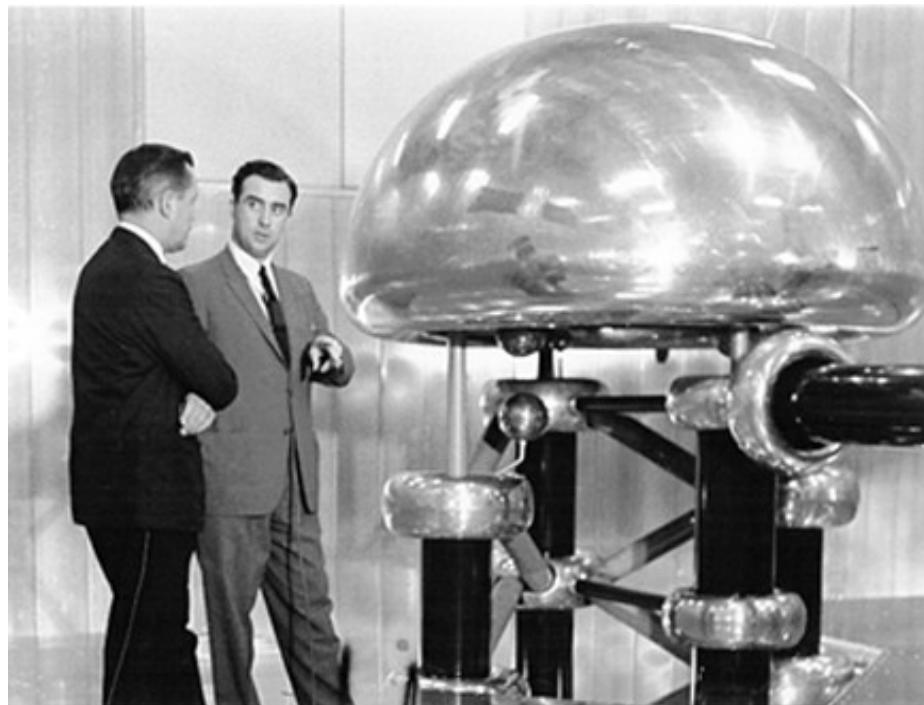


New Accelerator Technologies for Particle Therapy



Niels Bassler, PhD
Department of Physics and Astronomy
Aarhus University, Denmark

Heidelberg,
28th April 2010



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

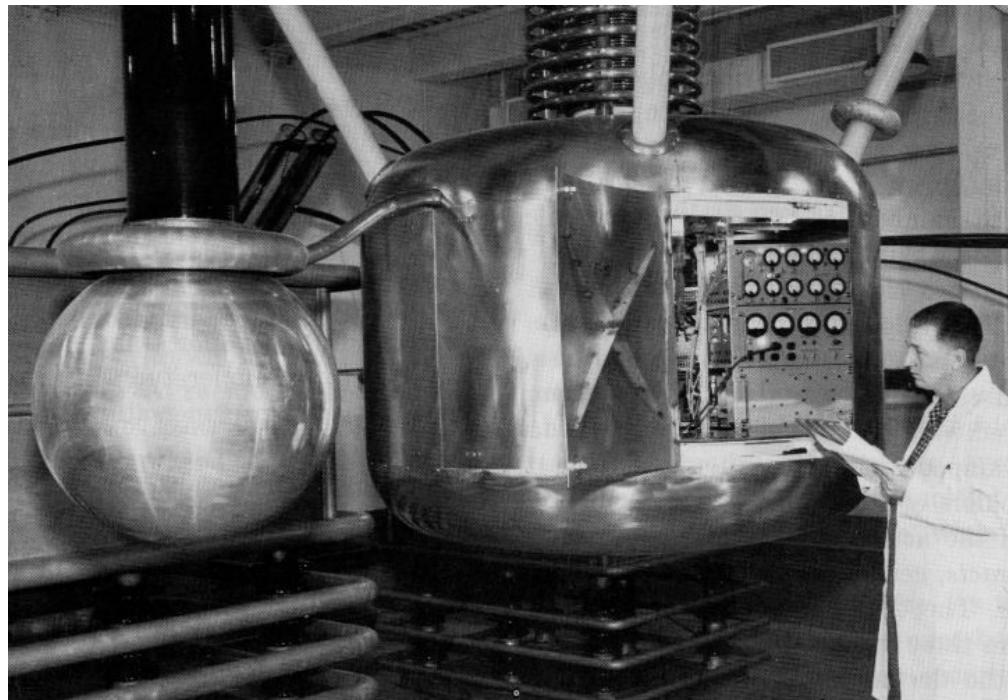
- Accurate beam positioning
- Stable beam intensity
- Safety (e.g. spill abortion system)

..and some additional Options:

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



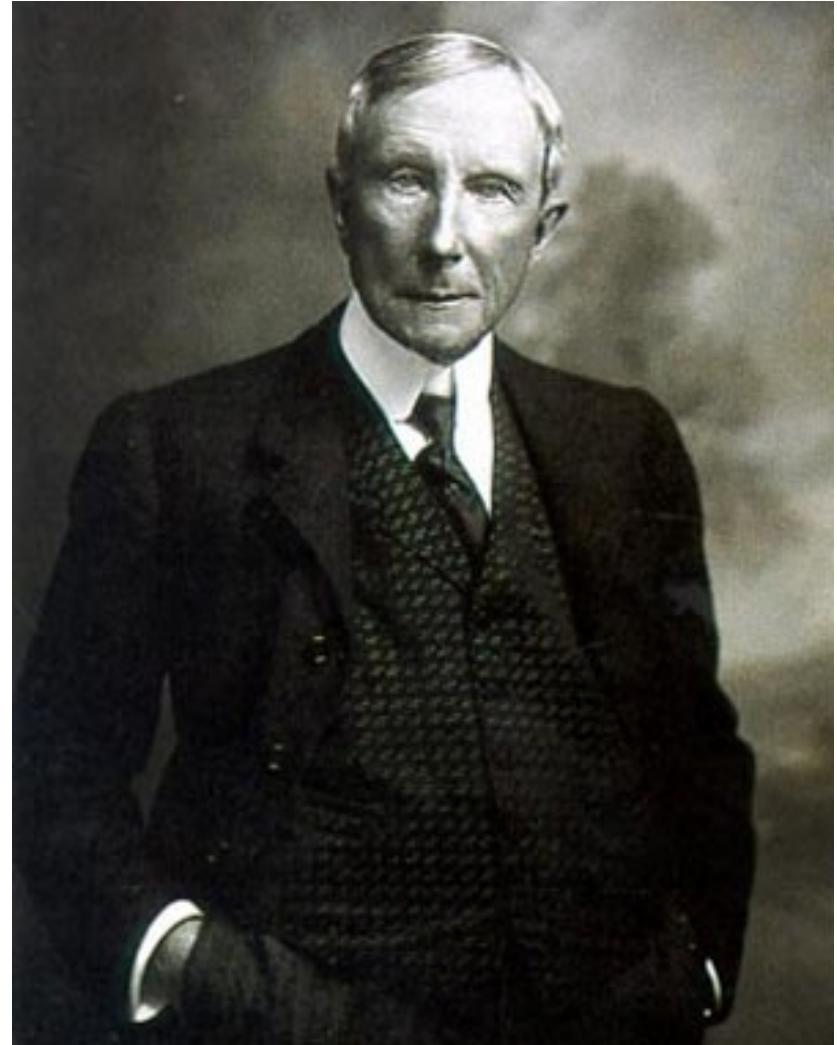
General requirements



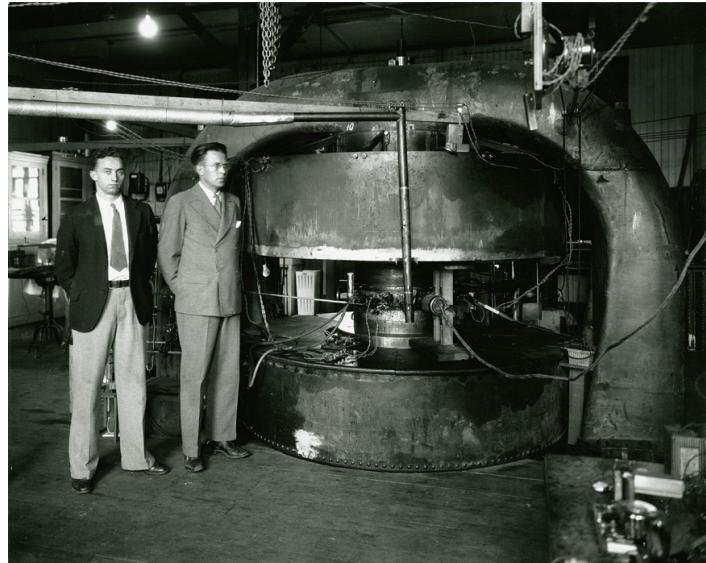
- 1000 patients/yr (throughput)
 - Reliability
 - Easy to operate
-
- Certified for patient treatment

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
($dB/dr \neq 0$)
- Synrocyclotron
($df/dt \neq 0$)

SYNCHROTRONS

- Strong focusing
- Weak focusing
- Rapid cycling

FFAG

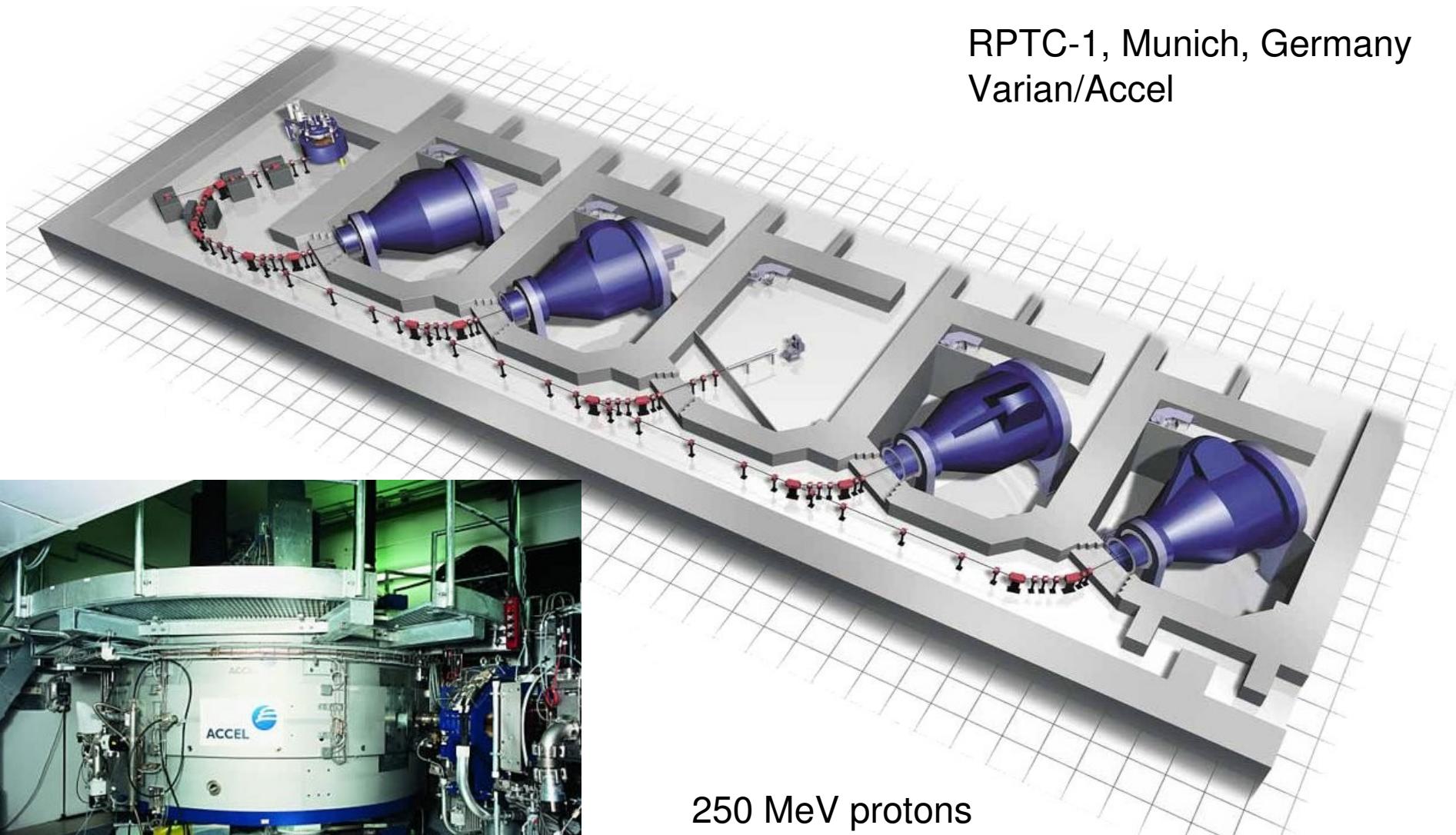
NEW TECHNOLOGIES

- Wakefield acceleration
- Dielectric wall



Typical Proton Cyclotron Facility

RPTC-1, Munich, Germany
Varian/Accel



250 MeV protons
3.2 meter diameter

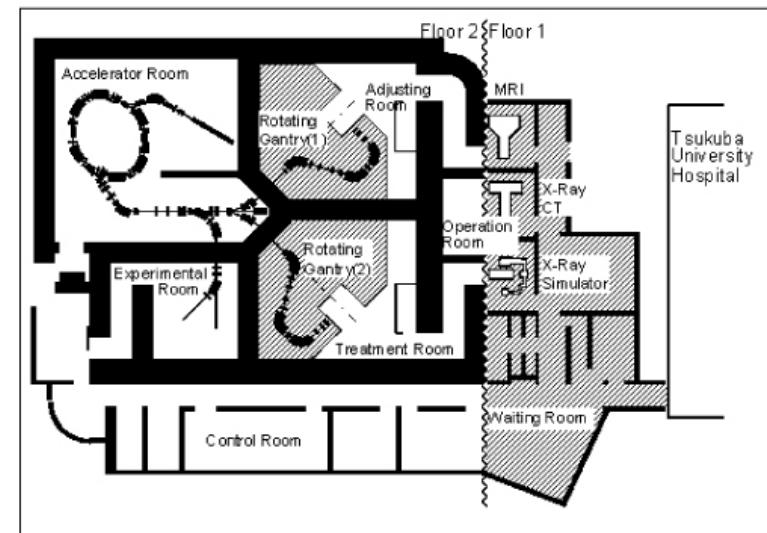


Typical Proton Synchrotron Facility

PMRC, Tsukuba, Japan
(Hitachi)



