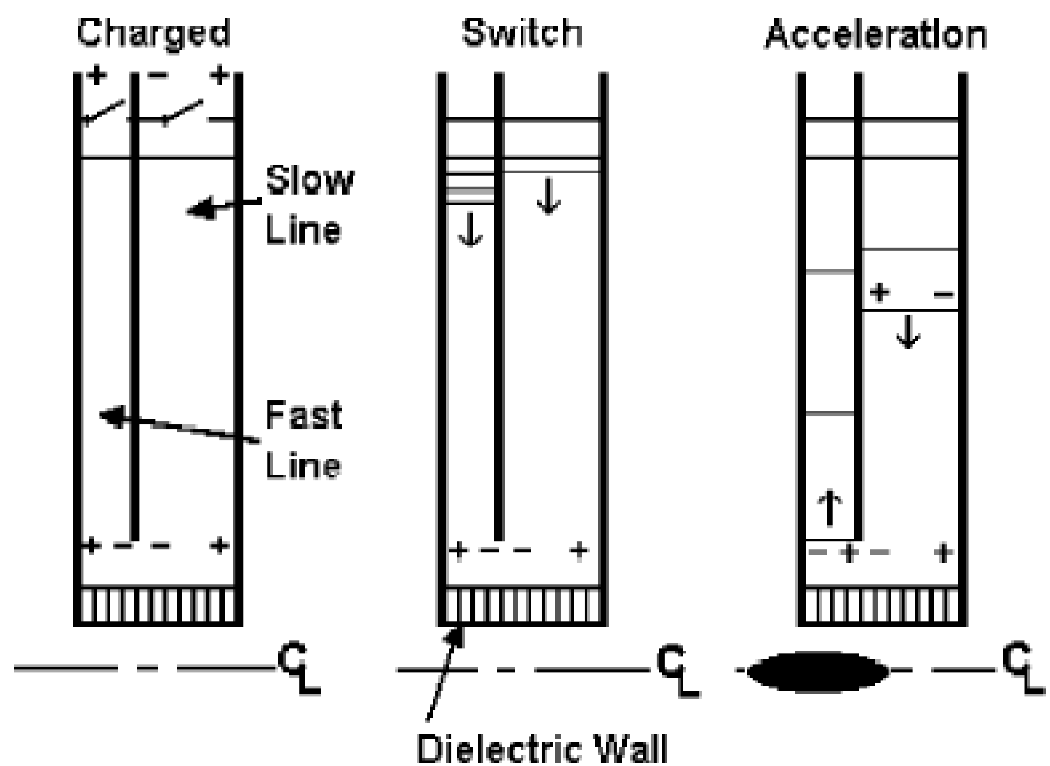
HGI: sandwich layered structure, layers are less than mm thick

Achieved 100 MV/meter

Blumlein Pulse Generator



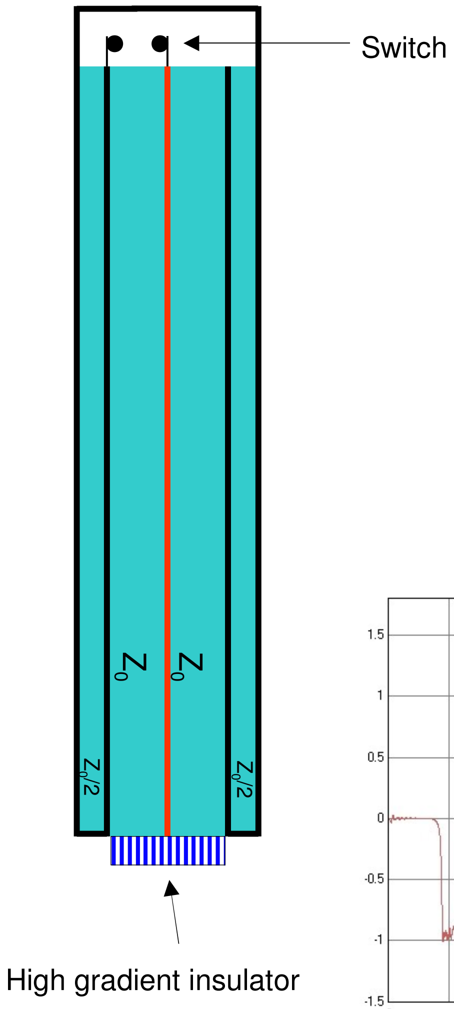


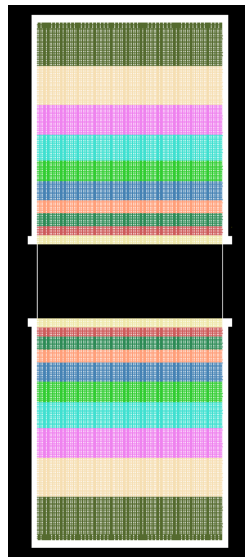


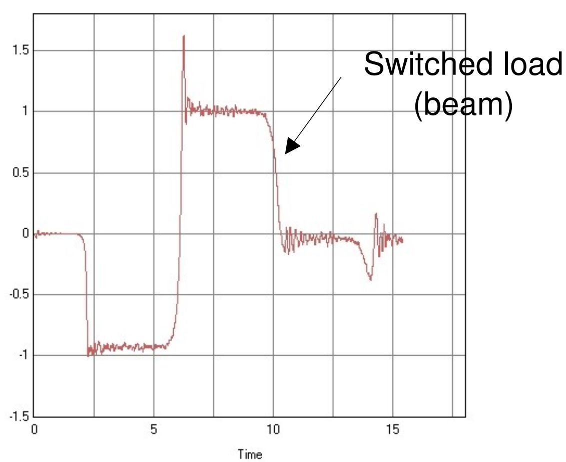
Sampayan et al.