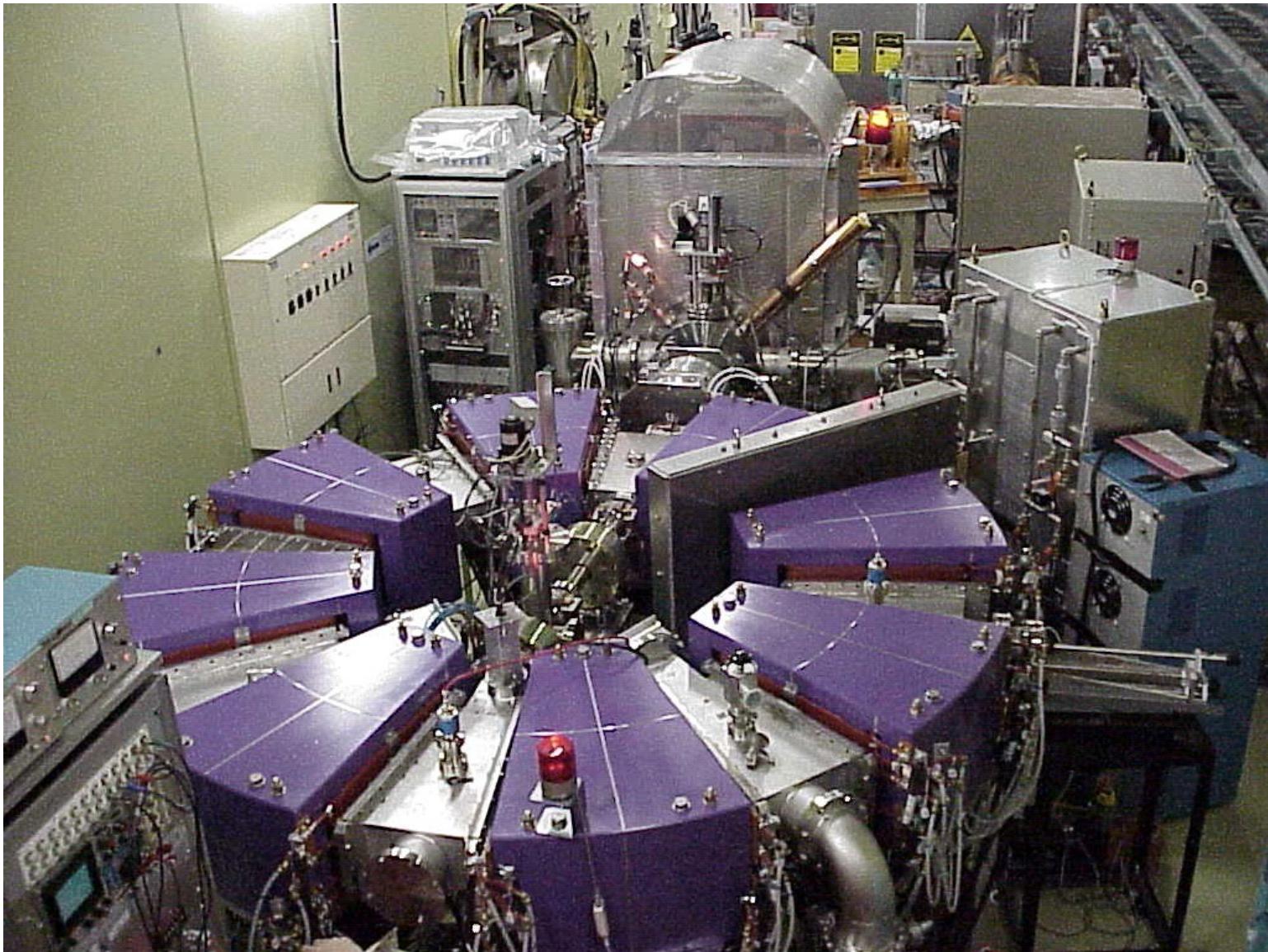
- 250 MeV
- 23.3 m circumference
- 0.5 Hz, 7 nA → 2 Gy/min



Layout of the proton therapy facility

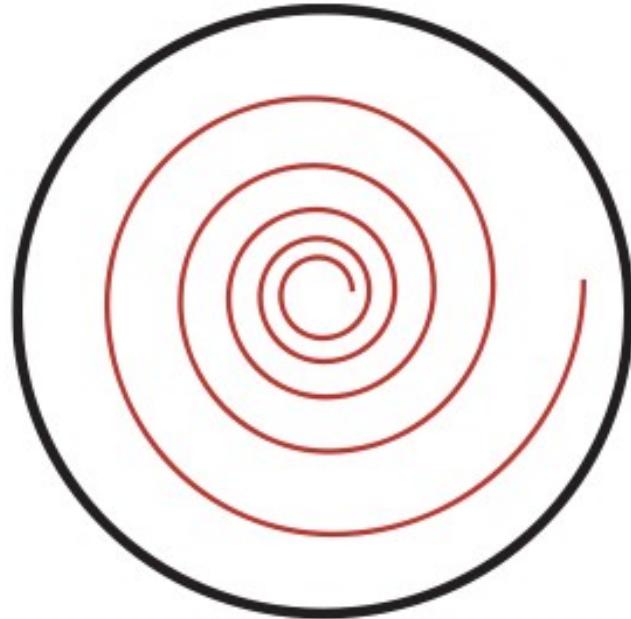


Fixed-Field Alternating-Gradient (FFAG)



Cyclotron/Synchrotron/FFAG

Yoshiharu Mori, KEK.



CYCLOTRON

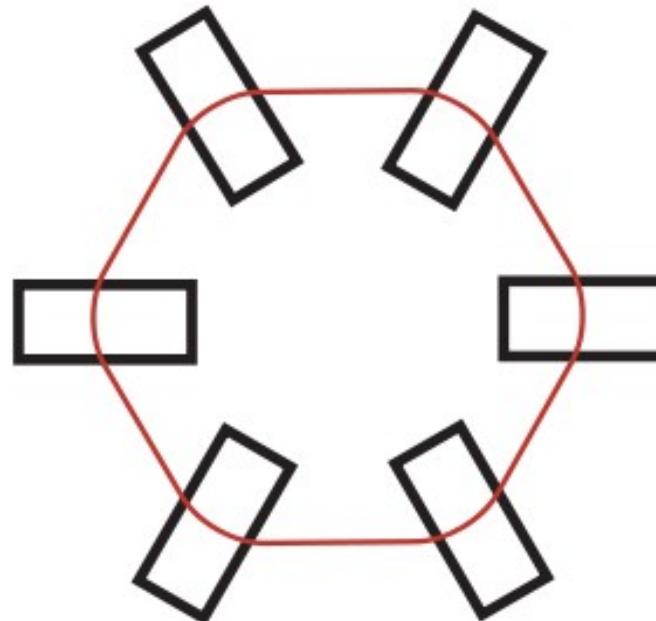
- Isochronous cyclotron

$$dr/dt > 0$$

$$df/dt = 0 \text{ (*not sync.cycl*.)}$$

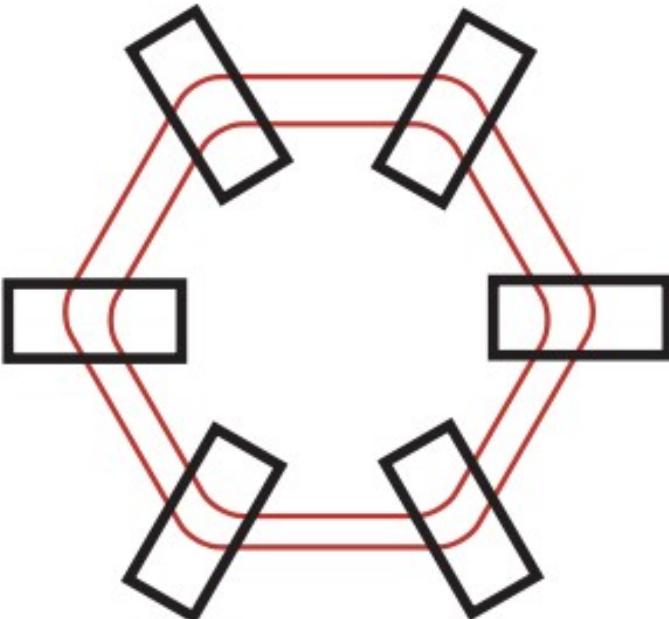
$$dB/dt = 0$$

$$dB/dr > 0$$



SYNCHROTRON

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

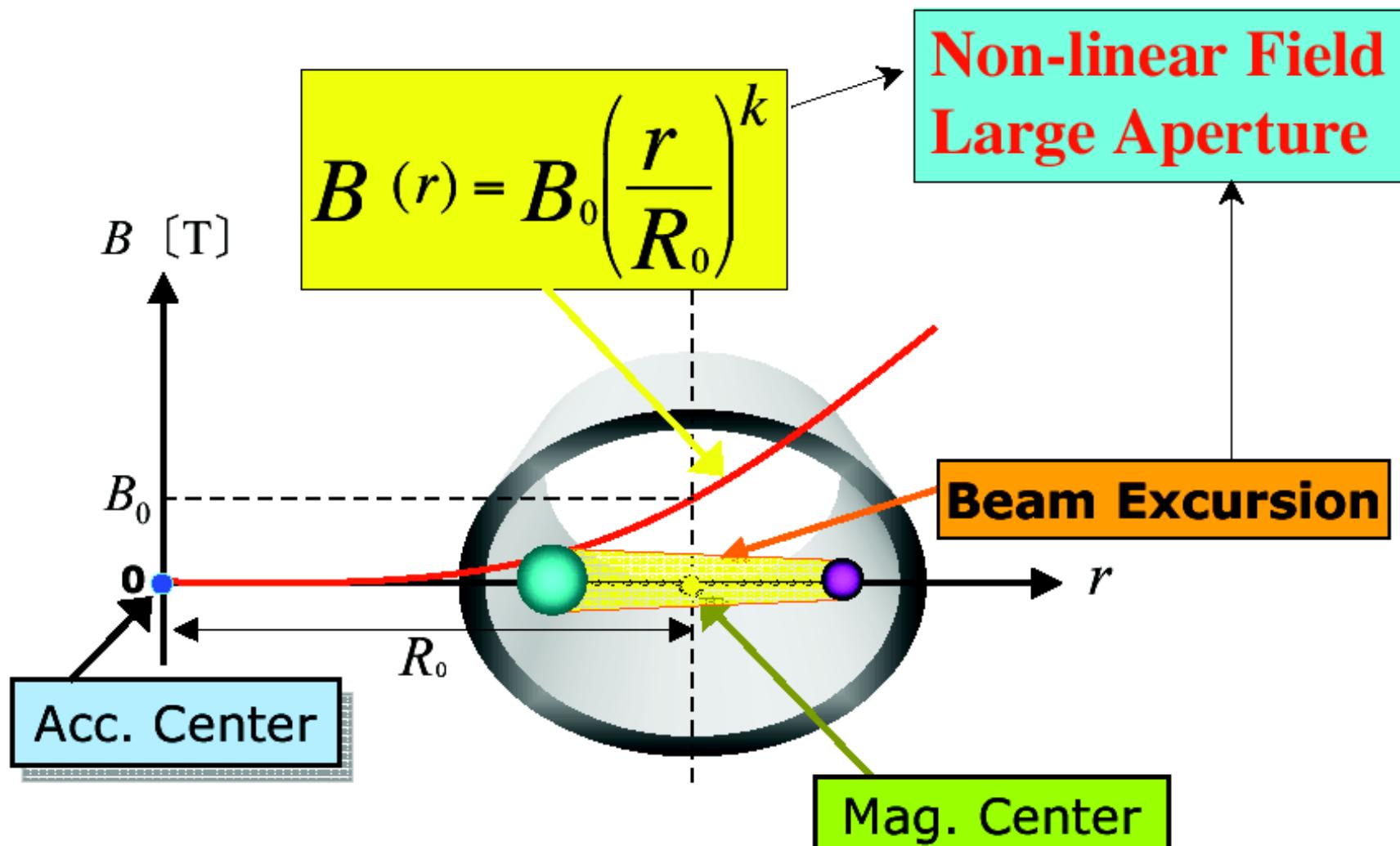


FFAG

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



Scaling FFAG Bending Magnet



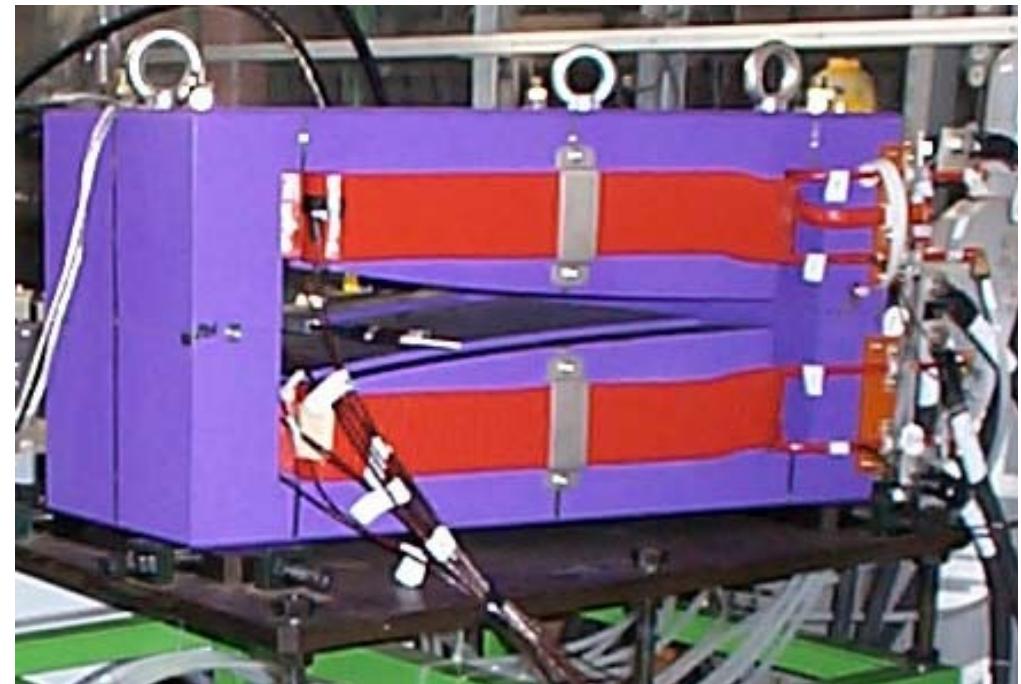
Disadvantage for high proton/carbon energies. Fix: “Non-scaling FFAG”.

Yoshiharu Mori, KEK.



FFAG Bending Magnet

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

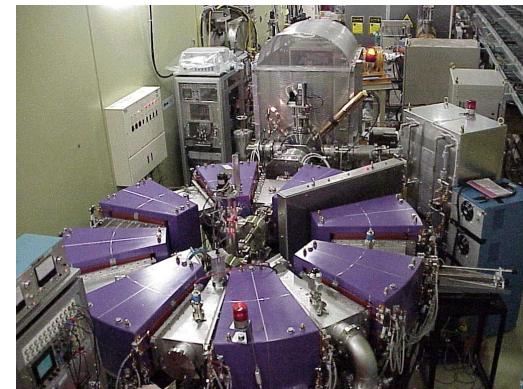
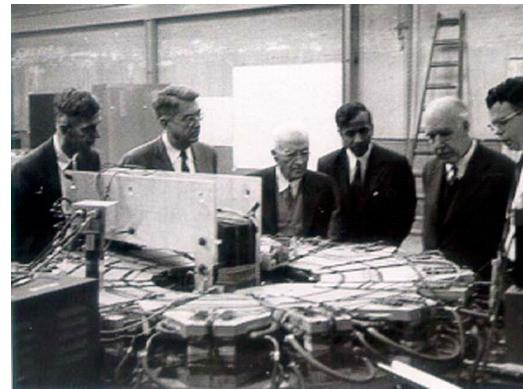


Yoshiharu Mori, KEK.



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>



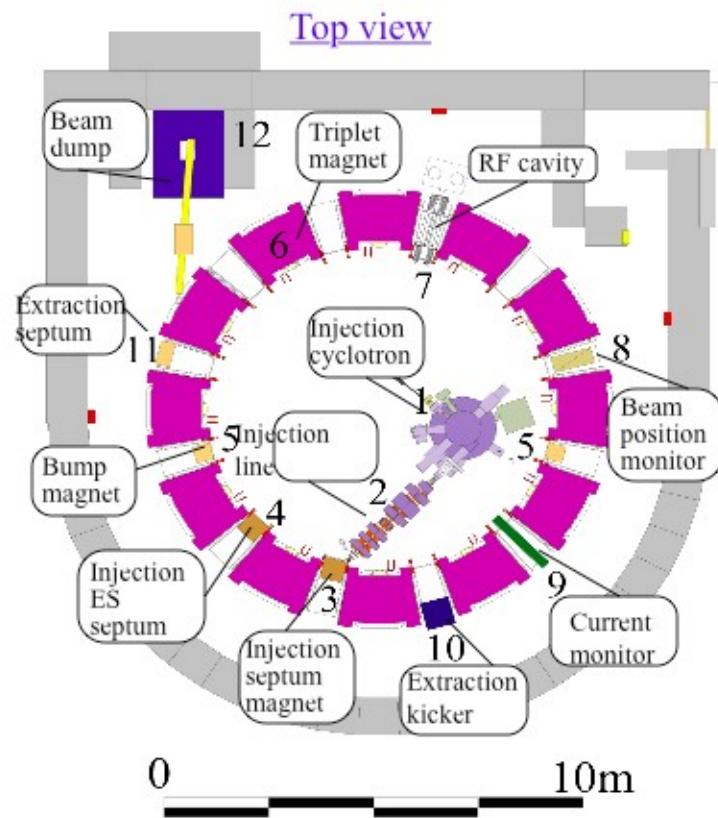
C. Ohkawa and Y. Mori

AARHUS PARTICLE THERAPY GROUP



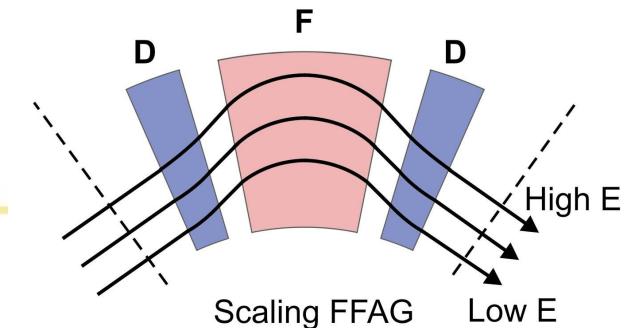
150 MeV Proton Scaling-FFAG

150MeV Proton FFAG



Design parameter

Magnet	radial sector type (DFD triplet)
Num. of cell	12
k-value	7.6
E _k	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



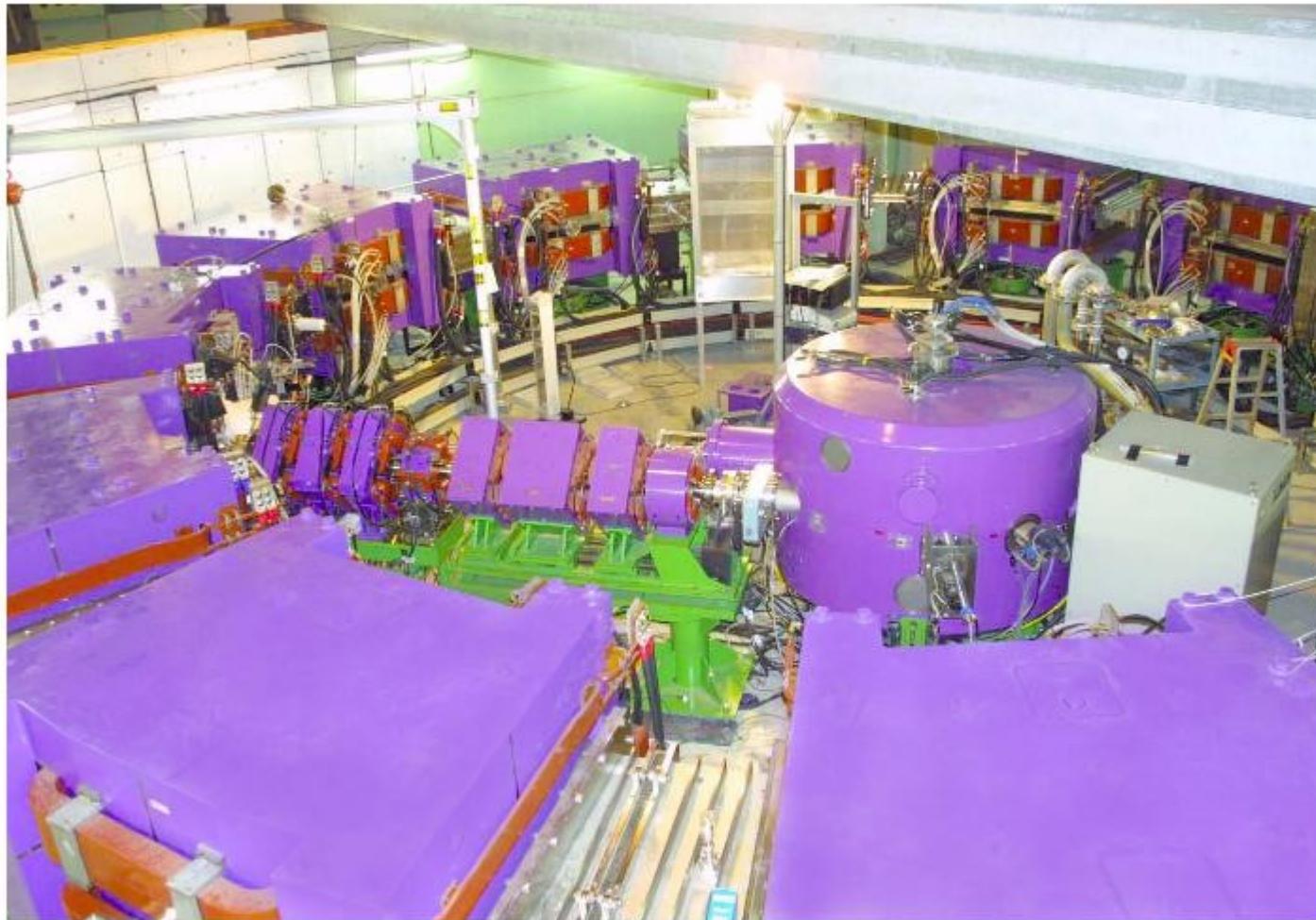
Focusing using
alternating
gradients.

27th Mar, 2005 / 日本物理学会 @ 東京理科大學

5

Yoshiharu Mori, KEK.

Proton FFAG Accelerator

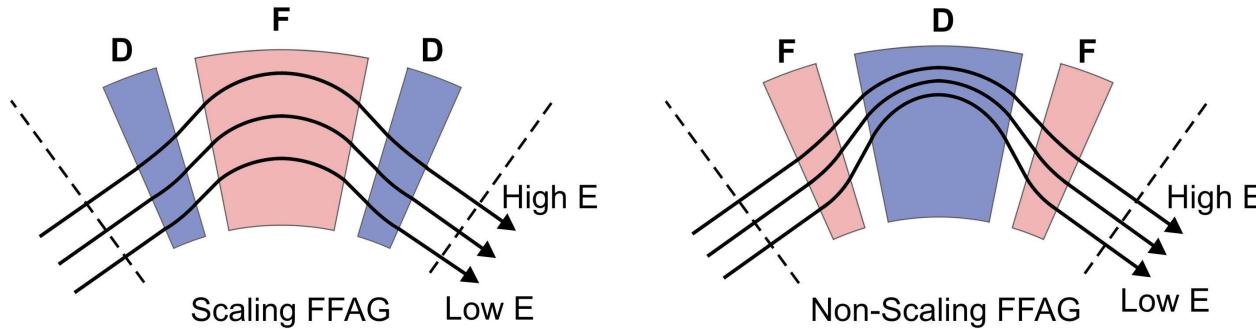


2006 @ KEK,
Tsukuba, Japan.

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

Yoshiharu Mori, KEK.

Non-scaling FFAG for Particle Therapy

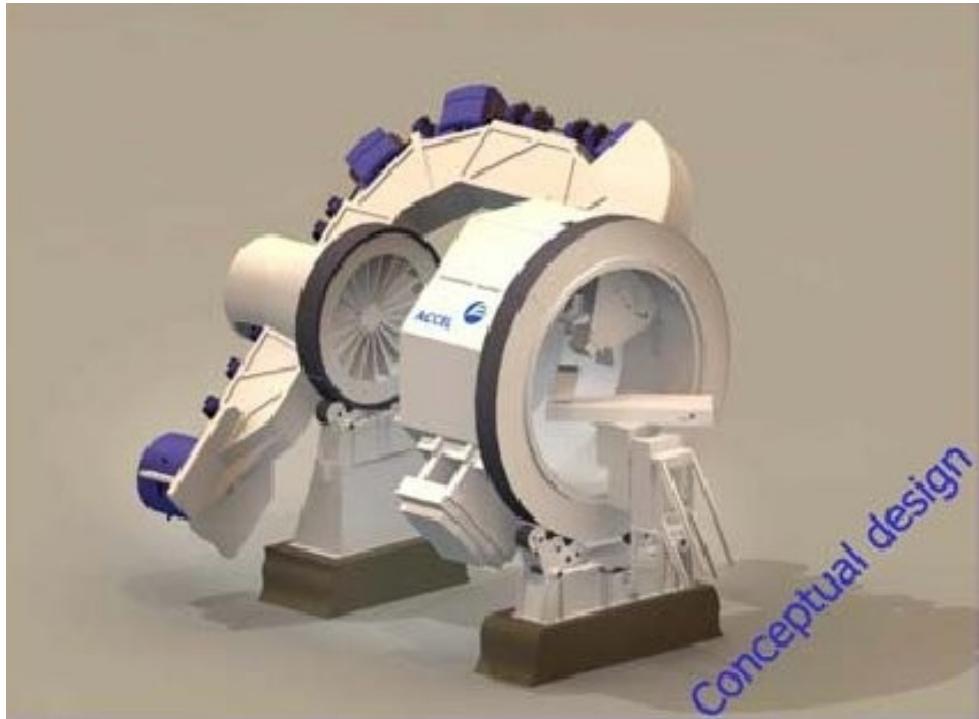


- Non-scaling FFAG
 - Breaks $B(r)=B(r/R_o)^k$
- Fast cycling: perhaps up to 1 kHz ---> high currents
- Fixed magnetic field: eases operation, similar to cyclotron.
- FFAGs can also accelerate heavier ions
- Variable beam energy extraction (cyclotron are monoenergetic)
- Compact ring, easy accessible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

Downscale existing technology

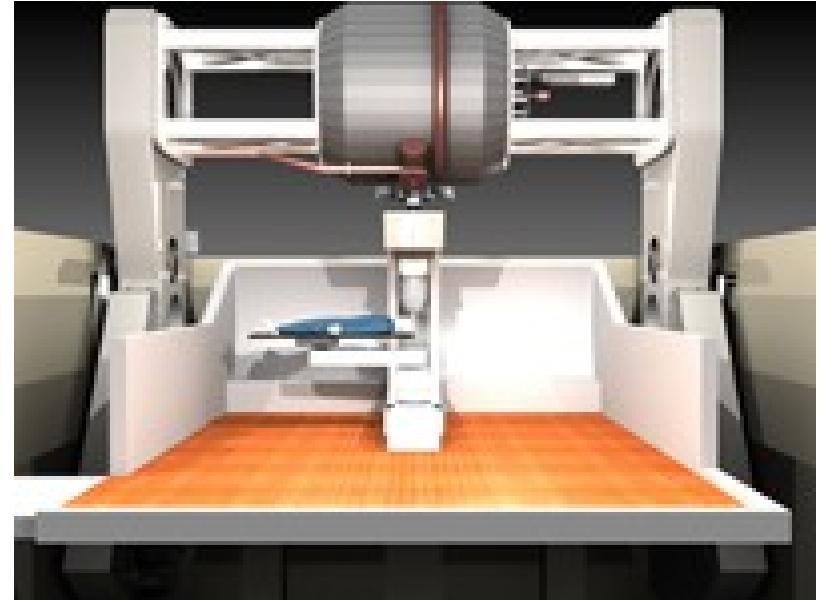
Reducing size of CYCLOTRON based facilities

Reducing Size of Cyclotron Based Facilities



Varian

- 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.