http://pulsedpower.eu

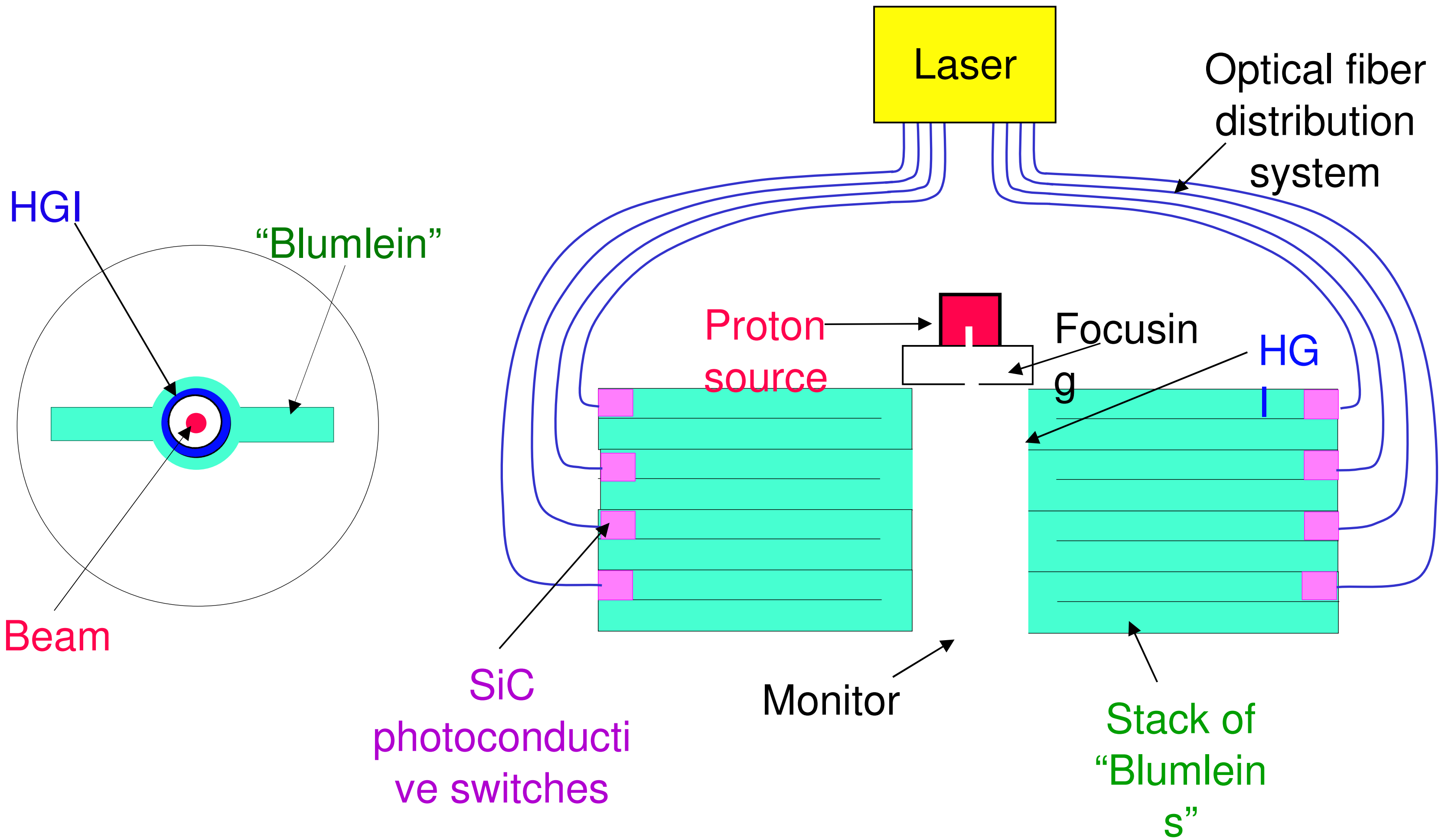
Blumlein Pulse Generator





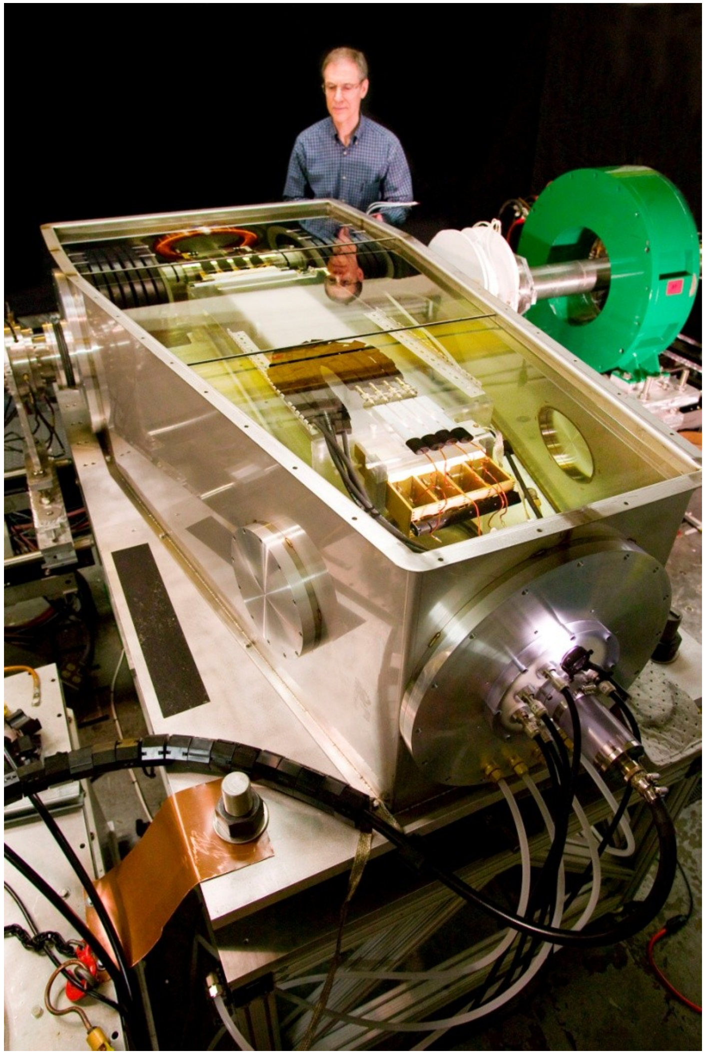


(Yu-Jiuan Chen , LLNL)



(Yu-Jiuan Chen , LLNL)

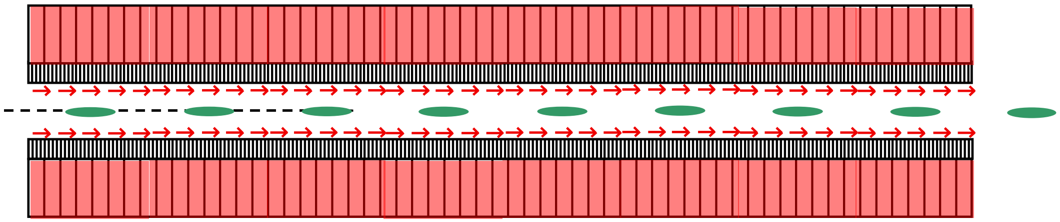