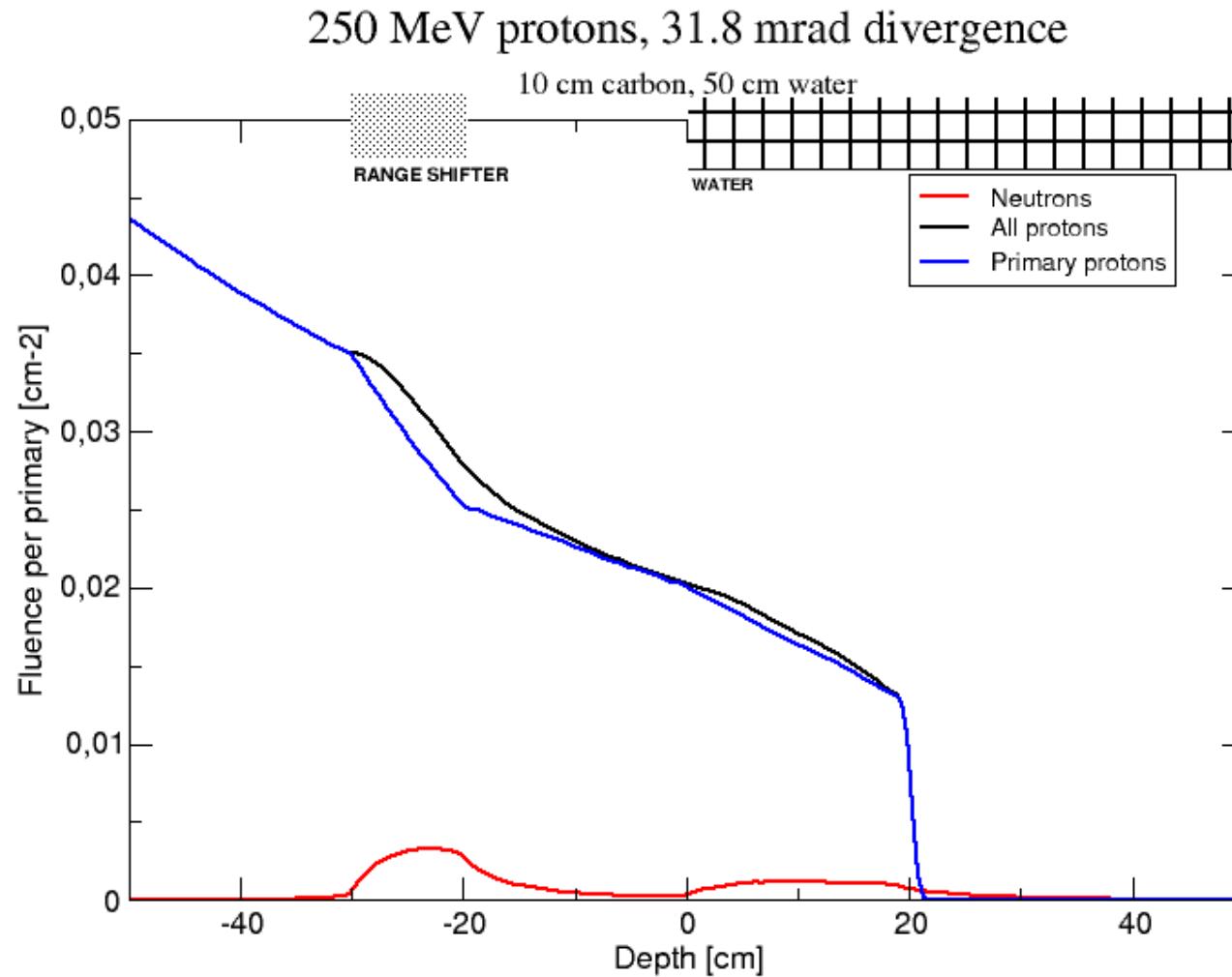
StillRiver



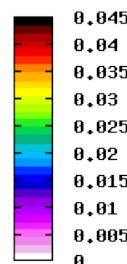
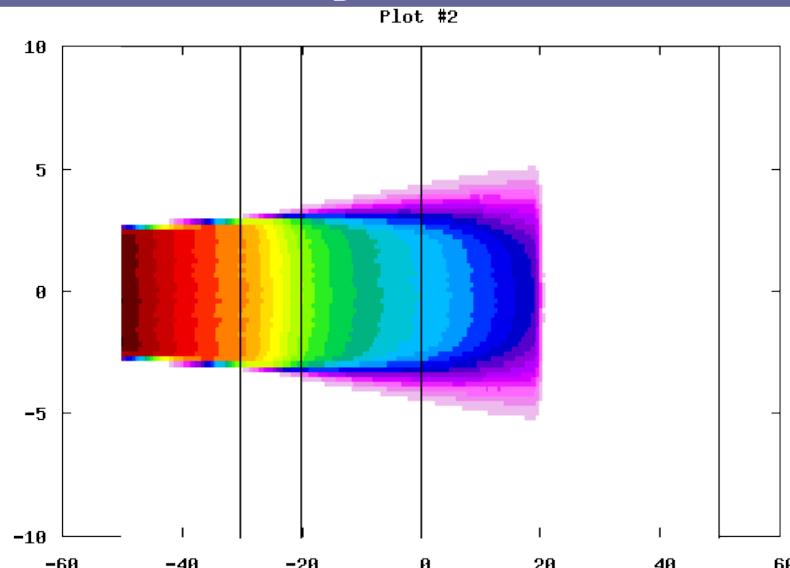
StillRiver



Secondary neutrons?



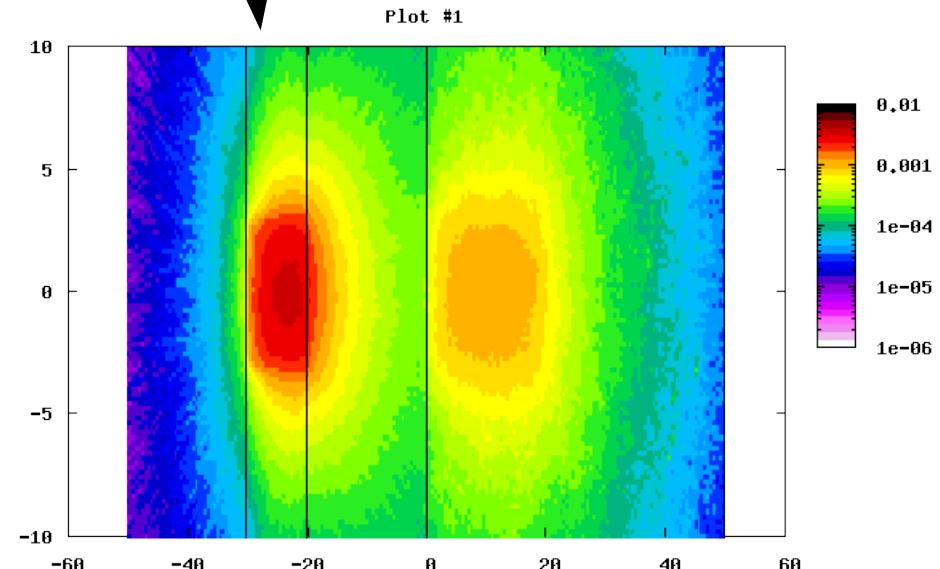
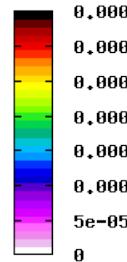
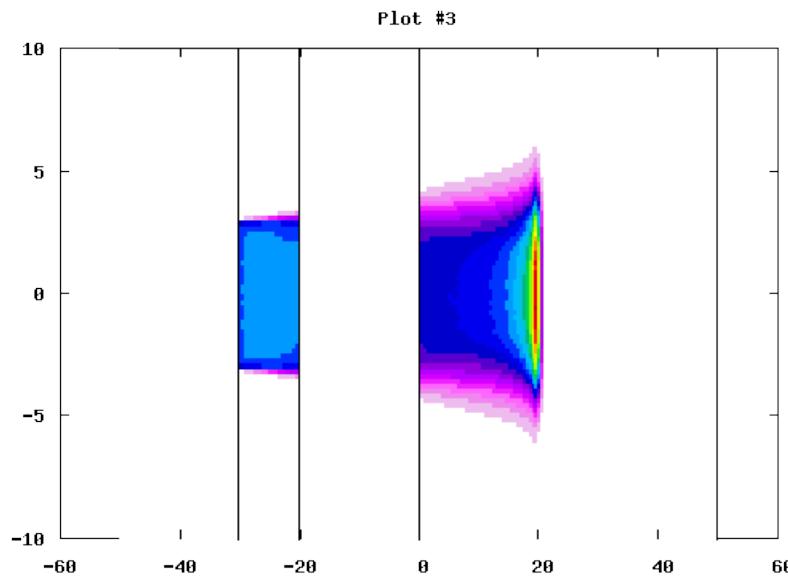
Secondary neutrons?



Carbon range shifter



Neutron fluence map



Water target

Reducing size of **SYNCHROTRON** based facilities



Decrease size, Russian way



Reducing size of synchrotrons?



Loma Linda, Ca.

- Russian technology
- Bought by “ProTom”
- Small, simple, inexpensive
- But is it really small?