- Flash X-ray radiography

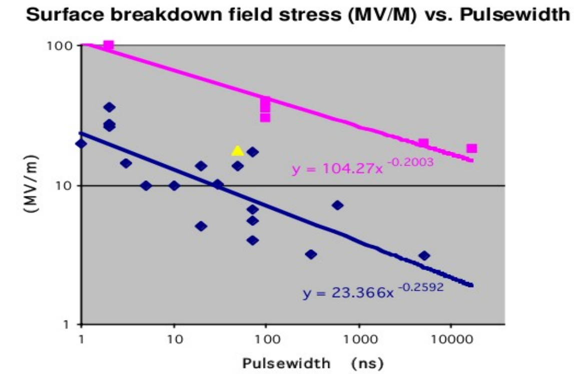


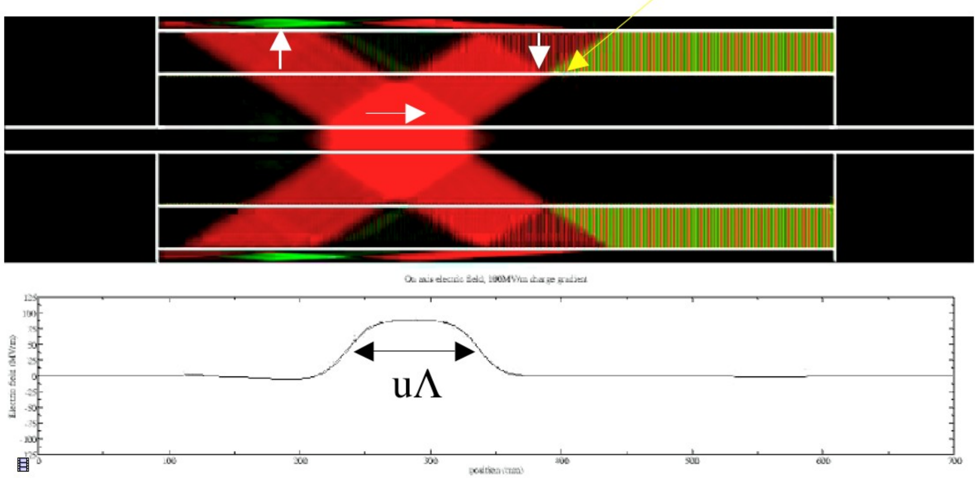
3 MV/m gradient (600 kV) across stack and HGI's with 1 kA electron beam load

(Yu-Jiuan Chen , LLNL)