Decrease size, Russian way



Table-top synchrotron, BINP, Novosibirsk

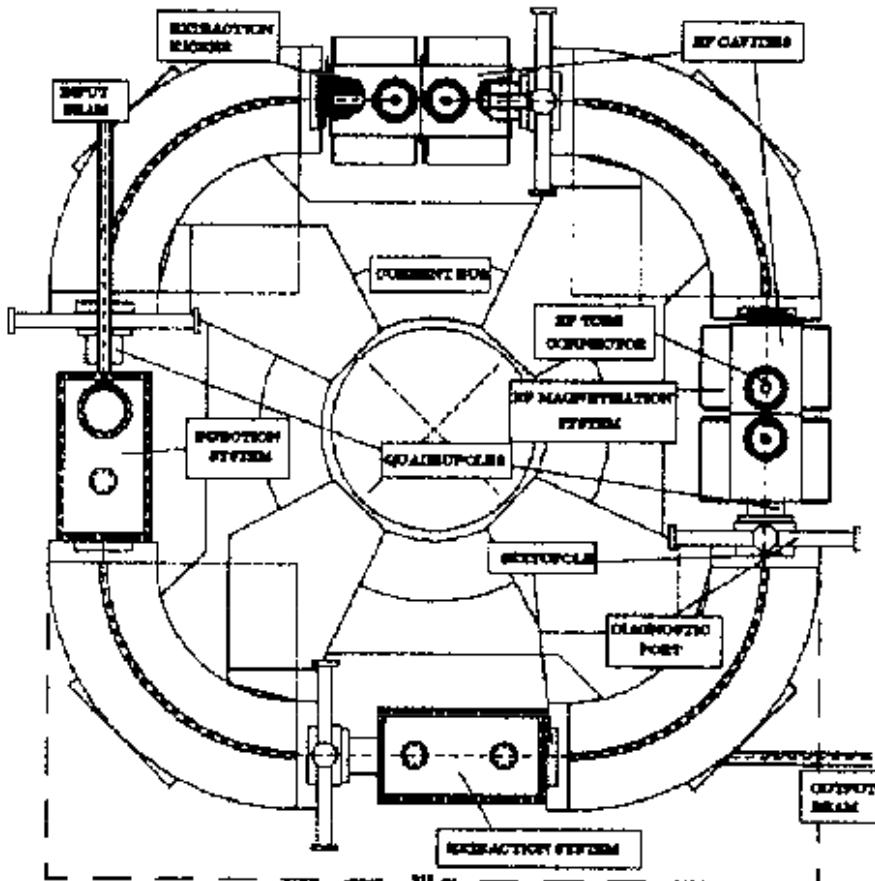


Fig. 1 - Schematic design of the proton synchrotron

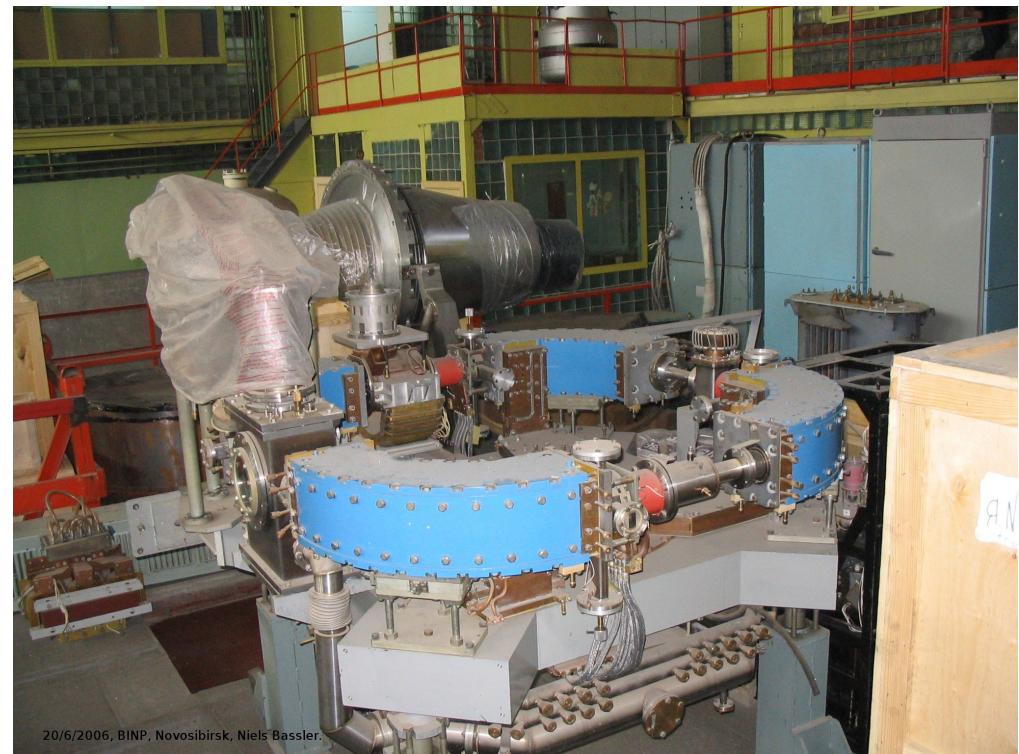
- Down-scale all known components to technical limits
- 1.6 m x 1.6 m

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

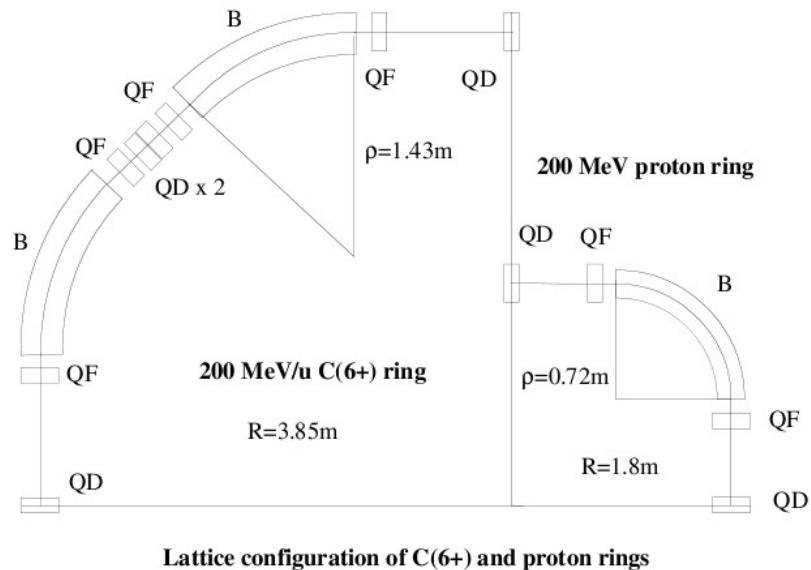


Figure 1: Magnet configuration for a superperiod of the proton (right half) and carbon ion ring (left half).

- Project restarted with more “realistic” parameters, with Japanese group KEK/NIRS
 - $E_{\max} = 200 \text{ MeV}$
 - $E_{\text{inj}} = 2 \text{ MeV}$
 - $< 10 \text{ Hz}$ repetition
 - RF 1.7 – 15.0 MHz
 - 11.3 m circumference
- Carbon version
 - $E_{\max} 200 \text{ MeV/u}$
 - $< 10 \text{ Hz}$ repetition
 - 24.2 m circumference
- ***Abandoned for unknown reasons after ~ 1 year.***

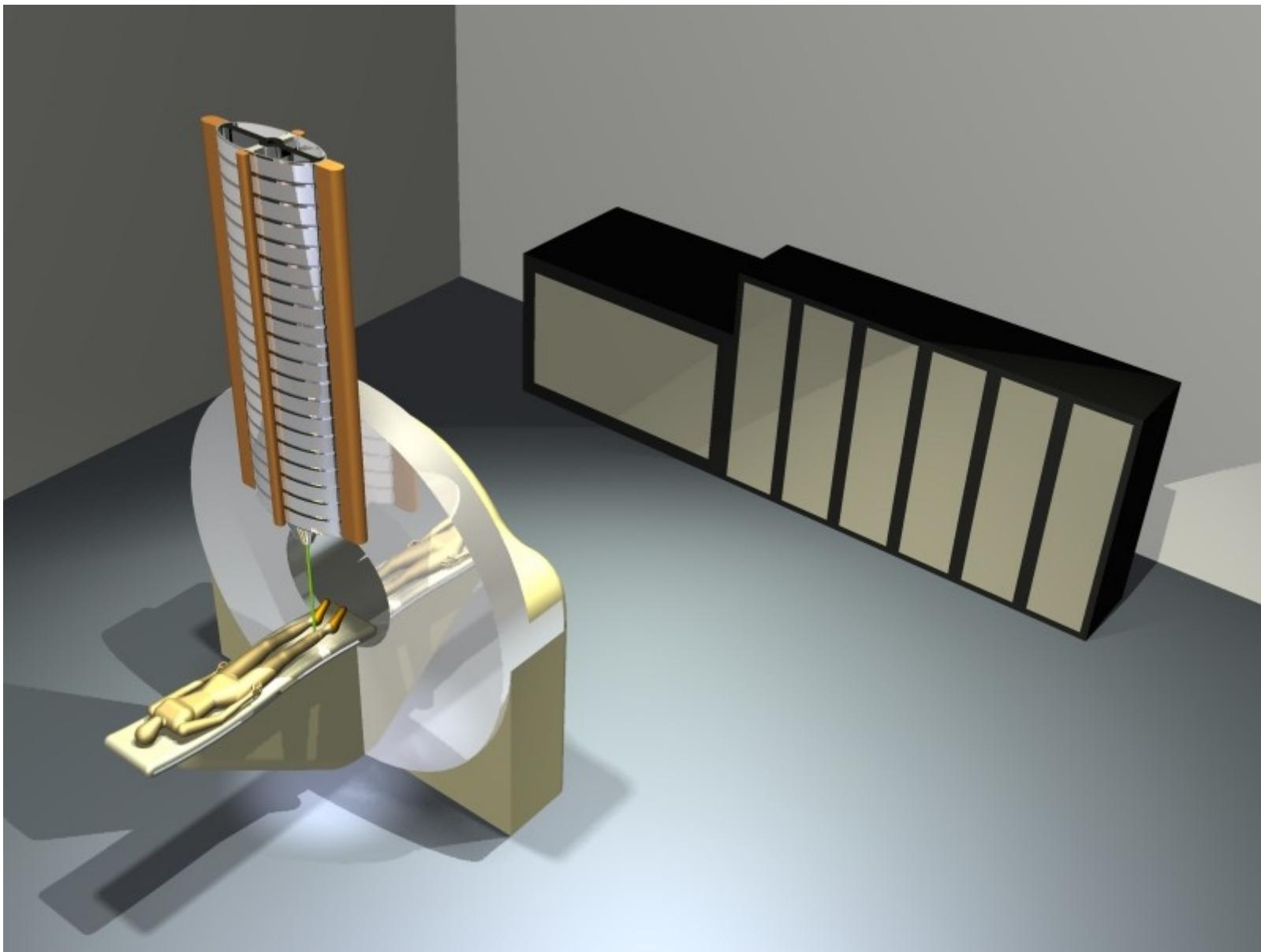


Dielectric Wall Accelerator

Dielectric Wall Accelerator (DWA)

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

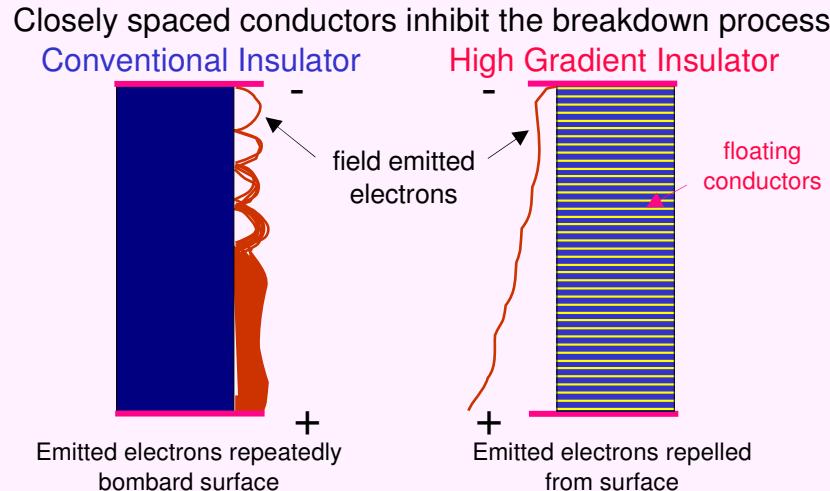




Proton ThomoTherapy.

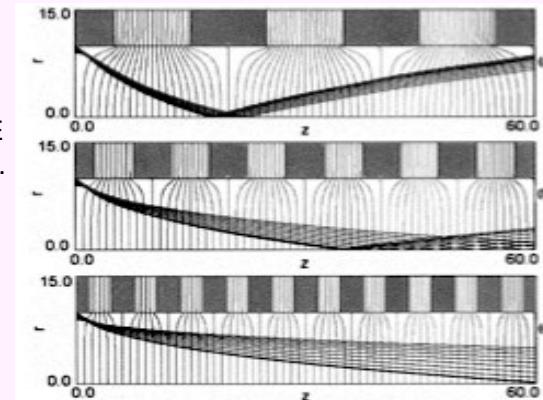
Wednesday seminar, HIT

High Gradient Insulator (HGI)

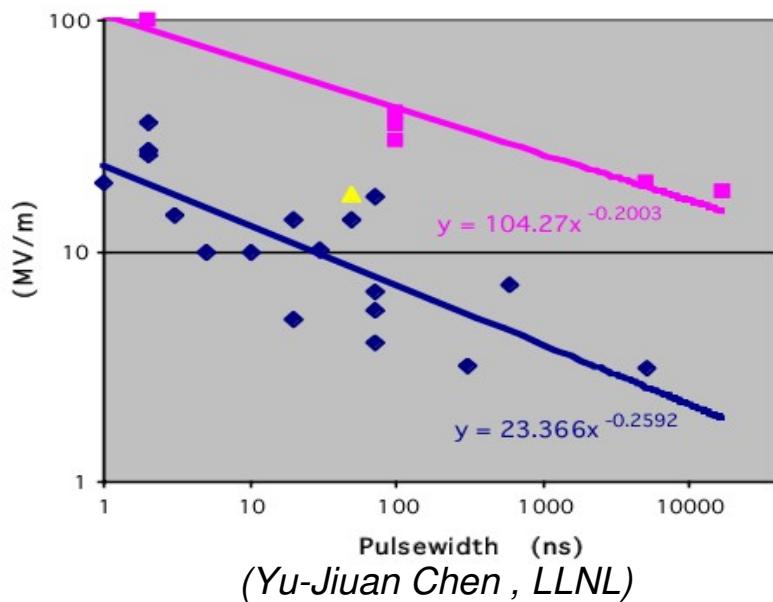


HGI structure forms a periodic electrostatic focusing system for low energy electrons