DWA - Traveling Wave Acceleration

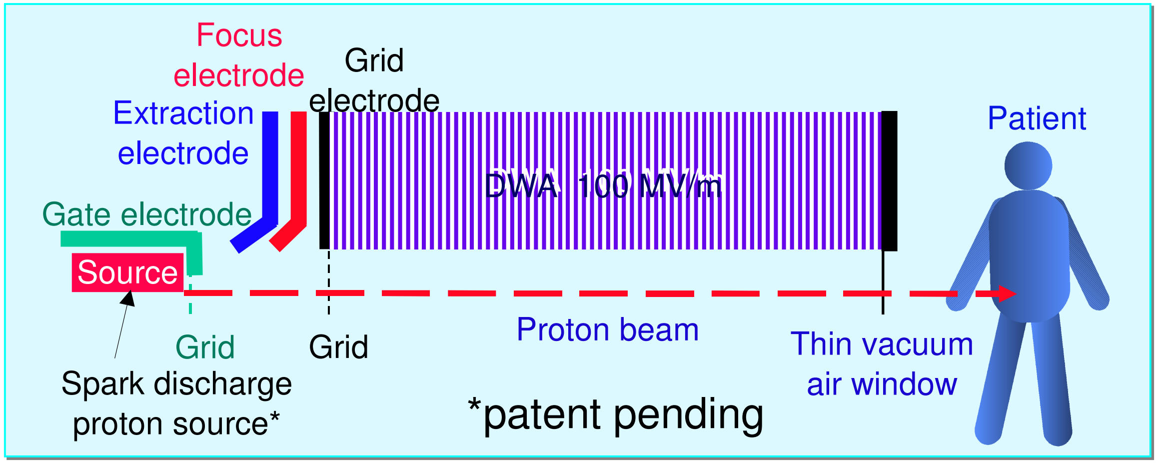






HGI : shorter pulse → higher achievable gradient.

(Yu-Jiuan Chen , LLNL)

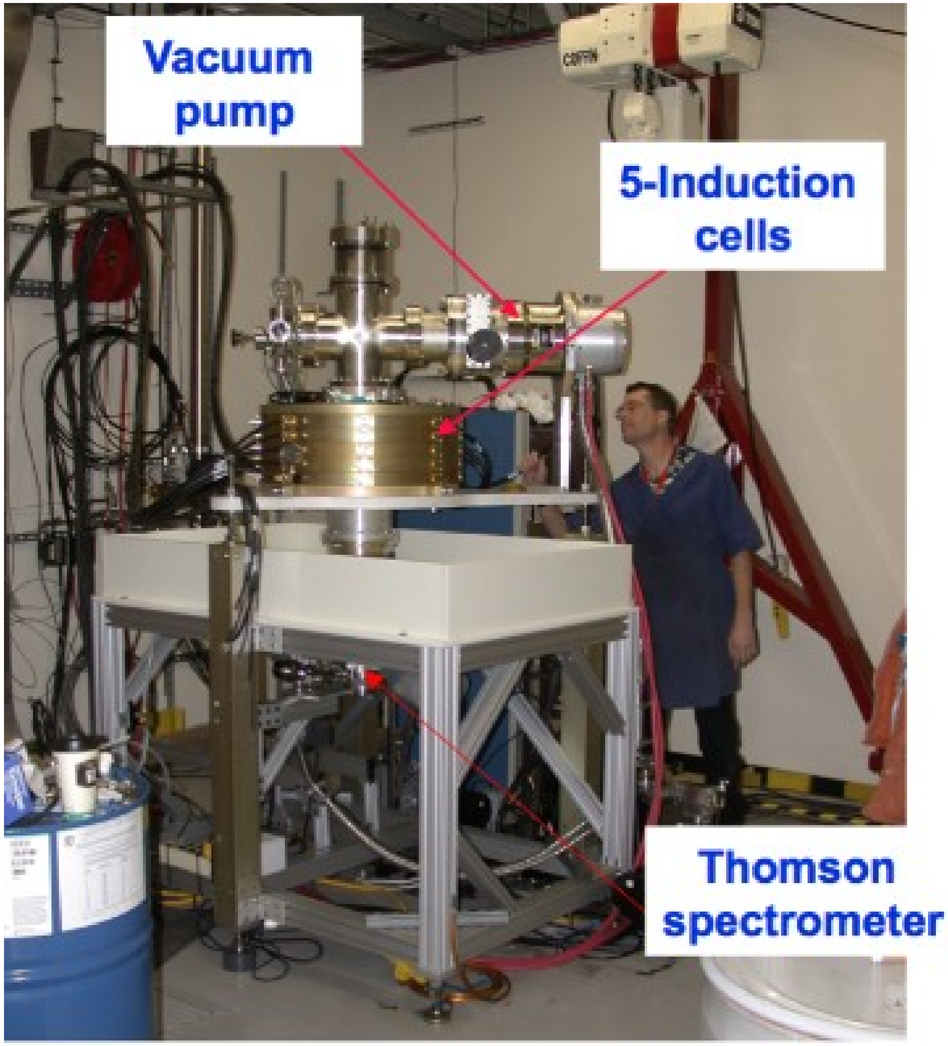


- Focusing before acceleration.
- Space charge - acceleration time is short.

(Yu-Jiuan Chen , LLNL)