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



Surface breakdown field stress (MV/m) vs. Pulsewidth

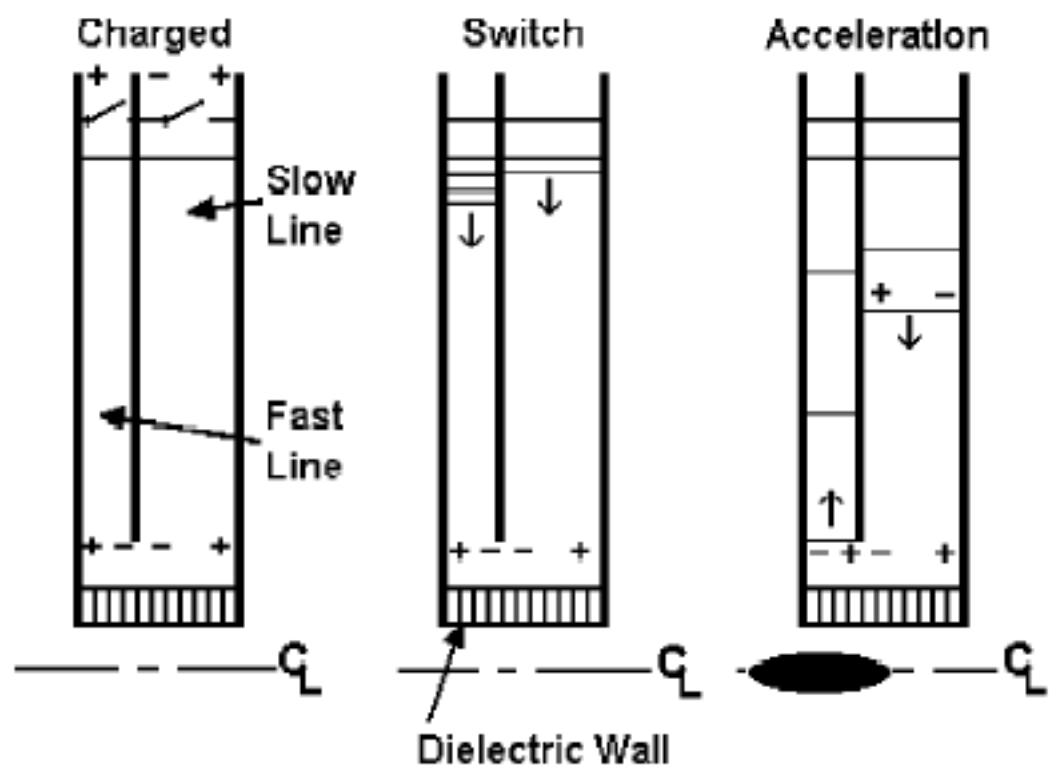
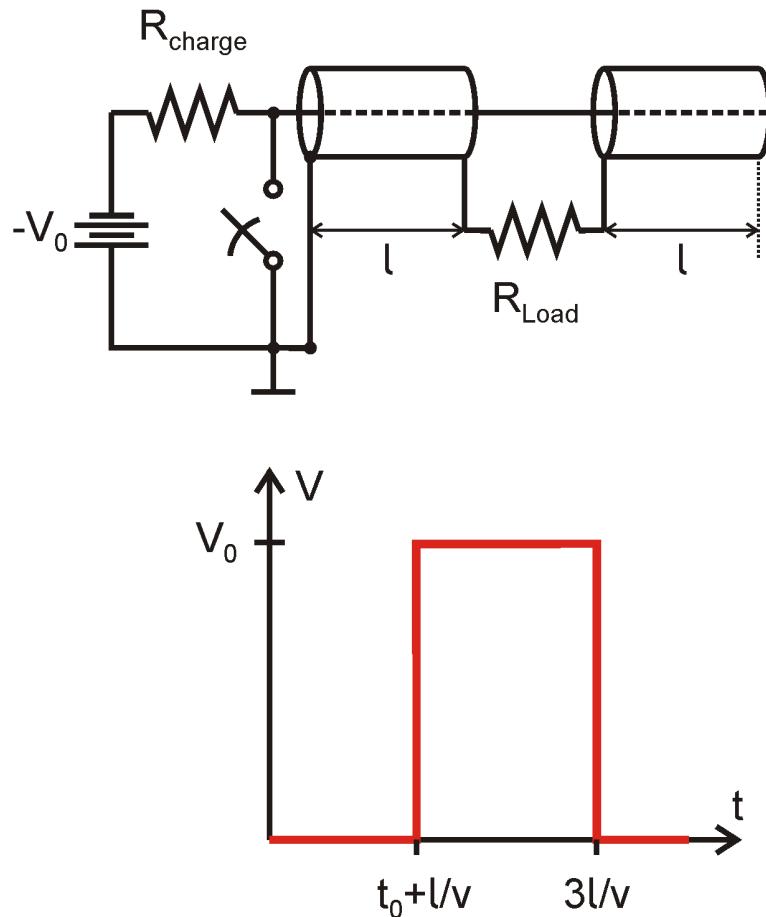


HGI: sandwich layered structure,
layers are less than mm thick

Achieved 100 MV/meter

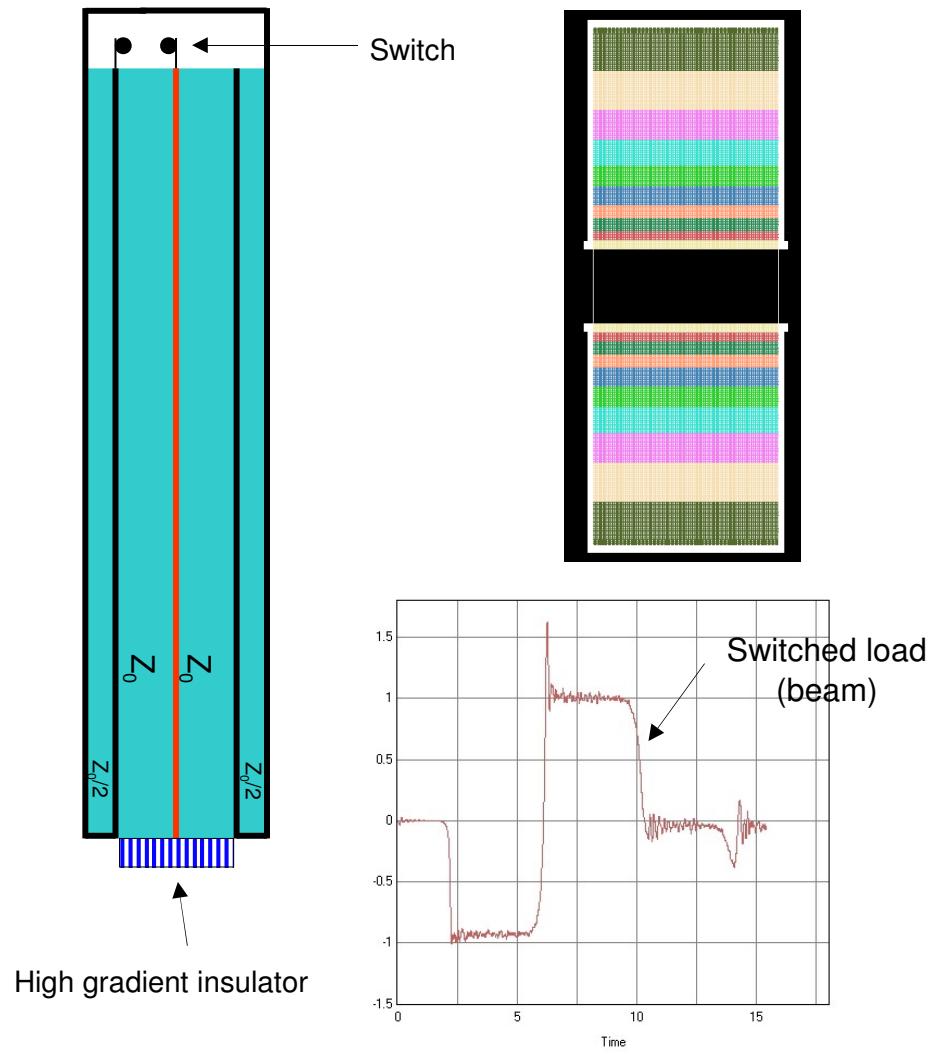


Blumlein Pulse Generator

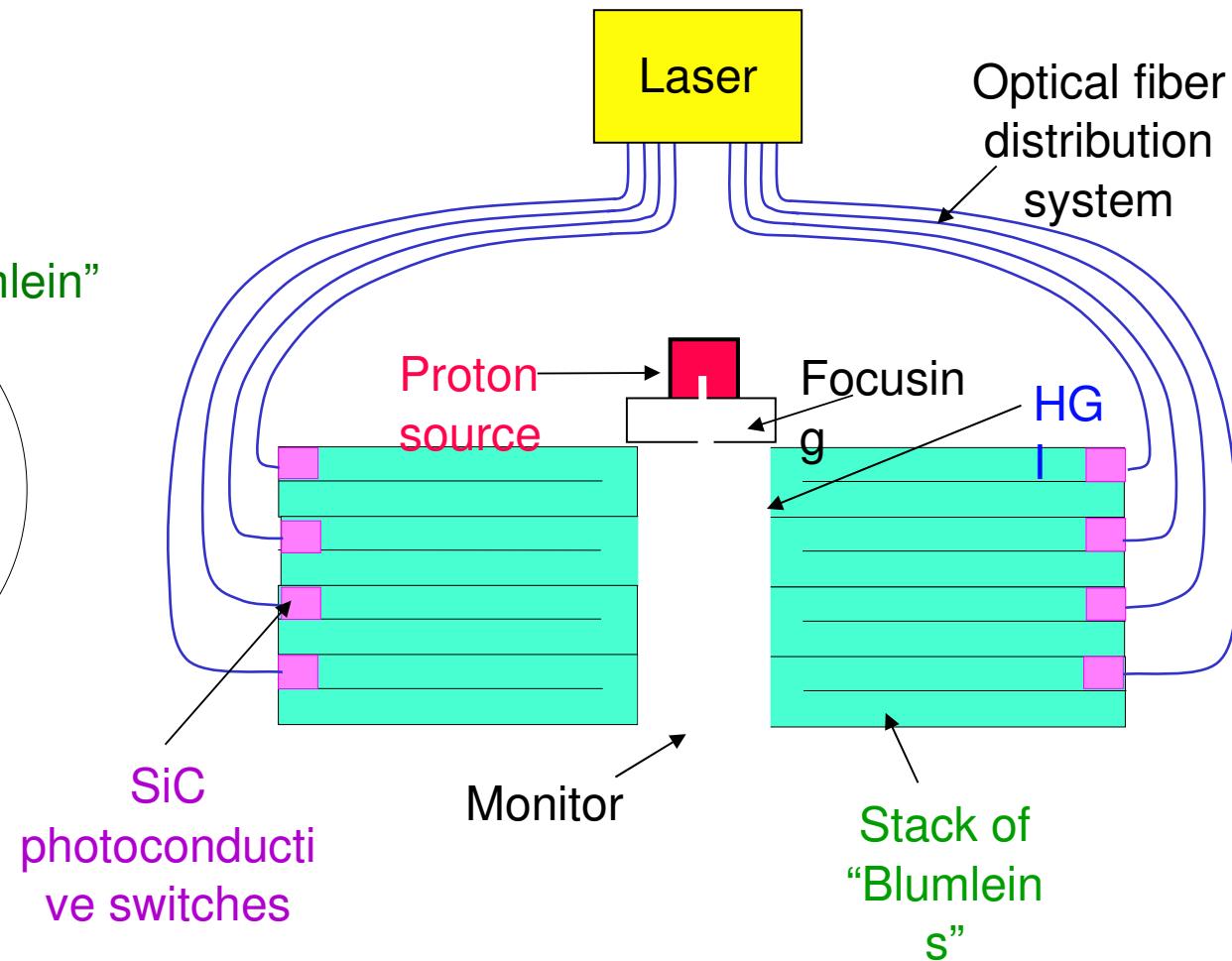
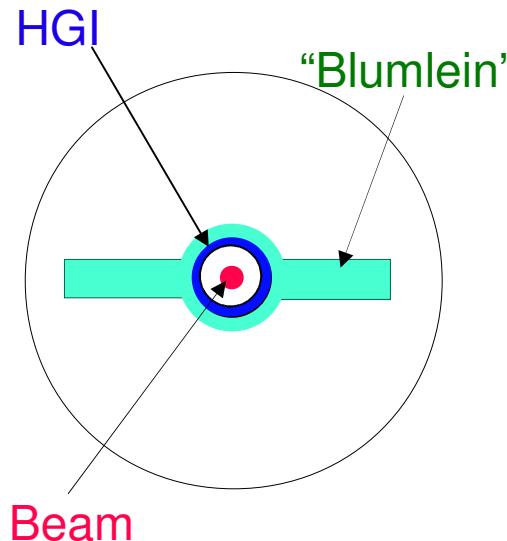


<http://pulsedpower.eu>

Blumlein Pulse Generator



(Yu-Jiuan Chen , LLNL)

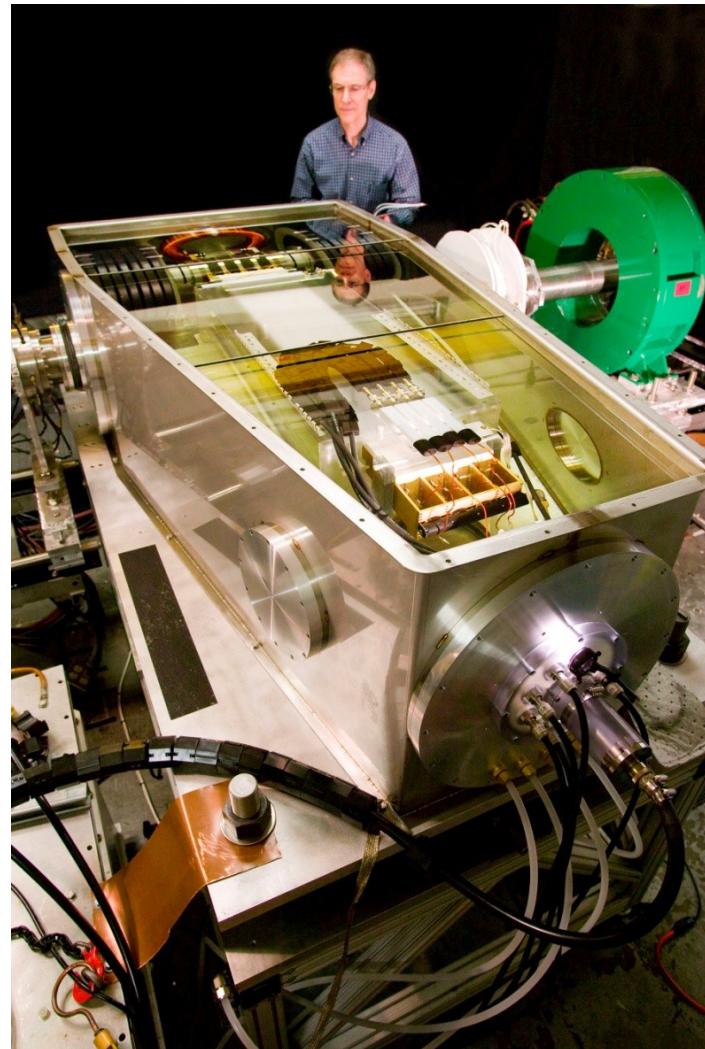


(Yu-Jiuan Chen , LLNL)