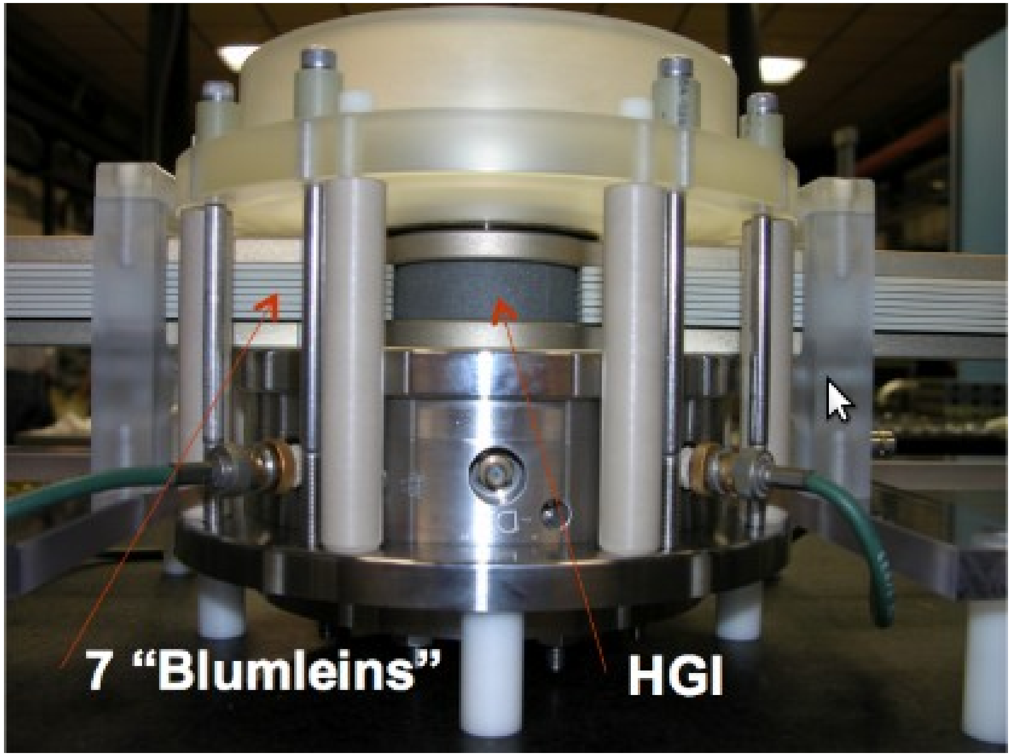
DWA – Status: Proton Injector

- F.A.S.T. concept:
  - First Article System Test
- "easy disassembly to repair failed components at modest cost"
- Acceleration pulse is only 3 ns, protons must therefore be at 200 keV before injection into F.A.S.T.



(Caporaso et al. , LLNL)

DWA Status - F.A.S.T.



- Have demonstrated accelerated electron beam through 7 Blumleins
- Energy?

- Proton beam through one Blumlein,
- demonstrated acceleration and deceleration of protons.
- Energy?

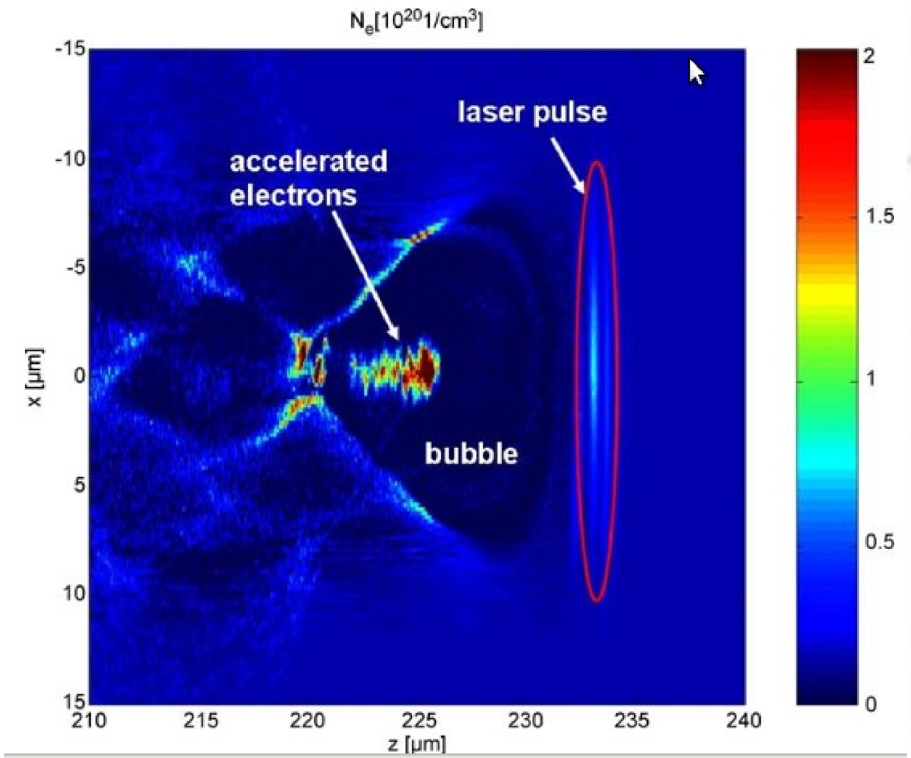
(Caporaso et al. , LLNL)