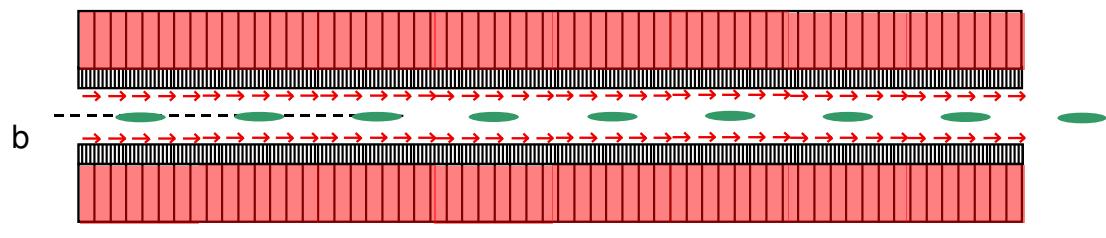
- Flash X-ray radiography

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

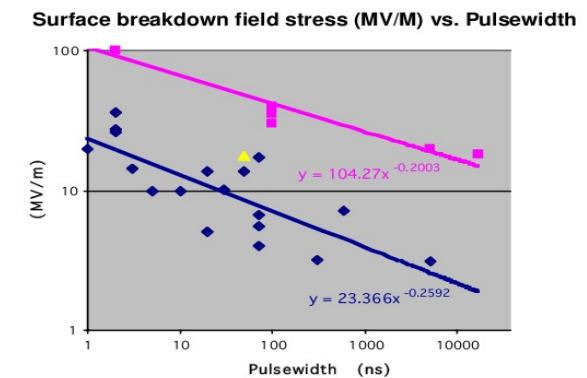
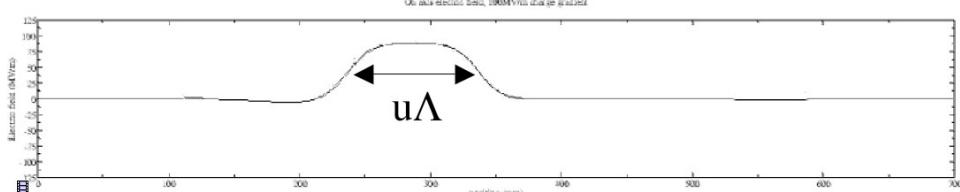
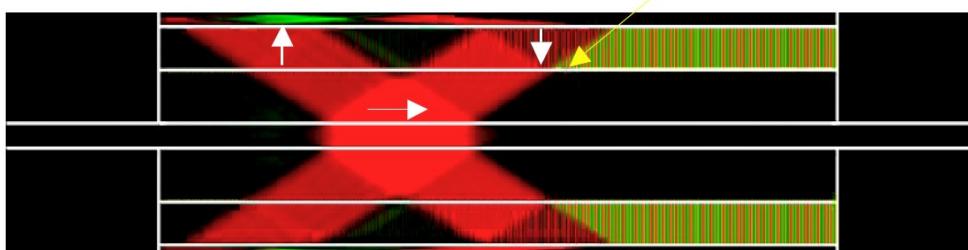
(*Yu-Jiuan Chen , LLNL*)



DWA - Traveling Wave Acceleration

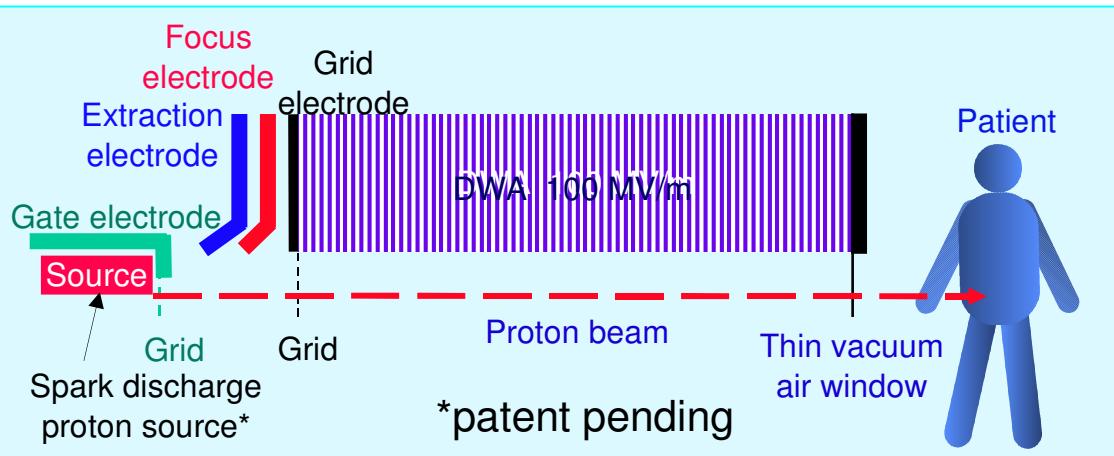


Charged Blumleins



HGI : shorter pulse → higher achievable gradient.

(Yu-Jiuan Chen , LLNL)

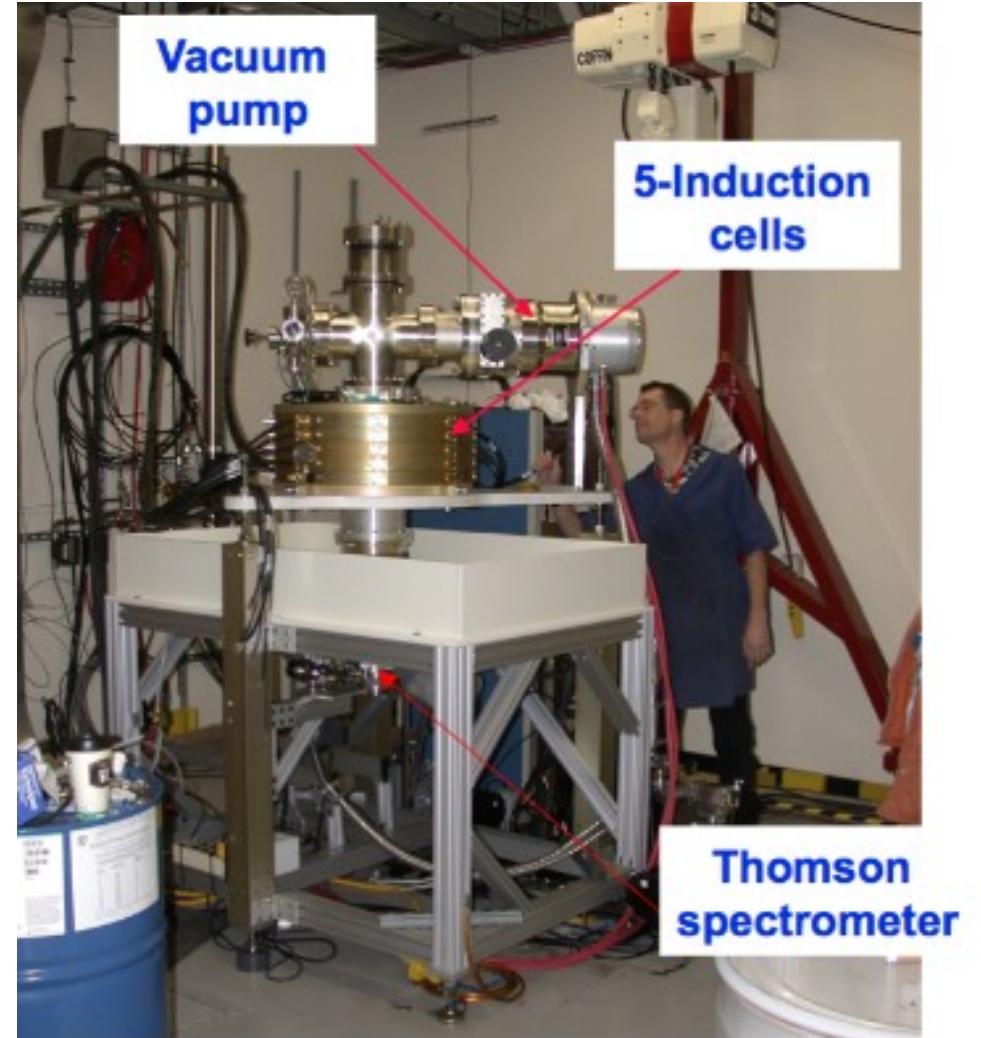


- Focusing before acceleration.
- Space charge - acceleration time is short.

(Yu-Jiuan Chen , LLNL)

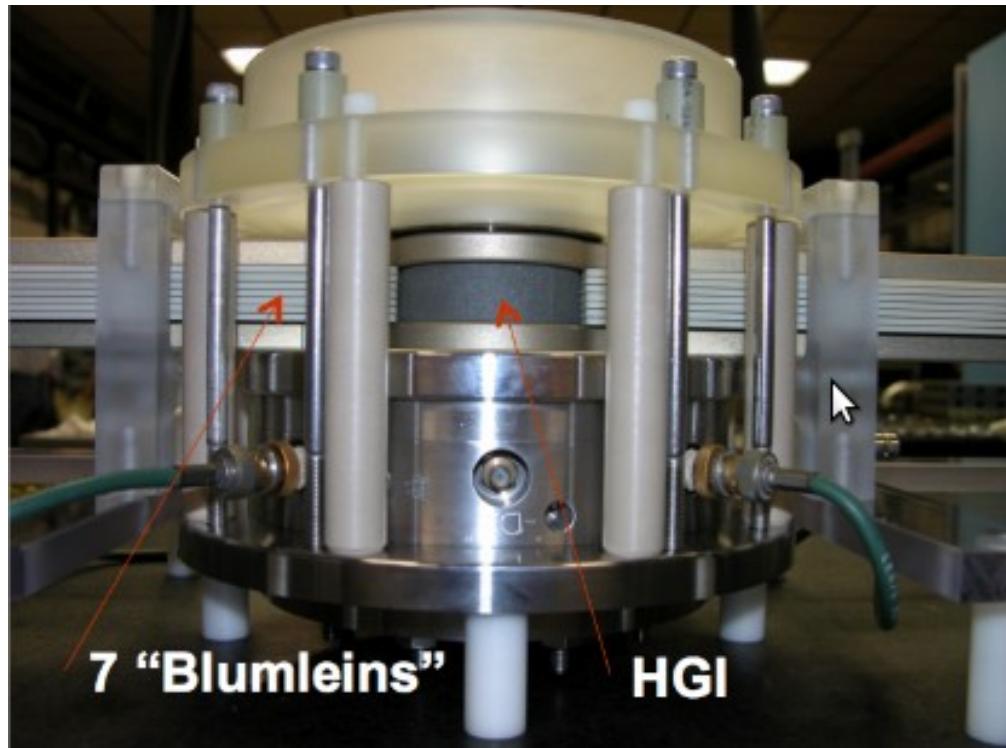
DWA - Status: Proton Injector

- 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.



(Caporaso et al. , LLNL)

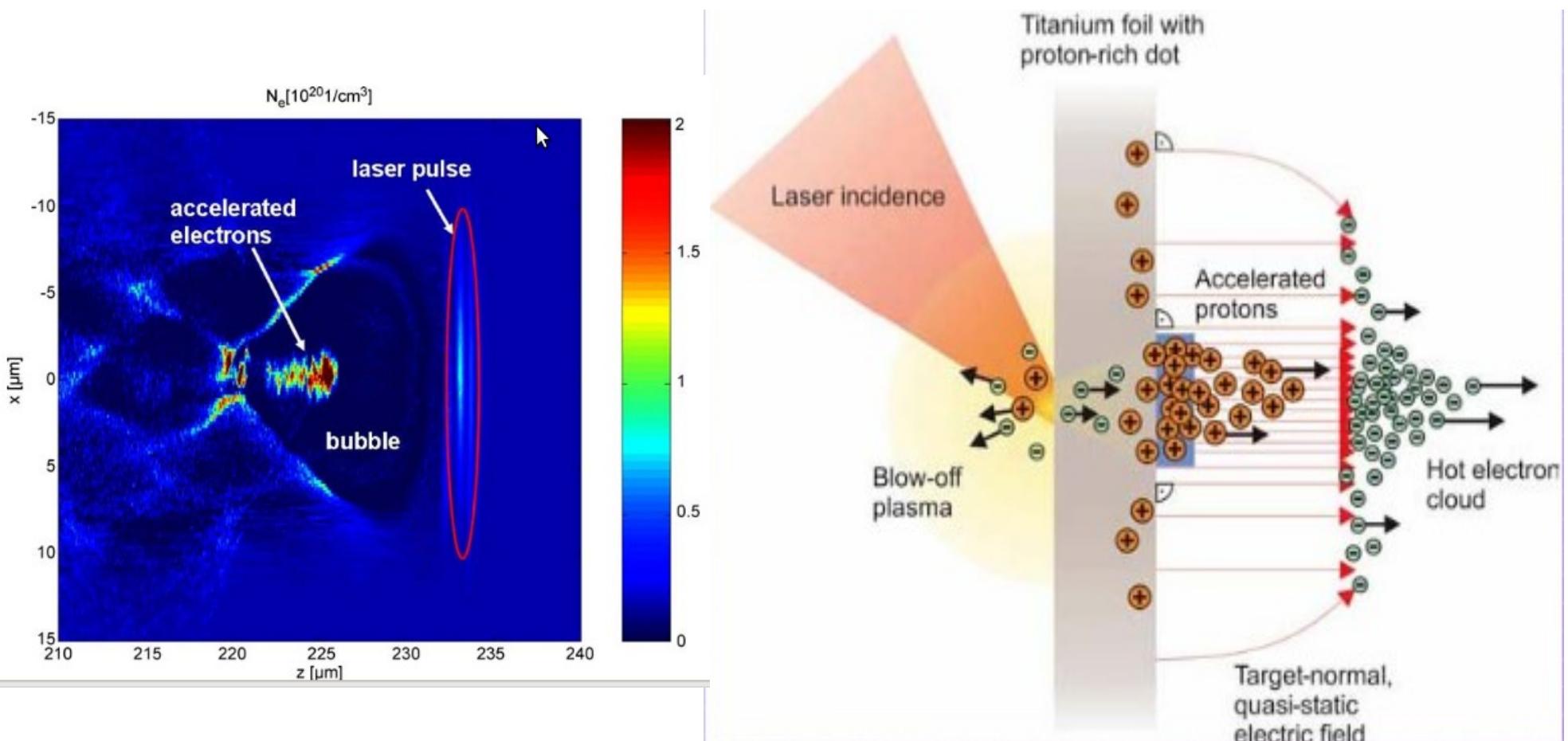
- Have demonstrated accelerated electron beam through 7 Blumleins
- Energy?
- Proton beam through one Blumlein,
- demonstrated acceleration and deceleration of protons.
- Energy?