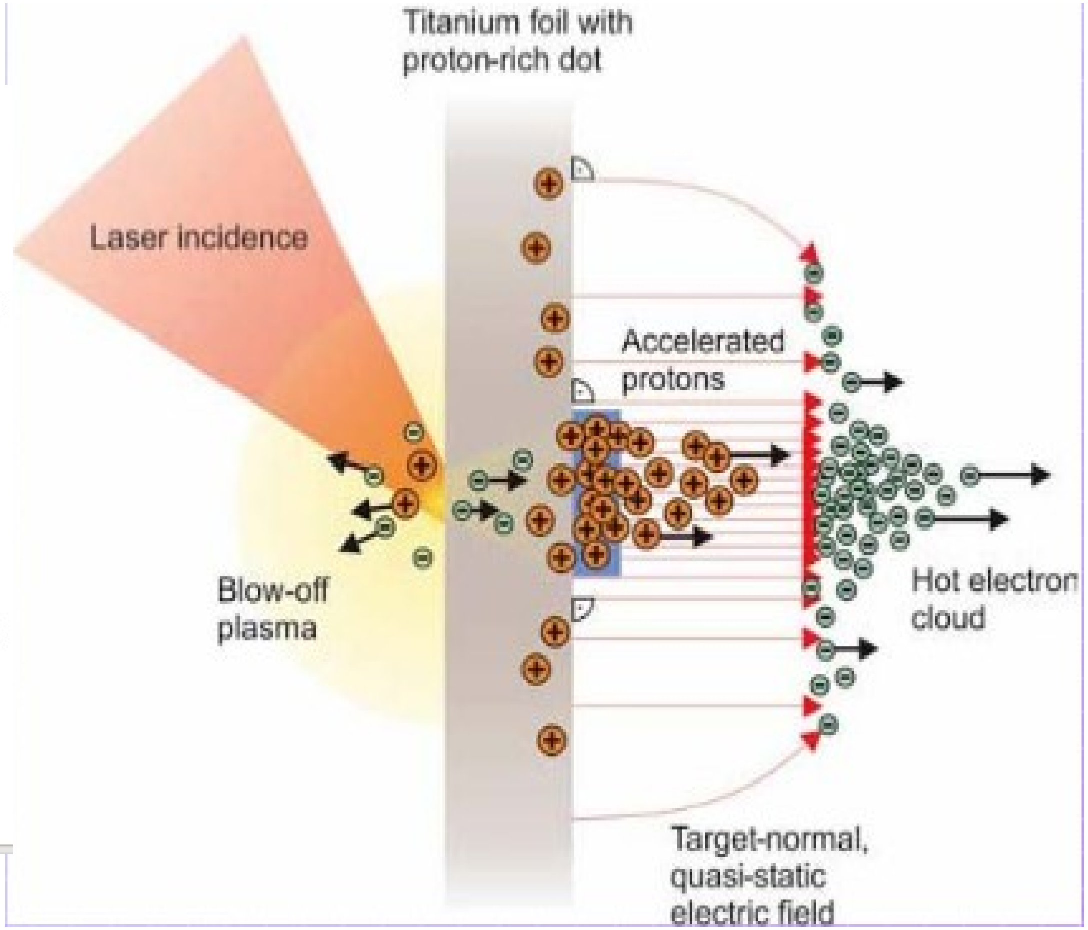
Wakefield acceleration / Laser acceleration

- Idea first conceived **1979** by T. Tajima and J.M. Dawson, UCLA
- Use electric field from intense laser light for electron acceleration
  - But no lasers readily available with required intensity, since aplification optics break down
  - Chirped pulse amplification: expand laser pulse in spectra and or time domain, amplify and bundle again.

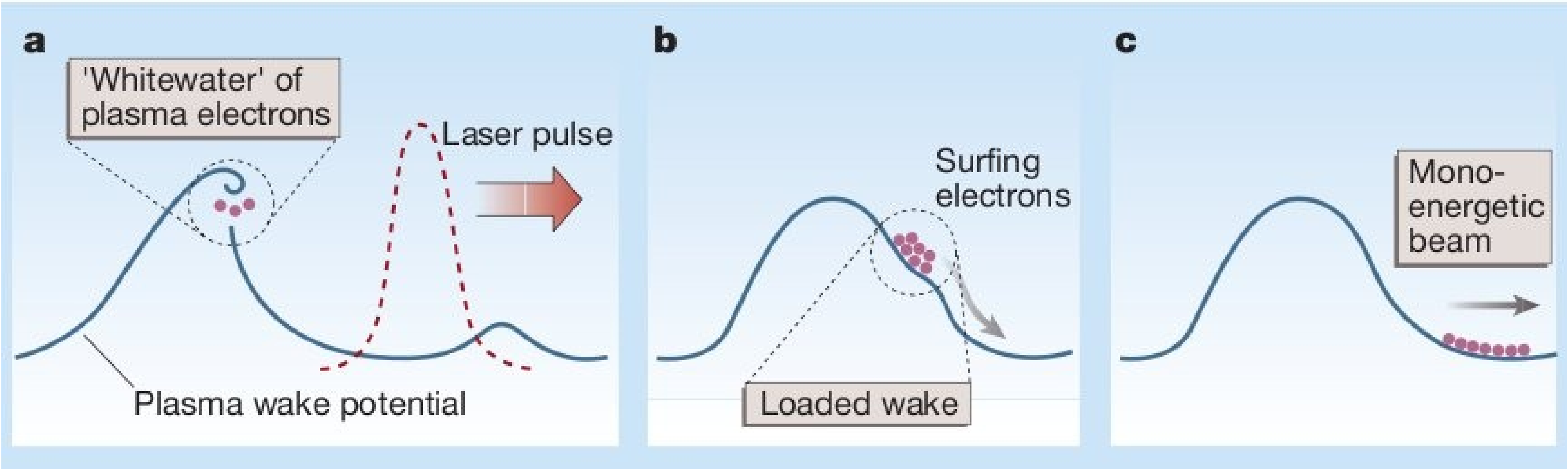
    Can reach TW in e.g 20 J over 600 femto seconds.
  - Reach 100 GV/m (RF is in the 10 MV-50MV range)
  - Have shown 1 GeV electron acceleration