Wakefield acceleration / Laser acceleration

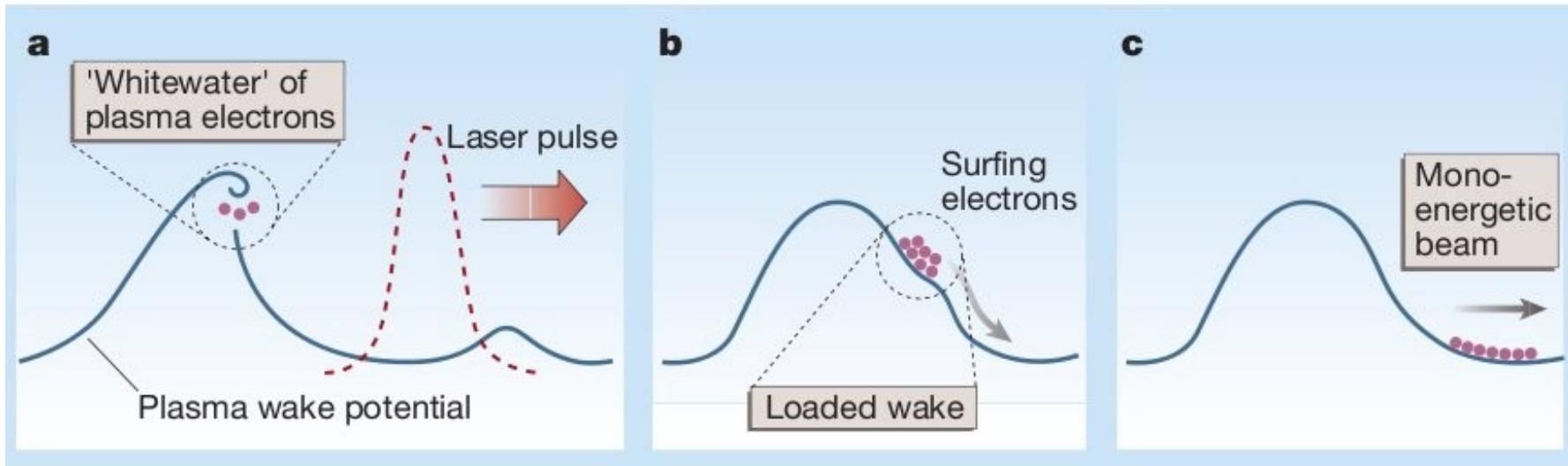


- Idea first conceived **1979** by T. Tajima and J.M. Dawson, UCLA
- Use electric field from intense laser light for electron acceleration
 - But no lasers readily available with required intensity, since amplification optics break down
 - Chirped pulse amplification: expand laser pulse in spectra and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



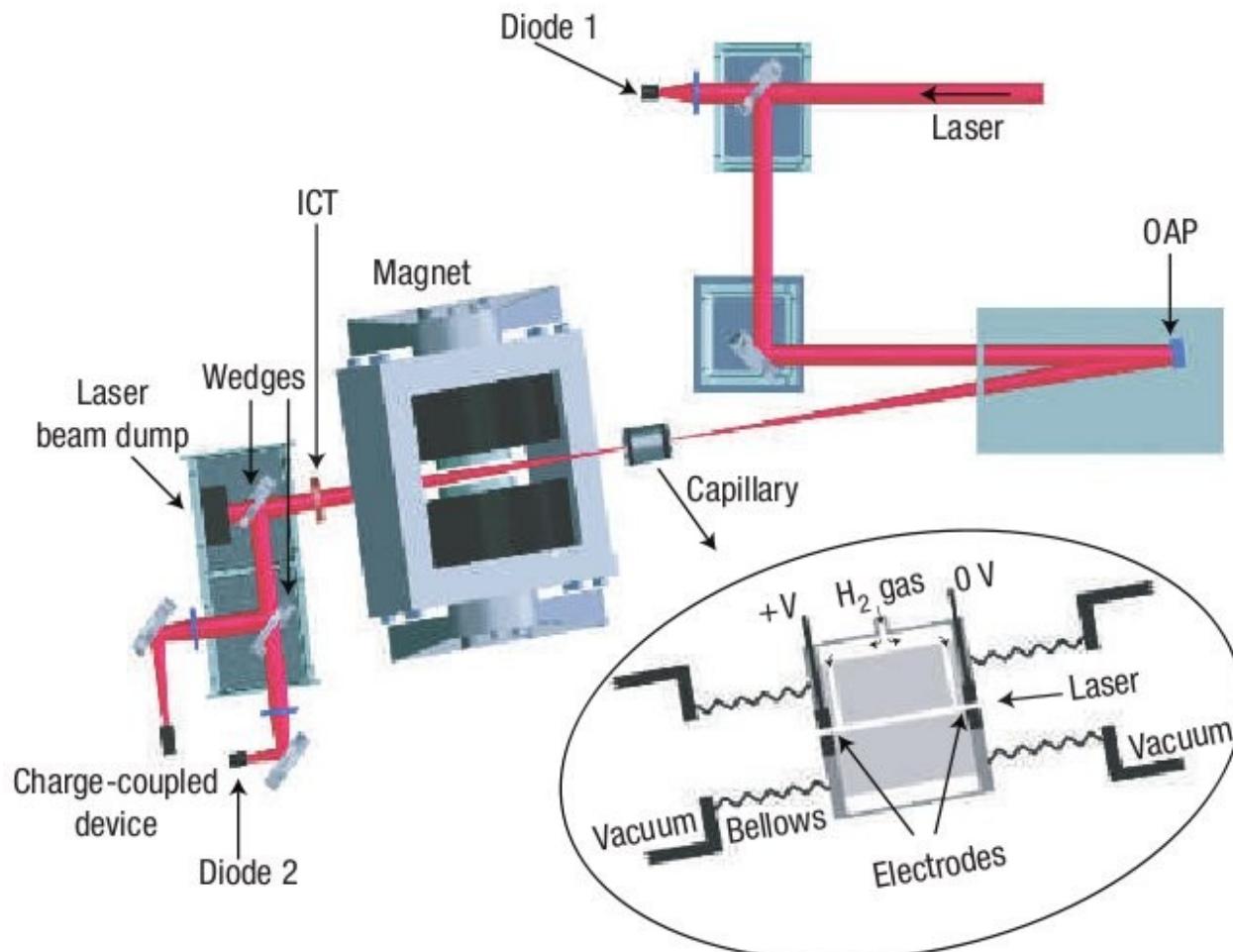
Wakefield acceleration



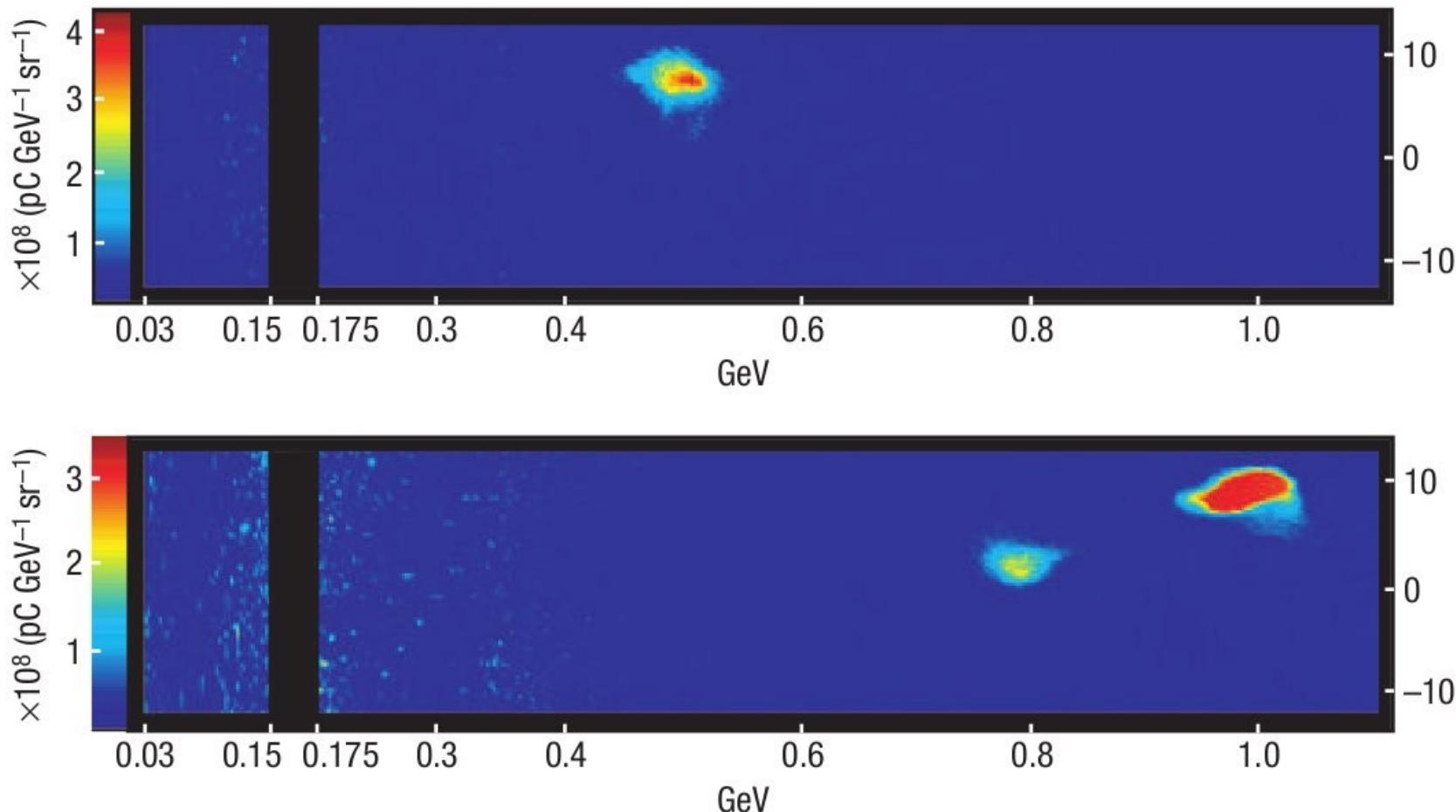
- Gradients achieved: 10 – 100 GeV/m easily
- But $\Delta E / E = 100 \%$
- 2004, breakthrough: using gas jets, % level energy spread.
- Gas must be ionized, then heated
 - Can be done with two laser pulses, but laser heating is inefficient at low densities
 - Leemans et al use a capillary discharge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



Wakefield acceleration

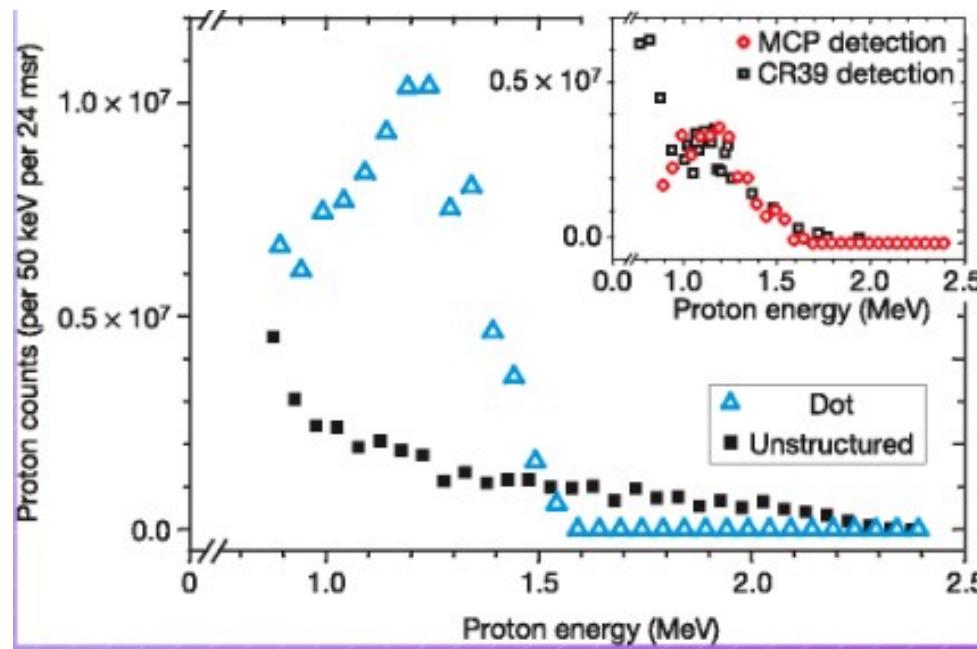


Wakefield acceleration



Protons

- 60 MeV protons
- 100 MeV fluorine 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).