Laser acceleration



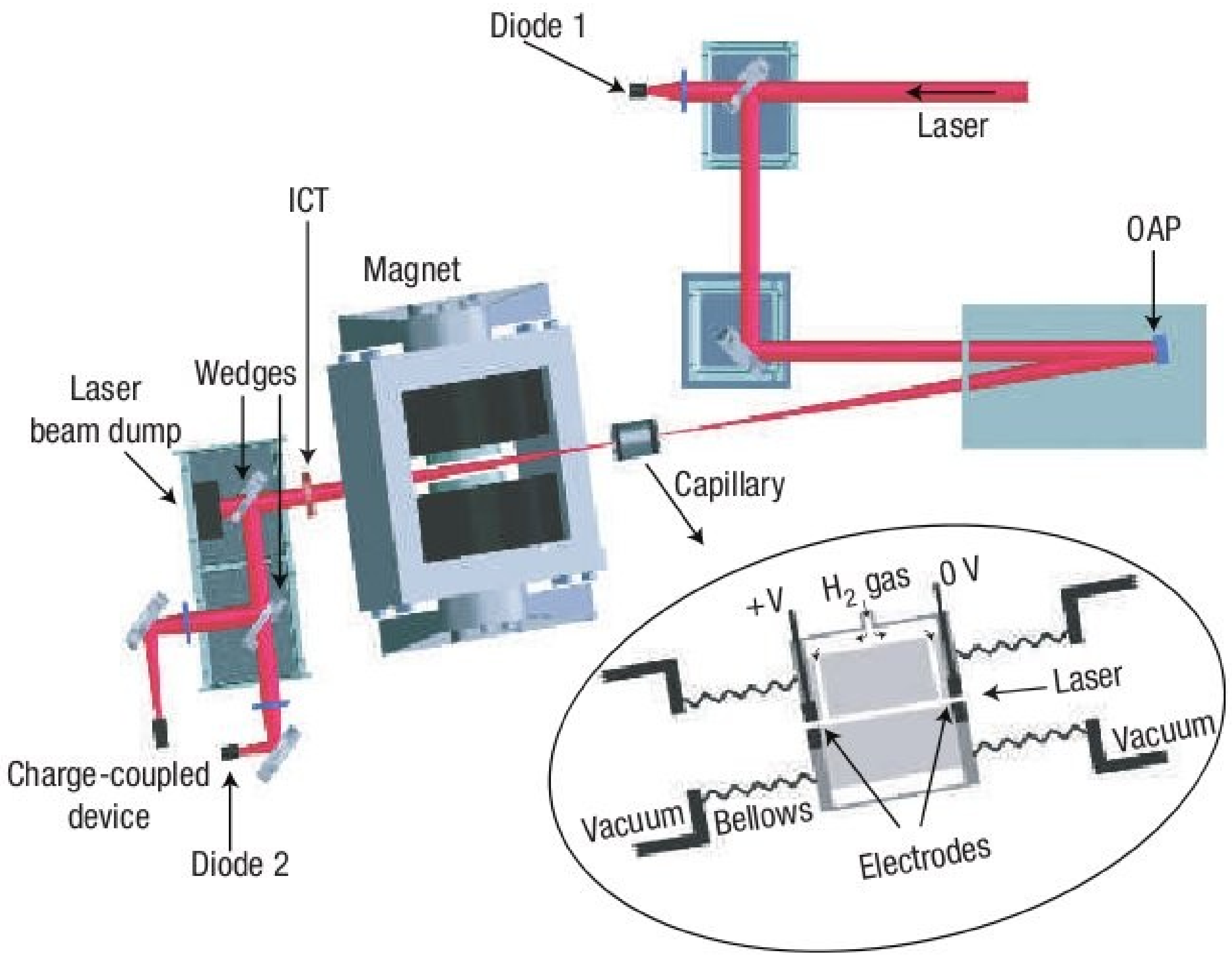


Wakefield acceleration

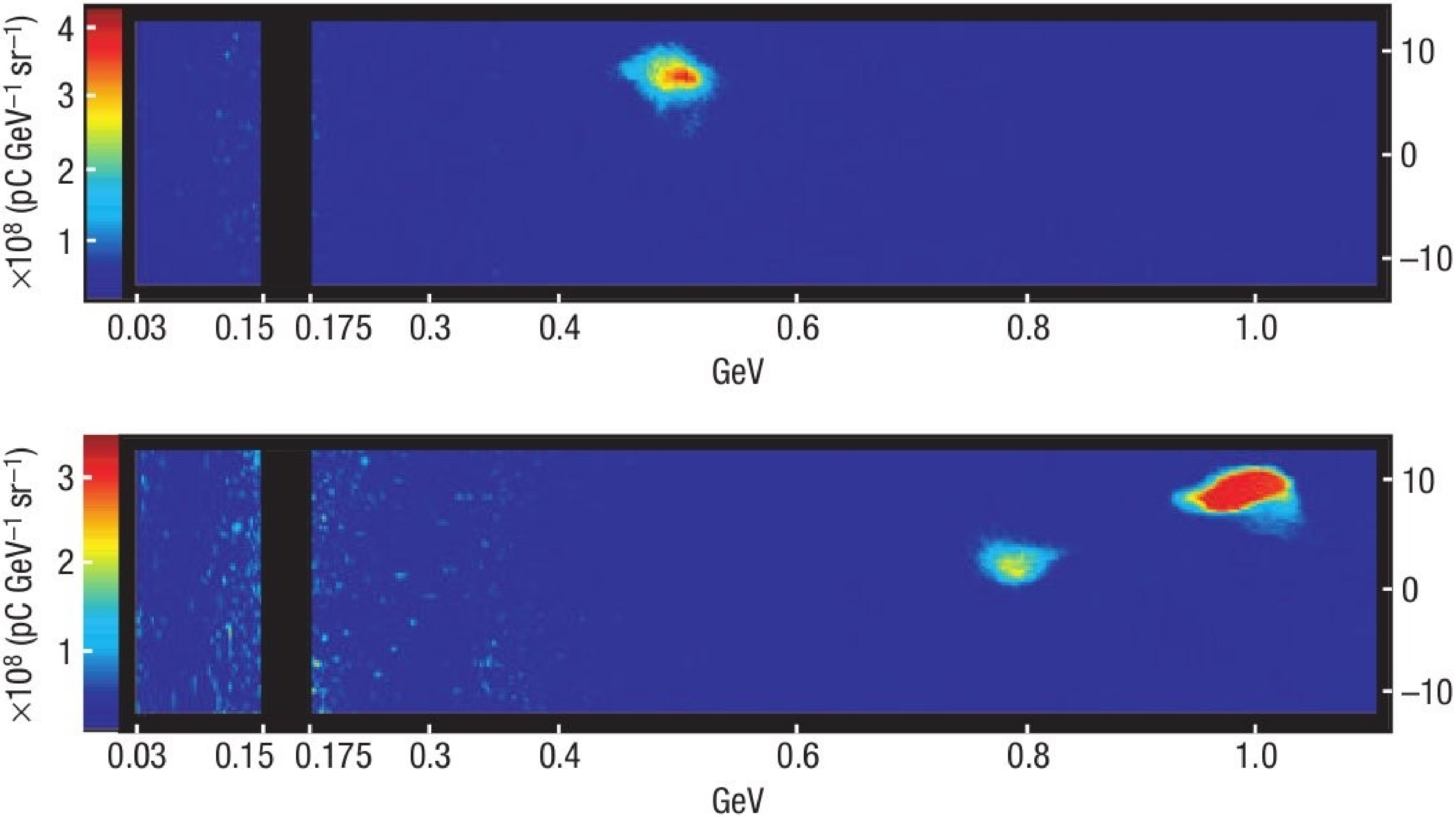


- Gradients achieved: 10 – 100 GeV/m easily
- But delta E / E = 100 %
- 2004, breakthrough: using gas jets, % level energy spread.
- Gas must be ionized, then heated
  - Can be done with two laser pulses, but laser heating is inefficient at low densities
  - Leemans et al use a capillary discharge waveguide
  - Guides laser, reduces energy spread
  - 40 TW peak laser pulse

Wakefield acceleration



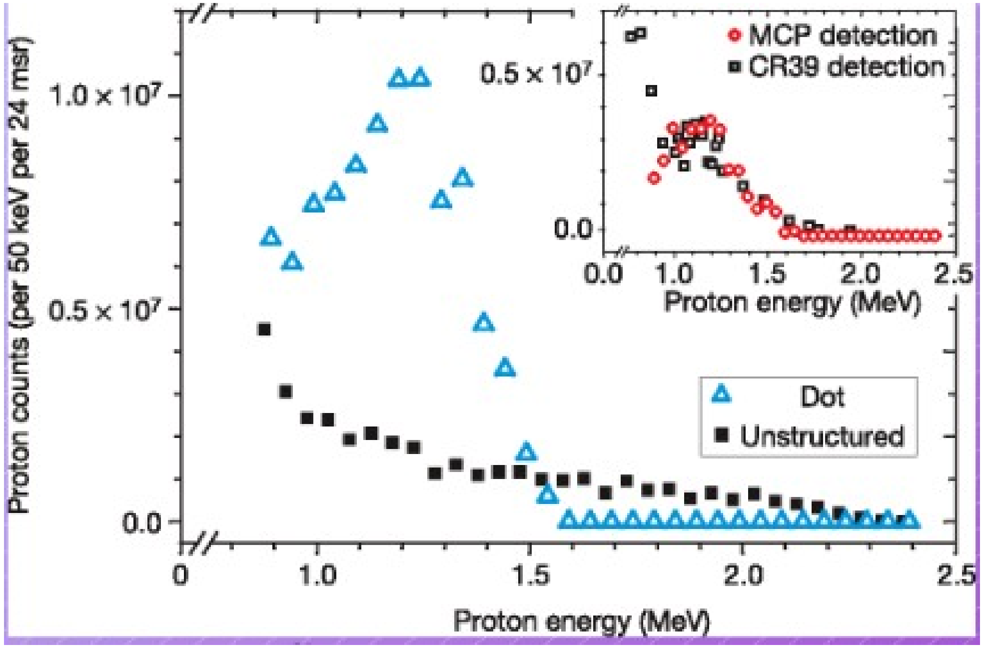
Wakefield acceleration



AARHUS PARTICLE THERAPY GROUP

Protons

- 60 MeV protons
- 100 MeV flourine ions
- 225 MeV (2 MeV/u) Palladium ions
- Carbon ions a few MeV/u dE/E = 17 %
- Recently Schnell and Wilkens (PMB 54, 2009) show using a spectrum of energies to effectively build a SOBP.



Things to Worry About

- Medical equipment certification
- "Heidelberg Ion (HIT) facility has the smallest possible size which still fulfills requested parameters AND reliability AND reproducibility, needed for certification".
- *"Build new accelerator on ship, do treatment in international waters."* (Inspired by Prof. O. Jäkel).